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Phenomenological analysis of breakup of ^{9}Be nuclei into two α-particles and neutron in peripheral interactions with emulsion nuclei

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Phenomenological Monte Carlo model of peripheral interactions of ^{9}Be nuclei with emulsion nuclei at $1.2A$ GeV with formation of an excited ^{9}Be* nucleus and its subsequent breakup, either directly or through formation of an intermediate ^{8}Be nucleus, into two α-particles and a neutron was constructed. A comparative analysis of the experimental data on angular correlations and momentum spectra of α-particles, coming from a breakup event, with the Monte Carlo model calculations was made. The constructed Monte Carlo model described quite satisfactory the total momentum and transverse momentum distributions of α-particles and the distribution of angles between the total momentum (as well as transverse momentum) vectors of two α-particles in ^{9}Be* nucleus breakup events in experiment. For the first time, the total momentum and transverse momentum distributions of neutrons, accompanying two α-particles from ^{9}Be* decay, in

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peripheral interactions of ^{9}Be nuclei with emulsion nuclei were reconstructed using the Monte Carlo model.

Keywords: Peripheral interactions of nuclei; Monte Carlo modeling of breakup of excited beryllium nuclei; breakup of nuclei into alpha particles.

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1. Introduction

Investigation of fragmentation of light nuclei in peripheral collisions with nucleons and nuclei allows one to obtain unique information about an initial structure of fragmenting nuclei and its interrelation with the yield and composition of the final reaction products. Peripheral interactions are characterized by formation of narrow jets of projectile fragments with the total charge and baryon number being close to those of the fragmenting nucleus. In some peripheral interactions of relativistic nuclei with the emulsion nuclei, the latter ones do not fragment, acquiring just small transverse momentum and only an impinging nucleus does fragment, conserving an initial charge and the number of baryons in its fragments — the breakup products. For such collisions, an assumption about approximate conservation of an incident momentum per nucleon is quite justified.[1–3] Such assumption makes it possible to bring investigation of fragmentation processes down to an analysis of angular spectra of fragments of an initial nucleus. The nuclear emulsion, having the best space resolution ($\Delta x = \Delta y \approx 0.5\,\mu$m) among the other track methods, permits to measure emission angles of traces of relativistic fragments with a precision $\Delta\theta \sim 10^{-4}$–$10^{-3}$ radians. The charges of singly and doubly charged fragments are determined visually with a high precision, and those of the other fragments with $z_{\rm f} > 2$ are identified reliably by a density of δ electrons on their tracks.

Fragmentation characteristics of relativistic ^{9}Be nuclei in interactions with the emulsion nuclei at an incident energy $1.2A\,$GeV were studied in detail by BECQUEREL collaboration,[4,5] founded on the basis of Nuclotron of the Laboratory of High Energies (LHE) at Joint Institute for Nuclear Research (JINR, Dubna). Analysis of distribution of fragmentation ^{9}Be$\rightarrow 2\alpha + n$ events on the number and types of accompanying target nucleus fragments showed that approximately 40% of such events consisted of (2He) topology (breakup channel ^{9}Be$\rightarrow 2\alpha + n$), in which the traces of target fragmentation were absent. This type of events is called "white" stars.[4,5] The fraction of events with formation of $2\alpha + n$ and singly charged relativistic particles proved to be ≈22%.

In Refs. 4 and 5, the contributions of various emulsion nuclei into the fragmentation channel ^{9}Be$\rightarrow 2\alpha + n$ were estimated. The fraction of ^{9}Be$\rightarrow 2\alpha + n$ fragmentation events on hydrogen nuclei of emulsion proved to be 9.1 ± 1.7%. Due to the complexity of separation of events occurring on C, N and O nuclei of emulsion, the separate contributions for such nuclei could not be estimated, and the remaining 90.9% events were attributed to the summed interactions on two group, CNO+AgBr, nuclei.

In a two-particle (core+n) model,[6–8] the ^{9}Be nucleus is represented as a system of a neutron in a $p_{3/2}$ state and a core ^{8}Be nucleus in the states 0^+(ground state) and 2^+ with the thresholds of a neutron separation 1.67 MeV and 4.71 MeV, respectively. The wave function of the ^{9}Be nucleus in its ground state can be represented as[6]

$$|^9\mathrm{Be}(3/2^-)\rangle = \omega_{0^+}|[^8\mathrm{Be}(0^+) \otimes n_{p(3/2)}]_{3/2^-}\rangle + \omega_{2^+}|[^8\mathrm{Be}(2^+) \otimes n_{p(3/2)}]_{3/2^-}\rangle,$$

where $\omega_{0^+} = 0.535$ and $\omega_{2^+} = 0.465$ are the corresponding weighting factors.

