Breakup and core coupling in ^{14}N(^{7}Be,^{8}B)^{13}C

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Several approximations are commonly made when studying transfer reactions with ^{8}B, in particular, those used for extracting astrophysical information. We study the influence of the spin and deformation of the ^{7}Be nucleus on the asymptotic normalization coefficients extracted from the reaction ^{14}N(^{7}Be,^{8}B)^{13}C and find that it has little influence in the value of the extracted astrophysical *S*-factor $S_{17}(0)$. We also discuss the weak continuum effects found for this reaction under the light of new breakup calculations.

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The reaction ^{14}N(^{7}Be,^{8}B)^{13}C at 84 MeV was measured with the aim of extracting an asymptotic normalization coefficient (ANC) for the ^{8}B vertex [1], using the DWBA method. A direct relation between the ANC and the zero energy *S*-factor S_{17} enables the determination of the astrophysical rate of the proton capture on ^{7}Be, within a 10% uncertainty, competitive with the direct capture measurements.

Following that work, two theoretical contributions have looked into specific approximations, corroborating the initial results. In Ref. [2], the effect of inelastic couplings of the target are studied using coupled channels Born approximation (CCBA) and rotational couplings for the target excitations. Due to the spherical nature of ^{14}N, these effects are shown to be unimportant in this reaction. In Ref. [3], the effect of the breakup of ^{8}B is studied using the CDCC-BA formalism (continuum discretized coupled channels Born approximation). It is shown that, even if at large angles the couplings to the continuum of ^{8}B have a strong influence in the elastic process ^{8}B+^{13}C, the transfer cross section ^{14}N(^{7}Be,^{8}B)^{13}C is not affected significantly, specially in the forward angular region where data was taken. In this short contribution we address further aspects related to the transfer reaction, namely, the breakup channel and the spin of the core.

Earlier CDCC studies of the breakup of ^{8}B [4,5], show that couplings from the ground state to the continuum are strong, due to the proximity to threshold of the bound state. In addition, those calculations show a very large effect due to the couplings between continuum states themselves, implying that these couplings, too, are strong. One could then suspect that, in a transfer reaction involving ^{8}B, these continuum couplings could change the features for the angular and/or energy distributions in a way that would not be accounted for by an optical model description. This was the motivation for the work in Ref. [3]. However, the results show that, when including the couplings from the ^{8}B ground state (g.s.) to the continuum, the transfer cross section hardly changes and, moreover, continuum-continuum couplings have no effect on the transfer. The scheme in Fig. 1 represents the various physical processes that may occur: one-step transfer to the g.s., transfer into the continuum of ^{8}B, and inelastic (de)excitation of ^{8}B following the transfer.

We study the breakup channel in more detail, in order to distinguish first-order and higher-order couplings. Our recent work [6] includes calculations for the breakup of ^{8}B on ^{13}C at 78 MeV, corresponding to the exit channel of the transfer reaction under study. Results are presented in Fig. 2. As expected, the magnitude of the breakup to the relevant energy bins is large when compared to the transfer cross section ^{14}N(^{7}Be,^{8}B$_{\rm g.s.}$)^{13}C. Breakup couplings are indeed strong, as seen in other reactions [4,5]. However, by comparing the full breakup CDCC calculation [solid line in Fig. 2(a)] with the truncated calculation where continuum-continuum couplings are switched off [dashed line in Fig. 2(a)], we find that

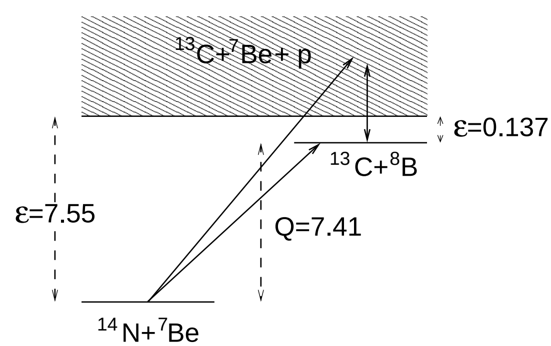

FIG. 1. Schematic illustration for the various processes involving the one proton transfer from ^{14}N to ^{7}Be. The arrows represent the transfer to the ^{8}B ground state, the transfer coupling to the continuum of ^{8}B and the ^{8}B breakup couplings.

