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Double-folding model potential for anomalous large-angle ^{4}He + ^{40}Ca scattering

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It is shown that a double-folding model potential based on a realistic nucleon-nucleon G matrix yields a real ^{4}He + ^{40}Ca optical potential extremely similar to that found empirically by Michel and Vanderpoorten. With only a 7% renormalization this folded potential, combined with the imaginary potential of Michel and Vanderpoorten, provides a good description of ^{40}He+ ^{40}Ca scattering over the full angular range.

[NUCLEAR REACTIONS ^{40}Ca(^{4}He, ^{4}He), $E = 29$ MeV, calculated $\sigma(\theta)$.]

There has been, in the past several years, an unusually intense interest[1-3] in the apparently anomalous large-angle scattering of α particles (ALAS) from selected light- and medium-weight nuclei. Numerous models[3-7] have been proposed and experiments[2,3,8] performed in an effort to understand this phenomenon.

Very recently, Michel and Vanderpoorten[3] have studied the classic case of $\alpha + {}^{40}$Ca scattering in the energy range $20 < E < 50$ MeV and were able to describe the scattering (over the full angular range) with a static real potential and an imaginary potential whose radius alone was allowed to vary with energy. The real and imaginary potential shapes they found (upon searching) were both of the form of a Woods-Saxon potential raised to the 2.65 power. The resulting real potential is ~290 MeV deep at the origin.

Brink and Takigawa[6] (and Hartmann[7]) have recently explained within a WKB framework why a potential model description of ALAS requires *both* relatively weaker absorption than "nonanomalous" scattering and a real potential deep enough to provide a "classical pocket" inside the Coulomb barrier. Since in this interpretation,[6] ALAS arises from the wave reflected at the internal barrier, the bombarding energy cannot be too far below the Coulomb-centrifugal barrier; otherwise not enough particles tunnel through the barrier and into the pocket to exhibit the effect.

It is the purpose here to show that a double-folded potential (U_F) using a realistic nucleon-nucleon G matrix provides a very good description of both the potential found by Michel and Vanderpoorten[3] and the resulting scattering of ^{4}He by ^{40}Ca. Since the double-folded potential, like the real part of the phenomenological potential of Ref. 3, is nearly energy independent over the range of bombarding energies studied, it should also provide a good description of the real part of the optical potential in this energy range.

Two different static representations[9] of the G matrix used for double folding were considered. One of these (M3Y) has been used rather extensively[10] to calculate the real part of the heavy-ion (HI) optical potential. Typically it predicts the correct magnitude of the real potential to within ~15% at the strong absorption radius. Perhaps more significantly, for purposes here, it has been used[11] to describe the scattering of ^{12}C + ^{12}C which is sensitive in to $R \sim 2$ fm with only a ~5% renormalization. The second representation of the G matrix (M245) was determined[12] by fitting the matrix elements of a sum of three Yukawa terms to the *same* G matrix elements. The main difference between these two representations is that M245 does not include a one pion exchange potential (OPEP) tail in *any* channel. It does, however, give a slightly better fit to the G matrix elements than does the M3Y form. The M3Y representation is given in Ref. 10. The scalar-isoscalar part of M245 including knock-on exchange[10,13] is

$$V_{\mathrm{M245}}(r) = 13119\frac{e^{-5r}}{5r} + 591.1\frac{e^{-2.5r}}{2.5r} - 972.6\frac{e^{-2r}}{2r} - 674\delta(\vec{r})\,.$$

A limited number of cases suggest that M245 gives ReU larger at the strong absorption radius by ~20–30% compared with M3Y.

For these $N = Z$ nuclei the neutron and proton point densities were assumed equal. The charge densities were deduced from electron scattering data via the three-parameter Fermi-model fits quoted in Ref. 14. The proton charge form factor ($\langle r^2\rangle_{\mathrm{prot}} = 0.757$ fm^2) was unfolded.

Figure 1 shows the phenomenological potential of Michel and Vanderpoorten (ReU_p) compared with the two folded-model potentials with no renormal-

