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Fragment Momentum Distributions and the Halo

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A review is presented of fragment momentum distributions from the breakup of halo nuclei. The nature of the distributions and relationship to the structure of the halo is discussed in the light of recent experimental and theoretical investigations, including those for ^{19}C . Particular emphasis is given to core longitudinal momentum distributions and neutron distributions from core-breakup reactions.

1. Introduction

After more than a decade of study the nuclear halo has become a well established phenomenon [1]. During this time halo nuclei have been studied experimentally using techniques of ever increasing complexity. The present discussion addresses one of the simpler probes, namely the momentum distributions of the products — core fragments or halo neutrons — from the breakup of high energy beams of the nuclei of interest.

The pioneering measurements of Kobayashi et al. [2] of the momentum distributions of charged fragments from the breakup of beams of light, neutron-rich nuclei provided important evidence supporting the existence of an extended valence neutron distribution for ^{11}Li ¹. Following on from this work, a large number of measurements have been undertaken of both core fragment and neutron momentum distributions (Table 1).

Given the relatively low intensities presently available, classical spectroscopic tools, such as single nucleon transfer reactions cannot be easily applied to the study of halo systems. As described by Riisager in these proceedings, β -decay studies present one alternative probe. The relatively high cross sections for the breakup of halo nuclei and the possibility of a relatively simple interpretation have lead to the examination of fragment momentum distributions not only as a signature of a halo distribution, but also as a probe of the structure [3].

Historically the target independence observed for the single neutron angular distributions from the breakup of ^{11}Li [12] and later the ^9Li longitudinal momentum distributions [16] (Fig. 1) was interpreted as indicating that the reaction mechanism (nuclear/Coulomb for light/heavy targets) played a negligible role². The momentum distributions were consequently assumed to be a direct measure of the intrinsic momenta of the halo neutrons.

¹Note that in itself a narrow momentum distribution did not establish the existence of the halo.

²Subsequent measurements have confirmed a weak target dependence [17].

Table 1

Summary of measurements of fragment momentum distributions

Nucleus	Energy (MeV/nucleon)	Technique ^{a)}	Fragment	Quantity Measured	Ref.
⁶ He	790	M	α	p_t	[2,23]
	400	M	α	p_t	[23]
	60	ELS	α	$p_{ }$	[4]
	65	M	α	$p_{ }$	[5]
	800		n	p_t	[6,7]
	83		n	p_t	[8]
⁸ He	800	M	⁶ He	p_t	[7,9]
	790	M	⁶ He	p_t	[2]
	60	ELS	⁶ He, α	$p_{ }$	[4]
	240	M	⁶ He	p_t	[10]
	800		n	p_t	[7]
	240		n	p_t	[10]
⁹ Li	27		n	p_t	[11]
	800		n	p_t	[7]
¹¹ Li	32		n	p_t	[12]
	800	M	⁹ Li	p_t	[13]
	790	M	^{8,9} Li, ^{6,8} He	p_t	[2]
	470,650	ELS	⁹ Li	$p_{ }$	[14]
	280	ELS,M	⁹ Li	$p_{ }, p_t$	[15]
	66	ELS	⁹ Li	$p_{ }$	[16,17]
	37	M	⁹ Li	$p_{ }$	[18]
	28	T	⁹ Li	p_{total}	[19]
	800		n	p_t	[6,7]
	28,280		n	p_t	[20]
¹¹ Be	800	M	¹⁰ Be	p_t	[22,23]
	460,680	ELS	¹⁰ Be	$p_{ }$	[14]
	72	M	¹⁰ Be	p_{total}	[52]
	63	ELS	¹⁰ Be	$p_{ }$	[24]
	32	T	¹⁰ Be	$p_{ }$	[25]
	800		n	p_t	[22]
¹² Be	41,460		n	p_t	[20]
	460		n	p_t	[21]
	41		n	p_t	[26,27]
	32		n	p_t	[25]
	56	T	¹⁰ Be	$p_{ }$	[28]
¹⁴ Be	790	M	¹² Be	p_t	[29]
	56,65	T,ELS	^{10,12} Be	$p_t, p_{ }$	[28]
	35		n	p_t	[11]
¹⁷ C	97	ELS	¹⁶ C	$p_{ }$	[30]
	62	ELS	¹⁶ C	$p_{ }$	[31]
¹⁸ C	86	ELS	¹⁷ C	$p_{ }$	[30]
¹⁹ C	77	ELS	¹⁸ C	$p_{ }$	[30]
	30		n	p_t	[32]
⁸ B	1471	ELS	⁷ Be	$p_{ }$	[33]
	41	T	⁷ Be	$p_{ }, p_t$	[34]
	38	T	⁷ Be	$p_{ }$	[35]

