Exposure of nuclear track emulsion to thermal neutrons, heavy ions and muons

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Physical analysis of exposures of test samples of reproduced nuclear track emulsion (NTE) is presented. In boron enriched NTE the angular and energy correlations of products of the reaction induced by thermal neutrons $n_{th} + ^{10}B \to ^{7}Li + (\gamma) + \alpha$ are studied. NTE was exposed to ions $^{86}Kr^{+17}$ and $^{124}Xe^{+26}$ of energy about 1.2 A MeV. Measurements of the heavy ion ranges of in NTE allowed one to determine their energy on a basis of the SRIM model. Nuclear stars of large multiplicity of target nuclei are observed in exposure of NTE to ultrarelativistic μ-mesons. The kinematical characteristics of the events of splitting of carbon nuclei into three α-particles studied in this exposure point to a nuclear diffractive mechanism of interactions.

INTRODUCTION

Featuring an excellent sensitivity and spatial resolution nuclear track emulsion (NTE) maintains the position of a universal and inexpensive detector for survey and exploratory research in microcosm physics. Use of this classical technique on the beams of modern accelerators and reactors turns out highly productive. In a number of important tasks the completeness of observations provided in NTE can not be achieved for electronic detection methods. In particular, in the last decade clustering of a whole family of light nuclei including radioactive ones was investigated in the processes of dissociation of relativistic nuclei in NTE [1-4]. Decays of ^{8}He nuclei implanted in NTE [5] and 3α-breakup of ^{12}C nuclei of the NTE composition by thermonuclear neutrons [6] were analyzed recently at low energy.

Currently, there arises a new range of problems concerning the calibration of ranges of heavy ions in NTE. Their solution will expand the methodical basis for the study by the NTE method of new aspects of the physics of fission of heavy nuclei. Use of automatic microscopes enables one to approach to the application of NTE at a new level. The development of NTE with a submicron resolution opens a new horizon for the search for hypothetical particles of dark matter via tracks of recoil nuclei. Thus the feasibility of an impressive variety of tasks turns out to be related with the return of the NTE method to the practice of nuclear experiment at a modern level. Status of the NTE technique and its future were discussed recently at a subject meeting [7].

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In the framework of the BECQUEREL project [8] NTE samples produced by the Micron workshop which is part of the Slavich Company [9] are irradiated. Samples are manufactured by pouring of NTE layers of 50 to 200 micrometers on glass substrates. The main features of this NTE are close to NTE BR-2 which provided sensitivity to relativistic particles. Production NTE BR-2 was carried out over four decades and finished about ten years ago. The reproduced NTE [9] was already used for a spectrometry of α-particles over ranges [3,4].

Test exposures aimed primarily at an overall quality control and sensitivity of NTE to relativistic particles as well as at the comparison of the ranges of slow strongly ionizing nuclei of low energy with the values computed in the simulation program SRIM [10]. Exposures of the reproduced NTE on beams of modern accelerators and reactors allow one not only to perform range-energy calibration for the future, but also to make physical observations and draw conclusions that are valuable in itself. In turn, these exposures stimulate the development of the NTE method because they provide a new material for progress of automated microscopes and nuclear physics education. The present paper combines the results of the analysis of recent exposures of NTE to thermal neutrons, heavy ions and low-energy ultrarelativistic μ-mesons. Such a variety of experiments, including [3] and [4] are related to a common methodical use of the new NTE for coordinate measurements of tracks of length from a few to tens of microns. Video materials on the interactions studied in NTE are available on the website [8].

EXPOSURE TO THERMAL NEUTRONS

Adding of boric acid in NTE allows one to solve practical problems for thermal neutron beams (n_{th}) specify their profiles and flows. Enrichment of NTE with boron makes it possible to observe charged products of the reaction $n_{th}+^{10}$B $\to^{7}$Li $+(\gamma)+^{4}$He. This reaction giving an output of energy of 2.8 MeV occurs with a probability of about 93% with the emission of γ-ray of energy of 478 keV by the ^{7}Li nucleus from a single excited state.

