Leading order calculations in the Coulomb breakup of halo nuclei

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Introduction

Away from the β-stability valley, towards the drip line region, one finds nuclei having properties strikingly different from stable ones, such as halo nuclei [1]. Their ground states are often characterized by weak binding energy and low angular momentum content. While many of them have been identified in the low mass region, recently there are indications that they may be found even in the medium mass region eg. ^{31}Ne, ^{34}Na and ^{37}Mg.

Breakup reactions have been the preferred method while studying these nuclei. In fact, the Coulomb dissociation of these nuclei in the field of a heavy target have been performed at various experimental facilites like RIKEN, GSI, GANIL and MSU.

From the point of view of nuclear astrophysics too, these studies assume importance as the Coulomb dissociation method can be used as an indirect tool to calculate photodisintegration and radiative capture cross sections [2].

In this contribution, we investigate the breakup reaction ^{11}Be+^{208}Pb $\rightarrow n+^{10}$Be+^{208} Pb with two methods: first a fully quantum mechanical all order theory using pure Coulomb wave functions and the post form finite range distorted wave Born approximation, the so called Coulomb wave Born approximation (CWBA) and the second a first order approximation of CWBA using momentum space Coulomb wave functions.

The CWBA, which owes alleigence to the post form reaction theory includes the electromagnetic interaction between the fragments and the target nucleus to all orders and the breakup contributions from the entire nonresonant continuum corresponding to all the multipoles and the relative orbital angular momenta between the fragments are accounted for. Because the only input to the theory is the ground-state wave function of the projectile, of any orbital angular momentum configuration, the method is free from the uncertainties associated with the multipole strength distributions occurring in many other formalisms which require the exact positions and widths of the continuum states.

The momentum space or Fourier transformation method on the other hand is relatively simpler and requires less computational time when compared with the all order CWBA theory. The upshot of the method is that it can be extended to the case of proton halo, which in turn opens up the opportunity to use the Coulomb dissociation as an indirect method to estimate charged particle radiative capture reactions in astrophysics.

Formalism

Consider the elastic breakup reaction $a + t \rightarrow b + c + t$, where the projectile a breaks up into its sub-structures b and c in the field of the target t. The triple differential cross section for the breakup reaction is given by :

$$\frac{d^3\sigma}{dE_b d\Omega_b d\Omega_c} = \frac{2\pi}{\hbar v_a}\rho(E_b, \Omega_b, \Omega_n)\sum_{lm}|\beta_{lm}^{CWBA}|^2 \quad (1)$$

where, $\rho(E_b, \Omega_b, \Omega_n)$ is three-body phase space factor [3], v_a is velocity of projectile 'a '. The reduced amplitude of the reaction (for the particular case of c being an uncharged particle) is [4, 5]:

$$\beta_{lm}^{CWBA} = Z_{lm}\int d\vec{r}_i \chi_b^{(-)*}(\vec{k}_b, \vec{r}_i)e^{-i\vec{k}_c\cdot\vec{r}_i}\chi_a^{(+)}(\vec{k}_a, \vec{r}_i) \quad (2)$$

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where, Z_{lm} contains the structue part and other integral, containing the distorted waves, is called the dynamics part, say D. On substituting the Coulomb distorted waves in eq.(2) and then substituting in eq.(1), we get

$$\frac{d^3\sigma}{dE_b d\Omega_b d\Omega_c} = \frac{32\pi^4}{\hbar v_a}\rho(E_b, \Omega_b, \Omega_c) \times \frac{\eta_a \eta_b}{(e^{2\pi\eta_a}-1)(e^{2\pi\eta_b}-1)} |I|^2 \sum_l |Z'_l|^2 \quad (3)$$

where, I is the Bremsstrahlung integral [5].

On the other hand, if we substitute momentum space wave functions corresponding to the Coulomb distorted waves in eq.(2), and consider only first order terms in α (fine structure constant), we get for the dynamics part to be:

$$D \approx \frac{8\pi c m_a \alpha \hbar^2 Z_t Z_b}{(\vec{k}_a - \vec{k}_b - \vec{k}_c)^2} \times \left[\frac{1}{[\vec{k}_a^2 - (\vec{k}_c + \vec{k}_b)^2]} + \frac{m_b}{m_a} \frac{1}{[\vec{k}_b^2 - (\vec{k}_c - \vec{k}_a)^2]} \right] \quad (4)$$

Then, the triple-differential cross-section becomes:

$$\frac{d^3\sigma}{dE_b d\Omega_b d\Omega_c} = \frac{8\pi^2}{\hbar v_a}\rho(E_b, \Omega_b, \Omega_c)\ |D|^2 \sum_l |Z'_l|^2 \quad (5)$$

which is considerably easier to evalute than eq.(3).

Results and discussions

The ground state of ^{11}Be is considered to be a $2s_{1/2}$ valence neutron coupled to the ^{10}Be(0^+) core with a binding energy of 504 keV. The interaction between the valence neutron - ^{10}Be is taken as Woods-Saxon type, whose depth is adjusted to reproduce the binding energy.

From preliminary calculations, shown in fig. 1, we see that for lower beam energies the all order theory and first-order results from the Fourier transform method differ from each other. They are nearly same for beam energies $\geq$ 70 MeV/nucleon. It is also easy to detect that post acceleration effects are clearly visible at low energies for the all order theory and is entirely absent in the first order theory. Hence, the higher order effects are minimal for ^{11}Be for beam energies $\geq$ 70 MeV/nucleon. This is similar to the results obtained in [4].

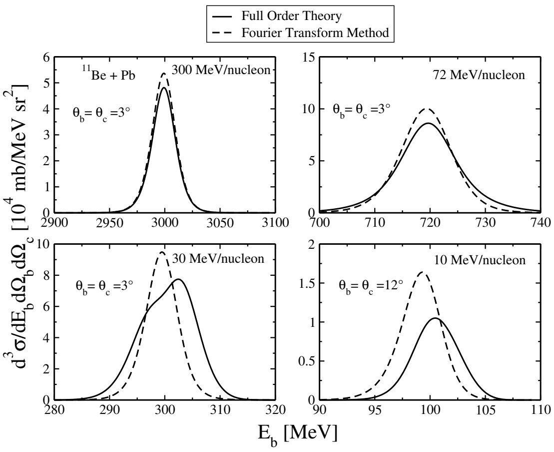

FIG. 1: Triple-differential cross section as a function of the energy of ^{10}Be core for the reaction $^{11}\text{Be}+^{208}\text{Pb} \rightarrow n+^{10}\text{Be}+^{208}\text{Pb}$ at beam energies between 10-300 MeV/nucleon. The resluts of full order CWBA and Fourier transformation theory are shown as solid and dotted lines, respectively.

Further calculations for the double differential cross sections and the relative energy spectra will be presented. We shall also give a brief overview of our extension of the Fourier transformation method to the case of one proton halo nuclei. This will open up the possibilty to semi analytically calculate charged particle capture reactions using Coulomb dissociation as an indirect method in astrophysics.

References

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