Towards a coupled-channel optical potential for rare-earth nuclei

G. P. A. Nobre, A. Palumbo, D. Brown, M. Herman, S. Hoblit, and F. S. Dietrich

1 National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
2 P.O. Box 30423, Walnut Creek, CA, 94598, USA

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We present an outline of an extensive study of the effects of collective couplings and nuclear deformations on integrated cross sections as well as on angular distributions in a consistent manner for neutron-induced reactions on nuclei in the rare-earth region. This specific subset of the nuclide chart was chosen precisely because of a clear static deformation pattern. We analyze the convergence of the coupled-channel calculations regarding the number of states being explicitly coupled. A model for deforming the spherical Koning-Delaroche optical potential as a function of quadrupole and hexadecupole deformations is also proposed, inspired by previous works. We demonstrate that the obtained results of calculations for total, elastic, inelastic, and capture cross sections, as well as elastic and inelastic angular distributions are in remarkably good agreement with experimental data for scattering energies around a few MeV.

I. INTRODUCTION

Optical potentials (OP) have been widely used to describe nuclear reaction data by implicitly accounting for the effects of excitation of internal degrees of freedom and other nonelastic processes. Such optical potentials are normally obtained through proper parametrization and parameter fitting in order to reproduce specific data sets. An OP is called global when this fitting process is consistently done for a variety of nuclides.

Even though existing phenomenological OP’s might achieve very good agreement with experimental data under certain conditions, as they were specifically designed to do so, they are not reliable at regions without any measurements, for deformed nuclei, or for the ones away from the stability line. In such circumstances, a more fundamental approach becomes necessary.

The coupled-channel theory is a natural way of explicitly treating nonelastic channels, in particular those arising from collective excitations, defined by nuclear deformations. Proper treatment of such excitations is often essential to the accurate description of reaction experimental data. Previous works have applied different models to specific nuclei with the purpose of determining angular-integrated cross sections.

There are global spherical OP’s that have been fit to nuclei below and above the region of statically deformed rare-earth nuclei, but these potentials have been viewed as inappropriate for use in coupled-channels calculations, since they do not account for the loss of flux through the explicitly included inelastic channels. On the other hand, a recent paper [1] shows that scattering from rare earth and actinide nuclei is very near the adiabatic (frozen nucleus) limit, which suggests that the loss of flux to rotational excitations might be unimportant. In this paper we test this idea by performing coupled channel calculations with a global spherical optical potential by deforming the nuclear radii but making no further adjustments. We note an alternative approach (Kuneida et al. [2]), which has attempted to unify scattering from spherical and deformed nuclei by considering all nuclei as statically deformed, regardless of their actual deformation.

II. PROPOSED MODEL FOR RARE-EARTHS

To test our proposed model, we deform the widely-used spherical Koning-Delaroche optical potential [3] and perform coupled-channel calculations for 34 deformed nuclei, namely, 152,154Sm, 153Eu, 155,156,157,158,160Gd, 159Tb, 162,163,164Dy, 165Ho, 166,167,168,170Er, 169Tm, 171,172,173,174,176Yb, 175,176Lu, 177,178,179,180Hf, 181Ta, and 182,183,184,186W. For such calculations we used the reaction model code EMPIRE, which has the direct reaction process calculated by the code ECIS. We then compared the agreement to experimental data of direct-reaction observables.

Even though the Koning-Delaroche potential is well known to agree very well with existing experimental data for spherical and stable nuclei, it was not designed to describe the ones in the rare-earth region, due to the high deformation of such isotopes. Nevertheless, after deforming this potential in the approach of coupled channels,
a good agreement with experimental data for total cross sections is observed, as can be seen in the examples shown in Fig. 1.

![Graphs showing total cross sections for different nuclei](image)

**FIG. 1.** Total cross sections for the nuclei $^{152}$Sm, $^{156}$Gd, $^{162}$Dy, and $^{180}$Hf obtained through deforming the spherical Koning-Delaroche optical potential using coupled channels (solid black curves). For comparison purposes the calculation with spherical model is also plotted (green dashed curves).

### A. Volume Conservation

When an originally spherical configuration assumes a deformed shape, defined by quadrupole and hexadecupole deformation parameters $\beta_2$ and $\beta_4$, respectively, the volume and densities are not conserved. In order to ensure volume conservation we apply a correction to the reduced radius $R_0$, as defined in Ref. [3], which is

$$R'_0 = R_0 \left(1 - \sum_{\lambda} \beta_{\lambda}^2 / 4\pi \right),$$

where terms of the order of $\beta_3^2$ and higher have been discarded. The effect of such correction is not negligible and seems to bring the calculation to a slightly better agreement with the experimental data, as can be seen in Figs. 2 and 3. This behavior is observed even though the relatively high deformation of $\beta_2 = 0.236$ in the case of $^{184}$W, shown in Figs. 2 and 3, correspond to a correction in the radius lower than one half percent. As a matter of fact, of the nuclei studied in this work, the one with highest deformation ($\beta_2 = 0.353$ for $^{160}$Gd) has a radius correction of less than 1%.

