RMP Colloquia

This section, offered as an experiment beginning in January 1992, contains short articles intended to describe recent research of interest to a broad audience of physicists. It will concentrate on research at the frontiers of physics, especially on concepts able to link many different subfields of physics. Responsibility for its contents and readability rests with the Advisory Committee on Colloquia, U. Fano, chair, Robert Cahn, S. Freedman, P. Parker, C. J. Pethick, and D. L. Stein. Prospective authors are encouraged to communicate with Professor Fano or one of the members of this committee.

Nuclear halo states

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Halo states extend over an unusually large space where many of their properties hinge on the tail of the wave functions. Their levels lie mainly just below the thresholds for neutron-emission channels. This short review covers the main distinguishing features of halos and how they are revealed in experiments. Special emphasis is placed on the large variety of experiments apt to study halo structures. Some aspects of current research are treated in greater detail.

CONTENTS

I. INTRODUCTION

"Thresholds," the transition points between bound discrete states and a continuous spectrum, give rise to many fascinating phenomena. Among the newest of them are the so-called halo states that occur in some nuclei near the limit of particle stability. Appearance of a halo is actually a general phenomenon common to loosely bound particles held in short-range potential wells. Just as cross sections immediately above a threshold are often described in general terms (Wigner, 1948; Newton, 1966; Abramovich *et al.*, 1992), properties of states immediately below a threshold are amenable to a general description. Briefly, a very loosely bound particle can tunnel into the space surrounding a potential well in a process represented by an extended dilute wave-function tail. Such a structure—typified by, but more extreme than, the deuteron's exponential wave function—differs greatly from that of normal nuclei, whose surface is quite well defined. As an illustration of the basic halo structure, Fig. 1 shows the calculated density profile for the one-neutron halo nucleus ^{11}Be. Note the large difference in density between the core region and the halo region. Although halos have been sought mainly in nuclear systems, a bias reflected in the present article, they could also appear, for example, in molecular physics.

Halos have only a few active constituents. In the relevant energy ranges a halo involves a nuclear core and typically one or two neutrons, implying a major role of single-particle properties. This role contrasts with general nuclear physics as exemplified by the bulk of the electric dipole strength usually concentrated in the giant dipole resonance (GDR), whereas halos display a strength of the order of a single-particle unit at low excitation energies.

We understand now the main features of the single-neutron halos, although many details still have to be figured out. A major remaining challenge lies in handling the more complex two-neutron halos, in which the two-neutron interaction is known to be important. Much work has already been devoted to this problem, the structure of ^{11}Li appearing qualitatively understood, but no consensus has emerged on interpreting many experiments.

Several existing reviews (Bertulani *et al.*, 1993; Hansen, 1993; Mueller and Sherrill, 1993; Zhukov, Danilin, Fedorov, Bang, Thompson, and Vaagen, 1993) cover different aspects of halo nuclei: their production, their structure, etc. I shall start here with a general view of the halo structure including a discussion of the known halo states, cover the major types of experiments that provide information on halo structure, and end by commenting on the present and on the progress to be expected in the near future. Important subjects connected particularly with the many suggested theoretical models have been left out for brevity. These and more complete

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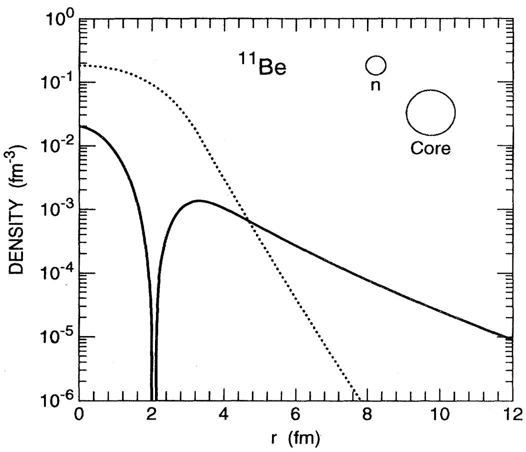

FIG. 1. Plot of the ^{11}Be density (after Sagawa, 1992). The upper right corner shows the simplified picture of a halo nucleus as a two-body system with an inert core and a halo neutron. Dotted line, core density as a function of radius; solid line, the density obtained in a Hartree-Fock calculation with the neutron in a $2s_{1/2}$ orbital and a single-neutron separation energy adjusted (to agree better with experiment) to 0.51 MeV. Note the very far-extended, dilute tail that is the characterizing feature of a halo.

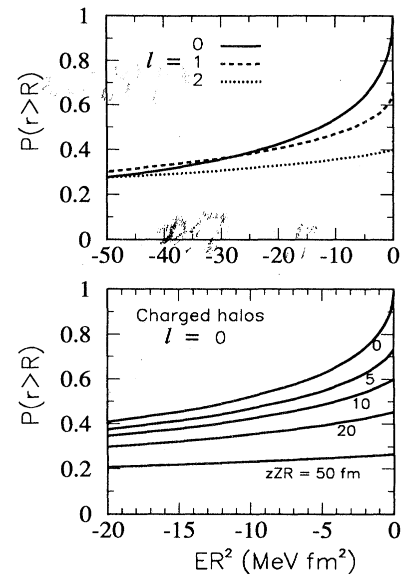

FIG. 2. The probability for a single halo particle of being outside a square well (the core), plotted vs the energy times the square of the well radius. The results then fall on universal curves. The top part shows probabilities for neutral particles of angular momenta 0, 1, and 2; the bottom part those for s waves in systems of different changes. The curves are denoted by the product of the halo charge number, the core charge number, and the well radius.

references to the literature are provided by the reviews cited above and by conference proceedings (Delbar, 1991; Bruandet *et al.*, 1992; Morrissey, 1993).

II. A GENERAL PICTURE

Important features should emerge clearly if we approached the halo structure in three steps, discussing first the ideal halo, then realistic halo states, and finally actual halo systems.

A. The ideal case

Consider first a single particle around an inert core. In an ideal halo this particle will lie far from the core most of the time, whereby properties of the system are determined almost exclusively by the wave function's tail. The main role of the core is thus to provide the binding potential that keeps the system together. All reasonable short-range potentials will then yield equivalent answers, and one can model the system in a simple way (Riisager *et al.*, 1992). Only very loosely bound neutrons in an s state relative to the core provide an ideal halo; any other angular momenta and any system with charges will ultimately be confined. Only for s-wave neutrons will the probability of staying inside the potential well vanish as the separation energy decreases. This behavior is illustrated in Fig. 2, whose top part shows the probability for neutrons of different angular momenta to lie outside a square well. Only s waves afford a chance of attaining the ideal halo at very low separation energies. We do not presently know of any nucleus approaching this limit.

