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Absorption Effects in $d + \alpha$ Scattering*

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Abstract: Absorption effects in $d + \alpha$ scattering are taken into account by a simple modification in the resonating-group formulation. It is shown that this modification results in the elimination of spurious resonances and leads to a satisfactory agreement with measured values for differential scattering and total reaction cross sections.

[Nuclear scattering $\propto (d,d)$, $E = 0 - 22$ MeV; calculated phase shifts and $\sigma(\theta)$. Resonating-group method with absorption.]

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In a previous investigation,¹ we have examined the effect of deuteron specific distortion in the $d + \alpha$ problem by means of a microscopic procedure. This procedure consists in the addition of a large number of square-integrable distortion functions with linear variational amplitudes into the usual no-distortion resonating-group wave function. The result shows that this effect is indeed quite important and its proper treatment leads to the consequence that the same nucleon-nucleon potential can now be used to yield a consistent and satisfactory treatment of both the $\alpha + \alpha$ and the $d + \alpha$ systems.

The addition of these distortion functions into our calculation resulted in the appearance of resonances in the energy region above 14 MeV. However, it should be emphasized that the appearance of these resonances is expected in a calculation of this type and one must not consider their presence as indicating the existence of true resonance states in the compound system. In fact, it has been pointed out recently by Schmid and Schwager² that this type of resonance structure merely reflects the omission of open reaction channels in the calculation, and they have proposed a rather formal procedure by which these resonances may be eliminated. In the present communication, we show that a more physical prescription can also be used to eliminate these spurious resonances.

For a proper description of the behavior of a nuclear system, a calculation should, in principle, include all open channels. In practice, however, such a calculation is usually not possible in energy regions where many-particle channels are open, and one must account for the presence of these open channels in a phenomenological manner. The procedure we employ is to add an

imaginary potential to the direct nuclear potential and to allow the characteristic levels, introduced into our theory through the use of distortion functions, to decay into the neglected channels. In what follows, we shall illustrate this procedure using the $d + \alpha$ system as an example.

The wave function which describes the $d + \alpha$ system is written as

$$\Psi_N = \Psi_0 + \sum_{i=1}^N \sum_{l=0}^{\infty} \tilde{B}_{li} \tilde{\Psi}_{li}, \quad (1)$$

where the notation is the same as that of Ref. 1. The first term in Eq. (1) represents the $d + \alpha$ no-distortion resonating-group wave function, while the second term contains the distortion functions. Using the projection equation

$$\langle \delta \Psi_N | H - E' | \Psi_N \rangle = 0, \quad (2)$$

we obtain the equation

$$\begin{aligned} & \langle \phi_\alpha \phi_d \xi | H - E' | \Psi_0 \rangle_{\vec{r}} \\ &= \sum_{i=1}^N \sum_{l=0}^{\infty} \frac{\langle \phi_\alpha \phi_d \xi | H - E' | \tilde{\Psi}_{li} \rangle_{\vec{r}} \langle \Psi_{li} | H - E' | \Psi_0 \rangle}{E_{li} - E'} \end{aligned} \quad (3)$$

with

$$\begin{aligned} & \langle \phi_\alpha \phi_d \xi | H - E' | \Psi_0 \rangle_{\vec{r}} \\ &= \eta_0 \left\{ \left[-\frac{\hbar^2}{2\mu} \nabla^2 - E + V_D(r) + V_C(r) \right] F(\vec{r}) + \int K(\vec{r}, \vec{r}') F(\vec{r}') d\vec{r}' \right\} \end{aligned} \quad (4)$$

and again the same notation as Ref. 1. To crudely account for transitions from the $d + \alpha$ channel into omitted channels, we replace $V_D(r)$ in Eq. (4) by $V_D(r) + iW(r)$, with³

$$W(r) = -W_0 \left\{ \frac{1}{1 + e^{(r-R)/a}} + \frac{4e^{(r-R)/a}}{[1 + e^{(r-R)/a}]^2} \right\}, \quad (5)$$

and replace the characteristic energies $E_{\lambda i}$ in Eq. (3) by $E_{\lambda i} - i \frac{1}{2} \Gamma$. The rationale for the addition of the imaginary potential is well known, and in fact we have employed such a procedure to obtain good agreement with experimental data in previous resonating-group calculations.⁴ Our main concern in the present work is to examine the effect of allowing the characteristic energies $E_{\lambda i}$ to become complex.

Our motivation for the above modification of the characteristic energies is based on the idea that a metastable state can be described in terms of a complex characteristic energy, with the lifetime of the state inversely proportional to the imaginary part.⁵ Thus, in the present example, we replace the characteristic energy $E_{\lambda i}$ by $E_{\lambda i} - i \frac{1}{2} \Gamma$, where the adjustable parameter Γ represents roughly the decay width of the characteristic level into all channels except the elastic channel. In this way, we can roughly account for the decay of these levels into the neglected reaction channels. The number of parameters has been limited by assuming that Γ is the same for all characteristic levels, and by neglecting the level shift which, in general, arises from the coupling of the compound system to the open channels. However, we feel that these approximations should not be critical, as long as one considers scattering in the low-excitation region only.

