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INVESTIGATION OF TIME-OF-FLIGHT LIFETIME MEASUREMENT METHODS OF CHARGED π MESONS AT THE PHASOTRON OF **JINR**

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1. Introduction

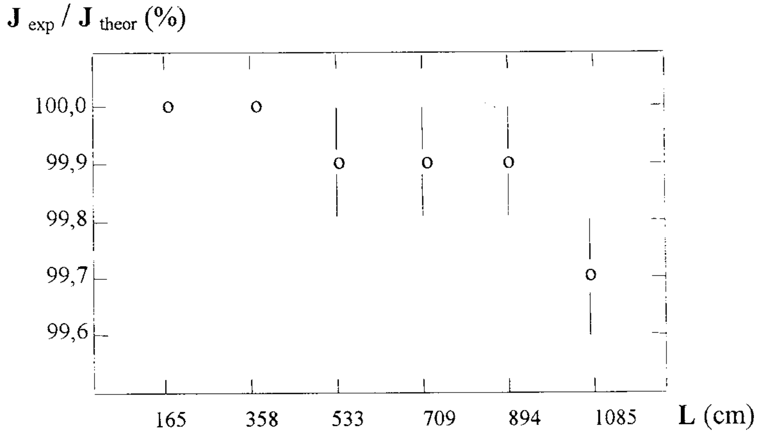
Precise measurement of the mean lifetime (τ) of elementary particles is an important prerequisite for the development of a number of directions in the modern nuclear physics. Basing on the last measurements of this property of charged π–meson, its averaged value is considered to be $2.6033 \pm 0.0005 \cdot 10^{-8}$ s (relative error ~ 0.02%) [1]. Both the given value τ and the error are obtained by averaging the available experimental information on this issue, i.e. they are a kind of compromise. It should be especially stressed that even the results of most precise, as of today, measurements of the value τ for charged π-meson [2,3] differ from each other for a magnitude, which is several times greater than the above error [1].

The methods of the work [2] is remarkable not only for elaborate reasoning of its 1 main components but also for a unique original idea to register not stopped charged π-meson themselves, but the decay μ-meson with a certain momentum. Unfortunately, a statistical error in this work exceeds by far the summarized systematic error and that is particularly noted in the official European Physical Journal Review of Particle Physics [1]. Statistical error is a function of an amount of sampling that is why this contradiction shows that the amount of experimental data is not sufficient. Furthermore, relative discrepancies of the measured τ for charged π-mesons that were stopped in various targets (made of copper, carbon, quartz) exceed many times relative summarized systematic error in the given work. Should these discrepancies still persist when an amount of experimental data (and correspondingly that of statistical error, too) achieves a required level, one can conclude, with a high degree of probability, an influence on the experiment of a permanent "target factor" as most important systematic factor that limits the measurement precision of τ of charged π-meson by means of such methods. As in the subsequent work [3], the main reason of the given systematic factor is likely to be an impossibility of exact control of scattering coefficient of charged π-mesons, which are stopped in the surface layer of the target.

The work [3] reproduces substantially the methods of work [2], i.e. these papers have similar methods advantages and disadvantages. In particular, the scattering factor of charged π-mesons, which are stopped in the surface target layer, causes also a substantial systematic error limiting the measurement precision of their τ by means of measurement of decay μ-meson intensity, what was noted by the authors themselves. It is to remark that the accounted relative summarized error in this work is higher than 0,05%.

The τ measurement methods of charged π-meson as a part of controlled narrow in-flight beams allow to account much more precisely for the scattering of π-mesons. But these methods are somewhat more complicate to account for the contribution of admixture charged particles thus the known results of such measurements [4-8] vary greatly. Even the most exact of them, the [8], carried out at a high technical level, shows non-compensated systematic errors that are clearly seen if you compare the calculated and experimental data (Fig.1). At the maximum length of particle flying path that was investigated (here it is even less than half-decay path), the relative value of this error achieves already 0.3%. The summarized relative error 0.15% (two times lower), claimed by the authors, is obtained owing to the fact that the authors neglected in the final calculations the data obtained for the given path length. Nevertheless, some methods principles [8] can be accepted as a basis for solving the problem of improved precision in the measurement of τ of charged π-meson.

