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PROTON, DEUTERON AND TRITON EMISSION IN $^{14}N + Ag$ REACTION AT 52 MeV/NUCLEON*

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1 Introduction

Emission of fast light charged particles is an interesting problem in heavy ion physics, especially in the energy range between 20 and 100 MeV/nucleon. In this energy range the reaction mechanisms are thought to change from mean field phenomena at low energies, where an energy of projectile particles comparable with the nuclear binding energy and Coulomb barrier, to localized interaction regions, where single nucleon-nucleon scattering become important, at higher energies. The underlying mechanism of light fragment formation and the mechanism which results in particle velocities larger than the beam velocity, in spite of considerable dissipation of the initial energy in the entrance channel are interesting problems. Numerous experimental data are available below 40 MeV/nucleon and above 90 MeV/nucleon (see for example [1–6]), but there are only a few experiments in 50–60 MeV/nucleons range [7,8]. Existing experimental data are insufficient to clarify the mechanism of light particle emission. Measurements of light particles spectra, angular distributions, and correlations for a wide range of kinematic variables, up to kinematic limit, are very important. Multiplicity measurements are also important for elucidating the reaction mechanism.

In this paper we present new experimental data on spectra and multiplicity of light charged particles generated in the $^{14}N + Ag$ reaction at 52 MeV/nucleon.

2 Experiment

The measurements were carried out with a 52 MeV/nucleon ^{14}N beam of JINR Flerov Laboratory of Nuclear Reactions heavy-ion cyclotron U-400M. The average beam current was about 1 nA. A 0.1-mm-thick Ag target was placed inside of the evacuated beam pipe with the 0.4-mm-thick stainless steel walls in the center of the BGO-ball, a 4π spectrometer, LAMPF BGO-ball [9], consisting of 30 phoswich detectors, used to detect the reaction products. The detectors of the array are of pentagonal and hexagonal shape and are tightly packed to form a truncated icosahedron of 32 sides of approximately equal solid angle. Two of the 32 sides are opened for the beam entry and exit. The detectors are distributed around an inner radius of 6.1 cm from the center of the array to the center of each crystal face, and are arranged in six groups centered at the laboratory scattering angles $\theta = 37°, 63°, 79°, 102°, 116°$ and $142°$. Five detectors located at the scattering angle of 37° were not used in these measurements. Each detector has a solid angle of about $\frac{1}{32} \times 4\pi$ sr, 0.05-mm-thick nickel entrance window and consists of a 3-mm-thick NE102 plastic scintillator optically coupled to the front of a 5.6-cm-thick bismuth germanate (BGO) crystal, with a 7.62-cm-diameter photomultiplier tube on the back. The crystal is thick enough to stop the protons of up to 185-MeV energy. The phototube signals from each detector were split for energy and time measurements. Time resolution of each detector is about 1 ns. The timing measurements were used for accidental coincidence rejection. Since the decay constant of the BGO scintillator is much longer than that of the plastic scintillator (250 ns vs 1.5 ns) it is possible to measure the energy losses of outgoing particles. The anode signal is time sliced to provide both ΔE (fast) and E (slow) signals for the charged (pions, protons, deuterons etc.) and neutral (neutrons and gamma rays) particle identification. A detailed description of the raw data analysis can be found elsewhere [9]. Figure 1 shows an example of the two-dimensional $\Delta E - E$ distribution. One can observe clear particle identification between protons, deuterons and tritons. A coincidence of at least two detectors in the BGO-ball was used as an event trigger.

Cosmic ray muons were used to calibrate the BGO-ball detectors. We used standard Monte Carlo techniques based on GEANT code [10] to calculate the energy losses of cosmic muons in real detectors. We used known muon spectrum from Ref. [11] for this simulation. The cosmic ray muons energy spectrum from Ref. [11] for this simulation. The cosmic ray muons with an average energy of about 2 GeV with a trajectory along crystal axis through its center deposit about 60 MeV in the BGO crystal. For calibration we selected events for which muon passed through the center of the BGO-ball. The measured energy loss spectra are in a good agreement with the simulations. This calibration procedure could be performed simultaneously with the data acquisition, in time intervals between beam macro bursts. This provided real time corrections to the data set. The data were corrected for the energy losses in target and other materials between the target and the detectors, efficiency loss due to particle interaction in scintillator and dead time. The typical dead time was $< 20\%$ in this experiment.

