Special features of the ^{9}Be→2He fragmentation in emulsion at an energy of 1.2 A GeV

D. A. Artemenkov,* V. Bradnova, N. A. Kachalova, A. D. Kovalenko, A. I. Malakhov, P. A. Rukoyatkin, V. V. Rusakova, T. V. Shchedrina, P. I. Zarubin,† and I. G. Zarubina

Joint Insitute for Nuclear Research, Dubna, Russia

M. M. Chernyavsky and G. I. Orlova

Lebedev Institute of Physics, Russian Academy of Sciences, Moscow, Russia

M. Haiduc and E. Stan

Institute of Space Sciences, Magurele, Romania

R. Stanoeva and I. Tsakov

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

(Dated: May 22, 2006)

Abstract

The results of investigations of the relativistic ^{9}Be nucleus fragmentation in emulsion which entails the production of two He fragments of an energy of 1.2 A GeV are presented. The results of the angular measurements of the ^{9}Be→2He events are analyzed. The ^{9}Be→^{8}Be+n fragmentation channel involving the ^{8}Be decay from the ground (0^+) and the first excited (2^+) states to two α particles is observed to be predominant.

PACS numbers: 21.45.+v, 23.60+e, 25.10.+s

*Electronic address: artemenkov@lhe.jinr.ru

†Electronic address: zarubin@lhe.jinr.ru; URL: `http://becquerel.lhe.jinr.ru`

I. INTRODUCTION

The ^{9}Be nucleus is a loosely bound n+$\alpha+\alpha$ system. The energy threshold of the ^{9}Be$\rightarrow$ $n+\alpha+\alpha$ dissociation channel is 1.57 MeV. Investigations of the ^{9}Be fragmentation are of interest for astrophysics, in particular for the problems of nuclear synthesis of chemical elements with atomic number A>8.

The study of the ^{9}Be fragmentation at relativistic energies gives the possibility of observing the reaction fragments which are the decay products of unbound ^{8}Be and ^{5}He nuclei[1]. The method of nuclear emulsions used in the present paper allows one to observe the charged component of the relativistic ^{9}Be$\rightarrow$2He+n fragmentation channel. Owing to a good angular resolution of this method it is possible to separate the ^{9}Be fragmentation events which are accompanied by the production of an unstable ^{8}Be nucleus with its subsequent breakup to two α particles. In this case, the absence of a combinatorial background (of three and more α particles) for ^{9}Be which is typical of heavier Nα nuclei ^{12}C and ^{16}O makes it possible to observe distinctly this picture. The present paper is of importance for estimating the ^{8}Be role in more complicated Nα systems.

II. EXPERIMENT

Nuclear emulsions were exposed to relativistic ^{9}Be nuclei at the JINR Nuclotron. A beam of relativistic ^{9}Be nuclei was obtained in the ^{10}B$\rightarrow$^{9}Be fragmentation reaction using a polyethylene target. The ^{9}Be nuclei constituted about 80% of the beam , the remaining 20% fell on Li and He nuclei.

The exposed emulsion stack consistent of 15 layers of the BR-2 emulsion. The layer thickness and dimensions were 600 μm and 10$\times$20 cm^{2}, respectively. Events were sought by viewing the particle tracks by mean of the MBI-9 microscope. We found about 160 events of the ^{9}Be fragmentation involving the two He fragment production in the forward fragmentation cone with a polar angle of 6°(0.1 rad). The requirement of conservation of the fragment charge in the fragmentation cone was fulfilled for the detected events. We allowed 5–7 tracks of various types in a wide (larger than 6°) cone for the purpose of accumulating additional statistics. The charge of the He fragment tracks was estimated by sight, for the emulsion method makes it possible to distinguish reliably the H and He isotopes. An