a) for charged fragments: M = magnet/spectrometer; ELS = energy-loss spectrometer; T = charged-particle telescope.

Figure 1. Summary of widths of the longitudinal momentum distributions for ${}^9\text{Li}$ from the breakup of ${}^{11}\text{Li}$ (upper panel) and ${}^{10}\text{Be}$ from the breakup of ${}^{11}\text{Be}$ (lower panel).

Such a result was somewhat surprising but must be viewed in the context of the relatively simple descriptions used to describe ${}^{11}\text{Li}$. Given the uncertainty surrounding more sophisticated descriptions of ${}^{11}\text{Li}$ and that breakup could proceed sequentially, via ${}^{10}\text{Li}$, measurements employing the one neutron halo nucleus ${}^{11}\text{Be}$, the structure of which is well characterised by a $2s_{1/2}$ valence neutron, were subsequently undertaken [24,26]. In this case the neutron angular distributions were seen to be clearly influenced by the interaction governing the breakup and could be successfully described by nuclear and Coulomb induced breakup for light and heavy targets respectively [26,27]. The ${}^{10}\text{Be}$ core longitudinal momentum distributions, however, displayed no variation with breakup target and could be reasonably well described by a direct mapping of the halo wavefunction [24] (very similar results have recently been obtained, as in the case of ${}^{11}\text{Li}$ [14,15,18], at energies an order of magnitude higher [14], Fig. 1). This result along with theoretical work [58] lead

to the acceptance that, provided effects such as sequential breakup could be neglected, the core longitudinal momentum distributions (LMD) provided an unperturbed measure of the ground state wavefunction of the halo.

Parallel to these experimental developments, a detailed theoretical investigation of the breakup of ^{11}Li was carried out by Barranco et al. [45]. The calculations, which included the effects of nuclear breakup (stripping and diffractive dissociation), Coulomb dissociation and sequential breakup, reproduced well the measured single neutron angular distributions [12]. Importantly, the target independence was seen to be a coincidence arising from relative contributions of the various dissociation mechanisms³.

The Coulomb dissociation of ^{11}Li has also been studied by Esbensen et al. [42,43] using a relatively sophisticated three-body wavefunction [44] and the ^9Li LMD and neutron angular distributions were successfully reproduced. More recently the Coulomb dissociation of ^{11}Be and ^8B has also been treated with success [40,41,59]. While breakup on heavy targets is well understood, very few detailed calculations of core momentum distributions from light target breakup have been made. Thus, although sophisticated wavefunctions are available, in particular for the two-neutron halo systems [49], these have typically been interpreted to be directly mapped by the core LMD from light target breakup [48,49].

In section 3 recent investigations of the core LMD arising from light target breakup are reviewed. A discussion of neutron distributions from the so-called core-breakup reactions is presented in section 4. Both discussions are illustrated with reference to recent measurements, including those for ^{19}C . Before proceeding further the various experimental techniques employed in measuring momentum distributions are outlined.

2. Experimental Techniques

2.1. General Considerations

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 for reaction studies the method suffers important limitations for measurements of momentum distributions; namely a large momentum spread and poor emittance in the secondary beam. These effects, which arise from the fragmentation reaction kinematics coupled with thick target effects, are defined experimentally by the acceptances of the separator being used for the collection and purification of the reaction products. The momentum acceptance may be some few percent — $\sim 100\text{ MeV}/c$ at intermediate energies. The angular spread is typically $1 - 2^\circ$, corresponding to $\sim 100\text{ MeV}/c$ in momentum transverse to the beam direction.

