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Cite as: AIP Conference Proceedings **791**, 146 (2005); https://doi.org/10.1063/1.2114703
Published Online: 12 October 2005

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Is the optical model valid for the scattering of exotic nuclei?

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Abstract. The optical model, and its applications to elastic, inelastic and transfer reactions is reviewed. The applicability of the optical model to the collisions of exotic nuclei is discussed. The sensitivity of recent experimental data of elastic scattering of ^{6}He on ^{208}Pb to the characteristics of the optical potential is investigated.

Keywords: Optical model, Exotic nuclei, Coupled Channels, Continuum discretization, Elastic scattering, Break-up
PACS: 24.10.Ht, 24.10.Eq, 25.60.Bx, 25.70.Bc

INTRODUCTION

In the study of nuclei, the structure properties are often inferred from reaction measurements. This can only be done if the dynamics of the collision of the projectile with the target is properly described. For that, one would need to solve the many body problem, including all degrees of freedom. In practise, this is not possible, and one has to select certain states which are relevant, and define the proper effective interactions. From formal point of view, the optical model defines the expression of these effective interactions. However, from the practical point of view, the optical model introduces a phenomenological object, the optical potential, which is fitted to some experimental observables (usually the elastic scattering cross sections), and then it is used to describe other scattering observables (inelastic, transfer, etc). In this way, important structure parameters from the colliding nuclei, such as deformation lengths and spectroscopic factors, can be obtained. This procedure has been broadly successful for the description of the structure of stable nuclei. However, as we shall dicuss throughout this paper, it is not trivial that it should also be valid for the scattering of weakly bound exotic nuclei.

Let us recall the main features of the optical model. When two nuclei collide, the scattering wavefunction will have, in general, components of all possible reaction channels. The complete solution of this scattering wavefunction would require to solve a many body Schrödinger equation, containing the interaction $\mathcal{V}$, that will depend in general on the relative as well as on the internal coordinates of the colliding nuclei. This is not possible in general. However, if we restrict our description of the collision to some specific channels, characterized by the projector P, and $Q = 1 - P$ as the complementary projection operator, then the "model" wavefunction $P\Psi$ is the solution of a Schrödinger equation which contains an interaction given by

$$U(E) = P\mathcal{V}P + P\mathcal{V}Q\frac{1}{E^{+} - QHQ}Q\mathcal{V}P. \tag{1}$$

The formal derivation of this optical potential was due to Feshbach [1]. In this work, we will make use of Feshbach formalism, as presented by Satchler [2].

The optical model in elastic scattering

Let us first consider elastic scattering. Then, P projects on the ground state of projectile and target. The optical potential U is a function of the variables associated to the relative motion ($\vec{r}$ and $\vec{p}$, in general). The expression (1) of the optical potential is, in principle, of little practical use, because it would require to solve the scattering problem with all the relevant degrees of freedom. The success of the optical model relies on the fact that one is able to approximate the complicated non-local operator U by a local, L-independent complex function which can be written as the sum of

CP791 Reaction Mechanisms for Rare Isotope Beams, 2nd Argonne/MSU/JINA/INT RIA Workshop
edited by B. Alex Brown

a real and an imaginary potential

$$U(E) \simeq V(r,E) + iW(r,E). \tag{2}$$

It is by no means trivial that this can be achieved. However, the experience of several decades of studies of nuclear collisions indicates that, for stable nuclei, local optical potentials, obtained taking some usual analytic forms (usually Woods-Saxon), and fitting the parameters to reproduce elastic scattering data, give a sensible approach to the complicated object $U(E)$ of eq. (1).

The real part of the optical potential $V(r,E)$ is obtained in some cases by double folding of an effective nucleon-nucleon interaction over the densities of projectile and target. This procedure is justified when the "direct" term PVP dominates in eq. (1). The imaginary potential $W(r,E)$ comes from the "dynamic polarization" term $P\mathscr{V}Q\frac{1}{E^+-QHQ}Q\mathscr{V}P$ and cannot, in general, be obtained by folding. The imaginary optical potential can be parameterized in terms of some analytic form (Woods-Saxon). The study of the fenomenology of nuclear collisions indicates that the imaginary potential vanishes at distances in which there is not a significant overlap of the nuclear densities. However, it has been found that there is an enhanced surface absorptions in the case of weakly bound projectiles [3].

