ISSN 1063-7788, Physics of Atomic Nuclei, 2007, Vol. 70, No. 7, pp. 1222–1225. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © D.A. Artemenkov, V.Bradnova, P.I. Zarubin, I.G. Zarubina, N.A. Kachalova, A.D. Kovalenko, A.I. Malakhov, G.I. Orlova, P.A. Rukoyatkina, V.V. Rusakova, E. Stan, R. Stanoeva, M. Haiduc, M.M. Chernyavsky, T.V. Shchedrina, 2007, published in Yadernaya Fizika, 2007, Vol. 70, No. 7, pp. 1261–1265.

ELEMENTARY PARTICLES AND FIELDS
Experiment

Features of the ^{9}Be → 2He Fragmentation in an Emulsion for an Energy of 1.2 A GeV

D. A. Artemenkov[1)*], V. Bradnova[1)], P. I. Zarubin[1)], I. G. Zarubina[1)], N. A. Kachalova[1)], A. D. Kovalenko[1)], A. I. Malakhov[1)], G. I. Orlova[2)], P. A. Rukoyatkina[1)], V. V. Rusakova[1)], E. Stan[1),3)], R. Stanoeva[1)], M. Haiduc[3)], S. P. Kharlomov[2)], I. Tsakov[4)], M. M. Chernyavsky[2)], and T. V. Shchedrina[1)]

Received April 13, 2006; in final form, August 7, 2006

Abstract—The results of investigation of the fragmentation of relativistic nuclei ^{9}Be in an emulsion, which is accompanied by the formation of two 1.2-A-GeV He fragments, are presented. The angular measurements of the $^9\text{Be} \to 2\text{He}$ events are analyzed. The $^9\text{Be} \to ^8\text{Be} + n$ fragmentation channel with the decay of ^{8}Be from the ground (0^+) and first excited (2^+) states into a pair of α particles appears to be dominant.

PACS numbers: 21.45.+v, 23.60+e, 25.10.+s
DOI: 10.1134/S1063778807070125

INTRODUCTION

The ^{9}Be nucleus is a loosely bound system ($n + \alpha + \alpha$). The energy threshold of the $^9\text{Be} \to n + \alpha + \alpha$ dissociation channel is equal to 1.57 MeV. Investigations of the fragmentation of the ^{9}Be nucleus are of interest for astrophysics including the problem of the nuclear synthesis of chemical elements with the atomic numbers $A > 8$.

Study of the fragmentation of the relativistic ^{9}Be nuclei opens the possibility of observing the reaction fragments that are the products of the decay of the ^{8}Be and ^{5}He unstable nuclei [1]. The nuclear emulsion method used in this work makes it possible to observe the charge component of the relativistic fragmentation channel $^9\text{Be} \to 2(He) + n$. Owing to a high angular resolution of the method, ^{9}Be fragmentation events accompanied by the formation of the unstable ^{8}Be nucleus with its subsequent decay into two α particles can be separated. In this case, since the combinatory background (three and more α particles), which is characteristic of heavier $N\alpha$ nuclei ^{12}C and ^{16}O, is absent for ^{9}Be, this pattern can be observed clearly. The results of this work can be used to estimate the role of ^{8}Be in more complex $N\alpha$ systems.

EXPERIMENT

The irradiation of emulsions by relativistic ^{9}Be nuclei was performed on the JINR Nuclotron. The relativistic beam of ^{9}Be nuclei was obtained in the $^{10}\text{B} \to ^9\text{Be}$ fragmentation reaction on a polyethylene target. The ^{9}Be nuclei constitute approximately 80% of the beam, whereas the Li and He nuclei constitute remaining 20%.