Fig. 1 Ratio of the measured [8] and the computed intensity of the charged π-meson beams under present lengths of trajectory



J_{exp} / J_{theor} - ratio of the mean experimental and of the computed intensities for the charged π-meson beams under present lengths of trajectory;
L - length of the π-meson trajectory.

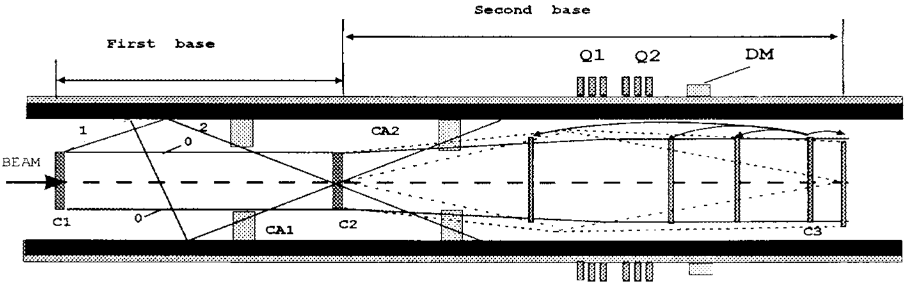
At present, a complex of the necessary technique and the methodical possibilities (including high-intensive, homogeneous π–meson beams in «meson factories» with well controlled features) as well as advanced methods of mathematical control of systematic factors are available that enable us to bring the measurement precision of τ of charged π–meson to a value that would exceed the precision of the above compromised evaluation. In order to achieve a reliable mathematical control of systematic factors, particle momentum and beam intensity monitoring of various flight path sections provided, and mathematical modeling used, a modified in-flight measurement methods of τ is the most acceptable one.

2. The experimental methods

The τ in-flight measurement methods of charged π-meson, with a possibility of control of a complex of main systematic factors (Coulomb scattering, foreign particles admixtures, momentum spread, and others) has been worked through and optimized at the phasotron of the Laboratory of Nuclear Problems of the JINR. The aim of the experiment is to measure the τ of the charged relativistic π-meson (relativistic factor $\gamma = 2.63$) taking into consideration all possible systematic errors. The general scheme of the experimental set-up chosen in the process of the adjustment of the equipment and preliminary measurements is presented in Fig. 2

Fig. 2

General scheme of the plant measuring the mean lifetime of relativistic charged mezons on the fly with different positions of scintillation counter C3.



0 - main particles trajectories that were produced by "electronic collimator" ;
1, 2 - trajectories of particles under multiple Coulomb scattering on the walls of the vacuum tube ;
---- trajectories of particles under multiple Coulomb scattering in C2 counter

The proton beam with 660 MeV momentum is extracted from the phasotron chamber and is focused by means of the magnetic quadruple lens on the beryllium target, 20 cm thick. Then the protons which passed through the target, are focused by the lens on the carbon target, 20.0 g/cm^2 thick, installed in front of the collimator with the transversal dimension of 10 x 15 mm^2 and 40 cm long. The next lens focuses the π-mesons at the collimator entrance, which provides the extraction momentum interval of π-mesons of about 1%. A vacuum scintillation counter C1 (scintillator diameter 25 mm and 1.5 mm thick) provides the start signal for the charged particles' time-of-flight registration. Then π–mesons cover 1404.3 cm in vacuum and are registered by the vacuum scintillation counter C2, with the scintillator diameter 25 mm and 1.5 mm thick. The C1 and C2 counters form an electronic collimator, which produces a narrow π–meson beam with angle distribution of $1.8 \cdot 10^{-3}$ rad $\approx 0.1^0$ and emittance $\Sigma = 3{,}14 \cdot 2.25$ cm $\cdot$ mrad. The vacuum counter of anticoincidences CA1 is installed between counters C1 and C2 in the distance of 1086.4 cm with a ring scintillator which has the inner diameter of 35 mm, 10 mm thickness and the outer diameter of 130 mm. The vacuum counter of anticoincidences CA1 excludes fully the particles which are once reflected from the tube walls due to multiple Coulomb scattering (trajectories 0, 1 and 2 in Fig.2).