The next step deals with two particles surrounding a core. This is now a three-body system, whose behavior can become much more complex. Simple model estimates (Fedorov *et al.*, 1993) show that here all systems ultimately will be confined, with the caveat that an "intermediate region" may occur that is larger than typical core radii but still below the asymptotic region. In certain cases, three-body states appear whose intermediate region extends quite far out with most of the wave function residing there; we are thus again reaching the ideal situation of a structure independent of details of the interactions. The Efimov states[1] are a good example of this phenomenon. They can occur when at least two of the two-body subsystems are close to a threshold and thus extend over a large region. The effective interaction in the three-body system would in this case also be long ranged (and, furthermore, universal in the intermediate region), yielding states of very large spatial extent. A quite transparent derivation of the Efimov effect in coordinate space has recently been given (Fedorov and Jensen, 1993). Efimov states have been sought in different

[1]Efimov pointed out that in certain "pathological" cases many bound states, also infinitely many, could appear in a three-body system even with unbound two-body subsystems (Efimov, 1970).

systems in nuclear, molecular, and condensed-matter physics (Efimov, 1990), without detecting so far any convincing example.

B. Realistic halos

A study of less extreme systems serves to connect theory with experiments; we thus turn to "real halos" that are large but that have up to $\sim 50\%$ of the wave function remaining within the potential well. In such cases core degrees of freedom can emerge, obscuring the experimental distinction between halo and core effects. A rough idea of where to expect halos can be obtained from the simple models mentioned above (Riisager *et al.*, 1992; Fedorov *et al.*, 1993). One treats here the system as a core plus one or two nucleons, describing quite generally the wave function outside the range of the forces, e.g., a spherical modified Bessel function for the case of one neutron. The normalization of this outer wave function will of course depend somewhat on the details of the core potential, but all properties depending mainly on the tail are then amenable to explicit evaluation.

Scaling laws for all the low-energy, i.e., tail-dominated halo properties hold in parallel to the deuteron and to the trinucleon system (Efimov, 1990). The effect of an angular momentum barrier was shown in the upper part of Fig. 2, with the corresponding effect of a Coulomb barrier illustrated in the lower part for *s*-wave protons. Both figures pertain to square wells, but any short-range potential will give similar results. The general results for neutral systems are sufficiently simple to be quoted here. The "recipe" for an arbitrary potential shape relates the relevant radius parameter to the radius R of the equivalent square well via the equation

$$\frac{\int Vr^3dr}{\int Vr\,dr}=\frac{\int V_{\text{sq}}r^3dr}{\int V_{\text{sq}}rdr}=\frac{R^2}{2}\ . \tag{1}$$

As an example this equation would give $R=b\sqrt{2}$ for a Gaussian potential $S\exp(-r^2/b^2)$. Results for a one-neutron system are then expressed *via* the combination ER^2, where E indicates the (negative) energy of the state. The mass dependence should also be taken into account explicitly for halo particles other than neutrons. A two-neutron system requires replacing R by a weighted average ρ_0 of the radii in the three two-body potentials. In most cases ρ_0 can be taken from

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

where $\mu_{cn}=A_c/(A_c+1)$ and $\mu_{nn}=\frac{1}{2}$ indicate reduced masses in units of the nucleon mass.

Halo states are often characterized by their mean-square radius. By expressing the halo's contribution to the total mean-square radius as

$$\langle\rho^2\rangle=A\langle r^2\rangle_{\text{tot}}-A_c\langle r^2\rangle_{\text{core}}\ , \tag{3}$$

where A and A_c denote the mass numbers of the nucleus and of its core, one can derive the following asymptotic scaling laws for a one-neutron halo:

$$\frac{\langle\rho^2\rangle}{R^2}\simeq\begin{cases}10.4\ \text{MeV fm}^2/(-ER^2), & l=0\ ,\\ 3.65\ \text{MeV}^{1/2}\ \text{fm}/(-ER^2)^{1/2}, & l=1\ ,\\ 1.40, & l=2\ .\end{cases} \tag{4}$$

The mean-square radius diverges for s and p waves with decreasing energy; arbitrarily large values of $\langle\rho^2\rangle$ could thus occur in nuclei, at least in principle. Higher angular momenta give finite results. A two-neutron halo may often be described adequately by a single value of the so-called hypermoment K (a generalization of the normal angular momentum), yielding the corresponding asymptotic scaling laws

$$\frac{\langle\rho^2\rangle}{\rho_0^2}\simeq\begin{cases}-7\ln(-E\rho_0^2/3\ \text{MeV fm}^2), & K=0\ ,\\ 9, & K=1\ ,\\ 3, & K=2\ .\end{cases} \tag{5}$$

The values of 0, 1, and 2 for K correspond to the two neutrons' being in s waves, in a superposition of s and p waves, or (mainly) in p waves relative to the core. Figure 3 compares results for one- and two-neutron halos for nuclei of mass 11. The difference in asymptotic behavior is striking, but one should note that one- and two-neutron systems yield comparable radii for binding energies of a few hundred keV, marked by the hatched area in the figure.

As a general "rule of thumb" halos can appear for separation energies less than 5–10 MeV fm^2/R^2. Real halos can thus also occur for neutrons in p waves and for protons if the core charge does not exceed about 10.

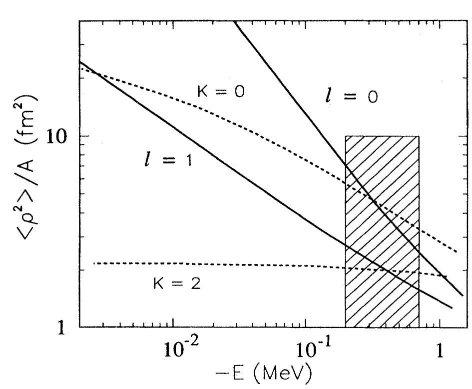

FIG. 3. The contribution from the halo neutron(s) to the total mean-square radius, as a function of the total binding energy of the halo neutrons for nuclei of mass 11 (after Fedorov *et al.*, 1993): solid lines, results for one-neutron halos; dashed lines, results for two-neutron halos. The hatched area marks the region with binding energies of a few hundred keV where the best halos at present are to be found and where the one- and two-neutron halos are of comparable size. Note that both scales are logarithmic.

