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ELEMENTARY PARTICLES AND FIELDS
Experiment

Investigation of Clustering in Light Nuclei by Means of Relativistic-Multifragmentation Processes

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Abstract—New results concerning the topology of the fragmentation of relativistic nuclei ^{7}Li and ^{10}B are presented. A program is proposed for studying the cluster structure of stable and radioactive nuclei. The use of emulsions in the investigation of nuclear clustering in the fragmentation of light nuclei at energies are in excess of 1 GeV per nucleon is discussed. © *2004 MAIK "Nauka/Interperiodica"*.

Advances in experiments with relativistic nuclear beams gives impetus to developing new approaches in solving some nuclear-structure problems of great importance. In this connection, we would like to indicate investigation of collective degrees of freedom in excited nuclei, where individual groups of nucleons behave as constituent clusters. Such clustering in excited nuclei is especially pronounced in light nuclei, where the possible number of cluster configurations is relatively small. Few-nucleon systems having no intrinsic excitations are natural components of such a pattern. First of all, these are alpha particles, as well as deuterons, tritons, and ^{3}He nuclei, but paired states of protons and neutrons can also play this role. Perhaps, investigation of the fragmentation of stable and radioactive nuclei into clusters at relativistic energies would reveal some new special features of the origin of clusters and their role in nucleosynthesis processes.

The use of nuclear beams of energy above 1 GeV per nucleon in solving the problem being discussed is based on the known effect of limiting nuclear fragmentation. In the present case, this implies that the isotopic composition of projectile fragments is independent of the target-nucleus type. This gives sufficient grounds to employ, for a target and a detector of relativistic-fragmentation products, a nuclear emulsion, which is a material of rather complicated composition. The absence of an energy threshold for detecting a fragmentation process is one of the advantages of the emulsion method. Emulsions ensure the detection of multiparticle relativistic-fragmentation processes, which enables one to reveal the most probable charge channels of such processes. Measurement of multiple-scattering angles makes it possible to determine the total momentum of the relativistic fragments of hydrogen and helium, whereby one can estimate their mass. Owing to a record angular resolution, the emulsion technique permits reconstructing the invariant mass (that is, the excitation energy) of the fragmenting system.

Interactions of relativistic nuclei that lead to minimal mutual excitations of colliding nuclei and which do not involve charged-meson production are the most advantageous in studying the cluster structure of nuclei. In this case, projectile- and target-fragmentation products can be clearly separated in momentum. The requirement that the electric charge and the mass number of the projectile nucleus be

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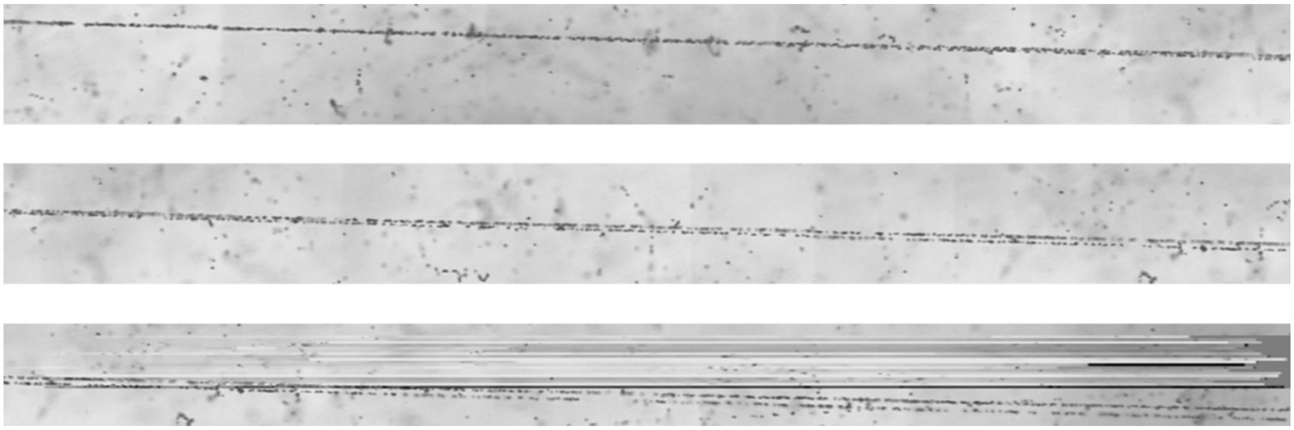

