Core excitation in the elastic scattering and breakup of $^{11}$Be on protons

N. C. Summers$^{1,2,3}$ and F. M. Nunes$^{3,4}$

$^1$Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996
$^2$Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854
$^3$National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824
$^4$Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824

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The elastic scattering and breakup of $^{11}$Be from a proton target at intermediate energies is studied. We explore the role of core excitation in the reaction mechanism. Comparison with the data suggests that there is still missing physics in the description.

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I. INTRODUCTION

Nuclear reactions offer the most diverse methods to study nuclei at the limit of stability. Understanding reaction mechanisms in nuclear processes involving nuclei near the driplines is of great importance, particularly at this time, when there is such a high demand for accuracy on the structure information to be extracted from the data. Reaction and structure models are undoubtedly devoted to the analysis of experiments within this framework. A large amount of work has been devoted to the analysis of experiments within this framework, for example elastic and inelastic scattering, quasi-elastic scattering and breakup at 64 MeV/nucleon [11] as well as transfer at 35 MeV/nucleon [12].

$^{11}$Be proton elastic scattering at 49.3 MeV/nucleon was performed in GANIL [10], at the same time as the elastic scattering of the core $^{10}$Be at 59.4 MeV/nucleon. Even though the outgoing $^{11}$Be measurements correspond to quasi-elastic, these are essentially elastic as the contribution from the first excited state is negligible. Standard optical potentials (either density folding as in JLM [13] or global optical potentials coming from elastic fits as in CH89 [14]) could reproduce the $^{10}$Be elastic reasonably well, requiring small renormalizations of the real and imaginary parts of the interaction (λ_V = 0.9 and λ_W = 1.1 for CH89) [10]. Larger renormalizations were required in order to reproduce the distribution of $^{11}$Be (λ_V = 0.7 or λ_W = 1.3 for CH89) [10].

It is clear from Ref. [10] that the global optical potential overestimates the elastic cross section for $^{11}$Be. In Ref. [15] the elastic scattering of $^{11}$Be on $^{12}$C was successfully described using a $^{10}$Be+n two-body model, incorporating breakup effects. As the $^{10}$Be-target interaction was fixed by the $^{10}$Be elastic scattering data, the large modification in the $^{11}$Be+$^{12}$C elastic data was described, without renormalization, purely through breakup effects. Due to the loosely bound nature of the last neutron in $^{11}$Be this loss of flux from the elastic channel can be attributed to breakup into $^{10}$Be+n. It is thus possible that the large renormalizations for $^{11}$Be scattering on protons [10] are also due to breakup effects.

In Ref. [11], elastic data is only described after large renormalizations of both the real and imaginary part of the $^{10}$Be+p interaction (λ_V = 0.75 and λ_W = 1.8), much larger than those used in Ref. [10]. These same renormalizations can no longer describe the $^{10}$Be+p elastic data from Ref. [10], and are inconsistent with few-body reaction theory. We will re-examine the elastic scattering of...
\(^{10/11}\)Be+\(^{p}\) to see if one can consistently describe both sets of data using the same interaction for \(^{10}\)Be+\(^{p}\), by including continuum and core excitation.

In addition to elastic and inelastic measurements, breakup data from NSCL exist at 63.7 MeV/nucleon \cite{11}. This breakup data is integrated into two wide energy bins due to statistics. The lower energy bin covers the 1.78 MeV resonance and a reasonable angular distribution is obtained, which underpredicts the cross section \cite{11}. The higher energy bin covers resonances that are thought to be built on excited core states. The calculations presented in Ref. \cite{11} failed to reproduce the shape of this higher energy bin, and the authors suggest that the source of the disagreement may be due to an active core during the reaction. Now that it is possible to include core excitation in the reaction mechanism \cite{3} we will re-examine the breakup data using a consistent \(^{10}\)Be+\(^{p}\) interaction, and including systematically the coupling to the \(^{2}\)\(^{+}\) state in \(^{10}\)Be.

Transfer reactions have also been performed with the \(^{11}\)Be beam, at 35.3 MeV/u in GANIL \cite{12} with the aim of extracting spectroscopic factors for the ground state. While the reaction mechanisms proved to be more complicated than the 1-step DWBA theory, results for (p,d) show evidence for a significant core excited component. The inverse reaction, \(^{10}\)Be(d,p)\(^{11}\)Be, has also been studied in GANIL \cite{13}, the main interest being the resonance structure of \(^{11}\)Be. This illustrates how transfer is being used beyond the standard application of spectroscopy of bound states, underlining the need to better understand the transfer mechanism and its coupling to the continuum.

All these different data offer a good testing ground for theory. A comprehensive theoretical study \cite{17} focusing on \(^{10}\)Be(d,p) show inconsistencies of the extracted spectroscopic factors for data at different energies. Optical potential uncertainties and core excitation effects could be at the heart of the problem.