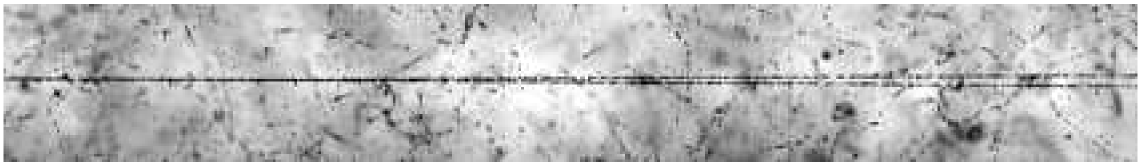

FIG. 1: An event of the type of “white”star from the fragmentation of a relativistic ^{9}Be nucleus into two He fragments in emulsion. The photograph was obtained on the PAVIKOM (FIAN) complex.

example of the ^{9}Be$\rightarrow$2He fragmentation event in emulsion is given in Fig. 1 [2]. This event belongs to the class of “white”stars as far as it contains neither target nucleus fragments, nor produced mesons.

The angles of the tracks in emulsion for the detected events were measured by the KSM-1 microscope. We measured the coordinates of ten points on the primary nucleus track and of ten points on each of the fragment tracks. The points were selected to be spaced by a step of 100 μm, the overall track length used for measurement being 1 mm. By suggesting a linear dependence between the coordinates of the track points the least square method was used to find the p_0 and p_1 coefficients of the first-degree approximating polynomial of the z(x) and y(x) coordinate dependences. The coordinates of a supposed interaction point (vertex) were suggested to be equal to zero. The angles were calculated by the found coefficients. At present angular measurements were carried out for 70 fragmentation events.

The accuracy of measurements of the He fragment emission angles was estimated on the basis of the p_{0z} coefficient distribution for $z(x)=p_{0z}+p_{1z}\cdot x$ in experiment (Fig. 2). The p_{0z} value shows a divergence between the measured and calculated z coordinates of the event vertex. In this case, the z coordinate was measured less accurately which is explained by a specific treatment of the emulsion layers as well as by measurement errors. For example, due to treatment the emulsion layer thickness decreases by about a factor of two and the error in z coordinate measurements depends on an exact focusing on the track. For the track length of 1 mm the measurement accuracy was found to be not worse than $4.5\cdot10^{-3}$ rad., which was about 34 MeV/c (see eq.1) after evaluating it in the α particle transverse momenta.

The opening angle Θ of two He fragments was measured as the angle of one of the tracks with respect to the other. This way enabled us to determine the opening angle more accurately by decreasing distortion effects in a layer. Thus in experiment a mean value

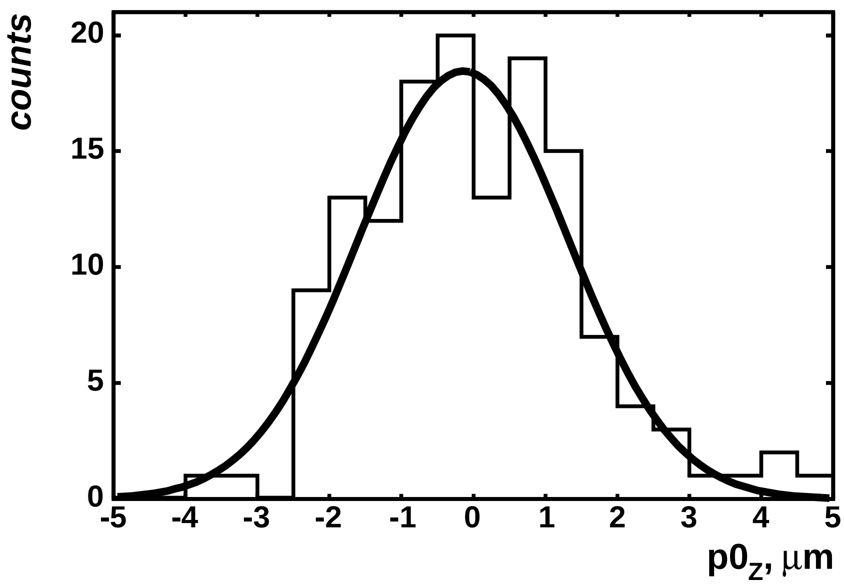

FIG. 2: The distribution of the p_{0z} coefficients for the z(x) coordinate dependence for He fragment tracks.

of the measurement error was $1.3{\cdot}10^{-3}$ rad., which was quite enough for separating events involving the ^{8}Be production. A distinctive feature of the experiment using the emulsion method consists in that the quality of measurements of small Θ angles between tracks (4–$6{\cdot}10^{-3}$ rad.) depends on the conditions of treatment and storage of layers, as well as on the positioning of an event in the layer. For example, distortions for small Θ are seen to depend on the mutual orientation of the plane of an emulsion layer and that of a track pair. The strongest distortions are observed when the planes are perpendicular to each other which affects the shape of the angular distribution for Θ(Fig. 4) by approaching it to zero.