C. Nuclear halos

The picture painted so far looks rather transparent, but do known nuclei fit into it? Actual instances of halo states always display small idiosyncrasies, obscuring some of the above distinctions. The main problem is that it is not enough to have a state with one or two nucleons of appropriate separation energy and angular momentum and (for charged halos) sufficiently small core charge; one has to check that the core really is inert, i.e., that there is a decoupling into core and halo parts. Phrased in other words, we do not yet have any sufficiency condition for the emergence of halos. The border between halos and nonhalos is thereby blurred, and it is by consensus more than by application of strict rules that a given nucleus is placed in one or the other category.

There are two classical cases—in a way, "pre-halo halos"—that should be mentioned first. These are the well studied deuteron with a binding energy of 2.225 MeV and the hypertriton [consisting of a neutron, a proton, and a lambda (see, for example, Congleton, 1992)] that has a lambda separation energy of only 0.13±0.05 MeV; this hypertriton has been considered repeatedly. The deuteron binding energy is quite high (~ 2 MeV), but counteracted by its reduced mass of only half a nucleon mass. The deuteron also lacks a core, being a true two-body system (to within quark effects). The hypertriton, with an excited nucleon, is probably best described as a three-body system; very little experimental data, mainly 20 years old, is available on this system, but more is likely to come forth soon.

The best-known examples are the one-neutron halo ^{11}Be and the two-neutron halo ^{11}Li, which are listed in Table I along with the other reasonably well established states, with angular momenta and K quantum numbers given when known. Note that both the ground state and the first excited (and only other particle stable) state of ^{11}Be are halos. The two-neutron halos ^{6}He and ^{14}Be, not as favorable as ^{11}Li, have not been studied as intensely. The falloff of the wave function's tail (Fig. 1) is described by a decay-length parameter λ, similar to that of the Yukawa wave function $r^{-1}\exp(-r/\lambda)$. For a single neutron's s wave the decay length is $\lambda=\hbar(-2\mu E)^{-1/2}$, where μ stands for its reduced mass and E for its energy, namely 4.3 fm for the deuteron and 6.8 fm for ^{11}Be. These values contrast with the typical root mean-square radii of p-shell nuclei, about 2.5 fm. The density profile of ^{11}Be has already been shown in Fig. 1 and the one of ^{11}Li will appear in Fig. 6.

TABLE I. Halo states. For each state the excitation and separation energies and the angular momentum of the halo particle(s) are listed.

Nucleus	E_x (MeV)	$S-E^{a}$ (keV)	Configuration	l	K
^{11}Be	g.s.	504	$n+{}^{10}$Be	0	
^{11}Be	0.32	184	$n+{}^{10}$Be	1	
^{17}F	0.50	105	$p+{}^{16}$O	0	
^{6}He	g.s.	973	$n+n+{}^{4}$He		2
^{11}Li	g.s.	310	$n+n+{}^{9}$Li		?
^{14}Be	g.s.	1340	$n+n+{}^{12}$Be		?

[a]From Audi and Wapstra, 1993.

D. Connections to other fields

The appearance of divergent (or just very large) radii mentioned in Sec. II.B bears a striking similarity to the threshold anomalies—often called cusps—of collisions. The opening of a new channel emerges in the cross-section spectrum of other channels, in extreme cases as an infinite derivative of the cross section (see Fig. 4). The large literature on cusps (see Newton, 1966 and Dalitz, 1993, and references therein) shows them to arise mainly in s-wave channels when Coulomb forces are absent, as do the halo divergences. Repulsive Coulomb potentials remove the pathologies in the cusp; some effects remain detectable if the charge is not too large. No cusp appears if the relevant threshold is a true three-body threshold (insofar as two-body resonances can be disregarded) or if the angular momentum is nonzero. All of this closely parallels the pattern observed for halos. Threshold phenomena have been studied in detail in electron-molecule scattering (Morrison, 1988; Domcke, 1991), in which further effects occur, e.g., from attractive (dipole) r^{-2} potentials.

Atomic and molecular halos have been discussed in some detail by Hansen (1993). The above discussion applies when attractive Coulomb forces have been screened off at short distances; it is a matter of taste whether or not electrons bound in a dipole field should count as halos. For atoms and molecules one must correct the "rule of thumb" for the occurrence of halos with the appropriate mass ratio. Inserting the electron mass gives a separation energy limit of 1–2 eV Å$^2/R^2$ (where R indicates again the radius of the effective binding potential), whereas for molecules a loosely bound atom of mass number A corresponds to a numerical factor $A^{-1}\times(0.5-1)$ meV Å^2. To my knowledge no clear ana-

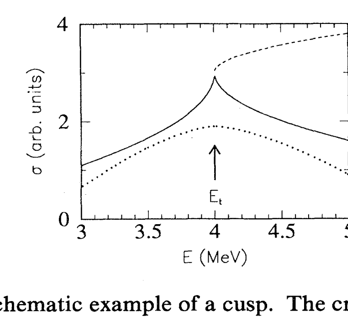

FIG. 4. A schematic example of a cusp. The cross section for a given channel can have an infinite derivative at the threshold E_t where a new channel (not shown) opens up, involving a neutral particle in an s wave. This can give either a cusp (solid line) or a "step" or "S-shaped cusp" (dashed line). The corresponding behavior for the threshold of a p wave is shown by the dotted curve.

log of the nuclear halo states has yet emerged in atoms; at most one may hope to find parallels to the one-neutron halos, as the electron-electron interaction has such a long range that true three-body states must be tackled by other means.

Before turning to experiments it might be appropriate to comment on some confusion in the nomenclature. The term "neutron halo" was introduced more than 20 years ago (Burhop *et al.*, 1969) in the context (now called "neutron skin") of the bulk of the neutron density extending further out than the proton density. The interest was then in K^- and anti-proton absorption on heavy nuclei providing information mainly on the surface properties of the nucleus (see, for example, the review by Batty *et al.*, 1989). Some authors still fail to discriminate between the terms "halo" and "skin," but the trend seems to be to regard them as corresponding to two physical situations different in principle. The halo is characterized by an abnormal slope of the density distribution tail, the skin by a larger-than-normal extension of the main part of the density.

