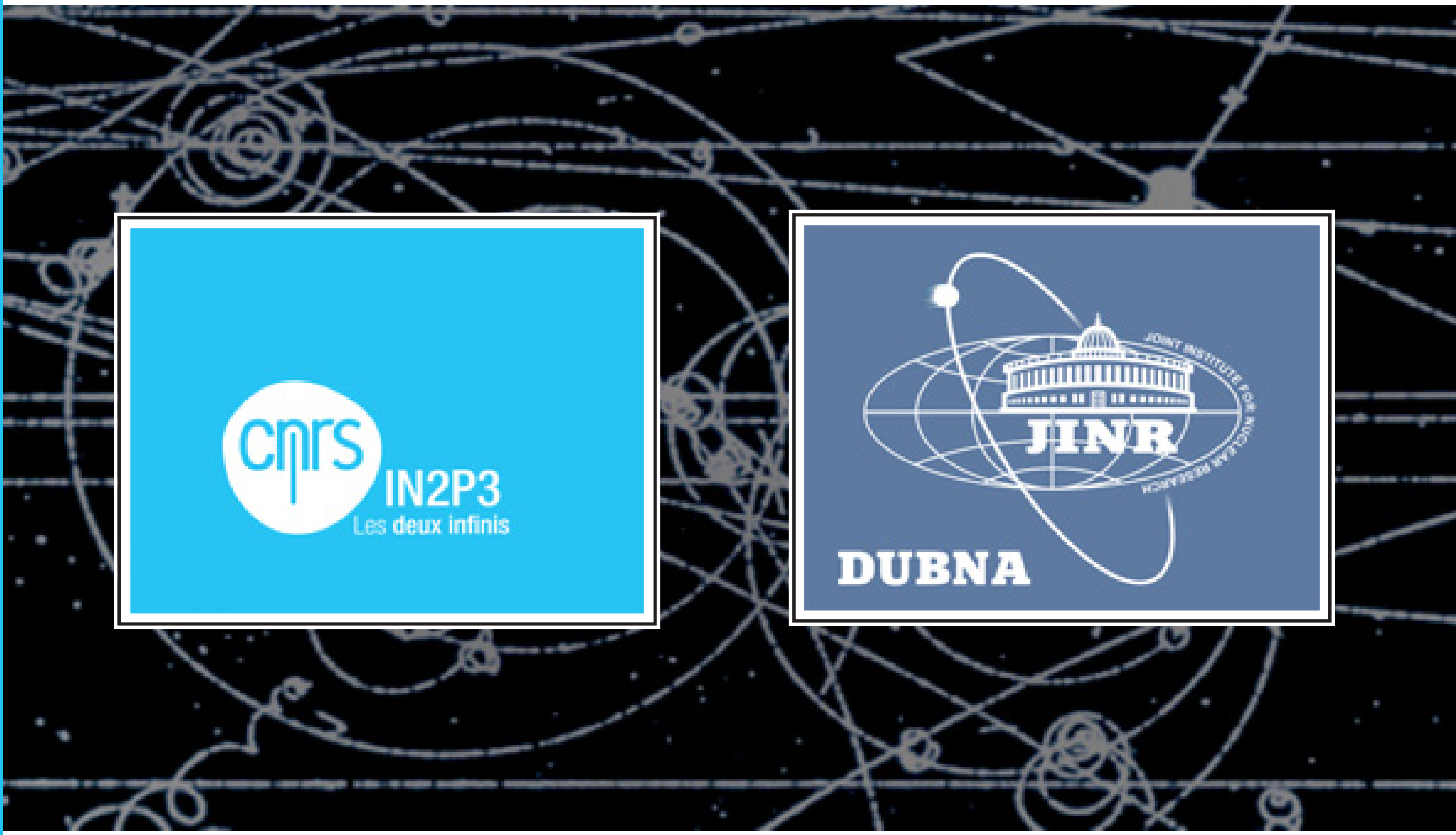
40 YEARS OF COLLABORATION BETWEEN JINR (DUBNA) AND IN2P3 (FRANCE)



40 YEARS OF COLLABORATION BETWEEN JINR (DUBNA) AND IN2P3 (FRANCE)

Anniversary meeting
January 14–15, 2013

Dubna • 2013

F75

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F75 **40 years** of Collaboration between JINR (Dubna) and IN2P3 (France): Anniversary meeting, Jan. 14–15, 2013. — Dubna: JINR, 2013. — 106 p., ill.

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The collection of articles is devoted to the longstanding collaboration between physicists of the Joint Institute for Nuclear Research (JINR) and Institut national de physique nucléaire et de physique des particules (IN2P3) in France. The collaboration was officially established in 1972 when the Protocol of Agreement for Collaboration was signed. Different aspects of collaboration are presented in the articles. The reader can find there not only interesting scientific results obtained due to the mutual efforts, but also memories about establishing and evolution of joint studies as well as personal impressions of collaboration members about common work and human relations. A part of the feature was presented at the Anniversary Meeting which took place in Dubna in January 2013.

40 лет сотрудничества ОИЯИ (Дубна) и IN2P3 (Франция): Юбилейное совещание, 14–15 янв. 2013 г. — Дубна: ОИЯИ, 2013. — 106 с., ил.

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Сборник статей посвящен долголетнему научному сотрудничеству физиков Объединенного института ядерных исследований (ОИЯИ) и Национального института ядерной физики и физики частиц Франции (IN2P3), официальное начало которому было положено соглашением, подписанным в 1972 г. Содержание статей разнопланово. В них представлены не только полученные совместными усилиями интересные научные результаты, но и воспоминания о становлении и развитии сотрудничества, личные впечатления участников коллабораций о совместной работе и жизни. Часть публикуемых материалов была представлена на юбилейном совещании, состоявшемся в Дубне в январе 2013 г.

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Foreword

***Jacques Martino**, IN2P3*

I have been very much impressed by the very dense presentations that spanned our meeting, celebrating the 40th anniversary of our IN2P3–JINR collaboration agreement.

It was a very clear proof of how lively and fruitful our collaboration has been, but more than this it shows us how we have to proceed. This future appears clearly very promising.

Our friendship, the common understanding of how we like to collaborate, the exciting and very relevant scientific topics on which we are working are clearly our best assets for the future.

As I already mentioned, the topics spanning our common interest will continue to cover the already studied topics, like nuclear physics, hadronic physics, neutrinos, dark matter and if possible radiochemistry. But I feel that we could welcome any additional topics.

It has to be underlined that both experimental and theoretical collaborations exist is a very good point, showing that our common work does cover our questions on their many facets.

I have been quite impressed by the quality and the forefront position of our studies. As a matter of personal taste, and probably because I am not a nuclear physicist, I would like to quote the very considerable achievement on the super-heavy elements that exist here, and that would like to promote in France, at GANIL.

Be sure that from the IN2P3 side we will work towards supporting the best we can our common work, and I am sure that this will be the case on the JINR side.

Let me now thank all of you for your very involved participation to this celebration, and especially the organizers both on the French and Russian side for the success of this event. In the name of the French participant, let me warmly thank our Russian colleagues, and you Victor especially, for your warmest hospitality.

Let me also thank you, and express how we appreciated yesterday's concert and the following party: the excellence you have put forward shall be our guide for the continuing collaboration we have in front of us.

Thank you to everybody, and very good luck for the next year, 40 years: let them be as fruitful as what as already been achieved.

Foreword

***Victor A. Matveev**, JINR*

I welcome the participants of this workshop devoted to the 40-year anniversary of the collaboration between JINR and IN2P3. I must say that you witness the real Russian winter, as the workshop starts the first day of the "old new year", in the Julian calendar, that Russians still celebrate.

The workshop that we are opening, together with Prof. J. Martino, is devoted to a remarkable event: 40 years of collaboration is a long period of time and a great history between laboratories of France and JINR. JINR is represented today by scientists from 18 member states and 6 associated states.

The collaboration concerns a wide area of fundamental and applied physics, starting from theoretical physics, elementary particle physics, search for superheavy elements, search for exotic nuclei, neutrino double beta decay, neutrino properties, neutron physics, nanostructure, structure of new materials, computing, development of information technology…Some results of these joint studies are going to be presented during the workshop.

The collaboration with the French physicists started indeed more than 55 years ago. Just after the organization of JINR in 1956, already during 1957, two French physicists Georges Loshak and Jeanne Laberrigue came to work in Dubna, for one year and half a year, respectively. In the same year Dubna was visited by the world famous physicists, Frederic Joliot-Curie, and later on by the "Haut Commissaire à l'Energie Atomique".

Based on this experience, in 1972 the Protocol of Agreement for Collaboration between JINR and IN2P3 was signed and a new history of mutual collaboration started at a new level. Today we discuss the heritage of such a great period of time. Let me express the belief and confidence of our Directorate that such a collaboration has rich perspectives and great future.

A short review of 40 years of collaboration from the IN2P3 point of view

Dominique Guillemaud-Mueller, IN2P3

Résumé

La collaboration internationale entre l'IN2P3 et le JINR commencée il y a plus de 40 ans est la première de ce type de l'histoire de notre institut et l'une des plus intenses jamais entreprise. Elle repose tout au long de ses années non seulement sur des thèmes scientifiques majeurs et variés en physique des infinis mais surtout sur des relations humaines exceptionnelles entre scientifiques qui ne se sont jamais émoussées au fil du temps.

Аннотация

Сотрудничество IN2P3 и ОИЯИ, начавшееся более 40 лет назад, было первым в истории IN2P3 и, кроме того, одним из наиболее глубоких и значительных. Все эти годы оно строилось не только на совместном изучении разнообразных самых актуальных проблем физики бесконечно малого, но и на исключительных человеческих отношениях между учеными, только крепнувших с течением времени.

The first agreement of collaboration between our institutes IN2P3 and JINR was signed in 1972 August 31 by the two directors Jean Teillac and Nikolai Bogoliubov. This was the outcome of different ongoing exchanges between scientists of our countries on various subjects. A starting point was the stay, at IPN Orsay, of Academician Yuri Oganessian in Prof. Lefort's team participating to a first experiment for the synthesis of SHE in the region $Z = 126$, $N = 184$ taking advantage of the availability of an intense Kr beam. Even if this search was not successful, this joint experiment has contributed to the longstanding friendship and fruitful collaboration around the quest for SHE. Much later in 1999 this history repeated at GANIL, when a collaboration around J. Peter, E. Kozulin and A. Eremin took advantage of the relatively intense GANIL's beams of Kr and Ge, combined with the performance of the LISE3 Wien filter. They addressed synthesis and structure studies of super-heavy nuclei between $Z = 105$ and $Z = 114$.

Inversely and benefitting from the intense stable beams provided by the U400 cyclotron as well as the radioactive actinide targets uniquely available at the FLNR, the collaboration GABRIELA-VASSILISSA today very successfully carries out spectroscopic studies of heavy nuclei.

Another important domain started in the 80s: mapping of the driplines and the study of exotic nuclei. Here, the starting point was a discussion of Claude Détraz with Academician Georgy Flerov convincing the latter that using fragmentation of ^{48}Ca at GANIL energies was the right

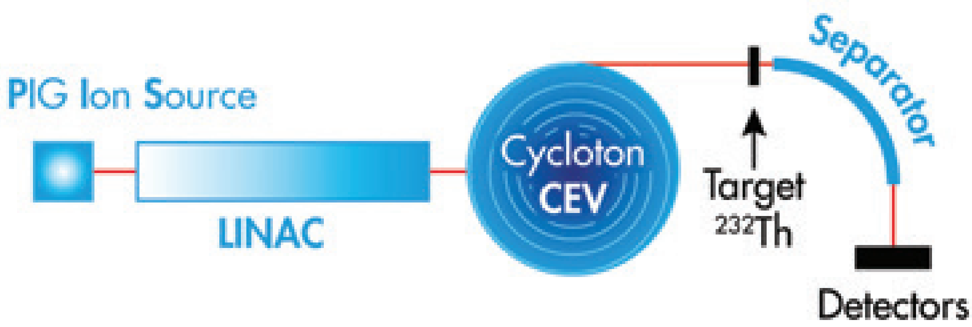


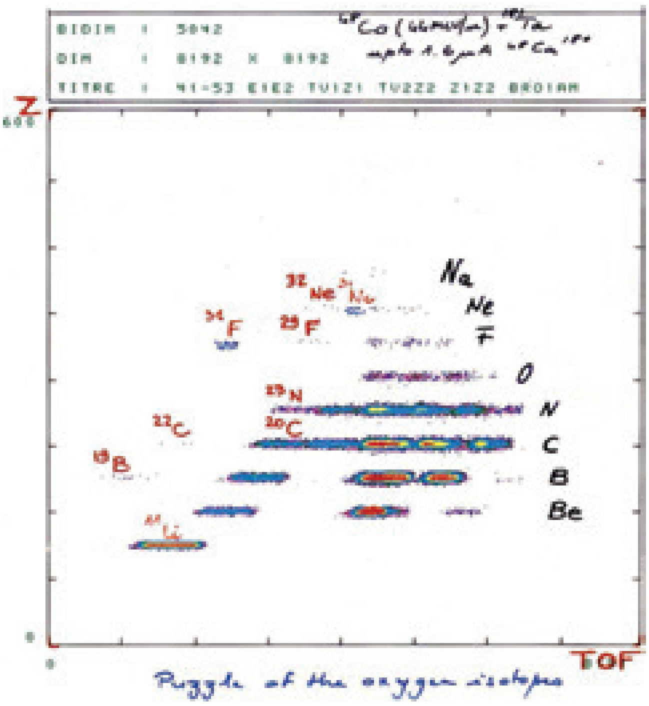
Illustration of a first experiment for the search of SHE in Orsay in 1971 at the CEV cyclotron initiated by Prof. Marc Lefort way to check the position of the limit of stability for light isotopes. The collaboration between the Flerov Laboratory which had the world record intensity ^{48}Ca at Dubna cyclotrons and the experience in heavy ion reactions at GANIL with the LISE spectrometer was born and a wealth of information was obtained through experiments on existence, mass measurements, decay properties at both drip lines.

This collaboration which has grown during the years has allowed a lot of joint experiments from the identification of new isotopes, mass measurements, beta-decay spectroscopy and isomer studies. Personally strongly involved in this collaboration since its beginning I would like to take the opportunity to thank my Russian colleagues Yuri Penionzhkevich and Serguey Lukyanov for their constant help in our joint scientific program and their warm friendship all over these 27 years. This joint adventure gave me the occasion to meet my friend Marek Lewitowicz with whom I continuously share professional and personal relationship.

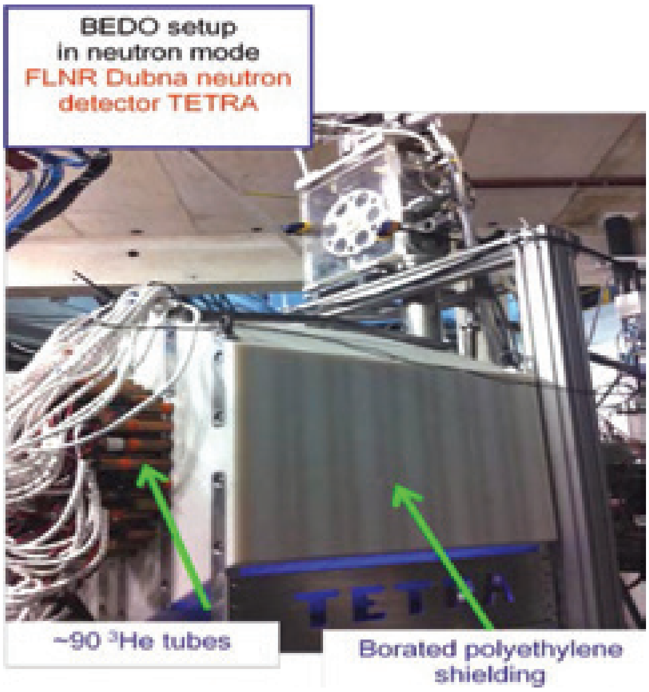
Photography of a discussion between C. Détraz and Yu. E. Penionzhkevich at GANIL

At present, this collaboration has found a further extension around the installation ALTO at Orsay using the photofission process to produce at low energy very neutron-rich isotopes. The installation of the Dubna ^{3}He neutron detector TETRA allows us to measure spectroscopic information like Pn for neutron-rich fission fragments around $N = 50$ and above. We are convinced that this will shed new light in a region of special interest far from stability where the shell structure is different from the one closer to stable nuclei.

Another domain studied in collaboration between IN2P3 and JINR is related to the physics of neutrino and dark matter through the experimental search for the neutrinoless double beta decay ($0\nu2\beta$). This is of major importance because if observed, it will reveal the Majorana nature of the neutrino and may allow an access to the absolute mass scale. The objective of the NEMO-3 experiment was the search for the



Photography of a two dimensional plot for the identification of new isotopes at the neutron drip line



The FLNR neutron detector TETRA installed on the ALTO fission fragment beam line

The NEMO-3 detector in the Modane underground laboratory

$0\nu2\beta$-decay and investigation of the $2\nu2\beta$-decay with 10 kg of different $\beta\beta$-isotopes. The NEMO-3 detector was installed in the Modane underground laboratory in the Frejus tunnel between France and Italy. During more than seven years of data taking, no evidence for $0\nu\beta\beta$ has been observed. From this one deduced a halflife exceeding: $T_{1/2}(0\nu) > 1.0 \times 10^{24}$ years, which corresponds to an upper bound on the Majorana neutrino mass of $\langle m_{\beta\beta} \rangle < 0.31–0.76$ eV.

Following the success of the previous experiment, a next–generation double beta decay experiment, "SuperNEMO", is started. It is based on the successful tracking plus calorimetry technology of the former NEMO-3 experiment. The SuperNEMO experiment aims to discover the neutrinoless double beta decay as well to determine the underlying physics mechanism. Construction of a prototype module has been started. The construction and commissioning of the demonstrator will be completed in 2013 with data taking expected to start in the second half 2013 in the LSM laboratory.

This short overview is obviously not complete and it is important to mention that many other domains of physics or even chemistry have been studied within IN2P3–JINR collaborations.

This is specially the case in theory where many subfields have been looked for. One can stress that the collaboration all over the 40 years has covered many facets from nuclear spectroscopy to high energy physics.

By finishing this modest and partial tour d'horizon of our common work, I would like to wish to the IN2P3–JINR collaboration many new successes in the future, based on our past experience of sharing our respective knowledge but more importantly to our longstanding friendship.

Collaboration before and after 1974 in the Field of Heavy Ion Physics

Yuri Oganessian, Flerov Laboratory of Nuclear Reactions, JINR

Аннотация

Сегодня, когда мы отмечаем сороковую годовщину со дня подписания протокола о сотрудничестве между ОИЯИ и IN2P3, интересно вспомнить, как возникло это сотрудничество, какие события легли в его основание. Я уверен, что эти воспоминания будут интересным путешествием в прошлое, хотя детали сейчас вспоминаются уже с трудом, многих друзей уже нет с нами и многое уже забыто.

Résumé

LAujourd'hui, dans l'année qui célèbre l'anniversaire de la signature du premier accord entre JINR et IN2P3, il semble intéressant de relater comme la collaboration entre nos Instituts est née et quelles sont ses fondations. Mon rapport consiste de fragments, loin d'être complets, et, je crains, pas les plus importants. Il sera très personnel. Je suis convaincu que ca pourra se révéler un voyage intéressant dans le passé, bien qu'il soit difficile, maintenant de rappeler tous les détails.

Today, in the year of celebrating the anniversary of signing the Protocol between JINR and IN2P3, it is interesting to tell how the collaboration between our institutes did arise and what it was that constituted its foundation. I am convinced that this could be an interesting journey to the past, although it is now difficult to recall all the details, many have passed away, others have forgotten a lot.

For my talk, I have chosen one subject and it concerns only one field — the field of heavy ion physics. To shorten history so as to be able to make a 30-minute talk is not an easy job. Because of this my report will consist of fragments, far from complete, and I am afraid, perhaps, not the most important. In addition it will be extremely personal. If any one of my colleagues can continue the theme, I would welcome the opportunity.

In 1958, I — as a 25-year-old researcher from the Joint Institute for Nuclear Research (JINR) that had been established just 2 years earlier — found out that our Institute would soon be visited by Frederic Joliot-Curie, whom we knew only from books and photos.

Although the laboratories of JINR were often visited by eminent scientists, the visit of Prof. Joliot-Curie was an outstanding event. At that time, a new Laboratory of heavy ions physics was being created and Prof. Joliot-Curie was interested in that field also. Obviously, on his return to Paris he drew the attention of his colleagues to our new, still under construction, laboratory. In 1959, well-known scientist M^{me} Faradji, who visited Dubna with a delegation of French physicists, asked me about the details of the construction of new heavy ion accelerator. This was just one year before its operation.

The interest in the production of heavy ion beams gradually increased with time *(I should mention that accelerator physics is still one of the high priority programs in our collaboration)*.

Heavy ion beam extraction from the cyclotron CEVIL

In 1964, together with G.N.Flerov and G.N.Vyalov, I published as Preprint of JINR (in Russian) a short article about the possibilities of extracting the internal ion beam from the cyclotron chamber by means of charge-exchange if the beam of ion with maximal energy pass through thin carbon foil [1]. Unfortunately, our classical U-300 cyclotron had a homogenous (non sector focused) magnetic field and this method could not be applied to it. To my surprise, the paper was translated into French and was widely discussed in Orsay. After that I received an invitation to visit IPN (Orsay) and demonstrate how this method could work at the new cyclotron CEVIL. In the next three months, I and my French colleagues André Gabrespine, Emil Martin, Henri Sergolle, M^{lle} Denise Langlois, M^{me} Nina Poffé and also Claude Bieth, Marie Paule Bourgarel, Eric Baron and Marcel Bish showed that the extraction method worked perfectly (Fig. 1).

The result of our work was published in a paper in the French academic journal Compte Rendue (May 1966), the paper being presented by Prof. Francis Perrin [2].

But, to our great regret, this method was not used in Orsay.

In 1980, the mentioned approach was used to extract the intense ion beam out of our cyclotron U-400 *(by the way method works successfully up till now at all our accelerators)*.

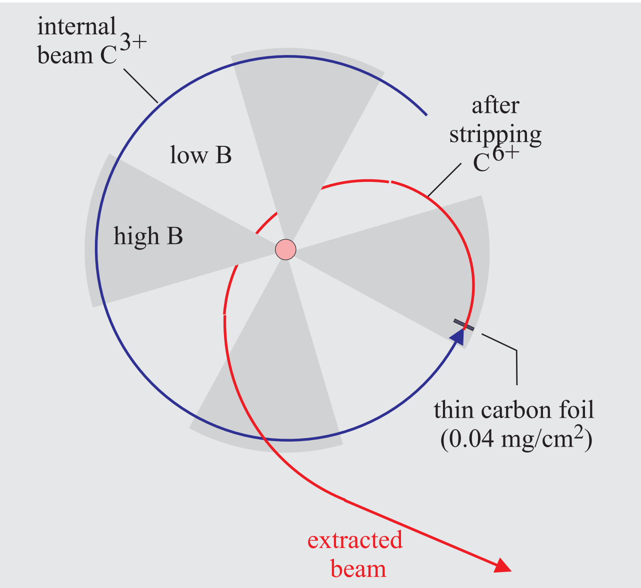


Fig. 1. Schematic view of the beam extraction by ion charge-exchange technique

But then, in 1966, I did not give up. The impressions from Paris, with its unique architecture, museums, theatres, its antiquities and astonishing charm — all that I had read about in the books, but never hoped to see — and, most important, my new friends aroused in me great enthusiasm. (I have no idea what emotions are felt by our French colleagues when they visit Dubna, but definitely the spiritual contacts are a very important and humanly understandable side of our collaboration.)

First experiment devoted to the synthesis of superheavy element in IPN (Orsay)

In 1969 I received again an invitation from Prof. Mark Lefort to visit Orsay for one year in order to participate in the experiments aimed at the synthesis of new elements. It was expected that in the reaction ^{232}Th + ^{82}Kr $\rightarrow$ ^{310}126 + 4n the doubly magic superheavy nucleus, with 126 protons and 184 neutrons, would be synthesized (Fig. 2).

For this purpose, in IPN (Orsay) a linear accelerator was built (now under a hood, as a monument, on the territory of the Institute), which, together with the existing cyclotron CEVIL (the ALICE complex), could accelerate ^{82}Kr ions up to an energy of about 8 MeV/nucleon with a beam intensity up to $5 \cdot 10^9$ pps. In order to produce ^{82}Kr atoms with high ion charge, our version of a plasma ion source was chosen, its design transferred to Orsay, while some removable parts were manufactured in Dubna (Fig.3)

(It is interesting to note that 26 years later, when at Dubna the work was started with the aim to obtain ^{48}Ca beam with high intensity at the U-400 cyclotron, necessary for the synthesis of superheavy elements, we chose the ECR-4 ion source. It was manufactured in GANIL and after some modification made in FLNR still works at our accelerator [3].)

For the separation of the atoms of element 126 from the unwanted reaction products, a

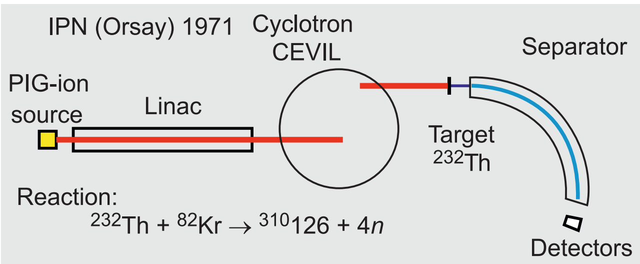
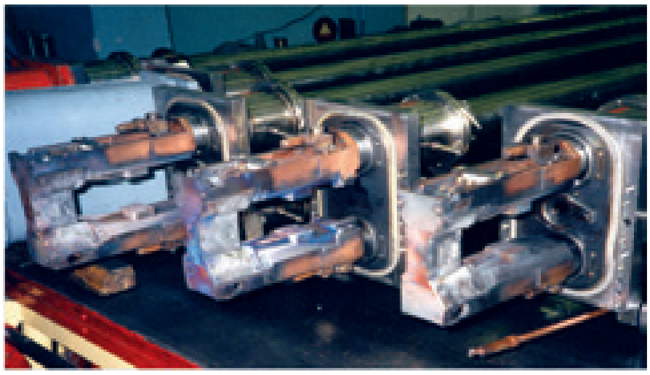


Fig.2. Experimental setup used for the synthesis of element 126



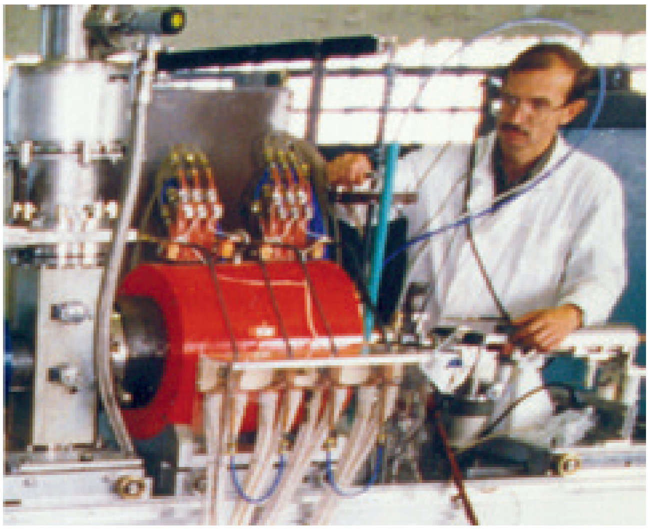


Fig. 3. Ion sources: PIG (FLNR) in Orsay and ECR-4 (GANIL) in FLNR

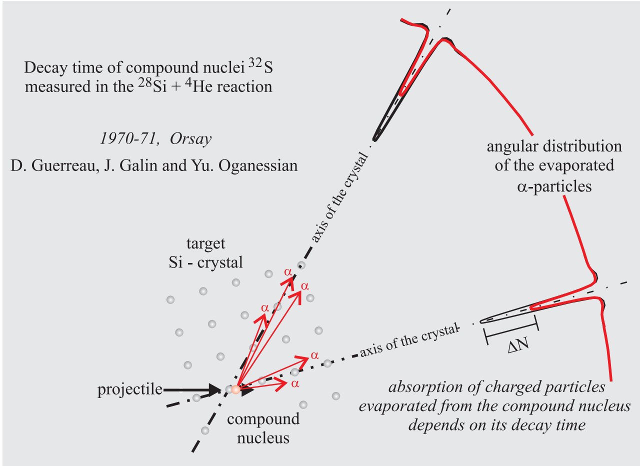


Fig. 4. Blocking effect used for the measurement of the decay time of the excited nucleus $^{32}S^*$ produced in the $^{28}Si + {}^{4}He$ reaction with thin Si crystalline target

magnetic spectrometer was constructed, together with a quite modern for that time registration technique. All was done correctly, with one exception — the participants in the experiment expected a cross section of the order of 0.1–1 mb [4].

Half-life of the compound nucleus measured by means of "blocking effect"

I did not share their optimism and decided to engage myself with another task — to measure by means of so-called "blocking effect" the lifetime of compound nuclei formed in heavy ion induced reactions. Two students were to help me — Joel Galin and Daniel Guerreau, for whom this could be a diploma work.

Actually, this experiment was from the field of solid state physics. The Si target (~ 20 μm thick) has a crystalline structure (Fig. 4).

In the $^{28}Si + {}^{4}He$ reaction the excited compound nucleus ^{32}S is knocked out from the optical axis (or plane) of the crystal. The alpha particles, evaporated from the compound nucleus, do not "feel" the well-ordered structure of the Si atoms, if the process takes place at a few Angstrom units out of the crystal plane (or axis). On the contrary, if the decay of the nucleus takes place very quickly, strong absorption of the α-particles in the direction of the axes or the crystal plane is observed. The extent of absorption is defined by the half-life of the compound nucleus [5].

The chief of the Van de Graaff accelerator — Jean Paul Schapira — generously let us have 30 days of beam time, but without technical assistance, and Daniel and I (Joel was ill) day and night ran our experiment with great enthusiasm. Luckily, Daniel turned out to be a talented young man (this can be seen even now) and we happily finished our investigations *(when I returned to Dubna, in our group we continued these investigations for nuclear fission. My colleague Sarkis Karamian together with other physicists from Moscow University received a USSR State Prize for their work in this field. Many years later, blocking effect again attracted attention of French physicists in studying fission of superheavy compound nuclei [6])*.

Search for heavy and superheavy nuclei as a fragment in reaction $^{238}U + {}^{136}Xe$

At this time in Dubna the two cyclotrons U-300 and U-200 were combined to obtain beams of ^{136}Xe ions. For the synthesis of superheavy nuclei it was decided to change reaction of synthesis (Fig. 5). It was assumed that if uranium was irradiated with a beam of the massive ions, like ^{136}Xe, among the fragments of the composite system with $Z = 146$ and $N = 228$ one could find neutron-rich isotopes ($N \sim 180$) of elements with $Z = 108 \div 114$ [7, 8]. Not wishing to miss this thrilling event, I returned to Dubna in the beginning of 1971 (3 months earlier than previously planned).

The ^{86}Kr and ^{136}Xe ion beams with intensities of up to 10^{11} pps (beam intensities not at all small, especially for the first cyclotron tandem) were accelerated, but we did not manage to observe the elements with $Z \geq 100$. *(Eight years later these experiments were repeated in GSI. The reactions Xe + U and U + U were studied at the more powerful accelerator — the UNILAC [9]. Again the heaviest nuclei produced were the isotopes of element 100. Recently, interest in using reactions like $^{238}U + {}^{238}U$ and even $^{248}Cm + {}^{238}U$ [10, 11] for the synthesis of superheavy elements arose again. By now nuclei with $Z > 100$ could not be produced in such reactions.)*

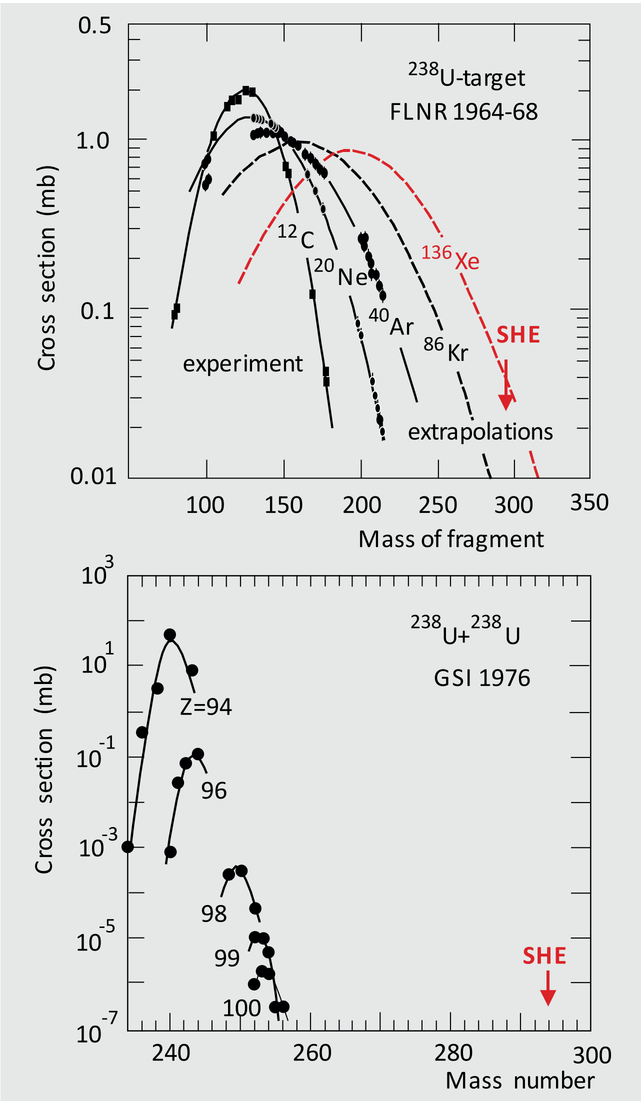


Fig. 5. Mass distribution of correlated fragments in the reactions: $^{238}U + {}^{12}C$, ^{22}Ne, ^{40}Ar (experiment); ^{86}Kr and ^{136}Xe projectiles (extrapolation)

The idea of cold fusion of the massive nuclei and its implementation

When considering the process of asymmetric fission as a way of synthesizing superheavy nuclei we naturally asked ourselves what kind of fission takes place with the superheavy nucleus itself? Say, the nucleus of element 126 with mass 314 that could not be produced in Orsay in the reaction $^{84}Kr + {}^{232}Th$? The question remained open since we have not got the nucleus $^{314}126$. However, at that time the so-called cold fission of ^{235}U was studied and it was clearly demonstrated that asymmetric mass distribution of fission fragments of ^{236}U is determined by the effect of closed shells $Z=50$ and $N=82$. In other words, by preferred yield of the group of heavy fragments in the vicinity of ^{132}Sn and their complementary light partners (Fig. 6).

Thus the question arises: is it not better to irradiate a ^{104}Mo target with ^{132}Sn ions so as to produce a weakly excited ^{236}U nucleus? At a first glance, in particular in the far 1972, the idea seemed to be an absurd one: the two partners, because of the large neutron excess are unstable. Even if one could take instead of ^{104}Mo the stable isotope ^{100}Mo, the other nucleus, ^{132}Sn, has a very short lifetime, only 39 s. *(But later on the beam of ^{132}Sn was produced at Oak-Ridge and now working and projected facilities in Europe, Asia, and in US — all of them plan to obtain a ^{132}Sn ion beam.)*

If ^{132}Sn is not available, we supposed together with A. G. Demin that we could use, as a target, another magic nucleus — viz. ^{208}Pb, and bombard it with less heavy projectile. The ^{40}Ar ion beam seemed to be suitable for this purpose (Fig. 7). The $^{208}Pb + {}^{40}Ar$ leads to the formation of the light isotopes $^{244–246}Fm$, whose properties were very well known. In this way in 1973 the heavy elements — the Fm isotopes — were obtained in a "cold fusion reaction" for the first time [12] (see also experimental studies of the formation of isotopes with $Z = 104–109$ [13]). *(It is well known that for many years GSI, RIKEN, GANIL and LBL have been using this method of synthesis of new elements. Last year, 39 years after the described experiments, the observation of the third event marked the completion of the 9-year long experiment at RIKEN (Japan) on the*

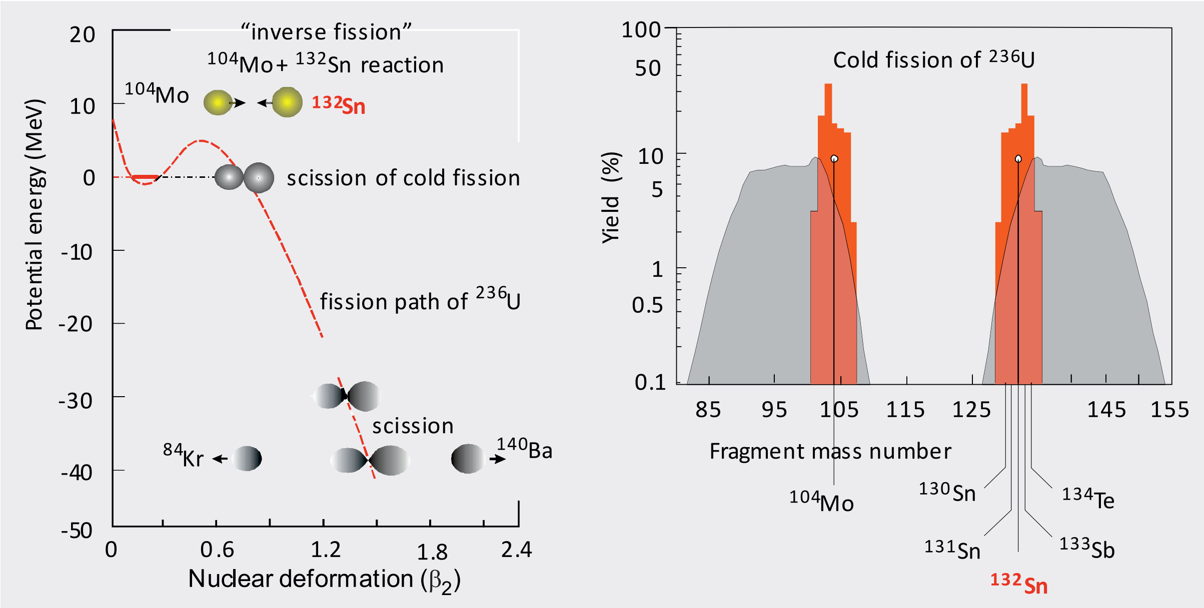


Fig. 6. Right: mass distribution of ^{236}U fission fragments at two total kinetic energies TKE = 176 MeV (grey) — regular fission and TKE = 194.6 MeV (red) — cold fission. Two modes of fission correspond to position of scission points on the left graph [10]

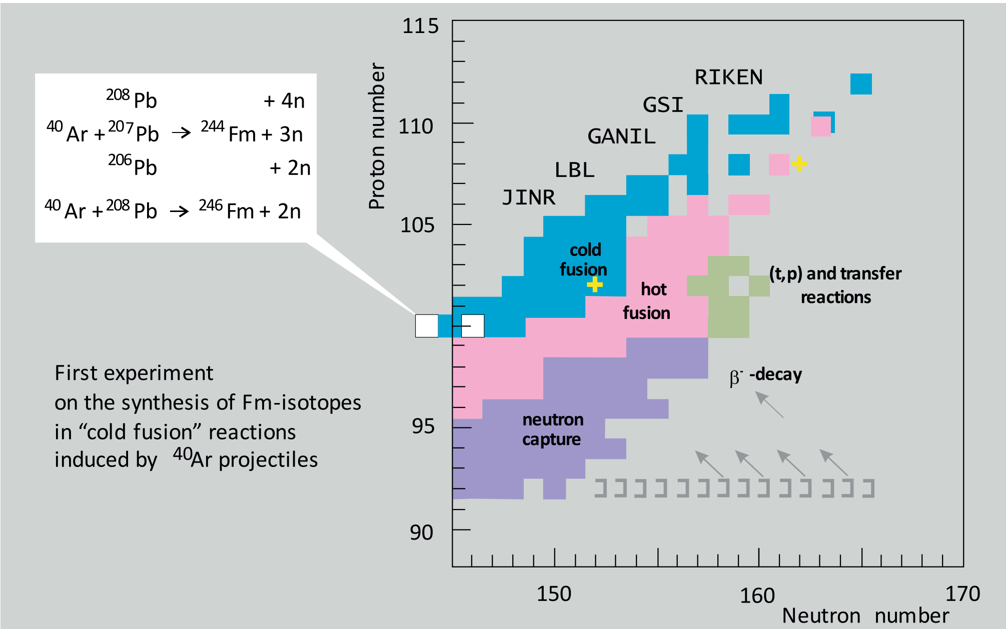


Fig. 7. Cold fusion reactions: Pb + ^{40}Ar (first experiment) — left side and ^{208}Pb, ^{209}Bi + ^{50}Ti, ^{54}Cr, ^{58}Fe, $^{62,64}N$ and ^{70}Zn, in which elements up to Z = 112 were synthesized

synthesis of element 113 in the reaction $^{209}Bi + {}^{70}Zn \rightarrow {}^{278}113 + n$ [14].)