III. RESULTS

In analyzing the data both He fragments observed in the ^{9}Be$\rightarrow$2He+n channel were supposed to be α particles. This assumption is motivated by the fact that at small angles the ^{9}Be$\rightarrow$2^{4}He+n fragmentation channel with an energy threshold of 1.57 MeV must dominate the ^{9}Be$\rightarrow$^{3}He+^{4}He+n channel whose energy threshold is 22.15 MeV. The ^{3}He fraction will not exceed a few percent in this energy range [3] and all the He fragments in the detected events may be thought of as α particles.

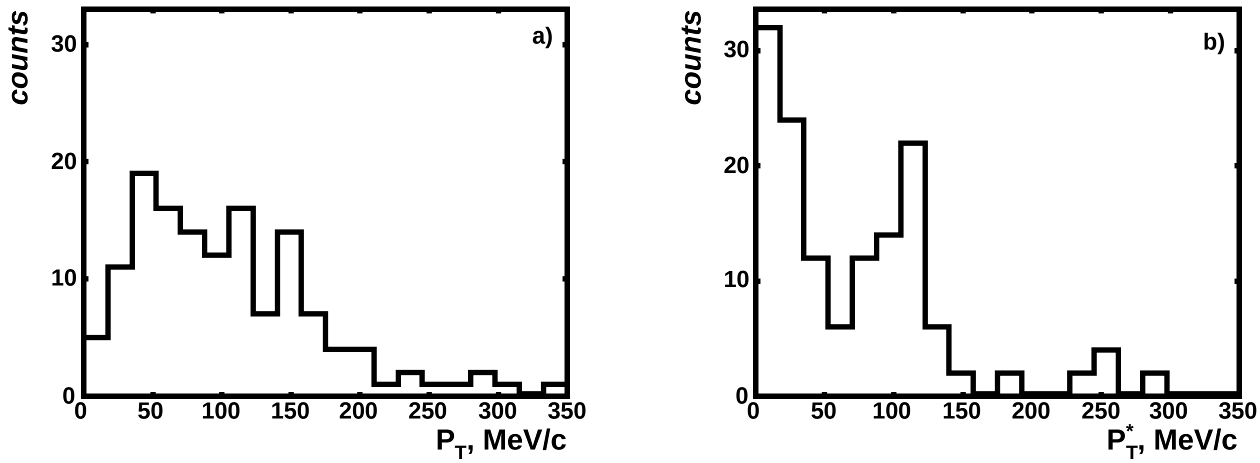

FIG. 3: The P_T transverse momentum distribution of α particles in the laboratory system (a), and the P^*_T momentum distribution in the c.m.s. of an α particle pair (b).

In Fig. 3a the P_T transverse momentum distribution of α particles in the laboratory frame of reference is calculated without the account of particle energy losses in emulsion by the equation

$$P_T = p_0 \cdot A \cdot sin\theta \tag{1}$$

where p_0, A and θ are the momentum per nucleon, the fragment mass and the polar emission angle, respectively. The mean value of the transverse momentum in the laboratory system was $< P_T >$=109 MeV/c, and the distribution FWHM was σ=66 MeV/c. This may be an indication of the fact that the experimental data are not of the same kind which can be pronounced when going over to the c.m.s. of two α particles.