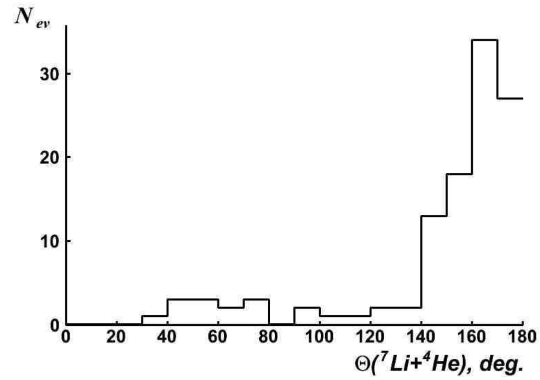

FIG. 1: Distribution over the opening angle $\Theta(^7Li+^4He)$ for pairs of ^{7}Li and ^{4}He nuclei produced by thermal neutrons in 112 events $n_{th} +^{10} B \rightarrow^7 Li + (\gamma) +^4 He$.

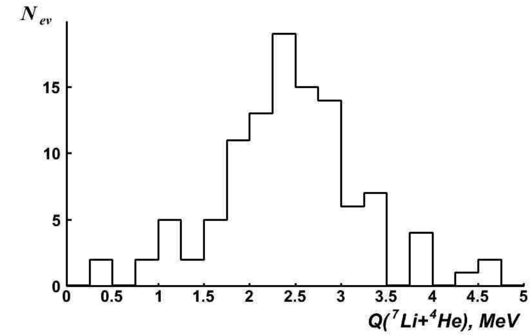

FIG. 2: Distribution over the energy $Q(^7Li +^4 He)$ for pairs of ^{7}Li and ^{4}He nuclei produced by thermal neutrons in 112 events $n_{th} +^{10} B \rightarrow^7 Li + (\gamma) +^4 He$.

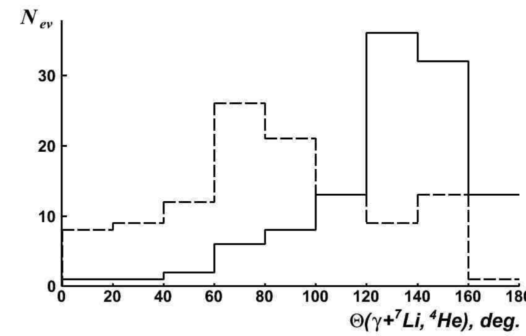

FIG. 3: Distribution over the angle $\Theta(\gamma +^7 Li,^4 He)$ between the calculated directions of emission of γ-quanta and the directions of emission for of ^{7}Li and ^{4}He nuclei solid and dashed histogram, respectively) produced by thermal neutrons in 112 events $n_{th} +^{10} B \rightarrow^7 Li + (\gamma) +^4 He$.

Samples of NTE prepared with the addition of boric acid were exposed to thermal neutrons n_{th} at an intensity of about 10^7 n_{ths}^{-1} for 30 min in the channel #1 of the reactor IBR-2 of JINR.

The selected duration allowed one to avoid an overexposure and perform coordinate measurements of tracks of 112 events ^{7}Li $+^4$He at KSM microscope with a 90% magnification objective. Due to a distinct difference in the ionization of the reaction products, the coordinates of its vertices are determined with an accuracy of 0.5 - 0.8 μm. The average length of tracks of Li nuclei was (3.1 $\pm$ 0.3) μm (RMS 0.8 μm) at an average thickness of (0.73 $\pm$ 0.02) μm (RMS 0.05 μm), and for tracks of ^{4}He nuclei (5.5 $\pm$ 0.5) μm (RMS 1.1 μm) and (0.53 $\pm$ 0.01) μm (RMS 0.04 μm), respectively. The directions of emission in pairs arent collinear as a consequence of emission of γ-rays. A value of the average opening angle Θ(^{7}Li $+^4$He) is (148 $\pm$ 14)$^\circ$ (RMS 35°). There are several events Θ(^{7}Li $+^4$He) ¡ 90° in the distribution Θ(^{7}Li $+^4$He).(Fig. 1) Their origin may be associated with a visually indistinguishable scattering of α-particles on initial parts of escape from the reaction vertices.

