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ELEMENTARY PARTICLES AND FIELDS
Experiment

Fragmentation Channels of Relativistic ^{7}Be Nuclei in Peripheral Interactions

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Abstract—At the JINR Nuclotron, ^{7}Li nuclei are accelerated. The charge-exchange reaction involving these nuclei at an external target provides a secondary 1.23-A-GeV ^{7}Be beam. This beam is used to irradiate emulsion chambers. The mean free path $\lambda_{\rm inel}(^7\mathrm{Be}) = 14.0 \pm 0.8$ cm for inelastic ^{7}Be interactions in an emulsion coincides within the errors with those for ^{6}Li and ^{7}Li nuclei. More than 10% of the ^{7}Be events are associated with the peripheral interactions in which the total charge of the relativistic fragments is equal to the charge of the ^{7}Be nucleus and in which charged mesons are not produced. An unusual ratio of the helium isotopes is revealed in the composition of the doubly charged fragments of the ^{7}Be nucleus: the number of the ^{3}He fragments is twice as large as that of the ^{4}He fragments. Each of 50% of peripheral interaction events includes two doubly charged fragments. The channels of the ^{7}Be fragmentation into charged fragments are presented. In 50% of events, the ^{7}Be fragmentation occurs only into charged fragments without the emission of neutrons. The $^3\mathrm{He} + {}^4\mathrm{He}$ channel dominates, whereas each of the $^4\mathrm{He} + d + p$ and $^6\mathrm{Li} + p$ channels constitutes 10%. Two events without neutron emission are observed in the $^3\mathrm{He} + t + p$ and $^3\mathrm{He} + d + d$ three-body channels. The mean free path for the coherent dissociation of relativistic ^{7}Be nuclei into $^3\mathrm{He} + {}^4\mathrm{He}$ is equal to 7 ± 1 m. The main features of the fragmentation of relativistic ^{7}Be nuclei in such peripheral interactions are explained by the $^3\mathrm{He} + {}^4\mathrm{He}$ two-cluster structure of the ^{7}Be nucleus.

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IRRADIATION OF EMULSIONS BY THE ^{7}Be NUCLEAR BEAM

In order to form a ^{7}Be nuclear beam, ^{7}Li nuclei are accelerated at the JINR Nuclotron to an energy of 2.87 Z GeV. The ^{7}Li nuclear beam extracted from the accelerator is directed onto a Plexiglas target. The ^{7}Be nuclei appearing in the target in the process of charge exchange of the ^{7}Li nuclei are focused by means of the magnetic elements and are formed in a secondary beam. The particle charges in the formed beam are determined from the particle energy losses in a scintillation monitor. According to these measurements, the admixture of particles with the charge number $Z = 3$ in the beam is equal to 7% of the number of particles with the charge number $Z = 4$.

Emulsion chambers consisting of 10×20-cm emulsion layers 550 μm in thickness are irradiated by the ^{7}Be nuclear beam [1]. The emulsion layers are arranged in parallel to the ^{7}Be nuclear beam; the long sides of the layers are placed along the beam direction so that the beam particles enter into the end of the emulsion layer. The standard BR-2 emulsion is used and singly and doubly charged relativistic particles are easily identified in it. The tracks of relativistic particles with a charge number larger than two are identified from the density of breaks in the particle traces using computer analysis of the digitized image of the microscope field of view with the automatic scanning through a trace. According to the measurements of particle charges in the emulsion, the fraction of three-charged particles in the beam is approximately 15% of the number of four-charged particles. To seek the interaction events involving ^{7}Be nuclei in the emulsion on the microscope, the traces with highest ionization density are visually selected.

