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EXPERIMENTS WITH RADIOACTIVE BEAMS

Paper presented at the International Conference on Nuclear Structure at the Extremes Lewes, Great Britain, 17-19 June 1998

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1. INTRODUCTION

The advent of fast mass- and element-separated radioactive beams from fragmentation reactions of heavy ions at intermediate and high energies has allowed the use of radioactive nuclei as projectiles in nuclear reaction studies at energies ranging typically from 30 MeV/u to 1000 MeV/nucleon. These beams have over the past decade stimulated a wave of experimental and theoretical interest in exotic nuclei. Interesting results have been obtained in many areas of nuclear physics [1,2] of which I shall deal with only one, namely the structure of very proton- and neutron rich light nuclei. Let me, however begin with some brief comments on experimental methods.

As you will soon see, one major problem in this kind of experiments is how to extract information on nuclear structure at low excitation energies with a very fast beam. It is therefore very valuable that a second wave of techniques tilling the gap below 30 MeV now is arriving. These start from the method of "Isotope Separation On Line" (ISOL), which produces mass- and element-separated beams of slow radioactive ions at typically 60 keV total energy, a method that for many years was the main tool for doing experiments with short-lived radioactive nuclei [2,3]. They combine the ISOL system with a post-accelerator (cyclotron, tandem accelerator, linac). Two are already in operation and more still are under construction and will allow experiments in the range of OS-10 MeV/nucleon, thus at long last covering the essential region between energies of astrophysical interest and the Coulomb barrier. There are also ambitious plans [4] for a second-generation facility, an advanced ISOL Facility followed by a powerful accelerator.

Since the ISOL beams have existed for a long time it may seem strange that the post-acceleration method was not developed earlier. It was, in fact, discussed at a CERN workshop in 1977, which concluded [5]: "... .Finally we have discussed in the Workshop a scheme for accelerating radioactive ions, such as ^{6}He, ^{8}He, ^{9}Li, as projectiles for nuclear reactions. There is no doubt that this can be done in intensities that are high enough to have some interest; one can also point to some physics experiments that might be worth doing. On the whole, however, we do not feel any great enthusiasm for this kind of work for the moment, but we shall keep the possibility in mind." The main explanation for this conclusion is that the participants in the discussion had pondered the advantages of using rare radioactive beams as a supplement to the stable ones in use at the time. It had not yet been realiid that the main use of a radioactive beam would be to study the structure of the rare projectile itself. All of the experiments discussed in the following are for that purpose.

2. EXTREME SINGLE-PARTICLE STATES: NUCLEAR HALOS

Some of the first reaction experiments with radioactive beams measured total interaction cross sections [6,7] and served as a great eye opener by finding indications for the existence of nuclear halos [8,9] in very neutron-rich systems. The one-nucleon halos such as the neutron in ^{11}Be are the most pronounced examples of single-particle shell-model states that we know. Two-neutron halos such as the pair in ^{6}He or ^{11}Li owe their binding to the combined action of the core-neutron and the neutron-neutron interactions and almost certainly have important three-body features [10] reminiscent of Hylleraas's treatment of the helium atom. Recent analyses [11-13] seem to indicate comparable amounts of $1s^2$ and $0p^2$ in the ^{11}Li halo wave function, which is a direct indication of this kind of correlations, but the experimental situation is far from clear. It is a good approximation to think of the halo systems as molecule-like clusters in which the core and the valence nucleon(s) are distinguishable entities. Indeed, to deduce the radius of the ^{11}Li halo from its interaction cross section on a light target it is essential [14] to take the cluster nature of the system into account. We point to some phenomena that highlight the extreme single-particle and cluster nature of halo nuclei.

