Stripping channel contribution to the nonlocality of the deuteron optical potential

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It is shown that the effect of coupling $l=1$ stripping channels to the incident deuteron channel is to produce a nonlocality in the d-^{48}Ca optical potential which gives the right type of energy dependence for the equivalent local optical potential.

[NUCLEAR REACTIONS ^{48}Ca(d,d), $E=4.0$–16.0 MeV; calculated $\sigma(E,\theta)$, obtained energy dependent d-^{48}Ca optical potential.]

In the case of deuteron elastic scattering the effect of transitions to stripping channels is important when the stripping cross sections are large. In such cases, a systematic optical potential can be obtained by coupling the stripping channels[1,2] to the elastic channel. It is well known that the coupling of reaction channels introduces a nonlocal character in the effective interaction in the Schrödinger equation describing the elastic channel. The nonlocality arising from the coupling of $l=1$ stripping channels to the elastic channel for ^{48}Ca is reported in the present work. The coupled-channels (CC) treatment of the (d,p) reaction by Rawitscher and Mukherjee[3] was used to investigate the energy dependence of the d-^{48}Ca optical potential.

Rawitscher[4] studied the energy dependence of the deuteron optical potential for ^{40}Ca by analyzing the elastic scattering cross section obtained from a CC calculation neglecting spin in all the channels. However, only $l=1$ stripping channels were coupled in his calculation, neglecting the $l=3$ transition which is also quite strong for ^{40}Ca. Hence, we have chosen ^{48}Ca for our analysis since $l=3$ stripping is not present and the coupling of $l=1$ levels only, is more justified. Calculations were performed at eight incident deuteron energies between 4 to 16 MeV including spin in all the channels.

The coupled equations were solved numerically and the elastic scattering cross section along with the $2p_{3/2}$ and $2p_{1/2}$ stripping cross sections were obtained. This CC predicted deuteron elastic scattering angular distribution at each incident deuteron energy was then fitted by a simple deuteron optical potential. Any energy dependence in this optical potential obtained by fitting the CC predicted scattering cross sections can be attributed solely as due to coupling effects.

The energy independent deuteron optical potential used in the CC calculation was taken to be the one found[5] suitable for analyzing ^{48}Ca(d,p) stripping at low energy. The proton optical potential in the stripping channels was taken from the literature[6-8] for appropriate outgoing proton energies. The bound neutron wave function was calculated using a central potential of a Woods-Saxon form plus a spin-orbit potential of a Thomas form. The radius and diffuseness parameters for the central and spin-orbit potentials were $r_0=r_{so}=1.15$ fm, $a_0=a_{so}=0.65$ fm as used by Roy and Boggards.[9] The spin-orbit potential depth was kept fixed at 8 MeV. The real central potential depth was adjusted to reproduce the correct binding energy and number of nodes in the radial wave function. The depths obtained for the $2p_{1/2}$ and $2p_{3/2}$ neutrons were 54.814 and 54.776 MeV, respectively.

The CC computer code DPDJ4 used previously[3,5] to study the ^{40,48}Ca(d,p) reactions was used in the present work. The fitting of the CC calculated elastic scattering cross section with a simple optical model was performed with the help of the automatic search code OPS1.[10] The deuteron optical potential, whose parameters were searched upon, has the standard form

$$U(r)=V[\exp(x)+1]^{-1}-4i\,W_D(d/dx')[\exp(x')+1]^{-1}-(\hbar/m_\pi C)^2V_{LS}(\vec{\sigma}\cdot\vec{L})r^{-1}(d/dr)[\exp(x'')+1]^{-1}+V_{\text{Coul}}\,,$$

where

$$x=(r-r_V A^{1/3})/a_V,\quad x'=(r-r_W A^{1/3})/a_W,$$
$$x''=(r-r_{LS} A^{1/3})/a_{LS},$$

and A is the mass number of the target nucleus.

Starting with the same parameter set for each incident deuteron energy, preliminary searches showed that r_V and a_W were fairly energy independent and average values of 1 and 0.5 fm, respectively, were used. Next, four parameter searches on V, a_V, W, r_W were carried out and a_V was found to be weakly energy dependent. An average value of 0.97 fm was taken for it. Then three parameter searches on V, W, r_W were performed and the final values are plotted in Fig. 1 against incident deuteron energy. The optical model fits to the CC predicted d-^{48}Ca elastic scattering cross sections are shown in Fig. 2. The spin-orbit part of the deuteron optical potential was taken to be the same as that used in CC calculation and was kept fixed throughout the search procedure.

As shown in Fig. 1, r_W starts decreasing quite rapidly with an increase of deuteron energy. Indeed, such an observation has been made by Schwandt and Haeberli in simple optical model analysis[11] of d-^{40}Ca elastic scattering from 5 to 34 MeV. The increase of imaginary potential depth with deuteron energy as found in Fig. 1 has also been noted by the same workers. Similar observations have been made by Rawitscher[4] in the study of the effect of stripping channels on the d-^{40}Ca optical potential. Since real transitions to nonelastic channels from the elastic channel are mainly responsible for the energy dependence of the imaginary part of the optical potential, the above resemblance suggests that the CC technique correctly describes the real transitions from elastic to stripping channels. This also shows the importance of stripping channels for ^{48}Ca as envisaged earlier.

