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Exotic nuclei/Les noyaux exotiques

Probing the halo structure

Filomena M. Nunes

Universidade Fernando Pessoa, Praça 9 de Abril, 4200 Porto, Portugal

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Abstract

Halo nuclei are characterized by outer nucleons that reside mostly in the classically forbidden region. The large average distance of halo nucleons suggests the decoupling of core and halo degrees of freedom. This is the basis for the few-body structure models developed in the past decade. Few-body models have been the most frequent tool when probing the halo structure. Coulomb dissociation, Knock-out or Transfer reactions have provided detailed structure information for exotic nuclei. Nowadays, the accumulating data impose severe tests for the few-body models. We discuss the achievements of these models as well as their limitations. ***To cite this article: F.M. Nunes, C. R. Physique 4 (2003).***

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Résumé

Sonder la structure des noyaux à halo. Les noyaux à halo sont caractérisés par des nucléons externes qui résident la plupart du temps dans la région classiquement interdite du potentiel nucléaire. La grande distance moyenne des nucléons du halo suggère le découplage des degrés de liberté du coeur et du halo. Cela sert de base aux modèles de structure à petit nombre de corps développés durant la décennie passée. Les modèles à petit nombre de corps ont été l'outil le plus fréquemment employé pour déterminer la structure des noyaux à halo. La dissociation coulombienne, les réactions d'éjection (*knock-out*) ou de transfert ont fourni des informations structurelles détaillées pour ces noyaux exotiques. Aujourd'hui, l'ensemble des données accumulées, permet des tests rigoureux des modèles de noyaux à halo. Nous discutons les succès de ces modèles aussi bien que leurs limitations. ***Pour citer cet article : F.M. Nunes, C. R. Physique 4 (2003).***

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Keywords: Halo nuclei; Few-body structure; Driplines

Mots-clés : Noyaux halo ; Modèles de structure de peu-corps ; Dripline

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1. Few-body structure in halos

Over the last few years, the many simple models that were suggested in the early days of halo physics have been refined in order to accommodate the numerous detailed data that have since become available. In the chart of nuclei (Fig. 1), unstable nuclei are represented in white and the known halos in yellow. Given the notably large radii of halo nuclei, relative to their neighboring isotopes, connected with their very low binding energy, halo nucleons do not feel the nuclear short-range interaction with each nucleon of the core. Instead, they are subject to a *mean field* that has a longer range than the one that characterizes the core nucleons and typically larger diffuseness. In fact, the term *mean field* is not appropriate for these systems, as the correlations between halo nucleons are crucial for their description. Correlations need to be included properly in situations where traditionally (in stable nuclei) one would happily make innumerable approximations to the dynamical problem. Consequently, mean field theories have found it rather challenging to obtain reasonable descriptions for halo nucleons. Indeed,

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E-mail address: filomena@wotan.ist.utl.pt (F.M. Nunes).

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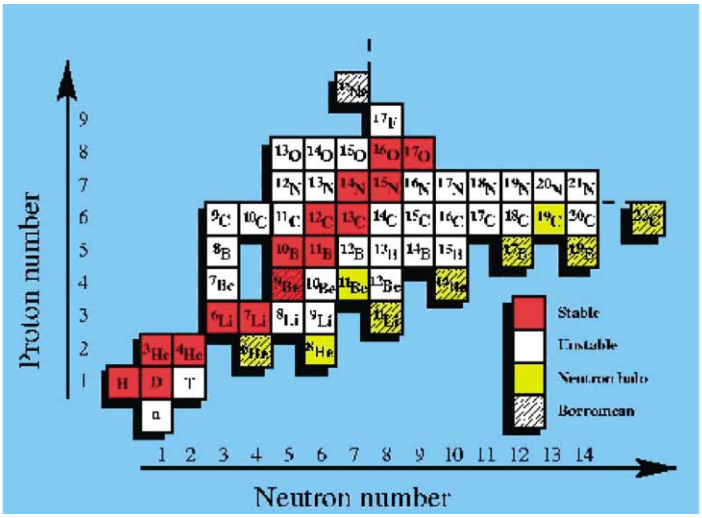

Fig. 1. The chart of light nuclides.

