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Momentum distributions for ^{12,14}Be fragmentation

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Data on the fragmentation of ^{12,14}Be on ^{12}C at 56 and 65 MeV per nucleon have been obtained. The ^{12}Be fragments from the breakup of ^{14}Be display both a narrow longitudinal momentum distribution and a distinctive angular distribution that is consistent with an extended neutron "halo" in this nucleus. This is the first experiment in which both longitudinal and transverse fragment momentum distributions of exotic nuclei have been simultaneously measured.

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The exotic nature of very neutron-rich nuclei such as ^{6,8}He, ^{11}Li, and ^{11,14}Be was first established through observation of anomalously large reaction cross sections for these nuclei at energies of approximately 800 MeV per nucleon [1]. This work has prompted a flurry of activity to investigate the "neutron halo" which has been proposed as being responsible for this anomaly. Reviews of the most important experiments, essentially all of which address either ^{11}Be or ^{11}Li nuclei, are given in Refs. [2] and [3]. On the other hand, the ^{14}Be system might be of even more interest than ^{11}Li since the wave function of the last two neutrons in ^{14}Be is expected to contain a larger $(2s_{1/2})^2$ shell-model component. In this configuration, the "tail" of the wave function should extend to large distance as it does not encounter an angular momentum barrier. In addition, the two-neutron separation energy of ^{14}Be is much larger than that of ^{11}Li, and it could prove very interesting to study the effect of this extra binding on the properties of the neutron halo.

The observation [4] of a narrow peak in the transverse momentum distribution of ^{9}Li nuclei produced in the fragmention of ^{11}Li on a ^{12}C target was one of the first indications, beyond the enhanced reaction cross sections, of the unusual structure of these neutron drip-line nuclei. This narrow peak was interpreted as evidence for the existence of a weakly bound two-neutron halo extending out to distances of 7 fm or more, as compared with the 2.5 fm radius [1] of the ^{9}Li "core." Similar observations have recently been made for the longitudinal momentum distribution for reactions with a wide range of targets (Be-U) by Orr *et al.* [5]. However, *simultaneous* measurements of both fragment momentum components have not as yet been made for halo nuclei incident on any target. In the present experiment, we have for the first time been able to make such a simultaneous measurement for the fragmentation of ^{14}Be on ^{12}C. The results indicate that both components can in this case be fit by Lorentzian forms having the same intrinsic width parameter.

Motivated by the considerations discussed above, we studied the momentum distributions from the reaction of ^{12,14}Be with ^{12}C at incident energies of 56 and 65 MeV/nucleon. The secondary beams were produced by fragmentation of an 80 MeV/nucleon ^{18}O beam on a 790 mg/cm^2 Be target, and separated using the A1200 Fragment Separator at Michigan State University. The purity of the beams was enhanced for the telescope part of the experiment (see below) by the use of a 515 mg/cm^2 plastic achromatic wedge. All remaining beam impurities were identified by time-of-flight techniques. The energy width of the beam, defined by the momentum acceptance of the A1200 spectrometer, was 6%. The beam intensity was adjusted to $<10^4$ particles per second (pps) for ^{12}Be, while the on-target rate of ^{14}Be varied from 100–200 pps during the course of the telescope experiment and was 350 pps for the spectrometer experiment.

The longitudinal momentum distributions of the fragments after interaction in a ^{nat}C target were measured using two different experimental techniques. The first of these, discussed in detail in Ref. 5, involves the use of the dispersion matched mode of the A1200 spectrometer to correct for the large momentum spread in the secondary beam. The method is capable of obtaining very high resolution [up to ~0.3% full width at half maximum (FWHM)] in the fragment momentum, but the limited transverse acceptance of the spectrometer may lead to possible distortions in the measured momentum spectrum. Though small [5] for momentum widths of the order of 45 MeV/c, these distortions might become significant for wider distributions. Furthermore, the spectrometer is limited to measurement at 0° with relatively small angular acceptance ($\Delta\theta \cong 30$ mrad; $\Delta\phi \cong 10$ mrad) so that the transverse momentum distribution can-

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not easily be obtained with this method. This is important since there has been considerable discussion of the interpretation of transverse momentum distributions and their relationship to the widths determined from neutron angular distributions [3,5,6]. We therefore decided to measure the ^{12,14}Be momentum distributions via a second technique which involved transporting the secondary beam to a scattering chamber.

