Nuclear Structure Approach to the Calculation of the Imaginary Alpha-Nucleus Optical Potential

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MASTER

[NUCLEAR REACTIONS (α, α) scattering, calculation of imaginary
optical potential at $E = 31$ and 100 MeV.]

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Abstract

A microscopic calculation of the second-order imaginary optical potential for $^{40}\text{Ca}(\alpha, \alpha)$ is made for incident energies of 31 and 100 MeV using RPA transition densities for intermediate excited states. The projectile is treated as an elementary particle, and the alpha-nucleon interaction is normalized by fitting 3^- inelastic cross sections with a folded M3Y potential. The use of an optical Green's function for the intermediate propagator is found to be important. Equivalent local potentials are obtained and used to calculate elastic scattering cross sections. Agreement with low-angle experimental data is fair at 31 MeV but at 100 MeV the calculated cross sections indicate much too little absorption.

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I Introduction

Elastic scattering of alpha particles is one of the longest and best known nuclear processes. The rapid, regular diffraction pattern, a result of quantum mechanical scattering of a heavy nuclear particle from a rather well defined region of the nuclear surface, was explained by Blair¹⁾ using the sharp cutoff model. As is the case with other projectiles, later work with the optical model has given us a fairly accurate, detailed description of the process. The optical potentials consist of a real part whose radius is somewhat larger than that of the nuclear mass or charge distribution and an imaginary part which accounts for the loss of flux to other open inelastic and rearrangement channels. Both real and imaginary part are usually to be taken of volume type (Saxon-Woods).

Although the real part of the alpha-nucleus potential has been successfully calculated by folding some sort of alpha-nucleon interaction with the nuclear density^{2,3,4)}, the imaginary part of the potential W has usually been obtained phenomenologically⁴⁾. Recently Vinh Mau has reported microscopic calculations⁵⁾ of W for $^{40}\text{Ca}(\alpha, \alpha)$ treating the alpha particle as a distinguishable elementary particle. The alpha-nucleon interaction was determined by folding a nucleon-nucleon interaction⁶⁾ with the nuclear density of the alpha particle. The calculations were simplified by use of an average excitation energy and the closure approximation for the intermediate spectrum. Because of the use of closure, the resulting potential would not be expected to be applicable at low projectile energies where only a few inelastic channels are open, nor should it show energy-dependent effects due to opening of new inelastic channels. The resulting potential is of the volume type and increases in strength with increasing energy.

In this paper we present a microscopic calculation of the imaginary optical potential for $^{40}\text{Ca}(\alpha, \alpha)$ using the nuclear structure approach^{5,7,8)}. As in ref. 8) we use RPA densities⁹⁾ to characterize the intermediate states. Since we treat the alpha particle as elementary, no exchange effects are included explicitly. The intermediate alpha-particle propagator is calculated in an optical potential, which for α scattering gives rather different results than a free-particle propagator does. We use a folded alpha-nucleon interaction, renormalized by fitting the transition to the first inelastic 3^- state at each energy considered.

Section II describes briefly the theory and computational method. Section III contains some of the details of the calculation and the dependence of the results on parameters. In section IV the results for the calculated imaginary optical potentials are shown. Both the nonlocal form $W(r, r')$ and the local-equivalent potentials $\tilde{W}(r)$ are presented for incident alpha-particle energies of $E_\alpha = 31$ MeV and 100 MeV. At each energy $^{40}\text{Ca}(\alpha, \alpha)$ differential cross sections are calculated with phenomenological potentials in which the imaginary part has been replaced by the theoretical potential $\tilde{W}(r)$. The results are compared in Section IV with $^{40}\text{Ca}(\alpha, \alpha)$ data and with calculations using totally phenomenological potentials. Section V contains a brief summary and conclusions.

