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ELEMENTARY PARTICLES AND FIELDS
Experiment

Dissociation of Relativistic ^{7}Be Nuclei through the ^{3}He+^{4}He Channel on a Proton Target

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Abstract—The differential cross section for the interaction of ^{7}Be nuclei with protons was measured in the momentum-transfer region extending up to a value of 0.5 GeV/c at which ^{7}Be decay to ^{3}He and ^{4}He fragments was not accompanied by the emergence of other charged particles. In the momentum-transfer region extending up to about 100 MeV/c, the cross section is strongly suppressed in just the same way as in the case of the dissociation of ^{7}Li nuclei on a proton target through the ^{3}H+^{4}He channel. The total reaction cross section is 10 ± 4 mb. The mean transverse-momentum transfer in observed events is 233 ± 6 MeV/c, the dispersion of its distribution being about 63 MeV/c. The interactions in question were detected in photoemulsion irradiated with ^{7}Be nuclei originating from a charge-exchange process involving ^{7}Li nuclei accelerated to the momentum of 1.7 GeV/c per nucleon at the nuclotron of the Joint Institute for Nuclear Research (Dubna).

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1. INTRODUCTION

In order to study mechanisms of nucleus–nucleus interactions and the structure of nuclei, use is made of data on the fragmentation of relativistic nuclei. The early studies reported in [1] and performed at projectile-nucleus energies of several GeV units per nucleon with the aid of spectrometers and the counter procedure furnished information about interaction channels, total cross sections, and the relative contributions of Coulomb and nuclear fragmentation. Commensurate contributions come from the decay of the giant dipole resonance in the projectile nucleus to nucleons, and this is of particular interest for studying collective excitations in radioactive nuclei. More recent investigations devoted to the fragmentation of relativistic nuclei and performed at the synchrophasotron and nuclotron of the Joint Institute for Nuclear Research (JINR, Dubna) with a propane bubble chamber [2, 3] and photoemulsions [4–8] were aimed primarily at detecting events involving the emission of protons and extremely light nuclei, including deuterons, tritons, ^{3}He nuclei, and alpha particles, and at determining to a considerable extent the cluster structure of light nuclei. An extensive survey of investigations on the subject is given in [9]. Despite moderately small statistics of visual methods, they permit performing the charge and mass identification of fragments, measuring the transverse momenta, and estimating differential cross sections for specific channels on the basis of the projectile mean free path. Fragmentation channels for which one identifies all final-state particles and measures their transverse momenta are quite promising for testing theoretical approaches. In order to study the electromagnetic and nuclear interaction mechanisms in such processes, it is reasonable to measure the transverse-momentum-transfer (Q) distribution of events. Such reactions include the dissociation of ^{6}Li, ^{7}Li, and ^{7}Be nuclei to pairs of extremely light nuclei—^{2}H+^{4}He, ^{3}H+^{4}He, and ^{3}He+^{4}He, respectively—in which case a theoretical analysis of data is much more straightforward than in the case of multiparticle processes. A comparatively large number of such events observed in a nuclear emulsion [6, 7, 10, 11] is indicative of a high probability for two-cluster components in the wave functions that describe primary nuclei. This idea was confirmed in interpreting the results obtained by measuring the Q dependence of the differential cross section for the two-cluster fragmentation of a ^{7}Li nucleus on photoemulsion nuclei at the projectile momentum of 3 GeV/c per nucleon [12, 13]. Within the two-body model of the ^{7}Li nucleus [14, 15] and with the aid of the cluster version of diffraction theory [16, 17] developed by analogy with the Akhiezer–Sitenko theory [18] of deuteron breakup to a neutron and a proton, diffrac-