In addition to an unstable ^{8}Be nucleus, there is a possibility of formation of an intermediate ^{5}He nucleus[9,10] with an energy threshold 2.44 MeV. The product of dissociation of ^{5}He+α in the final state is also the $2\alpha + n$ system.[11]

The present work is devoted to a phenomenological analysis of a breakup reaction ^{9}Be$\to 2\alpha + n$ in peripheral collisions of ^{9}Be nuclei with the emulsion nuclei at $1.2A$ GeV. The experimental data were obtained using the stacks of nuclear emulsions of a type GOSNIIHIMFOTOPROEKT BR-2, irradiated by a beam of ^{9}Be nuclei with an energy $1.2A$ GeV at the Nuclotron of LHE of JINR.[4,12] The beam of ^{9}Be nuclei was obtained in a fragmentation reaction ^{10}B$\to$ ^{9}Be.[12] The fraction of ^{9}Be nuclei in a beam was 67% and the remaining 33% consisted of isotopes of He and Li nuclei. The emulsion stack, used for an exposition, consisted of 15 emulsion layers of a type BR-2 having a size of $10\times 20\,\mathrm{cm}^2$ and thickness of 600 μm. The statistics of the analyzed data consisted of 500 "white" two prong (two doubly charged fragments) stars. Since we deal with the "white" stars, formed from a breakup of ^{9}Be nuclei in peripheral collisions with the emulsion nuclei, we can assume that the doubly charged fragments observed experimentally are ^{4}He nuclei. However, these α-particles are produced together with the neutrons, whose kinematical characteristics cannot be defined using the experimental method of nuclear emulsions. On top of this, the method does not allow to determine unambiguously the mass number of an emulsion nucleus involved in an interaction.[13] Nevertheless, the kinematical characteristics of products of a breakup of an excited ^{9}Be* nucleus depend on the mass number of an emulsion nucleus, on which an interaction occurred. Due to the above, it is of particular interest to construct a Monte Carlo model, which could account correctly for the contributions of emulsion nuclei in formation of excited ^{9}Be* nuclei and its decay channels with the aim to calculate the kinematical characteristics of the final reaction products, including those of neutrons. Then, if the Monte Carlo model results would agree with the corresponding experimental data for the charged fragments, one could assert that the satisfactory and reasonable estimates of the kinematical characteristics of neutrons were also obtained.

An algorithm of the constructed Monte Carlo model of ^{9}Be nucleus interaction with emulsion at $1.2A$ GeV with formation of an excited ^{9}Be* nucleus and generation of its breakup into two α-particles and a neutron is presented below. The following two channels of breakup of an excited ^{9}Be* nucleus were taken into account: a two-particle one — ^{9}Be*$\to$ ^{8}Be$\,+\,n$ (with the probability 55%), and a three-particle one — ^{9}Be*$\to 2\alpha + n$ (with the probability 45%). In a two-particle breakup, the mass of ^{8}Be was being generated as $M_{8\mathrm{Be}} = 2m_\alpha + 0.10\,\mathrm{MeV}$ with the probability

60%, and as $M_{8\mathrm{Be}} = 2m_\alpha + 3.04\,\mathrm{MeV}$ with the probability 40%. Here, 0.10 MeV and 3.04 MeV correspond to excitation levels of ^{8}Be in the states 0^+ and 2^+, respectively. Further, a breakup of ^{8}Be in its rest frame into two α-particles was being generated. Since an incident beam of ^{9}Be nuclei was unpolarized, it was assumed, for simplicity of calculations, that ^{8}Be nucleus also did not have polarization in its rest frame. Therefore, a breakup of ^{8}Be nucleus into two α-particles, in its rest frame, was being generated in accordance with an isotropic angular distribution.

The present work is organized as follows. An algorithm of the constructed Monte Carlo model is described in Sec. 2. The comparison of the experimental data with the Monte Carlo model calculations is presented in Sec. 3. Section 4 contains the summary and conclusions of the present paper.

