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Dissociation of relativistic ^{7}Li in photoemulsion and structure of ^{7}Li nucleus

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Abstract
The dissociation of relativistic ^{7}Li nuclei was studied with the photoemulsion technique. The nuclear photoemulsions have been exposed in the beam of ^{7}Li at the momentum of 3 A GeV/c at the JINR synchrophasotron in Dubna. Along the scanned length 239.76 m of ^{7}Li tracks, 1675 inelastic interactions have been found. For the first time the coherent dissociation of the relativistic ^{7}Li nuclei into the (α + t) channel in the nuclear photoemulsion has been detected. The mean free path of this channel in emulsion is equal to 5.4 m and corresponds to the cross section which is equal to 23 ± 5 mb. Previously in the dissociation of the relativistic ^{6}Li nuclei it was found that the main di-cluster configuration of the ground state of ^{6}Li manifests itself as the main channel of coherent dissociation into α-particle and deuteron. The close values of relative yields and kinematic features of these two-particle dissociation channels of ^{7}Li and ^{6}Li suggest that a similar di-cluster configuration consisting of α-particle core and bound together outer nucleons predominates in the dissociating nuclei at relativistic energies also. The data presented prove the validity of the relativistic nuclei dissociation as an effective complementary method for the study of nuclear structure.

1. Introduction

The programme of investigation of multi-particle production and fragmentation in inelastic interactions of stable nuclei, accelerated to 4.5 GeV/c per projectile nucleon at the JINR synchrophasotron in Dubna, was carried out for the nucleus mass range from ^{4}He to ^{32}S. In the experiments detecting nucleus–nucleus interactions in bubble chambers and nuclear emulsions the characteristics of such processes depending on projectile mass and degree of overlap with target nuclei were studied. The obtained experimental data on charge and isotope

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composition of fragments and the data on their momentum distribution are used for the study of internal features of the interacting nuclei. The experiments at relativistic energies are complementary to the classic investigation of the disintegration of nuclei used as targets at low energies. The relativistic velocity of the projectile fragments and high spatial resolution of nuclear photoemulsions allow us to study the reactions near threshold. The observation of the interaction events in 4π-geometry and the registration of all charged secondary particles allow us to identify the reactions and to study the correlations of reaction products. At relativistic energy the high probability of α-particle clustering leads to dissociation of ^{12}C nuclei into three α-particles [1, 2] and ^{16}O nuclei into four α-particles [3]. The obvious manifestation of the influence of internal nucleus structure was observed in inelastic interactions of relativistic ^{6}Li nuclei in photoemulsion. The loosely bound α- and d-clusters configuration of the ^{6}Li nucleus enhances the deuteron fragment production in inelastic interactions [4–7] and manifests itself as the main channel of relativistic nuclei dissociation into α-particle and deuteron in the extreme peripheral interactions [7]. This result is in accordance with the classical investigations of disintegration of the ^{6}Li nucleus at low energy. The structure of ^{6}Li and ^{7}Li nuclei at low energies both in the theoretical treatments and in the many experiments shows a pronounced two-cluster configuration. In these nuclei an easily formed α-cluster core leaves the other nucleons, less tightly connected with the core, free to form the other charged cluster with relatively high probability. Thus it may be natural to expect that a definite similarity in dissociation features of both ^{6}Li and ^{7}Li should be observed. However, the work [8] devoted to the analysis of the meson production in inelastic interactions of relativistic Li isotopes in nuclear photoemulsion found (α + d) clustering in ^{6}Li, but no (α + t) clustering structure in ^{7}Li, suggesting rather (α + p + 2n) configuration. This paper is devoted to the study of the most peripheral interactions of relativistic ^{7}Li nuclei in nuclear photoemulsion with the hope of clarifying the situation with the different behaviour of these nuclei. As was shown, the full identification of the composition of the projectile fragments may represent an efficient method for clearing up the question about the clusterization probabilities in these nuclei.

