FORMATION OF Li^8 *FRAGMENTS IN THE INTERACTION OF 9 BeV PROTONS WITH LEAD NUCLEI*

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The production probability, energy spectrum, and angular distribution of Li^8 fragments produced in disintegration of lead nuclei by 9 BeV protons are obtained. The experimental data are compared with the predictions of the evaporation theory. The best agreement is obtained with the following parameters: temperature T = 14.9 MeV, barrier V = 9.6 MeV.

1. INTRODUCTION

RECENTLY numerous experimental data have been obtained on the process of the formation of Li^8 fragments from the action of fast particles on the heavy nuclei Ag and Br in nuclear emulsions. [1-8] Analysis of these results has been made, as a rule, by comparing them with the predictions of evaporation theory. It has been assumed that the fragments are evaporated isotropically from an excited nucleus moving in the direction of the incident particle with some mean velocity in the laboratory system. It turned out that this rather simple scheme of fragment production can describe in principle the experimentally observed angular and energy distributions. However, a difficulty arises in interpretation of the parameters, temperature T and Coulomb-barrier height V, for which agreement is obtained between theory and experiment. Very high values of T are obtained, of the order of or even greater than 10 MeV, which according to the formulas of evaporation theory correspond to an excitation energy exceeding the total binding energy of the nucleus. The values obtained for the barrier V are too low, which also requires explanation.

In view of these aspects of the study of fragment formation in Ag and Br nuclei, it becomes necessary to investigate this phenomenon in other target-nuclei. For this purpose it is convenient to use the sandwich method (an emulsion chamber with metal foils). Possessing all of the merits of the usual nuclear emulsion method, it has the advantage of permitting observation of the disintegration of a single type of nucleus, and not a whole set, as in an emulsion. The purpose of the present work was to study by the sandwich method the characteristics of Li^8 fragment formation from lead nuclei.

2. EXPERIMENTAL METHOD

A chamber consisting of layers of type NIKFI-K emulsion with metal foils located between them was irradiated by 9 BeV protons in the internal beam of the JINR synchrotron. The incident beam was parallel to the plane of the emulsion. The dimensions of the layers were $10 \times 10 \times 0.04$ cm. The foil thickness was 18 μ. The proton flux in the emulsion was 8×10^6 cm^{-2}. The NIKFI-K emulsion allowed recording photons up to ~100 MeV.

Stars containing Li^8 fragments were detected by area scanning from the side of the emulsion in contact with the foil. Disintegrations were recorded which contained at least three tracks in this one layer. In these stars all tracks were further scanned for hammer tracks to their end or to their exit into the next layer. The scanning was done at a magnification of 630×. With the aid of a reference grid on the emulsion surface we were able to compare stars in the upper and lower emulsion layers originating from a single disintegration occurring in a foil. In scanning 44.80 cm^2 of emulsion we found 179 cases of disintegration with Li^8 fragments, among which were six with two Li^8 fragments.

In 153 of these disintegrations we observed stars with a number of black prongs $N_h \geq 3$ on both sides of the foil, and in twenty-six cases we observed stars on only one side of the foil. In addition we recorded nine cases of the emission of solitary Li^8 fragments from a foil into the emulsion. Since in these cases it is impossible to determine the point of their formation in the foil, they were not used for further analysis.

All necessary measurements were made in a KSM-1 microscope. By setting the assumed pro-

Method of fragment loss	Probability of fragment loss q, %	Ratio of the number of fragments which should have been found to the observed number I/(I − q)
Absorption by the foil of fragments which could not escape from it for any value of azimuth angle (theoretically unobserved events)	3.8	1.04 ±0.01
Absorption by the foil of fragments which could escape for some values of azimuth angle (theoretically observed events)	10.9	1.29 ± 0.10
Exit of fragments from the emulsion layer	1.6	1.29 ±0.10
Loss of fragments connected with the magnitude of the projection of the path in the foil and in the air gap on the plane of the emulsion	10.2	1.29 ±0.10
Loss connected with unfavorable location of the Li^8 tracks and an α-particle decay	18.0	1.22 ±0.14
Total loss	39	1.04×1.29×1.22 =1.64 ±0.17

jection of the center of the disintegration on the emulsion plane in the center of the microscope field of view and by rotating the cross hairs, it is possible to select among the background tracks only those associated with a given star. Fragment energies in emulsion and lead were determined from the range-energy tables of Barkas,[9] corrected to the density of NIKFI-K emulsion.