The P^*_t transverse momentum distribution of α particles in the c.m.s. of two α particles described by the equation

$$\mathbf{P}^*_{Ti} \cong \mathbf{P}_{Ti} - \frac{\sum_{i=1}^{n} \mathbf{P}_{Ti}}{n_\alpha} \tag{2}$$

where P_{Ti} is the transverse momentum of an i-th α particle in the laboratory system n_α=2 is given in Fig. 3b. There is observed a grouping of events around two peaks with the values $< P^*_{Ti} >$≈25 MeV/c and $< P^*_{Ti} >$≈102 MeV/c. In [4] the appropriate mean values of the α fragment transverse momenta are $< P^*_{Ti} >$≈121 MeV/c for ^{16}O→4α, $< P^*_{Ti} >$≈141 MeV/c [5] for ^{12}C→3α and $< P^*_{Ti} >$≈200 MeV/ for ^{22}Ne→5α (processing of the available data). There by we clearly see a tendency toward an increase of the mean α particle momentum

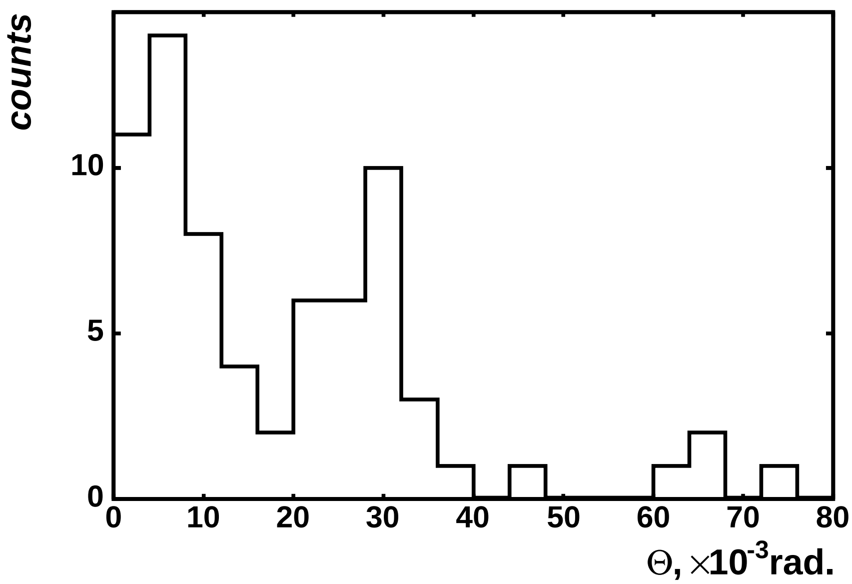

FIG. 4: The opening Θ angle distribution of α particles in the ^{9}Be→2α fragmentation reaction at 1.2 A GeV energy.

with increasing their multiplicity. This implies a growth of the total coulomb interaction of alpha clusters arising in nuclei.

A particular feature of the observed ^{9}Be→2α fragmentation is a total deflection of an α particle pair with respect to the axis associated with the primary nucleus direction. The average value of a “missing”transverse momentum P_{Tmiss} for 28 events of the type of the “white”star is $< P_{Tmiss} >$≈127 MeV/c. This effect can be explained both by the influence of a neutron which is “invisible”in emulsion and by the recoil nuclei. The ^{8}Be production channel is not the only possible one which involves the two He fragment production. In particular, in [6] one discusses the possibility of observing a channel ^{9}Be→^{5}He+α →2α+n. In the present paper, this channel is not considered as far as it is impossible to observe a neutron (the latter leaves no track in emulsion).

In the opening angle Θ distribution (Fig. 4) one can also see two peaks with mean values $4.5{\cdot}10^3$rad. and $27{\cdot}10^{-3}$rad. The ratio of the numbers of the events in the peaks is close to unity.

The $|Theta$ distribution entails the invariant energy $Q_{2\alpha}$ distribution which is calculated as a difference between the effective invariant mass $M_{2\alpha}$ of an α fragment pair and the doubled α particle mass by the equation

$$M_{2\alpha}^2 = -(\sum_{j=1}^{2} P_j)^2$$
$$Q_{2\alpha} = M_{2\alpha} - 2 \cdot m_\alpha \qquad (3)$$

where P_j is the α particle 4-momentum.

