The isovector imaginary neutron potential and its impact on the r-process nucleosynthesis

Stéphane Goriely[1,*]

[1]Institute of Astronomy and Astrophysics, Université Libre de Bruxelles, CP 226, 1050 Brussels, Belgium

Abstract. The need for nuclear data 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 present nuclear models. The isovector contribution to the imaginary component of the microscopic optical model potential remains unconstrained at keV energies. Within the Brückner–Hartree–Fock approximation of Jeukenne-Lejeune-Mahaux, it is shown that experimental neutron strength function data favours a strong isovector component that can have a drastic impact on the radiative neutron capture cross section for neutron-rich nuclei. If confirmed, this result strongly inhibits the neutron capture by exotic nuclei, so that the traditional r-process picture of fast neutron captures during the nucleosynthesis r-process needs to be revisited in depth. Reliable microscopically founded calculations of the optical potential are needed to better understand the neutron capture by exotic nuclei.

1 Introduction

The radiative neutron captures by exotic nuclei are known to be of fundamental importance in many nuclear applications, including energy or astrophysics applications. A well established evaluation procedure for cross sections is to assess the experimental database for each isotope of interest and to then combine theoretical analyses with experimental data. In all cases, the evaluator relies upon the theoretical analysis for at least part of the evaluation, the extent depending upon the amount of the experimental data available. Almost all existing theoretical analyses of the neutron capture cross sections rely on nuclear ingredients extracted from phenomenological models. These include ground state or fission structure properties, nuclear level densities, photon strength functions, and optical model potentials. Such approaches consider almost all model parameters as free in order to be able to achieve accurate description of experimental cross sections. Although such adjustments respond to the high-accuracy needs of some nuclear applications, their predictive power remains poor due to the large number of free parameters and often nonphysical approximations considered. Uncertainties affecting the evaluation of cross section are obtained by propagating the parameter uncertainties into cross section calculations, but remain based on the same phenomenological models.

For the last decades, important progress has been achieved in fundamental nuclear physics, making it now feasible to use more reliable, but also more complex microscopic or semi-microscopic models provided by physically sound theories based on first principles for practical applications. In particular, it has been shown that Hartree-Fock-Bogolyubov (HFB) models can be extremely successful in predicting ground state as well as fission observables [1]. Going beyond mean-field approach, Quasi-particle Random Phase Approximation (QRPA) also proved its capacity to predict reliably nuclear level densities [2], photon strength functions [3] or β-decay half-lives [4]. These models significantly differ from the more traditional phenomenological ones and can give rise to predictions that cannot be mimicked by parameter variations. Such model uncertainties are usually not taken into account in data evaluations. Eric Bauge was visionary in this respect and knew that nuclear data evaluation could or should also include a sensitivity study, not only relative to parameter variations, but also to model defects. His key contribution in determining optical model potentials (OMP) from such a microscopic description has been extremely beneficial and open new perspectives in the prediction of neutron capture cross section that may have important implication for nucleosynthesis applications, as discussed below.

2 The JLMB potential

The neutron capture rates are commonly evaluated within the framework of the statistical model of Hauser-Feshbach, in which the nucleon-nucleus OMP of Jeukenne-Lejeune-Mahaux [5] is used. This so-called JLM potential derived from a Reid's hard core nucleon–nucleon interaction by applying the Brückner–Hartree–Fock approximation to nuclear matter has been updated by Eric Bauge and collaborators [6, 7] who empirically renormalized the energy dependence of the potential depth to reproduce scattering and reaction observables for spherical and quasi-spherical nuclei between ^{40}Ca and ^{209}Bi in a

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[*] e-mail: stephane.goriely@ulb.be

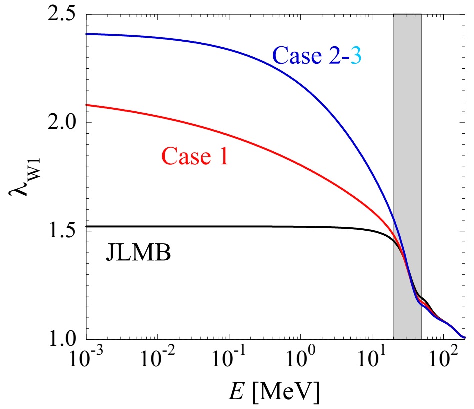

Figure 1. Energy dependence of the λ_{W_1} factor for the JLMB potential [7] and the 3 modified cases (Cases 1-3). The box around 20 to 50 MeV represents the energy range in which the uncertainties on λ_{W_1} are minimum and estimated to be of the order of 10% [7].