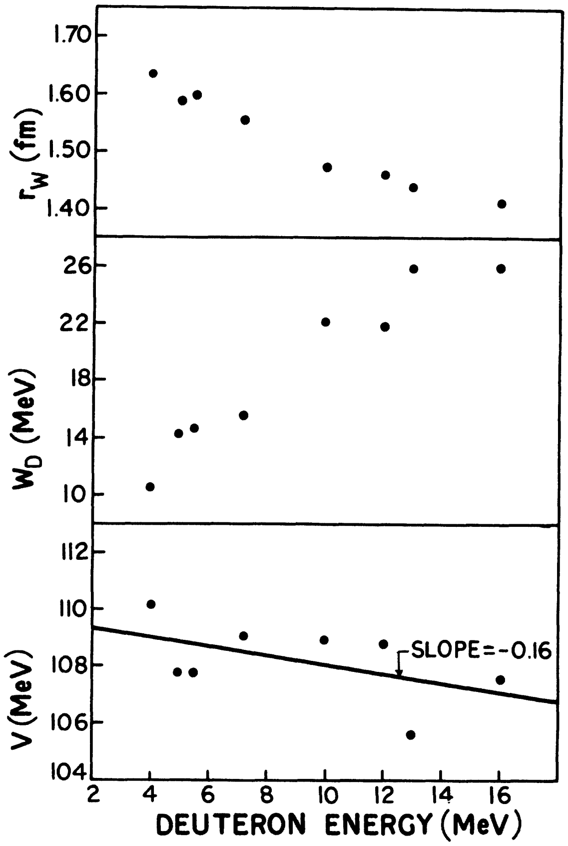

FIG. 1. Energy dependence of the optical model parameters which fit the elastic scattering cross sections calculated by the coupled-channels (cc) method.

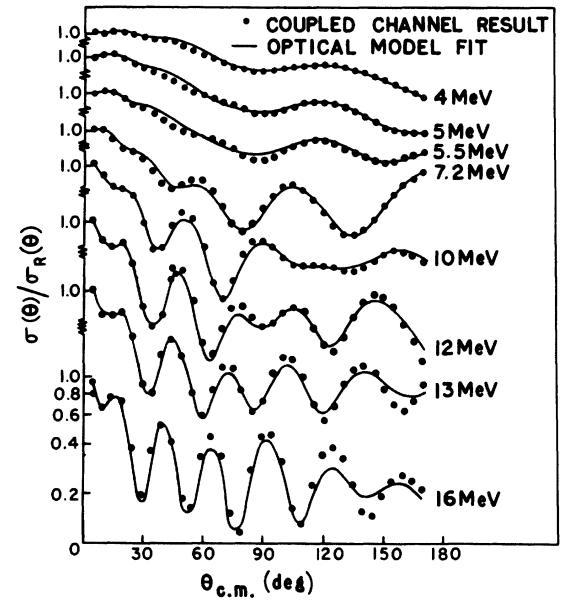

FIG. 2. Optical model fits to coupled-channels predicted d-^{48}Ca elastic scattering cross sections at different incident deuteron energies.

The radial variation of the absorbing potential at different energies is shown in Fig. 3. The close matching of the imaginary potential at different energies in the tail portion suggests that the stripping probability is nearly the same for all energies in this region but increases with increasing penetration at higher energies.

The energy dependence of the real well depth from the present analysis, as shown in Fig. 1, can be approximated by a straight line of gradient −0.16. Rawitscher's analysis[4] of the d-^{40}Ca optical potential shows a much weaker energy dependence. However, the number of energy points in his case is not sufficient to find any quantitative

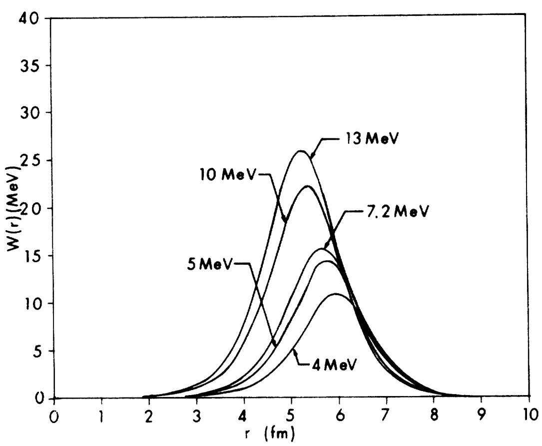

FIG. 3. Radial variation of the imaginary part of the optical potential obtained by fitting coupled-channels predicted elastic scattering cross sections at different deuteron energies.

energy dependence. The energy dependence we find reflects the effect of coupling which describes virtual transitions from elastic to stripping channels. The phenomenological deuteron optical potential has[11] a linear energy dependence of slope -0.5 for its real well depth. This indicates that coupling of the p stripping channels to the elastic channel is responsible for approximately 30% of the observed energy dependence of the real well depth in the case of ^{48}Ca. The remaining energy dependence can be attributed to the exchange of nucleons between target and projectile, other nonelastic channels, and intrinsic energy dependence of the two-body effective interaction. Of these, the last contribution for the proton optical potential has been theoretically estimated by Sinha, Srivastava, and Ganguly[12] which gives a linear energy dependence of gradient -0.05. If we take the same value for the neutron optical potential also, then the intrinsic energy dependence for the deuteron optical potential is expected to be approximately -0.1. This leaves an energy dependence of approximate slope -0.24 which perhaps can be accounted for by exchange contribution and coupling of breakup channels.

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