PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1998 **356**, 2063-2081
doi: 10.1098/rsta.1998.0263

Halos and halo excitations

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A brief overview is given of the present status of our knowledge on halo states. Emphasis is put on general ideas and concepts. A discussion of what the central ingredients in the halo structure are is followed by a comparison between the established and proposed halo states. The various experimental probes of halos are reviewed. Particular attention is given to simple excitations built upon halo states, including isobaric analogue states.

Keywords: nuclear halos; fragmentation; exotic nuclei; halo excitations; β-decay

1. Introduction

For most people a halo is a system of luminous rings or arcs around the Sun or the Moon, caused by reflection or refraction of light rays illuminating ice crystals floating in the air. In cosmology, astrophysicists use the word to describe a vast and essentially invisible outer mass shell that surrounds most galaxies. In microcosmos the word 'halo' has now also appeared. Ten years ago it was realized that some very exotic nuclei, in the vicinity of the drip-lines, can be described as consisting of a core nucleus surrounded by a veil of dilute nuclear matter (neutrons or protons) extending far out into the classically forbidden region. This nuclear stratosphere is referred to as a halo state in the nucleus (Hansen & Jonson 1987).

A halo state is basically a threshold phenomenon resulting from the presence of a bound state close to the continuum. The combination of the low separation energy and the short range of the nuclear force allows the nucleon (or cluster of nucleons) to tunnel into the space surrounding the nuclear core so that they are present at distances much larger than the normal nuclear radius with appreciable probability. In this very open structure, simple few-body or cluster models will largely account for the most general properties of the halo states.

To study the halo structure experimentally it is necessary to turn either to the static properties of the halo, or, more often, to processes in which it is created or destroyed. An early expectation was that one could let the halo free for detailed investigations in the laboratory by some simple dissociation mechanism. It turns out, however, that reaction mechanisms and final-state interactions have major influences on the experimental results and it is not easy to extract a clear halo signal from the data. The weak interaction provides an alternative probe via β-decays from or into halo states, and is especially interesting if the halo is an excited nuclear state.

There have been several recent reviews on the physics of halos (Zhukov *et al*. 1993; Riisager 1994; Hansen *et al*. 1995; Tanihata 1996) describing the main experimental and theoretical developments over the past ten years. Here we shall point to some very recent results that might give an indication of the general trend in future experiments

Phil. Trans. R. Soc. Lond. A (1998) **356**, 2063–2081
Printed in Great Britain

TEX Paper

on halo states in particular, but may be more in the development of physics at the drip-lines. Drip-line physics appears to be a major field of physics for the next century.

This review is organized as follows: first, general features of halos are described; second, a brief status of the present situation concerning halo states is given; third, a more detailed discussion is given of different types of 'halo excitations'.

2. Halos

In a rapidly expanding field like this, where even central concepts are being refined only gradually through the interplay between experimental and theoretical progress, it might appear tactless to make use of precise definitions in a review. This will certainly lead to a biased presentation of the field. We believe, however, that such a stance will allow a clearer presentation and shall therefore use a somewhat strict definition of what a halo is. Our point of view is that many interesting physics phenomena occur close to the neutron and proton drip-lines—halos, although important, being only one of them—and that this richness should be reflected properly in the terminology.

Halos are a threshold phenomenon, they occur only for states with small particle-separation energy. Not any state situated close to a threshold will, however, develop a halo. Some general conditions can be stated, among these the most important is that the threshold and the state should 'match', in the sense that the nuclei and/or nucleons in the channel that opens up at the threshold should be the same as those used in a 'cluster' description of the state (the cluster description should obviously be a good first approximation for the state). This must be fulfilled for several of the interesting halo signals to appear. As an example, the low separation energy then implies that the distance between the clusters will be larger than normal; this is the halo signal par excellence. We shall require that the radius of the halo system is larger than the normal nuclear radius by an appreciable amount. For smaller differences in the radii we expect the state to have a more complex structure than the halo one, such transitional states will of course be interesting to study as well.

There is a large sensitivity of the spatial structure to separation energy close to a threshold. The increase in size occurs due to quantum-mechanical tunnelling out from the normal nuclear volume, and will only take place if no significant potential energy barriers are present. General conditions for the angular momentum quantum numbers, the orbital angular momentum l for a halo consisting of one nucleon, and the hypermomentum K for one of two nucleons, can be established (Fedorov *et al.* 1993). Very large spatial extensions will occur for s- and p-wave one-neutron halos and for two-neutron halos in the most symmetric spatial configuration (hypermomentum $K = 0$, i.e. pure s-waves in relative states). Explicit results are shown in figures 1 and 2. Coulomb barriers will in a similar way retard proton halos that should be much less pronounced than neutron halos; this will be seen clearly when we come to the question of where halo states exist.

Let us comment briefly on a few extensions of the simple picture presented so far. First, there is no basic reason why halo structures cannot appear in excited states (several are actually known), but they will be much harder to study experimentally and are therefore often not considered. Second, the implicit assumption of the spherical core used above is not needed; it has been shown recently how halos emerge in the low binding energy limit and decouple from the rest of the system also in the

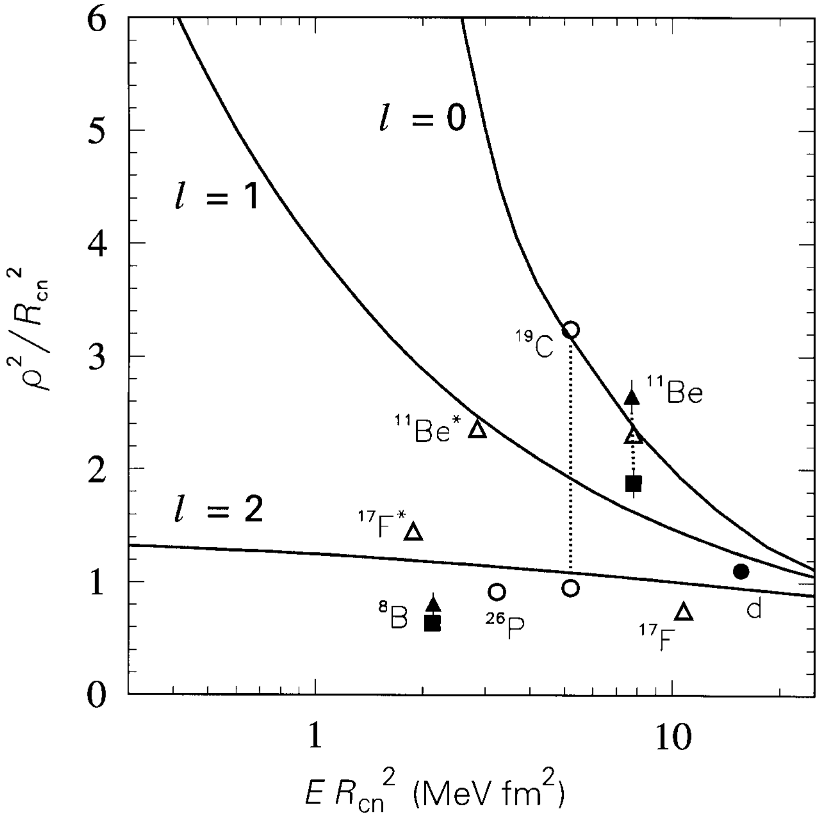

Figure 1. Scaling plot for one-nucleon halos. The ratio of halo and core potential square radii is plotted versus the scaled separation energy. The full lines are theoretical results (Federov *et al*. 1993) for neutron halos for s-, p-, and d-waves. The filled symbols are experimental points, squares based on data in Tanihata *et al*. (1988) and Obuti *et al*. (1996), triangles based on the analysis in Al-Khalili *et al*. (1996). The open symbols are based on calculated values, the triangles use a simple Woods–Saxon potential, the circles are taken from Ridikas *et al*. (1997) and Brown & Hansen (1996).