One important aspect about the description of elastic scattering is the presence of strong absorption [2]. In the nuclear collisions of heavy ions, it is found that, when the angular momentum of the relative motion is below a certain critical value, which is called grazing angular momentum, there is a strong damping of outgoing waves. That means that the S matrix, for angular momenta well below the grazing, has very small values. This makes that the elastic scattering is not really sensitive to the values of the optical potential at distances well below the strong absorption radius, which is the distance of closest approach corresponding to the classical trajectory associated to the grazing angular momentum.

In strong absorption situations, the elastic scattering is mostly sensitive to the value of the optical potential at the strong absorption radius. For smaller distances, the optical potential may be very strong, but the S matrix tends to vanish. For larger distances the optical potential is very small (apart from the monopole Coulomb potential), and both direct and dynamic polarization potentials tend to vanish.

The real and imaginary parts of the optical potential (1) are, in general, energy dependent. Then, it can be shown that the energy dependence of the real and imaginary parts are linked by the expression

$$\Re(U(E) - U(E_0)) = \frac{\mathscr{P}}{\pi}\int dE' \frac{\Im(U(E') - U(E_0))(E_0 - E)}{(E - E')(E_0 - E')}. \tag{3}$$

Assuming that the complicated operator $U(E)$ can be substituted by the local, L-independent potentials given by eq. (2), the dispersion relation become

$$V(E,r) - V(E_0,r) = \frac{\mathscr{P}}{\pi}\int dE' \frac{(W(E',r) - W(E_0,r))(E_0 - E)}{(E - E')(E_0 - E')} \tag{4}$$

The validity of this relation has been investigated in detail, within the context of the study of the "threshold anomaly". This refers to a sharp maximum in the real potential, at energies around the Coulomb barrier, associated to a sharp increase imaginary potential. This effect has been observed in the scattering of ^{16}O+^{208}Pb [4], and in many other systems. In some systems, however, there is not a threshold anomaly, in the sense that there is not any sharp energy dependence of the optical potential. In any case, the dispersion relations (4) are fulfilled.

The optical model in inelastic scattering

The optical model can be applied to the description of inelastic scattering. In this case, the projector operator P includes the relevant states of the projectile and target. The only change is that both real and imaginary potentials in eq. (2) will become matrices $\mathbf{V}(\vec{r},E) + i\mathbf{W}(\vec{r},E)$, and they will depend explicitly on the direction of $\vec{r}$. A multipole expansion gives rise to the usual formfactors:

$$U(E) \simeq \mathbf{V}(\vec{r},E) + i\mathbf{W}(\vec{r},E) = \sum_{\lambda\mu}(\mathbf{V}_{\lambda\mu}(r,E) + i\mathbf{W}_{\lambda\mu}(r,E))Y^*_{\lambda\mu}(\hat{r}) \tag{5}$$

The determination of the real and imaginary formfactors $\mathbf{V}_{\lambda\mu}(r,E) + i\mathbf{W}_{\lambda\mu}(r,E)$ is not trivial. In the collective model, when the excited states included in the calculation can be considered in terms of surface oscillations, the

formfactors can be obtained deforming the phenomenologic optical potentials. This procedure, plus some additional assumptions, leads to formfactors given by the derivatives of the optical potential multiplied by the deformation length operator $\delta_{\lambda\mu}$.

$$\mathbf{V}_{\lambda\mu}(r,E) + i\mathbf{W}_{\lambda\mu}(r,E) \simeq \delta_{\lambda\mu}\left(\frac{dV(r,E)}{dr} + i\frac{dW(r,E)}{dr}\right) \tag{6}$$

This expression may be justified for the real formfactors, assuming that the direct term $P\not{V}P$ is dominant, but it is not at all justified for the imaginary formfactors. However, in general, one assumes that the deformation lengths of the real and imaginary potentials are the same, and in this way one obtains in general a reasonable agreement with inelastic scattering data. This procedure allows to extract the values of the matrix elements of the deformation length operator from the inelastic cross section data.