It has been suggested that the acceptances or configuration of the device used to measure the momentum distributions may influence the observed distribution [24,62]. As discussed in section 3, this may not be the case for core LMD [37]. While space does not permit a lengthy discussion here of such effects, the most appropriate approach is to incorporate in the model calculations (which should include the reaction) a filter which simulates the experimental arrangement. The comparison of different experimental results is probably best done via such simulations, rather than a direct comparison which

³Interestingly, for breakup on a light target, the calculations favoured a very low lying state in ^{10}Li . A similar narrowing of the neutron angular distribution was seen by Zinser et al. [21].

may often be biased by the choice of lineshapes and the unfolding of efficiencies.

2.2. Charged Fragments

Three methods have been used to measure the charged fragment (typically the core) momentum distributions: dispersive magnets/spectrometers; energy-loss spectrometers; and charged particle telescopes (Table 1). Systems employing a single dispersive dipole element, such as the HISS magnet at LBL or ALADIN at GSI, have been used principally for the measurement of transverse momentum distributions (usually perpendicular to the bending plane). Such measurements require the determination of the trajectory of the incoming ion as well as that of the outgoing fragment.

Charged particle telescopes have also been used [19,25,28,34,35]. Transverse momentum distributions may be obtained if, as for the previous method, the trajectories before and after the breakup target are measured. The determination of the energy of the beam on a particle-by-particle basis from a time-of-flight measurement may be used to overcome the inherent energy spread and allow the LMD of the outgoing fragments to be derived from the energies measured in the telescopes. Given the intrinsic resolution of charged particle telescopes, such a method is limited to energies below ~ 100 MeV/nucleon. While the absence of any magnetic analysis allows a number of different breakup channels and beam species to be measured simultaneously, measurements at zero degrees are severely hampered by reactions in the telescope.

Probably the most elegant and powerful approach applied so far is the use of an energy-loss spectrometer. To date fragment separators such as the A1200 at MSU and the FRS at GSI have been adapted to such a role. Here the beam of interest is produced and collected in the first stage of the device, reacted with a breakup target located at an intermediate dispersive image plane and the momentum analysis of the outgoing fragment is performed by the second stage of the device [63]. Operated in such a dispersion matched mode, final momentum resolutions of the order of 1000 have been attained, thus facilitating high quality measurements of longitudinal momentum distributions [15–17,24,30]⁴. Trajectory determination of the secondary beam and breakup fragments may also be used to determine the transverse momentum distributions. As only fragment separators have been used until now, measurements have been confined to zero degrees with, at intermediate energies, the additional constraint of relatively limited transverse momentum acceptances. The use in the near future of dedicated energy-loss spectrometers, such as SPEG at GANIL and the S800 at MSU, should enable such limitations to be overcome and allow for the purification of the beam using an independent separator.

2.3. Neutron Detection

Two principle methods have been employed for the detection of neutrons from breakup reactions: modular liquid scintillator arrays [19,27,32] and plastic scintillator "walls" [10,22]. In both cases the flight-time is used to determine the neutron energy. The principle advantages of the modular liquid scintillator arrays are good n- γ discrimination characteristics, high granularity and variable geometry. While offering a higher total solid angle at modest cost, the relatively low intrinsic detection efficiencies of plastic scintillator arrays are often augmented by the use of a series of walls [50] or layers of scintillators

⁴Such high resolutions are essential to measure the LMD at relativistic energies.

[51]. At very high energies where the neutron detection efficiency is low, a converter such as iron may be used to create hadronic showers that are detected by the scintillator [51].

Recently some of the advantages of both systems have been incorporated in a liquid scintillator array with a wall type configuration [54]. As in the case of other such configurations, including closely packed modular arrays, the effects of cross-talk and other scattering phenomena must be carefully treated.

3. Core Longitudinal Momentum Distributions

As outlined in section 1, core LMD for breakup on light targets have been interpreted, based on the Serber model [57], as a direct measure of the intrinsic momentum distribution of the halo nucleons. The basic tenant of the Serber (or sudden) approximation is one of effectively instantaneous removal of the stripped nucleon(s) whereby reaction effects, including final-state interactions, are assumed negligible. The momentum distribution of the core fragments is then simply the square of the Fourier transform of the spatial wavefunction of the halo. While originally developed for very high energies, it is generally agreed that the sudden approximation should remain valid even at intermediate energies for very weakly bound nuclei.

