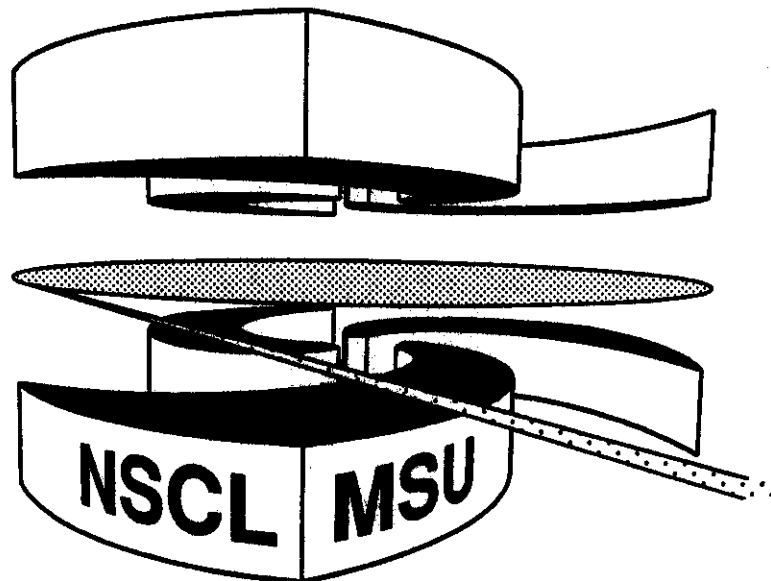# Michigan State University

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Momentum Distributions of ^{9}Li Fragments Following the Breakup of ^{11}Li

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Using a fragment separator as an energy loss spectrometer the parallel momentum distributions of 9Li nuclei produced in the breakup of ^{11}Li at 66 MeV/nucleon have been measured. Distributions with Gaussian widths of $\sigma_{//} \approx$ 19 MeV/c were observed for ^{9}Be, ^{93}Nb and ^{181}Ta targets - the first time such a narrow structure has been observed for high mass targets. From the weak dependence of width on breakup target it appears that the parallel momentum distributions are relatively insensitive to the interaction governing the breakup and reflect an extended neutron distribution for ^{11}Li.

The ability to produce beams of nuclei at the proton or neutron drip lines offers a unique opportunity to investigate systems in which the proton-to-neutron composition of the nucleus is at the very limits allowed by nuclear binding. Experiments have indicated that the very weak binding of the last few nucleons leads to systems with qualitatively new structures and surface densities. As such, the properties of these nuclei provide a stringent test of nuclear models which have for the most part been developed to describe properties close to or on the line of stability.

Of the light neutron-rich nuclei, the drip-line nucleus ^{11}Li exhibits some of the most intriguing characteristics. It is very weakly bound ($S_{2n} = 0.34 \pm 0.05$ MeV [1]), whilst the nucleus with one less neutron, ^{10}Li, is unbound. Clearly the interaction between the valence neutrons is important to the stability of ^{11}Li and it appears that a strong correlation may exist between the two outermost neutrons, perhaps even in the form of a di-neutron [2]. It is generally agreed that the very weak binding of these last two neutrons leads to a neutron density distribution which extends well beyond the matter radius expected from systematics [3] - the so-called "halo". Such a description is in qualitative accord with the experimental observations of abnormally large total reaction [4] and Coulomb dissociation cross sections [5,6], very sharply forward peaked angular distributions for neutrons observed in coincidence with ^{9}Li fragments from the breakup of ^{11}Li [7-9] and a narrow structure in the transverse momentum distribution for the ^{9}Li fragments [10]. In this Letter we present the first measurements of the parallel momentum distributions of ^{9}Li fragments following the breakup of ^{11}Li. In order to investigate any possible target dependent effects, reactions on ^{9}Be, ^{93}Nb and ^{181}Ta targets were studied.

The measurement of the transverse momentum distribution (i.e. perpendicular to the beam direction) of ^{9}Li fragments from the breakup on a carbon target of a ^{11}Li beam at 800 MeV/nucleon [10] was interpreted as consisting of two Gaussian components of different widths

- one very narrow ($\sigma_\perp = 21 \pm 3$ MeV/c) and a second much broader ($\sigma_\perp = 80 \pm 4$ MeV/c). Distributions from fragmentation of more normally bound nuclei typically display widths of the order of 100 MeV/c (see for example [11]). In simple terms the narrow component can be interpreted as reflecting, via the uncertainty principle, the extended distribution of the very weakly bound valence neutrons stripped from ^{11}Li.

