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Momentum distributions of ^{9}Li fragments from the breakup of ^{11}Li and the neutron halo

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The inclusive parallel momentum distributions of ^{9}Li fragments from the breakup of a secondary ^{11}Li beam have been measured at 66 MeV/nucleon over a wide range of targets (^{9}Be to ^{238}U). The measurements were performed using a zero-degree fragment separator as an energy-loss spectrometer operating in a dispersion matched mode. Earlier measurements have been extended here to the case of breakup by ^{238}U where a distribution with a width of FWHM=38.1 $\pm$ 1.9 MeV/c was observed. Together with a remeasurement of breakup on ^{93}Nb (FWHM=42.8 $\pm$ 2.6 MeV/c) a weak dependence of distribution width on target nucleus was observed. A discussion of the nature of the momentum distributions and relationship to the structure of the halo is presented in the light of recent calculations. It is concluded that the ^{9}Li fragment parallel momentum distributions are relatively insensitive to the reaction and reflect the extended neutron distribution of the halo.

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I. INTRODUCTION

A fundamental aspect of the study of the nuclear system has long been the spatial extent and distribution of matter within the nucleus [1]. The availability of beams of nuclei far from stability in the last decade has enabled such studies to be extended over a broad range of isospin. In particular, there has been intense interest in recent years in the light, neutron-rich drip-line nuclei [2]. The experimental and theoretical activity surrounding these nuclei has derived from the discovery of the so-called "halo" whereby the very weak binding of the last neutron(s) leads to the formation of an extended matter distribution well beyond that expected from systematics. Such a distribution is quite unique, not only offering possible insights into the behavior of neutron matter but also access to nuclear matter at densities considerably different from that of normal or compressed nuclear matter. To date a number of examples of two-neutron halo systems have been discovered—^{6}He,[1] ^{11}Li, and ^{14}Be—while only one case of a one-neutron halo system is known—^{11}Be. The former are characterized, in addition to low two-neutron binding energies, by systems with one less neutron (e.g., ^{10}Li in the case of ^{11}Li) which are unbound. Clearly the interaction of the valence neutrons is vital to the stability of the two-neutron halo nuclei. Given that the free dineutron is also unbound (by $\sim$ 70 keV [3]) these nuclei also represent interesting examples of the three-body problem [4] in the limit of very weak binding [5] and as such have attracted a great deal of theoretical interest (see, for example, [6,7] and references therein).

The first nucleus found to exhibit such an extended neutron distribution and the one as a result most extensively studied is ^{11}Li ($S_{2n} = 295 \pm 26$ keV [8–11]). The earliest indications of such a structure resulted from measurements of the total interaction cross sections for secondary beams of light neutron-rich nuclei [12–14]. In particular, the observation for ^{11}Li of a cross section much larger than that expected on the basis of the systematics of the neighboring lithium isotopes suggested an abnor-

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[1]In the context of "halos" and "skins," ^{6}He (and ^{8}He) may be classed among the latter.

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mally large matter radius or a strong deformation [12]. The subsequent measurement of the spin ($I = \frac{3}{2}$) and a magnetic moment of $3.6673 \pm 0.0025\,\mu_N$ [15] very close to that of ^{9}Li ($3.4391 \pm 0.0006\,\mu_N$ [16]) and the single-particle Schmidt limit favored the former picture.

A measurement of the transverse momentum distribution of ^{9}Li fragments from the breakup of ^{11}Li on a carbon target at 0.79 GeV/nucleon [17] provided additional evidence for a halo structure. The observation of a narrow feature in the momentum distribution was interpreted, on the basis of the Goldhaber model of fragmentation [18], as due to an increased size associated with the two weakly bound valence neutrons. More recently measurements of single-neutron angular distributions [19,20] have been made and seen to exhibit very narrow, forward peaked distributions for the channel ^{9}Li + neutron. Moreover the distributions were almost identical in shape and width over a wide range of targets (Be, Ni, and Au)—such behavior again being consistent with a neutron distribution of large spatial extent.

Measurements of the total interaction [21–23], two neutron removal [22,23], and charge changing [24] cross sections over a wide range of targets, together with the quadrupole moments of ^{9}Li [25] and ^{11}Li [26] have further confirmed the existence of a long, low density tail in the neutron distribution. The measurements of Kobayashi *et al.* [23] of a very large Coulomb dissociation cross section were interpreted as supporting the proposed "soft dipole mode" for dissociation [27], in which a very large $E1$ strength is expected at very low excitation energy ($\sim$ 1 MeV). In an effort to search for this mode and further probe the structure of the half (e.g., the degree of correlation between the halo neutrons) kinematically complete measurements of the breakup, wherein the momenta of the incident ^{11}Li and the outgoing ^{9}Li and both neutrons are measured, have recently been undertaken [28–31]. A number of elastic scattering studies [32–34] have also been reported, all of which indicate the need to take account of the extended neutron distribution to reproduce the measurements.

Finally, it should also be noted that the β decay of ^{11}Li and other halo nuclei have been investigated. Initially these studies, which were begun prior to the discovery of the halo, were motivated by the possibility of many exotic forms of β-delayed particle emission, such behavior being due to the high Q_β (20.7 MeV) and weak binding of the daughter nucleus ^{11}Be ($S_n = 0.504 \pm 0.006$ MeV [35]). Indeed, delayed n [36], $2n$ [37], $3n$ [38], α [39], and τ [40] emission have been observed. As has been pointed out recently, the halo structure of the neutron-rich nuclei may manifest itself in β decay [41], whereby the transitions involving the weakly bound halo neutrons may account for the strong feeding of states high in excitation energy in the daughter within only a few MeV of the mother nucleus ground state. Additionally, correlations between the halo neutrons may exhibit themselves through β-delayed deuteron emission [42], a decay mode so far only observed for ^{6}He [43,44].

Given the relatively low production rates of nuclei at the drip line most of the experimental work to date has concentrated, as seen above, on relatively high-energy secondary reaction studies. In the present paper we report on a continuation and more detailed examination of our earlier measurements [45] of the parallel momentum distributions of ^{9}Li fragments from the breakup of ^{11}Li at intermediate energies ($\sim$ 66 MeV/nucleon). In particular we wish to investigate the relationship of the distributions to the structure of the halo.

A spacially extended distribution such as the halo is characterized, quantum mechanically, by a narrow distribution in momentum of the halo neutrons. Thus, in principle, the measurement of the momenta of the breakup products (neutrons or fragment) may serve as a measure of the nature of the halo. This approach, first employed by Kobayashi *et al.* [17], while attractive due to its simplicity, ignores any interfering effects arising from the reaction and experimental technique. As outlined in a recent paper [45], we have attempted to overcome some of the difficulties by measuring the parallel momentum distributions of the ^{9}Li fragments following the breakup of ^{11}Li. Importantly, by observing the core fragments only peripheral reactions are selected, i.e., reactions involving the removal of the neutrons from the halo—the weakly bound halo neutrons being very unlikely to remain bound following (the more violent) core neutron removal reactions. The measurement of the core fragments (^{9}Li) will, therefore, also provide information complementary to that from measurements of the neutron distributions in which, for example, a contribution from core-target reactions is expected [46]. It is worthwhile noting that measurements of the reaction cross sections only probe single-particle densities and are thus not particularly sensitive to the details of the wave functions (see, for example, [47]). In contrast, the momentum distributions offer a possible probe, for example, of the correlations between the halo neutrons.