2. Algorithm of Monte Carlo Method

The ^{9}Be nucleus with the mass $M_{^9Be} = 8.3723\,\mathrm{GeV}$ and total kinetic energy $T = 10.8\,\mathrm{GeV}$ (in the laboratory system), impinging on an emulsion, does not posses a transverse momentum. Its longitudinal momentum $P_{L^9\mathrm{Be}}$ and total energy $E_{^9\mathrm{Be}}$ (in a system where $c = 1$) are given by

$$P_{L^9\mathrm{Be}} = \sqrt{T^2 + 2TM_{^9\mathrm{Be}}} \quad \text{and} \quad E_{^9\mathrm{Be}} = T + M_{^9\mathrm{Be}} = \sqrt{P^2_{L^9\mathrm{Be}} + M^2_{^9\mathrm{Be}}}. \tag{1}$$

For calculation of interaction probability of an impinging beryllium nucleus with the emulsion nuclei, firstly, we took into account the nuclear composition of an emulsion[13]: Ag (1.028×10^{22} atoms/cm^3), Br (1.028×10^{22} atoms/cm^3), (C+O+N) ($(1.4 + 1.083 + 0.374) \times 10^{22}$ atoms/cm^3), and H (1.028×10^{22} atoms/cm^3). Secondly, it was observed experimentally that, in the present experimental material, the interaction probability of a beryllium nucleus with the emulsion hydrogen was $9.1 \pm 1.7\%$ or $\approx 10\%$. Therefore, first we calculated the relative interaction probability of ^{9}Be with the emulsion nuclei taking into account their concentrations: $P(\mathrm{Ag}) = 0.209, P(\mathrm{Br}) = 0.209, P(\mathrm{C+O+N}) = 0.582$. Further, we took into account that the radius of a nucleus was $r \approx A^{1/3}$ and the geometric interaction cross-section $\sigma \approx \pi r^2 \approx \pi A^{2/3}$, where A is the mass number of the nucleus. Taking radii of the emulsion nuclei into account, we obtained the following interaction probabilities: $P_A(\mathrm{Ag}) = 0.482, P_A(\mathrm{Br}) = 0.395, P_A(\mathrm{C+O+N}) = 0.123$. Hence, the total interaction probabilities of an impinging beryllium nucleus with the emulsion nuclei proved to be

$$\begin{aligned} P_{\mathrm{total}}(\mathrm{H}) &= 0.1, \\ P_{\mathrm{total}}(\mathrm{Ag}) &= (1-0.1)\cdot P(\mathrm{Ag})\cdot P_A(\mathrm{Ag})/P_{\mathrm{sum}}, \\ P_{\mathrm{total}}(\mathrm{Br}) &= (1-0.1)\cdot P(\mathrm{Br})\cdot P_A(\mathrm{Br})/P_{\mathrm{sum}} \quad \text{and} \\ P_{\mathrm{total}}(\mathrm{C+O+N}) &= (1-0.1)\cdot P(\mathrm{C+O+N})\cdot P_A(\mathrm{C+O+N})/P_{\mathrm{sum}}, \end{aligned} \tag{2}$$

where

$$P_{\mathrm{sum}} = P(\mathrm{Ag})\cdot P_A(\mathrm{Ag}) + P(\mathrm{Br})\cdot P_A(\mathrm{Br}) + P(\mathrm{C+O+N})\cdot P_A(\mathrm{C+O+N}). \tag{3}$$

We obtained the following numerical results for the above probabilities:

$$P_{\text{total}}(\text{H}) = 0.100, \quad P_{\text{total}}(\text{Ag}) = 0.356,$$
$$P_{\text{total}}(\text{Br}) = 0.291 \quad \text{and} \quad P_{\text{total}}(\text{C} + \text{O} + \text{N}) = 0.253. \tag{4}$$

Using the probabilities given in (4), the type of an emulsion nucleus on which an interaction of an impinging beryllium nucleus occurred, was being simulated.

Having interacted with the emulsion nucleus, ^{9}Be nucleus gets excited (undergoes transformation into ^{9}Be* with the invariant mass greater than that of ^{9}Be) and acquires a transverse momentum $P_{T^9\text{Be}*}$, with components $P_{x^9\text{Be}*}$ and $P_{y^9\text{Be}*}$, which we simulated (in the laboratory system) according to a Gaussian law with the parameter $\sigma = 0.06\,\text{GeV}$. According to a law of momentum conservation, the emulsion nucleus also acquires a transverse momentum, i.e., the part of an energy of longitudinal motion of an initial ^{9}Be nucleus gets transferred to transverse motion (momentum) of an emulsion nucleus, and the part goes to transverse motion (momentum) of ^{9}Be and its excitation to the ^{9}Be* nucleus. We assumed that no longitudinal momentum was being transferred from the impinging ^{9}Be to an emulsion nucleus.