deformed single-particle model (Misu *et al*. 1997). Third, some descriptions of halo states now also include explicitly core excitations (Nunes *et al*. 1996*a*, *b*). As we go from very good halo states to normal nuclear systems, such degrees of freedom will become more and more important. Note in this connection the recent calculation (Kuo *et al*. 1997) showing that core polarization is suppressed in halo nuclei.

Halos should be a general quantum mechanical phenomenon and could appear in systems other than nuclei, e.g. in atomic or molecular physics (Hansen 1993; Riisager 1994; Hansen *et al*. 1995). Here, we shall not go beyond nuclear systems, but will discuss in some detail the question of multi-neutron halos before looking at what halo states have been found so far.

(*a*) *Multi-nucleon halos?*

As argued above, halo states must be describable in a cluster picture; most often the states decompose into a nuclear core and one or more halo particles. The estab-

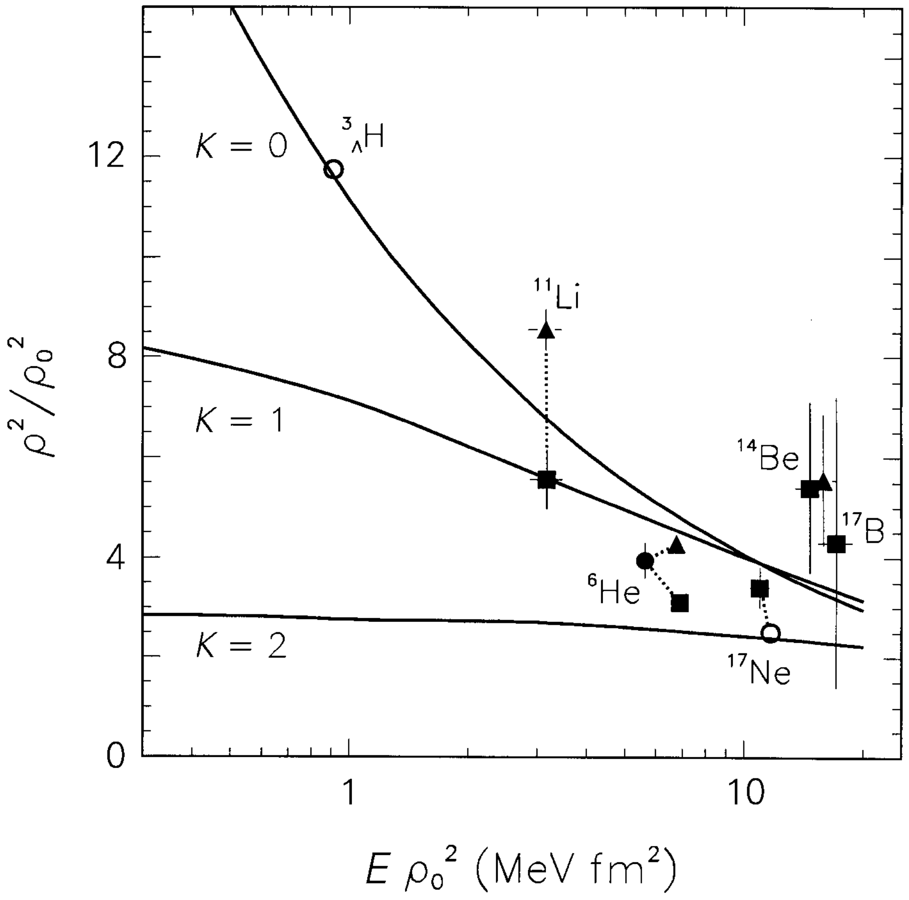

Figure 2. Scaling plot for two-nucleon halos. The ratio of the halo square radius to the effective potential size parameter is plotted versus the scaled separation energy. The full lines are theoretical results (Federov *et al.* 1993) for two-neutron halos for hypermomenta 0, 1, and 2. The filled symbols are experimental points, squares based on data in Tanihata *et al.* (1988, 1992) and Ozawa *et al.* (1994, 1996), triangles based on the analysis in Al-Khalili *et al.* (1996) and Tostevin & Al-Khalili (1997), the circle from the analysis in Alkhazov *et al.* (1997). The open circles are based on calculated values from Cobis *et al.* (1997) and Zhukov & Thompson (1995).

lished halo structures are those with one neutron, a two-body system; and with two neutrons, a three-body system. (We shall mainly be concerned here with neutron halos, and return to proton halos in the next subsection.) In order to see how many clusters there can be for a good halo state, we generalize to an n-body system, i.e. where there are $n-1$ nucleons (or clusters in the general case) around a (more massive) core. By subtraction of the centre-of-mass degrees of freedom, one thus ends up having $d = 3(n-1)$ spatial coordinates. These can also, in the general case, be divided into a radial coordinate ρ and 'angular' parts. Looking only at the most symmetric states this gives, as in Fedorov *et al.* (1993), an equation for the radial wavefunction containing an effective potential that incorporates the expectation values of the contributing short-range, two-body potentials. Provided that the effective potential can be neglected at large distances, the radial equation reduces to that for an effective two-body system with an effective angular momentum, $l^* = (d-3)/2 = 3n/2-3$. For $n = 2, 3, 4, \ldots,$ we get $l^* = 0, 3/2, 3, \ldots.$ The effective angular momentum barrier thus increases rapidly with the number of outer nucleons. From this we conclude that multi-nucleon halos cannot extend out to large distances (the 'asymptotic region') even in the limit of vanishing binding energy, and that, generally speaking, for the very small binding energies two-body halos will be larger than three-body halos, etc.

However, this argument depends on the vanishing of the effective potential. This vanishing does not always take place, as demonstrated clearly in the case of Efimov states (Efimov, 1970*a*, *b*; Fedorov & Jensen 1993; Fedorov *et al*. 1994*a*). Briefly, these three-body 'super-halos' owe their existence to large two-body scattering lengths a, i.e. to large spatial extensions in a subsystem. When this occurs, three-body states of large extent can be built reaching out to dimensions of order a. In this sense, Efimov states are still smaller than the corresponding two-body systems, but the interesting feature is of course that here we have a mechanism for 'creating' three-body systems of the same spatial extent as two-body systems. The experimentalist should note that Efimov states of large spatial extension probably only appear as excited states. Whether a similar effect might appear for a larger number of clusters is debatable (see, for example, Adhikari & Fonseca 1981). It is in any case unlikely that an effect would appear for multi-nucleon halos, since the Pauli-principle restricts the number of particles that can be in the most favourable configuration to at most two. (The number two comes from the spin degeneracy, it only applies if spin–spin interactions are neglected. There will be no orbital degeneracy, since only s-waves will allow for the effect). As a somewhat more theoretical exercise, one can also keep to a three-body system but change the number of spatial dimensions. Here it appears that the Efimov effect only occurs for three spatial dimensions (Nielsen *et al*. 1997).