The measurement of the parallel momenta has been undertaken as it negates the broadening effects introduced by Coulomb deflection and multiple scattering in the thick breakup targets that plague measurement of the transverse momenta. For example, the latter contributed $\sim$ 40 MeV/c (FWHM) to the ^{9}Li transverse momentum distribution in the case of breakup of ^{11}Li at 790 MeV/nucleon on a carbon target [17]—to be compared to a final distribution with FWHM = 70 MeV/c. Moreover, a contribution of $\sim$ 120 MeV/c was present in the case of a lead target, thus precluding any observation of a narrow structure in the momentum distribution. Additionally, the broadening effect of diffractive dissociation, of importance for light targets, is avoided by measurement of the parallel distributions. Indeed, recent calculations [48] employing a cluster model within the framework of the spectator model for breakup have suggested that the nuclear and Coulomb interactions should induce identical parallel momentum distributions which depend essentially on the Fourier transform of the ground-state wave function of the projectile.

In an effort to probe any differences due to the reaction mechanism governing the breakup, a range of targets from Z = 4 to 73 (^{9}Be, ^{93}Nb, and ^{181}Ta) were employed in our first study. Coulomb breakup, for example, is expected for heavy targets to dominate the reaction strength at the present energies [49]. The resulting momentum distributions were characterized by narrow widths that had only a relatively weak dependence on target (weighted average Gaussian widths from $\langle\sigma_{\rm Be}\rangle = 19.6 \pm 0.8$ MeV/c to $\langle\sigma_{\rm Ta}\rangle = 16.2 \pm 0.8$ MeV/c). In order to extend these measurements the present study with ^{93}Nb and ^{238}U breakup targets was undertaken.

The paper is organized as follows. In Sec. II a description of the experimental technique is presented. As this was only outlined in our earlier paper it is recapitulated in more detail here. Section III contains the results of the present measurements while Sec. IV provides a discussion of these results and those of the earlier study. The nature of the distributions and a comparison with some three-body calculations are also presented. Finally a summary and outlook is given in Sec. V.

II. EXPERIMENTAL TECHNIQUE

Presently the only available technique for the production of high-energy beams of nuclei far from stability is that of projectile fragmentation. While providing sufficiently intense beams ($\gtrsim$100 pps) for reaction-type studies the method suffers from a serious limitation for the present measurements, namely a large momentum spread in the secondary beam. This spread, which arises from the fragmentation reaction kinematics and thick target effects, is experimentally defined by the acceptance of the separator being used for the collection and purification of the reaction products—typically of the order of a few percent, thus corresponding to $\sim$ 100 MeV/c at intermediate energies. This must be compared to features in the breakup momentum spectra of interest of $\sim$ 20 MeV/c. To overcome such an inherently large spread two possibilities exist. First, the time of flight over a sufficiently long path length and hence the energy of each secondary beam particle may be measured [50]. Such a method is somewhat complicated in practice and may also suffer from losses in transporting a secondary beam of inherently high emittance.

A rather more elegant and potentially more powerful method is that of dispersion matching [51]. In practice, in the case of an achromatic device such as the A1200 separator [52], this technique simply involves the use of a secondary reaction target at a dispersive focal plane. Thus the second stage of the device acts as a dispersion matched spectrograph for the first stage. Consequently any energy-loss processes (i.e., reactions, straggling, etc.) are reflected by the position of the ion at the final focal plane as a result of the momentum analysis performed by the second stage. As noted in our first paper [45], by operating the A1200 as a zero-degree energy-loss spectrometer in such a dispersion matched mode a final momentum resolution of 0.3% (FWHM) was attained despite the large (3%) spread in the ^{11}Li beam.

In the present series of experiments, the secondary ^{11}Li beam was produced via the fragmentation on a 0.79 g/cm^2 ^{9}Be target of an 80 MeV/nucleon ^{18}O beam from the K1200 cyclotron of the National Superconducting Cyclotron Laboratory at Michigan State University. Collection of the ^{11}Li ions were performed using the first stage magnetic separation of the A1200. The mean energy of the secondary ^{11}Li beam was 66.11 MeV/nucleon and the energy spread 4 MeV/nucleon. With a collection acceptance of $\Delta\Omega \approx 0.8$ msr ("medium acceptance" mode) and a primary beam intensity of 50 particle nA, a rate of 500 ^{11}Li per second at the breakup target was obtained. In the earlier work a higher acceptance mode, $\Delta\Omega \approx 4.3$ msr (the so-called "high acceptance" mode), was also employed for some of the measurements. It should be noted, however, that while providing for a more intense ^{11}Li beam there was a corresponding decrease in the acceptance of the second half of the device for the collection of the ^{9}Li secondary fragments as well as a poorer resolution (as may be seen from the measured resolutions, Table I).

The breakup targets were placed at the second intermediate image plane and the second stage of the device, set to a mean rigidity $\frac{9}{11}$ that of the first stage, was used to momentum analyze the ^{9}Li fragments emitted around zero degrees ($\Delta\theta \approx 40$ mr and $\Delta\phi \approx 20$ mr). Two parallel plate avalanche counters (PPAC's) located approximately 40 cm apart and just upstream of the targets were used to determine the position and angles of the secondary beam. Thus it was possible to reject in the

TABLE I. Summary of experimental conditions and results.

Spectrometer mode[a]	Beam energy[b] (MeV/nucleon)	Target[c]	$\sigma_{\rm res}$[d] (MeV/c)	$\sigma(\pm)$[e] (MeV/c)	FWHM MeV/c
Medium	65.25	Be	4.1	20.5(1.4)	48.2(3.3)
High	66.24	Be	5.9	19.2(1.0)	45.1(2.3)
Medium	66.11	Nb	4.1	18.2(1.1)	42.8(2.6)
High	66.15	Nb	4.6	20.0(0.9)	47.0(2.1)
Medium	65.25	Ta	4.4	15.9(1.2)	37.4(2.8)
High	66.24	Ta	6.3	16.8(0.9)	39.5(2.1)
High	66.15	Ta	5.1	17.2(0.9)	40.4(2.1)
Medium	66.11	U	4.9	16.2(0.8)	38.1(1.9)

[a]Medium: $\Delta\theta \approx 40$ mr and $\Delta\phi \approx 20$ mr; high: $\Delta\theta \approx 30$ mr and $\Delta\phi \approx 15$ mr (see text).
[b]Mean energy of beam incident on target ($\Delta E/\langle E\rangle = 6\%$).
[c]Thicknesses in mg/cm^2: Be 202, Nb 256, Ta 298, and U 278.
[d]Experimental resolution.
[e]Width of fitted Gaussian distribution ($\pm$ uncertainty) in the ^{11}Li frame after accounting for experimental resolution and efficiency for collection of ^{9}Li ions.

off-line analysis any ions which were scattered in the first half of the device or impinged on the target frame or ladder.

Ion identification at the focal plane was performed using a combination of energy loss from a gas ionization detector and time of flight—cyclotron rf versus a plastic stop detector. The latter, it may be noted, due to the zero Q value of the breakup reaction was identical to that of ^{11}Li ions with the spectrometer stages set to equal rigidities for the transmission of the ^{11}Li secondary beam (this further simplified the identification of the ^{9}Li ions from breakup). The thick plastic stop detector located downstream of the ionization chamber provided redundant particle identification through the measurement of the residual energy of each ion. Two PPAC's separated by $\sim$ 40 cm and straddling the ionization chamber were used to determine the angles of entry of each ion arriving at the focal plane, thus providing for the rejection of any events scattered in the second half of the device. The position and hence momentum measurement was derived from the PPAC lying on the focal plane. The position was calibrated using a beam of ^{9}Li ions of known rigidity which was stepped across the focal plane. This measurement also facilitated a determination of the efficiency across the focal plane for the collection of reaction products by the second stage of the device. The same ^{9}Li beam was also used to determine the resolution of the device and PPAC's as well as target effects (see Table I).

III. RESULTS

As in the previous study the central 2% of the momentum distributions were sampled for each target and these are displayed in Fig. 1. A summary of the experimental conditions and final results are presented in Table I for both the present and the earlier [45] measurements. The results have been corrected for experimental resolution (spectrometer, detector, and target effects) and efficiency across the PPAC for the collection of the ^{9}Li ions by the second stage of the A1200. The final widths are quoted in the ^{11}Li frame.