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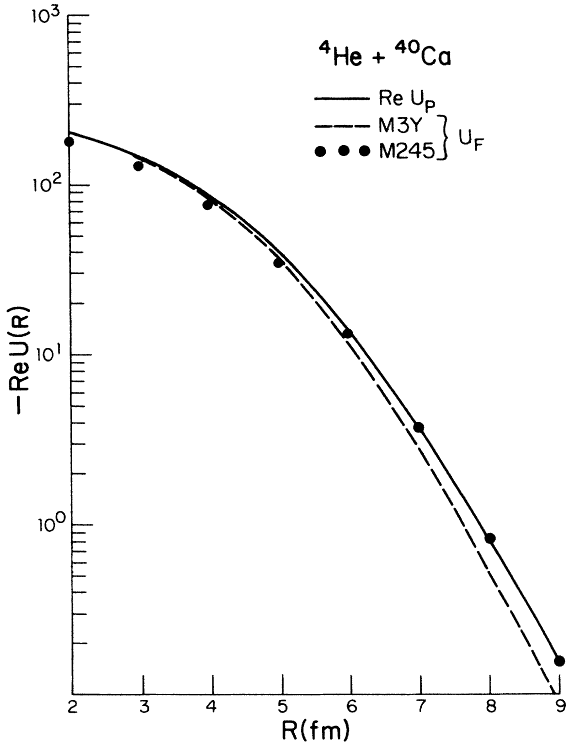

FIG. 1. A comparison of empirical and double-folded potentials for ^{4}He+^{40}Ca scattering. U_p denotes the empirical potential from Ref. 3. M3Y denotes the folded potential calculated using the interaction in Ref. 10. M245 corresponds to the folded potential (U_F) described in the text.

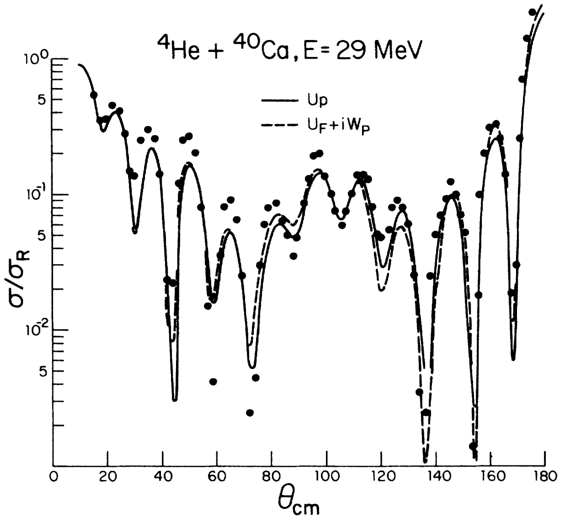

FIG. 2. ^{4}He+^{40}Ca elastic cross section data at $E_\alpha = 29$ MeV compared with the scattering predicted by the empirical potential of Ref. 3 and the M245 folding-model potential (with $N=1.07$).

ization. They are all quite similar with the M245 version being especially close to ReU_p in the surface region. The M3Y folded potential is smaller than ReU_p by ~25% at $R=7$ fm. To examine the scattering at $E_\alpha=29$ MeV using the folded potentials the imaginary part of the potential was taken directly from Ref. 3. (Subsequent adjustment of W led to little improvement.) The real part of the folded potentials was multiplied by N and this parameter was adjusted to minimize χ^2. Without any renormalization ($N=1$) the forward and backward angle data were reasonably well represented, especially using the M245 interaction. Upon optimization little improvement was noted for the M3Y force for which N(M3Y) $=0.99$. For the M245 force the search resulted in N(M245) $=1.07$ and led to a fit to the data over the full angular range quite comparable to that obtained with the phenomenological form.[3] The scattering results are shown in Fig. 2. Although we have not made any calculations of inelastic scattering for this system, it is shown in Ref. 3 that the phenomenological potential U_p leads to a substantial improvement in the large-angle data for excitation of the 3^- state at 3.74 MeV when compared with calculations using earlier[2] potentials. In view of the similarity of U_p and U_F we anticipate comparable results for inelastic scattering.

Although it may be (and has been) argued that the folding model should only be appropriate for $R \gtrsim$ strong absorption radius, we find here another[11] case where the folded potential using a realistic nucleon-nucleon interaction effectively describes scattering which is sensitive to much smaller distances of closest approach. The 7% renormalization is believed to be well within the uncertainty[10] of the folding model (at all radii) and is only necessary to describe the mid-angle data which is especially sensitive to the interference[6] between the internal and barrier reflected waves. It clearly remains to be shown how the numerous corrections to the folding model cancel at the ~7% level for $R \gtrsim 2$ fm. A very recent calculation[15] indicates that corrections to the folding model arising from polarization of the target are primarily imaginary and alter the real potential by ~1%. It should be stressed that the G-matrix folding model used here does not determine the imaginary part of U_p which in this framework must (and does[6,16]) provide the primary source of energy and A dependence of ALAS. The point is, when the absorption is weak enough to render the scattering sensitive to the interior part of the nuclear potential, the G matrix provides a reasonable description of that potential.

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