Some years ago it was suggested (Jensen & Riisager 1991, 1992; see also Hansen *et al*. 1995) that new structures might appear beyond the drip-line driven by (angular) correlations between several nucleon-pairs. Such a mechanism would take place in the intermediate region that lies somewhat beyond the nuclear core, but not so far out that the interactions within the n-body system cease to be important. Only simplified calculations have been carried out so far, and it is not known whether such an intermediate region exists and will be able to support these more complex structures, or whether such systems perhaps would 'collapse' spatially and rather should be thought of as neutron skins (Myers & Swiatecki 1969).† In a different approach, multi-neutron correlations have also been treated within the cluster orbital shell model approximation (Zhukov *et al*. 1994) for the case of ^{8}He.

(*b*) *Established halo states*

Due to the inherent difficulties in producing nuclei close to the drip-lines (in particular the neutron drip-line) in amounts sufficient for experiments, there are not many well-established ground-state halos. Excited state halos are experimentally difficult to study in detail, so also not too much is known here. Still, several states have been investigated experimentally and/or theoretically. The states can be compared in an essentially model-independent way as follows.

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† Good experimental evidence for neutron skins only appeared recently (Suzuki *et al*. 1995). One should note there is some differences in terminology in the earlier literature: what we today call neutron skin has been called neutron halo (Burhop *et al*. 1969; Nolen & Schiffer 1969). Similarly, neutron halo has been called neutron atmosphere (Allison 1960).

Properties of a system should become independent of details of the potential as the separation energy is decreased. One would thus expect scaling to be present, not only for two-body systems (this has been known for a long time to be the case for the deuteron), but also for three-body systems. A practical demonstration of this scaling was given in Fedorov *et al.* (1993), and we shall make use of it here in order to compare different halo states and halo candidates. The main point in such a comparison is that one must compensate for the different core size in different systems. Several equivalent ways of doing this exist, e.g. comparison of probabilities that the halo particles are outside the core, or, the method used here, comparison of ratios of the mean square radii for the halo particles and the core.

We use the following scaling variables (Fedorov *et al.* 1993). The measured mean square core radius is converted to an equivalent (square well) potential radius:

$$R_{\mathrm{cn}}^2 = \tfrac{5}{3}(\langle r^2\rangle_{\mathrm{core}} + 4\ \mathrm{fm}^2). \tag{2.1}$$

This will be the measure of core size for one-nucleon halos; for two-nucleon halos, one must replace it by a weighted average ρ_0 of the radii in the three two-body potentials. We take ρ_0 as

$${\rho_0}^2 = \tfrac{2}{3}\mu_{\mathrm{cn}}R_{\mathrm{cn}}^2 + \tfrac{1}{3}\mu_{\mathrm{nn}}R_{\mathrm{nn}}^2, \tag{2.2}$$

where $\mu_{\mathrm{cn}} = A_{\mathrm{c}}/(A_{\mathrm{c}}+1)$ and $\mu_{\mathrm{nn}} = 1/2$ are the reduced masses in units of the nucleon mass, and $R_{\mathrm{nn}} = 2.65$ fm; see Fedorov *et al.* (1994*b*) for details on the parameter choice. The halo's contribution to the total mean square radius is

$$\rho^2 = A\langle r^2\rangle_{\mathrm{tot}} - A_{\mathrm{c}}\langle r^2\rangle_{\mathrm{core}}, \tag{2.3}$$

where A and A_{c} are the mass numbers of the nucleus and of its core. (ρ is the weighted square-sum of the distances to the centre-of-mass. For one-nucleon halos it is simply the core–nucleon distance except for a factor $\sqrt{A_{\mathrm{c}}/A}$; see Fedorov *et al.* (1993) for details.) To obtain scaling one must also scale the separation energies E with the size of the potential, i.e. E is replaced by ER_{cn}^2 or $E\rho_0^2$, respectively.

Figures 1 and 2 show the halo size and its mean square radius divided by the square of the equivalent potential radius, versus the scaled separation energy for one- and two-nucleon halo systems, respectively. The curves give the results for neutron halos calculated with square-well potentials; other potentials were shown in Fedorov *et al.* (1993) to give essentially the same results. To include proton halos one needs an extra parameter (the product of the halo charge, the core charge, and R_{cn} or ρ_0). Such curves are not displayed here but obviously would lie below the neutron results, the more so, the larger the charge. Selected experimental and theoretical results are plotted as well. Before commenting on them, let us note that the scaling only can be expected to be relevant for large systems, but that the plots nevertheless may be useful for comparing sizes of different systems, and thus serve as a rough indicator of where halo effects should be most pronounced. Error bars are not given for the theoretical points, but one should note that some of the relevant separation energies are not well-known experimentally.

The experimental determinations of radii we use are, except for the classical example of the deuteron, derived from reactions performed at relativistic energies. The original analysis of the measurements of total interaction cross-sections (Tanihata *et al.* 1988) has been questioned recently (Al-Khalili *et al.* 1996; Tostevin & Al-Khalili 1997), and we choose to show both results. (See next section for more details.) For some other halo candidates, theoretical values are used (open symbols), triangles indicate results from simple calculations of single particles moving in a Woods–Saxon potential, circles are from various more realistic calculations. There is little experimental information on one-nucleon halos. The only clear case is in the ground state of ^{11}Be. The first excited state in ^{11}Be is believed also to be a halo, but there is not very much direct evidence. Recently, ^{19}C has been the subject of both experimental and theoretical activity, but there is as yet no clear outcome, as shown in figure 1 by the large span of the theoretical calculations (the two points correspond to ground-state spins 1/2 and 3/2, respectively (Ridikas *et al*. 1997)). Proton halos are clearly more confined. The best case seems to be the first excited state in ^{17}F, whereas the state where most effort has been spent is ^{8}B. There are some indications that the ^{8}B structure is more complex than being mainly the ^{7}Be ground state plus a proton (such a simple picture gives a ρ^2/R_{cn}^2 value of 1.19 for a Woods–Saxon potential).

More experimental points are available for two-nucleon halos. There is quite a large uncertainty in the data for ^{14}Be and ^{17}B, both nuclei are so bound with two-neutron separation energies of 1.3–1.4 MeV that interaction with core degrees of freedom can be expected to be important. The difference in experimental and calculated extent of ^{17}Ne stems from a difference in core radii; the total mean square radii is the same in the two determinations. The hypertriton seems to have the most pronounced halo structure and has the further advantage that it is a true three-hadron system. Its separation energy is not sufficiently well known, therefore the absolute magnitude of its extent can not be predicted accurately; see Cobis *et al*. (1997) for calculations at other energies.