In this work we perform calculations including elastic, inelastic, and breakup channels of \(^{11}\)Be on protons at intermediate energies. We explore explicitly the effect of the inclusion of core excitation in the reaction mechanism. Comparison to elastic and breakup data will be presented here. The analysis of the inelastic channel is presented in \cite{18} and we leave a detailed study of the transfer channel for a future publication. In section III we provide the details of the calculations. In section IIII we present the results: first for the elastic channel (III A), then for the breakup (III B). Finally, in section IV we draw our conclusions and provide an outlook into the future.

### II. DETAILS OF THE CALCULATIONS

The calculations for breakup of loosely bound systems on protons have a rather different convergence requirement as compared to the breakup on heavier systems.

### Table I: \(^{10}\)Be-proton Woods-Saxon potential parameters.

| energy | V   | Rv  | av  | W   | Rw  | aw  |
|--------|-----|-----|-----|-----|-----|-----|
| 40     | 60.84 | 1.000 | 0.7 | 23.16 | 0.600 | 0.6 |
| 60     | 31.64 | 1.145 | 0.69 | 8.78  | 1.134 | 0.69|

The model space needs to span large excitation energies, while the radial dependence can be reduced significantly.

For the CDCC calculations at 40 MeV/nucleon, the continuum was discretized upto 35 MeV, with 10 bins upto 10 MeV for s-, p-, and d-waves, and 8 bins from 10–35 MeV. We include 12 bins from 0–35 MeV for all other partial waves up to \(l_{\text{max}} = 4\). The same binning scheme was used for the XCDCC calculations, except that the higher bin density upto 10 MeV was only used for channels with outgoing ground state core components. Partial waves up to \(l_{\text{max}} = 4\) were used for the coupled channels projectile states.

For the 60 MeV/nucleon CDCC calculations, a slightly different binning scheme was adopted to match the experimental energy bin integrations. From 0–0.5 MeV, 2 bins were used; over the observed energy bins from 0.5–3.0 and 3.0–5.5 MeV, 3 bins were used in each case; and from 5.5–30 MeV, 6 bins. For the XCDCC calculations where the outgoing channel had excited core states, only 1 bin was used from 0–0.5 MeV, 1 bin for each observed energy range, and 5 bins above.

The radial integrals for the bins were calculated upto 40 fm in steps of 0.1 fm. The radial equations in the CDCC method were calculated for 30 partial waves with the lower radial cutoff for the integrals set to 4 fm inside the point Coulomb radius, and matched to the asymptotic Coulomb functions at 150 fm.

The \(^{11}\)Be bound state potential parameters are taken from Ref. \cite{19}, using the Be12-pure interaction for the CDCC calculations and the Be12-b for the XCDCC calculations. The \(^{10}\)Be-proton interaction is fitted to the proton elastic data available at the two energies. A good fit could be obtained from a renormalized CH9 interaction \cite{14}. The parameters are given in Table I. For the cases including \(^{10}\)Be excitation, the OM potentials were deformed with the same \(\beta_{2}\) deformations as used in the \(^{11}\)Be bound state. The coupling matrix elements to the excited state in \(^{10}\)Be assume a rotational model with the deformation fitted to the experimental \(B(E2)\) strength \cite{20}. The deformation length is in good agreement with that obtained from inelastic scattering at the \(2^{+}\) state in \(^{10}\)Be \cite{21}, and the optical potential used here reproduces the angular distribution of the inelastic scattering well.
optical model for the 10Be and theoretical calculations at \( \sim 10 \) MeV/nucleon. The experimental data are from GANIL [22].

In Fig. 1 we show the 10Be elastic and various 11Be reaction models for the 11Be data. The experimental data are from Ref. [11] (10Be) and Ref. [11] (11Be).

FIG. 1: (Color online) 10/11Be elastic scattering on a proton target at \( \sim 40 \) MeV/nucleon, using an optical model fit to the 10Be elastic and various 11Be reaction models for the 11Be data. The experimental data are from GANIL [22].

The elastic scattering is the first test on the reaction model. In Fig. 1 we show the 10Be and 11Be elastic data and theoretical calculations at \( \sim 40 \) MeV/nucleon. The optical model for the 10Be (dashed/black line) is fitted to the 10Be elastic data (open circles). The cluster folding model (dotted/red line) folds the 10Be+p and n-p interactions over the 11Be ground state wave function to produce the 11Be+p potential. Also shown in Fig. 1 is the effect of the 11Be continuum within CDCC (dot-dashed/blue line) and core excitation within XCDCC (solid line). Even though there is significant improvement over the simple optical model when including breakup, results still overestimate the 11Be elastic cross section at larger angles, and no improvement is found by including excited core contributions.