II Theory and Method of Computation

For scattering of non-identical particles, Feshbach¹⁰⁾ has given a formula for the imaginary optical potential which, to second order¹¹⁾ in the projectile target-nucleon interaction is

$$W(\vec{r}, \vec{r}') = \text{Im} \sum_N \langle \psi_0 | V | \psi_N \rangle_{\vec{r}} g_N(\vec{r}, \vec{r}') \langle \psi_N | V | \psi_0 \rangle_{\vec{r}'} \quad (1)$$

where ψ_N are the intermediate states of the target, $g_N(\vec{r}, \vec{r}')$ is the intermediate projectile Green's function with kinetic energy $E - E_N$, and V is the projectile target-nucleon interaction. Following ref. 8) eq. (1) can be written for α particle (spin = 0) scattering from a target nucleus with spin $J_A = 0^+$ in the following simple form:

$$W(\vec{r}, \vec{r}') = \text{Im} \left[\frac{1}{16\pi^2} \sum_{\ell, \ell_c, L} \delta_{L, J_N} \hat{\ell}^{-2} \hat{\ell}_c^{-2} \hat{L}^{-2} (\ell 0 \ell_c 0 | L 0)^2 \right. \quad (2)$$

$$\left. F_{J_N, L O L}^D(r) g_{\ell_c}(r, r') F_{J_N, L O L}^D(r') P_2(\cos \theta) \right]$$

where $\hat{\ell} = (2\ell+1)^{1/2}$. The quantity $g_{\ell_c}(r, r')$ in eq. (2) is the radial part of the optical Green's function describing the propagation of the intermediate projectile, and the direct transition form factor F^D is defined by

$$F_{J_N, L O L}^D(r) = \int dr_1 r_1^2 \rho_{L O L}^{J_N}(r_1) v_L(r, r_1) \quad (3)$$

In eq. (3) the coefficients v_L arise from the multipole expansion¹²⁾ of the effective, central α -target nucleon interaction and the nuclear transition density $\rho_{LSJ}^{J_N}$ is defined by

$$\rho_{LSJ}^{J_N}(r) = \sum_{n_1 \ell_1 j_1} \sum_{n_2 \ell_2 j_2} (X_{j_1 j_2}^{J_N} + Y_{j_1 j_2}^{J_N}) \frac{1}{\sqrt{4\pi}} \frac{1}{2} \hat{S}_{j_1 j_2} \hat{L} \hat{J} \hat{\ell}_1$$

$$(\ell_1 0 L 0 | \ell_2 0) \begin{pmatrix} \ell_2 & \frac{1}{2} & j_2 \\ \ell_1 & \frac{1}{2} & j_1 \\ L & S & J \end{pmatrix} R_{n_2 \ell_2 j_2}(r) R_{n_1 \ell_1 j_1}(r)$$

where the $X_{j_1 j_2}$ and $Y_{j_1 j_2}$ are the RPA particle-hole amplitudes¹³⁾ and the $R_{n_i \ell_i j_i}$ denote the radial single-particle wave functions.

Although eq. (2) is clearly nonlocal, the Green's function is peaked at $r=r'$ and oscillates like a diffraction pattern. The sum over N gives cancellations of the oscillations because of a range of frequencies, and the sum over intermediate nuclear states gives additional weighting in the locality region of $\vec{r}, \vec{r}'$. In the closure approximation, for example, an average Green's function $\bar{g}$ is used, and the sum over intermediate nuclear states is done by closure. The integral over the resulting local nuclear coordinate with the potential V can be carried out for a Gaussian interaction and a Gaussian-like density to give a nonlocal factor multiplying $\bar{g}(r, r')$. This factor has a range of about 1.5 times the range of the projectile target-nucleon interaction, and it helps to damp out the oscillations of the Green's function. However, for projectiles of high wave number the average Green's function will oscillate too rapidly to be affected much by this additional factor. As we shall see in Section IV the resulting non-locality may not be so well behaved as for low-energy nucleon projectiles.

The local approximation^{7,8)} has nevertheless been made, but, because of the oscillatory nature of the nonlocality, not only the usual Gaussian form was used to fit the nonlocal potential, but also an oscillatory form for comparison. The equivalent local potentials $\tilde{W}(r)$ are then calculated from these forms, and the differential cross sections are determined using otherwise phenomenological potentials with this theoretical local potential $\tilde{W}(r)$.

