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Abstract. Two types of optical model interactions, namely the double-folding density dependent São Paulo potential (SPP) and the Woods-Saxon potential (WSP) are used to study the appearance of the Threshold Anomaly (TA) or the Breakup Threshold Anomaly (BTA) for the nuclear systems $^6$Li+$^{28}$Si for energies around the Coulomb barrier. In the first case, the presence of the anomaly is determined from the energy dependence of the normalization parameters $N_R$ and $N_I$ as found from fittings to elastic scattering angular distributions. In the second case, the presence of the anomaly is investigated by the energy variation of the fusion and direct reaction parts of the Woods-Saxon potential. In this case, the parameters of the fusion and direct reaction potentials are calculated by a simultaneous analysis of elastic scattering, fusion and total reaction cross sections. It is found in both cases that the BTA appears for the $^6$Li+$^{28}$Si reaction. As for $^7$Li+$^{28}$Si, the calculation with the SPP shows that the usual TA appears but the dispersion relation is not satisfied, however the WSP indicates that indeed the BTA shows up.

1. Introduction

The presence of the Threshold Anomaly (TA), i.e., the distinctive energy dependence behavior of the real and imaginary parts of the optical potential obtained from elastic scattering fits around the Coulomb barrier, has been well established in reactions with stable tightly bound nuclei. The characteristic behavior of the imaginary part of the optical potential is such that its strength sharply drops as the energy decreases towards the barrier energy. On the other hand, the real part presents a strong localized peak just around the barrier[1]. This phenomenon is understood in terms of the strong coupling between the elastic channel to other reaction channels that produces an additional attractive polarization potential $\Delta V(E)$. The absolute value of this attractive real polarization potential increases the strength of the already attractive nuclear potential $V_0$ which in turn lowers the fusion barrier and consequently produces an enhancement of the fusion cross sections at energies below the Coulomb barrier. This energy dependence of the real potential is expressed so by,

$$V(E) = V_0 + \Delta V(E),$$

(1)
where $V_0$ is the real nuclear potential at high energies and $\Delta V(E)$ the polarization potential. As the energy approaches the barrier, the imaginary potential $W(E)$ decreases as a consequence of the closing of reaction channels. That is, fusion and non-elastic peripheral reactions gradually become less important as coupling to the corresponding reaction channels decrease. The dispersion relation connects the energy variation of the real and imaginary parts of the polarization potential, this relation is expressed by the principal integral value[2],

$$\Delta V(E) = \frac{P}{\pi} \int_{0}^{\infty} \frac{W(E')}{E' - E} dE'.$$

(2)

It is clear that any strong change in $W(E)$ must be accompanied by a localized strong variation in $\Delta V(E)$ as occurs in the TA. Recently, several studies have been dedicated to the case when weakly bound are involved instead of tightly bound nuclei. In this case, the energy dependence of the real $V(E)$ and imaginary $W(E)$ potentials around $V_B$ is quite different. Weakly bound projectiles with a low threshold energies present strong couplings between the breakup and elastic scattering channels. That is, around and even for energies below the Coulomb barrier, reactions with weakly bound nuclei show strong direct reaction yields, particularly breakup or transfer cross sections. In such a situation, the imaginary part $W(E)$ of the optical potential can not sharply decrease, as it does for tightly bound nuclei. According to Eq.(2), the real polarization potential $\Delta V(E)$ does not contribute to increase the strength of the attractive nuclear potential, but instead has a repulsive character. This in turn increases the fusion barrier instead of lowering it and thus hinders fusion cross sections. This new phenomenon has been named the Breakup Threshold Anomaly (BTA) in contraposition to the usual Threshold Anomaly (TA)[3].