(i) Electric Dipole Transitions in Neutron Halo Systems. The first identification of a neutron halo by Millener et al. [15] was based on the surprisingly short lifetime of the $½^-$ excited state, which decays to the ground state, a $½^+$ intruder state. This transition probability has been re-determined in intermediate-energy Coulomb excitation experiments, see [16] and references therein, which confirm that the reduced transition probability B(E1) indeed is as large as 0.1 e^2fm^2. Still, this very large value is dwarfed by the low-energy E1 transitions from the ground state to the ^{10}Be+n continuum. (The neutron separation energy is only 0.50 MeV). The differential cross section for Coulomb dissociation of ^{11}Be on a heavy target has been shown [17,18] to be accounted for quantitatively by a model in which both the ground state and the continuum final state are taken to be extreme single-particle states in a Woods-Saxon potential. Since all possible excitation channels are included in this picture, this implies that this excitation exhausts the appropriate sum rules. These are the approximate non-energy-weighted (NEW) and energy-weighted (EW) sum rules

$$S_0 = \int_{-\infty}^{\infty} dE \frac{dB(E1)}{dE} = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \langle r^2 \rangle$$

and

$$S_1 = \int_{-\infty}^{\infty} dE \frac{dB(E1)}{dE}[E - E_{gs}] = \frac{9}{4\pi}\left(\frac{Ze}{A}\right)^2 \frac{\hbar^2}{2\mu}$$

where μ is the reduced mass. The ratio of the two defines the average excitation energy. We see immediately that a large halo (i.e. low neutron separation energy) implies E1 strength at very low energies. The NEW sum rule has been verified directly by Nakamura et al [19], who measured the integrated B(E1) to be 1.3±0.3 e^2fm^2. The theoretical value is 1.4 for an *rms* halo radius of 6.7 fm.

The E1 dissociation strength of a two-neutron halo systems is best discussed in terms of an energy-weighted molecular cluster sum rule introduced by Alhassid et al. [20], which is derived as the difference between the usual sum rule and the sum rule for each cluster. In the case of a nucleus with mass number *A* and one halo neutron, the molecular sum rule is identical to the second expression given above. For a more general neutron halo the molecular sum rule expressed in units of the total EW sum simplifies to

$$\frac{S_{MC}}{S_1} = \frac{HZ}{(A-H)(A-Z)}$$

with H being the number of halo neutrons. Applied to ^{11}Li and for H=2 this gives 8.3%, which agrees exactly with the measured value from Coulomb excitation [21] of 8±2%. This suggests that the dissociation leads predominantly to ^{9}Li and a di-neutron. This is supported by the experiment by Shimoura et al [22], who found that the final state had a small relative nn excitation energy compared with that contained in the relative motion of ^{9}Li and the center of mass of the di-neutron. Applied to ^{6}He and still for H=2 the molecular sum rule gives a relative strength of 25% as compared with the experimental value of 10% measured by Aumann et al. [23]. If, however, we assume H=1 the theoretical value is exactly 10%, which suggests that the breakup in this case goes predominantly to ^{5}He. That ^{6}He breaks up in this manner is maybe understandable in view of the fact that its halo is more bound than that of ^{11}Li. An observable consequence would be that the energy of one of the neutrons will reflect the subsequent decay of the $p_{3/2}$ resonance of ^{5}He.

(ii) *Shakeoff of Halo Neutrons*. We may consider the Coulomb excitation processes discussed above as an example of a nuclear shakeoff mechanism. In this, momentum is suddenly imparted to the core. After the impact the nucleus, no longer in an eigenstate of the Hamiltonian, will either remain in the ground state or be excited to the continuum. (We assume that the halo has no other bound states than the ground state.) Shakeoff processes are commonly encountered in atoms following nuclear or inner-shell processes, and their complement, the elastic process, is analogous to the recoilless emission or absorption in the Moessbauer effect. The probability of the latter as a function of the momentum transfer is referred to as the Debye-Waller factor, which is shown in Fig. 1 for a typical light nucleus and for different neutron binding energies. For a typical momentum transfer of the order of 100 MeV/c the Debye-Waller factor is seen to be large and consequently the shakeoff probability is small.