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Table 1. Mean free paths of the ^{6}Li, ^{7}Li, and ^{7}Be nuclei for inelastic interactions in the emulsion

Nucleus	$\lambda_{\rm expt}$, cm	$\lambda_{\rm calc}$, cm	Nuclear energy, GeV	Reference
^{6}Li	14.1 ± 0.4	16.5–17.2	27	[2–7]
^{7}Li	14.3 ± 0.4	16.0–16.3	21	[3–5]
^{7}Be	14.0 ± 0.8	16.0–16.3	8.6	This work

MEAN FREE PATH FOR INELASTIC INTERACTIONS OF ^{7}Be NUCLEI IN THE EMULSION

The events of inelastic nucleus–nucleus interactions in emulsion layers are sought by scanning of the traces of beam particles in the emulsion with a microscope of a magnification of 900. In order to determine the mean free path λ (^{7}Be) for the inelastic interactions of ^{7}Be nuclei in the emulsion, we use a set of 294 inelastic interaction events detected in a length of 41.222 m in one emulsion chamber. Table 1 shows the result obtained for the ^{7}Be nucleus, as well as the mean free paths for the inelastic interactions of the ^{6}Li and ^{7}Li nuclei in the emulsion obtained in [2–7]. The values measured for all these nuclei coincide with each other within the errors. Table 1 also presents the values calculated in the geometrical model with the parameter sets used in [2–7] to describe the mean free paths for inelastic interactions of nuclei in the emulsion with a uniform density. The experimental mean free paths are smaller than the calculated values for all these nuclei, because the peripheral inelastic interactions of nuclei with a loosely bound cluster structure make an additional contribution.

ISOTOPIC COMPOSITION OF THE FRAGMENTS AND THE CHANNELS OF ^{7}Be FRAGMENTATION IN PERIPHERAL INTERACTIONS IN THE EMULSION

Among 1400 detected events of inelastic nucleus–nucleus interactions, there are more than 200 peripheral-interaction events in which the total charge Q of relativistic particles emitted into a cone of 15° is equal to the charge of the ^{7}Be primary nucleus. Charged mesons are not observed in approximately 150 peripheral-interaction events. The structural features of the nucleus in such events most strongly affect the character of the nuclear fragmentation (primarily the charge and mass compositions of the fragments). Table 2 presents the charge topology of such events. The numbers of events without target fragments ($n_b = 0$) and events containing one or several target fragments ($n_b > 0$) are shown separately.

Table 2. Charge composition of the fragments in the events with $Q = 4$

Relativistic fragments	Target fragments	Event number
^{2}He	$n_b = 0$	41
	$n_b > 0$	18
He + ^{2}H	$n_b = 0$	42
	$n_b > 0$	33
^{4}H	$n_b = 0$	2
	$n_b = 1$	1
Li + H	$n_b = 0$	9
	$n_b > 1$	3
Total		149

Each half of the events contains two doubly charged fragments and each of the remaining events contains one helium and two singly charged fragments. The relativistic Li nucleus accompanied by a singly charged fragment appears in 10% of events. A large fraction of events of the dissociation of ^{7}Be nuclei into two helium fragments indicates a high probability of such clustering in the structure of the ^{7}Be nucleus.

The isotopic composition of the fragments is analyzed by measuring the multiple Coulomb scattering of particles in the emulsion. We determine the particle velocity $p\beta c$, where p is the momentum. The momenta of singly and doubly charged particles are measured in 240 events of the interaction of ^{7}Be nuclei with the emulsion nuclei. The experimental distribution of doubly charged relativistic particles in $p\beta c$ is satisfactorily described by two Gaussians with the maxima for $p\beta c = 4.5$ and 6.3 GeV. The relative content of the ^{3}He- and ^{4}He fragments, which is estimated from the areas under the approximating curves, is equal to 70 и 30%, respectively. In the interactions of all other relativistic nuclei previously studied in emulsions, the content of ^{4}He is higher than the content of ^{3}He fragments. Such an unusual relation between the contents of helium isotopes that is observed in interactions of ^{7}Be nuclei is explained by the two-cluster structure of the ^{7}Be nucleus, where the nucleons that do not enter into the α-particle core of the nucleus form a ^{3}He cluster. The $p\beta c$ distribution of singly charged relativistic particles in the interval up to $p\beta c = 5$ GeV is satisfactorily described by two Gaussians with the maxima for $p\beta c = 1.5$ and 3.2 GeV. The ratio of the proton number to the deuteron number is estimated as 3:1. The number of particles with momenta above 5 GeV/c is equal