Alternatively, the formfactors can be obtained by folding nucleon-nucleon interactions with transition densities. Again, this procedure is reasonable for the real formfactors, assuming that the direct term is dominant, but it does not apply to the imaginary formfactor. Usually, what it is done is to multiply the real formfactors obtained from the folding procedure by a complex factor $N_r(E) + iN_i(E)$, and in this way all the formfactors in the coupled channels systems are expressed in terms of two parameters, which are a function of the energy, and should be linked by dispersion relations. This procedure is purely empirical, but it has been used successfully by several authors [5, 6].

The optical model in transfer reactions

The measurement of transfer cross sections plays a crucial role in the description of the single particle structure of nuclei. It allows, in principle, to measure the spectroscopic factors of the colliding nuclei. However, this requires a precise understanding of the reaction mechanism. The description of a transfer process implies two logical steps. First, one approximates the complicated many body problem of all the participant nucleons in terms of a three-body problem,

$$(A+C)+B \rightarrow A+(C+B) \tag{7}$$

where one has two "cores", A and B and a transferred particle C. Indeed, the fact that one reduced the many body problem to a three body problem implies that the interactions become complex, and will be given in general by an operator U given by eq. (1), where P projects in the internal states considered of the clusters A, B and C. This operator would be, in general, a three body potential, which is a function of the relative coordinates and momenta of the clusters. Note that there is a priori no reason for which this effective interaction should be written as the sum of two-body potentials which depend only on the relative coordinates or momenta of each pair of clusters $A+C$, $B+C$ and $A+B$. This will only be the case if the dynamic polarization terms in (1) is neglected. Even for the direct term $P\not{V}P$, writing it as a sum of $A+C$, $B+C$ and $A+B$ potentials implies that one neglects the effects of the Pauli principle, because the presence of, say, particle A affects the states to which $B+C$ can scatter. Despite of these problems, what it is usually done is to take for the interaction the sum of the two-body optical potentials of $A+C$, $B+C$ and $A+B$, obtained (when possible) from the fit of elastic scattering data at some average energies E_{AC}, E_{BC}, E_{AB}.

$$U(E) \simeq U_{AC}(\vec{r}_{AC}, E_{AC}) + U_{BC}(\vec{r}_{BC}, E_{BC}) + U_{AB}(\vec{r}_{AB}, E_{AB}) \tag{8}$$

Note that this approach has some consistency problems. In the incident channel, the system $A+C$ is bound. So, the energy E_{AC} is negative, and the interaction U_{AC} should be purely real, to be able to maintain an stationary bound state. In the incident channel, it would be reasonable to take the same energy per nucleon for the fragments as the one for the projectile, so that E_{BC} and E_{BA} are positive. Hence, the interactions U_{BC} and U_{BA} will be complex. However, in the final channel, $B+C$ is bound, E_{BC} is negative, and the interaction U_{BC} should be purely real, while the others are complex.

The second step is to solve the three body problem. This could be done, in principle, solving the Faddeev equations. However in practise this is more commonly done using a DWBA approach, the validity of which depends on how accurately is the exact three-body wave function described in terms of the distorted waves in the incident or outgoing channels. Thus, the DWBA approach, and also its extensions as the CCBA or the CRC approach, depend on whether the break-up components of the exact three-body wavefunctions affect significantly the transfer process.

