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Gamma Emission Spectra Gd, Au, and Eu Isotopes

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Abstract

The gamma emission spectra for Gd, Au, and Eu isotopes were calculated using the Hauser-Feshbach statistical model, and their results were compared with available experimental data. The model uses the gamma ray transmission coefficients described by a strength function. Although the Kopecky-Uhl method based on the giant resonance turned out to reproduce the experimental data relatively well, it failed to reproduce the anomalous bumps shown in many experiments especially for the rare earth nuclei. In the present work, the pygmy resonance was added to the Giant Dipole Resonance (GDR) in order to describe the anomalous bumps, providing more improved gamma emission spectra. In addition, we could describe the gamma ray strength functions below the neutron binding energy which is very difficult to obtain from the photonuclear reaction data.

I. Introduction

As the gamma emission spectrum has the characteristics of isotopes which constitute material, we can determine which isotopes are included in the material through analyzing the gamma emission spectrum. For example, these days, industrial applications for the rare earth nuclei (from La to Lu and Y) and the rarest earth nuclei (Ru, Rh, Pd, Te, Re, Os, Ir, Pt, Au) are very active. That is, the diverse nuclear, metallurgical, chemical, catalytic, electrical, magnetic and optical properties of the rare earth nuclei have led to an ever increasing variety of applications. In order to investigate these rare earth nuclei, the gamma emission spectrum can be employed to analyze them.

In this work, we adopted Gd, Au and Eu isotopes of these rare earth nuclei as the target ones. But there are few experimental data and evaluation files for the gamma emission spectrum. It is the objective of this work to create a library to complement this insufficiency. The spectrum was calculated using the Hauser-Feshbach statistical model[1] for nuclei which do not have experimental data. Moreover, as we compared the calculated spectrum with the experimental data, it makes it possible to extend the gamma strength functions for the low energy gamma below the neutron binding energy. Important factors for the Hauser-Feshbach statistical model are the nuclear level density and the gamma transmission coefficient[2]. In this work, the Gilbert-Cameron approach was used to search the nuclear level density[3]. This approach is known as very accurate for the incident neutron energies below 20 MeV. The gamma transmission coefficient is described well by the strength function based on the giant resonance. To obtain the gamma emission spectrum, we used the EMPIRE code[4] which was a modular system of the nuclear reactions.

II. Statistical model

The statistical model for the nuclear reactions is described well as the Hauser-Feshbach theory. Input data required in the calculation are the transmission coefficient and the nuclear level density. We can obtain the gamma emission spectrum expressed by the Hauser-Feshbach method as follows:

$$\sigma(E') = \sigma_{com}(E)\frac{T_{XL}(E')}{\int_0^E T_{XL}(E'')\rho(J,\Pi,E-E'')dE' + \sum_{E'} T_{XL}(E')}. \qquad (1)$$

where $\sigma_{com}(E) = \pi\lambdabar^2 \sum_l (2l+1)T_l(E)$ is the probability of producing a compound nucleus. l is the neutron angular moment and $\lambdabar$ is the reverse of the wave number. XL is the multipolarity for the gamma emission types such as E1 and M1, J is the spin and Π is the parity. To solve Eq. (1), We have to determine the level density ρ and the transmission coefficient T.

Although several level densities can be applied to Eq. (1)[5][6][7], we adopted the Gilbert-Cameron approach because it is known to be appropriate for the incident neutron energies below 20 MeV.

The transmission coefficient of the gamma can be shown as follows:

$$T_{XL}(E_\gamma) = 2\pi E_\gamma^{2L+1} f(E_\gamma). \quad (2)$$

where f is the gamma strength function. Unfortunately, it is not as accurate as the neutron strength function. But the Brink-Axel method based on the giant resonance and its developed forms give results near the experimental data.

III. Strength function

Up to now, many strength functions have been introduced to describe the gamma ray behaviors[2]. Representatives are the Weisskopf method which uses the concept of a single particle model and the Brink-Axel method which uses the giant resonance of the photon absorption. Especially, the Kopecky-Uhl method is known as the most developed form based on the giant resonance[8].