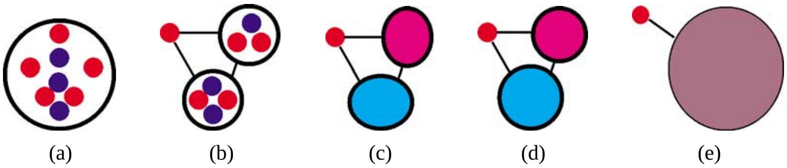

Fig. 2. Structure models for ^{8}B: (a) fully microscopic description; (b) semi-microscopic; (c) three-body $p + t + \alpha$ but retaining some degree of freedom of the cores; (d) same as (c) with inert cores; (e) two-body with an inert ^{7}Be core.

shell model calculations attempting to describe halo structures were mostly reformulations: the residual interaction was updated, and configuration mixing became an unavoidable issue [1–3]. Eventually, the halo structure will be successfully described in terms of the most sophisticated models in the market (e.g., the stochastic variational method [4] and the Green's function Monte Carlo method [5]). One can even start thinking of effective field theories for halo nuclei [6]. Nevertheless, rather than discussing the advances made on the structure of exotic nuclei within a microscopic description, here we will focus our attention on few-body models. Few-body models have been the most frequent tool when probing the halo structure. Simplicity is the prime reason for their usefulness. Few-body models can provide immediate insight and intuitive understanding of the general properties of the nuclear halo.

In order to successfully describe a halo nucleus, the structure model needs to take into account: (i) the very low density region in which the halo nucleons move, subject to an interaction that is closer to the free NN interaction than the realistic in-medium nuclear interaction; (ii) the long tails of the wavefunctions and correct asymptotics of these tails, which contribute decisively to many nuclear properties; (iii) the few-body dynamics of the few valence nucleons relative to the core and between themselves.

For halo nuclei, it is acceptable to decouple the halo degrees of freedom from the core's, simplifying the non-intuitive microscopic treatment: this is the basis for applying few-body models to these systems [7]. The many-body problem then reduces to a two or three-body problem, where the essential ingredient is the effective interaction between the halo nucleons and the central core, generally defined in terms of known properties of the N-core subsystem. The structure is obtained through the exact solution of either the Schrödinger equation, for one-nucleon halos [8], or the Faddeev equations, for the two-neutron halos[1] [9,10].

In few-body models, the halo-dynamics is exact, contrary to what happens in microscopic models [1,3] or cluster-models [12–15]. On the other hand, while microscopic models have a natural antisymmetrization procedure in terms of a Slater determinant, in few-body models the antisymmetrization of the wavefunction is a non-trivial problem. It is approximately

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[1] Note that no 3-nucleon halo nucleus has been found and only simplified approaches have been suggested for the four-nucleon halo case [11].

taken into account, through either a Pauli projection procedure, a phase equivalent potential, or other methods [16]. In my view, this is one of the main drawbacks of these models. Fortunately, though, antisymmetrization effects are strong in the nuclear interior but less important outside. Thus, for observables which are dictated by the exterior part of the wavefunction, few-body models are in principle well suited.

There have been so many diversified contributions toward probing the halo structure that a complete coverage cannot be attained in a short review. Instead, we will present some of the achievements in the understanding of the structure of halo nuclei (Section 2), and discuss the reaction processes that are used to probe this structure (Section 3). Finally, in Section 4, we will comment on the possible future directions of the field.

2. Some achievements of few-body structure models

The work performed in the last decade on halo structure is extensive. Reviews on this topic can be found in [17]. In this section we can only highlight some of the important contributions that illustrate the insight gained in developing few-body models.

2.1. Astonishingly large radii

The first evidence for the existence of halo nuclei was the very large radius extracted from total reaction cross sections [18]. In that work, the theory connecting radii and total reaction cross sections did not account for the granularity of the projectile. When including the few-body nature of these halo projectiles in the reaction mechanism, the derived radii increased [19]. One could then conclude that halo nuclei are even larger than initially thought. In Fig. 3 the nucleus ^{11}Li is represented, showing the large spatial extension of the halo when compared to the core nucleons.