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tion patterns (versus the momentum transfer) were obtained for the dissociation channel ^{7}Li $\rightarrow ^3$ H+^{4}He in the cases of the reactions on light (C, N, and O) and heavy (Ag and Br) emulsion nuclei. An oscillating shape of the differential cross sections is predicted for either group of nuclei. The superposition of two groups of diffraction cross sections provides an acceptable description of observed irregularities in the Q distribution of events. The contribution of electromagnetic dissociation on heavy nuclei is not more than 10%, its maximum lying in the low-Q region. Direct pieces of evidence of the predicted diffractive oscillations in the cross sections could come from experiments with pure target nuclei, but it is hardly possible to identify them in photoemulsions. Protons are the only pure nuclear target in photoemulsions. Since the contribution of Coulomb dissociation on protons is negligible, the whole process proceeds via nuclear interaction. Events of the disintegration of ^{7}Li nuclei at the projectile momentum of 3 GeV/c per nucleon through the ^{3}H+^{4}He channel in interactions with protons were studied in [19]. It turned out that the shape of the Q dependence of the diffraction cross section for the reaction on protons differed sharply from the shape of the Q dependence of the cross sections for the respective reactions on complex nuclei: for $Q \leqslant 100$ MeV/c, the cross section is very strongly suppressed, its maximum being shifted toward higher values of Q in relation to the cross-section maximum for reactions on nuclei. The Q distribution of events in ^{7}Li dissociation on a proton has a larger mean value of Q and a substantially smaller dispersion in relation to their counterparts for reactions on nuclear targets. It should be noted that data on fragmentation induced by interactions with nuclear and protons targets are obtained in the same experiment—that is, with the same photoemulsion block irradiated with a preset beam of nuclei. In the present study, we analyze events in which relativistic ^{7}Be nuclei, which are a member of the ^{7}Li–^{7}Be isospin doublet, undergo fragmentation through the ^{3}He+^{4}He channel upon experiencing interaction with photoemulsion protons.

2. EXPERIMENTAL PROCEDURE

A secondary beam of ^{7}Be nuclei was formed at the JINR nuclotron in the charge-exchange process involving ^{7}Li nuclei accelerated to the momentum of 1.7 GeV/c per nucleon [20]. An emulsion chamber formed by 15 layers of BR-2 photoemulsion was irradiated with ^{7}Be nuclei. The emulsion layers had a thickness of 600 μm and were 10×20 cm in transvers dimensions. In the course of irradiation, the emulsion layers were oriented along the beam axis. Searches for the interactions of relativistic ^{7}Be nuclei with photoemulsion nuclei were performed with an MPE-11 microscope via viewing the tracks of beam nuclei and via scanning over the area. Doubly charged relativistic fragments of ^{7}Be nuclei were determined visually from the ionization density associated with the tracks. The direction of a relativistic-nucleus track before interaction was determined from the coordinates of several points on the track. The emission directions for relativistic fragments were determined from the coordinates of the interaction vertex and the track-point coordinates measured at the distances of 500 and 1000 μm from the vertex. The values averaged over several measurements were taken to be the results of the measurements. The accuracy in measuring the spatial angles θ_f of the emission of relativistic fragments with respect to the direction of the ^{7}Be-nucleus momentum was about 0.5 mrad, and the spread of the fragment-track azimuthal angles ψ_f was about 3° to 5°. The masses of relativistic fragments were estimated by the method of multiple Coulomb scattering of fragments in the horizontal plane of the photoemulsion used. In order to determine the mean scattering angle along a track at distances t, we successively measured the Y coordinates of a track [10, 19, 21]. The second differences of the Y coordinates, D, characterize the deviation of the track under study in the horizontal plane, while the ratio D/t characterizes the scattering angle over the length t. In the case of multiple Coulomb scattering, the scattering angle and the second differences of the Y coordinates obey a normal distribution. The mean value $\langle |D| \rangle$ over a cell of length t is given by $\langle |D| \rangle = KZ_f t^{3/2}/(p\beta c)$, where Z_f, p, and βc are the particle charge, momentum, and speed, respectively. For the scattering constant, we used the standard value of $K = 28.5$. This relationship between $\langle |D| \rangle$ and $(p\beta c)$ makes it possible to estimate particle momenta and to perform a mass separation of fragments that have identical charges. In the $(p\beta c)$ distributions of doubly charged fragments, 5.4 GeV was taken for the minimum value of $(p\beta c)$ for alpha-particle fragments [10]. In the dissociation of ^{7}Be nuclei through the ^{3}He+^{4}He channel on a proton target, a recoil proton is observed in addition to relativistic fragments. The total- and transverse-momentum transfers are determined on the basis of the proton path length and emission angle with respect to the direction of motion of the primary ^{7}Be nucleus. A low energy threshold for proton detection in photoemulsions is of paramount importance for studying differential reaction cross sections at low momentum transfers. It can be assumed that a charged particle can be reliably detected in a photoemulsion if the path length of this particle is longer than 2 μm. The momentum of a