III. 1. Kopecky-Uhl method

It is assumed that the photo-absorption cross section of the excitation state is equal to that of the ground state and then, the resonance width has energy dependence. This method was created to complement the unsuitableness which the Lorentzian function has when E_γ ->0. The Kopecky-Uhl formula is as follows:

$$f_{XL}(E_\gamma) = K\left(\frac{E_\gamma \Gamma(E_\gamma)}{(E_\gamma^2 - E_i^2)^2 + E_\gamma^2 \Gamma(E_\gamma)^2} + \frac{0.7\Gamma 4\pi^2 T^2}{E_i^5}\right)\sigma_0 \Gamma, \quad (3)$$

where $K = \frac{1}{3\pi^2 \hbar^2 c^2}$.

And E_γ is the energy of the gamma-ray, K is the physical constant and σ_0, Γ

and E_i are the peak cross section, the resonance width and the i's hump energy of the giant resonance, respectively, where Γ is dependent on the energy,

$$\Gamma(E_\gamma) = \Gamma \frac{E_\gamma^2 + 4\pi^2 T^2}{E_i^2}. \quad (4)$$

III. 2. Pygmy resonance

Much work has been done to observe an anomalous bump around 5.5 MeV in the gamma spectra from the (n, γ) and (d, pγ) reactions on several nuclei 110<A<140 and 180<A<210[9]. This anomalous bump called the pygmy resonance is known as a common physical phenomenon[9][10]. The two approaches of the theoretical background for the resonance can be summarized. One is the approach using the concept of particle-hole, the other is the approach using the hydrodynamic model[11].

The former explains the pygmy resonance as a concentration of the electric dipole strength on a few low-energy states composed of certain one-particle-one-hole states which do not virtually participate in the giant electric-dipole resonance. Studying the distribution of the dipole strength in heavy nuclei has shown how the differences in the radial integrals for a realistic particle-hole integral bring the dipole strength down in the distribution.

The latter has shown that two normal modes of dipole vibration are excited in the incompressible three-fluid composed of the protons, the neutrons of the same orbits as protons(the blocked neutrons), and the excess neutrons. One is the vibration of the protons against the two types of neutrons, and the other is the vibration of the excess neutrons against the protons and the blocked neutrons. For ^{208}Pb, the former eigen-energy state was located at 13.3 MeV and the latter at about 4.4 MeV. The 13.3 MeV mode was more than two orders stronger in magnitude, compared with the 4.4 MeV mode. Thus, it was identified with the giant electric-dipole resonance. The 4.4 MeV mode was considered to be the pygmy resonance, although its calculated strength was too weak.

To represent the pygmy resonance, we used the Brink-Axel formalism:

$$f_p(E_\gamma) = K_p \frac{\sigma_p E_\gamma \Gamma_p^2}{(E_\gamma^2 - E_p^2)^2 + (E_\gamma \Gamma_p)^2}. \quad (5)$$

where K_p is the physical constant given similarly in Eq. (3), σ_p, Γ_p and E_p is the peak cross section, the resonance width and the peak energy of the pygmy resonance, respectively. Here we adopted the resonance width dependent on the energy like the giant dipole resonance one used in the Kopecky-Uhl method:

$$\Gamma(E_\gamma) = \Gamma \frac{E_\gamma^2 + 4\pi^2 T^2}{E_p^2}. \quad (6)$$

To consider the pygmy resonance, Eq. (5) must be added into the giant electric dipole resonance in Eq. (3). Since the EMPIRE code did not include the pygmy resonance, we changed the gamma strength function in the EMPIRE code as follows:

$$f(E_\gamma) = f_{XL}(E_\gamma) + f_p(E_\gamma). \quad (7)$$

IV. Results

To justify the calculated results, we compared the results of Gd and Au with the experimental data and obtained the result for Eu which does not have the experimental data but was evaluated in the ENDF/B-VI library.

When the incident neutron energy is 0.5 MeV and the targets are Au and Gd isotopes, the results are as shown in Figs. 1-4. The parameters required to consider the pygmy resonance are excerpted from M. Igashira[9], and listed in Table 1. All the figures show that the strength functions including the pygmy resonance produce better results than the contrary. Especially, as seen in the case of ^{197}Au, the consideration of the pygmy resonance produced an excellent agreement with the experimental gamma emission data, which the current ENDF/B-VI failed to reproduce.

Table 1. Pygmy resonance parameters

Isotopes	E_p(MeV)	σ_p(mb)	Γ_p(MeV)
^{156}Gd	2.5	0.5	1.0
^{157}Gd	2.7	1.0	1.2
^{158}Gd	2.8	1.0	1.0
^{198}Au	5.6	30.0	2.0

Additionally, we could extend the E1 photo-absorption strength function (GDR shape) below the neutron binding energy which was almost impossible to obtain from the photo nuclear experiment. We can derive the strength from the gamma spectrum data of the (n,γ) or (d, pγ) reactions. Figs. 5 - 8 show the GDR shapes, their characteristics are determined by the parameters shown in Table 1. If the gamma spectrum of (n,γ) or (d, pγ) does not exist, it is difficult to observe the effect of the pygmy resonance.

