Structure of halo nuclei — overview of the experimental data

K. Riisager

Department of Physics and Astronomy
Aarhus University
DK 8000 Aarhus C, Denmark

Abstract

An overview is given of the experimental techniques used for halo nuclei, with examples taken mainly from recent measurements. The main body of data come from reaction work, but other subjects will also be covered. Work done at European laboratories is treated in more detail. A brief assessment of present and future halo candidates is given at the end.

1 Introduction

It is not possible to give an exhaustive review of halo nuclei in a short paper, so I shall here give examples taken from recent experiments to illustrate the many different established ways of accessing and probing halo structures, and refer to previous reviews [1, 2, 3, 4, 5] and to the two volumes of overview papers on radioactive beam physics [6, 7] for a more complete overview. See also the other contributions to this meeting.

Halos occur in loosely bound nuclei when one or more nucleons decouple from a core and tunnel into the surroundings. Apart from the general structure aspects in the physics of halo systems there is for nuclei also strong relations to the question of clustering in nuclei and to few-body physics. Furthermore, there will be a strong coupling to the continuum both in static and dynamic descriptions. There are presently only a few good examples of pronounced halo nuclei and a large part of the recent activity has implictly been concerned with "intermediate" systems that are more bound or have a mixed composition. The latter could happen in two different way: two-neutron halos could have several components when described in terms of (shell model) orbits or — more severely — the halo nucleus could consist of several components, only one of which being of type halo nucleon(s) plus core nucleus in ground state. Examples of this will be given below.

2 The experimental situation

We can do experiments with 1–10 ions/s and get interesting physics out, but to obtain a complete understanding and do all the needed crosschecks takes a lot of beamtime. Luckily, there has been a steady advance in yields (and in detection techniques) which means that at the same time as we have been able to go further up the dripline to new systems, we have also been able to perform more challenging experiments that deepen our understanding of the already known halo nuclei.

2.1 First generation experiments

Interaction cross sections and rms radii deduced from them have been used since the start of halo physics and remain a good indicator for where interesting physics might be found. In the existing data [8, 9] only few nuclei stand out as clearly as ^{11}Li, some halo candidates such as ^{15}C even show almost no effect (this could be due to beam energy dependence [10]; the suggestion that ^{16}C is a halo [11, 12] would then be replaced by ^{15}C being a "moderate" halo, which would be more consistent with the separation energies $S_n = 1.218$ MeV for ^{15}C and 4.25 MeV for ^{16}C). Note that the N, O and F isotopes with $N = 15, 16$ all have an anomalously large radius, this will be discussed shortly.

Several experiments have contributed to the present systematic knowledge of reaction cross sections, one of the latest additions being from HIRFL (Lanzhou) where measurements have been done at about 30 MeV/u and see increased cross sections for some loosely bound protonrich nuclei such as ^{23}Al and ^{27}P [13, 14]. A particularly interesting set of data is the measurement of one-neutron removal reactions [15] for a wide range of isotopes, where also momentum distributions were recorded.

With sufficient beam intensities one can obtain a more detailed mapping of the radial density distribution by elastic scattering. The accurate experiments on ^{6,8}He scattering on protons at 0.7 GeV/u at GSI [16, 17] are sensitive to the density range 10^{-1}–10^{-3} fm^{-3}. To probe the higher density range in the core of the nucleus more weakly interacting probes such as electron scattering must be used, to probe the outer tail at even lower densities one might employ antiproton annihilation or direct radiative capture processes at low energy (for one nucleon halos). At lower energies both elastic and inelastic scattering data confirm the halo picture for ^{6}He, one example being the recent data taken at ACCULINA in Dubna [18]. A series of experiments at GANIL [19, 20, 21] have led to an increased understanding of the potentials used for describing ^{6}He interactions with p and C targets and are being contined now at SPIRAL.

The measurement of core or halo momentum distributions after break-up can, when analyzed within a proper reaction model, provide important information on the structure of a halo nucleus. One recent example is the measurement at RIPS of the longitudinal momentum distribution of ^{15}B fragments following break-up of ^{17}B on a Be target at 70 MeV/u [22]. The two-neutron removal cross section is sizable and the momentum distribution found is narrow with a FWHM of 80 ± 10 MeV/c. This is consistent with ^{17}B being a two-neutron halo ($S_{2n} = 1.39$ MeV). Model calculations to reproduce the momentum distribution indicate that the two halo neutrons are in a mixed state, with the $(2s_{1/2})^2$ component having a stronger weight than the $(1d_{5/2})^2$ component. A pure d^2 configuration would be spatially confined.