Even assuming that the break-up components are not important for the transfer process, it is clear that the integrals that appear in the DWBA expressions depend on the values of the wavefunctions in the incident and outgoing channels at all distances, and not only the asymptotic part. The use of optical potentials to generate distorted waves ensures, at

best, that the asymptotic behavior of the wavefunctions is correct, but it does not say much about the wavefunctions in the interior. Nevertheless, in situations of strong absorption, it could be argued that the only configurations that affect transfer are those in which the colliding nuclei just touch each other, and these should be well described if the asympotics is correct.

The success of the optical model

Despite the limitations discussed above, the optical model, with optical potentials obtained from elastic cross sections, has been very successful in allowing us to understand the mechanisms of nuclear collisions, as well as extracting structure information from the scattering data of stable nuclei. Some of the highlights of the optical model are the following:

- Elastic cross sections are reproduced with optical potentials which depend smoothly on the energy and the target mass.
- Deformation parameters are obtained from the fits to inelastic scattering.
- Spectroscopic factors are obtained from the fits to transfer reactions.
- Sub-barrier fusion enhancement is explained through coupled channels effects in the entrance channels.
- The sharp energy dependence in the elastic optical potential, where present (threshold anomaly), is explained as the effect of coupling to collective states or transfer channels.

Why does the optical model work so well? There is no clear answer to this question. However, the success could be related to the fact that the relative short range of the nuclear interaction, plus the presence of strong absorption makes that the relevant scattering observables are sensitive to a peripheral region of the configuration space. Hence, the optical model wavefunctions describing the reaction channels may be sufficiently accurate in the peripheral region.

THE OPTICAL MODEL IN THE COLLISIONS OF EXOTIC NUCLEI

The optical model, which is very successful to describe the collisions of stable nuclei, as previously discussed, may not be adequate to describe exotic nuclei. Exotic nuclei are, in general, less bound than stable nuclei. Hence, the dynamics of the collision may be much more affected by the excitation of the internal degrees of freedom.

In general, the optical potential defined by eq. (1) is applicable to all nuclei, stable or exotic. The difference relies on the fact that the role of the dynamic polarization component will be more important in the case of exotic nuclei, because the excited states not included in the calculation (described by the projector Q) have lower energies, and are more easily accessible. This means that non-local effects, as well as the energy and L-dependence of the optical potential can be more important in the case of exotic nuclei.

The success of the optical model for the description of elastic scattering relies on the fact that one is able to express the complicated non-local operator U by a local, L-independent complex function which can be written as the sum of a real and an imaginary potential. This is by no means trivial in the case of scattering of exotic nuclei. One can indeed fit a local, L independent potential to reproduce the elastic scattering of exotic nuclei at a given energy. However, these potentials may display unexpected radial and energy dependences.

The use of double folding interactions to obtain the real potential is adequate, assuming that the direct term $P\mathscr{V}P$ dominates the interaction. This assumption will not be adequate for exotic nuclei. Dynamic polarization effects should be taken into account. In the case of dipole coulomb excitation, an analytic expression of the polarization potential can be used to describe this effect [7, 8].

The relevance of strong absorption for exotic nuclei is also, a priori, less important for exotic nuclei than for stable nuclei. Exotic nuclei do not have a compact structure. It should be not expected that they will abandon the elastic channel completely when the distance of closest approach between the centers of the projectile and target gets below a certain value. Exotic nuclei, in their ground state, may be described as a combination of several configurations of their fragments. Some of these configurations will be strongly absorbed for a certain distance of the centers of mass, but not others. Thus, one should expect that absorption does not appear at some fixed distance. Instead, it could be spread over a range of distances, and hence of orbital angular momenta.

Let us consider inelastic phenomena. The use of the collective model, which is based on the existence of a well defined nuclear surface, may not be adequate to describe neutron-rich exotic nuclei, with extended neutron skins

or halos. Folding potentials may not be adequate, for the same reasons described for elastic scattering. The main uncertainty, however, is related to the values of imaginary formfactors. There is no reason for which the imaginary deformation parameter of the optical potential should be equal to the real one, and neither of these should be simply related to the structure properties of exotic nuclei.