Denoting the mass and energy of the emulsion nucleus as $M_{\text{emuls}}, E_{\text{emuls}}$, and E'_{emuls} before and after the interaction, respectively, the law of energy conservation in the laboratory frame can be written as

$$E_{\text{emuls}} + E_{^9\text{Be}} = E'_{\text{emuls}} + E'_{^9\text{Be}*}, \tag{5}$$

where

$$E_{\text{emuls}} = M_{\text{emuls}}, \quad E_{^9\text{Be}} = \sqrt{P^2_{L^9\text{Be}} + M^2_{^9\text{Be}}},$$
$$E'_{\text{emuls}} = \sqrt{P^2_{T^9\text{Be}*} + M^2_{\text{emuls}}} \quad \text{and} \quad E'_{^9\text{Be}*} = \sqrt{P^2_{T^9\text{Be}*} + P^2_{L^9\text{Be}*} + M^2_{^9\text{Be}*}}. \tag{6}$$

It follows from Eq. (5) that

$$E'_{^9\text{Be}*} = E_{\text{emuls}} + E_{^9\text{Be}} - E'_{\text{emuls}}. \tag{7}$$

Substituting $E'_{^9\text{Be}*}$ in (7) according to the last expression in (6), we obtained

$$\sqrt{P^2_{T^9\text{Be}*} + P^2_{L^9\text{Be}*} + M^2_{^9\text{Be}*}} = E_{\text{emuls}} + E_{^9\text{Be}} - E'_{\text{emuls}} \tag{8}$$

or

$$P^2_{L^9\text{Be}*} + M^2_{^9\text{Be}*} = (E_{\text{emuls}} + E_{^9\text{Be}} - E'_{\text{emuls}})^2 - P^2_{T^9\text{Be}*}. \tag{9}$$

All the terms on the right side in (9) are already known. Therefore, for convenience, we denoted the whole right side of Eq. (9) as A. Then, Eq. (9) became

$$P^2_{L^9\text{Be}*} + M^2_{^9\text{Be}*} = A \tag{10}$$

or

$$P^2_{L^9\text{Be}*} = A - M^2_{^9\text{Be}*}. \tag{11}$$

The right side of Eq. (11) shows that $P^2_{L^9\text{Be}*}$ varies in some interval from $(P^2_{L^9\text{Be}*})_{\min}$ to $(P^2_{L^9\text{Be}*})_{\max}$. Let us now define these boundaries.

In the Monte Carlo model, as in experiment, the ^{9}Be* nucleus decays either directly into two α-particles and a neutron or through the channel of formation of a neutron and an intermediate ^{8}Be nucleus (with two possible (states) excitation levels), which breaks up subsequently into two α-particles. Therefore, not to break an independence of formation of all the three channels, we chose the maximal value of binding energy $E_{\mathrm{binding}} = 0.00304\,\mathrm{GeV}$ and determined the minimal mass of an excited beryllium nucleus as (using $m_\alpha = 3.72741\,\mathrm{GeV}$ and $m_{\mathrm{neutron}} = 0.93957\,\mathrm{GeV}$)

$$(M^2_{^9\mathrm{Be}*})_{\min} = 2m_\alpha + m_{\mathrm{neutron}} + E_{\mathrm{binding}}. \tag{12}$$

Then, we obtained from Eq. (11):

$$(P^2_{L^9\mathrm{Be}*})_{\max} = A - (M^2_{^9\mathrm{Be}*})_{\min} = A - 2m_\alpha - m_{\mathrm{neutron}} - E_{\mathrm{binding}}, \tag{13}$$

and formulas in Eqs. (9)–(11) resulted in

$$(P^2_{L^9\mathrm{Be}*})_{\min} = 0. \tag{14}$$

The process investigated in the present work is analogous to the diffractive one. Therefore, the values of $P^2_{L^9\mathrm{Be}*}$ close to $(P^2_{L^9\mathrm{Be}*})_{\max}$ had to be realized more often. Hence, for changing $P^2_{L^9\mathrm{Be}*}$ in the interval from $(P^2_{L^9\mathrm{Be}*})_{\min}$ to $(P^2_{L^9\mathrm{Be}*})_{\max}$, we can choose the simulation law given by

$$r = \frac{\displaystyle\int_{x_{\min}}^{x} F(x)dx}{\displaystyle\int_{x_{\min}}^{x_{\max}} F(x)dx}, \tag{15}$$

where r is a random number, distributed evenly in the interval $(0, 1)$ and

$$F(x) = \frac{1}{(x_{\max} - x)^2}, \quad x \in (x_{\min}, x_{\max}),$$
$$x = P_{L^9\mathrm{Be}*}, \quad x_{\min} = (P_{L^9\mathrm{Be}*})_{\min}, \quad x_{\max} = (P_{L^9\mathrm{Be}*})_{\max}. \tag{16}$$

Having generated, using formulas in (15) and (16), the longitudinal momentum $P_{L^9\mathrm{Be}*}$ of an excited ^{9}Be* nucleus, its mass $M_{^9\mathrm{Be}*}$ was determined from Eq. (11).