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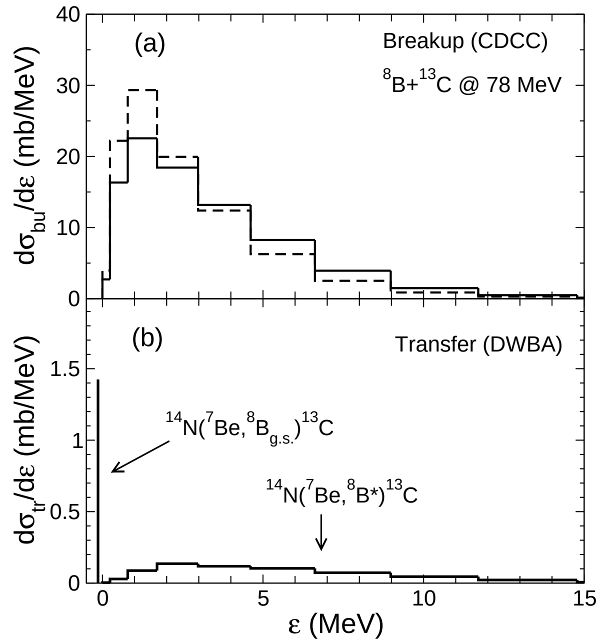

FIG. 2. (a) CDCC breakup cross section for $^{8}B+{}^{13}C$ at 78 MeV: results including continuum-continuum couplings (solid line) and switching them off (dashed line). (b) DWBA cross section for the transfer to the g.s. and the continuum states of ^{8}B at 84 MeV.

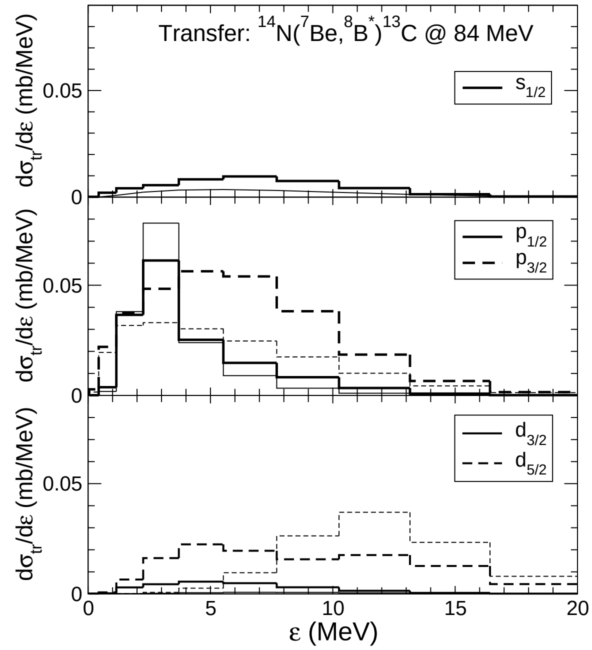

FIG. 3. The partial wave decomposition of the one proton transfer from ^{14}N into the ^{8}B continuum: the energy distribution for the one-step DWBA calculation (thin lines) and the energy distribution for the full CDCC-BA calculation (thick lines).

continuum-continuum couplings do not change the magnitude of the cross section but rather redistribute the flux within the continuum. This is verified by the numerical values of the total breakup cross sections: calculations with and without continuum-continuum couplings produce $\sigma_{bu}=125$ mb and $\sigma_{bu}=123$ mb, respectively.