Ordinarily in the sandwich method corrections are made to the energy and angular distributions by taking into account the experimental geometry with the assumption of isotropic emission of the particles.[10-12] In our experiment this assumption is not justified. Therefore we developed a method of introducing geometrical corrections with the sole assumption of isotropic emission of particles in a plane perpendicular to the incident beam. For each fragment found we computed the probability of its observation p_i. This value permitted determination of the corrections to the observed energy and angular distributions. The data on the corrections introduced are assembled in the table. The total correction to the 185 cases found amounted to 64%.

3. EXPERIMENTAL RESULTS

1. Emission probability of Li^8 fragments. In our experiment it was impossible to determine the complete distribution of stars in number of tracks, since stars with $N_h < 6$ were not recorded, and it is impossible to evaluate the scanning loss of stars with a small number of tracks. However, the scanning carried out provides the possibility of determining the emission probability of Li^8 as a function of the number of charged particles recorded in the disintegration. In addition to Li^8, tracks of Li^9 and B^8 can be encountered among the hammer tracks. In the case of Li^9, we can be confident that its admixture does not exceed 1% (see Gajewski et al.[2]). Discrimination of Li^8 and B^8 tracks was done visually. It was found that there should not be more than one B^8 fragment in the analyzed set. Taking into account all of the corrections described above, the probability of emission of Li^8 in disintegrations with $N_h \geq 7$ turned out to be 4.95 ± 0.68%.

Figure 1 shows the variation of the probability of formation of Li^8 fragments with the number of tracks in the disintegration. It is evident that the distribution resembles the similar distribution for the emulsion nuclei Ag and Br. However, since our emulsion does not record very fast particles, there is no possibility of a quantitative comparison of our results with the data obtained for Ag and Br. We have made a comparison only with preliminary data on the emission of Li^8 fragments in disintegrations recorded in a similar emulsion

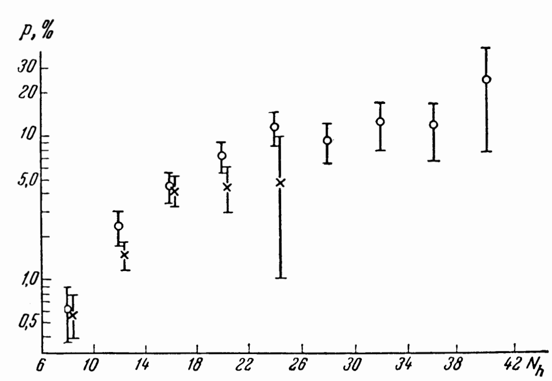

FIG. 1. Variation of Li^8 fragment emission probability with number of tracks N_h in the disintegration: o — Pb, E = 9 Bev; × — Ag, Br, E = 3 BeV.

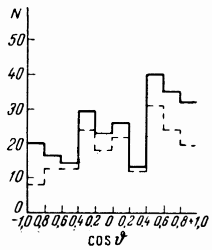

FIG. 2

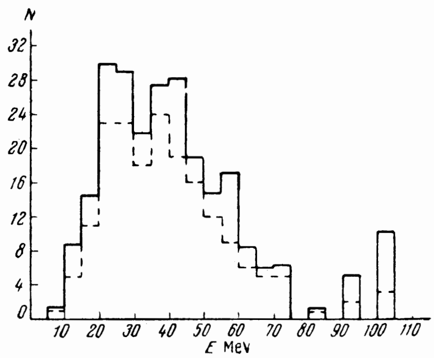

FIG. 3

FIG. 2. Angular distribution of Li^8 fragments in the laboratory system; ϑ is the angle between the fragment and the incident beam. The dashed line is the observed distribution; the solid line is the corrected distribution.