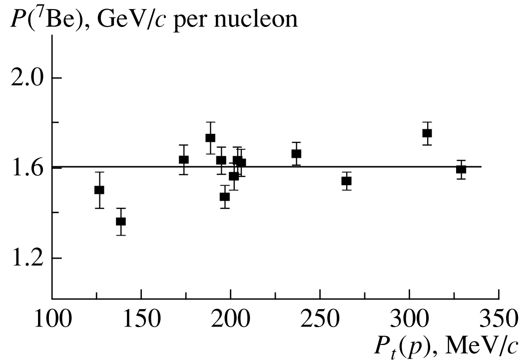

Fig. 1. Estimated momenta of ^{7}Be nuclei, $P(^7\mathrm{Be})$, in the events listed in Table 1. The values of $P(^7\mathrm{Be})$ that were calculated by the formula $P(^7\mathrm{Be}) = P_t(p)/(7\sin\theta_Q)$ are plotted along the ordinate. The errors quoted for the $P(^7\mathrm{Be})$ values correspond to the errors of 0.5 mrad in the angles θ_Q. The proton transverse momenta $P_t(p)$ are plotted along the abscissa.

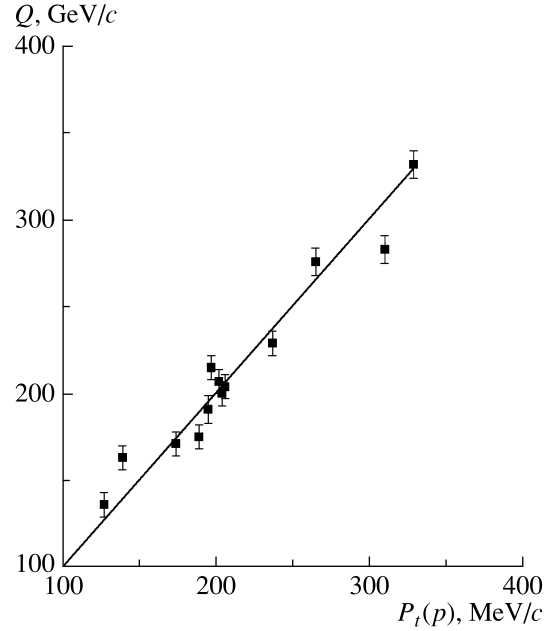

Fig. 2. Transverse momenta of recoil protons, $P_t(p)$, along with transverse momenta of relativistic fragments, Q (at $P(^7\mathrm{Be}) = 1.6$ GeV/c per nucleon), in events of the reaction $^7\mathrm{Be} + p \rightarrow {}^3\mathrm{He} + {}^4\mathrm{He} + p$. The approximation of the relation between $P_t(p)$ and Q by a linear dependence corresponds to nearly equal values of these momenta.

proton that has such a path length is approximately equal to 25 MeV/c. A low threshold for the detection of protons in photoemulsions makes it possible to identify the dissociation of a nucleus on protons in the region of low momentum transfers, and it is difficult to do this with the aid of other methods for detecting charged particles. By way of example, we indicate that, in the propane bubble chamber used in [2], protons were detected only in the case where their momenta exceeded 150 MeV/c.

3. EXPERIMENTAL RESULTS

In the dissociation of ^{7}Be nuclei through the ^{3}He+^{4}He channel, the vector sum of the transverse momenta of relativistic fragments, $\mathbf{Q} = \mathbf{P}_t(^3\mathrm{He}) + \mathbf{P}_t(^4\mathrm{He})$, and the proton transverse momentum, $\mathbf{P}_t(p)$, are equal in magnitude and opposite in direction in the azimuthal plane. The accuracy in determining the azimuthal angle of the total momentum of relativistic fragments, ψ_Q, in events is estimated at about 3° to 5°. The recoil-track emission angles θ_p and ψ_p were determined from the track-point coordinates measured with the aid of an ocular micrometer in the microscope field of vision. The errors in measuring the angles θ_p range between 1° and 2°, while the accuracy in measuring the angles ψ_p is 3° to 5°. In the present article, we quote the features of 18 events of the dissociation of ^{7}Be nuclei such that, in these events, the difference of the angle ψ_Q and the angle ψ_p is compatible with 180° within the errors. The angles ψ_Q and ψ_p are measured from the Y axis lying in the emulsion plane. In 13 events, recoil protons are stopped within the photoemulsion block, while, in five events, their escape from it is seen. For events in which the recoil proton is stopped, Table 1 gives the proton path lengths and the proton momenta $P(p)$ corresponding to these path lengths. In order to determine the momentum of a proton from its path length, we used the relation between the path length and momentum in the Ilford nuclear emulsion. The accuracy in determining the momentum of a proton from its path length was estimated at about 2%. Table 1 gives the values of the polar proton-emission angle θ_p and the respective values of the proton transverse momentum $P_t(p) = P(p)\sin\theta_p$. In [22], it was found that the process in which ^{3}H nuclei of momentum 3 GeV/c per nucleon undergo the charge-exchange transformation into ^{3}He nuclei proceeds primarily via the formation of a $\Delta(3/2, 3/2)$ isobar and involves an energy loss. In the case of the change-exchange transformation of ^{7}Li nuclei whose momentum is 1.7 GeV/c per nucleon into ^{7}Be nuclei with the above energy loss, the mean momenta of product ^{7}Be nuclei should decrease to 1.65 GeV/c per nucleon. For stopped protons, the ^{7}Be momentum $P(^7\mathrm{Be})$ can be estimated by using the recoil-proton transverse momentum $P_t(p)$ and the spatial angle θ_Q at which the vector $\mathbf{Q}$ is directed. The accuracy of this determination of $P(^7\mathrm{Be})$ in individual events is