Figs. 9 and 10 present the spectra for ^{151}Eu and ^{153}Eu which do not have the experimental data. Although we could adopt the peak energy of the pygmy resonance from M. Igashira[9], we did not use the pygmy resonance for two nuclei because there are no experimental data. Existing files usually show lower spectra than the present work for the high energy part for the 1 MeV incident neutrons.

V. Summary

We calculated the gamma emission spectra by using the Hauser-Feshbach statistical theory. The Gilbert-Cameron approach was applied to describe the nuclear level density and the Kopecky-Uhl method was applied to describe the gamma emission coefficient. By introducing the pygmy resonance into the giant dipole we could describe the anomalous bumps appeared in many nuclei, and extend the E1 photo-absorption strength function below the neutron binding energy which was hard to estimate from the photonuclear experimental data

Acknowledgement

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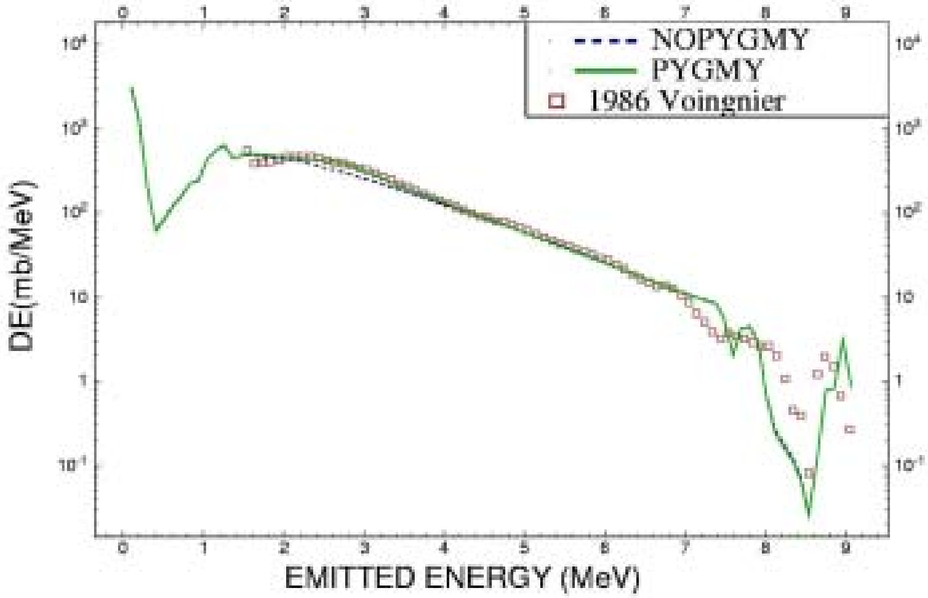

Fig. 1. The gamma emission spectra for ^{155}Gd with a 0.5 MeV incident neutron.