Calculations were repeated for a higher energy, around 60 MeV/nucleon, where both 10Be and 11Be elastic data exist. Once again, when the 10Be data is fitted with an optical model, and the 11Be elastic is described within the CDCC approach, the cross section is overestimated (see Fig. 2). Note that the data at this energy does not span a large angular range, but it is evident that the pattern of over-predicting the 11Be cross section remains.

Other reaction calculations have been performed in an effort to describe this data [23], which consisted of a transfer to the continuum approach in which the breakup continuum was described using the deuteron basis. This also failed to describe the data when the 10Be potential was fixed to the elastic data. The same pattern of over-predicting the 11Be elastic was also seen at a lower energy of \( \sim 40 \) MeV/nucleon [23].

As pointed out earlier, in [10, 11] large renormalization factors were needed to reproduce the elastic cross section. By including more relevant reaction channels, one might account for a part of the renormalization required, corresponding to flux that is being removed from the elastic channel. This suggests that there are still channels coupled to the elastic that have not been considered. Preliminary calculations including the deuteron transfer channel along with the breakup in the 11Be basis show improvement at small angles, but the disagreement still remains at large angles. Due to large non-orthonality corrections, CDCC calculations including the deuteron transfer coupling turn out to be numerically challenging. They will be discussed in a later publication.

III. RESULTS

A. Elastic channel

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B. Breakup: comparison with data at \( \sim 60 \) MeV/nucleon

Breakup data was also obtained at 63.7 MeV/nucleon [11], summed into two energy bins. The first covers the energy range 0.5–3.0 MeV, which spans the 1.78 MeV resonance, predominantly a d-wave neutron coupled to the ground state of the core. The second energy bin is over the energy range 3.0–5.5 MeV, which spans a resonance at 3.89 MeV, thought to be predominantly an s-wave neutron coupled to a 10Be(2+) core [11]. In Ref. [11], CDCC results were presented which underestimated the cross section for the lower energy bin, but did not reproduce the higher energy bin. It was suggested that since the higher energy bin spanned a resonance with a possible excited core component, the disagreement could be due to the spectator core approximation in the standard CDCC theory. Since XCDCC can handle excited core components, this data is re-examined.

The breakup angular distribution data and the associated theory prediction for the lower energy bin (0.5–3.0 MeV) and the higher energy bin (3.0–5.5 MeV) are presented in Figs. 2 and 3 (the equivalent of Figures 3b and 3c of Ref. [11]). Firstly, the CDCC calculations of Ref. [11] were redone, with a higher CDCC bin density.
also shows the breakup cross section to the 0 and 2+ states of 10Be (red/dotted line and the dot-dashed/blue line respectively). We see that whereas the ground state of the 11Be(0+) and 11Be(2+) multiplied by 10 by the dashed/blue line). The reason for this maybe that the large number of resonances in this region are not reproduced well by our particle-rotor model for 11Be. The only resonance that appears in this model is the 3/2+, for which the width is not narrow enough to attract significant cross section. Some suggest that more exotic structures are responsible for resonances in this region [21]. Without exotic resonances built on excited core components in our structure model, the breakup cross section is still dominated by ground state 10Be fragments.

IV. CONCLUDING REMARKS

A consistent analysis of reactions involving the halo nucleus 11Be on protons, at two intermediate energies (∼40 and ∼60 MeV/nucleon) are performed and compared with data. An optical model approach, based on a cluster folding potential constructed from the 10Be+p potential fitted to the appropriate elastic data, is unable to describe the 11Be elastic data. The inclusion of breakup effects improve the description, but theoretical predictions still overestimate the elastic cross section at larger scattering angles. The inclusion of core excitation does not affect the elastic distribution significantly. Note however that these results include no artificial renormalization of the optical potential. Elastic scattering experiments with radioactive beams at large facilities have repeatedly been undermined. The fact that the best reaction models are still unable to fully describe the mechanisms for the 11Be case, shows the need for a more varied and better elastic scattering experimental program.

In this work we also study the breakup channel explicitly. Core excitation in the description of the continuum, within XCDCC, produces a slight modification of the distribution. These breakup calculations are compared to the data at 63.7 MeV/nucleon, for two energy bins 0.5–3.0 MeV and 3.0–5.5 MeV. For the lower energy bin, the shape of the angular distribution is well reproduced by the models. The same cannot be said for the higher energy bin.

The XCDCC calculations predict breakup states to specific states of the core 10Be. This level of detail is still not available in the data, but it could be helpful information, even at an integrated level, to identify possible causes for the remaining disagreement with the data.

Another important point is related to the basis used to describe the breakup states. As discussed in Ref. [25], within CDCC, one can describe the three body final state continuum 10Be+n+p in the 11Be continuum basis or in the deuteron continuum basis. In this work we used the 11Be basis. Work in Ref. [25] shows that in practice the two choices do not provide the same result. Efforts are underway to tackle this problem within a Faddeev frame-
work [26]. These results may have important implications to the theory-experiment mismatch.

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