Table 1. Features of $^7Be + p \to ^3He + ^4He + p$ events in which recoil protons are stopped in the photoemulsion used

Recoil proton				$^3He+^4He$		$\psi_Q - \psi_p$, deg	$Q - P_t(p)$, MeV/c
Path length, μm	$\theta(p)$, deg	$P(p)$, MeV/c	$P_t(p)$, MeV/c	θ_Q, deg	Q, MeV/c		
1713	81.6	191	189	0.894	175	175	−14
10027	77.6	318	310	1.448	283	170	−27
430	83.5	128	127	0.696	136	−178	9
5791	78.1	271	265	1.414	276	175	11
3726	82.1	239	237	1.173	229	−172	−8
573	82.1	140	139	0.835	163	179	24
1293	82.6	176	174	0.876	171	168	−3
1950	80.6	198	195	0.978	191	−173	−4
2230	81.3	206	204	1.024	200	168	−4
12576	75.6	342	329	1.697	332	176	3
2032	80.0	200	197	1.102	215	−176	18
2337	80.7	209	206	1.057	204	−174	−2
2049	77.1	207	202	1.061	207	−177	5
Mean value	80.2	217	213	1.10	214	174	±13

Table 2. Features of $^7Be + p \to ^3He + ^4He + p$ events in which recoil protons are not stopped in the photoemulsion used (the values of Q were calculated with allowance for the fact that the momentum of ^{7}Be nuclei is 1.6 GeV/c per nucleon)

Proton				$^3He+^4He$		$\psi_Q - \psi_p$, deg
Path length, μm	$\theta(p)$, deg	$P(p)$, MeV/c	$P_t(p)$, MeV/c	θ_Q, deg	Q, MeV/c	
>1642	79.6	>189	>186	1.056	204	−174
>3725	73.8	>238	>228	1.485	287	−171
>3101	69.4	>226	>212	1.366	264	177
>5549	77.0	>268	>261	1.564	302	175
>3067	76.6	>226	>220	1.852	357	175
Mean value	75.3			1.46	283	173

estimated at (0.04–0.08) GeV/c. Figure 1 shows the results of such estimations for events indicated in Table 1. The value obtained for $P(^7Be)$ upon averaging the resulting estimates over these events is 1.6 GeV/c per nucleon. The dispersion of the distribution of $P(^7Be)$ is 0.10 GeV/c. The errors in the values of $P(^7Be)$ correspond to the errors of 0.5 mrad in the angles θ_Q. In Table 1, the values of Q at $P(^7Be) = 1.6$ GeV/c per nucleon are given along with the difference of Q and the recoil-proton transverse momentum $P_t(p)$. In Fig. 2, events are represented in the form of points whose coordinates are $P_t(p)$ and Q. Upon approximating the behavior of these points by a linear dependence, the values of $P_t(p)$ and Q prove to be nearly identical. The respective events are identified as those of interaction of ^{7}Be nuclei with free protons contained in the photoemulsion used. In events where relativistic nuclei interact with a free proton, the proton momentum is equal to the total momentum transfer. In these interactions, one therefore determines total, transverse, and longitudinal momentum transfers. The average value of the proton emission angle is $\theta_p = 80°$. In these 13 interactions, the mean proton momentum is $P(p) = 217 \pm 5$ MeV/c, while the mean proton