The data are well characterized, as found in our first series of measurements, by single Gaussian distributions. It should be noted that the effect of the acceptance of the spectrometer on a three-dimensional Gaussian distribution (in the ^{11}Li frame) is only to lower the transmission efficiency while retaining the Gaussian line shape. At the present beam energy, distortions in the line shape in the laboratory frame are negligible. It was estimated, assuming a Gaussian distribution of width $\sigma = 20$ MeV/c that approximately 90% of the ^{9}Li ions are transmitted under the present experimental conditions.[2] In Fig. 2 a compilation of the widths measured in our present and pre-

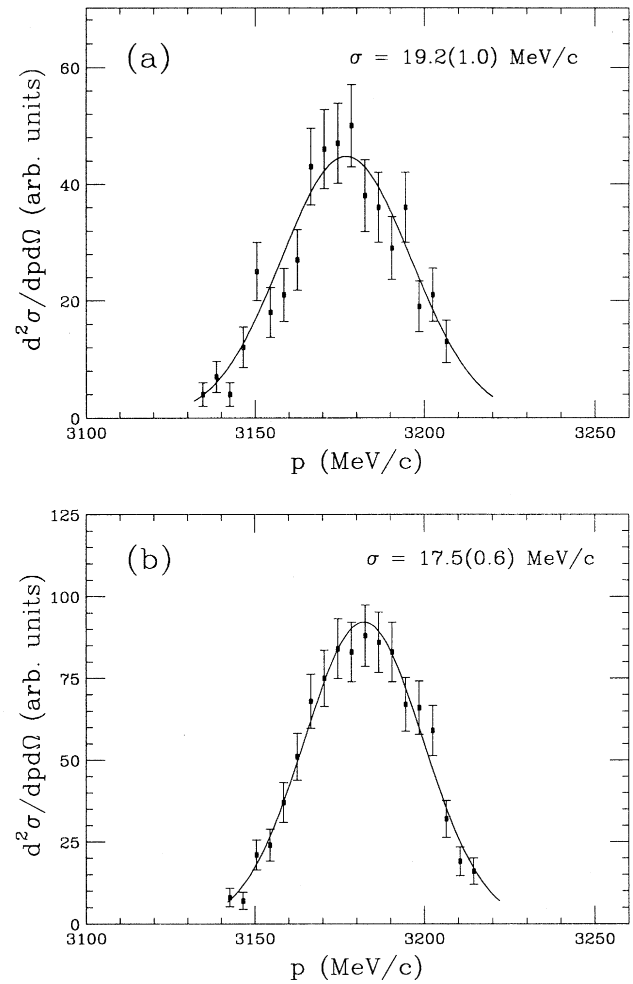

FIG. 1. Measured momentum distributions covering the central 2% of the breakup ^{9}Li momenta for (a) the ^{93}Nb and (b) the ^{238}U targets. Single Gaussian fits are shown *prior* to applying corrections (see text) by the solid line.

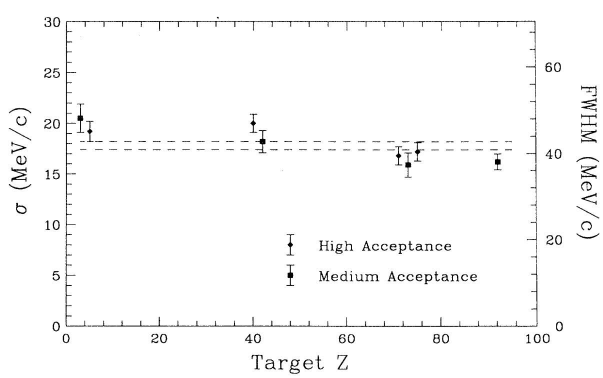

FIG. 2. Widths of the parallel momentum distributions versus Z of the breakup targets employed in the present and previous (Ref. [45]) work. The data are labeled according to the different optical modes of the whole device (see text). Note that in the cases of targets for which more than one measurement has been made the results have been slightly displaced in Z for clarity.

[2]The figure of 50% quoted in our earlier paper [45] referred to the more limited acceptance ($\Delta\theta \approx 30$ mr and $\Delta\phi \approx 10$ mr) used for some of the measurements.

vious studies is provided. For comparison the weighted average width, $\langle\sigma\rangle = 17.8 \pm 0.4$ MeV/c, of the eight measurements is also indicated. Although all the measurements are within two standard deviations of this, there is a small systematic decrease in width with increasing target Z; the decrease in width of the distributions from the ^{9}Be ($\langle\sigma\rangle = 19.6 \pm 0.4$ MeV/c) to the ^{238}U ($\sigma = 16.2 \pm 0.8$ MeV/c) breakup targets being 17 ± 6%. In addition, the corresponding FWHM, which are more readily compared to other available data, are also noted in Table I and Fig. 2. It should be noted that the choice of line shape for parametrizing the results is, for the most part, a matter of convenience that allows estimation of the effects of the finite acceptances. In order to relate the data to different theoretical descriptions it is more appropriate to make the comparison using model predictions calculated using the experimental acceptances (see Sec. IV).

IV. DISCUSSION

The results of our present and earlier series of measurements agree very well with the recent determination [28] of FWHM $= 42 \pm 9$ MeV/c for a measurement of the total momentum from the dissociation of a 28 MeV/nucleon ^{11}Li beam on Pb assuming a three-dimensional Gaussian distribution ($\sigma = 18 \pm 4$ MeV/c) in the ^{11}Li frame.

At much higher energies ($\sim$ 800 MeV/nucleon) measurements have been made, as noted in the Introduction, of the ^{9}Li transverse momentum with widths (FWHM) of 69 ± 5, 62 ± 5, and 170 ± 35 MeV/c observed for fragmentation on d [47], C [47], and Pb [17] targets, respectively.[3] The distributions have been interpreted, for the two lightest targets, in terms of two Gaussian components with widths of $\sigma \approx 20$ MeV/c and $\sigma \approx 80$ MeV/c. The narrow feature was associated with reactions in which the two weakly bound halo neutrons are removed and the broader with the removal of core neutrons—the latter being consistent with the widths observed for the fragmentation of normally bound nuclei. Such a picture is, however, untenable as the core fragmentation reactions, i.e., those involving the removal of core neutrons and subsequent decay without particle emission of the excited ^{9}Li (a highly unlikely process), must contribute, based on the areas of the two components in the momentum distributions, $\sim$ 60–70 % of the reaction strength.

The apparent discrepancy between these results and the present data may arise from those effects which influence the transverse momenta and not the parallel. As noted earlier, the measurement made for the Pb target was almost certainly dominated by the multiple scattering in the (relatively) thick breakup target. In the case of the light target measurements, calculations including the nuclear effects in the breakup of ^{11}Li have been made by Barranco, Vigazzi, and Broglia [53] for the ^{9}Li momentum distributions, employing the same model as for their calculations of the single-neutron angular distributions [54]. The calculations predict a significant influence on the transverse momenta of diffractive dissociation, corresponding to a broad component of similar width and magnitude as that observed [17]. Interestingly a much narrower component (again of similar width to that observed) arising from absorption of a halo neutron is predicted.

We now turn to the question of the nature of the momentum distributions measured in our work. As is evident from Fig. 2, the ^{9}Li parallel momentum distributions are relatively insensitive to the target nucleus and, therefore, presumably on the interaction inducing the breakup. Such a result, as outlined earlier, suggests that the inclusive parallel momentum distribution of the ^{9}Li fragments may provide a measure of the two-neutron halo in ^{11}Li. Indeed, in the Serber model [55] the resulting inclusive fragment momentum distribution is interpreted as a measure, via the Fourier transform, of the internal ground-state wave function of the projectile. There are a number of factors, however, that may render this "sudden approximation" invalid; namely the influence of the reaction mechanism and final-state interactions.