In "cold fusion reactions" the formation of the relatively cold compound nucleus ^{248}Fm is the consequence of the doubly magic target nucleus ^{208}Pb. What is the contribution of the shell effect in the projectile? It was shown in the next experiment $^{208}Pb + {}^{50}Ti$ ($N = 28$) $\rightarrow {}^{256}104 + 2n$ that the yield of element 104 (Rf) was even higher than of Fm. A stronger effect could be expected in the $^{208}Pb + {}^{48}Ca$ ($Z = 20$, $N = 28$) reaction where both partners are doubly magic. For the first time a beam of ^{48}Ca ions was produced at the U-300 cyclotron with a PIG ion source in 1976. The cross section for formation of element 102 in the $^{208}Pb + {}^{48}Ca \rightarrow {}^{254}102 + 2n$ reaction amounted to $3 \cdot 10^6$ pb — an enormous value in the scale of formation of elements of the second hundred [15]. *(Nowadays this reaction is* *used to tune kinematical separators of recoil nuclei and for calibrations of detectors.)*

Heaven-born chemist

In order to find out how the nuclear structure influences the probability of fusion, we started a series of experiments aimed at the study of reactions leading to the formation of the heavy elements with Z = 104–109, using different isotopes of Pb and different projectiles. We were interested in all reaction channels, something that is difficult to achieve, especially at cross sections of about 10^{-36}–10^{-33} cm^2. Most efficient seemed to be the radiochemical separation of the products with the subsequent measurement of rare events of decay using extremely sensitive detectors. All tasks were connected with production of intense ion beam by acceleration of ^{40}Ar, ^{44,48}Ca, $^{48–50}$Ti, $^{52–54}$Cr, ^{55}Mn, $^{56–58}$Fe and ^{76}Ge ions, and with the manufacturing of targets from the stable separated isotopes $^{204–206}$Pb. The detector system were performed by the physicists and engineers of FLNR, while the basic work for the radiochemical separation of the reaction products was done by another group of chemists led by Michel Hussonnois. Michel is a heaven-born chemist. He alone chose the chemical methods, alone carried out the basic operations, analyzed and, if necessary, changed the methods bringing them to their limit of efficiency. Watching him work, not only the physicists (whose snobbism with respect to chemists is a quite wide-spread phenomenon), but also the skeptical chemists were pleased. The paper in Radiochimica Acta *"Experimental studies on the formation and radioactive decay of isotopes with Z = 104–109"* is an enormous effort of many people in the course of many years [16].

M. Hussonnois and O. Constantinescu at the FLNR (by Yu. Tumanov)

Radiochimica Acta 37, 113 (1984)

Experimental studies on the formation and radioactive decay of isotopes with Z=104–109

Yu. Oganessian, M. Hussonnois, A. Demin, Yu. Kharitonov, H. Bruchertseifer, O. Constantinescu, Yu. Korotkin, S. Tretiakova, I. Shirokovsky and I. Estevez

Fission and fission modes of the excited nuclei

At that time, preparations were on for the first joint experiment with the Rene Bernas Laboratory (CSNSM, Orsay) to study nuclear fission on the U-300 beams using the mass-separator for isotopes of elements of the 1st group of Mendeleev's Table. Robert Klapish, together with an international team: C. Thibault, M. De Siant-Simon, L. Lessard, E. Roeckl and W. Reisdorf (both from GSI), L. Remsberg (from MSU) et al. (altogether about 20 people, including children and wives — all wishing to visit the Soviet Union) arrived at Dubna on June 9th, 1974, with a big bottle of champagne (Fig. 8).

On the following day a large truck brought the separator from Orsay. The synchronization at all levels — drivers, workers, engineers and physicists, took a short time, and in 7 days everything was ready to start a 3-months experiment. People say that it never works from the first try, but in our case it did work. This was the first on-line experiment using a mass-separator on a heavy-ion beam.

Its results were published in 12 papers in prestigious journals and proceedings of international conferences (see, for example, [17, 18]). This was the first experiment of the two laboratories, and it attracted a lot of attention. Many funny stories can be related to the visit to Russia of our foreign colleagues in 1974, but we all were young and had a great sense of humor.

(Much later, similar investigations with the use of an on-line mass-separator of reaction products, initially at a proton beam, but later on a heavy ion beam, were carried out at CERN and many other laboratories.)

Deep-inelastic collision. Towards to the neutron drip line

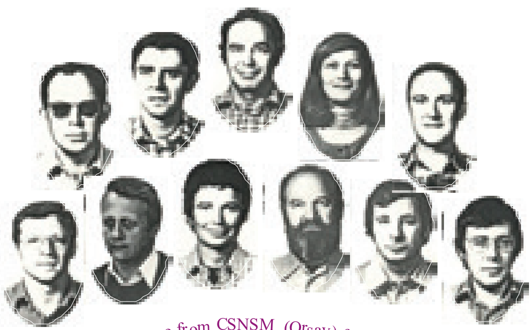
As is seen from the above, the early 70s were quite productive not only for our collaboration but for the heavy-ion physics on the whole. I would like not to miss another important event that is discovery of the new type of interaction of the complex nuclei that later were named Deep Inelastic Collision (DIC). In 1974 in interaction of ^{232}Th and ^{40}Ar V.V.Volkov and colleagues found out that these nuclei stay in contact for 10^{-21}–10^{-20} s that is quite a long time on nuclear scale. As a result, these nuclei exchange a large number of nucleons which process is accompanied by large-scale redistribution of primary energy brought by projectile particle (Fig. 9). In addition to unusual evolution of the system including collective motion of 262 nucleons in the output reaction channel there appear two fragments whose charge and mass strongly differ from ^{232}Th and ^{40}Ar [19].

Among the light fragments are formed the nuclei that have large excess of neutrons; many of these were observed for the first time. Even in very first experiments more than 30 new nuclei were synthesized (see bottom plot in Fig. 9).

Now I shall make a digression.

New heavy ion accelerator facilities

Already in 1974 it became clear that the existing accelerators were quite old — accelerators of new generations were necessary. In Dubna we started the discussion about the possibility to



French team came from CSNSM (Orsay) for joint experiment
Dubna, June 1974

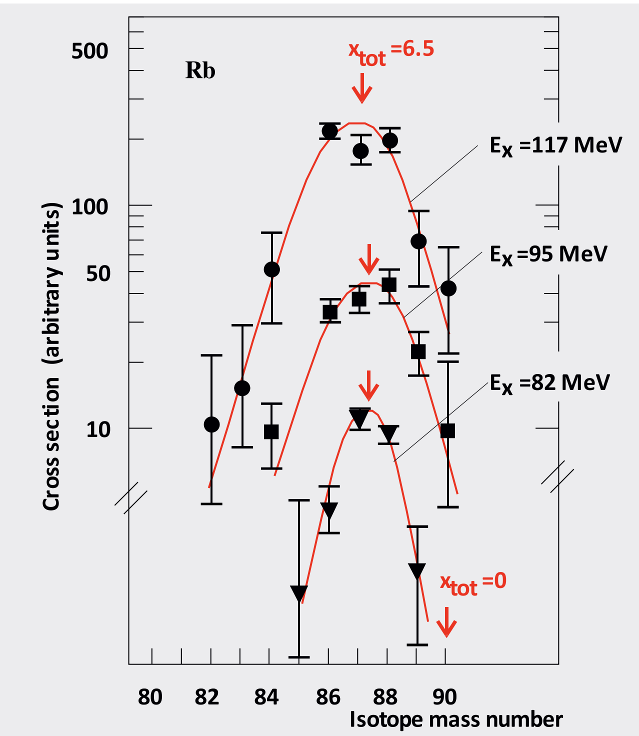


Fig. 8. Mass distribution of Rb isotopes from the symmetric fission in th ^{158}Gd + ^{22}Ne → $^{90\text{-}x1}$Rb + $^{90\text{-}x2}$Rb reaction

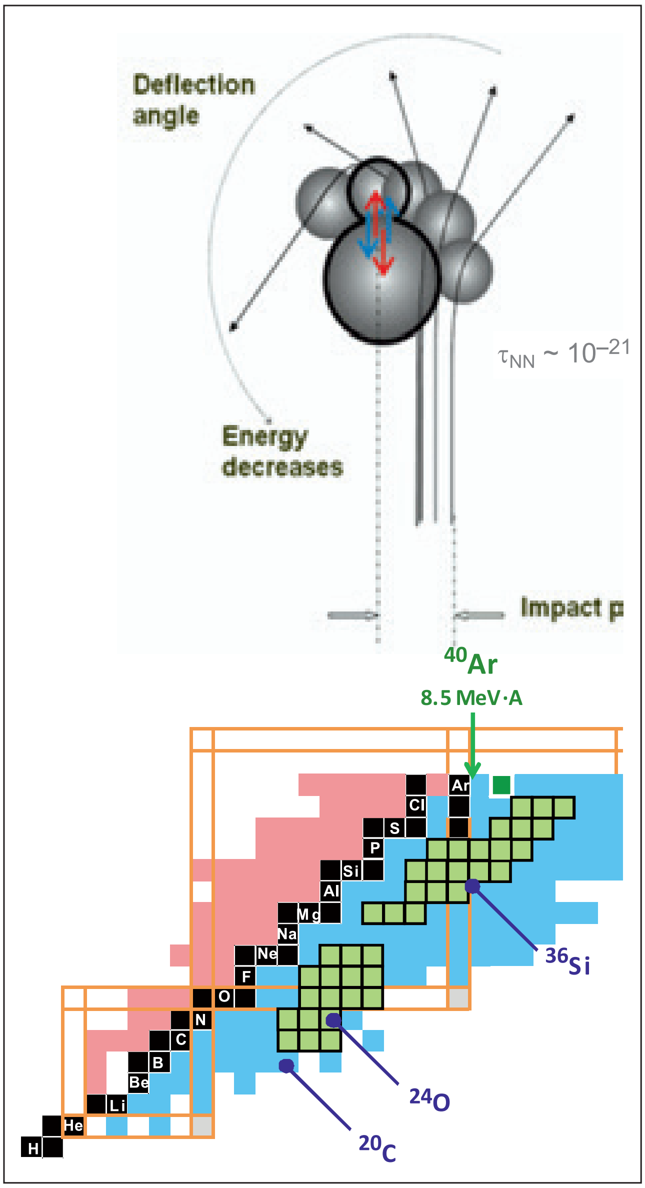


Fig. 9. Upper graph: deep inelastic collisions of the complex nuclei at the various impact parameter. Green squares at the bottom panel — neutron-rich isotopes synthesized in ^{235}Th + ^{40}Ar reaction at the energy 8.5 MeV·A

create a new accelerator in a new building, located 130 m away from the operating cyclotron U-300, in France it was decided to build the new accelerator complex GANIL in Normandy within 250 km away from Paris (Fig. 10).

Nuclei at the limit of stability

When in 1983 we discussed in Dubna the development of heavy ion physics, we, of course, desired that our accelerator could produce beams of high intensity and mass A = 40–80 (in particular ^{48}Ca ions) with an energy up to 10 MeV/nucleon, which could be used for the synthesis of superheavy elements. Claude Detraz pointed out that if the energy of the beam could be increased to several tens MeV/nucleon, then the fragmentation of the ^{48}Ca ions would make it possible to synthesize neutron-rich isotopes with Z = 6–18. *(Both fields, as is well known, have led to very interesting results. In GANIL, about 30 of the heaviest isotopes of B, C, O, F, Ne, Na, Mg, Al, Si, P and S located close to the neutron drip line [20], were synthesized in ^{48}Ca fragmentation reactions (Fig. 11). In FLNR, in fusion reactions of the heavy actinide isotopes with a ^{48}Ca ion beam, the superheavy elements with Z = 112–118 were synthesized [21].)*

Nuclear reactions with rotating nuclei

The high spin $I^{\pi} = 16^{+}$ in ^{178}Hf is of great interest for many reasons. Its lifetime of 31 years and excitation energy of 2.45 MeV are interesting to explore for nuclear physics studies in many experiments if this exotic material could be used as targets [22].

A fruitful collaboration between JINR-Dubna and Orsay (CSNSM and IPN) succeeded to reach this objective in developing irradiation methods

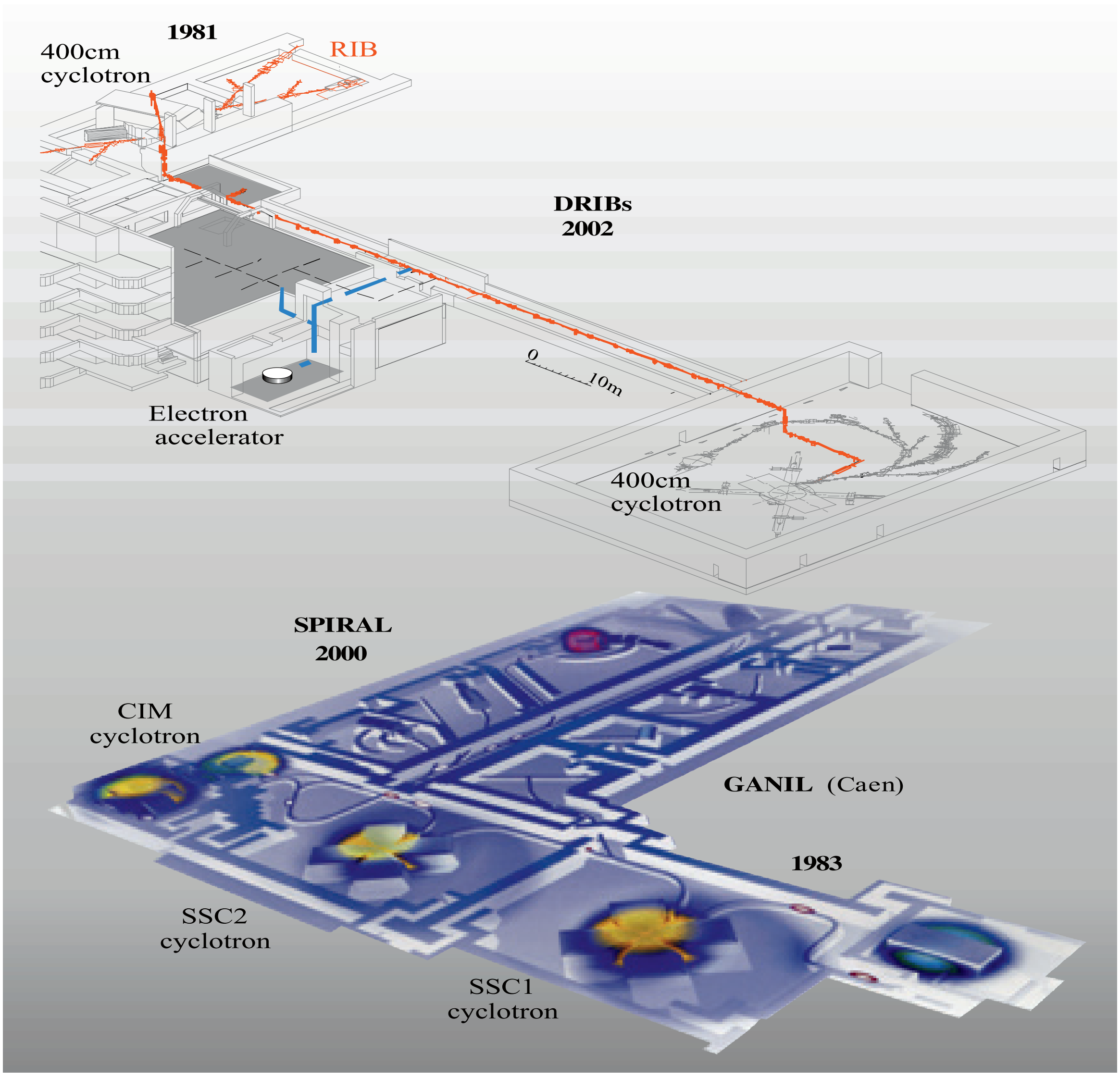


Fig. 10. New heavy ion accelerator facilities in JINR and in GANIL

at high current beams (8000 hours at U200 cyclotron in Dubna), high efficiency of chemical separations as well as mass separations (P.A.R.I.S separator of CSNSM-Orsay). Numerous targets of the isomer ^{178m2}Hf have been prepared in Orsay (IPN and CSNSM) according to the need of each type of experiment [23, 24] (see below).

K isomerism. The simultaneous presence, close to the Fermi surface, of neutrons and protons orbitals with high spins (j) [9/2$^+$*n* [424], 7/2*n* [514], [9/2$^-$*p* [514] is responsible for the presence of isomeric states in these nuclei in particular states with 2 quasi-particles (K^π = 8$^-$) and 4 quasi-particles (K^π = 16$^+$). A vast nuclear physics program was engaged implying about 70 physicists from 15 laboratories from 6 countries.

In order not to overload the reader by describing all the experiments we limit ourselves to pointing their directions and listing the corresponding laboratories.

Intrinsic nuclear properties of the ^{178m2}Hf isomer. The decay properties of the isomer have been studied by electron and γ-ray spectroscopy at CSNSM, IPNO, LMRI. After that ^{178m2}Hf nucleus became an international standard of the conversion electron and γ-transitions with obtained energies and intensities (LMRI, CEA, Saclay).

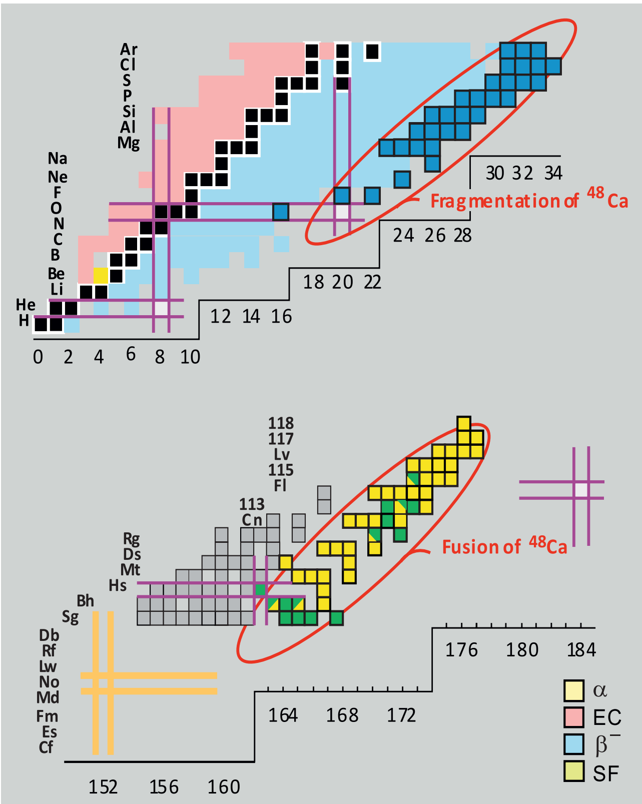


Fig. 11. Upper graph — neutron-rich isotopes with Z =6–18, produced for the first time by the fragmentation of ^{48}Ca at the energy ~ 60 MeV·A. Lower graph — the heaviest nuclei synthesized in fusion reaction ^{226}Ra, ^{238}U, ^{242,244}Pu, ^{243}Am, ^{245,248}Cm, ^{249}Bk and ^{249}Cf + ^{48}Ca

Collective nuclear properties of the ^{178m2}Hf. The measurement of the rotational band on the K^π = 16$^+$ isomer has been performed in two types of experiments:

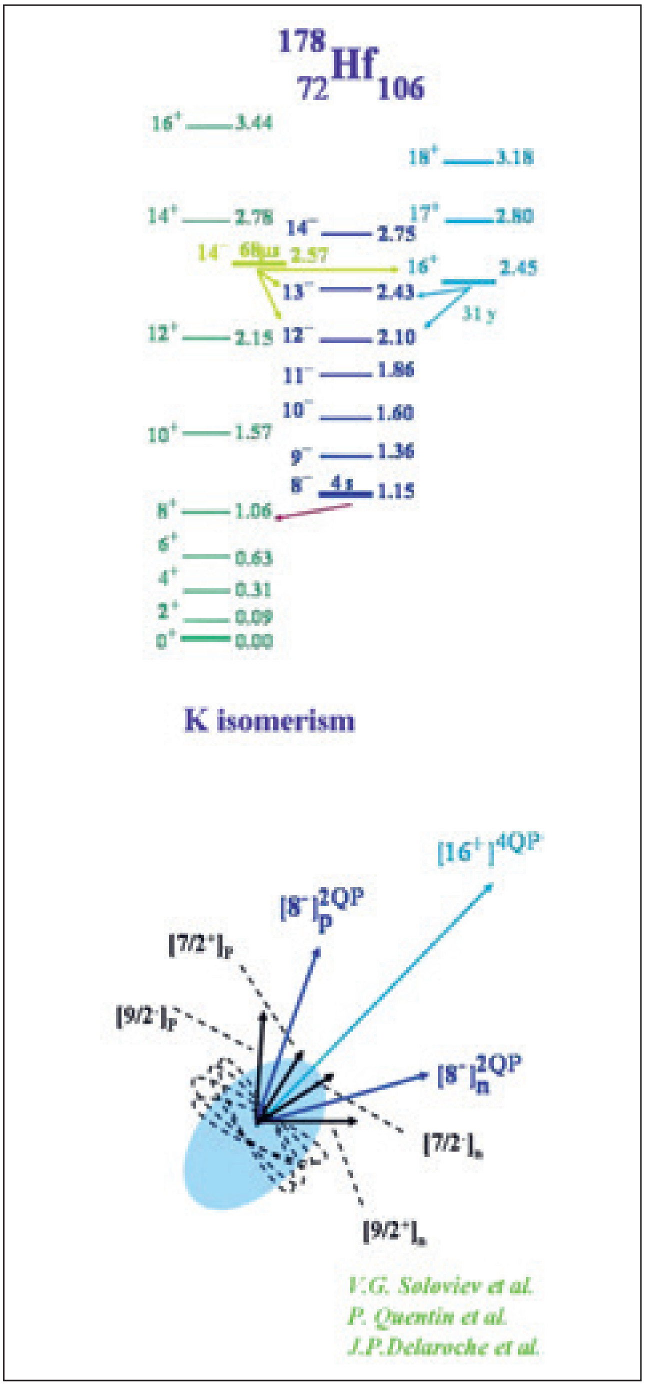


Fig. 12. Rotational levels of ^{178}Hf nucleus based on ground state (0$^+$) and the isomeric states (8$^-$) and (16$^+$). Theoretical interpretation of K isomerism as 2 and 4 quasi-particle states in ^{178}Hf nucleus is shown at the bottom

- an inelastic scattering of protons and deuterons at the Q3D München. TANDEM (MU–TU); Coll. CSNSM, IPN, GSI, Krakow
- the moment of inertia has been obtained through Coulomb excitation with ^{208}Pb at UNILAC GSI. TANDEM, by a collaboration GSI, CSNSM, IPNO, FLNR

The nuclear reactions with charge particles and γ-rays were studied:

- one and two neutron transfer, probing the pair correlations through (t, p) reaction at the split-pole at MP TANDEM-Orsay by a collaboration LMU, TU, GSI, IPNO, CSNSM, Krakow, FLNR
- one neutron transfer (d, p) and (d, t) reactions, through photonuclear reaction
- (γ, n) reaction (giant resonance excitation) at MICROTRON MT25–JINR, the high-spin resonances at GELINA accelerator at Geel, Kurchatov Institute, CSNSM, IPNO, FLNR, CEA/BRUYERES, IR.

Nuclear reactions with neutrons

- neutron capture of the thermal neutrons by ^{179m2}Hf isomer, (n_{th}, γ) reaction at ORPHEE reactor–Saclay and at IBR2 reactor–JINR.
- Search for a neutron resonances (n_{res}, γ) at the FAKEL electron accelerator of Kurchatov Institute at Moscow and at GELINA accelerator at Geel.

The structure of isomeric states in ^{178}Hf

- Predictions and recent calculations done at CSNSM, BLTP, BRUYERES-LE-CHÂTEL.
- Measurement of the magnetic moment through the nuclear orientation at low temperature (DLNP-JINR, Sussex. Univ), the quadrupole moment and the nuclear radius through collinear laser spectroscopy with the P.A.R.I.S separator of CSNSM.

Conclusion

This is only a fragment of the history of our joint work. One can see that the interest in the collaboration in the new field of nuclear physics arose and developed during a period of more than 10 years, long before the agreement between IN2P3 and JINR was signed. The "attractive force" between the two scientific communities of physicists in France and the member-states of JINR can be the theme of another talk, this theme is perhaps connected not only with physics. We should point out that the interest in this collaboration had a big resonance among the scientific community and the brave steps done by the leaders of the two centers in the period of the "cold war" brought forth the signing of the agreement IN2P3–JINR.

It is good luck that this took place.

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АКАДЕМИК
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114
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Flerovium

Fusion, fission and other things

Neil Rowley, *Theoretical Physics Group, IPN Orsay*

Résumé

Un ancien président du PAC se souvient de son temps passé à Dubna.

Аннотация

Воспоминания председателя ПКК по ядерной физике в 2000–2005 гг. о времени, проведенном в Дубне.

In July 1999, the journal *Nature* published the first Dubna paper on the discovery of the superheavy element (SHE) $Z = 114$ (Oganessian Yu. Ts. et al., *Nature* 400 (1999) 242), and it decided to make this discovery a major topic of that issue. I was asked to write the leading "News and Views" article to accompany the Dubna paper, and I entitled it *Charting the Shores of Nuclear Stability*. I did not, however, realise that I would soon be in a privileged position from which to observe the Flerov Laboratory's "chart makers" at close quarters — because later that year I was appointed as a member of the JINR Programme Advisory Committee (PAC) for Nuclear Physics, and would become its chairman from 2000 to 2005.

This was a fascinating period for me; not only did I learn much about many of JINR's exciting scientific projects outside my own field, but I was also encouraged to think beyond the realms of my previous work on heavy-ion fusion reactions. In this earlier work, in the enormous majority of events where one atomic nucleus captures another, the composite system evolves into an equilibrated compound nucleus which then cools by emitting light particles (neutrons, protons, alpha particles) to form long-lived evaporation residues that can be detected recoiling in the direction of the beam. How different this is from the very heavy systems studied in Dubna that can "quasi-fission" (re-separate before forming a compound nucleus) or undergo true fission in strong competition with particle evaporation, leaving few or no detectable residues.

From experiments that measure the total kinetic energy of the two outgoing fragments as a function of one of their masses, much information can be extracted on the reaction dynamics and on the shift from fusion to quasi-fission (thus limiting heavy-element production) as the reaction "charge product" Z_1Z_2 increases. I learned much about these phenomena from close contacts with the many experimental and theoretical members of the Flerov fusion-fission group, for whose valued collaborations I am very grateful.

Quasi-fission increases rapidly with Z_1Z_2, switching on around $Z_1Z_2 = 1200$ and becoming dominant for $Z_1Z_2 > 1600$. At the lower end of this scale I was also involved in experiments proposed by the Flerov group to use calcium beams on samarium targets ($^{40,48}Ca + {}^{144,154}Sm$) at the Laboratori Nazionale in Legnaro (for example, G. N. Knyazheva et al., Phys. Rev. C 75 (2007) 064602). These experiments provided valuable information on the dependence of quasi-fission on the neutron content of the participants and on the target deformation.

At the higher end of the Z_1Z_2 range, Robert Bark and I proposed an experiment at the iThemba Laboratory in South Africa, to measure the capture barrier distribution in a particular superheavy nucleus-nucleus collision. The work studied the $^{86}Kr + {}^{208}Pb$ reaction (S. S. Ntshangase et al., Phys. Lett. B651 (2007) 27) that had been exploited in several laboratories in a search for the super-heavy element $Z = 118$. For this system, quasi-fission is dominant and there are essentially no recoils to measure. Instead, one has to probe the barrier distribution through the quasi-elastic flux scattered back at large angles from the various Coulomb barriers. Although the Flerov group was not actively involved in this work its theme resonated perfectly with the fact that South Africa was to become an associate member of JINR at around that time.

Given the driving interest in SHE at the Flerov Laboratory, it was almost inevitable that it would become host to a project to study the nuclear structure of very heavy elements. This project would of course be GABRIELA, whose installation

Members of a French delegation visiting the Flerov Laboratory in 2003 to discuss the GABRIELA project

was proposed during my time as chairman, and was strongly supported by PAC members. This important IN2P3–JINR project is, of course, discussed in detail elsewhere in this report. Suffice it to say that the spectroscopy of transfermium nuclei can provide valuable information on the single-particle states that play a role in heavier nuclei, and even around the super-heavy "island of stability". Along with several other laboratories that couple together gamma-ray and recoil detection (VASSILISSA in the case of the Flerov Laboratory; K. Hauschild et al., AIP Conf. Proc. 1224 (2010) 269), new inroads into the structure of very heavy nuclei are being made through this research.

So where have the SHE map makers taken us over this period? As noted at the beginning of this contribution, $Z = 114$ was discovered just before my term (1999). Elements $Z = 117$ and 118 came around ten years later (in 2009 and 2011 respectively) but during the time that I was present to witness the developments, $Z = 116$ came in 2000, with $Z = 113$ and 115 following in 2003; indeed there was rarely a PAC meeting where we did not have some exciting new results to discuss — if not in the meeting itself, then over a welcome glass of vodka later in the day.

In the crowning achievement of $Z = 118$, the present "waiting point" of the SHE story, the fruitless krypton-lead system was superceded by the more successful "hot-fusion" calcium-californium reaction ($^{249}Cf(^{48}Ca,3n)^{294}118$). And of course the question of what reactions might allow us to go even higher in Z has now become a major pre-occupation for both experimentalists and theorists.

The original discovery of element 114 in 1999 was met with some scepticism because, unlike the lower-Z elements produced by "cold fusion" (mainly at GSI), its alpha decays did not link it to other known nuclides. However, after years of meticulous, painstaking work in Dubna and at other laboratories, the evidence for $Z = 114$ and 116 became overwhelming and now IUPAC (the International Union of Pure and Applied Chemistry) has accepted these as new elements and named them flerovium and livermorium, respectively, in honour of the laboratories whose efforts have led to these outstanding results.

My term as PAC chairman also left me with many pleasant memories outside the scientific arena: long walks along the banks of the Volga — once (in June 2004) watching the transit of Venus through the glasses provided by CNRS to view the solar eclipse of August 1999 — visits to Moscow to marvel at the Kremlin, St Basil's Cathedral, the Bolshoi Ballet, the Tretyakov Museum, Yuri Gagarin's honoured resting place in the Kremlin wall... I would like to thank all of my Russian colleagues and friends who helped me to enjoy these and many other trips, and who generously offered me their warm hospitality.

Collaboration between the Institute for Nuclear Physics (Orsay) and JINR Flerov Laboratory of Nuclear Reactions (Dubna)

Michel Hussonnois

Résumé

Grâce à l'accord de coopération entre l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) en France et l'Institut Unifié de Recherches Nucléaires (JINR) de Doubna, j'ai effectué, entre 1969 et 2007, environ 45 séjours de plus ou moins longue durée pour un total de 1400 jours, dans le Laboratoire FLEROV des Réactions Nucléaires. Cette collaboration m'a permis de participer activement aux recherches sur la production et la décroissance radioactive de 14 isotopes des éléments de numéros atomiques allant de 104 à 115 et à des études sur les propriétés chimiques des éléments Rutherfordium (Z = 104) et Dubnium (Z = 105). Mon apport dans ce domaine de recherches a été jugé suffisamment important pour qu'un jury d'Académiciens russes me décerne le prix de l'Académicien G.N. FLEROV.

Аннотация

Благодаря соглашению о сотрудничестве между Национальным институтом ядерной физики и физики частиц Франции (французы сокращенно обозначают его IN2P3) и Объединенным институтом ядерных исследований в Дубне я 45 раз приезжал в Дубну, в Лабораторию ядерных реакций, которой руководил Г. Н. Флеров и которая впоследствии была названа его именем, и в общей сложности провел в ОИЯИ 1400 дней. Коллаборация в основном была посвящена изучению образования и распада изотопов элементов Z = 104–115, а также определению некоторых химических свойств резерфордия (Z = 104) и дубния (Z = 105). В 2007 году я стал лауреатом премии им. академика Г. Н. Флерова «за цикл работ, посвященных внедрению радиохимических методов в физику тяжелых ионов».

In May 1969, a few months after the defense of my thesis, I met Professor Academician Georgy Nikolaevich FLEROV, Director of the Laboratory of Nuclear Reactions in Dubna, at the Orsay Nuclear Physics Institute. On the recommendation of my Professor in radiochemistry, Professor Moïse HAISSINSKI, I asked him for the possibility to make a post-doc in his laboratory. He agreed immediately. So I arrived in Dubna in October 1969 to stay for 6 months. But twice, Georgy Nikolaevich (this is how I have always respectfully addressed him) proposed to extend my collaboration which finally ended after 15 months. It was an honour and a great pleasure for me to work in the group supervised by Professor Ivo ZVARA. I want to thank him deeply for his warm welcome. I was lucky to take part in the first experiments on the chemistry of the 105 element produced by irradiation of a ^{243}Am target by a ^{22}Ne ion-beam. We studied the 105 element chloride and that of other various elements (fission products as indium, cadmium, palladium, rhodium, ruthenium, molybdenum, niobium and hafnium) by gaseous thermochromatography. We could conclude that the 105 element chloride is less volatile than the nobium chloride, but not less volatile than that of hafnium. With the same method, we confirmed that the 104 element has the same chemical properties of an eka-hafnium. These results were taken into account by IUPAC to accept the name of "Dubnium" proposed by the Flerov Laboratory for the 105 element.

This first long stay and also a second one of 6 months in 1972 allowed me to acquire a good knowledge of the "life" of this laboratory which became my second Lab. That way I could arrive in this laboratory and the very next day start to work with a high efficiency during 3 or 4 weeks, then return to Orsay to prepare new experiments. This process was repeated 3 or 4 times a year during several years, which means a total

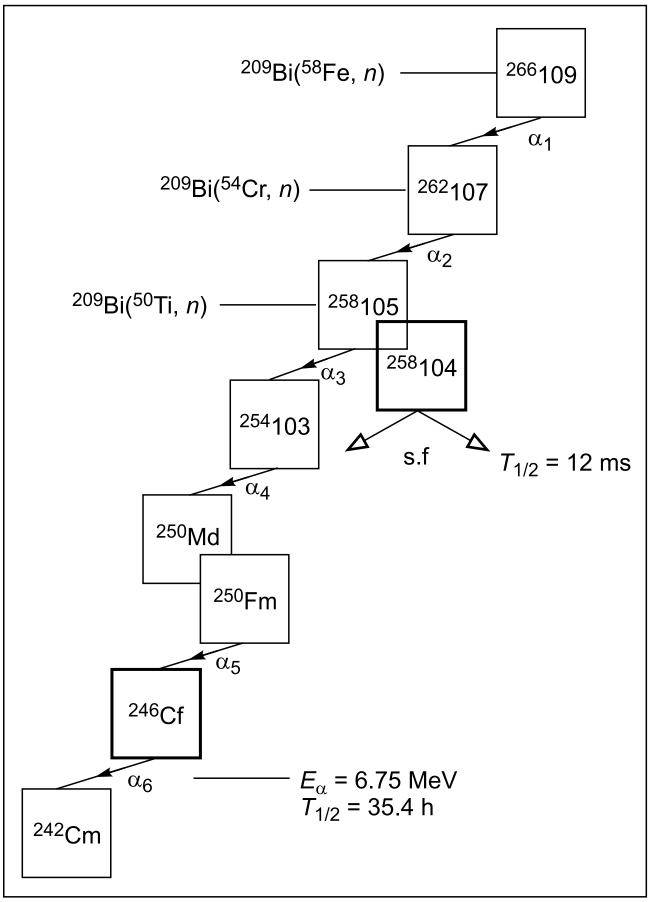


Fig. 1. Sequential α-decay chain for nuclei $^{258}105$, $^{262}107$ and $^{266}109$, leading to ^{246}Cf production. The reactions used for the synthesis of these nuclides are given on the left

of about 45 stays and almost 4 years spent in Dubna. During each of my stays my first and last meetings were fruitful discussions with Georgy Nikolaevich.