III Calculations

A The alpha-nucleon interaction

The projectile-target nucleon interaction has been calculated starting with the V_{00} part of the M3Y effective interaction of Bertsch et al.¹⁴⁾ This potential was then converted from a Yukawa-form to an equivalent Gaussian form according to the criterion that terms through second order in the power series expansion of the Fourier transform of the potential must agree. The volume integrals then agree, and the range parameters in $e^{-\gamma r}$ and $e^{-\alpha r^2}$ satisfy the relationship $(\alpha)^{1/2} = \gamma/2$. The resulting equivalent Gaussian form was folded¹⁵⁾ with a Gaussian internal wave function to give the result

$$V = V_{01}^G e^{-\alpha_1 r^2} + V_{02}^G e^{-\alpha_2 r^2} \quad (5)$$

This interaction was then folded with the 3^- RPA transition densities for the target, and the resulting form factor was used with the optical parameters given in table I to calculate DWBA cross sections at $E_\alpha = 31$ and 100 MeV. The resulting differential cross sections, with the interactions renormalized by factors of 1.25 and 1.00, respectively, are compared with data^{18,19)} in Fig. 1.

B Optical parameters for calculating $W(\vec{r}, \vec{r}')$

Optical parameters for the intermediate Green's function eq. (1) were chosen to be the phenomenological^{19,20)} potentials of table I, except that W at each energy was reduced to 8 MeV. Test calculations using only 2 MeV or the full phenomenological W showed that the resulting calculated imaginary potential is rather insensitive to the amount of absorption of the intermediate projectile, except that enough must be used to damp out potential resonances. See ref. 8) for further discussion of this point.

It would have been preferable from the point of view of determining an energy dependence of the calculated W to use again the interaction eq. (5) folded with the nuclear matter density as the real optical potential. This procedure was attempted, but the resulting potential appeared to be too deep and gave a wildly oscillating nonlocality in $W(\vec{r}, \vec{r}')$ of eq. (2).

C Calculation of $W(\vec{r}, \vec{r}')$

The nonlocal potential is calculated as described in section III using ^{40}Ca RPA vectors⁹⁾ for the intermediate states N of eqs. (1) and (2). These vectors were obtained from a $3\hbar\omega$ basis for multipolarities $\lambda \leq 6$. All open inelastic channels are included in the N sum of eq. (1) for $E_\alpha = 31$ MeV but at 100 MeV only states with $E_N \leq 70$ MeV, the limit of the RPA basis states, were used. See section V for some discussion of the adequacy of this basis.

IV Results

A The nonlocal potential $W(\vec{r}, \vec{r}')$

In figs. 2 and 3 are shown the nonlocal potential $W(\vec{r}, \vec{r}')$ in perspective drawings for zero angle, $\hat{r} \cdot \hat{r}' = 1$, at 31 and 100 MeV. It is clear from these results that the nonlocality is very large, especially at $E = 100$ MeV projectile energy. The nonlocality length at the nuclear surface is approximately equal to $b = 0.69$ fm for $E = 31$ MeV and to $b = 0.42$ fm for $E = 100$ MeV. The positive oscillations of the potential are quite large. This is presumably due to the ineffectiveness of the sums over N in eq. (2) in damping the oscillations. The nonlocal behavior of $W(\vec{r}, \vec{r}')$ is very close to that of the Green's function itself. By contrast, for low energy nucleon

projectiles the oscillations are usually very effectively damped. The local approximation then consists essentially of an integration of the nonlocal coordinate $\vec{s} = \vec{r} - \vec{r}'$ over the main peak of $W(\vec{r}, \vec{r}')$, leaving a function $\tilde{W}(\frac{\vec{r} + \vec{r}'}{2})$ as the equivalent local potential. By contrast the positive oscillations in the non-local alpha-particle potentials sometimes have a larger volume integral than the main peak.

