Yields of ^8Be Fragmenta in the ^{10}B Fragmentation in Photoemulsion at an Energy of 1 GeV per Nucleon

Abstract. It is shown that the channel fraction $^{10}B \rightarrow ^8 Be \rightarrow 2\alpha$ is estimated to be 18 ± 3 percent and the distribution constants for the angles of alpha particles and the angles between them equal to 20.5 ± 0.7 and 31.7 ± 2.0 mrd , respectively, are in agreement with these quantities calculated prior to experiment on the basis of the limiting fragmentation of relativistic nucleus. In these calculations, the only parameter taken from earlier experiments is the quantity $r_0 = 1.54$ fermi determining the ^{10}B radius.

The major goal of the present experiment was to determine the probability of formation of the ^8Be nucleus in the ground state in the process of fragmentation of relativistic ^{10}B nuclei. The ^8Be nucleus is well identified by its decay into two alpha particles. If in the case of the ^{10}B fragmentation with an energy of 1 A GeV the momentum per nucleon P_0 of the ^8Be fragment is equal to that of the ^{10}B nucleus, then the angle between the two alpha particles produced due to ^8Be decay from the 0^+ state is expected to be, with a large probability, about 5.5 mrd. This fact makes it possible to separate the events containing two double-charged fragments due to ^8Be decay from the same events with the same fragments emitted from $^{10}B \rightarrow 2\alpha + all$ independently of each other. Estimation of the ^8Be fragment formation probability is of interest in connection with both the study of the cluster structure of light nuclei and the role played by this nucleus in nucleosynthesis.

The second implication of this paper is to demonstrate, taking the ^8Be formation in the relativistic ^{10}B fragmentation as an example, the level of understanding of the relativistic nucleus fragmentation mechanism. This makes it possible to calculate, prior to experiment, not only the characteristic features of inclusive angular and momentum distributions of any secondary fragments, but also the probabilities of observation of any fragmentation channels without the recourse to any free parameters. As is shown below, for the ^{10}B nucleus at an energy of 1 A GeV these calculations practically coincide with experiment. If one succeeds in obtaining such an agreement for other light nuclei and at other primary relativistic nucleus energies, then the substantial part of experimental research of the relativistic nuclear fragmentation will be reduced to search for deviations of experimental data from these calculations. The level of our understanding of the nuclear fragmentation mechanism will become still higher.

In the present experiment, a photoemulsion chamber consisting of 500 mkm thick 10×20 cm^2 sheets of BR emulsion was irradiated by a beam of ^{10}B ions from the nuclotron of the Laboratory of High Energies at JINR. Events were searched for by scanning along a track. The total length of all the sections of the scanned primary tracks prior to inelastic interactions with the emulsion nuclei, or prior to departure from the sheet, was 234 m. A total of 1823 inelastic interactions were detected on this length. Thus, the mean free path prior to interaction was 13.3 ± 0.3 cm. In 217 events, which contain two double-charged ^{10}B fragments, the X, Y and Z coordinates of eleven points with a step of 100 mkm along the X-axis were measured on both double-charged fragment tracks and on the primary particle track. Measurements were performed by means of a MPE-11 microscope with a $90^\times$ objective having a 1.30 aperture (with emmersion). The resolving power was thus provided in the field of vision of about 0.2 mkm. The coordinates of the points on particle tracks and the method of least squares were used to calculate the tangents of the angles φ and α in the emulsion plane and in the plane perpendicular to it. They were also used to calculate the tangent of the angle θ between the track of each fragment and the primary track, as well as the angle θ_{12} between the tracks of the two fragments. In the range of small angles $\theta \simeq 5-6$ mrd, the standard deviation in multiple measurements of the same angle was shown to be about 1.5 mrd. This enables one to assert that the events with angles $\theta_{12} < 8.5$ mrd may be due to a ^{8}Be decay into two alpha particles.