This collaboration was greatly and efficiently helped by the Scientific Collaboration agreement existing between IN2P3 and JINR of which we celebrate the 40 years of existence today.

Since 1978, Professor Academician G. N. FLEROV and Professor Academician of Russia and of Armenia, Yuri Tsolakovich OGANESSIAN, head of the research program "Experimental study of the production and radioactive decay of various isotopes of elements with atomic numbers Z from 104 up to 110", proposed to me an intense collaboration as leader of the chemical part of this project. From the decay scheme of the Dubnium isotope with the mass 258, discovered at GSI–Darmstadt, we thought about a new detection method of the production of these isotopes. As seen in Fig. 1, if one of these isotopes decays by alpha emission, it generates a chain of radionuclides and one of them may have a lifetime long enough to be radio-chemically purified and identified without ambiguity by its alpha decay and its lifetime at the end of the irradiation. As seen in Fig. 1, this is the case of ^{246}Cf which ended the filiation generated by the nuclides $^{258}105$, $^{262}107$ and $^{266}109$. With a very small group of chemists, we took up the challenge to detect some alpha particles with accuracy during several days of measurements. The observation of one alpha particle corresponded to a production cross-section of ***0.5 picobarn, world record***. In order to reach such a sensitivity, we developed a delicate and complex chemistry allowing us to isolate the actinide searched for (in the previous example it was the californium fraction) with a purification degree higher than 108. Moreover, in order to detect with precision a few alpha particles with a precise energy during several days of measurements, a 4π geometry alpha spectrometer was developed. Two surface barrier detectors are placed face to face, the radioisotope to be measured being *deposited directly on the gold surface of one of the detectors by electrospraying of an acetic solution*.

This way we contributed to the identification of 13 isotopes of elements with atomic numbers from $Z = 104$ up to 109.

This method was very effective, since 25 years later, it was used to confirm the results obtained by physical methods on the production and the alpha decay of the isotope with the mass 288 of the element $Z = 115$. The physicists found that the alpha decay chain of this isotope ended with the fission of a Dubnium isotope. In a series of new experiments, we separated, purified, and measured the Dubnium fraction at the end of each irradiation of a ^{243}Am target with ^{48}Ca ions. In 8 irradiations of 48 hours, 15 fissions with a mean lifetime of 32 hours attributed to ^{268}Db were detected, whereas the physicists observed only 3 fissions during several months of experimenting, a new proof of the efficiency of chemistry.

During the year 2007, "for a cycle of works devoted to the implementation of radiochemical methods in heavy ion physics" I had the great honour, pleasure and pride to be the laureate of the Academician G. N. FLEROV prize together with two distinguished Russian radiochemists Boris MYASSOEDOV and Serguei DMITRIEV.

My collaboration with FLNR also allowed us to develop experiments in the Laboratory of

With my friend Olimpiu-Marius CONSTANTINESCU and his wife Maria, during the experiment on chemical identification of $^{266}109$ isotope synthesis

Nuclear Physics at Orsay. We wished to study the chemical properties of the two first transactinides, the elements of atomic number $Z = 104$ (Rutherfordium) and 105 (Dubnium). With the support of the IPN and FLNR directorates, we implanted a new method, initiated at Dubna, at the Orsay Tandem accelerator. In concrete terms, the chemical behaviour of the ^{261}Rf nuclide, produced by irradiation of a ^{248}Cm target with an ^{18}O ion beam, could be determined, on line, by the partition between a solution and an anion-exchanger, and compared with the behaviour of its homolog, the hafnium, simultaneously produced in the reaction Gd + ^{18}O. From these experiments we have deduced that the Rutherfordium makes strong anionic complexes in hydrofluoric solutions. Similarly, studies in chloro-hydrofluoric solutions were realized. But primarily, with the intense ^{19}F ion beam delivered by the Tandem accelerator, we were able to produce the ^{262}Db nuclide by irradiation of our ^{248}Cm target and to determine the chemical behavior of the Dubnium in hydrofluoric solutions.

Now some words on the influence of the Flerov Laboratory on my research at the IPN. In 1984, I was working in the FLNR when the discovery of the new type of natural radioactivity by emission of ^{14}C of ^{223}Ra was published. I had the opportunity to discuss it with Professor SANDULESCU, one of the theorists who had predicted this radioactivity. So when I went back to Orsay, I could efficiently contribute to the confirmation of the ^{14}C radioactivity of ^{223}Ra and ^{222}Ra and in the measurement of the one of ^{226}Ra. Finally I took an important part in the "First evidence of a fine structure in the ^{14}C radioactivity", similar to the one of alpha emission and its qualitative interpretation. I presented all these results at the "International School Seminar on Heavy ion Physics" in Dubna in October 1989 for the first time. Being obviously completely involved in my subject, I did not notice it myself, but one friend told me that Georgy Nikolaevich stood up to applaud this discovery. This anecdote summarizes my very good relations with Georgy Nikolaevich.

To extend the search of these new types of radioactivity, I used a method mastered at the Flerov Laboratory by Svetlana TRETYAKOVA. If the ^{22}Ne emission by ^{230}U was not observed, the registration of ^{28}Mg cluster emitted by a very active ^{236}Pu source was a new example of the good collaboration between our two laboratories.

Some people must be associated to the success of this collaboration. An affectionate thought for my wife, Monique, who bravely supported all my stays at Dubna. A sad thought for my assistant at Orsay, Lucette BRILLARD. Many of my works would have been impossible without her help. I wish to celebrate the memory of my friend, Olimpiu-Marius CONSTANTINESCU, who contributed to all these researches with a constant optimism and a great generosity. All my gratitude and thankfulness to my friend, Yuri Tsolakovich, a physicist who has always believed in the power of chemistry to help his research and who associated me to some very interesting and marvellous experiments.

Spectroscopy of transfermium nuclei using the GABRIELA set up at the focal plane of the VASSILISSA recoil separator

O. Dorvaux

Araceli Lopez-Martens and ***Olivier Dorvaux***
for the ***GABRIELA*** *collaboration*

Résumé

Les études spectroscopiques des éléments lourds ont commencé dans le monde depuis une dizaine d'années et font l'objet d'une forte compétition. En 2003, nous avons organisé une collaboration franco-russe afin de réaliser des expériences originales auprès du séparateur VASSILISSA, installé au cyclotron U400 du FLNR au JINR, Dubna. Ce qui rend notre approche unique par rapport à celle de nos principaux concurrents est la possibilité d'utiliser des réactions de fusion chaude sur des cibles d'actinides radioactifs. Un ensemble nouveau de noyaux très lourds devient alors accessible à l'observation. Cette contribution raconte l'histoire de la collaboration en faisant un bilan des travaux effectués et en présentant les perspectives d'avenir.

Аннотация

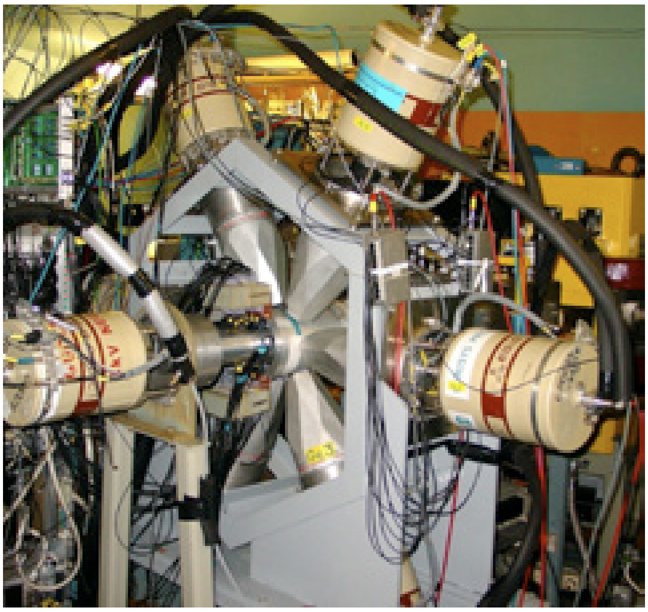
В последнее десятилетие исследования по спектроскопии тяжелых элементов были начаты во многих странах мира и стали предметом острой конкуренции. В 2003 году была организована франко-российская коллаборация, имевшая целью проведение уникальных экспериментов с использованием сепаратора ВАСИЛИСА, установленного на циклотроне У400 Лаборатории ядерных реакций им. Г.Н. Флерова (ОИЯИ, Дубна). Возможность использования реакций “горячего” слияния с радиоактивными актинидными мишенями сделала наш подход оригинальным по сравнению с основными конкурентами. Благодаря этому методу новая область тяжелых ядер стала доступной для изучения. Эта заметка рассказывает об истории коллаборации, полученных ею результатах и планах на будущее.

The heaviest elements provide a unique laboratory to study nuclear structure and nuclear dynamics under the influence of large Coulomb forces and large mass.

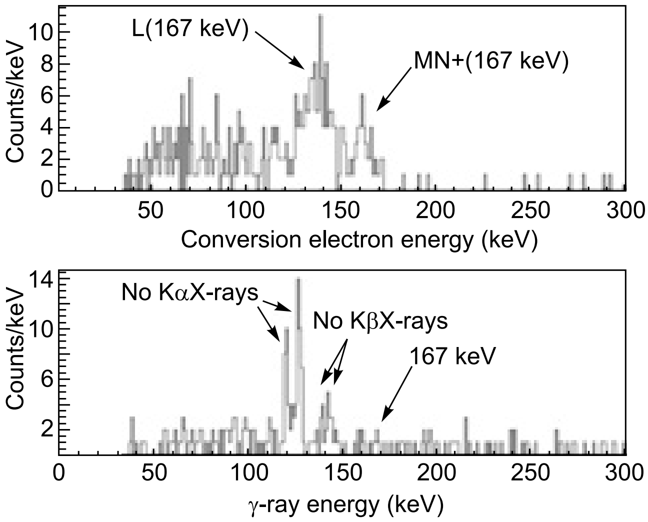
To benefit from the intense stable beams provided by the U400 cyclotron and the radioactive actinide targets uniquely available at the FLNR, an IN2P3–JINR (CSNSM–IPHC–FLNR) collaboration launched a project of electron and gamma-ray spectroscopic studies of heavy nuclei at the FLNR in 2003.

A compact and efficient detector array was then jointly designed to be able to identify the fusion-evaporation residues at the focal plane of the recoil separator VASSILISSA and detect their subsequent radioactive decays involving the emission of alpha and beta particles, fission fragments, gamma and X rays and internal conversion electrons (ICEs).

In the early spring of 2004, the name **GABRIELA** (**G**amma **A**lpha **B**eta **R**ecoil **I**nvesti-



Photography of the Compton-Suppressed Germanium-detector array of GABRIELA (the Germanium detectors and BGO anti-Compton shields come from the French–UK Loan Pool)



Top: Spectrum of ICEs emitted by the 31 ms isomer of ^{253}No. Bottom: Corresponding gamma-ray spectrum

gations with the **EL**ectromagnetic **A**nalyser) was imagined by a Russian collaborator in a car 'en route' from Orsay to Strasbourg and by the summer of 2004, GABRIELA had been assembled, commissioned and the detector array fully characterized [1].

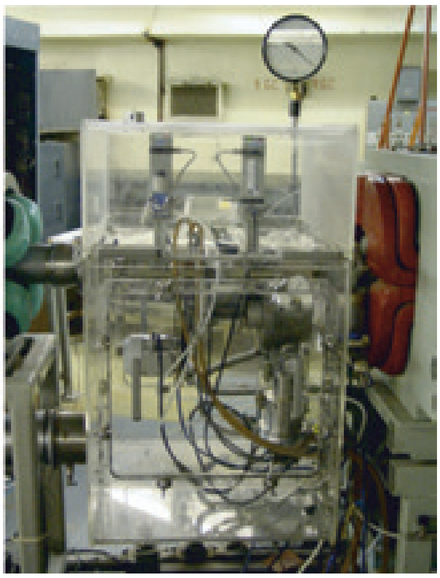
In the fall of 2004, the first very heavy nuclei were studied with GABRIELA using ^{48}Ca-induced fusion-evaporation reactions on ^{208}Pb and ^{209}Bi targets. A new excited state was observed in ^{249}Fm and internal conversion coefficients were extracted for all the observed transitions [2]. A long-lived isomer in ^{255}Lr was observed for the first time via delayed gamma and ICE spectroscopy [3]. In ^{253}No, the excitation energy, spin and parity of the low-lying 31 ms isomer was firmly established through combined gamma and ICE spectroscopy and the presence of a high-K isomer could also be inferred [4].

These results put FLNR on the world map of facilities where heavy-element spectroscopy is carried out [5] and the end of the first physics campaign using VASSILISSA with GABRIELA was celebrated with a memorable party in the Dubnium cafeteria of the FLNR.

In 2005, a radioactive ^{210}Pb target was used. The aim was to investigate the magnitude of the fusion-evaporation cross section induced by such a neutron-rich Pb isotope, to produce ^{257}No via the 5-neutron evaporation channel and to study its alpha decay to ^{253}Fm. All the radioprotection tests were carried out and the special target containment holder installed at the target position of VASSILISSA. These were exciting times! Unfortunately, no events were observed.

In 2006, the 35-degree magnetic dipole situated at the end of the VASSILISSA separator was replaced by the less dispersive 8-degree magnet and the detection efficiency of GABRIELA's Germanium array was increased by a factor of 2. The 2006 physics campaign started with a test-run with a ^{22}Ne beam and ^{238}U targets and the transmission and detection efficiency of ^{255}No recoils was estimated to be of the order of 1%. Unfortunately, problems with the ^{242}Pu targets did not allow us to perform the scheduled experiment to study the decay properties of ^{259}Rf.

During February/March 2008, we were ready to produce and study ^{259}Rf, but problems with the transmission of VASSILISSA forced us to mo-



Left: Physicists prepare to install the ^{210}Pb radioactive-target chamber. Right: Target containment chamber in place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GABRIELA makes the headlines of the local newspaper!

mentarily abandon the use of asymmetric reactions at VASSILISSA.

In 2009, our collaboration lost one of its members: A. Kabachenko — the father of GABRIELA's Time of Flight detector. We will always remember you!

The same year, the nucleus ^{253}No produced with a ^{48}Ca beam was revisited with new focal plane Silicon detectors and associated electronics [6]. This, together with the above-mentioned modifications to the setup, allowed us to improve the previously collected statistics by an order of magnitude and observe the complex gamma and ICE decay of the isomer we had observed during the first campaign in 2004 [7].

The poor transmission of VASSILISSA, with which we had been battling since the beginning of the GABRIELA project, led us to apply for funds to modernize the separator. A grant obtained in 2006 from the French funding agency ANR and funds from JINR have provided the necessary financial resources to upgrade the VASSILISSA separator and its detection system.

It has taken a little over 6 years to design [8], build, deliver and assemble the new optical elements of VASSILISSA separator. The new VASSILISSA should be commissioned early 2013. The commissioning will then be followed by a physics campaign. It is foreseen that the transmission and detection efficiency will be

Russian and French physicists enjoy some shashliki and pickles in the forest multiplied by a factor of 5 for asymmetric projectile/target combinations and by a factor of 2 for more symmetric reactions — so the future looks bright for the spectroscopy of heavy elements at the FLNR!

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Synthesis and study of decay properties of the isotopes of heavy and superheavy elements

A. Yeremin

***A. Yeremin, A. Popeko, O. Malyshev, A. Isaev**, JINR, Dubna*
***Ch. Stodel, H. Savajols, E. Clement, J. Piot**, GANIL, Caen*

Аннотация

В этой заметке мы с удовольствием вспоминаем франко-российскую коллаборацию, инициированную Жаном Петером из Лаборатории элементарных частиц (LPC, Laboratoire de Physique Corpusculaire, Caen) совместно с Э. Козулиным «с целью экспериментального изучения слияния и деления сверхтяжелых систем», впоследствии продолженную с группой Александра Еремина (ОИЯИ, Дубна). Это соглашение с физиками ГАНИЛ продолжается до сих пор под номером 01-52, сначала с названием «Синтез новых элементов и изотопов», а с 2011 года «Изучение сверхтяжелых элементов в рамках сотрудничества S3-SPIRAL2 и физустановки Дубны». В основном соглашение ориентировано на обмен визитами физиков двух лабораторий для участия в экспериментах и конференциях/симпозиумах. Также оно позволило начать некоторые совместные проекты благодаря богатому опыту российских коллег, имеющемуся в синтезе и исследовании свойств сверхтяжелых элементов. Совместные планы нашли отражение в Письме о намерениях о проведении разработок для SPIRAL2, в частности с целью изучения возможностей использования актинидных мишеней.

Résumé

Dans ces quelques lignes, nous sommes heureux d'évoquer la collaboration franco-russe initiée par Jean Péter du LPC (Laboratoire de Physique Corpusculaire, Caen) sur le sujet «Etude expérimentale de fusion et fission dans les systèmes super-lourds» avec Eduard Kozulin et ensuite avec le groupe d'Alexander Eremin, JINR, Dubna. Cet accord s'est poursuivi avec les physiciens du GANIL. Il est identifié sous le numéro 01-52 et après être intitulé «Synthèse de nouveaux éléments et isotopes», depuis 2011 il a été rebaptisé par «Etude des éléments super-lourds dans le contexte des installations S3-SPIRAL2 et JINR Dubna». L'accord est principalement orienté sur des échanges de physiciens dans les deux laboratoires dans le cadre d'expériences ou de conférences/symposium. Il a également permis d'initier des projets communs grâce à l'expertise de nos collègues russes dans la synthèse des noyaux Super-Lourds et de leurs études spectroscopiques concrétisés par la présentation de Lettres d'Intentions de SPIRAL2 et par des études technologiques telles que l'approvisionnement et l'utilisation des cibles d'actinide.

We will mention some experiments where LPC and GANIL scientists were kindly invited to take part in 2000–2001. It concerns the experiments performed with CORSET and DEMON for fusion-fission studies of various systems (^{48}Ca/^{58}Fe + Pu and Cm). Part of the data analysis was the work of N. Amar for her PhD diploma (N. Amar, these de doctorat, Université de Caen, LPC "Etude expérimentale de la formation de noyaux composés super-lourds dans la réaction: ^{58}Fe + ^{244}Pu → ^{302}120" (25/11/2003); http://tel.archives-ouvertes.fr/tel-00004000).

Then since 2002, the recoil separator VASSILISSA was upgraded with a 37° dipole magnet, allowing one to determine the masses of synthesized ERs and with the gamma and electron detection system thanks to the strong collaboration with CSNSM and IPHC physicists (see GABRIELA set-up from A. Lopez-Martens described in the 04-63 agreement "Gamma Spectroscopy towards super heavy nuclei at FLNR"). In this context, a campaign of experiments studying spectroscopy of heavy and super-heavy nuclei took place with VASSILISSA

Electromagnetic Analyser. The involvement of LPC and GANIL physicists was to participate time to time to these experiments, giving them the great opportunity to learn more from JINR's scientists about their know-how in this field where they are unmistakably the worldwide experts.

With the relatively intense GANIL's beams, the performance of the LISE3 Wien filter and the development of a dedicated FULIS (Fusion on LISE) set-up (rotating targets, appropriate detection set-up), experiments on synthesis and structure studies of super-heavy nuclei began to be performed in 1999–2008 at Caen. Russian colleagues were invited to take part to these experiments which enabled us to reinforce some discussions about some technological issues/developments and share some physics studies.

Here is a summary of some of these studies:

In 2002, we investigated complete fusion reaction in inverse kinematics with a ^{208}Pb beam on ^{51}V targets producing the recoil nucleus ^{257}Db ($Z = 105$) (E369, J. Peter)

In 2003, the complete fusion reaction with a ^{76}Ge beam on ^{208}Pb targets producing the recoil nucleus ^{293}114 (E440) was performed (Ch. Stodel, International Symposium on Exotic Nuclei (EXON) – Peterhof, Russia – July 5–12, 2004 and Proceeding World Scientific – p. 180 Tours Symposium on Nuclear Physics VI – September 5–8, 2006 – AIP Conference Proceedings 891(2007) p. 55). The cross section limit of 1.2 pb was reached. In order to prepare this experiment, a test experiment was successfully undertaken. It consisted in irradiating ^{208}Pb targets with a ^{58}Fe beam at 3 incident beam energies. Several decay chains assigned to the isotope ^{265}Hs ($Z = 108$) were observed. This experiment was followed by an experiment aiming at studying the structure of ^{251}Md (E375) where α particles were detected in coincidence with electrons and gamma rays (A. Chatillon, EPJA 2006 30 397).

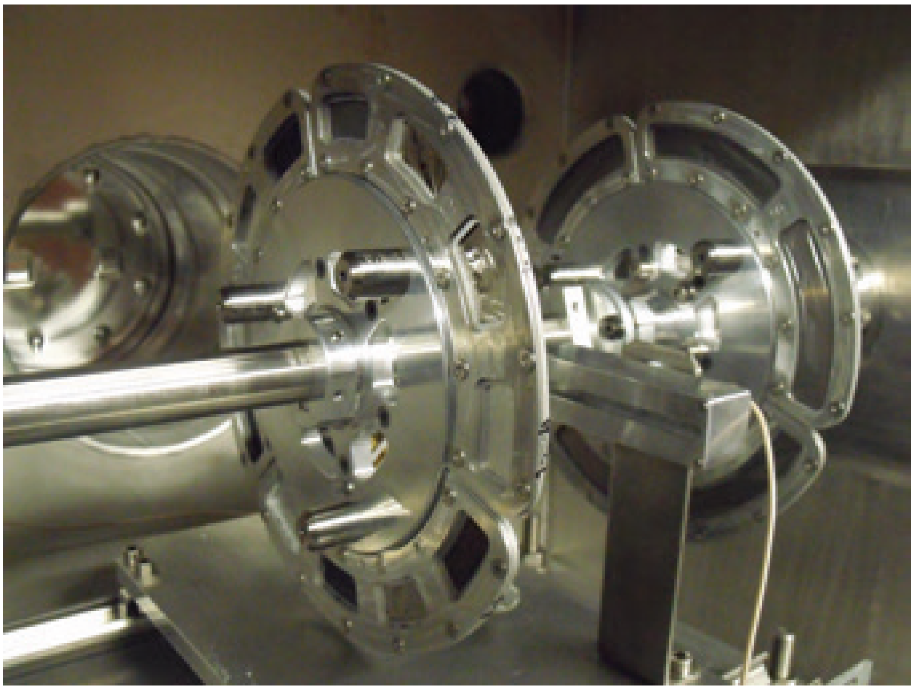
In 2005, Recoil (Decay) Tagging Tests experiments with the system ^{18}O + ^{208}Pb with VAMOS and EXOGAM were performed. The results were promising in terms of the rejection power and transmission.

The experiment (E533) for symmetric systems to synthesise Super-Heavy Elements (^{136}Xe + Zr, ^{122,124}Sn) took place in November 2008. The aim of this experiment was to study the isospin dependence of the fusion process in the region of SHE nuclei by producing ^{260}Rf and ^{258}Rf isotopes. The data collected from the galotte and BEST detectors were analysed by B. Avez from Saclay. This analysis was a part of his PhD work. In these conditions no expected events from Rf isotopes were observed and this result leads to a limit cross sections of channels 1, 2 and 3 neutrons of 235, 80 and 172 pb respectively (B. Avez, Mouvements collectifs dans les noyaux: de la vibration à la fusion, Thèse de doctorat Irfu-09-15-T (2009)).

The year 2006 was a great turning point for French nuclear physics with the SPIRAL2 project where study of super-heavy nuclei was strongly supported. So, large discussions and meetings in collaboration between France and Dubna (see invited talks of A. Eremin at the 2006 Colloque GANIL; of Ch. Stodel for the International Symposium "Periodic Table of D. I. Mendeleev. The new super-heavy elements", Dubna, January 20–21, 2009…) and other countries took place to analyze the opportunities offered by LINAG and SPIRAL2 beams for studying and synthesizing SHE. This work led to propose some common letters of Intent for the physics cases. They were submitted and approved by the SAC ("S3: The Super Separator Spectrometer for LINAG beams" A. Drouart, J. Nolen, A. Villari et al.; "From Actinides to Super-heavy Elements with SPIRAL2: Reaction dynamics and structure" P. Greenless et al.). It was followed by a rough sketch of the Separator needed (S3) including the separator but also the target technology and detection.

In the annual 2007 S3-meeting, five working groups (target, optical, low energy branch, detection, physics) were formed in order to achieve a conceptual design of the S3 separator. A French–Russian collaboration was strengthened for targets with the expertise of using actinides targets at Dubna. Since then, discussions about the feasibility of such targets took place between the labs.

In March 2011, French scientists visited Dubna laboratories in order to present a common LOI based on Super-heavy elements synthesis and requiring actinide targets. The discussion was fruitful in terms of collaboration and both parties agreed to investigate the supply and fabrication of actinide targets in the framework of joint physics program either at Dubna or SPIRAL2/S3 facilities. The IN2P3/JINR conventions facilitated the continuation of the discussion and the writing of the proposed LOI, by the visit of Russian



Wheels of the prototype of the actinide target chamber built for the project S3

colleagues at the 2011 colloquium GANIL at Belgodère and of French scientists during some workshop at Dubna at the end of 2011.

The LOI “Towards the study of $Z = 115$ via the reaction $^{48}Ca + {}^{243}Am$” signed with French and Russian physicists was presented in January 2012 to the SPIRAL2 SAC&SC; the latters approved the LOI and strongly encouraged the collaboration to pursue their efforts.

Considering the years of the 21st century, the IN2P3/JINR agreement on the synthesis and study of super-heavy elements was of great importance for French physicists. The main fruits of this collaboration were the access of the experimental facility of Dubna, the writing of some joint physics program and the will of helping in special targets supply.

Exploring of neutron drip line (GANIL–FLNR experiments on neutron-rich nuclei of light elements)

S. M. Lukyanov and **Yu. E. Penionzhkevich**, *FLNR, JINR*

Аннотация

Изучение свойств нейтронно-избыточных ядер, удаленных от линии стабильности, составляет одну из наиболее интересных областей современных ядерно-физических исследований. Многие совместные эксперименты GANIL и Лаборатории ядерных реакций им. Г. Н. Флерова были посвящены изучению нестабильных нейтронно-избыточных ядер с числом нейтронов, близким к магическим значениям N = 20 и 28. В этих экспериментах, проводившихся в основном в GANIL, было получено много интересных данных о стабильности и свойствах ядер указанной области.

Résumé

L'étude des propriétés des noyaux riches en neutrons loin de la vallée de stabilité est actuellement l'un des domaines les plus intéressants dans la recherche en physique nucléaire. Plusieurs expériences jointes GANIL–FLNR se sont adressées a l'étude des noyaux instables riches en neutrons avec un nombre de neutrons proche des couches magiques N = 20 et N = 28. Beaucoup de résultats intéressants concernant la stabilité et les propriétés des noyaux dans cette région ont été obtenus par ces expériences, tout particulièrement à GANIL.

The study of the properties of neutron-rich nuclei far from stability is one of the most intriguing areas of modern research in nuclear physics. Joint GANIL–FLNR experiments were devoted to study of neutron-rich unstable nuclei with neutron numbers near the magic shells $N = 20$ and $N = 28$. A lot of interesting results on stability and properties of nuclei in this region were observed during these experiments, mainly performed at GANIL.

The achromatic spectrometer LISE installed at GANIL was used for the production and identification of very neutron- or proton-rich nuclei obtained in the fragmentation of intermediate-energy heavy-ion beams at 0°. The characteristics and advantages of the system are described in ref. [1]. M. Brian and M. Fleury motivated (in the scientific council of GANIL June 4th 1981) to build the LISE magnetic spectrometer with an interest of atomic physics study. It was great and more fruitful idea of C. Detraz, M. Langevin and R. Anne to adjust this fragment spectrometer for nuclear physics.

To explore the neutron drip line, there are two important requirements: on the one hand, effective magnetic separator with large angular acceptance and high value of resolution, such as the LISE spectrometer, and on the other hand, an exotic beam. The exotic spectrometer was needed for an exotic application by means of exotic beams. The idea of the GANIL director Prof. C. Detraz to accelerate a beam of ^{48}Ca ions was supported by the director of our Laboratory, Academician G. N. Flerov. A beam of ^{48}Ca ions at rather good quality was already elaborated and obtained at our laboratory. Production of the ^{48}Ca ion beam is the key problem in synthesizing new nuclei. The goal was to achieve the maximum intensity of the ^{48}Ca ion beam at energies $E \sim 40 \div 60$ MeV/A at a minimal consumption of this expensive rare isotope. The production and acceleration of ^{48}Ca-beam with an Electronic Cyclotron Resonance ion source were performed successfully [2] by the groups of J. Ferme (GANIL) and V. Kutner (FLNR). The world record was obtained: mean rate of consumption of ^{48}Ca was about 2 mg/h and the beam intensity was about 15 μA on the charge state 6. Since, this method to obtain beam of ^{48}Ca ions was effectively used in many laboratories (RIKEN Japan, NSCL USA). In 1995, a High Intensity Transport safety system was studied and validated in 1998 in order to allow sending a several kilowatt beam to a maximum of 200 pnA.

The first experiment on search for neutron-rich isotopes in the region of $8<Z<20$ was carried out in 1988, the harvest was very-very reach [3]. After magnetic separation by the LISE spectrometer, the identification through time of flight and $\delta E \times E$ measurements has allowed the observation of the new nuclei, ^{29}F, ^{35,36}Mg, ^{38,39}Al, ^{40,41}Si, ^{43,44}P, ^{45,46,47}S, ^{46,47,48,49}Cl; ^{49,50,51}Ar from the interaction of a ^{48}Ca beam of 55 MeV/u with a tantalum target.

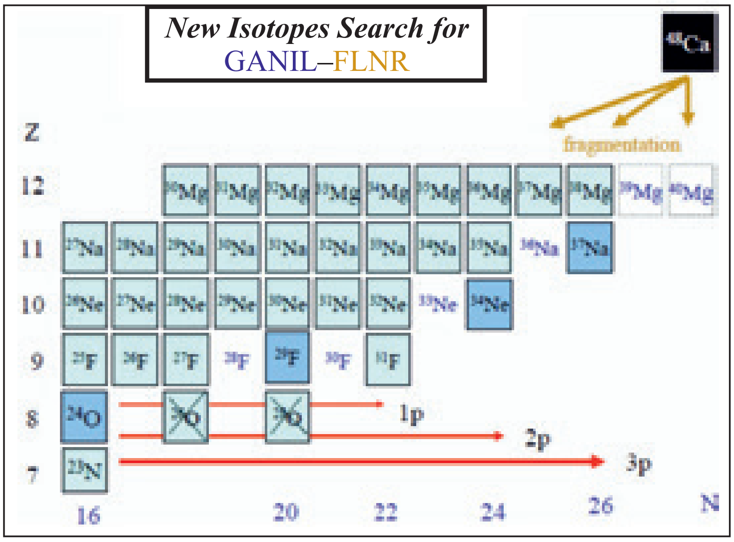


Fig. 1. Part of the chart of nuclides obtained in the fragmentation of the ^{48}Ca beam. Experimental evidences of the instability of ^{26,28}O were clearly obtained [5, 6]. Particle bound character for ^{29}F, ^{34}Ne, ^{37}Na, ^{35,36}Mg was observed for the first time in the frame of this collaboration and detailed results were published in [4–7]

Among recent results dedicated to the exploration of the neutron drip line in the region of elements from O to Mg one could mention the experiments on the particle instability of neutron-rich oxygen isotopes ^{26,28}O [5,6] and the discovery of particle stability of ^{34}Ne and ^{37}Na [7]. The appearance of a so-called "island of inversion" with respect to the particle stability of isotopes has been claimed through various theoretical predictions. A particular feature in this region is the progressive development of prolate deformation in spite of the expected effect of spherical stability due to the magicity of the neutron numbers $N=20$ and $N=28$. It was argued that the deformation may lead to enhanced binding energies in some of yet undiscovered neutron-rich nuclei. The particle instability of ^{26,28}O isotopes gives strong evidence of the onset of the deformation in the region. Our pioneer study and clear results on particle unbound character of neutron-rich oxygen isotopes ^{26,28}O has initiated further studies (both experimental and theoretical) in various Laboratories (in USA, Japan, etc.). One might expect that the drip line for the fluorine-magnesium elements could move far beyond the presently known boundaries.

In our next experiment [7], we made an attempt to determine the neutron drip line for the F–Ne–Mg isotopes in the region of the neutron numbers $N=20$–28. In particular, our experiment was dedicated to the direct observation of the ^{31}F, ^{34}Ne, ^{37}Na and ^{40}Mg nuclei.

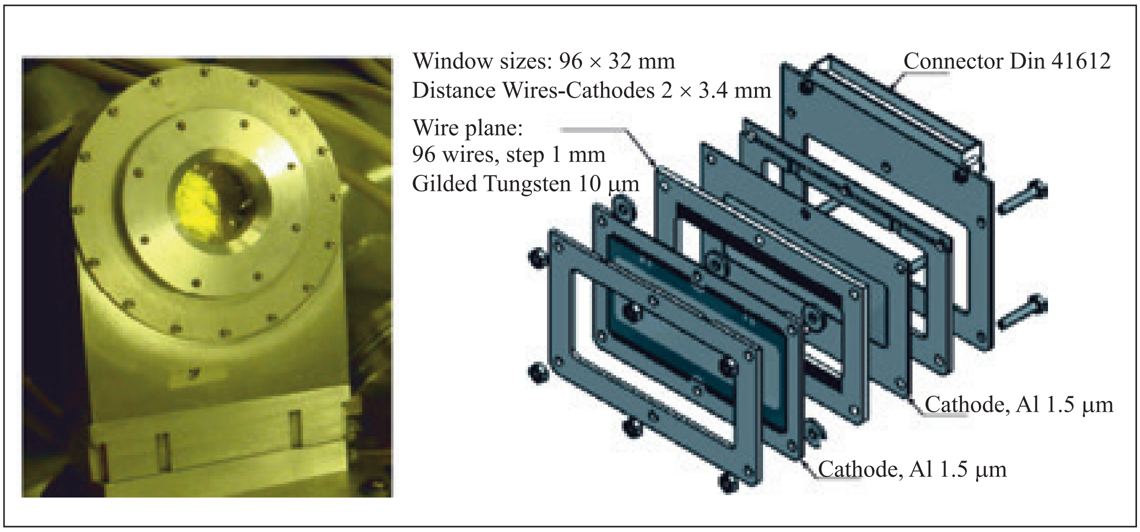


Fig. 2. View and schematic presentation of the CAVIAR proportional position-sensitive detector for particle-tracing in the intermediate plane of the LISE spectrometer

The experiment benefited from a recent update of the LISE spectrometer to the LISE 2000 level. The upgrade includes: an increase of the maximum magnetic rigidity to 4.3 T·m, an increase by a factor of 2.5 of the angular acceptance and a new line with improved optics. In addition to the standard identification method of the fragments via time-of-flight (ToF), energy loss (dE) and total kinetic energy (TKE), a multiwire proportional detector (due to high granularity was called CAVIAR detector by R. Hue (GANIL)) was placed in the dispersive plane of the LISE 2000 spectrometer. This detector allowed one to measure the magnetic rigidity of each fragment via its position in the focal plane, improving the mass-to-charge resolution (A/Q). A spatial resolution of 0.5 mm was achieved for a counting rate of 10^4 particles per second.

The mass-to-charge ratio (A/Q) was obtained with an accuracy of 0.8%, which could be considered as a next world record in the experimental technique in heavy ions physics. According to our experimental practice, the CAVIAR is a powerful tool for research nuclear spectroscopy on nuclides produced with very low cross section, especially concerning the nuclides close to the proton or the neutron drip-line. In addition, the CAVIAR detector became an important part of the LISE detector system and was very useful for a plenty of the future experiments. The result of the particle identification based only on the dE, ToF, and TKE is shown in Fig. 3*a*, where the energy loss measured in the first detector of the telescope is plotted versus the time of flight (ToF) between the dE silicon telescope and the cyclotron radiofrequency. This matrix was obtained from the data accumulated during 2.5 days with a mean intensity of primary beam of 150 pnA. The new isotopes ^{34}Ne (two events) and ^{37}Na (one event) are clearly visible. The ^{34}Ne and ^{37}Na have also been unambiguously identified by using the calculated value of A/Z. This value was obtained from the ToF and from Br, measured by means of the multiwire detector. Two-dimensional *A/Z* versus *Z* plot is shown in Fig. 3*b*. The presence of the events corresponding to ^{34}Ne and ^{37}Na confirms that these nuclei are bound.

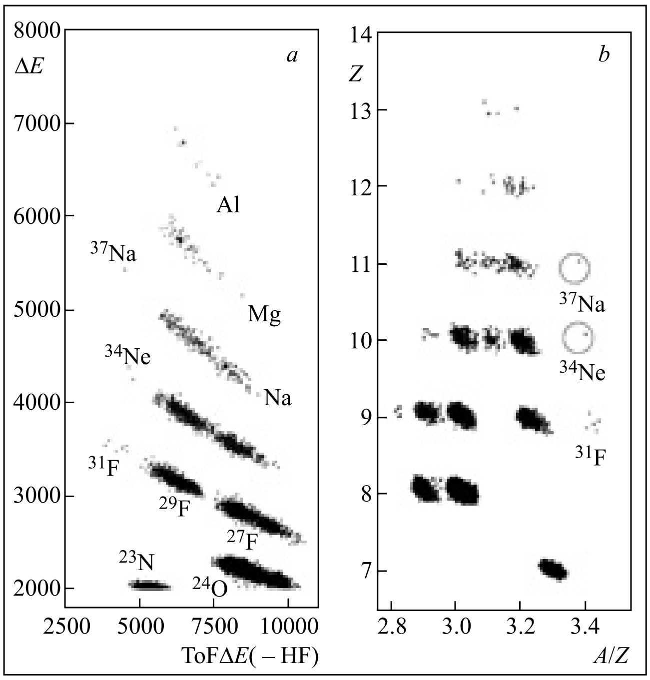


Fig. 3. (*a*) Energy loss versus ToF identification matrix. (*b*) Two-dimensional *A/Z* versus *Z* plot, which was obtained in the reaction of a 58.9 A MeV ^{48}Ca beam on tantalum target. The new isotopes ^{34}Ne (two events) and ^{37}Na are clearly visible

An outstanding issue is following: oxygen isotopes with magic proton number $Z = 8$ could keep only 16 neutrons as maximum, adding one or two protons above $Z = 8$ allows one to have got ^{31}F or ^{34}Ne as particle-bound nuclei and to keep 6 or even more additional neutrons inside!

