Structure of halo nuclei — overview of theoretical status

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Abstract

The past decade has seen an explosion of theoretical interest in the structure and dynamics of halo nuclei. Their basic defining features of weak binding and large radial extent due to the extended tail in their densities is now well-described within few-body models. This has led to impressive advances in few-body reaction theories which crucially take into account this few-body nature. This paper will review some of the recent advances in both structure and reaction studies, and will focus on the issues currently of interest along with possible directions for future advances. On the structure side, improvements to few-body models are being explored to take into account the role of antisymmetrization more accurately and the importance of core polarization and excitation. The successes of fully microscopic approaches will also be reviewed.

1 Introduction

Over the past few years, a number of review articles covering the field of halo nuclei, from both experimental and theoretical perspectives [1, 2, 3, 4, 5, 6, 7, 8] have been written. This brief paper will not therefore attempt to reproduce in condensed form the material that has been much more carefully and meticulously put together elsewhere. Instead, it is an attempt to give a bird's-eye-view of how the field has developed from its beginnings two decades ago to the present and beyond.

Halo nuclei are very weakly-bound exotic states of nuclear matter in which the outer one or two valence nucleons (usually neutrons) are spatially decoupled from a relatively tightly bound core such that they spend more than half their time beyond the range of the binding nuclear potential. In this sense, the halo is a threshold phenomenon in which the 'halo' nucleons quantum tunnel out to large distances, giving rise to extended wavefunction tails and hence large overall matter radii. The halo nucleons tend to be in low relative orbital angular momentum states (s or p) so as not to be confined by the centrifugal barrier.

The field of halo nuclei represents a paradigm shift in the study of nuclear structure and is still regarded as a 'hot' topic almost twenty years after their discovery. But when did the field actually begin? The consensus view is that this was in 1985 with the Berkeley experiments carried out by Tanihata and his group in which they measured the interaction cross sections of He [9] and Li [10] isotopes and found much larger values for the rms matter radii than would be predicted by the normal $A^{1/3}$ dependence. A less obvious but more appropriate landmark would be the 1987 paper by Hansen and Jonson [11] that first proposed the large size of these nuclei as being due to the halo effect. They explained the large matter radius of ^{11}Li by treating it as a binary system of ^{9}Li core plus a dineutron and showed how the weak binding between the pair could form an extended halo density.

Ever since then, the community of nuclear physicists interested in the structure and reactions of halo nuclei has grown steadily. A number of light neutron rich nuclei are now known to have a pronounced halo ground state, such as ^{6}He, ^{11}Be, ^{11}Li, ^{14}Be, ^{15}C and ^{19}C and others, like ^{17}B, ^{19}B and ^{22}C wait in the wings to be properly understood. Other nuclei on the neutron dripline, such as ^{8}He, seem to be more appropriately regarded as having a thick neutron skin rather than a halo. The distinction between the two is still rather nebulous but in general we can say that the asymptotic behaviour of the density for a halo state is rather more diffuse than that of a skin. Of course neutron skin of ^{8}He (with a matter radius of 2.4-2.5 fm compared to its alpha particle core with radius 1.5 fm) is an extreme case.

Nuclei exhibiting proton halos are not so common due to the confining effects of the Coulomb barrier. Nevertheless, there are a number of candidates along the proton dripline, such as ^{8}B, ^{13}N, ^{17}Ne and the first excited state of ^{17}F.

In this paper I will divide the historical development of the field into three distinct periods.

2 The three phases of halo studies

2.1 Back-of-the-envelope period (1985 – 1992)

During the late eighties and early nineties, both theorists and experimentalists seemed satisfied with quick and dirty estimates of various halo properties by reproducing experimental reaction observables, such as total reaction and

Coulomb dissociation cross sections and momentum distributions following nuclear breakup. Thus the matter radii are deduced by comparing calculated reaction cross sections with experimentally measured interactions cross sections [for such loosely-bound systems, these two quantities are essentially equal]. The high beam energies – the Berkeley experiments involved nuclear beams of about 800 MeV/nucleon – meant that semi-classical approaches could be reliably used, such as the Glauber model [12]. In fact, if one were to assume simple Guassian density distributions for both the halo projectile and the target nucleus, then in the optical limit of the Glauber model a simple analytical expression can be evaluated for the reaction cross section [13]. The rms matter radius thus enters through the Gaussian parameter in the density. Such an analysis was used widely during that period and the deduced radii were known as an 'experimental' ones on the assumption that the calculated reaction cross section was model independent. It has since been shown that this is far from true.