III. THE RELEVANT EXPERIMENTS

The interest in halos began with the experiment by Tanihata and collaborators at the Bevalac on total interaction cross sections (Tanihata *et al.*, 1985). The field has since been driven, to a large extent, by the developments in nuclear reaction experiments, more specifically in the field of radioactive beams. No fair account is attempted here of the important progress that has taken place both on the accelerator and detector side, but an impression of the complication level reached in these experiments can be drawn from Fig. 5. Further details on the experimental procedures are provided by a review (Mueller and Sherrill, 1993) and by recent conference proceedings (Delbar, 1991; Morrissey, 1993). Here, I cover first the high-energy radioactive-beam experiments where most of the work has been done, remark briefly on other reaction experiments, and go into some detail on beta decays, which have been used very little up to now, mainly in experiments at ISOLDE (CERN).

A. High-energy reactions

A halo consists of nuclear density escaping from the nuclear core, thus making the nucleus spatially larger and boosting its total reaction cross section by typically 10–20 %. How large the cross section becomes depends on the basic nucleon-nucleon (NN) cross section; one may then take advantage of the known variation in the nucleon-nucleon cross section by varying the beam ener-

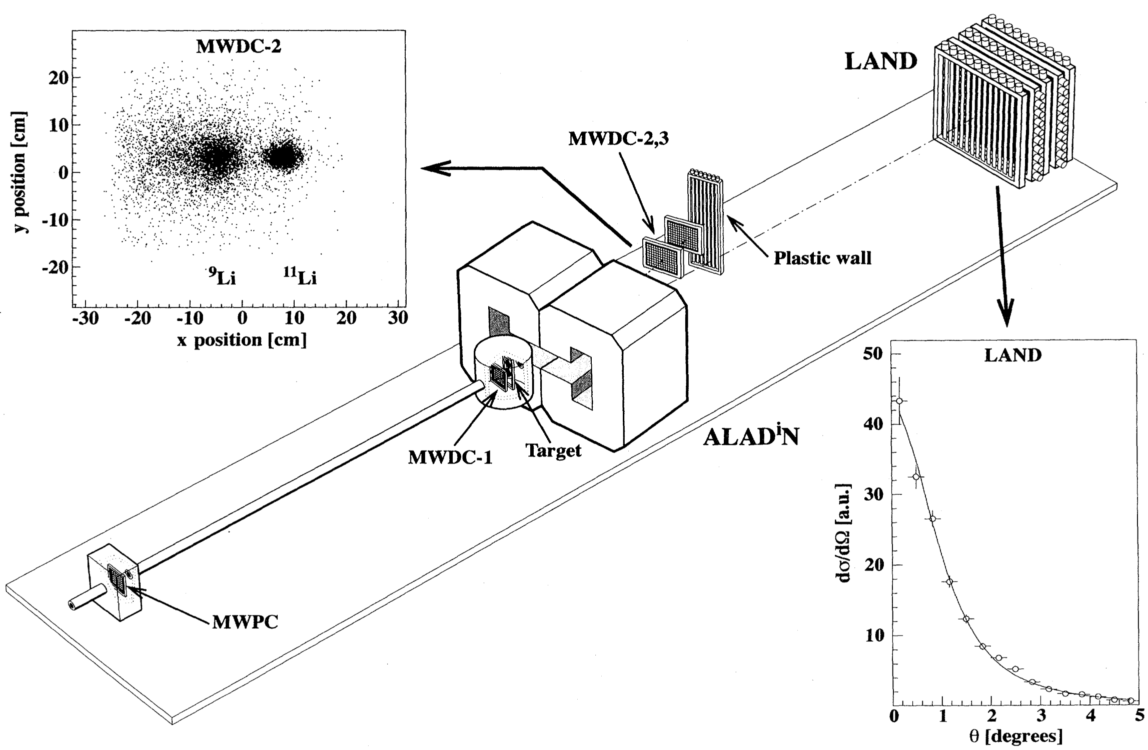

FIG. 5. The experimental setup used in Humbert *et al.* (1993) for detection of reactions with ^{11}Li at 280 MeV/nucleon at GSI. The beam enters from the lower left and is put onto a reaction target just in front of the ALADIN magnet that separates charged reaction fragments from the primary beam. The charged particles are detected by multiwire drift chambers (MWDC), as illustrated in the upper left figure. Neutron fragments continue at zero degrees and are detected by the LAND detector; a sample neutron spectrum is shown as the lower right figure. Both spectra were taken with a carbon target. The total distance from target to LAND is 11 m.

gy, thus effectively probing the halo at different radii.[2] This procedure has been employed to determine the density profiles of ^{11}Be (Fukuda *et al.*, 1991) and ^{11}Li (Shimoura, 1991), the latter one illustrated in Fig. 6 in which different assumptions about the density profiles are seen to yield a clear difference of cross sections. Similar information can be obtained by varying the target as done for ^{11}Li (Tanihata *et al.*, 1992). Nuclear reactions will prevail as long as the target charge remains small, but the heaviest targets will receive a large—sometimes even dominant—further contribution from Coulomb dissociation reactions with an ensuing increase in cross section.

Since these effects originate from the halo, larger relative variations of the cross section follow from observing the "halo-removal" channel instead of the sum over all channels. Figure 7 reproduces a transparent example of this result (Blank *et al.*, 1992). Total reaction cross sections were measured together with charge-changing cross sections for the isotopes ^{8}Li, ^{9}Li, and ^{11}Li. The drastic changes in the total cross sections accompanied by essentially constant charge-changing cross sections support strongly the idea that the core of a halo state is hardly influenced by the halo neutrons.