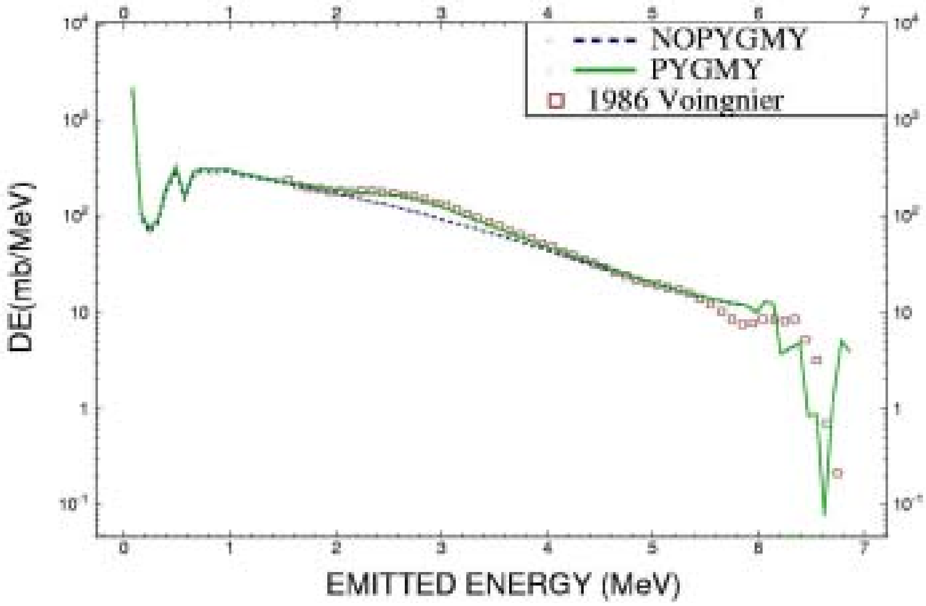

Fig. 2. The gamma emission spectra for ^{156}Gd with a 0.5 MeV incident neutron.

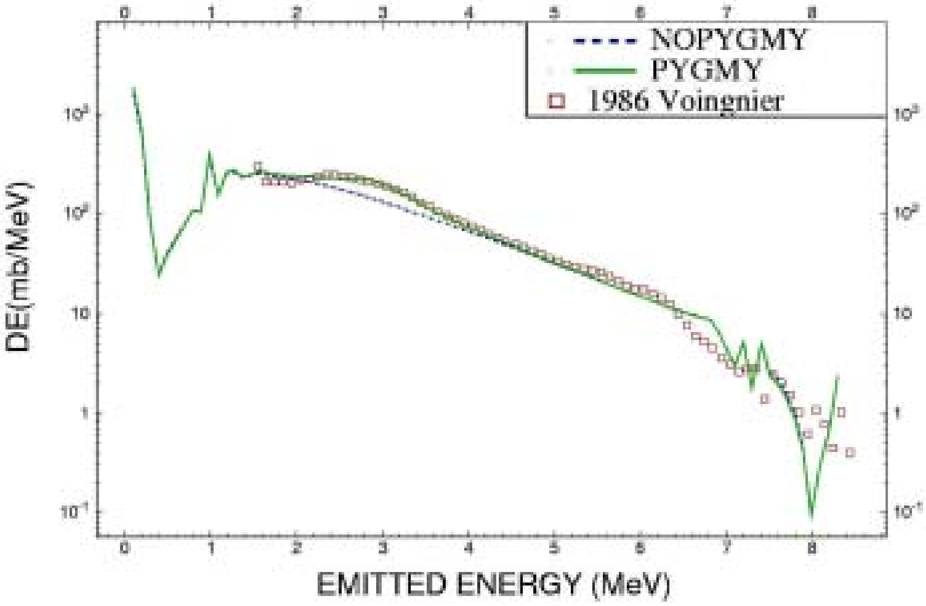

Fig. 3. The gamma emission spectra for ^{157}Gd with a 0.5 MeV incident neutron.

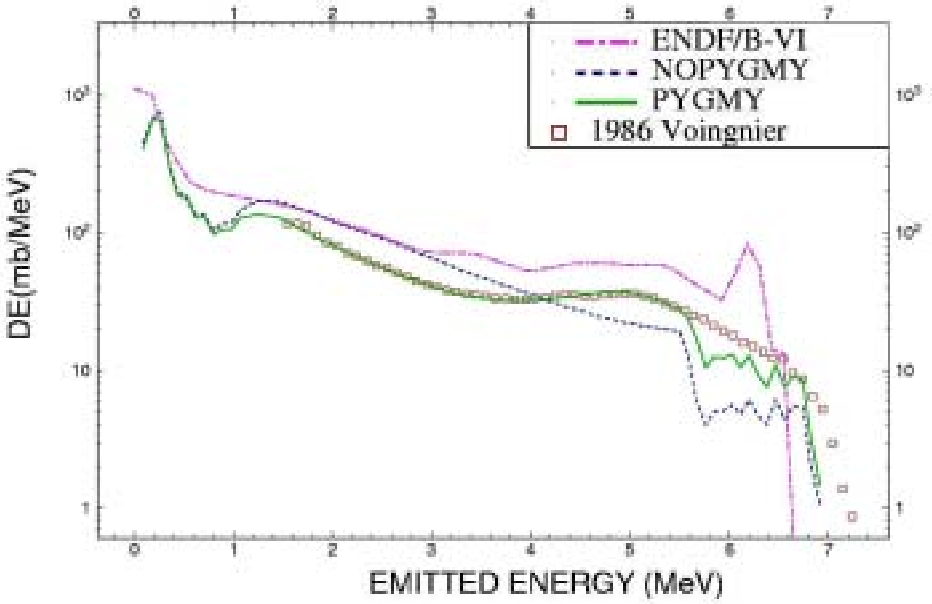

Fig. 4. Gamma emission spectra for ^{197}Au with a 0.5 MeV incident neutron.