Further, we simulated the breakup channel of this excited ^{9}Be* nucleus directly into three particles (two α-particles and a neutron) or into ^{8}Be nucleus and a neutron with the probabilities:

$$45\%(^9\mathrm{Be}* \to \alpha + \alpha + n) \quad \text{and} \tag{17}$$

$$55\%(^9\mathrm{Be}* \to {}^8\mathrm{Be} + n \to \alpha + \alpha + n). \tag{18}$$

The breakup process in (17) was being generated isotropically in the rest frame $K_{^9\mathrm{Be}*}$ of the ^{9}Be* nucleus, where the longitudinal axis $z_{^9\mathrm{Be}*}$ was directed along the momentum vector $\mathbf{P}_{^9\mathrm{Be}*}$ of the ^{9}Be* nucleus in the initial laboratory system K_{Lab}. In the $K_{^9\mathrm{Be}*}$ system, the momentum components p_{xi}, p_{yi}, p_{zi} of two α-particles and a neutron were being generated according to a Gaussian law with the parameter

σ, and then, for fulfillment of a momentum conservation, they were being shifted, as given by

$$p_{xi} \to p_{xi} - \frac{p_{x1} + p_{x2} + p_{x3}}{3}, \quad p_{yi} \to p_{yi} - \frac{p_{y1} + p_{y2} + p_{y3}}{3} \quad \text{and}$$
$$p_{zi} \to p_{zi} - \frac{p_{z1} + p_{z2} + p_{z3}}{3}. \tag{19}$$

It should be noted that the used value of the parameter σ did not matter, since, for fulfillment of the momentum and energy conservation in ^{9}Be* decay, the momentum components were subjected to a shift and proportional deformation, which depended both on the generated quantities and mass of a ^{9}Be* nucleus.

Having calculated the energies E_i $(E_{\alpha 1}, E_{\alpha 2}, E_{\text{neutron}})$ of two α-particles and a neutron, for fulfillment of the momentum conservation with a relative precision 10^{-10}, the momenta of the particles were subjected to a proportional change to satisfy the inequality

$$\left| \frac{E_{\alpha 1} + E_{\alpha 2} + E_{\text{neutron}} - M_{^9\text{Be}*}}{M_{^9\text{Be}*}} \right| < 10^{-10}. \tag{20}$$

Further, using the mass $M_{^9\text{Be}*}$, momentum $P_{^9\text{Be}*}$ and energy $E_{^9\text{Be}*}$ of the ^{9}Be* nucleus, the parameters of Lorentz transformation of the momentum components and energies of α-particles and a neutron, from the rest frame $K_{^9\text{Be}*}$ of an excited ^{9}Be* nucleus to the laboratory system K', were determined, where, however, the z'-axis was directed along the momentum vector $\mathbf{P}_{^9\text{Be}*}$ of the excited ^{9}Be* nucleus in the initial laboratory frame K_{Lab} in which the z_{Lab} was already along the momentum vector of an initial impinging ^{9}Be nucleus. These Lorentz transformation parameters are given by

$$\beta = \frac{P_{^9\text{Be}*}}{E_{^9\text{Be}*}}, \quad \gamma = \frac{E_{^9\text{Be}*}}{M_{^9\text{Be}*}}. \tag{21}$$

Having transformed the momenta and energies of two α-particles and a neutron from the $K_{^9\text{Be}*}$ frame into K' system, the three-dimensional rotation was made to transform the momentum components of α_1 and α_2 particles and a neutron to the laboratory frame K_{Lab}, using formulas[14]:

$$\begin{aligned}
(p_{xi}^{\text{Lab}}) &= -p'_{xi}\cos\theta\cos\varphi - p'_{yi}\sin\varphi - p'_{zi}\sin\theta\cos\varphi, \\
(p_{zi}^{\text{Lab}}) &= p'_{xi}\sin\theta - p'_{zi}\cos\theta, \\
(p_{yi}^{\text{Lab}}) &= -p'_{xi}\cos\theta\sin\varphi + p'_{yi}\cos\varphi - p'_{zi}\sin\theta\sin\varphi,
\end{aligned} \tag{22}$$

where the angles θ and φ were defined as

$$\cos\theta = \frac{-P_z}{\sqrt{(P_x)^2 + (P_y)^2 + (P_z)^2}}, \quad \cos\varphi = \frac{-P_x}{\sqrt{(P_x)^2 + (P_y)^2}} \quad \text{and}$$
$$\sin\varphi = \frac{-P_y}{\sqrt{(P_x)^2 + (P_y)^2}}, \tag{23}$$

where $P_x,\ P_y,\ P_z$ are the $P_{^9\mathrm{Be}*}$ momentum components of the excited ^{9}Be* nucleus in the K_{Lab} system.

