JOINT INSTITUTE FOR NUCLEAR RESEARCH

D15-2004-126

Manuscript
UDK: 539.172.16 + 539.172.17

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STUDY OF FUSION REACTIONS INDUCED BY ^{4,6}He AND ^{7}Li BEAMS

Specialty: 01.04.16 — Physics of Atomic Nuclei and Elementary Particles

Summary report of the thesis for the
Ph.D. Degree of Physics and Mathematical Sciences

Dubna 2004

Thesis is prepared at the Laboratory of Nuclear Reactions (FLNR), Joint Institute for Nuclear Research (Dubna).

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Defense of the thesis will take place on "___" _________ 2004 in "___" hours at the meeting of the Dissertation Scientific Council D.720.001.06 Joint Institute for Nuclear Research, to the address: 141980, Dubna, Moscow region, Joint Institute for Nuclear Research

Thesis is available at the Library of JINR.

Summary report of the thesis is distributed on "___" _______2004

Scientific Secretary of Dissertation Scientific Council, Candidate of Physics and Mathematical Sciences — **A.G. Popeko**

Status of the thesis

In the past few years, in different scientific centers, intensive experimental studies have been performed using secondary beams formed from the radioactive products of nuclear reactions. Lately there has been a growing trend to use secondary beams as a means of investigating the interaction cross sections of these exotic nuclei with the target nuclei. These data help getting information on the structure of nuclei far from the line of stability, on the distribution of nuclear matter and on charge radii. Lately there has been a growing trend to use secondary beams as a means of investigating the interaction cross sections of these exotic nuclei with the target nuclei. These data help getting information on the structure of nuclei far from the line of stability, on the distribution of nuclear matter and on charge radii.

The study of fusion reactions involving weakly-bound or radioactive beams (^{6}He, ^{11}Li) are one of the most challenging experimental and theoretical problems in nuclear physics. It is well established that the coupling of collective degrees of freedom to the fusion channel enhances significantly the tunneling probability at sub-barrier energies [1]. On the other hand, the low binding energy of radioactive nuclei may cause important loss of incoming flux due to the breakup process.

The effects on the reaction mechanisms due to the exotic structure of weakly-bound or radioactive nuclei are expected to be greatest in ^{11}Li because of its halo nature. However, the effects predicted for ^{11}Li are also expected for ^{6}He. Currently, ^{6}He beams of the appropriate energy are more intense and of higher quality than ^{11}Li. In the case of ^{6}He there is a neutron skin outside an α-particle core even though the wave function is not as extended as in the case of ^{11}Li. However, for unequivocal conclusions there is a question on comparison of these reactions with the reactions caused by particles of a stable beam nucleus.

Clearly, the available data in the literature for ^{6}He induced fusion reactions are not sufficient to draw any firm conclusion about a possible suppression above the barrier. Measurement of the all ^{209}Bi(^{6}He, xn) decay-channels and fission at higher energies are important in the determination dynamics of the collision.

Comparing the fission and evaporation channel cross sections in the reactions $^{6}He+^{209}Bi$ and $^{4}He+^{209}Bi$, one has to take into account that different compound nuclei are obtained in these reactions with different excitation energies and different decay properties. To avoid additional ambiguities one may propose to measure the fission and evaporation channel cross sections in reactions, in which the same compound nucleus is formed, such as $^{6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ of the same compound nucleus ^{215}At in example. In that case any difference fission and evaporation channel cross sections may originate from the difference in the entrance channels of the two reactions.

The main goal of the present work is the attempt to reveal any peculiarities that might manifest themselves in reactions induced by weakly bound light nuclei at a broad range of energies near and above the Coulomb barrier. One way to do this is to measure the fission and evaporation channel cross sections for one and the same composite nucleus, produced in different target-projectile combinations.

Main Results and Scientific Novelty Obtained in This Research

1 Fission and [4*n*-8n] evaporation channel cross sections were measured for the first time in the reaction induced by a ^{6}He beam on a ^{209}Bi target in the energy range near the barrier and up to 180 MeV.

2 Fission and [2*n*-3n] evaporation channels cross sections were measured for the first time in the reaction induced by a ^{4}He beam on a ^{209}Bi target in the energy range near the barrier and up to 110 MeV.

3 Fission and [3*n*-9*n*] evaporation channels cross sections were measured for the first time in the reaction induced by a ^{7}Li beam on a ^{208}Pb target in the energy range 29 to 117 MeV.

4 Fission and [3*n*, 4*n*] evaporation channels cross sections were measured for the first time in the reaction induced by a ^{7}Li beam on a ^{209}Bi target in the energy range 32 to 220 MeV.

Main items of the present work

1 A setup is constructed for on-line measurements of fission and evaporation cross sections by detecting in parallel both fission fragments and evaporation residues.

2 The experimental fission and evaporation cross sections are measured for the reactions $^{4,6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ in a broad range of energies above the Coulomb barrier.
3 The experimental fission and evaporation cross sections are measured for the reaction $^{7}Li+^{209}Bi$ in a broad range of energies above the Coulomb barrier.
4 The experimental fusion excitation functions obtained for different reactions ($^{4,6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$) and leading to the same composite nuclei $^{213,215}At$ are analyzed using different models. Conclusions obtained from the analysis are carried out from the point of view of the fusion reaction mechanism induced by weakly bound nuclei.

<u>Structure and volume of the thesis</u>

The thesis consists of 4 chapters, introduction, the conclusions and list of literatures. Thesis is written in English and it contains 90 pages, including figures.