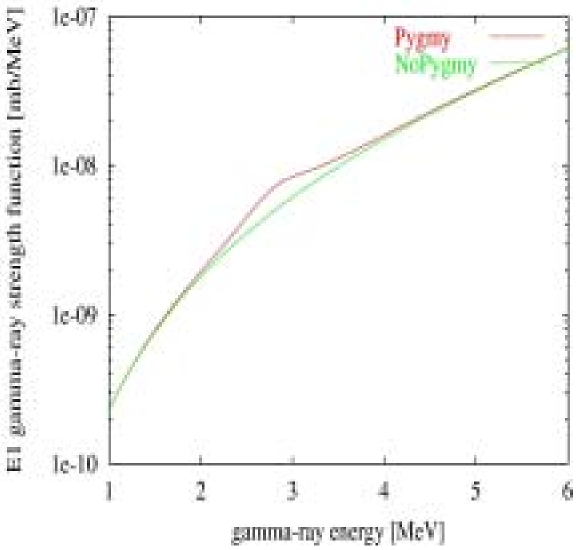

Fig. 5. E1 Photo-absorption strength functions (GDR shape) for ^{156}Gd.

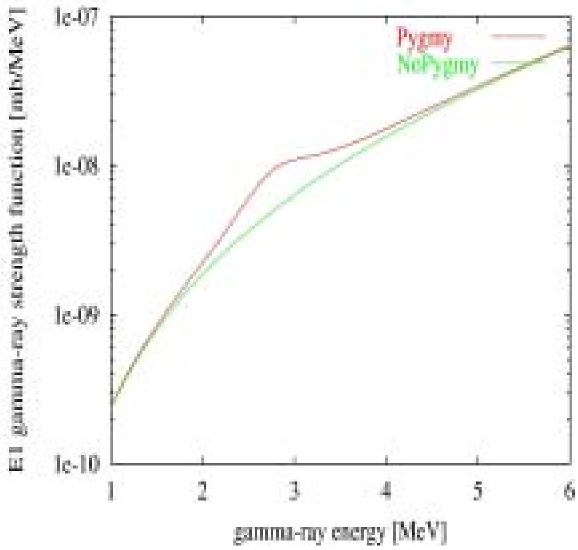

Fig. 6. E1 Photo-absorption strength functions (GDR shape) for ^{157}Gd.

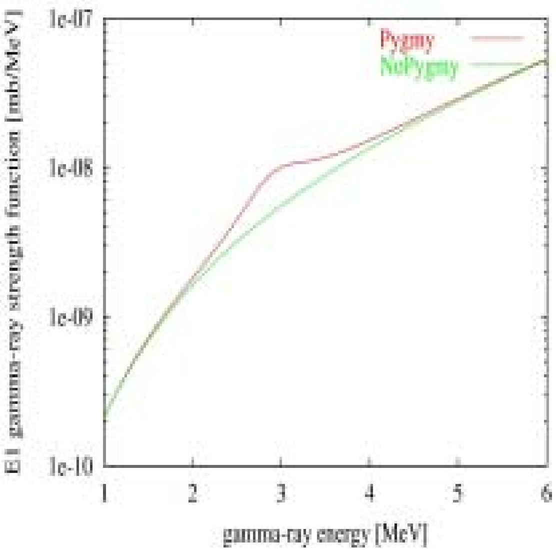

Fig. 7. E1 Photo-absorption strength functions (GDR shape) for ^{158}Gd.

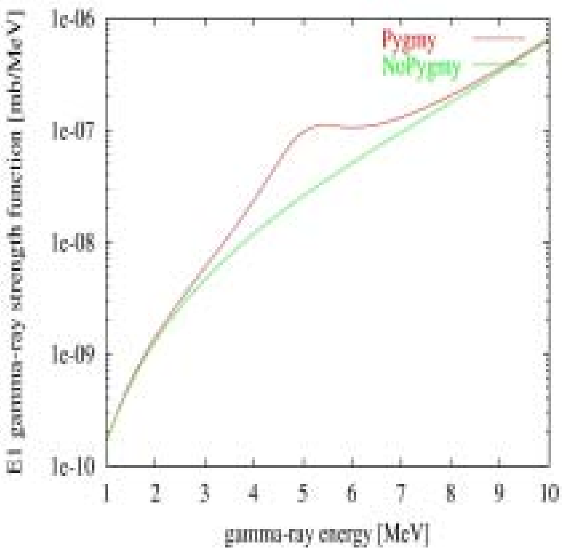

Fig. 8. E1 Photo-absorption strength functions (GDR shape) for ^{198}Au.

