Evaluation of Neutron Reaction Cross Sections for Astrophysics

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We have developed a code system to evaluate nuclear reaction cross sections for the nucleosynthesis. The system includes an interface to Reference Input Parameter Library (RIPL), as well as some systematics to extrapolate the parameters into unstable regions. We are focusing on neutron capture processes important for s- and r-processes. The structure of the system is reviewed, and calculated capture cross sections in the fission product mass region are compared with experimental data available.

1. Introduction

The Hauser-Feshbach statistical model with width fluctuation correction has been widely used for neutron nuclear data evaluations, and the input parameters have been improved extensively. In many cases this model calculation gives a satisfactory fitting to experimental data, and this is regarded as one of the standard technique to evaluate nuclear data nowadays. This model calculation is also applicable to calculate nuclear cross sections which are needed for nucleosynthesis. One of the different aspect of the HF calculations for astrophysics is that many of the target nuclei are unstable, and a quality of calculation strongly depends on the model parameters. We have developed a code system to evaluate nuclear reaction cross sections for nucleosynthesis. The system includes an interface to Reference Input Parameter Library (RIPL)[1], as well as some systematics to extrapolate the parameters into unstable regions. In this paper the structure of the system is reviewed, and calculated capture cross sections are compared with experimental data available.

2. HFM Code System

2.1 Program CoH

The code system to calculate reaction cross sections consists of the Hauser-Feshbach-Moldauer code CoH and some databases. Since global parameterization is adequate for cross section calculation of unstable nuclides, the code has built-in global optical potentials — Koning-Delaroche Global Potential[2] for n and p, and Lemos' Potential[3] for α-particle. For γ-ray emission, an E_1 transition is taken into account.

2.2 Database for Input Parameters

Nuclear masses and reaction Q-values are calculated with the KUTY mass formula[5] if the data is not found in the Audi-Wapstra mass table[4]. The KUTY mass formula is also used to calculate level density parameters. Groud-state J^{π} values for many unstable nuclei are also unknown quantities. Those values are estimated by the Nilsson-Strutinsky method.

Reference Input Parameter Library (RIPL)[1] was compiled at IAEA, which is a library containing nuclear model parameters mainly for the statistical Hauser-Feshbach model calculation. Nuclear masses, excited levels, optical potential parameters, level densities, GDR parameters, fission barriers are stored in RIPL. The calculation system retrieves the excited level data, level density parameters, γ-ray strength function, and GDR parameters from RIPL-2. This retrieval is automated by some small utility programs. The procedure of cross section calculation is schematically shown in Fig. 1.

We employ a generalized Lorentzian-form for the γ-ray strength function given by

$$f_{\mathrm{E1}}(E_\gamma) = C\sigma_0\Gamma_0 \left\{ \frac{E_\gamma \Gamma(E_\gamma, T)}{(E_\gamma^2 - E_0^2)^2 + E_\gamma^2 \Gamma^2(E_\gamma, T)} + 0.7 \frac{\Gamma(E_\gamma = 0, T)}{E_0^3} \right\}, \tag{1}$$

where the constant C can be obtained by an experimental $2\pi\langle\Gamma_\gamma\rangle/D_0$ value taken from RIPL if available, otherwise $C = 8.68 \times 10^{-8}$ mb^{-1} MeV^{-2}, the GDR parameters σ_0, Γ_0, and E_γ are calculated with the systematics given in RIPL-2.

We adopt the Ignatyuk type level density parameters which includes shell effects,

$$a = a^* \left\{ 1 + \frac{\delta W}{U} \left(1 - e^{-\gamma U} \right) \right\}, \tag{2}$$

where a^* is the asymptotic level density parameter, U is the excitation energy, δW is the shell correction energy, and γ is the damping factor. The asymptotic level density parameters a^* was estimated based on the Gilbert-Cameron type level density parameters in RIPL-2 and the shell correction and pairing energies taken from the KUTY mass formula. The systematics of a^* parameter can be expressed by a smooth function of the mass number A, as shown in Fig. 2. The dashed and dot-dashed lines are similar systematics but they used different shell and pairing energies. We obtained $a^* = 0.140A + 2.65 \times 10^{-5}A^2$, which is shown by the solid line.

3. Calculated Capture Cross Section

Capture cross sections of Gd isotopes were calculated with this system. The model parameters used were "default" to show a quality of evaluation with our input parameters. The calculated capture cross sections σ_γ are compared with experimental data of Wisshak *et al.*[6] in Fig. 3. Evaluated cross sections in ENDF/B-VI and JENDL-3.3 are also shown in this figure. The evaluated cross sections fall down to zero at certain energies because unresolved resonance parameters are given below there. The comparison shown here is, of course, in the case of stable nuclides, and those agreements with the experimental data do not necessarily ensure that the system gives us reasonable cross sections for unstable nuclides. However, if we anchor the cross section calculations to the experimental data available, extrapolation of the parameter systematics to the unstable region becomes more reliable.