The two parameters W_0 and Γ are energy dependent⁶ and can be varied to obtain agreement with experimental data, subject to the condition that they both equal zero for energies below the first reaction threshold at $E = 2.225$ MeV. To further simplify the determination of these parameters, we assume the simple relation

$$\Gamma = \lambda W_0, \quad (6)$$

and we find that with $\lambda \geq 10$, spurious resonances are eliminated for values of W_0 which yield satisfactory results for the total reaction cross section. The choice of λ is not critical, nor in fact is the relation of Eq. (6), as long as the threshold behavior of Γ is given reasonably. Therefore, a value of $\lambda = 10$ has been adopted in all our computations.

The values of the only adjustable parameter W_0 are determined by requiring that the calculated differential cross sections in the angular region around the diffraction maximum agree as well as possible with the experimental data.⁷⁻⁹ The resultant values of W_0 at c.m. energies of 5.31, 5.98, 8.00, and 9.31 MeV are equal to 0.76, 0.85, 1.15, and 1.30 MeV, respectively.

To illustrate our results, we show the calculated differential cross section at 8 MeV in Fig. 1. At this energy, the calculated total reaction cross section is 340 mb, which compares favorably with measured values at nearby energies.¹⁰ Also, one can see from this figure that the agreement with experiment is quite good, except in the region of diffraction minima. This discrepancy is most likely due to the omission of noncentral components in our nucleon-nucleon potential.

It should be mentioned that in our previous calculations of ${}^3\text{He} + \alpha$

and $^3\text{He} + ^3\text{He}$ scattering,⁴ it was found that an odd-even orbital angular-momentum dependence in the imaginary potential, characterized by a parameter C_I , led to an improved agreement with experiment. In the present case, we have examined the sensitivity of our calculation to the parameter C_I , and find that because of the relatively poor fit at the diffraction minima, a rather wide range of C_I is acceptable. Therefore, we have simply taken C_I equal to zero in this analysis.

To obtain values of W_0 at energies where experimental data are not available, we have used an interpolation procedure based on the four values of W_0 given above and the value of $W_0 = 2$ MeV at $E = 55$ MeV determined in Ref. 1. The dashed curve in Fig. 2 represents our interpolated values for W_0 . It should be emphasized that since our main purpose is to examine the influence of reaction channels on the real part of the scattering phase shift, precise values of W_0 are not required.

Using values of W_0 determined from Fig. 2, we have calculated $d + \alpha$ phase shifts up to an energy of 22 MeV. The real parts of the $\ell = 0$ and $\ell = 2$ phases are shown by the solid curves in Fig. 3. In this figure, the dashed curves show the result of a calculation with $\Gamma = W_0 = 0$ at all energies. It can be clearly seen that the addition of absorption effects into our calculation eliminates the spurious resonances in both the $\ell = 0$ and $\ell = 2$ partial waves.¹¹ Phase shifts in $\ell = 1$ and $\ell = 3$ partial waves are not shown, but here also spurious resonances (see Fig. 5 of Ref. 1) are eliminated.

A comparison of the real parts of the calculated and empirical phase shifts is also shown in Fig. 3. Here, the empirical results are those of

Schmelzbach et al.¹² and Darriulat et al.¹³ As can be seen, the agreement is indeed rather satisfactory.

In conclusion, we have shown in this study that even a relatively crude phenomenological consideration of absorption effects provides a significant improvement in the description of the $d + \alpha$ scattering problem. In particular, the procedure proposed here eliminates the spurious resonances and yields good agreement with the experimental differential scattering and total reaction cross-section data. To further ascertain whether this procedure will yield similarly satisfactory results in other nuclear systems, we are presently examining the importance of distortion and absorption effects in the $\alpha + \alpha$ and $n + t$ systems. The results of these studies will be reported in a future publication.

Footnotes and References

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Figure Captions

Figure 1: Comparison of calculated differential cross sections with experimental data at $E = 8.0$ MeV. The solid dots represent the experimental data of Ref. 8, while the crosses represent the experimental data of Ref. 9.

Figure 2: Imaginary-potential depth W_0 as a function of energy. The solid dots represent the four values of W_0 determined from fitting experimental data as explained in the text.

Figure 3: Real parts of the $\ell = 0$ and $\ell = 2$ phase shifts as a function of energy. The solid curves represent the results of our calculation which includes absorption effects. The dashed curves represent the results when no absorption is included. The data points represent the real parts of the phase shifts δ_ℓ^J given in Refs. 12 and 13, with $\text{Re } \delta_\ell^{\ell+1}$ represented by solid dots, $\text{Re } \delta_\ell^\ell$ represented by open circles, and $\text{Re } \delta_\ell^{\ell-1}$ represented by crosses.

Fig. 1

Fig. 2

Fig.3