Approximate Lane consistency of the dispersive coupled-channels potential for actinides

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A previously derived dispersive coupled-channels optical model potential for nucleon scattering on ^{232}Th and ^{238}U nuclei [Capote, Soukhovitskii, Quesada, and Chiba, Phys. Rev. C **72**, 064610 (2005)] has been tested against experimental data on quasielastic (p, n) scattering to the isobaric analog states of corresponding target nuclei. The Lane potential derived from the isovector term of the dispersive coupled-channels optical model potential has been shown to approximately reproduce available experimental differential cross-section data for the quasielastic (p, n) reaction; therefore the approximate Lane consistency of that potential has been established.

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An isospin dependent coupled channel optical model potential containing a dispersive term including nonlocal contribution derived previously for ^{232}Th and ^{238}U nuclei [1] has been extended to describe neutron and proton scattering on strongly deformed actinide nuclei [2,3]. The isovector terms and the observed very weak linear dependence of the geometrical parameters on mass number A were instrumental to extend the dispersive coupled-channels optical model (DCCOM) potential parameters for ^{238}U and ^{232}Th to neighboring actinide nuclei. However, the derived DCCOM potential has not been tested on quasielastic (p, n) scattering to the isobaric analog states (IAS) of the target nucleus; being such exercise the best test of the quality of the isovector part of the optical potential. A results of these calculations will be reported in the present contribution. It has been pointed out by Lane [4] that the optical model potential can be written in a charge-independent form. The extent to which we can state that a derived optical model potential is *Lane-consistent* can be established from the basic Lane equations [4]:

$$\begin{aligned} V_{pp} &= V_0 + \frac{N-Z}{4A} V_1, \\ V_{nn} &= V_0 - \frac{N-Z}{4A} V_1, \\ V_{pn} &= \frac{\sqrt{N-Z}}{2A} V_1, \end{aligned} \tag{1}$$

where V_0 and V_1 are the isocalar and isovector components of the DCCOM potential in Refs. [1–3] with the Coulomb interaction switched off. In such way one is able to calculate the charge-exchange channels in a (p, n) reaction (to the *elastic IAS* and excited states of the rotational band of the residual nucleus).

An accurate calculation of the nucleon scattering from actinide nuclei must include the coupling to the low-lying collective states. A very successful computational method to account for the importance of the multistep processes is the coupled-channels (CC) method using Tamura's formalism [5], which permits an exact solution of the Lane CC equations. Calculations for ^{238}U$(p, n)^{238}$Np and ^{232}Th$(p, n)^{232}$Pa reactions have been done with FRESCO [6] CC code. The Coulomb displacement energy, Δ_C, between the ground state and its corresponding IAS is well approximated by the empirical relation [7], $\Delta_C = 1.444Z/A^{1/3} - 1.13$ MeV with Z being equal the average charge of the target and residual nuclei in the reaction. For the studied targets, the value of Δ_C is about 20 MeV. Inelastic scattering to the first three levels 0^+,2^+,4^+ of the ground-state rotational band and charge-exchange to their IAS were included in the calculations. All possible pairs of coupling between the target ground state rotational band and IAS (corresponding to the residual nucleus) had been taken into account. All multipolarities allowed by conservation of angular momentum were considered. The coupling form factors are externally calculated according to

$$\begin{aligned} &\langle \nu; 0^+_{\mathrm{IAS}} | V(\tau, \vec{r}) | \pi; 0^+_{\mathrm{g.s.}} \rangle \\ &\quad = \langle \nu | \mathcal{T} | \pi \rangle \langle 0^+_{\mathrm{IAS}} | V_1^{\mathrm{diag}}(\vec{r}) | 0^+_{\mathrm{g.s.}} \rangle \\ &\quad = \frac{\sqrt{(N-Z)}}{2A} \langle 0^+_{\mathrm{IAS}} | V_1^{\mathrm{diag}}(\vec{r}) | 0^+_{\mathrm{g.s.}} \rangle \end{aligned} \tag{2}$$

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for the "quasielastic" $0^+_{\text{g.s.}} \rightarrow 0^+_{\text{IAS}}$ excitation of the IAS, as a particular case of

$$\begin{aligned}&\langle \nu; I^+(\text{residual})|V(\tau,\vec{r})|\pi; I^+(\text{target})\rangle \\ &\quad = \langle \nu|\mathcal{T}|\pi\rangle\langle I^+(\text{residual})|V_1(\vec{r})(|I^+(\text{target})\rangle \\ &\quad = \frac{\sqrt{(N-Z)}}{2A}\langle I^+(\text{residual})|V_1(\vec{r})|I^+(\text{target})\rangle \end{aligned} \quad (3)$$

for the coupling between analog states of both rotational bands, and

$$\begin{aligned}&\langle \nu; I^{+\prime}(\text{residual})|V(\tau,\vec{r})|\pi; I^+(\text{target})\rangle \\ &\quad = \langle \nu|\mathcal{T}|\pi\rangle\langle I^{+\prime}(\text{residual})|V_1^{\text{coupl}}(\vec{r})(|I^+(\text{target})\rangle \\ &\quad = \frac{\sqrt{(N-Z)}}{2A}\langle I^{+\prime}(\text{residual})|V_1^{\text{coupl}}(\vec{r})|I^+(\text{target})\rangle \end{aligned} \quad (4)$$

for the coupling between $I' \neq I$ states. In these expressions $\mathcal{T}$ is the isospin operator, ν and π represent the entrance and exit isospin states of projectile and ejectile, respectively, and V_1^{diag} and V_1^{coupl} are the usual spherical and deformed components of the potential, as defined in the Tamura's *canonical* work [5]. According to Eqs. (4)–(7) of Ref. [1], the energy dependence of the isovector components of the DCCOM potential are given by

$$V_1^{HF}(E) = -C_{\text{viso}}\exp(-\lambda_{HF}(E-E_F)) \quad (5)$$

and

$$W_1^s(E) = -C_{\text{wiso}}\frac{(E-E_F)^2}{(E-E_F)^2+(B_s)^2}\exp(-C_s|E-E_F|) \quad (6)$$

together with the well known dispersion relation

$$\Delta V_1^s(E) = \frac{\mathcal{P}}{\pi}\int_{-\infty}^{\infty}\frac{W_1^s(E')}{E'-E}dE'. \quad (7)$$