It should be noted, however, that other experimental data for ^{11}Li are not completely consistent with these results and interpretations. In particular, measurements of the narrow angular distributions of neutrons resulting from the breakup of ^{11}Li at 29 MeV/nucleon are more compatible with a momentum width of $\sigma_\perp \approx 10$ MeV/c for the ^{9}Li fragments [7,8]. A more general related issue is whether the momentum distributions reflect only the structure of ^{11}Li or are also dependent on the interaction governing the breakup process. One means of answering this question is to perform measurements on heavy nuclei in order to compare results for Coulomb induced breakup to data for low Z targets, where the breakup is presumably mediated by the nuclear interaction. However, for reactions on heavy nuclei, transverse momenta are strongly affected by Coulomb deflection [12] and multiple scattering in the (relatively thick) breakup targets. These effects precluded any possible observation of a narrow structure in the transverse momentum distributions when a lead target was used [10], where a width of $\sigma_\perp = 71 \pm 15$ MeV/c was measured. Furthermore, transverse momentum distributions measured in the breakup of weakly bound nuclei have been shown to be sensitive to diffractive broadening [13].

In contrast, the parallel momentum distributions are not perturbed by these effects. Indeed, in simple fragmentation models such as that of Friedman [14], the width of the parallel momentum distribution reflects only the binding of the stripped cluster within the projectile. More recent calculations [13] have demonstrated that both the nuclear and Coulomb interactions induce parallel

momentum distributions which depend essentially on the Fourier transform of the ground state wave function of the projectile. Consequently, measurements of the parallel momentum distributions of the breakup products from [11]Li (and other weakly bound "halo" nuclei) provide an important test for models of its structure and the breakup process.

A severe limitation in making measurements using secondary beams is their inherently large energy spread as they are produced by the fragmentation of a primary beam in a thick target. To obtain the necessary final resolution despite the large spread in the energies of the [11]Li ions, the A1200 fragment separator [15] was employed in the present work as a zero degree energy loss spectrometer operated in a dispersion matched mode [16]. Such operation allowed the full 3% momentum acceptance $(\Delta p([11]Li) \approx 120 \text{ MeV/c})$ of the device to be utilized whilst retaining a final resolution of 0.1%. Although the total momenta of the fragments were measured, this effectively represented a determination of the parallel momenta since the two are identical under the present experimental conditions to within 0.02%.

The [11]Li secondary beam was produced via bombardment of a 790 mg/cm^2 [9]Be target by a beam of 80 MeV/nucleon [18]O ions (~30 particle nA) provided by the K1200 cyclotron. The fragments were separated by the first section of the A1200 using two different optical modes - the so-called medium $(\Delta\Omega \approx 0.8 \text{ msr})$ and high $(\Delta\Omega \approx 4.3 \text{ msr})$ acceptance modes [15]. Breakup targets of approximately equal energy loss of [9]Be, [93]Nb and [181]Ta were located at the second dispersive image plane. The mean energy of the incident [11]Li ions was ~66 MeV/nucleon (Table 1) with intensites of ~10 and ~50 pps/particle nA for the two acceptance modes. The final section of the A1200 was set to a rigidity to sample the central region of the momentum distribution of [9]Li ions from the breakup reaction. Particles arriving at the final image plane were identified by measurement of energy loss in an ion chamber, residual energy deposited in a thick plastic stop

detector and time-of-flight (stop detector versus cyclotron RF). The momenta were determined from a measurement of position using a parallel plate avalanche counter. The momentum calibration was obtained by stepping a secondary beam of ^{9}Li ions of known rigidity across the image plane. A direct measurement of the breakup target thickness was performed by measuring the energy lost in the target by the same ^{9}Li beam. In addition, the width of this ^{9}Li momentum distribution provided a measure of the resolution of the spectrometer, detector system and target straggling effects combined, labeled σ_{res} in Table 1.

As noted in Table 1, measurements were made for ^{9}Be and ^{181}Ta breakup targets using the two different optical modes of the A1200. The acceptances for the collection of the ^{9}Li ions from the breakup reaction which corresponded to the medium and high acceptance modes, were $\Delta\theta \approx$ 40 mrad, $\Delta\phi \approx$ 20 mrad and $\Delta\theta \approx$ 30 mrad, $\Delta\phi \approx$ 10 mrad, respectively. The ^{93}Nb target measurement was performed using only the high acceptance mode. In each case the central 2% of the momentum distributions was sampled and single Gaussian functions were fitted to each of the spectra (fig 1a - c). The results are presented in Table 1. Data were also taken encompassing a range of breakup ^{9}Li momenta from 5% below the mean momentum to 5% above. Figure 1d shows the data for the ^{9}Be breakup target. Additionally, the centroids of the individual momentum distributions were used, after accounting for target thickness effects, to compare the outgoing ^{9}Li energy to that of the incoming ^{11}Li.

