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Distinction between elastic scattering of weakly bound proton- and neutron-rich nuclei: The case of ^{8}B and ^{11}Be

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Experimental data show that the elastic scattering cross sections of the neutron-rich nucleus ^{11}Be are greatly reduced by the coupling effects from the breakup channels, while those of the proton-rich nucleus ^{8}B are not. Such difference is found to persist in results of systematic calculations of ^{8}B elastic scattering from ^{208}Pb at 60 and 170.3 MeV and from ^{64}Zn at 32 and 86 MeV, and ^{11}Be elastic scattering from ^{208}Pb at 55 and 143 MeV and from ^{64}Zn at 29 and 66 MeV with the continuum-discretized coupled channel (CDCC) method. The Coulomb and centrifugal barriers experienced by the valence proton in the ground state of ^{8}B, which do not exist for the valence neutron in the ground state of ^{11}Be, are found to be the reason for such differences in the angular distributions of elastic scattering cross sections of these two weakly bound nuclei.

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I. INTRODUCTION

Atomic nuclei that are away from the β-stability line, namely, the radioactive nuclei, may have exotic structure and behave peculiarly during their interaction with the other nuclei when compared with stable nuclei [1–3]. Such new results are very useful to constrain models of nuclear interactions and to improve theories of nuclear structure and reactions, which are indispensable for studies in, for example, the nuclear power industry and nuclear astrophysics, where nuclear data that are not accessible by direct measurements in laboratories are needed [4].

Unlike stable nuclei, radioactive nuclei are normally weakly bound and can be seen as consisting of a core nucleus and a valence particle (a single nucleon or a cluster). With small binding energies, these valence particles may have very extended radial distributions outside the composite nuclei [5,6]. Also, because of their weakly bound nature, they are easily excited into continuum states during their collisions with the other nuclei, igniting breakup reactions [7]. Such breakup channels may have strong coupling effects on the other reaction channels. For example, fusion cross sections of weakly bound nuclei, such as ^{6}He and ^{17}F, are found to be dramatically increased at incident energies near the vicinity of the Coulomb barrier due to their coupling to the breakup channels [8–10]. Another example is the elastic scattering of the neutron-halo nucleus ^{11}Be from ^{64}Zn at $E_{\text{c.m.}} = 24.9$ MeV. Its cross sections were greatly reduced compared to those of ^{9}Be and ^{10}Be [11]. Such reduced cross sections were soon understood to be caused by the coupling effects from the breakup channels [12].

Coupling between the elastic scattering and breakup channels can be treated with the continuum-discretized coupled channel (CDCC) method [7,13]. An example of the CDCC calculations is shown in Fig. 1 for ^{11}Be elastic scattering from ^{64}Zn at $E_{\text{c.m.}} = 24.9$ MeV. For comparison, calculations without taking into account the continuum-continuum couplings are also shown. Clearly, the Coulomb rainbow phenomenon, which is typical in the angular distributions of elastic scattering induced by stable heavy ions, is greatly reduced due to the breakup coupling effects, and this helps to reproduce the experimental data well. Without taking into account the coupling effects from the breakup channels, such a Coulomb rainbow will show up, and it fails to reproduce the experimental data.

Small binding energies of the valence nucleons, however, are not the only thing that determines if the breakup channels have strong coupling effects on the elastic scattering cross sections of radioactive nuclei. The binding energy of the valence proton in the ground state of ^{8}B, for instance, is only 0.136 MeV, which is even smaller than the binding energy of the valence neutron in the ground state of ^{11}Be, which is 0.502 MeV. Naively, one would expect similar or even stronger breakup coupling effects to be shown in the angular distributions of elastic scattering cross sections of ^{8}B. However, experimental results of ^{8}B with a lead target at 170.3 MeV show that there are no such strong breakup coupling effects in its differential cross sections [14]. As is shown in Fig. 2, CDCC calculations with and without taking into account the continuum states of the $p + {}^{7}$Be system did not show much difference, which differs from the result shown in Fig. 1. Actually, the experimental data can be rather well reproduced with optical model calculations using a systematic nucleus-nucleus potential obtained from the analysis of elastic scattering data of stable nuclei [15]. The same were found in the elastic scattering of other proton-rich nuclei, such as ^{10}C, ^{11}C, and ^{17}F [16,17].