The transverse acceptance of the A1200 spectrometer and beam transport lines is approximately 40π mm mrad, leading to a beamspot that is typically 9 mm in diameter, with a divergence of about 0.8° full width at half maximum (FWHM). In order to achieve the required angular resolution of better than 0.4°, we used a system that reconstructed the angle and position of each incident particle as it stuck the target. A schematic view of the experimental setup is given in Fig. 1. The incident particles were tracked onto the target using two x-y position-sensitive parallel plate avalanche counters (PPACs) separated by 1 m; their position resolution of 2 mm in the vertical and horizontal planes led to an angular uncertainty of 0.15° FWHM in the direction of the beam. The scattered particles were detected in one of three Si-CsI telescopes which spanned the angular range from 0° to 10° in the laboratory frame (the zero-degree telescope also monitored the composition and intensity of the ^{12,14}Be beam). All the telescopes consisted of a 300 μm thick by 5 cm square Si ΔE detector, a 300 μm thick by 5 cm square double-sided (x-y) strip detector having 16 strips in each direction, and a CsI stopping detector. The corresponding angular resolution was 0.19° in the forward telescopes and 0.44° in the backward telescope; multiple scattering in the 250 mg/cm^2 thick secondary target gave an additional contribution that was typically 0.3° FWHM. Thin scintillators placed just upstream of the first PPAC (see Fig. 1) and right after the A1200 (separation of 30 m) allowed us to measure the scattered particle energy to about 1.35%, corresponding to a total momentum resolution of 28 MeV/c FWHM (Fig. 2). While inferior to that obtained with the first method (19 MeV/c FWHM), this resolution is sufficient to make reasonably accurate width measurements for distributions as narrow as that observed for ^{11}Li ($\sim$45 MeV/c). Furthermore, the transverse acceptance of the apparatus ($\sim$250 MeV/c) is about 2–5 times greater than that of the A1200 in dispersion-matched mode, so that questions of spectrum distortion could easily be addressed. The beam energy at the center of the target was 56.75 ± 0.15 MeV per nucleon in this part of the experiment, for both ^{14}Be and ^{12}Be projectiles.

Energy distributions for some of the particles detected in the telescope at 100 cm, corrected for the energy

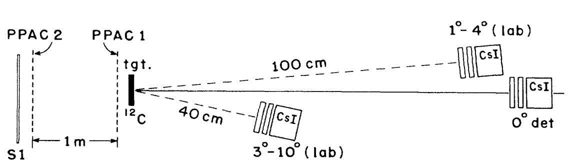

FIG. 1. Schematic diagram of the experimental setup for the telescope part of the experiment.

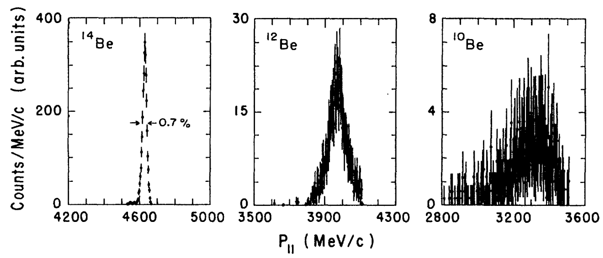

FIG. 2. Typical fragment momentum distributions observed via the CsI-Si telescopes. These were computed from the corresponding scattered-particle energy spectra, corrected for the incident particle energy using the time-of-flight information. The momentum resolution of the system (0.7% FWHM) was determined from the width of the ^{14}Be peak.