Event of the coherent dissociation of a ^{10}B nucleus to triply charged (top) and doubly charged (bottom) fragments on three consecutive sections of the tracks. A three-dimensional image of the event was reconstructed as a plane projection by means of an automated microscope (Lebedev Institute of Physics, Moscow) of the PAVIKOM complex.

conserved within a narrow angular cone of fragmentation is the main criterion for selecting such events. The application of this criterion leads to a sharp decrease in the mean multiplicity of target-fragmentation products.

These considerations formed a basis for our experimental program (BECQUEREL project [1]) aimed at systematically studying the channels of fragmentation of stable and radioactive nuclei in beams from the nuclotron at the Joint Institute of Nuclear Research (JINR, Dubna) by employing the emulsion technique. The investigation of the cluster fragmentation of ^{6}Li (α–d) [2–5], ^{12}C (3α) [6–9], and ^{16}O (4α) [10] nuclei by means of the emulsion technique served as a guideline for our project. Below, we discuss the results obtained by studying the cluster structure of the ^{10}B and ^{7}Li nuclei. These results provide a basis for the development of investigations into the clustering in light neutron-deficit nuclei and heavier stable nuclei.

Clustering in the ^{10}B nucleus. Nuclei of ^{10}B were accelerated at the JINR nuclotron, and their beam of energy 1 GeV per nucleon was formed. This beam was used to irradiate stacks of layers of BR-2 emulsion, the layer thickness and dimensions being, respectively, 550 μm and 10×20 cm^2. The emulsions used were sensitive even to singly charged relativistic particles. The exposed emulsion layers were parallel to the beam axis. Nucleus–nucleus interaction was sought by viewing the particle tracks by means of microscopes with a magnification of 900. Over the viewed-track length of 138.1 m, we found 960 events of inelastic interactions of ^{10}B nuclei. The mean range of ^{10}B nuclei to an inelastic interaction in the nuclear emulsion was 14.4 ± 0.5 cm. This value agrees well with the dependence of the mean range on the projectile atomic number for light nuclei having a uniform nucleon density.

We obtained information about the charge composition of charged fragments and about the channels of ^{10}B fragmentation in peripheral interactions. Those events were associated with peripheral interactions in which the total charge of relativistic fragments was equal to the charge of the primary nucleus ^{10}B and in which charged mesons were not produced, but slow fragments of emulsion nuclei could be formed. In order to separate these events, we estimated the charge of relativistic particles (mainly singly and doubly charged ones) emitted at angles smaller than 15° with respect to the momentum of ^{10}B nuclei. For a primary-beam energy of 1 GeV per nucleon, this value of the emission angle corresponds to the proton transverse momentum of 0.44 GeV/c. The mass of singly charged fragments was estimated by the method of multiple-scattering measurement.

The number of detected events in which the total charge of fragments is equal to five and in which charged mesons are not observed is 93 (10% of the total number of events); of these, 41 feature no fragments originating from target-nucleus breakup. An analysis revealed that the presence (absence) of the target fragmentation has virtually no effect on the distribution in the projectile-fragment charge.

In 65% of peripheral interactions, a ^{10}B nucleus decays to two doubly charged particles and one singly charged particle, with the latter being a deuteron in 40% of these events. In 10% of events, triply and doubly charged fragments (isotopes of Li and He) appear simultaneously. The production of a ^{6}Li nucleus accompanied by an alpha particle can be treated as an already established correlation of the alpha-particle and deuteron clusters. In 2% of events, there are fragments of charge equal to four and unity (^{9}Be and proton, respectively). The photograph shows an example of a two-body decay to a lithium and a helium fragment. The fraction of the fragmentation channel involving one doubly charged fragment and three singly charged fragments (products originating from the breakup of one of the alpha-particle clusters) is 15%.