3 Results

The inclusive energy spectra for protons, deuterons and tritons and their multiplicity were measured at five angles and light particle multiplicities were measured. The measured spectra are presented in Fig. 2, 3, 4. Particle multiplicities are shown in Fig. 5. The energy spectra exhibit exponential fall-off, which become steeper with increasing detection angle. The slopes of protons, deuterons and tritons spectra are nearly the same at large angles. However, for angles in forward hemisphere, the behavior is rather different. At kinetic energies up to 140 MeV the spectra of p, d, t have different exponential slopes. Above 140 MeV they have the same slopes and the yield of protons, deuterons and tritons become equal. Change of the slopes is possible with the appearance of the new reaction channels. (For example, π-meson production).

We compared experimental spectra with the calculations within a framework of the Dubna version of the Cascade Model (DCM), which was originally proposed as a description of particle and light fragment production in both $N + A$ and $A + A$ reactions at high energy [12,13]. In this model inelastic nucleus-nucleus interactions are treated as successive quasi-free two-particle collisions described by a set of coupled relativistic kinetic equations of the Boltzmann type. In our approach the mean-field evolution is treated in a simplified way. We keep the scalar nuclear potential of the initial state, defined in the local Thomas-Fermi approximation, changing only the potential well's depth according to the number of knocked-out nucleons [14]. This procedure allows one to take into account nuclear binding and the Pauli principle. This approximation is good enough for hadron-nucleus or peripheral nucleus-nucleus collisions where there is no large disturbance of the mean field but it is questionable for violent central collisions of two nuclei.

The model is also capable of describing the production of fast composite particles d, t, ^3He and ^4He by taking into account the final state interaction of cascade particles in the framework of the of dynamical coalescence model [13] on an event-by-event basis. The values for the coalescence radii in the momentum space, initially estimated from experimental spectra of particles produced in interactions of neon nuclei with uranium at 400-2100 MeV/nucleon, turned out to be independent of either the primary energy of nucleus or the mass numbers of colliding nuclei.

Upon completing the cascade stage of the reaction, light particles may be emitted both from the equilibrium and non-equilibrium state of excited residual nuclei at a subsequent slower stages of interaction. We have taken into account the pre-equilibrium emission effects within the exciton model [15]. For ^{14}N + ^{108}Ag interactions at 52 MeV/nucleon, 100000 events were generated.

In the experiment two particles that hit the same detector at the same time, could not be separated and were lost from the data set. The calculated energy spectra were filtered by simulating the experimental biases and a misidentification correction function (MCF) was obtained from comparison of these spectra with pure DCM calculations. The measured p, d and t spectra were corrected using this function and then normalized to the calculated one at a single point at an energy of 60 MeV and at an angle of 63° for proton spectrum. This single normalization coefficient was used for all measured spectra at all angles.

The inclusive spectra, shown in the left parts of Fig. 2, 3, 4 are in quite satisfactory agreement with measured data. The DCM slightly underestimates high energy part of the proton yield at large angles. This is also reflected in the deuteron and triton spectra, which are overestimated at the same angles. The momentum coalescence radii in this model (90 MeV/c for deuteron and

108 MeV/c for tritium [13,14]) are independent of both the beam energy and colliding nucleus size. The difference noted shows that nucleon correlations in the coordinate space may be important in this energy domain. We note that the DCM reproduces the abundance of different light particles correctly. The contributions from all stages of reaction are shown in the right parts of Fig. 2, 3, 4. One can see that high energy deuterons and tritons are produced mainly via coalescence mechanism, which decreases the primordial cascade proton yield.

The inclusive spectra of composites can be related to the spectra of protons by a power low [16] due to thermodynamic consideration. Composite particles are formed by the coalescence of free nucleons which happen to occupy the same region of the momentum space similarly to the dynamic model. The size of this region is defined by coalescence radius ρ_0. We have extracted this parameter from the measured spectra. It is 136 ± 4 MeV/c and 162 ± 4 MeV/c for the deuteron and the triton respectively. Using these coalescence radii we estimated radii of deuteron and triton formation sources. The values are 1.45 ± 0.04 fm and 1.22 ± 0.03 fm for deuteron and triton respectively. These values are in a rough agreement with the compilation of radii of fragment-formation sources from [17]. It is worth noting that the coalescence radius extracted in this way corresponds to the spectra integrated over impact parameter and will depend both on the beam energy and combination of colliding nuclei so this is only a rough estimate.