This simple picture is supported by the experiment [22], which for ^{11}Li favors a direct breakup mechanism. An illuminating discussion of Coulomb dissociation in this spirit has been given by Pushkin et al. [24]. Using a simplified three-body wave function for ^{11}Li they derive an analytical expression for the energy spectrum following breakup and compare it with the corresponding formula for the two-body system, which has been used by many authors. It is characteristic that the expressions in both cases contain only the binding energy of the initial state, which determines the asymptotic properties of the s-state wave function. The parameters of the final state do not enter explicitly. We may say that in this simple first-order approach, the continuum which is observed just above the reaction threshold is nothing but a mirage of the bound state just below the threshold, cfr. the sum rule argument given above.

The shakeoff process must play a role in all situations in which momentum is transferred to the core in the presence of a halo. More examples are given below. Let me mention here the inelastic scattering data for protons from ^{11}Li (in inverse kinematics), which have been interpreted as indicating [25,26] the existence of a state at 1.3 MeV. Karataglidis et al. [27] show that in such a picture it is difficult to understand the cross section and angular distribution . Both, however, fall into place if it is assumed that the basic process is shakeoff following elastic scattering of a proton from the ^{9}Li core.

(iii) *Diffraction Dissociation*. The large size of the neutron halo makes diffractive scattering of the quasi-free neutron from light targets an important process. This entails a characteristic broad angular distribution, which has been observed in two experiments on ^{11}Be [17,18,28] at 41 and 460 MeV/u. Calculations of dissociation cross sections by stripping and diffraction reactions have been performed by Hencken et al. [29]. The angular distribution in the laboratory system resembles that of a free neutron, but Bonaccorso and Brink [30] have recently succeeded in calculating the ^{11}Be angular distribution by a technique that applies equally well to more deeply bound nucleons. The agreement is very good except for the small angles, where an excess of intensity seems to be most naturally explained by small contributions from Coulomb excitation and shakeoff [31]. (Estimates [16] show that Coulomb dissociation can contribute appreciably to the dissociation of ^{11}Be, even on light targets.)

Experiments that reconstruct the total excitation energy of the final three-body system will detect the diffractive component as a broad distribution towards higher energies. At low energies there will be a contribution from Coulomb and shakeoff processes. A recent estimate [31] illustrated in Fig. 2 shows that such a picture can account well for the invariant-mass spectrum [21] of the final states from ^{11}Li breakup. Recent data on ^{6}He [23] seem to reflect a very similar pattern.

(iv) *The shadow effect*. The longitudinal momentum width of the residual fragment in a stripping reaction that removes the halo particle(s) was for some time believed to reflect the true momentum wave function. Qualitatively this is certainly correct in the sense that the large spatial size in the spirit of Heisenberg's uncertainty principle must translate into a narrow momentum width. An analysis in an eikonal model [32,33] shows that the final momentum distribution is the same as the original one for wave functions that factorize in Cartesian coordinates such as Gaussians and plane waves. However, the correct asymptotic wave functions of a halo do not have this property. In the more general case, the reaction measures the actual parallel-momentum content in the region sampled, which, in general, means narrower distributions at large impact parameters [33]. A good example [32] is provided by a neutron state represented by a Yukawa wave function. In this case the (unphysical) high-momentum tail arising from the singularity at the origin disappears because the reaction can sample the neutron only outside the nuclear surface. For this reason the effect is sometimes referred to a "shadow effect". Other quantum numbers should be affected in a similar way. The analytical expressions [33] clearly show that the final m-state distributions must be non-statistical. It is tempting to speculate that this effect plays a role at some level in the analysis of the angular correlations observed in peripheral fragmentation of halo nuclei [34,35].