An emulsion roll used in exposition consisted of 15 10×20-cm BR-2 emulsion layers with a thickness of 600 μm. The events are sought by scanning the area using an MBI-9 microscope. We found approximately 200 events of the ^{9}Be fragmentation with the formation of two He fragments in the forward fragmentation cone with the polar angle up to 6°. Found events satisfy the condition of the conservation of the charge of the fragments in the fragmentation cone. For measured events, up to 5–7 tracks of various types in a wide cone (larger than 6°) are allowed in order to increase the statistical sample. The charge of He-fragment tracks is determined visually, because the emulsion method makes it possible to reliably identify the tracks of the H and He relativistic isotopes. A $^9\text{Be} \to 2\text{He}$ fragmentation event in the emulsion is exemplified in Fig. 1 [2]. This event belongs to

1) Joint Institute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia
2) Lebedev Physical Institute, Russian Academy of Sciences, Leninskii pr. 53, Moscow, 117924 Russia
3) Institute for Space Sciences, Ro-76900, Bucharest-Magurele, Romania
4) Institute for Nuclear Research, Academy of Sciences of Bulgaria, Sophia, Bulgaria
* E-mail: artemenkov@lhe.jinr.ru

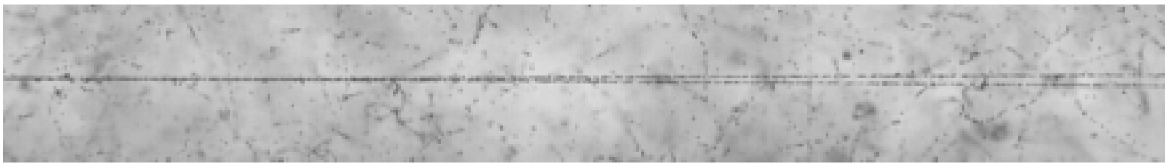

Fig. 1. Fragmentation of the relativistic ^{9}Be nucleus into two He fragments in the emulsion (white star). The photograph is obtained at the PAVIKOM measuring facility at the Lebedev Physical Institute.

the "white star" class, because it does not contain the fragments of the target nucleus and produced mesons.

Track angles in the emulsion for found events are measured using the KSM-1 microscope. The coordinates of ten points on the track of the primary nucleus and ten points on each of the fragment tracks are measured. The points are chosen with a step of 100 μm, whereas the total track length used for measurement is equal to 1 mm. Under the assumption of the linear dependence between the coordinates of the track points, the coefficients $p0$ and $p1$ of the first-order approximating polynomial for the coordinate dependences $z(x)$ and $y(x)$ are determined by the least squares method. The angles are calculated using these coefficients. To date, the angular measurements have been performed for 131 ^{9}Be → 2He fragmentation events.

The accuracy of the measurement for He fragment emission angles is estimated from the distribution of the coefficients $p0_z$ for $z(x) = p0_z + p1_z x$ in the experiment. The coordinates of the assumed interaction point (vertex) are set to zero in this case. The quantity $p0_z$ (Fig. 2) shows the discrepancy between the measured and calculated z coordinates of the event vertex. In this case, the z coordinate is measured with the lowest accuracy, which is associated with the features of the emulsion layer treatment and measurement errors. In particular, the treatment reduces the thickness of the emulsion layer by one half in average and the measurement error of the z coordinates depends on the focusing accuracy on the track. For a track length of 1 mm used in the measurements, the measurement accuracy is no worse than 4.5×10^{-3} rad. The recalculation of this value to the transverse momenta of the α particle provides approximately 34 MeV/c [see Eq. (1) below].

The pair angle Θ of the scattering of two He fragments is measured as the angle between the tracks. This method allows one to determine the pair angle with a high accuracy, which makes it possible to reduce the effect of distortions in the layer in the measurement region. Thus, the average error of measuring the pair angle Θ is equal to 1.3×10^{-3} rad, which is sufficient for identifying events with the formation

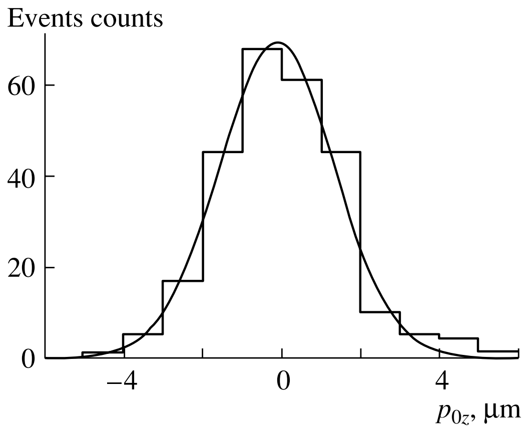

Fig. 2. Distribution of the coefficients $p0_z$ in the $z(x)$ coordinate for tracks of the He fragments.