In the case of breakup on heavy targets the reaction is believed to be dominated at intermediate energies by Coulomb breakup [49]. As this process is mediated by the dipole operator the reaction will, for example, in the case of a 0^{+} initial state populate a 1^{-} final state. The result will be an anisotropic distribution of the breakup products and distributions characteristic of this have been observed, for example, in both the single-neutron [46,56] and ^{10}Be [57] angular distributions from the breakup of ^{11}Be on a heavy target. Moreover, both relatively simple [58] and detailed three-body calculations [49,59] of the Coulomb breakup of ^{11}Li demonstrate a sensitivity of the dipole strength distribution and consequently the momentum distributions on not only the n-n correlations in the ground state but also the n-n and n-core final-state interactions.

In the case of light target breakup the much shorter range of the nuclear interaction which mediates the breakup implies a very short reaction time scale (on the order of the nuclear transit time of the projectile) and a process, in principle, close to that of the sudden approximation. In the peripheral direct reaction description formulated by Hüfner and Nemes [60] the fragment momentum distribution reflects the momentum distribution of the nucleon removed from the surface of the projectile. Although developed to describe the very high energy fragmentation (> 500 MeV/nucleon) of normal nuclei, such an approach should remain valid at lower energies for weakly bound nuclei. This approach has been applied to ^{11}Li by Sagawa and Takagawa [61] using the simple dineutron cluster wave function [27]. The calculated parallel momentum distributions for breakup on a ^{9}Be target are in very good agreement with the present results—FWHM = 46 MeV/c compared to a weighted

[3]Note that the results displayed in Fig. 2 of Ref. [47] have not been corrected for experimental effects, such as multiple scattering. The widths quoted here are derived from the results of the fits as given on the figures, which do include these effects.

average here for the ^{9}Be target of 46 ± 2 MeV/c. The caveat must be added, however, that such calculations do not include final-state interactions. In particular, possible sequential processes must also be considered. In the case of nuclear breakup, unless the neutrons are highly spatially correlated (a dineutron), breakup might proceed via the removal of one halo neutron followed by the subsequent particle decay of ^{10}Li. In such a process, the ^{9}Li momentum distribution would measure the single neutron distribution in ^{11}Li modified by the effects of the recoil neutron from decay of ^{10}Li. Such effects are included in the calculations of Barranco, Vigazzi, and Broglia [53] whereby nuclear induced breakup—diffraction or absorption—proceeds via ^{10}Li (with a resonance at very low energy) and a simple independent particle model for the halo neutrons, which reproduces the neutron density of ^{11}Li, is employed. The resulting distribution is relatively narrow but considerably wider (FWHM = 61 MeV/c) than that observed here. This result is of course dependent on the properties of ^{10}Li (a subject of some debate as described later) and the validity of a simple independent particle description for the halo neutrons.

Thus, while it is a simplification to directly link the inclusive ^{9}Li fragment parallel momentum distributions to the ground-state wave function of the ^{11}Li projectile, the distributions do reflect an extended valence neutron distribution. This may be demonstrated using the simple zero range Yukawa for the spatial wave function (first introduced by Hansen and Jonson [27] in the context of a ^{9}Li core plus dineutron, $l = 0$, model) the form of which should provide a reasonable description of the asymptotic behavior of the wave function (i.e., the region from where the majority of the strength for peripheral reactions should arise),

$$\psi(\mathbf{r}) = 1/\sqrt{2\pi\rho}\exp(-\mathbf{r}/\rho)/\mathbf{r}$$

where ρ is the range parameter. We note that in order to calculate the shape of the momentum distribution it is not necessary to consider the finite-size correction for the potential [27]. The momentum distribution is therefore, via the Fourier transform, a Lorentzian of the form

$$d\sigma/d\mathbf{p} \sim \Gamma/[\mathbf{p}^2 + \Gamma^2/4]^2 \ ,$$

where $\Gamma = 2\hbar/\rho$ and the distribution projected on the axis parallel to the beam direction is (for very large transverse acceptances)

$$d\sigma/dp_{\|} \sim \Gamma/[p_{\|}^2 + \Gamma^2/4]$$

with FWHM = Γ [62]. Such a distribution is almost identical to a Gaussian distribution over the central region (Fig. 3). The width of the momentum distribution can then be used to estimate the range parameter and hence give an indication of the size of the halo. The effect of the finite acceptances used here on such an intrinsic Lorentzian momentum distribution is illustrated in Fig. 3. The effect is a reduction, with respect to Γ, of the observed width (FWHM) and a reduction in the

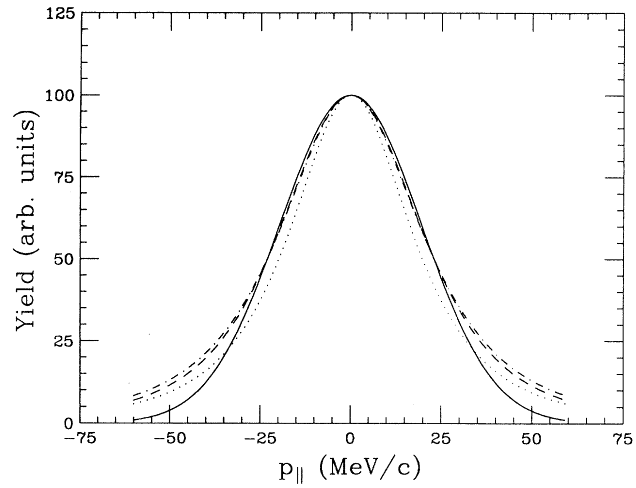

FIG. 3. Effects of the finite angular acceptances on the parallel momentum distributions (in the projectile frame). Solid line: Gaussian distribution, FWHM = 46 MeV/c. Dashed line: Lorentzian distribution, Γ = 46 MeV/c, very large acceptances, FWHM = 46 MeV/c. Dotted line: Lorentzian distribution, Γ = 46 MeV/c, $\Delta\theta \approx 40$ mr, and $\Delta\phi \approx 20$ mr (medium acceptance—see text), FWHM = 39.5 MeV/c. Dot-dashed line: Lorentzian distribution, Γ = 55 MeV/c, $\Delta\theta \approx 40$ mr, and $\Delta\phi \approx 20$ mr, FWHM = 46 MeV/c. For ease of comparison the curves have been normalized to the same peak yield.

strength of the distribution at large and small momenta.[4] Hence, to reproduce the observed width, the Γ parameter of the intrinsic distribution must be somewhat larger—$\sim$ 15% and $\sim$ 27% for the medium and high acceptance measurements, respectively—than the measured FWHM. Thus, for the ^{9}Be target, $\Gamma \approx 56$ MeV/c and $\rho \approx 7$ fm. The corresponding rms halo radius ($\langle r^2\rangle^{1/2} \approx \rho/\sqrt{2}$ neglecting the finite-size correction) is about 5 fm. This can be compared to the ^{9}Li rms matter radius of 2.3 fm [14] and to a rms halo radius of $\sim$ 5 fm for ^{11}Li derived from Glauber model analyses of interaction cross-section measurements [47,63]. A rms halo radius of 4.6 fm is obtained if the range parameter is deduced simply from the two-neutron binding energy (ε) and the reduced mass (μ) – $\varepsilon = 0.3$ MeV and $\rho = \hbar/\sqrt{2\mu\varepsilon} = 6.5$ fm. It should be noted, however, that rms radii furnish a somewhat deceptive comparison as they are strongly dependent on the profile of the density distribution.