spread in the incident ^{14}Be beam using the time-of-flight information from the two scintillators and converted to momentum spectra, are shown in Fig. 2. Note that all these distributions were measured simultaneously without the need to reset the magnets as in the spectrometer method. The width of the ^{12}Be group is clearly quite narrow compared to that of ^{10}Be, which is the same effect as that noted previously [4,5] for ^{11}Li. All other fragment groups observed in this experiment (including ^{10}Be coming from ^{12}Be fragmentation) are as wide as the ^{10}Be group. We tried to fit various functional forms to the ^{12}Be data, and found that the most satisfactory result [Fig. 3(a)] was obtained with a single Lorentzian line shape $[\Gamma/2]^2/(p^2+[\Gamma/2]^2)$ having width $\Gamma=87.9\pm5.1$ MeV/c, when expressed in the ^{14}Be rest frame and after unfolding a Gaussian detector resolution function having

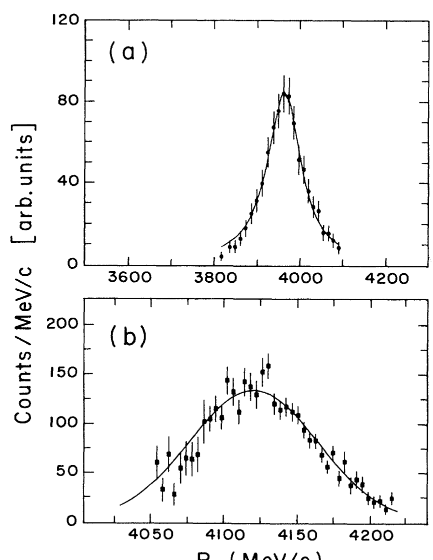

FIG. 3. (a) The ^{12}Be longitudinal momentum distribution from ^{14}Be fragmentation on ^{12}C at an incident energy of 56.8 MeV per nucleon, obtained via the telescope method. (b) The ^{12}Be longtindinal momentum distribution from ^{14}Be fragmentation on ^{12}C at an incident energy of 64.8 MeV per nucleon, obtained via the spectrograph method. See text for a discussion of the curves fit to these data.

FWHM=28 MeV/c. This line shape is expected from the Fourier transform of a simple Yukawa wave function for the valence neutrons [3]. The ratio of the width parameter to that of ^{11}Li is in good agreement with the factor of 2 deduced from the tighter binding of the two neutrons in ^{14}Be (1.31±0.011 MeV [7]) vs ^{11}Li (0.34±0.05 MeV [8]). The corresponding widths of the ^{10}Be distributions coming from fragmentation of ^{14}Be and ^{12}Be projectiles are $\Gamma=185\pm11$ and 194 ± 9 MeV/c, respectively. (These width parameters are also given in the projectile rest frame, after correction for the experimental momentum resolution.)

The longitudinal momentum distribution measured with the dispersion-matched mode of the A1200 spectrometer is shown in Fig. 3(b). The incident beam energy was 64.8±0.1 MeV per nucleon for this part of the experiment, the target thickness was 320 mg/cm^2, and the data were taken using three overlapping magnetic field settings. The best fit to this distribution is a single Gaussian having FWHM=95.6±4.2 MeV/c in the ^{14}Be frame, after applying corrections for the spectrometer and detector efficiencies and detector resolution. This value is consistent with that quoted above from the first method, within the mutual uncertainties of the two measurements. The two methods therefore give the same result for the width parameter, even for a distribution that is twice as broad as that for ^{11}Li. On the other hand, the two distributions do differ in the wings, with the first one extending out to larger values of the momentum such that a Lorentzian rather than a Gaussian line shape is more appropriate. This may be related to the spectral distortion expected from the limited transverse acceptance of the A1200 spectrometer (~125 and ~45 MeV/c in the horizontal and vertical planes, respectively, in this experiment) and the more limited range of ^{12}Be momenta.