of ^{8}Be. The feature of the experiment is that the accuracy of measuring small angles Θ between tracks ($\approx$ 4–6 $\times 10^{-3}$ rad) in the emulsion method depends on the layer treatment and storage conditions, as well as on the location of an event in a layer. For example, for small Θ angles, the dependence of distortions on the mutual orientation of the emulsion-layer plane and track-pair plane is observed. The largest distortions for the indicated angles are observed for the perpendicular arrangement of the planes, which affects the shape of the angular distribution for the pair angle Θ (see Fig. 4), tending it to zero. This circumstance is caused by distortions in measurements of z coordinates on the KSM-1 microscope, measured angle range, and deformations of the emulsion layer in the process of chemical treatment.

MEASUREMENT RESULTS

The data are analyzed under the assumption that both He fragments observed in the ^{9}Be → 2He + n channel are α particles. This assumption is justified, because the ^{9}Be → 2^4He + n fragmentation channel with an energy threshold of 1.57 MeV must prevail for small angles over the ^{9}Be → ^{3}He + ^{4}He + $2n$ channel with an energy threshold of 22.15 MeV. In this case,

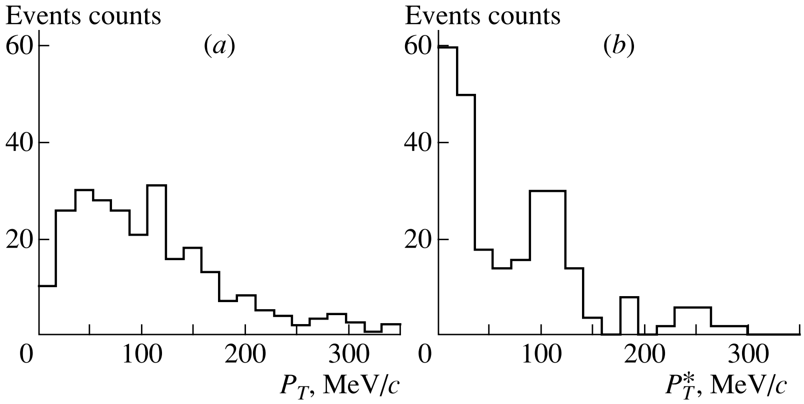

Fig. 3. Distributions (a) in the transverse momentum P_T of the α particles in the laboratory system and (b) in the transverse momentum P_T^* in the c.m.s. of a pair of α particles.

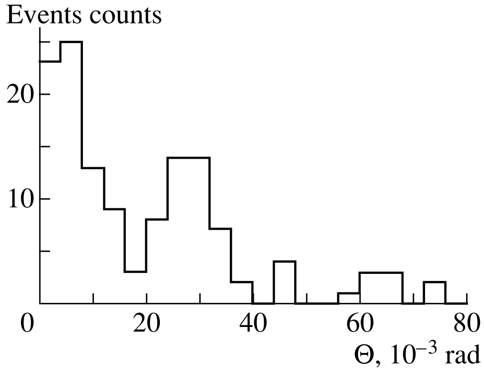

Fig. 4. Distribution in the pair angle Θ between the He fragments in the ^{9}Be $\to$ 2He fragmentation reaction for an energy of 1.2 A GeV.

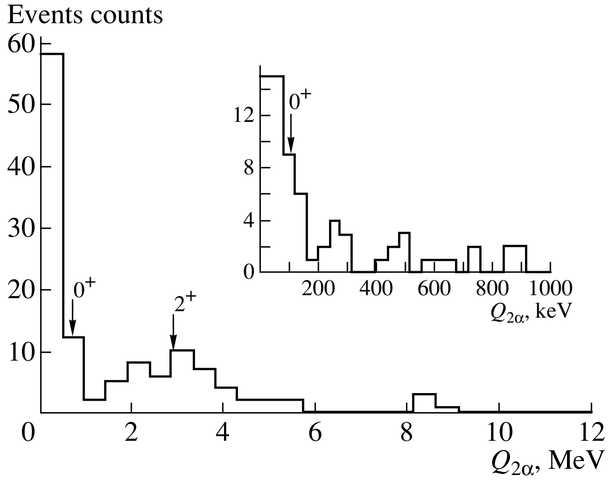

Fig. 5. Distribution in the excitation energy $Q_{2\alpha}$ of α-particle pairs in the ^{9}Be $\to 2\alpha$ fragmentation reaction for an energy of 1.2 A GeV. The inset shows the $Q_{2\alpha}$ range from 0 to 1 MeV. The arrows indicate the position of the 0^+ and 2^+ levels of the ^{8}Be nucleus.

