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Improved Nuclear Inputs for Nuclear Model Codes Based on the Gogny Interaction

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The need for cross sections far from the valley of stability, for applications such as nuclear astrophysics or future nuclear facilities, challenges the robustness as well as the predictive power of nuclear reaction models. Traditionally, cross section predictions rely on more or less phenomenological approaches, depending on parameters adjusted to generally scarce experimental data or deduced for systematic relations. While such predictions are expected to be reliable for nuclei not too far from the experimentally accessible regions, they are clearly questionable when dealing with exotic nuclei. To improve the predictive power of nuclear model codes, one should use more fundamental approaches, relying on sound physical bases, when determining the nuclear inputs (ingredients) required by the reaction model. Thanks to the high computer power available today, all these major ingredients have been microscopically or semi-microscopically determined, starting from the information provided by a Skyrme effective (and efficient) nucleon-nucleon interaction. These microscopic inputs have shown their ability to compete with the traditional classical methods as such, but also when they are used in actual nuclear cross sections calculations. We will discuss the current efforts made to improve the predictive power of such microscopic inputs using a more coherent nucleon-nucleon interaction, namely the finite-range Gogny force.

I. INTRODUCTION

With the development of new innovative facilities, as well as for astrophysical purposes, nuclear data far from the valley of stability are required. This challenges the nuclear reaction models. Indeed, so far, cross section predictions have mainly relied on more or less phenomenological approaches, depending on parameters adjusted to scarce experimental data or deduced from systematics. Such predictions are expected to be reliable for nuclei not too far from experimentally accessible regions, but are questionable when dealing with exotic nuclei. To face such difficulties, it is preferable to rely on as fundamental (microscopic) as possible methods based on physically sound models. For the nuclear reactions models, the situation is rather positive today since several years of efforts have provided the community with robust and well tested nuclear reactions codes, such as TALYS or EMPIRE for instance, in which the modern nuclear reaction models are coherently implemented. In our case this code is the TALYS code [1–3].

II. THE MICROSCOPIC INGREDIENTS WITH THE GOGNY INTERACTION

Several ingredients are required to perform nuclear reaction cross section calculations: (i) the optical model potential (OMP), (ii) the nuclear level densities (NLD), (iii) the γ-ray strength functions (GSF), and (iv) the fission properties (FP). Thanks to the high computer power available today, all these major ingredients have been microscopically or semi-microscopically determined. These microscopic inputs have shown their ability to compete with the traditional classical methods as such, but also when they are used in actual nuclear cross sections calculations. Until now they have all been derived out of a zero-range Skyrme nucleon-nucleon effective interaction. An improvement would consist in replacing such an interaction by the finite-range Gogny interaction. Work along this line has been started improving the ability of the Gogny force to reproduce experimental nuclear binding energies [4]. With the so-called Gogny D1M [4] parameterization the final rms deviation with respect to the 2149 measured masses is 798 keV. In addition, this new Gogny force is shown to predict nuclear and neutron matter properties in agreement with microscopic calculations based on realistic two- and three-body forces. In the following we focus on the NLD and the GSF.

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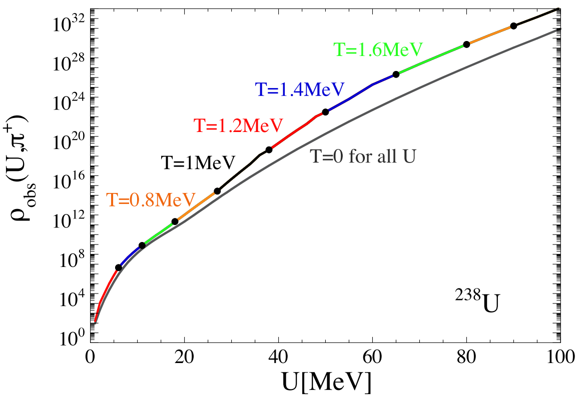

FIG. 1. Total NLD for positive parities of ^{238}U calculated for several temperatures connected smoothly thanks to the procedure described in Ref. [7]. The reference points, i.e., those not affected by the smoothing procedure, are identified by circles. The level density obtained using the HFB ingredients determined at $T = 0$ at all excitation energies U is shown for comparison (lower grey curve).