Table 3. Fragmentation channels of ^{7}Be nuclei

Fragmentation channel	2He		He + 2H		4H		Li + H		Total event number
	$n_b = 0$	$n_b > 0$	$n_b = 0$	$n_b > 0$	$n_b = 0$	$n_b > 0$	$nb = 0$	$n_b > 0$	
^{4}He + ^{3}He	30	11							41
^{3}He + ^{3}He	11	7							18
^{4}He + $2p$			13	9					22
^{4}He + $d + p$			10	5					15
^{3}He + $2p$			9	9					18
^{3}He + $d + p$			8	10					18
^{3}He + $2d$			1						1
^{3}He + $t + p$			1						1
$3p + d$					2				2
$2d + 2p$						1			1
^{6}Li + p							9	3	12
Total event number	41	18	42	33	2	1	9	3	149

to about 2% of the total number of singly charged fragments. From the results of the measurements, the masses of the fragments are determined in each event and ^{7}Be fragmentation channels are identified.

Table 3 presents the number of the events detected in various ^{7}Be fragmentation channels. The reaction in approximately 50% of events proceeds without the emission of neutral particles. The ^{4}He+^{3}He channel noticeably dominates among them and each of the ^{4}He + $d + p$ and ^{6}Li + p reactions constitutes 10%. Two events without neutron emission are detected in the ^{3}He + $t + p$ and ^{3}He + $d + d$ three-body channels. Among the events free of other secondary charged particles, there is no event of the reaction of the charge exchange of ^{7}Be nuclei into ^{7}Li nuclei.

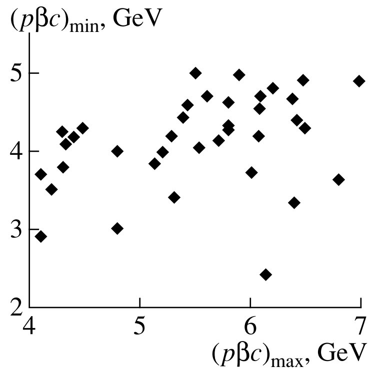

Fig. 1. Distribution of 2He events in the plane of the fragment momenta. The points are the coordinates of the measured $p\beta c$ values of the fragments. The abscissa and ordinate are the larger and smaller $p\beta c$ values in an event, respectively.

Events containing only two helium fragments are shown in Fig. 1 as points whose coordinates are the measured $p\beta c$ values of the fragments. The larger and smaller $(p\beta c)_{\max}$ values in an event are taken as the abscissa and ordinate of a point, respectively. Almost all events lie below 5 GeV in the ordinate axis. This value is taken as a lower boundary of $p\beta c$ for the ^{4}He nucleus. In Fig. 1, the ^{3}He+^{3}He events lie on the left side of the $(p\beta c)_{\max} = 5$ GeV boundary, whereas the ^{4}He+^{3}He events lie on the right side of the boundary. The fraction of the ^{4}He+^{3}He channel with respect to all events of ^{7}Be dissociation is equal to about 30%, which can be considered as estimate of a lower probability of such configuration in the ^{7}Be nucleus. The mean free path for the coherent dissociation of the relativistic ^{7}Be nuclei into ^{4}He+^{3}He in the emulsion is equal to 7 ± 1 m. The mean free paths for the coherent dissociation of the ^{6}Li, ^{7}Li, and ^{7}Be nuclei into two-body channels without neutrons are close to this value. The probability of the ^{6}Li state in the form of the α-particle core and quasifree deuteron cluster, which is directly estimated by probing of a ^{6}Li target with 1-GeV π^- mesons in the experiment reported in [8], is no more than 0.75. Figure 2 shows the distribution of the ^{4}He+^{3}He events in the quantity $E = 1.59\text{MeV} + E_t$, where E_t is the transverse kinetic energy of the fragments and 1.59 MeV is the threshold energy of the channel. The E values in more than 80% of events do not exceed