Figure 4 shows a comparison of calculated capture cross sections, σ_γ, with those in JENDL-3.3 in the fission-product (FP) mass range — from ^{69}Ga to ^{204}Hg. We have calculated the capture cross section (at 1 MeV) of 195 nuclides without any adjustment, and these cross sections are expressed by ratios to the JENDL-3.3 data. Many of calculated σ_γ 's were from

0.1×(JENDL) to 2×(JENDL), but the CoH calculation tends to underestimate. One of the possible reasons is level densities. When we have a few discrete level data, the calculation becomes more sensitive to the level density parameters, because the level density representation is used for the compound excited states even the excitation energy is low. We need to improve the level density systematics for unstable targets to obtain a reasonable agreement with the evaluated cross sections.

4. Conclusion

Our goal is to generate cross sections of more than 3000 nuclides for astrophysics applications. We have developed an automated cross section calculation system which consists of the optical model and the Hauser-Feshbach-Moldauer theory. The system links to modern theories of nuclear mass and ground state J^π value estimation, and links to RIPL level density parameters, discrete level data, and photo reaction data. We have shown some examples; capture cross sections for Gd isotopes, and comparison with JENDL-3.3 FP data. Our HFM calculation still tends to underestimate capture cross section for some cases. We need to improve the level density systematics for unstable targets.

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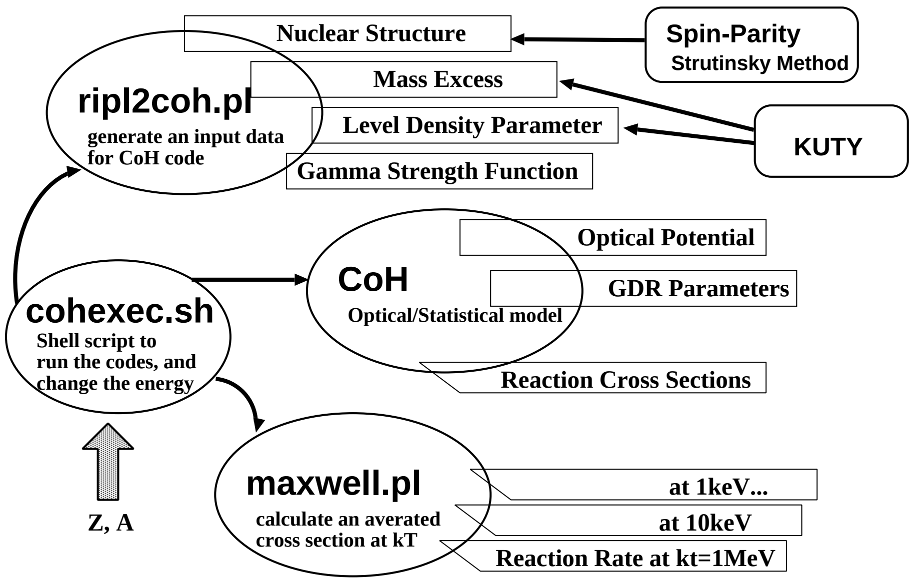

Fig. 1: Nuclear reaction cross section calculation system.