2.2. Ground state properties in inert-core models

The first generation of few-body structure models for light exotic nuclei consists of an inert-core plus the valence nucleons (e.g., $^{11}\mathrm{Li} = {}^{9}\mathrm{Li} + n + n$ and $^{6}\mathrm{He} = {}^{4}\mathrm{He} + n + n$) [7]. The effective N-core interaction is phenomenologically determined by fitting the properties of the subsystem. However, knowledge of the N-core subsystem is not always sufficient (for instance, when the first calculations for ^{11}Li appeared, nothing was known about the subsystem ^{10}Li). Unfortunately, the N-core effective interaction is the main source of uncertainty in the few-body model. This is particularly serious when the system is borromean (all two-body subsystems are unbound).

Under these circumstances, many three-body calculations explore various scenarios for the ground state properties of the halo nucleus (binding energy, radius, momentum distributions) that are (can be) subsequently validated as data becomes available. Results for the ^{6}He [7], ^{11}Li [9,20,21] and ^{14}Be [22,23] are rather successful in reproducing the g.s. properties.

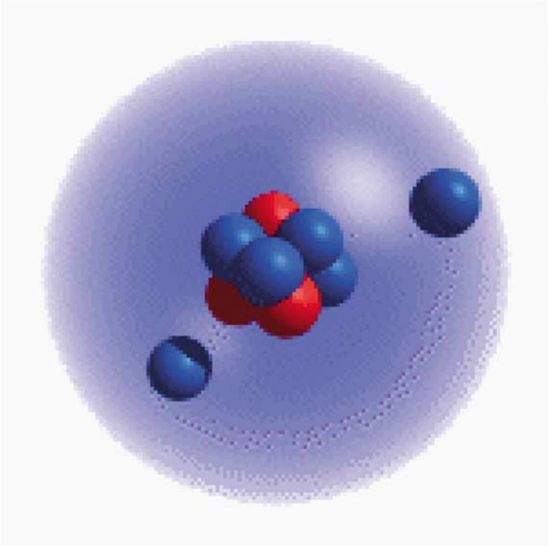

Fig. 3. Three body model for ^{11}Li based on realistic relative sizes of the core and the halo.

Yet, whenever the N-core subsystem is known enough to pin down the N-core interaction, three-body models based on pure two-body interactions are not able to account for all the binding energy of the system [7,10].

2.3. *The core excitation model*

The underbinding problem is well known in few-body physics and can be interpreted as strong coupling to degrees of freedom of the core, that are neglected in the inert-core model. Few-body models, that account for these core degrees of freedom, were subsequently developed. This second generation of few-body models, work in an extended subspace, expanding the full wavefunction on a set of core states which are coupled either rotationally [8,24,25] or vibrationally [26]. These core excited few-body models provided the solution to the underbinding problem and offered a better description of the properties of exotic nuclei. In Fig. 2 a schematic illustration of the structure models for ^{8}B is shown. Model (c) contains core degrees of freedom whereas in model (d) those degrees of freedom are neglected.

Note that, for observables where the core nucleons actively take part, such as electromagnetic transitions, it may be impossible to obtain an accurate description when the core is forced to remain statically in the ground state. Undoubtedly, core excited models offer a significant improvement, although still limited to the extension of the basis considered (typically one or two excited states).

2.4. *The existence of proton halos*

From the early days of radioactive nuclear beams, ^{6}He, ^{11}Li and ^{11}Be occupied a privileged place, due to their extreme properties. Soon after, ^{14}Be [22,27] and ^{19}C [25] were added to the list, but for a few years, the discussion of halo nuclei concentrated on the neutron dripline. The work by Zhukov and collaborators [28], predicting the existence of halos on the proton dripline, was an important breakthrough. The three-body problem $core + p + p$ adds technical difficulties, due to the three charged particles involved. Today, after many experiments on the light proton dripline, it is well accepted that ^{8}B and ^{17}Ne exhibit halo features and that the first excited state of ^{17}F has perfect halo properties, not to mention the cases that have been recently found for $A > 20$.