The similar vacuum counter of anticoincidences CA2 is installed between counter C3 and lens Q1 in the distance of 283.5 cm from counter C2. To exclude the correction for the multiple Coulomb scattering of π–mesons in counter C2, which may be 2-3 %. Then π–mesons cover up to 22 m in vacuum and are registered in coincidence by the butt counter C3 with the following dimensions: diameter 100 mm, thickness 30 mm. Counter C3 for the measurement of the mean decay length is installed in different distances from counter C2. Lenses Q1 and Q2 focus π–mesons, which have passed through the CA2 aperture, compensating the angle distribution of the π–meson beam, determined by the C1 and C2 counters' geometry and multiple Coulomb scattering in C2 and producing almost a parallel beam in the distance up to 15 m. The bending magnet BM allows one to eliminate the decay μ -mesons with a different momentum than that of π–mesons in the beam. The intensity of the positive π–meson beam in the first base is 3-4 s^{-1} that provides statistical precision 0.5-0.6 % for different attitudes of the C3 counter during the statistics acquisition in each seance of 4-8 hours.

The compact scintillation counter C4 (scintillator's dimensions 10 x 10 x 5 mm^3) is used to measure the transversal dimensions of the π–meson beam. The precision not worse than 1 % in the measurements of the mean lifetime of relativistic 227.3 MeV π–meson is achieved by a combination of a number of favorable peculiarities of the chosen experimental scheme, such as the conditions of "good beam geometry" with the sufficient beam intensity of positive π–mesons, the application of magnetic optics to form an almost parallel beam to the end of the flight base, elimination or a considerable decrease of corrections for multiple Coulomb scattering and registration of decay μ-mesons, as well as the precise determination of such parameters of beam particles as momentum and time of flight.

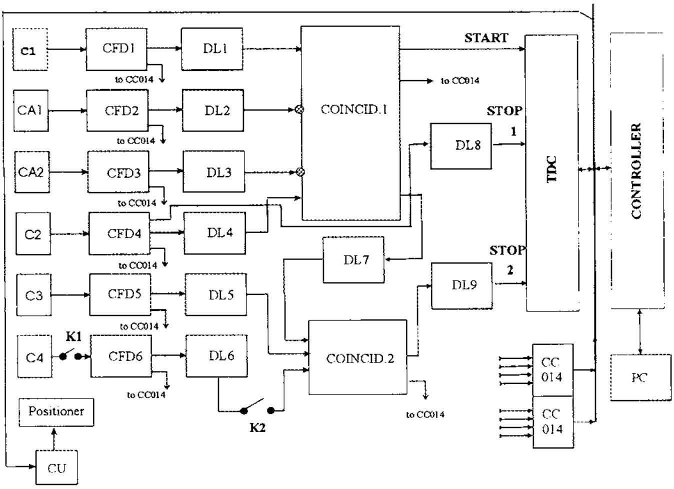
To eliminate the influence of the scattered magnetic fields of the accelerator (about several Oersted) and the Earth magnetic field on the beam in such a "good beam geometry" the vacuum tubes were covered with 3-4 layers of a steel band 180 micron thick. The screen coefficient inside the tubes with the 12 cm diameter is from 20 to 80, depending on the band type and the value of the magnetic field.

The particle time-of-flight spectrum between counters C1 and C2 allows one to determine precisely the π–meson momentum on the distance between the proton and π–meson peaks and to control its measurements in the process of statistics acquisition from seance to seance. This last circumstance allows one to correlate the measured value of the mean lifetime of π–meson with the measured value of their momentum in the measurements and thus compare with theoretical values of the mean lifetime, calculated with employment of the relativistic formulae.

3. Electronics and Soft-Hard Ware

The block-scheme of the ns-electronics for the experiment in the measurement of the mean lifetime of relativistic π–meson is presented in Fig. 3.

Fig. 3 Block diagram recording equipment



Electric impulses from the photomultipliers come to shapers F1, F2, F3, F4 and F5 of the KL 352 type with time mode. The signals from the shapers come to the counters of electric pulses KC 014 and through delay lines DL1, DL2, DL3, DL4 and DL5 they go to the inputs of coincidence schemes CC1 (1, not 2, not 3, 2) andCC2 (1, not 2, not 3, 2, 3). Counters CA1 and CA2 are switched on to anticoincidences. From the outputs of the coincidence schemes the signal come to counters KC 014 and converter Time-Code 2228 Le Croy. Delay lines DL7 and DL8 are used to shift time spectra into the medium part of the converter scale. To measure the transverse distribution of the beam a three-axis positioner with a scintillation counter C4 is used together with a control block CB and shaper S6, the number of momentum from which is counted by the counter KC 014, directly and from the coincidence schemeCC2 (1, not 2, not 3, not, 2, 3, 4).