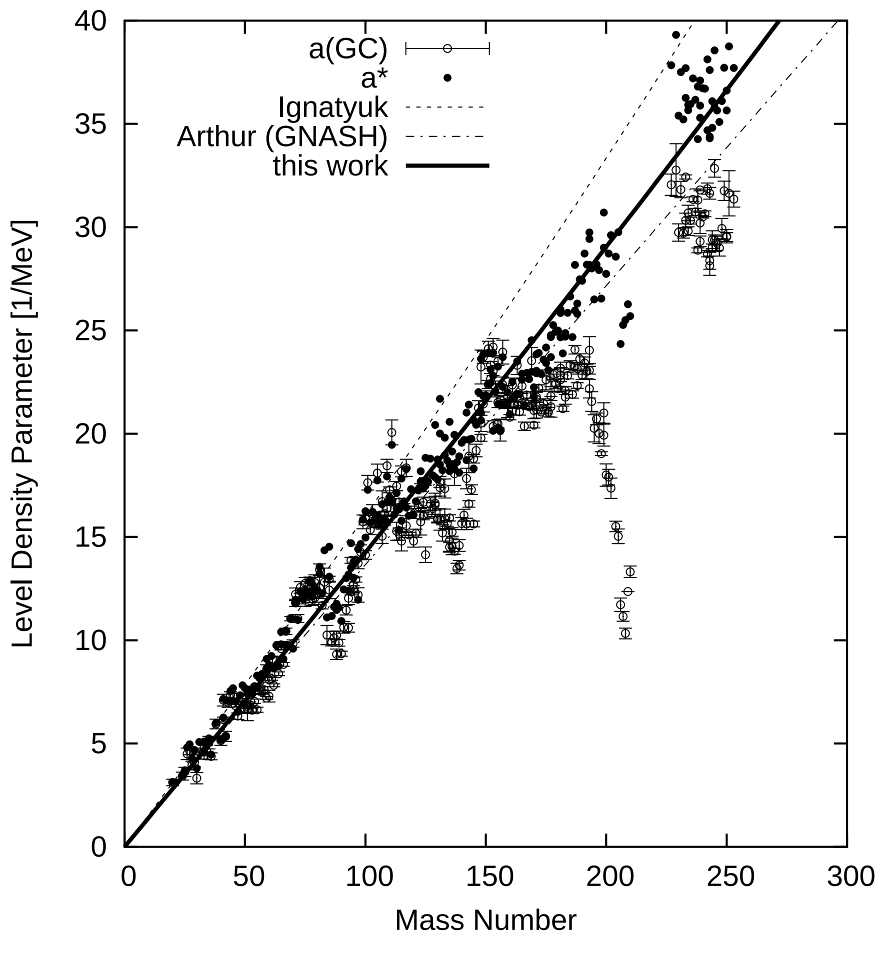

Fig. 2: Level density parameters a and a^* as a function of A.