2.5. *Efimov states*

The study of three-body borromean nuclei unveiled the possibility of Efimov states just below threshold. These bound states, already known in Atomic Physics, would be orders of magnitude larger than the nuclear scale [29]. The experimental verification of this discovery in nuclear physics is extraordinarily demanding and it is difficult to predict when it will become feasible.

2.6. *Decays and more structure*

Given the favourable Q-value, some of these nuclei β-decay to a halo analogue state in one of the isotone nuclei. This is the case for the g.s. of ^{11}Li. In the three-body model, the two valence neutrons can be in either an $\mathrm{L} = 0$ or an $\mathrm{L} = 1$ motion, relative to the core. The decay of ^{11}Li was measured with precision and allowed, in the light of the three-body model, the determination that the $\mathrm{L} = 0$ and the $\mathrm{L} = 1$ components have approximately equal weights [30]. Few-body wavefunctions have also been used for the analysis of the β-decay studies of ^{8}He into $^{6}\mathrm{Li} + n + n$ [31].

2.7. *A green card into the continuum*

The very low binding of halo nuclei implies that: (i) usually there are no bound excited states but low lying narrow resonances; and (ii) these nuclei are easily excited into the continuum. In recent years a major effort has been put into exploring the continuum structure. From the theoretical point of view, many technical issues arise and have been trimmed in order to provide continuum wavefunctions that can then be incorporated in the reaction process. It is reassuring that the first results presented for ^{6}He [32] reproduce the dipole and quadrupole excitation strength correctly. Additionally, some other resonances are predicted. The excitation functions and other continuum observables of ^{11}Li calculated in [33] mostly agree with the available data. It is worth noting that experiments are progressing fast in this direction. For example, a very recent study provides detailed information on the continuum structure of ^{8}He [34].

2.8. *Halos in astrophysics*

For non-borromean systems, the three-body basis is not always the best alternative. In particular, when determining two-body capture rates, associated with one of the subsystems. This is the case of the neutron capture on ^{7}Li for the synthesis of ^{8}Li or the proton capture on ^{7}Be for the synthesis of ^{8}B. The mixed few-body model, using a two-body extension of the three-body basis, allowed the determination of the capture rates of these systems [35] with reasonable accuracy.

2.9. *Driplines and beyond*

In a number of occasions, few-body models have stretched the dripline and allowed insight into regions of nuclear physics that were beforehand completely unexplored (see for example predictions for the existence of a narrow resonance in ^{10}He already in 1993 [36]). Two-proton emitters are a good example (for more details see the contribution on two-proton emitter in this volume). In [37] the importance of preserving the few-body structure in order to obtain a reliable description of the exotic two-proton decay is shown.

As beams keep flying, extraordinary nuclei appear and offer true challenges for a good theoretical description. This is the case of ^{5}H, which has been described within a three-body model $(t + n + n)$ [38].

3. Halo structure with reactions

In stable nuclear physics it is a standard procedure to factorize structure information from reaction details. Irrefutably, the structure/reaction dialectic is enhanced when reaching the dripline. If in one hand, unstable nuclei exist in a beam, their structure inputs inevitably derive from reaction studies; on the other hand, one cannot understand the reaction mechanism unless a correct account is made for the halo structure properties, mentioned in Section 1. In practice, one needs to adjust the structure details in order to obtain a consistent description of the phenomenon.

Learning more about the structure of halo nuclei, implies learning about the reaction process. No doubt there has been a rapid evolution of the quality of the experiments since the first days of halo nuclei, where information came from integrated total cross sections. Nowadays, there are good statistics for triple differential cross sections, in complete kinematics, providing thorough tests for reactions models. Below, we comment on a few contributions in order to illustrate the state of the art of the field. More details can be found in recent reviews [39].

3.1. *Elastic and inelastic studies*

Elastic scattering studies yield information not only on the size of the nucleus, but also on the interaction with the target. Historically, elastic studies have played a fundamental role in nuclear physics, in order to pin down the optical potential. These ideas have been applied to unstable nuclei (for example to ^{6}He scattering off protons [40]). When dealing with exotic nuclei, the usual process of defining the optical model in terms of double folding potentials needs to be reviewed (e.g., [41]). The inclusion of few-body structure aspects in the reaction formalism has proved to be essential to understand the process and very useful when performing the correct simplifications to the model (e.g., [42–44]).