3. Spectroscopy of Halo and Core States in Stripping Reactions

In the development of nuclear spectroscopy, transfer reactions at energies close to the Coulomb barrier have played an important role. An essential feature was that the distorted-wave analysis provided a tool that could link predictions from nuclear models to the observed cross sections. It has now been found [36-39] that stripping reactions at high energies combined with the detection of gamma rays can provide some of the same information for fast radioactive beams. The missing ingredient has been provided by the development a theoretical technique [39] suitable for calculating single-particle stripping cross sections in an eikonal model. Combined with the shell-model spectroscopic factors they lead to absolute values for the partial cross sections. Professor Tostevin will discuss these results in the presentation following this one.

The large reaction cross section for the reaction $^{9}Be(^{11}Be,^{10}Be)$, approximately 300 mb at 41 MeV/u [18], is due to the large size of the halo and leads predominantly to the ground state. However, in a recent experiment [36] in which gamma rays were observed in coincidence with the outgoing fragment it was found that there is an appreciable cross section for feeding of excited states, see Fig.3. From the known level scheme of ^{10}Be [40] we tentatively identify these as negative-parity levels arising from a core hole coupled to the $1s_{1/2}$ intruder state. Re-scaling the cross section from 41 MeV/u to 60 MeV/u we get 220 mb so that 20-25% arises from the core excitations near 6 MeV. At first sight it seems surprising that the halo neutron can remain bound after an impact that strips a neutron from the core. However, the neutron in the final levels of ^{10}Be is still bound by 0.5-1 MeV, and with a momentum transfer of typically 100 MeV/c the Debye-Waller factor is, in fact, close to unity, see Fig. 1. Shell-model calculations [37] predict comparable spectroscopic factors for the three levels in question (0^+, 1^-, 2^-) and considerably less for the 2^+ rotational state. The large cross section to the 0^+ level clearly must arise from the halo in the initial state.

Similar experiments [38] have very recently been obtained for proton stripping reactions on ^{25}Al and $^{26,27,28}P$. The first is an interesting test case well studied in many other experiments, while the three phosphorus isotopes are interesting by having the proton in the $1s_{1/2}$ state, which conveys some of the characteristics of a proton halo [41] to them. The s states are favored in the stripping reactions.

Stripping reactions offer a very promising approach to detailed nuclear spectroscopy at beam energies around 100 MeV/u. The most serious limitation in the present generation of experiments clearly has been the mediocre energy resolution of the scintillation detectors. The extension to high-resolution germanium detectors has not been straightforward because of the Doppler broadening due to the finite detector size. The NSCL now has started the construction of an array [42] of 18 segmented position-sensitive detectors with a granularity of 1 cm (quoted as the rectangular spatial response in the direction of interest). This should offer a wide variety of possibilities in studies of far-unstable nuclei with radioactive beams.

