Strong pickup-coupling effect on p + ^{10}Be and ^{11}Be elastic scattering around 40 A.MeV incident energy

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Abstract

To explore the nature of the coupling effects on p + ^{10}Be and p + ^{11}Be elastic scattering at incident energies of 39.1 A.MeV and at 38.4 A.MeV, respectively coupled reaction channels (CRC) calculations were performed for the ^{10}Be(p,d)^{9}Be and ^{11}Be(p,d)^{10}Be* pickup to the ground state of ^{9}Be and the 5.960 MeV 1^- and 6.263 MeV 2^- doublet of excited states in ^{10}Be at the corresponding incident energies. We show that within the CRC framework the coupling effect on the elastic scattering is significant in both cases and produces effective absorption in the entrance channel. This suggests that the use of a fitted p + ^{10}Be optical model potential may lead to too much absorption in the core plus proton interaction in XCDCC-type calculations for the p + ^{11}Be system and that coupling to the ^{11}Be(p,d)^{10}Be* pickup should be explicitly included in such studies.

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Direct nuclear reactions provide a valuable means of probing the structure of nuclei and in recent years single-nucleon transfer reactions such as (d,p) stripping and (p,d) pickup have been extensively employed with radioactive beams to extract spectroscopic factors and other nuclear structure information for exotic nuclei. However, many of the lighter exotic nuclei are weakly bound and exhibit few-body cluster structures so that the question of an adequate reaction framework for the analysis of these reactions remains open to a large extent. Various reaction models based on the coupled reaction channels (CRC) formalism have investigated the role played by breakup, excitation of bound states of the projectile and transfer processes, but the interplay between all these effects remains to be clarified.

Due to the weak binding of these nuclei, attention in this area has naturally concentrated on extensions of the well established coupled discretized continuum channels (CDCC) method [1] to enable the breakup of nuclei that exhibit three-body cluster structures [2–4] and where the assumption of an inert core is no longer realistic [5, 6] to be modeled. The latter technique is referred to as the XCDCC method. However, transfer reactions have also been found to be important for certain light exotic nuclei, such as ^{8}He [7, 8] and ^{10}Be [9]. Both nuclei exhibit an important (p,d) pickup coupling effect on the elastic scattering and for ^{8}He the use of the CRC formalism to model these strong couplings was essential in obtaining a consistent set of spectroscopic amplitudes from the available (p,d) and (p,t) data [8]. Therefore, any framework that aims at a comprehensive description of direct nuclear reactions induced by light exotic nuclei will need to incorporate these couplings together with effects due to breakup in a coherent fashion.

Data for p + ^{10}Be and p + ^{11}Be elastic scattering at incident energies of 39.1 A.MeV and 38.4 A.MeV, respectively were analyzed in Ref. [10] and the question of coupling effects was addressed phenomenologically. It was suggested that reaction channel couplings such as (p,d) pickup could explain the observed discrepancies between optical model calculations using the JLM potential [11] and the data. As ^{11}Be has a filled 1p$_{3/2}$ sub-shell like ^{8}He and ^{10}Be the (p,d) pickup coupling could play a significant role, although this possibility has not yet been examined.

