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Towards a Coupled-channel Optical Potential for Rare-earth Nuclei

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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 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

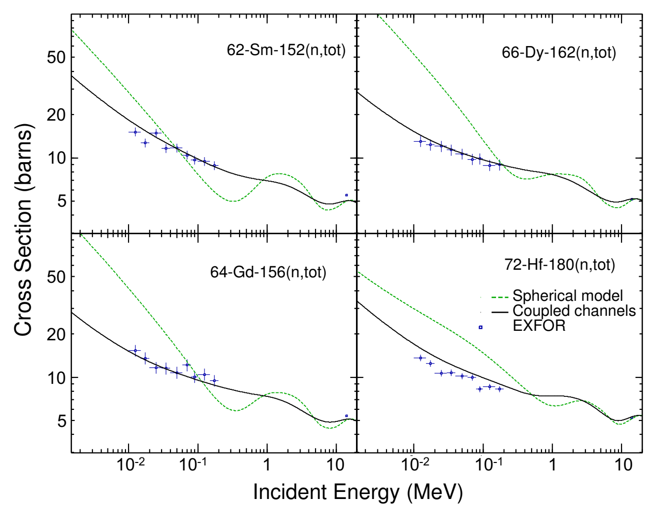

FIG. 1. Total cross sections for the nuclei ^{152}Sm, ^{156}Gd, ^{162}Dy, and ^{180}Hf obtained through deforming the spherical Koning-Delaroche optical potential using coupled channels (solid black curves). For comparison purposes the calculation with spherical model is also plotted (green dashed curves).

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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, ^{152,154}Sm, ^{153}Eu, ^{155,156,157,158,160}Gd, ^{159}Tb, ^{162,163,164}Dy, ^{165}Ho, ^{166,167,168,170}Er, ^{169}Tm, ^{171,172,173,174,176}Yb, ^{175,176}Lu, ^{177,178,179,180}Hf, ^{181}Ta, and ^{182,183,184,186}W. 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.

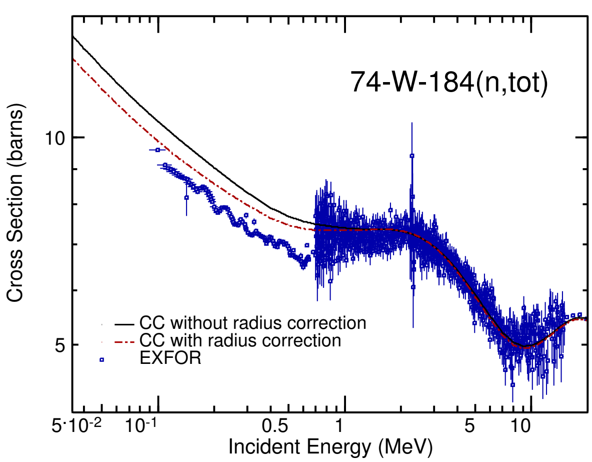

FIG. 2. Comparison between coupled-channel calculations with (dash-dotted red curve) and without (solid black curve) the radius correction to ensure volume conservation (see discussion in text) for ^{184}W total cross sections.

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.

A. Volume Conservation

When an originally spherical configuration assumes a deformed shape, defined by quadrupole and hexadecupole deformation parameters β_2 and β_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. [4], which is

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

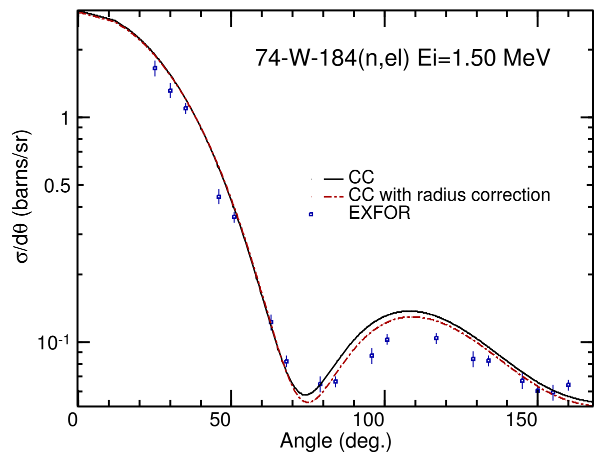

FIG. 3. Comparison between coupled-channel calculations with (dash-dotted red curve) and without (solid black curve) the radius correction to ensure volume conservation (see discussion in text) for ^{184}W elastic angular distribution at the incident energy of 1.50 MeV.

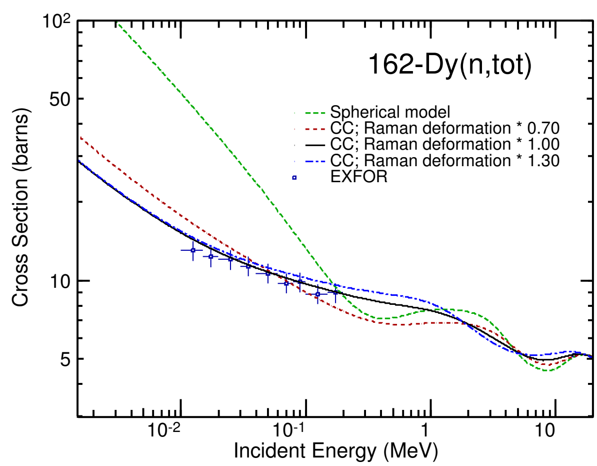

FIG. 4. Example of the effect of deformation uncertainty in the case of ^{162}Dy, depicted by the results of performing coupled-channel calculations with the value for β_2 from [5] (solid black curve) increased (dash-dotted blue curve) and decreased (short-dashed red curve) by 30%. For comparison purposes the calculation with spherical model is also plotted (long-dashed green curve).