The BTA has been studied in a large number of nuclear systems involving weakly bound projectiles with a variety of medium and large mass targets. For instance the weakly bound projectile $^9$Be with targets such as $^{27}$Al[4], $^{65}$Zn[5, 6, 7, 8], $^{144}$Sm[9, 10] and with $^{208}$Pb, $^{209}$Bi [11, 12]. Projectiles such as $^6$Li and $^7$Li have been investigated in reactions with $^{208}$Pb[3, 13], $^{27}$Al[14, 15, 16], $^{144}$Sm[17], $^{58,64}$Ni [18, 19], $^{59}$Co [20], $^{90}$Zr [21], $^{138}$Ba [6, 22, 23], $^{28}$Si [24]. As a general trend, the BTA is observed in all systems involving $^6$Li, but for $^7$Li its presence is observed for some systems and not for others. This may probably be due to the competition between the attractive polarization potential due to the bound excited state of $^7$Li [23] and the repulsive breakup polarization potential [25]. The BTA has also been observed is some neutron and proton radioactive halo nuclei such as, $^6$He with $^{209}$Bi[26], and $^8$B with $^{58}$Ni[19, 27].

In this paper, we consider the extensive experimental work for elastic scattering, transfer and breakup cross section for the systems $^6,7$Li + $^{28}$Si done by A. Pakou and collaborators[24, 28, 29, 30, 31, 32, 33, 34, 35]. For these nuclear systems, their measurements show that transfer cross sections become higher than the breakup cross sections at near barrier energies. They argue that transfer channels can also be important at low energies for some weakly bound systems, and therefore those channels may be the main responsible for the non-decreasing of the imaginary potential at near barrier energies. We intend to study the presence of the TA or BTA for the $^{6,7}$Li + $^{28}$Si, by using two different polarization potentials, so that the conclusions reached are potential independent. The parameter-free non-local São Paulo potential (SPP)[36] has been extensively used to describe elastic scattering of nuclei such $^6,7$Li and $^9$Be with medium and heavy mass targets while Woods-Saxon potentials (WSP) with volume and surface parts have also been applied to the simultaneous description of fusion and elastic scattering data of various systems[9, 19, 37]. In the latter case, the volume potential is determined so as to fit fusion cross section data, whereas the surface part is responsible for direct reactions, including breakup and transfer processes. In the search of the volume part of the Woods-Saxon potential, fusion cross sections measurements of M. Sinha et al., will be considered[38, 39, 40]. In the next section, a brief description of the SPP and WSP will be given. Section III will be concerned with the
results for the Threshold Anomaly for the systems studied and finally, section IV is dedicated
to a brief summary and conclusions.

2. Brief description of the theoretical framework
The Hamiltonian \( H \) for the nuclear system is of the form,

\[
H_a = T_a + V_a,
\]

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,

\[
V(r, E) = V_{Coul}(r) - U_N(r, E),
\]

where the subindex \( a \) has been suppressed. Here, \( V_{Coul}(r) \) is the Coulomb potential and \( U_N(r, E) \)
is the energy dependent nuclear potential which is the sum of a bare potential with a slow energy
dependence, plus the dynamic polarization potential which may have rapid variations at near
barrier energies.

For the dynamical polarization potential, the best physical approach might be to use a double-
folding potential for the real part with realistic matter densities and any reasonable approach for
the imaginary part. This imaginary part can be constructed with the same radial dependence
as the real part (double-folding potential) with a strength coefficient obtained at energies well
above the barrier. However, when one studies the optical potential at near barrier energies,
strength coefficients are needed to account for dynamic polarizations. A normalized version of
the São Paulo optical potential \([36, 41]\) reads as,

\[
U_{SP}(r, E) = \left[N_R(E) + iN_I(E)\right]F(r, E),
\]

where \( F(r, E) \) is the double-folding potential, i.e.,

\[
F(r, E) = V_F(r)e^{-4v^2/c^2}.
\]

Here \( c \) is the speed of light, \( v \) the relative velocity of the colliding ions given by,

\[
v^2(r, E) = \frac{2}{\mu} \left[E - V_{Coul}(r) - U_N(r, E)\right],
\]

and \( V_F(r) \) is the folding potential given in terms of the matter densities of the ions i.e.,

\[
V_F(r) = \int \rho(r_1)\rho(r_2)V_0\delta(r - r_1 + r_2)dr_1dr_2,
\]

where a zero-range approximation is assumed with strength \( V_0 = -456 \) MeV-fm\(^3\). In order
to provide a parameter-free description of the interaction an extensive systematics of nuclear
densities has been proposed by L.C. Chamon\([41]\). It has been found within the two-parameter
Fermi distribution approach to describe the densities that the radii of the distributions are given
by,

