CONTRIBUTION TO THE
4th International Seminar on Interaction of Neutrons with Nuclei
“Neutron Spectroscopy, Nuclear Structure, Related Topics”
Dubna (Russia), April 1996

EXOTIC PROPERTIES OF LIGHT NUCLEI
AND THEIR NEUTRON CAPTURE CROSS SECTIONS

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Abstract

We have investigated the implications of the neutron halo configuration, observed in the ground-state of some neutron-rich light nuclei, on neutron radiative transition processes. In particular, we have studied the influence of the neutron halo on the direct radiative capture (DRC) process. The energy dependence as well as the strength of E1 emission due to incident p-wave neutrons is strongly influenced by the halo configuration of the residual nucleus capturing state. We have compared the calculated \(^{10}\text{Be}(n, \gamma)^{11}\text{Be}\) DRC cross section with that derived from the experiment in the inverse kinematics (Coulomb dissociation of \(^{11}\text{Be}\)). We show from the comparison that some important information on the structure of the halo nucleus \(^{11}\text{Be}\) can be derived.

1 Introduction

In the category of “exotic” nuclear structure properties we can include the neutron skin and the neutron halo observed in ground-state configurations of light neutron rich nuclei \(^{16}\text{O}\) and \(^{28}\text{O}\). A rigorous definition of neutron skin and of neutron halo cannot be given. Therefore, we will show here an example of both structures to elucidate their features and to show their basic properties. The effect of neutron skin structure has been recently investigated \cite{3, 4} and has been shown to be responsible for a low energy excitation mode, decoupled from the isoscalar giant quadrupole resonance \cite{5}. Here we will concentrate on the effects of the neutron halo structure. In particular, we will show its importance in relation to the low energy electric dipole transition mechanism in \(^{11}\text{Be}\).

1.1 Neutron skin

An example of neutron skin structure is shown in Figure 1. There, the result of a mean-field calculation using Hartree-Fock method \cite{5} is shown for the two nuclei \(^{16}\text{O}\) (in the upper part) and \(^{28}\text{O}\) (in the lower part). The calculations were performed using the common Skyrme-S3 interaction, but the general features of the result can be deduced with any other kind of effective interaction. In the upper part of the figure, the mean-field potential for protons (left) and neutrons (right) is shown together with the bound single-particle energy spectrum. In this double-magic nucleus, neutrons and protons occupy analogous single-particle orbits located at comparable energies.

In the lower part of the figure, the same type of calculation is shown for the very neutron rich \(^{28}\text{O}\) (N=20) nucleus, a double-magic nucleus too. In this case the neutrons occupy single-particle states with energies very different compared to the proton case. Moreover, the Fermi
energies of protons and neutrons are very different here due to the much larger neutron number. A plot of the densities for these two nuclei would reveal a thick neutron configuration “covering” the proton density distribution.

A typical shell model configuration can be seen in the mean-field calculation shown in Figure 1. In the case of $^{28}$O, the $s$ and $d$ shells are both occupied and the single-particle ordering of the states is the usual $1d_{5/2}^2, 2s_{1/2}, 1d_{3/2}$. The last occupied orbit is therefore the $1d_{3/2}$ orbit.

1.2 Neutron halo

A different situation is encountered when similar calculations are performed for the neutron rich $^{11}$Be nucleus. It is well known that its ground state is a $J^\pi = 1/2^+$ state with a dominant $|^{10}\text{Be}(0^+) \otimes (2s_{1/2})_\nu >$ configuration. This is in contrast with the normal single-particle ordering, where the $1p_{1/2}$ orbit is occupied before the $2s_{1/2}$ orbit. This peculiar configuration, together with the very low binding energy, 0.505 MeV, builds up the neutron halo structure of the $^{11}$Be ground state.

The mean-field potential for $^{11}$Be is shown in Figure 2. The tail component of the corresponding neutron density, extending well outside the nuclear surface (defined by a root-mean-square radius of 2.86 ± 0.04 fm) can be seen in Figure 3. There, the neutron and proton densities are shown as calculated by the Hartree-Fock method with a Skyrme-m* interaction. The standard Hartree-Fock calculation would produce a ground-state with a $1p_{1/2}$ configuration. To simulate the experimental situation, the results shown in the figure are obtained forcing the ground-state to be a $2s_{1/2}$ state. Also shown in the figure is a neutron density with an added Yukawa-tail determined by fixing the binding energy of the ground-state. In this way, the resulting neutron density compares well with the experimentally derived density. It should be noted that the wave function corresponding to the $2s_{1/2}$ orbit in a Woods-Saxon potential itself can reproduce
the external part of the neutron density. In the calculations of the capture cross section shown below we have used this wave function to evaluate the electric dipole matrix elements.

2 Neutron direct radiative transitions

The peculiar structure properties briefly described in the previous section have been shown to exhibit strong influence on nuclear excitation modes \cite{3, 4, 8, 9}. In what follows, we will show the results of the effect of the neutron halo structure on electric dipole transitions. These can be investigated, in principle, in both the reaction directions: in the neutron capture as well as in the Coulomb dissociation process.

Our group has recently investigated the effect of the nuclear wave function component in the external region on the neutron capture process \cite{8, 9}. We have calculated several neutron capture cross sections of light nuclei using the direct radiative capture (DRC) model. The calculations for $^{12}\text{C}(n, \gamma)$ and $^{16}\text{O}(n, \gamma)$ reactions have been compared with recent experimental results from direct measurements \cite{9, 10, 11}.