Optical model parameters $C_{\text{viso}}, C_{\text{wiso}}, \lambda_{HF}, B_s$, and C_s fully determine the energy dependence of the isovector component of the DCCOM potential and were taken from Table I of Ref. [1]. The geometrical parameters of the "Hartree-Fock" potential r_{HF} and a_{HF} and surface absorptive potential r_S and a_S uniquely define the radial form factor. The dispersive integral (7), which gives the important surface component of the real interaction potential, was calculated analytically [8,9]. The calculated angular distributions for the ^{232}Th$(p,n)^{232}$Pa and ^{238}U$(p,n)^{238}$Np reactions are compared with experimental data [10,11] in Figs. 1 and 2. The intrinsic width of the measured isobaric analog level of the ground state does not allow a separate measurement of the scattering cross section to each of the IAS (i.e., to the states of the rotational band in the residual nucleus) [10]. However, theoretically calculated partial cross sections for the scattering to excited $(0^+,2^+,4^+)$ IAS are shown. Calculated isobaric analog cross section to the 2^+ level (dashed line) above $\approx 100^\circ$ is higher than the cross section corresponding to the isobaric analog ground state (thin line); therefore, the need for a coupled-channels treatment is clearly demonstrated. Since the contribution of the scattering to the 4^+ IAS (dotted line) is very small, the 6^+ and 8^+ states and their couplings can be safely neglected in the charge-exchange calculation. A small underestimation

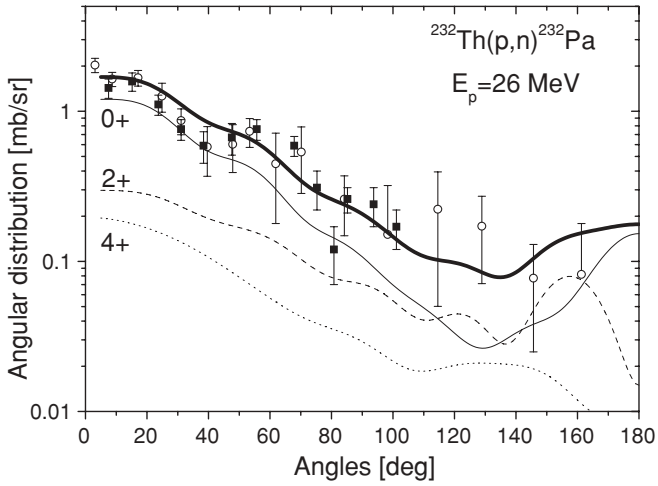

FIG. 1. Angular distributions for reaction ^{232}Th$(p,n)^{232}$Pa(IAS) at 27 MeV calculated with the FRESCO code. Circles are experimental data from Ref. [10] and squares from Ref. [11]. The thick line is the coupled-channels calculation including the contribution of the ground-state analog (thin), the first 2+ (dashed), and the second 4+ (dotted) analog states.

of experimental data at forward angles can be appreciated for uranium, which obviously is a consequence of the noninclusion of the (p,n) channel in the optical model fitting procedure. Present calculations show a fair agreement with experimental data, especially since the DCCOM potential was not fitted to those charge-exchange measurements.

In conclusion, we have shown that our previously derived isospin dependent DCCOM potential for actinides is approximately *Lane-consistent* which encourages further developments to achieve full consistency. Work on that direction is in progress.

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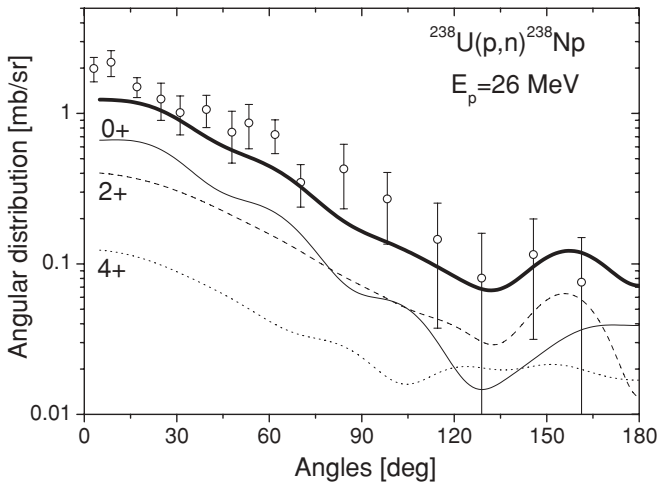

FIG. 2. Angular distributions for reaction ^{238}U$(p,n)^{238}$Np(IAS) at 27 MeV calculated with the FRESCO code. Circles are experimental data from Ref. [10]. The thick line is the coupled-channels calculation including the contribution of the ground-state analog (thin), the first 2+ (dashed), and the second 4+ (dotted) analog states.

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