<u>Conferences and Seminars</u>: This study was presented on:
1 VII International School-Seminar on Heavy Ion Physics. (27 May-1 June, 2002, Dubna, Russia).
2 VIII International Conference on Nucleus-Nucleus Collisions (17-21 Jun.2003, Moscow, Russia).
3 Conference on Nuclear and Particle Physics (11-15 Oct., 2003, Cairo, Egypt).
4 Conference of Young Scientists and Specialists (3-8 Feb., 2003, Dubna, Russia).
5 Conference of Young Scientists and Specialists, (4-8 Feb., 2004, Dubna, Russia).
6 International Meeting on Nuclear Spectroscopy and Nuclear Structure NUCLEUS-2004) (22-25 JUNE, 2004, LIV, Belgorod, Russia).
7 International Symposium on Exotic Nuclei, (5-12 July, 2004, Peterhof, Russia).

<u>Contents of the thesis:</u>

Introduction: This part of thesis contains introduction to the fusion reactions mechanism induced by weakly bound nuclei or radioactive beams at energies near and above Coulomb barrier. Also, it contains an overview of the previous research activities and related to the same topic as well as the main items of the present work.

Chapter1: In this chapter the fission and evaporation cross sections in the reactions induced by weakly bound and radioactive beams and measured by different authors were discussed in details. The theoretical calculation predictions for the fusion reaction mechanism induced by exotic nuclei were described. The conclusions obtained from the experimental and theoretical situations for the fusion reaction mechanism were summarized in table.

Chapter2: In this chapter the experimental measurements were performed using the accelerator U400M at FLNR, JINR-DUBNA. ^{208}Bi and ^{208}Pb targets were bombarded by the collimated beams of ^{4,6}He and ^{7}Li. The variation of energy necessary for measuring the excitation functions of the reactions ^{4,6}He+^{209}Bi, ^{7}Li+^{208}Pb and ^{7}Li+^{209}Bi, from the near of Coulomb barrier up to 220MeV was carried out using a thick absorber of Be-target with thickness 5 mm and the subsequent monochromatic of ions ^{4,6}He and ^{7}Li transport through the magnetic system 3QDQQD2Q of accelerator U400M. The value of energy of ^{4,6}He and ^{7}Li beams changed due to change of a magnetic field of system 3QDQQD2Q. Further the beam was transported on a special setup.

Setup for on-line measurements: The experimental setup was constructed for "on-line" measurements of fission and evaporation cross sections by detecting in parallel both fission fragments and evaporation residues. A schematic view of the experimental setup is presented in Fig. 1. The setup can hold up to three targets. The targets are placed at 45° with respect to the secondary beam direction. Two silicon detectors (diameter 5 cm), located with distance 3 cm from the target, face each target from either side. This makes it possible to increase the effective solid angle up to 30%. This array of three targets allows increasing the statistics by a factor of three, as the maximum energy loss of the beam particles between the three targets is less than 1 MeV. If energy degraders are inserted between the targets, it would be possible to get measurement at three different energies of the beam in one run.

To eliminate the background like alpha and other particles emitted in the prompt reaction from our measurements "beam-on", special modulation for the secondary beams ^{6}He and ^{7}Li was used. This procedure allows to regist the α-particles while the beam switched off and the prompt fission fragments, while the beam switched on.

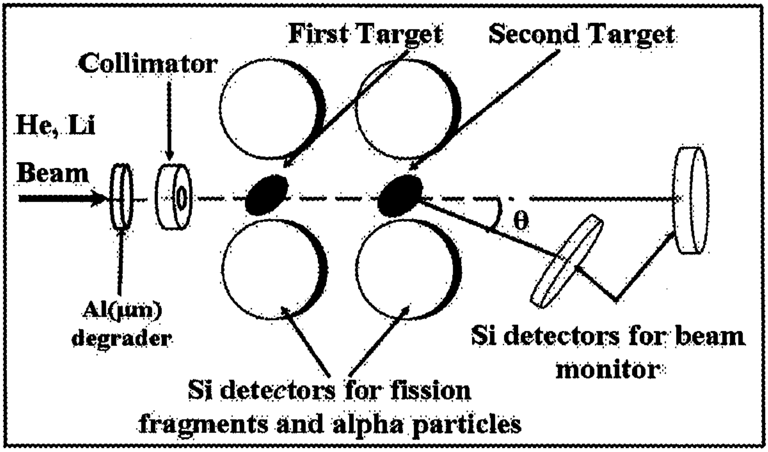

Fig. 1 Layout of the experimental setup: showing the arrangement of detectors and targets for fission and evaporations cross section measurements "on-line".

Chapter 3: This chapter contains the experimental results for the fission and evaporation cross sections obtained from the reactions $^{4}He+^{209}Bi$, $^{6}He+^{209}Bi$, $^{7}Li+^{208}Pb$ and $^{7}Li+^{209}Bi$ at a broad range of energies near and above Coulomb barrier of each reaction. The fission cross sections were measured "beam-on". The x*n*-evaporation channel cross sections were measured on line by detecting α-particles emitted from the evaporation channels with short live times, and "beam-off" by detecting α-particles emitted from the evaporation channels with long live times. For the evaporation channels with small α-decay branching ratio we used the γ-ray detection method off-line to measure the x*n*-evaporation cross sections.

I α-particle energy spectrum of the evaporation channels in the reactions $^{4,6}He+^{209}Bi$, $^{7}Li+^{208}Pb$ and $^{7}Li+^{209}Bi$:

The characteristics of the main α-decay modes of the nuclei, which can be formed in the reactions $^{4,6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$, are shown in Table1 and formed in the reaction $^{7}Li+^{209}Bi$ is shown in Table2.