The simulation program SRIM allows one to evaluate the kinetic energy of nuclei by measuring the lengths of tracks. Knowledge of the energy and emission angles enables one to obtain the energy distribution Q(^{7}Li $+^4$He) of pairs of ^{7}Li and ^{4}He nuclei (Fig. 2). The variable Q is defined as a difference between the invariant mass of the final M^* and the mass of the decaying nucleus M. $Q = M^* - M.M^*$ is defined as a sum of all products of the 4-momenta $P_{i,k}$ fragments, i.e., $M^{*2} = (\Sigma P_j)^2$. Its relativistic-invariant character makes it possible to compare various data by a unified manner. The average value of Q(^{7}Li $+^4$He) which amounted to 2.4 $\pm$ 0.2 MeV (RMS 0.8 MeV), match the expected one taking into account the energy carried away by γ-quanta.

The distribution over the angle $\Theta(\gamma+^7$Li) between the directions of emission of γ-quanta computed according to the condition of conservation of momentum and the directions of emission of the nuclei ^{7}Li shows a clear anticorrelation (Fig. 3). It is characterized by the average value of $\Theta(\gamma+^7$Li) (128 $\pm$ 3)$^\circ$ (RMS 31°) and the coefficient of asymmetry with respect to the angle of 90° equal to 0.75 $\pm$ 0.07. In the case of ^{4}He nuclei the average value of $\Theta(\gamma+^4$He) was (84 $\pm$ 4)$^\circ$ (RMS 40°), with a coefficient of asymmetry of 0.14 $\pm$ 0.01.

Thus, α-calibration on the basis of decays of ^{8}He nuclei [5] and the disintegration of ^{12}C nuclei [6] are supplemented by the use of the thermal neutron beam and extended onto the ^{7}Li nucleus.

EXPOSURE TO HEAVY IONS

Of interest is the application of NTE in the physics of ternary fission [11]. Spontaneous fission of ^{252}Cf or fission of ^{235}U initiated by thermal neutrons is a source of search for molecular-like nuclear systems. Emission of fission fragments may turn out to be a collinear one. In the decay of 3-body system one of the heavy fragments can enthrall the light one. NTE enables one to investigate correlation down to smallest angles between the directions of emission of the fragments of a collinear ternary

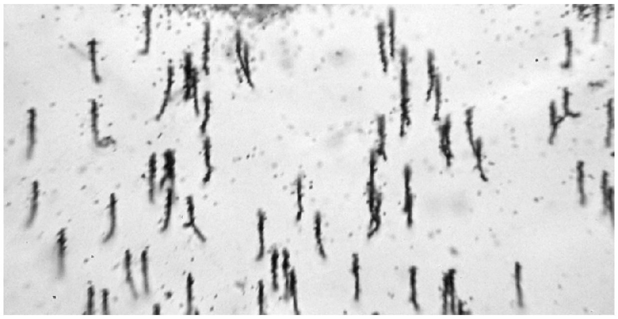

FIG. 4: Macrophotography obtained at 90-fold magnification of microscope objective of area of NTE with tracks of stopped Xe ions; entrance of ions from the top.

fission. It is assumed that NTE will be exposed to fission fragments by contacting with a film on which the explored isotope is plated. Currently, NTE exposed to a ^{252}Cf source giving mainly α-particles and spontaneous fission fragments (6% probability) and, for the sake of comparison, to a source ^{241}Am giving only α-particles is analyzed.

It is necessary to calibrate the ranges and estimate the angular resolution for the greatest variety of heavy ions of a known energy which are implanted in NTE. It is important to advance the energy calibration to values below the Coulomb barrier of nuclear reactions. Experience of spectrometry of heavy nuclei by ranges will be useful in search for hypothetical particles of the dark matter.

NTE is exposed to ions ^{86}Kr^{+17} and ^{124}Xe^{+26} accelerated to energy of about 1.2 A MeV at the cyclotron IC-100 of the Flerov Laboratory of Nuclear Reactions, JINR. Since energy of these ions is small the exposure of NTE is performed without a light protective paper. Therefore, fixing of the NTE plates in the irradiation chamber was performed at a light which is ordinary for a photographic laboratory. For 5 seconds of exposure the track density amounted to about $10^5 - 10^6 cm^{-2}$. The NTE layers measuring 9×12 cm^2 and thickness of (161 ± 10) μm for krypton and (119 ± 3) μm for xenon were installed with an inclination angle of 45° to the beam axis which provided observation of ion stops. Fig. 4 shows a close-up of the portion of NTE with xenon tracks made by a microscope MBI-9 at 90-fold magnification of the objective.