While measuring time spectra, the impulse from the shaper S6 to the coincidence scheme CC2 does not come.

The data from the converter, KC 014 counters and the control block through the CAMAC KK-012 controller is transmitted to a personal computer PC where they are interpreted, reflected and stored for further processing. The block-scheme has also a high-voltage power source, a transition block KL 351 ESL-NIM and a brancher for three channels. The software for the experiments includes the following components:

1) A specially developed on-line program to measure spectra and adjust the beam route. The program Izmer pi.exe allows one to read time-of-flight information in several channels of the time-digital converter simultaneously, to visualize it graphically, to make preliminary analysis (the quantity of π–mesons, calculated for the monitor, their ratio to protons etc.) and to record in figures the measured values for further processing into a file. The program is written in B. Pascal 7.0.

2) For a more detailed processing of the measured spectra software is developed in Delphi 4.0, which was used to analyze mathematically the data accounting for the concrete experiment geometry (the quantity of π–mesons in a strict interval of time-of-flight spectrum without the background, addition of spectra, gravitation centre of peaks calculation, width in half-height).

3) To fit the particle spectrum in the full base by three Gaussian distributions and to fit the exponential function for measured values the Origin program packet of scientific graphics was applied. Program components for the work with CAMAC system include standard functions of the connections with electronic blocks of the crate controller KK-012 and KK-09.

The procedures of the data graphical interpretation allow one to control on-line the main parameters of the beam and time-of-flight spectrum on two bases and to make corrections in the control system if necessary.

4. Measurements and Analysis of the Obtained Data

For each position of the counter C3 the spectrum of charged particles was measured time-of-flight on the first base (length is 1404.3 cm) between counters C1 and C2, with anticoincidence counters CA1 and CA2 switched on, and on the second base between the counters C1 and C3 in logic C1, C2, C3,CA1,CA2. The examples of such spectrum for the first and the second base with the distance between counter C3 and C2 of 2179.8 cm.

The position and dimensions of the particle beam after the magnet BM in the end of the vacuum tube were determined by the three-axis positioner with a flexible counter C4 10 x 10 x 5 mm^3. The width of the beam distribution in half-height was 43 mm horizontally and 35 mm vertically that corresponds well to the calculated value of about 50 mm and to the dimensions of the counter C3 with the 100 mm diameter.

The time-of-flight spectrum between the counters C1 and C2 makes it possible precisely to determine in the distance between the peaks of π–mesons and protons the π–meson momentum and to control its measurement in the process of statistics acquisition. During 7 seances of the statistics acquisition the mean distance between protons and π–meson peaks was 862 channels of the time-of-flight spectrum with the maximal spread ± 2 channels. The calibration of the Time-Code converter Le Croy 2228A was realized with a quartz generator with about 0.01% precision and was 0.1032 ± 0.0001 ns/channel for the first base and 0.1046 ± 0.0001 ns/channel for the second base. The integral non linearity of the converter was < ± 0.1 % of the full scale, the temperature dependence was ± 0.02 % per C degree of the full scale. According to these calibrations the difference of the proton and π–meson times-of-flight on the base L_{12} 1404.3 was 88.96 ± 0.21 ns, accounting for the correction for the proton braking in the counter scintillator C1 (1.4 ± 0.1 %) of the full time-of-flight of protons on the first base 140 ns, the final difference of time-of-flight of proton and π–meson was determined as 87.00 ± 0.21 ns. The time-of-flight difference of proton and π–meson ($\Delta t_{p\pi}$) was tied with the proton and π–meson momentum (P_p P_π) with the following formula:

$$\Delta t_{p\pi}= L_{12}/C(\surd(P^2_p+ m^2_p) / P_p- (\surd(P^2_\pi + m^2_\pi) / P_\pi$$

where L_{12} = 1404.3 cm ; C- velocity of light ; m_p= 938.26 MeV; m^2_π = 139.57 MeV.