A channel-fraction ratio of $(2\mathrm{He}+d)/(2\mathrm{He}+p)\approx 1$ is indicative of an analogy with ^{6}Li fragmentation, where $(\mathrm{He}+d)/(\mathrm{He}+p)\approx 1$, and of an abundant yield of deuterons in the ^{10}B case as well [2, 3]. A low value of the mean transverse momentum of deuterons ($\langle P_t^d\rangle = 0.14\pm 0.01$ GeV/c) in these events, in just the same way as in the case of ^{6}Li fragmentation, where $\langle P_t^d\rangle = 0.13\pm 0.02$ GeV/c, is yet another indication of deuteron clustering.

It should be noted that, along with the deuteron and the ^{6}Li and ^{14}N nuclei, the ^{10}B nucleus belongs to the rare class of odd–odd stable nuclei. Therefore, it would be of interest to reveal signals from deuteron clustering in the fragmentation of relativistic ^{14}N nuclei.

Clustering in the ^{7}Li nucleus. In the nuclear photoemulsion exposed to a beam of ^{7}Li nuclei accelerated to a momentum of 3 GeV/c per nucleon at the JINR Synchrophasotron, 1274 events of inelastic interaction were found over a viewed-track length of 185 m. The mean range of ^{7}Li nuclei to an inelastic interaction in the emulsion was 14.5 ± 0.4 cm, which agrees within the errors with the mean range of ^{6}Li [2, 3]. Close values of the mean range and of the total cross sections for the inelastic interactions of ^{6}Li and ^{7}Li nuclei suggest close effective interaction ranges.

Peripheral interactions (92 events), which involve only charged fragments of the relativistic nucleus and no other charged secondaries and in which the total charge of the fragments is equal to the charge of the fragmenting nucleus, constitute about 7% of all the inelastic interactions of ^{7}Li nuclei. Of these, 80 events are the two-body decays of a ^{7}Li nucleus to one doubly and one singly charged fragment. The reconstruction of the mass of relativistic fragments revealed that half of these events are due to ^{7}Li decay to an alpha particle and a triton (40 events). The fraction of decays to an alpha particle, a deuteron, and a neutron is equal to 30%, while the fraction of decays to an alpha particle, a proton, and two neutrons constitutes 20%. The isotopic composition of decay fragments implies that these events are associated with the structure in the form of alpha-particle and triton clusters. A greater fraction of tritons in the isotopic composition of singly charged fragments suggests the dominance of the triton cluster in the fragmentation of a ^{7}Li nucleus in extremely peripheral interactions with emulsion nuclei.

Earlier, similar two-body decays of ^{6}Li nuclei to an alpha particle and a deuteron, which reflect a loosely bound two-cluster structure of the nucleus, were detected in inelastic peripheral interactions of ^{6}Li nuclei of momentum 4.5 GeV/c per nucleon in photoemulsions. Therefore, the structure formed by an alpha-particle core and superficial nucleons bound into a cluster is typical not only of the ^{6}Li but also of the ^{7}Li nucleus. The value obtained for the cross section describing the coherent decay of a ^{7}Li nucleus to an alpha particle and a triton (27 ± 4 mb) appeared to be nearly identical to that given in [2] for the decay of a ^{6}Li nucleus to an alpha particle and a deuteron (22 ± 4 mb). This can be treated as an indication of the fact that the mechanisms of the decays under consideration are of the same nature.

It is of interest to pursue further the investigation of the possible role of tritons as cluster elements in dissociation of the ^{11}B, ^{15}N and ^{19}F nuclei.