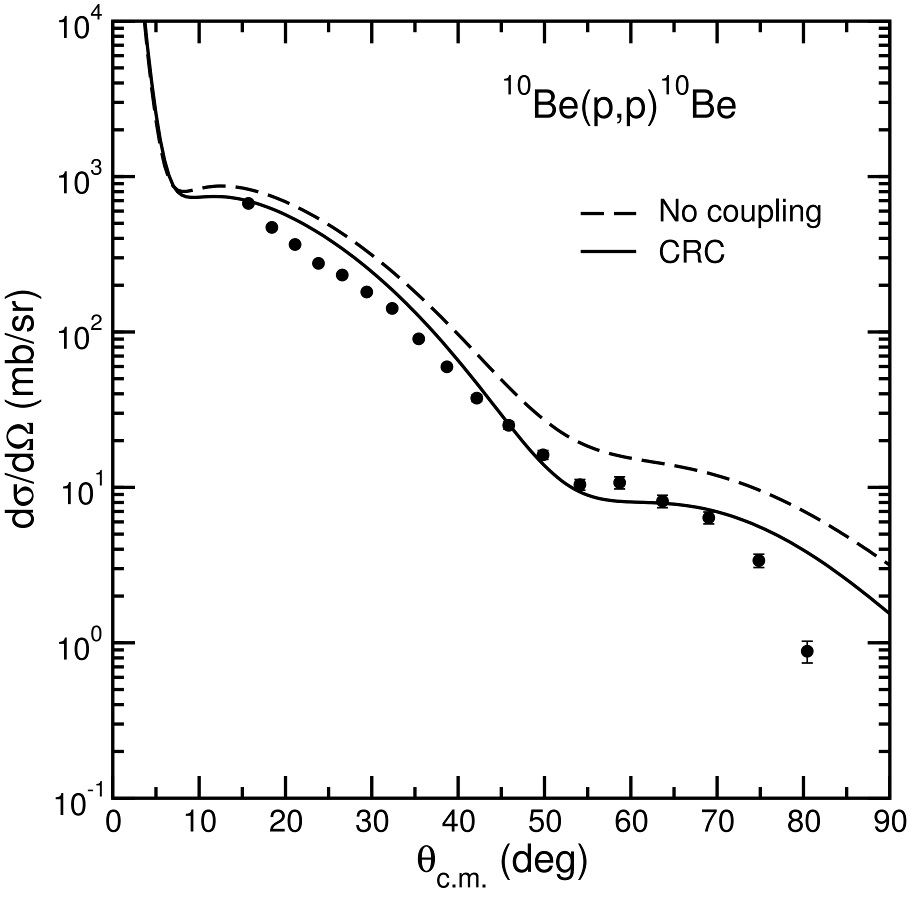
A recent article [12] addressing ^{11}Be breakup coupling effects on p + ^{11}Be elastic scattering found that realistic calculations including excitation of the ^{10}Be core within the XCDCC method overestimated the experimental elastic scattering cross section at larger angles. It was suggested that the discrepancy was due to couplings to other channels not included in the calculations, with the (p,d) pickup being a possible contributor [12]. In addition, as the (p,d) pickup coupling has an important effect on the p + ^{10}Be elastic scattering at lower incident energies [9], it is also relevant to pose the question whether an empirical optical model potential obtained from a fit to p + ^{10}Be elastic scattering data provides the appropriate input to an XCDCC-type calculation for p + ^{11}Be elastic scattering, as a fitted optical potential could contain strong coupling effects not present in the core plus proton interaction.

In this article we examine the influence of the (p,d) pickup coupling on the p + ^{10}Be and p + ^{11}Be elastic scattering data [10] at 39.1 A.MeV and 38.4 A. MeV, respectively. We show that a significant (p,d) coupling effect on the p + ^{10}Be elastic scattering persists at these energies and that pickup of a 1p$_{3/2}$ neutron from ^{11}Be to the 1^-, 2^- doublet at $\sim$ 6 MeV excitation energy in ^{10}Be also has an important effect on the p + ^{11}Be elastic scattering, and could account for at least part of the discrepancy between the XCDCC calculations and the data.

We first performed CRC calculations for the 39.1 A.MeV p + ^{10}Be elastic scattering data of Ref. [10], similar to those in Ref. [9]. The entrance channel potential was calculated using the JLM formalism [11] and the ^{10}Be density of Ref. [13], as in Ref. [10] to allow ease of comparison with the optical model analysis presented therein. We recall here that the JLM formalism has been found [14] to describe reasonably well within the optical model framework a wide range of proton elastic scattering data from several light targets with real and imaginary potential normalization factors of $\lambda_V = 1.0$, $\lambda_W = 0.8$, respectively. All other details were as in Ref. [9], with the exception of the n,p + ^{9}Be potentials used as a basis for the Watanabe-type folding potentials in the exit channel where the central part of the global parametrization of Koning and Delaroche [15] was used unaltered, there being no suitable d + ^{9}Be data available in the literature. All calculations were performed with the code FRESCO [16]. The results are presented in Fig. 1.