According to this formula, and keeping in mind that protons and π–mesons into the XI channel with the same momentum, the proton and π–meson momentum was calculated with high precision (339.26 ± 1.24 MeV/c). The kinetic energy of π–mesons 227.28 ± 1.15 MeV and relative velocity of π–mesons (β=0.92480 ± 0.00049), necessary for the comparison of the experimentally determined mean lifetime of π–meson and that calculated in the relativistic formulae for this energy.

The relative momentum spectrum of the extracted π–meson beam, which is formed by the spectrometer geometry and does not depend on the value of the momentum, is determined in the widening of the 600 MeV/c proton peak in time-of-flight spectrum between the counters C1 and C3, at distance measurements from C3 to C1 1785.6 cm to 3575.1 cm. The width of the proton peak in the time-of-flight spectrum, determined by the equipment resolution and momentum spread, changed from 25.1 ns to 30.8 ns. The partial time spread Δt_p, related to the width of the momentum distribution, is 2.06 ns, while the relative momentum spectrum $\Delta P/P = (P^2_P + m^2_P \Delta L_P) / m^2_P L_P$ was 1.4 % . The equipment time resolution was 2.3 ns.

During the measurements on the second base at five positions of the counter C3 the total count of particles in each point was 30-40 thousand events that corresponds to the statistical precision of about 0.5-0.6 %. These experimental data in monitor count N_M and count $N_{\pi\mu e}$ for coincidence with the counter C3 are presented in the table, in lines 2 and 3, depending on the C3 counter position (line 1). A correction was inserted into the data, which was connected with the double and multiple scattering of π–mesons from the walls of the vacuum tube in the first base that was not excluded by the CA1 counter of anticoincidences, and another correction due to the momentum spread of the beam and dispersion in the magnet BM was made (the tails of the momentum distribution in large distances from BM because of the dispersion do not fit into the dimensions of the counter C3). This correction, shown in line 4, was determined experimentally in the ratio of the proton count in the first and the second base for each position of the counter C3 and was from 2 to 8 % for 600 MeV/c protons, that corresponds to the equal angle with π–mesons of the multiple Coulomb scattering. Calculated for the monitor count C1, C2, CA1, CA2 numbers of particles in the second base for 5 positions of the counter C3 in dependence of its distance L from the counter C2, are shown in line 5. Line 6 presents the statistical error of the results of this ration measurement.

1	L (cm)	381.5	861.8	1268.5	1845.8	2170.8
2	N_M	44937	68791	75745	74237	89181
3	$N_{\pi\mu e}$	35457	43150	39357	28849	28776
4	K	1.0216 ±0.003%	1.0199 ±0.0027%	1. 0217 ±0.0024%	1. 0445 ±0.003%	1. 0801 ±0.0058%
5	$Y = N_{\pi\mu e}K / N_{m\,m}$	0. 8060 ±0. 53%	0.6398 ±0. 48%	0. 5309 ±0. 51%	0. 4059 ±0. 59%	0. 3485 ±0. 59%
6	Δy_1	0.0043%	±0.0031%	0.0027%	±0.0024%	±0.0021%
7	Δy_2	±0.0049%	±0.0036%	±0.0031%	±0.0027%	±0.0023%

The obtained experimental data were fitted according to the least quadratic function methods: $Y = A_1 \exp(-x/t_1) + y_0$, where t_1 is the mean decay length of π–meson, y_0 is the infusion of e^+ and μ^+ calculated for the monitor count.

The value y_0 was determined from the particle spectrum time-of-flight between the counters C1 and C3 in the longest base L = 1404.3 cm + 2170. 8 cm = 3575.1 cm. In this case the e^+ and μ^+ infusions are extracted most clearly. The obtained spectrum was fitted according to the program of particle separation with a fixed position of maximum distributions of particles and their widths at half height, and for this position of the counter C3 they were the following: $\Delta n_{\pi\mu}=$ 38.6 channels, $\Delta n_{\pi e}$ = 92.4 channels for the distance between the maximum distributions and width at half height – 24 channels. The fitting of experimental points gives the value y_0= 0.05% with the statistical error ± 0.001 and a possible mathematical error ± 0.002, which is related to the difference of the spectrum form from the Gaussian one.