The two figures do not provide a foolproof way of identifying halos, but should give a good indication of where interesting physics can be found. The (conservative) criteria suggested in Fedorov *et al*. (1993) for approximate limits above which good halos might be expected to occur were ρ^2/R_{cn}^2 larger than about 2, and ρ^2/ρ_0^2 larger than about 5. This would leave ^{11}Be and ^{11}Li as the only experimentally well-established halos, but several other systems look very interesting. Note in particular the deuteron and the hypertriton that are good two- and three-body systems (provided quark degrees of freedom are neglected), as well as ^{6}He and ^{17}F*, where the core nucleus is doubly magic and core degrees of freedom can apparently be neglected; see Zhukov *et al*. (1993) and Riisager *et al*. (1992) for references to the experimental evidence.

During the past few years, several papers have emerged suggesting that proton halos are present for mass 20 or above. We shall take the opportunity to discuss these candidates in a bit more detail, but note from the outset that here also the experimental information is scarce and the arguments consequently concentrated on the radii of the systems. If the Coulomb barrier could be neglected and intruder states were not important, the best ground-state proton halos should be found midway in the sd-shell, where s-orbits are filled. A recent calculation (Brown & Hansen 1996) identifies ^{26,27}P and ^{27}S as the best candidates. However, the Coulomb barrier is already sufficiently large to be the limiting factor for the size as seen by the best one-proton result, for ^{26}P, plotted in figure 1. At this core charge there is not much sensitivity to the separation energy close to the threshold and the experimental uncertainty in the energy is not important for the structure. One measure for the importance of the Coulomb barrier is that the s-wave proton halo ^{26}P, according to the calculations in figure 1, would correspond to a d-wave neutron halo in ^{19}C.

For two-proton halos one may expect halo-formation to be even more retarded due to an increased influence of the Coulomb forces. Only one candidate is given in figure 2, namely ^{17}Ne (Zhukov & Thompson 1995), which has a two-proton separation energy just below 1 MeV. It is too early to decide whether a halo is present, but large effects are clearly not expected. There are very few other candidates; even when scaling the separation energy with $A^{-2/3}$, the only lighter one is ^{9}C at 1.4 MeV. For heavier systems, ^{27}S seems a bit worse, whereas ^{31}Ar is better when judged purely on separation energies, but halos cannot realistically be expected for such core charges. The experimental difficulties one runs into are well illustrated by the recent work on the mass 20 isobars (Chulkov *et al*. 1996*a*). Tentative evidence for the occurrence of proton and neutron skins was given there. This requires separate determinations of proton and neutron radii, often derived from total matter and charge radii, but the charge radii are generally not known experimentally for isotopes far from stability and had to be obtained by extrapolation for the mass 20 case. Theoretical calculations might give supporting indications, but are still not able to reproduce quantitatively the experimental matter radii. This situation is unfortunate since, as pointed out in Chulkov *et al*. (1996*b*), the ^{20}Mg structure might be a tetraproton around ^{16}O, which would be very interesting to study. This could form a parallel structure to that of ^{8}He (Zhukov *et al*. 1994).

We note finally that the name ‘neutron halo’ has also been used recently (Lubiński *et al*. 1994) to describe the neutron excess appearing in the outer periphery of heavy (stable) nuclei. The excess is probed via antiproton annihilation and occurs at very low absolute density values. This phenomenon has nothing in common with the halo structure found in the light nuclei and should not be confused with it. It is unfortunate that a similar terminology has been used.

3. Studies of halos

Before reviewing the recent progress made in studies of halo nuclei, we would like to sound a word of caution. Often the distinction between primary experimental data and quantities derived from them is forgotten. Unfortunately, this has given rise to much unneeded confusion in discussions. A prime example is the question of what the radii of halo states are. The new numbers that are presented are often in reality only new derivations based on the same *experimental* results as, for example, total reaction cross-sections. There are recent examples of this, as we shall see.

The Glauber theory or variations upon it has often been the basis for the analysis of reaction experiments at high energy. It appears (Al-Khalili *et al*. 1996) that halo nuclei might need to be treated in a special way in the sense that one cannot use a smeared-out density for the outer part of the nucleus, an average over reactions taking place at different spatial configurations of the halo must be used instead. Note that it might be important whether one uses zero-range or finite-range NN amplitudes, the inclusion of the latter for ^{6}He (Tostevin & Al-Khalili 1997) reduced ρ^2/ρ_0^2 from 4.9 to the 4.3 shown in figure 2. It will be interesting to see whether such a difference occurs also for other nuclei. Recently, this approach has been extended to treat lower beam energies and elastic scattering (Al-Khalili *et al*. 1997). For other recent work, see Formánek & Lombard (1995, 1997), which generalizes the treatment of the deuteron. A compilation of existing experimental data can be found in Ozawa *et al*. (1996).

Precision elastic scattering on protons should be an excellent tool for studying density distributions as demonstrated in the experiment (Alkhazov *et al*. 1997) on ^{6}He and ^{8}He performed at about 700 MeV per nucleon at GSI. The radii derived from this experiment were included in figure 2. There has also been recent activity at RIKEN, e.g. the demonstration (Korsheninnikov *et al*. 1997*a*) of a difference in elastic scattering between ^{6,8}He and ^{11}Li, interpreted as an indication of a difference in structure: neutron skin versus neutron halo.

Much effort has gone into the experimental determination and the theoretical interpretation of momentum distributions of fragments from break-up reactions. The first important step when interpreting distributions is to understand how to pass the bridge between experiment and theory—the experimental filter. This has to be included to correct for the distortions of the picture and *must* be known in order to make a meaningful comparison. An overview is given in Hansen *et al*. (1995), so we shall only comment on a few aspects. It has turned out that most distributions are distorted in some way and thus do not reflect the halo momentum distributions directly. For three-body halos, one must in general expect (Garrido *et al*. 1997*a*) that the two-body subsystems have low-lying continuum structure, i.e. final-state interactions are important. There may also be a bias in that reactions leaving the core intact will occur preferentially at large impact parameters so that one does not ‘probe’ the whole of the original wavefunction (Hansen 1996; Hencken *et al*. 1996), which leads to narrower distributions. A similar effect must also be present in core break-up channels (Nilsson *et al*. 1995), where one should also look out for final-state interactions. These effects are not purely detrimental, since one may learn about the two-body substructure in three-body systems from the final-state interactions as shown in the case of ^{10}Li (Zinser *et al*. 1995; Garrido *et al*. 1997*b*); see figure 3.

‘Complete kinematics’ experiments are now also being performed in which all emerging fragments from break-up reactions are measured. Here one may obtain excitation energy spectra from the complete system or any subsystem and begin to search for correlations in a more systematic way. Two recent examples from GSI are the measurements of ^{11}Li (Zinser *et al*. 1997) and of ^{6}He (Chulkov *et al*. 1997). In the latter, evidence was seen for a spin alignment, as shown in figure 4. It seems that fragmentation takes place mainly by one-neutron removal to the ^{5}He resonance. In the subsequent break-up, the decay products preferentially go parallel to the ^{5}He direction. This angular correlation might appear in a simple way due to the two-step nature of the process (in which case the detailed properties of ^{6}He are not necessarily reflected), but other explanations might also come into play.