Several theoretical efforts have proven that recoil and breakup effects need to be taken into account. A schematic representation of the breakup of ^{11}Be is shown in Fig. 4, where coupling effects excite the halo nucleus during the reaction time. Under an adiabatic approximation, when the valence particle interaction with the target is neglected, it is possible to factorize the elastic scattering cross section of the halo in terms of a *halo form-factor* and the corresponding point-like cross section [42]. This approach, resembling the standard approach in the analysis of electron scattering, offers an intuitive picture for the finite range effect of the halo in the elastic process.

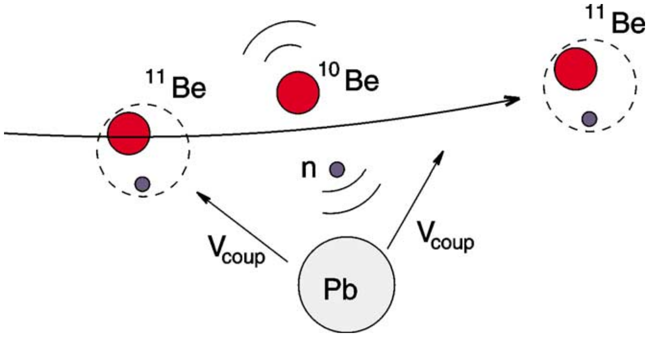

Fig. 4. Elastic scattering on ^{11}Be: due to the interaction with the target it can excite into the continuum.

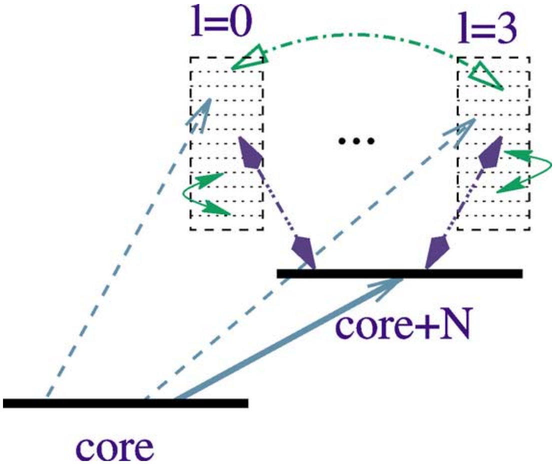

Fig. 5. The CDCC method: inclusion of continuum couplings in the reaction mechanism.

Inelastic processes offer more structure detail, in particular on excited states. The latest multiple scattering calculations for $^{11}\mathrm{Li} + p$ at high energies [45] illustrate the form in which the structure scenarios can be narrowed down, when analyzing inelastic data.

3.2. *Breakup reactions*

The very large breakup cross sections are one of the main evidences for halo structure. Breakup reactions have provided information of the continuum structure of these nuclei: resonant continuum, but mostly non-resonant continuum. Constantly, different approaches have concluded that there are strong couplings between the ground state and the continuum, and specially for low energy reactions when the reaction time is large, rearrangements within the continuum need to be taken into account [46]. The couplings to a discretized continuum are illustrated in the right-hand side of Fig. 5. CDCC calculations [47] or time-dependent calculations [48] predict a large hindrance of the cross section due to these continuum couplings.

Due to the large spatial extension of the halo, nuclear effects are strong even for impact parameters much larger than the sum of the radii. Consequently, Coulomb and nuclear effects need to be included on the same level, as interference is often present [47]. In any case, nuclear free processes are desirable to reduce the uncertainties associated with the optical parameters. At high energies, and keeping the detectors sufficiently forward, one may expect to have a pure Coulomb process which may be described in first order perturbation theory. When that is the case, the extraction of structure information becomes *cleaner*. Some checks concerning higher order corrections in this regime, are still under investigation [49].

3.3. *Knockout and transfer reactions*

After decades of using transfer reactions for spectroscopy in the valley of stability, it is unnecessary to argue for transfer reactions on unstable nuclei. Transfer reactions are indeed a necessary path for a more detailed understanding of the structure of dripline nuclei [51,52].