The stability/instability of the present nuclei can be explained by taking into account a different degree of mixing in *sd* and *fp* shells, which is related to the deformation effects. According to our results, the neutron drip line is extended beyond $N = 20$ and reaches $N = 24$ for neon and even $N = 26$ for sodium isotopes as a consequence of the mixing of $d_{3/2}$ and $f_{7/2}$ states, while the $N = 20$ shell closure disappears.

The nuclei in this region are spectacular examples of shape coexistance between spherical and deformed configurations, for example, ^{32}Mg. In the frame of shell model, the deformed ground state in ^{32}Mg is a consequence of the strong correlation energy of 2*p*-2*h* neutron excitations from *sd* shell to *pf* for the magnesium. It was suggested that the extra binding energy was gained by the deformation associated with the particle-hole excitation across the $N = 20$ shell gap. If a nucleus gains binding energy through the deformation, the drip line extends further from the one expected by closed shell. Recent experiments at GANIL were dedicated to the stability study of the neutron-rich nuclei with $Z > 7$ and around $N = 20$. The variation of the shell gap and deformation as a function of *N* and *Z* could be a major challenger.

Within a naive shell model picture, magic nuclei are associated with particle configurations where orbits are fully occupied and for which a large energy gap exists at the Fermi surface. For these reasons correlations are hindered in magic nuclei that are characterized by (i) a high excitation energy of their first excited state, (ii) a low transition probability from the ground state to the first excited state, and (iii) a spherical shape. Appearing for the nucleon numbers 2, 8, 20, 28, 50, 82, and 126, magic numbers are the pillars supporting the chart of nuclei usually represented from the proton to the neutron drip lines. However, this picture originating from our knowledge of stable nuclei has to be refined: the spherical magic numbers are now known not to be a valid concept from drip line to drip line. This experimental fact has been first established in the $N = 20$ neutron-rich nucleus, ^{32}Mg, in the early 1980s [8].

The first indication of modification in the shell structure of exotic $N = 28$ nuclei south of ^{48}Ca came in the 1990s from the measurement performed, of the unexpectedly short beta decay half-life and high neutron emission probability of ^{44}S (4 protons less than ^{48}Ca) [9].

Figure 4 summarizes this experimental information for even Z isotopes from Ca to Si, with a neutron number ranging from $N = 20$ to $N = 28$. From these pictures, one observes a drastic difference in the evolution of nuclear structure at $N = 20$ and $N = 28$. While remaining high for each of considered $N = 20$ isotones, the excitation energy of the first 2^+ state progressively decreases at $N = 28$ when going away from the

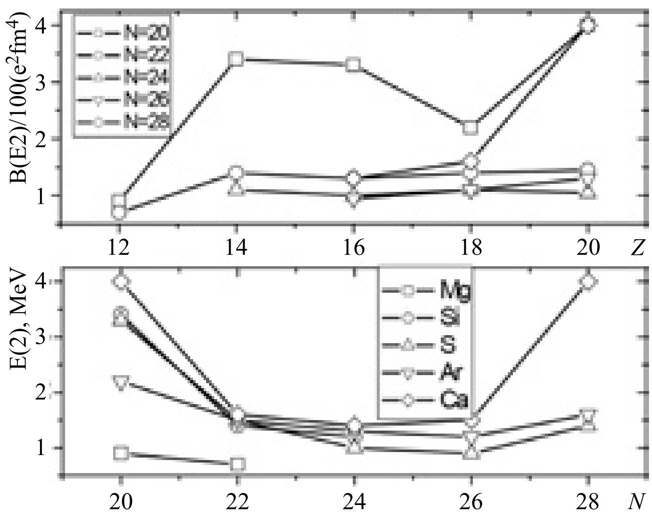


Fig. 4. Bottom: Excitation energy of the first 2^+ state for the Ca, Ar, S, and Si isotopes from $N = 20$ to $N = 28$. Top: Reduced transition probabilities B(E2) for the same isotopes

stable Ca isotone. Similarly, the reduced transition probabilities B(E2) increase at $N = 28$ going farther from ^{48}Ca while keeping a very low value at $N = 20$ [10].

Therefore, there is a great interest in study of nuclei in the region of neutron closure $N = 28$. Experimentally, the properties of ^{44}S have been studied and it was concluded there that the ground state of ^{44}S is deformed. This result suggests a significant breaking of the $N = 28$ closure for nuclei near ^{44}S.

It should be mentioned that experiments were carried out not only at GANIL, they were performed in parallel in Dubna — in the beginning at the U400 cyclotron and later at the new cyclotron U400M with parameters close to the parameters of GANIL. At the U400 cyclotron a joint experiment was carried out to study the production of different nuclei using ^{32,34}S-beams in the energy range 5–20 MeV/A [11]. The comparison of these results with the ones obtained at GANIL at 60 MeV/A showed that the production cross section of some nuclei at low energies is a few times larger than at intermediate energies. This fact allows one to make conclusions concerning the possibilities of producing secondary beams at U400M whose primary beams are of very high intensity. These results may have an important impact on the new concept of the radioactive beam factory in LNR–JINR. It is noteworthy that during 1998 such a factory (the SPIRAL project) starts operation at GANIL. This will allow us to start a new-quality collaboration of the Dubna and GANIL physicists and accelerator specialists in this very promising field of nuclear physics.

Acknowledgments

The authors would like to express their gratitude to the members of the FLNR (JINR, Dubna)–GANIL (France) collaboration for the fruitful experimental efforts and discussions of the experimental results obtained in the joint experiments. This research has been carried out by an international crew: C. Detraz, G. Flerov, Yu. E. Penionzhkevich, Yu. Ts. Oganessian, D. Guillemaud-Mueller, M. Lewitowicz, R. Anne, A. Artukh, R. Astabatyan, D. Bazin, A. Belozerov, P. Chomaz, C. Borcea, A. Buta, R. Hue, F. Ibrahim, D. Verney, F. de Oliveira Santos, Z. Dlouhy, S. Grevy, G. Georgiev, F. Ibrahim, W. Mittig, H. Savajols, I. Matea, J. Mrazek, A. C. Mueller, F. Negoita, F. Pougheon, O. Sorlin, O. Perru, I. Matea, Yu. Sobolev, I. Stefan, O. Tarasov, V. V. Kamanin and many others. We appreciate P. Leheressier, C. Barue, C. Canet, B. A. Gvozdev, V. B. Kutner, M. P. Bourgarel, L. Bex, M. Bajard, M. Bisch and J. Ferme for their tremendous efforts to make a ^{48}Ca beam possible as intensive and reliable beam at energy above 44 MeV/A.

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Very light exotic nuclei

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Аннотация

Группа сепаратора АКУЛИНА (ЛЯР им. Г. Н. Флерова, ОИЯИ) имеет долговременное сотрудничество с коллегами из лабораторий Франции. Французские физики внесли свои идеи и экспериментальные методики, содействующие успешным совместным исследованиям нейтронно-избыточных ядер водорода и гелия. Высокая эффективность исследований показана на примере ядра ^{5}H, когда объединились возможности работы мощной детекторной системы DEMON, доставляемой из Франции, с криогенной тритиевой мишенью на установке АКУЛИНА.

Résumé

Le groupe ACCULINNA du Laboratoire Flerov des Réactions Nucléaires, au JINR, a une longue collaboration avec les laboratoires de physique nucléaire en France. Les chercheurs français ont ajouté leurs suggestions originales et leur contribution expérimentale, apportant un progrès significatif dans les études communes des noyaux d'hydrogène et hélium très riches en neutrons. Les résultats exceptionnels obtenus en combinant les cibles cryogéniques de tritium à ACCULINNA avec le puissant détecteur DEMON France sont démontrés par l'exemple d'une étude sur le noyau ^{5}H.

The ACCULINNA separator [http://aculina.jinr.ru/] was built in 1996 and the earliest successful experiments, shedding light on the halo structure of ^{6}He, were performed in 1997. At that time we became aware that our anticipated research of very light exotic nuclei could benefit from collaboration with colleagues coming from GANIL known as a research center that had pioneered the study of exotic nuclei. In response to the offer made by Yury Oganessian, Patricia Roussel-Chomaz and Wolfgang Mittig, together with their young colleague Herve Savajols, began dynamic participation in the principal experiments that were carried out at the radioactive ion beams (RIBs) provided in Dubna by the ACCULINNA separator and the DRIBs ISOL facility. Since that time, other French groups of researchers co-operated with us adding their original suggestions and experimental powers and, in that way, enriching appreciably contribution to the RIB physics made by means of the facilities in Dubna. Introduced chronologically these were Drs. N. Alamanos, V. Lapoux, F. Auger, R. Raabe, L. Nalpas, and E. C. Pollacco (DSM/DAPNIA/SPhN, CEA Saclay), Drs. O. Dorvauxe and L. Stuttge (IPHC Strasbourg), Drs. S. Fortier, D. Beaumel (IPNO, Université Paris-Sud-11-CNRS/IN2P3, Orsay), Drs. Ch. Briançon, K. Hauschild, A. Korichi, and M.-H. Ha (CSNSM, IN2P3-CNRS, Orsay).

The data from the experiments done at ACCULINNA in its early days with rather simple equipment, suggested a reduction of the *t*–*t* ^{3}He clustering in ^{6}He in respect to the analogous *t*–^{3}He clustering in ^{6}Li. Reaction angular distributions re-measured at GANIL with more efficient instrumentation including the SPEG spectrometer, provided support to the early finding. Later on, ACCULINNA people participated in the development of the active-target detector MAYA made at GANIL and took part in the first study of the ^{8}He resonance scattering and reactions carried out with this innovative instrument. With the advent of SPIRAL beams at GANIL ACCULINNA group participated in a study of the $p(^{8}\mathrm{He}, d)^{7}$He and $p(^{8}\mathrm{He}, t)^{6}$He reactions — a cooperation with V. Lapoux, worked with D. Beaumel on the search for a tetra-neutron, studied resonance scattering $^{17}\mathrm{Ne} + p$ providing high quality spectroscopic data on unbound ^{18}Na system — this was done in a cooperation with F. de Oliveira.

Accomplishments made by this collaboration are recognized by the researcher community working in the field. A novel approach to the investigation of resonant states of nuclei in proximity and beyond the neutron drip-line has been proposed here, developed and practically applied. This work was not restricted to the derivation of the invariant/missing mass spectra. It succeeded to show that, in the experiments per-

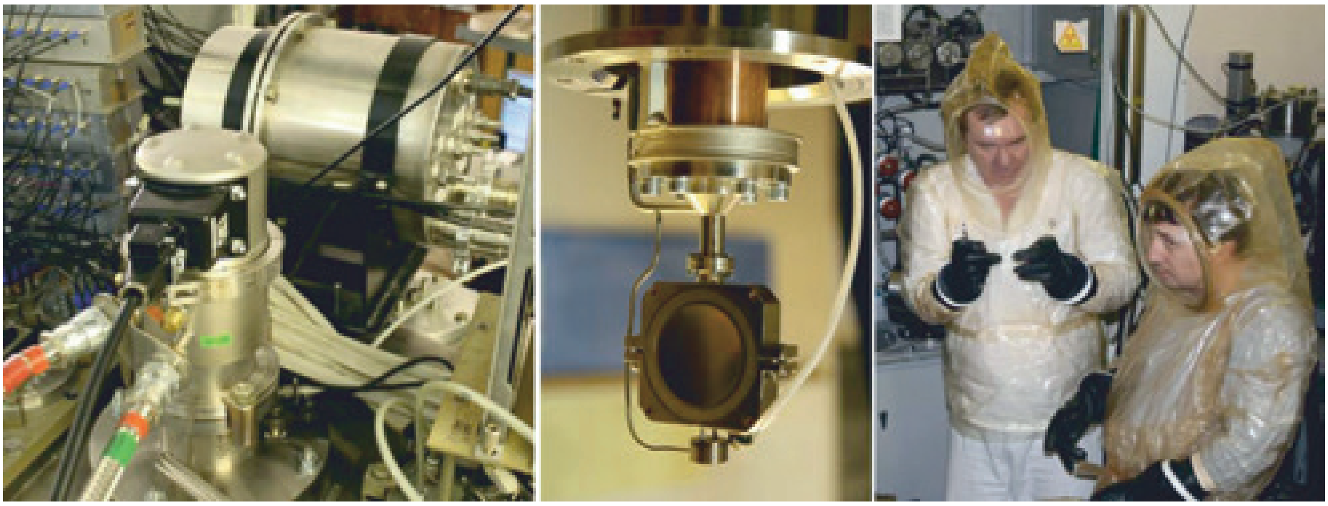


Fig. 1. Cryogenic tritium target cell installed in the center of the ACCULINNA reaction chamber (in middle). Above the chamber (on the left) seen is the refrigerator head cooling the target cell down to 26 K. Work with the tritium target system (on the right)

formed with certain kinematical settings, correlations inherent to the reaction products become an extremely rich source of the information. The following main results were obtained at these facilities in Dubna:

1. The dineutron and the $t+t$ configurations in the structure of the ^{6}He neutron halo nucleus were experimentally established as a result of measurements done for the elastic ^{4}He + ^{6}He scattering and the ^{6}He+$p \to {}^4$He + t reaction cross sections.
2. For the first time the ^{3}H(^{2}H, p)^{4}H and ^{3}H(^{3}H, d)4H reaction products originating from the population of the ^{4}H ground state resonance were unraveled unequivocally and the ^{4}H ground state was reliably established.
3. A lower limit for the decay energy of the still hypothetical ^{7}H nucleus was established.
4. The spectrum of the ^{5}H nucleus has been reliably established. This result was achieved in a series of experiments in active polemics with the results coming from other groups.
5. Novel and powerful experimental methods for the investigation of the three-body decay of spin-aligned states were worked out and applied.
6. Another novel approach to the finding of the critical characteristics of collision parameters characterizing transition from complete fusion to breakup reactions initiated by the loosely bound dripline RIBs was formulated and applied in a dedicated experiment.
7. The ^{8}He, ^{9}He, and ^{10}He spectra were revised. Before these works, doubtful data on the low-lying spectra of these nuclei have been considered as reliably established for more than a decade.

Results achieved in collaboration with the French laboratories were reported in more than 40 papers published in refereed journals and presented at many major international conferences.

A unique technical feature of the ACCULINNA separator is the availability of tritium beams and cryogenic tritium targets. At the moment it is the only place in the world where the availability of the tritium target and the beam is combined with the RIB research. Work with radioactive tritium requires strict adherence to the regulations and radiation safety standards. Therefore, a set of environmental safe equipment (see in Fig. 1) was developed, which made it possible to fill the target cell with tritium gas, evacuate the gas from the target and recover tritium, perform radiation monitoring in technological lines and in work rooms. These demands are worth of fulfillment as tritium gives essential advantages which were used in full in this experiment. This part of our work can be seen as an excellent example of the conversion of military technology for application in fundamental science.

Another major power acquired by the work done in Dubna due to the IN2P3–JINR collaboration was DEMON — the unique neutron-detector facility (see in Fig. 2) created jointly by the French researchers in collaboration with the group of the Université Libre de Bruxelles. We acknowledge the invaluable contribution to the

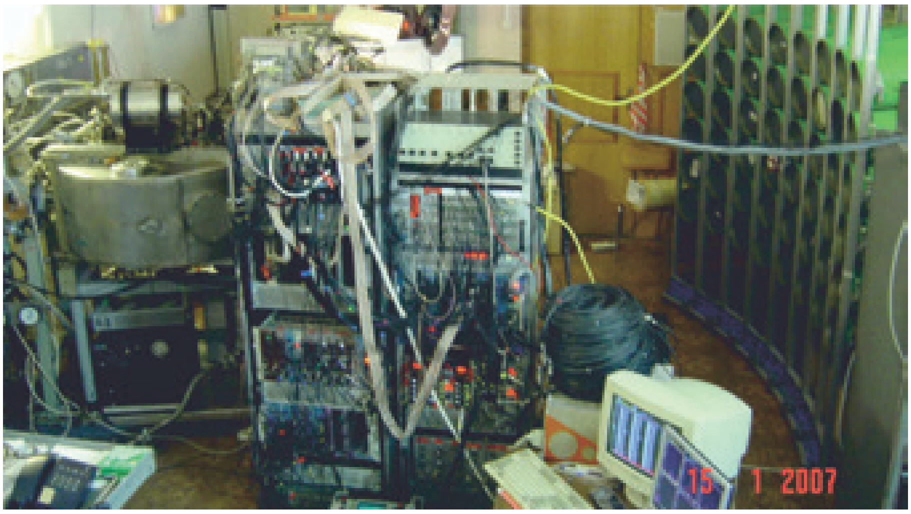


Fig. 2. Experimental room of ACCULINNA. RIBs enter the reaction chamber from the left side. Seen at a 3-m distance after the chamber is a wall of DEMON detectors (48 units)

Fig. 3. Synergy of experiment and theory. A hot discussion of ^{5}H results obtained in the ^{3}H(t,p)^{5}H reaction. From left to right are Drs. W. Mittig, L. Grigorenko and P. Roussel-Chomaz

RIB works in Dubna made by Drs. F. Hanappe, V. Bouchat, V. Kinnard, and T. Materna (Brussels, Belgium) and by Dr. C. Angulo (Louvain-La-Neuve, Belgium).

The study of the super-heavy hydrogen isotope ^{5}H made at ACCULINNA is a dramatic example of essentially new results throwing light on the structures of very light few-nucleon systems. The keystone of the first successful experiment carried out in 1999 was the combination of the exotic ^{6}He beam at ACCULINNA (FLNR JINR), the hydrogen cryogenic target from GANIL, and the detection system based on the RIKEN telescope. Starting from 2001 new world-class results were obtained in the domain of the lightest exotic nuclei due to the power of joint operation of the tritium targets available at FLNR with the French (European) DEMON setup.

The ^{5}H case demonstrates the power of the (t, p) reaction study which has been extended in Dubna to the case of ^{10}He where the breakdown of the doubly magic $Z=2$, $N=8$ structure, being the subject of long-term interest, was unambiguously established. Very promising will be the broadening of a similar approach to the heavier drip-line nuclei with halo structures, and to the region extending to oxygen — fluorine and beyond. This will be a prospective field for the further collaboration with our French colleagues.

Investigation of fusion-fission and quasi-fission processes in the reactions with heavy ions

E. M. Kozulin *on behalf of the French–Russian collaboration, Sector n°5 FLNR-JINR*

Аннотация

В 1995 году была основана коллаборация CORSET-DEMON между Лабораторией ядерных реакций им. Г. Н. Флерова ОИЯИ и IN2P3 (Франция) с целью объединения усилий в проведении экспериментов по изучению спонтанного и вынужденного деления ядер и механизма реакций деления между сложными ядрами. В течение более 15 лет была выполнена большая серия экспериментов, в которых исследовались процессы слияния-деления сверхтяжелых ядер в области Z = 102–122. Были получены функции возбуждения сверхтяжелых ядер, массово-энергетические распределения продуктов реакций, множественности нейтронов и γ-квантов. Большое внимание уделялось исследованию оболочечных эффектов в реакциях горячего и холодного слияния. В этом цикле работ были проведены оценки сечения деления сверхтяжелых ядер, что позволило более точно оценить сечения образования сверхтяжелых компаунд-ядер, решая, таким образом, проблему выбора оптимальных конфигураций ион-мишень и оптимальной энергии возбуждения для синтеза сверхтяжелых элементов. Благодаря этой многолетней совместной работе были получены новые экспериментальные данные о свойствах и динамике процесса слияния-деления, о временных характеристиках деления ядер, а также о реакциях слияния сложных ядер. Нашей коллаборации удалось получить научные результаты высокого уровня, представленные в более чем 30 публикациях в научных журналах. По результатам совместных экспериментов участниками коллаборации было защищено 6 кандидатских диссертаций. Коллектив авторов совместно с коллегами из коллаборации CORSET-DEMON был удостоен первой премии ОИЯИ за 1999 г. в области экспериментальной физики и второй премии ОИЯИ за 2000 г. в разделе «Научно-методические работы».

Résumé

La collaboration CORSET-DEMON entre FLNR JINR et IN2P3 (France) fut établie en 1995, dans le but de faire converger les efforts pour mener a bien des experiences dediées à l'étude de la fission induite et spontanée des noyaux ainsi que de la dynamique des réactions avec les ions lourds. Pendent plus de 15 ans, plusieurs expériences de fusion-fission de noyaux super-lourds avec Z=102–122 furent menées à bien. Fonctions d'excitation, distributions en masse et énergie des produits de reactions, multiplicités de neutrons et de rayons γ ont été obtenues. Une attention particulière a été portée à l'étude des effets de couches dans les réactions de fusion chaude et froide. Dans le cadre de ce programme le sections efficaces de fusion-fission pour les noyaux super-lourds ont été évaluées. Cette information nous a permis de connaitre plus précisement les sections efficaces pour la formation du noyau composé super-lourd et de trouver les conditions optimales pour la synthèse des éléments superlourds comme les configurations projectile-cible et la meilleur énergie d'excitation. Sur le long terme, le travail commun a fourni des nouvelles données expérimentales concernant les propriététs et la dynamique du processus de fusion-fission insi que de l'echelle en temps de la fission nucléaire. Cette coopération a permis a notre groupe d'obtenir des résultats scientifiques de haut niveau, reportés dans plus de 30 publications dans des revues scientifiques. Les données de ces expériences ont été à la base de 6 thèses de doctorat. Nos travaux communs ont été récompensé par le premier prix du JINR dans le domaine de la physique expérimentale en 1999 et par le deuxième prix pour les méthodes scientifiques en 2000.

One of the basic problems of modern nuclear physics is definition of extreme conditions of atomic nuclei existence. The interest in multi-detector systems creation has considerably increased in heavy ions physics. The spectrometer of such a kind was designed and built in the Flerov Laboratory of Nuclear Reactions (FLNR) at the Joint Institute for Nuclear Research (JINR). The spectrometer was named CORSET (CORrelation-SET-up) as it allows measuring the correlation characteristics of neutron and γ-quanta emissions in coincidence with fission-like products of the reaction under study. CORSET spectrometer has good time and position resolutions. The time-of-flight measurements technique and experimental data treatment methods have also been developed in FLNR.

Study of correlation dependences of reaction products at simultaneous measurement of fission-like products mass and energy distributions (MED), energy and angular distributions of neutrons and multiplicities of γ-quanta, have shown necessity of increase of accompanying radiations registration efficiency. This has resulted in association of two experimental set-ups — CORSET and a multi-detector neutron spectrometer DEMON being developed by French–Belgium collaboration. Such association has enabled one to raise not only reliability of the experimental information on average neutrons multiplicity in reactions with heavy ions, but also to have an opportunity to receive the information on the second moment of neutrons multiplicity distribution. To realize this project the collaboration between FLNR JINR, the Universite Libre de Bruxelles (Brussels, Belgium) and Institut des Sciences Nucléaires (ISN, Grenoble, France) was created in 1995.

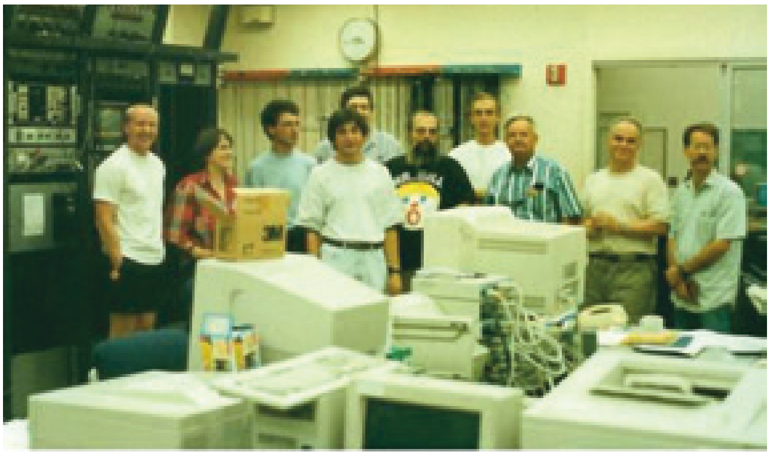
With the aim to combine their efforts in carrying out experiments relevant to investigations of spontaneous and induced nuclear fission and to studies of the mechanism of fusion reactions between complex nuclei in the spirit of the future development of radioactive neutron-rich beams, the Protocol of the collaboration between Universite Libre de Bruxelles, Physique Nucleaire Theoretique et Physique Mathematique, Bruxelles, Belgium and the Institut des Sciences Nucleaires, Grenoble, France and the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research, Dubna, Russia has been signed.

The collaborative work should result in new experimental data on properties and dynamics of the fusion-fission process, on time scale of nuclear fission, as well as on mechanism of fusion reactions between complex nuclei at energies of up to novel experimental techniques. The protocol was signed: from JINR — by Prof. V. G. Kadyshevsky, Prof. Yu. Ts. Oganessian, Prof. M. G. Itkis and Dr. Yu. A. Lazarev, from IN2P3 (Grenoble) — by B. Vignon and Dr. E. Liatard, and from ULB (Bruxelles) — by Prof. E. Vanmergen and Prof. F. Hanappe.

The first joint experiment with use of CORSET and DEMON set-ups was carried out on SARA cyclotron of ISN. The experiment was devoted to study of Pt and $Z = 110$ nuclei fission dynamics, produced in various projectile-target combinations. It should be noted that it was the very first experiment using DEMON setup.

The obtained mentioned above results have shown necessity of deeper studying of the neutron emission accompanying the fission process of the specified nuclei. Study of the multiplicities of neutrons emitted from fission of ^{226}Th nucleus was performed on a tandem accelerator VIVITRON at the Institut de Recherches Subatomiques (IreS, Strasbourg, France). In these experiments the dependence of pre-fission neutron multiplicity on a way of nuclear fission was experimentally shown for the first time. The research coordinators of these projects were: from IN2P3 (Strasbourg) Prof. G. Rudolf, Prof. N. Rowley and Dr. L. Stuttge, from JINR — Prof. M. G. Itkis and Dr. E. M. Kozulin. The main part of the experimental data was obtained in FLNR JINR on the extracted beams from U-400 cyclotron using CORSET-DEMON setup.

Within the framework of the cooperation between FLNR and a number of the West-European scientific centers, namely Institut de Recherches Subatomiques (Strasbourg, France), Universite Libre de Bruxelles (Brussels, Belgium), Laboratoire de Physique Corpusculaire (Caen, France), Cyclotron Institute (Texas A&M University, College Station, USA), University of Messina (Messina, Italy), Laboratori Nazionale del Sud (INFN, Catania, Italy), and Department of Physics of University Jyvaskyla (Jyvaskyla, Finland), a large series of the experiments devoted to study of fusion-fission processes in reactions of a synthesis of superheavy nuclei ($Z = 102$–122) were carried out in 1999–2012. Excitation functions, MED of reactions products,



The participants of the common experiment DEMON-CORSET, Texas A&M University Cyclotron Institute (USA)

Collaboration FLNR JINR–IN2P3. The participants of the common experiment DEMON-CORSET, FLNR JINR (Dubna)

neutron and γ-quanta multiplicities were measured. The steadfast attention was given to the study of shell effects in hot and cold fusion reactions. In this cycle of works the fission cross-sections of superheavy nuclei were estimated. This allowed us to estimate more precisely the cross-sections of super-heavy compound-nucleus formation, solving a problem of choice of optimum projectile-target configurations and preferable excitation energy choice for the synthesis of super-heavy elements.

The successful international cooperation with western scientific centers has allowed our collaboration to obtain high-level scientific results:

1. The most important and basic result was obtained in studying the mechanism of super-heavy element fusion-fission. It was the first observation of asymmetry in fission of super-heavy nuclei. This asymmetry appears to be determined by spherical shells of the light fragment. In a sense this fact encloses a circle of modern theoretical representations about a modality of nuclear fission which is extremely important for the further development of physics of nuclear fission as well as nuclear physics as a whole;
2. Capture and fission cross-section dependences on excitation energy of the compound-nucleus production have been studied for ^{256}No, ^{266,274}Hs, ^{286}112, ^{292}114, ^{296}116, ^{294}118, ^{306}122 nuclei in a range of excitations 15–60 MeV;
3. It was shown for the first time that the ratio between fission and quasi-fission changes dramatically with transition from ^{238}U + ^{44}Ca reaction to ^{244}Pu + ^{48}Ca reaction. At that the fission cross-section (σ_{fis}) and the cross-section of the compound-nucleus formation consequently is nearly the same for the ^{292}114 and ^{286}112 nuclei while quasi-fission cross-section for the ^{292}114 nucleus is 6–8 times smaller than that for the ^{286}112 nucleus;
4. It was found that fission fragment mass distributions of ^{286}112, ^{292}114, ^{290,296}116, ^{294}118, ^{302}120, ^{306}122 compound nuclei are asymmetric ones. The nature of this asymmetry, on the contrary to the asymmetry of actinides fission, is determined by the light fragment shell structure in a mass region A ~ 132–134. It was also established that the total kinetic energy, neutron and γ-rays multiplicities of fission fragments differ significantly for the fission and quasi-fission processes;

5. It was found for the first time that neutron and γ-rays multiplicities from fissioning compound nucleus is a criterion to distinguish between processes which are physically close. This allows one to define both processes characteristics more precisely;
6. The analysis of neutrons angular and energy distributions and multiplicities of γ-quanta has shown that values of multiplicities in fission $\langle M_\gamma^{FF} \rangle$ are significantly higher than the one in quasi-fission $\langle M_\gamma^{QF} \rangle$. At the same time, total neutron multiplicity $\langle M_{tot} \rangle$ and total γ-rays multiplicity $\langle M_\gamma \rangle$ grow monotonously with increasing of the atomic number Z as well as with excitation energy increasing;
7. The multimodal fission phenomenon was studied in a region of superheavy nuclei (^{256}No, ^{270}Sg, ^{271}Hs) for the first time.

Now in the framework of the collaboration between the FLNR (JINR) and IN2P3–Institut Pluridisciplinaire Hubert Curien, Departement de Recherches Subatomiques (Strasbourg, France), the analysis of the data on fission-like fragments formed in the reactions $^{36}S + {}^{238}U$, $^{26}Mg + {}^{248}Cm$, $^{58}Fe + {}^{244}Pu$, $^{64}Ni + {}^{238}U$ has been done in order to clarify the origin of these fragments (fission or quasifission). The following new results were obtained:

- While the relative contribution of quasi-fission to the capture cross section mainly depends on the reaction entrance channel properties, the features of asymmetric quasifission are determined essentially by the driving potential of a composite system.
- The major part of the asymmetric quasifission fragments peaks around the region of the $Z = 82$ and $N = 126$ (double magic lead) and ($Z = 28$ and $N = 50$) shells, and the maximum of the yield of the quasifission component is a mixing between all these shells. Hence, shell effects are everywhere present and determine the basic characteristics of fragment mass distributions.
- The further progress in the SHE synthesis can be achieved using the deep-inelastic or quasifission reactions. To estimate the formation probabilities of SHE in these reactions, additional investigations are needed.

Basing on the data of our joint experiments 6 PhD theses have been defended by our collaborative colleagues and by employees of the group. These series of joint investigation were awarded by the JINR First Prize in the field of experimental physics in 1999 and the Second Prize for scientific methods in 2000.

Collaboration FLNR JINR–IN2P3. The participants of the common experiment DEMON-CORSET, FLNR

Search for Super Heavy elements In Nature (SHIN experiment in LSM)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(IN2P3–JINR collaboration (N° 04-66))

Résumé

Il n'est pas exclu que, dans la nature, de faibles quantités d'éléments plus lourds que l'uranium ,soient encore présentes. D'après l'analyse des résultats expérimentaux sur la synthèse des noyaux super-lourds ainsi que les prédictions des calculs effectués dans différents modèles théoriques ,la recherche d'éléments super-lourds de vie longue dans la nature a été reconsidérée. De tels éléments de vie longue subissent des décroissances α et β et/ou de la fission spontanée (en cas de séquences de décroissance α et β, les noyaux fils subissent une fission spontanée). Nos expériences visent à rechercher, dans un échantillon d'osmium, son homologue physico-chimique l'élément $Z = 108$ (EkaOs) en détectant l'émission multiple de neutrons accompagnant la fission spontanée.Un multidétecteur de flashs de neutrons de grande efficacité comprenant 60 compteurs cylindriques à ^{3}He a été construit au FLNR-Dubna et installé dans le Laboratoire Souterrain de Modane (LSM) avec tous les méthodes appropriées de blindage contre tous bruits de fond. L'expérience se poursuit sur une longue durée avec 550 g d'osmium.

Аннотация

Небольшое количество ядер тяжелее урана может существовать в природе. Наиболее вероятными кандидатами являются тяжелые изотопы элемента $Z = 108$ с $N \sim 180$. Такие долгоживущие ядра испытывают спонтанное деление либо сами, либо дочерние продукты их α- или β-распадов. Элемент $Z = 108$ является химическим гомологом Os, и поэтому для поисков этого элемента в природе был взят образец осмия массой 550 г. Для обнаружения редких ядер использовался метод регистрации множественной эмиссии мгновенных нейтронов спонтанного деления. Для этого в ЛЯР ОИЯИ (Дубна) был создан высокоэффективный 60-канальный детектор нейтронов на базе ^{3}He-счетчиков, который был установлен в низкофоновой подземной лаборатории LSM, Модан. В измерениях длительностью более 13000 часов был достигнут предел концентрации EkaOs 10^{-22} г/г в земной коре (в предположении, что его время жизни составляет 10^9 лет).

Motivation

The recent studies of fusion reactions between ^{48}Ca ions and ^{233,238}U, ^{242,244}Pu, ^{243}Am, ^{245,248}Cm, ^{249}Cf nuclei resulting in the synthesis of super-heavy nuclides with $Z = 114$, 115, 116 and 118 made it possible to determine radioactive properties of the new nuclides situated in the region of $Z = 110$–118 and $N = 170$–176 [1–3]. The new nuclei undergo sequential α-decays chains which terminate by spontaneous fission.

The total decay time for the isotopes of elements 114–116 ranges from1 to 100 seconds, depending on the charge and mass of the nucleus. For the isotope of element 115 ($N = 163$) the total decay time is ~ 30 hours. It follows from the comparison of the properties of the new nuclides and those of lighter isotopes with $Z = 110$–112 and $N = 160$–165. With an increase in the neutron number the stability of nuclei grows by 10^4–10^5 times. Experimental results confirm theoretical predictions on a substantial enhancement in stability when approaching the closed neutron shells $N = 162$ and $N = 184$. Until now there is no agreement between various theories on the location of the closed proton shell in the region of super-heavy nuclei. Previous experiments (20 years ago) were searching for SHEs in nature, expecting that the most stable nuclei should have $Z \sim 112$–114.

But thanks to the new experimental results on the α- and β-decays as well as spontaneous fission probabilities, it became possible to measure the α-decays probabilities in the neutron number region much higher than the neutron closed shell $N = 162$ and compare them with the theoretical calculations as shown in Fig. 1.

One may remark in Fig. 1 that the experimental values of Log T_α are systematically a few orders of magnitude higher than the calculated values, while the general trend of fast increasing is reproduced for the nuclei with $Z = 110$–118 and $N = 170$–176. Since there are no direct arguments at present in favour of SHEs existence in nature, it seems however appropriate to search for extremely long-lived isotopes around element 108. At the same time, the non-discovery of these nuclides will give an experimental upper limit of lifetimes of $Z = 108$ nuclei and yield new insights into an exquisite test for the theoretical models.

The concept of the experiment

Element 108 is a chemical homologue of Osmium, which is a rare element (its abundance on earth is 10^{-8} g/g. Chemical experiments carried out within a PSI–Dubna–Darmstadt–Mainz collaboration [4] on the determination of the EkaOs chemical behaviour showed that the temperature of HsO_4 condensation is $T = -43$ °C while that of Osmium is –82°C. This is the basis of the assumption that in a sample of metallic Os its homologue Hs ($Z = 108$) should be present and enriched at the same level.

In contrast to stable Os isotopes, the atoms with $Z = 108$ must undergo radioactive decay. In the scenario of the decay of nuclei with $Z = 108$, spontaneous fission of either the initial nucleus or the alpha-, beta-decay daughters products ($Z = 106$–104) will always be present and detectable by spontaneous fission events.

Registration of rare events of spontaneous fission

To increase the sensitivity of the experiment, it is proposed, as in the previous experiment [3], to detect the neutron flashes arising in spontaneous fission.

Some useful numbers:

- Average time of slowing down fission neutrons from 1.5 MeV to thermal velocity: 5 μs;
- Lifetime of thermalised neutrons in moderator 20 μs;
- Registration efficiency for a single neutron coming from the central sample in the set-up: 70±5%;
- Osmium: Content in the earth crust: 10^{-9} g/g.