A. Nuclear Level Densities

The combinatorial model of NLD has now reached a level of accuracy comparable to that of the best global analytical expressions without suffering from the limits imposed by the statistical hypothesis on which the latter expressions rely. In particular, it provides naturally non-Gaussian spin distribution as well as non-equipartition of parities which are known to have a significant impact on cross section predictions at low energies [5]. Our previous global model suffered from a deficiency, in particular in the way the collective effects both vibrational and rotational were treated. The Gogny interaction has shown its ability to predict quite well low-energy quadrupole collective levels, both rotational and vibrational [6]. As a consequence, among other applications, it can be used in the combinatorial method for level density determination, thus reducing the phenomenological part of such an approach. This was done in a recent paper [7] on the basis of temperature-dependent Hartree-Fock-Bogoliubov (HFB) calculations which provide consistently all the nuclear inputs for the combinatorial model as a function of the nuclear temperature. This T-dependent approach presents the advantage of accounting for shell, pairing and nuclear deformation variations with increasing excitation energy. As an illustration we present in Fig. 1 the total NLD for positive parities of ^{238}U calculated for several temperatures connected smoothly thanks to the procedure described in Ref. [7].

The new method presented in Ref. [7] gives reasonable results with respect to available experimental data. Further possible improvements concern the microscopic determination of octupole and hexadecapole vibrational level energies for which a phenomenological expression is still employed. Such modes can be obtained using the quasiparticle random phase approximation (QRPA) briefly sketched in the next subsection.

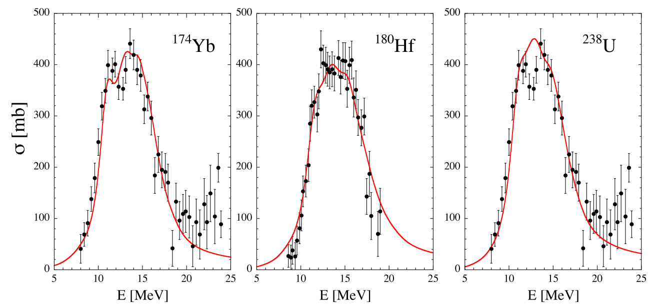

FIG. 2. Comparison of the experimental photoabsorption cross sections for ^{174}Yb, ^{180}Hf and ^{238}U nuclei [13] with QRPA predictions (solid line) obtained with the broadening explained in the text.

B. QRPA and the γ-ray Strength Function

A large number of analytical models and parameterizations for the GSF are available in the literature reflecting the lack of knowledge that we have about this ingredient in particular at low γ energies. Several adjustable analytical models are included in TALYS as well as the tabulated microscopic HFB plus QRPA predictions [8]. In Ref. [8], a zero-range Skyrme force was used and deformed nuclei were described through a phenomenological generalization of the approach. The present method is based on axially-symmetric-deformed HFB+QRPA calculations in a fully consistent way using the finite-range Gogny force.This approach is essential in open-shell nuclei, where pairing correlations and deformation effects play an important role. It has already been applied to study giant resonances in Si and Mg isotopes [9], dipole excitations in Ne isotopes and $N = 16$ isotones [10] as well as electromagnetic excitations up to the octupole one of the heavy deformed ^{238}U [11]. On top of the giant resonances which are in a reasonable agreement with experimental data, the results presented in Ref. [11] also contain information on the spectroscopy at low energy. Wave functions of low-energy QRPA excited states up to $J^\pi = 8^+$ have been included in reaction model to improve the theoretical description of double-differential cross section for neutron on Uranium [12].