The large cross sections—up to several barns in extreme cases—for the "gentle" peripheral reactions of halo-neutron removal afford a unique signature for halos. Much work has been directed to measuring the two-neutron removal cross section of ^{11}Li at many beam energies and on other targets. The small energy transfer in these reactions can often be interpreted in terms of quite simple models. Standard assumptions are that nuclei are "black," insofar as strong interactions take place whenever two nucleons meet, that the halo is well developed so that one can resolve the behavior of the core from that of the halo, and that the beam velocity is sufficiently larger than the internal halo motions to justify a "sudden approximation." Reactions have so far been studied in the energy range from 25 to 800 MeV/nucleon, corresponding to velocities of $0.23c$ to $0.84c$. The lower limit is close to the nucleon velocities inside the core, but still appreciably larger than the velocities in the halo, thus affording the sudden approximation. This theoretical approach rests on Glauber's simple geometrical model (Glauber, 1955) and on Coulomb excitation theory as formulated, e.g., by Bertulani and Baur (1988). It gives strong support to the halo model, showing also that a major part of the dissociation reactions takes place at quite large internuclear distances. The nuclear dissociation is reminiscent of free-neutron diffraction around a target, whereas Coulomb dissociation originates from the

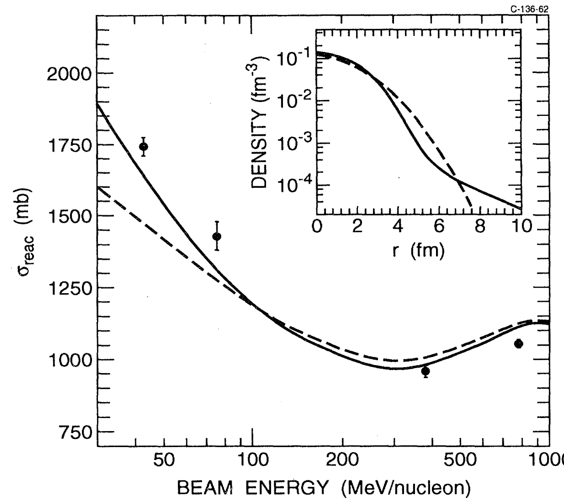

FIG. 6. The total reaction cross section for ^{11}Li on a carbon target (after Shimoura, 1991): ●, experimental values; dashed line, Glauber-type calculation with a harmonic-oscillator density for the core; solid line, halo density obtained from a single-particle wave function. The inset shows the corresponding density distributions. Note that the halo part must be included in order to reproduce the trend of experimental data.

kick received by the charged core during the collision. The core is then accelerated relative to the neutrons; the resulting momentum transfers, even when small, can lead to breakup owing to the low binding energies. This process corresponds to a sizable part (of the order of a single-particle unit) of the dipole strength function's remaining at low energies in halos. The average excitation energy in dissociation reactions will thus be low, particularly at the lower beam energies. The Glauber theory also provides a practical way of testing halo formation by a given nucleus ^AZ through the relation (Yabana *et al.*, 1992)

$$\sigma_{\rm tot}(^AZ)=\sigma_{-\rm halo}(^AZ)+\sigma_{\rm tot}(^AZ-{\rm halo})\ , \qquad (6)$$

which will hold to a good approximation if the total wave function factorizes into a halo part and a core part.

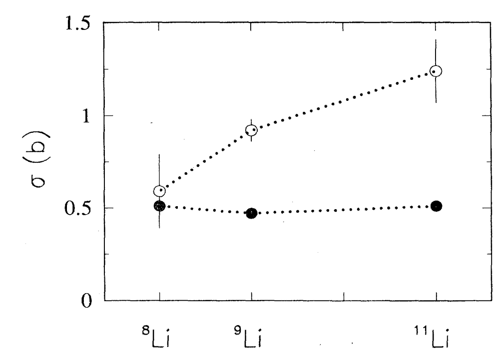

FIG. 7. The charge-changing (●) and total reaction (○) cross sections for Li isotopes on a carbon target at 80 MeV/nucleon (after Blank *et al.*, 1992).

[2]Cross sections were at first often quoted in terms of equivalent root-mean-square radii for the nucleus. This translation unfortunately was only valid for a limited range of halo sizes (rms radii can diverge but cross sections cannot) and is hardly used now.

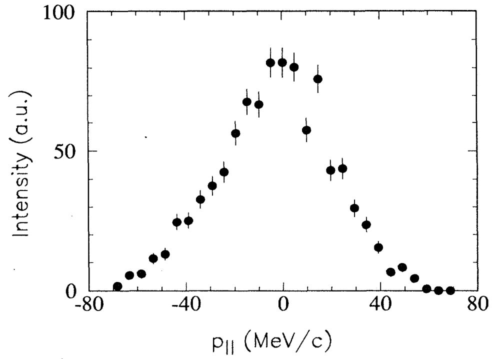

FIG. 8. The longitudinal momentum distribution of ^{9}Li fragments from dissociation of ^{11}Li on an Al target measured at the FRS at GSI (Geissel, 1993), with a beam energy of 319 MeV/nucleon. The momentum distribution of the nonreacting ^{11}Li beam was narrower by a factor four.

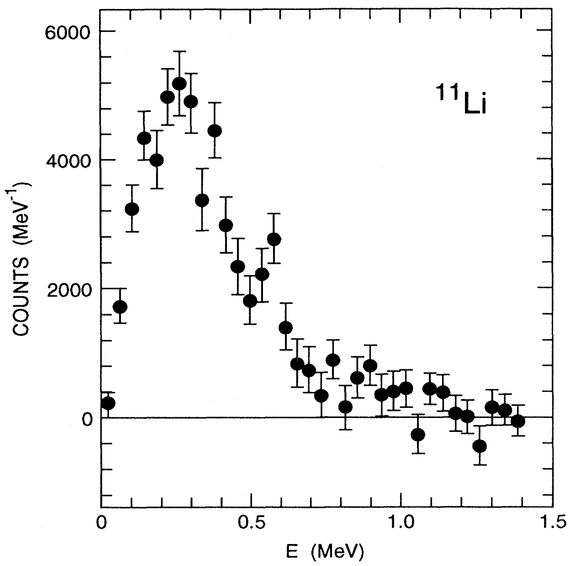

FIG. 9. The excitation energy spectrum resulting from dissociation of ^{11}Li into ^{9}Li and two neutrons on a Pb target at 28 MeV/nucleon (after Sackett *et al.*, 1993). The excitation energy is measured by constructing the invariant mass of the final-state products. The finite detector acceptances distort the spectrum considerably; a Monte Carlo simulation of these effects points to an original strength function peaking close to 1 MeV.