Table1 α-decay characteristics of the At-isotopes formed in the $^{4,6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ reactions.

xn (**^{4}He**)	**xn** (**^{6}He,^{7}Li**)	**Evaporation Channels**	**$T_{1/2}$**	**E_α MeV**
-	**1*n***	^{214}At	558 ns	8.82
0*n*	**2*n***	^{213}At	125 ns	9.08
1*n*	**3*n***	^{212}At	314 ms	7.68
2*n*	**4*n***	^{211}At	7.21 h	5.87 7.28 (^{211}Po 516 ms)
3*n*	**5*n***	^{210}At	8.1 h	5.36 - 5.52 5.3 (^{210}Po 138.4d)

Table2 α-decay characteristics of the Rn-isotopes, formed in the reaction $^{7}Li+^{209}Bi$

X*n*	**Evaporation residue**	**$T_{1/2}$**	**E_α (MeV)**
3*n*	^{213}Rn	25.0 ms	8.0843
4*n*	^{212}Rn	23.9 min	6.285

As an example of "on-line" measurements, α-particle spectrum emitted from the decay of At-isotopes in the reaction $^{7}Li+^{208}Pb$ is Fig.2. In the figure the 3n-evaporation channel is clearly visible with the α-particle energy spectrum E_α=7.8 MeV.

The α-decay spectrum measured "off-line" in the decay of At-isotopes produced in the reactions $^{6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ are shown in Figs. (3, 4). From the figure one can identify the 4n-evaporation channels (^{211}At-isotop) produced in the two reactions.

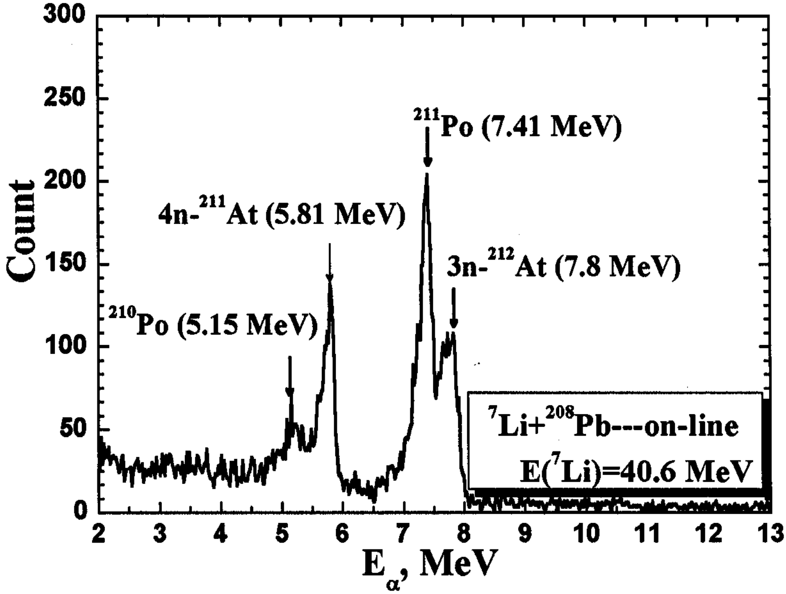

Fig. 2 α-particle energy spectrum for the 3*n* evaporation channel in the reaction $^7Li+^{208}Pb\rightarrow ^{215-3n}At$ at E(^{7}Li)= 40.6 MeV.

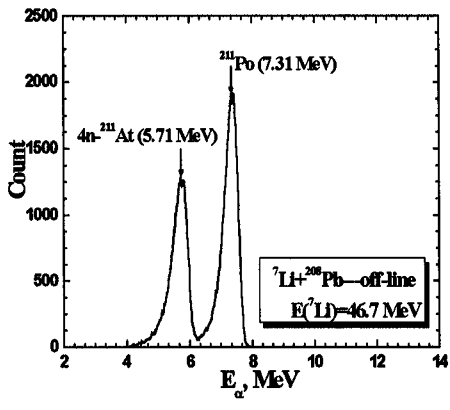

Fig. 3 α-particle energy spectrum for 4n evaporation channel in the reaction $^7Li+^{208}Pb\rightarrow ^{215-4n}At$ "off-line".

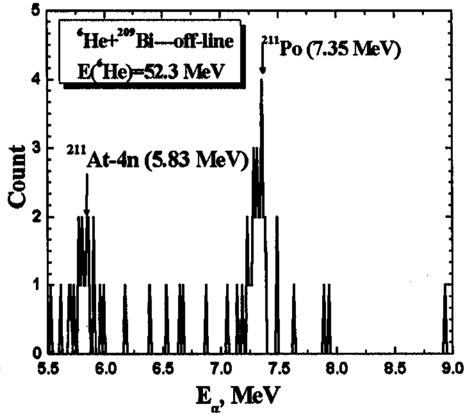

Fig. 4 α-particle energy spectrum for 4n evaporation channel in the reaction $He+^{209}Bi\rightarrow ^{215-4n}At$ "off-line"

II gamma rays energy spectrum of the evaporation channels in the reactions $^{7}Li+^{208}Pb$:

5n-9n evaporation channels were measured off-line in the reactions $^{7}Li+^{208}Pb$ and $^{6}He+^{209}Bi$ by detecting the γ-rays emitted from the evaporation channels. The evaporation channels were identified by both of γ-rays energy and half live time for each channel as shown in Figs. (5, 6).