The best description of the data was obtained with renormalizations of the real and imaginary parts of the JLM potential by factors of $\lambda_V = 1.0$, $\lambda_W = 0.3$, respectively. The description of the elastic scattering data is virtually identical to that obtained in Ref. [10] by an optical model calculation using the JLM potential where the renormalization factors were adjusted to give the best agreement with the data, yielding renormalization factors of $\lambda_V = 1.0$, $\lambda_W = 0.8$. While the (p,d) coupling does not significantly improve the description

FIG. 1: Data for ^{10}Be(p,p) elastic scattering at 39.1 A.MeV [10] compared with the full CRC calculation (full curve) and the no-coupling calculation (dashed curve).



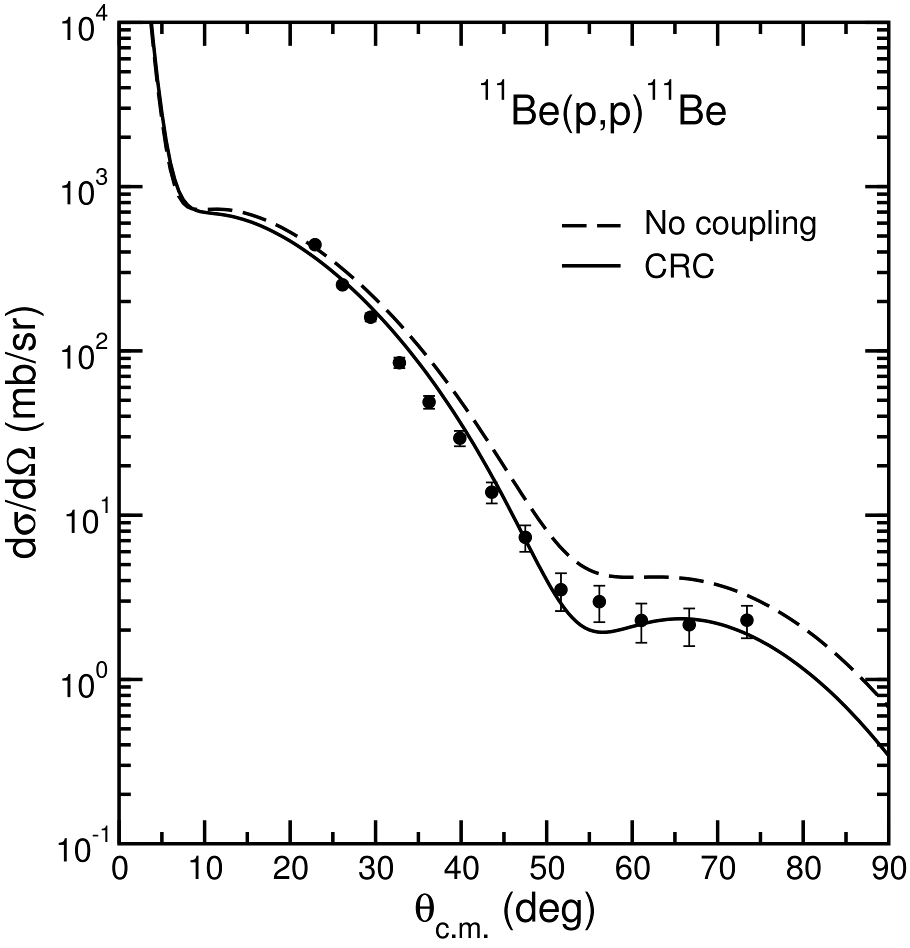
of the data, which remains rather poor for angles $\theta_{\mathrm{c.m.}} < 35^\circ$, it is able to account for about 60 % of the absorption. This is consistent with previous results for p + ^{8}He [7] and p + ^{10}Be [9] elastic scattering. We therefore find that the significant (p,d) coupling effect persists at these energies (cf. the solid and dashed curves in Fig. 1) and that the use of a fitted optical model potential as input to XCDCC-type calculations for p + ^{11}Be elastic scattering could lead to there being too much absorption in the core plus proton interaction. Note that the potential parameters for the no-coupling calculation (dashed curve in Fig. 1) are the same as those for the full CRC calculation, i.e. $\lambda_{\mathrm{V}} = 1.0$, $\lambda_{\mathrm{W}} = 0.3$.

