Effect of dynamical polarization potentials on fusion radial potential barriers and on fusion cross sections for the proton-halo system $^8\text{B}+^{58}\text{Ni}$

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Abstract. Fusion radial potential ($l = 0$) barriers of $^8\text{B}+^{58}\text{Ni}$ are determined from a simultaneous optical model analysis of elastic scattering angular distributions and fusion data at energies around the Coulomb energy. Dynamical energy dependent Woods-Saxon polarization potentials, $U_F$ (volume) and $U_{DR}$ (surface) are used in the calculation of the barriers, where $U_F$ is a potential that accounts for polarization effects emerging from couplings to the fusion channel and $U_{DR}$ for effects due to direct reaction absorption couplings. Each of these potentials, $U_F$ and $U_{DR}$ are in turn, split into real and imaginary potentials $V_F$, $W_F$ and $V_{DR}$, $W_{DR}$, which are related via the dispersion relation. The parameters of these potentials are determined during the simultaneous fitting process. The effect on fusion cross section from the competitive barrier lowering and rising produced respectively by $V_F$ and $V_{DR}$ is investigated. Also, the net effect of breakup couplings on the fusion cross section is studied by analyzing the particular effect from both direct reaction polarization potentials $V_{DR}$ and $W_{DR}$. Finally, it is shown that energy dependence of the total polarization potential $U(E) = U_F(E) + U_{DR}(E)$ at the strong absorption radius $R_{sa}$ is consistent with the Breakup Threshold Anomaly as expected for weakly bound nuclei.

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1. Introduction
In the last years, nuclear reactions with weakly bound projectiles have been extensively investigated[1]. Several experiments have been performed and theoretical models have been proposed recently to study the characteristic reaction mechanisms that take place in reactions with these nuclei, such as direct and sequential complete fusion, incomplete fusion and the appreciable breakup/transfer processes observed mainly at the lower energies. Due to the small threshold energies, reactions with weakly bound systems show large breakup/transfer cross sections even at energies well below the Coulomb barrier. In fact, the strong coupling between the incident channel to those in the continuum affects also the couplings to other reaction channels such as fusion[1, 2]. Due to their halo structure, reactions with projectiles $^6\text{He}$ and $^8\text{B}$, have also been the source of intense research. It is expected that the large radial extension of such nuclei may have some important effects on the couplings between the different reaction channels. For this reason, a complete series of experiments have been performed for the neutron-halo nucleus $^6\text{He}$ with $^{209}\text{Bi}$. Fusion[3], total reaction and transfer[4, 5] cross sections...
have been measured for energies around and below the Coulomb barrier. On the other hand, measurements for elastic scattering of $^8$B and its core nucleus $^7$Be on a $^{58}$Ni target[6] and fusion cross sections of $^8$B with the same target $^{58}$Ni[7] have been carried out. These measurements have shown strong evidence for $p$-halo ($^8$B) and 2$n$-halo ($^6$He) effects on couplings to elastic and other reaction channels. It has been established, that a characteristic feature for any halo state such as $^8$B or $^6$He, an underlying decoupling between the core and the valence nucleons occurs. That is, the $^8$B ($^6$He) reaction cross section could be entirely accounted for, by the breakup (transfer) cross section of the halo state ($p$ or $2n$) plus reactions that occur with core nucleus $^7$Be ($^4$He)[8, 9, 10]. Another important feature of halo systems is their behavior in the space of reduced cross sections and reduced energies. In this space, the experimental data of the interaction cross sections for $^8$B (proton halo) and $^6$He (neutron halo) with different targets, lie on the same trajectory[8]. Similarly, "normal" weakly bound (non halo) and tightly bound systems follow characteristic paths. That is, in the space of reduced cross sections $\sigma_{\text{red}}$ and reduced energies $E_{\text{red}}$, defined respectively by,

$$\sigma_{\text{red}} = \frac{\sigma_R}{\eta}, \quad E_{\text{red}} = \frac{E_{\text{c.m.}}}{\xi},$$