\[
R_0 = 1.31A^{1/3} - 0.84,
\]

where \( A \) is the number of nucleons in the nucleus. The systematics also shows that the matter
diffuseness \( a \) 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. The energy dependent normalization parameters \( N_R(E) \) and \( N_I(E) \) of Eq. (6) take into account the effects of the dynamic polarization potentials (DPP) arising from direct channel couplings. The real and imaginary parts of the DPPs should be related by the dispersion relation\([3]\), \( i.e.\),

\[
N_R(E) = N_{R0} + \Delta N_R(E),
\]

while,

\[
\Delta N_R(E) = \frac{1}{\pi} \mathcal{P} \int_0^\infty \frac{N_I(E')}{E' - E} dE'.
\]

\( N_{R0} \) is energy independent and is determined at some high enough energy for which the values of \( \Delta N_R(E) \) and \( N_I \) are known. The energy dependence of the parameters \( N_R \) and \( N_I \) are calculated by fitting the elastic scattering angular distributions.

In order to obtain model independent conclusions about the threshold anomaly, a combined use of different approaches for determining the energy dependence of the optical potential is desirable. For this reason, we also use Woods-Saxon shape polarization potentials to calculate the energy dependence of such nuclear polarization potential. In this case, the total interaction between projectile and target of Eq.(5) is

\[
V(r, E) = V_{\text{Coul}}(r) - V_0(r) - U_N(r, E),
\]

where \( V_0(r) \) is the energy independent average nuclear potential and \( U_N(r, E) \) is the nuclear dynamic polarization potential given by,

\[
U_N(r, E) = V(r, E) + iW(r, E).
\]

The real and imaginary potentials \( V(r, E) \) and \( W(r, E) \) are split into a fusion and direct reaction parts. That is, \( V(r, E) = V_F(r, E) + V_{DR}(r, E) \) and \( W(r, E) = W_F(r, E) + W_{DR}(r, E) \). The fusion potentials account for nuclear fusion processes \( \sigma_F \) whereas direct reaction potentials for direct reaction cross sections \( \sigma_{DR} = \sigma_R - \sigma_F \). The potentials \( V_F \) and \( W_F \) are assumed to have Woods-Saxon volume shapes with the same parameters while \( V_{DR} \) and \( W_{DR} \) have surface geometrical forms also with the same parameters. The parameters of the potentials are calculated by a simultaneous \( \chi^2 \)-analysis of elastic scattering and fusion cross section data. It should noticed that that real fusion and direct reaction potentials are connected by the dispersion relation as in Eq.(2),

\[
\Delta V_{F,DR}(E) = \frac{1}{\pi} \mathcal{P} \int_0^\infty \frac{W_{F,DR}(r, E')}{(E' - E)} dE'.
\]

Fusion and direct reaction cross sections are calculated by the well known equation,

\[
\sigma_i = \frac{2}{\hbar v} < \chi^{(+)}(i)|W_i|\chi^{(+)}> , i = F, DR
\]

being \( \chi^{(+)} \) distorted wave the solution of Eq.(4). For the nuclear systems under study, namely \( ^6,^7\text{Li}+^{28}\text{Si} \), the energy variation of the parameters \( N_R(E) \) and \( N_I(E) \) of the SPP is thus studied as the collision energy approaches the Coulomb barrier. These parameters are obtained by fitting the experimental elastic scattering angular distributions for each system. On the other hand, the same energy dependence of \( V_{F,DR}(E) \) and \( W_{F,DR}(E) \) of the Woods-Saxon potential is also searched from a simultaneous fitting of elastic scattering and fusion data. Conclusions about the presence of the usual Threshold Anomaly or the Breakup Threshold Anomaly can be drawn from the energy dependence of all these functions as will be shown in the next section.
Figure 1. Real $N_R$ and imaginary $N_I$ parameters of the SPP as obtained from elastic scattering angular distributions and the dispersion relation calculation for $^6\text{Li}^+\text{Si}$. 