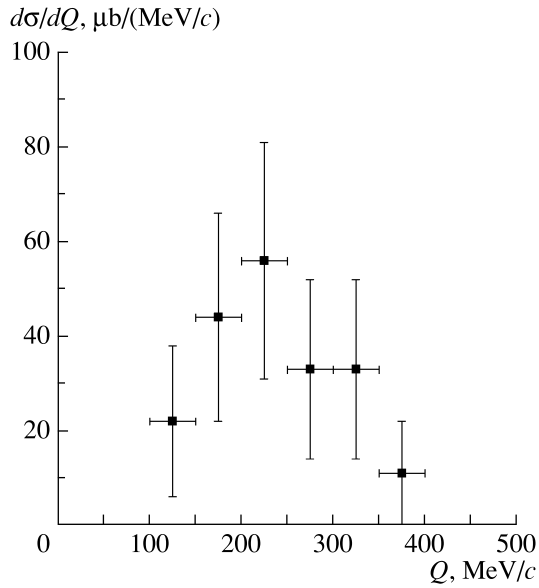

Fig. 3. Differential cross section $d\sigma/dQ$ for the reaction $^7\mathrm{Be} + p \rightarrow {}^3\mathrm{He} + {}^4\mathrm{He} + p$. The horizontal lines show the intervals of $\Delta Q = 50$ MeV/c in which 18 observed events are distributed. The vertical lines indicate the statistical measurement errors.

transverse momentum is $P_t(p) = 213 \pm 5$ MeV/c. The dispersion of the momentum distribution is 57 MeV/c. Features of five interactions in which protons are not stopped in the photoemulsion are given in Table 2. The relativistic-fragment transverse momenta $P_t(^3\mathrm{He})$ and $P_t(^4\mathrm{He})$ and the momentum transfer Q were calculated by using the momentum of ^{7}Be nuclei, which is equal to 1.6 GeV/c. In the majority of these events, the calculated values of Q are close to 300 MeV/c. Upon taking into account these events, the mean transverse momentum increases to a value of 233 ± 6 MeV/c. The dispersion of the respective distribution is 63 MeV/c. On the basis of six events found upon scanning the length of $L = 205$ m along the tracks of ^{7}Be nuclei, the reaction cross section was estimated at 10 ± 4 mb. Figure 3 shows the differential cross section $d\sigma/dQ$ with respect to the momentum transfer Q over the range extending up to 0.5 GeV/c. In all of these events, the values of Q exceed 100 MeV/c. Thus, a strong suppression effect observed earlier for cross sections in studying the diffractive dissociation of ^{7}Li nuclei through the $^3\mathrm{H}+^4\mathrm{He}$ channel on a proton target was also discovered in the dissociation of ^{7}Be nuclei to ^{3}He and ^{4}He fragments.

4. CONCLUSIONS

Features of events in which ^{7}Be nuclei whose mean momentum is 1.6 GeV/c per nucleon and which interact with free protons in a nuclear photoemulsion undergo dissociation through the $^3\mathrm{He}+^4\mathrm{He}$ channel are presented in this article. The reaction cross section was estimated at 10 ± 4 mb. A low energy threshold for proton detection in nuclear photoemulsions makes it possible to identify the interactions of relativistic nuclei with protons in the region of low momenta nearly without limitations on the momentum transfer. The mean transverse-momentum transfer Q is 233 ± 6 MeV/c. The dispersion of the respective distribution is 63 MeV/c. In the differential cross section $d\sigma/dQ$, the effect of a strong suppression in the Q region extending up to about 100 MeV/c was observed. A similar form of the momentum-transfer dependence of cross sections and a close value of the total cross section, 8 ± 2 mb, were obtained earlier in [19] for the dissociation of ^{7}Li nuclei on protons through the $^3\mathrm{H}+^4\mathrm{He}$ channel. An interpretation of the observed cross sections for the two-cluster dissociation of relativistic ^{7}Li and ^{7}Be nuclei on protons and a comparative analysis of the results concerning the dissociation of ^{7}Li nuclei on complex photoemulsion nuclei [12] are given in [23]. With the aim of additionally testing theory, it would be of interest to perform similar investigations of the two-cluster fragmentation process $^6\mathrm{Li} \rightarrow {}^2\mathrm{H}+^4\mathrm{He}$.

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