Momentum distributions of the fragments, after nuclear breakup of the halo projectile, were another observable that was analysed within a simple semi-classical (geometric) picture. By assuming that the target nucleus represented a fully absorptive black disk, then making a Serber (or sudden) approximation [14, 15] and neglecting any reaction mechanisms or final state interactions, it could be shown that the momentum distribution of the fragments was a good approximation to the momentum distribution of those clusters in the initial bound nucleus. The ground state wavefunction of the halo nucleus was thus just the Fourier Transform of the measured momentum distribution. Indeed the narrow distributions that were found for many of the halo candidates was confirmation of their large spatial extent.

2.2 Few-body models period (1992 – 2000)

By the early nineties, a number of groups around the world began serious attempts at modelling the structure of halo nuclei. It is fair to say that, for such light and neutron-rich systems, the shell model is not very useful. Indeed, it is unable to predict their large matter radii and small separation energies very well, nor should we expect it to. Such nuclei typically have just one bound state and any (small) excitation will be into the continuum. It was found, however, that simple few-body models treating these nuclei as inert core+valence nucleons were able to describe the essential features very well. In addition, a rather interesting feature of two-neutron halo nuclei, such as ^{6}He and ^{11}Li was that no bound state of any of the two-body subsystems existed.

Such nuclei were dubbed ‘Borromean’ [1] and it was necessary that the three-body asymptotic behaviour of their wavefunctions was treated correctly, in scattering [16], reaction cross section [17] calculations, as well as other reaction calculations [8].

Simple few-body cluster models of halo nuclei involved a decoupling of the degrees of freedom of the core nucleons from those describing the relative motion of the valence nucleons relative to the cm of the core. Thus the full A-nucleon wavefunction of a two-neutron halo nucleus is written as $\Psi^A \approx \Phi_{\rm core}(\xi)\, \psi^{(3)}(1,2)$, where $\psi^{(3)}$ is the three-body wavefunction of relative motion. Of course, projecting the full many-body wavefunction onto two- or three-body model spaces means that the resulting wavefunctions are not fully antisymmetrised, and a number of studies have been carried out to investigate possible Pauli blocking mechanisms to address this problem (e.g. [18]). The relative motion wavefunction could then be calculated by solving the quantum three-body problem and a number of techniques were employed to do this [1, 19, 20, 21, 22, 23]. Such approaches assumed two-body pairwise potentials between the three constituents.

In modelling reactions involving halo nuclei, it is important to note that the few-body correlations that are built into these structure models have to be retained. An important consideration in the study of reactions with halo nuclei is that they are easily broken up in the nuclear and Coulomb fields of the target nucleus. Therefore, excitations of the halo nucleus into the continuum must be included in the reaction model. Such intermediate state coupling rules out ‘one-step’ models such as DWBA for most reactions of interest. Thus, it has been shown that any reliable reaction model must also take into account the few-body nature of these nuclei.

Thus, in parallel with advances in developing few-body structure models, theorists also developed few-body reaction models. At high (fragmentation) energies at which many of the experiments have been performed, a number of simplifying assumptions can be made to make the calculation of the reaction observables both tractable and transparent.

The most precise method of dealing with this problem is to map the continuum onto a discrete square-integrable basis that is orthogonal to the bound states. This amounts to "chopping up" the continuum into energy bins that act as effective discrete excited states of the projectile and allows the problem to be solved within a coupled channels approach. This is the so called coupled discretised continuum channels (CDCC) method [24, 25].

One of the most common approaches is to make use of the adiabatic, or ‘sudden’, approximation [26] whereby it is assumed that the interaction time between the projectile and target is sufficiently short that the halo degrees of freedom can be regarded as frozen. The most successful few-body approach for calculating probabilities and cross sections for a range of reactions involving halo nuclei has been based on Glauber's multiple scattering diffraction theory for composite systems [12, 27]. This model requires making an eikonal assumption in addition to the sudden approximation.