Before giving the results obtained in the experiment we show what we expect to observe starting from our calculations. The simplest task is to predict the characteristic features of the inclusive distributions of the fragment transverse momentum projections $P_{\perp} = A_F \cdot P_0 \cdot tg(\theta)$ onto two mutually perpendicular directions $P_Y = A_F \cdot P_0 \cdot tg(\varphi)$ and $P_Z = A_F \cdot P_0 \cdot tg(\alpha)$, as well as transverse module distribution in an independent emission of fragments by the ^{10}B nucleus. As is well known, the former are expected to be distributed normally with the mean value equal to zero. The dispersion of this normal distribution σ_F^2 is at the same time the Rayleigh distribution constant which the distribution of the transverse momenta of fragments $P_{\perp}$ should obey. This constant and the dispersion of the normal distribution of the transverse momentum projections are determined by the parabolic law established by Goldhaber [1] . This law links the dispersion of the momentum distribution of fragments in the rest frame of a fragmenting nucleus σ_F^2 with the dispersion of the momentum distribution of nucleons in a nucleus σ_0^2 prior to its interaction with another nucleus. The latter , in its turn, is determined by the Fermi momentum P_{Fermi} of a fragmenting nucleus in its ground state ($\sigma_0^2 = P_{Fermi}^2/5$).

For many nuclei, this value is determined from experiments on electron-nucleus scattering [2] . Unfortunately, one has not been engaged in determining it for the ^{10}B nucleus. In ref.3 , it is shown that the product of the two quantities $\sigma_0 \cdot r_0$ is equal to 134.4 MeV/c fermi, where r_0 is the constant connecting the mass number of the nucleus A_0 with its radius $R = r_0 \cdot A_0^{1/3}$. The value of r_0 for the ^{10}B nucleus is given in ref. 4 . It equals 1.54 fermi. Consequently, the Fermi momentum and the constant σ_0 for ^{10}B nucleus are 195.2 and 87.3 MeV/c, respectively.

In our experiment, the standard deflection of the normal distributions for the angles φ and α should be 21.0 mrd. The Rayleigh distribution constant should have the same value and the distribution of the alpha particle angles θ in our experiment should obey the latter. If two alpha particles are emitted in an event independently of each other, then the standard deflection of the sum of all the φ and α angles in this event should be 42.0 mrd.

The angle θ_{12} between the particle tracks is to be a selection from the Rayleigh distribution with a constant equal to $\sqrt{2} \cdot 21.0 = 29.7$ mrd [5]. As we deal with peripheral interactions, transverse momenttum transferred to the nucleus as whole, is small. And it is still distributed between all fragments proportionally to their masses. Therefore the accounts based only on the Fermi momentum of nucleus, will be couincidence with experiment. Certainly, it is a rather rough picture. At exacter measurements longitudinal and transverse momenta a deviation from this calculations will be seen.

The simplest characteristic feature of the two-particle correlations in the transverse plane is the azimuthal asymmetry coefficient A which is determined as a variance of the probability of observation of the difference between the azimuhal angles of two particles larger and smaller than 90° . This coefficient should be zero for an independent particle emission. In this case, the angular distribution between the vectors of the transverse momenta of two particles should be uniform. When an excited system is disintegrated into n particles with respect to the phase volume there inevitably arise kinematic correlations in the transverse plane. In this case, the coefficient A should be equal to $1/(n-1)$. In ^{10}B fragmentation the total number of n

particles could not be so large for A not to differ from zero. In a ^8Be decay into two alpha particles, provided that it is emitted from ^{10}B, all the differences of the azimuthal angles of two particles should be less than 90°. The azymuthal asymmetry coefficient for these events should be close to -1. This is just the fact that we have to verify.

The technique of calculation of the probabilities of various fragmentation channels without free parameters is presented in ref. [6]. It consists in that the probability of any feasible fragmentation channel is determined by the Gibbs distribution. Its formula includes the energy difference of the initial and final states and the "temperature" T is $T = \sigma_0^2/m_N$. All posible fragmentation channels for light nuclei can be enumerated. For example, their number for the ^{10}B nucleus is 73. Then it is possible to calculate the statistical sum that normalizes the sum of the probabilities of all the fragmentation channels to unity. The absolute probabilities are also become known. A significant number of fragmentation channels have so small probabilities that there is no point in discussing them.

