Sensitivity of $^8$B breakup cross section to projectile structure in CDCC calculations

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Given the Astrophysical interest of $^7$Be($p, \gamma$)$^8$B, there have been several experiments applying the Coulomb dissociation method for extracting the capture rate. Measurements at Michigan State were dominated by $E1$ contributions but have a small $E2$ component. On the other hand, a lower energy measurement at Notre Dame has a much stronger $E2$ contribution. The expectation was that the two measurements would tie down the $E2$ and thus allow for an accurate extraction of the $E1$ relevant for the capture process. The aim of this brief report is to show that the $E2$ factor in breakup reactions does not translate into a scaling of the $E2$ contribution in the corresponding capture reaction. We show that changes to the $^8$B single particle parameters, which are directly related to the $E2$ component in the capture reaction, do not effect the corresponding breakup reactions, using the present reaction theory.

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Breakup reactions are one of the best probes to study nuclei on the dripline. The loosely bound nature of the nuclear systems imply that the continuum plays a very important role in the reaction mechanism. In the past few years, the Continuum Discretized Coupled Channel method [1] has been successfully applied to exotic nuclei. This method is fully quantum mechanical and is non-perturbative: it includes the couplings to breakup states to all orders. The projectile is treated as a perturbative: it includes the couplings to breakup states. In order to have the same interaction in all partial waves in both bound and scattering states, in order to be able to treat continuum-continuum couplings, the scattering states are bunched into energy bins. Apart from the core + target interaction, the CDCC method also requires the optical potentials for core + target and $N + target$ which are typically well known.

One of the first applications of CDCC to dripline nuclei involved the description of the breakup of $^8$B on $^{58}$Ni at $E_{beam} = 26.5$ MeV [2]. The corresponding experiment was performed at Notre Dame [3]. The calculations in [2] involved no fitting. The potential model for $^8$B+$^7$Be+p was taken from [4]. It assumes that, in the ground state, the valence proton in $^8$B is a single particle $1p_{3/2}$ coupled to the ground state of the $^7$Be core. Note that a simplified version of the interaction from [4] was used in order to have the same interaction in all partial waves in the continuum as the interaction for the ground state. In [2], three body observables are calculated and integrated to enable a direct comparison to the experimental data. The optical potentials for $p, ^{58}$Ni and $^7$Be,$^{58}$Ni are the same as those in [2, 3]. The agreement for the angular and energy distributions of the heavy fragment was extremely good.

The experiment [3] measured only the heavy fragment $^7$Be which means that the data contains both breakup (which is also referred to as diffraction) and stripping. However it was shown [6] that stripping only contributes for larger angles. The CDCC calculations performed make predictions for breakup only. Therefore our discussion will focus on the smaller angles only.

Another experiment at MSU measured the breakup of $^8$B on Au and Pb at 40-80 MeV/A [7, 8]. Amongst other observables, detailed momentum distributions for $^7$Be were extracted. CDCC calculations for these data were performed in [9]. Starting with the same $^7$Be+p interaction as in [2], results show that good agreement with the data for the various angular sets and both targets can only be obtained if the quadrupole excitation couplings are artificially increased by a factor of 1.6.

In this brief report we wish to highlight the differences between the quadrupole strength of higher-order reaction theory and the $E2$ capture strength of the astrophysically relevant inverse reaction. We will examine how the 1.6 factor from Ref. [9] translates into the $E2$ component of $^7$Be($p, \gamma$)$^8$B. For this purpose, we have repeated the calculations for both breakup reactions with a modified $^7$Be+p interaction. We show that this interaction, chosen to have a drastic effect on the $E2$ capture cross section, has a minimal effect on both breakup reactions. In addition, we discuss the implications of the findings in [9] for the Notre Dame experiment, and show that the results of both experiments cannot be consistently described within the same CDCC single particle model used until now.

It is important to clarify the difference between the quadrupole strength used in breakup reactions and the $E2$ strength of the astrophysically relevant capture. In perturbation theory, the link is direct, but in a fully quantum mechanical description of the scattering, this relationship is not so transparent. In CDCC, the excitation operator for the breakup reaction is the coupling potential for the sum of the core-target and proton-target

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interactions, expanded in multipoles,

\[ V(R, r) = \sum_K (2K + 1)V^K(R, r)P_K(r \cdot R), \]  

where \( P_K \) are the Legendre polynomials. These multipoles are then averaged over each bin state, generated by a single particle model for \(^7\)Be,

\[ V^K_{\alpha'\alpha}(R) = \langle \phi_{\alpha'}(r)|V^K(R, r)|\phi_\alpha(r) \rangle \]  