We have not treated Coulomb dissociation explicitly since this subject is covered in earlier reviews. However, the work of Catara *et al*. (1996) should be mentioned. Here the nature of the extra low-lying strength seen in loosely bound systems is exposed in a quite transparent way. The strength is due to single-particle transitions, not to resonances.

4. Halo excitations

One of the major attractive features of halo structures from a conceptual point of view are their simplicity, that they can be described as two- or three-particle systems. A key question that has not yet been answered is how much of this simplicity is a consequence of the state being close to a threshold. Put in another way: how does

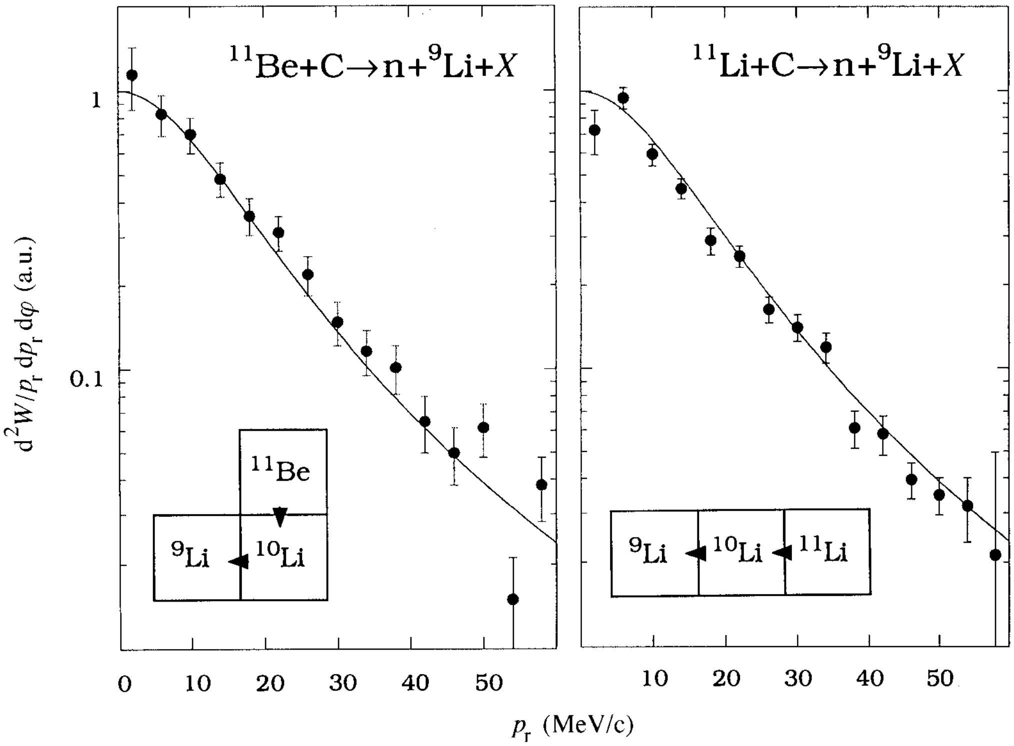

Figure 3. Radial momentum distributions of neutrons in coincidence with ^{9}Li fragments after proton and neutron stripping reactions of the radioactive beams ^{11}Be and ^{11}Li in carbon targets (Zinser *et al.* 1995). The two distributions are similar in shape and characterized by almost identical width parameters, $\Gamma \simeq 36$ MeV/c. The similarity of the widths is partly accidental, but demonstrates in a transparent way the effect of the (^{9}Li+n) final-state interaction. The combination of the two data-sets, taking into account the recoil correction in the proton pick-up from the ^{10}Be core, shows that the ^{10}Li ground state is an $l = 0$ state which is almost bound. Furthermore, the ^{11}Li data can only be understood assuming $(1s_{1/2})^2$ and $(0p_{1/2})^2$ components are about equal in the ^{11}Li ground-state wavefunction.

the halo structure emerge as thresholds are approached? One way of attacking this question is to study many nuclear states covering the transition from extreme halos to normal nuclear states; another independent way to proceed will be presented in this section. Here we shall look at states related to good halo states via simple operations. By seeing how much the structure changes under these operations (under which the states and the corresponding thresholds can move more or less independently), we might learn more about halo formation.

The simple operations we have in mind are orbital excitations (keeping the clusters intact), excitations within one of the clusters and various exchanges of neutrons and protons. Among the latter are pure Fermi transitions (where the total isospin is conserved), Gamow–Teller transitions (affecting also the spin of the changed nucleon), and complete reversals of all protons and neutrons, i.e. comparison of mirror states. We do not consider removal of one or more nucleons, since this normally changes the structure in an appreciable way, cf. the previous section.

Let us first consider orbital excitations. The classical example is that of ^{11}Be