We also compared a measured probability of the number of light particles of specific kind per event with DCM calculations Fig. 5. An agreement for composite particles (d, t) is rather good, while for protons one can see a disagreement for higher multiplicity, which could be explained by uncertainty in the MCF.

To study the particle source, we have parameterized the light particle spectra assuming equilibrium (Maxwellian) emission in the rest frame which moves with some velocity intermediate between target and projectile velocities:

$$\frac{d^2\sigma}{d\Omega dE} = N_0 \cdot \sqrt{(E-U_c)} \cdot \\ \cdot \exp\{-[E - U_c + E_1 - \sqrt{2E_1(E-U_c)} \cdot \cos\Theta]/T\}. \quad (1)$$

Here U_c is kinetic energy gained by the Coulomb repulsion from emitting system, $E_1 = \frac{1}{2}mv^2$, where m is the mass of the particle and v is the source velocity in the in the laboratory system, T is the source temperature, Θ is the detection angle and N_0 is normalization constant. In the present analysis, temperature and velocity parameters have been determined by fitting while the Coulomb barrier has been chosen as $V_v = 0$ because our measurements deal with the region with $E >> U_c$. Values of v, T and N_0 were obtained for protons, deuterons and tritons by fitting each particle spectra separately. They are given in Table 1 We also estimated the total cross sections for light particle emission according to:

$$\sigma = 2N_0(\pi T)^{3/2} \tag{2}$$

which is obtained by integrating Eq. 1

Table 1
Moving source parameters

particle	v/c	T (MeV)	N_0	σ (b)
p	0.129 ± 0.001	16.8 ± 0.1	3455 ± 8	2.65 ± 0.2
d	0.129 ± 0.001	16.8 ± 0.1	1529 ± 8	1.17 ± 0.1
t	0.129 ± 0.001	16.8 ± 0.1	689 ± 8	0.53 ± 0.1

Energy spectra and moving source calculations for protons, deuterons and tritons emission are presented in Fig. 6. The moving source parameterization gives a good description of these particles at backward angles but overestimate the high energy part of the spectra at forward angles.

A contour plot of invariant cross section for protons, deuterons and tritons is shown in Fig. 7 as a function of longitudinal and transverse velocity. Contour lines for isotropic source with parameters obtained from the moving source parameterization are also shown. It is evident the data can be described with an emission mechanism from a single source which is moving with a velocity between center-of-mass system and beam velocities.

We compared our experimental spectra with the data from other experiments [7] and [8] (Fig. 6). In Ref. [7] the reaction $^{197}Au(^{40}Ar, X)$ at $E/A = 60$ MeV, where $X = p, d, t$, was studied, in Ref. [8] – $^{108}Ag(^{40}C, p)$ at $E/A = 58$ MeV. One can see that general behavior of these spectra is similar, however the spectra from Ref. [8] have a rather different slope.

The next step in this research is to use a forward detector to measure projectile-like particles. This should allow the impact parameter to be determined so that the contributions of peripheral and central collisions to the particle spectra can be separated, and more detail of the dynamics of reaction mechanisms can be provided.

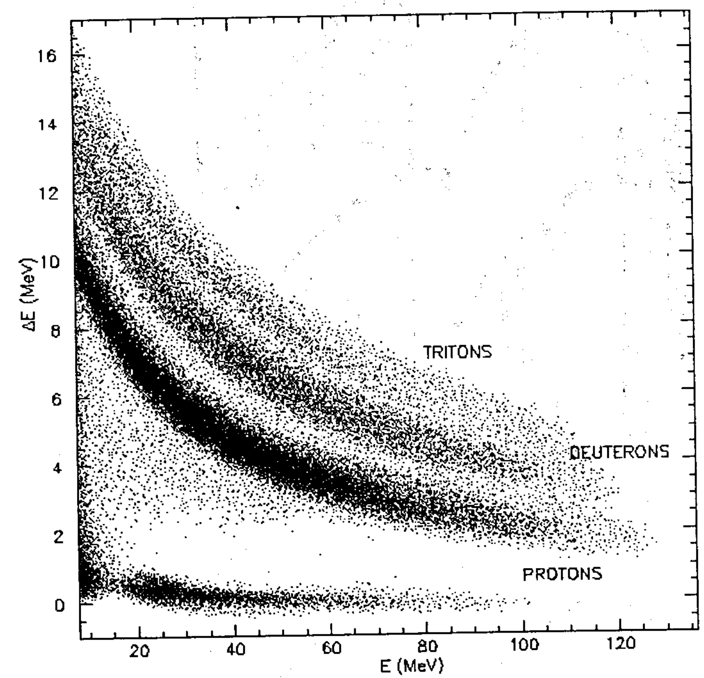

Fig. 1. Two-dimensional $\Delta E - E$ distribution.