2. Experimental technique

The beam of relativistic ^{7}Li nuclei with momentum 3 GeV/c per nucleon provided by the JINR synchrophasotron was used to irradiate the emulsion stack. The emulsion stack was composed of layers of nuclear photoemulsion of BR-2 type. The emulsion layers were 550 μm thick and of dimensions 10 $\times$ 20 cm^2. The stack was exposed in the beam parallel to the emulsion plane, so that the particles traversed the layers along its longer side. The detection of nucleus–nucleus interactions by the scanning of beam particle tracks with microscopes at the magnification $\times$900 was fulfilled. In total 1675 inelastic interactions over the length of 239.76 m of scanned tracks were recorded. Thus the mean free path $\lambda_{7\mathrm{Li}} = 14.3 \pm 0.4$ cm. These results are in agreement with the results of the work [6] and within the errors are not different from the mean free path of nuclei ^{6}Li equal to 14.1 $\pm$ 0.4 cm. These experimental values for the mean free paths of lithium nuclei in photoemulsion are less than the values of 16.5 cm and 15.9 cm, evaluated according to the overlapping geometry model [9, 10]. This result, in turn, indicates that the total cross sections of interactions of lithium nuclei and the effective radii of interactions exceed the calculated values.

From the sample of found inelastic interactions we selected the extreme peripheral interactions. Those events in which the sum of the charges of relativistic fragments is equal to the charge of the initial projectile nucleus and there are no other secondary charged particles, were accepted as the peripheral interactions.

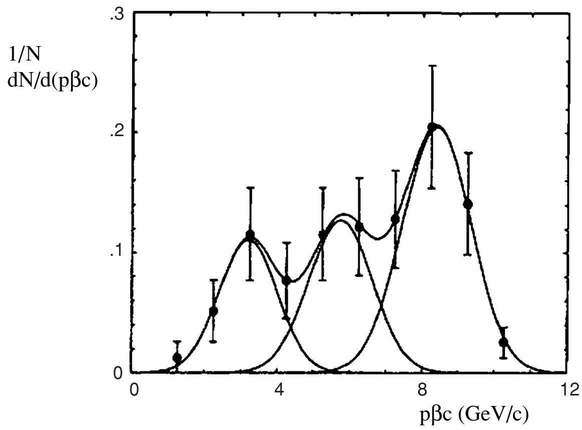

Figure 1. Distribution of H fragments versus ($p\beta c$).

The charged fragments were searched for in the 6° forward fragmentation cone. In this cone the transverse momenta of proton fragments may be up to 0.3 GeV/c. The photoemulsion used is sensitive to minimum ionization relativistic particles so that the singly and doubly charged relativistic particles in emulsion are easily distinguished visually according to the ionization density on their tracks. There were found 114 events fulfilling the presented criteria. Among them 103 events are two-particle events with one He fragment and one singly charged particle and in 11 cases ^{7}Li nuclei disintegrated into three singly charged particles. For the determination of masses of relativistic fragments the multiple Coulomb scattering of particles was measured. The mean deviation $|D|$ of a track over a cell of length t is related to the quantity $p\beta c$ by the equation $\langle|D|\rangle = K\, Z_f\, t^{3/2}/(p\beta c)$, where K is the empirical scattering constant for the nuclear photoemulsion, Z_f, p, βc are the fragment charge, momentum and velocity, respectively. The distribution of $|D|$ for the particles with identical charges and momenta must be close to a normal distribution [11]. The distribution versus variable $x = 1/(p\beta c)$ for the mixture of nucleus fragments with identical charges is a superposition of Gaussian distributions for different isotopes. The triton fragment is the heaviest of the singly charged isotopes and therefore the value of multiple scattering of tritons is smaller than that of protons and deuterons. The mean value of $\langle|D|\rangle$ of the tritons on lengths 2 mm is equal to 0.5 μm and that on lengths 3 mm is equal to 0.9 μm. Therefore, identification of the tritons in a spectrum of singly charged relativistic fragments by multiple scattering measurements is quite demanding from the point of view of both the emulsion quality needed and the requests to the accuracy of measurements. The statistical errors of the measurements are about 15%. For the identification of fragments also the distribution versus variable $p\beta c$ is quite representative and useful. The fragments with the mass A_f have momenta equal $A_f p_0$, where p_0 is the momentum of a nucleon of beam nucleus. Thus the fragments with different masses A_f in this distribution versus variable $p\beta c$ will be concentrated near the corresponding values of $A_f p_0$, as is seen in figure 1. This plot presents the quality of the measurements most obviously.