Different optical potentials for the fragments and the target, as well as different \(^p\)\(^7\)Be wave functions, modify these couplings. The quadrupole strength in CDCC is the strength of these couplings, which include both nuclear and Coulomb contributions, and can have multistep effects. Any modification to the \(^8\)B single particle parameters will effect the breakup cross section through these couplings. The inclusion of multistep and nuclear effects complicates the link between the magnitude of the couplings and the cross section. In contrast, the \(E2\) operator in capture reactions comes from the expansion of the electromagnetic field and is very well understood \(^4\). The cross section is obtained directly from the \(E2\) operator. Differences in \(E2\) components for the capture reaction translate directly into differences in the \(^p\)\(^7\)Be interaction \(^1\). 

First we consider the effect of the \(^8\)B single particle parameters. Given that in \(^2\) simplifications were made to the \(^p\)\(^7\)Be interaction in the continuum, we have explored the dependence of the breakup observables on this final state interaction. A slight modification of the strength of the \(p\)-wave is needed to reproduce the correct \(1^+\) resonance. Even though this resonance dominates the direct capture cross section, it has been shown to produce no effect on the Coulomb Dissociation cross sections \(^10\). Several modifications to the interaction generating the scattering waves that can be reached through \(E2\) (\(p\)- and \(f\)-waves) were explored (using the methods of Ref. \(^11\)).

The strongest modification of the \(E2\) capture cross section was obtained when \(p\)- and \(f\)-waves are generated by a potential half as deep as the ground state potential (Fig. \(^1\)). This is completely unphysical for the breakup reaction in two ways: the resonance structure that is known is not reproduced and the ground state becomes non-orthogonal to the \(p\)-wave continuum states. We only perform these calculations, in this extreme case, to highlight the differences between the quadrupole couplings in breakup and the \(E2\) capture cross section. In Fig. \(^4\) we show the results for the \(E2\) component of capture cross section for \(^7\)Be\((p, \gamma)^8\)B: the solid line refers to the structure model where the depth is the same for bound and continuum states (as in \(^2\)) and the dashed line where the potential depth in \(p\)- and \(f\)-wave scattering states is reduced to one half of its original value.

We now apply this modified \(^8\)B interaction to the MSU breakup data. We reproduce the calculations of Ref. \(^9\), using the code FRESCO \(^12\), within the same model space for the CDCC calculations, keeping the same optical potentials, and the same single particle parameters for the \(s\)- and \(d\)-waves, but with our modified interaction for the bound state, \(p\)- and \(f\)-waves in the continuum. We chose the Pb target as an example and performed the calculations at both 44 MeV/A (Fig. \(^2\)) and 81 MeV/A (Fig. \(^3\)). The solid line corresponds to previous calculations with no artificial factors on the quadrupole strength; the dot-dashed line corresponds to the results of solving the CDCC equations with a quadrupole excitation multiplied by 1.6 and the dashed line is the result when the interaction for the \(p\)- and \(f\)-waves of the \(^p\)\(^7\)Be system is reduced to one half without the additional 1.6 normalization (dot-dashed line) and the result using 0.5*V(\(^p\)\(^7\)Be) for the final state (dashed line).
The energy distribution at $\theta_{\text{lab}}(^7\text{Be})=20^\circ$ is displayed in Fig. 5 and the angular distribution is presented in Fig. 6. We reproduce the calculations from [5], but with our modified $^8\text{B}$ single particle model for p- and f-waves (dashed line). The data is taken from [3]. In both figures the solid line represents the calculations of Ref. [5], where no scaling of the quadrupole strength was introduced. As with the MSU data, the modified $^8\text{B}$ single particle potential, which produced a large modification to the $E2$ capture strength, has a negligible effect on the breakup cross section within the CDCC reaction model.

Given that quadrupole excitations have a larger contribution in the lower energy reactions, the obvious question arising from the work [9] is whether the error bars capture is mostly different for the higher excitation energies, one might expect the 44 MeV/A and 81 MeV/A reaction to be sensitive to this change even though the $E2/E1$ cross section ratio decreases with beam energy. However, data was only taken at forward angles, which effectively imposes small relative energies. With the angular truncation of $\theta_{\text{max}} = 1.5^\circ$ there is virtually no effect due to the change of the $p$-$^7\text{Be}$ scattering potential (Figs. 2 and 3) and a small effect can be seen when angles up to $\theta_{\text{max}} = 3.5^\circ$ are considered (Fig. 4).