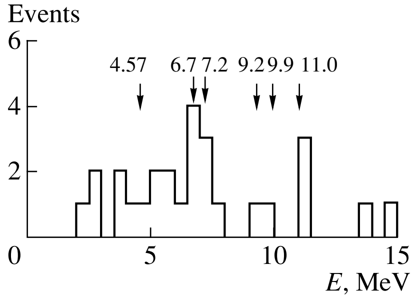

Fig. 2. Distribution of the ^{4}He + ^{3}He events in E. The numbers near the arrows are the excitation energies in the ^{7}Be nucleus in MeV.

10 MeV. The excitation energies of the ^{7}Be nucleus, which are indicated by the arrows in the figure, are also in this energy region. The splitting of individual levels in the experimental distribution is not observed. The energy of the system of the fragments can also be characterized by the transverse momenta of the fragments in the coordinate system of the nucleus undergoing fragmentation. The difference between the mean momenta of the fragments for mirror nuclei can be considered as the manifestation of the effect of the Coulomb interactions between the charged clusters in nuclei and in the process of the fragmentation of these nuclei. The mean value of the transverse momenta of the fragments in the ^{4}He+^{3}He channel in the c.m.s. is equal to 147 ± 5 MeV/c. The fact that this value is much higher than the mean value 108 ± 2 MeV/c of the transverse momenta of the fragments in the $^7\mathrm{Li} \to ^4$ He+^{3}H fragmentation channel can be considered as the effect of the Coulomb interaction of the clusters in these nuclei. Figure 3 shows the distribution of the ^{4}He+^{3}He events in the angle ψ between the ^{4}He and ^{3}He fragments in the azimuthal plane. Large angles between the fragments prevail in the distribution. This distribution is significantly determined by the momenta transferred to the fragmenting nuclei. The ψ angles close to 180° correlate with low momenta transferred to the ^{7}Be nucleus. A relatively large number of events with the ψ angles near 180°, where the momenta transferred to the nucleus are low, can be associated with the Coulomb dissociation of ^{7}Be nuclei on heavy emulsion nuclei.

CONCLUSIONS

The basic characteristics of the fragmentation of relativistic ^{7}Be nuclei are determined by the two-helium cluster configuration of the ^{7}Be nucleus. The excess of the mean value 147 ± 5 MeV/c of the transverse momenta of the fragments in the ^{7}Be coherent fragmentation into ^{4}He+^{3}He over a value of 108 ± 2 MeV/c for the ^{7}Li dissociation into ^{4}He+^{3}H is

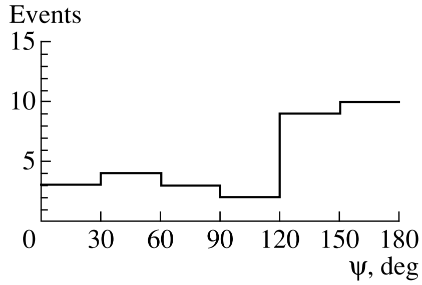

Fig. 3. Distribution of the ^{4}He + ^{3}He events in the angle ψ between the ^{4}He and ^{3}He fragments in the azimuthal plane.

possibly attributed to the Coulomb interaction between the fragments in these processes. A relatively large number of events with ψ angles near 180° and with low momenta transferred to the nucleus can be associated with the contribution of the Coulomb dissociation of ^{7}Be nuclei on heavy emulsion nuclei.

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