Microscopic approaches to the scattering of exotic nuclei

Break-up channels play an important role in the scattering of weakly bound nuclei. The explicit description of break-up channels can be done by means of some continuum discretization procedure. Let us consider some exotic nucleus P, which can be described as a weakly bound system $A+C$. It collides with a target B, and as a result many different processes may occur. The exotic nucleus may survive in the elastic channel, or go to some other bound state of the system $A+C$ (inelastic). The exotic nucleus may be broken, and then the fragments A and C will come out, with some angular and energy distribution (break-up). The fragment C may be transferred to the target, forming a compound system $B+C$.

One can consider explicitly the channels in which the fragments A, C and B remain in their ground state. In this situation, one explicitly considers the elastic and inelastic channels, transfer channels and break-up states. The optical potential will be given by an operator U which is given by eq. (1), where P projects on the ground state of the clusters A, C and B, and Q projects into the states in which these clusters suffer any excitation. It should be noticed that the optical potential is a three-body operator, depending on the three relative co-ordinates, and it may not be written, a priori, as a sum of optical potentials. However, as previously discussed, one might, with many reservations, assume that the interactions are given as a sum of optical potentials between the fragments (8).

When the projectile is weakly bound, it is important to consider explicitly the break-up channels. One possibility is to expand the complete three-body wavefunction in terms of the bound and continuum states of the $A+C$ subsystem. We will refer to this treatment of the continuum, which emphasizes on the $A+C$ continuum states, as "direct break-up". To do this consistently requires to consider that the interaction between the fragments $A+C$ is purely real $U_{AC}=V_{AC}$. The continuum discretization procedure would substitute the infinite range, non-normalizable continuum wavefunction of $A+C$ by normalizable "bins" or "pseudostates", which would in general have a large spatial extension. From these wavefunctions, one obtains the transition densities, which can be bound-bound, bound-continuum or continuum-continuum. Note that the bound-continuum, and specially the continuum-continuum transition densities have a very long range.

The usual approach to obtain the coupling formfactors between the ground state and the continuum states is called the cluster folding. It consists in folding the cluster optical potentials U_{AB} and U_{CB}, obtained from the elastic scattering of the fragments of the projectile with the target, with the very extense transition densities. Note that this procedure can lead to important uncertainties in the transition potentials, associated to the fact that the optical potentials U_{AB} and U_{CB} are very uncertain at small distances r_{AB}, r_{CB}. These short range contributions affect the coupling formfactors at larger projectile-target separations, due to the long range of the transition densities.

The direct break-up plus cluster folding approach has been used for deuteron scattering [9], and also for ^{6,7}Li scattering [5]. This approach may be adequate when the scattering energy is relatively high, and the relative momenta of the break-up fragments is small, compared with the momentum of the projectile. This approach is in principle inadequate to describe transfer, because the complex potential U_{CB} cannot hold bound states [9].

An alternative treatment of the continuum is to expand the complete three-body wavefunction in terms of the bound and continuum states of the $B+C$ subsystem. We will refer to this treatment of the continuum, which emphasizes the $B+C$ continuum states, as "transfer to the continuum". This treatment requires that the interaction between the fragments $B+C$ is purely real $U_{BC}=V_{BC}$. The bound and continuum states would be obtained solving the Schrödinger equation for the $B+C$ system. Then, the continuum states can be discretized. The interactions U_{AB} and U_{AC} can be taken as the corresponding optical potentials, and then transfer and break-up can be consistently calculated [10].

It is an open question whether "transfer to the continuum" is more adequate than "direct break-up", for the purpose of evaluating break-up cross sections. One would expect that when the fragment C is left with a small relative energy with respect to the target B, then transfer to the continuum would be a more adequate approach than direct break-up.

OPTICAL POTENTIALS OF ^{6}HE ON ^{208}PB

In this section we will present the preliminary analysis of experimental data taken at the CRC at Louvain la Neuve. We performed measurements of the elastic scattering of ^{6}He + ^{208}Pb at energies ranging from 14 to 22 MeV. We also measured the alpha particles coming from break-up. We have also considered the elastic scattering of this same system at 27 MeV, which was recently published [11].