As noted above, the model and approach used are simplistic and are only intended to illustrate the extended nature of the neutron distribution and the possible effects of finite spectrometer acceptances. Indeed the results from our present series of experiments when compared

[4]Such a departure from the form prescribed by the asymptotic wave function is also expected at large relative momenta as these momenta correspond to small core-neutron separations.

to the single-neutron angular distributions would appear to be consistent, in a simple picture, with the emission of spatially uncorrelated neutrons—$\Gamma_9 = \sqrt{2}\Gamma_n$ [2]. The results of a recent kinematically complete measurement of the breakup of ^{11}Li also appear to favor the existence of the halo neutrons in a relatively uncorrelated state [28], as may the very weak β-delayed deuteron branching ratio—at present only an upper limit has been determined [64]. Such a result is not surprising as recent studies of ^{10}Li [65–67] appear to support theoretical predictions [68,69] that the ground state is only very weakly ($\sim$ 150 keV) unbound—most probably with the last neutron occupying the $2s_{1/2}$ single-particle orbital. Thus, the interaction of the two valence neutrons in ^{11}Li need only provide about 500 keV of binding energy.

Turning now to more detailed theoretical descriptions of ^{11}Li, a large variety of approaches have been employed, ranging from mean-field theories [70,71] and the shell model [72,73] to two-body [27] and three-body [74–76] cluster descriptions. Due to the importance of correlations at some level to ^{11}Li, mean-field calculations are expected to have limited validity. Similarly, any classical shell-model approach requires an untractably large basis to provide an accurate description. Although some limited success has been obtained by two-body cluster model calculations, the lack of evidence for any very strong spatial correlation between the halo neutrons suggests that a more realistic view of ^{11}Li may be provided by true three-body calculations.

A wide variety of approaches has been applied to the three-body description with varying degrees of complexity and success. In particular, variational calculations [74], the hyperspherical harmonics method [77], the coordinate space Fadeev approach [78], and the Green's function method [75] have been used. All have treated ^{11}Li as an inert ^{9}Li core together with two valence neutrons and all have required information on the ^{9}Li $+n$ interaction. The structure of ^{10}Li is, however, far from well known with various experiments providing evidence for resonances at $S_n = -0.80$ MeV [79,80], -0.54 MeV [67], -0.42 MeV [80], and -0.150 MeV [65–67]. The former three have been interpreted as corresponding to $\nu 1p_{1/2}$ single-particle states. The lowest lying would, however, most probably correspond, given the systematics of the $N = 7$ isotones [68] and the recent shell-model calculations [69], to a $\nu 2s_{1/2}$ intruder state such as that which occurs as the ground state of ^{11}Be [81]. As noted by McVoy and Van Isacker [82] and Young [67], the positions of these levels close to threshold are dependent on the associated line shapes.

In our earlier paper [45] the results obtained for breakup on the Ta target were compared to the Coulomb dissociation predictions of the three-body model of Esbensen and Bertsch [59] and found to be in very good agreement. More recently these calculations have been extended [49] to predict the distributions observed in the kinematically complete measurement [28,29]. While reproducing well the n-n relative momenta and single-neutron momentum distribution, the predictions do not compare well with the measured ^{9}Li total momentum distribution and decay energy spectrum. The deviations between theory and experiment were ascribed to the effects of Coulomb postacceleration [49]. Importantly, the calculations were adjusted to produce a $p_{1/2}$ ^{9}Li $+n$ resonance at 0.8 MeV and a two-neutron separation energy for ^{11}Li of 0.2 MeV. It would thus be interesting to see the effects of the inclusion of a low lying s-wave ^{9}Li $+n$ resonance and a stronger binding for ^{11}Li.

The effects of such a low lying resonance have been studied recently within the framework of the three-body Faddeev calculations by Thompson and Zhukov [83]. They have found, after comparing various combinations of the positions of the s- and p-wave resonances, that the inclusion of a low lying s-wave resonance significantly alters the ground-state wave function of ^{11}Li from one dominated by the $\nu(1p_{1/2})^2$ configuration to one containing a considerable admixture (up to $\sim$ 60%) of $\nu(2s_{1/2})^2$. Previous calculations assuming only a p-wave resonance [78] gave momentum distributions much broader than those observed in the present work. However, with an s-wave resonance located just above the ^{9}Li $+n$ threshold and a p-wave resonance at $\sim$ 0.3 MeV, the ^{9}Be target data are well reproduced, as shown in Fig. 2(b) of [83] where the effects of the finite acceptances of the present experiment have been included. That such a significant s-wave admixture results in a narrower momentum distribution is not surprising as the centrifugal barrier is reduced, thus leading to an increased halo size. The calculations also reproduce well the ^{11}Li two-neutron separation energy and matter density [6]. It should be noted, that the momentum distributions were predicted on the basis of the Serber model and hence assume the effects of the reaction mechanism and final-state interactions to be negligible.

V. CONCLUSIONS AND OUTLOOK

As is clearly evident from the foregoing discussion one of the most complicating aspects (and also one of the most intriguing) is the three-body nature of ^{11}Li. In particular, the effects of sequential decay and other final-state interactions may distort the momentum distributions. The former has been suggested [84,85] to be of particular importance for the single-neutron distributions. As we have also seen, considerable uncertainty surrounds the ^{11}Li ground-state wave function. A handle on some of these problems can be gained, however, from corresponding studies of the one-neutron halo nucleus ^{11}Be. Importantly the ground-state structure of ^{11}Be is well established (77% $\nu 2s_{1/2}$ [81]) and breakup, at least in the case of a heavy target, is direct [57].

In this spirit we have recently studied the parallel momentum distributions of the ^{10}Be fragments from the breakup of ^{11}Be at 63 MeV/nucleon using the techniques presented here [86]. The resulting distributions displayed no dependence on the breakup target and could be well reproduced by the momentum distribution derived from a single-particle ($\nu 2s_{1/2}$) shell-model ground state. The single-neutron angular distributions have also been measured [56] and found to be equally well reproduced for breakup on a Au target using the same wave function in conjunction with Coulomb dissociation. The simple zero range wave function (as defined by the single-neutron binding energy and reduced mass) was also, in both cases, found to give a good description of the data. Furthermore, the very recent kinematically complete measurement of the breakup of ^{11}Be at 72 MeV/nucleon on a Pb target [57] found a dipole strength distribution which could be well described using the zero range wave function and direct breakup. This confirms, as pointed out by Anne *et al.* [56], that the halo manifests itself through the asymptotic behavior of the wave function. Moreover, these results indicate that the core-n and target-n final-state interactions do not significantly affect the distributions. Additionally, while Coulomb breakup does affect the transverse neutron distributions the effect on the parallel ^{10}Be core distributions is apparently very small. If we extend these results to ^{11}Li, we might conclude that the parallel distributions from the Coulomb breakup represent, to a first approximation, that of the ^{11}Li ground state modified by the n-n final-state interaction.

As we have seen, the data for breakup on a light target seem to be fairly well reproduced by peripheral direct reaction models employing simple wave functions (see, for example, [61]). Interestingly preliminary measurements of ^{9}Li $+n$ coincidences from the breakup of ^{11}Li on a light target [84] indicate that sequential breakup may occur, though the influence on the inclusive core distributions is thought to be small. The first attempts to calculate these effects have, however, found inclusive ^{9}Li parallel momentum distributions much broader than measured [53].

It is obvious from an experimental viewpoint that further kinematically complete measurements of breakup on both light and heavy targets at intermediate and very high energies are required. Additionally, the investigation of the parallel distributions at very high energies (several hundred MeV/nucleon) will provide a more stringent test in the Serber model limit as well as obviating, as a result of the very strong forward focusing of reaction products, any uncertainties regarding the intrinsic form of the momentum distributions due to finite acceptances. Preliminary results [87,88] from these measurements seem to support the data obtained in the present work.

Another approach to approximating the Serber limit is that of the so-called restricted inclusive measurements [46]. Here neutrons in coincidence with any charged fragment other than the core of the halo system are measured; such reactions corresponding to those involving core-target interactions. Thus, given the large average core-neutron separation, these reactions should leave the neutron in a relatively unperturbed state, i.e., approximating a sudden removal of the core (an approach complementary to that presented here whereby reactions in which the halo neutron is removed are observed). Following the preliminary work using a ^{11}Be beam [46], more complete investigations of this and the ^{11}Li system are underway [87,89,90].