The DRC reaction mechanism may be responsible for the most part of the capture reaction cross section in the particular condition in which the density of states is low enough to hinder the compound nucleus formation. Furthermore, because the halo structure arises mainly from loosely bound $s$ orbits (see the discussion above), electric dipole $\gamma$-ray emissions can only be induced by incident $p$-wave neutrons. In fact, the DRC process is essentially determined by the $E1$ transition matrix elements

$$Q_{i\rightarrow f}^{(E1)} = \langle \Psi_f | \hat{T}^{E1} | \Psi_i \rangle .$$

In the case of incident $p$-wave neutrons, these matrix elements are very much sensitive to the tail...
component of the final capturing state wave function $\Psi_f$ and very little sensitive to the treatment of the incident channel neutron scattering state $\Psi_i$ [8]. The energy dependence as well as the strength of E1 emission due to incident $p$-wave neutrons is therefore strongly influenced by the neutron halo structure of the residual nucleus capturing state. Whether this state is the ground or an excited nuclear state makes no difference in this scheme. As mentioned above, we can compare the $^{10}$Be$(n, \gamma)^{11}$Be DRC cross section with that derived from the experiment in the inverse kinematics: the Coulomb dissociation of $^{11}$Be. A recent Coulomb dissociation experiment has been performed using the radioactive beam line RIPS at RIKEN [7]. A schematic view of the process is shown in Figure 4. Note that in the actual experiment, the dissociation from the first excited state at $E_x = 0.320$ MeV ($J^\pi = 1/2^-$) does not take place because all the nuclei of the incident beam are in their ground state.

The electric dipole strength distribution $dB(E1)/dE_x$, as measured in the Coulomb dissociation experiment, can be related to the neutron capture cross section, $\sigma_{n,\gamma}^{E1}$, by

$$\frac{dB(E1)}{dE_x} = \frac{9}{8\pi^3} \left( \frac{\hbar c}{E_x} \right)^3 k_n^2 \sigma_{n,\gamma}^{E1}(E_x)$$

where $E_x$ is the excitation energy and $k_n$ the emitted neutron wave number. This relation is only valid for the present combination of angular momentum values.

The results of the DRC calculation in comparison to the experimental values derived from the Coulomb dissociation experiment and converted into the neutron capture channel are shown in Figure 5. As a first comment to this result, one has to note that the experimental values have to be compared only to the calculation including the $p \rightarrow s$ transition because, as noted above, the experiment only includes incident $^{11}$Be nuclei in their ground-state.

The next feature which can be seen in the Figure is that the low energy part, where the experimental uncertainty is lowest, is quite well reproduced by the calculation. This can be interpreted as a confirmation of the halo structure of the ground-state of $^{11}$Be. In fact, the matrix elements which enter in the expression for the DRC capture given above can be decomposed
Figure 4: The Coulomb dissociation of $^{11}\text{Be}$ into $^{10}\text{Be}+n$. The spectroscopic factors of the two bound states are those derived from a $^{10}\text{Be}(d,p)$ measurement [6].

into a product of three factors

$$Q_{i\rightarrow f}^{(E1)} \equiv \sqrt{S_f} I_{i,f} A_{i,f}$$

where $S_f$ is the spectroscopic factor of the bound state, $A_{i,f}$ a geometrical factor containing only angular momentum coupling constants and $I_{i,f}$ is the radial part of the overlap between the initial and final state. Now, if the initial state only consists of $p$-wave neutrons in the continuum, its wave function is simply given by

$$\Psi_{lm}(r) \equiv w_{l}(r) Y_{l,m}(\theta, \phi)$$

with $w_{l=1}(r) \propto j_1(k_n r)$ ($j_1$ is a spherical Bessel function). The DRC cross section is proportional to the square of the overlap integral

$$I_{i,f} \equiv \int_0^\infty u_{l_f}(r) r w_{l_i}(r) dr$$

and is, therefore, nothing but a Fourier-Bessel transformation of the bound state radial wave function $u_{l=0}(r)$. A measure of the capture cross section (or of the Coulomb dissociation cross section) is a measure of the wave function in the Fourier space. Then, the low energy part of the capture cross section plot corresponds to large values of the radial coordinate which is influenced by the halo configuration.

Finally, the fluctuations in the measured values at $E_x \approx 2$ MeV, though still masked by a large experimental uncertainty, may contain information on a $^{11}\text{Be}$ excited state. In fact, the first state above the neutron emission threshold is at $E_x = 1.778$ MeV (corresponding to $E_{cm} = 1.273$ MeV) [6] and has $J^\pi = 3/2^+$ or $J^\pi = 5/2^+$. It can be populated by electric quadrupole excitation with the emission of $d$-wave neutrons. Should the experimental uncertainty be reduced to the level of the low energy part, the structure of this $^{11}\text{Be}$ excited state could be deduced.

3 Conclusion

We have shown that the halo structure of light neutron-rich nuclei can be investigated in the frame of a simple DRC model. We have shown this in the particular case in which the cross section was not obtained in a direct measurement but derived from an experiment in the inverse kinematics. This technique can be very useful to study “exotic” nuclear structure properties.
Figure 5: Neutron capture cross section of $^{10}\text{Be}$ as a function of the center of mass energy. The experimental values are deduced, as described in the text, from a Coulomb dissociation experiment [7]. The large uncertainty on the experimental values at high energy is amplified by the rapid decrease of the B(E1) strength distribution with increasing excitation energy.

In addition, it can be utilized to obtain neutron capture cross sections for unstable nuclei where direct measurements are not possible. This possibility is particularly important for applications in nuclear astrophysics [12] where neutron capture reaction rates are needed to investigate primordial (big-bang) as well as stellar nucleosynthesis.

Acknowledgments

We thank Y. Nagai, T. Shima and N. Fukunishi for many useful discussions that greatly helped to generate the present contribution. This work has been supported by the Japan Science and Technology Agency through the STA fellowship program (ID 194102).

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