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Optical model potential parameter optimization for nucleon-induced reactions on ^{40}Ca: Implications on γ-ray production cross sections for residual Argon nuclei

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Abstract. We have optimized the optical model potential (OMP) parameters for nucleon (protons and neutrons) induced reaction on 40Ca using the OPTMAN code available on the RIPL-3 data library. The potentials, geometrical and nuclear deformation parameters were extracted via fitting angular distribution data for proton/neutron elastic and inelastic scattering (Ep,n = 0 – 200 MeV) taken from the EXFOR data library. Our results demonstrate improvement in the prediction of the angular distribution cross sections compared to the Koning-Delaroche OMP. We have, then, calculated the γ-ray production cross sections of the most intense transitions emitted by 38Ar (Eγ = 2167.47 keV) and 36Ar (Eγ = 1970.38 keV) residual nuclei produced in 40Ca(p,xγ)(38,36)Ar, using both our OMP parameters and TALYS build-in OMP parameters. The results of the calculations were compared with preliminary cross section data extracted in the analysis of 40Ca(p,xγ2168 keV)38Ar, and 40Ca(p,xγ1970 keV)36Ar for incident proton energies ranging from 30 – 125 MeV.

Nuclear reactions can occur in different stellar and interstellar sites like the stars, supernovae and the interstellar medium. They can also be induced in laboratories using accelerators for example. One observable of relevant importance when studying nuclear reactions are reaction cross sections. Several theoretical models have been developed in order to explain how those reactions occur and help in calculating cross sections (used in astrophysics in proton therapy) where experimental data are absent. One of these models is the optical model potential (OMP). Several OMP parametrizations have been extracted for different incident particles and target nuclei. Our goal is to build a dispersive OMP that reproduces elastic, inelastic and nonelastic channels in nucleon-induced reaction on 40Ca for particle incident energies in the range 0-200 MeV. Then, we use this OMP to predict γ-ray production cross sections for 36,38Ar residual nuclei produced in p+40Ca reactions for incident proton energies of 30-125 MeV.

We have derived a new set of parameters for a dispersive OMP for nucleon-induced reactions on 40Ca, considering all potentials as deformed, in the framework of the Davydov-Filippov (DF) model to account for the γ asymmetry using the OPTMAN code [1] (available in the RIPL-3 data library [2]). The expression of the energy dependent interaction potential can be found in Ref. [1].

The potential, geometrical and nuclear deformation parameters were extracted via the fitting of elastic and inelastic angular distribution cross section data for protons/neutrons of energy Ep,n = 0 – 200 MeV, as well

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as reaction cross section (to better constrain the imaginary potentials), taken from the EXFOR data library [3]. Figures 1 and 2 show the result of fitting angular distribution cross sections for elastically and inelastically scattered protons by 40Ca nuclei. Inelastic scattering was considered in our work in order to extract the quadrupole (β2) and the octupole (β3) nuclear deformation parameters using the DF model with rigid axial octupole deformation. The low-energy levels couplings used was taken from the RIPL-3 data library [2]. The resulting potential and geometrical parameter values are listed in Table 1 and the results of the fit, compared to the predictions of the Koning-Delaroche OMP [4] used in TALYS. The obtained values of the deformation parameters β2 and β3 are higher than the suggested ones in the RIPL-3 data library given by Kibedi (β2 = 0.123) and Raman (β3 = 0.411) and corresponds to an increase of 8% and 28% respectively. Moreover, our deformation parameters are higher by 53% and 62% compared to the values suggested in the TALYS deformation database obtained from a spherical non-dispersive OMP.