Next, we compare the transfer $^{14}N(^{7}Be,^{8}B)^{13}C$ to the g.s. of ^{8}B with that into its continuum $^{14}N(^{7}Be,^{8}B^{*})^{13}C$. Note that both the above mentioned processes are first order, and, by summing all the bin contributions for the transfer into the continuum of ^{8}B, one obtains a total cross section $\sigma_{tr}^{cont}=1.2$ mb, of the same order as the g.s.-transfer cross section $\sigma_{tr}^{g.s.}=1.4$ mb. Results are presented in Fig. 2(b) where the g.s.-transfer transition, represented by the discrete line is given in mb, and the energy distribution cross section for the transfer to the continuum is given in mb/MeV.

When studying the influence of ^{8}B breakup in the transfer to the ground state, the continuum path is a second-order process, or higher, and for this reason typically suppressed. It could still have an effect if, in compensation, couplings involved were stronger than the g.s.-transfer coupling. Yet, even if the inelastic couplings between ground state and continuum of ^{8}B are very strong, the continuum-transfer couplings are comparable to the g.s.-transfer coupling. Consequently, we find the small effect of breakup in $^{14}N(^{7}Be,^{8}B_{g.s.})^{13}C$.

The partial wave decomposition of the cross section for transferring the proton into the continuum of ^{8}B, as a function of the p-^{7}Be relative energy, is shown in Fig. 3: thin lines are for one step cross sections, where the proton is transferred directly into a specific angular momentum bin in the continuum, and thick lines are for the full CDCC-BA calculation, where the proton is allowed to jump between the g.s. of ^{8}B and the various continuum bins, in a multistep path. Calculations were performed using the same optical potentials and binding potentials as those in Ref. [3]. Furthermore, the p-^{7}Be continuum is discretized using, for each partial wave, 10 bins of equal momentum width, such that the minimum p-^{7}Be energy is $E_{min}=0.01$ MeV and the maximum energy is $E_{max}=20$ MeV. In order to make the calculations feasible, we did not include f waves. In fact, f waves are only necessary for precise quantitative results, and will not change the conclusions from this discussion. In Fig. 3, the p-wave contribution evidently dominates over the s- and the d-wave cross sections. When comparing DWBA and CDCC-BA results, one realizes that continuum couplings do affect the transfer differential cross section. Generally the continuum produces a slight enhancement of the cross section and changes the shape of the energy distributions. Nevertheless, these effects are insignificant when compared with the dominant channel, the transfer to the ground state.

The CDCC formalism [7] spans the continuum space by taking a finite set of continuum bins. This space is truncated by the maximum radius for the integration of the continuum bins, the maximum number of the partial waves for the p-^{7}Be relative motion, the maximum p-^{7}Be relative energy and the width considered for each bin. Generally, in order to get converged results, CDCC calculations become very large. Therefore, it is common practice to neglect the spin of ^{7}Be in CDCC calculations for reactions involving ^{8}B, with the aim of reducing the number of channels that need to be coupled [3–5,8]. Then, the ^{8}B ground state, for instance, is represented by $[p_{3/2}\otimes 0^{+}]_{3/2^{-}}$ instead of $[p_{3/2}\otimes 3/2^{-}]_{2^{+}}$.

For spin-independent interactions, the transfer process is identical whether ^{7}Be is considered spinless or not. As discussed in Ref. [3], one should just take care of statistical factors. When coupling the real spin of ^{7}Be with a $p_{3/2}$ proton, several spins can be obtained for the composite system ^{8}B: 0^+, 1^+, 2^+, and 3^+. All of them are contained in $[p_{3/2} \otimes 0^+]_{3/2^-}$, the representation for ^{8}B when the ^{7}Be is assumed to be spinless. As the transfer reaction ^{14}N(^{7}Be,^{8}B$_{g.s.}$)^{13}C selects only the g.s. with spin 2^+, the transfer cross section calculated assuming zero spin for ^{7}Be needs to be multiplied by 5/16, representing the relative weight of the 2^+ component. This is included in the results presented in Ref. [3] for a meaningful comparison with the data.