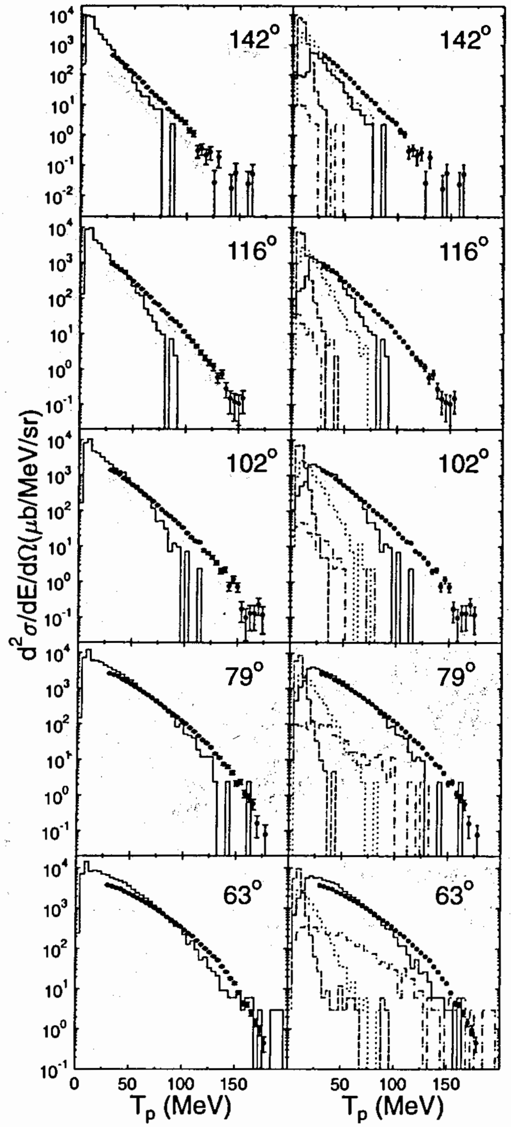

Fig. 2. The inclusive energy spectra of protons measured at different scattering angles $\theta = 63°, 79°, 102°, 116°$ and $142°$ compared to calculated ones using Dubna version of the Cascade Model (DCM) and contributions to the spectra from different mechanisms. Circles – this experiment, solid line in the left parts – DCM calculation, solid line in the right parts – cascade for p and coalescence for d, t, dotted – preequilibrium, dashed – equilibrium, dotted-dashed – Fermi decay.