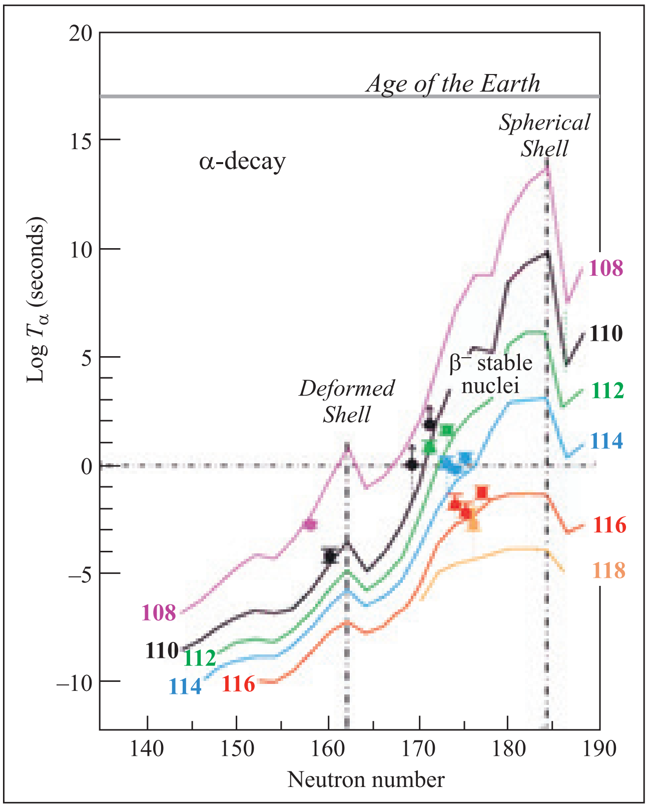


Fig. 1. Partial lifetimes of α-decay of nuclei with different Z and A values. Dots: experimental values. Solid lines: MM type calculations. Dashed lines show the location of the closed neutron shells 162 and 184

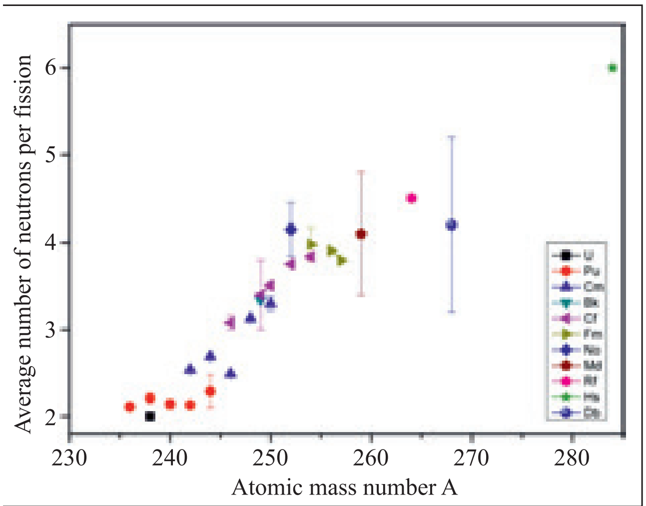
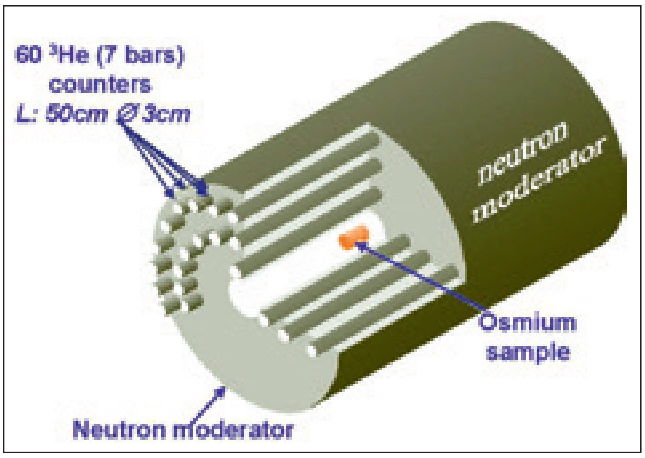


Fig. 2. Average number of neutrons. Dots: experimental data for U, Cf, Db isotopes. Squares: calculated values for the nuclei with $Z = 104$ and 108 (the calculations involve the TKE and excitation energies of the fission fragments, estimated from the systematics of experimental data obtained in the induced fission of heavy nuclei [6])

Figure 2 shows the average neutron number per fission as a function of the nuclear mass of the fissionning nuclei.

The neutron detector

The neutron detector consists of 60 counters filled with ^{3}He at 7 bars situated in a polyethylene moderator. The sample to be measured is placed in the central cavity.



Background conditions

i) Background in the detector due to ^{238}U:

The concentrations of ^{238}U have been determined separately for all the elements of the set-up and the Osmium sample. It follows from these measurements that the expected number (n_i) of *n-n* coincidences of different multiplicities from spontaneous fission of an ^{238}U admixture can be neglected.

ii) Other sources of backgrounds of multiple neutron emission in LSM:

The other sources of background, external to the detector itself, are mainly due to:

- Interaction of the cosmic rays (only 4 muons/ m^2/day in LSM).
- Thermal and epithermal neutrons.

To minimize all types of backgrounds, the detector has been installed in a grounded copper screen and surrounded by a box made in borated polyethylene (8 cm thick).

Results and Status of the experiments

We have carried out two measurements with the 550 g Os sample during 13000 hours: taking into account the neutron flashes with multiplicities n1, n2, n3, n4, n5, n6. We obtained 15 events of such types during 13000 hours. The concentration of $Z = 108$ in the Os sample is found to be not more than $\sim 10^{-14}$ g/g of osmium, which means: $\sim 10^{-22}$ g/g in the earth crust, assuming a half-life of $T_{1/2} \sim 10^9$ years, result obtained from counting rate of events with neutron multiplicities ≥ 3. We have carried out background measurements during 7700 hours and only 3 events have been detected during that period. It is very difficult to control all sources of background at the counting rate equal to several events of multiple neutrons emission per year. That is why only the limit of possible concentration of element $Z = 108$ in the sample of osmium is presented above if the total counting rate was originated from spontaneous fission.

That means that one gram of osmium contains up to $3 \cdot 10^8$ atoms of element 108. That is enough for identification of this element by high-sensitivity methods of mass spectroscopy.

The SHIN experiment is now running and it is possible to increase considerably the sensitivity by increasing the mass of Osmium till 2.5 kg without any change of the detector.

Following the results of experiments which are now undergoing in FLNR-JINR on superheavy elements, we prepare ourselves to apply such sensitive measurements to other "good" candidates for super-heavies in nature.

Acknowledgements

The authors would like to deeply thank the Laboratoire Soputerrain de Modane staff for their excellent technical assistance in running the experiment.

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TETRA neutron detector for beta delayed studies at ALTO

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Résumé

Cette collaboration à long terme a été fondée en 2005 par Yuri Penionzkevich de JINR et Fadi Ibrahim et David Verney de l'IN2P3. Motivée par l'étude des propriétés des noyaux exotiques riches en neutrons, qui devaient être produit à ALTO, il est venu, la décision a été prise de créer une système de détection, incluant les détecteur neutron de grande efficacité TETRA, dédié aux mesures de décroissances radioactives: BEDO (BEta Decay studies at Orsay). L'installation BEDO/TETRA, désormais achevée et en cours d'utilisation à ALTO constitue un outil puissant pour les recherches sur les noyaux exotiques très riches en neutrons.

Аннотация

Этому долговременному сотрудничеству начало было положено в 2005 году Юрием Пенионжкевичем со стороны ОИЯИ и Фади Ибрагимом и Давидом Верне со стороны IN2P3 с целью изучения свойств экзотических нейтронно-избыточных ядер, получаемых на ALTO. Было принято решение о создании установки, включающей высокоэффективный нейтронный детектор TETRA для исследования свойств бета-распада. Сегодня установка BEDO–TETRA является мощным инструментом для исследования нейтронно-избыточных ядер.

Motivation

There are two main ways to study nuclear properties — in prompt radiation from nuclear reactions and in delayed radiation from decays. Decay experiments benefit from the much longer time-scale which allows one to separate the particular nuclei of interest. Once a particular nucleus proven to exist — a rough measurement of half life, Q_β value, can be performed with a few number of atoms and can provide an important clue to its properties.

The β^- decay process, governed by weak interactions, is a typical example of delayed radioactivity on the neutron-rich side of stability and can provide information about nuclear properties in a wide range of A, Z. For some isotopes Q_β-value is large enough to emit a neutron(s) after β^- decay. The β-delayed neutron emission is a basically multistep process consisting of a β^- decay of the precursor (A, Z) which results in feeding the excited states of the emitter nucleus (A, Z + 1) followed by the gamma de-excitation to the ground state or neutron emission to an excited state or to the ground state of the final nucleus (A – 1, Z + 1).

Beta delayed neutron emission (Pn1) only occurs on the neutron-rich side of the stability and has been observed so far for somewhat about 200 isotopes. Double (Pn2) or more neutron emission was measured experimentally for the range of light nuclei (^{11}Li, ^{14}Be, ^{15}B, ^{17}B, ^{30,32,34}Na) and only for ^{98,100}Rb in the ranges of medium and heavy nuclei. However, there are theoretical predictions for 2n emission for the isotopes ^{86}As, ^{94}Br, ^{112}Nb, ^{134}In, ^{136}Sb, ^{150}Cs and others. Multi-neutron emission can lead to wrong Pn1 values which can result in errors of half-lives determined from the decay by neutron intensity. Additionally, study of correlations between neutrons emitted can give information about neutron clusters since neutrons are not distributed by Coulomb force.

In β^- decay for the allowed transitions orbital angular momentum is zero, transitions in which orbital angular momentum is different from zero are called forbidden — they occur in reality but with a smaller probability. However, moving away from the line of stability the Q_β value will increase with the consequence that the relative probability of forbidden transition will grow (with the increase in energy released). Most of the calculations for β decay for Gamow–Teller (GT) (allowed) transition and first-forbidden (FF) decays are performed in QRPA — Quasi Random Phase Approximation. According to available experimental and predicted decay schemes crossing the major shells $N = 50$, 82, the impact of FF transitions in the half life and beta delayed

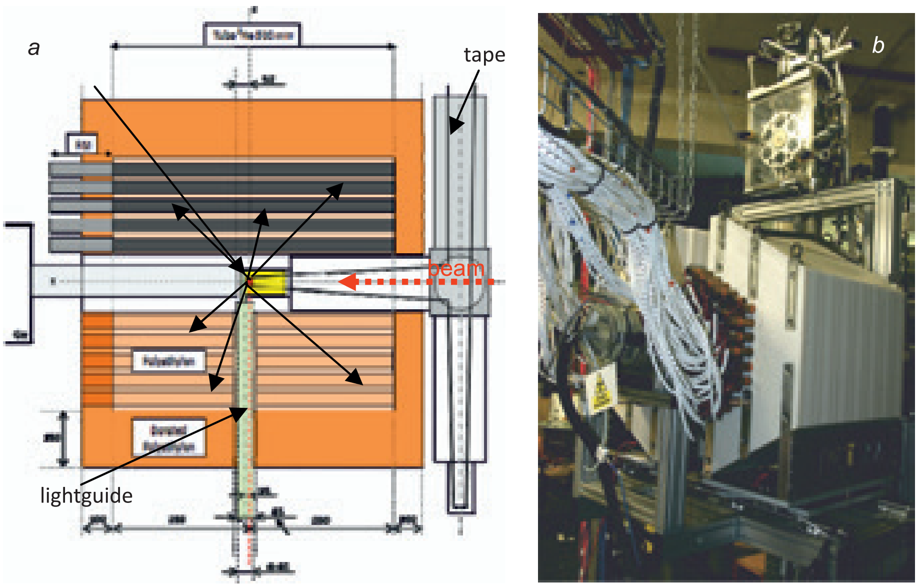

Fig. 1. The scheme (*a*) and the picture (*b*) of the BEDO–TETRA setup at ALTO. See text for the detailed description

neutron emission probability of the isotopes significantly increases [1]. A simultaneous analysis of the β-decay observables — half life and Pn in order to reconstruct the beta-strength function is needed. Going beyond the allowed beta-decay approximation in order to figure out the relative contribution of the Gamow–Teller and First Forbidden decays is an exciting experimental task.

Studying these properties around double magic nuclei $Z=28$ and $N=50$ (^{78}Ni) and $Z=50$, $N=82$ (^{132}Sn) experimentally is also important for astrophysics. The r-process, which constitutes one of the major processes in which elements heavier than iron are formed, consists of a series of rapid neutron captures followed by β decays and passes through a net of nuclei with the large Q value far from stability [2]. Although a detailed study of the r-process involves both theoretical and experimental data, most of the data needed (β-decay half-lives and β-delayed neutron emission probabilities) is currently derived from theoretical models due to the lack of measured β^--decay properties of isotopes participating in the r-process.

BEDO–TETRA setup at ALTO

At the ALTO (ISOL type) facility [3] the electron driver delivers a primary electron beam at the energy of 50 MeV with a nominal intensity of 10 μA at the thick ^{238}UCx target. Fission fragments are extracted at 30 kV voltage towards the on-line isotope separator PARRNe or can be selectively ionised with a laser ion source. The facility provides physicists with quite intensive exotic neutron-rich beam in the regions of double magic ^{78}Ni and ^{132}Sn.

To study the delayed beta activity of neutron-rich isotopes in the frame of collaboration JINR–IN2P3 a new experimental BEDO (BEta Decay studies in Orsay)–TETRA setup was developed, produced and commissioned. The design overview is shown in Fig. 1*a* and Fig. 1*b* illustrates the installation in the experimental hall. The collection point is surrounded by 4π beta detector (in yellow), and 4π TETRA neutron detector. Background neutrons are almost completely suppressed by 15 cm of borated polyethylene shielding. The identification of the isotopes is performed via Ge-detector placed from the back. The radioactive isotope beam is delivered to the collection point and collected by mylar tape which evacuates long-lived radioactivity.

The neutron detector TETRA [4] built at JINR has 90 counters (^{3}He at 7 atm) placed in the high-density polyethylene moderator around the collection point. The efficiency of single neutron registration measured in the present geometry for ^{252}Cf neutron source at the centre is 52 ± 2% (MCNP calculations – 49%).

The recent commissioning of the experiment performed on the mass separated beam of ^{123}Ag, ^{124}Ag proved its workability.

In the foreseen scientific program is to study neutron (possible multiple) emission for $^{83–86}$Ga, and ^{134}In, ^{136}Sb to measure the absolute branching ratios. The brilliant experimental setup created, the warm collaborative atmosphere, the highly skilful scientists involved in the research from both France and Russia are gradually leading to the new breathtaking experiments and discoveries.

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Precision low energy electron spectroscopy (spectrometer ESA-50)

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Аннотация

Уникальный электростатический спектрометр электронов ESA-50, с энергетическим разрешением в несколько эВ, стал ярким примером возможности плодотворного сотрудничества физиков Франции и СССР. Идея создания спектрометра принадлежит Ц. Д. Вылову и напрямую связана с его визитом в CSNSM (Орсэ) в 1979 году, организованным Ш. Бриансон. Запуск спектрометра в Дубне с участием французских коллег состоялся в 1982 году. За 30 лет работы созданный при поддержке CSNSM спектрометр ESA-50 и разработанная в НЭОЯСиРХ ЛЯП методическая база низкоэнергетической ядерной электронной спектрометрии позволили решить целый ряд задач в атомной и ядерной физике, о чем свидетельствуют многочисленные (свыше 60) публикации в ведущих международных научных журналах. Наглядным отражением достигнутых успехов является каталог низкоэнергетических дискретных и непрерывных электронных спектров, измеренных на ESA-50. Каталог содержит более 100 спектров электронов радионуклидов в области Z = 24÷95.

Résumé

Le spectromètre électrostatique ESA-50 avec une résolution d'énergie de l'ordre de l' eV c'est un exemple unique de coopération fructueuse entre les physiciens de France et du USSR. L'idée de créer le spectromètre à électron ESA-50 à Dubna doit être attribuée à Tzvetan Vylov, pendent sa visite au CSNSM (Orsay) en 1979, organisée par Chantal Briançon. Le spectromètre a été produit et mis en service à Dubna avec le support des collègues français en 1982. La coopération des scientifiques du CSNSM (Orsay) et JINR Dubna pour la création du spectromètre ESA-50 avec le développement d'une base méthodique unique pour la spectroscopie d'électrons de basse énergie du Département de Spectroscopie Nucléaire et de Radiochimie (JINR, Dubna) a produit des résultats scientifiques de haut niveau avec plus de 60 publications dans des revues de haut niveau pendent les derniers 30 ans. Le Catalogue des spectres d'électrons de basse énergie des radionuclides publié par le JINR illustre clairement les résultats obtenus avec le spectromètre ESA-50. Le catalogue contient des centaines de spectres d'électrons continus et discrets, mesurés avec le spectromètre ESA-50 pour des radionuclides avec valeurs de Z entre 24 et 95.

Ts. Vylov, Ch. Briançon, R.J. Walen:
founders of low energy precision electron spectroscopy at JINR with ESA-50 spectrometer

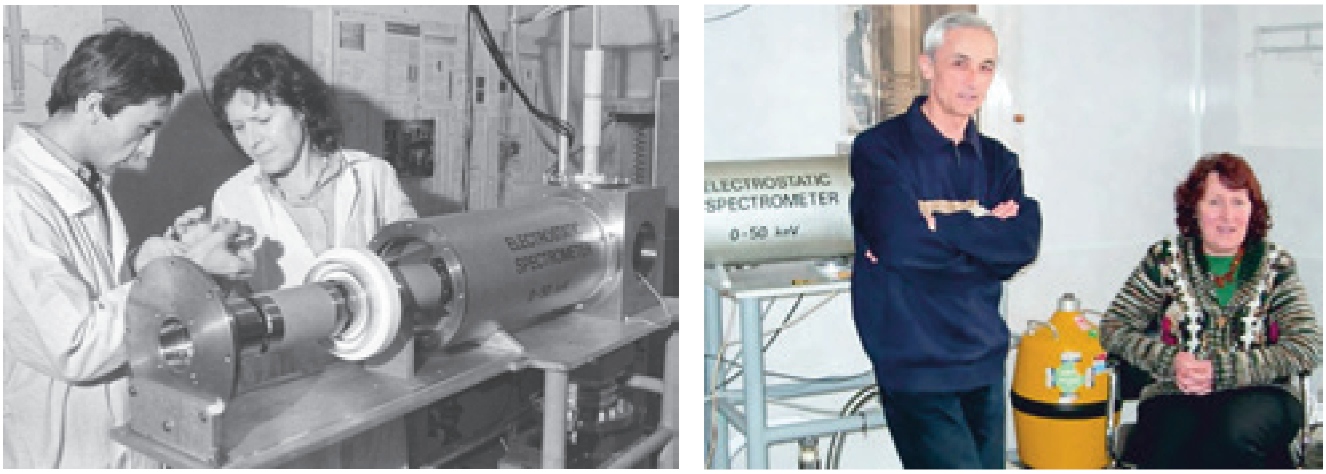

Collective of the ESA-50 spectrometer (1982)

The idea to create the ESA-50 electron spectrometer in Dubna belongs to Tzvetan Vylov, and appeared during his visit together with Ani Minkova to CSNSM (Orsay) in 1979 organized by Chantal Briançon. At that time a smaller version of such a spectrometer had been just built at CSMSM. A unique feature of the ESA-50 spectrometer is that it's the first instrument in nuclear physics which combines two types of analyzers, integral (spherical decelerator) and differential (double cylindrical mirror) ones. The relativistic effects arising in spectrometry of fast electrons and typical for one analyzer spectrometers are eliminated in this combination. As a result, the instrumental resolution can be as low as several eV for electrons' energies up to 50 keV. The motivation for making of bigger spectrometer (with higher transmission) at Dubna was determined by many actual tasks of nuclear and atomic physics, including direct neutrino mass measurement from analysis of beta spectra's shapes at end point.

The spectrometer has been produced at Dubna under the supervision of Ts. Vylov. Thanks to support of French colleagues (Ch. Briançon, R. J. Walen, B. Legrand) the spectrometer was commissioned in May 1982. The first measurements of low energy conversion electrons from ^{169}Yb decay demonstrated excellent parameters of the spectrometer: instrumental energy resolution 3.5 eV for 20 keV electrons, a world leading result! (NIM 221 (1984) 547). The creation of the unique spectrometer ESA-50 was highly appreciated by JINR directorate: the Institute honor prize for development of scientific methods was awarded in 1986 to Ch. Briançon, R. J. Walen, Ts. Vylov, A. Inoyatov, B. Legrand, A. Minkova, B. Pokrovsky and V. Chumin (participants in the creation of the spectrometer).

The launching of the ESA-50 spectrometer coincides with people great interest around the globe to investigate properties of neutrino. In particular, the direct determination of electron antineutrino mass from tritium beta spectrum. Soon after the famous result ITEP positive neutrino mass in 1980, many laboratories in different countries started their own tritium experiments. With its unique energy resolution and relatively high transmission, the ESA-50 spectrometer was able to address some fundamental methodic questions related to the problem. The performed measurements of natural widths of the internal conversion electron lines in ^{57}Co, ^{169}Yb (main calibration source for tritium experiments) and ^{201}Tl together with calculations (based on the measurements) demonstrated for the first time the possibility of generation of a non zero neutrino mass due to uncertainties with response

An adjustment of the spectrometer
(A. Inoyatov, R. Walen)



Left: Ani Minkova and Anvar Inoyatov assemble the ESA-50 spectrometer. Right: 25 years later

(instrumental line shape) of a complex system: spectrometer-solid state radioactive source.

In 1997–2001, in cooperation with the Nuclear Physics Institute of ASCR, ESA-50 spectrometer was used for the search of an admixture of heavy neutrinos in β-decay. From measurements of ^{241}Pu β-spectrum, the upper limit for the admixture of hypothetical neutrinos with rest masses between 14 and 17 keV/c^2 was derived to be less than 0.40% and 1% for the 5 to 14 keV/c^2 (the lowest limit being 0.10% for the 16 keV/c^2 mass) at the 95% C.L., independently of any free phenomenological parameter.

The ESA-50 spectrometer is now applied for investigation of the influence of physicochemical environment of atoms on energies of low energy internal conversion and Auger electrons. This research has an important impact on direct measurement of electron antineutrino mass due to task in frame of international tritium experiment KATRIN (http://www.katrin.kit.edu) of creation of radioactive sources emitting electrons with discrete energies which will be an extremely stable with time (on a meV level). Another task targeted with ESA-50 in frame of the KATRIN experiment is development of implanted stable calibration source of ^{83}Rb.

Besides the research connected with neutrino physics, the ESA-50 spectrometer was successfully used for systematic investigations of Auger relaxation of atomic systems occurring after nuclear decay. Precise experimental information about energies and intensities of LMM-, KLL-, KLM- and KMM-Auger transitions for 26 elements with $10 \le Z \le 70$ has been obtained. The accumulated data allowed us for the first time to perform a detailed test of different models describing Auger relaxation in atoms. In general, experimental results related to Auger processes of excited atomic systems obtained with ESA-50 spectrometer widely extended our understanding of Auger processes in atoms after nuclear decay.

The Catalogue of Radionuclide Low-Energy Electron Spectra published by JINR in 2003 became an important milestone and clearly reflected the results achieved with ESA-50 spectrometer. The catalogue contains hundreds of continuous and discrete electron spectra measured with ESA-50 spectrometer for radionuclides with Z in range from 24 to 95. The obtained experimental spectra with high energy resolution and with thin radioactive sources are definitely highly useful for researchers in nuclear physics, applied physics, surface physics and of course for electron spectrometry.

The cooperation of scientists from CSNSM (Orsay) and JINR (Dubna) in the creation of ESA-50 spectrometer together with the development of a unique methodical base for low energy electron spectroscopy at the Department of Nuclear Spectroscopy and Radiochemistry (JINR, Dubna) produced a highly fruitful scientific yield, with more than 60 works published in leading scientific journals.

AnCor — angular correlations with neutrinos in semi-leptonic processes

V. B. Brudanin, V. G. Egorov, DLNP, JINR

V. G. Egorov

Аннотация

Целью коллаборации AnCor являлось использование высокопрецизионной ядерной спектроскопии в целях изучения свойств нейтрино. В процессах с участием нейтрино (β-распаде, электронном или мюонном захвате) наблюдение доплеровского сдвига гамма-лучей при релаксации дочернего ядра позволяет определить отдачу, возникающую в результате испускания нейтрино, и таким образом полностью реконструировать кинематику процесса. Таким образом, удается изучать процесс без прямого детектирования нейтрино, требующего создания дорогостоящих детекторов большой массы с низким фоном. 20 лет назад первые эксперименты такого рода были проведены в Дубне физиками ОИЯИ и IN2P3 с поляризованным ^{56}Co. Для нескольких гамма-линий с энергиями 2–3 МэВ, возникающих при электронном захвате в ^{56}Co, удалось измерить 10–20 эВ доплеровский сдвиг и получить данные по спиральности нейтрино. В дальнейшем, в течение десяти лет похожие эксперименты были выполнены совместно с CSNSM (Орсэ), LPC (Кан) и ILL (Гренобль) для ^{14}O, ^{18}Ne, ^{24}Na и ^{32}Ar. Угловые корреляции между импульсом нейтрино и β-частицами были изучены с использованием твердых и газообразных мишеней, облученных нейтронами, ^{3}He и другими пучками на реакторе ILL, ускорителях Tandem и GANIL. Развитием проекта стало изучение кинематики процессов с участием нейтрино при мюонном захвате. Данный процесс не только оказался интересен сам по себе, но и позволил получить важнейшую информацию о матричных элементах ядер, испытывающих двойной бета-распад.

Résumé

La collaboration AnCor a étudié les propriétés des neutrinos avec des méthodes de spectroscopie nucléaire de haute précision. Dans des réactions semi-leptoniques avec neutrinos (décroissances β, EC ou capture électronique ou muonique) l'observation du shift Doppler des rayons γ secondaires permet d'accéder à l'impulsion du recul causée par le neutrino. De cette façon, on peut reconstruire la cinématique complète même sans détection directe du neutrino. Il y a vingt ans, le premier de ce type de mesures a été mené a bien .par des physiciens du JINR et de l'IN2P3 à Dubna avec ^{56}Co polarisé à une température de 10 mK. La mesure de plusieurs pics γ-dans la région de 2–3 MeV suivant la capture électronique du ^{56}Co est compatible avec un shift Doppler de 10–20 eV en directions opposées par rapport à l'axe de polarisation, ce qui nous a permis d'extraire l'élicité du neutrino. Des expériences similaires (mais avec la décroissance β de ^{14}O, ^{18}Ne, ^{24}Na et ^{32}Ar) ont été effectuées avec la collaboration des collègues du CSNSM (Orsay), LPC (Caen) et ILL (Grenoble) pendent les dix ans suivants. Les corrélations angulaires entre les impulsions du neutrino et de la particule β ont été étudiés avec des cibles solides et gazeuses, irradiées avec neutrons, ^{3}He et d'autres faisceaux auprès du réacteur ILL, et des accélérateurs Tandem et GANIL. Le développement ultérieur du projet était lie avec l'étude de la cinématique des processus de capture muonique. Au-delà de l'étude des propriétés du neutrino ces réactions ont apporté une information fiable sur les éléments de matrice nucléaire, pour les noyaux plus intéressants des isotopes de décroissance double beta.

AnCor collaboration controls Tandem accelerator (IPN, Orsay)

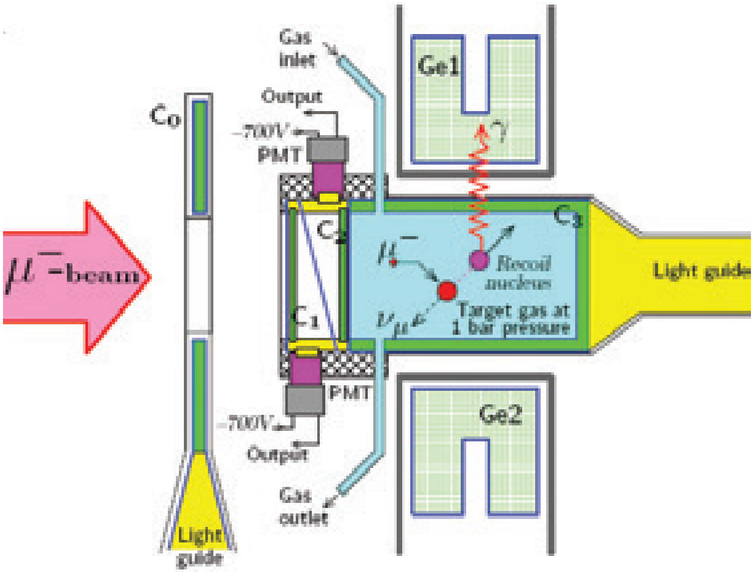
The nature of Neutrinos is an enigmatic puzzle for the physicists today. Being probably the most widespread particle in the Universe, the neutrino is at the same time the least explored one because of its extremely weak interaction with other particles and fields (the attenuation length for 1 MeV neutrino in water would be about 100 light years). It is very difficult to detect this elusive particle directly, but with high-precision nuclear spectroscopy it is quite possible to observe Doppler shift of the secondary γ-rays and thus to deduce the recoil momentum caused by the neutrino emission in β-decay, electron- or muon-capture. In this way one can reconstruct the full kinematic pattern of the process even without direct neutrino detection.

In the Standard Model (SM) all weak interaction processes are of the V-A type. Although there are strong experimental evidences for the V-A form of the charged weak current, the possible admixture of genuine scalar (S) and tensor (T) type interactions cannot be excluded and — as a matter of fact — is even present in most scenarios for physics beyond the SM, such as leptoquarks or R-parity violating interactions in supersymmetry. In principle, charged Higgs particles could also induce such a coupling. As a consequence, considerable efforts were undertaken in the β-decay sector to search for possible effects, which could signal deviations from the SM.

Twenty years ago we decided to perform some of such measurements and thus started collaboration with IN2P3 physicists. The first of our common experiments was done with ^{56}Co polarized at 10 mK temperature in Dubna. Several γ-lines in the 2–3 MeV region following the electron capture of ^{56}Co were measured to be Doppler-shifted by 10–20 eV at opposite directions with respect to the polarization axis, which allowed us to extract the neutrino helicity.

Similar experiments (but with β-decay of ^{14}O, ^{18}Ne, ^{24}Na and ^{32}Ar) were performed together with CSNSM (Orsay), LPC (Caen) and ILL (Grenoble) colleagues during the next ten years. Angular correlations between momenta of the neutrino and β-particle have been investigated using solid and gas targets irradiated with neutron, ^{3}He and other beams of the ILL reactor, Tandem and GANIL accelerators.

Much higher Doppler shift takes place in nuclear ordinary μ-capture (OMC), when the momentum transferred to the muonic neutrino occurs to be up to 100 MeV/c. In this case specific shape of the Doppler-broadened γ-lines provide important information about induced form factors — g_P/g_A, g_S/g_V, etc. After couple experiments with ^{28}Si target placed in magnetic field (thus exploiting the mSR-techniques) and irradiated by polarized muons from the JINR Phasotron, we started ten-year research program R-97-03 at PSI “meson factory” (Villigen, Switzerland). Within the program, solid and gas targets containing ^{12}C, ^{16}O and ^{20}Ne were investigated at μE4 and μE1 PSI muon beams and angular correlations among the muon spin, nuclear spin and neutrino momentum were extracted.



Scheme of the experiment with gas target operating at atmospheric pressure

Leaders of AnCor collaboration Ch. Briançon and V. Egorov

Working with muons, we realized that OMC could be a very useful tool for 2β studies, namely — to be an experimental test of the 2β nuclear matrix elements calculation. From this point of view it would be very important to study OMC with the (A, $Z+2$) target which is principal daughter of 2β-decaying (A, Z) parent nucleus and to measure partial μ-capture rates to 1^+ states of the intermediate (A, $Z+1$) nucleus. To perform these measurements one more PSI program R-02-02 was started and numerous natural and isotopic-enriched targets measured: ^{nat}Ca, ^{48}Ca, ^{48}Ti, ^{nat}Se, ^{76}Se, ^{nat}Kr, ^{76}Kr, ^{nat}Cd, ^{106}Cd, ^{nat}Sm, ^{150}Sm.

Dubna, January 14–15, 2013









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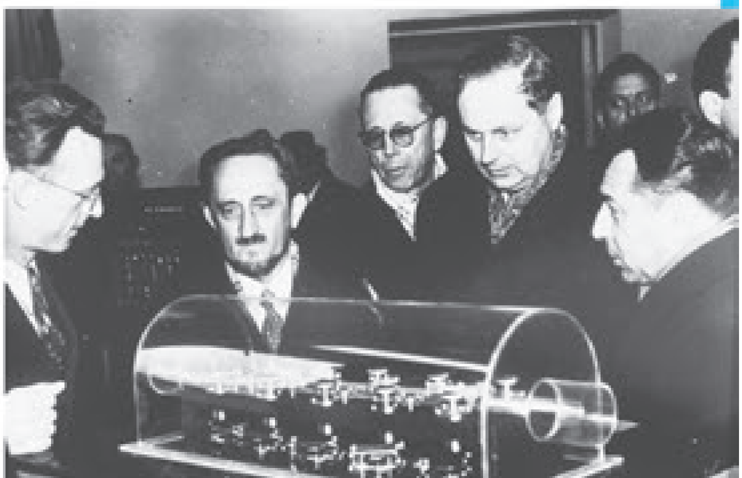

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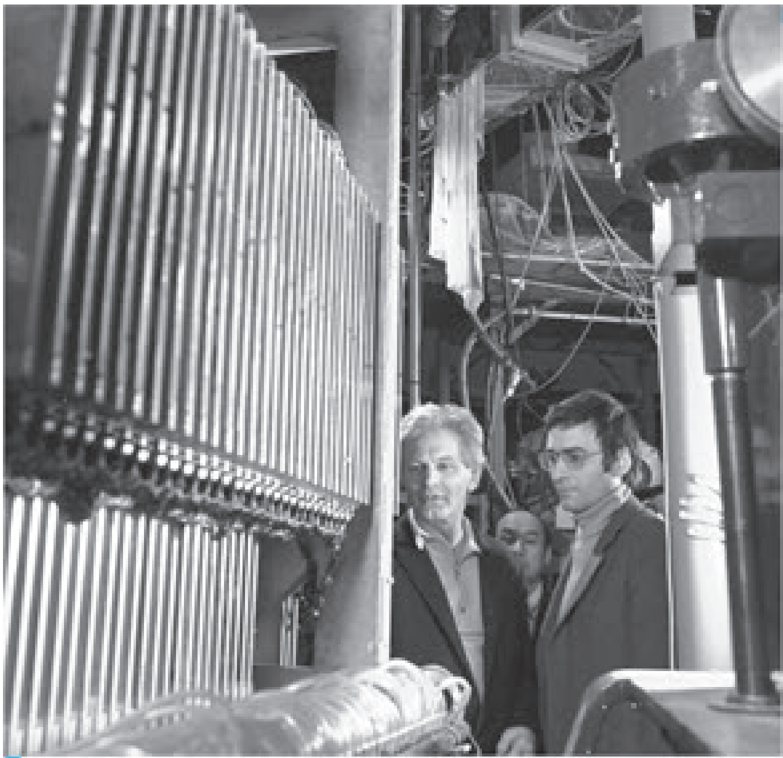

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Experiment TGV

***V. B. Brudanin, N. I. Rukhadze**, DLNP, JINR*

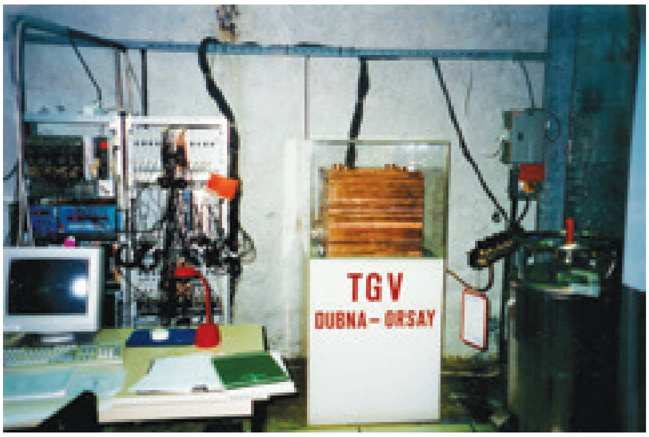
Аннотация

Сотрудничество ОИЯИ и IN2P3 в эксперименте TGV имеет целью исследование двойного бета-распада с использованием многодетекторных германиевых спектрометров.

Résumé

La coopération entre JINR et IN2P3 dans les expériences TGV (Telescope Germanium Vertical) est dédiée aux études de décroissance double beta avec plusieurs générations de spectromètres de multi-détecteurs germanium.

The JINR and IN2P3 collaboration in investigations of double beta decay (experiment TGV) was started at the end of 80s by Tsvetan Vylov (LNP) and Chantal Briançon (CSNSM). Ts. Vylov proposed to create a new type of multi detector spectrometer for investigation of rare nuclear processes. The base of the spectrometer is planar type HPGe detectors mounted one over another together with double beta emitters in the same cryostat. Such construction of the detector part provides a highly efficient detection of two correlated particles emitted in double beta decay together with rejection of background events. LNP JINR has a good experience in production of germanium detectors and its scientists were able to create detector part of the spectrometer, electronic scheme and software. The IN2P3 provided a possibility of measurement in the LSM underground laboratory (Modane) and participated in creation of electronic scheme of the spectrometer. Construction of the spectrometer took several years as it was a difficult problem. At the first stage the prototype of a cryostat has been developed to test detectors, detector holders, vacuum and cooling systems. Finally 16 planar type HPGe detectors with the sensitive volume 1200 mm^{2}x6 mm each were mounted in the cryostat of the spectrometer. The detector part of the cryostat was made from materials with low radioactive contaminations. Several months were spent on adjustment of electronic channels and on creation and testing of the data acquisition software. At the end of 1993 the spectrometer was ready. It was installed at the Modane underground laboratory and test measurements of the spectrometer background were started. At that time the spectrometer was named TGV (Telescope Germanium Vertical).



The TGV spectrometer mounted at the Modane underground laboratory

On the base of the results obtained in background measurements the copper shielding of the spectrometer was modified and the neutron shielding made from borated polyethylene was installed around the detector part. The search for double beta decay of ^{48}Ca ($Q_{\beta\beta} = 4271$ keV) was performed in 1996–1997 with the TGV spectrometer and samples made from mixture of 80% calcium carbonate ($CaCO_3$) and 20% polyvinyl formal on a mylar support. Eight sources contained ^{48}Ca with enrichment of 77.8%, another eight natural Ca (for an estimate of the source contribution to the registered background). The results of $T_{1/2}(2\nu\beta\beta) = 4.2^{+3.3}_{-1.3} \times 10^{19}$ y and $T_{1/2}(0\nu\beta\beta) > 1.5 \times 10^{21}$ y (90% CL) were obtained for double beta decay of ^{48}Ca after processing of experimental data accumulated during 8700 hours with approximately 1 g of enriched ^{48}Ca. This measurement showed a capability of the TGV spectrometer in investigation of rare nuclear processes with small amount of enriched isotope.

TGV-2 spectrometer mounted at the Modane underground laboratory

On the basis of the experience gained from application of the Ge multi detector spectrometer TGV for studying double beta decay of ^{48}Ca, a new low-background spectrometer TGV-2 intended for the investigations of $\beta^-\beta^-$, $\beta^+\beta^+$, β^+/EC, EC/EC decays has been developed. The detector part of the spectrometer TGV-2 is composed of 32 HPGe planar detectors each with sensitive volume of 20.4 cm^2 × 0.6 cm. The basic detection cell is a sandwich-like pair of face-to-face detectors with thin foils (52 mm in diameter, ~50 μm thickness, and a distance to the detector 1.5 mm) made of a double beta emitter placed between them. The 16 pairs are mounted one over another in a common tower of U-style cryostat. The total mass of the detectors is about 3 kg of Germanium, and the total sensitive volume is as large as 400 cm^3. The detector design allows high detection efficiency for multiple coincidence events resulting in strong suppression of the background. A method of filtering the electronic and microphone noise by digitizing the detector response with different shaping times (2 and 8 μs) was used for additional background suppression in the low-energy region (<50 keV). Several long-term experimental runs were performed at LSM (4800 m w.e.) from 2006 till the present time to search for double beta decay of ^{106}Cd (QEC/EC = 2775 keV). In the last one 16 samples made of 75% enriched ^{106}Cd with a total mass of 13.582 g were exposed during 12900 h. The coincidences between two characteristic KX-rays of Pd (~21 keV) detected in neighboring detectors were analyzed to search for 2νEC/EC decay of ^{106}Cd to the ground 0^+ state of ^{106}Pd. The search for 0νEC/EC resonance decay of ^{106}Cd to the excited states of ^{106}Pd was based on the analysis of KX-γ coincidences. Investigations of other branches of ^{106}Cd decay were based on the analysis of KX-γ and γ–γ coincidences. The analysis of KX-KX coincidences showed a small increase in the number of measured events in the region of ~21 keV, which might be the 2νEC/EC decay of ^{106}Cd. But the statistics was not enough to make any significant claim about the presence of the searched. A larger statistics should be accumulated with a higher process mass of enriched ^{106}Cd. New half-life limits were obtained for 2νEC/EC decay of ^{106}Cd to the ground state of ^{106}Pd — $T_{1/2} > 4.2 \times 10^{20}$ y, and for 0νEC/EC resonant decay of ^{106}Cd to 2741 keV and 2718 keV excited states of ^{106}Pd — $T_{1/2} > 1.8 \times 10^{20}$ y and $T_{1/2} > 1.6 \times 10^{20}$ y respectively. Our results improved the previous experimental ones on the 2νEC/EC decay of ^{106}Cd by more than two orders of magnitude and reached the region of theoretical predictions.

