Momentum Distributions of $^4$He Nuclei from the $^6$He and $^6$Li Breakup


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Abstract—Experimental data on the momentum distributions of $^4$He nuclei originating from $^6$He and $^6$Li breakup on various targets are presented over a wide beam energy range. The experiment with $^6$He was performed at the DRIBs accelerator complex for radioactive beams at the Joint Institute for Nuclear Research (JINR, Dubna). The intensity of the $^6$He beam used was $5 \times 10^6$ particles per second and its energy was 10 MeV per nucleon. The momentum distributions of breakup products were measured by means of the MSP-144 magnetic spectrometer. The distribution width was shown to be virtually independent of the target mass. A small value of this width, $\sigma \sim 28$ MeV/c, confirms the presence of a halo in $^6$He. The measurements performed with $^6$Li beams of energy 18 and 46 MeV per nucleon at the U-400M accelerator yielded a width value of $\sigma \sim 50$ MeV/c for the momentum distributions of $^4$He nuclei, which is intermediate between that for $^6$He and those for stable nuclei. A compilation of the widths of the momentum distributions of fragments originating from the breakup of various nuclei is presented versus the binding energy of one or two neutrons in these nuclei, the target mass and the projectile energy.

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1. INTRODUCTION

The advent of intense heavy-ion beams made it possible to use projectile-fragmentation products to form secondary beams of radioactive nuclei and to perform physics experiments with such secondary beams. The development of this line of investigations in nuclear physics over the past 15 years has revealed that it is promising for studying the structure of exotic nuclei and the mechanism of reactions induced by these nuclei. Experimental measurements of respective interaction cross sections, momentum distributions of products originating from the breakup of the nuclei under study, and correlations between these products furnished new information about the structure of these nuclei. This brought about important new results, including the discovery of a neutron halo in $^{11}$Li and $^{11,14}$Be [1, 2] and the synthesis of new highly neutron-rich nuclei ($^{10}$He, $^7$H [3] and others). The root-mean-square radii of the nucleon distribution in the $^6$He and $^8$He nuclei were determined in [4] from the measured interaction cross sections, and the increase in the radii was found there to be faster than that which is suggested by a conventional systematics ($\sim A^{1/3}$), whence it was concluded that $^6$He and $^8$He are halo nuclei. The $^6$He nucleus is the lightest nucleus that involves a halo, consisting of a core (alpha particle) and two valence neutrons (the threshold for the breakup reaction $^6$He $\rightarrow$ $^4$He + $n$ + $n$ is $E_{\text{thr}} = 0.973$ MeV). We note that it is of importance to obtain accurate values of nuclear radii, since this information is required for developing theoretical models for describing halo nuclei. Two neutrons in the $^6$He nucleus are quite far from the $^4$He core, occupying the outer shell. The $^4$He core and the neutrons execute vibrational motion within the $^6$He nuclear system in the region of action of nuclear forces. The weaker these forces, the lower the frequency of these vibrations and the larger the radius; therefore, the momentum distribution is narrower here than in ordinary nuclei. If one removes two neutrons from $^6$He rather fast, the $^4$He core will continue moving in just the same way as in the nuclear system. Measuring its momentum distribution, we obtain information about the structure of $^6$He.

A number of studies have been devoted to measuring the momentum distribution of fragments originating from the breakup of various light exotic nuclei (including $^6$He, $^8$He, $^{11}$Li, and $^{11,14}$Be). Kobayashi et al. [2] were the first to measure the transverse-momentum distribution of $^9$Li produced in $^{11}$Li frag-
It appeared to comprise two components: wide, which corresponds to values peculiar to the fragmentation of ordinary nuclei [5], and narrow. In accordance with the Heisenberg uncertainty principle, it was concluded that the narrow component of the distribution indicates that the remote valence neutrons have a small momentum fluctuation, which, in turn, is due to an extended character of the neutron-density distribution in the halo. Thus, a great radius and a narrow momentum distribution were the first pieces of evidence that a neutron halo exists in nuclei in the vicinity of the drip line.

The fragmentation of $^6\text{He}$ nuclei at energies of about 400 and 800 MeV per nucleon was investigated in [2, 6, 7], where momentum distributions were measured both for the $^4\text{He}$ nuclei and for the neutrons from $^6\text{He}$ breakup on carbon and lead targets. It was shown that sequential $^6\text{He}$ breakup to $^4\text{He}$ via an intermediate $^5\text{He}$ resonance is a dominant mechanism of $^6\text{He}$ fragmentation. Korsheninnikov and Kobayashi [8] obtained a better description of experimental data, assuming a mechanism where one neutron interacts with a target nucleus and where there is an interaction in the final state corresponding to the $^5\text{He}_{\text{g.s.}}$ resonance.

Various research groups studied the structure of $^6\text{He}$ on the basis of the momentum distributions of the $^4\text{He}$ core or neutrons, employing beams of energy ranging from 24 to 800 MeV per nucleon and targets from H, C, Al, Cu, Sn, Au, Pb, and U [2, 6, 7, 9–14]. The use of light and heavy targets made it possible to compare the contributions of Coulomb and nuclear dissociation. It follows from the experiments that the momentum-distribution width ($\sigma$ is the Gaussian

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**Fig. 1.** Layout of the experimental facility featuring an MSP-144 magnetic spectrometer. The notation for the focal detector is the following: C is the cathode; FG is the Frisch grid; $\Delta E_1$, $\Delta E_2$, $\Delta E_3$, and $\Delta E_4$ are the anode electrodes; $E$ is the scintillation detector; and PPC1 and PPC2 are the proportional counters.

**Fig. 2.** Momentum distribution of $^4\text{He}$ from $^6\text{He}$ breakup on gold nuclei at 10 MeV per nucleon. The points represent experimental data. The dashed and dotted curves correspond to the distributions characterized by $\sigma = 28 \pm 1$ and 100 MeV/$c$, respectively. The solid curve is the sum of two components (see main body of the text).

**Fig. 3.** As in Fig. 2, but for carbon targets. The points represent the experimental data. The curve shows the distribution characterized by $\sigma = 29 \pm 3$ MeV/$c$. 

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