the fraction of ^{3}He is no more than several percent in this angular interval [3] and all He fragments in the found events can be treated as α particles.

Figure 3a shows the distribution of α particles in the momentum transfer P_T in the laboratory system calculated disregarding particle energy losses in the emulsion (the contribution of these losses is relatively small) by the formula

$$P_T = p_0 A \sin\theta, \quad (1)$$

where p_0, A, and θ are the momentum per nucleon, fragment mass, and emission polar angle, respectively. The average transverse momentum in the laboratory system is equal to $\langle P_T \rangle \approx 107$ MeV/c and the distribution width is $\sigma \approx 71$ MeV/c. A relatively large σ value indicates the nonuniformity in the experimental data sample, which is manifested in the c.m.s. of two α particles.

Figure 3b shows the distribution of the α particles in the transverse momentum $\mathbf{P}_T^*$ in the c.m.s. of two α particles:

$$\mathbf{P}_{Ti}^* \cong \mathbf{P}_{Ti} - \sum_{i=1}^{n_\alpha} \mathbf{P}_{Ti}/n_\alpha, \quad (2)$$

where $\mathbf{P}_{Ti}$ is the transverse momentum of the ith α fragment in the laboratory system of a pair of α particles and $n_\alpha = 2$. The concentration events near two peaks with $\langle P_T^* \rangle \approx 24$ and 103 MeV/c is observed. In [4], the corresponding mean values of the transverse momenta of the α fragments were equal to $\langle P_T^* \rangle \approx 121$ MeV/c for ^{16}O $\to 4\alpha$, $\langle P_T^* \rangle \approx$ 141 MeV/c for ^{12}C $\to 3\alpha$[5], $and \langle P_T^* \rangle \approx 200$ MeV/c for ^{22}Ne $\to 5\alpha$ (existing data are processed). These values clearly exhibit the tendency of increasing

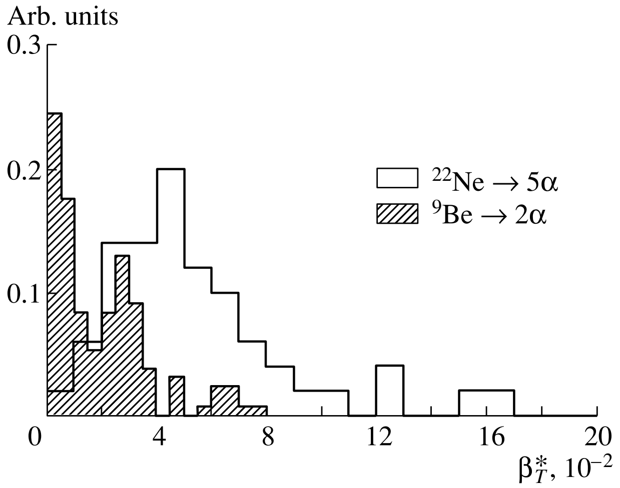

Fig. 6. Distribution in the velocities β_T^* of the scattering in the c.m.s. of the α particles in the ^{9}Be → 2α and ^{22}Ne → 5α fragmentation processes for an energy of 1.2 and 3.7 A GeV, respectively.

the average momentum of the α particles with its multiplicity and, correspondingly, the total Coulomb interaction of the α clusters appearing in the nuclei.