Figure 2. Same as Fig.1 but for $^7\text{Li}^+\text{Si}$. 

3. Results and discussion

In the calculation of the parameters $N_R$ and $N_I$ of the double-folding interaction SPP and the fusion and direct reaction parameters of the Woods-Saxon potentials $W_F$ and $W_{DR}$ as described above, we consider the extensive elastic scattering angular distribution measurements by A. Pakou et al.,[28] for $^6\text{Li}^+\text{Si}$ at the near barrier energies $E_{lab}$ = 7.5, 9, 11 and 13 MeV. At higher energies, $E_{lab}$ = 20, 27 and 30 MeV, the data from Refs.[42, 43, 44] are also used. For fusion cross sections $\sigma_F$, the recent sub- and above barrier measurements of M. Sinha et al., are considered[38]. Total reaction cross sections $\sigma_T$ are those from Refs.[29, 45]. As for the system $^7\text{Li}^+\text{Si}$, elastic scattering, fusion and total reaction cross section data are those of Refs. [24, 39, 40] and [29, 30], respectively. The dots in Figs.(1a), (1b), (2a) and (2b) show the results for $N_R$ and $N_I$ that best fit the elastic scattering angular distributions for both systems. The error bars shown are calculated by increasing the $\chi^2/N$ value in one unity, where $N$ is the number of data points for each energy.

The linear fits shown for $N_I$ are used to integrate the dispersion relation whose results are shown by the curves in the figures for $N_R$. These results show that for $^6\text{Li}^+\text{Si}$ the BTA is present, since considering the error bars at the lowest energies an increasing trend is observed.
for \( N_I(E) \) of Fig.(1b) as the collision energy is decreased towards the barrier \( V_B \). On the other hand, the results for \( N_R \) of Fig.(1a), show a repulsive character as the energy decreases from high energies towards the barrier energy. Besides, it is observed that the result of the dispersion relation calculation shown by the curve in Fig.(1a) is close to the values obtained for \( N_R \) from the \( \chi^2 \)-analysis of elastic scattering distributions and so, the dispersion relation is satisfied. As for the \( ^7\text{Li}+^{28}\text{Si} \) system, the results for \( N_R \) and \( N_I \) are given in Figs.(2a) and (2b). It can be observed in Fig.(2b), the linear fits to the values obtained (dots) for \( N_I \) from the \( \chi^2 \)-fitting to the elastic distributions are more congruent with the usual TA. This is more evident precisely around the barrier \( E_{c.m.}/V_B \approx 1 \) where \( N_I \) decreases as the energy is decreased. The dots in Fig.(2a) are the results for \( N_R \) as obtained from the analysis of the data while the curves are the results of the integration of the dispersion relation that correspond to the linear fits of \( N_I \). As observed, the results of the integration do not agree with the fitted values of \( N_R \) as the energy diminishes towards the barrier. As a matter of fact, a contrary character appears, that is the integration predicts an attractive polarization potential whereas the the fitting a repulsive character. The calculations of A. Pakou et al.[24] for the system \(^7\text{Li}+^{28}\text{Si} \) for the parameters \( N_R \) and \( N_I \) of the double-folding BDM3Y1 interaction show a similar behavior as ours.