In this paper, we discuss the reason why proton-rich nuclei, in our case ^{8}B, show such different behavior from neutron-rich nuclei, such as ^{11}Be, in the breakup coupling effects on their elastic scattering cross sections. Both nuclei have been extensively studied individually previously [18–25]. The effects of continuum-continuum coupling in the scattering of ^{11}Be are rather well understood within the framework

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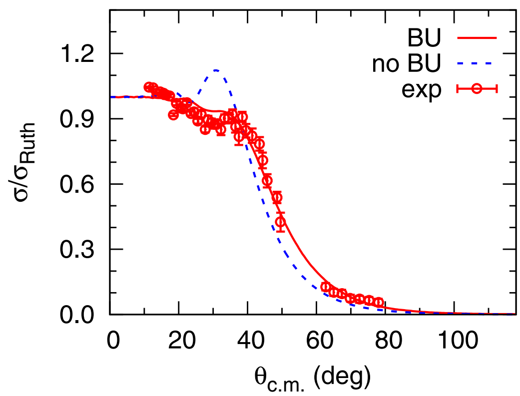

FIG. 1. CDCC calculation of the elastic scattering of ^{11}Be from ^{64}Zn at $E_{\text{c.m.}} = 24.9$ MeV and its comparison with experimental data [11]. The results with and without taking into account the breakup coupling effects are designated as "BU" and "no BU," respectively.

of the CDCC method including contributions from nuclear and Coulomb breakup mechanisms and their interferences [18–20]. However, to our knowledge, systematic comparisons between the breakup coupling effects to the elastic scattering of these two typical proton- and neutron-rich nuclei have not yet been made. We study this by doing CDCC calculations for ^{8}B and ^{11}Be elastic scattering from ^{208}Pb and ^{64}Zn targets at energies both close to and about three times the Coulomb barriers. We will show that the distinctions in the elastic scattering of ^{8}B and ^{11}Be are due not only to their valence nucleons being proton and neutron, respectively, but also due to the differences in the angular momenta of the valence nucleons in their ground states. The details of calculations are given in Sec. II. Our conclusion is given in Sec. III.

II. NUMERICAL CALCULATIONS

In order to see if such strong differences between the breakup coupling effects in the elastic scattering cross sections of ^{8}B and ^{11}Be persist at different incident energies and target masses, we make systematic CDCC calculations for ^{8}B and ^{11}Be elastic scattering from heavy (^{208}Pb) and intermediate mass (^{64}Zn) targets at different energies. These targets are

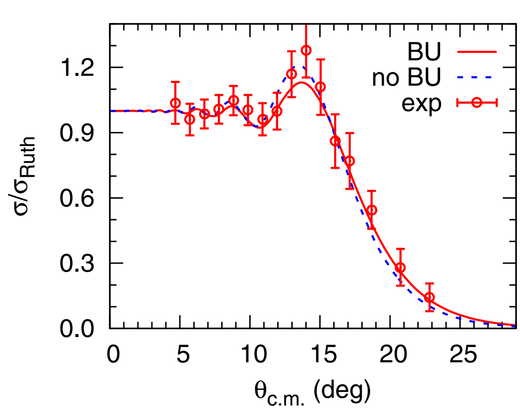

FIG. 2. The same as Fig. 1 but for the elastic scattering of ^{8}B from ^{208}Pb at 170.3 MeV [14].