In the present work the finite acceptance of the spectrometer limited the measurements to zero degree double differential cross-sections. For distributions characterised by widths of the order of 100 MeV/c only a relatively small fraction (~5%) of the full breakup yield could be measured. In the case of distributions having widths of $\sigma_{//} \approx$ 20 MeV/c, the subject of the present study, approximately one half of the ions were accepted. Monte Carlo simulations have demonstrated

that the finite acceptances do not affect the measured lineshapes. This conclusion was also verified empirically by the identical results obtained with the two acceptances for the different optical modes of the A1200. Furthermore, the results obtained for the $\pm 5\%$ momentum scan taken using a ^{9}Be target (fig. 1d) indicate that inclusion of a broad underlying component does not alter significantly the determination of the width of the narrow peak from observations of the central 2% of the momentum spectrum.

Perhaps the most striking feature of the present results, illustrated in figure 2, is the weak dependence on target of the width of the parallel momentum distributions. Kobayashi et al. [6] and Riisager et al. [8] have shown that for heavy targets the dominant reaction process for the breakup of ^{11}Li to ^{9}Li is Coulomb dissociation, whilst for light targets the reaction should proceed almost exclusively by nuclear induced breakup (an effect which appears more pronounced at low energies [8]). It appears that the nature of the interaction governing the breakup plays only a weak role in determining the parallel momentum distributions of the outgoing ^{9}Li fragments. It is interesting to note that the narrow neutron angular distributions measured at 29 MeV/nucleon [7,8] display widths that are also independent of the breakup target.

The above results support the prediction of Bertulani and McVoy [13] and that the parallel momentum distributions provide a measure of the internal momentum distribution of the ^{11}Li projectile, which in turn may be given by the Fourier transform of the spatial wavefunction. If we assume a simple Yukawa form for the two neutron spacial distribution with a range parameter ρ (i.e. $\exp(-r/\rho)/r$), then the ^{9}Li momentum distributions should have a Lorentzian form, in accord with the data. From our data the average width of the Lorentzian when transformed to the frame of the ^{11}Li, $\Gamma \approx 45$ MeV/c, gives a Yukawa range parameter ($\rho = 2\hbar/\Gamma$) of 8.8 fm, which corresponds to a RMS halo radius ($<r^2>^{1/2} = \rho/\sqrt{2}$) of 6.2 fm. This value is in good agreement

with that derived from the two neutron binding energy (~5.8 fm) [23,24] and that estimated from the neutron angular distribution measurements (~7.5 fm assuming an uncorrelated pair of neutrons) [8].

Although there has been limited experimental data to compare with, a large amount of theoretical work has been undertaken to describe the structure and breakup of ^{11}Li. Models have ranged from a shell model approach [17] to those embodying three-body effects [18-21] and clustering [2,22]. Momentum distributions are predicted by many of the models. For example, the ^{181}Ta target data is compared in figure 1c with the model proposed by Esbensen and Bertsch [21] (shown as a dashed line). This approach incorporates a three-body description of ^{11}Li and dissociation proceeds via Coulomb excitation. As noted earlier, this should be the dominant mechanism for breakup on heavy nuclei. The agreement with the present data is very good.

In summary, we have made the first measurements of the parallel momentum distributions for ^{9}Li fragments following the breakup of a secondary ^{11}Li beam. Narrow distributions having widths of $\sigma_{//} \approx 19$ MeV/c were observed for targets of ^{9}Be, ^{93}Nb and ^{181}Ta. The weak dependence of the distribution width on target indicates that the parallel momentum distributions are relatively insensitive to the interaction leading to breakup. Importantly the present measurements are free of the problems which plague measurements of the transverse momenta and yield a more accurate estimate of the internal momentum distribution of ^{11}Li that reflects an extended neutron distribution. Finally, we note that the technique used - dispersion matching - is a relatively simple yet powerful method for undertaking secondary beam reaction studies.

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Figures

Figure 1 : Momentum distributions covering the central 2% of the breakup ^{9}Li momenta with single Gaussian fits (solid line) for high acceptance mode measurements using (a) ^{9}Be, (b) ^{93}Nb and (c) ^{181}Ta targets. The dashed line in (c) shows the prediction of Esbensen and Bertsch [21]. (d) displays the high acceptance mode distribution for a 10% range of ^{9}Li momenta using a ^{9}Be target. A two Gaussian fit is shown ($\sigma = 20.9 \pm 0.6$ MeV/c and 112 ± 13 MeV/c).

Figure 2 : Target Z dependence of the widths (Table 1) of the momentum distributions for the medium (squares) and high (diamonds) acceptance mode measurements. The result of Kobayashi et al. [10] is indicated by the circle.