The large increase in interaction cross section for ^{22}N, ^{23}O and ^{24}F ($N = 15$ nuclei) was suggested [23] to be due to an enlargement of the core of these nuclei. Longitudinal momentum distributions of ^{21,22}O fragments from ^{23}O break-up [24] might support this, whereas the data presented by T. Aumann at this workshop do not fit naturally in this picture (see also [25]). Whatever the correct explanation turns out to be a one-neutron halo structure will not in itself be able to explain the increase in cross section even though the neutrons are believed to reside in s-orbits. Since S_n for these nuclei are 1.2, 2.7 and 3.9 MeV one would in any case at most expect moderate halos to develop.

The detection of γ-rays emitted from the outgoing fragments allows to assess experimentally whether core excited components are present in a halo state. Only a small component of about 13% is present for ^{8}B [26], whereas the situation is more complex for ^{19}C where different experimental results ([27] and references therein) are harder to combine into a consistent picture.

2.2 New analysis methods

The increased experimental coverage has enabled several new approaches to be introduced, including the construction of invariant mass spectra and of angular distributions as well as the elucidation of correlations among fragments by use of event mixing techniques. Several good examples are given in the presentations here by Aumann and Simon.

Studies of break-up reactions of the known lighter halo nuclei have continued several places [28], but the most complete data have emerged from a series of experiments at the GSI. Highlights include the detailed investigation of ^{6}He, see [29, 30, 31] and references therein, and the demonstration of interference between s and p waves in ^{11}Li [32] that now has been extended also to apply to specific excitation energy intervals (Simon, these proceedings).

An important step has been to include for study also systems outside the neutron and proton driplines. These very shortlived nuclei, apart from being of interest in themselves, provide important structural information that is used to obtain a more complete picture of the structure of the bound systems. Such information can naturally be extracted from the complete kinematics experiments just mentioned, one recent outcome being the results on excited states in ^{7}He [33]. Information on unbound nuclei have been obtained also in more dedicated experiments, one example being the study of ^{11}N at GANIL through elastic resonance scattering [34] whereby the mirror symmetry in this region was cheched, another example being the demonstration [35] that the only excited bound state in ^{9}Li at 2.7 MeV is only weakly (9±%) populated in break-up of ^{11}Be and that the very low-energy neutrons observed earlier after break-up of ^{11}Be to ^{9}Li therefore corresponds to the ground state of ^{10}Li (a virtual s state).

Good examples of a more complete detection system at intermediate energies are given by the work of Marques et al. [36, 37] at GANIL, such as the adaption of the two-neutron interferometry method to ^{6}He, ^{11}Li and ^{14}Be that yields r_{nn} values consistent with theoretical structure models that fit other known properties of these nuclei.

Where statistics remain limited more advanced analysis techniques can also sometimes be of value, a recent example being the use of robust statistics [38] for the analysis of shapes of momentum distributions.

As described by T. Glasmacher at this meeting detailed investigations of one-nucleon knockout reactions have been carried out at MSU. Among the recent results should be mentioned the determination of spectroscopic factors for ^{8}B [39] and the explanation through a coupled discretized continuum channels calculation of the asymmetry between low and high momenta in longitudinal momentum spectra after one-neutron removal in ^{11}Be and ^{15}C [40], an asymmetry that has been observed for many systems earlier but only explained satisfactorily through this work.

The break-up or knock-out reactions (on light as well as heavy targets) have reached a high level of sophistication by now. Other types of reactions, to which we turn now, have only recently been introduced.

2.3 Reaction probes not yet fully exploited

Charge-exchange reactions have only been employed in a limited number of cases, an important example being the reaction ^{14}Be(p,n)^{14}B* measured at 74 MeV/u at RIKEN [41]. By comparing with a (d,2n) reaction one could identify clearly the IAS through its subsequent decay into the ^{12}Be+n+p channel. The structure of the IAS and the original halo state being essentially identical, one can probe both by looking at the decay patterns of the IAS or at the Coulomb energy shift between them. Another example of an charge-exchange reaction is the MSU measurement of ^{6}Li(t,^{3}He)^{6}He performed at 336 MeV [42] where also the excited state spectrum of ^{6}He was probed.

A number of low-energy transfer reaction experiments have been done, a recent development coming from REX-ISOLDE where ^{9}Li+d and ^{9}Li+^{9}Be were studied at 2.3 MeV/u. The (d,t) reaction feeding known states in ^{8}Li has been clearly identified and analysis of the (d,p) reaction that would feed the (unbound) states in ^{10}Li is going on presently. Another example is the population of excited states in ^{12}B and ^{13}C via the (d,p) reaction at 11.8 MeV [43] where the extracted asymptotic normalization constant might indicate the presence of extended structures in some low-lying states. This is one of the methods that could be sensitive also to excited state halos, but complimentary experiments would be needed in order to reach firm conclusions.