chosen because experimental data of ^{8}B with ^{208}Pb at higher energies and ^{11}Be with ^{64}Zn in the vicinity of the Coulomb barriers exist [11,14]. Thus, the extended calculations reported here will not only allow us to compare the breakup coupling effects to the elastic scattering cross sections of these two projectiles, but also serve as predictions for possible future experiments with these two nuclei. All CDCC calculations reported here are made with the computer code FRESCO [26]. Both low (around $1.3V_b$, where V_b is the hight of the Coulomb barrier of the projectile-target system) and higher (around $3.3V_b$) energies are examined. To be specific, these calculations are made for ^{8}B+^{208}Pb at 64 and 170.3 MeV, ^{8}B+^{64}Zn at 32 and 86 MeV, ^{11}Be+^{208}Pb at 55 and 143 MeV, and ^{11}Be+^{64}Zn at 29 and 66 MeV. Such systematic analysis is made possible by using the systematic optical model potentials. In a CDCC calculation, the projectile nucleus is assumed to be composed of a core nucleus and a valence nucleon, which are ^{7}Be and a proton and ^{10}Be and a neutron, for ^{8}B and ^{11}Be, respectively. We use the systematic single-folding nucleus-nucleus potential in Ref. [15] for the core-target interactions and the systematics of KD02 for the valence nucleon-target potentials [27]. In these calculation, the continuum states of the $n + {}^{10}$Be system were discretized into nine bins up to a maximum excitation energy of $E_{\text{max}} = 19.1$ MeV (corresponding to the maximum relative momentum being $k_{\text{max}} = 0.9$ fm^{-1}) for each angular momentum ℓ between the neutron and the core nucleus. The maximum value of ℓ is $\ell_{\text{max}} = 5$. For the $p + {}^{7}$Be system, the corresponding values are $E_{\text{max}} = 15.7$ MeV (in eight bins with $k_{\text{max}} = 0.8$ fm^{-1}) and $\ell_{\text{max}} = 3$. The model spaces were chosen large enough to ensure the convergence of the elastic scattering and breakup cross sections. For the interaction between the valence nucleon and the core nucleus, the potential parameters of Capel *et al.* were used for ^{11}Be, which can give the binding energies of the neutron in the ground state, the first excited state, and the 1.274 MeV resonant state of ^{11}Be [28]. For the p-^{7}Be system, a Woods-Saxon potential with parameters $r_0 = 1.149$ fm and $a_0 = 0.602$ fm is used [29]. The results are shown in Fig. 3. Clearly, the strong differences shown in Fig. 1 and 2 persist in all cases here: with both targets at all energies, the breakup coupling effects to the elastic scattering cross sections with ^{11}Be are much stronger than those with ^{8}B. These results agree well with the work of Kucuk and Aciksoz and of Lubian *et al.* for ^{8}B elastic scattering from different target nuclei from ^{27}Al to ^{208}Pb at energies around the Coulomb barriers [30,31].

The fact that elastic scattering of the proton-halo nucleus ^{8}B is much less affected by the breakup coupling effect than ^{11}Be (and some other weakly bound neutron-rich nuclei, such as ^{6}He and ^{11}Li as well; see, e.g., Refs.[25,32]) albeit its valence proton also has very small binding energy has been thought to be *exotic* [22]. We notice that there are two main differences between ^{8}B and those neutron-rich nuclei: (1) there is a Coulomb interaction between the valence proton and the core nucleus ^{7}Be, and (2) the valence proton is mainly in the $1p_{3/2}$ level in the ground state of ^{8}B. Therefore, there will be *both* Coulomb and centrifugal barriers for the valence proton to tunnel through in order to make the breakup reaction happen. In contrast, the valence neutron in the ground state of ^{11}Be is in the $2s_{1/2}$ shell, so there are neither centrifugal nor Coulomb