Table 1

Summary of experimental results

Spectrometer Mode	Beam Energy MeV/nucleon	Target (mg/cm^2)	σ_{res} [a) MeV/c	$\sigma (\pm)$ [b) MeV/c	$\Delta (\pm)$ [c) MeV/nucleon
medium	65.25	Be (202)	4.1	20.5 (1.4)	0.19 (0.18)
medium	65.25	Ta (298)	4.4	15.9 (1.2)	0.06 (0.18)
high	66.24	Be (202)	5.9	19.2 (1.0)	-0.09 (0.18)
high	66.24	Ta (298)	6.3	16.8 (0.9)	-0.15 (0.18)
high	66.15	Nb (256)	4.6	20.0 (0.9)	-0.05 (0.18)
high	66.15	Ta (296)	5.1	17.2 (0.9)	-0.08 (0.18)

a) Experimental resolution

b) Width of fitted Gaussian distribution ($\pm$ uncertainty) in the ^{11}Li frame after accounting for experimental resolution and detector efficiency .

c) E/A (^{9}Li) - E/A (^{11}Li) ($\pm$ uncertainty)

Figure 1

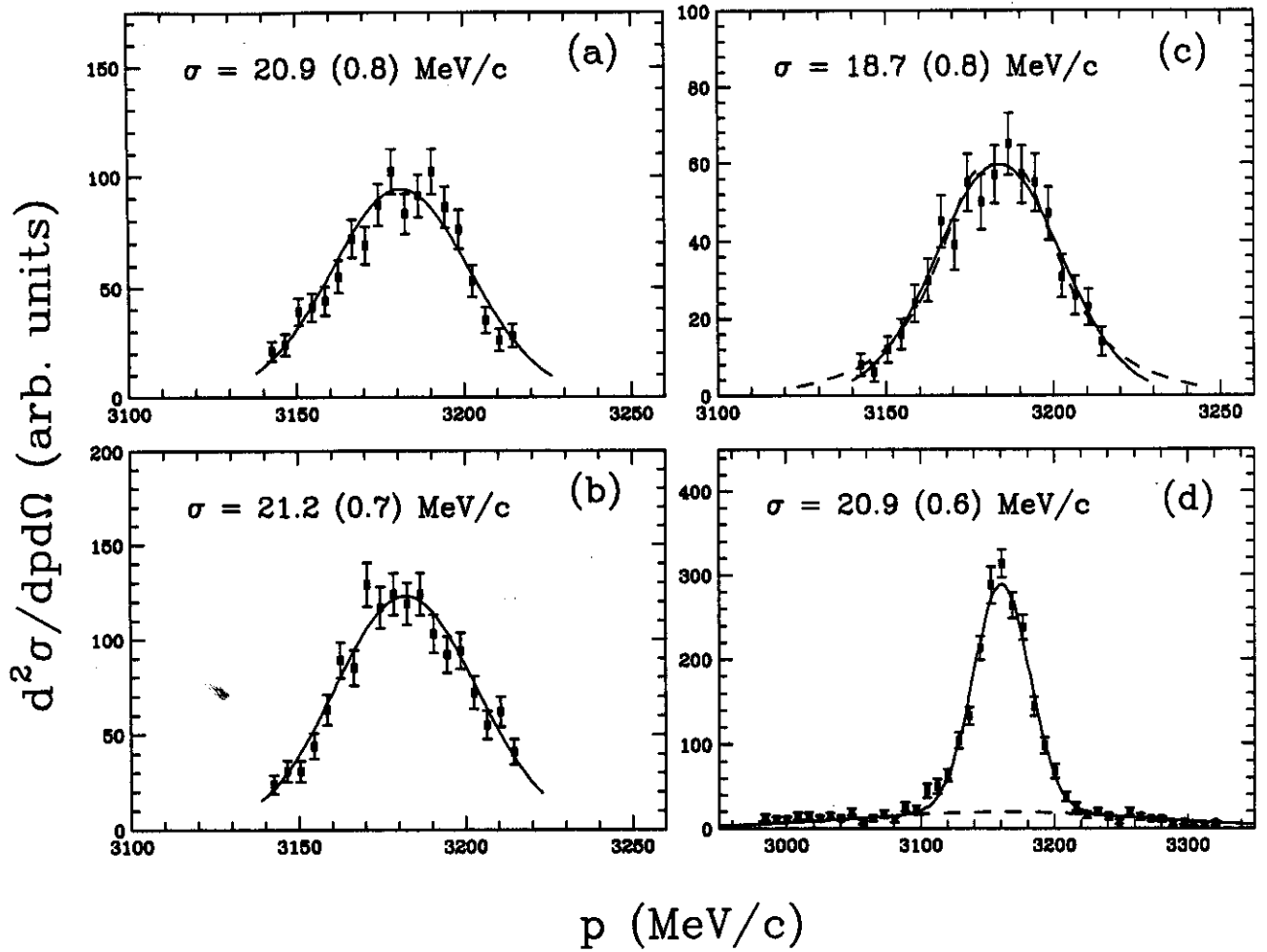Figure 2