Few-body reactions at lower incident energies are far more difficult to treat consistently. Not only do nuclear and Coulomb interactions need to be treated within the same model to account correctly for interference effects, but multi-step processes are even more important than at higher energies. An advantage of the CDCC method is its applicability at low energies where approximation schemes used in many other few-body approaches break down.

2.3 Microscopic models period (2000 –)

The few-body models of the structure of halo nuclei suffered from several shortcomings, namely that antisymmetrisation was often treated only approximately and that excitation and polarisation effects of the core were often ignored, although a number of studies are still in progress to improve on these deficiencies. In their favour of course is that the important few-body dynamics and asymptotics are included correctly. More recently, however, a growing number of groups have began to develop fully microscopic (*ab initio*) structure models. These would of course be fully antisymmetric, would start from a realistic NN interaction and would even include 3-body forces. On the other hand of course, they would only be treating the dynamics approximately. In any case, since halo nuclei are so short-lived we can only ever learn about their structure by studying their reactions. However, there is no *practical* many-body reaction theory!

Reaction theorists were thus faced with a stark choice: 1) to restrict their interest to studying high energy reactions where the mechanisms are simple, such as knockout reactions[28], 2) to study reactions that can be modelled by factorising out the structure information as one- or two-body overlap functions or 3) to develop reaction models that could recover the important few-body dynamics from the microscopic many-body structure models.

3 Recent developments

3.1 In structure models

While the standard shell model fails to describe many of the essential features of halo nuclei it has still proved to be of vital importance in providing spectroscopic information on a number of exotic nuclei that can then be tested against experiment data. However, many theorists acknowledge that there is a real need to go beyond the conventional shell model. For instance, the Continuum Shell Model and Gamow Shell Model [29] are showing promising early results. For very light systems, progress is being made with the No-Core Shell Model [30], and the hope is that there will be a convergence of these two methods. Will they be able to predict a matter radius for ^{11}Li of 3.5 fm?

The acknowledged front runner among such *ab initio* microscopic structure models is the Greens Function Monte Carlo method (GMC) [31]. This approach involves calculating an approximate A-body wavefunction using the variational Monte Carlo method then using Greens function projection methods to obtain the desired bound state wavefunction. To date, the GMC method has been applied to describe the bound states of nuclei up to $A = 12$. However, it will have problems going to systems any higher in mass.

Another promising approach is the Coupled Cluster Method [32]. This has been used widely in a number of other fields such as chemistry and atomic and condensed matter physics and has only recently been applied seriously to nuclear structure. While still in its early stages, it has been tested successfully against GMC for ^{4}He. Its supporters are hopeful that it will be more successful in reaching heavier dripline nuclei than GMC.

3.2 In reaction theory

Progress in modelling the reactions of halo and other exotic loosely-bound light nuclei is being made on several fronts: 1) extending the range of applicability of few-body reaction models, either to lower (ISOL) energies by including corrections to the various high energy approximations usually employed, or by extending accurate coupled reaction channels methods such as CDCC to deal with reactions involving three-body projectiles; 2) including reaction mechanisms more carefully (e.g. via coupling to additional channels, including exchange effects, etc); 3) including microscopic structure information in reaction models and treating antisymmetrisation more carefully.

4 Electromagnetic probes of halos

New experimental facilities planned for electron-radioactive beam colliders, at RIKEN and GSI, will provide novel new ways of probing the structure of light exotic nuclei through electron elastic and inelastic scattering, knockout and electro-production reactions. It is thus of vital importance that theorists investigate the suitability of electron scattering as a probe of core polarization effects in halo nuclei and as a spectroscopic tool in inelastic scattering and knockout $(e, e'x)$ reactions from a range of exotic nuclei, including halos.

A related area is the use of meson photo-production reactions by reaching the nuclei of interest through an electromagnetic charge exchanging process. Preliminary work [33] has already shown that (γ, π) reactions will provide an interesting probe of the halo, particularly for those short-lived states which cannot be studied in radioactive beam experiments, such as the first excited state of ^{17}F. In addition, while fragmentation reactions tend to probe the long range tail of the halo wavefunction, pion photo-production reactions are also sensitive to the interior, and as such can give new insights into their structure.

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