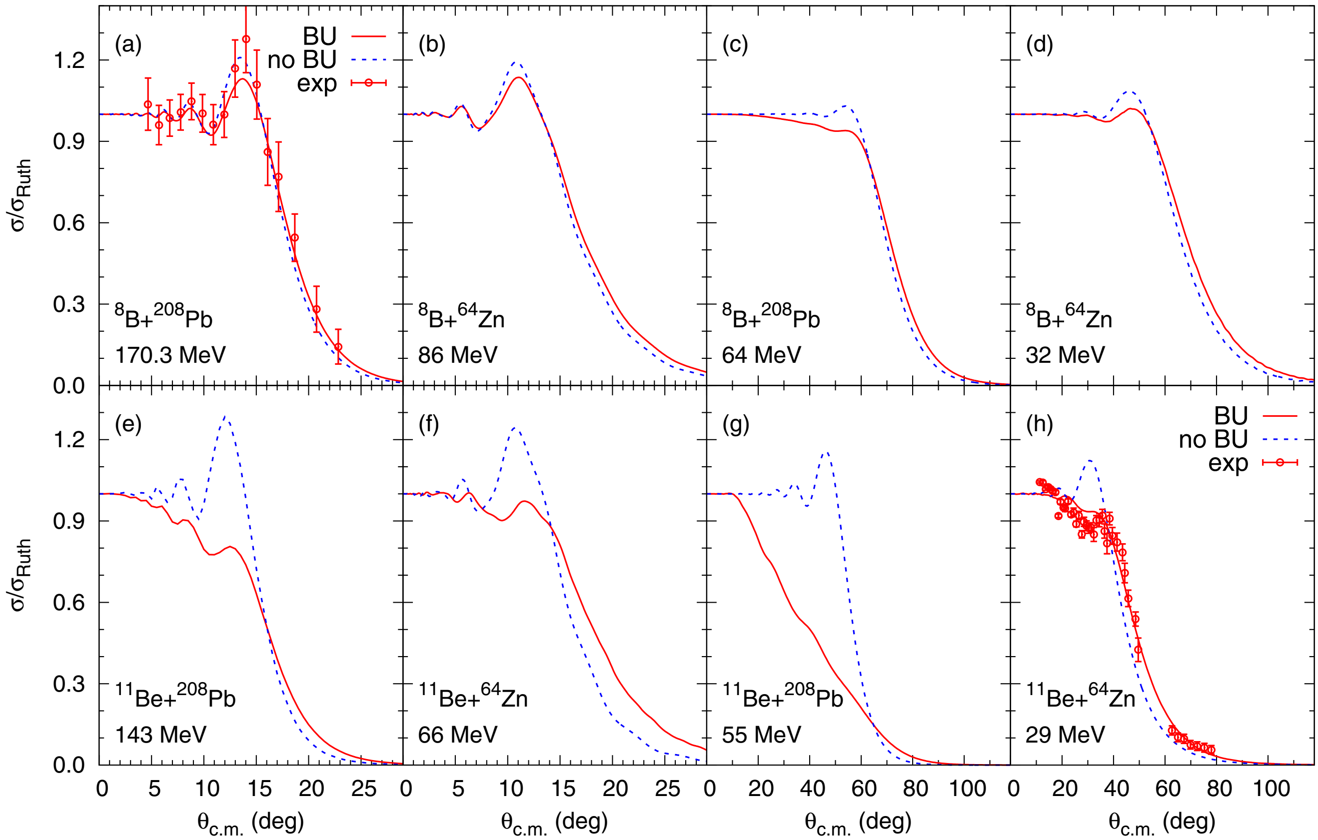

FIG. 3. Results of CDCC calculations for differential cross sections of elastic scattering as ratios to the Rutherford cross sections for ^{8}B [panels (a)–(d)] and ^{11}Be [panels (e)–(h)] from ^{64}Zn and ^{208}Pb at low and higher energies. The incident energies are indicated in the figures.

barriers to keep the valence neutron inside ^{11}Be. These facts are clearly shown in Fig. 4, where the Coulomb and centrifugal barriers are depicted for the valence proton in the ground state of ^{8}B. The radial wave functions of the valence proton are also shown for the proton to have (1) both the Coulomb and centrifugal barriers, (2) only the Coulomb barrier, and (3) no Coulomb and centrifugal barriers. The depths of the binding Woods-Saxon potentials in these cases were refit so that the binding energy, 0.136 MeV, of the proton in the ground state of ^{8}B is kept the same. One sees that with these barriers the proton wave functions are enhanced in the interior region. On the other hand, without these barriers, it will have a very long tail. The root-mean square radii of these radial wave functions are 4.50, 5.49, and 10.58 fm for the three cases, respectively. To further check how the Coulomb and centrifugal barriers affect the breakup coupling effects to the elastic scattering of proton-rich nuclei, we make CDCC calculations for ^{8}B elastic scattering from ^{64}Zn at 32 MeV for the three cases. The results are shown in Fig. 5. Clearly, without the Coulomb and centrifugal barriers, the elastic scattering cross sections of ^{8}B at around Coulomb rainbow angles are also greatly decreased due to couplings to the breakup states, and they become the same as those of the neutron-rich nuclei.