We next performed CRC calculations for the 38.4 A.MeV p + ^{11}Be elastic scattering data of Ref. [10]; the ^{11}Be(p,d)^{10}Be pickup data at the similar incident energy of 35.3 A.MeV [17] provide a valuable control of the coupling strength. The calculations were similar to those described above for p + ^{10}Be. The entrance channel potential was again calculated using the JLM formalism [11] and the ^{11}Be density of Ref. [13], as in Ref. [10]. The CDCC formalism was employed in the exit channel, as in Refs. [7, 9], with the n,p + ^{10}Be optical potentials needed as input to the Watanabe-type folding potentials calculated using the central part of the potential of Watson *et al.* [18], known to give a good description of the p + ^{10}Be elastic scattering data in the relevant energy region [19]. The n + ^{10}Be binding potential was of Woods-Saxon form, with radius parameter $R = 1.25 \times 10^{1/3}$ fm and diffuseness 0.65 fm. The n + p binding potential was the Reid soft-core [20], including the small D-state component.

The ^{11}Be(p,d)^{10}Be pickup measurement of Ref. [17] presents angular distributions for the ^{10}Be 0^+ ground state, 3.37 MeV 2^+ state and an unresolved quartet of states at $\sim$ 6 MeV excitation energy comprising the 5.958 MeV 2^+, 5.960 MeV 1^-, 6.179 MeV 0^+ and 6.263 MeV 2^- states. The quartet of states is much more strongly populated than either the ground state or 3.37 MeV 2^+ state, its cross section in the measured angular range being approximately four times the peak cross section for pickup leading to the ground state of ^{10}Be. Pickup of a $1p_{3/2}$ neutron feeding the $p_{3/2}^{-1}$ 5.960 MeV 1^- and 6.623 MeV 2^- states, with possible smaller contributions from pickup to the 5.958 MeV 2^+ and 6.179 MeV 0^+ states, provides a plausible explanation for this strong population. Winfield *et al.* [17] were able to obtain a fit to the (p,d) data assuming that the contribution from the positive parity states is negligible and using the same binding potential geometry as employed here with a summed spectroscopic factor approximately 10 % larger than the shell model value given in Ref. [21] when an adiabatic model deuteron potential was used in the exit channel; a standard DWBA calculation required a summed spectroscopic factor twice the shell model value. Winfield *et al.* [17] also point out that the shape of the experimental angular distribution suggests that any $\ell = 0$ or $\ell = 2$ contribution is small. We therefore only included pickup to the 5.960 MeV 1^- and 6.623 MeV 2^- states in our calculations.

