Nuclear ingredients for cross section calculation of exotic nuclei

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Abstract. The increasing need for cross sections far from the valley of stability, especially for applications such as nuclear astrophysics, poses a challenge for nuclear reaction models. So far, predictions of cross sections have relied on more or less phenomenological approaches, depending on parameters adjusted to available experimental data or deduced from systematic relations. While such predictions are expected to be reliable for nuclei not too far from the experimentally known regions, it is clearly preferable to use more fundamental approaches, based on sound physical bases, when dealing with very exotic nuclei. Thanks to the high computer power available today, all major ingredients required to model a nuclear reaction can now be (and have been) microscopically (or semi-microscopically) determined starting from the information provided by an effective nucleon-nucleon interaction. All these microscopic ingredients have been included in the latest version of the TALYS nuclear reaction code (http://www.talys.eu/).

1. Introduction

The calculation of nuclear reaction cross sections involves several models such as the optical model, the pre-equilibrium model and the compound nucleus model connected one with another in a nuclear reaction code. These models rely on parameters (or ingredients) which are usually adjusted to reproduce experimental data. However, when one has to deal with nuclear reactions involving exotic targets located far from the valley of stability, the lack of experimental information makes it necessary to extrapolate the parameters on which the reaction models are based. One has then to face a situation where (1) the predictive power and robustness of the nuclear reactions models is crucial and (2) the extrapolations of the models’ ingredients have to be trusted. 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 [1] or EMPIRE [2] for instance, in which the modern nuclear reaction models are coherently implemented. The same holds for phenomenological ingredients which have been used since the infancy of nuclear physics, and have proven their ability in fitting available experimental nuclear data. These ingredients have been assembled in libraries, among which the most famous one is certainly the Reference Input Parameter Library (RIPL) developed for nearly 15 years under the coordination of the IAEA [3]. However, these phenomenological approaches are often based on simple empirical approximations to represent the complexity of nuclear physics from a universal point of view, and it is therefore quite clear that their extrapolations are likely to...
be more uncertain than those based on sound physical bases usually referred to as microscopic approaches. This is the reason why several years of efforts have been devoted to derive all the ingredients required by nuclear reaction models from theoretical approaches based on first principles of physics and to include them in a nuclear reaction code. In our case this code is the TALYS code [1], and within the RIPL project (Phase 3), almost all microscopic ingredients implemented in TALYS have also been made available to the nuclear physics community. The present contribution summarizes the various microscopic models developed and implemented in the TALYS code and discusses some future improvements.

2. From phenomenological to microscopic approaches

For astrophysics, but also in other fields, a large amount of nuclear data need to be extrapolated far away from experimentally known regions. In these situations, two major features of the nuclear theories have to be considered. The first one is the accuracy of a model. In most applications, this criterion has been the main, if not the unique, one for selecting a model. The second one is the reliability of the predictions. A physically sound model based on first principles and that is as close as possible to a microscopic description of the nuclear systems is expected to provide the best possible reliability of extrapolations far away from experimentally known regions. Of course, the accuracy of such microscopic models in reproducing experimental data may be poorer than the one obtained from more phenomenological models in which enough free parameters can guarantee a satisfactory agreement with the data at the expense of the quality of the input physics, and consequently of the reliability.

The most fundamental quantity concerns the nuclear structure properties. These include the nuclear mass, the deformation, the nuclear radius, ... of the nucleus in its ground state as well as in its excited states. A series of Hartree-Fock-Bogolyubov (HFB) mass formulas have recently been constructed. Such HFB calculations are based on a conventional Skyrme force with a density dependent or independent pairing interaction treated in the full Bogolyubov framework with restoration of broken symmetries. Among the various mass model, the BSk14 [4] and BSk21 [5] interactions have been implemented in TALYS. Their respective rms deviations with respect to all measured nuclear masses amount to 0.729 and 0.577 MeV. While the latter gives a much higher accuracy and has been constrained to many more observables, the former has also been used to coherently determined additional nuclear inputs, such as nuclear level density and fission properties. For this reason, BSk14 remains one of the favored interactions for reaction calculations and to estimate the various nuclear ingredients of relevance, i.e (i) the optical model potential (OMP), (ii) the nuclear level densities, (iii) the $\gamma$-ray strength functions, and (iv) the fission properties, as discussed below.