The reduction of the elastic scattering cross sections may also be caused by strong coupling to other inelastic channels. A well-known example is ^{18}O elastic scattering from ^{184}W at 90 MeV [22,33,34], whose cross section is greatly reduced at angles forward of the Fresnel shadow region [35]. In our case, with the ^{208}Pb and ^{64}Zn targets, whose inelastic coupling

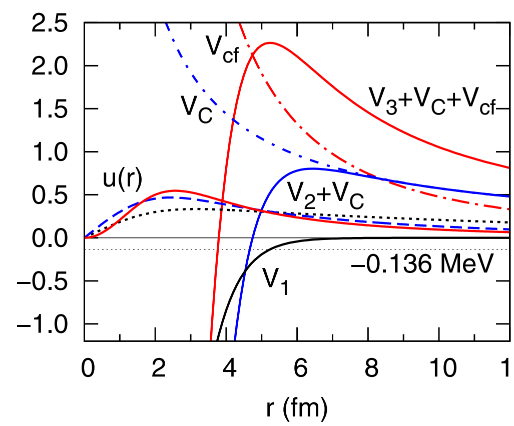

FIG. 4. Single-particle wave functions, $u(r)$ ($\int_0^\infty u^2(r)dr = 1$), of the valence proton in the ground state of ^{8}B with and without the Coulomb ($V_{\rm C}$) and centrifugal potentials ($V_{\rm cf}$). The corresponding total potentials V_1, $V_2 + V_{\rm C}$, and $V_3 + V_{\rm C} + V_{\rm cf}$ are also shown, where V_1, V_2, and V_3 represent the nuclear potentials refitted to reproduce the experimental binding energy of the valence proton in the ground state of ^{8}B without $V_{\rm C}$ and $V_{\rm cf}$, with $V_{\rm C}$ only, and with both $V_{\rm C}$ and $V_{\rm cf}$, respectively. For clearness of the figure, V_2 and V_3 are not plotted. The binding energy of this proton is indicated as the thin dotted line.

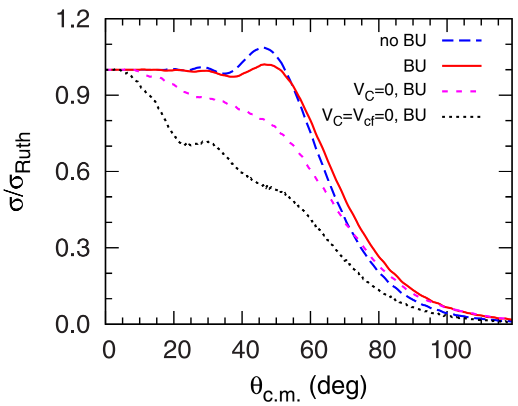

FIG. 5. Results of CDCC calculations for the angular distributions of ^{8}B elastic scattering from ^{64}Zn at 32 MeV with all barriers (solid curve), with only the centrifugal barrier (dashed curve), and with no barriers (dotted curve).

effects are small in their inelastic scattering by a projectile nucleus [36], whether there is reduction (as in the ^{11}Be case) or small/no reduction (as in the ^{8}B case) in the elastic scattering cross sections with weakly bound nuclei is dictated by the breakup coupling effects of the projectile. Such effects are not only determined by the charge of the valence nucleons, but also by the angular momenta of their single-particle wave functions. In other words, the angular distribution of elastic scattering cross sections of weakly bound nuclei reflect the character of their single-particle structure. However, theoretical studies of these cross sections suffer from the uncertainties of the optical model potentials. Capel *et al.* suggest that under certain conditions the ratios between elastic scattering and breakup reactions are directly linked to the form factors of the single-particle states of the weakly bound nuclei and they depend very weakly on reaction mechanisms and optical model potentials [37,38]. The ratio method is thus very promising in studying the single-particle structure of weakly bound nuclei with combined measurements of their elastic scattering and breakup reaction data.

III. CONCLUSIONS

In this work, we make systematic calculations for elastic scattering cross sections of the proton-halo nucleus ^{8}B and the neutron-rich nucleus ^{11}Be from both intermediate and heavy targets at both low and higher energies (from near Coulomb barrier to about three times the Coulomb barriers) using the CDCC method. Systematic differences in the breakup coupling effects in the angular distributions of the elastic scattering cross sections are found for these two nuclei in all cases. We show that such differences are due to the Coulomb and centrifugal barriers encountered by the valence proton in the ground state of ^{8}B.

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