FIG. 3. Energy spectrum of Li^8 fragments in the laboratory system. The dashed line is the observed distribution; the solid line is the corrected distribution.

and produced by 3 BeV protons. No noticeable difference was observed. However, this result requires verification with better statistics.

2. Angular and energy distributions. Figure 2 shows the angular distribution of Li^8 fragments. The anisotropy of this distribution (the front-to-back ratio $F/B = 1.39 \pm 0.21$) is indistinguishable from the anisotropy obtained for the same incident proton energy in interactions with Ag and Br nuclei.

Figure 3 shows the energy spectrum of Li^8 fragments.

4. DISCUSSION OF RESULTS

We have attempted to explain our experimental results with the aid of evaporation theory. For easy visualization of the angular and energy correlations, all events have been plotted in a special coordinate system (Fig. 4; see also Gajewski et al.[13]).

Following Skjeggestad and Sörensen[1] we have assumed that the observed anisotropy of the angular distribution is the result of motion of the excited nuclei with some mean velocity in the direction of the incident proton beam. Therefore it was necessary to find a moving coordinate system in which the angular distribution of the fragments would be as nearly isotropic as possible. For this purpose we considered fragments with $E > 20$ MeV. As a criterion of goodness of fit we used the Kolmogorov test. By this minimization we obtained a system velocity for best isotropy of $v = 0.014c$. In this system the angular distribution of fragments with energies $E > 20$ MeV is isotropic within one standard deviation. The angular distribution of fragments with energies less than 20 MeV in this system turns out to be anisotropic (see Fig. 4). As has been previously shown[8,13] this is the result of the existence of an energy

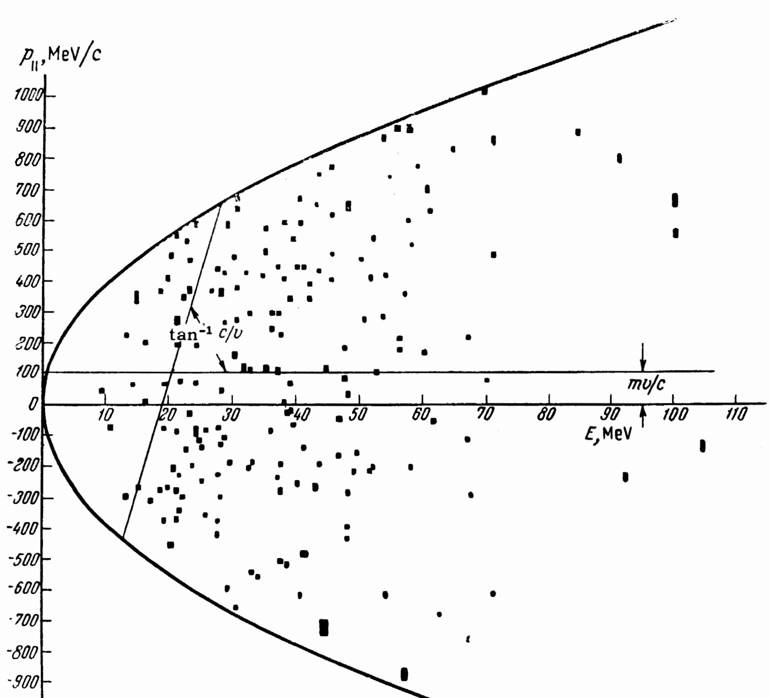

FIG. 4. Distribution of correlations between energy E and longitudinal momentum $p_{\parallel} = \sqrt{2mE} \times \cos\vartheta$ of the fragments in the laboratory system. The line parallel to the axis of abscissas determines the velocity v of the system of best isotropy (see text); the line of slope c/v separates the low energy fragments whose angular distribution in the system of best isotropy is anisotropic.

