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^{7}Be breakup on heavy and light targets

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We present all-order quantum mechanical calculations of ^{7}Be breakup on heavy (^{208}Pb) and light (^{12}C) targets. We examine the issues concerning the extraction of the astrophysical S-factor $S_{34}(0)$ from the breakup data. We discuss the peripherality of the breakup reactions and the interplay between Coulomb and nuclear breakup.

1. Introduction

At present, the capture rate ^{3}He(α,γ)^{7}Be is now more uncertain than ^{7}Be(p,γ)^{8}B, both belonging to the pp chain and with connections to the solar neutrinos [1]. Also, the ^{3}He(α,γ)^{7}Be reaction is the only important production channel for ^{7}Li in big-bang nucleosynthesis [2]. Reference [1] recommends a value of $S_{34}(0) = 0.53 \pm 0.05$ keV b. At the low energies of astrophysical relevance, capture rates are exceptionally hard to measure directly and thus rely on extrapolations. Recent theoretical studies claim that the extrapolation of $S_{34}(0)$ can be significantly more uncertain [3] than the one quoted above.

Consequently, measurements with alternative methods have been considered. There are two main methods in use: i) the Coulomb dissociation method proposes the measurement of radiative capture rates from breakup data on heavy targets [4], ii) the asymptotic normalization coefficient (ANC) method proposes the measurement of the capture rate from transfer reactions or breakup reactions [5].

The uncertainties on the direct capture measurements for the ^{3}He(α,γ)^{7}Be reaction have motivated two breakup experiments: one at the NSCL, measures the ^{7}Be breakup on ^{208}Pb at 100 MeV/nucleon, and the other, at the Cyclotron Lab at Texas A & M, will use a ^{7}Be 25 MeV/nucleon beam on a ^{12}C target.

The cross sections for measuring the breakup of $A \to c + x$ via the Coulomb field of a heavy target T are much larger than the low energy direct capture cross sections. From the Coulomb dissociation data involving low relative breakup energies between the $c + x$ fragments, one can extract the inverse reaction $c + x \to A$ at astrophysical energies [4,6]. There are three main breakup mechanisms which can complicate this relation: i) nuclear breakup, present whenever the projectile gets close to the target, ii) E2 transitions, may be negligible in radiative capture, but are typically significant in Coulomb dissociation [7],

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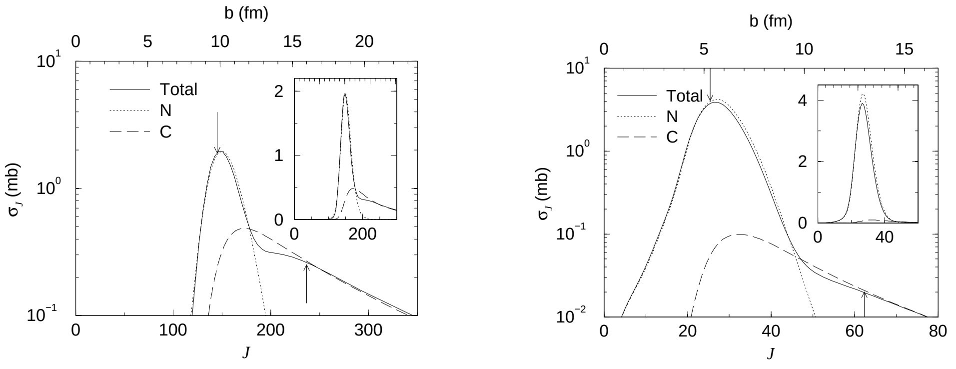

Figure 1. J-distribution of the cross section for the ^{208}Pb (left) and ^{12}C (right) target. The total breakup cross section is shown by the solid line while the broken lines give the nuclear (dotted) and Coulomb (dashed) contributions. The top scale relates the angular momentum to the impact parameter via the semi-classical relation $J = Kb$. The insert is the same plot on a linear scale. The arrows are discussed in the text.

iii) final state interactions (continuum-continuum (CC) couplings) that distort the final energy spectrum of the emitted fragments [8]. All of these entangle the information on the capture reaction.

The ANC method requires a peripheral collision, which can be modeled with a first-order distorted wave Born approximation (DWBA) theory. Therefore the contribution to the breakup from the interior and the effect of higher-order couplings have to examined.

In this paper we present fully-quantum mechanical calculations, in the CDCC framework using the coupled-channels code FRESCO [10], of ^{7}Be breakup on ^{208}Pb and ^{12}C targets at energies of 100 and 25 MeV/nucleon respectively [11]. We examine these various issues for the particular case of the ^{7}Be breakup, making use of the continuum discretized coupled channels (CDCC) method, reviewed in Ref. [9]. Within CDCC, nuclear and Coulomb are consistently included and the contribution from CC couplings can be explicitly explored.

2. Results

In Fig. 1 we show the J-distribution of the breakup cross section for the ^{208}Pb (left) and ^{12}C (right) target. The impact parameters that correspond to each partial wave, using the semi-classical relation $J = Kb$, are shown across the top scale. The total breakup cross section (solid line) is shown along with the nuclear breakup (dotted) and Coulomb breakup (dashed). The sum of the radii for the projectile and target is marked on the figures by the down-pointing arrow.