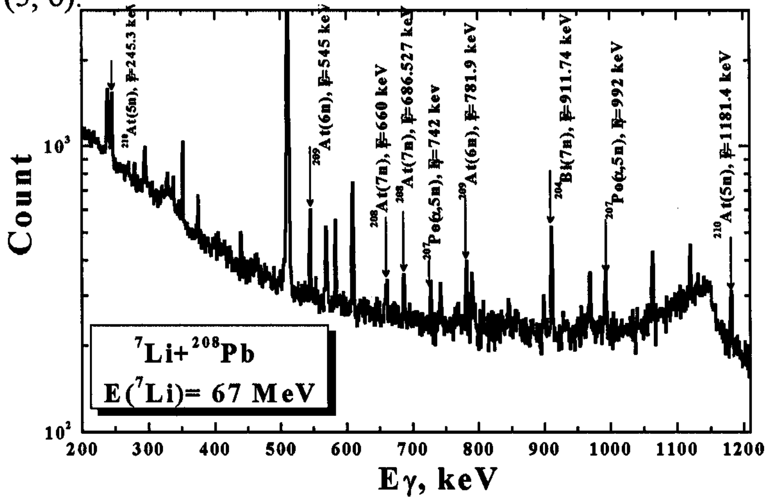

Fig. 5 γ rays spectra emitted from (5*n*-7*n*) evaporation channels produced in reaction $^{7}Li+^{208}Pb$ at ^{7}Li beam energy 67 MeV.

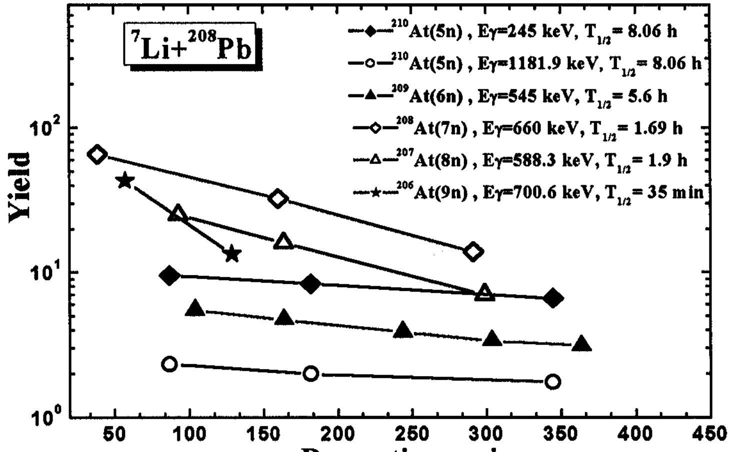

Fig. 6 The decay curves of the γ-rays activity of the (*5n-9n*) evaporation channels in the reaction ($^{7}Li+^{208}Pb\rightarrow ^{215-xn}At$).

III fission fragments measured in the reactions $^{4,6}He+^{209}Bi$, $^{7}Li+^{208}Pb$ and $^{7}Li+^{209}Bi$:

The fission fragments in the reactions $^{209}Bi(^{4,6}He, f)$, $^{208}Pb(^{7}Li, f)$ and $^{209}Bi(^{7}Li, f)$ were recorded on-line at energies near the coulomb barrier up to 220 MeV. In the fission reactions two correlated fission fragments were registered in coincidence by a couple of silicon detectors in "on-line" method. These silicon detectors were placed at a defined position to get two correlated fission fragments in the center of mass system. These detectors were calibrated with fission fragments from a thin ^{244}Cm source. By using this calibration the energies E_1 and E_2 of fragment 1 and 2 were measured, respectively. The fission fragments obtained in the reaction $^{208}Pb(^{7}Li, f)$ is shown in Figs. 7.

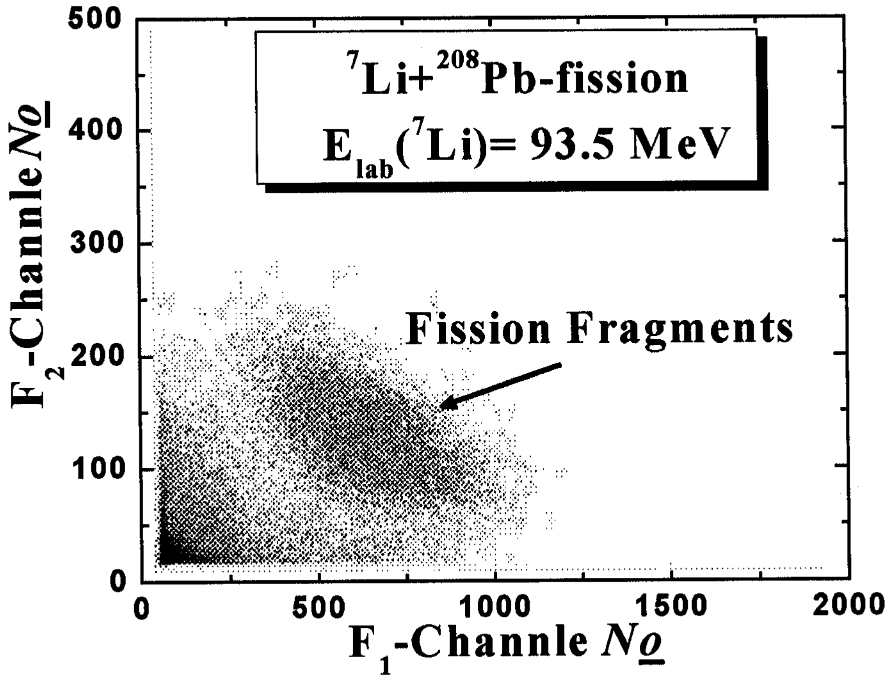

Fig. 7 The typical two-dimensional plot of the correlated fission fragments obtained in the reaction $^{7}Li+^{208}Pb$ at $E(^{7}Li)$= 93.5 MeV.

Chapter4:

The experimental fission cross sections measured in the reactions $^{4}He+^{209}Bi$, $^{6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ with the theoretical calculations are shown in Fig. 8.

Fig.8a shown the fission excitation functions obtained in the reaction $^{4}He+^{209}Bi$. Fission cross sections at energies near the barrier were measured by [Itkis et al.[2]]. Fig.8b shown the fission excitation function obtained in the reaction $^{6}He+^{209}Bi$ at energy 50 up to 180 MeV. Fig. 8c shown the fission excitation function obtained in the reaction $^{7}Li+^{208}Pb$ at energy near the barrier and up to 100 Mev.