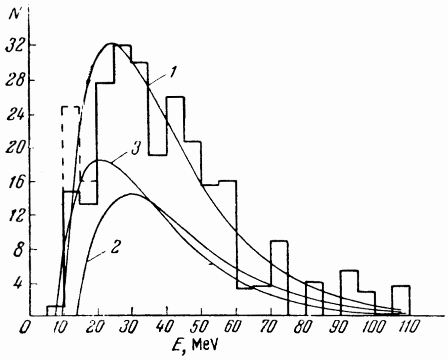

FIG. 5. Energy spectrum of the fragments in the system of best isotropy. The histogram represents the experimental data for all fragments. The dashed line is the correction for loss of low energy fragments (see text). The solid curves are calculated as follows: 1 – for all fragments, 2 – for fragments from few-pronged stars, 3 – for fragments from many-pronged stars, with the following parameters:

Curve:	1	2	3
Nh:	22.5	15.2	29.3
v/c:	0.014	0.007	0.020
T, MeV:	14.9	15.3	13.9
V, MeV:	9.6	13.6	7.6

threshold for the recording of fragments. In order to remove this anisotropy, it is necessary to introduce an additional correction to the number of fragments with low energies, so that their angular distribution will be isotropic. However, it must be noted that, unlike all of the corrections discussed previously which are of a purely geometrical nature, this correction turns out to depend on the model of fragment production assumed. In particular it turns out to depend on the velocity of the coordinate system in which the fragment angular distribution is isotropic.

Figure 5 shows the energy spectrum of fragments in the system found to have the best isotropy. The spectrum obtained has been compared with the spectrum shape predicted by evaporation theory:

$$P(E)\,dE = \frac{E-V}{T^2}\exp\left\{-\frac{E-V}{T}\right\}dE.$$

Values of the parameters temperature T and barrier V were obtained from the mean energy and the dispersion of the spectrum. They turned out to be T = 14.9 MeV and V = 9.6 MeV. The curve calculated with these parameters agrees with the experimental histogram within one standard deviation.

The values of T and V confirm the situation noted in the introduction, which was established in the study of disintegrations of Ag and Br nuclei. The temperature T turned out to be even higher than the value obtained for emulsion nuclei, and the barrier height V is considerably less than the nominal Coulomb barrier.

In order to explain such a large spectrum width, we attempted to obtain it by superposition of spectra with a lower temperature. The basis of this approach is the fact that after the cascade stage there arises a set of different nuclei with different excitation energies. The latter can be roughly estimated from the number of black prongs in the disintegration; on the average they turn out to be of the order of 800 MeV in disintegrations with Li^8 (in ordinary disintegrations they are ~ 400 MeV). In these evaluations we used the mean proton and α-particle energies obtained in these same disintegrations. The excitation energies determined in this way from the formula $U = AT^2/10$ give temperatures distributed over the range 3–9 MeV. The mean temperature is ~ 7 MeV. Superposition of spectra with these values of T and various values of the barrier V does not lead to a noticeable broadening of the combined spectrum. Hence it follows that the value T = 14.9 MeV obtained from the Li^8 spectra cannot be the result of superposition of spectra with lower values of T.

We looked for a difference in the energy spectra for disintegrations with a different number of black prongs N_h. For this purpose all the disintegrations were broken down into two groups: few-pronged, with $\bar{N}_h = 15.2$; and many-pronged, with $\bar{N}_h = 29.3$. For each of these groups we found the energy spectrum in the same way as the combined spectrum (Fig. 5). The mean energies in the spectra turned out to be 44.2 ± 2.4 MeV for the few-pronged stars and 35.4 ± 2.0 MeV for the many-pronged stars; from these spectra we obtained the parameters T and V. No difference in temperature was found for these two spectra. However, we observed a tendency for reduction of the barrier V in going from the few-pronged to the many-pronged stars.

5. CONCLUSIONS

An attempt to explain the energy and angular distributions of Li^8 fragments with the aid of evaporation theory leads to the following two alternative conclusions:

1) the evaporation theory describing the process of fragment formation in the decay of highly excited nuclei is valid but requires refinement (initially we should consider the dependence of nuclear temperature and Coulomb barrier height on the excitation energy); or

2) evaporation theory is not applicable to de-

scription of the production process for the majority of Li^8 fragments.

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