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Summary: Electric Excitations of Nuclear Halos and Shakeoff Processes

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The use of radioactive nuclei as projectiles in nuclear reaction studies at energies ranging typically from 30 to 1000 MeV/nucleon has yielded interesting results in many areas of nuclear physics, see e.g. [1-4]. In the following, I shall restrict my comments almost exclusively to single-particle and giant-resonance phenomena in the lightest nuclei, a subject that has been discussed by a number of speakers at this conference. There are two main points that I would like to make. The first is that neutron and proton halo states offer examples of an extreme single-particle behavior, and the second is that their reactions in many cases tend to be dominated by *the* special *structure* of *the initial* state.

Theoretical calculations of the isovector response of neutron-rich systems including the hypothetical drip-line nucleus ^{28}O were presented by Sagawa and also by Reinhard, Coló, and Lanza. The main feature is the appearance of apparently non-collective dipole strength at low energies An experimental search for high-energy gamma rays representing the “Be giant dipole resonance was presented by Beene. He and also Austin pointed out that the sequence of the stable oxygen isotopes ^{16,17,18}O already shows an increase of El strength below the giant resonance. During the conference, new data for the oxygen isotopes with masses 17-20 were presented by Aumann together with results for the two-neutron halo nucleus ^{6}He.

There is already much experimental evidence on the one and two-neutron halos of “Be and ^{11}Li which have one and two-neutron separation energies of 0.5 and 0.3 MeV, respectively. The data seem to suggest that we are faced with a more extreme situation in which the halo neutron(s) are decoupled almost completely from the giant resonance of the core. This could mean that there is less to be learned from studies of giant resonances of halo systems than is often assumed.

We consider first the status for “Be. The first identification of its neutron halo by Millener et al. [5] 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 [6] and references therein which confirm that the reduced transition probability B(E1) indeed is as large as 0.1 e^{2}fm^{2}. By normal standards, this is a very large value for a transition between low-lying bound states. Still, it is more than an order of magnitude smaller than that of the El transitions of low energy leading from the ground state to the ^{10}Be+n continuum. This absolute differential cross section has also been measured. It can be accounted for essentially quantitatively by a model [7] in which both the ground state and the continuum fmal state are taken to be extreme single-particle states in a

Woods-Saxon potential. This is a most unusual situation for a nucleus (the deuteron excepted) and is reminiscent of a photoelectric process in an atom. Since all possible excitation channels are included in this picture, it follows that the low-energy spectrum exhausts the appropriate sum rules for a single neutron coupled to a supposedly inert nuclear core. These, used by many people, see e.g. [8,9], are the approximate non-energy-weighted and energy-weighted sum rules expressed in terms of the fragment kinetic energy E

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

and

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

where μ is the reduced mass. The non-energy-weighted sum rule has been verified directly by Nakamura et al [10], who measured the integrated B(E1) to be 1.3±0.3 $e^2 fm^2$. The theoretical value is 1.4 for an *rms* halo radius of 6.7 fm. The ratio of the two sum rules defines the average excitation energy, which is approximately

$$\langle E^* \rangle = \frac{3\hbar^2}{2\mu \langle r^2 \rangle} \cong \frac{6 S_n}{1+x} \quad ,$$

where x represents a finite-size correction of order unity. This result was used in [8] in combination with a di-neutron picture of the halo to give a rough prediction of 0.9 MeV for the ^{11}Li excitation energy in Coulomb excitation in agreement with subsequent experiments. It follows immediately from the sum rules that a large halo (associated with a small neutron separation energy) implies E1 strength at very low energies. The intense continuum strength at low energy becomes, so to say, a mirror image of the bound state existing just below the particle threshold. In a moment, we shall come back to approximate formulas describing these distributions.