While generating the isotropic decay given in (18), the mass of ^{8}Be nucleus could take up two values, corresponding to two values of binding energies, $E_{\mathrm{binding}} = 0.00010\,\mathrm{GeV}$ and $0.00304\,\mathrm{GeV}$, according to the probabilities

$$40\%(M_{^8\mathrm{Be}} = 2m_\alpha + 0.00304) \quad \text{and} \tag{24}$$

$$60\%(M_{^8\mathrm{Be}} = 2m_\alpha + 0.00010). \tag{25}$$

While considering beryllium ^{8}Be decay into two α-particles (see the reaction in (18)), the emission angles of an α_1 particle, θ'_1 and φ'_1, in the rest frame of ^{8}Be nucleus were being generated also according to an isotropic angular distribution. While transforming into an initial K_{Lab} system, the corresponding Lorentz transformations and three-dimensional rotations of the momentum components of α-particles and neutron were being made in the analogous way as in the case of a decay process given in (17).

The energy–momentum conservation was implemented with the relative precision 10^{-10} at all the stages of generation. For instance, for each generated event, the following quantity was being calculated in the laboratory system K_{Lab}:

$$\begin{aligned}\psi = {} & \left(\frac{E^{\mathrm{Lab}}_{\alpha 1} + E^{\mathrm{Lab}}_{\alpha 2} + E^{\mathrm{Lab}}_{\mathrm{neutron}} - E_{^9\mathrm{Be}*}}{E_{^9\mathrm{Be}*}}\right)^2 \\ & + \left(\frac{P^{\mathrm{Lab}}_{L\alpha 1} + P^{\mathrm{Lab}}_{L\alpha 2} + P^{\mathrm{Lab}}_{\mathrm{Lneutron}} - P_{L^9\mathrm{Be}*}}{P_{L^9\mathrm{Be}*}}\right)^2 \\ & + \left(\frac{P^{\mathrm{Lab}}_{x\alpha 1} + P^{\mathrm{Lab}}_{x\alpha 2} + P^{\mathrm{Lab}}_{\mathrm{xneutron}} - P_{x^9\mathrm{Be}*}}{P_{x^9\mathrm{Be}*}}\right)^2 \\ & + \left(\frac{P^{\mathrm{Lab}}_{y\alpha 1} + P^{\mathrm{Lab}}_{y\alpha 2} + P^{\mathrm{Lab}}_{\mathrm{yneutron}} - P_{y^9\mathrm{Be}*}}{P_{y^9\mathrm{Be}*}}\right)^2 .\end{aligned} \tag{26}$$

A condition $\psi < 10^{-10}$ was being fulfilled for each generated Monte Carlo event.

3. Comparison of Experiment and Monte Carlo Method

We simulated 5000 events according to the above described Monte Carlo model procedures. The experimental and Monte Carlo model transverse momentum spectra of α-particles are presented in Fig. 1. The experimental values of transverse momentum of α-particles were determined assuming that an incident momentum per nucleon was retained by the fragments, i.e., $p_t = 4 \cdot p_0 \cdot \sin\theta$, where θ is an emission angle of an α-particle, and p_0 is an incident momentum per nucleon. As observed from Fig. 1, Monte Carlo model described quite satisfactorily the experimental transverse momentum distribution of α-particles. The mean values of transverse

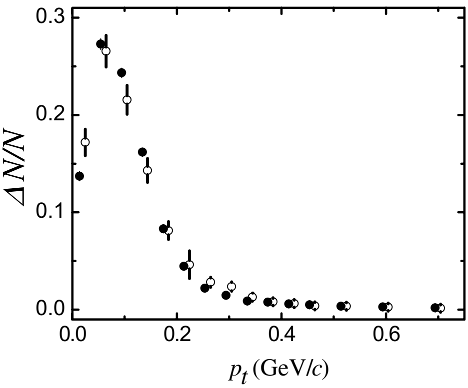

Fig. 1. Transverse momentum distribution of α-particles in experiment ($\circ$) and Monte Carlo model calculations ($\bullet$).

momentum of α-particles proved to be $115.4 \pm 3.0\,\text{MeV}/c$ and $112.1 \pm 1.1\,\text{MeV}/c$ in experiment and Monte Carlo model calculations, respectively.