Albeit the large modification on the $E2$ capture cross sections, the modification of the interaction has an insignificant effect on the breakup reaction observable here. This clearly shows the difference between quadrupole strength in higher order reaction theory and the $E2$ capture strength.

Now let us consider the Notre Dame experiment.
in the Notre Dame data could allow for this rather large increased quadrupole strength. Note that in this low energy regime, Coulomb-nuclear and E1-E2 interference are very strong and it is not clear how a larger quadrupole excitation would affect the predictions.

We reproduce the calculations from [6] within the same model space, keeping the same optical potentials, and the single particle parameters for $^8$B [4] but multiplying the generated quadrupole strength by the factor of 1.6 as suggested by $^6$Be. We compare it with the previous results, where no artificial increase is imposed. The coupled channel code Fresco [12] was used. The resulting energy distributions are presented in Fig. 4 and angular distributions in Fig. 5. It is clear from the figures that, by imposing such a large quadrupole term, one no longer can describe the data satisfactorily.

The results at 20$^\circ$ are not completely nuclear free and are certainly influenced by multi-step effects [2]. Therefore the scaling of 1.6 cannot be directly translated into a scaling of the cross section. We have performed E2 only calculations for both the original $^8$B model and the scaled 1.6 model. The ratio of the E2 cross sections at the peak of the energy distribution for 20$^\circ$ is 2.7. The final numbers when E1 and nuclear are included show a 1.7 ratio between the new calculations and the old. This demonstrates the importance of interference and makes a reliable extraction of the E2 strength from a particular set of data less transparent although still possible.

Compared to this strong quadrupole effect, there is a much weaker dependence on the optical potentials. In fact, the results in [6] are very weakly dependent on the $^7$Be-$^58$Ni interaction and depend only slightly on the proton optical potential which is well known (solid and dotted-dashed lines in Fig. 4a of [6]). Consequently, the disagreement would not disappear by readjusting optical potentials. As to possible experimental problems, even if the Notre Dame data suffered from a 50% error in the absolute normalization, which is extremely improbable, the energy distributions would be much broader than the model’s prediction.

Given the series of exploratory calculations performed, we claim that within the present single particle description of $^8$B, a 1.6 factor in the quadrupole breakup couplings cannot be accounted by modifying the E2 component of the $^7$Be($p, \gamma$)$^8$B within a single particle $p-^7$Be picture.

Altogether, these results suggest that there is additional physics not included in the present calculations relevant for the breakup of this nucleus. For example, our breakup model uses a detailed description of the reaction process based on a simplistic description of the structure of the projectile. Although it is standard practice to assume that $^8$B is a single particle proton $p_{3/2}$ built on the ground state of $^7$Be, it is known that it contains a 15% core excited component [13]. It is not understood how this component would dynamically interfere throughout the reaction process. One possibility is that this component affects the MSU data differently, enhancing the quadrupole excitation. At present, dynamical core excitation is not possible within a fully coupled quantum calculation. Future work on an extension of the standard CDCC method is needed.

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[1] Y. Sakuragi, M. Yahiro, and M. Kamimura, Prog. Theor. Phys. Suppl. 89, 136 (1986).
[2] F. M. Nunes and I. J. Thompson, Phys. Rev. C 59, 2652 (1999).
[3] J. J. Kolata et al., Phys. Rev. C 63, 024616 (2001).
[4] H. Esbensen and G. F. Bertsch, Nucl. Phys. A600, 37 (1996).
[5] J. A. Tostevin, F. M. Nunes, and I. J. Thompson, Phys. Rev. C 63, 024617 (2001).
[6] H. Esbensen and G. F. Bertsch, Phys. Rev. C 59, 3240 (1999).
[7] B. Davids et al., Phys. Rev. Lett. 81, 2209 (1998).
[8] B. Davids, Sam M. Austin, D. Bazin, H. Esbensen, B. M. Sherrill, I. J. Thompson, and J. A. Tostevin, Phys. Rev. C 63, 065806 (2001).
[9] J. Mortimer, I. J. Thompson, and J. A. Tostevin, Phys. Rev. C 65, 064619 (2002).
[10] F. M. Nunes, R. Shyam and I. J. Thompson, J. Phys. G 24, 1575 (1998).
[11] F. M. Nunes, R. Crespo and I. J. Thompson, Nucl. Phys. A615, 69 (1997); Nucl. Phys. A634, 527 (1998).
[12] I. J. Thompson, Comput. Phys. Rep. 7, 3 (1988).
[13] D. Cortina-Gil et al., Nucl. Phys. A720, 69 (2003).