The question of how large contribution the ground state in ^{11}Be can have from core excited components have been studied in an experiment at GANIL [44] via the ^{11}Be(p,d)^{10}Be reaction performed at 35.3 MeV/u. Only a small component of the 2^{+} state can be present, in agreement with the conclusion from e.g. the measurement of γ-rays from break-up of ^{11}Be in coincidence with detection of the longitudinal momentum of ^{10}Be fragments [45].

2.4 Not nuclear reactions

The halo experiments taking place at very low energy at ISOLDE have been reviewed in [4] and were also mentioned in the contribution of Neyens here. An example of the use of electromagnetic moments is the measurement of the magnetic moment of ^{11}Be [46], where the obtained value of $-1.6816(8)\mu_N$ is consistent with the above picture of ^{11}Be having only a small contribution of a excited core component. Also mass measurements are important as they constrain the theoretical modelling. A remeasurement of the mass of ^{11}Li is being done at MISTRAL/ISOLDE, but measurements of other near-dripline nuclei at the ESR in line with the results presented here by Scheidenberger would clearly also be valuable.

Concerning beta decay studies, let me just mention the recent results on the high energy part of the beta-strength from the decay of ^{14}Be [47] that confirm the picture of a “factorization” of the β-decay process into a core part and a halo part and are consistent with the ground state of ^{12}Be being a good core in ^{14}Be. A more systematic account of the role of beta decays in studies of halo nuclei can be found in [4].

3 Classification of halo nuclei

An overview of existing halos and halo candidates is given in the figure that shows scaling plots for two- and three-body halos. As explained in [48] the ordinate is a measure of radial extent of the halo. The best nuclear two-body halo systems are the deuteron and the hypertriton (whose properties are not known precisely, it is predicted to be a Λ-halo) followed by ^{11}Be and ^{19}C, where the last seems to have a more complex structure. Among the two-body systems of more moderate size are ^{8}B and ^{15}C. For the three-body halos ^{11}Li is clearly the best nuclear example, followed by ^{6}He. Several nuclei, ^{14}Be, ^{17,19}B and ^{17}Ne, are of more moderate size, but all need to be studied in more detail. There are not yet any known nuclear examples of the extreme Efimov states, more detailes on these can be found through [5].

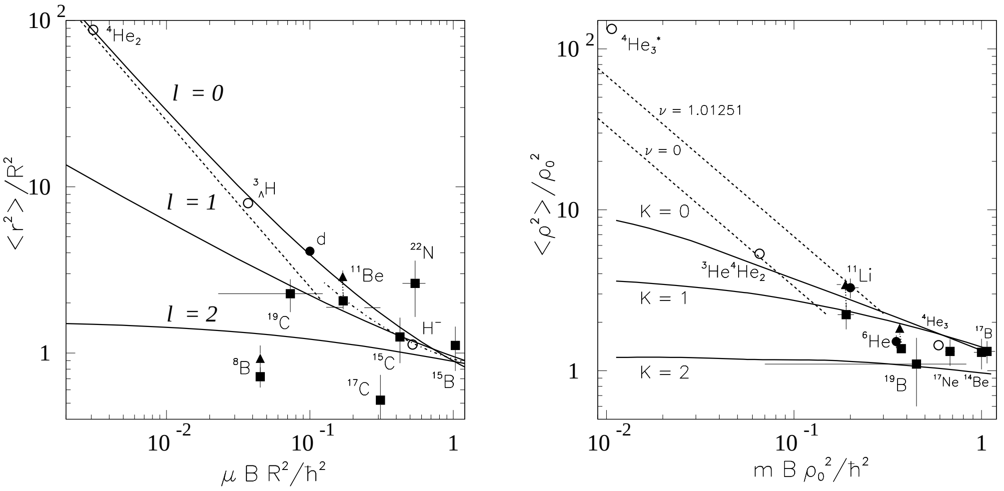

Fig. 1: Scaling plots [5, 48] for two- and three-body halos. Halo mean square radius is plotted versus scaled binding energy. Both nuclear and molecular halos are shown, the former are discussed in the text.

Except for d and $^3_\Lambda$H all known halos have the halo particle in the lowest p-orbit and/or the second s-orbit. It seems we have found all ground state halos built upon these orbits, except possibly for the $N = 15, 16$ nuclei and perhaps nuclei around $Z = 15$ where, however, the Coulomb potential will limit their extension drastically. If we disregard excited state halos (such as the first excited states in ^{11}Be and ^{17}F) that are harder to study, we therefore need to proceed to the second p-orbit to reach more nuclear halos. We would most likely have to look quite closely to the neutron dripline [49], the most neutronrich Ne and Na nuclei being the first possible candidates. With ^{34}Ne and ^{37}Na just being discovered [50, 51] this undertaking will clearly have to wait to the next generation of radioactive beam facilities.

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