In such reactions, however, an important constraint must be considered: for the core fragment to be observed it must survive the reaction. Consequently the reaction must proceed peripherally, i.e., $b > R_{\text{target}} + R_{\text{core}}$. As the full range of impact parameters cannot be probed, the fragment momentum distributions will, as noted by Hüfner and Nemes [46], only provide a measure of the momentum distribution on the nuclear surface (such a strong absorption limit, as pointed out by Esbensen [36], was already foreseen in the original work of Serber [57]). For a halo system then, that part of the wavefunction residing in the core will be inaccessible and some departure of the measured momentum distribution from the intrinsic one must be expected. As the momenta of the halo nucleons will in general decrease with increasing radius, a narrowing of the measured distribution compared to that of the total halo wavefunction should be expected. The details of such an effect will be related to the character of the wavefunction.

In the light of such considerations the core LMD from light target breakup have been investigated by Esbensen [36], within the framework of the spectator model [61], and Hansen [37] in a Glauber type approach [27]. In order to provide a transparent interpretation of the reaction effects only single nucleon halo systems were considered. Similarly, to avoid ambiguities arising from structural considerations ^{11}Be and ^8B were investigated, the ground states of which may be well described by single-particle wavefunctions. The different orbital angular momentum of the halo nucleons ($l = 0$ for ^{11}Be and 1 for ^8B) and consequently different radial extensions also provide an important test of the interplay of structural and reaction effects.

In the case of ^{11}Be (Fig. 2), the reaction leads to a slight narrowing of the ^{10}Be LMD, $\text{FWHM} \simeq 40 \text{ MeV}/c$, as compared to the intrinsic momentum distribution with $\text{FWHM} \simeq 47 \text{ MeV}/c$. The agreement with the distributions measured at $63 \text{ MeV}/\text{nucleon}$, $\text{FWHM} = 42 \pm 2 \text{ MeV}/c$ [24], is very good. Interestingly, the narrowing predicted to arise from the reaction is approximately that attributed to the finite acceptances [24,62]. However, as noted by Hansen [37], the localisation of the wavefunction that arises in the reaction

Figure 2. Comparison of the intrinsic (dashed) and core LMD (solid line) distributions for ^{11}Be at 63 MeV/nucleon (left panel) and ^8B at 1471 MeV/nucleon (right panel). Adapted from Hansen [37].

process results in the effective factorisation of the wavefunction. Experimentally then, restricted transverse momentum acceptances (i.e. integration of the transverse components over finite limits) should not influence the lineshape of the core LMD. Indications of such behaviour have been observed, for example, in the telescope and spectrometer based measurements of the ^{12}Be LMD from the breakup of ^{14}Be [28].

As shown in figure 2, in the case of ^8B the reaction leads to a drastic narrowing of the ^7Be LMD, $\text{FWHM} \simeq 75 \text{ MeV}/c$ [37] - $82 \text{ MeV}/c$ [36], as compared to the intrinsic momentum distribution ($\text{FWHM} \simeq 160 \text{ MeV}/c$); a result in good accord with the measured distributions — $81 \pm 6 \text{ MeV}/c$ at 1471 MeV/nucleon [33] and $81 \pm 4 \text{ MeV}/c$ at 41 MeV/nucleon [34]. A similar result has also been obtained by Obuti et al. using a Glauber model approach [47]. The phenomenological cutoffs introduced by a number of authors to reproduce the ^7Be LMD [35,60], can now be understood in terms of the narrowing arising from the reaction. The effects of absorptive cutoffs have also been examined by Sagawa and Takigawa [38] for ^{11}Be and ^{11}Li in a peripheral direct reaction model.