where $\eta = (A_P^{1/3} + A_T^{1/3})^2$, $A_P$ and $A_T$ being the mass numbers of the projectile and target nuclei, $\sigma_R$ the total reaction cross section, and $\xi = Z_P Z_T / \eta^{1/2}$, where $Z_P$ and $Z_T$ are the charges of the nuclei. It has been determined that, reactions with different types of projectiles describe distinctive behaviors, regardless of their nuclear structure, binding energies or reaction mechanisms, as shown in Fig.(1) for a number of systems. It is observed that, for an energy range from $0.68$ MeV $< E_{\text{red}} < 2.1$ MeV, the trajectory described by the reduced total reaction cross section data for the halo systems with $^8$B and $^6$He with several targets, lies above that for "normal" weakly bound and this in turn lies above that for the tightly bound system $^{16}$O+$^{64}$Zn. Thus, it could be established that if the trajectories of Fig.(1) should be characterized by the mean value of the projectile binding energies, then these trajectories lie progressively lower as the binding energy increases. The lines in Fig.(1) are Wong’s model[16] $\chi^2$-fits to the three different trajectories as described by Kolata et al.[8].

On intuitive grounds, the radial extension of the halo structure of $^8$B and its low threshold energy (0.137 MeV) can affect the potential barriers. As a matter of fact, the large radial
extension of $^8\text{Be}$ lowers the barrier, this effect is important in the whole energy interval at near Coulomb barrier energies\cite{17}. Also, the small value for the threshold energy of $^8\text{Be}$ favors the production of breakup processes ($^8\text{Be} \rightarrow^7 \text{Be} + p$) particularly important at low energies. This fact has an important effect as regards fusion reactions. Since, the breakup processes represented by a direct reaction polarization potential, has an opposite effect, that is, it becomes repulsive particularly at energies around and below the Coulomb barrier\cite{18}, thus, it rises the fusion barrier and consequently the fusion cross section results hindered. It is well known that fusion is strongly affected by couplings to different reaction channels. Particularly important is the coupling between the incident elastic channel and the fusion one, represented by a fusion polarization potential $U_F(r, E) = V_F(r, E) + i W_F(r, E)$, where $W_F(r, E)$ is related to the loss of incident flux that goes to fusion. Here, $V_F(r, E)$ is a virtual real potential that arises from the dispersion relation\cite{19, 20}, that represents fusion excitations. Similarly, the fusion process is strongly affected by couplings to direct reaction channels, especially breakup reactions in the case of weakly bound systems ($^8\text{Be} \rightarrow^7 \text{Be} + p$, where the continuum part of the spectrum is fed) at low incident energies. The associated polarization potential is called the direct reaction polarization potential $U_{DR}(r, E) = V_{DR}(r, E) + i W_{DR}(r, E)$, where, as before, $W_{DR}(r, E)$ accounts for the loss of incident flux going to direct reactions and $V_{DR}(r, E)$ arises from couplings to DR channels. The fusion barrier is affected by the action of competitive contributions included in $U_F(r, E)$ and $U_{DR}(r, E)$ i.e., an attractive fusion contribution $V_F(r, E)$ that lowers the barrier, and a direct reaction effect from $V_{DR}(r, E)$, (repulsive for weakly bound systems) that rises it. These real polarization potentials should reflect the effect of the halo structure of $^8\text{Be}$ on the fusion barrier height and barrier position.

It is the purpose of the present work to calculate the effects that the real polarization potentials $V_F(r, E)$ and $V_{DR}(r, E)$ have on the dynamic fusion barriers for $^8\text{Be}+^{58}\text{Ni}$. These dynamic polarization potentials are calculated from simultaneous $\chi^2$-analysis of elastic scattering angular distributions and fusion cross section data for several bombarding energies. $V_F(r, E)$ is assumed to have a volume Woods-Saxon geometrical shape, while $V_{DR}(r, E)$ has a surface form. The potential parameters are extracted from the simultaneous fit. Dynamical fusion barriers can be calculated once the radial real potentials $V_F(r, E)$ and $V_{DR}(r, E)$ are obtained by,

$$V_F(r, E) = V_{\text{coul}}(r) - V_{\text{bare}}(r) - V_F(r, E) - V_{\text{DR}}(r, E),$$