The greater part of the work to date on neutron halo nuclei has been directed toward the two $A = 11$ systems ^{11}Li and ^{11}Be and to a lesser extent ^{6}He. While proving very fruitful it is necessary to extend our view to encompass other systems in order to understand better the halo through, for example, the evolution with binding energy and orbital angular momentum of the constituent neutrons. To this end other weakly bound nuclei, such as ^{14}Be [50,91], which represent candidate halo systems (see Table II) should be investigated. Work on β-delayed deuteron decay would also seem to offer a possible source of information on correlations in the two-neutron halos [42,92], as may direct reaction experiments involving the transfer of two neutrons, e.g., $p(^{11}\text{Li}, {}^9\text{Li})\,t$—the branching ratios and reaction cross sections, respectively, being enhanced in the case of a strong spatial n-n correlation in the halo.

TABLE II. Weakly bound, light, neutron-rich nuclei.

Nucleus	S_n [a] (keV)	S_{2n} [a] (keV)
^{6}He		973 ± 1
^{11}Li		297 ± 26 [b]
^{11}Be	504 ± 6	
^{14}Be		1340 ± 110
^{14}B	970 ± 21	
^{17}B		1390 ± 140
^{17}C	729 ± 18	
^{19}B		500 ± 420 [c]
^{19}C	160 ± 110	
^{22}C		1120 ± 930 [c]
^{22}N	1220 ± 220	
^{27}F	1310 ± 440	
^{29}F		900 ± 710 [c]
^{29}Ne	1330 ± 320	

[a] From the compilation of Audi and Wapstra [35].
[b] References [8–11].
[c] Extrapolated from measured masses [35].

Finally, in terms of the development of theoretical models for ^{11}Li it is clearly apparent that the uncertainties in the low-lying level structure of ^{10}Li must be resolved. It would also be desirable to have a detailed model of the nuclear breakup, including a realistic ground-state wave function and final-state interactions, such as has been developed for ^{6}He [85] and for the Coulomb breakup of ^{11}Li [49,59].

In summary, we have undertaken a study of the target systematics of the inclusive parallel momentum distributions of ^{9}Li fragments from the breakup of ^{11}Li. Distributions with narrow widths (FWHM $\approx$ 42 MeV/c) which are only weakly dependent on the target nucleus were observed. It is concluded that these distributions reflect the extended valence neutron distribution of ^{11}Li.

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[1] See, for example, Roger C. Barrett and Daphne F. Jackson, *Nuclear Sizes and Structure* (Oxford University Press, Oxford, England, 1979); C. J. Batty, E. Friedman, H. J. Gils, and H. Rebel, Adv. Nucl. Phys. **19**, 1 (1989).

[2] See, for example, P. G. Hansen, in *Proceedings of the International Conference on Nuclear Physics,* Wiesbaden, Germany, 1992 [Nucl. Phys. **A553**, 465c (1993)]; K Riisager, Rev. Mod. Phys. **66**, 1105 (1994); A. C. Mueller and B. M. Sherrill, Annu. Rev. Nucl. Part. Sci. **43**, 529 (1993).

[3] Kamal K. Seth and Brett Parker, Phys. Rev. Lett. **66**, 2448 (1991).

[4] V. Efimov, Comments Nucl. Part. Phys. **19**, 271 (1990).

[5] D. V. Fedorov, A. S. Jensen, and K. Riisager, Phys. Lett. B **312**, 1 (1993); Phys. Rev. C **49**, 201 (1994); **50**, 2372 (1994).

[6] I. J. Thompson, in *Proceedings of the 3rd International Conference on Radioactive Nuclear Beams,* East Lansing, Michigan, 1993, edited by D. J. Morrissey (Editions Frontières, Gif-sur-Yvette, 1993), p. 199.

[7] H. Esbensen, in [6], p. 189.

[8] B. M. Young, W. Benenson, M. Fauerbach, J. H. Kelley, R. Pfaff, B. M. Sherrill, M. Steiner, J. S. Winfield, T. Kubo, M. Hellstöm, N. A. Orr, J. Stetson, J. A. Winger, and S. J. Yennello, Phys. Rev. Lett. **71**, 4124 (1993).

[9] C. Thibault, R. Klapisch, C. Rigaud, A. M. Poskanzer, R. Prieels, L. Lessard, and W. Reisdorf, Phys. Rev. C **12**, 644 (1975).

[10] J. M. Wouters, R. H. Kraus, Jr., D. J. Vieira, G. W. Butler, and K. E. G. Löbner, Z. Phys. A **331**, 229 (1988).

[11] T. Kobayashi, K. Naki, R. Gilman, H. Baer, S. Greene, J. M. O'Donnell, H. T. Fortune, M. Kagarlis, K. Johnson, and S. Mukhopadyay, KEK Report No. 91-22, 1991 (unpublished).

[12] I. Tanihata, H. Hamagaki, O. Hashimoto, Y. Shida, N. Yoshikawa, K. Sugimoto, O. Yamakawa, T. Kobayashi, and N. Takahashi, Phys. Rev. Lett. **55**, 2676 (1985).

[13] I. Tanihata, H. Hamagaki, O. Hashimoto, S. Nagamiya, Y. Shida, N. Yoshikawa, O. Yamakawa, K. Sugimoto, T. Kobayashi, D. E. Greiner, N. Takahashi, and Y. Nojiri, Phys. Lett. **106B**, 380 (1985).

[14] I. Tanihata, T. Kobayashi, O. Yamakawa, S. Shimoura, K. Ekuni, K. Sugimoto, N. Takahashi, T. Shimoda, and H. Sato, Phys. Lett. B **206**, 592 (1988).

[15] ISOLDE Collaboration, E. Arnold, J. Bonn, R. Gegenwart, W. Neu, R. Neugart, E. W. Otten, G. Ulm, and K. Wendt, Phys. Lett. B **197**, 311 (1987).

[16] F. D. Correll, L. Madansky, R. A. Hardekopf, and J. W. Sunier, Phys. Rev. C **28**, 862 (1983).

[17] T. Kobayashi, O. Yamakawa, K. Omata, K. Sugimoto, T. Shimoda, N. Takahashi, and I. Tanihata, Phys. Rev. Lett. **60**, 2599 (1988).

[18] A. S. Goldhaber, Phys. Lett. **53B**, 305 (1974).

[19] R. Anne, S. E. Arnell, R. Bimbot, H. Emling, D. Guillemaud-Mueller, P. G. Hansen, L. Johannsen, B. Jonson, M. Lewitowicz, S. Mattsson, A. C. Mueller, R. Neugart, G. Nyman, F. Pougheon, A. Richter, K. Riisager, M. G. Saint-Laurent, G. Schrieder, O. Sorlin, and K. Wilhelmsen, Phys. Lett. B **250**, 19 (1990).

[20] K. Riisager, R. Anne, S. E. Arnell, R. Bimbot, H. Emling, D. Guillemaud-Mueller, P. G. Hansen, L. Johannsen, B. Jonson, A. Latimier, M. Lewitowicz, S. Mattsson, A. C. Mueller, R. Neugart, G. Nyman, F. Pougheon, A. Richard, A. Richter, M. G. Saint-Laurent, G. Schreider, O. Sorlin, and K. Wilhelmsen, Nucl. Phys. **A540**, 365 (1992).

[21] B. Blank, J.-J. Gaimard, H. Geissel, K.-H. Schmidt, H. Stelzer, K. Sümmerer, D. Bazin, R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, H.-G. Clerc, and M. Steiner, Z. Phys. A **340**, 41 (1991).

[22] B. Blank, J.-J. Gaimard, H. Geissel, K.-H. Schmidt, H. Stelzer, K. Sümmerer, D. Bazin, R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, H.-G. Clerc, and M. Steiner, Nucl. Phys. **A555**, 408 (1993).