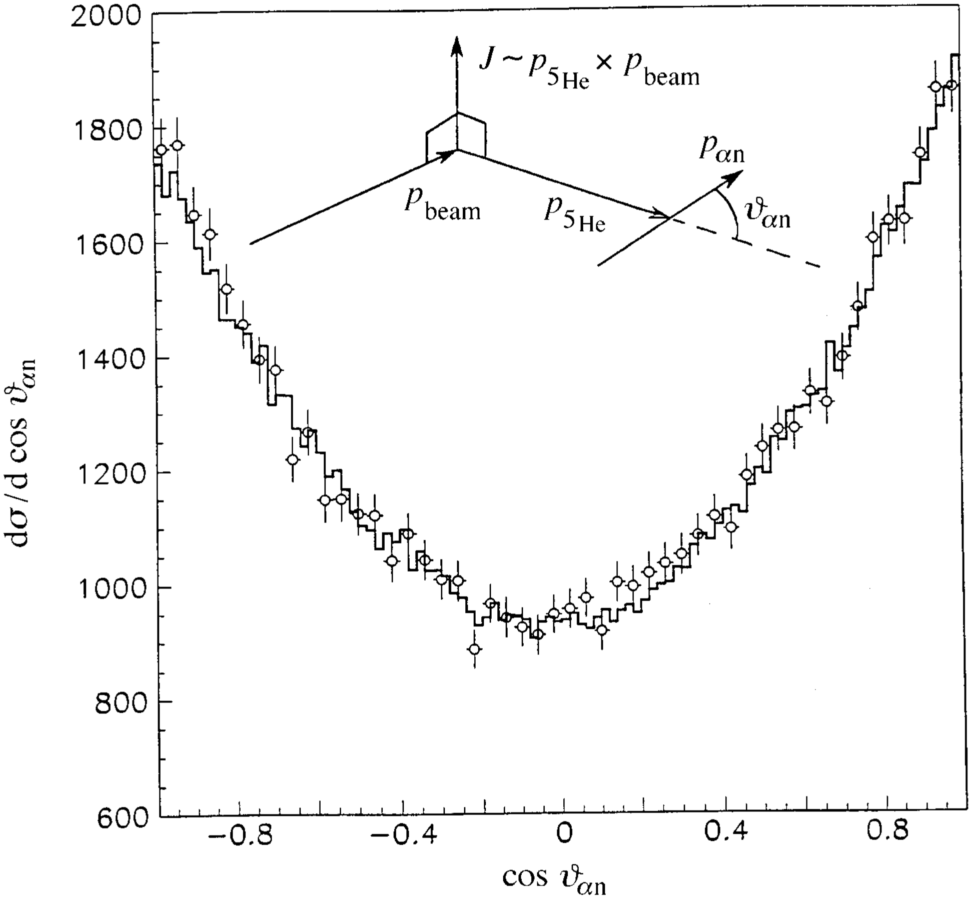

Figure 4. Angular distribution of the $\boldsymbol{p}_{\alpha n}$ vector on polar angles ($\vartheta_{\alpha n}$) in a coordinate system with the z-axis parallel to the direction of the $\boldsymbol{p}_{^5\mathrm{He}}$ momentum and the x-axis in a direction perpendicular to the reaction plane ($\boldsymbol{p}_{^5\mathrm{He}} \times \boldsymbol{p}_{\mathrm{beam}}$). The histogram is the result of a Monte-Carlo calculation (Chulkov *et al.* 1997) with an anisotropy of the ^{5}He decay products described by a correlation function $W(\vartheta_{\alpha n}) = 1 + A\cos^2(\vartheta_{\alpha n})$ demonstrating a spin alignment of ^{5}He in a plane perpendicular to the ^{5}He momentum vector.

(Millener *et al.* 1983); here an E1 excitation can lead to the excited state that has the extra attractive feature of also being bound and therefore is also a halo state. The neutron is in a p-wave rather than the s-wave of the ground state. The signature of this is the large enhancement of the transition strength, historically one of the first pieces of experimental evidence for halos. This transition has now been probed via Coulomb excitation and more sophisticated analyses of the excitation processes have begun (Nakamura *et al.* 1997; Fauerbach *et al.* 1997). Theoretical calculations of excitations in two-neutron halos are now appearing for the ^{6}He case (Danilin *et al.* 1997). Recently, experimental investigations of the low-lying excited states in ^{11}Li have also been performed, these states are all unbound. Noteworthy are the results (Korsheninnikov *et al.* 1997*b*) on the lowest excited state at about 1.3 MeV, seen by scattering from protons. From an analysis of the angular distribution, this transition was suggested to have a transferred orbital angular momentum L of 1. The natural explanation is that this excitation, in analogy with the one in ^{11}Be, involves only the halo particles and one might even derive constraints on the structure of ^{11}Li itself. Note, however, that an alternative interpretation has been suggested (Karataglidis *et al*. 1997) not involving excited states of ^{11}Li but phrased in terms of scattering directly to the continuum. It should be investigated whether these two interpretations are compatible or not.

We next turn to states where the core is excited. Such states will be particle-unbound (if not, the core would be too 'soft' to form a good halo), and therefore hard to study experimentally in detail. However, based simply on the observed excitation spectrum of ^{11}Li, it has already been suggested (Korsheninnikov *et al*. 1996) that the second, third and fourth excited states might have this configuration. The second excited state would, for example, then have the structure with two neutrons around the ^{9}Li first excited state. A general discussion of threshold states built on excited states is given in Abramovich *et al*. (1992), several candidates are given there. Some such states in ^{11}B will be discussed below, but to do this properly we need first to look more closely at isobaric analogue states of halos, the next point on our list.

Formally, we apply the Fermi operator to a halo state to create the isobaric analogue state, i.e. we change the isospin projection. This changes the Coulomb interactions and might thus change the structure of the weakly bound state. This problem has received little attention (Suzuki & Yabana 1991; Hansen *et al*. 1993) so far. Based on the discussion of halo structures in § 2, the problem can be divided into two questions. Is the cluster structure for the new state similar to that of the original halo state? If so, is the spatial extent the same?

The first question can to a large extent be circumvented by only considering cases where the core has isospin 0, examples being ^{6}He and ^{17}F*. Due to the Coulomb energy, the isobaric analogues of proton halos will be more bound, often so much that the spatial extent becomes essentially normal as in the mass 17 nuclei. Conversely, the isobaric analogues of neutron halos will be less bound, most likely even particle-unbound. The only investigated exception is for ^{6}He where the corresponding 'proton–neutron halo', the $T = 1$ state in ^{6}Li at 3.563 MeV, is also bound with respect to the α + p + n threshold and is even calculated (Danilin *et al*. 1991; Fedorov *et al*. 1994*b*; Arai *et al*. 1995) to be a bit larger spatially than ^{6}He. The Coulomb potential, of course, limits the total extent of 2p- and np-halos, the calculations in Fedorov *et al*. (1994*b*) give asymptotic limits on ρ^2/ρ_0^2 of about 5, even for as small a core charge as 3.

When the core has a non-zero isospin, the situation is a bit more complex. We shall discuss this starting from the simplest possible case of the one-neutron halos in ^{11}Be. The lowest $T = 3/2$ states in the mass 11 nuclei are shown in figure 5, where also the one-neutron and/or one-proton thresholds (involving the $T = 1$ core nuclear states) are given. There is only one threshold for ^{11}Be and ^{11}N, but two for the nuclei in between. For a given nucleus, the one-proton threshold is lower than the one-neutron threshold by the sum of the neutron–proton mass difference and the difference in Coulomb energy of the two core nuclei. This difference is sufficiently large to make the isobaric analogues of the ^{11}Be halo states proton-unbound. Assuming that a cluster decomposition will still make sense, the isobaric analogue states will be linear combinations of the two structures corresponding to the two thresholds. In a normal situation, the relative weights of these two configurations will be given simply

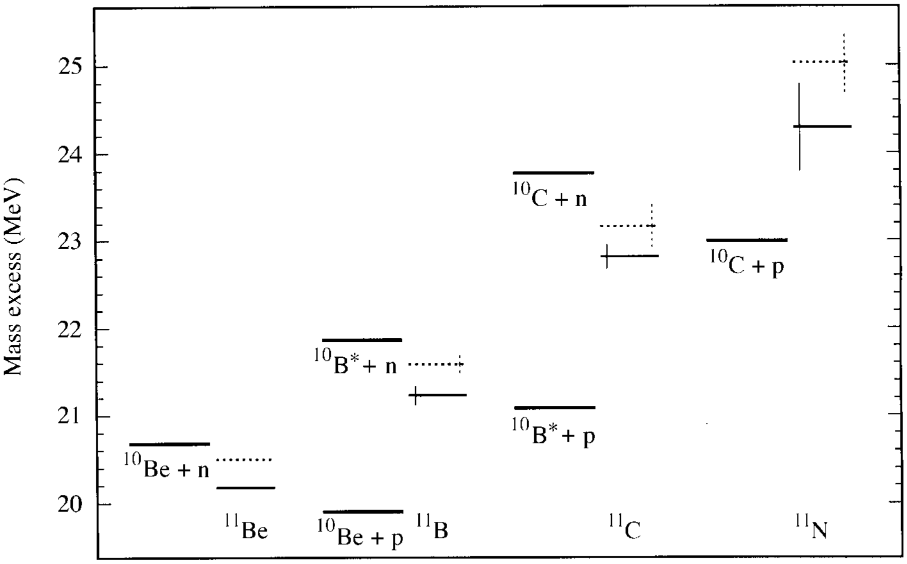

Figure 5. The mass excess for the two lowest $T = 3/2$ states in the mass 11 nuclei, the $1/2^+$ states are marked by the thin full lines and the $1/2^-$ states by dotted lines. The relevant single-neutron or single-proton thresholds are also shown, $^{10}\mathrm{B}^*$ is the lowest $T = 1$ state in ^{10}B at 1.740 MeV. The vertical 'error bars' have a total length equalling the full-width half-maximum of the unbound levels.