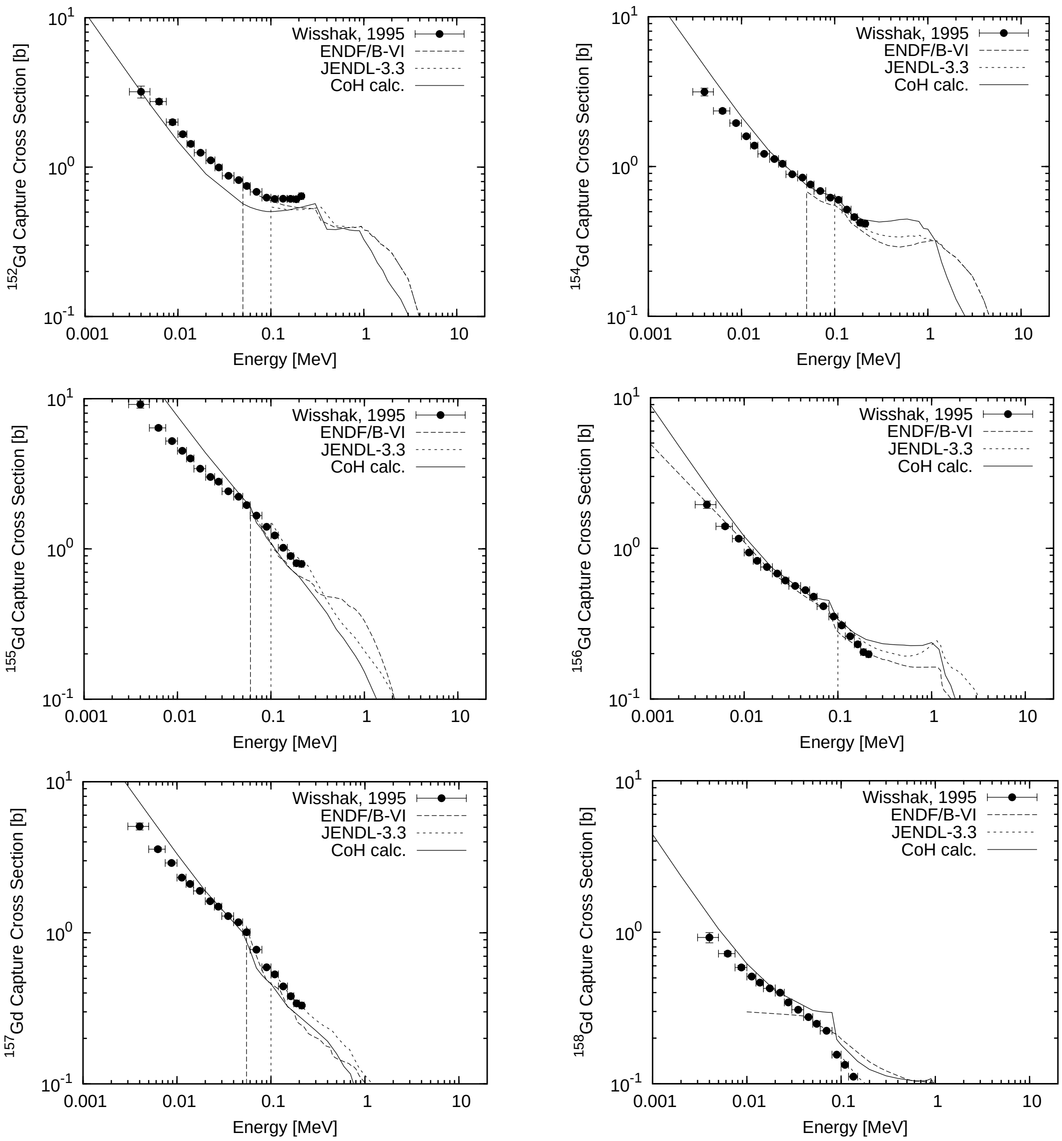

Fig. 3: Comparison of calculated capture cross sections for Gd isotopes with experimental data.

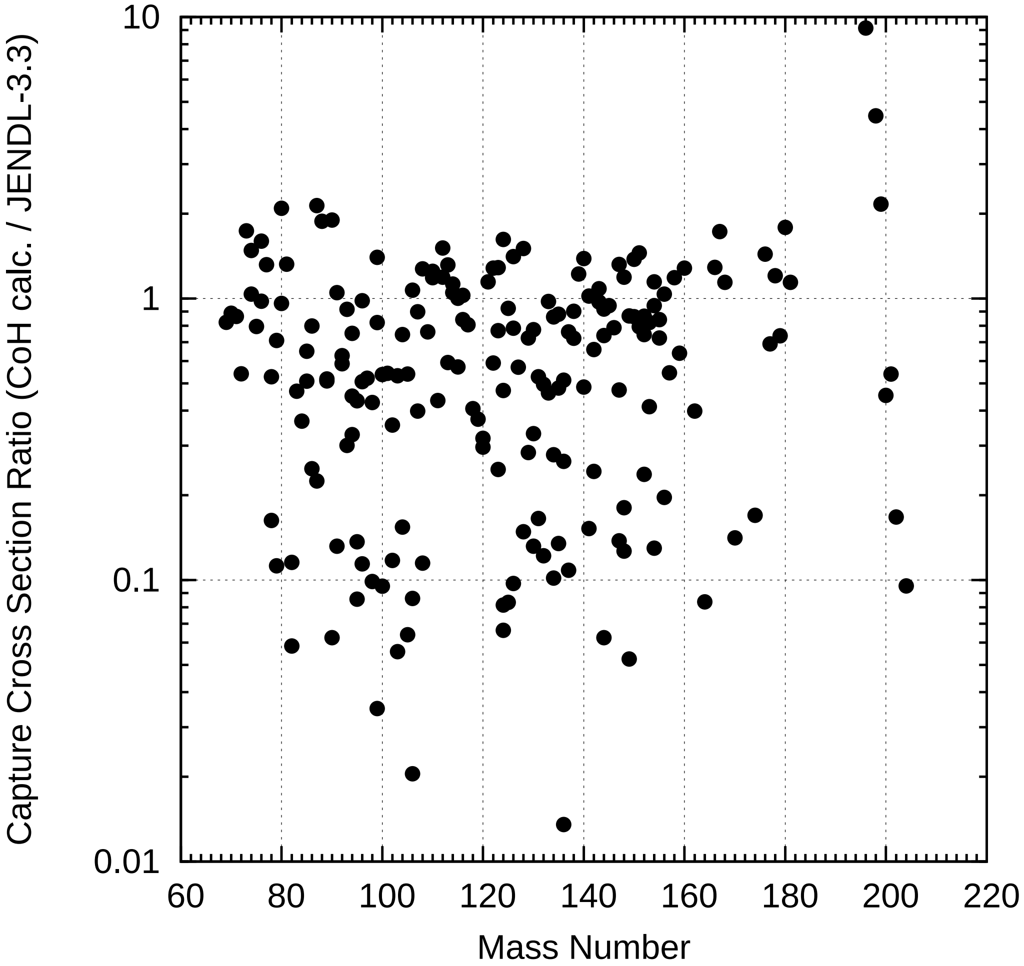

Fig. 4: Calculated capture cross section ratio to JENDL-3.3. The neutron incident energy is 1 MeV, and no adjustments of model parameters were made.