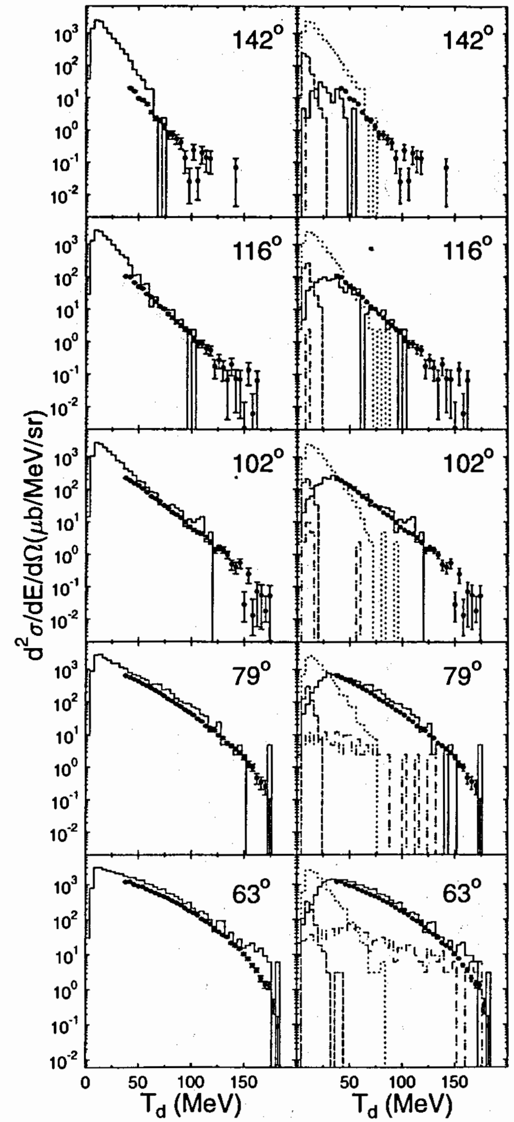

Fig. 3. The inclusive energy spectra of deuterons. The same as in in Fig. 2.

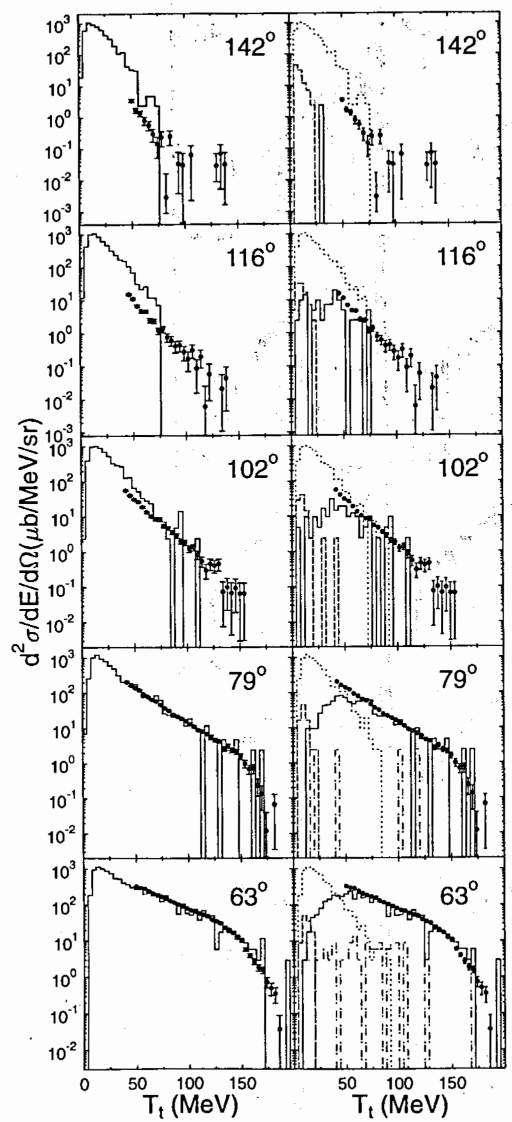

Fig. 4. The inclusive energy spectra of tritons. The same as in in Fig. 2.

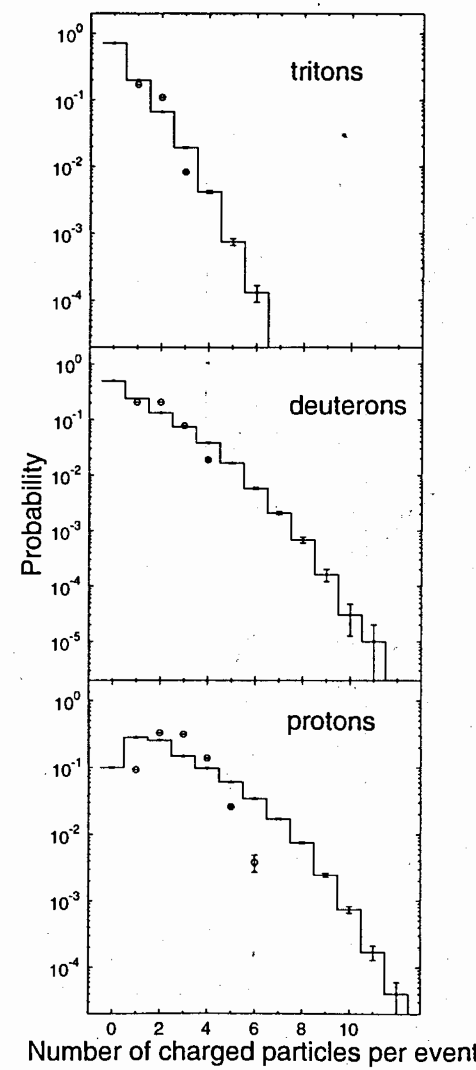

Fig. 5. The light particle multiplicity distributions. Circles – this experiment solid line – DCM calculation