The experimental and Monte Carlo model distributions of an angle between momentum vectors of two α-particles in a breakup event are shown in Fig. 2. As seen from Fig. 2, both the experimental and Monte Carlo model spectra are characterized by two peaks: the first one at $\Delta\theta < 0.5^{\circ}$ is due to a breakup of ^{8}Be nucleus in its ground state (0^{+}) with an energy release of 0.1 MeV, and the second one at $\Delta\theta \approx 1.5^{\circ}$ is caused by a decay of ^{8}Be nucleus in the main state (2^{+}) with an energy release of 3.04 MeV. As evident from Fig. 2, Monte Carlo model depicted quite satisfactorily the experimentally observed angular correlations of two α-particles in a breakup event. The mean values of an angle between momentum vectors of two α-particles coincided within the statistical uncertainties in experiment $(1.06 \pm 0.04^{\circ})$ and Monte Carlo model calculations $(1.05 \pm 0.01^{\circ})$.

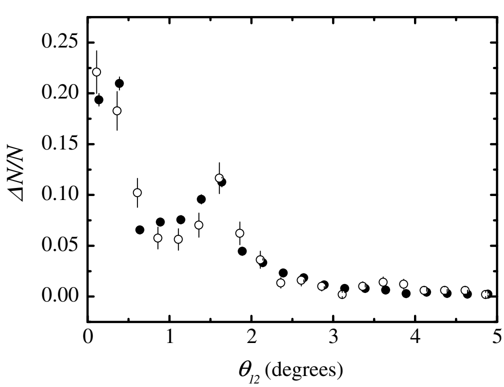

Fig. 2. The experimental ($\circ$) and Monte Carlo model ($\bullet$) distributions of an angle between momentum vectors of two α-particles in a breakup event in the laboratory system.

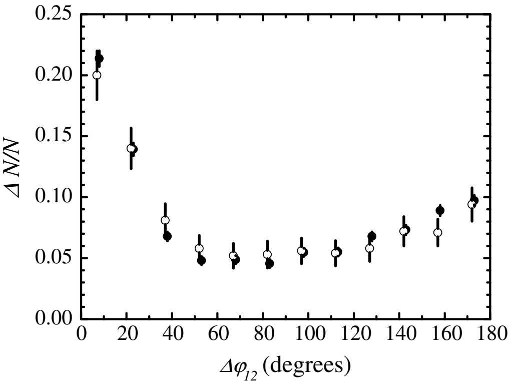

Fig. 3. Distribution of a difference between azimuthal angles of transverse momentum vectors of two α-particles in a breakup event in experiment (○) and Monte Carlo model calculations (●).

Quite good agreement was observed also between the experimental data and Monte Carlo model calculations of distribution with a difference between azimuthal angles of transverse momentum vectors of two α-particles in a breakup event (see Fig. 3). The mean values of a difference of azimuthal angles of two α-particles in an event also coincided in experiment $(74.9 \pm 2.6^\circ)$ and Monte Carlo model calculations $(75.2 \pm 1.0^\circ)$.

Quite satisfactory agreement between the experimental data and Monte Carlo model calculations for α-particles, observed in Figs. 1–3, implied that also the total momentum and transverse momentum distributions of neutrons, generated by the same model, should be realistic and reasonable. The calculated theoretical total momentum and transverse momentum distributions of neutrons, accompanying two α-particles in a breakup event, are shown in Figs. 4 and 5, respectively. It is seen from Figs. 4 and 5 that both spectra posses quite narrow single peak structures. The mean values of the calculated total momentum and transverse momentum

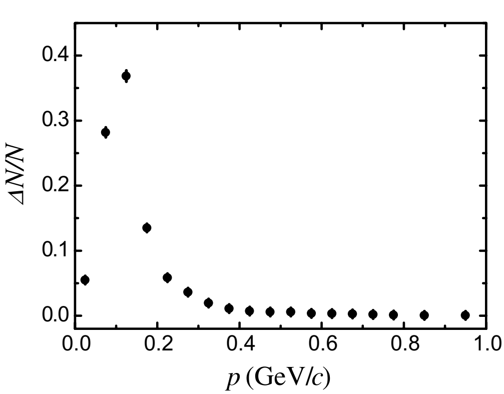

Fig. 4. Total momentum distribution of neutrons (in the ^{9}Be nucleus rest frame) calculated using Monte Carlo model.