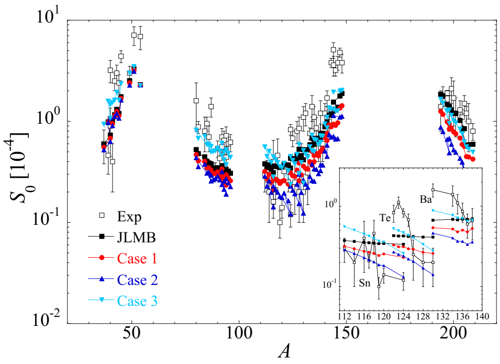

Figure 2. Comparison between the experimental S-wave strength function (S_0) [8] and the values obtained with the JLMB OMP and the modified imaginary potentials corresponding to Cases 1, 2 and 3 (see text). The insert zooms on the three spherical or quasi-spherical Sn, Te and Ba isotopic chains.

large energy range from the keV region up to 200 MeV. In this JLMB version, the renormalization factors are rather well constrained by experimental data, except the λ_{W_1} factor affecting the isovector imaginary component in the low-energy regime. The major constraint imposed on the OMP isovector component comes from the quasi-elastic (p, n) scattering data as well as the angle-integrated quasi-elastic (p, n) cross sections to the isobaric analog states at energies above some 20 MeV. For lower energies, the λ_{W_1} factor was extrapolated from the confident region around 20 MeV to a constant value of approximately 1.52, as shown in Fig. 1. Due to the lack of scattering data in the keV region, the low-energy extrapolation of the λ_{W_1} factor remains essentially unconstrained. Since the low-energy part of the factor λ_{W_1} strongly affects the absorption characteristics by exotic neutron rich nuclei, the corresponding neutron capture at astrophysically relevant energies (i.e. typically about 100 keV for incident neutrons) remains poorly described.

For this reason, additional experimental information that could possibly constrain the isovector component of the imaginary potential, i.e. the λ_{W_1} factor, at low energies, has been considered in Ref. [9]. In this respect, the S-wave neutron strength function (S_0) experimentally determined at energies ranging between 1 and 100 keV provide an extremely valuable set of constraints, which is particularly sensitive to the isospin dependence of the OMP. Interestingly, experimental S_0 data is available for the long spherical or quasi-spherical isotopic chains of Sn, Te and Ba isotopes, as shown in Fig. 2 which reveals that the isospin trend is not properly described by the standard JLMB renormalization. This low-energy data is particularly sensitive to the adopted value of the λ_{W_1} factor. To study this sensitivity, three cases corresponding to modified renormalizations of the JLM imaginary potential were considered in Ref. [9]. Case 1 corresponds to a modified value of λ_{W_1} at energies below 1 MeV which is larger by 30% with respect to the JLMB value and Case 2 by about 50% (see Fig. 1). Case 3 corresponds to the same λ_{W_1} as in Case 2, but with a λ_W value (affecting both the isoscalar and isovector parts of the imaginary potential) twice larger than the JLMB value for energies below 1 MeV (see [7] for more details on λ_W). The impact of these modified OMPs on the S-wave neutron strength function is shown in Fig. 2 with a special emphasis on the Sn, Te and Ba isotopes. Case 1 already presents a relatively small slope, in contrast to the JLMB case. Cases 2 and 3 predict a strong slope in better agreement with experimental data. Case 3 is found necessary to improve the agreement for the neutron strength functions in the Pb region and for the Ba isotopic chain, as seen in Fig. 2.

3 Impact on rates and the r-process

On the basis of these OMPs, the Maxwellian-averaged reaction rates of astrophysics interest have been estimated with the TALYS code [10], including the compound nucleus, pre-equilibrium and direct contributions [11]. As illustrated in Fig. 3, the experimental constraints introduced have a drastic impact on the reaction rate. At large neutron excesses, the enhanced λ_{W_1} factor strongly reduces the imaginary component, i.e. the neutron absorption channel, and consequently the radiative neutron capture cross section. In particular, it can be seen that the rates obtained in Case 3 rapidly drop by orders of magnitude half way before the neutron drip line, leading to a totally insignificant neutron capture. Case 2 gives a rather similar evolution with the neutron excess, while Case 1 gives a less drastic decrease of the rate, but still significant [9]. According to Fig. 2 insert, Cases 2 and 3 better reproduce the slope seen in the isospin dependence of the experimental S_0 values and could therefore be expected to provide a more reliable input for the calculation of reaction rates.