In the invariant energy $Q_{2\alpha}$ distribution there are two peaks in the ranges 0 to 1 MeV and 2 to 4 MeV. The shape of the distribution does not contradict the suggestion about the ^{9}Be fragmentation involving the production of an unstable ^{8}Be nucleus which decays in the 0^+ and 2^+ states. The values of the peaks of the invariant energy $Q_{2\alpha}$ and the transverse momenta P_T^* in the c.m.s. relate to each other. To the $Q_{2\alpha}$ range from 0 to 1 MeV with a peak at 100 keV there corresponds a peak P_T^* with $< P_{Ti}^* > \approx 25$ MeV/c , and to the $Q_{2\alpha}$ range from 2 to 4 MeV there corresponds a peak with $< P_{Ti}^* > \approx 102$ MeV/c.

Fig. 6 gives the β_T^* velocity distribution of α particles in their c.m.s. which were produced in the 1.2 A GeV ^{9}Be$\rightarrow 2\alpha$ fragmentation process as compared to the 3.7 A GeV ^{22}Ne$\rightarrow 5\alpha$ process. In both cases the velocity values are in a non-relativistic domain. The distribution for the ^{22}Ne nucleus is essentially wider, its larger average value reflects the increase in the α particle transverse momenta. Thus the study of the relativistic ^{9}Be fragmentation in emulsion will make it possible in future to employ the obtained data in the analysis of the angular distributions of more complicated systems.

IV. CONCLUSION

We summarize the results of the study of the relativistic ^{9}Be fragmentation in emulsion. 160 events of the ^{9}Be$\rightarrow$2He fragmentation were found. Angular measurements for 70 events were carried out with an accuracy not worse than $4.5 \cdot 10^{-3}$rad. The results were used to obtain the average value of the α particle transverse momenta $< P_T > \approx 109$ MeV/c in the laboratory frame of reference.

When going over to the c.m.s. of two α particles, in the P_T^* momentum distribution of ^{4}He fragments there is observed the formation of two peaks with the mean values $< P_{Ti}^* > \approx 25$ MeV/c and $< P_{Ti}^* > \approx 102$ MeV/c which is in agreement with the suggestion about the ^{9}Be fragmentation involving the ^{8}Be production.

In the $Q_{2\alpha}$ invariant energy distribution of an α particle pair there is observed a separation of virtually all the events over the two energy intervals: from 0 to 1 MeV with a peak at 100 keV and from 2 to 4 MeV. This fact suggests the dominance of the $^{9}Be \to ^{8}Be+n$ fragmentation accompanied by a ^{8}Be decay from the ground (0^{+}) and the first excited (2^{+}) states to two α particles.

The data obtained from ^{9}Be angular measurements can be employed for the estimation of the role of ^{8}Be in more complicated $N\alpha$ systems.

Acknowledgments

The work was supported by the Russian Foundation for Basic Research (Grants 96-159623, 02-02-164-12a,03-02-16134, 03-02-17079 and 04-02-16593), VEGA 1/9036/02. Grant from the Agency for Science of the Ministry for Education of the Slovak Republic and the Slovak Academy of Sciences, and Grants from the JINR Plenipotentiaries of the Republic of Bulgaria, the Slovak Republic, the Czech Republic and Romania in the years 2002-2005.

In conclusion, the authors are indebted to the JINR collaborators A.M. Sosulnikova, I.I. Sosulnikova and G.V. Stelmakh who performed visual searches for events. Our special thanks are to F.G. Lepekhin (St.Petersburg Institute of Nuclear Physics) for useful methodical recommendations concerning the treatment procedure.