Clustering that involves a ^{4}He nucleus. Within the present study, we have launched anew the investigation of emulsions exposed to beams of ^{22}Ne, ^{24}Mg, ^{28}Si, and ^{32}S nuclei accelerated to a momentum of 4.5 GeV/c per nucleon. It is planned to seek and explore the fragmentation of these nuclei by observing final states that involve a few alpha particles. Searches for states that can be interpreted as nuclear molecules are of particular interest. Our approach will enable us to decide whether this resonance is a configuration formed by a few bound alpha particles or we have a resonance arising only in nuclear scattering. We can expect that the applicability range of the pattern where alpha-particle clustering in a nuclear core is combined with peripheral clustering in the form of deuterons, tritons, ^{3}He, and nucleon pairs would become still wider. A further investigation of relativistic multiparticle fragmentation will provide an experimental basis for cluster models of light nuclei.

Clustering that involves a ^{3}He nucleus. The ^{3}He nucleus is a natural element of the cluster pattern of excitations of light neutron-deficit nuclei like ^{6}Be, ^{7}Be, ^{8}B, ^{9}C, ^{10}C, ^{11}C, and ^{12}N, as well as heavier ones. Going over from alpha particles to ^{3}He nuclei, one can obtain similar cluster states of the ^{8}Be, ^{9}Be, ^{10}B, ^{12}C, and ^{14}N nuclei. Within this approach, the ^{6}Be nucleus is a loosely bound ^{3}He–^{3}He resonance whose properties are similar to those of the α–α system in the ^{8}Be nucleus.

By analogy with the ^{9}Be nucleus, ^{7}Be can have the n–^{6}Be and ^{3}He–n–^{3}He excitations in addition to the α–^{3}He state. In the case of the ^{8}B nucleus, the ^{3}He–d–^{3}He cluster excitation is possible in addition to the p–^{7}Be and p–α–^{3}He states. It is of interest to reveal the ^{3}He–^{3}He–^{3}He state in the ^{9}C nucleus as an analog of the α–α–α state in ^{12}C and to compare the intensity of its excitation with that of the p–^{8}B and p–p–α–^{3}He states.

We would like to indicate some other interesting states like pp–α–α and α–^{3}He–^{3}He in the ^{10}C nucleus, α–α–^{3}He in ^{11}C, and α–^{8}B in ^{12}N. The existence of such molecular quantum states formed by nuclei may imply that there are alternative scenarios of the nucleosynthesis of light nuclei via the formation of intermediate radioactive nuclei in the burning of complex isotopic mixtures of hydrogen and helium nuclei owing to fusion reactions, including the simultaneous fusion of a few particles belonging to an intermediate bound state.

As a first step along these lines, we exposed emulsions at the JINR nuclotron to a secondary beam containing a considerable fraction of ^{7}Be nuclei. The beam was formed by tuning the magneto-optical channel to optimally choosing the products of the charge-exchange reaction involving accelerated ^{7}Li and ^{7}Be nuclei. The cross section for this reaction is about 10^{-4} of the inelastic cross section. The results of this exposure are presently being analyzed.

We hope that the charge-exchange reactions $^{10}\mathrm{B} \to {}^{10}\mathrm{C}$, $^{11}\mathrm{B} \to {}^{11}\mathrm{C}$, and $^{12}\mathrm{C} \to {}^{12}\mathrm{N}$ will make it possible to form secondary beams. We propose to form a ^{8}B beam via the fragmentation reaction $^{10}\mathrm{B} \to {}^{8}\mathrm{B}$. In the case of the observation of two events of boron-nucleus scattering accompanied by a high-momentum recoil of target fragments, the probability of obtaining a ^{8}B beam at the available nuclotron energy can be estimated at about 10^{-3} of the inelastic cross section. This method of the beam formation requires a careful verification by means of spectrometric measurements. An exposure involving ^{9}C nuclei presents the most serious problem because, in this case, accompanying ^{3}He nuclei, which have the same magnetic rigidity, generate an irremovable background.

We believe that the use of emulsions in experiments where they are exposed to beams of relativistic radioactive nuclei is the most reasonable in the case of light neutron-deficit isotopes. Owing to the possibility of completely observing the results of the interaction, the most significant channels of decay of excited nuclei can be determined by analyzing the charge in the final state. For these channels, one can study the mass and angular spectra, reveal correlations, and estimate characteristic excitation energies.

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