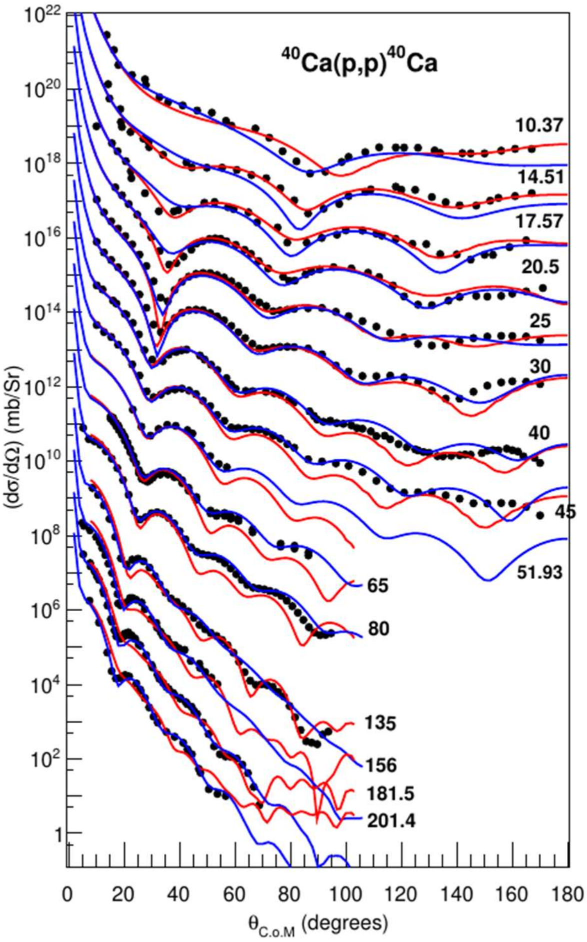

Figure 1. Angular distributions of protons scattered off ^{40}Ca nuclei. Black dots correspond to experimental data taken from EXFOR library while the red and blue curves are the result of fitting using OPTMAN code and the predictions of TALYS built-in OMP. Angular distributions are multiplied by a factor to avoid overlapping.

We have, then, used our OMP in TALYS nuclear reaction code [5] to calculate the γ-ray production cross sections of the γ-ray lines at Eγ = 2167.47 keV and Eγ = 1970.38 keV emitted by 38Ar and 36Ar, respectively, to compare them to our preliminary experimental data. Two experimental campaigns [6,7] were conducted with the AFRODITE array at iThemba LABS (Cape Town, South Africa). Proton beams of energies ranging from 30 up to 125 MeV were directed onto a natCa target. The γ-ray spectra were recorded using eight Compton-suppressed HPGe clover detectors placed at 90° and 135°. Total γ-ray production cross sections were extracted after fitting the γ-ray angular distribution cross sections with a Legendre polynomial, depending on the multipolarity of the emitted γ-ray lines, expressed as:

$$W(\theta) = \sum_{l=0}^{l=lmax} a_l Q_l P_l\big(cos(\theta)\big) \qquad (1)$$

with $P_l\big(cos(\theta)\big)$ the Legendre polynomial of order *l*, Q_l γ-ray geometric attenuation factors and a_l are parameters determined by the fit with a_0 being proportional to the total production cross section. An example of an angular distribution for the 1970.80 keV γ-ray line obtained with 42 MeV protons is shown in Fig. 3.

Table 1. OMP parameters obtained in this work for nucleon-induced reactions on ^{40}Ca.

Potentials	Potentials parameters	R_X (fm)	a_X (fm)
Real volume	V_{HF} = 52.80 MeV λ_{HF} = 0.00426 MeV^{-1}	1.093	0.749
Imaginary volume	W_V = 2.38 MeV W_{VWID} = 133.80 MeV	1.093	0.749
Imaginary surface	W_D = 11.89 MeV λ_D = 0.00311 MeV^{-1} W_{DWID} = 19.75 MeV	1.223	0.576
Real spin-orbit	V_{SO} = 5.81 MeV λ_{SO} = 0.00351 MeV^{-1}	0.964	0.576
Imaginary spin-orbit	W_{SO} = -3.36 MeV W_{SOWID} = 189.24 MeV	0.964	0.576
Coulomb	C_{coul} = 3.2	1.131	0.129
β_2 = -0.133	β_3 = 0.527		

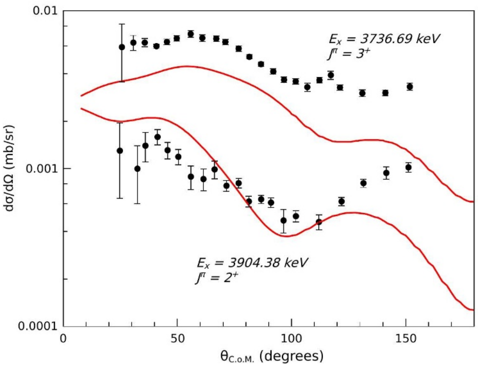

Figure 2. Same as Fig. 1, for inelastically scattered protons to the J$^{\pi}$=3$^+$ (3736.69 keV) and J$^{\pi}$=2$^+$(3904.38 keV) states in ^{40}Ca.