To extract the ANC from which $S_{34}(0)$ can be determined, breakup data from a range of targets can be used. The fundamental requirement is peripherality. A simple sum of radii would imply that there should be no contribution to the breakup from impact

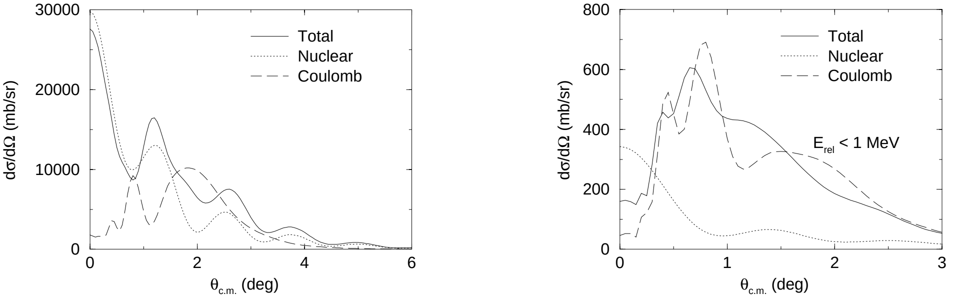

Figure 2. Left: Angular distribution of cross sections for ^{7}Be elastic breakup on ^{208}Pb at 100 MeV/nucleon. The CDCC (solid) calculation is broken down into nuclear (dotted) and Coulomb (dashed) contributions. Right: Breakup cross section for lowest two energy bins from each j^π set. This gives the relative energy between the α and ^{3}He fragments an upper limit of approximately 1 MeV.

parameters below 9.8 (5.3) fm for the lead (carbon) target. The plots of Fig. 1 suggest that this may not be the case. The breakup cross section for impact parameters below the sum of radii is 28% (16%) of the total breakup cross section for the lead (carbon) target.

In Fig. 1 (left) we see that for the lead target, the nuclear breakup is the dominant process for the lower partial waves and Coulomb breakup dominates the higher partial waves. The impact parameter, beyond which nuclear effects can be considered negligible (up-pointing arrow on figures), is around 16 (13) fm the lead (carbon) target, values much larger than the sum of the projectile and target radii. In the Coulomb dissociation method, data are typically taken at forward angles since then it is assumed to be nuclear free. For pure Rutherford trajectories, there is a relationship between the impact parameter and the scattering angle: for ^{7}Be+^{208}Pb at 100 MeV/nucleon, an impact parameter of 16 fm corresponds to a center-of-mass scattering angle of 2.5°. However, the determination of this cutoff angle is rather simplistic.

We can directly examine the angular distribution of the breakup cross section on the lead target, shown in Fig. 2 (left). The nuclear (dotted) and Coulomb (dashed) contributions to breakup are plotted along with the coherent sum (solid). We see that the nuclear breakup is the dominant process, having a diffractive nature which peaks at zero degrees. Contrary to expectations, we see that the nuclear and Coulomb breakup cannot be separated into angular regions and both have to be considered.

However, the nuclear breakup contribution can be reduced by imposing an upper cut on the relative energy between the α and ^{3}He fragments. To show the effect of this energy cut on the angular distribution we sum up the angular cross section from the lowest two energy bins from each j^π set. This restricts the maximum final state relative energy to approximately 1 MeV (0.846 MeV for all j^π except the $f_{7/2}$ which has a maximum energy of 1.268 MeV). The angular distribution of the breakup cross section with this energy cut is shown in Fig. 2 (right). We now see that Coulomb breakup is dominant.

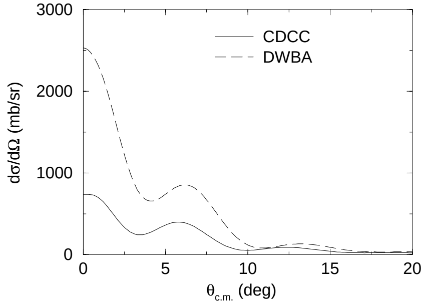

Figure 3. Angular distribution of the cross section for ^{7}Be breakup on ^{12}C at 25 MeV/nucleon. The different calculations of the cross section are: CDCC, which includes all couplings to all orders, and a DWBA calculation which includes only first order couplings from the ground state.

In Fig. 3 we show the importance of higher-order couplings on the breakup cross section for the ^{12}C target. The first-order DWBA calculation dramatically overestimates the cross section. It is important to take into account these higher-order effects to extract astrophysical quantities.

3. Summary

The Coulomb dissociation of ^{7}Be at forward angles does not in itself mean that the cross section is nuclear free, but by imposing an upper limit on the relative energy of the final fragments, the nuclear and quadrupole contributions to the breakup can be significantly reduced. For the extraction of the ANC from these breakup experiments we show that contributions from the interior are significant and require consideration. In addition, higher-order couplings play a significant role, reducing the validity of the first-order relation between the ANC and the S-factor. Careful kinematic cuts may be able to select regions where these conditions can be satisfied.

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