Search for neutrinoless double beta decay with NEMO-3

V. B. Brudanin, O. I. Kochetov*, DLNP, JINR*

Аннотация

Эксперимент NEMO-3, направленный на поиск безнейтринного двойного бета-распада, был расположен в подземной лаборатории г. Модана, Франция. Сотрудничество между ОИЯИ и институтами IN2P3 сыграло решающую роль при создании экспериментальной установки, а в дальнейшем было ключевым на всех этапах проведения эксперимента. Набор данных в эксперименте осуществлялся с 2003 по 2011 год с рядом изотопов. Основные изотопы были ~ 7 кг ^{100}Mo и ~ 1 кг ^{82}Se. В результате было получено лучшее в мире ограничение на период полураспада для безнейтринного бета-распада и верхний предел на эффективную массу майорановского нейтрино. В NEMO-3 также проводились прецизионные измерения в рамках стандартной модели процессов двойного бета-распада для 7 изотопов: ^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te и ^{150}Nd.

Résumé

L'expérience NEMO-3 ayant pour but la détection de la décroissance double beta sans émission de neutrons était située auprès du Laboratoire souterrain de Modane dans le tunnel du Fréjus entre la France et l'Italie. La coopération entre IN2P3 et JINR a joué un rôle clé dans toutes les étapes de l'expérience, depuis la construction a l'obtention des résultats importants jusqu'au démantèlement. L'expérience a pris des données entre 2003 et 2011 avec sept isotopes: ^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te et ^{150}Nd. Les deux isotopes principales étaient ~ 7 kg de ^{100}Mo et ~ 1 kg de ^{82}Se. Aucune evidence de $0\nu\beta\beta$ a été observée par l'expérience. Les données cumulées ont établi la contrainte plus sévère sur la masse effective du neutrino Majorana.

Experimental search for the neutrinoless double beta decay ($0\nu 2\beta$) is of a major importance in particle physics because if observed, it will reveal the Majorana nature of the neutrino ($\nu \equiv \nu$) and may allow an access to the absolute mass scale. The $0\nu 2\beta$-decay violates the lepton number and is therefore a direct probe for the physics beyond the standard model. A possibility of this process may be related to right-handed currents in electroweak interactions, supersymmetric particles with R-parity non conservation massless Goldstone bosons, etc. The two-neutrino double beta decay ($2\nu\beta\beta$) is a rare second-order weak interaction process. The accurate measurement of the$2\nu\beta$-decay is important since it constitutes the ultimate background in the search for 0ν-signal. It is useful for the test of the nuclear structure and provides valuable input for the theoretical calculations of the $0\nu 2\beta$-decay NME. The objective of the NEMO-3 experiment is the search for the $0\nu 2\beta$-decay and investigation of the $2\nu 2\beta$-decay with 10 kg of different $\beta\beta$-isotopes.

The beginning of NEMO-3 collaboration

The NEMO-3 detector was located in the Modane underground laboratory (LSM, France) in the Frejus tunnel between France and Italy. The LSM is shielded from cosmic rays by 1700 m of rock overburden (4800 m w.e). The detector is a cylinder made of detector segments containing different samples of double beta decay enriched isotopes. The source foils of $\beta\beta$ emitters were constructed from either a metal film or powder bound by organic glue to mylar strip. The source hangs between two concentric cylindrical tracking volumes consisting of 6180 open octagonal

Left: V. Timkin (JINR) assembles NEMO-3. Right: Finalizing of NEMO-3 setup

drift cells operating in Geiger mode. The tracking detector has an average position resolution of $\sigma = 0.3$ mm (transverse) and $\sigma = 0.8$ cm (longitudinal). The external walls of the tracking volume are covered by a calorimeter made of large blocks of plastic scintillator (1940 blocks in total) coupled to low radioactivity 3″ and 5″ PMTs. The energy resolution of the NEMO-3 calorimeter is $\Delta E/E = 14$–17%. The electron track curves under the influence of a 25 G magnetic field to reject positrons and external electrons. The detector is substantially shielded from external gamma ray background by 18 cm of low activity iron and 30 cm of water with boron acid to suppress the neutron flux.

There are seven different isotopes studied in NEMO-3. The two isotopes with largest mass are ^{100}Mo (6.9 kg) and ^{82}Se (0.93 kg). The other five isotopes ^{130}Te (620 g, 454 g in the enriched and 166 g in the natural Te source foils), ^{116}Cd (405 g), ^{150}Nd (37 g), ^{96}Zr (9.4 g), ^{48}Ca (7 g) were used for $2\nu2\beta$-decay and background studies. NEMO-3 took data from February 2003 to January 2011.

The $\beta\beta$ events are selected by requiring two reconstructed electron tracks with a negative charge curvature, originated from a common vertex in the source foil. Such a clear topological signature allows unambiguous reconstruction of $\beta\beta$ events and a very powerful background rejection. A radon trapping facility was installed at LSM in October 2004. This reduced the radon activity around the detector by three orders of magnitude while the radon activity inside the tracking chamber was reduced by a factor of ~ 6. The installation of this facility subdivided the NEMO-3 data taking period into two phases. The average radon activity inside the tracking chamber during Phase 1 (February 2003 – September 2004) was 35 mBq/m^3, while in Phase 2 (December 2004 – January 2011) it was reduced to 6 mBq/m^3.

The tracking plus calorimetry technique employed in NEMO-3 provided an accurate and efficient identification of background events. A comprehensive background model has been built using event topologies and energy distributions. Measurements of $2\nu\beta\beta$-decay half-life have been performed with unprecedented precision for seven isotopes studied in NEMO-3. The most precise measurement was obtained for ^{100}Mo. The signal-to-background ratio is ~ 76 yielding the result: $T^{2\nu}_{1/2} = 7.11 \pm 0.01(\text{stat.}) \pm 0.54(\text{sys.}) \times 10^{18}$ years.

The distribution of the two electron energy sum around the $Q_{\beta\beta}$ of ^{100}Mo was used to search for the $0\nu\beta\beta$-decay. No evidence for $0\nu\beta\beta$ has been observed with the result: $T^{0\nu}_{1/2} > 1.0 \times 10^{24}$ years, which corresponds to an upper bound on the Majorana neutrino mass of $\langle m_{\beta\beta}\rangle < (0.31–0.76)$ eV where the range reflects the spread in the NME calculations. Other mechanisms of $0\nu\beta\beta$-decay have been investigated. $V+A$ currents in the electroweak Lagrangian lead to $T^{0\nu}_{1/2} > 5.4 \times 10^{23}$ years giving an upper bound on the right-handed current admixture parameter, $\lambda < 1.4 \times 10^{-6}$. The $0\nu\beta\beta$ decay proceeding through a Majoron emission yields $T^{0\nu}_{1/2} > 2.1 \times 10^{22}$ years. We note that this limit corresponds to the world's most stringent constraint on the Majoron-neutrino coupling, $\eta < 0.5 \times 10^{-4}$.

The table below shows a summary of the main result obtained with 7 isotopes in NEMO-3. These are the most precise measurements of the $2\nu\beta\beta$ half-life for these isotopes. In case of ^{130}Te this is the first 5σ observation of its $2\nu\beta\beta$ process in a direct experiment. The ^{130}Te measurement provides a reference point to a long dispute between geochemical experiments that yielded inconsistent results for the ^{130}Te half-life.

Isotope	**Mass, g**	$T^{2\nu}_{1/2}$**, yrs**	$M^{2\nu}$	$T^{0\nu}_{1/2}$**, yr**
^{100}Mo	6914	$(7.11\pm0.54) \times 10^{18}$	0.126 ± 0.006	$> 1 \times 10^{24}$
^{82}Se	93	$(9.6\pm1.0) \times 10^{19}$	0.049 ± 0.004	$> 3.2 \times 10^{23}$
^{130}Te	454	$(7.0\pm1.4) \times 10^{20}$	0.0173 ± 0.0025	$> 1.0 \times 10^{23}$
^{116}Cd	405	$(2.88\pm0.17) \times 10^{19}$	0.0685 ± 0.0025	$> 1.3 \times 10^{23}$
^{150}Nd	37	$(9.11\pm0.68) \times 10^{18}$	0.030 ± 0.002	$> 1.8 \times 10^{21}$
^{96}Zr	9.4	$(2.35\pm0.21) \times 10^{19}$	0.049 ± 0.002	$> 9.2 \times 10^{21}$
^{48}Ca	6.99	$(4.40\pm0.64) \times 10^{19}$	0.0238 ± 0.0015	$> 1.3 \times 10^{22}$

Main results obtained with 7 isotopes studied in NEMO-3. $T^{0\nu}_{1/2}$ limits are shown at 90% CL.
The NME values, $M^{2\nu}$ are scaled by the electron rest mass

The next generation double beta decay experiment SuperNEMO

V. B. Brudanin, O. I. Kochetov, *DLNP, JINR*

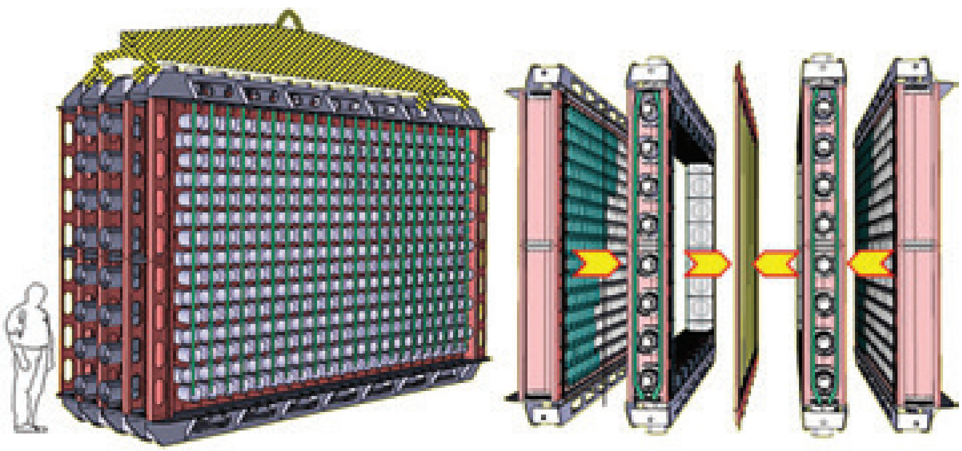
Аннотация

SuperNEMO — это эксперимент нового поколения по исследованию двойного бета-распада на базе успешной треко-калориметрической методики, использованной в эксперименте NEMO-3. Благодаря уникальному трекингу и возможности идентификации частиц эксперимент SuperNEMO может не только обнаружить безнейтринный двойной бета-распад, но и определить лежащие в основе физики элементарных частиц механизмы. Благодаря тому, что в SuperNEMO источник и детектор разделены, можно одновременно изучать несколько изотопов, таких как ^{82}Se и ^{150}Nd. Общая масса изотопов может быть 100–200 кг. С этой массой изотопа чувствительность по периоду полураспада может достигнуть 10^{26} лет. Это даст возможность достигнуть эффективной майорановской массы нейтрино около 50 мэВ в зависимости от ядерных матричных элементов. В настоящее время ведется создание модуля-прототипа детектора. Основными проблемами для R&D проекта, решаемыми физиками ОИЯИ и IN2P3 совместно, являются: производство фольг-источников, радиоактивная чистота конструкционных элементов, энергетическое разрешение калориметра и конструкция трекового детектора.

Résumé

SuperNEMO représente la future génération d'expériences de décroissance double beta basée sur la technologie réussie de tracking plus calorimétrie de l'expérience NEMO-3. Dû a ses capacités uniques d'identification et tracking des particules l'expérience SuperNEMO pourrait être capable de découvrir la décroissance double beta sans neutrino ainsi que de déterminer le mécanisme sous-jacent. Dû à la separation de la source et du detecteur, SuperNEMO peut étudier une variete d'isotopes comme le ^{150}Nd et le ^{82}Se. La masse totale des isotopes sera dans l'interval 100–200 kg. Avec cette masse des isotopes, une sensibilité à une demi-vie plus grande que 10^{26} ans peut etre atteinte.Ceci pourrait donner acces a masses des neutrino Majorana de l'ordre de 50 meV, dependant de la valeur des elements de matrice nucleaire. La construction d'un module du prototype a commencé. Les défis les plus importants pour le projet international de R&D sont la production de la source, la radiopurité, la resolution du calorimetre et la construction du tracker.

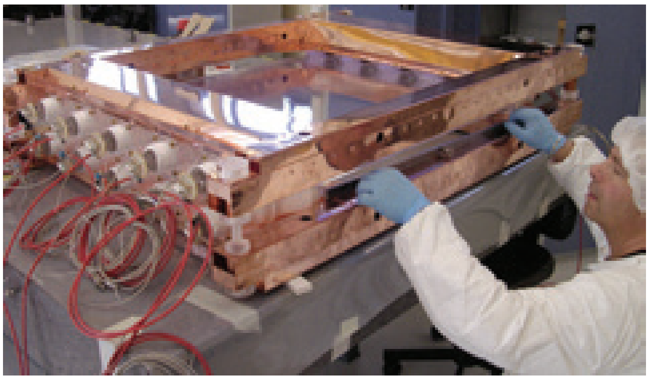
SuperNEMO is the next-generation double beta decay experiment based on the successful tracking plus calorimetry technology of NEMO-3 experiment. Due to its unique tracking and particle identification capabilities the SuperNEMO experiment might be able to discover neutrinoless double beta decay as well to determine the underlying physics mechanism. Due to the



SuperNEMO Detector Module. Main detector sub-modules are shown on the right with a source foil frame in the center surrounded by two tracker sub-modules on either side and followed by two calorimeter sub-modules separation of source and detector, SuperNEMO can study a range of isotopes such as ^{150}Nd and ^{82}Se. The total isotopes mass will be in the range 100–200 kg. With this isotope's mass a sensitivity to a half-life greater 10^{26} years can be reached. This could give access to Majorana neutrino masses of about 50 meV, depending on the value of the nuclear matrix elements. Construction of a prototype module has been started. The main challenges for the international R&D project are source foil production, radiopurity, calorimeter resolution and tracker construction.

The SuperNEMO design envisages twenty identical modules, each housing 5 kg of isotope. The module will be 6 m long, 4 m high and 2 m wide with the source foil to calorimeter wall distance of 44 cm. The source is a thin (40 mg/cm^2) foil inside the detector. It is surrounded by a gas tracking chamber followed by calorimeter walls. The tracking volume contains 2000 wire drift cells operated in Geiger mode in a gas mixture of He (95%), Ar (1%) and ethyl alcohol (4%). The cells are arranged in nine layers parallel to the foil. The calorimeter is divided into 500 plastic scintillator blocks with a cross-section of 26 cm x 26 cm coupled to low radioactive 8-inch PMT. A 25 G magnetic field is envisaged for SuperNEMO to reject positron events from external γ-background. The modules will be surrounded with ultra-pure water passive shielding. The detector will be located in a new extended LSM laboratory which is expected to become operational after 2013.

The sensitivity of SuperNEMO has been studied extensively with a full chain of GEANT-4 based simulation software and modeling the detector effects and backgrounds based on NEMO-3 experience. An exposure of 500 kg x years will give a sensitivity for ^{82}Se of $T^{0\nu}_{1/2} > 10^{26}$ years at 90% CL corresponding to an upper bound on the effective Majorana neutrino mass of 50–100 meV.



Radiopurity of SuperNEMO source foils is controlled by the BiPo dedicated detector designed for this purpose

An extensive R&D carried out between 2006–2010 by scientists from JINR and IN2P3 has addressed three main challenges: improvement of the calorimeter energy resolution, radiopurity of the source foils, and optimization of the tracker. The expected improvement in performance of SuperNEMO compared to NEMO-3 is shown in the Table below.

A good energy resolution is important for discrimination of the $0\nu\beta\beta$ peak in the energy sum of the two electrons from background of the $2\nu\beta\beta$-decay. A large number of studies have been carried out to investigate the material, size, shape and coating of the calorimeter blocks as well as performance and intrinsic activity of the PMTs. Test bench studies have been backed up by optical simulations which were also verified on the NEMO-3 calorimeter. As a result the feasibility to reach the required energy resolution

Expected improvements in SuperNEMO performance compared to NEMO-3

Detector Parameter	NEMO-3	SuperNEMO
Isotope/mass	7 kg of ^{100}Mo	100 kg of ^{82}Se (or other)
Detector efficiency	18%	30%
^{208}Tl (in $\beta\beta$ source) ^{214}Bi (in $\beta\beta$ source) ^{222}Rn (in tracker)	~ 100 μBq/kg ≤ 300 μBq/kg ~ 5 mBq/m^3	≤ 2 μBq/kg ≤ 10 μBq/kg ≤ 0.15 mBq/m^3
Calorimeter FWHM At $Q_{\beta\beta}$ = 3 MeV	8%	4%
$T^{0\nu}_{1/2}$, 90% CL	1 x 10^{24} yr	1 x 10^{26} yr

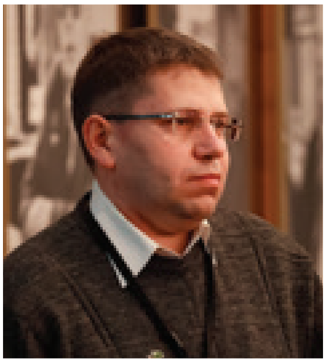
has been experimentally demonstrated. Building blocks of the SuperNEMO calorimeter will be large PVT-based scintillator blocks coupled to a low radioactivity PMT.

Having successfully completed the R&D stage the SuperNEMO collaboration has started construction of the first module, the demonstrator. The main goals of the demonstrator are: to demonstrate feasibility of mass production of detector components under ultra-low background conditions; to measure backgrounds especially from radon emanation; to finalize the detector design; to produce a competitive $\beta\beta$ physics result. To accomplish the latter goal on a competitive time scale the demonstrator module will house 7 kg of ^{82}Se isotope. The construction and commissioning of the demonstrator will be completed in 2013 with data taking expected to start in the second half of 2013. The module will be placed in the LSM laboratory. The expected sensitivity of the demonstrator after 17 kg x yr of exposure is 6.5×10^{24} yr (90% CL) which is equivalent to 3×10^{25} yr obtained with ^{76}Ge assuming equal NME and using the phase space ratio for these isotopes. This sensitivity will be reached by the end of 2015 and will match the sensitivity of the GERDA-Phase1 experiment allowing experimental verification of a recent claim of evidence for $0\nu\beta\beta$ decay.

The modular design of the SuperNEMO makes it possible to proceed with construction and data taking in parallel. The full detector construction is expected to start in 2014 (in parallel with demonstrator running). The 500 kg x yr exposure will be reached in 2019 pushing the sensitivity to the effective Majorana neutrino mass down to 50–100 meV.

Direct detection of dark matter particles in EDELWEISS experiment

V. B. Brudanin, E. A. Yakushev, *DLNP, JINR*



E. A. Yakushev

Аннотация

Международный эксперимент EDELWEISS (Франция, Германия, Россия, Великобритания), проводящийся в подземной лаборатории LSM (Франция), направлен на прямое детектирование слабовзаимодействующих массивных частиц из галактического гало, считающихся основными кандидатами на роль темной материи. ОИЯИ участвует в эксперименте с 2005 года и отвечает за самые различные стороны эксперимента, начиная со сборки, отладки и запуска установки, за тестирование новых детекторов, наладку электроники; разработку процедур и методов понижения радиоактивного уровня, в частности, процедур по сертификации радиоактивных источников, по их использованию, по работе в чистой комнате и т. д.; набор данных (как каждодневные процедуры, так и подготовку и проведение специальных калибровочных измерений с γ- и нейтронными источниками для выяснения характеристик детекторов и их стабильности во времени; экспериментальное изучение фона и разработку методов детектирования нейтронов и радона; создание новых детекторов; моделирование детекторов и анализ данных.

Résumé

L'expérience EDELWEISS (Expérience pour DEtecter Les Wimps En Site Souterrain) est dédiée à la détection directe des particules de Matière noire, sous forme de WIMPs prises au piège dans le halo Galactique. L'expérience est construit et maintenu par une collaboration internationale (France, GB, Germany et Russie) dans le Laboratoire Souterrain de Modane dans les Alpes françaises. Le JINR participe à ce projet depuis 2005. Le groupe de Dubna a été constitué dans le cadre du Département de Spectroscopie Nucléaire du DLNP. Depuis 50 ans, ce département a une grande expérience dans la spectroscopie nucléaire de haute précision, utilisant les détecteurs semi-conducteurs et les scintillateurs. Il a aussi 20 ans d'expérience dans l'étude de processus rares dans un environnement souterrain. JINR participe et a la responsabilité de plusieurs parties du projet: l'assemblage et la mise en service, la prise des données (qui comprend les procédures journalières de routine ainsi que les runs spécifiques de calibration; les études à bas bruit de fond et le développement de méthodes de détection des neutron et du radon, le développement de nouveaux detectors; la simulation du detector et l'analyse des données.

After 1992 when the scientists who analyzed data from COBE experiment announced the discovery of the primary temperature anisotropy of cosmic microwave background it became clear that in combination with other astronomical and astrophysical data analysis of this anisotropy gives undoubted evidence that Universe includes non-luminous, nonbaryonic matter. As the precision of cosmological and astronomical observations improves, there are stronger indications that the mass of galaxies and of clusters is mostly made of Dark Matter, a new form of matter that neither emits nor absorbs electromagnetic radiation. At the same time, it is very intriguing that the most favoured solution to the problem of hierarchy in particle physics, Supersymmetry (SUSY), predicts very naturally that the Universe is filled with weakly interacting massive particles (WIMPs). The prospect of discovering SUSY particles at the LHC is thus very exciting. However, a key element to confirm that WIMPs are indeed present in our Galactic halo would be to observe the nuclear recoils arising from the rare collisions of these particles with atoms in the laboratory. EDELWEISS international collaboration was formed to make an experiment to detect such

EDELWEISS collaboration meeting at Dubna (excursion to Sergiyev Posad, October 2007)





Few pictures representing the EDELWEISS cryostat assembly and detectors installation and wiring collisions. SUSY cannot predict very precisely the rate of these collisions per kilogram of target matter. Reasonable values lie in the range from 10^{-45} to 10^{-43} cm^2. In particular, an important class of SUSY models ("Focus Point") predicts cross-sections of the order of 10^{-44} cm^2, corresponding approximately to one collision per day per 500 kg of matter, assuming standard values for the local WIMP density and velocities. The identification of a WIMP interaction in a detector is therefore challenging, because the rate of WIMP interactions is very small compared with the event rates expected from background radioactivity of present detectors with highest purity and from cosmic radiation. In addition, the recoil energies produced by elastic WIMP-nucleus scattering are very small, in the range of a few keV to a few tens of keV. To address these experimental challenges, a new generation of cryogenic detectors has been developed by EDELWEISS, exhibiting powerful background discrimination in combination with unprecedented energy threshold and resolution. The detectors allow highly efficient identification of nuclear recoils (caused by WIMP and also neutron interaction) by eliminating electron recoils due to radioactivity. With such technique EDELWEISS experiment was the first experiment to reach sensitivity below 2×10^{-42} cm^2. The EDELWEISS collaboration is searching for WIMP Dark Matter using natural HPGe cryogenic detectors. The experiment is located in deep LSM (France) underground laboratory. EDELWEISS is currently in the exploitation phase, involving Dark Matter data taking for several years with simultaneous continuous improvement of background rejection technique and increasing of the detector's mass.

Recently EDELWEISS collaboration demonstrated that main background limiting sensitivity of the experiment is arising from the inability to reject events occurring close to the surface of the detector, for which a deficient charge collection can mimic the ionization yield of nuclear recoils. Despite successes in reducing the surface contamination in EDELWEISS (mostly due to ^{210}Pb daughters), sensitivity levels were still limited to 5×10^{-43} cm^2. Within EDELWEISS were therefore developed detectors with an innovative interleaved electrodes design (ID detectors), able to discriminate against events occurring within 1 mm from the detector surface. With 4-kg of such ID detectors at EDELWEISS cross-section of 4.4×10^{-44} cm^2 for WIMP nucleon interaction is excluded at 90% CL for WIMP mass of 85 GeV/c^2. In 2011 new 800 g FID detectors with significantly increased fiducial volume were tested in a few months run for its applicability in EDELWEISS and for its potential in further suppression of the surface background. New 800 g FID detectors will be added progressively to the experiment (40 detectors) to enhance the sensitivity to WIMPs. The aim is to have in next 2 years 3500 kg·d with no surface background events at nuclear recoil band above 15 keV threshold. This will provide the sensitivity on the 4×10^{-45} cm^2 level in successful competition with other world leading Dark Matter search experiments (Xe, Ar based, and CDMS).

Dubna team joined the EDELWEISS project in September 2005. JINR started its participation in the project from commitment to assembly of experimental setup from commissioning of EDELWEISS-II environment (clean room operation and procedures, developing procedures of operation with radioactive sources on the site, etc.) to participation in cryostat assembly and detector installation and wiring. Main responsibility of JINR group in EDELWEISS experiment is connected with experimental and MC studies of backgrounds. For unbiased interpretation of results of Dark Matter search experiments it is critically important to have a wide knowledge and under-

Members of JINR EDELWEISS group E. Yakushev and S. Rozov perform installation of 241 g point contact detector into a cryostat. Photo taken in June 2011, EDELWEISS clean room in the LSM laboratory standing of all background sources. But not only value of background but also changes of it with time are important. Experimental studies conducted: a) participation in low radioactive materials selection process; b) continuous monitoring of fast neutrons with detection system built at JINR, started in 2006 and going in parallel with WIMP data taking at EDELWEISS-II; c) measurement of fast neutrons produced by muons in coincidence with EDELWEISS-II muon veto system; d) measurement of thermal neutrons with low background neutron detection system built at JINR; e) monitoring of radon level at proximity to EDELWEISS-II cryostat and at detector storage with high sensitive (1 mBq/m^3) and low background radon detection system built at JINR. Recently EDELWEISS collaboration has decided to extend its research area to low mass WIMPs with using low threshold point contact HPGe detectors developed by JINR. As first step one 241 g detector has been delivered to EDELWEISS site, it has been installed in an available cryostat, and test inside of EDELWEISS-I shield has been started.

The target tracker of OPERA experiment

Marcos Dracos, IPHC, **Yuri Gornushkin**, JINR

Résumé

A la suite d'une longue collaboration fructueuse sur la décroissance Double Beta sans neutrinos, le Laboratoire Dzhelepov des Problèmes Nucléaires et l'Institut Pluridisciplinaire Hubert Curien ont commencé une collaboration sur OPERA, l'expérience d'oscillations de neutrinos. Cette collaboration a commencé en 2001 et est toujours active. Le résultat de ce travail commun a été la construction du détecteur principal électronique de l'expérience, le tracker de la cible. Ce détecteur, composé de strips de scintillateur de plastique et de PMT multianode a été entièrement construit à Strasbourg avec la forte participation des physiciens, ingénieurs et techniciens de Dubna.

Аннотация

После многолетнего плодотворного сотрудничества по поиску безнейтринного двойного бета-распада Лаборатория ядерных проблем им. В.П. Джелепова (ОИЯИ) и Междисциплинарный институт имени Юбера Кюрьена начали новый проект — поиск нейтринных осцилляций в эксперименте OPERA. Это сотрудничество началось в 2001 году и все еще продолжается. Результатом совместной работы стало создание основного детектора установки — так называемого Target Tracker. Этот детектор, состоящий из сцинтилляционных стрипов и многоканальных ФЭУ, был построен в Страсбурге при активном участии специалистов из Дубны: физиков, инженеров и техников.

JINR Dzhelepov Laboratory of Nuclear Problems (LNP) and Institut Pluridisciplinaire Hubert Curien (IPHC) have been collaborating on neutrino oscillation OPERA experiment since 2001. This collaboration was a natural continuation of a previous one on neutrinoless double beta NEMO3 experiment.

The aim of OPERA experiment is to study neutrino oscillations making use of the neutrino beam from CERN (CNGS) and placing the OPERA detector in the Gran Sasso Underground Laboratory in Italy. Contrarily to other "disappearance" experiments, OPERA tries to observe the appearance of a neutrino flavour not existing in the initial neutrino beam. More precisely, this experiment tries to detect tau neutrinos in the muon neutrino CNGS beam and prove unambiguously the oscillation $\nu_\mu \rightarrow \nu_\tau$.

Although the detector is based on the idea of the emulsion cloud chambers packed in bricks, an essential part of it is the Target Tracker detector (TT). The aim of the TT is to find the neutrino interaction location and give kinematical and calorimetric information about the observed events.

The TT detecting technique is based on the use of plastic scintillator strips from which the light is collected by WLS fibres. The strips are packed with 64 to form flat detection modules equipped by multianode PMTs for light detection.

The 7 m long strips have been produced in Kharkov (Ukraine) in the AMCRYS institute partner of JINR, where physicists of Dubna provided all the necessary equipment for better technological control of the production and of the quality of the strips. In order to have high detection efficiency, it was required that at least 4 photoelectrons had to be observed on each side of the strips for a signal induced by a minimum ionizing particle crossing the strips at their middle in length. Thanks to this collaboration, this criterion was not only fulfilled but also the mean value of photoelectrons was of the order of 6 inducing a detection efficiency higher that 99%.

After shipping the strips to Strasbourg, the TT modules were assembled and calibrated by the joint IPHC–LNP team. From 2004 to 2006 more than 500 modules have been fabricated able to cover a surface of 6000 m^2. For this work requiring 14 people permanently working at IPHC, more than 12 Dubna physicists, engineers and technicians have participated coming periodically at Strasbourg to join the local construction team.

The assembly and insertion inside the OPERA detector of the TT walls started in the Gran Sasso

Laboratory in 2005, during the construction of the modules in Strasbourg. The physicists and engineers of both institutes took an active part in this work as well.

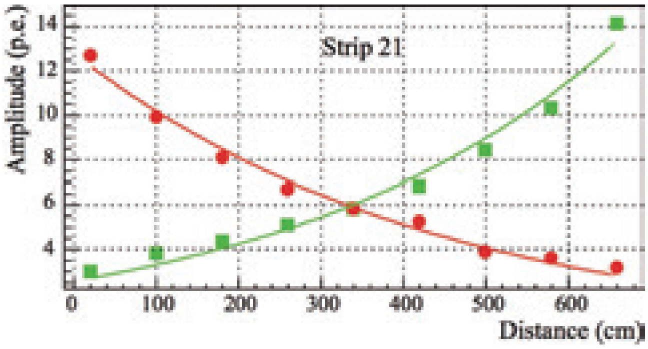
This work has required very strong efforts and close collaboration between the two teams for the successful accomplishment of this task. Not only the TT walls (62) were assembled in situ using the modules constructed in Strasbourg, but also they were inserted inside the OPERA detector, tested and aligned.

Another example of the close cooperation of IPHC and LNP is the development, in parallel with the construction, of algorithms and software for the TT data analysis necessary for a successful exploitation of the TT signal. In the same framework of this cooperation a valuable contribution has been done on the TT simulation necessary to well understand the behaviour of this detector.

During 2006 the two groups, Dubna and Strasbourg, jointly proceeded to the commissioning of the OPERA Target Tracker. For the preparation of the detector all information extracted during the calibration made in Strasbourg has been implemented and used by the main OPERA analysis programmes. This work allowed the collaboration to observe the first neutrino interactions as soon as the CNGS neutrino beam was ready.

Intensive data taking periods started in 2008 necessitating quick reaction in case of problems and development of massive simulation and analysis tools. During this period a close monitoring of the Target Tracker performance was needed.

An aging monitoring system has been prepared in Strasbourg consisting of one full Target



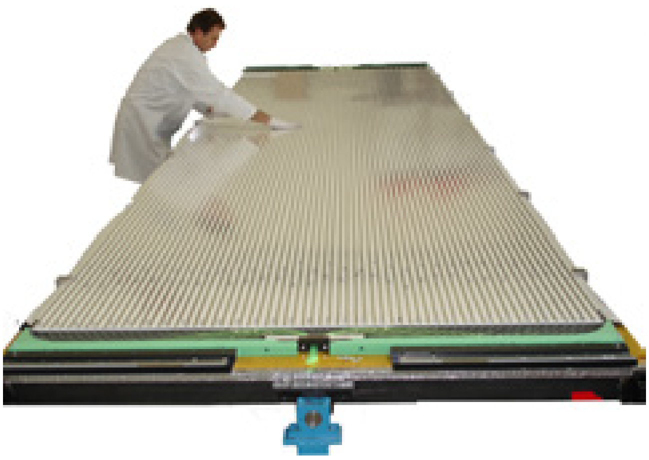
Number of photoelectrons observed on the two sites (red and green) of a scintillating strip versus the distance from the two photomultipliers

Tracker module built with scintillating strips representing the whole scintillator production. This setup is still in use.

Periodic maintenance campaigns of the TT are done where both groups participate. Thanks to this maintenance the TT detection efficiency remained constant and high during all the data taking period.

In 2010 the OPERA Collaboration discovered the first ν_τ candidate event. This was a great achievement of the OPERA experiment. Stable and excellent performance of the Target Tracker detector has played important if not crucial role in this success.

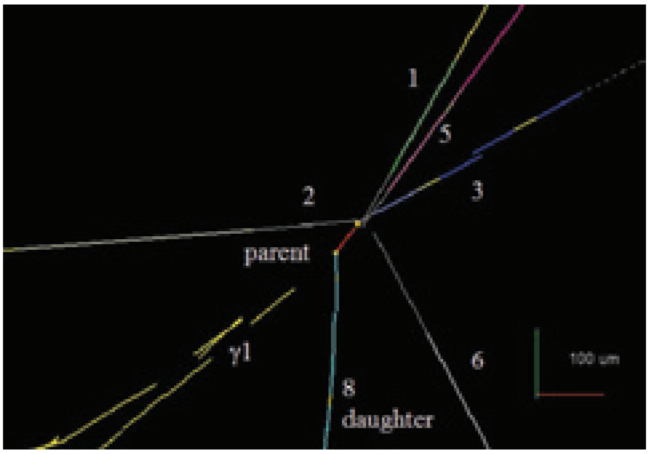
A successful work on brick finding algorithms at JINR resulted in the adoption by the Collaboration of these tools for the neutrino interaction vertex search. At the same time the Strasbourg group worked on the hadronic energy reconstruction in the Target Tracker detector. Both tasks are in close relation in terms of event reconstruction as well as Monte Carlo simula-



Production of one module of the OPERA Target Tracker. The dimensions of each module are 1.7 x 7 m^2

Celebration by both teams of the construction of the 200th Target Tracker module out of 500

Insertion of the first Target Tracker wall in OPERA detector in 2004. Each wall has a dimension of 8x8 m^2



First OPERA ν_τ candidate discovered in 2010. This event could come from the decay of the tau lepton into hadrons produced by a tau neutrino interaction

tion. This work was done again in a close contact of the two groups.

2012 is a full data taking run the end of which will mark the end of the CNGS running. During this year the Collaboration has discovered a second ν_τ candidate event.

The running of the Target Tracker will continue up to the moment where all interesting bricks will be extracted in order to record cosmic rays crossing the detector and which could induce background delaying the scanning of the emulsions.

We hope that the two groups will continue collaborating on future neutrino oscillation projects as those devoted to the discovery of CP violation in the leptonic sector and to determination of the neutrino mass hierarchy.

For all these years, this collaboration between the two groups has been supported by both institutions, IN2P3 and JINR, through a French–Russian Collaboration Agreement.

BLTP–IPNO collaboration on nuclear structure problems

A. I. Vdovin and **V. V. Voronov**, BLTP, JINR


V. V. Voronov

Аннотация

Представлен краткий исторический обзор сотрудничества сектора структуры ядра Лаборатории теоретической физики им. Н.Н. Боголюбова ОИЯИ с учеными Института ядерной физики в Орсэ. Кратко обсуждены перспективы будущих совместных исследований.

Résumé

Nous présentons une courte revue historique d'une collaboration entre les groupe de structure nucléaire du Laboratoire Bogoliubov de Physique Théorique et de l'IPN (Orsay). Les perspectives pour les études futures de cette collaboration sont discutés brièvement.

Theoretical studies on nuclear structure physics at the Laboratory of Theoretical Physics at JINR were initiated by N. N. Bogoliubov. The methods invented by N. N. Bogoliubov in his fundamental works on the superconductivity theory were then successfully employed by his disciple V. G. Soloviev and other Dubna theorists in constructing the microscopic nuclear structure theory.

At the beginning of the seventies a discovery of the so-called "new giant resonances'' gave a strong impact on further developments of nuclear structure physics. To incorporate the new phenomena, which occur at rather high excitation energies, into the framework of current microscopic approach V. G. Soloviev has formulated a new model which was named the Quasiparticle-Phonon nuclear Model (QPM) [1]. Within this model one can take into account an interplay between the single-particle and collective nuclear modes. The QPM is very convenient to perform calculations in large configuration spaces that is the case to study the nuclear structure at high excitation energies.

The use of random phase approximation (RPA) phonons as building blocks of a model wave function appears to be very suitable for involving an essential part of long-range nuclear correlations. A large variety of collective vibrational states is a conspicuous feature of nuclear spectra. Many of their properties can be described in RPA since, at least approximately, nuclear vibrations evidently exhibit bosonic properties. On the other side, most of the RPA states are of almost pure two-quasiparticle (or particle-hole) character, and including them into a model wave function one takes into account a coupling with a sea of numerous non-collective states. Certainly, treating these noncollective states as bosons one should be cautious with violation of the Pauli principle. The corresponding procedure was also elaborated within QPM.