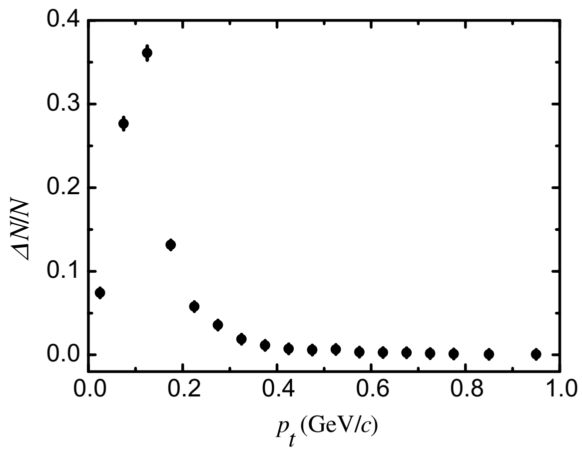

Fig. 5. Transverse momentum distribution of neutrons calculated using Monte Carlo model.

distributions of neutrons in Figs. 4 and 5 proved to be 143.2 ± 1.5 MeV and 142.8 ± 1.5 MeV, respectively.

4. Summary and Conclusions

Phenomenological Monte Carlo model of ^{9}Be nucleus interaction with emulsion at $1.2A$ GeV with formation of an excited ^{9}Be* nucleus and its breakup, either directly or through formation of an intermediate ^{8}Be nucleus, into two α-particles and a neutron was constructed. The Monte Carlo model described quite well the transverse momentum distribution of α-particles, distribution of an angle between momentum vectors of two α-particles and that of a difference between azimuthal angles of transverse momentum vectors of two α-particles in a breakup event in experiment. The total momentum and transverse momentum distributions of neutrons, accompanying two α-particles in a breakup event, in peripheral interactions with emulsion nuclei at $1.2A$ GeV, were reconstructed using the Monte Carlo model. Quite good agreement between the experimental data and Monte Carlo model calculations for α-particles implied that the obtained theoretical spectra of neutrons, generated by the same model, were realistic and reasonable. The results of comparison of Monte Carlo model calculations with the experimental data showed that the model accounted correctly for the contributions of different emulsion nuclei (given in Sec. 2) into the breakup processes of excited ^{9}Be* nuclei. It should be noted that the best agreement between Monte Carlo model calculations and experimental data was obtained using the following probabilities of ^{9}Be* breakup channels: 45% ($^9\text{Be}^* \to \alpha + \alpha + n$) and 55% ($^9\text{Be}^* \to {}^8\text{Be} + n \to \alpha + \alpha + n$), taking into account the following weighting factors for two states of ^{8}Be decaying into two α-particles: $\text{W}(^8\text{Be}(0^+)) = 0.60$ and $\text{W}(^8\text{Be}(2^+)) = 0.40$, which were in a reasonable agreement with the results of the theoretical work.[6]

References

1. V. V. Belaga *et al.*, *Phys. At. Nucl.* **58** (1995) 1905.
2. N. P. Andreeva *et al.*, *Phys. At. Nucl.* **59** (1996) 102.
3. V. V. Belaga *et al.*, "Effective masses and relative angles of pairs of α particles from coherent dissociation reaction ^{12}C$\rightarrow 3\alpha$ at a momentum of 4.5 GeV/c/nucleon", JINR Preprint P195-40, Dubna (1995).
4. N. P. Andreeva *et al.*, *Phys. At. Nucl.* **68** (2005) 455.
5. D. A. Artemenkov *et al.*, *Phys. At. Nucl.* **70** (2007) 1222.
6. Y. L. Parfenova and Ch. Leclercq-Willain, *Phys. Rev. C* **72** (2005) 054304.
7. Y. L. Parfenova and Ch. Leclercq-Willain, arXiv: nucl-th/0502032v4.
8. V. Chavchanidze, *Phys.-Usp.* **43** (1957) 106.
9. C. W. Wang *et al.*, *Phys. Rev. C* **31** (1985) 1662.
10. K. Arai, *Nucl. Phys. A* **738** (2004) 342.
11. N. Keeley *et al.*, *Phys. Rev. C* **64** (2001) 031602(R).
12. P. A. Rukoyatkin *et al.*, *Czech. J. Phys.* **56** (2006) 379.
13. D. O. Krivenkov, Investigation of coherent dissociation of relativistic ^{9}C nuclei, PhD Dissertation, LHE of JINR, Dubna (2010).
14. V. M. Chudakov and V. V. Lugovoi, *Z. Phys. C* **59** (1993) 511.