In the nonlocal potentials shown in figs. 2 and 3, therefore, the nonlocality extends beyond the main peak in a rather complicated way. These results suggest that the imaginary optical potential for α particles and heavier ions is highly nonlocal, and the smallness of the width of the main peak is not an appropriate criterion for the validity of the local approximation. The consequences of the large non-locality should be further investigated by doing scattering calculations with a nonlocal imaginary potential of the type shown in figs. 2 and 3.

The presence of positive oscillations in the nonlocal optical potential does not mean that particles are produced. There is no local continuity equation for the Schrödinger equation in the case of a nonlocal potential. One must at least integrate over a region of the size of the nonlocality to obtain a continuity equation. This equation shows that there is always absorption when eq. (1) is used for the imaginary potential.

In spite of these difficulties we have made calculations of elastic scattering with an equivalent local potential $\tilde{W}(r)$ which is obtained by fitting a Gaussian form to the main peak of $W(r, r')$ of figs. 2 and 3. These potentials are shown in section IV B and D below.

However because of the positive oscillations, we have also used a damped free particle Green's function, DFPGF, form for $W(r, r')$

$$W(r, r') = W(R, R) e^{-\alpha s} \frac{\sin k s}{k s} \quad (6)$$

where $R = |\vec{r} + \vec{r}'|/2$, $\vec{s} = \vec{r} - \vec{r}'$. At each radius R , the effective wave number k and damping parameter α averaged over angular and radial directions are determined from the results of numerical calculations. The use of Perey and Saxon's¹⁶⁾ formulation of the equivalent local potential gives

$$\tilde{W}(R) = W(R,R) \frac{8\pi\alpha}{[\alpha^2 + (k-\kappa)^2] [\alpha^2 + (k+\kappa)^2]} \quad (7)$$

where κ is the local wave number for elastic scattering. This form, eq. (6), is unfortunately restricted to a spherically symmetric nonlocality, which is often a poor approximation, whereas the Gaussian form can be easily made nonsymmetric.⁸⁾

B Contribution from different multipoles

In order to show the distribution of absorption strength over intermediate states, we have graphed in fig. 4 for $E_\alpha = 31$ MeV only the contributions to the diagonal $W(r,r)$ from 0^+ , 1^- , 2^+ , 3^- . The contributions to the $W(r,r)$ from higher multipolarity are very small. The local equivalent potential $\tilde{W}(r)$ is obtained by multiplying $W(r,r)$ by a function which emphasizes the surface region, ref. (8), giving increased emphasis to the 3^- and 2^+ multipoles. The large 0^+ contribution in the nuclear interior comes mostly from a single isoscalar monopole resonance at about 19 MeV excitation energy.

The $\lambda=0$ multipolarity has a significant effect on the shape of the final local optical potential, being the main contributor to the peak in $W(r)$ at $r \sim 1$ fm. Its effect is relatively much less important in nucleon scattering, due to the large constructive effect of exchange,⁸⁾ which is much greater for high multipoles.¹⁷⁾ The 0^+ state is therefore deemphasized by the inclusion of exchange. Since exchange is also in fact present in alpha scattering, where it would have characteristics similar to those in nucleon scattering, we believe that the inner peak in W is overestimated in our calculation. Fortunately, the inner region of the potential is not very important for alpha scattering.

Since the effective interaction strength is fitted to the 3^- inelastic excitation data, exchange effects are therefore roughly included for $\lambda=3$. They are then not only overestimated for low multipoles, as discussed above for the 0^+ states, but they are also underestimated for higher multipoles. Since the 3^- state is dominant and peaks in the surface region, this error is probably not too serious, the overestimate of exchange for $\lambda=2$ being partially

compensated by the underestimate for $\lambda=4$ and 5. The difference in normalization factors for the DWBA calculation of the 3^- inelastic transition is probably due to decreasing importance of exchange at higher energies.