(2)

where $V_{\text{coul}}(r)$ is the Coulomb potential and $V_{\text{bare}}(r)$, the average nuclear potential that correctly gives the nominal Coulomb barrier. As it will be seen for the present nuclear system, $V_F(r, E)$ becomes attractive for the range of energies studied, and thus, its effect is of lowering the barrier and consequently fusion is enhanced. On the other hand, $V_{DR}(r, E)$ becomes repulsive, it rises the fusion barrier, and its effect is of suppressing fusion reactions. Fusion barrier heights $V_{B,F}$ and positions $R_{B,F}$ are estimated from Eq. (2) as the maximum of this functional, and the radial distance where the maximum is achieved, respectively. The competitive effect of $V_F(r, E)$ and $V_{DR}(r, E)$ on lowering and rising the fusion barrier is determined. Also, the effect of the direct reaction polarization potentials (breakup) on fusion cross section is calculated by considering the particular effect of each $V_{DR}$ and $W_{DR}$. That is, the barrier rising given by $V_{DR}$ and the loss of incident flux that goes to breakup reactions given by $W_{DR}$. Finally, it is shown that the energy dependent real and imaginary parts of the polarization potential $U(r, E) = V(r, E) + i W(r, E)$, where $V(r, E) = V_F(r, E) + V_{DR}(r, E)$ and $W(r, E) = W_F(r, E) + W_{DR}(r, E)$, which are linked by the dispersion relation, satisfy the so-called Breakup Threshold Anomaly (BTA)\cite{21, 22}.

The paper is organized as follows: the basic features of the model are given section 2, the results of the calculations and a discussion are presented in section 3, finally a summary is given.

2. Brief Model Description.

The Hamiltonian $H$ for the nuclear system is of the form,
where the distorted wave $\chi^{(+)}_a$ in the incident elastic channel $a$ satisfies the expression,

$$ (T_a + V_a)\chi^{(+)}_a = E_a\chi^{(+)}_a. $$

The potential $V_a$ is defined by,

$$ V(r, E) = V_{coul}(r) - V_{bare}(r) - U(r, E), $$

where the subindex $a$ has been suppressed. Here, $V_{coul}(r)$ is the Coulomb potential between the reacting ions, $U(r, E)$ is the polarization potential[20] and $V_{bare}(r, E)$ is double-folding density dependent nuclear bare potential (São Paulo Potential) given by,

$$ V_{bare}(r, E) = V_{SP P}(r, E) = V_{F ol}(r) \exp \left(-\frac{4v^2}{c^2}\right), $$

where,

$$ v^2(r, E) = \frac{2}{\mu} [E - V_{coul}(r) + V_{bare}(r, E) + U(r, E)], $$

is the relative velocity of the colliding nuclei and,

$$ V_{F ol}(r) = V_0 \int \rho(r_1)\rho(r_2) \delta(r - r_1 + r_2) \, dr_1 \, dr_2. $$

An extensive systematics of nuclear densities of the SPP has been proposed by L.C. Chamon et al.,[23, 24], in which, within the two-parameter Fermi distribution approach to describe the densities, the radii of the distributions are given by,

$$ R_{density} = (1.31A^{1/3} - 0.84) \, fm, $$

where $A$ is the number of nucleons in the nucleus. In a zero-range approximation the strength $V_0 = -456$ MeV-fm$^3$ is assumed. Also, within the systematics, the matter diffuseness of the density distributions has an average value $a = 0.56 \, fm$ throughout the periodic table. The normalization of the double-folding potential $e^{-4v^2/c^2}$ arising from the Pauli non-locality due to exchange of the nucleons vanishes at near barrier energies, and therefore the São Paulo potential becomes an usual double-folding potential.

Now, regarding the polarization potential $U(r, E)$ of Eq.(5), this consists of two parts, i.e.,

$$ U(r, E) = U_F(r, E) + U_{DR}(r, E), $$

where, $U_F(r, E)$ and $U_{DR}(r, E)$ are the fusion and DR polarization potentials given in terms of their real and imaginary parts[25, 26, 27],

$$ U_F(r, E) = V_F(r, E) + iW_F(r, E), \quad U_{DR}(r, E) = V_{DR}(r, E) + iW_{DR}(r, E). $$

where the real and imaginary parts satisfy the dispersion relation[19, 20], i.e.,

$$ V_{F,DR}(R_{sa}, E) = \frac{1}{\pi} P \int_0^\infty \frac{W_{F,DR}(R_{sa}, E')}{(E' - E)} \, dE', $$

at the strong absorption radius $R_{sa}$.