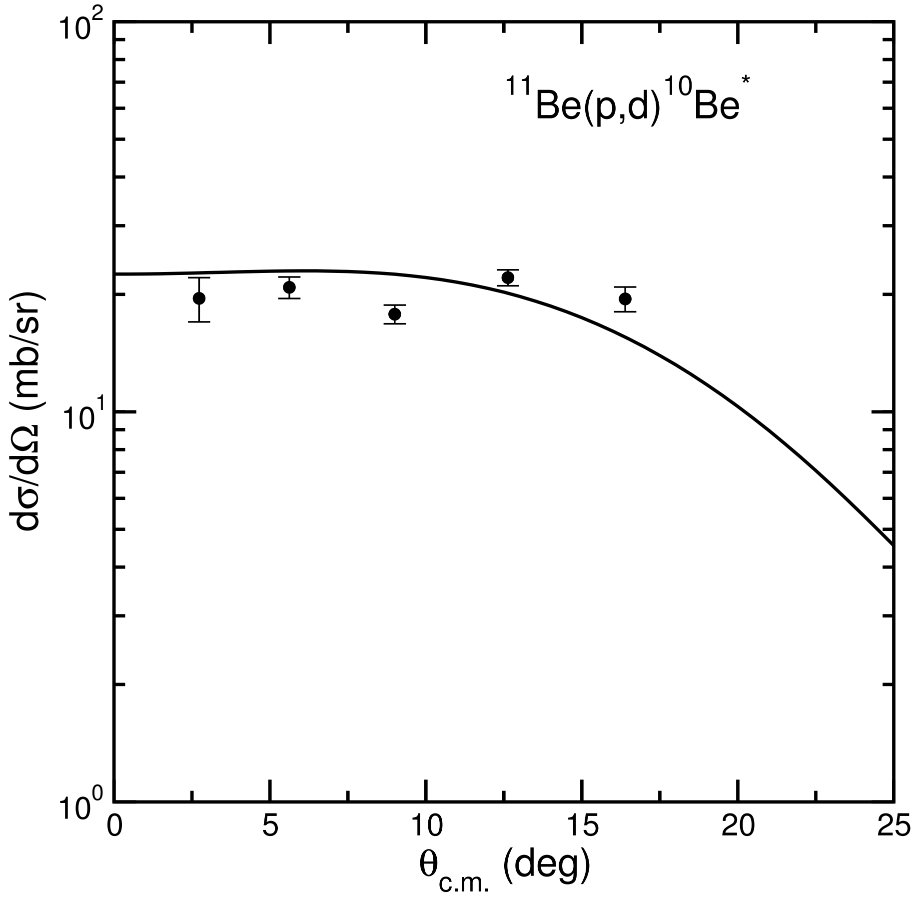
The normalization factors of the real and imaginary parts of the entrance channel optical potential, λ_{V} and λ_{W}, respectively and the spectroscopic factors for pickup to the 5.960 MeV 1^- and 6.623 MeV 2^- states in ^{10}Be were adjusted to obtain the best description of the elastic scattering and pickup data, retaining the relative weights of the shell model spectroscopic factors. The results are presented in Figs. 2 and 3. The best fit to the data was obtained with renormalizations $\lambda_{\mathrm{V}} = 0.80$ and $\lambda_{\mathrm{W}} = 0.65$ and summed spectroscopic factors about 1.3 times the shell model value [21], i.e. $C^2S = 0.87$ and 0.73 for pickup to the 5.960 MeV 1^-

FIG. 2: Data for ^{11}Be(p,p) elastic scattering at 38.4 A.MeV [10] compared with the full CRC calculation (full curve) and the no-coupling calculation (dashed curve). Spectroscopic factors were adjusted to fit the (p,d) data of Ref. [17].



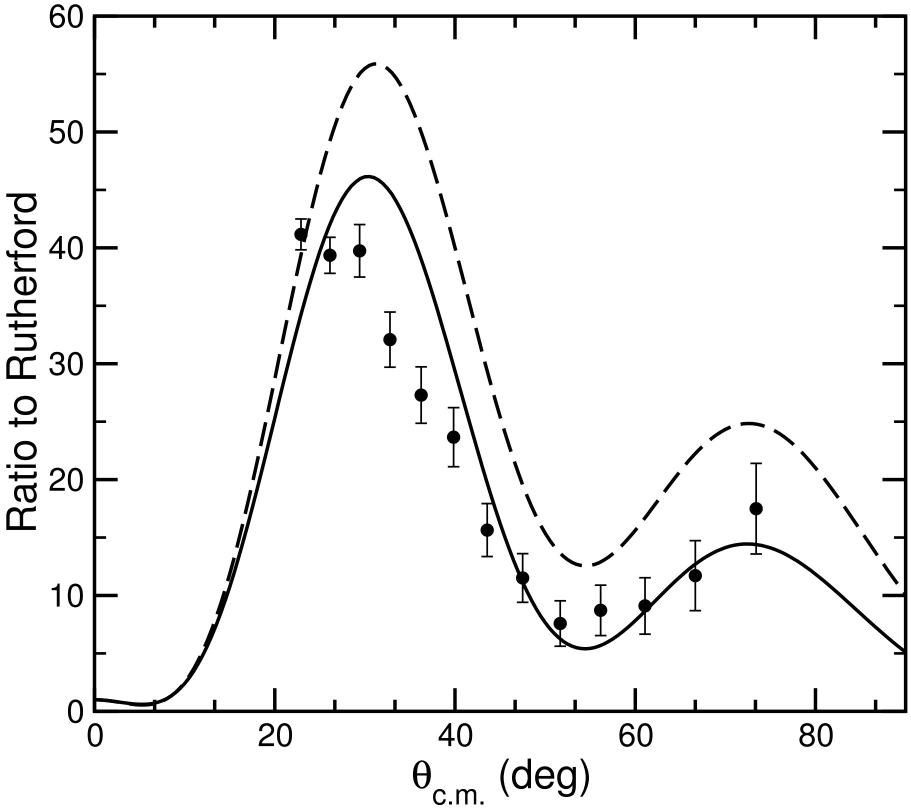
and 6.263 MeV 2^- states of ^{10}Be, respectively. The description of the elastic scattering data is virtually identical to that obtained in Ref. [10] by an optical model calculation using the JLM potential with renormalization factors of $\lambda_{\rm V} = 0.75$ and $\lambda_{\rm W} = 0.8$. The (p,d) coupling is able to account for a small (~ 6 %) part of the renormalization of the real part of the JLM and provides about 20 % of the absorption. This is again consistent with previous results for p + ^{8}He [7] and p + ^{10}Be [9] elastic scattering and suggests that the need to renormalize the real part of the JLM potential is mostly due to other couplings, probably breakup, although this is difficult to confirm directly. Again, the potential parameters for the no-coupling calculation (dashed curve in Fig. 2) are the same as those for the full CRC calculation, i.e. $\lambda_{\rm V} = 0.80$, $\lambda_{\rm W} = 0.65$.