Measurements of the track lengths of ions stopped without scattering in the NTE layer are performed on a microscope KSM with 90-fold magnification of the objective. Average ranges of tracks without scattering for Kr ions is (14.3 ± 0.15) μm (RMS 0.9 μm) and for Xe ions (17.5 ± 0.1) μm (RMS 1.0 μm) which are close to the values calculated by the model SRIM - for Kr (18.5 ± 1.3) μm (RMS 1.3 μm) and Xe (20.1 ± 2.2) μm (RMS 1.3 μm). On the basis of spline-interpolation of range-energy calculations measurements of the ion ranges allow one to estimate their kinetic energy using the SRIM model. Its average values amounted for Kr was (0.74 ± 0.01) A MeV (RMS 0.1 A MeV) and for Xe (0.92 ± 0.01) A MeV (RMS 0.1 A MeV). The average values which are below the expected ones show that it is necessary to make modeling more accurate. The average angle of implantation into the NTE layer for Kr ions is (43.8 ± 0.6)0 (RMS 40) and for Xe ions (44.7 ± 0.6)0 (RMS 40) which corresponds to the orientation angle of the NTE plate with respect to the beam axis.

Many of primary tracks are completed by "knees"or "forks"as a result of scattering by nuclei composing NTE. At braking before scattering energy of ions is reduced to an order of magnitude smaller than the Coulomb barrier. On the basis of detailed measurements of coordinates it is supposed to identify observed recoil nuclei and extend the study of energy resolution to extremely low energy. This aspect is important for future calibration of NTE of submicron resolution designed for searching for dark matter particles.

EXPOSURE TO μ-MESONS

Deep inelastic scattering of ultrarelativistic μ-mesons is a recognized approach to study the parton structure of nucleons and nuclei. Exposure of NTE to these particles allows one to perform the study of nuclear multifragmentation under the action pf a purely electromagnetic probe. Multiphoton exchanges or transitions of virtual photons to vector mesons leading to nuclear interactions may serve as fragmentation mechanisms. NTE was irradiated by μ-mesons of energy of 160 GeV at CERN. Earlier such an exposure was not carried out. The purpose of this irradiation was the study of experimental downloads near the beam axis and the preliminary assessment of the nature of μ-meson interactions.

TABLE I: Distribution of the number N_b of strongly ionizing $b-$ and $g-$particles in stars $N_b + N_g > 13$ produced by μ-mesons.

N_b	N_g
13	1
11	4
11	6
12	6
11	5
13	2
12	3
5	10
11	7
6	9

NTE samples were placed in front of the target of the COMPASS experiment at a distance of about 25 cm from the beam axis (halo) where the intensity was about 10^6 particles/cm^2 per cycle. The samples of an area of $9 \times 12 cm^2$ and a thickness of about 100 μm were installed

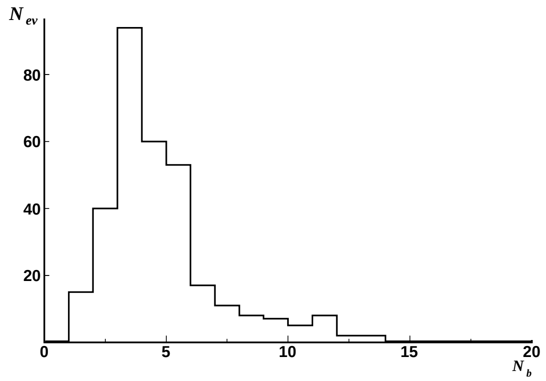

FIG. 5: Distribution of nuclear stars over the number N_b of strongly ionizing b-particles in NTE exposed to μ-mesons.

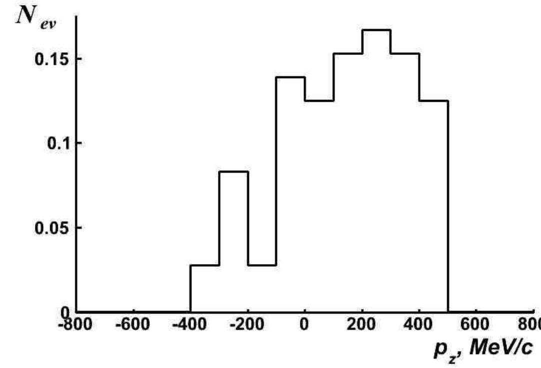

FIG. 6: Distribution over the total longitudinal momentum P_z of 72 triples of α-particles in NTE exposed to μ-mesons; normalization of the histogram to the number of events.

