Diffraction Dissociation of $^7\text{Li}$ and $^7\text{Be}$ Relativistic Nuclei on Proton Targets through the $^3\text{H}(^3\text{He}) + ^4\text{He}$ Channels

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Abstract—For the fragmentation of $^7\text{Li}$ and $^7\text{Be}$ relativistic nuclei (with momenta of, respectively, $P = 3$ GeV/c and $P = 1.6$ GeV/c per nucleon) on proton targets through the $^3\text{H}(^3\text{He}) + ^4\text{He}$ channels, the differential cross sections with respect to the momentum transfer $Q$ to the fragments were calculated on the basis of the cluster version of Akhiezer–Glauber–Sitenko diffraction theory by employing the two-body cluster model for the $^7\text{Li}$ ($^3\text{H} + ^4\text{He}$) and $^7\text{Be}$ ($^3\text{He} + ^4\text{He}$) nuclei. These calculations, performed in the impulse approximation in the interaction of intranuclear clusters with the target nucleus, explained a strong suppression of the cross sections for reactions on protons at $Q$ lower than 100 MeV/c and higher than 350 MeV/c and the observed irregularities in the behavior of the cross section for $^7\text{Li}$ fragmentation on complex track-emulsion nuclei. Cross-section values close to their experimental counterparts were obtained upon setting the coefficient of two-body clustering in the $^7\text{Li}$ and $^7\text{Be}$ nuclei to $k \approx 0.7$.

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1. INTRODUCTION

A number of experiments devoted to studying peripheral reactions involving the fragmentation of relativistic light nuclei that have momenta of several GeV/c units per nucleon and which collide with track-emulsion nuclei have been performed over the past fifteen years [1]. From the mass and charge composition of emerging fragments, it follows that not only proton emission but also the emission of deuterons, tritons, $^3\text{He}$ nuclei, alpha particles, and more complex nuclei may occur in such reactions. These results are usually treated, at least at a qualitative level, as manifestations of respective cluster degrees of freedom in the structure of incident nuclei. The main objective of track-emulsion experiments, in which one can study the spatial picture of events, identify charged particles, measure particle momenta and cross sections for proceeding processes, and obtain various distributions of events with respect to kinematical variables was to collect data that can be used both to study fragmentation mechanism (nuclear and Coulomb ones) and to obtain information about the structure of nuclei. It should be borne in mind, however, that a theoretical analysis of the properties of reactions involving the emission of three or more charged particles presents a very complicated problem. For this reason, multiparticle fragmentation channels observed in track emulsions have not yet been interpreted adequately.

The situation around the application of already developed theoretical approaches to studying the structure of nuclei and fragmentation mechanisms is more favorable in those cases where the disintegration of a relativistic nucleus in a track emulsion (without the breakup of the target nucleus) leads to the formation of only two charged fragments. As examples of such reactions, one can consider the disintegration of three two-cluster nuclei $^6\text{Li}(^2\text{H} + ^4\text{He})$, $^7\text{Li}(^3\text{H} + ^4\text{He})$, and $^7\text{Be}(^3\text{He} + ^4\text{He})$ through the respective cluster channels, which are dominant in the ground states of these nuclei. A relatively large yield of such events in which the masses and charges of cluster pairs were identified was observed in nuclear track emulsions [2–4]. Track emulsions make it possible to detect all events concentrated in a very narrow cone along the direction of the beam of primary nuclei and to measure the transverse momentum of the center of mass of the final fragment pair, $Q$, for any polar and azimuthal emission angles of individual fragments, this being equivalent to integrating the momentum distribution for the relative motion of two clusters. As a result, one can get an idea of the distribution of all events (this is of importance in the case of a moderately small data sample, which is characteristic of the track-emulsion method) with respect to the variable $Q$ alone and single out, in the differential cross section $d\sigma/dQ$, regions where the diffraction and Coulomb
reaction mechanisms are operative. In addition, this representation of the results permits comparing the theoretically predicted diffraction oscillations in the inelastic-reaction cross section with the diffraction picture observed in elastic scattering.

