ELECTROMAGNETIC TRANSITIONS IN HALO NUCLEI

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1 Introduction

Exotic nuclear structure properties such as neutron halo and neutron skin have been recently revealed by experiments carried out using radioactive ion beams. These exotic properties can be studied in the measurement of interaction cross sections at high energies (of the order of several hundreds of MeV/nucleon), nucleon inelastic scattering, transfer and break-up reactions.

An alternative way of looking at exotic structures is to investigate nuclear electromagnetic excitations and/or decays. In particular, one can measure the Coulomb excitation and/or Coulomb dissociation cross sections to investigate the exotic nuclear structure properties expected in nuclei far from stability.

The basic idea underlying Coulomb dissociation experiments is to measure the ejectiles of a binary break-up process generated by the Coulomb field of a (usually high Z) target. Together with the development and availability of radioactive ion beams, this method is becoming a key technique for investigating nuclear structure properties of nuclei far from stability, with the possibility of immediate applications to nuclear astrophysics.

In fact, the time-reversal invariance of nuclear reactions makes it possible to relate the Coulomb dissociation cross section to capture reaction process [1]. This technique may be particularly useful to study the wide nuclear reaction networks required in primordial as well as in stellar nucleosynthesis modeling. For example [2], in the inhomogeneous big-bang scenario there are several capture reaction rates involving radioactive targets. The synthesis of elements beyond ^{7}Li may proceed through the sequence

$$^{7}\mathrm{Li}(n,\gamma)^{8}\mathrm{Li}(\alpha,n)^{11}\mathrm{B}(n,\gamma)^{12}\mathrm{B}(\beta^-\nu)^{12}\mathrm{C}(n,\gamma)^{13}\mathrm{C}(n,\gamma)^{14}\mathrm{C}(n,\gamma)^{15}\mathrm{C}... \quad (1)$$

with the possible variant

$$^{8}\mathrm{Li}(n,\gamma)^{9}\mathrm{Li}(\beta^-\nu)^{9}\mathrm{Be}(n,\gamma)^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}(\beta^-\nu)^{11}\mathrm{B}(n,\gamma)... \quad (2)$$

A direct measurement of the capture cross section for reactions like $^{14}\mathrm{C}(n,\gamma)^{15}\mathrm{C}$ or $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$ is very difficult, if not impossible. To overcome this difficulty the

Coulomb dissociation of the time-reversal reaction can be used to derive the reaction rates involved in networks such as those shown above.

2 Coulomb dissociation and radiative capture

We will specialize here only on break-up and capture mechanisms generated by the electric dipole (E1) component of the electromagnetic field. Under defined kinematic conditions, the $B(E1)$ strength distribution for the dissociation of the incident $^{A+1}$X nucleus into, say, ^{A}X+n is measured. The $B(E1)$ strength distribution is related to the matrix elements $Q^{(E1)}_{b\to c} =< \Psi_c|\hat{T}^{E1}|\Psi_b >$ for a transition starting from a bound state Ψ_b (usually the ground state of the projectile) to the two-body continuum Ψ_c by [3]

$$\frac{dB(E1)}{dE_x} = \frac{k_n^2}{\pi^2 \hbar v}\ \bar{e}^2\ \frac{2J_c+1}{2J_b+1}\ |Q^{(E1)}_{b\to c}|^2. \tag{3}$$

Here, $\hat{T}^{E1}$ is the electromagnetic dipole operator, E_x is the excitation energy (defined as the sum of the neutron-residual nucleus relative energy plus the neutron binding energy), k_n and v are the neutron wave number in the continuum and the relative velocity respectively, J_b is the total angular momentum of the bound state, J_c the spin of the residual nucleus in the continuum and $\bar{e}$ the neutron effective charge.

A first noticeable application of this method has been the measurement of the Coulomb dissociation of ^{11}Be [4]. This is a very well known example of halo nucleus. In fact, its ground state is bound by only 505 keV and is dominated by the $|^{10}\mathrm{Be}(0^+)\otimes(2s_{1/2})_\nu >$ configuration. The $dB(E1)/dE_x$ strength distribution can be well reproduced [4] by a calculation made using the two-body continuum $< \psi_\nu^{l=1}\otimes {}^{10}\mathrm{Be}(0^+)\ |$, where $\psi_\nu^{l=1}$ represents the p-wave component of the wave function for the neutron scattering off ^{10}Be. A detailed description of the methods and parameters used in the calculation can be found in the reference [5]. The result of this analysis [5, 3] fully supports the direct break-up description of the Coulomb dissociation experiment.

The $B(E1)$ strength distribution can be immediately related to the neutron capture cross section for the time-reversal transition by

$$\sigma_{n,\gamma}(E_{rel}) = \frac{16\pi^3}{9}\ \frac{k_\gamma^3}{k_n^2}\ \frac{2J_b+1}{2J_c+1}\ \frac{dB(E1)}{dE_x} \tag{4}$$

where $k_\gamma = \epsilon_\gamma/\hbar c$ the emitted γ-ray wave number. A model for the capture process which is altogether equivalent to the direct break-up process just described has been known since quite a long time and has been referred to as direct radiative capture mechanism (DRC) [6].

	$N_A\langle\sigma v\rangle$ [cm^3/mole-sec]
^{10}Be(n,γ)	$76.7 + 2900T_9 + 5.54\times10^5\ T_9^{-3/2}\ exp[-13.427/T_9]$
^{14}C(n,γ)	$3912T_9 + 2.0\times10^3\ T_9^{-3/2}\ exp[-21.14/T_9]$

The reaction rate can be derived from the analysis of the Coulomb dissociation experiment [4], supported by our theoretical estimates. The result is given in the table. There, the term independent of T_9 comes from the $s\to p$ transitions. The term linear in T_9 is due to the p-wave neutron capture and the last term is a resonance term. A discussion on this result can be found in the reference [5, 7]. The result for $n+{}^{14}\mathrm{C}(n,\gamma)$ is still ambiguous in the sense that the only experimental value available[8] is a factor of 5 smaller than the present result which, in turn, agrees with a previous theoretical calculation[9]. The disagreement with the experimental value remains to be explained. We would like to stress here, however, that our DRC calculations are based on experimental information on the structure of the two bound states in ${}^{15}\mathrm{C}$. A direct experiment at FzK-Karlsruhe as well as a Coulomb dissociation experiment in RIKEN-RIPS are planned and this discrepancy is going to be clarified within a short time.

3 Conclusion

Our DRC model yields a reaction rate for the ${}^{10}\mathrm{Be}(n,\gamma){}^{11}\mathrm{Be}$ process which is up to a factor of 10 higher than value previously known [10], for temperatures $T_9 > 0.2$. Our calculation takes into account the halo structure of the final state in the capture reaction. The calculated rate of the ${}^{14}\mathrm{C}(n,\gamma){}^{15}\mathrm{C}$ reaction is sensibly larger than the present experimental value. Given the result of the present investigation we can conclude that exotic nuclear structure properties such as the neutron halo are expected to play an important role in further calculations of capture reaction rates for primordial as well as for stellar nucleosynthesis.

References

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