C Effect of optical Green's function on $\tilde{W}(r)$

For the simplified special case of a single 3^- collective intermediate state, we show in fig. (5) the sensitivity of the calculated results to the type of intermediate Green's function used. In contrast to our results for 30 MeV (n,n) scattering,⁸⁾ the resulting imaginary optical potential is highly dependent on the intermediate Green's function. The imaginary potential is substantially reduced when the optical Green's function is used instead of the free particle and Coulomb propagator. By examining the numerically calculated nonlocal potential, we have noted that it behaves for alpha scattering, somewhat like a free-particle Green's function with the local wave number. This would then depend on wave number as k^{-1} and therefore suppressing the imaginary potential calculated with the optical Green's function. Furthermore, the transformation to a local equivalent potential contains a damping factor which is small for large local wave numbers. We see, in fact, in Fig. 5 that the three equivalent local potentials for optical, free-particle, and Coulomb Green's function, have magnitudes which have an inverse relation to the local wave number in the nucleus. It is clear from Fig. 5 that calculations of imaginary alpha-nucleon potentials using a free-particle Green's function cannot be taken seriously. As discussed in section III B, the effect of changing the absorbing potential for the intermediate alpha particle is not large.

D Equivalent local potentials

In figs. 6 and 7 are shown comparisons of the local equivalent potentials $\tilde{W}(r)$ with phenomenological potentials for $E_\alpha = 31$ and 100 MeV. Results of calculations with both RPA and pure particle-hole intermediate states are

included, so one can assess the importance of nuclear structure effects for low and high energy projectiles. The potentials of figs. 5 and 6 for 31 MeV alpha particles were obtained from the non-local potential eq. (2) by using the local approximation^{7,8)} to a Gaussian fitted to the main peak. Because of the strong positive oscillations in the non-local potentials, the use of a Gaussian fit is highly questionable. In the inner region of the nucleus the nonlocality turns out to be fairly nearly spherically symmetric in s , so eq. (6), which takes into account the oscillations in $W(r,r')$ with s can be used. The resulting eq. (7) gave an equivalent local potential which was similar but 20 to 30% larger than the Gaussian fit. This near equivalence justifies the use of the Gaussian fit to the nonlocality; the (non-symmetric) Gaussian was then used over the whole radial range. Eq. (6), which is spherically symmetric in s , could not be justified for the nuclear surface because of a large disparity between radial and angular nonlocalities at the 31 MeV energy.

At 100 MeV the nonlocality is much more nearly spherically symmetric and eq. (6) could be used. In contrast to the Gaussian fit which ignores the non-locality oscillations, the Perey-Saxon approximation takes advantage of them in eq. (6) when the local wave number κ of the projectile is nearly equal to nonlocality wave number k , eq. (7). This is more nearly the case at the $E_\alpha = 100$ MeV, where eq. (7) gave about twice as strong a local equivalent $\hat{W}(r)$ as Gaussian fit. The potentials shown in fig. (7) were then calculated with eq. (7). The low values of $\hat{W}(r)$ in the interior and the larger values in the nuclear surface are

due to the poorer matching of the two wave numbers k and κ in the interior of the nucleus. In the Schrödinger equation with a non-local potential of the form eq. (6) such effects would be expected to be smoothed out by a distribution of wave numbers in the true optical wave function.

In fig. 6 the phenomenological potential, table I, is shallow, and the real part of the same shallow potential was used for the calculation of the optical Green's function. As in the case of 30 MeV neutron projectiles⁸⁾, it is clear that nuclear structure effects are highly important. Residual nuclear interactions produce collective states which are shifted in and out of the open channel region depending on the nature of the states. The net result of nuclear structure is to increase the imaginary potential particularly in the region of the nuclear surface. This effect should be large for low energy projectiles. It is not so clear whether this effect should still be present at $E_\alpha = 100$ MeV. From fig. 7 it can be seen, however, that nuclear structure effects still make a substantial contribution. In this connection one must not forget that in contrast to TDA, the RPA gives not only a redistribution of particle-hole strength, but includes also the effect of ground state correlations, not present for particle-hole intermediate states.