Taking into account a coupling between single-particle states with the collective excitations enables theorists of BLTP to investigate the strength distributions of different nuclear subshells. Experimental study of deep hole and high-lying single-particle modes via one-nucleon transfer reactions has been done by S. Gales, H. Langevin and collaborators in IPN, Orsay. It was naturally to compare and discuss experimental data and theoretical calculations that results in an establishing of the BLTP–IPNO collaboration in the early eighties. One can find a review of the experimental and theoretical results on the damping of high-lying single-particle modes in heavy nuclei in [2].

As was shown in [3], using of the microscopic form factors is very important to analyze the nuclear reaction experimental data. The investigation of the decay of high-lying single-particle states enables one to study their damping process through the determination of the relative contributions of the direct and statistical components.

A method for calculating a non-statistical particle decay of excited states in odd nuclei developed by theorists from Dubna and Orsay was used to evaluate partial cross sections and branching ratios for the neutron decay of the

A. I. Vdovin, V. V. Voronov, H. Langevin-Joliot and V. G. Soloviev (Dubna, 1986). Discussion of new experimental data on damping of deep-hole states

high angular momentum single-particle states in Pb and Zr [4]. The calculated branching ratios were compared with existing experimental data of IPNO group. A general agreement was found.

Among the great variety of microscopic nuclear models aiming at a description of nuclear excitations one can distinguish one approach in which the emphasis is put on the consistency of the picture by employing an effective interaction which must describe, throughout the periodic table, the ground states in the framework of the Hartree–Fock (HF) approximation and the excited states in time-dependent HF, or RPA or approximations beyond. To this class belong the Skyrme-type interactions. This approach is quite successful for calculating the main features of giant resonances in closed-shell nuclei. The main difficulty is that the complexity of giant resonance calculations beyond standard RPA (e.g., for studying damping mechanisms of collective excitations) increases rapidly with the size of the configuration space and one has to work within limited spaces. When the residual particle-hole (p-h) interaction is separable, the RPA problem can be easily solved no matter how many p-h configurations are involved. In this case the RPA eigenvalues are obtained as the roots of a single secular equation and then the corresponding RPA amplitudes can be calculated by performing only summations.

Starting from an effective interaction of Skyrme type, a finite rank separable approximation (FRSA) was proposed by Nguyen Van Giai, Ch. Stoyanov and V. V. Voronov [5] for the residual particle-hole interaction with the aim to allow one to perform structure calculations in very large particle-hole spaces. The FRSA was applied to study many properties of nuclear excitations [6, 7]. The investigation of the charge-exchange modes within the FRSA has been started recently [8]. Many scientists from IPNO participated at the traditional Nuclear Structure Conferences in Dubna and contributed a lot to their successful work.

Nguyen Van Giai gives a lecture at the International School "Nuclear Theory and Astrophysical Applications" (Dubna, 2005)

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The Quasiparticle-Phonon Model in the light of the Skyrme Energy-Density Functional

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Résumé

Dans cette note nous évoquons certains aspects de la collaboration entre les théoriciens nucléaires du JINR Dubna et leurs collègues de l'IPN Orsay. Cette collaboration a commencé il y a plus de 30 ans et se poursuit activement sur des sujets de spectroscopie nucléaire. Une des particularités de l'approche Dubna-Orsay est de concilier les avantages respectifs des fonctionnelles de la densité du type Skyrme et des interactions séparables de rang fini, permettant des calculs QRPA rapides et fiables dans le cadre des fonctionnelles de la densité.

Аннотация

В этой заметке освещены некоторые аспекты сотрудничества теоретиков ОИЯИ (Дубна) с коллегами из ИЯФ (Орсэ). Эти совместные исследования проблем теоретической ядерной спектроскопии начались более 30 лет назад и активно продолжаются и сейчас. Одна из особенностей разработанного нами подхода Дубна-Орсэ состоит в объединении преимуществ функционала плотности Скирма с сепарабельным взаимодействием конечного ранга, что позволяет выполнять расчеты с функционалами плотности надежно и быстро.

In this short note I would like to convey some personal recollection of the long standing collaboration between the nuclear theorists of JINR Dubna and IPN Orsay. As far as I can remember, it all started with a visit to Dubna that I did in the late 1970s. In those years there were already collaborations between experimental groups at IPN and Vadim Soloviev's theory group at JINR. However, there were not many exchanges between theorists of the two communities. Furthermore, I had never been to the former Soviet Union and I was looking forward to this new experience with much excitement. From the point of view of discovering a different lifestyle and environment I must say that my expectations were fully met. My Dubna colleagues took good care of me, and I still vividly remember a full day spent with Victor Voronov — a then junior member of Soloviev's team — who took me through a detailed discovery of the hotspots of Moscow. Even now, we often talk about this first encounter whenever we meet.

The cooperation between the nuclear theorists of IPN Orsay and JINR thus started some 30 years ago, and it is still active today. It has taken place entirely in the framework of the IN2P3–JINR collaboration agreement, a flexible structure allowing for bilateral exchanges on research projects mutually agreed upon. Since 2011 a new dimension to the collaboration has been added with the PICS program "**Charge-exchange excitations and weak-interaction processes**" jointly funded by IN2P3-CNRS and the RFBR.

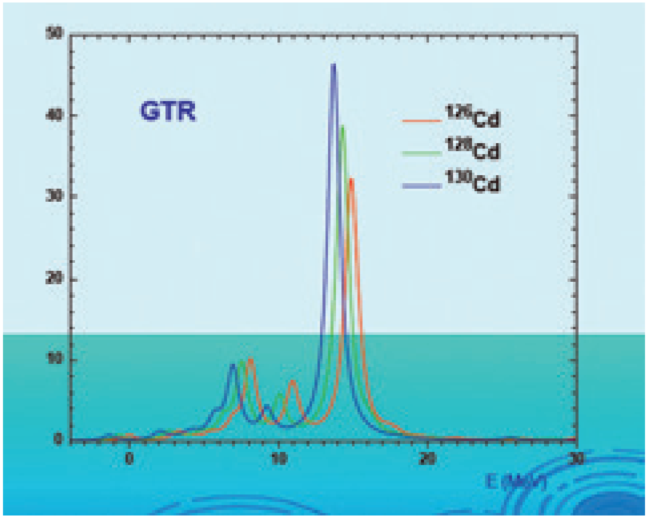
During this long lasting collaboration about 15 articles and contributions to conference proceedings have been published together. The list can be found elsewhere and I shall not quote it here. They can be divided into two main categories: nucleon emission from nuclear excited states in the 1980s, and the study of collective nuclear excitations within the Skyrme Energy-Density Functional (EDF) framework later on. It is on this latter collaboration that I wish to focus in the remaining part of this contribution.

The success of Soloviev's quasiparticle-phonon model (QPM) is mainly due to its numerical simplicity along with a very satisfactory description of the low-energy spectroscopic properties of atomic nuclei. The main inputs to the traditional QPM are phenomenological mean fields like Woods–Saxon single-particle potentials, and schematic separable residual interactions between quasiparticles. It is easy to understand the major advantage of having a separable residual interaction. With a non-separable interaction — even if it is of zero-range type — the eigenvalue problem requires one to diagonalize a secular matrix whose dimension grows like the configuration space dimension N. These eigenvalues are the excitation energies of the Tamm–Dancoff Approximation (TDA), or the Random Phase Approximation (RPA). Thus, the amount of numerical work required to perform RPA calculations away from closed shells can be quite large. It is well-known since the early work of Brown and Bolsterli [1] that separable particle-hole (p-h) interactions lead to a very simple form for the secular equation and thus, there is no longer a need to diagonalize large matrices in configuration space to find the RPA eigenfrequencies. Once these eigenenergies are known it is relatively simple to find the corresponding eigenvectors.

In the early 1980s the energy density functional (EDF) approach based on Skyrme-type effective interactions was already widely used in nuclear physics and interesting results had been obtained in Skyrme–Hartree–Fock-RPA studies of collective states and giant resonances. In the Dubna–Orsay collaboration was raised then the question of how to adapt the QPM method to the Skyrme EDF.

Now, how can one build a separable form of particle-hole interaction in the framework of self-consistent mean field, or Energy-Density Functional (EDF) approaches which have become the generally accepted background of nuclear structure? This is difficult if one needs to keep all the terms of the Skyrme particle-hole interaction, but this becomes feasible if one replaces it by its Landau–Migdal approximation, a generally reasonable assumption. Then, it is easy to see [2] that the particle-hole matrix element between the particle-hole configurations (ph) and $(p'h')$ can be expressed as a sum of N products $F(ph; i) \times F(p'h'; i)$, $i = 1, 2, \ldots, N$, where N does not depend on the size of the configuration space.

One can thus generalize the separable form of Brown–Bolsterli from the one-product case to the sum of N-products case. The value of N can be typically 20–50 depending on the required accuracy and it defines the rank of the separable approximation, hence the name of Finite Rank Separable Approximation (FRSA). Many RPA and QRPA studies have been done in the FRSA framework by the Dubna–Orsay collaboration. The most recent applications concern charge-exchange excitations in Cd isotopes [3]. As an example Fig. 1 shows the Gamow–Teller strength distributions calculated in Cd isotopes using the Skyrme parametrization SGII.



The Gamow–Teller strength distributions in Cd isotopes, calculated in QRPA with the interaction SGII

This particular example of QRPA calculations with the FRSA method just illustrates how beneficial the collaboration has been, by bringing together teams with different and complementary viewpoints. This must encourage us to keep developing the cooperation.

I wish to the IN2P3–Dubna collaboration many new successes in the future, based on the past experience of sharing our respective knowledge.

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Intrinsic vortical motion and the spectroscopy of well deformed atomic nuclei

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Résumé

Le groupe de Dubna de I. N. Mikhailov a développé une approche microscopique novatrice de la dynamique nucléaire dans l'espace de phase. Au sein d'une collaboration Dubna–Orsay–Bordeaux, elle a été appliquée de façon détaillée à l'étude du couplage entre le mouvement de rotation globale et les mouvements intrinsèques vorticaux apparaissant dans les noyaux bien déformés. Ce couplage correspond étonnamment bien aux mouvements décrits par Chandrasekhar sous le vocable d'ellipsoides-S. Il a été quantitativement montré que ces modes vorticaux ont pour origine les corrélations d'appariement et que leur comportement en fonction de la vitesse angulaire est analogue à celui de supraconducteurs de type-I en présence d'un champ magnétique. A ce propos, une équivalence utile entre des calculs de Routhian Hartree-Fock-Bogoliubov et des calculs beaucoup plus simples de Routhian Hartree-Fock sous contrainte sur le moment de Kelvin a été mise en évidence. Ces concepts ont fourni une explication alternative possible du phénomène de staggering des énergies gamma de transition dans certaines bandes superdéformées. Une analogie intéressante entre ce phénomène ainsi expliqué et l'existence de courants persistants dans des anneaux mésoscopiques a été suggérée.

Аннотация

Группа дубненских ученых, лидером которой был И. Н. Михайлов, разработала новаторский микроскопический подход к описанию ядерной динамики в фазовом пространстве. В рамках коллаборации Дубна–Орсэ–Бордо этот подход был использован для изучения взаимодействия глобального вращения ядра с внутренним вихревым движением в деформированных ядрах. Эта связь соответствует движениям, описанным еще Чандрасекаром под названием S-эллипсоидов. Было количественно показано, что эти вихревые моды имеют своим источником сверхтекучие парные корреляции и что как функции скорости они ведут себя подобно сверхпроводникам в магнитном поле. Была установлена полезная эквивалентность между расчетами рутиана в приближении Хартри–Фока–Боголюбова и более простыми расчетами рутиана в приближении Хартри–Фока при заданной величине циркуляции Кельвина. Эти идеи привели к альтернативному объяснению явления стагеринга — скачущего поведения энергий гамма-переходов в некоторых супердеформированных полосах. Была также выявлена интересная аналогия между этим явлением и существованием незатухающих токов в мезоскопических кольцах, помещенных в магнитное поле.

A very fruitful collaboration between the JINR Dubna, the CSNSM Orsay and later the CENBG Bordeaux, in the domain of nuclear structure has been established more than 30 years ago. It has produced more than 50 papers or other written contributions. In an earlier stage, involving as main contributors I. N. Mikhailov and C. Briançon, it has been concerned among other topics with the study of octupole degrees of freedom and their coupling with rotational degrees of freedom [1] and more generally with the nature of negative parity collective modes [2].

We will concentrate here on studies started more than twenty years ago. They originate from the method of virial theorems introduced in classical mechanics by S. Chandrasekhar. It had been adapted for nuclear physics in Dubna, long ago, by the group of I. N. Mikhailov [3]. It was first used to describe semi-microscopically giant resonances and later large amplitude collective modes as encountered in nuclear fusion. One of its great merits has been to emphasize and make it explicit that during such nuclear excitation processes not only space variables but also momenta are undergoing specific collective motion, the latter being coupled to the former (see e.g. [4]).

The rotational modes are no exception to that general rule. Actually, within a simple yet very rich parametrization of the velocity field and assuming ellipsoidal body shapes, S. Chandrasekhar has studied the coupling of a global rotation with intrinsic vortical currents [5]. One case of particular relevance for nuclear physics corresponds to what S. Chandrasekhar has dubbed as S-Ellipsoids where the vorticities of global rotation and intrinsic velocity fields are aligned. Introducing these concepts in the study of nuclear rotations was the subject of a collaboration started almost twenty years ago between the BLTP Dubna, the CENBG Bordeaux, the CSNSM Orsay and the INRNE Sofia. Two somewhat connected questions have been raised. First of all, what is the relevance of such a seemingly simplistic approach, a question encompassing a research of its possible signatures? Second, could we render explicit the expected connexion between the intrinsic currents and pairing correlations? As we will see, important yet so far incomplete answers have been brought up on both issues over the years.

In a first paper [6], one has realized that the above mentioned coupling properly quantized could generate a staggering of gamma transition energies in a rotational band within the right order of magnitude for particular values of the Kelvin circulation. Whether or not this was related precisely to the few superdeformed rotational nuclear states where it had been observed remained to be demonstrated.

This has prompted microscopic studies of the microscopic coupling of the currents in rotating nuclei [7]. To that effect one has developed calculations of the Routhian type yet generalized to allow for a double constraint on both the angular momentum projection on a global rotation axis and on the so-called Kelvin circulation operator measuring the intrinsic vortical currents within the S-ellipsoid model approach. They were first performed semi-classically à la Wigner–Kirkwood as well as in a simple oscillator mean field approach [8] or within the more elaborated Skyrme–Hartree–Fock framework [9]. In the latter case, it has been shown [10] from realistic microscopic calculations of the yrast superdefomed band of ^{150}Gd (near ^{148}Gd, ^{148}Eu, ^{149}Gd where such a staggering had been observed) that intrinsic vortical currents could indeed yield a ratio of angular momentum and Kelvin circulation close to the critical value for such a bizarre phenomenon to occur. However, the exact amount of intrinsic vorticity was supposed (and has been quantitatively later shown, see below) to be contingent upon the exact amount of pairing correlations yet to be specified.

On the side of this main stream of research, two interesting approaches are worth mentioning. The first one [11] has consisted in transforming the virial equations of motion into a rotating frame so as to provide a firm basis for studying the coupling of space coordinates and momenta for the rotational mode. The second [12] has taken stock of the formal well-known analogy between magnetic field and angular velocity. In mesoscopic rings embedded in a magnetic field *B*, boundary conditions entail a quantification of the energy *E* which can be formally identified with the quantization of the S-ellipsoid energy resulting from the quantization of the Kelvin circulation *J* at a given angular momentum I. The electric current being defined as minus the derivative of *E* with respect to *B* is thus periodic. Similarly, one obtains a periodic contribution (generating thus a staggering) of the intrinsic modes to the derivative of the energy with respect to the angular momentum. This derivative is nothing but the gamma transition energy.

The next issue is concerned with the connexion between intrinsic vortical currents and pairing correlations. Upon increasing the angular velocity, two antipairing mechanisms are possible and actually encountered. Both correspond to the disappearance of the anti alignment between the two members of a Cooper pair. One is sudden and individual in nature. The other is gradual and collective. The latter is the one which has been shown to be very well described indeed within our approach. Owing to the already mentioned analogy between magnetic moment and angular velocity, the physics which is described here is similar to what is observed with type-I supraconductors in a magnetic field and is referred to in nuclear physics as the Coriolis anti-pairing effect, first discussed by Mottelson and Valatin [13].

We have compared quantitatively relevant results (like the kinetic and dynamical moments of inertia) of two series of calculations. The first ones were usual Routhian–Hartree–Fock–Bogoliubov calculations. The second were Routhian–Hartree–Fock calculations with a constraint on the specific value of the Kelvin circulation which had been obtained at a given angular momentum in the first type of calculations. The results have been found [14] astonishingly similar for a sample of three rotational bands (the yrast superdeformed bands in ^{150}Gd and ^{192}Hg and the yrast normally deformed band in ^{258}No). While this result was of some theoretical importance in assessing such a simple vortical current nature of the pairing correlations effect on global rotations, it carried a rather elusive practical value. Indeed, to be able to perform the uncorrelated Routhian calculations one needed to perform prior correlated Routhian calculations.

Avoiding these Routhian–Hartree–Fock–Bogoliubov calculations has been successfully realized. Following the lines drawn in the approach of Mottelson and Valatin [13], a simple model has been shown to correlate adequately the angular velocities of the global rotation and of the intrinsic vortical mode [15]. It has allowed a very good reproduction of the results of Reference [12] needing only as non-fitted ingredients the pair condensation energy at zero angular momentum and the rigid moment of inertia at low angular velocities. This approach is of course valid only in so far as quasiparticle degrees of freedom do not intervene in the rotational dynamics.

The task that remains ahead is to understand microscopically the reasons behind these successful results, quite unexpected to be sure at such a quantitative level. This is currently attempted [16] following the steps taken by I. N. Mikhailov in a work unfortunately not totally completed.

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Cluster decay of excited nuclei and production of neutron-rich isotopes in transfer-type reactions with radioactive beams

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Résumé

Nous présentons les resultantsrécents relevant de l'interpretation théorique des résultats obtenus par le relevateur 4π INDRA à GANILconcernant l'étude des modes de decroissance des noyaux excités avec les réactions ^{78,82}Kr+^{40}Ca à 5.5 MeV/nucléon et les prédictionsdes taux de production des isotopes riches en neutron ^{52,54,56,58,60}Ca and ^{136,138,140,142}Sn dans les réactions de transfert de multinucléons ^{124,130,132,134}Sn,^{136,140,142,146}Xe+^{48}Ca en vue des experiences futures à SPIRAL-2.

Аннотация

Представлены результаты недавних теоретических расчетов мод распада возбужденных ядер, образовавшихся в реакциях ^{78,82}Kr + ^{40}Ca с энергией пучка 5,5 МэВ/нуклон, проведенных в связи с соответствующими экспериментами в GANIL с использованием детектора 4π INDRA. Кроме того, в связи с планируемыми экспериментами на установке SPIRAL-2 предсказан выход нейтронно-избыточных четно-четных изотопов кальция с массовыми числами 52-60 и изотопов олова с массовыми числами 136-142 в реакциях передачи нескольких нуклонов с пучком ^{48}Ca на мишенях ^{124,130,132,134}Sn и ^{136,140,142,146}Xe.

Cluster emission from hot nuclei

In this section we present the results of a study of decay modes of excited nuclei formed in ^{78,82}Kr + ^{40}Ca reactions at 5.5 MeV/nucleon [1]. The experiments in the reverse kinematics were performed at the GANIL facility. The kinetic energy and atomic number of the ejectiles were measured by means of the 4π INDRA array. The 4π INDRA array, which is very well suited to study the fate of violent collisions at intermediate energies, has been exploited here for the first time in low bombarding energy regime. The kinetic energy spectra, the angular distributions and the Z-distributions of $3 \le Z \le 28$ show the characteristics of fission-like phenomenon (Fig. 1). Analysis of the fragment-light particle coincidences indicates that fragments of $Z \le 12$ are produced either cold or at excitation energies below the particle evaporation thresholds. A strong odd-even staggering was observed in the yields of lightest fragments. The magnitude of the staggering does not significantly depends on the neutron-to-proton ratio of the emitting system. The fission-like component is found to be larger by ~ 25% for the reaction with the lower neutron-to-proton ratio. The cross sections of the light clusters (Li, Be, B) were astonishingly low [1]. To understand these observations, we compared the predictions of various theoretical approaches assuming either the formation of compound nucleus (CN) (BUSCO, GEMINI) or describing both the collisional stage preceding the CN formation and the competition with quasifission (QF) process (dinuclear system (DNS) model [2] developed at JINR). The better global agreement is obtained with the DNS model. The DNS model describes the evolution of the interacting nuclei along the charge and mass-asymmetry degrees of freedom and decay in the relative distance coordinate [2]. For the ^{78,82}Kr + ^{40}Ca reactions at 5.5 MeV/nucleon, the DNS model describes quantitatively the evaporation residue cross sections, the odd-even staggering of the light fragments and their low cross sections as well as a large portion of σ_Z for $12 \le Z \le 28$ (Fig. 1). In agreement with the experimental findings the staggering of the yields decreases as the atomic number increases. Since the pairing energy of the DNS light nucleus decreases with increasing mass number A, the odd-even effect becomes weaker for larger Z-values. Moreover, the magnitude of the staggering is also influenced by the excitation energy stored in the primary fragments. For nuclei with $Z \le 10$, the average calculated excitation energy is below the particle emission threshold and these nuclei do not de-

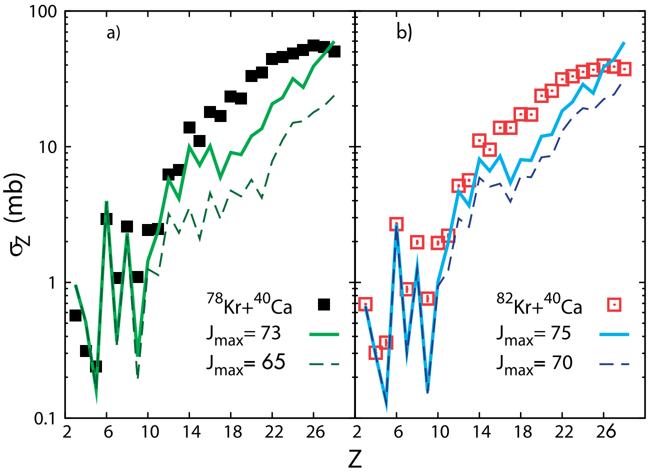

Fig. 1. Comparison between measured (symbols) and calculated (lines) production cross sections as function of charge number Z of fragment. The calculated results with maximal angular momenta $J_{max} = 65$ ($J_{max} = 73$) for the ^{78}Kr + ^{40}Ca reaction and $J_{max} = 70$ ($J_{max} = 75$) for the ^{82}Kr + ^{40}Ca reaction are shown by dashed (solid) lines in panel a (b), respectively

cay further except by γ emission. For heavy fragments, the average excitation energy and spin are high enough to open up the decay by light particles which strongly attenuates the odd-even structures of the Z-distributions. Such results agree with our conclusions from the analysis of the fragment-particles coincidences.

Finally, the features of the charge distribution for $3 \leq Z \leq 28$ are consistent with a strong competition between fusion-fission and quasifission processes. The quasifission mechanism is the dominant production mode for heavy fragments while light clusters such as C, O, and Ne are predominantly populated by decay of CN. The dominant reaction mechanism (CN or QF) strongly depends on the angular momentum *J*. For the reactions studied at low *J* the CN configuration is energetically more favorable than any DNS configurations. At higher *J*, the symmetric DNS are energetically preferable and the charge (mass) drift pushes the system towards the symmetry. Consequently CN configuration becomes energetically unfavorable and the high partial waves lead to QF. However, both mechanisms coexist in a wide range of angular momenta. For example, in the case of the ^{78}Kr + ^{40}Ca reaction at 5.5 MeV/nucleon, the evaporation residues cross-section accounts for about 10% of the partial cross-section at $J = 65$. Thus, the angular momentum strongly influences the competition between the binary decay channels and, correspondingly, the probability of light fragments emission. It would be very instructive to probe the competition between CN and QF components in the same mass region by studying very mass-asymmetric reactions where the flux going to CN is expected to dominate over a large range of incident partial waves. Experiments using a spin spectrometer with high capabilities could be an appropriate tool for such investigations [1].

Production of neutron-rich isotopes

In this section we demonstrate the possibilities for producing neutron-rich isotopes of ^{52,54,56,58,60}Ca in the diffusive multinucleon transfer reactions ^{130,132,134}Sn, ^{136,140,142,146}Xe + ^{48}Ca with stable and radioactive beams for future experiments, for example, at SPIRAL-2 [3]. Since the production cross sections of neutron-rich isotopes ^{56,58,60}Ca are quite small, the choice of optimal projectile-target combinations and bombarding energies is important. With the radioactive beams the neutron-rich isotopes are expected to be produced with larger cross sections. However, one should bear in mind smaller intensity of these beams in comparison with the intensity of stable beams. Our aim is to find the global trend in the production cross section of exotic nuclei with the charge (mass) number of the projectile in the multinucleon transfer reactions. Based on this trend one can find a consensus between the cross sections resulted from certain beam and the intensity of this beam.

In the reactions ^{124,130,132,134}Sn, ^{136,140,142,146}Xe + ^{48}Ca with stable and radioactive beams the maximal expected production cross sections for ^{52,54,56,58,60}Ca are presented in Figs. 2 and 3. The production cross section for ^{A}Ca decreases strongly with increasing A. For all reactions, the decrease of the production cross section occurs in the similar way. The cross section for ^{52}Ca is about (6–8) orders of magnitude larger than the cross section for ^{60}Ca. One can see that the production cross section in reaction with stable beam is smaller than the one in the reaction with radioactive beam. Replacing the stable nucleus by the radioactive one, one can increase the yield of neutron-rich Ca by about (1–3) orders of magnitude. For example, replacing ^{124}Sn (^{136}Xe) by ^{130}Sn (^{142}Xe), one can increase the yields of neutron-rich ^{58,60}Ca by about 165 (28) and 174 (57) times, respectively. As seen, the yields of heavier isotopes of Ca

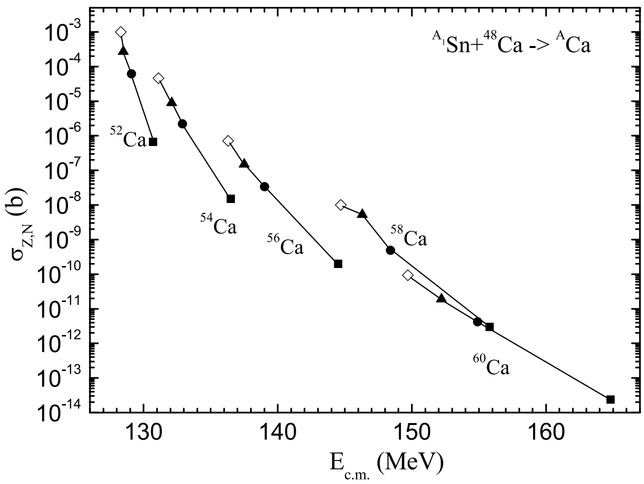

Fig. 2. The expected maximal cross sections for the indicated neutron-rich isotopes ^{52,54,56,58,60}Ca produced in the reactions ^{124}Sn + ^{48}Ca (solid squares), ^{130}Sn + ^{48}Ca (solid circles), ^{132}Sn + ^{48}Ca (solid triangles), and ^{134}Sn + ^{48}Ca (open rhombus) at the values of $E_{c.m.}$ corresponding to the thresholds for neutron emission from the produced Ca isotopes. The symbols for the same isotopes are traced by the solid lines

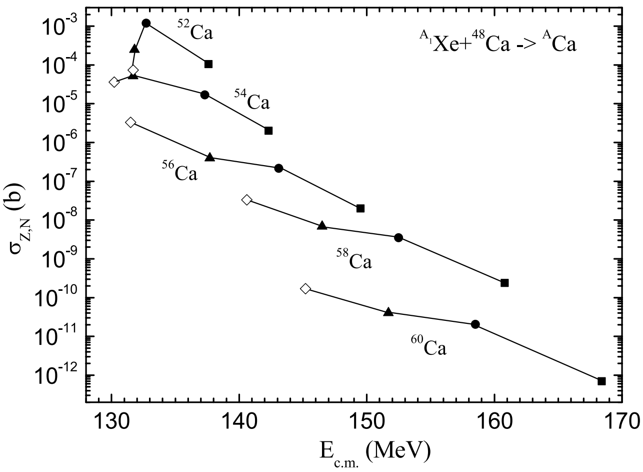

Fig. 3. The same as in Fig. 2, but for the reactions ^{136}Xe + ^{48}Ca (solid squares), ^{140}Xe + ^{48}Ca (solid circles), ^{142}Xe + ^{48}Ca (solid triangles), and ^{144}Xe + ^{48}Ca (open rhombus)

increase more with mass number of projectile than the yields of lighter isotopes of Ca.

There is optimal number of neutrons in the projectile which results in the minimum Q-value for producing certain isotope of Ca. Exceeding this optimal number, one can obtain smaller cross section. See, for example, the case of ^{52}Ca in Fig. 3. To plan the experiments with radioactive beams, one should take into consideration the intensities of these beams with respect to the intensities of the stable beams. Note that the production cross section for ^{58}Ca in the reactions ^{48}Ca + ^{238}U and ^{92,94}Kr, ^{130}Sn, ^{140}Xe, ^{142,144}Ba + ^{48}Ca are comparable [3]. Therefore, the radioactive beams are expected to be useful for producing the Ca isotopes with A > 58. In Fig. 4 we present for the future experiments the possibilities for producing neutron-rich isotopes of nuclei with Z = 50 in the multinucleon transfer reactions ^{132,134}Sn + ^{48}Ca. The production cross sections of new neutron-rich ^{138,140,142}Sn isotopes are between nanobarn and picobarn levels, and they can be detected with the present experimental setups.

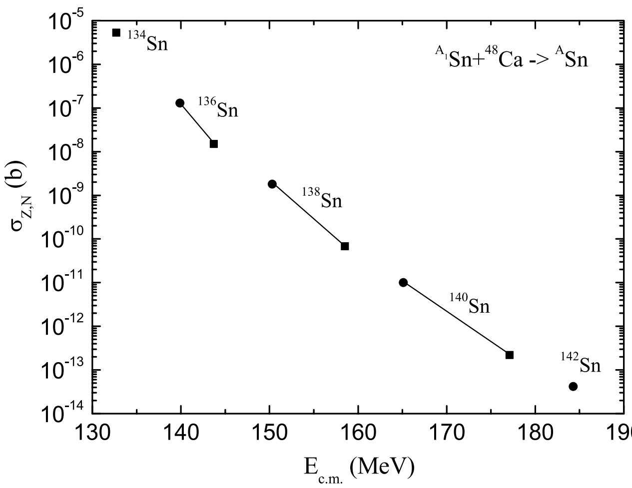

Fig. 4. The expected maximal cross sections for the indicated neutron-rich isotopes ^{134,136,138,140,142}Sn produced in the reactions ^{132}Sn + ^{48}Ca (solid squares) and ^{134}Sn + ^{48}Ca (solid circles) at the values of $E_{c.m.}$ corresponding to the thresholds for neutron emission from the produced Ca isotopes. The symbols for the same isotopes are traced by the solid lines

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The joy of supersymmetry

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Résumé

Je raconte mon expérience de collaboration avec des théoriciens de Dubna; les experts en theories supersymétriques, en particulier, en modèls avec une supersymétrie étendue dans le cadre d'une approche de superespace harmonique dévéloppée en Dubna. En une décénnie de travail, nous avons obtenu quelques résultats intéressants en théories supersymétriques multidimensionnelles, en mécanique quantique supersymétrique et meme en mathématiques pures (géometrie différentielle).

Аннотация

Я рассказываю об опыте сотрудничества с группой дубненских теоретиков, специалистов по суперсимметричным теориям, в особенности по моделям с расширенной суперсимметрией на основе разработанного в Дубне подхода гармонического суперпространства. За годы работы мы получили ряд интересных результатов, относящихся к многомерным суперсимметричным калибровочным теориям, к суперсимметричной квантовой механике и даже к чистой математике (дифференциальной геометрии).

Our project differs in thematics from the other projects in the IN2P3–Dubna collaboration. It does not concern experiment, neither does it concern phenomenological theory in hep-ph spirit, but its subject rather belongs to "theoretical theory" on the border between hep-th and math-ph.

On the French side, the project involved myself and my (by now, former) PhD student Maxim Konyushikhin.

The Dubna part is represented by three theorists, members of BLTP — Evgeny Ivanov, Boris Zupnik, and Sergei Fedoruk.

The unique know-how developped in Dubna is the *harmonic superspace* technique which allows one to represent the Lagrangians in theories with extended supersymmetries in terms of *unconstrained* superfields. This technique was invented by Ivanov, Kalitsin, Ogievetsky, and Sokatchev. Nowadays, it is widely known and used also outside of Dubna. Still, three people mentioned above (especially, E. Ivanov) are the leading world experts in harmonic superspace. They feel really comfortable there, knowing well its bright spots and dark corners.

The collaboration was very efficient. During ~10 years, we have written together 8 large papers (listed below). It is impossible to discuss in details all of them, and will only dwell on few highlights — the results that seem to be more interesting than the others.

1. In my personal opinion, our most interesting papers [2,3] are dedicated to 6-dimensional supersymmetric Yang–Mills theory (pure SYM theory or a theory including extra matter hypermultiplets) involving higher derivatives, the Lagrangian having the canonical dimension 6. The motivation for this study was an attempt to explore an alternative approach to the construction of the fundamental Theory of Everything, compared to the String Theory approach — the main paradigm of modern research.

The idea was simple.

(i) There are conceptual difficulties in defining what quantum gravity is. To begin with, quantum gravity is not renormalisable, but the problems are deeper than just that. The basic notion of quantum mechanics, the quantum evolution operator is well defined only when the time is universal and flat. And when space-time is curved, it is not.

(ii) One can imagine then that TOE is a conventional field theory (not involving gravity) formulated in a higher-dimensional bulk space, and gravity emerges as an effective theory on the surface of some brane-like (or soap-bubble-like) classical solution in the bulk. This solution must involve strong dependence on transverse coordinates, but should not depend in the first approximation on three spatial dimensions and time — physical coordinates of our World.

(iii) If we want this conventional theory to be renormalisable, it should involve a dimensionless coupling. In higher dimensions, this means higher derivatives[1]. To construct the Lagrangian of this theory carrying canonical dimension 6, we used harmonic superspace technique. Actually, this is a problem where this technique seems to be nearly indispensible. At least, I do not know any other way to derive the Lagrangian. Its gauge part is simple: $\sim(1/g^2)\ \mathrm{Tr}\{(D_\mu F_{\mu\nu})\}^2$, but there are many other complicated terms...

This theory involves a dimensionless coupling and is renormalisable. At the classical level, it is conformal, but conformal symmetry is broken by quantum anomaly. We calculated the 1-loop beta function there, and it turned out to be negative meaning asymptotic freedom and suggesting the emergence of the mass scale by the dimensional transmutation mechanism, like in QCD. Unfortunately, being a higher-derivative theory, this theory suffers from ghost instability mentioned above.

At the moment, we do not know how to cure it.

2. Most of our papers [1, 5–8] were devoted to supersymmetric sigma models of different kind. This is an interdisciplinary subject on the border between physics and pure mathematics. Basically, the same problems are studied in different, mathematical and theoretical physical communities. These communities use different languages: what a physicist calls gauge field a mathematician calls connection of a principal fiber bundle; a physicist studies different supersymmetric quantum mechanical systems describing the motion on curved manifolds, and mathematician knows them as complexes of different kind: de Rham complex, Dolbeault complex, etc. Supercharges for a physicist are exterior derivative operators for a mathematician... More often than not, we simply do not understand each other due to this language barrier.

In this respect, I would like to mention our recent paper [7]. To some extent, it is a review, where purely mathematical problems, like the relationship of the Dolbeault and Dirac complexes or the Atiyah–Singer theorem, are discussed using the physical language and physical methods. Besides review material, this paper includes also many original observations. In particular, we construct and study, using superfield formalism, a certain supersymmetric quantum mechanical model describing the Dolbeault complex and give a new physical proof of the Atiyah–Singer theorem.

In that paper we only considered the special class of Kähler manifolds where the proof is simpler. But later I generalised this proof for the non-Kähler case. I should believe mathematicians when they say that the proof was earlier constructed also in this difficult generic complex manifold case. But the proof constructed by me is the only one that I understand. And the latter refers, I bet, to all other physicists.

3. Let me say also few words about our paper [4] devoted to a special subject — nonanticommutative field theories. More known and rather well studied are noncommutative theories living in spaces where coordinates do not commute, $[x_{\mu 0}, x_\nu] = A_{\mu\nu}$ with some antisymmetric $A_{\mu\nu}$. Nonanticommutative theories (introduced by N. Seiberg) are supersymmetric theories formulated in superspace where odd variables do not anticommute, $\{\theta_\beta, \theta_\alpha\} = B_{\alpha\beta}$ with some symmetric $B_{\alpha\beta}$.

In our paper, we disprove some prejudices and myths associated with these theories. People used to believe, for example, that they can only be formulated in Euclidean space, while in Minkowski space-time such theories make no sense because their Hamiltonians are not Hermitian. We showed, however, that it is not so. The Hamiltonians of these theories belong to the class of so-called crypto-Hermitian (alias, pseudo-Hermitian, alias, quasi-Hermitian) Hamiltonians. They have a real spectrum, and their hidden Hermiticity may be made manifest by applying a proper similarity transformation. Later I disproved another superstition and showed that these theories enjoy full supersymmetry, to the same extent as the theories with anticommuting θ_α do.

To conclude, it was a honor and pleasure for me to work with my Dubna colleagues.

We plan to continue our collaboration and hope to obtain new results, maybe still more interesting than the results already obtained.

[1]Unfortunately, higher-derivative theories are generically unstable due to the presence of ghosts. One can only hope that this serious problem will be resolved one day...

