Proc. 14th Int. Symp. on Nuclei in the Cosmos (NIC2016)
JPS Conf. Proc. **14**, 011003 (2017)
https://doi.org/10.7566/JPSCP.14.011003

Enhancement of Neutron Capture Rates for Deformed Nuclei and Impact on the r-process Nucleosynthesis Calculations

Toshihiko Kawano, Matthew R. Mumpower, and John L. Ullmann

Los Alamos National Laboratory, Los Alamos NM 87545, USA

E-mail: kawano@lanl.gov

(Received September 6, 2016)

We calculate neutron radiative capture cross sections for medium to heavy mass nuclei with the statistical Hauser-Feshbach theory, and compare with recommended cross sections in the evaluated nuclear data libraries, ENDF/B-VII.1 and JENDL-4. We introduce an M1 scissors mode into the γ-ray decay channel, and estimate the strength of M1 by comparing calculated cross sections with the evaluated data. We show the estimated M1 enhances the neutron capture cross sections for deformed nuclei. A simple sensitivity study is performed to test this enhancement for the nucleosynthesis calculations.

KEYWORDS: neutron capture, γ-ray strength function, Hauser-Feshbach theory, r-process

1. Introduction

Statistical Hauser-Feshbach calculations with the width fluctuation correction for the neutron radiative capture process in the keV to MeV energy region are still unsatisfactory, in particular to obtain reasonably accurate neutron capture cross sections for r-process nucleosynthesis calculations. This is mainly due to relatively large uncertainties in the model parameters used; the level density, the spin and parity distributions in the continuum, and the γ-ray strength function $f_{XL}(E_\gamma)$. Ullmann et al. [1] showed that the calculated neutron capture cross section for a deformed system strongly influenced by the M1 scissors mode [2], although the amplitude of collective motion is expected to be small. The shell model calculations by Schwengner et al. [3] also show enhancement of M1 radiation at low energies, and this was applied to the nucleosynthesis calculations [4].

When the energy of emitted γ-ray from a compound nucleus is very low ($E_\gamma < 1$ MeV), such decay process has no impact on the calculated neutron capture cross section, because the γ-ray transmission coefficient carries a factor of E_γ^{2L+1}, where L is the multipolarity of photon emission. While the M1 scissors mode, which is often seen in a few MeV region for deformed nuclei, might play an important role in de-excitation of a compound nucleus. We examine the enhancement in the calculated neutron capture cross sections for deformed nuclei due to the additional M1 strength, and show how this enhancement has an impact on the r-process nucleosynthesis calculations [5]. Since the enhancement could be remarkable for strongly deformed nuclei, we focus on the nuclei in the mass $A = 100 – 200$ region.

2. Calculation Method and Results

2.1 Neutron Radiative Capture Cross Section

The Hauser-Feshbach formula with the width fluctuation correction for the neutron radiative capture process is written in the form

$$\sigma_{\mathrm{capt}}(E_n) = \frac{\pi}{k_n^2} \sum_{J\Pi} g_c \frac{T_n T_\gamma}{T_n + T_\gamma} W_{n\gamma} , \tag{1}$$

where g_c is the spin statistical factor, k_n is the wave-number of incoming neutron, T_n is the neutron transmission coefficient, T_γ is the lumped γ-ray transmission coefficient, and $W_{n\gamma}$ is the width fluctuation correction factor. For calculating $W_{n\gamma}$, we use the model of Moldauer [6] with the Gaussian Orthogonal Ensemble (GOE) parameterization [7]. The capture cross section is related to the γ-ray strength function through the lumped γ-ray transmission as

$$T_\gamma = \sum_{J'XL} \int_0^{S_n+E_n} 2\pi E_\gamma^{2L+1} f_{XL}(E_\gamma)\rho(E_x, J')dE_x , \tag{2}$$

where E_x is the excitation energy of residual nucleus, S_n is the neutron separation energy, E_n is the incident neutron energy, and $\rho(E_x, J)$ is the level density. The summation runs over all allowed spin and parity combinations. For the γ-ray strength function $f_{XL}(E_\gamma)$, we typically include the giant dipole resonance (GDR) E1 [8], the spin-flip M1 mode, and small contributions from higher multipolarities, E2 and M2.

2.2 Capture Enhancement by the M1 scissors mode

In addition to these commonly used strengths, we add the M1 scissors mode in a standard Lorentzian shape, then adjust the strength ($\Gamma_{\mathrm{M1}}\sigma_{\mathrm{M1}}$, where Γ is the Lorentzian width and σ is the peak cross section) to reproduce evaluated neutron capture cross sections in the fast energy range in the mass region A = 100–200 [9]. This allows us to study a correlation between nuclear deformation and the M1 strength. The coupled-channels and Hauser-Feshbach theory CoH$_3$ [10] is used for calculating the cross sections. The nuclear deformation parameters are taken from the finite range droplet model (FRDM) [11].