The contribution of diffractive dissociation to the core LMD from light target breakup has been included in the analysis of Hansen [37]. The momentum distributions and cross sections are predicted to be identical to that produced by stripping reactions. These results are supported not only by the agreement with the observed core LMD but also the measured one-nucleon removal cross sections. Support may also be found in the preliminary results of measurements made using telescopes, which can in principle distinguish stripping and diffractive processes [25,35]. Additionally, the treatment of Esbensen, which includes only stripping, finds a cross section of only 68 mb for one-proton removal on ^8B

Figure 3. Comparison of the measured ^{18}C LMD [30] to the calculated core LMD assuming an $l = 0$ (solid line) and 1 (dashed) valence neutron and $S_n = 200$ keV [64]. The widths of the corresponding intrinsic momentum distributions are 31 and 102 MeV/c, respectively.

as compared to the measured value of 94 ± 4 mb [33].

In figure 3, the results of the recent measurement of the ^{18}C LMD from the breakup of ^{19}C at 77 MeV/nucleon on a beryllium target [30] are compared to preliminary calculations employing single-particle wavefunctions and including the reaction effects discussed above [64]. While shell model calculations favour a ^{19}C ground state containing a strong $\nu 2s_{1/2}$ component [30], the data alone would not appear to allow any definite conclusions to be drawn. Interestingly, the calculated one-neutron removal cross section is 280 mb for $l=0$ and 130 mb for an $l=1$ valence neutron [64], as compared to a measured value of 105 ± 17 mb [30].

4. Core-Breakup Reactions

As outlined in section 1, measurements of the neutron distributions for the exit channels core+neutron may be significantly influenced by the reaction mechanism and final-state interactions. Recent studies, employing a wide range of breakup targets at both intermediate [27] and very high energies [20], have suggested that the so-called “core-breakup” reactions are much less likely to be influenced by such effects. In this approach, reactions in which the core suffers a collision with the target ($b \leq R_{\text{target}} + R_{\text{core}}$) are selected. Owing to the large average separation between the halo neutrons and the core, an appreciable fraction will not be involved in the core-target collision. These halo neutrons, being minimally perturbed by the reaction, are therefore expected to reflect the nature

Table 2
Summary of secondary beam parameters and results.

Nucleus	$\overline{E}$ ^{a)} [MeV/nucleon]	I [pps/ μ Ae]	σ_{frag} ^{b)} [b]	σ_n ^{c)} [b]	$\theta_{1/2}$ ^{d)} [°]	FWHM ^{e)} [MeV/c]
¹⁹ C	30.3	15	0.59 ± 0.10	2.5 ± 0.4	7.6 ± 2.0	64 ± 17
narrow	—	—	—	0.24 ± 0.11	5.1 ± 1.4	42 ± 12
broad	—	—	—	2.2 ± 0.3	18.9 ± 1.8	165 ± 17
²¹ N	33.4	12	0.44 ± 0.06	2.6 ± 0.4	18.1 ± 1.3	165 ± 12
²² O	40.4	75	0.80 ± 0.18	4.4 ± 0.6	15.7 ± 0.9	156 ± 9
²⁴ F	42.3	70	0.77 ± 0.06	4.5 ± 0.6	16.4 ± 0.6	168 ± 7

a) Mean energy at target mid-point ($\Delta E/\overline{E} \simeq 2\%$).

b) Cross section measured in telescope for $Z_{\text{frag}} < Z_{\text{proj}}$.

c) Angular distribution integrated out to 42° .

d) Half width at half maximum of Gaussian fit.

e) $\text{FWHM} = 2 \overline{p}_n \tan \theta_{1/2}$; $\overline{p}_n$ = the mean neutron momentum assuming breakup at target mid-point.

of the halo and form a narrow component in the angular and momentum distributions. The neutrons produced in the core-target collision⁵ should form a broad distribution with a width characteristic of normal nuclei [27]; halo neutrons involved in the core-target collision (see below) may also contribute to such a component.

Recently, as part of the E133 series of experiments at GANIL [12,26,27], a measurement of the neutron distributions for the core-breakup reaction channels of a 30 MeV/nucleon ¹⁹C beam has been carried out [32]. For comparison measurements were carried out simultaneously for the neighbouring neutron-rich nuclei ²¹N, ²²O and ²⁴F for which no halo states are expected.