The result of the Y function fitting with a chosen value y_0 = 0.058, leads to the following: $Y = 0.9166 \cdot \exp(-x / 18999) + 0.058$, so the mean decay length of π–meson is t_1 = (1899.9 ± 15.9) cm.

The analysis of possible systematic errors allows one to make the following remarks. The account of the maximum correction error for the registration of decay μ-mesons, determined in Enclosure 2, gives an additional error of ± 0.3 % in the value y, given in line 5. It increases the total error of the value y to Δy_2, given in line 7 in the table. Accounting for this additional error, the result of the Y function fitting for the chosen y_0 = 0. 058 gives : $Y = 0.9167 \cdot \exp(-x / 18993) + 0.058$, with the mean decay length error ± 17.9 cm.

The systematic error due to y_0 inaccuracy in the limits ± 0.002 as a result of the Y functin fitting for $y_0 = 0.056$ and $y_0 = 0.060$ leads to an additional error in the mean decay length in the limits of ± 8.3 cm. Thus the processing of the obtained experimental data allows one to determine the mean decay length of the π–meson $L_0 = t_1$ = 1899.3 cm with a total error (with given volume of the data) ± 19.7 cm or precision ~ 1 %.

Taking into account the methods proposed to control the complex of systematic errors, the degree of eventual precision (providing the expedient mathematical data processing) is a function of the derived volume of data.

In the appendix to the given methods, a detailed calculation of its following aspects is proposed: a correction for the multiple Coulomb scattering in counter C2; a correction for the decay μ-meson registration.

5. Conclusions

The methods has following features:

1) The length of base for time-of-flight measurements of charged π–meson beam is comparable with their decay length what minimizes, when an optimal beam geometry is chosen, the influence of admixture particles on the results of τ measurement.

2) There exist a principle possibility for monitoring the momentum of the investigating charged π–mesons at different sections of the their trajectory.

3) For the reached resolution of scintillator detectors combined with electronics and precision of π–meson momentum measurement the method enables one to substantially increase the measured precision of τ.

4) Since the thickness of scintillator in such detectors may be less than 1mm one can exactly position the presence of survived π–mesons in every particular point provided corresponding resolution of the detector is ensured.

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Евтухович П. Г. и др. E1-2003-19
Исследование времяпролетной методики измерения времени
жизни π-мезонов на фазотроне ОИЯИ

Описана методика измерения среднего времени жизни заряженных π-мезонов на лету, прошедшая апробацию на фазотроне ЛЯП ОИЯИ. Особенности этой методики заключаются в следующем: 1) использование времяпролетного метода исследования состава пучка частиц при относительно протяженной траектории полета (базы); 2) выбор оптимальной для данной базы геометрии пучка исследуемых π-мезонов; 3) мониторинг импульса π-мезонов по всей длине исследуемой траектории; 4) использование сцинтилляционных детекторов с высоким разрешением. Эти приемы, наряду с корректным математическим расчетом, обеспечили возможность контроля влияния основных систематических факторов на точность получаемых данных. Методика позволяет рассчитать необходимый объем выборки для получения той или иной заданной точности измерения времени жизни заряженных π-мезонов на основе предварительных оценок случайных и систематических ошибок.

Работа выполнена в Научном центре прикладных исследований ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2003

Evtoukhovitch P. G. et al. E1-2003-19
Investigation of Time-of-Flight Lifetime Measurement Methods
of Charged π Mesons at the Phasotron of JINR

The methods of time-of-flight lifetime measurement of charged π mesons that have been realized at the Phasotron of the LNP of JINR are described. The distinguishing feature of the given methods consists in the use of the following techniques: 1) time-of-flight investigation of particle beam composition for relatively long flight path (base); 2) an optimal choice (for the given base) of beam geometry under investigation; 3) monitoring of π-meson momentum along the whole explored trajectory; 4) the use of high resolution scintillation detectors. These techniques together with correct mathematical calculations provided a possibility of controlling the influence of main systematic factors on the precision of the data obtained. These methods allow one to compute an amount of sampling that requisites a given precision based on preliminary evaluations of random and systematic errors of charged π-mesons measured lifetime.

The investigation has been performed at the Scientific Center of Application Research, JINR.

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