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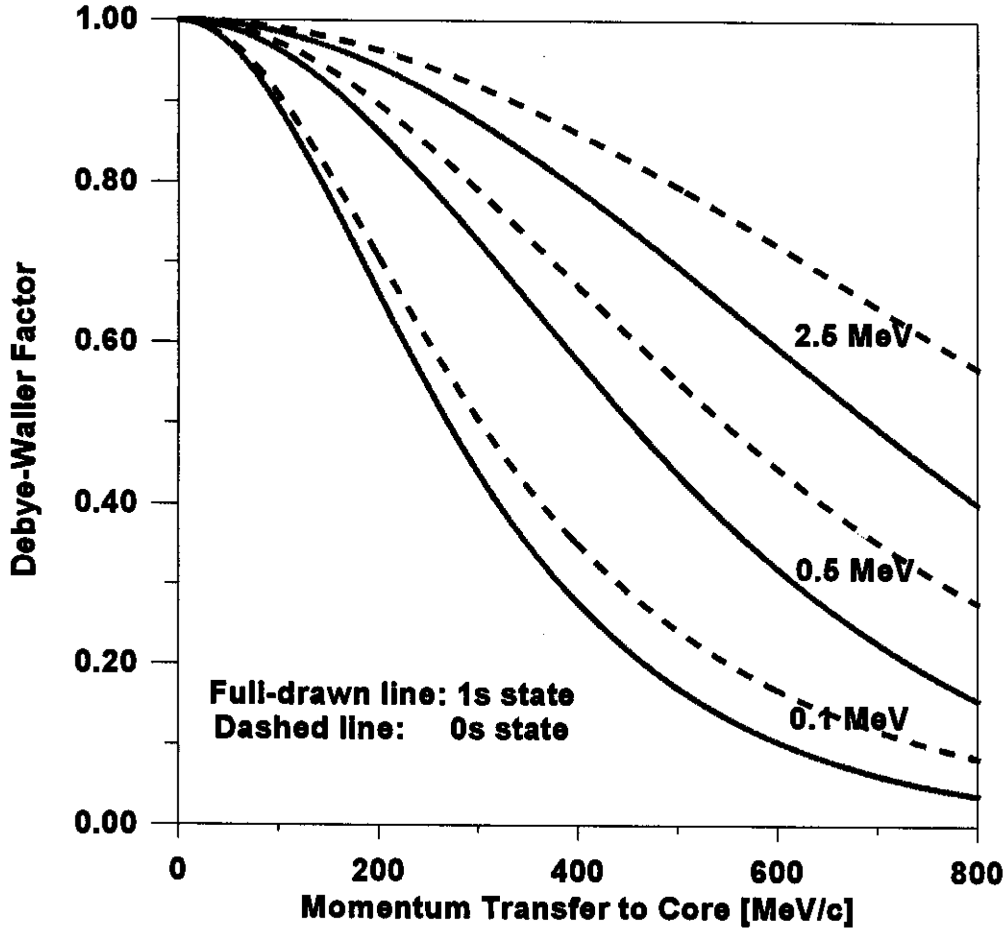

Fig. 1. The probability of ^{10}Be+n remaining in the bound *s* state as a function of the momentum transfer to the core. (Debye-Waller factor.) The calculation is based on Woods-Saxon single particle wave functions. It is seen to be rather insensitive to the node in the 1*s* state.