3. Results

The distribution of singly charged particles versus the variable $p\beta c$ is presented in figure 1. A smooth curve, representing the sum of three Gaussian functions, is fitted to experimental

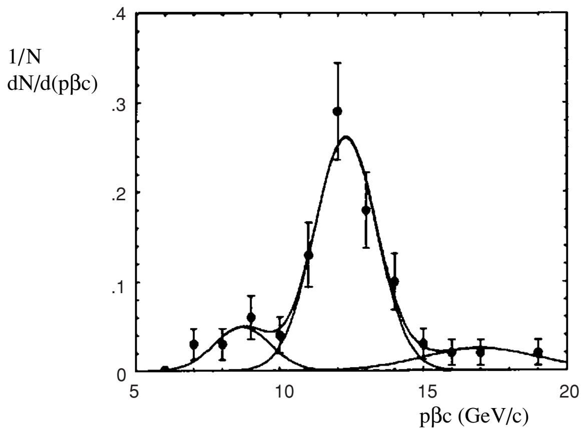

Figure 2. Distribution of He fragments versus ($p\beta c$).

points with maxima at 3.2, 5.8 and 8.4 GeV/c. These values are very close to the momenta of one-, two- and three-nucleon fragments of the 3 A GeV/c projectile nuclei. Each of the approximating functions for protons, deuterons and tritons are presented in the figure also. Dispersions of these functions are 0.8 GeV/c for protons, 0.9 GeV/c for deuterons and 0.95 GeV/c for tritons. The degrees of overlap of curves allow us to define the momentum and mass of particle reliably enough and to distinguish tritons in particular. The joint analysis of this distribution and the distribution versus variable $x = 1/(p\beta c)$ (not presented here) permitted us to define the threshold value for the tritons separation at 7.2 GeV/c. The isotope separation cuts were defined from the requirement of equality of the areas under Gaussian tails. The mean value obtained from two mentioned plots was used. About half of all singly charged particles have momenta exceeding the cut value. The admixture of deuterons in the sample of particles with higher momentum is less than 10%, and there are no protons. In all the previously investigated nucleus–nucleus interactions with other projectiles the fraction of triton fragments was essentially lower than the fractions of protons and deuterons and did not exceed 10% with respect to all singly charged fragments. For the proton–deuteron the separation cut was set at $p\beta c = 4.3$ GeV/c. The lower cut for the protons was set at $p\beta c = 1$ GeV/c.

The same analysis of multiple Coulomb scattering measurement of doubly charged fragments was done to estimate the masses of doubly charged fragments. In figure 2 the momentum distribution of doubly charged particles is presented. The three Gaussian functions satisfactorily describe the experimental data. The main contribution is provided by α-particles, described with a Gaussian function having a maximum at $p\beta c = 12.2$ GeV/c. The momentum threshold for the separation of helium isotopes ^{3}He and ^{4}He, defined on the basis of this distribution and the distribution of particles versus variable $x = 1/(p\beta c)$, is equal to 9.7 GeV/c. The contribution of ^{3}He nuclei to the sample of doubly charged fragments was found to be about 15%, and their admixture in the ^{4}He sample does not exceed 2% with this cut.

The dissociation channels of ^{7}Li projectiles were sorted out using the obtained mass values for decay products. In two two-prong events the momentum of one of the particles was not measured and the identification of the decay channel for these two events was not done. In the majority of ^{7}Li dissociations the α-particle is observed. In 14 events He fragments were defined as ^{3}He nuclei. Another five events, in which the helium particle has momentum close to the

Table 1. Disintegration channels of ^{7}Li with $Q = 3$.

Channel formula	Number of events
^{3}He + X	14
^{4}He + X	82
^{6}He + p	5
Three singly charged particles	11
Total	112

Table 2. Dissociation channels of the lithium nuclei, containing α-particle.

Channel formula	^{4}He + p	^{4}He + d	^{4}He + t	Total
^{7}Li, number of events	14	24	44	82
^{6}Li, number of events	24	23		47

Table 3. Mean values of transverse momentum $\langle p_t \rangle$ (GeV/c) of fragments in two-particle dissociation of the lithium nuclei.

Nucleus	^{2}H	^{3}H	^{4}He
^{6}Li	0.13 ± 0.02		0.15 ± 0.01
^{7}Li		0.12 ± 0.01	0.10 ± 0.01

momentum of the ^{6}He nucleus (>15.5 GeV/c) and the accompanying singly charged particle has momentum close to proton fragment momentum, may be identified as the dissociation of ^{7}Li nuclei into ^{6}He and proton. The dissociation rate into the symmetric channel $^7\mathrm{Li} \to {}^6\mathrm{Li} + \mathrm{n}$, which cannot be detected with our technique, should likely be not much different. No events of charge exchange process $^7\mathrm{Li} \to {}^7\mathrm{Be}$ or events with two He fragments were observed.