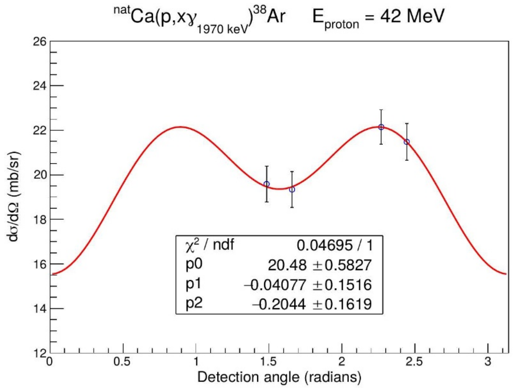

Figure 3. Angular distribution of the 1970.38 keV γ-ray line produced in the ^{40}Ca(p,xγ)^{38}Ar reaction. Blue open circles are experimental data and the solid red line the result of fitting using Equation (1).

The total production cross section of the 1970.38 keV and the 2167.47 keV γ-ray lines are presented in Figs. (4-5).

In Fig. 4, we can see that both calculations using TALYS built-in OMP and our newly built OMP do not reproduce fully the experimental data. However, our new OMP succeeds at reproducing the experimental data specially in the proton energy region between 30 MeV and 66 MeV for the 1970.38 keV γ-ray line. Above 66 MeV protons energies we observe discrepancies between both TALYS calculations and the experimental data. The same couldn't be said for the 2167,47 keV line (Fig. 5) where our OMP underestimates the cross-section results compared to both TALYS default OMP and the experimental data. The energy region above 66 MeV is dominated by the preequilibrium emission, and no modifications were brought to TALYS at this stage. By default, the level density and preequilibrium models used in TALYS are the constant temperature + fermi-gas model and the exciton model, which we also used in our calculations. Varying the level density model can have an impact on the results of TALYS since the preequilibrium emission is tightly influenced by the level density at high nuclear excitation energy in both the target nucleus as well as the daughter nuclei.

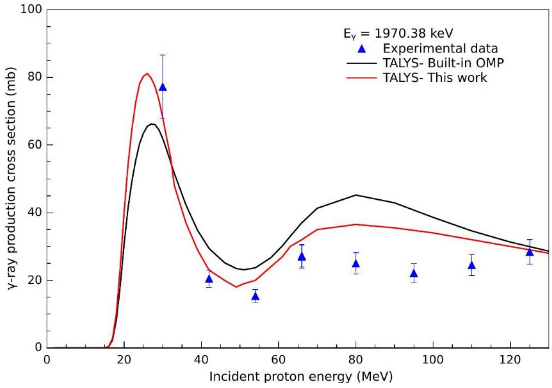

Figure 4. Total γ-ray production cross section for the energy line at 1970.38 keV. Blue triangles are experimental data, red and black curves are TALYS calculations using both our aforementioned newly built OMP and the TALYS default OMP (König and Delaroche), respectively.

Assuming that our OMP is valid over the whole energy range from 0 - 200 MeV, we proceed to the next step which is to fine tune the level density model and preequilibrium model parameters in TALYS in order to better reproduce the experimental data. However, to do so in our case, more γ-ray production cross section data for more residual nuclei produced in p+40Ca reaction must be used to help determine the best level density models for the different residual nuclei appearing in the outgoing channels following multistep emission. This work is the first step in our study of nucleon-induced γ-ray production cross section and reaction cross sections on 40Ca, and the analysis of more γ-ray lines is still ongoing.

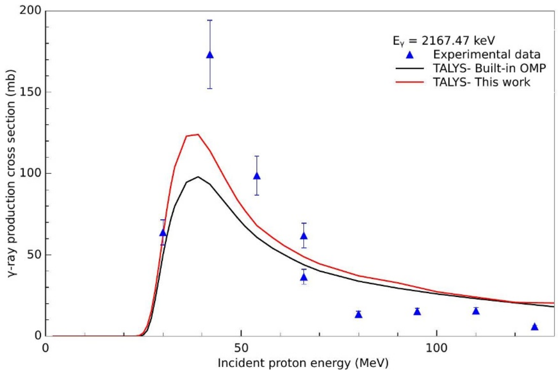

Figure 5. Total γ-ray production cross section for the energy line at 2167.47 keV. Blue triangles are experimental data, red and black curves are TALYS calculations using both our aforementioned newly built OMP and the TALYS default OMP (König and Delaroche), respectively.

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