The comparison between the fission excitation functions for the three reactions $^{4,6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ can help in study of the fission mechanism reaction induced by weakly bound nuclei and leading to the same composite nuclei $^{213,215}At$. This comparison is shown in Fig. 9.

Fig.9 shown that the fission cross sections for the three reactions $^{4,6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ are the same within the experimental error for a broad range of energies and the fission reaction mechanism in the three reaction systems have the same behaviour.

The experimental *xn*-evaporation channel cross sections measured in the reactions $^{4}He+^{209}Bi$, $^{6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ with the theoretical calculations are shown in Fig. 10. Fig. 10a shown the (1*n*-6*n*) evaporation excitation functions obtained in the reaction $^{4}He+^{209}Bi$. 1n evaporation channel was measured by Ref. [3] and (4*n*-6*n*) evaporation channels were measured by. [4]. Fig. 10b shown the (4*n*-8*n*) evaporation channel excitation function obtained in the reaction $^{6}He+^{209}Bi$. Fig. 10(c, d) shown the (3*n*-9*n*) evaporation channels excitation function obtained in the reaction $^{7}Li+^{208}Pb$.

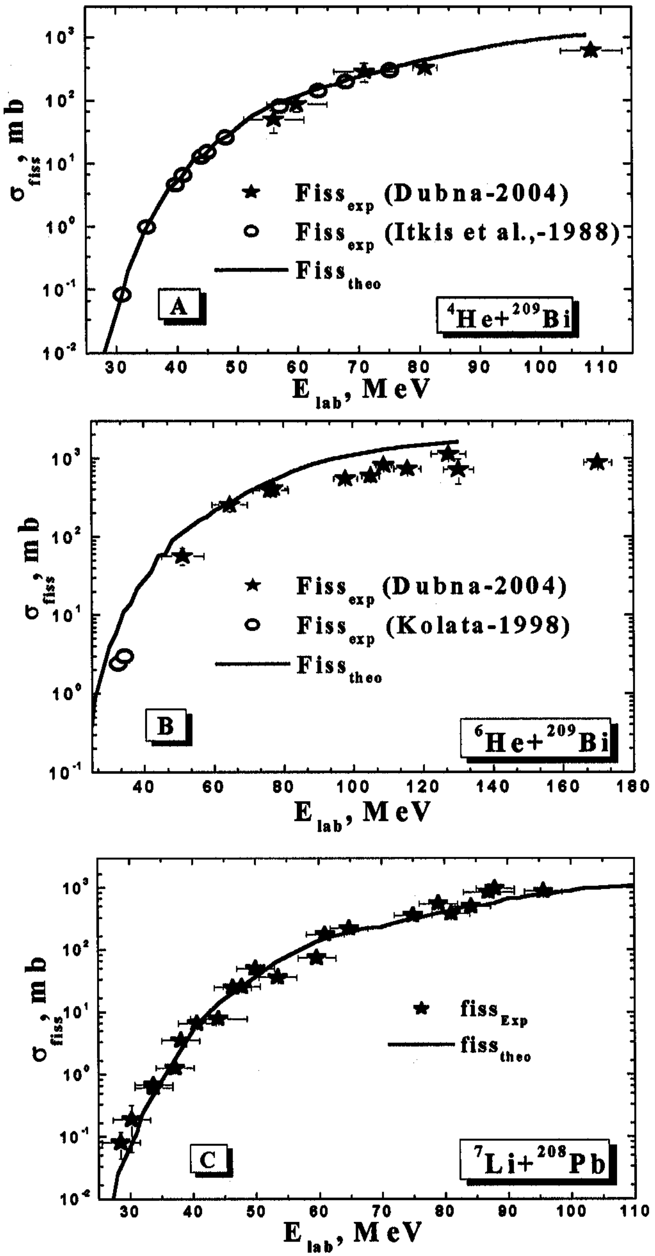

Fig. 8 Fission excitation functions for the reactions $^4He+^{209}Bi$, $^6He+^{209}Bi$ and $^7Li+^{208}Pb$. The symbols denote the experimental data and the line represents the theoretical calculations using the PACE-4 code.

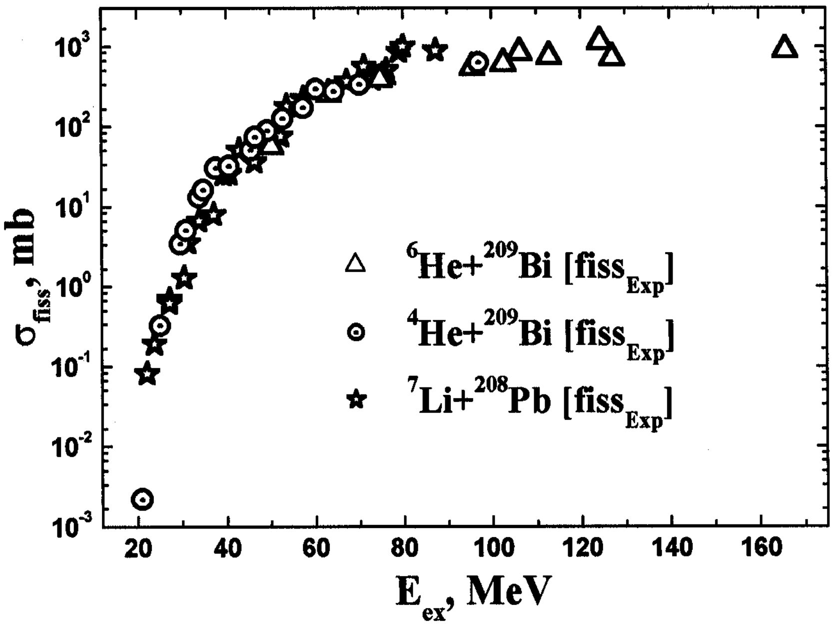

Fig. 9 Fission excitation functions for the reactions $^{4,6}He+^{209}Bi$ and $^7Li+^{208}Pb$.