The secondary beam (Table 2) was produced via the fragmentation of an intense ⁴⁰Ar beam on a thick carbon target, which, in order to increase the fragment collection efficiency, was located between the superconducting solenoids of SISSI. The reaction products were subsequently selected using the alpha-shaped beam analysis device as a recoil separator and transported to the experimental area. The secondary beam particles were identified on a particle-by-particle basis and tracked onto the secondary breakup target (0.53 g/cm² tantalum) using two position sensitive parallel plate avalanche counters. The charged reaction products were detected around zero degrees using a large area position sensitive silicon detector telescope. The neutrons were detected using the 98 elements of the DEMON array [56] which were mounted in a forward geometry — 37° to -32° horizontally and 17.5° to -17.5° vertically — 4 m downstream of the breakup target; such a large angular range being essential to identify any broad component of the angular distribution. A detailed description of the experiment may be found in ref. [32].

In principle, the core-breakup reaction channels are those for which any charged fragment other than the core is observed; for ¹⁹C, any fragment other than ¹⁸C. The iden-

⁵In principle these neutrons arise from two sources other than the excited target residue: preequilibrium emission ($v \sim v_{\text{beam}}/2$) and the excited core-like fragment ($v \sim v_{\text{beam}}$) [55].

Figure 4. Upper panel: neutron angular distribution for core-breakup reactions for ^{24}F . The contribution arising from reactions in the telescope is also shown (triangles). Lower panel: results for ^{19}C , where the dashed line represents the broad component (see text). Inset: comparison of the result of the present study, after subtracting the broad component, with that of ref. [30] (shaded) and a simple Yukawa model (thin lines) after filtering both through the present experimental arrangement. The shading and thin lines correspond, respectively, to the uncertainty in the result of ref. [30] and that in the S_n (240 ± 100 keV).

tification of the channels corresponding to the removal of only neutrons is complicated, however, by a significant background arising from reactions in the telescope [11]. In order to simplify the analysis and reduce the background, the present analysis was based on those events for which a charged fragment with $Z < 6$ was detected in the telescope. Similar criteria, $Z < Z_{\text{proj}}$, were applied to the data acquired for ^{21}N , ^{22}O and ^{24}F (the term core breakup is also used for convenience to describe such channels for these nuclei).

The neutron angular distributions associated with core-breakup reactions for ^{19}C and ^{24}F are displayed in figure 4 (a lower limit of $E_n=10$ MeV was chosen so as to eliminate neutrons arising from the excited target-like residue). The background arising from reactions in the telescope was determined from measurements made with the target removed and the beam energy reduced by an amount equivalent to the energy loss in the target (Fig. 4). The distributions for ^{21}N , ^{22}O and ^{24}F were well described by single Gaussian distributions, while that for ^{19}C could only be satisfactorily characterised using two components. The distribution for ^{19}C is clearly much narrower than those for ^{21}N , ^{22}O and ^{24}F ; the corresponding momentum widths being $\text{FWHM} \sim 160$ MeV/ c for the latter as compared to 64 ± 17 MeV/ c for ^{19}C . The results are summarised in Table 2.

As noted above, a two component decomposition of the neutron angular distribution for the ^{19}C core-breakup reaction channels was necessary to satisfactorily reproduce the observed angular distribution (Fig. 4). Within the framework of the core-breakup reaction model the narrower of these, $\text{FWHM} = 42 \pm 12$ MeV/ c , may be identified with a halo distribution for ^{19}C arising from the last, very weakly bound neutron. This width corresponds to $\Gamma = 55 \pm 16$ MeV/ c when expressed in terms of the commonly used Lorentzian parameterisation. The broader component, $\text{FWHM} = 165 \pm 17$ MeV/ c , is consistent with that expected from a core formed by a normal nucleus such as ^{18}C .

Support for a one-neutron halo may also be found in the multiplicity, M_n , associated with the halo neutrons. For core-breakup reactions M_n will be less than one as a result of scattering/absorption of the halo neutron by the target or core in some reaction geometries. A rough estimate of this effect, based on a simple Yukawa approximation for the external halo wavefunction [53], leads in the present case to an upper limit of $M_n \sim 0.4$ (a limit which would rise to ~ 0.6 for a carbon target). This is in accord with the value of $M_n = 0.41 \pm 0.20$ for the narrow component.