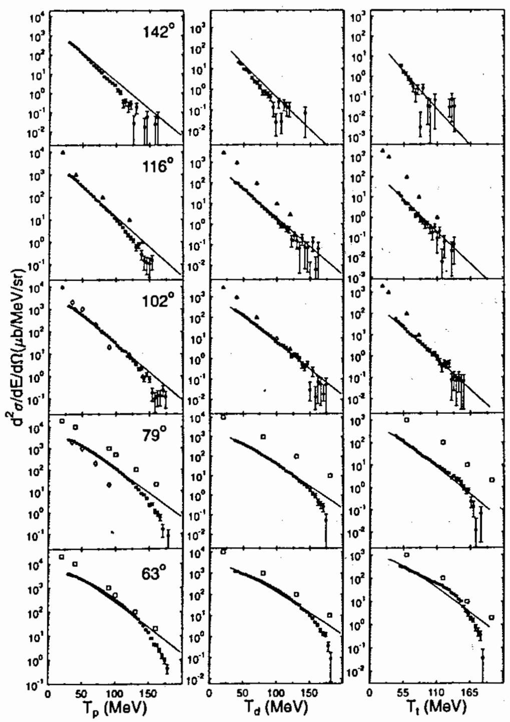

Fig. 6. The inclusive energy spectra of p, d, t measured at different scattering angles $\theta = 63°$, $79°$, $102°$, $116°$ and $142°$. Solid line is a moving source parameterization with Eq. 1. Squares and triangles – data from Ref. [7] for the reaction $^{197}Au(^{40}Ar, X)$ at $E/A = 60$ MeV, where $X = p, d, t$ at $\theta = 70°$ and $110°$ respectively, diamonds – data from Ref. [8] – $^{108}Ag(^{40}C, p)$ at $E/A = 58$ MeV at $\theta = 90°$

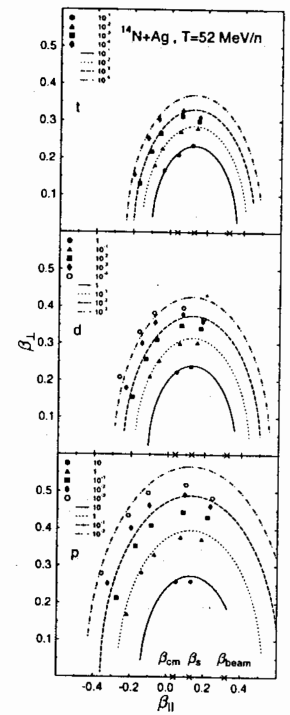

Fig. 7. Invariant cross section in the $\beta_\perp$ versus $\beta_\parallel$ plane for p, d, t. Circles, triangles, squares, diamonds and open circles represent experimental data of cross sections $\sigma_{inv} = (1/pc)d^2\sigma/(dEd\Omega)$ in $\mu b/(MeV^2 sr)$. Contour lines represent calculated cross sections assuming isotropic source with the parameters in Table 1. The cross section rises by a factor of 10 between subsequent contour lines. The crosses on the $\beta_\parallel$ axis indicate a center mass velocity (β_{cm}), moving source velocity (β_s) and beam velocity (β_{beam})

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Эмиссия протонов, дейтронов и тритонов в реакции ^{14}N + Ag при энергии 52 МэВ/нуклон

В реакции ^{14}N (Ag, X), $X = p, d, t$ при $E/A = 52$ МэВ были измерены инклюзивные спектры частиц p, d, t и их множественности. Экспериментальные данные сравнены с дубненской версией модели CASCADE (DCM) и проанализированы в рамках модели движущегося источника.

Работа выполнена в Лаборатории ядерных реакций им. Г.Н.Флерова ОИЯИ.

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Proton, Deuteron and Triton Emission in ^{14}N + Ag Reaction at 52 MeV/nucleon

Inclusive energy spectra of p, d, t and multiplicities from the reaction ^{14}N (Ag, X), $X = p, d, t$ at $E/A = 52$ MeV were measured. The experimental data are compared with Dubna version of the Cascade Model (DCM) and are analyzed in a framework of moving source model.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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