The experimental fission and evaporation cross sections obtained in the reactions $^4He+^{209}Bi$, $^6He+^{209}Bi$ and $^7Li+^{208}Pb$ were analyzed using the statistical model within the PACE-4 code [5]. The fission and evaporation cross section calculations had the same parameters in the reactions $^4He+^{209}Bi$ and $^7Li+^{208}Pb$ [r_o=1.3 fm (the interaction radius which connected to geometrical size of the nuclear part of the interaction potential), l_{max}=35 (maximum angular momentum) and v_o=67 MeV (nuclear interaction potential)]. While the parameters [r_o=1.35 fm, l_{max}=40 and v_o=45 MeV] were used in the calculations of fission and evaporation cross sections for the reaction $^6He+^{209}Bi$.

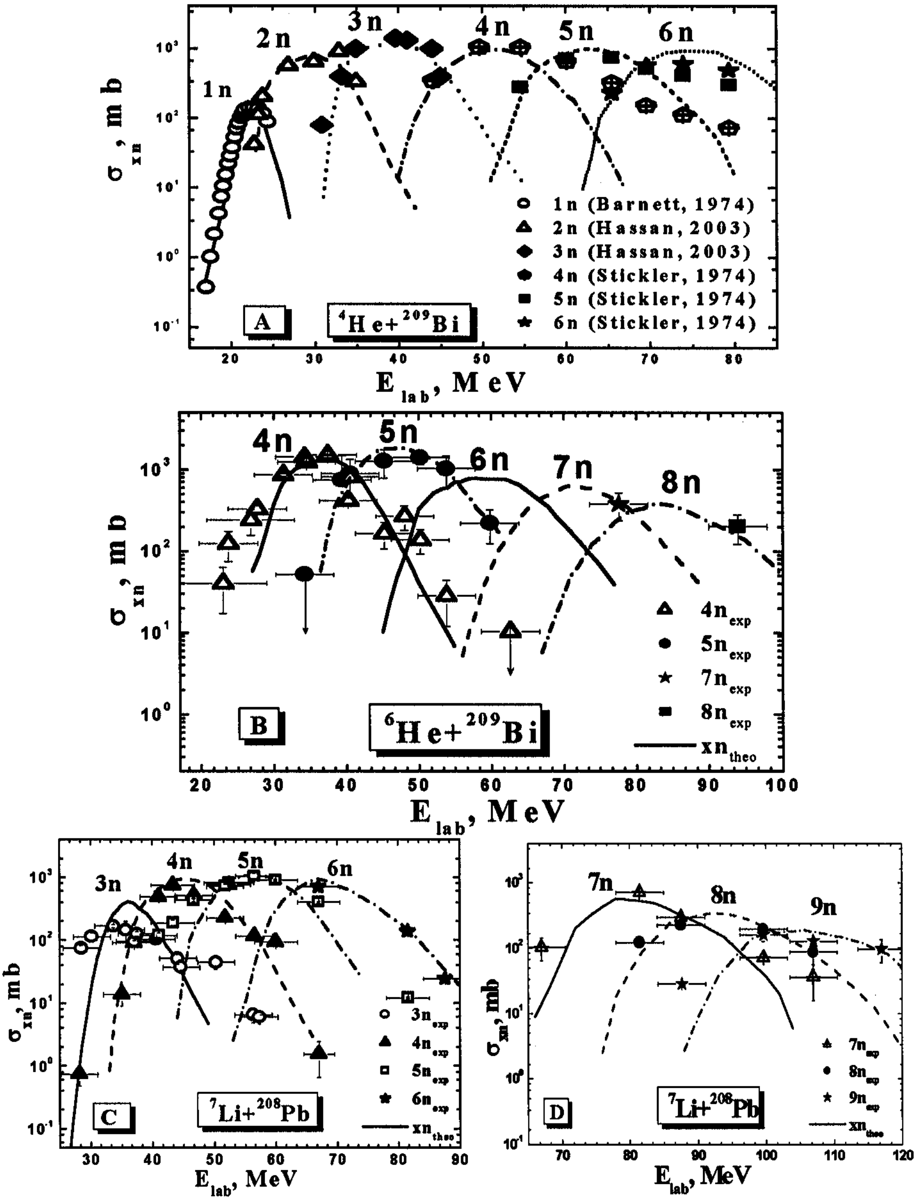

Fig. 10 Evaporation excitation functions for the reactions ^{4}He+^{209}Bi, ^{6}He+^{209}Bi and ^{7}Li+^{208}Pb. The symbols denote the experimental data and the line represents the theoretical calculations using the PACE-4 code.

On the basis of the fission and evaporation cross section measurements, fusion excitation functions in the reactions $^{4,6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ were determined by summing both of fission and evaporation cross sections at each center mass of energy. The results are shown in Fig. 11. The Theoretical calculations of the fusion cross sections were made using the Couple Channel model within the "CCFULL"-code [6].

Fig. (11A) shown the fusion excitation function obtained in the reaction $^{4}He+^{209}Bi$ by summing both of (1*n*-6*n*) evaporation channels and fission cross sections at each center mass of energy. Fig. (11B) shown the fusion excitation function obtained in the reaction $^{6}He+^{209}Bi$ by summing both of (3*n*-5*n*) evaporation channels and fission cross sections. Fig. (11C) shown the fusion excitation function obtained in the reaction $^{7}Li+^{208}Pb$ by summing both of (3*n*-9*n*) evaporation channels and fission cross sections.