Starting with the OMP, we have at our disposal the so-called semi-microscopic JLMB approach [7] which essentially requests as inputs the nuclear matter densities. Such an approach is clearly less accurate than phenomenological or local OMP which have been fitted for years to reproduce experimental data in the valley of stability. Yet, since it is not based on a free parameter adjustment, but rather on symmetric nuclear matter properties within the Brückner-Hartree-Fock approach, its predictive power far from the experimentally known regions is increased. The only required inputs of this OMP are the proton and neutron radial matter densities which can be and have been tabulated and stored in databases [1, 3, 6].

Another crucial quantity required, in particular for the statistical decay of the compound nucleus, is the nuclear level density. As for the OMP, a large collection of more or less refined analytical expressions are available in the literature. However these analytical models suffer from severe limitations due to the crude approximations on which they rely. For this reason, we have developed an alternative method to go beyond these severe restrictions. It consists in using a microscopic combinatorial model essentially based on HFB nuclear structure properties. This approach provides nuclear level densities which can compete with the historically employed...
global phenomenological approaches and simultaneously account for non statistical features [8]. Systematic calculations of nuclear level densities have been performed and made available in a table format. These tables can be used, but also adjusted if need be to fit experimental reaction cross sections (more details can be found in Refs [6, 9, 10]).

A decay channel which always have to be considered in competition with the light particle emission is the photon emission. For this specific channel, the $\gamma$-ray strength functions are the counterpart of the particle transmission coefficients obtained from the OMP. Again, a large number of analytical models are available in the literature (see Ref. [3] for an extensive review) reflecting the lack of knowledge that we have about this ingredient in particular for low photons’ emission energies. The $\gamma$-ray strength function has also been determined from microscopic approaches such as the Quasiparticle Random Phase Approximation for instance. Within this framework, the E1 $\gamma$-ray strength functions have been systematically and successfully determined [11] and made available in a table format [3, 6].

Last but not least is the fission channel which is probably the most complex process to model. Phenomenological approaches lead to accurate description of experimental fission cross sections, but at the price of the adjustment of several tens of free parameters whose fine tuning is particularly subtle and makes it almost impossible to make any predictions. Microscopic fission barriers can also be determined coherently with all the previously mentioned ingredients. As pointed out in Ref. [4], the global model of HFB barriers obtained with the BSk14 Skyrme force reproduces the empirical barriers [3] of nuclei with $Z \geq 88$ with an rms deviation of about 0.65 MeV. It remains difficult nowadays to improve such an accuracy with global models, even on the basis of macroscopic-type approaches. Such an accuracy is clearly not sufficient for practical applications, but with a simple normalization, a fair description of experimental fission cross section can be achieved [10]. Such an approach has also the advantage of avoiding the simple picture of double-humped inverted parabolic shapes (whose height and width are freely adjusted among other parameters) and of providing fission paths (along with nuclear level densities at the saddle points) on the same footing for both measured and unknown nuclei.

3. What’s coming next

All the previously mentioned microscopic ingredients have been tabulated either directly within the TALYS nuclear reaction code or in publicly available libraries [3, 6]. Yet, they have all been derived on the basis of a Skyrme-type effective interaction. A future improvement would consist in replacing this interaction by a finite-range interaction of the Gogny type with an explicit and microscopic account of collective correlations beyond mean field. Work along this line has already started improving significantly the ability of the Gogny HFB model to reproduce experimental masses [12]. Thanks to this new interaction, we plan to derive all the microscopic ingredients within a coherent framework.

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