The QRPA procedure described and employed in Refs. [9–11] has now been applied to calculate dipole strengths of nuclei for which experimental photoabsorption data exist. The QRPA provides an accurate description of the giant dipole resonance (GDR) centroid and the fraction of the Energy-Weighted Sum Rule exhausted by the E1 mode. However, it is necessary to go beyond this approximation scheme in order to take into account complex configurations as well as coupling with phonons. The GDR is known experimentally to have a large energy width and therefore a finite lifetime. Different microscopic theories exist. For the sake of simplicity and

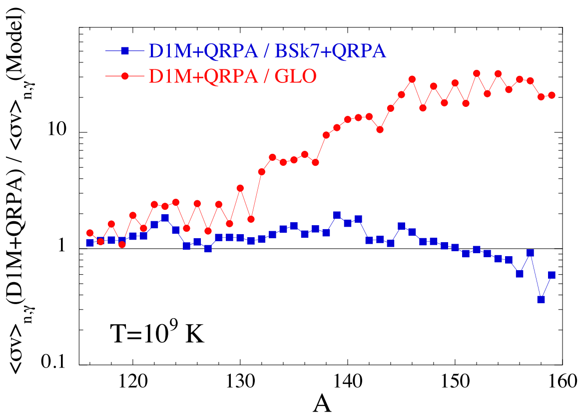

FIG. 3. Ratio of the Maxwellian-averaged neutron capture rate (for a temperature of 10^9 K) for the Sn isotopes predicted with the microscopic E1-strength taken from the QRPA (with the Gogny D1M force) to the one obtained with the generalized Lorentzian model (circles) [13] and to the one predicted with the Skyrme-QRPA of [8] (squares).

applicability to large scale calculations, we restrict ourselves to a semi-empirical broadening of the GDR. Such a broadening is obtained by folding the QRPA strength $S_{E_1}(\omega)$ by a normalized Lorentzian function

$$L(E,\omega) = \frac{1}{\pi}\frac{\Gamma^2 E^2}{[E^2-(\omega-\Delta)^2]^2+\Gamma^2E^2}.$$

The Γ width is adjusted on experimental data while the energy shift is deduced from the following energy-dependent parametrization: $\Delta(\omega) = \Delta_0 + \Delta_{4qp}(\omega)$, where Δ_0 is a constant shift due to the coupling between quasiparticle (qp)-states and phonons and the quantity $\Delta_{4qp}(\omega)$ is taken to be proportional to the number of 4-qp states, which is obviously a function of the excitation energy ω and depends on the nucleus considered. QRPA photoabsorption cross sections are compared with experimental data [13] in Fig. 2 for a sample of 3 deformed nuclei, namely ^{174}Yb, ^{180}Hf and ^{238}U. Correspondig results for ^{76}Ge, ^{156}Gd and ^{192}Os can be found in Ref. [14]. A more systematic comparison between our results and experimental data will be provided in a forthcoming paper. We remind here that the split into two components (one for each value of the projection K of the angular momentum $J = 1$) of the dipole response in deformed nuclei is naturally taken into account in our approach.

The present QRPA approach can also be applied to the GSF predictions of exotic nuclei. If qualitatively speaking, the microscopic E1 strength functions rather look like the phenomenological Lorentzian for nuclei close the valley of stability, this may not be the case for exotic neutron-rich nuclei, in particular in the low-energy region where some extra strength, the so-called pygmy resonance, is known to become significant. The differences between analytical and microscopic GSF for nuclei far from the valley of stability are also known to have a significant impact on the predicted neutron-capture cross section of astrophysical interest. This is illustrated in Fig. 3, where the Maxwellian-averaged neutron capture rate obtained using the GSF calculated with the present QRPA approach are compared, for the Sn isotopes, with those obtained using either the Generalized Lorentzian (GLO) model [13] or the Skyrme-HFB+QRPA model of Ref. [8]. The ratio is close to one for stable or nearly stable nuclei but, with respect to the GLO approach, our present GSF is shown to give rise to reaction rates that can be about 20 times larger for exotic neutron-rich nuclei. In contrast, rather similar predictions are obtained when considering the Skyrme-HFB plus QRPA calculations of Ref. [8].

III. CONCLUSIONS

The results obtained with the Gogny force for the nuclear masses, the NLD and the GSF are quite promising. We are thus planning to include, one by one, the ingredients required to perform microscopic cross section calculation out of an optimized Gogny interaction. We believe that work along such a path is a way to progress and be able, in the future, to obtain satisfactory evaluations on the basis of reliable and accurate microscopic inputs only.

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