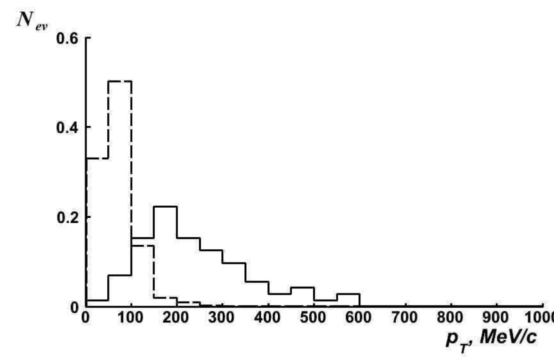

FIG. 7: Distribution over the total transverse momentum P_T of 72 triples of α-particles in NTE exposed to μ-mesons (solid histogram) and 400 triples of α-particles from reaction $n(14.1) +^{12} \rightarrow 3\alpha + n$ [3] (dashed histogram); normalization of the histogram to the number of events.

along the beam as well as across it. The transverse exposure which lasted nine hours turned out to be productive for physical analysis. Such a long exposure became possible because of the small cross section of interaction of μ-mesons and a small effect of a beam ionization compared to the longitudinal disposition of NTE plates. The duration of the exposure was limited due to the risk of a possible overload by interaction tracks of in a glass substrate. In principle, this duration could be increased by two orders of magnitude without difficulty for the analysis.

When viewing about 300 stars produced in NTE with at least three target fragments were found. The topology of stars is determined by the number of strongly ionizing $b-$ and $g-$particles (N_b and N_g). Fig. 5 shows the distribution of N_b. In 10 of the most interesting events the total number of tracks N_b and N_g (N_h) is not less than 14 (Table). In spite of the fact that the solid angle in which tracks can be observed is limited one can see the formation of stars with a high multiplicity reaching about half of the charge of heavy nuclei from the NTE composition.

72 stars containing only triples of $b-$particles stopped in NTE are assigned to the disintegration of nuclei ^{12} $\rightarrow 3\alpha$. Their ranges and spatial emission angles are determined on the basis of coordinate measurements. The average length of ranges of α-particles amounted to (23.1 $\pm$ 0.6) μm (RMS 8.4 μm). Energy of α-particles is evaluated by the SRIM model. Its mean value is (5.3 $\pm$ 0.1) MeV (RMS 1.3 MeV). Fig. 6 shows the distribution over a total longitudinal momentum of triples of α-particles P_z. As expected, it is mainly concentrated in the region $P_z > 0$, indicating the direction of arrival of the beam particles. A small number of events $P_z < 0$ corresponds to the contribution of background particles produced in the backward direction on the target material or the experimental setup.

A definite interpretation of this group of events allows one to evaluate the nature of their formation by the total transverse momentum of α-particle triples P_T. The distribution over P_T (Fig. 7) is characterized by a mean value (241 $\pm$ 28) MeV/c (RMS 123 MeV/c). The distribution is described by the Rayleigh distribution with a parameter (190 $\pm$ 13) MeV/c. These parameters are typical for the nuclear diffraction interaction. In the case of a purely electromagnetic exchange the distribution P_T would be confined to a region $P_T <$ 100 MeV/c. It is useful to compare this distribution P_T with a much narrower distribution for the reaction $P_T n(14.1MeV)+^{12}$C $\rightarrow 3\alpha+n$ (Fig. 7 [3]), which has an average value of 69 $\pm$ 4 MeV/c (RMS 38 MeV/c) and the Rayleigh distribution parameter of 55 $\pm$ 28 MeV/c.