In [5], the results of measurements of the differential cross section $d\sigma/dQ$ for the disintegration of $^7$Li nuclei (at a momentum of $P = 3$ GeV/c per nucleon) on track-emulsion nuclei through the $^3$H + $^4$He channel were presented and were interpreted within the two-body model of the $^7$Li nucleus [6, 7] and the cluster version of Akhiezer–Glauber–Sitenko diffraction theory [8–11]. One of the conclusions of that study was that the irregularities observed in the $Q$ dependence of the cross section arise owing to the superposition of two diffraction cross sections for reactions on a mixture of light (C, N, and O) and heavy (Br and Ag) track-emulsion nuclei. Each of the masked cross sections [5, 12] has its own pronounced oscillating shape, with the first maximum being shifted (and the number of subsequent oscillations being accordingly smaller) toward the region of high values of $Q$ for the light target nuclei, whose radii are approximately one-half as large as the radii of the heavy target nuclei. In order to discover and study the theoretically predicted features of cross-section oscillations, such as the numbers of peaks and their intensities and shifts for various values of the target mass number, one needs data on two-cluster fragmentation on individual nuclei. In track emulsions, protons are the only pure nuclear target on which one can study two-cluster fragmentation. The disintegration of $^7$Li (at a momentum of $P = 3$ GeV/c per nucleon) and $^7$Be (at a momentum of $P = 1.6$ GeV/c per nucleon) nuclei on proton targets in a track emulsion were recently studied in [13, 14]. The sections that follow present the elements of the formalism used here and the results obtained by calculating cross sections for two-cluster fragmentation on protons on the basis of the two-body model for the $^7$Li and $^7$Be nuclei and with the aid of diffraction theory. The results are compared with experimental data.

2. FORMALISM OF DIFFRACTION THEORY FOR THE TWO-CLUSTER FRAGMENTATION OF NUCLEI

Following the formalism developed in [8] and used there to derive expressions for the amplitudes and cross sections for the diffraction dissociation of a deuteron to the constituent neutron and proton, we will consider the analogous differential cross section for the fragmentation of a relativistic nucleus whose ground-state wave function $\varphi_{f,\mu_s}(r)$ has a two-cluster form and for which $\varphi_{f,\mu_s}(r)$ denotes the wave function for the pair of fragments in the continuous spectrum. Within this formalism, the cross section in question has the form

$$d\sigma/dQ = \frac{1}{k^2(2\pi)^3} \left\{ \frac{1}{(2j_i + 1)} \right\}$$

$$\times \sum_{\mu_s,\mu_i} \int |T(f, Q; \mu_s, \mu_i)|^2 df d\psi_Q Q,$$

where $k$ is the projectile-nucleus momentum, $Q$ is the momentum of the fragment center of mass, $\psi_Q$ is the azimuthal angle of the vector $Q$, and $f$ is the momentum of the relative motion of fragments. The reaction amplitude corresponding to the impulse approximation can be written in the standard form [10, 11]

$$T = \frac{k}{k_1} f_1(Q) F(\beta_1 Q, f)$$

$$+ \frac{k}{k_2} f_2(Q) F(-\beta_2 Q, f).$$

In this expression, $k_1$ and $k_2$ are the cluster momenta in the relativistic projectile nucleus ($k = k_1 + k_2$); $\beta_1 = m_2/(m_1 + m_2)$, where $m_i$ are the cluster masses; $\beta_2 = 1 - \beta_1$; and $f_i(Q)$ are the amplitudes for the elastic scattering of individual projectile clusters on the nuclear target. These amplitudes can be expressed in terms of the integral of the product of the Bessel function $J_0(x)$ and the profile function $\omega_i(b)$ with respect to the impact parameter $b$ as

$$f_i(Q) = ik_i \int_{0}^{\infty} J_0(Qb) \omega_i(b) db,$$

$$\omega_i(b) = \frac{1}{2\pi i k_i} \int \exp(-iqb) f_i(q) dq.$$

The inelastic form factors

$$F(\beta Q, f) = \int \exp(i\beta Qr) \varphi_{f,\mu_s}(r) \varphi_{j_i,\mu_i}(r) dr$$

and, hence, the cross section $d\sigma/dQ^2$ vanish, in contrast to what we have in the case of elastic scattering, at $Q = 0$ by virtue of the orthogonality of the wave functions $\varphi_{f,\mu_s}(r)$ and $\varphi_{j_i,\mu_i}(r)$.

Taking into account the completeness of states of the two-cluster Hamiltonian in performing integration with respect to the momentum $f$, we can express the cross section in (1) in terms of the amplitudes $f_i = (k/k_i)f_i(Q)$ and the radial integrals of the spherical Bessel functions $j_{L}(qr)$ over the bounded states $R_{ij}$ as

$$d\sigma/dQ = \frac{2\pi}{k^2} (|\bar{f}_1|^2 + |\bar{f}_2|^2)$$