Higher-quality radioactive beams have permitted increasingly ambitious experiments. The next step beyond the measurement of the integral cross sections in a channel is the measurement of differential cross sections. The main emphasis has been on measuring momentum distributions of either the halo neutrons or the core in the "halo-removal" channel. Very-high-quality data now exist, particularly for the longitudinal momentum distribution of the ^{9}Li core from breakup of ^{11}Li. This result hinged on the ingenious use of fragment separators[3]—the production sites for the radioactive beams—as spectrometers, a technique first tried at Michigan State University (Orr *et al.*, 1992). An example with data from GSI is given in Fig. 8. Neutron momentum distributions have also been measured in detail at many different laboratories: Berkeley, GANIL, GSI, MSU, and RIKEN. The distributions from one-neutron halo nuclei are understood by now, as will be discussed in greater detail in Sec. IV.A, whereas questions remain concerning the two-neutron nuclei.

A further step forward is reached by simultaneous detection of all the fragments emerging from the reactions, a procedure sometimes referred to as a "complete kinematics" experiment, allowing the excitation energy in the final state to be determined from the fragments' invariant mass. Experiments of this type have been performed at MSU (Ieki *et al.*, 1993; Sackett *et al.*, 1993), RIKEN (Shimoura *et al.*, 1993), and GSI (Humbert *et al.*, 1993). The results presented so far are quite encouraging, although, in particular, the first two experiments were rather limited in total efficiency. These experiments observed the Coulomb dissociation of ^{11}Li by a Pb target yielding excitation energy spectra rather structureless, and peaking around 1 MeV (see Fig. 9) in perfect agreement with the expected low position of the halo part of the electric dipole strength.

B. Other reaction studies

In the "fragmentation regime" the slow motion of halo neutrons allows a high beam-energy approximation to extend further down for halo nuclei than for normal nuclei. Lowering the beam energy, one will eventually reach the domain of the well-tested, "classical" lower-energy reaction techniques. Experiments of this type are barely starting, most noticeably on elastic scattering at 30–60 MeV/nucleon. Their results seem compatible with the halo hypothesis, but these experiments have not yet probed details of the density distribution.

Particle transfer reactions have served to study several of the very neutron-rich nuclei. One can even go beyond the stability line and get information—including spin and parity assignments—for particle unbound states. Work has been done earlier in this direction for multineutron systems and heavy H and He isotopes (Ogloblin and Penionzhkevich, 1988); prominent recent examples include ^{10}Li and ^{13}Be. The structure of ^{10}Li serves to cross check the parameters used in calculations of ^{11}Li: the character of its ground state remains uncertain (although several recent experiments indicate it is a slightly unbound *s* wave). This uncertainty carries over to ^{11}Li,

[3]The recoil separators in operation today are LISE at GANIL (Grand Accelerateur National d'Ions Lourds) in France, RIPS at RIKEN (The Institute of Physical and Chemical Research) in Japan, the A1200 at MSU (Michigan State University) in the USA, and, at somewhat higher energy, FRS at GSI (Gesellschaft für Schwerionenforschung) in Germany.

making the relative angular momentum between the core and each of the two halo neutrons a recurrent point of debate.

The process inverse to Coulomb dissociation is radiative capture. A large probability for Coulomb breakup therefore corresponds to an enhanced probability for capturing a halo particle on the core nucleus. Only one-particle halos can be formed by capture and only if the core is stable (or long lived) against beta decay, restrictions that limit the applicability of radiative capture. This is counterbalanced by capture being possible also to "excited-state halos" that cannot be studied by Coulomb dissociation. Radiative proton captures have been studied quite intensely in nuclear astrophysics as they play an important role in stellar energy production. The first excited state of ^{17}F provides an example of a halo state appearing there (see, for example, Rolfs, 1973). Note the close parallel to the photoionization and radiative recombination in atomic physics, the latter also a process studied in detail during the last decade.

C. Beta decay and ground-state properties

The energy windows accessible to beta decay become quite large (10–20 MeV) close to the dripline,[4] and the states resulting from beta decays are often particle unbound. Most measurements take advantage of this circumstance to detect beta-delayed particles rather than (or in coincidence with) the beta particles themselves, thus affording a better signal-to-background ratio.

The beta decays involving a halo in their mother or daughter state can be modified in two different ways. First, the beta decay matrix elements may be altered in their spatial overlap; typically by at most a factor two and thus hard to verify experimentally. Second, qualitatively new types of decay might appear, namely, direct decays to continuum states. The energy windows open for beta-delayed proton and deuteron emission from one-neutron and two-neutron ground-state halos are defined by

$$Q_{\beta p}(N,Z)=m_n-m_H-S_n(N,Z)$$
$$=0.782\ \text{MeV}-S_n$$

and

$$Q_{\beta d}(N,Z)=2m_n-m_d-S_{2n}(N,Z)$$
$$=3.006\ \text{MeV}-S_{2n}\ .$$

At low separation energies one can therefore imagine halo particles, already spatially removed from the core, decaying directly into continuum protons or deuterons leaving the "unperturbed" core behind.

[4]The neutron (proton) dripline is where the single neutron (proton) separation energy vanishes.

This process, amounting to a new beta decay mechanism, may have been observed in the decay of ^{6}He. Two experiments on the beta-delayed deuteron decay of this nucleus have been published, the latest one (Borge *et al.*, 1993) giving a branching ratio of about 10^{-5} (not all of the spectrum could be observed owing to a detector cutoff) with the spectrum shown in Fig. 10. This example is particularly simple, with its alpha particle core quite inert and well-known relevant interactions. Its alternative daughter nucleus, ^{6}Li, has also been well studied, allowing reliable theoretical predictions on the whole decay. The decay rate turned out to be sensitive to the wave function's value at 10 fm and beyond, i.e., very far out in the tail. The shape of the ejected deuteron's energy spectrum will depend on details of the outer part of the wave function (Zhukov, Danilin, Grigorenko, and Shul'gina 1993; Baye *et al.*, 1994), boosting the interest in higher-quality data not only for ^{6}He, but also for other halo nuclei. Several detailed theoretical calculations are being performed starting both from a direct decay model and from a "more conventional" R-matrix approach (Barker, 1994); further experiments are also being prepared, e.g., at ISOLDE and TRIUMPH.