In principle, however, one should consider spin-dependent interactions. ^{7}Be is known to have a large quadrupole moment, and the low lying excited state has a strong $E2$ coupling with the ground state. Both these factors induce additional physics that cannot be investigated when the spin is neglected. Let us then consider the various ^{8}B components of the ground state that should be included when the spin couplings of the ^{7}Be core ($3/2^-$) and its first excited state ($1/2^-$) are correctly taken into account: (a) $[p_{3/2} \otimes 3/2^-]$, (b) $[p_{1/2} \otimes 3/2^-]$, (c) $[p_{3/2} \otimes 1/2^-]$.

We repeat the CDCC-BA calculations of Ref. [3] using the spectroscopic amplitudes taken from Ref. [9]: 0.9884 for (a), -0.2364 for (b), and 0.4303 for (c). In Fig. 4, we present the full transfer differential cross section obtained: the dotted curve corresponds to taking only the first component (a), the dashed curve also includes the $p_{1/2}$ component (a)+(b), and the solid curve is the result obtained when the excited component $1/2^-$ of the core is included, yet not coupled to the core ground state. Finally, the dots are the results when introducing the reorientation and excitation couplings. We take an approximate value of $\beta_2 = 0.5$ and use the rotational model to calculate these couplings. We do not introduce deformation in the continuum bins.

In conformity with other calculations [1], we obtain a small $p_{1/2}$ cross section, such that the effect on the total transfer cross section is a slight enhancement, mostly visible at very forward angles. The effect of core excitation is also modest, having its maximum value of 2% around the peak of the distribution. The dynamical effects of core deformation are hardly noticeable, as can be verified in Fig. 4. These various effects are below the precision of the data [1].

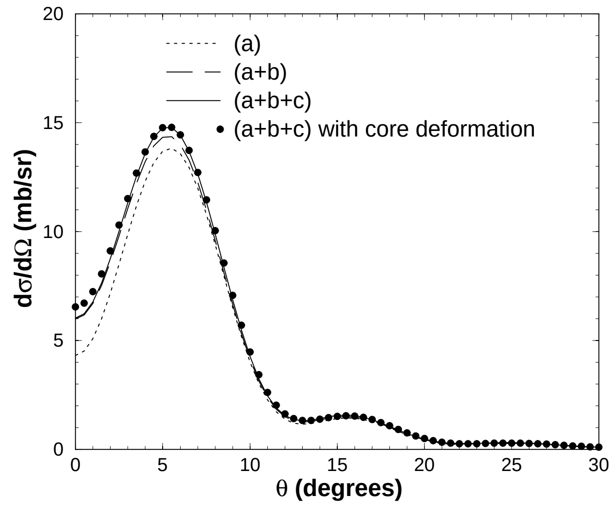

FIG. 4. The differential cross section for the ^{14}N(^{7}Be,^{8}B)^{13}C reaction: the dashed line includes only the $p_{3/2}$ proton coupled to the g.s. of the core, the long-dashed line contains also the $p_{1/2}$ component and the solid line contains the core excitation component (c) as well. The dots correspond to the same calculation (a)+(b)+(c) but introducing core deformation.

In conclusion, we understand the negligible effect of the breakup of ^{8}B in the transfer ^{14}N(^{7}Be,^{8}B)^{13}C as due to the superposition of two facts: (i) breakup only enters through second-order processes, or higher; (ii) there is a larger Q-value mismatch than for direct transfer, resulting in a continuum-transfer coupling slightly smaller although comparable to the g.s.-transfer one. We also prove that, in this case, core spin, core excitation, and core deformation have a minor effect in the transfer process. Given the $\approx 10\%$ error bars existent in the data [1], these core effects do not introduce additional uncertainties in the extracted ANC.

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