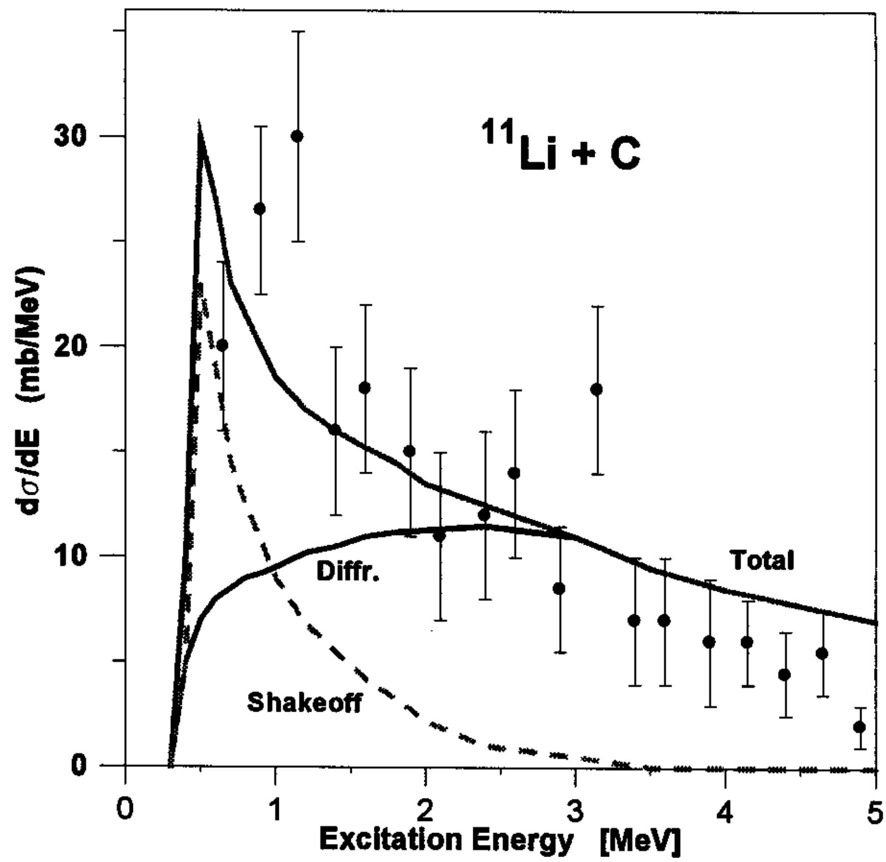

Fig. 2. Contributions from diffraction dissociation and shakeoff calculated on an absolute scale in an eikonal approximation [27]. The data [24] are for the reaction ^{11}Li+C at 200 MeV/u on a carbon target. Note that the estimate obtains the shakeoff part in a two-body model, hence the low-lying peak. Better agreement would be obtained by using three-body estimate of Pushkin et al., which reproduces the experiment [18] very well.

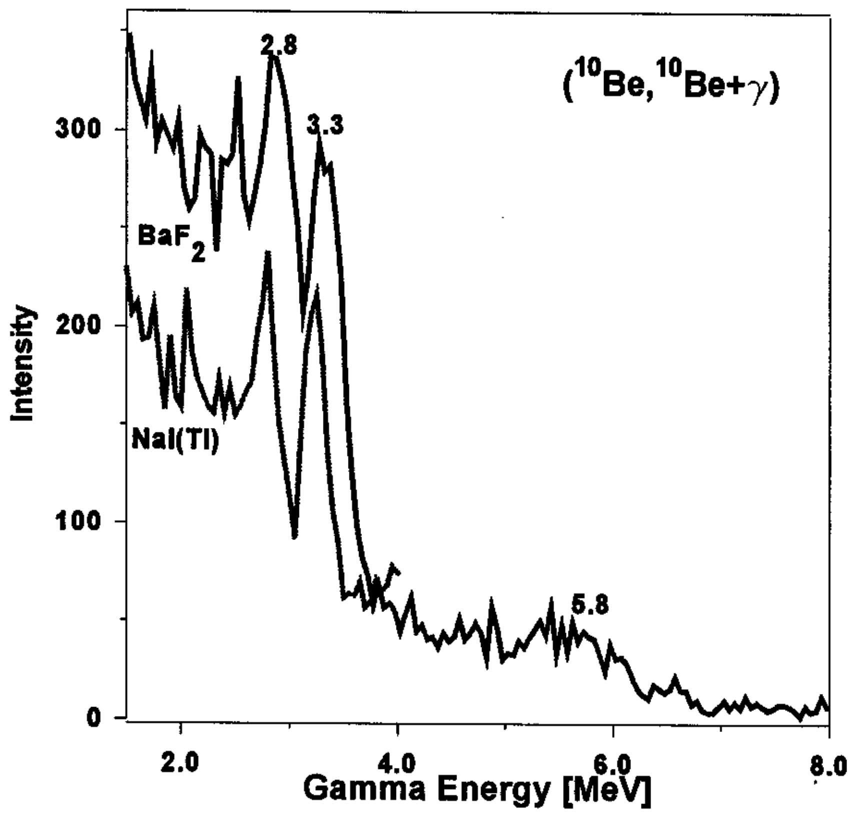

Fig. 3 Gamma spectra [31] from the reaction ^{9}Be(^{11}Be,^{10}Be+γ) measured at 60 MeV/u with a NaI and a BaF_2 array. The three gamma rays seen are interpreted as representing predominantly the de-excitation of a pair of negative-parity states (1^-,2^-) arising from the sripping of a $p_{3/2}$ neutron from the core. The cross section to each of these states is about 25 mb, while direct feeding of the excited 2^+ state, represented here by the 3.3 MeV line, is believed to be smaller.