The static properties of halo states can also sometimes yield information. The study of electromagnetic moments of halo states or of transitions involving a halo state should be stressed, as the electric multipole operators

$$\mathcal{M}(E\lambda,\mu)=\left[Z_c e\left[\frac{A-A_c}{A}\right]^\lambda +(-1)^\lambda Z_h e\left[\frac{A_c}{A}\right]^\lambda\right] r^\lambda Y_{\lambda\mu}$$

explicitly contain factors of r enhancing the large distance behavior, i.e., the halo region. The electric dipole

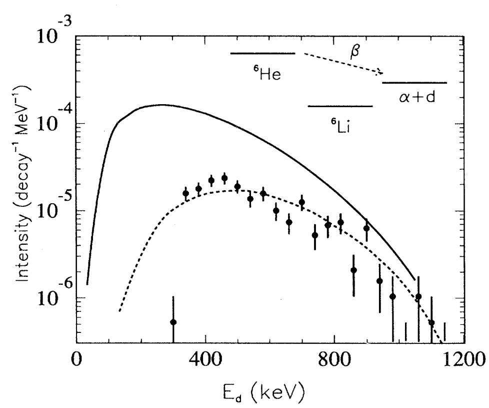

FIG. 10. The beta-delayed deuteron spectrum from ^{6}He. The number of deuterons per decay and per MeV laboratory energy is shown vs the energy: ●, data points from Borge *et al.* (1993). The experimental cutoff is at 360 keV. Solid line, calculation of Zhukov, Danilin, Grigorenko, and Shul'gina (1993); dashed line, the model named EH3 by Baye *et al.* (1994). Both Zhukov *et al.* and Baye *et al.* assume the decays to proceed directly to continuum states.

transition between the first excited state and the ground state in ^{11}Be provide the "classic" example of such a halo observation (Millener *et al.*, 1983), valid only for small or well-known core contributions to the multipole.

IV. PRESENT POINTS OF DISPUTE

This section is intended to convey a feeling for the present status of the field by presenting three unresolved problems that are actively being investigated at the moment.

A. What do the momentum distributions tell?

It was at first hoped that the experimental momentum distribution from fragmentation reactions might have a simple interpretation (the Fourier transform of halo wave functions), but this hypothesis looks no longer tenable. The nuclear reaction mechanism has a marked influence on the final momentum distribution. This is seen quite directly in the recent GANIL measurement (Anne *et al.*, 1993) of neutron distributions from ^{11}Be colliding with different targets. Changes of the reaction mechanism emerge as changes in the neutron angular distribution. Coulomb dissociation dominates collisions with heavy targets yielding a narrow distribution. Measured distributions showed a FWHM (full width at half maximum) of 60 MeV/c, about one fifth of the width obtained in the fragmentation of normal nuclei. Nuclear dissociation dominates collisions with light targets, mainly through quasifree neutron diffraction, thus yielding a broader distribution.

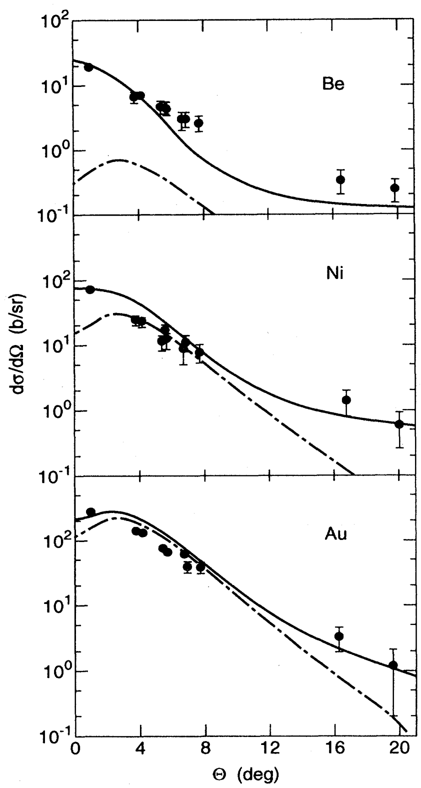

FIG. 11. The neutron angular distribution from (^{11}Li,^{9}Li) collision with Au, Ni, and Be targets at 28 MeV/nucleon (after Anne *et al.*, 1990). The calculated cross sections are from Barranco *et al.* (1993). Solid lines, total cross sections; dot-dashed lines, contribution from Coulomb breakup. The FWHM of 25 MeV/c is about one-tenth of that observed for more bound nuclei. The close similarity between the shapes obtained on different targets seems to be accidental (see the text).

Two-neutron halos may furthermore lead to final-state interactions between fragments that do not react with the target, thus complicating the picture and possibly, for ^{11}Li, even wiping out the difference between targets to a large extent, as shown in Fig. 11 (Barranco *et al.*, 1993). In the limit of very strong final-state interactions one would énvisage reactions leading to excited final states that subsequently decay (Kobayashi, 1993). No agreement exists yet on the severity of such effects (e.g., the longitudinal momentum distributions might be less affected); the earlier hope—often expressed just a few years ago—to read off the halo momentum distribution directly from observations seems much too optimistic. Halo reactions appear too gentle, allowing time for complications to intrude. Somewhat paradoxically, the more violent collisions with core interactions might afford a better chance for viewing the halo momentum distribution. Reactions in such collisions would be sufficiently violent to justify the sudden approximation, thus distorting halo neutrons only slightly as a component of the total neutron distribution, as indicated by some experimental data (Riisager, 1993).

Another idea prominent in the literature would interpret the low-lying electric dipole strength as a soft dipole resonance. This concept has been questioned, particularly by Ieki *et al.* (1993) and Sackett *et al.* (1993), who found a shift in the centroid of the momentum distributions hard to reconcile with a resonance in the final state if interpreted as a Coulomb pre-deceleration/post-acceleration. Dipole transitions would instead proceed directly to continuum states, a question to be resolved by additional observations.

B. Correlations in two-neutron halos

The first models of ^{11}Li neglected the neutron-neutron degree of freedom completely by using a core plus dineutron model (Hansen and Jonson, 1987), but succeeded nevertheless in capturing most of the system's essential features. The question of correlations between the two neutrons has remained elusive. They are certainly important, as ^{11}Li is bound whereas ^{10}Li is not, but the energy gain when going from a two-body to a three-body system may arise from the neutron-neutron interaction as well as from changes in the kinetic energies owing to lower reduced masses. Both effects contribute, but would lead to different types of spatial correlations. The latter is of course only effective as long as the core is not too heavy compared to the neutrons; vanishing neutron-neutron interaction might even yield energy gains in the 10–100 keV range for ^{11}Li. This interaction seems likely to have a larger impact, but no positive experimental indication for any sort of correlations has yet emerged.