The impact of such a drastic reduction of the neutron capture rates on the r-process nucleosynthesis is illustrated in Fig. 4 showing the final composition of the ejecta from

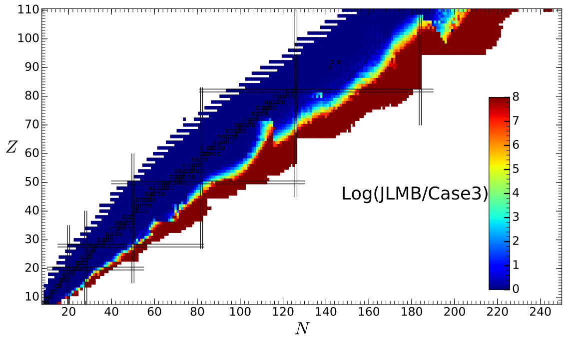

Figure 3. Illustration in the (N, Z) plane of the ratio (in log scale) of the (n, γ) rates at $T = 10^9$ K obtained with the JLMB OMP and the Case 3 modified imaginary potential.

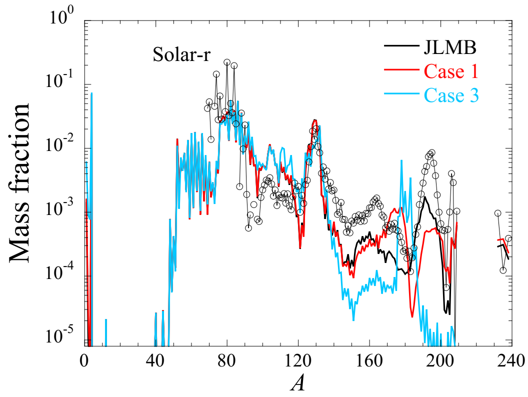

Figure 4. Final r-process mass fractions of stable nuclei (and long-lived Th and U) of the material ejected by a binary 1.375-1.375 $M_\odot$ neutron star merger as a function of the atomic mass A obtained with the JLMB OMP (black line) and the modified imaginary potentials, Case 1 (red line) and Case 3 (blue line).

a 1.375-1.375 $M_\odot$ neutron star merger (NSM) [12]. Rates obtained using the JLMB potential give rise to a rather well established $(n, \gamma) - (\gamma, n)$ equilibrium during the neutron irradiation. This is, however, not the case when adopting rates with renormalized OMP (Case 1 or 3). In these cases, the neutron capture is slow despite the very high neutron densities and the nuclear flow remains close to the valley of stability, so that it takes significantly more time to produce heavier and heavier species. With Case 1 OMP, the flow still manages to reach the actinide region, but this is not possible anymore with Case 3. If indeed the neutron absorption is significantly reduced, the traditional picture of a possible fast r-process neutron capture up to the exotic neutron-rich region needs to be revisited. Such a new calculation of radiative neutron capture rates, if confirmed, could have far-reaching astrophysics implications, as detailed in Ref. [9]. However, before drawing any firm conclusion, the present calculations need to be further constrained by additional theoretical and experimental works. More accurate and microscopically founded calculations of the OMP are needed, in particular using nuclear structure information from microscopic calculations [13]. For astrophysics applications, it is consequently of crucial importance to devote more theoretical as well as experimental effort to better understand the neutron capture by exotic nuclei.

4 Conclusions

Experimental S-wave neutron strength functions provide a rather strong constraint on the low-energy isovector imaginary component of the OMP. Within the BHF approximation, they favour a large renormalization of the isovector imaginary potential that can have a drastic impact on the neutron capture cross section by exotic neutron-rich nuclei of astrophysical interest. The need to introduce such a renormalization factor may be partially related to the fact that the asymmetry component of the JLM semi-microscopic model is obtained by differentiating a symmetric nuclear BHF matter calculation with respect to the asymmetry parameter. Future BHF calculations of the asymmetric nuclear matter would be most useful to test this crucial effect at large neutron excesses. Besides, the strong renormalization factors point to major deficiencies inherent to the nuclear matter approach to microscopic optical model at low energy where strong nuclear structure effects on reaction observables are present. In the energy regime of astrophysical interest, the OMP central component is expected to depend on both the parity and the angular momentum, so that a nuclear structure approach to the OMP would be more appropriate (see e.g. Potel Aguilar *et al., This conference*).

The enhancement of the isovector imaginary potential has a drastic impact on the resonant capture by exotic neutron-rich nuclei. The renormalized OMP constrained on S-wave neutron strength functions leads to radically smaller rates by neutron-rich nuclei (at least within the Hauser-Feshbach approach), so that the traditional picture of a fast r-process neutron capture up to the exotic neutron-rich region, including the establishment of an $(n, \gamma) - (\gamma, n)$ equilibrium, may be strongly questioned.

Acknowledgement

This work has been supported by the Fonds de la Recherche Scientifique (F.R.S.-FNRS; Belgium) under Grant No IISN 4.4502.19 as well as under the EOS Project No O022818F co-funded by the Research Foundation Flanders (FWO, Belgium). The computational resources have been provided by the Consortium des Equipements de Calcul Intensif (CECI), funded by the F.R.S.-FNRS under Grant No 2.5020.11 and by the Walloon Region.

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