FIG. 3: Data for ^{11}Be(p,d)^{10}Be* at 35 A.MeV [17] compared with the CRC calculation with spectroscopic factors adjusted to fit the data assuming that the cross section is dominated by neutron stripping to the 1^- and 2^- $p_{3/2}$ hole states.



The spectroscopic factors are reasonably consistent with the adiabatic model analysis of Winfield *et al.* [17] and the results of an eikonal model analysis of the single neutron knockout to these states by Aumann *et al.* [21] where the data were well described using the shell model values. The most important thing to note is that the (p,d) coupling has a significant effect on the elastic scattering, particularly at the larger angles where the XCDCC calculations of Ref. [12] over predict the data. It is therefore plausible that coupling to the (p,d) pickup is responsible for at least part of this discrepancy. This is more easily seen in Fig. 4, where we plot the elastic scattering as ratio to Rutherford on a linear scale, as in Fig. 1 of Ref. [12]. The (p,d) coupling reduces the elastic scattering cross section by about a factor of two in the angular region around 75° in the center of mass frame.

FIG. 4: Data for ^{11}Be(p,p) elastic scattering at 38.4 A.MeV [10] compared with the full CRC calculation (full curve) and the no-coupling calculation (dashed curve) plotted as ratio to Rutherford with spectroscopic factors adjusted to fit the (p,d) data of Ref. [17].



In summary, we have shown that coupling to the ^{10}Be(p,d)^{9}Be pickup has a significant effect on the p + ^{10}Be elastic scattering at an incident energy of 39.1 A.MeV, similar to that found previously at much lower incident energies [9]. This suggests that the use of an empirical optical model potential obtained from a fit to p + ^{10}Be elastic scattering data in an XCDCC-type calculation such as that of Ref. [12] could give too much absorption in the core plus proton interaction. We also showed that coupling to the ^{11}Be(p,d)^{10}Be* pickup to the 1^{-}, 2^{-} doublet at approximately 6 MeV excitation energy has a significant effect on the p + ^{11}Be elastic scattering at 38.4 A.MeV. It is consistent with previous studies of the (p,d) coupling in the p + ^{8}He [7] and p +^{10}Be [9] systems where the coupling gave rise to a small repulsive contribution to the real part of the entrance channel optical potential plus an important absorptive contribution to the imaginary part. This coupling could therefore provide a significant part of the missing absorption noted in a recent XCDCC study of p +

^{11}Be elastic scattering [12]. However, incorporating both breakup and (p,d) pickup effects consistently in a single calculation could prove to be challenging [12, 22].

Acknowledgments

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