The obtained M1 strengths for the target nuclei are fitted by assuming a quadratic form in the nuclear deformation; $\Gamma_{\mathrm{M1}}\sigma_{\mathrm{M1}} \propto \beta_2^2$, and put it back into the Hauser-Feshbach calculations. This additional strength enhances the calculated capture cross sections on deformed nuclei by a factor of 2–3 in a wide mass range, which is shown in the left panel of Fig. 1 as ratios to the evaluated cross sections. Since we assumed the amplitude of scissors mode is proportional to β_2^2, the calculated cross sections for spherical nuclei are unchanged. We also show the deviations for the absolute cross sections in the right panel. The average deviations are -34 mb for the no-M1 case, and -7 mb for the with-M1 case.

2.3 Impact on r-Process Nucleosynthesis Calculation

In the reaction rate calculations with the Hauser-Feshbach theory, we empirically know that phenomenological GDR parameters for E1 often underestimate available average γ-ray width data, $\langle\Gamma_\gamma\rangle$. We now claim this is partly due to the missing M1 strength. However there are also other contributions to the total γ-ray emission channel, such as the E1 pygmy dipole resonance. These missing components are phenomenologically averaged out by adopting the equality

$$2\pi \frac{\langle\Gamma_\gamma\rangle}{D_0} = T_\gamma , \tag{3}$$

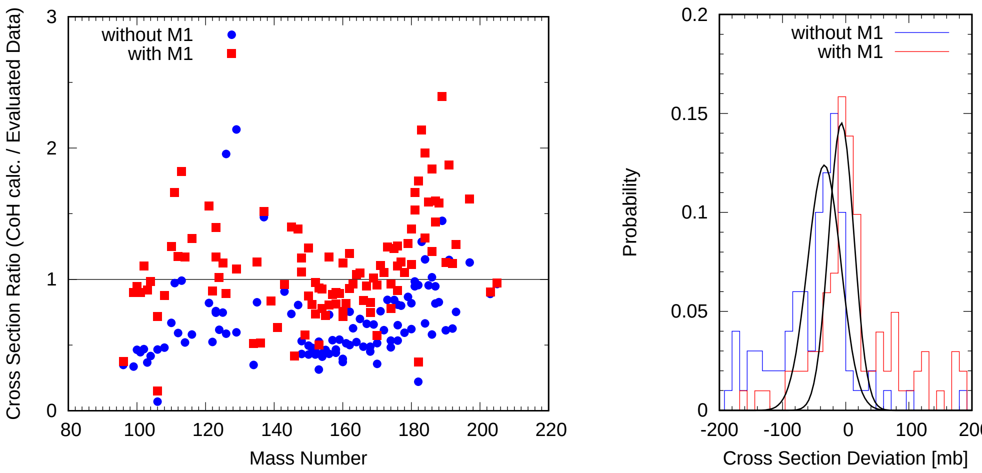

Fig. 1. The calculated capture cross sections at 200 keV are compared with those in the evaluated cross sections in ENDF/B-VII.1 and JENDL-4. The left panel shows the ratios to the evaluated data. The blue symbols show the case when the Hauser-Feshbach calculations do not include the M1 scissors mode. The red symbols are with the scissors mode. The histograms shown in the right panel are the deviations.

which is satisfied for stable nuclei by renormalizing the γ-ray transmission coefficient. For example, CoH_3 renormalizes T_γ by a simple estimate of $\langle \Gamma_\gamma \rangle \simeq 2970A^{-2.08}$ eV. This is one of the caveats to consider when using some existing Hauser-Feshbach codes for calculating neutron capture rates.

In order to study the impact of the capture enhancement, we performed the r-process nucleosynthesis calculations [5], and investigate the capture rate enhancement due to the scissors mode in a relative sense. Instead of re-generating all the reaction rates, we simply multiply the neutron capture rates by a factor of three, which was estimated in our capture cross section calculation, to see the relative impact on the nucleosynthesis. The calculated solar abundances $Y(A)$ with the increased capture rates are shown in Fig. 2 by the ratios to the original capture rates. Three cases are shown; the low entropy hot r-process, the cold r-process, and the neutron star merger (NSM). We expect that inclusion of M1 scissors mode will have a large impact on the calculated abundances in the mass range 150–190, particularly reduction near $A = 150$. The NSM case has the largest sensitivity to the capture rates, especially near $A = 170$, since the r-process path is controlled by a balance between neutron captures and β-decays in this scenario. We are conducting full nucleosynthesis calculations by removing the phenomenological renormalization of γ-ray strength functions, from which we will be able to perform the sensitivity studies for the E1 GDR and the M1 scissors mode separately.