[23] T. Kobayashi, S. Shimoura, I. Tanihata, K. Katori, K. Matusa, T. Minamisono, K. Sugimoto, W. Müller, D. L. Olson, T. J. M. Symons, and H. Wieman, Phys. Lett. B **232**, 51 (1989).

[24] B. Blank, J.-J. Gaimard, H. Geissel, K.-H. Schmidt, H. Stelzer, K. Sümmerer, D. Bazin, R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, H.-G. Clerc, and M. Steiner, Z. Phys. A **343**, 375 (1992).

[25] ISOLDE Collaboration, E. Arnold, J. Bonn, W. Neu, R. Neugart, and E. W. Otten, Z. Phys. A **331**, 295 (1988).

[26] ISOLDE Collaboration, E. Arnold, J. Bonn, A. Klein, R. Neugart, M. Neuroth, E. W. Otten, P. Lievens, H. Reich, and W. Widdra, Phys. Lett. B **281**, 16 (1992).

[27] P. G. Hansen and B. Jonson, Europhys. Lett. **4**, 409 (1987).

[28] D. Sackett, K. Ieki, A. Galonsky, C. A. Bertulani, H. Esbensen, J. J. Kruse, W. G. Lynch, D. J. Morrissey, N. A. Orr, B. M. Sherrill, H. Schulz, A. Sustich, J. A. Winger, F. Deák, Á. Horváth, Á. Kiss, Z. Seres, J. J. Kolata, R. E. Warner, and D. L. Humphrey, Phys. Rev. C **48**, 118 (1993); D. Sackett, Ph.D. thesis, Michigan State University, 1993; A. Galonsky, NSCL Report No. MSUCL-951, 1994 and in *Proceedings of CORINNE II–International Workshop on Multiparticle Correlations and Nuclear Reactions,* Nantes, France, 1994 (unpublished).

[29] K. Ieki, D. Sackett, A. Galonsky, C. A. Bertulani, J. J. Kruse, W. G. Lynch, D. J. Morrissey, N. A. Orr, H. Schulz, B. M. Sherrill, A. Sustich, J. A. Winger, F. Deák, Á. Horváth, Á. Kiss, Z. Seres, J. J. Kolata, R. E. Warner, and D. L. Humphrey, Phys. Rev. Lett. **70**, 730 (1993).

[30] G. Schrieder, in *Proceedings of the 6th International Conference on Nuclei Far from Stability* and *9th International Conference on Atomic Masses and Fundamental Constants,* Bernkastel-Kues, Germany, 1992, edited by

R. Neugart and A. Wöhr (IOP, Bristol, 1993), p. 369.
[31] S. Shimoura, T. Nakamura, M. Ishihara, N. Inabe, T. Kobayashi, T. Kubo, R. H. Siemssen, and I. Tanihata, in [30], p. 271.
[32] J. J. Kolata, M. Zahar, R. Smith, K. Lampkin, M. Belbot, R. Tighe, B. M. Sherrill, N. A. Orr, J. S. Winfield, J. A. Winger, S. J. Yennello, G. R. Satchler, and A. H. Wuosmaa, Phys. Rev. Lett. **69**, 2631 (1992).
[33] C.-B. Moon, M. Fujimaki, S. Hirenzaki, N. Inabe, K. Katori, J. C. Kim, Y. K. Kim, T. Kobayashi, T. Kubo, H. Kumagai, S. Shimoura, T. Suzuki, and I. Tanihata, Phys. Lett. B **297**, 39 (1992).
[34] M. Lewitowicz, C. Borcea, F. Carstoiu, M. G. Saint-Laurent, A. Kordyasz, R. Anne, P. Roussel-Chomaz, R. Bimbot, V. Borrel, S. Dogny, D. Guillemaud-Mueller, A. C. Mueller, F. Pougheon, F. A. Gareev, S. N. Ershov, S. Lukyanov, Yu. Penionzhkevich, S. Skobelev, S. Tretyakova, Z. Dlouhy, L. Nosek, and J. Svanda, Nucl. Phys. **A562**, 301 (1993).
[35] G. Audi and A. H. Wapstra, Nucl. Phys. **A565**, 66 (1993).
[36] E. Roeckl, P. F. Dittner, C. Détraz, R. Klapisch, C. Thibault, and C. Rigaud, Phys. Rev. C **10**, 1181 (1974).
[37] R. E. Azuma, L. C. Carraz, P. G. Hansen, B. Jonson, K.-L. Kratz, S. Mattsson, G. Nyman, H. Ohm, H. L. Ravn, A. Schröder, and W. Zeigert, Phys. Rev. Lett. **43**, 1652 (1979).
[38] R. E. Azuma, T. Björnstad, H. A. Gustafsson, P. G. Hansen, B. Jonson, S. Mattsson, G. Nyman, A. M. Poskanzer, and H. L. Ravn, Phys. Lett. **96B**, 31 (1980).
[39] M. Langevin, C. Détraz, D. Guillemaud, F. Naulin, M. Epherre, R. Klapisch, S. K. T. Mark, M. de Saint Simon, C. Thibault, and F. Touchard, Nucl. Phys. **A366**, 449 (1981).
[40] ISOLDE Collaboration, M. Langevin, C. Dètraz, M. Epherre, D. Guillemaud-Mueller, B. Jonson, and C. Thibault, Phys. Lett. **146B**, 176 (1984).
[41] ISOLDE Collaboration, M. J. Borge, P. G. Hansen, L. Johannesen, B. Jonson, T. Nilsson, G. Nyman, A. Richter, K. Riisager, O. Tengblad, and K. Wilhelmsen, Z. Phys. A **340**, 255 (1991).
[42] B. Jonson and G. Nyman, in *Handbook of Nuclear Decay Modes* (unpublished).
[43] ISOLDE Collaboration, K. Riisager, M. J. G. Borge, H. Gabelmann, P. G. Hansen, L. Johannsen, B. Jonson, W. Kurcewicz, G. Nyman, A. Richter, O. Tengblad, and K. Wilhelmsen, Phys. Lett. B **235**, 30 (1990).
[44] ISOLDE Collaboration, M. J. G. Borge, L. Johannsen, B. Jonson, T. Nilsson, G. Nyman, K. Riisager, O. Tengblad, and K. Wilhelmsen Rolander, Nucl. Phys. **A560**, 664 (1993).
[45] N. A. Orr, N. Anataraman, Sam M. Austin, C. A. Bertulani, K. Hanold, J. H. Kelley, D. J. Morrissey, B. M. Sherrill, G. A. Souliotis, M. Thoennessen, J. S. Winfield, and J. A. Winger, Phys. Rev. Let. **69**, 2050 (1992).
[46] R. Anne, R. Bimbot, S. Dogny, H. Emling, D. Guillemaud-Mueller, P. G. Hansen, P. Hornshøj, F. Humbert, B. Jonson, M. Keim, M. Lewitowicz, P. Møller, A. C. Mueller, R. Neugart, T. Nilsson, G. Nyman, F. Pougheon, K. Riisager, M. G. Saint-Laurent, G. Schrieder, O. Sorlin, O. Tengblad, and K. Wilhelmsen Rolander, Nucl. Phys. **A575**, 125 (1994).
[47] I. Tanihata, T. Kobayashi, T. Suzuki, K. Yoshida, S. Shimoura, K. Sugimoto, K. Matsuta, T. Minamisono, W. Christie, D. Olson, and H. Wieman, Phys. Lett. B **287**, 307 (1992).
[48] C. A. Bertulani and K. W. McVoy, Phys. Rev. C **46**, 2638 (1992).
[49] H. Esbensen, G. F. Bertsch, and K. Ieki, Phys. Rev. C **48**, 326 (1993).
[50] M. Zahar, M. Belbot, J. J. Kolata, K. Lampkin, R. Thompson, N. A. Orr, J. H. Kelley, R. A. Kryger, D. J. Morrissey, B. M. Sherrill, J. A. Winger, J. S. Winfield, and A. H. Wuosmaa, Phys. Rev. C **48**, R1484 (1993).
[51] B. L. Cohen, Rev. Sci. Instrum. **30**, 415 (1959); H. G. Blosser, G. M. Crawley, R. Deforest, E. Kashy, and B. H. Wildenthal, Nucl. Instrum. Methods **91**, 61 (1971).
[52] B. M. Sherrill, D. J. Morrissey, J. A. Nolen, Jr., and J. A. Winger, Nucl. Instrum. Methods B **56/57**, 1106 (1991).
[53] F. Barranco, E. Vigazzi, and R. A. Broglia, Contribution to the Workshop on the Physics of Exotic Beams, GANIL, Caen, 1994, unpublished; F. Barranco, private communication.
[54] F. Barranco, E. Vigazzi, and R. A. Broglia, Phys. Lett. B **319**, 387 (1993).
[55] R. Serber, Phys. Rev. **72**, 1003 (1947).
[56] R. Anne, S. E. Arnell, R. Bimbot, S. Dogny, H. Emling, H. Esbensen, D. Guillemaud-Mueller, P. G. Hansen, P. Hornshøj, F. Humbert, B. Jonson, M. Keim, M. Lewitowicz, P. Møller, A. C. Mueller, R. Neugart, T. Nilsson, G. Nyman, F. Pougheon, K. Riisager, M. G. Saint-Laurent, G. Schrieder, O. Sorlin, O. Tengblad, K. Wilhelmsen-Rolander, and D. Wolski, Phys. Lett. B **304**, 55 (1993).
[57] T. Nakamura, S. Shimoura, T. Kobayashi, T. Teranishi, K. Abe, N. Aoi, Y. Doki, M. Fujimaki, N. Inabe, N. Iwasa, K. Katori, T. Kubo, H. Okuno, T. Suzuki, I. Tanihata, Y. Watanabe, A. Yoshida, and M. Ishihara, Phys. Lett. B **331**, 296 (1994).
[58] L. K. Chulkov, B. Jonson, and M. V. Zhukov, Europhys. Lett. **24**, 171 (1993).
[59] H. Esbensen and G. F. Bertsch, Nucl. Phys. **A542**, 310 (1992).
[60] J. Hüfner and M. C. Nemes, Phys. Rev. C **23**, 2538 (1981).
[61] H. Sagawa and N. Takagawa, Phys. Rev. C **50**, 985 (1994).
[62] K. Riisager, private communication; K. Riisager, in [7], p. 281.
[63] S. Shimoura, T. Nakamura, H. Okamura, H. Okuno, H. Sakai, M. Ishihara, N. Inabe, T. Kubo, H. Kumagai, T. Nakagawa, and I. Tanihata, RIKEN Report No. RIKEN-AF-NP-134 (unpublished).
[64] K. Wilhelmsen Rolander, Ph.D. thesis, Chalmers Tekniska Högskola, Göteborg, Sweden, 1993.
[65] A. I. Amelin, M. G. Gornov, Yu. B. Gurov, A. L. Il'in, P. V. Morokhov, V. A. Pechkurov, V. I. Savel'ev, F. M. Sergeev, S. A. Smirnov, B. A. Chernyshev, R. R. Shafigullin, and A. V. Shishkov, Yad. Fiz. **52**, 1231 (1990) [Sov. J. Nucl. Phys. **52**, 782 (1990)].
[66] R. A. Kryger, A. Azhari, A. Galonsky, J. H. Kelley, R. Pfaff, E. Ramakrishnan, D. Sackett, B. M. Sherrill, M. Thoennessen, J. A. Winger, and S. Yokoyama, Phys. Rev. C **47**, R2439 (1993).
[67] B. M. Young, W. Benenson, J. H. Kelley, R. Pfaff, B. M. Sherrill, M. Steiner, M. Thoennessen, J. S. Winfield, N. A. Orr, J. A. Winger, S. J. Yennello, and A. Zeller, Phys. Rev. C **49**, 279 (1993); B. M. Young, Ph.D. thesis, Michigan State University, 1993.