Figs. (11B,11C) shown that the experimental fusion cross section for the reactions $^{6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ have the same values at energies above the Coulomb barrier and suppressed approximately by the value 78 %. The amount of suppression at higher energies due to the effect of breakup but the breakup not clear at energies lower the Coulomb barrier.

The explanation of similar behaviour of fusion excitation functions is obtained. The possible explanation will consist in the identical processes occurring as in a case with beam ions ^{4}He, and in a case with weakly bound nuclei like ^{6}He and ^{7}Li

The structure of the weakly bound nucleus is ^{4}He nucleus connected with 2n (as ^{6}He) or ^{3}H (as ^{7}Li) and as shown in literatures, the contribution of fission reaction in the case with neutrons or triton on ^{209}Bi or ^{208}Pb target is very low in range of cross section μb [7]. On can say that ^{4}He nucleus plays the main role in the fusion reaction mechanism induced by weakly bound nuclei as ^{6}He and ^{7}Li at higher bombarding energies.

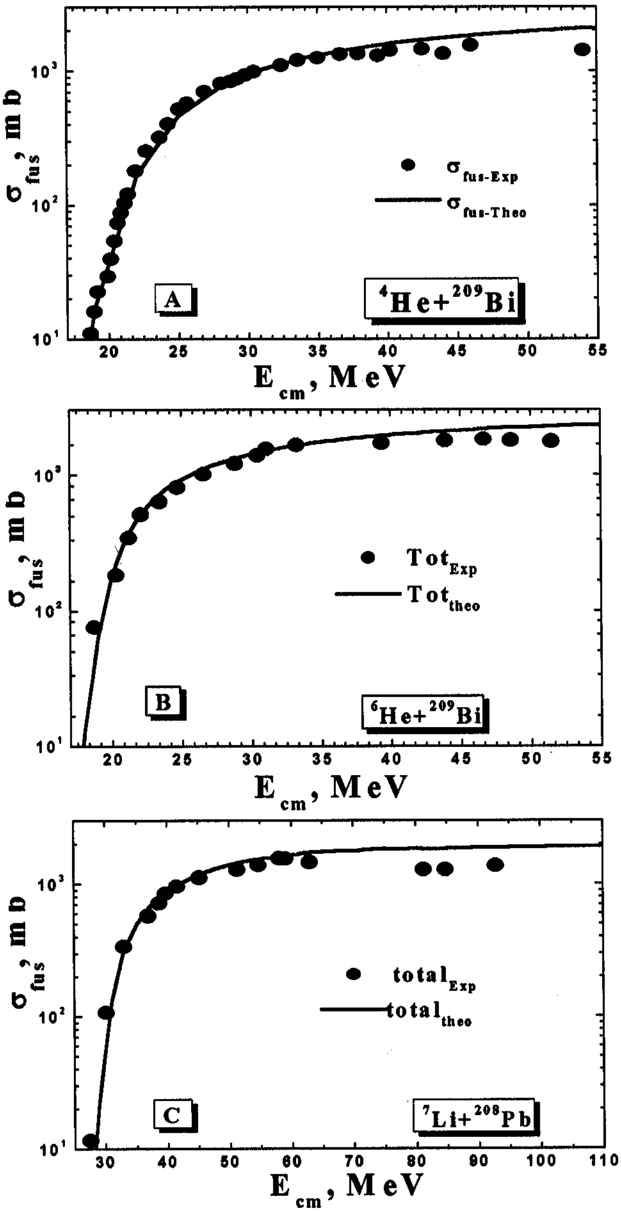

Fig. 11 Complete fusion cross excitation function of the reactions $^{4,6}He+^{209}Bi$ and $^{7}Li^{+208}Pb$. The symbols represent the experimental data and the lines correspond to the theoretical calculations using CC model.

Fusion excitation functions for the reactions $^{4}He+^{209}Bi$, $^{6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ were compared in the center mass of energy to study the fusion mechanism induced by weakly bound nuclei. To remove the effect of Coulomb barrier on the fusion mechanism the center mass of energies were divided by the Coulomb barrier (E_{cm}/V_b) for each system. The comparison is shown in Fig. 12. The figure was shown that the fusion cross sections for the three systems have the same values within the experimental error bars in a broad range of energy.

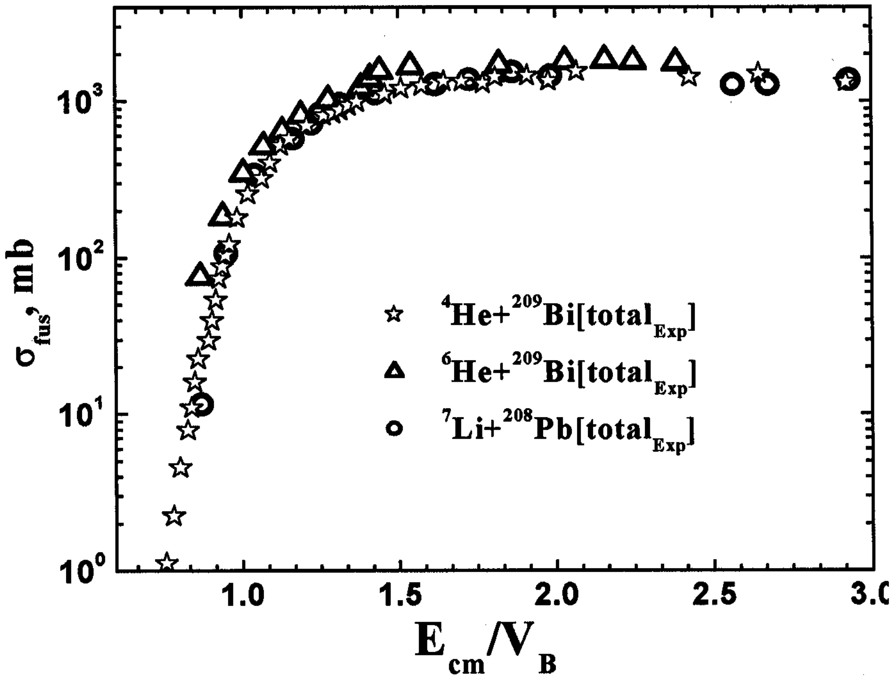

Fig. 12 Fusion excitation functions in the reactions $^{4,6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$.