Information has been sought by comparing momentum distributions of different fragments. This approach might prove quite tricky owing to limited understanding of reaction mechanisms or to experimental pitfalls, but comparison of neutron and core distributions from two-neutron removal reactions may nevertheless provide indications of weak correlations in ^{11}Li and strong correlations in ^{14}Be (Hansen, 1993; Zahar *et al.*, 1993). This result might still be heavily influenced by final-state effects, but is certainly intriguing. Experiments with complete kinematics can in principle do better, and the relative neutron-neutron momentum spectrum from breakup of ^{11}Li has been extracted (Sackett *et al.*, 1993), all data being again consistent with the absence of correlations between the two neutrons.

Some model calculations (Esbensen and Bertsch, 1992a, 1992b) actually suggest a slight anticorrelation between the two neutrons. The influence of the correlations on momentum distributions as well as on cross sections has been calculated and seems to be present, although not resulting in a very striking signal. It might take patience to prove its presence.

C. The case of ^{8}B

The nucleus ^{8}B is interesting for several reasons (Riisager and Jensen, 1993). It has a low proton separation energy, 137 keV, with the proton in a *p* state relative to the core and therefore a halo candidate. Many of the experiments mentioned above can extend to ^{8}B, several of them having already been done. This nucleus seems to be perfect for testing and comparing the sensitivity of different experiments that probe the wave function of the proton combined with the ^{7}Be core at different distances. It is, however, an open question whether the core can be counted as inert or whether it interacts with, and is modified by, the extra proton without impairing the assumed separability of the system into two parts. The halo nature of ^{8}B therefore cannot be taken for granted.

On the experimental side conflicting indications point both towards a vanishing halo and towards a very large halo, from data on the total reaction cross section (Tanihata *et al.*, 1988) and on the electric quadrupole moment (Minamisono *et al.*, 1992), respectively. The interpretation of the latter experiment has, however, been questioned (Csóto, 1993; Riisager and Jensen, 1993; Nakada and Otsuka, 1994). The proton radiative capture reaction points to an intermediate value. This process will in fact be the most sensitive one for the tail, with the repulsive Coulomb potential, probing increasingly large radii as the proton kinetic energy is decreased. The radiative capture cross section at very low kinetic energy (around 20 keV) is needed for solar model calculations; this is the reaction producing ^{8}B in the sun. Capture at such low energies takes place at around 50 fm from the nucleus and remains inaccessible to direct measurement in the laboratory. Its cross section is relevant to the solar neutrino problem (almost all high-energy neutrinos result from the decay of ^{8}B), being usually obtained by extrapolating data from higher energies. The extrapolation could be influenced at intermediate distances by three-body effects involving the proton and the pair of fragments, ^{4}He and ^{3}He, that are bound by only 1.6 MeV within the ^{7}Be core of ^{8}B. The detailed properties of the tail in ^{8}B are thus relevant beyond nuclear structure physics. Several theoretical groups are presently improving the theoretical description of ^{8}B, and new experiments are planned.

V. WHAT NEXT?

As just indicated important open questions need to be tackled. Part of them will be approached by improving existing techniques. Beam intensity, detector coverage, and detector resolution have all been improved during the last few years, affording hope for still further progress. Very promising are experiments with detection of all fragments that should lead to a quite detailed picture of the halo structure. Another trend, to emerge more strongly when production facilities with radioactive beams around the Coulomb barrier come into existence, would utilize "low-energy" spectroscopy reactions. Several interesting experiments can be foreseen; for example, all the good two-neutron halos seem to have unbound core-neutron subsystems whose parameters might be determined in transfer reactions.

Other halo nuclei clearly would have to be included in order to escape the specific mass 11 and to see how halo features emerge as, for example, the binding energy is decreased. Some of the obvious next candidates are shown in Fig. 12. It would be very interesting to consider halo structures from other fields of physics, thereby checking

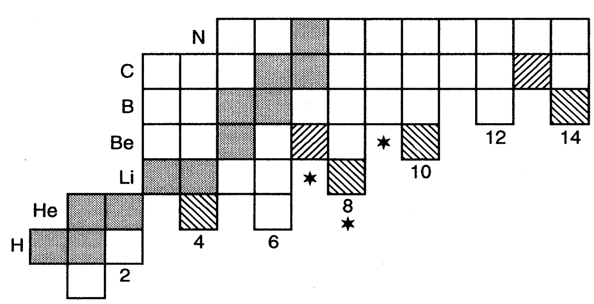

FIG. 12. The lowest part of a nuclide chart. The stable nuclei are represented by filled squares. Candidates for ground state one- and two-neutron halo states are marked by hatching; ^{11}Be and ^{19}C would form one-neutron halos, and the rest would be two-neutron halos. See Table I for details of established states. The stars denote particle-unbound nuclei that have been investigated recently.

what is independent of the interaction's form and what is instead specific to the residual neutron-neutron interaction. A deeper study of proton halos (including the interesting case of ^{8}B) would also be very helpful.

Other interesting questions have still barely been touched upon. Let me mention only two of them. First is the suggestion that the neutron halo might facilitate fusion reactions (Takigawa and Sagawa, 1991). The extreme fragility of halos could counteract the benefits of the extended neutron distribution, so that neutron skin nuclei might perhaps fare better in fusion; this remains to be investigated in detail. The second question concerns the "position of the dripline." New types of structure might emerge by placing several neutrons into a halo, leading perhaps (Jensen and Riisager, 1992) to particle-stable systems quite far off the "normal" dripline. This idea might sound unlikely, but the surprises encountered so far should caution us against quick judgements.

To sum up, reaction experiments on both barely bound and barely unbound nuclei along with, for example, suitably chosen beta-decay experiments should in the coming years give us a much more complete picture of halo structure, in particular the elusive neutron-neutron correlations at the very low halo densities. Most of the needed theoretical concepts seem to be established, but it is not unreasonable to expect important progress there also.

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