[68] F. C. Barker and G. T. Hickey, J. Phys. G **3**, L23 (1977).
[69] E. K. Warburton and B. A. Brown, Phys. Rev. C **46**, 923 (1992).
[70] W. Koepf, Y. K. Gambhir, P. Ring, and M. M. Sharma, Z. Phys. A **340**, 119 (1991).
[71] Z. Y. Zhu, W. Q. Shen, Y. H. Cai, and Y. G. Ma, Phys. Lett. B **328**, 1 (1994).
[72] T. Hoshino, H. Sagawa, and A. Arima, Nucl. Phys. **A506**, 271 (1990).
[73] T. Hoshino, H. Sagawa, and A. Arima, Nucl. Phys. **A523**, 228 (1991).
[74] L. Johannsen, A. S. Jensen, and P. G. Hansen, Phys. Lett. B **244**, 357 (1990).
[75] G. F. Bertsch and H. Esbensen, Ann. Phys. (N.Y.) **209**, 327 (1990).
[76] M. V. Zhukov, B. V. Danilin, D. V. Fedorov, J. M. Bang, and J. S. Vaagen, Phys. Rep. **231**, 151 (1993).
[77] M. V. Zhukov, B. V. Danilin, D. V. Fedorov, J. S. Vaagen, F. A. Gareev, and J. M. Bang, Phys. Lett. B **265**, 19 (1991).
[78] J. M. Bang and I. J. Thompson, Phys. Lett. B **279**, 201 (1992); University of Surrey Report No. CNP 93/4 (unpublished).
[79] K. H. Wilcox, R. B. Weisenmiller, G. J. Wozniak, N. A. Jelley, D. A. Ashery, and J. Cerny, Phys. Lett. **59B**, 142 (1975).
[80] H. G. Bohlen, B. Gebauer, M. von Lucke-Petsch, W. von Oertzen, A. N. Ostrowski, M. Wilpert, Th. Wilpert, H. Lenske, D. V. Alexandrov, A. S. Demyanov, E. Nikolskii, A. A. Korsheninnikov, A. A. Ogloblin, R. Kalpakchieva, Y. E. Penionzhkevich, and S. Piskor, Z. Phys. A **344**, 381 (1993).
[81] F. Ajzenberg-Selove, Nucl. Phys. **A506**, 1 (1990).
[82] K. W. McVoy and P. Van Isacker, Nucl. Phys. **A576**, 157 (1994).
[83] I. J. Thompson and M. V. Zhukov, Phys. Rev. C **49**, 1904 (1993).
[84] T. Kobayashi, in [7], p. 169.
[85] A. A. Korsheninnikov and T. Kobayashi, Nucl. Phys. **A567**, 971 (1994).
[86] J. H. Kelley, in [7], p. 345; Phys. Rev. Lett. **74**, 30 (1995).
[87] B. Jonson, in *Proceedings of the 5th International Conference on Nucleus-Nucleus Collisions* (unpublished).
[88] F. Humbert *et al.*, in preparation; B. Jonson, private communication.
[89] N. A. Orr, P. G. Hansen, and A. C. Mueller *et al.*, Experimental Proposition E133c, GANIL, 1993, GANIL R 93 14, p. 98.
[90] Th. Blaich *et al.*, in preparation; B. Jonson, private communication.
[91] M. Zahar, M. Belbot, J. J. Kolata, K. Lampkin, R. Thompson, J. H. Kelley, R. A. Kryger, D. J. Morrissey, N. A. Orr, B. M. Sherrill, J. A. Winger, J. S. Winfield, and A. H. Wuosmaa, Phys. Rev. C **49**, 1540 (1994).
[92] M. V. Zhukov, B. V. Danilin, L. V. Grigorenko, and N. B. Shul'gina, Phys. Rev. C **47**, 2937 (1993).