3. Conclusion

Recent progress on the study of γ-ray strength functions suggests a large enhancement in the neutron capture rates for deformed nuclei. Our systematic investigation on the M1 scissors mode correlating with the nuclear deformation also shows the capture enhancement by a factor of 2–3 in the medium to heavy mass region. Such enhancement was implicitly included in the past study by a phenomenological renormalization of γ-ray strength functions. However, we should separate the contributions from the E1 giant dipole resonance and the M1 scissors mode to the astrophysical simulations for better prediction.

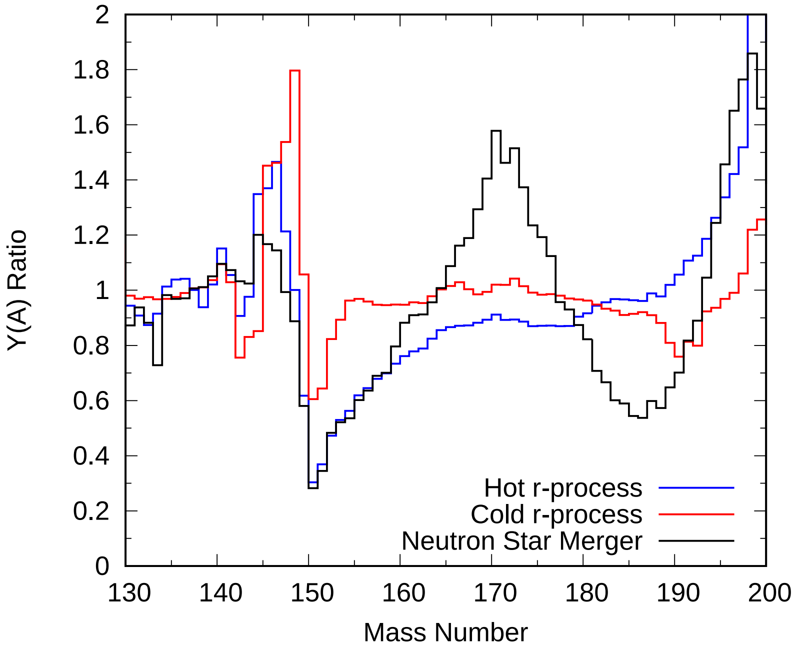

Fig. 2. Nucleosynthesis calculations for three different conditions; the cold r-process, the low entropy hot r-process, and the neutron-star merger. The calculated solar abundances $Y(A)$ are shown by the ratios of non-perturbed capture rates to the scaled case.

Acknowledgment

This work was carried out under the auspices of the National Nuclear Security Administration of the U.S. Department of Energy at Los Alamos National Laboratory under Contract No. DE-AC52-06NA25396.

References

[1] J. L. Ullmann, T. Kawano, T. A. Bredeweg, A. Couture, R. C. Haight, M. Jandel, J. M. O'Donnell, R. S. Rundberg, D. J. Vieira, J. B. Wilhelmy, J. A. Becker, A. Chyzh, C. Y. Wu, B. Baramsai, G. E. Mitchell, and M. Krtička, Phys. Rev. C **89** (2014) 034603.
[2] K. Heyde, P. von Neumann-Cosel, and A. Richter, Rev. Mod. Phys. **82** (2010) 2365.
[3] R. Schwengner, S. Frauendorf, and A. C. Larsen, Phys. Rev. Lett. **111** (2013) 232504.
[4] S. Frauendorf, M. Beard, M. Mumpower, R. Schwengner, and K. Wimme, EPJ Web of Conferences **93** (2015) 04002.
[5] M. Mumpower, R. Surman, D. L. Fang, M. Beard, P. Möller, T. Kawano, A. Aprahamian, Phys. Rev. C **92** (2015) 035807.
[6] P. A. Moldauer, Nucl. Phys. A **344** (1980) 185.
[7] T. Kawano, P. Talou, and H. A. Weidenmüller, Phys. Rev. C **92** (2015) 044617.
[8] J. Kopecky and M. Uhl, Phys. Rev. C, **41** (1990) 1941.
[9] T. Watanabe, T. Kawano, M. B. Chadwick, R. O. Nelson, S. Hilaire, E. Bauge, and P. Dossantos-Uzarralde, J. Nucl. Sci. Technol. **47** (2010), 470.
[10] T. Kawano, P. Talou, M. B. Chadwick, and T. Watanabe, J. Nucl. Sci. Technol. **47** (2010), 462.
[11] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data and Nucl. Data Tables **59** (1995) 185.