The feature of the observed ^{9}Be → 2α fragmentation events is the presence of the shift of a pair of α particles from the primary-nucleus direction. The mean value of the missing transverse momentum for 28 white star events is equal to $\langle P_{T\text{miss}}\rangle \approx$ 137 MeV/c. This effect can be attributed both to the effect of a neutron "invisible" in the emulsion and to the recoil-nucleus effect. The channel accompanied by the formation of two He fragments with the formation of the ^{8}Be unstable nucleus is not the only possible channel. In particular, the possibility of the observation of the $^9\text{Be} \to {}^4\text{He} + {}^5\text{He} \to 2\,{}^4\text{He} + n$ channel was discussed in [6]. In this work, this channel is not considered, because a neutron cannot be observed.

The distribution in the pair angle Θ between He fragments (Fig. 4) also exhibits two peaks with the central values 4.7×10^{-3} and 27×10^{-3} rad. The ratio of the counts in the peaks is close to one.

The distribution in the excitation energy $Q_{2\alpha}$ (Fig. 5) is a derivative of the distribution in the pair angle Θ between He fragments and is calculated as the difference between the effective invariant mass $M_{2\alpha}$ of a pair of α fragments and double mass m_α of the α particle (P_α is the 4-momentum of the α particle):

$$M_{2\alpha}^2 = -\left(\sum_{i=1}^{2} P_{\alpha_i}\right)^2, \quad Q_{2\alpha} = M_{2\alpha} - 2m_\alpha. \quad (3)$$

Two peaks are observed in the distribution in the excitation energy $Q_{2\alpha}$ in the regions 0–1 and 2–4 MeV. The form of the distribution does not contradict the assumption of the ^{9}Be fragmentation accompanied by the formation of the unstable ^{8}Be nucleus decaying in the (0^+) and (2^+) states. The peaks in the excitation energy $Q_{2\alpha}$ are related to the peaks in the c.m. transverse momenta P_T^*. The $Q_{2\alpha}$ region from 0 to 1 MeV with the peak near 100 keV corresponds to the peak in P_T^* with $\langle P_T^*\rangle \approx 24$ MeV/c, whereas the $Q_{2\alpha}$ region from 2 to 4 MeV corresponds to the peak with $\langle P_T^*\rangle \approx 103$ MeV/c.

Figure 6 shows the distribution in the c.m. velocity β_T^* of the scattering of the α particles from the ^{9}Be → 2α fragmentation for an energy of 1.2 A GeV and from the ^{22}Ne → 5α process for an energy of 3.7 A GeV. In both cases, velocities are nonrelativistic. The distribution for the ^{22}Ne nucleus is much wider and its higher mean value is associated with an increase in the transverse momenta of the α particles. Thus, the investigation of the fragmentation of relativistic nuclei ^{9}Be in an emulsion will make it possible to use the data for analyzing the angular distributions for more complex $N\alpha$ systems.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project nos. 96-1596423, 02-02-164-12a, 03-02-16134, 03-02-17079, and 04-02-16593), by the Agency of Science, Ministry of Education of the Slovak Republic and Slovak Academy of Sciences (grant no. VEGA 1/2007/05), and by the Plenipotentiaries of Bulgaria, Slovak Republic, Czech Republic, and Romania at JINR (projects in 2002–2005). We are grateful to A.M. Sosul'nikova, I.I. Sosul'nikova, and G.V. Stel'makh, who work at JINR, for identifying the events. We are deeply grateful to F.G. Lepekhin (Petersburg Nuclear Physics Institute) for valuable methodical recommendations on the processing procedure.

REFERENCES

1. F. G. Lepekhin and B. B. Simonov, Pis'ma Zh. Éksp. Teor. Fiz. **58**, 493 (1993) [JETP Lett. **58**, 493 (1993)].
2. The BECQUEREL Project, http://becquerel.jinr.ru/.
3. V. V. Belaga et al., Yad. Fiz. **59**, 869 (1996) [Phys. At. Nucl. **59**, 832 (1996)].
4. F. A. Avetyan et al., Yad. Fiz. **59**, 110 (1996)[Phys. At. Nucl. **59**, 102 (1996)].
5. V. V. Belaga et al., Yad. Fiz. **58**, 2014 (1995) [Phys. At. Nucl. **58**, 1905 (1995)].
6. B. R. Fulton et al., Phys. Rev. C **70**, 047602 (2004).

Translated by R. Tyapaev