For completeness, the distribution based on the Yukawa wavefunction for the halo neutron and filtered through the present experimental setup is also displayed in figure 4. While there is good agreement with the component identified as arising from a one-neutron halo, as in the case of the ^{18}C LMD (section 3) it would appear premature to draw any conclusions regarding the detailed structure.

5. Conclusions

It has been demonstrated that, in general, the reaction process cannot be ignored when interpreting momentum distributions. In particular, not only are the neutron distributions measured in the exit channel core+neutron influenced by the reaction, but so too are the core LMD. The interpretation that the latter were an unperturbed measure of the intrinsic momentum distribution of the halo wavefunction can now be seen as arising from the weak influence of the reaction on the large s-wave components (and hence, very

extended haloes) of the systems for which the majority of measurements have been made — ^{11}Be and ^{11}Li . In case of ^{11}Li , attempts to include the reaction in model calculations have employed for the most part simple Yukawa type wavefunctions [38,65]. More sophisticated wavefunctions, based on 3-body models, have been used to infer the proportion of $\nu 1p_{1/2}^2$ and $\nu 2s_{1/2}^2$ admixtures by direct comparison with the ^9Li LMD [48]. Inclusion of reaction effects, however, may produce a significant change in the relative contributions. In addition, for two-neutron halo nuclei such as ^{11}Li , the effects of sequential breakup must also be considered. Calculations including such final-state interactions indicate that the effect is small for the core fragments but can produce a significant reduction in the widths of the neutron distributions [10,21,39,66]; the size of the reduction depending strongly on the resonances in the core+neutron subsystem.

The neutron distributions from core-breakup reaction have been discussed with particular reference to a recent measurement for ^{19}C . While the narrow component of such distributions appears to be related quite directly to the intrinsic halo distribution [20,27], no rigorous calculations exist yet describing the influence of the reaction. In principle, the effects of final-state interactions arising from specific exit channels may be minimised by constructing the distribution, as in the ^{19}C measurement, from the sum over many channels. It thus remains to determine the degree with which core-breakup reactions probe the total halo wavefunction. Extending the available data sets to systems beyond ^{11}Be and ^{11}Li [20,27] should shed light on this question. Notwithstanding such uncertainties, the two component character of core-breakup distributions remains an important feature as their observation may provide direct evidence for a core+halo structure.

While the measurements for ^{19}C of both the ^{18}C LMD [30] and neutron distributions from core break [32] support the existence of a one-neutron halo, the extraction of any detailed structural information is at present premature. Not only is data of improved quality needed, including a more precise determination of the binding energy, but more realistic wavefunctions [67] coupled to calculations including reaction effects must be developed. Interestingly, the one-neutron removal cross section for a tantalum target (extracted from the experiment described in section 4 [32]) is only $0.8 \pm 0.3 \text{ b}^6$, as compared to a calculated cross section, assuming Coulomb dissociation and a $2s_{1/2}$ valence neutron, of 4 b [68]. Furthermore, the core-breakup cross section (Table 2) is very similar to that measured for one-neutron removal. In contrast, the one-neutron removal cross section for ^{11}Be on a gold target is some 2-3 times higher than that for core breakup. These results, along with the one-neutron removal cross section for a light target (section 3), suggest that a wavefunction involving higher l configurations, rather than the dominantly $\nu 2s_{1/2}$ configuration derived from shell model calculations [30], may provide a more appropriate description. Finally, in the light of the influence of the reaction on core LMD, the claims of halo and "skin" distributions for the valence neutrons of $^{17,18}\text{C}$ [30] would appear difficult to sustain.

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⁶Due to the background arising from reactions in the telescope and the weakness of this channel, the value given represents an upper limit.

interpretation of momentum distributions and to Björn Jonson for communicating the recent results of the FRS group. The core-breakup measurements for ^{19}C are the result of a collaboration between LPC-Caen, Aarhus, Birmingham, Daresbury, Göteborg, IPN-Orsay, CRN-Strasbourg, Surrey, UCL-Louvain and ULB-Bruxelles.

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