The fusion potentials $V_F(r, E)$ and $W_F(r, E)$ are assumed to have volume Woods-Saxon geometric forms,
\[ V_F(r, E) = V_{0,F}(E)f_F(r), \quad W_F(r, E) = W_{0,F}(E)f_F(r), \] (13)

where,
\[ f_i(r) = \frac{1}{1 + \exp[(r - R_i)/a_i]}, \quad i = F, DR. \] (14)

\( V_{F,0}(E) \) and \( W_{F,0}(E) \) are respectively the strengths of \( V_F(r, E) \) and \( W_F(r, E), \) \( a_F \) the diffuseness and \( R_F = r_F(A_p^{1/3} + A_T^{1/3}), \) \( r_F \) being the reduced radius parameter. That is, \( V_F(r, E) \) and \( W_F(r, E) \) have the same geometric shape with identical potential parameters.

Likewise, regarding the direct reaction polarization potentials \( V_{DR} \) and \( W_{DR}, \) these have the following surface forms,
\[ V_{DR}(r, E) = -4a_{DR}V_{0,DR}(E)\frac{df_{DR}}{dr}, \quad W_{DR}(r, E) = -4a_{DR}W_{0,DR}(E)\frac{df_{DR}}{dr}, \] (15)

where \( R_{DR} = r_{DR}(A_p^{1/3} + A_T^{1/3}), \ a_{DR} \) the diffuseness and \( r_{DR} \) the reduced radius parameters. As before, these potentials share the same shape and parameters. All the parameters of the real and imaginary fusion and direct reaction potentials are determined by a simultaneous \( \chi^2 \)-analysis of elastic scattering and fusion cross section data as it will be described in the next section.

Once the potential parameters are determined, the fusion and direct reaction cross sections are calculated by,
\[ \sigma_{F,DR}(E) = \frac{2}{hv} < \chi_a^{(+)\dagger} W_{F,DR}(E) | \chi_a^{(+)}> , \] (16)

\( v \) being the relative velocity between the nuclei. The total reaction cross section is then,
\[ \sigma_R(E) = \sigma_F(E) + \sigma_{DR}(E). \] (17)

The radial fusion barriers \( V_F(r, E) \) can be calculated from Eq.(2) and so, the particular effect of the fusion \( V_F(r, E) \) and direct reaction \( V_{DR}(r, E) \) real polarization potentials on the fusion barrier can be studied. On the other hand, the effect of the these polarization potentials on fusion, is quantified by the expression,
\[ R_{V_F, V_{DR}}(E) = \frac{\sigma_F(V_F(E), V_{DR}(E))}{\sigma_F(V_F = 0, V_{DR} = 0)}. \] (18)

In the numerator, \( \sigma_F(V_F(E), V_{DR}(E)) \), two cases are considered, that is, \( V_F(E) \neq 0 \) but \( V_{DR}(E) = 0 \), and both \( V_F(E) \neq 0, V_{DR}(E) \neq 0 \). The denominator, \( \sigma_F(V_F = 0, V_{DR} = 0) \) is the fusion cross section when both potentials are turned-off. Of course, \( \sigma_F(V_F \neq 0, V_{DR} = 0) \) corresponds to the actual calculation for fusion cross section resulting from the simultaneous analysis. In this manner, the particular effect on the barrier by considering the polarization potentials \( V_F(E) \) and \( V_{DR}(E) \) can be studied.

Similarly the net effect of breakup reactions on fusion due to the barrier lowering produced by, \( V_{DR} \) and the loss of incident flux into DR represented by \( W_{DR}, \) can be studied by,
\[ R_{V_F, W_{DR}}(E) = \frac{\sigma_F(V_{DR}(E), W_{DR}(E))}{\sigma_F(W_{DR} = 0, W_{DR} = 0)}, \] (19)
3. Results.