However the total observation probability of the two ^{10}B fragmentation channels containing ^8Be is equal to 19.7 percent. In our experiment, there should really be 36 events with angles $\theta_{12} < 8.5$ mrd. We take into consideration that of all the events found by track only 10 percent of them have the sum of the fragment charges equal to the primary nucleus charge [7].

All these calculations are based on the limiting fragmentation picture of nucleus fragmentation [8] in which it is suggested that after interaction the momentum distributions of particles coincide with the momentum distributions of them befor interection. This just allows us to make the above-mentioned predictions. All these predictions have been proved by the experiment . The experimental distributions of the angles φ and α really meet the normal distribution with the constant $\sigma = 20.5 \pm 0.7$ mrd.

Certainly the hypothesis that the fragment angles θ are in agreement with the Rayleigh distribution with the same constant has not been rejected. This result agrees with measurements of the mean transverse momentum of deuterons in ref. [7]. According to our calculations, this value is expected to be 145 MeV/ c, while in experiment of ref. 7 it is found to be 140 ± 10 MeV/c.

To estimate the distribution constant s for the angles $x = \theta_{12}$, under the assumption that the experimental selection of these angles which is truncated from the left and from the right by the angles $x(min) = 8.5$ and $x(max) = 100.0$ mrd where used the method of maximum likelihood. For a random choice of N values x from the Rayleigh distribution, we write the likelihood L in the form :

$$L = \prod_{i=1}^{i=N} \exp(-x^2(min)/2s^2) \cdot (1 - exp(-x^2(max)/2s^2)) \cdot (x_i/s^2) \cdot exp(-x_i^2/2s^2).$$

The maximum the likelihood is obtained with $s = 31.7 \pm 2.0$ mrd which practically does not differ from the value obtained earlier.

The standard deviation of the sum of two φ angles and two α angles was found from the experiment to be equal to 39.7 ± 2.7 mrd. Thus , the hypothesis of the independence of these angles of each other has not been rejected.

The azimuthal asymmetry coefficient for all events in experiment is 0.05 ± 0.03, while for events with $\theta_{12} < 8.5$ mrd it is found to be equal to -0.96 ± 0.04. This means that for all events the correlations of the transverse momentum directions are absent, while for events due to $^8Be \to 2\alpha$ decay these correlations are large.

Finally, it is observed in the experiment 33 events with angles $\theta_{12} < 8.5$ mrd (instead of 36 expected). This means that in the present experiment the probability of observation of ^8Be in the ^{10}B fragmentation amounts to 18 ± 3 percent instead of the calculated 19.7 percent.

The empirical distribution function $F(\theta_{12} < X)$ for 33 events observed experimentally is in agreement with the theoretical distribution function $F(\theta_{12})_{calc}$ under the assumption that all of them originate from the channel $^8Be \rightarrow 2\alpha$. As we can see from table, two goodness-of-fit tests at a level the significances equal 0.01 do not reject null hypothesis consisting that this two functions is the same.

Thus, as it is visible from a table, we have practically the total agriment between calculations and experiment.

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Table.

Calculated, and experimental values of various magnitudes describing fragmentation of the nucleus ^{10}B with emission of two $\alpha-$particles.

N	value	calc.	exper.
1	$< P_\perp >$ ^2H (MeV/c)	145	140 ± 10
2	$\sigma(\varphi) = \sigma(\alpha)$ mrd	21.0	20.5 ± 0.7
3	$\sigma(Rel, \theta_{12})$ mrd	29.7	$31,7 \pm 2.0$
4	$< \theta_{12} >$ mrd	37.2	34.6 ± 2.2
5	$\sigma(\varphi_1 + \varphi_2 + \alpha_1 + \alpha_2)$ mrd	42.0	39.7 ± 2.7
6	$N_{ev}(\theta_{12} < 8.5)$	36	33
7	$W_{obs}(^8Be \rightarrow 2\alpha)$ %	19.7	18 ± 3
8	A for all	0	0.05 ± 0.03
9	A for $^8Be \rightarrow 2\alpha$	-1.0	-0.96 ± 0.04
10	$< \theta_{12} >$ for $\theta_{12} < 8.5$ mrd	6.3	5.6 ± 1.0
11	D COLM.	1.63	0.32
12	$\omega^2 - CRIT$	0.743	0.3