One would like to be able to make some conclusions about the energy dependence of the imaginary optical potentials, by comparing the potentials in figs. 6 and 7. Such a comparison, however, is not meaningful, since the two potentials have been calculated with different input parameters. Although with the folded potential form eq. (5) it was possible to fit both the inelastic scattering to the 3^- collective state at both $E_\alpha = 31$ and 100 MeV with just a small change in normalization, the optical potentials in which the intermediate alpha particle propagates were not the same or even from the same family of

potentials. As mentioned in Sect. III B, attempts to use a folded real optical potential were not successful.

E Calculation of elastic differential cross sections

Figs. 8 and 9 show comparisons of elastic scattering differential cross sections calculated with each of the potentials of figs. 6 and 7 with data^{18,19)}. In each case the real potential was taken from phenomenological fits^{19,20)} to data for $20 \leq \theta \leq 70^\circ$, for which Woods-Saxon real potentials are available.

For the 31 MeV case, fig. 8, the data for $\theta \leq 75^\circ$ is well fitted by use of the phenomenological potential, and the RPA-theoretical potential also gives a fairly good fit to the oscillations, although the calculated cross section is somewhat too high, indicating too little absorption, the potential obtained from particle-hole intermediate states gives still higher oscillations because it is considerably weaker. Beyond 75° none of the potentials work very well, which is expected since they all use the same Woods-Saxon real potential, which was fitted to data for $\theta \leq 75^\circ$. At the back angles, however, the RPA-theoretical potential gives about the right magnitude, indicating a reasonable amount of surface transparency, whereas the phenomenological potential gives much too low a cross section. The microscopic potential seems to be a little too surface transparent.

At 100 MeV, fig. 9, none of the potentials, including the phenomenological one, do very well in fitting the data. The RPA-theoretical potential gives a cross section which is much too high, indicating too little absorption.

The failure of the theoretical potentials to give enough absorption is also shown in a comparison of reaction cross sections, which are included in figs. 8 and 9. At 31 MeV the RPA-theoretical potential gives 92% of the reaction cross section of the phenomenological potential, and the particle-hole theoretical potential gives 80%. At 100 MeV the RPA-theoretical potential gives only 78% of that of the phenomenological one.

V Summary and Conclusions

We have calculated the nonlocal optical potential for alpha-scattering at $E_\alpha = 31$ and 100 MeV incident alpha energy using the nuclear structure approach. The alpha particle is treated as an elementary particle, and its interaction with the nucleons of the target is determined, taken as a folded Gaussian equivalent of the $m3y$ potential, fitting the inelastic cross section to the first 3^- collective state at each energy. We find that the imaginary potential is highly nonlocal and that the local approximation usually made for nucleons is doubtful. The local approximation was nevertheless used to calculate an "equivalent" local potential. This potential is comparable in strength to the phenomenological potentials but is weaker. Collectivity of the RPA wave functions still plays a role even at 100 MeV projectile energy. The sum over intermediate RPA states gives a considerably larger cross section than the sum over the corresponding particle-hole states. The theoretical potential is sensitive to the type of the intermediate Green's function used in its calculation.

The differential cross sections obtained from the phenomenological-real and calculated-imaginary potential agrees fairly well with low angle data at 31 MeV but rather poorly at 100 MeV. The theoretical potentials in general underestimate the absorption, particularly at $E_\alpha = 100$ MeV.

At 31 MeV incident energy, we would not expect large contributions from breakup processes, and the RPA should account quite well for the absorptive strength. On the other hand, at 100 MeV the limitation of the RPA basis to $3\hbar\omega$ probably makes the RPA spectrum inadequate to describe the intermediate inelastic strength. Furthermore, at 100 MeV, breakup channels, not included in our calculation, will undoubtedly make a substantial contribution to absorption from the elastic channel. (The inelastic sum, through completeness of RPA particle-hole states, accounts in some approximate way for nucleon pickup-stripping type rearrangement processes²¹⁾.) It is likely that breakup accounts for a large fraction of the absorption outside the nucleus and for the long range of the phenomenological imaginary potential²²⁾. The restriction to intermediate inelastic channels probably accounts for the fact that at $E_\alpha = 100$ the calculated reaction cross section is only 78 % of that obtained from the phenomenological potential.