### B. Sensitivity to deformation

As part of our study we varied the deformation parameters up and down 10%, 20%, and 30%, in relation to the central adopted value, and we observed the corresponding effect in the direct-reaction observables. As an example, we show in Fig. 4 the total cross-section results for $^{162}$Dy obtained from coupled-channel calculations using three different values of $\beta_2$: the standard value taken from the compilation of Raman et al. [5] multiplied by 0.70, 1.00 and 1.30. For comparison purposes we also plot the result from the spherical model. As can be seen in Fig. 4, for values of incident energy $E_i$ around $E_i \sim $
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40 keV, 2 MeV, and 5 MeV, the calculated cross sections are insensitive to variations in the deformation. In the other regions, however, large deformation uncertainties lead to large cross-section uncertainties. This means that, in order to assess accurately the value of $\beta_2$, it would be more reasonable to obtain cross-section measurements in energy regions where this sensitivity is higher. Similar behavior was observed in total elastic cross sections.

![Graph](image)

**FIG. 4.** Example of the effect of deformation uncertainty in the case of $^{162}$Dy, depicted by the results of performing coupled-channel calculations with the value for $\beta_2$ from [5] (solid black curve) increased (dash-dotted blue curve) and decreased (short-dashed red curve) by 30%. For comparison purposes the calculation with spherical model is also plotted (long-dashed green curve).

### III. ANGULAR DISTRIBUTIONS

We also assessed the quality of our model in describing angular distributions. Fig. 5 shows, as an example, elastic angular distributions for neutrons scattered by $^{184}$W at different incident energies. As can be seen in Fig. 5, the predictions of our model are in a much better agreement with experimental data than spherical-model calculations. The interesting point to note is that, by deforming the spherical Koning-Delaroche potential, the data description is not only better than the spherical model, as expected, but also generally very good. This serves as an indication that the adiabatic limit is a good approach towards an optical potential for the rare-earths.

The same good description of experimental data is observed for inelastic angular distributions. As an example of our results, we show in Fig. 6 angular distributions for the first $2^+$ state (111.2 keV) of $^{184}$W for different incident energies. In this case, attempts of comparing to spherical model clearly do not make sense. Therefore we plot only the predictions of our model. It can be seen in Fig. 6 that, although the agreement with experimental data is not perfect, the fact that deforming the Koning-Delaroche optical potential allows to describe inelastic angular distributions reasonably well is very encouraging and supportive of the model. Subsequent minor adjustments and modifications may be able to account for the existing disagreements.

### IV. COMPOUND-NUCLEUS OBSERVABLES

The successful results of our approach in describing direct-reaction cross sections served as motivation to test the effect of our model assumptions on compound-nucleus quantities. We analyzed the results for total elastic, which includes contributions from shape and compound elastic, total inelastic and capture cross sections. In all cases a significant improvement in data description was obtained by our coupled-channel model, in comparison to spherical model calculations. To illustrate such results we plot in Fig. 7 the $^{184}$W($n,\gamma$) cross sections for both spherical and coupled-channel models. It is seen that, while the spherical model fails to accurately describe the shape of observed capture, the cross sections calculated through our coupled-channel approach is in impressive agreement with experimental data.
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V. CONCLUSION

In this work we have demonstrated that deforming the spherical Koning-Delaroche optical potential and using it in coupled channels calculations without further modification provides encouraging results in the description of neutron-induced reactions on the rare-earths, despite the fact this potential was not designed to describe such deformed nuclei. We assessed the effect of a correction in the reduced radius to ensure volume conservation when deforming an originally spherical configuration. This correction was found to produce small but significant effects in the direction of improving the agreement with experimental data, at least for the cases where tested. We achieved a good description of experimental data not only for optical-model observables (such as total cross sections, elastic and inelastic angular distributions), but also for those obtained through compound-nucleus formation (such as total elastic and inelastic, capture cross sections). These good results are consistent with the insight gained from Ref. [1] that the scattering is very close to the adiabatic limit. Although the presented results are not perfect, this simple method corresponds to a good, consistent and general first step towards an optical potential capable of fully describing the rare-earth region, filling the current lack of optical model potentials in this important region.

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