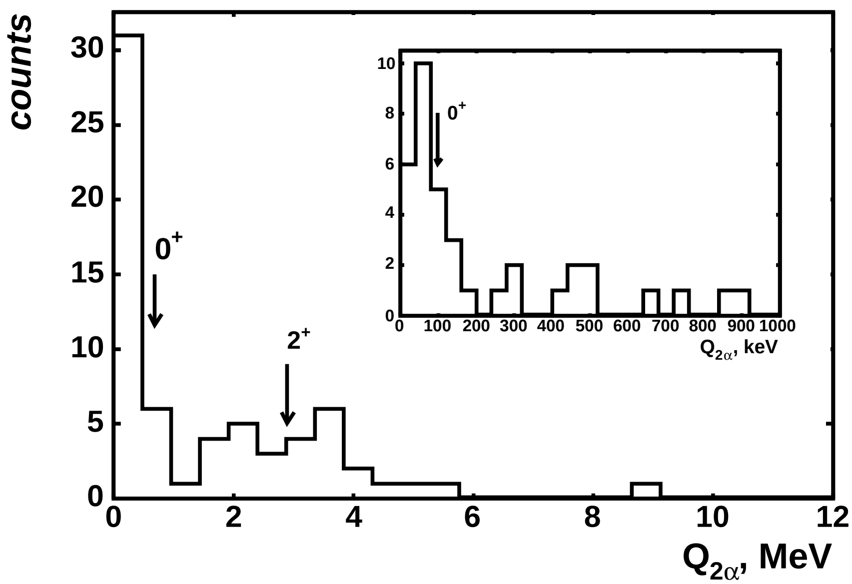

FIG. 5: The invariant energy $Q_{2\alpha}$ distribution of α particle pairs in the ^{9}Be$\rightarrow 2\alpha$ fragmentation reaction at 1.2 A GeV energy. On the intersection: the $Q_{2\alpha}$ range from 0 to 1 MeV. Arrows show the location of the ^{8}Be 0^+ and 2^+ nucleus levels.

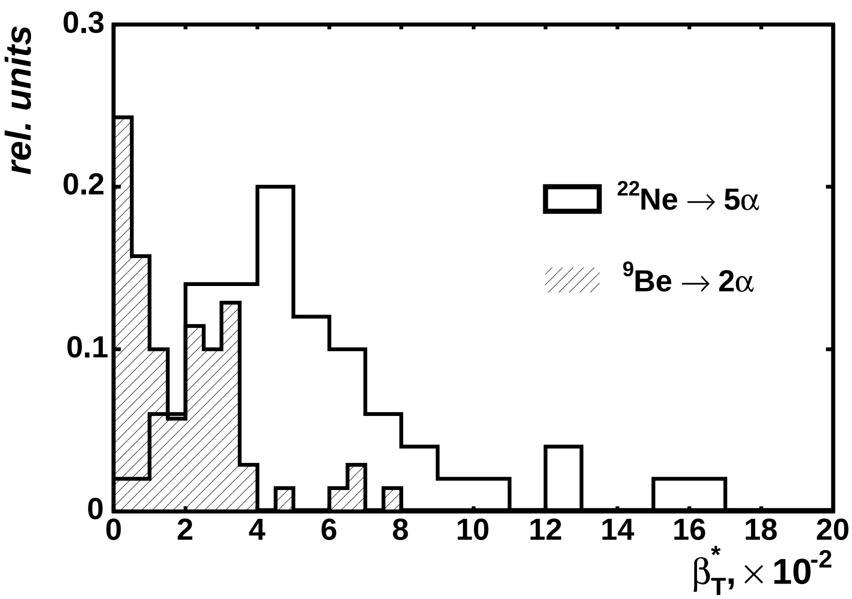

FIG. 6: The β_T velocity distribution in the c.m.s. of α particles in the fragmentation process ^{9}Be$\rightarrow 2\alpha$ at 1.2 A GeV and in the fragmentation process ^{22}Ne$\rightarrow 5\alpha$ at 3.7 A GeV.

[1] F. G. Lepekhin et al., Phys. Letters , **58**, 493-496 (1993).

[2] Web site of the BECQUEREL Project, http://becquerel.jinr.ru/

[3] V. V. Belaga et al., Phys. At. Nucl., **59**, 869-877 (1996).

[4] F. A. Avetyan et al., Phys. At. Nucl., **59**, 110-116 (1996).

[5] V. V. Belaga et al., Phys. At. Nucl., **58**, 2014-2020 (1995).

[6] B. R. Fulton et al., Phys. Rev., C **70** 047602(2004).