We conclude that the nuclear structure approach including only inelastic channels as doorways to absorption gives a sensible description of the imaginary optical potential at low energies. When E_α is much greater than the binding energy of the α particle, breakup effects are expected to make important contributions to alpha absorption. Serious questions remain concerning the adequacy of the local approximation, which we have used. The highly nonlocal form of this potential suggests that tests using the calculated nonlocal $W(\vec{r}, \vec{r}')$ in a fully nonlocal calculation would be valuable in assessing the validity of a local optical model for alpha and heavy-ion elastic scattering.

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Table I: $^{40}\text{Ca}(\alpha, \alpha)$ phenomenological optical potentials

E (MeV)	V (MeV)	W^a (MeV)	r_R (fm)	a_R (fm)	r_I (fm)	a_I (fm)
31 ^a	-50.03	-12.39	1.652	.585	1.652	.585
100 ^b	-126.	-23.	1.2	.8	1.55	.646

^a For calculation of the intermediate projectile Green's function the imaginary part of the potential was taken to be 8 MeV in each case.

a. Ref. 20.

b. Ref. 19.

Figure Captions

Fig. 1: Inelastic (α, α')-scattering cross sections to the lowest 3^- , 3.73 MeV state in ^{40}Ca for incident projectile energies of 31 MeV and 100 MeV. The data are taken from refs. 17) and 16), respectively. The interaction parameters of Eq. (5) are $V_{01}^G = -310.1$ MeV, $V_{02}^G = 319.2$ MeV for $E_\alpha = 31$ MeV, $V_{01}^G = -387.6$ MeV, $V_{02}^G = 398.9$ MeV for $E_\alpha = 100$ MeV and $\alpha_1 = .422 \text{ fm}^{-2}$, $\alpha_2 = .505 \text{ fm}^{-2}$ for both energies.

Fig. 2: Perspective drawing of the nonlocal, imaginary optical potential for 31 MeV incident alpha-particle energy calculated with RPA-intermediate doorway states.

Fig. 3: The microscopically calculated, nonlocal potential for 100 MeV alpha particles (see fig. 2).

Fig. 4: Contributions of the various multipolarities J^π of intermediate states to the diagonal part of the nonlocal imaginary optical potential at an incident projectile energy of 31 MeV.

Fig. 5: The local equivalent potential $\tilde{W}(r)$ of the nonlocal optical potential for alpha particles of 31 MeV incident energy. The three curves are calculated with an optical, a Coulomb, and a free particle Green's function, using only the collective 3^- state as intermediate state.

Fig. 6: Comparison of the microscopic imaginary potentials with the phenomenological potential.¹⁴⁾

Fig. 7: Same as fig. 6.

Fig. 8: Comparison of calculated elastic scattering angular distributions to the experimental data of ref. 16) at 31 MeV. The angular distributions have been calculated using either the phenomenological optical potential or that obtained by replacing the imaginary part of the phenomenological potential by our microscopic potentials. The reaction cross sections are $\sigma = 1410, 1292$, and 1124 for the phenomenological potential _____; microscopic RPA -----; and microscopic particle holes -.-.-.-.-, respectively.

Fig. 9: Same as fig. 8 but at $E_{\alpha} = 100$ MeV.

Fig. 1

Nonlocal imaginary optical Potential

$^{40}\text{Ca} (\alpha, \alpha)$

$E_{\text{inc}} = 31 \text{ MeV}$

Fig. 2

Nonlocal imaginary optical Potential

$^{40}\text{Ca}(\alpha,\alpha)$

$E_{\text{inc}} = 100 \text{ MeV}$

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9