Following these lines, a specific detection system has been developed at GANIL for measuring inverse kinematic transfers [50]. Pioneering work was performed at GANIL on the inverse kinematic reaction $^{11}\mathrm{Be(p,d)}^{10}\mathrm{Be}$ [51]. The data contains the transfer to the 0_1^+ and 2_1^+ states in $^{10}\mathrm{Be}$. A DWBA analysis including core excitation models for $^{11}\mathrm{Be}$ suggests that the ground state of this nucleus has $\approx 20\%$ d-wave in its ground state, in agreement with structure predictions [8,26]. Nonetheless, one should stress that there are serious difficulties that need to be tackled by the reaction theorist in order to pin down the uncertain ingredients.

Continuum effects in transfer reactions should also be considered. A schematic representation of the couplings are presented in Fig. 5: the transfer couplings to the continuum and the inelastic couplings between continuum states are represented along with the direct transfer shown as a solid arrow. The first results along these lines have shown that continuum couplings have less impact in transfer reactions then in breakup and elastic scattering [53].

A more ambitious project consists of calculating two-nucleon transfer, to study the properties of three-body halos. This study involves at least a full four-body reaction model. There is ongoing work to develop the best optimized method to deal with this complex problem. Applications to the two-neutron transfer of $^{6}\mathrm{He}$ can be found in the literature (e.g., [54]).

The recent systematic program in MSU measuring knock-out reactions ranges nuclei from A = 6 to 40 [55]. Knock-out data contain pure transfer contributions (absorption) and the elastic breakup contribution (diffraction). MSU energies are sufficiently high to allow for an eikonal treatment [57]. Results in [55] prove that whenever the ground state of the nucleus is dominated by one component, it is possible to extract an accurate spectroscopic factor for that component from knock-out momentum distributions. Unfortunately, more care is needed when the ground state has several strong components (e.g., see the case for the carbon isotopes [56]).

4. Few-body structure for the future

The few-body models are useful tools when analyzing reactions with halo nuclei. Few-body reaction theory has often preferred to use inert-core models, even knowing that core excited components are relevant in some nuclei (e.g., the Be isotopes). Reaction theories in general need to be extended, in order to incorporate core excitation.

Secondly, it has become clear that the continuum states need to be included in the reaction model, should the halo information be reliable. Given the computational demand of continuum discretization procedures, research into new methods is being developed. One of the most promising methods for discretizing the continuum, alternative to CDCC, uses transformed harmonic oscillators (see [58] for more detail).

Also limited by the computational demand, three-body halo is typically approximated to a two-body system, especially in cases where the eikonal approximation in not applicable. Aware that the three-body dynamics may change the reaction mechanism significantly, efforts are being made in order to improve this description (for instance the two-neutron transfer studied in [54]).

In addition, one should realise that few-body models have only been applied to light exotic nuclei $A < 20$. As the mass increases, the decoupling of core and halo degrees of freedom becomes a poor approximation. Core excited models may succeed if the chosen basis it sufficiently large. At a time when one expects to have high intensity beams for the heavier mass region [59], the future of the field depends on the successful description of $A > 20$ nuclei.

In fact, all the above mentioned points involve increasing the computational size of the calculations. It may be a rather straightforward problem and the solution may involve waiting a few years for faster/larger computers. Unfortunately, there has been the manifestation of other problems, related to the intrinsic limitations of the few-body model itself.

Recent results for Be isotopes show that as you move away from the dripline, few-body models become less successful [60,61]. The ^{12}Be study [61] is an excellent example as so many reaction measurements where performed recently. The results in [61] show that the model is unable to reproduce the correct E2 transition between the first excited state and the ground state, if all other observables are to be reproduced.

Looking more ahead, the next great ambition in our field may involve going beyond the few-body picture. It is not clear how accurate shell model calculations can determine radial overlaps in particular on the surface of these exotic nuclei, or for the continuum states. However, in a time where microscopic models are performing rather well, one needs to start considering an adequate representation of the microscopic structure, so that it can be efficiently incorporated in a future generation of reaction models.

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