We now consider the Woods-Saxon polarization potential with fusion and direct reaction parts. In the simultaneous \( \chi^2 \)-analysis of the fusion and elastic scattering angular distributions data, we fix the diffuseness and reduced radii of the fusion and direct reaction potentials for all energies as \( a_F = 0.6 \text{ fm}, r_F = 1.4 \text{ fm}, a_{DR} = 0.6 \text{ fm} \) and \( r_{DR} = 1.6 \text{ fm} \) for \(^6\text{Li}+^{28}\text{Si} \) and \( a_F = 0.6 \text{ fm}, r_F = 1.4 \text{ fm}, a_{DR} = 0.7 \text{ fm} \) and \( r_{DR} = 1.6 \text{ fm} \) for \(^7\text{Li}+^{28}\text{Si} \). As described in Refs.[9, 19, 37], the real \( V_F \) and imaginary \( W_F \) parts of the Woods-Saxon fusion polarization potential are assumed to have the same geometric volume shape, with the same diffuseness and reduced radius. On the other hand, the corresponding direct reaction real and imaginary polarization potentials \( V_{DR} \) and \( W_{DR} \) have the same surface geometric shape, with the same diffuseness and reduced radius. So, only the strengths \( V_F(E), W_F(E), V_{DR}(E) \) and \( W_{DR}(E) \) are the variables to be obtained in the simultaneous analysis of the data. The results of the potential strengths for the system \(^6\text{Li}+^{28}\text{Si} \) and \(^7\text{Li}+^{28}\text{Si} \) are presented in Fig.(3) and Fig.(4). As seen in Figs.(3d) and (4d), as the collision energy approaches the corresponding barrier energy \( V_B \), the fusion potentials \( W_F(E) \) decrease even above the barrier, while the real counterparts \( V_F(E) \) shown in Figs.(3c) and (4c) have an increasing behavior around the barrier. This is consistent with the expected behavior of the TA. Regarding the surface potential strengths \( V_{DR}(E) \) and \( W_{DR}(E) \), Figs.(3a) and (3b) for \(^6\text{Li}+^{28}\text{Si} \) system give the results obtained from the simultaneous fitting (dots). It can be observed that these are compatible with the BTA. This is so since within the error bars, \( W_{DR}(E) \) presents an increasing tendency as the collision energy approaches the barrier from higher energies, while \( V_{DR}(E) \) presents a slight decrease. That is, the total strength of the real nuclear potential decreases resulting in a less attractive potential and therefore fusion reactions are hindered. As for the system \(^7\text{Li}+^{28}\text{Si} \), the values for \( W_{DR}(E) \) (dots) shown in Fig.(4b) follow a slight increasing tendency as the energy decreases towards the barrier \( V_B \). The linear fit of Fig.(4b) indicates that indeed an increasing behavior is adequate for \( W_{DR}(E) \). This fact is an indicator that also the BTA is present for \(^7\text{Li}+^{28}\text{Si} \). On the other hand, it is true that for energies just around the barrier, a decreasing \( W_{DR}(E) \) is present. The values for \( V_{DR}(E) \) show a small repulsive behavior in the energy region where \( W_{DR}(E) \) increases, being also an indicator that the BTA is present for \(^7\text{Li}+^{28}\text{Si} \).

The curves shown in Figs.(3a), (3c), (4a) and (4c) are the results of the dispersion relation integral corresponding to the linear forms of Figs.(3b), (3d), (4b) and (4d). Clearly, the results of the dispersion relation agree with the values obtained from the fitting of the data.

It is interesting to notice that since the diffuseness parameters \( a_F \) and \( a_{DR} \) and reduced radii \( r_F \) and \( r_{DR} \) of the potentials are kept constant for all collision energies for both nuclear systems, thus the energy behavior of the potential strengths shown by Figs.(3) and (4) is the same for
Figure 3. Strengths for direct reaction and fusion potentials as obtained from the simultaneous \( \chi^2 \)-analysis of elastic scattering, fusion and total reaction cross section data for \(^6\text{Li} + ^{28}\text{Si}\).

Figure 4. Same as Fig.3 but for \(^7\text{Li} + ^{28}\text{Si}\).

The radial dependent volume and surface geometric functions \( V_{DR}(E, r) \), \( W_{DR}(E, r) \), \( V_F(E, r) \) and \( W_F(E, r) \), when these are evaluated at the strong absorption radius \( R_{sa} \). This is illustrated in Fig.(5) where it also seen that \( |W_F(E, R_{sa})| < |W_{DR}(E, R_{sa})| \) at all energies. That is, direct reactions dominate over fusion ones, particularly as the energy approaches the barrier energy \( V_B \). As claimed by Pakou et al., [28, 29, 24, 30, 31, 32, 33, 34, 35], direct reactions are not just breakup processes, but also transfer channels, which may even be more important than breakup at some energies for these systems.