The E1 dissociation strength for the two-neutron halo of ^{6}He was discussed in the talk by Aumann. Previous results for ^{11}Li have also been given by the GSI group [11]. The two-neutron systems are best discussed in terms of an energy-weighted molecular cluster sum rule introduced by Alhassid et al. [12]. This 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 expression for S_1 given above. For a more general neutron halo, the molecular sum rule expressed in units of the normal sum rule for the nucleus as a whole simplifies to

$$\frac{S_{MC}}{S_{tot}} = \frac{HZ}{(A-H)(A-Z)} \quad ,$$

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 [11] of 8±2%. This demonstrates that the excitation is dominated by the relative motion of the neutrons relative to ^{9}Li. Additional insight and support for this comes from the experiment by Shimoura et al [13], who found that their data for Coulomb excitation of ^{11}Li favored a direct breakup mechanism. In particular, the relative nn excitation energy of final state was small compared with that of 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% for excitation energies lower than 5 MeV measured by Aumann et al. [14]. If, however, it is assumed that H=1, then the theoretical value is exactly 10%, which suggests that the breakup in this case goes predominantly to the $p_{3/2}$ resonance of ^{5}He as an intermediate state. The full energy-weighted strength is recovered [14] if the integration is extended to 10 MeV excitation energy. Apparently, the molecular E1 strength is separated completely from that of the alpha-particle core.

We may view the Coulomb excitation of halos discussed above as particularly clean examples of nuclear shakeoff mechanisms, in which disintegration is caused by momentum suddenly is imparted to the core. For the case of a one-neutron halo, the energy spectrum, see e.g. [15,7,10], is proportional to

$$\frac{dB(E1)}{dE} \propto \frac{E^{3/2}}{(S_n + E)^4} \quad ,$$

where E is the kinetic energy of the final state and S_n the neutron separation energy. Note that the spectrum, which agrees well with experiment [7,10], is determined entirely by the initial state, and that the peak moves to lower energies with decreasing neutron separation energy. This is a manifestation of the sum-rule argument given above.

This treatment has been extended to two-neutron halos by Pushkin et al. [16], who used an asymptotic three-body wave function for ^{11}Li to derive the simple expression

$$\frac{dB(E1)}{dE} \propto \frac{E^{3}}{(1.8 S_{2n} + E)^{11/2}} \quad ,$$

which agrees well with the experimental results of Shimoura et al. [13]. Again, the shape of the spectrum is determined only by the binding energy of the initial state, which determines the bound-state wave function. (The final state is in this model approximated by plane waves, and the broad peak appearing near 1 MeV cannot in this picture be a manifestation of an excited state in ^{11}Li.)

The shakeoff process must play a role in all situations in which momentum is transferred to the core in the presence of a halo. An example is provided by the inelastic scattering data for protons from ^{11}Li (in inverse kinematics), which have been interpreted as indicating [17,18] the existence of an excited state at 1.3 MeV. Karataglidis et al. [19] 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 breakup following elastic scattering of a proton from the ^{9}Li core. The spectrum is then essentially that given by the formula above. Another example is provided by the diffractive dissociation of ^{11}Be [7] at 41 MeV/u. These data have been analyzed by Bonaccorso and Brink [20], who calculated the ^{11}Be angular distribution of the neutron and found very good agreement except for an excess at the smallest angles. This minor discrepancy seems to be accounted for by small contributions from shakeoff following Coulomb and nuclear elastic scattering [21] of the core. The same mechanism affects the elastic scattering of halo nuclei. For these the scattering cross section at large angles is reduced by a form factor representing the influence of the breakup channel, see the recent work of Johnson et al. [22].

In this summary I have emphasized the analogies between the halo states, atoms and molecules because they bring direct insight into and some quantitative understanding of the structures and reaction mechanisms. The molecular aspects of nuclear halos have also been stressed in a recent paper by Gai [23], who points to the importance of threshold effects for systems that are marginally bound. Among his examples are the argon-benzene molecule held together by van der Waals forces and, in particle physics, certain particle spectra observed near meson thresholds. In the limit, the structure of the final state can often be neglected to lowest order. Thus, the approximately 1 MeV final excitation energy that has been observed in a number of reactions of ^{11}Li can be traced back to a process in which the two neutrons are spectators. Participant-spectator behavior may also play an important role in other reactions than dissociation. An example could be the reaction C(^{11}Li,^{8}He+2n)X, where the 1.2 MeV peak observed in the invariant-mass spectrum [24] of the final state possibly reflects the presence of loosely bound neutrons in the initial state rather than a state in ^{10}He. At the same time it must, of course, be made clear that especially for the three-body systems the complex final-state interactions will become important at the next level of approximation and determine the details of the shapes of the spectra. A good illustration of how this comes about is provided by the analysis of ^{11}Li Coulomb excitation performed by Esbensen and Bertsch [9].

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