In table 1 the composition for ^{7}Li dissociation channels in which the sum of the charges of relativistic fragments Q is equal to the charge of the initial nucleus is presented. Among the 11 three-particle decays into singly charged fragments, one event (tdd) and two events (ttp) were identified as decaying only into charged particles without neutron emission.

In table 2 the numbers of events for ^{7}Li dissociation into channels containing α-particle and singly charged particle are given. The tritons amounted to about half of the observed singly charged particles, deuterons to 30% and protons to 20%. Thus, among the events observed in the experiment the main fraction belongs to the coherent dissociation of ^{7}Li projectile into α-particle and triton. In the table the number of dissociations of ^{6}Li projectile into α-particle and deuteron obtained in the work [6] is also quoted. The data presented show that in the extreme peripheral interactions, both Li isotopes predominately undergo coherent dissociation into two charged particles without neutron emission.

Compare the transverse momenta of the fragments in these coherent dissociations of ^{7}Li and ^{6}Li nuclei. In table 3 the mean transverse momentum values of the fragments in dissociation of ^{7}Li projectile into α-particle and triton are listed. The transverse momentum value $p_t(A)$ of the particle with mass number A is defined by the expression $p_t(A) = p_o A \sin(\theta)$, where $p_o = 3$ GeV/c is the nucleon momentum of the projectile nucleus and θ is the particle emission angle relative to the initial direction of projectile. In the same table the values for dissociation of ^{6}Li projectile into α-particle and deuteron are also quoted. The values obtained for ^{7}Li are close to that for decay products of ^{6}Li. At the same time, the mean value of transverse momentum of triton fragments created in inelastic interactions of ^{4}He nuclei in emulsion [12] is (0.18 ± 0.02) GeV/*c* and close to that (0.22 ± 0.02) GeV/*c* in ^{12}C projectile interactions [13]. The fact that the transverse momenta of tritons in ^{7}Li projectile dissociation are less than for other quoted nuclei points to some specific mechanism of production of relativistic tritons in the dissociation of ^{7}Li and again may be explained by the available triton cluster in the structure of ^{7}Li. The larger cross sections of coherent dissociation of Li isotopes and relatively small transverse momenta of the fragments in these processes point to the low thresholds of the dissociation channels and suggest that Coulomb excitation of the nuclei can be the main excitation mechanism.

4. Conclusions

The measured free path of ^{7}Li projectile nuclei for inelastic interaction in nuclear photoemulsion is equal within errors to that of ^{6}Li projectiles. The obtained value for ^{7}Li, as for the value for ^{6}Li, is less than the values calculated in the framework of the overlapping geometry model, using the parameters describing data for other compact nuclei from ^{4}He to ^{32}S, in which α-cluster structure is pronounced. About 7% of all inelastic interactions are extreme peripheral interactions, the majority of which leads to resulting two-particle configuration, representing dissociations of ^{7}Li into one singly charged and one doubly charged particle. For the first time the coherent dissociation of the relativistic ^{7}Li nuclei into the (α + t) channel in the nuclear photoemulsion has been detected. The mean free path for this specific channel in emulsion is equal to 5.4 m and corresponds to the cross section of 23 ± 5 mb. The mean value of transverse momenta of tritons from ^{7}Li decays is appreciably less than that for transverse momenta of tritons created in the fragmentation of nuclei without triton cluster. The close values of relative yields and kinematic features of these two-particle dissociation channels of ^{7}Li and ^{6}Li suggest that the similar di-cluster configuration consisting of α-particle core and bound together outer nucleons predominates in the dissociation nuclei also at the relativistic energies. The larger cross sections of coherent dissociation of Li isotopes and relatively small transverse momenta of the fragments in these processes point out to the low thresholds of the dissociation channels and suggest that the Coulomb excitation of relativistic Li nuclei in nucleus–nucleus collisions can be the main cause of the observed phenomena. The data presented prove the validity of the relativistic nuclei dissociation investigation as an effective complementary method for the study of nuclear structure.

Acknowledgments

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