The bare potential of Eq.(6) is a parameter-free potential since for a given nuclear system, it depends only on the incident energy. Nuclear matter densities are calculated with matter radii and diffuseness determined by the systematics.

The values of the fusion and direct reaction potential parameters resulting from a $\chi^2$-analysis of fusion and elastic angular distributions data[6, 7] for $^8\text{B}+^{58}\text{Ni}$ are listed in Table 1. The upper part of Fig.2 shows the fitting to elastic scattering angular distributions as obtained from the parameters of Table 1. The bottom part shows the total reaction cross section $\sigma_{R,exp}$ (full circles) as extracted from the elastic scattering angular distributions while the blank circles $\sigma_{R,th}$ represent the values obtained by the calculations. The full squares $\sigma_{F,exp}$ are the fusion measurements of Ref.[7], while the empty squares are the fusion cross sections at the energies $E_{c.m.} = 18.17, 20.56, 22.23, 23.90$ and $25.75$ MeV which are obtained by subtracting the CDCC breakup cross section $\sigma_{BU, CDCC}$ calculation of Ref.[6] (dotted-line) from the total reaction cross. These are the values used for fusion cross section in the $\chi^2$-analysis. sections.

Table 1. Parameters for the dynamical fusion and direct reaction polarization potentials as obtained by the $\chi^2$-analysis. Potential strengths in MeV, diffuseness and reduced radii in fm.

| $E_{c.m.}$ | $V_{0,F}$ | $W_{0,F}$ | $a_{F}$ | $r_{F}$ | $V_{0,DR}$ | $W_{0,DR}$ | $a_{DR}$ | $r_{DR}$ | $\chi^2/N$ |
|------------|-----------|-----------|---------|--------|------------|-----------|---------|--------|--------|
| 18.17      | 5.31      | 0.78      | 0.80    | 1.44   | -2.90      | 1.67      | 0.78    | 1.56   | 0.09   |
| 20.56      | 5.99      | 1.81      | 0.84    | 1.50   | -2.15      | 0.60      | 0.63    | 1.63   | 0.40   |
| 22.23      | 3.27      | 1.80      | 0.94    | 1.52   | -2.19      | 0.45      | 0.49    | 1.60   | 0.07   |
| 23.90      | 1.83      | 2.43      | 0.91    | 1.54   | -1.50      | 0.51      | 0.57    | 1.62   | 0.30   |
| 25.75      | 1.80      | 3.01      | 0.91    | 1.54   | -1.50      | 0.35      | 0.57    | 1.62   | 0.48   |

The radial dependence of the fusion barrier can now be calculated for the different energies. Fig.3 shows the result for the lowest energy $E_{c.m.} = 18.17$ MeV. The nominal Coulomb barrier calculated with the bare potential $V_{bare}$ shown by the solid line gives a barrier height and barrier position of approximately $20.8$ MeV and $8.89$ fm. This barrier is lowered by the action of the fusion potential $V_F$ (dashed-line) which means that fusion is enhanced. However, when the repulsive direct reaction polarization potential is considered, the barrier (dotted-line) is risen above the nominal barrier and slightly pushed to larger distances ($9.3$ MeV). So, the net effect of both potentials is to increase the barrier and therefore fusion is hindered. Figure 4, shows the results for the other energies, where it is observed that fusion suppression decreases as the energy increases.