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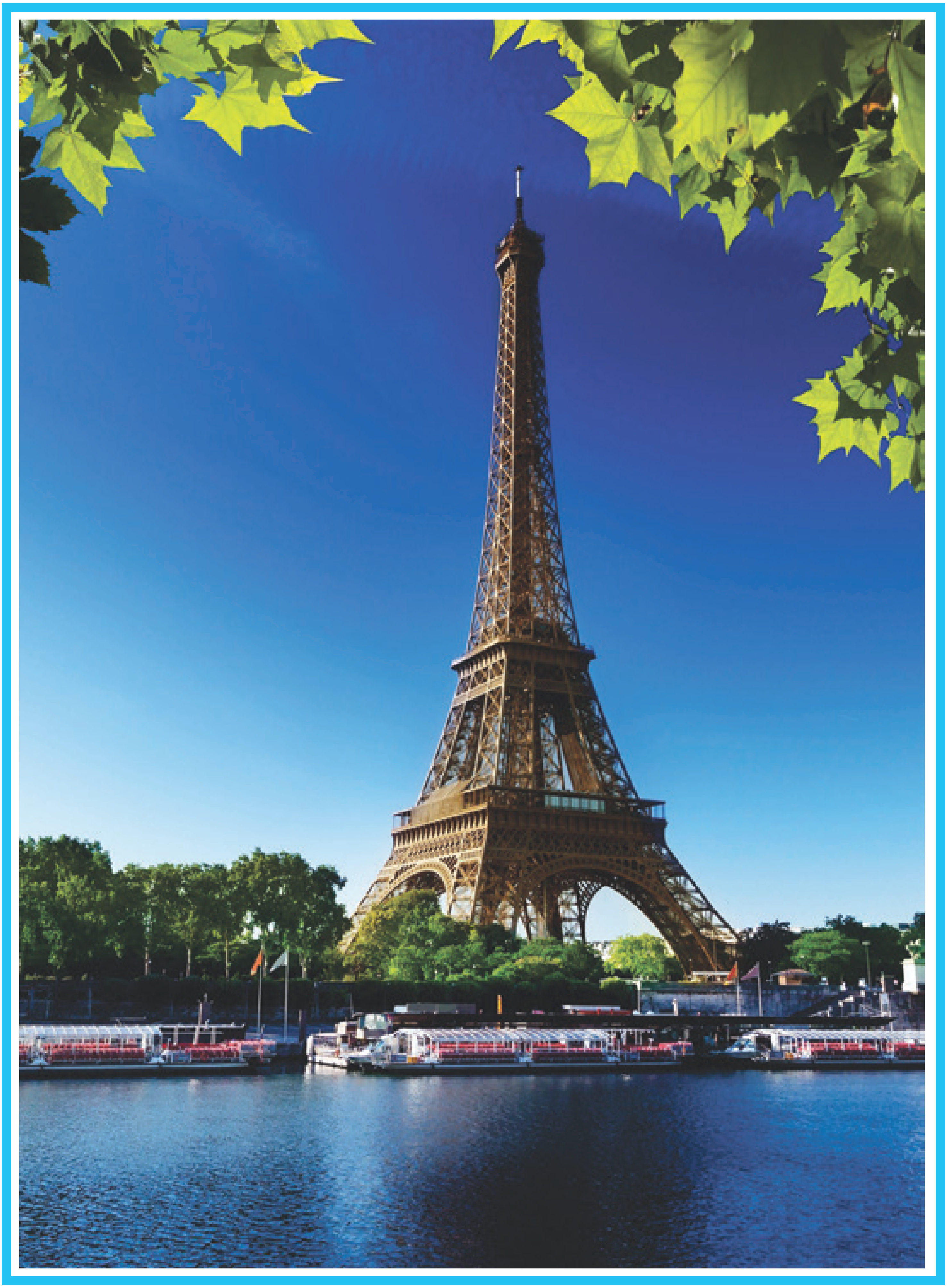

Hadron physics at the Laboratoire Nationale Saturne

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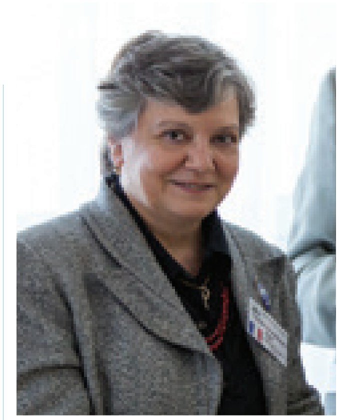
N. Piskunov, JINR/VBLHEP, JINR/DLNP



E. Tomasi-Gustafsson

Résumé

Cette contribution retrace (partie de) l'activité qui s'est déroulée au Laboratoire Nationale Saturne, pour rendre hommage au dynamisme, aux efforts et aux échanges entre les équipes des laboratoires français et du JINR. Nous rappelons quelques expériences et quelques résultats concernant la réponse des nucléons et des noyaux à la sonde hadronique, l'interaction nucléon-nucléon, la structure des noyaux légers et les mécanismes sous-jacents à la production de mésons…la sélection étant évidemment limitée et dictée par la subjectivité des auteurs. L'unicité des faisceaux de Saturne : protons, deutons, ions légers et lourds aux énergies de quelques GeV/A était liée tout spécialement aux phénomènes de polarisation. Les avancées en polarimétrie: cibles polarisées et polarimètres, ont été exploitées notamment à JLab, et permis le résultat le plus cité de ce laboratoire : la mesure précise des facteurs de forme électromagnétiques du proton.

Аннотация

Эта статья возвращает нас к части совместной работы в Национальной лаборатории SATURNE с целью почтить усилия и энтузиазм, а также обмен идеями между группами из французских лабораторий и ОИЯИ. Вспоминаются некоторые эксперименты и полученные результаты, касающиеся поведения нуклона и ядра при взаимодействии с адронами, нуклон-нуклонных взаимодействий, структуры легких ядер, механизмов реакций,ответственных за мезонообразование и возбуждение нуклонов (ограниченность выбора продиктована субъективностью авторов). Уникальность пучков SATURNE: протоны, дейтроны, легкие и тяжелые ионы с энергией в несколько ГэВ на нуклон в своей основе связаны с поляризационными явлениями. Технический прогресс, достигнутый при создании поляризованных мишеней и поляриметров, получил дальнейшее развитие, в частности, в Лаборатории Джефферсона, где это стало существенным при прецизионных измерениях электромагнитных формфакторов протона, наиболее цитируемых работах из этой лаборатории.

Saturne has been a unique accelerator in the world, for the quality of its beams, in particular the highly polarized, high intensity 3 GeV proton and 2 GeV deuteron beams. The high quality of the Saturne beams, the stability, the flexibility in changing energy and nature of the beam, as well as in the sharing between different experimental areas, made possible an optimized and intensive use of the each accelerated particle.

Among the experimental achievements of Saturne, we would mention:

- Fundamental data in an extended kinematical region of nucleon-nucleon and nucleon-nuclei interaction.
- Discovery of very intensive sources of eta-omega-mesons and virtual pions;
- Study of meson production through elementary processes and polarized particles;
- Probing the nucleon structure with complex projectiles as D and ^{4}He;
- Development of hadron polarimetry, in the GeV range which made possible the determination of the quadrupole form factor of the deuteron and the electromagnetic proton and neutron form factors at Jefferson Lab.

These scientific programs have been partly pursued elsewhere, in particular at COSY, RIKEN, J-Parc, and at the complex accelerator Nuclotron.

These results stimulated intensive research in theoretical physics and contributed to the present directions of hadronic physics, demonstrating the relevance of the following points:

- The non nucleonic degrees of freedom such as nucleon resonances and mesons which play an important role in the description of the nucleon-nucleon forces and the nuclear structure at short distances;
- The complexity of the the hadron interaction in the non perturbative QCD region of energy and momentum transfer;
- The importance of spin effect;
- The complementarity of the hadronic and of the electromagnetic probe for the study of the nuclear structure.

The nucleon-nucleon programme has been one of the pillar of the joint activities. Single, double, triple spin polarization observables have been measured, with different orientations of beam and/or target polarizations. Phase shifts analyses have been performed and interesting structures have been observed in the differential cross section, analyzing powers and other polarization observables as well. The search of dibaryons was not conclusive, and alternative explanations are still possible. The availability of a high quality neutron beam has allowed the first direct reconstruction of the *np* scattering amplitudes up to 1.1 GeV.

Let us remind the adventurous life of the NN-polarized target, which has been a real globetrotter: from FermiLab, to France, and finally to Russia, where it was refurbished (thanks also to an INTAS programme). Important and unique results were obtained, on the cross section for parallel and antiparallel orientations of projectile and target spins.

The light nuclei structure is a large chapter of this common history. The results on proton deuteron backward elastic scattering and the deuteron break-up reactions show peculiar features. A closer look at small internal distances gives evidence for peculiar structures. The simple picture of a proton and a neutron components, is contradicted by the data, which require different sorts of corrections, and give hints of a six-quark component of the deuteron wave function.

The structure of ^{3}He has been investigated in an original experiment, based on the reaction $p + {}^3\mathrm{He} \rightarrow d + X$, where the vector and tensor polarization of the outgoing deuteron has been measured by the HYPOM polarimeter.

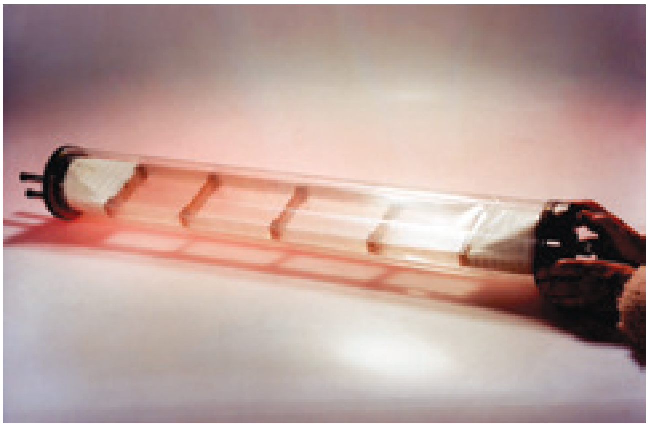


Fig. 1. The unique and original LH_2 target for the HYPOM polarimeter, installed at the SPESIV focal plane

Similar experiments have been pursued at VBLHE, where the investigation of three body forces and short range correlation is underway.

The optimization and the search for better efficiency and better polarizing reactions has been one of the important contributions of Saturne. The use of large carbon or LH_2 targets for extended focal plane polarimeters and the optimization of their thickness and geometry made possible the measurement of the polarization of proton and deuterons in the GeV range. The most spectacular results were obtained at Jeffereson Lab, by applying the polarization method suggested by A. I. Akhiezer and M. P. Rekalo in 1967, for the measurement of the electromagnetic proton form factors. Very precise and surprising results were obtained on the form factor ratio G_{Ep}/G_{Mp}, to $Q^2 = 3.5$ GeV^2, based on the Saturne calibration, which show that this ratio is not constant, as previously assumed. After the upgrade of the JLab beam energy to 6 GeV a proposal was submitted to extend these measurements Q^2 up to 9 GeV^2. For its approval, new data on the analyzing powers were required. Such an experiment was possible only at Dubna where a high energy polarized proton beam was available.

The **POMME** polarimeter (**PO**larimetre **M**obile **M**oyennes **E**nergies') was transported to Dubna and installed at the ALPHA set-up two weeks before the beam time started!

The preliminary data on p–CH_2 analyzing powers taken at ALPOM, were available almost on-line. They were presented to the JLab PAC and the GEpII experiment was approved. A second measurement was done few months later with new data acquisition system allowing us to increase the rate of data taking by a factor of

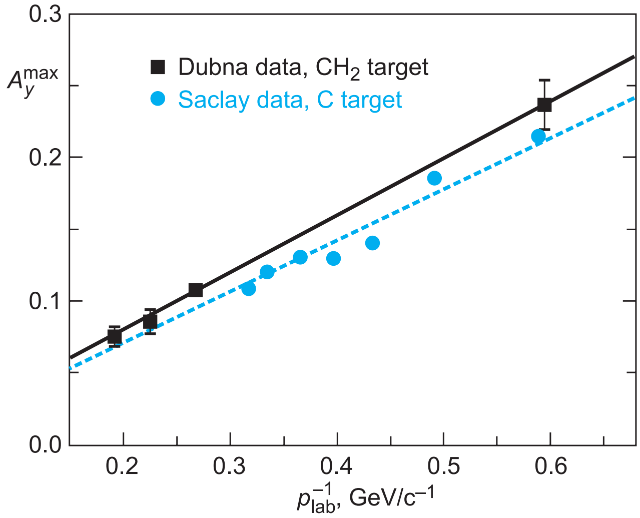


Fig. 2. The analyzing powers for the inclusive proton reaction, from the experiments POMME and ALPOM, at Saturne and at VBLHEP

100. The results are shown in Fig. 2. A proposal has been presented in Dubna, to extend the analyzing power measurements up to a proton momentum of 7.5 GeV/c with a new polarimeter by adding downstream a hadron calorimeter consisting of 25 modules, which was built in Dubna, and then used at COMPASS (CERN).

The deuteron constitutes a very interesting probe: it acts as an "isoscalar photon" and due to the possible (large) vector and tensor polarizations, one can select specific resonances and specific reaction mechanisms. Inelastic scattering on proton and nuclei has allowed measuring the spin-isospin response in the continuum, for nuclei and nucleons. The nucleon part of this program was taken in charge essentially in Dubna, where the analysis was carried on. The $N^* \to \pi N$ and $N^* \to 2\pi N$ channels were identified. The cross section and the analyzing powers were measured at different energies and angles. A fair agreement of the tensor analyzing powers is obtained, using the transition form factors of the interesting resonances, excited through ω-exchange.

These and many other results, which are available in the literature, are due to the ideas and the efforts of physicists from different countries, with different cultures and education but with a common passion and enthusiasm. A special memory is due to J. Arvieux, F. Lehar and M. P. Rekalo, who were the driving force of many of these experimental programs.

VBLHEP–JINR collaboration with IN2P3: Study of polarization phenomena

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Аннотация

Представлен краткий очерк сотрудничества физиков Лаборатории высоких энергий им. В. И. Векслера и А. М. Балдина Объединенного института ядерных исследований и Национальной лаборатории SATURNE (Сакле) в изучении поляризационных явлений. Это личный взгляд одного из участников коллаборации, поэтому автор просит извинить его за возможные аберрации, естественно возникающие по прошествии времени.

Résumé

Cette contribution retrace une brève histoire de la collaboration entre les physiciens du JINR-VBLNP et du Laboratoire Saturne, dédiée à l'étude des phénomènes de polarisation. C'est une vision personnelle d'un des participants, donc l'auteurs'excuse pour éventuels oublis et imprécisions.

About 30 year ago (since the 80s of the last century) high quality extracted beams of polarized deuterons accelerated to kinetic energy of several GeV/nucleon became available in LNS (Saclay) and JINR (Dubna) from SATURNE-II and the Synchrophasotron accelerators. Obviously this created mutual interest of physicists, carrying out research of polarization phenomena in JINR and in France, in possible cooperation in their work.

The interest of our team in the Laboratory for High Energy of JINR (now named as Veksler–Baldin Laboratory of High Energy Physics) was concentrated at those times on the study of deuteron, ^{3}He and ^{4}He structure at short inter-nucleon distances (<0.8 fm), when nucleons must overlap and their quark content, i.e. quark degrees of freedom, should manifest themselves. We have started such a study at LHE of JINR from breakup reactions of the lightest nuclei in a special kinematics, when fragments of the broken nuclei are being emitted in the direction of the nucleus-projectile momentum. We measured momentum distributions of the fragment-spectators almost up to kinematical limits of their momentum, i.e. above the most probable momenta (for $d \to p$ breakup it is half of the deuteron momentum, for $^3\text{He} \to d$, or $^3\text{He} \to p$ it is 2/3 or 1/3 of the ^{3}He momentum respectively, etc.). When polarized deuterons became available at the Synchrophasotron, an opportunity appeared to continue our research by studying polarization phenomena, i.e. by measuring the spin-dependent observables. The simplest observable was the so-called tensor analyzing power T_{20} in the deuteron breakup. A reaction which is complementary to the breakup is the backward elastic deuteron-proton scattering; the corresponding study was carried out in Saclay with use of polarized deuteron beam from SATURNE-II at the focusing SPES-4 spectrometer. A series of measurements of spin-dependent observables for other reactions with lightest nuclei was also done there.

It was probably in the winter of the year 1985–86 (if I remember correctly) when Prof. Jacques Arvieux visited JINR. Very good and fruitful exchanges took place in our Lab. Discussing the results obtained in our Laboratories on the deuteron short-distance structure, J. Arvieux mentioned that a new detector had been specially built at LNS: the high acceptance polarimeter POMME which could be used together with the high resolution SPES-4 spectrometer. Retrospectively, it was this discussion which gave us the first motivation to search for opportunity to collaborate with the Laboratoire Nationale Saturne, because we looked for a way to measure a new observable: the coefficient of spin transfer from deuteron to proton (κ_0) either in the $d \to p$ breakup or in the dp backward elastic scattering. To measure this coefficient, one needed a high acceptance polarimeter for protons, so POMME appeared to be a promising detector for this.

The real collaboration started in 1991, during the first biannual Dubna-Deuteron International Symposium organized by LHE (there have been four of such Symposia). During Deuteron-91 we met Prof. Charles Perdrisat (from the College of Willam and Mary, Virginia) who conducted experiments with deuteron beams at LNS. The idea of simultaneous measurements of T_{20} and κ_0 in the backward elastic scattering of polarized deuterons by unpolarized protons at SPES-4 with the POMME polarimeter was discussed with him during the Symposium. This and subsequent discussions resulted in our joint proposal submitted in 1992 to the PAC at LNS. We suggested to perform measurements of these observables at both accelerators: SATURNE-II and the Synchrophasotron; this was realized. So, it was one of the results of the Deuteron-91 Symposium: our collaboration was born.

The collaboration included physicists from LHE of JINR, Russia (PNPI, Gatchina), Ukraine (Kiev and Kharkov), Bulgaria, France and USA (the College of William and Mary and Norfolk University); on different stages other physicists joined the collaboration. It was the JINR–IN2P3 agreement on cooperation which gave to JINR physicists the possibility to realize these proposals. That was crucially important at that time.

Work within the JINR–IN2P3 agreement continued until the premature closing of SATURNE-II in December of 1997, but the core of the collaboration born in 1992 is alive up to now (with different goals, of course). The collaborative work was rather fruitful.

Using both accelerators, SATURNE-II and the Synchrophasotron, in a complementary way, we acquired a rather wide set of accurate, complete and unique data for both deuteron breakup and backward elastic scattering off protons, including data for spin-dependent observables. The data were obtained in a wide kinetic energy region: from several hundreds of MeV up to approximately 4 GeV. They revealed several unknown (and still not completely explained) features; the data sets obtained at both accelerators in overlapping energy regions are in excellent agreement. It was clearly demonstrated that quark degrees of freedom are important at small inter-nucleon distances in the structure of the lightest nuclei. The data were published, and have been cited up to now. Moreover, several PhD thesis were successfully defended in JINR member-countries and USA.

The collaboration of physicists from JINR and member-countries, including Russia, with physicists from LNS was not restricted by experiments on the deuteron structure only. Another fruitful direction of research was originated from previous studies performed in parallel at LHE and LNS on Delta-excitation in nuclei induced by $^3He \to t$ charge exchange. Again there was a complementarity because the Synchrophasotron energy was higher than the SATURNE-II energy. This allowed us to study Delta-excitations in a wide energy region (moreover, LHE physicists got some data for the $t \to {}^3He$ charge exchange using quasi-monochromatic triton beam from ^4He breakup). This common interest resulted in exclusive experiments on inelastic the $^4He \to {}^4He'$ and polarized $d \to d'$ scattering with excitation of the Delta- and Roper resonances, carried out with the modified SPES-4π two-arm spectrometer. Physicists from Denmark, Germany and Poland have joined us in these studies. The set of obtained data was published and again, PhD These were defended in France, at JINR and in the JINR member-countries.

This series of experiments has got European support within INTAS and INTAS–RFBR grants.

One important scientific-technical output, obtained within the JINR–IN2P3 agreement on cooperation, was the HYPOM polarimeter with its unique liquid hydrogen analyzing target. The uniqueness of this target is in its shape: it was not a usual cylinder but a parallelepiped instead. It was a difficult technical problem, requested by the physics (the target was surrounded by two sets of plane detectors for recoil particles) and successfully solved by ingenious cryogenic engineers from JINR.

Another important methodical result was obtained within the common Saclay–Dubna project ALPOM, realized in VBLHEP using the polarized deuteron beam from the Synchrophasotron.

This project provided a decisive step for success of the well-known JLAB experiment on the determination of the ratio of proton electric to magnetic form factors, where a method was used (known now as the Akhiezer–Rekalo polarization method) and it was discovered that this ratio is strongly dependent upon the transferred momentum in elastic electron-proton scattering. The key point for such measurement was the performance of polarimeter for the scattered protons. This was the ALPOM project where the prototype of the polarimeter was studied and

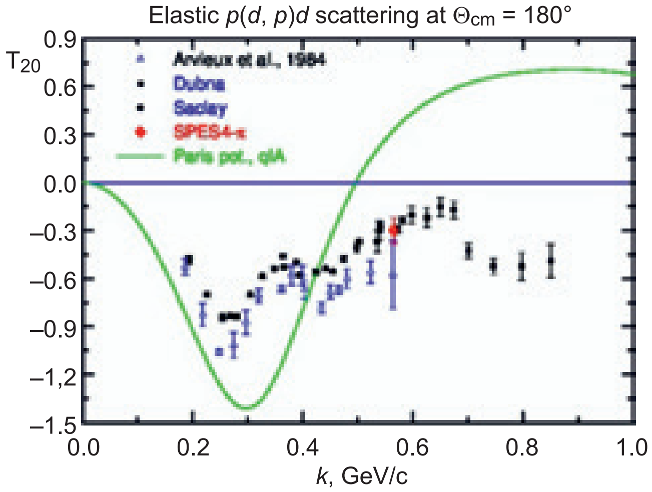

Fig. 1. Tensor analyzing power T_{20} of the elastic backward deuteron-proton scattering. Full black circles: data taken by the collaboration at Saclay; Full black squares: data taken in Dubna by the same collaboration. Red diamond: point obtained as a by-product of experiment E278C with SPES-4π in kinematically redundant measurement: the scattered deuteron and recoil proton are detected in coincidences and with measurements of their momenta; Open triangles: first Saclay data by J. Arvieux et al.; line: expected behaviour of the analyzing power for one-nucleon-exchange mechanism with the deuteron wave function based on Paris *NN*-potential. Abscissa: internal proton-neutron relative momentum in deuteron (κ) calculated from the beam kinetic energy

calibrated. The polarimeter was built and calibrated in Dubna using detectors from the Saclay POMME polarimeter within the JINR–IN2P3 agreement framework.

It is worthwhile to mention also that a short experiment on accelerator physics was performed within the JINR–IN2P3 agreement on cooperation together with P.-A. Chamouard and F. Lehar. It was devoted to the study of the first depolarizing resonance crossing at SATURNE-II. In fact it was a by-product but gave to me (as an experimentalist) big aesthetic pleasure, in particular due to the excellent instrumentation of the accelerator. (It is difficult not to mention such general features of the LNS as the excellent instrumental and beam infrastructure of the SATURNE-II...)

The collaboration born in 1991 is still alive but has been modified. Now many of its participants work together in experiments at JLAB, in the realization of the PANDA project, in experiments under preparation at VBLHEP of JINR at the Nuclotron. Members of the collaboration from France and USA contributed a lot to setting up **the movable polarized proton target** at VBLHEP. This target was constructed within a collaboration of Saclay, Argonne and FNAL scientists; after completing the experiments at FNAL, the collaboration, inspired by F. Lehar transferred this target to JINR. This project was supported by international grants including INTAS.

The common work of LHE physicists at LNS under the framework of the JINR–IN2P3 agreement had brilliant humanitary aspect as well: it created friendship and good understanding between all members of this really international team.

It was a big pleasure to work in shifts, to discuss scientific results as well as other topics, to build new plans and to prepare new experiments together. I'm happy that the mentioned events and collaborative work happened in my life.

Fig. 2. The first data taking run in LNS with SPES-4 was done successfully. Good data are ready for further analysis!

VBLHEP of JINR collaboration with IN2P3: Quarkonia production in the ALICE experiment at LHC using the muon spectrometer

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Аннотация

Представлены результаты совместных работ по измерению рождения квар542кониев в эксперименте ALICE, проведенных физиками из ОИЯИ и LPC Clermont-Ferrand (Франция) в рамках международного проекта, поддержанного со стороны РФФИ и CNRS/IN2P3 в 2009–2011 годах.

Résumé

Nous présentons les résultats des tra-vaux communs sur la mesure de la production de quarkonia dans l'expérience ALICE effectués par les physiciens du JINR et le LPC Clermont-Ferrand (France) dans le cadre du projet international soutenu par le RFBR et CNRS/IN2P3 en 2009–2011.

ALICE (A Large Ion Collider Experiment) [1,2] is a dedicated heavy ion experiment at LHC with a prime goal to study the physics of strongly interacting matter at extreme energy densities, produced in ion–ion (A–A) collisions, where the formation of the quark-gluon plasma (QGP) is expected. Our group from LHEP JINR is involved in the ALICE experiment since 1991. One of our priorities is the physics of the ALICE muon spectrometer (MS). The MS consists of a 4 m long front absorber placed 90 cm from the interaction point, a 15 m long small angle absorber, a large conventional dipole magnet with a 3 Tm integrated field, 10 high granularity tracking chambers, a muon filter made of a 1.2 m thick iron wall and 4 large area trigger chambers. The design and prototyping of the dipole magnet and construction of its iron yoke was done in JINR. We are collaborating closely with many laboratories from France involved in ALICE, especially with the LPC Clermont-Ferrand. The ALICE group of this laboratory, led by P. Dupieux, is responsible for the trigger system of MS. During 2009–2011 our two groups have participated in a project on quarkonia production measurement with ALICE MS, supported by the CNRS/IN2P3 and Russian Foundation for Basic Research (RFBR) within the framework of the International Scientific Cooperation Project (PICS).

Heavy quarkonium states are considered as one of the key observables for the study of the phase transition from the hadronic matter to QGP. In the last 25 years, experiments at CERN and Brookhaven have studied collisions of heavy ions looking for a suppression of charmonia (J/ψ, ψ') and bottomonia (Υ, Υ', Υ'') states, considered as a signature of the phase transition. The large cross section of charm quark–antiquark pair production at LHC energies is expected to induce a novel formation mechanism for charmonia in heavy ion collisions, related to a recombination of charm quarks from different pairs produced in the QGP. On the other hand, the cold nuclear matter (CNM) effects such as nuclear absorption and shadowing are also affecting the quarkonia yields in A–A as well as in proton–nucleus (*p*–A) collisions with respect to the proton–proton (*p*–*p*) collisions.

The basic objectives of our project was to develop data analysis methods for the measurements of the quarkonia production in dimuon mode in *p*–*p*, Pb–Pb and *p*–Pb (Pb–*p*) collisions at LHC and to perform these measurements using the ALICE MS operating at forward rapidities ($2.5 < y < 4$). The quarkonia studies in these different collision systems, besides their intrinsic interest, are also tightly interrelated. The *p*–*p* data will be used to benchmark perturbative QCD predictions and provide the reference for the *p*–Pb (Pb–*p*) data allowing one to measure the CNM effects. Since the rapidity shift of the centre of mass is in opposite direction for *p*–Pb and Pb–*p*, the two systems will allow the largest interval in Bjorken *x* to be covered for gluon distribution (Chapter 6.6 of [2]). In their turn, measurements in *p*–Pb (Pb–*p*) collisions are mandatory to unravel the QGP effects from the CNM ones in Pb–Pb collisions. To achieve the project goals the following main tasks have been fulfilled:

- A cocktail generator is developed to study the quarkonia production in Pb–Pb and *p*–Pb (Pb–*p*) collisions at LHC, including generators for the quarkonia, for the heavy flavour hadrons and for the underlying event. The quarkonia rapidity and p_t distribution parameterizations for these collisions are obtained using the *p*–*p* collision experimental data, the Glauber model and the nuclear gluon shadowing effects. The cocktail generator is included in the AliRoot — the ALICE software package. Predictions are obtained for the dimuon invariant mass spectrum and for the charmonia and bottomonia yields in *p*–Pb (Pb–*p*) collisions, based on the simulations and on the methods developed earlier in [2] for Pb–Pb collisions. Measuring the quarkonia signals is complicated due to the large dimuon background. The uncorrelated component of the background could be subtracted from the dimuon invariant mass spectrum, using the so-called "event mixing" method. For unravelling the quarkonia signals and the background correlated component (coming mainly from semi-leptonic decays of heavy flavour hadrons), a dedicated fitting procedure was developed. It is shown that the quarkonia expected yields in the MS acceptance, for one month of LHC running at nominal luminosity, will be enough to study the transverse momentum (p_t) and centrality dependences. The results are presented in [3].
- Methods are developed [4] to interpolate the quarkonia production data (cross section, p_t and rapidity spectra) measured in *p*–*p* collisions at the LHC for 7 TeV and at lower energy colliders to the LHC energies for Pb–Pb and *p*–Pb (Pb–*p*) collisions. The interpolated result with the use of the Glauber model could serve as a reference for the measured data in these collisions allowing one to estimate the CNM and QGP effects in quarkonia production. These methods were used for the Pb–Pb collisions at 2.76 TeV [5] and also for the *p*–Pb (Pb–*p*) collisions at 5 TeV.
- Simulation study of the ALICE MS perfor-mance to measure the open charm (*D*) and bottom (*B*) hadron production inclusive cross sections in *p*–*p* collisions using single muon and dimuon modes. Such measurements are important also for the quarkonia studies since the production mechanisms of *D*(*B*) hadrons and charmonia (bottomonia) are the same and these hadrons give the main contribution to the dimuon background of quarkonia. Results of this study [6] were used in the analysis of the data collected in *p*–*p* collisions at 7 TeV. The production cross section of muons from heavy flavour decays is measured as a function of p_t and rapidity in the MS acceptance [7].
- Participation in the data taking for *p*–*p* collisions at 7 TeV and 2.76 TeV and Pb–Pb collision at 2.76 TeV during 2009–2011. Preparation of the software for the simulation of the quarkonia production in these collisions to evaluate the dimuon acceptance and registration efficiencies of the ALICE MS and to test the quarkonia signal extraction methods. Analysis of the collected data for the J/ψ measurements using ALICE MS. For *p*–*p* collisions at 7 TeV and 2.76 TeV the J/ψ production differential cross sections are measured as a function of the p_t and rapidity. The results are published in [8, 9] and are in a good agreement with the measurements of the LHCb and CMS experiments. For Pb–Pb collision at 2.76 TeV the J/ψ yields and the nuclear modification factor (RAA) as a function of the collision centrality are measured [5]. The measured RAA shows a considerable suppression of the J/ψ yields in Pb–Pb collisions which is almost independent of centrality. However the suppression is smaller than the one measured at RHIC energies and its centrality behavior is also different. This interesting observation is in qualitative agreement with theoretical predictions that the quarkonia regeneration mechanisms should be important at LHC energies.

Further detailed measurements with larger statistics are mandatory in order to disentangle the different theoretical interpretations and to achieve a comprehensive understanding of the J/ψ and other quarkonia production in heavy ion collisions. Such an understanding still needs a precise knowledge of the CNM effects, which will be studied in the incoming *p*–Pb (Pb–*p*) collisions. Also, very crucial is the realization of the ALICE MS upgrade plans aiming to improve its performances strongly.

We thank our LPC colleagues for the fruitful work and are looking forward to the future cooperation in the wonderland of ALICE physics.

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Study of nanoparticles and storage of very cold neutrons in a trap with nano-structured walls

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Аннотация

Эффективность известных нейтронных отражателей была очень низкой для очень холодных нейтронов (ОХН), т.е. нейтронов со скоростями порядка сотни метров в секунду. Поэтому неэффективными были их производство и извлечение. Однако недавно мы предложили и продемонстрировали метод существенного улучшения отражателей ОХН, позволяющий заполнить пробел между стандартными реакторными отражателями на основе нейтрон-ядерного рассеяния и отражателями, использующими оптический потенциал вещества. При помощи новых наноструктурированных отражателей можно не только создавать намного более эффективные источники ОХН, а также холодных и ультрахолодных нейтронов (УХН), не только транспортировать их с минимальными потерями, но и хранить ОХН в замкнутой ловушке.

Résumé

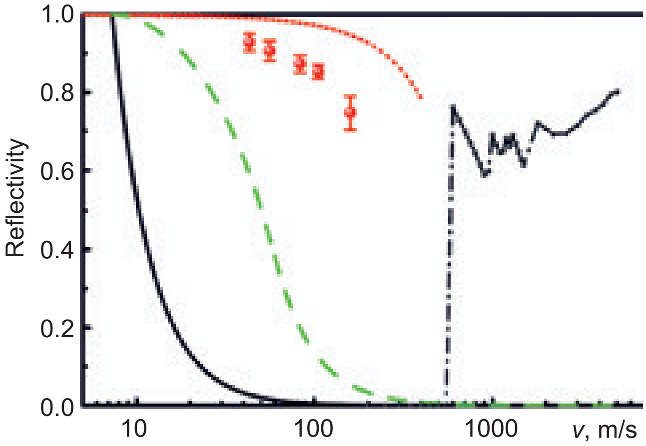
L'efficacité connue des réflecteurs de neutrons était très basse, en particulier pour les neutrons très froids (NTF), c'est-à-dire dire des neutrons avec des vitesses de l'ordre d'une centaine mètres par seconde. C'est pourquoi leur production et extraction n'étaient efficaces non plus. Récemment, nous avons proposé et testé une méthode qui permet améliorer d'une façon radicale l'efficacité des réflecteurs des NTFet qui permetde remplir un gap entre les réflecteurs standard utilisés dans les réacteurs et basés sur l'interaction neutron-noyau et les réflecteurs basés sur le potentiel optique d'un matériel. A l'aide de ces nouveaux réflecteurs à la base de nanoparticules on pourrait construire des sources beaucoup plus efficaces pour les NTF mais également pour les neutrons froids et ultra froids, ainsi que les transporter avec le minimum de pertes et même stocker les NTF dans un piège fermé.

The efficiency of known neutron reflectors is very poor in the velocity range of so-called very cold neutrons (VCN), which is of the order of one or a few hundred meters per second. That is why the efficiency of production and extraction of VCN and even cold neutrons (CN) is strongly compromised. Even reflectors for thermal neutrons in nuclear reactors and spallation neutron sources might gain if this shortcut is repaired.

Recently we proposed a method to improve dramatically VCN reflectors and showed that powders of nanoparticles could be used efficiently as first reflectors for VCN in the velocity range of up to 160 m/s [1], thus bridging the energy gap between efficient reactor reflectors [2] for thermal and cold neutrons, and optical neutron-matter potential for ultracold neutrons (UCN) [3].

The use of nanoparticles provides a sufficiently large cross-section for coherent scattering and inhomogeneities of the reflector density on a spatial scale of about the neutron wavelength [4]. A large number of diffusive collisions needed to reflect VCN from powder constrains the choice of materials: only low absorbing ones with high optical potential are appropriate. Thus, diamond nanoparticles were an evident candidate for such a VCN reflector. The formation of diamond nanoparticles by explosive shock was first observed more than forty years ago [5]. Since then very intensive studies of their production and of their various applications have been performed worldwide. These particles measure a few nanometers; they consist of a diamond nucleus (with a typical diamond density and optical potential)

Alexander Strelkov — one of the authors of the discovery of ultra-cold neutrons in the 60s — is ready to cover the nanoparticles saucepan to cook very cold neutron soup



The elastic reflection probability for isotropic neutron flux is shown as a function of the neutron velocity for various carbon-based reflectors: (1) Diamond-like coating (DLC) (thin solid line), (2) The best supermirror [16] (dashed line), (3) Hydrogen-free ultradiamond [15] powder with the infinite thickness (dotted line). Calculation. (4) VCN reflection from 3 cm thick diamond nanopowder at ambient temperature (points), with significant hydrogen contamination [this Letter]. Experiment. (5) MCNP calculation for reactor graphite reflector [2] with the infinite thickness at ambient temperature

within an onion-like shell with a complex chemical composition [6] (with lower optical potential).

A recent review of the synthesis, structure, properties and applications of diamond nanoparticles can be found in [7]. The first experiments on the reflection of VCN from nanostructured materials as well as on VCN storage were carried out in the seventies [8] and later continued in Ref. [9]. In [1] we extended significantly the energy range and the efficiency of VCN reflection by exploiting diamond nanoparticles. A reflector of this type is particularly useful for both UCN sources using ultracold nanoparticles [4, 10] and for VCN sources; it would not be efficient however for cold and thermal neutrons, as shown in [11].

We have observed for the first time the storage of VCN with velocities in the range of 40–160 m/s (the energy up to 10^{-4} eV) in a trap with walls composed of powder of diamond nanoparticles. The VCN storage will allow us to accumulate significant number (density) of VCN in a trap (much larger than that typical for UCN). Such a trap can be used as a reflector for VCN sources and in some cases for UCN sources. Further improvement of the VCN storage times could be achieved by removing a part of hydrogen from powder and by cooling the trap to a temperature at which the inelastic up-scattering of VCN at hydrogen is suppressed. Another option could consist in replacing the diamond nanoparticles by O_2, D_2, D_2O, CO_2, CO or other low-absorbing nanoparticles, free of hydrogen and other impurities with significant VCN loss cross-section. The probability of cold neutron isotropic flux reflection from diamond nanoparticles is compared with other well-known reflectors in the Figure above.

As clear from the Figure, the maximum energy of the reflected VCN and the reflection probability far exceeds the corresponding values for the best supermirrors available [16]. Thus nanoparticle reflector bridges the energy gap between efficient reactor reflectors for thermal and cold neutrons, and the optical potential for UCN. This phenomenon has a number of applications. Such a reflector can be used for VCN and UCN sources, for more efficient guiding of VCN and even faster neutrons at quasi-specular trajectories [17].

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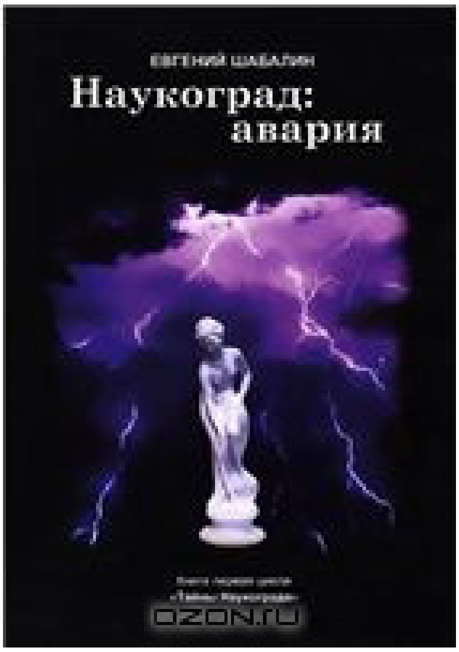

This series of articles about nanoparticles as a possible reflector for future nuclear reactors gave an inspiration to our famous colleague Eugeny Shabalin who wrote science fiction novels "Science town: break-down" and "Noble solitaire"

40 years of Collaboration between
JINR (Dubna) and IN2P3 (France)

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