The total energy distribution of α-particle triples $Q_{3\alpha}$ (Fig. 8) is considerably wider than in the case $n(14.1)+^{12}$ $\rightarrow 3\alpha$ [6] which clearly manifested cluster features of the ^{12}C nucleus. In this case it is concentrated above the α-cluster excitation levels of the ^{12}C nucleus. The energy distribution of α-particle pairs $Q_{2\alpha}$ (Fig. 9) also shows no similarity. There is practically no signal in it from decays via the ground state $^{8}Be_{g.s.}$ in $Q_{2\alpha} < 200keV$ (inset in Fig. 9) to be manifested as "narrow "pairs of

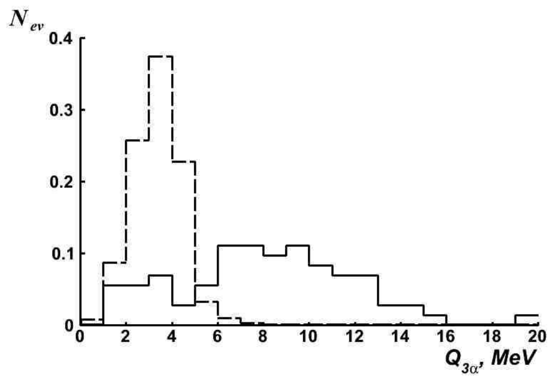

FIG. 8: Distribution over the total energy $Q_{3\alpha}$ of 72 α-particles in NTE exposed to μ-mesons (solid histogram) and 400 triples of α-particles from reaction $n(14.1) +^{12} \to 3\alpha + n$ [3] (dashed histogram); normalization of the histogram to the number of events.

α-particles [6]. The distribution $Q_{2\alpha}$ shows no peak due to the decays via the first excited state $^8Be_{2+}$ (3 MeV). Moreover, the distribution $Q_{2\alpha}$ is much wider than in the case of $n(14.1) +^{12} \to 3\alpha$ [6].

In general, these distributions $P_T, Q_{3\alpha}$ and $Q_{2\alpha}$ indicate on a hard character of the process without the appearance of known structural features of the ^{12}C nucleus with the formation of α-particle triples in the continuum. It should be emphasized that the contribution of 3α-disintegrations of ^{12}C nuclei should certainly be manifested in the channel in question ($N_b = 3, N_g = 0$). However, the fact that this channel having a minimum threshold is characterized by a nuclear diffraction mechanism, rather than "soft "electromagnetic one, is unexpected and worthy of theoretical consideration. Confirmation of this conclusion is important for the interpretation of not only the phenomenon of multifragmentation under the influence of ultrarelativistic μ-mesons. It can also be a basis for the interpretation of multifragmentation of relativistic nuclei in peripheral interactions without the formation of target nucleus fragments ("white"stars).

In spite of the fact that these observations are preliminary they show that a wholesome investigation of a complete disintegration of nuclei by μ-mesons based on multilayer assemblies of thick layers of NTE without a substrate is with good prospects. It is necessary to check the level of the hadron background in the place of NTE exposure for a reliable interpretation of the phenomenon as caused by ultrarelativistic μ-mesons. Data of such an exposure could be useful to plan experiments on the basis of silicon detectors or a time-projection chamber. Understanding of the nuclear fragmentation induced by μ-mesons is of practical interest for the development of approaches to the separation of π-and μ-mesons based on differences in the stars they create. In addition, they are useful for testing models of physical processes for lepton-nuclear colliders.

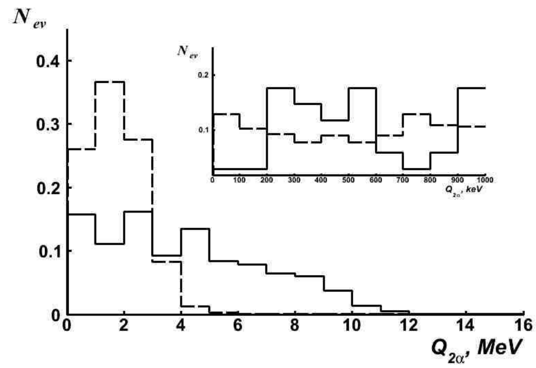

FIG. 9: Distribution over the total energy $Q_{2\alpha}$ of pairs of α-particles in NTE exposed to μ-mesons (solid histogram) and 400 triples of α-particles from reaction $n(14.1) +^{12} \to 3\alpha + n$ [3] (dashed histogram); normalization of the histogram to the number of events.

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