We used a detector array consisting of CD Silicon telescopes, covering forward as well as backward scattering angles. Details of the experiment as well as the measured cross sections will be published separately.

The most remarkable qualitative feature of the elastic scattering data, at all the energies measures, was the absence of a rainbow, this is, of a maximum in the ratio of the elastic differential cross section to the Rutherford value. This feature, which was also seen at 27 MeV [11], is a clear indication of the presence of long range absorption. Note that the rainbow occurs because the attractive nuclear force starts to overcome the deflection produced by the repulsive Coulomb force. If there is long range absorption, the trajectories for which the rainbow occurs get partly absorbed, and the rainbow dissapears.

Part of the long range absorption is due to dipole Coulomb excitation. This effect can be explicitly taken into account including the dipole polarization potential [7, 8], which is completely determined from the $B(E1)$ distribution of the projectile. This polarization potential accounts for part of the long range absorption required to fit the data. However, as it is shown in Figure 1, an additional long range absorption is needed to fit the data. To interpret this figure, it should be considered that the strong absorption radius is around 11.0 fm. So, one can see that the imaginary potentials that fit the data extend well beyond this distance.

We have performed several fits to the data, using different families of optical potentials. The real potentials used in the calculations had a radius of 7.86 fm, and a diffuseness of 0.811 fm. The depth depends on the energy, and it is shown in the figures. Our calculations, which will be reported in detail elsewhere, indicate clearly that the real potentials that fit the data are well determined in the vicinity of the strong absorption radius. However, as we see in the figure, the imaginary potentials are well determined around 13.0 to 13.5 fm, at which the real potential is negligible. This fact should be taken into account when investigating the energy dependence of the optical potentials. The question about the presence of a threshold anomaly in the optical potential cannot be investigated, as for stable nuclei, looking at the energy dependence of the real and imaginary potentials at the strong absorption radius.

The nature of this long range absorption has to be investigated. The imaginary potential which arises of (1) is a non-local operator. It is possible that the long range found in the phenomenologic imaginary potentials shown in figure 1 is an indication of this non-locality. It seems reasonable to consider that the long range absorption is associated to the effect of break-up channels. A proper description of the break-up of ^{6}He requires to consider four-body continuum states, which is very difficult, although there is rapid progress in this field. We have performed preliminary calculations making use of a di-neutron model for ^{6}He, which is considered as an α-particle plus a di-neutron cluster. The calculations indicate that the coupling to break-up channels indeed generates the long range absorption shown in the elastic data.

We have also investigated the distribution of α-particles coming from break-up. Data seem to indicate that the neutrons are left with a very small energy with respect to the target. This indicates that the transfer to the continuum approach may be more adequate to describe some break-up observables.

SUMMARY AND CONCLUSIONS

We have reviewed the applicability of the optical model for the scattering of exotic nuclei. Following Feshbach formalism, we expect that an optical potential (1) should describe consistently all the relevant channels (elastic, inelastic, break-up, transfer) in the collision of exotic nuclei, as it was the case for the collisions of stable nuclei. However, we expect that the difference will be that, in the scattering of exotic nuclei, dynamic polarization effects will play a much more important role than for stable nuclei.

The crucial aspect of the practical use of the optical model in the collisions of stable nuclei is the use of local imaginary potentials, which are obtained from the fit to elastic scattering data, and are then used in reaction calculations. It is not clear that the same procedure will be valid for exotic nuclei. Non-locality effects, break up effects, as well as long range absorption produced by the loosely bound structure of exotic nuclei, can modify the relation between elastic and reaction observables which is implicitly assumed when local imaginary potentials are used in reaction observables.