The results of the simultaneous fits are given in Figs.(6) and (7) for fusion and reaction cross section data. The calculated values for fusion cross sections \( \sigma_F \) are shown in Fig. (6) for both systems. Reaction cross sections \( \sigma_T \) are shown in Fig. (7). For those energies where elastic scattering measurements are available but fusion data were not explicitly measured, we assumed those values obtained from a Wong fitting to the existing data[46]. Similarly, for those energies where reaction cross sections are not directly measured, we considered those values extracted from the corresponding elastic scattering data.
4. Summary and conclusions

Simultaneous fits of elastic scattering, fusion $\sigma_F$ and total reaction cross sections $\sigma_T$ for the systems $^6\text{Li}+^{28}\text{Si}$ and $^7\text{Li}+^{28}\text{Si}$, at energies around and above the Coulomb barrier, have been presented. Two kinds of calculations have been performed: using a double-folding and Woods-Saxon potentials. In the calculations with the double folding Sã o Paulo potential, the strengths of the real and imaginary potentials were varied to fit the data. For the $^6\text{Li}+^{28}\text{Si}$ system, clear indication of the presence of the BTA was observed, and the dispersion relation between real and imaginary potentials was satisfied. For the $^7\text{Li}+^{28}\text{Si}$ system, this evidence is not so clear, due to the competition between attractive and repulsive polarization potentials. Furthermore, the dispersion relation is not observed for this system. This fact seems to occur for some systems, when double folding potentials are used, and the explanation for that has to be investigated. In the calculations using Woods-Saxon potentials, volume and surface polarization potentials have been used to describe fusion and direct reaction cross sections, respectively. In the simultaneous
Figure 7. Calculated reaction cross section values as obtained from the simultaneous $\chi^2$-analysis. To differentiate the systems, the experimental and calculated values corresponding to $^7$Li+$^{28}$Si have been multiplied by 10.

$\chi^2$-analysis, direct reaction cross section data are obtained from $\sigma_{DR} = \sigma_T - \sigma_F$. Also, in the present work, the energy dependence of the real and imaginary parts of the fusion potential and direct reaction potential have been determined. It has been found that the real and imaginary parts of the potentials, follow the dispersion relation for both systems. It is clearly observed that the fusion potential strengths, $V_F(E)$ and $W_F(E)$ behave according to the well known Threshold Anomaly. That is, $W_F(E)$ decreases as the energy approaches the barrier from higher energies and $V_F(E)$ has an increasing behavior for energies slightly above the barrier. On the other hand, the direct reaction potential strengths $W_{DR}(E)$ have a slight increasing tendency as the energy is lowered towards the barrier. The real $V_{DR}(E)$ manifests a small repulsive character in this same energy region. This conjugated effect for the energy dependence of the polarization potentials indicate that the systems $^6$Li+$^{28}$Si and $^7$Li+$^{28}$Si present the so-called Breakup Threshold Anomaly. This phenomenon is more clearly observed for the $^6$Li+$^{28}$Si system than for $^7$Li+$^{28}$Si. This fact can be understood because $^6$Li has a smaller breakup threshold energy and no bound excited state, as compared with $^7$Li. Since, the optical potential diffuseness and radial parameters of the fusion and direct reaction potentials are energy independent, the geometric functions $V_F(E, r)$, $W_F(E, r)$, $V_{DR}(E, r)$ and $W_{DR}(E, r)$ have the same energy dependence at the strong absorption radius $R_{sa}$ as their strengths $V_F(E)$, $W_F(E)$, $V_{DR}(E)$ and $W_{DR}(E)$. It is thus observed that at $R_{sa}$, direct reaction potentials dominate over fusion ones at all energies, particularly as the energy approaches the barrier. This is in agreement with the fact that direct reactions, particularly breakup and/or transfer cross sections, are important and non-vanishing at energies below the barrier energy. The simultaneous $\chi^2$-analysis of the data for both systems $^6$Li+$^{28}$Si and $^7$Li+$^{28}$Si are in close agreement to the data. Finally, in this work we have shown very clearly that the method of separating the optical potential into fusion and direct reaction potentials is a powerful tool to disentangle the opposite effects of production of attractive and repulsive polarization potentials by different reaction mechanisms. The two combining effects may lead to different net effects on the energy dependence of the total optical potential of different combinations of projectiles and targets.

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