This study allowed us to reveal target dependence on the fusion and fission reactions mechanism. For this study, fission and evaporation cross sections were measured for the reaction $^{7}Li+^{209}Bi$ at energies 30 up to 220 MeV. The fusion excitation functions obtained from the two reactions $^{7}Li+^{209}Bi$ and $^{7}Li+^{208}Pb$ were compared to study the effect of targets on the fission mechanism. This comparison is shown in Figs. (13). The figure was shown that the fusion cross sections for the two systems have the same values within the experimental error bars in a broad range of energy. One can say that the two reactions have the same fusion mechanism behaviour and there is no effect appeared due to the different targets on the fusion mechanism reaction induced by ^{7}Li beam.

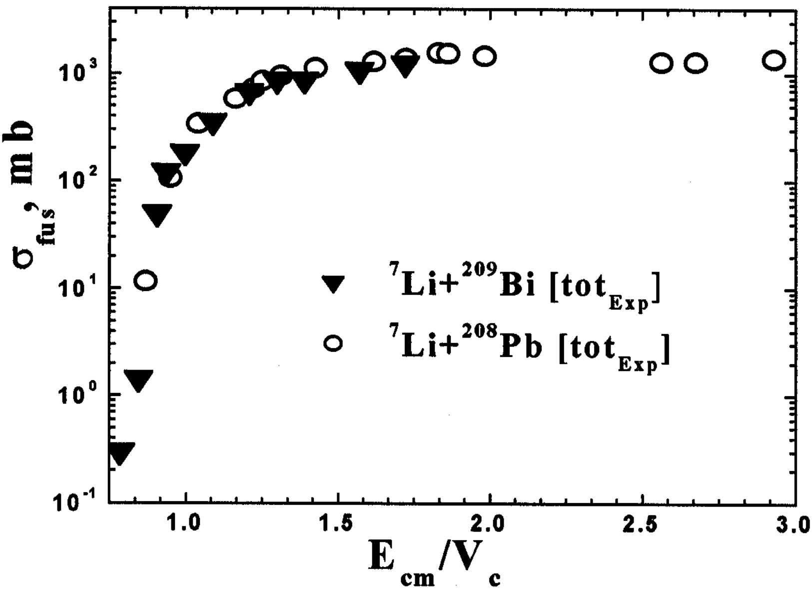

Fig. 13 Fusion excitation functions for the reactions ^{7}Li+^{209}Bi and ^{7}Li+^{208}Pb. The symbols represent the experimental data.

Conclusions

In the present work several experimental results were measured for the fission and evaporation cross sections in the reactions ^{4,6}He+^{209}Bi, ^{7}Li+^{208}Pb and ^{7}Li+^{209}Bi. The conclusions which obtained from the experimental results and the analysis using different models can be summarized in the following points.

1 A setup was constructed for on-line measurements of fission and evaporation cross sections by detecting in parallel both evaporation residues and fission fragments.

2 Cross sections for fission and the [3*n*-9*n*] evaporation channels were measured for the first time in the reaction induced by a ^{7}Li beam on ^{208}Pb and ^{209}Bi targets in the energy range 28 to 220 MeV.

3 Cross sections for fission were measured for the first time in the reaction induced by a ^{6}He beam on a ^{209}Bi target in the energy range 50 to 180 MeV.

4 Cross sections for [4*n*-8*n*] evaporation channels were measured for the first time in the reaction induced by a ^{6}He beam on a ^{209}Bi target in the energy range 23 to 95 MeV.

5 Cross sections for fission and the [2*n*-3*n*] evaporation channels were measured for the first time in the reaction induced ^{4}He on a ^{209}Bi target in the energy range 20 to 110 MeV.]

6 The comparison between the fission and fusion excitation functions for the three reactions $^{4,6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ has shown that they are the same within the experimental error for a broad range of energy.

7 The comparison between the fission and fusion excitation functions for the two reactions $^{7}Li+^{208}Pb$ and $^{7}Li+^{209}Bi$ has shown that they are the same within the experimental error for a broad range of energy and there is no effect has been shown on the fusion mechanism due to ^{208}Pb and ^{209}Bi targets.

8 The experimental fusion and fission excitation functions obtained for the different reactions $^{4}He+^{209}Bi$, $^{6}He+^{209}Bi$ and $^{7}Li+^{208}Pb$ and leading to the same composite nuclei $^{213,215}At$ were analyzed using the PACE-4, and CC codes from the point of view of the fusion mechanism induced by weakly bound nuclei.

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The basic results submitted in the thesis, are published in the following journals:

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2 **A.A. Hassan**, S.M. Lukyanov, Yu.E. Penionzhkevich, L.R. Gasques, L.C. Chamon, A. Szanto de Toledo "Study of the ^{4}He on ^{209}Bi fusion reaction", JINR–Preprint E15-2003-186, Dubna (2003) (Submitted to Physics of Atomic Nuclei).

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Received on August 9, 2004.

Макет *Н. А. Киселевой*

Подписано в печать 10.08.2004.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 1,19. Уч.-изд. л. 1,49. Тираж 100 экз. Заказ № 54555.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
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www.jinr.ru/publish/