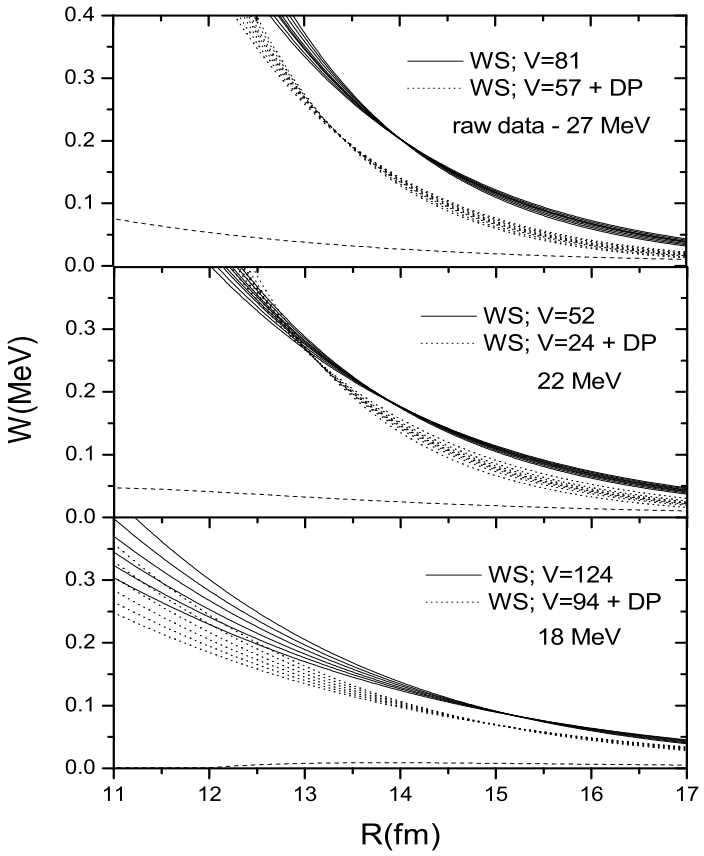

FIGURE 1. Imaginary potentials obtained from several fits to the data. The dashed lines correspond to the imaginary dipole coulomb polarization potential. Dotted lines correspond to the nuclear potentials needed to fit the data, once that the dipole polarization potentials are included. Full lines are the potentials needed to fit the data, without the explicit inclusion of dipole polarization effects.

The strong absorption argument, by which scattering observables are sensitive only to the optical potential around the strong absorption radius, is not applicable in the case of loosely bound exotic nuclei.

A preliminary analysis of experimental data of ^{6}He on ^{208}Pb at energies around the Coulomb barrier indicates that the optical potentials that fit the elastic scattering data show a long range absorption. This absorption is partly due to the Coulomb dipole polarizability, but there are other mechanisms generating absorption at relatively large separations of ^{6}He and ^{208}Pb. Microscopic calculations including break-up states indicate that the absorption mechanisms are associated to processes in which ^{6}He looses its weakly bound neutrons.

We consider that it is necessary to improve our understanding of the reaction mechanisms which are relevant in the collisions of weakly bound nuclei. For that purpose, one needs to have detailed and precise experimental data of elastic scattering and reaction cross sections of weakly bound systems, such as ^{6}He, for which the structure is reasonably well understood. The comparison of experimental data with the scattering calculation will indicate if the present approximation of the optical model, which is based on the use of local optical potentials between the fragments of the projectile and the target, is adequate for exotic nuclei. If this is not the case, then new concepts should be applied to correlate the different scattering observables, which do not rely on the use of local optical potentials. One such approach is the Uncorrelated Scattering Approximation [12, 13], in which elastic and break-up S matrices are obtained from the S-matrices of the fragments with the targets, and no optical potentials have to be used.

A better understanding of the relation between structure properties and reaction observables for exotic nuclei, for which the structure is reasonably well known, will facilitate to obtain reliable structure information for more exotic nuclei, from the measurement of reaction cross sections.

ACKNOWLEDGMENTS

This work has been supported by the spanish CICyT projects FPA2002-04181-C04-02, FPA2002-04181-C04-04, and FPA2003-05958.

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