by Clebsch–Gordan coefficients, but recent papers have explored the idea that halo states might differ. Zhukov *et al.* (1995) suggested that keeping the core unchanged and changing the halo part might lead to eigenstates in a neighbouring nucleus. This would in figure 5 correspond to the ^{11}B states having a ^{10}Be plus proton structure. (The paper also considered such states of lower isospin reachable in Gamow–Teller transitions. In Timofeyuk & Descouvemont (1996), it was conversely suggested that states of lower isospin exist in which the halo is intact and only the core changes.) It should be stressed that such models will not yield states of good overall isospin and they were therefore not considered in earlier works (Suzuki & Yabana 1991; Hansen *et al.* 1993).

A cursory look at the ^{11}B and ^{11}C states in figure 5 seems to indicate that they are indeed made up of more than one component. The full width at half maximum of the states is at least 200 keV and they cannot therefore mainly have the neutron-threshold configuration. On the other hand, they are only shifted a little down from this threshold compared to ^{11}Be, the shift is roughly the same for the two states and is about 115 keV in ^{11}B and about 440 keV in ^{11}C. A pure neutron-threshold configuration should lead to no shift at all, whereas a pure proton-threshold configuration should give a shift at least of the order of the neutron–proton mass difference, to which should be added the gain in Coulomb energy if the proton is more widely distributed in space than core protons. This therefore indicates that the states cannot mainly have the proton-threshold configuration.

Due to the sensitivity of the spatial extent to binding energy, one cannot expect a perfect spatial overlap between a halo state and its isobaric analogue state, even in the case where the latter is also clustered. It would be natural for this non-overlap

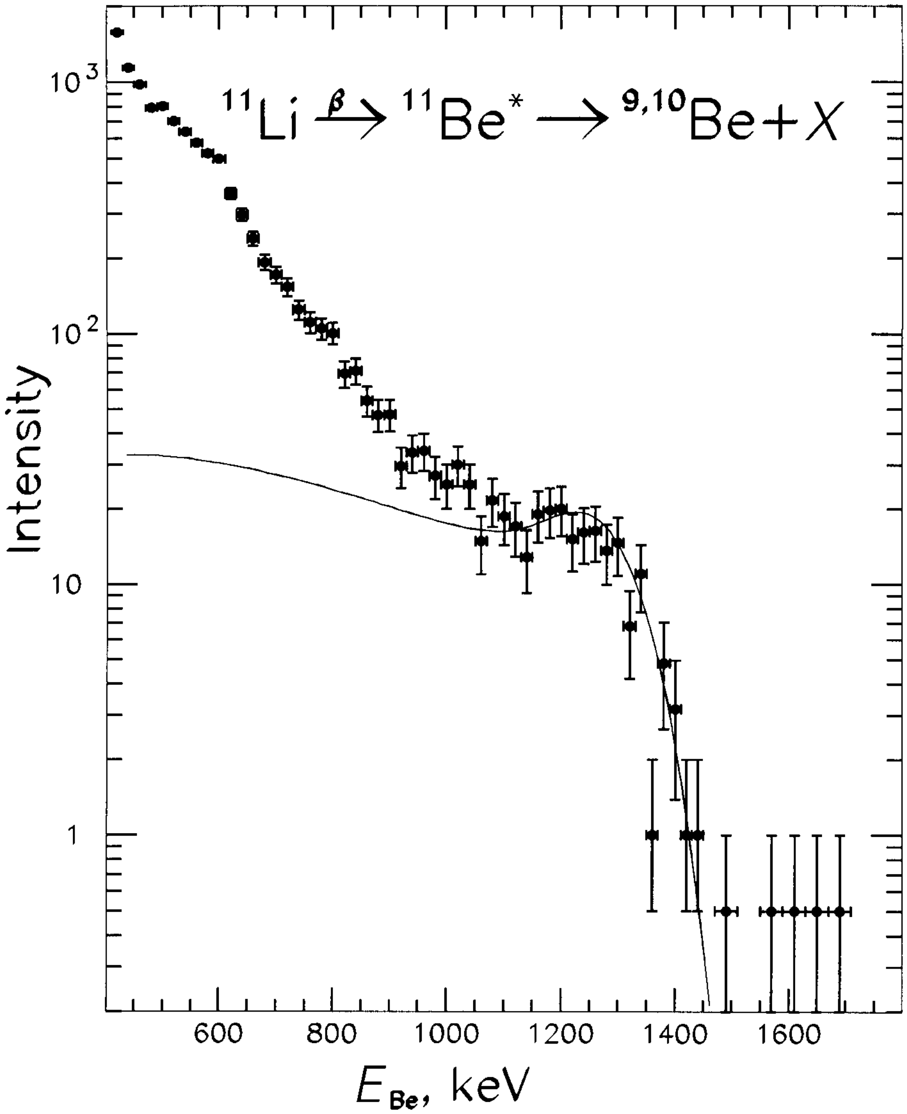

Figure 6. Energy spectrum of recoiling Be nuclei after β-delayed neutron and two-neutron emission (Borge *et al*. 1997*b*). The bump at about 1300 keV is interpreted as mainly stemming from neutron emission from a broad state in ^{11}Be at 18 MeV to the first excited 2^+ state in ^{10}Be (the solid line). This result can be interpreted as giving constraints on the mixture of $(1s_{1/2})^2$ and $(0p_{1/2})^2$ components in the ^{11}Li ground-state wave function.

to become larger the more pronounced the original halo state. In β-decays the Fermi strength might therefore be spread out and mixing can take place with other states (Hansen *et al*. 1993), perhaps also directly to continuum states. It is only possible to investigate this in β-decay experiments for proton-halos. The best case would be to have a spin 0 proton halo (then the Gamow–Teller operator cannot contribute to the transition); no such case is known. For other cases, it might be hard to separate Fermi and Gamow–Teller contributions experimentally, but a similar effect should