The quantitative effect of the real polarization potentials $V_F$ and $V_{DR}$ on the fusion barrier can be estimated from Eq.(18), respect to the nominal barrier. In Fig.(5a), $R_{V_F,V_{DR}=0}$ means that, the numerator of Eq.(17), is the fusion cross section calculated with $V_{DR} = 0$ while, $V_F$ and the imaginary potentials $W_F$ and $W_{DR}$ are those values obtained by the $\chi^2$-analysis. The denominator is the fusion cross section when, $V_{DR}$ and $V_F$ are turned-off while the imaginary parts $W_F$ and $W_{DR}$ are $\neq 0$. So, only the effects of the real polarization potentials are investigated. It is observed that $R_{V_F,V_{DR}=0} > 1$, so, fusion is enhanced respect to the nominal barrier. On the other hand, when both $V_F$ and $V_{DR}$ have the values determined by the analysis, the net effect is of suppression ($R_{V_F,V_{DR}} < 1$) in the whole range of energies. As observed, this effect diminishes as the energy increases. Now, regarding the effect on fusion produced by breakup reactions. This can be determined from Eq.(19). Fig.(5b) shows the results of three cases, namely, $R_{V_{DR}=0,W_{DR} \neq 0}$, $R_{V_{DR} \neq 0,W_{DR}=0}$ and $R_{V_{DR} \neq 0,W_{DR} \neq 0}$. In the last case, $\sigma(V_{DR} \neq 0,W_{DR} \neq 0)$ corresponds to the actual calculation of the fusion cross section as obtained by the simultaneous fitting of the data. As seen in Fig.(5a), fusion is suppressed in all cases ($R < 1$). As a matter of fact, the less is $R$ the bigger is the suppression effect. The energy
behavior of \( R_{DR=0,W_{DR} \neq 0} \) shows the increasing importance of loss of incident flux into breakup reactions as the energy decreases. The repulsive nature of \( V_{DR}(E) \) associated to \( W_{DR}(E) \) by means of the dispersion relation, has a even stronger effect on fusion suppression.

Finally, the energy dependence of the real and imaginary parts of the total polarization potential \( U(R_{sa}, E) \) at the strong absorption radius \( R_{sa} \) is shown in Fig.(6). As seen, these potentials show that the BTA[21, 22] is present for the weakly bound system \(^8\text{B}+^{58}\text{Ni}\). That is, for energies around and below the Coulomb, the imaginary potential \( W(R_{sa}, E) \) does not decrease, as it does for tightly bound nuclei. This is so, since it should account for significant breakup yields at these energies. The total real polarization potential \( V(R_{sa}, E) \) which include contributions from polarization effects coming from all the possible reaction mechanisms, that is, the attractive polarization effects from fusion and the repulsive contributions from couplings to the breakup channel. As seen in Figs.(3) and (4), the repulsive effects dominate at the lower energy regime.

In summary, the radial fusion barriers of the system \(^8\text{B}+^{58}\text{Ni}\) at energies around the Coulomb barrier have been calculated by means of fusion and direct reaction dynamical polarization potentials of volume and surface Woods-Saxon shapes, whose parameters are calculated from simultaneous \( \chi^2 \)-analysis of elastic scattering and fusion cross section data. The specific effects on the barriers from the fusion \( V_F \) and direct reaction \( V_{DR} \) real polarization potentials have

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**Figure 2.** (above) Elastic scattering angular distributions and (below) total reaction and fusion cross sections as obtained from the \( \chi^2 \)-analysis for \(^8\text{B}+^{58}\text{Ni}\). Data from Refs.[6, 7].
Figure 3. Radial dependence of the fusion barrier at $E_{c.m.} = 18.17$ MeV. Fusion and direct reaction polarization potentials are those obtained by the $\chi^2$-analysis.

Figure 4. Fusion barriers at $E_{c.m.} = 20.56, 22.23, 23.9$ and 25.75 MeV. The different lines correspond to those of Fig.3

been studied. It has been shown that fusion is enhanced by $V_F$ by a barrier lowering effect while it is suppressed by $V_{DR}$ due to a barrier rising effect. As the collision energy decreases the suppression effects overcome, due to the increasing importance of breakup couplings.

Also, the effect of breakup reaction couplings on fusion cross section has been determined by studying the separate effects on fusion from the barrier rising due to $V_{DR}$ and the loss of flux due to $W_{DR}$. It is found that the fusion suppression from $V_{DR}$ results stronger than that from $W_{DR}$. Finally, it has been found that, the energy dependence of the total polarization potential is consistent with the BTA, as is the case of many weakly bound systems
Figure 5. (a) Effect of fusion cross section due to by the barrier lowering and rising produced by the attractive and repulsive real polarization potentials $V_F$ and $V_{DR}$ respectively. (b) Effect due to direct reactions (basically breakup), on fusion cross sections from barrier rising ($V_{DR}$) and loss of flux ($W_{DR}$).

Figure 6. Total real $V(R_{sa}, E)$ and imaginary $W(R_{sa}, E)$ energy dependence of the polarization potentials at the strong absorption radius $R_{sa}$. 
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