The angular distribution obtained for the ^{12}Be fragmentation group is shown in Fig. 4. The cutoff at small momentum transfer (~80 MeV/c) was imposed to ensure that only particles interacting in the target are included in these data. The minimum required defection of 1° (3σ for the angular resolution) eliminates, for example, all events in which the ^{14}Be reacts in the zero-degree detector rather than in the target. The dashed curve is an extrapolation of the exponential behavior at large angle; the angular distributions for all of the other fragments observed with both beams follow this exponential trend. The solid curve is a fit to these data using the formula of Anne *et al.* [9], which is the appropriate functional form for a Lorentzian momentum distribution projected onto the scattering plane. The corresponding width parameter is $\Gamma=93.0\pm4.4$ MeV/c, in the small-angle approximation and expressed in the ^{14}Be rest frame after correction for multiple scattering effects in the target. This is the same value as that obtained for the longitudinal momentum distribution from the fits to the data in Fig. 3 above. It is tempting to speculate that the falloff of the data from the curve at larger values of the transverse momentum may be related to the deviation of the halo neutron wave function from a simple Yukawa form at small distances.

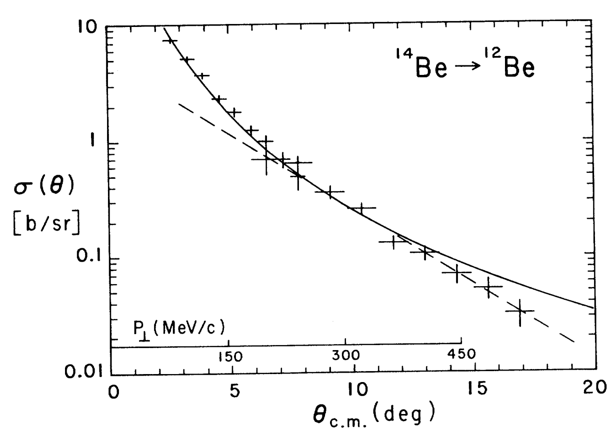

FIG. 4. The ^{12}Be angular distribution from ^{14}Be fragmentation on ^{12}C at an incident energy of 56.8 MeV per nucleon, obtained via the telescope method. The solid curve is a fit to the data using the formula given in Ref. [9], transformed to the ^{14}Be+^{12}C center-of-mass system. See text for further discussion.

We conclude that the transverse and longitudinal momentum distributions for the yield of ^{12}Be coming from the fragmentation of a 56 MeV per nucleon ^{14}Be beam on ^{12}C are much narrower than those for any other fragments produced with ^{12,14}Be beams, and they can be described by an intrinsic Lorentzian momentum distribution having a width parameter $\Gamma=92.2\pm2.7$ MeV/c. This result is in agreement with "neutron halo" structure for ^{14}Be. However, a naive interpretation of these fragment momentum distributions in terms of a "halo radius" for an $l=0$ point dineutron is apparently not meaningful here, as it leads to an rms halo radius of 3.0 fm, compared with 2.8 fm for the "normal" ^{12}Be core [1]. This small difference is then inconsistent with the much larger reaction cross section for ^{14}Be reported in Ref. [1], which suggests an rms halo radius of about 5.5 fm. Finally, we can compare our results with the measured [10] width of the neutron angular distribution ($\Gamma=50\pm5$ MeV/c) for fragmentation of ^{14}Be on a Be target. The ratio of the fragment to the neutron width of ~2 suggests a strong correlation between the two halo neutrons [3]. This might perhaps be expected due to the strong binding of the two neutrons in ^{14}Be ($S_{2n}=1.31$ MeV) and the fact that ^{13}Be is well unbound [11]: $S_n=-2.0\pm0.5$ MeV (though it is likely that this latter value does not correspond to the ground state, which is expected [11] to be less unbound by about 1.1 MeV). Thus, the n-n interaction must provide at least 2.3 MeV to produce the observed binding, compared to only about 0.5 MeV in the case of ^{11}Li.

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