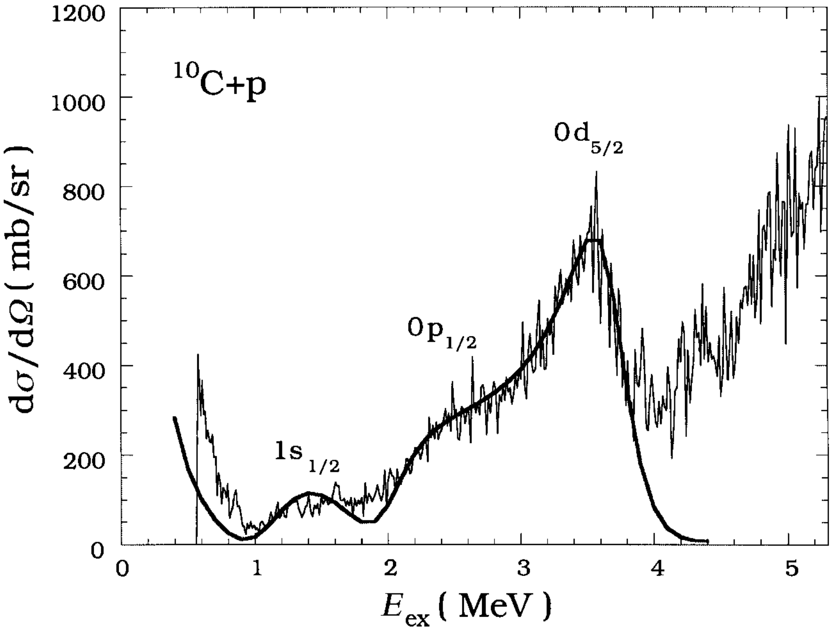

Figure 7. The low-energy excitation function of $^{10}\mathrm{C}+\mathrm{p}$ elastic scattering (Axelsson *et al*. 1996). The structure above 1 MeV corresponds to the ground state and the first two excited states in ^{11}N, the mirror system of ^{11}Be. The curve shows a potential model fit to the data, which indicates a structure with the same level inversion for ^{11}N as is known for ^{11}Be.

be present anyway. An indication of an effect is found in the case of the mass 8 nuclei where the mirror β-decays to the doublet at 16 MeV in ^{8}Be differ in intensity (see Barker (1989) and references therein), but it would be more interesting to have positive evidence for such a spread in β-decay strength.

Experimental tests in β-decay are fundamentally limited by the Q_β-value. In particular for neutron-rich nuclei, the decay will be dominated by Gamow–Teller transitions, but the corresponding operator also has a rather simple structure—now involving both isospin and spin—and strong Gamow–Teller transitions will also yield information on halos. During the past few years, the decay of ^{11}Li has been studied with emphasis on possible signatures due to its neutron halo (Mukha *et al*. 1996; Borge *et al*. 1997*a*, *b*), of which one example is given in figure 6.

The alternative to β-decay experiments is charge exchange reactions. Here (p,n) reactions in inverse kinematics with a ^{6}He beam have been done (Cortina-Gil *et al*. 1996; Brown *et al*. 1996) at several beam energies, but no clear halo signature was found. Preliminary results from similar (p,n) and (d,2n) experiments on a ^{11}Li beam have also appeared (Shimoura *et al*. 1997). The isobaric analogue state was identified, and from its decay pattern it seems possible to extract information about the halo structure in ^{11}Li.

We finally turn to the subject of mirror states of halos. As mentioned above, mirror states of proton halos will be more bound, whereas mirror states of neutron halos will be particle-unbound. None of these can be expected to be good halo states, but they might still have a similar amount of clustering. This is of course an extreme example of the proton–neutron asymmetry introduced by the Coulomb interaction. An

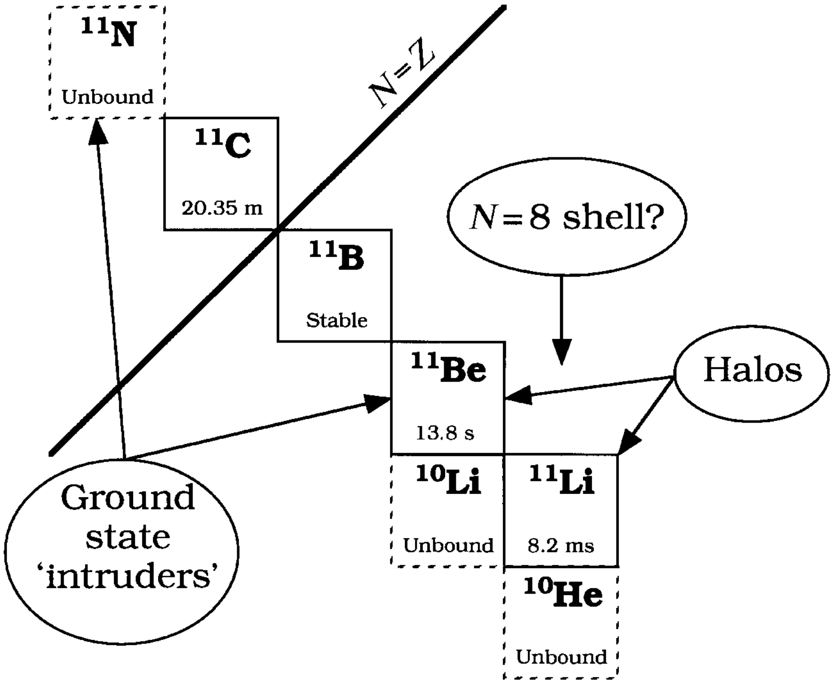

Figure 8. Many, partly interconnected, physics phenomena occur around the $A = 11$ isobars. With only five nuclei bridging the stability island from one shore to the other it is remarkable that three of them are in the forefront of the present interest in the drip-line physics. See the text for details.

immediate consequence of the proton–neutron asymmetry is the Thomas–Ehrman shift (Bohr & Mottelson 1969; Barker 1991). This is seen very clearly for the $1/2^+$ state in ^{11}N in figure 5. The recently provided experimental data (Axelsson *et al.* 1996) on the (unbound) states in ^{11}N (shown in figure 7) will in general give valuable constraints for theoretical calculations attempting to describe the structure in the two systems at the same time (see Descouvemont (1997) and references therein).

5. Conclusion

A coherent picture of halo formation and halo properties has still not been reached, but from the recent experimental and theoretical progress mentioned above we can see that advances are made steadily. We discussed in particular the limits of occurrence for halos and gave a comparison of the sizes of different halo candidates. We would like to reiterate our warning that one must distinguish the primary data on halos (these are scarce and suffer from lack of statistics but are otherwise of good quality) from the interpretations built upon them leading to quantities that can be compared directly to structural calculations, e.g. matter radii. Care must also be taken when interpreting various distributions, since experimental distortions might be important. A 'trend' in the experiments performed during the last few years is to look now also at excitations of halo states, be it orbital or other excitations within the nucleus, or isobaric analogue states and other states reached in β-decays and charge exchange reactions. Our understanding of the halo phenomenon should thus grow in the coming years.

Just as important as understanding the halo structure will be the unveiling of the other types of structural changes taking place at or near the drip-lines. Different structural changes may be intertwined as illustrated in figure 8 by the example of the mass 11 isobaric chain. Halos appear in ^{11}Be and ^{11}Li; in ^{11}Be the halo is enhanced because the ground state is an intruder due to a neutron s-state transfer from the next shell, a phenomenon also seen in ^{11}N; similarly the $N = 8$ shell closure at ^{11}Li might be partly washed out due, again, to the outer neutrons being in s-states (different configurations give rather different extents of the halo). The properties of the ground state of ^{11}Li and the course of reactions where it breaks up are also strongly correlated with the structure of the neighbouring unbound nuclei. Put briefly, there is much other interesting physics at the drip-line that will coexist with and/or complement halos. We believe research in these connections will gain in importance in the future.

The authors are indebted to Aksel S. Jensen, Ivan Mukha and Mikhail V. Zhukov for discussions and comments.

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