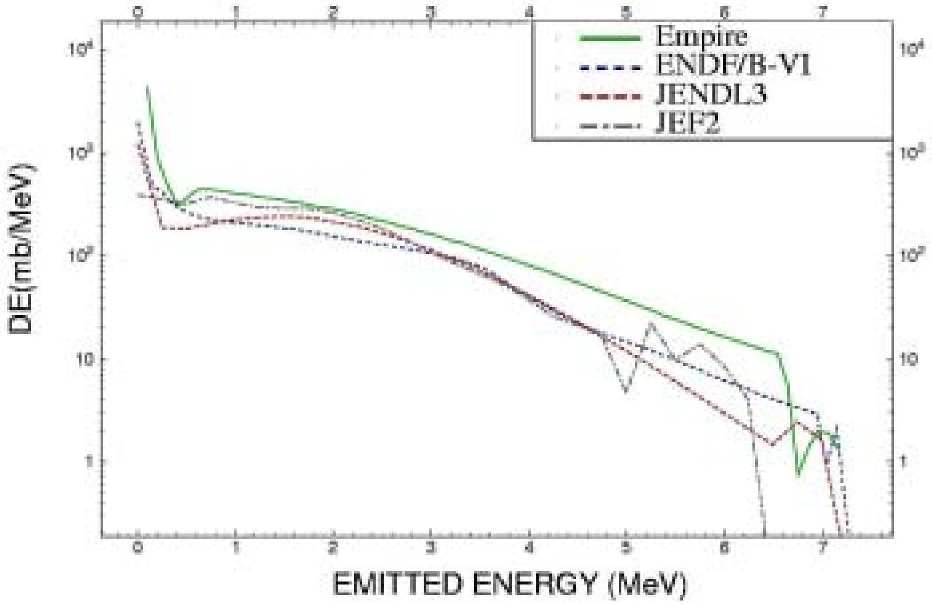

Fig. 9. Comparison of the gamma emission spectra for ^{151}Eu with a 1 MeV incident neutron.

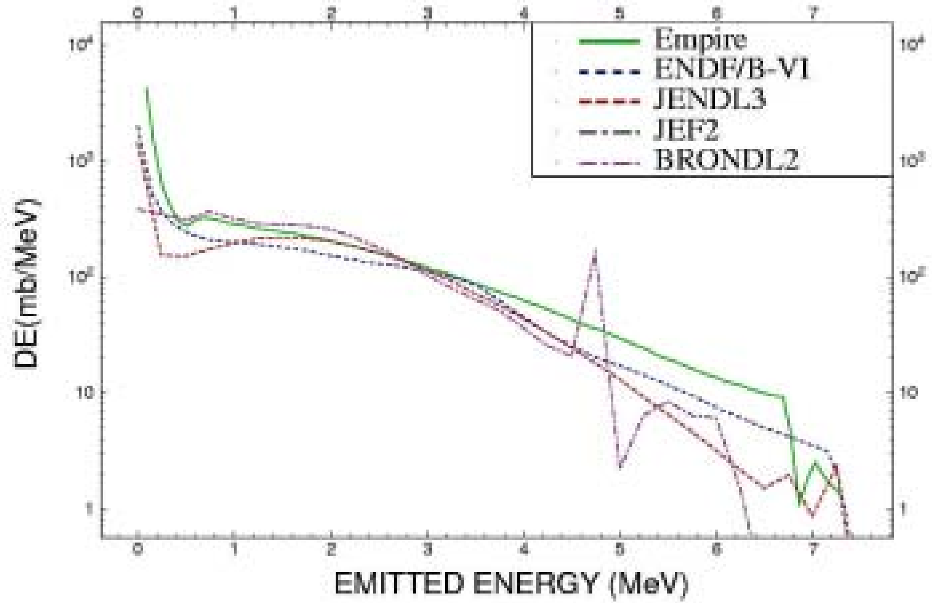

Fig. 10. Comparison of gamma emission spectra for ^{153}Eu with a 1 MeV incident neutron.