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CALCULATION OF GAMMA-RAY SPECTRUM OF AGGREGATE FISSION PRODUCT NUCLIDES AND FITTING OF THE GAMMA-RAY SPECTRUM

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Abstract: Gamma-ray spectrum data of fission product nuclides has been compiled as a data library. The data library contains the theoretically estimated spectra for application to the nuclides with no and/or deficient measured spectra. The gamma-ray energy spectra from aggregate fission product nuclides calculated by using the library showed a rather good agreement with measured ones for a wide range of cooling time after a fission burst of important fissile nuclides. By using the results, the gamma-ray spectra were converted into coarse energy group structure. The time dependence of the energy release of the each energy group was expressed as a sum of exponentials. The fitted results and their errors will be described.

(Gamma Ray Spectrum, Fission Product Nuclides, Exponential Fit)

Introduction

Gamma-ray spectrum from aggregate fission product nuclides after a fission burst is calculated by summing up all gamma rays emmitted from contributing nuclides. Most of the nuclides have a short half-life and their decay schemes are not experimentally confirmed. In this situation, there are many gamma rays, which are not identified by usual spectroscopic method, contributing to the spectrum from aggregate fission product nuclides. Therefore, the calculated gamma-ray spectrum based on the experimental decay schemes could not reproduce the measured data, especially, at a short cooling time region after a fission burst when the fission product nuclides having incomplete or no measured decay schemes contribute to the spectrum.

In order to complement the defect, we introduced the estimated spectra/1,2/ for the nuclides with incomplete and/or no measured spectral data by theoretical calculation/1/. By using the estimated spectra for the complement of the defect, the calculated gamma-ray spectra were improved for a wide range of cooling time after a fission burst of fissile nuclides from ^{232}Th through ^{241}Pu/2/.

By taking the results into consideration, the calculated spectrum was rebined into coarse energy group(20 groups). The energy release rates of each energy group were expressed by a sum of exponentials. The parameters of the exponentials were fitted by a least-square method. The exponential fit is useful to provide the spectrum with a simple manner.

In this paper, we will describe a brief description of the calculation of the gamma-ray spectrum and the exponential fit of the energy release rate of the each energy group. The fitting error will be also described.

Calculation of gamma-ray spectrum

Gamma-ray spectrum was calculated with data libraries/2,3/ compiled by Japanese Nuclear Data Committee. The nuclides concentrations of the fission product nuclides were calculated by summation method with the nuclear data library/3/ which contains the decay and the yield data needed in the calculation. After the concentrations of the nuclides at a time after a fission burst were obtained, the gamma-ray spectrum from aggregate fission product nuclides was calculated by summing up all gamma rays emmitted from the contributing nuclides with an aid of a gamma-ray spectrum data library. The library includes the energy values and the intensities of the gamma rays emmitted from the decay of individual fission product nuclide and the estimated spectra by theoretical calculation.

The estimated spectra were prepared to complement the missing gamma rays. There are many nuclides which have a short half life and a high Q values. For these nuclides, the decay schemes are not confirmed because of the difficulty of usual β-γ spectroscopy measurement and the gamma rays emmitted from them are incompletely or not measured. Therefore, there may be missing gamma rays for these nuclides. This fact has been indicated from a study of decay heat/4/. In the decay heat calculation, average decay energy values of beta and gamma rays play an important role. The average energy value of gamma ray is underestimated for the nuclides with missing gamma rays. Yoshida and Nakasima/5/ introduced theoretically estimated values of the average energy and showed a good prediction of the decay heat. The introduced average values are different from those derived from the experimental decay schemes. The estimated spectra are used to complement the difference. They were calculated by using the beta strength function derived from the gross theory of beta decay/6/ and the cascade gamma-ray transition model/1/ for typical fission product nuclides. They are applied to the nuclides with no and/or incompletely measured data.

The effect of the adoption of the estimated spectra is shown in Fig.1. This is the comparison of gamma-ray spectrum at 19 sec after a fission burst of ^{235}U by fast neutron between the

measurement/7/ and the calculation. The energy group structure and the width of the gamma-ray peaks were taken into account to match the experimental conditions. As seen in this figure, it is recognized that the estimated spectra are effective to complement the defect of the missing gamma rays.

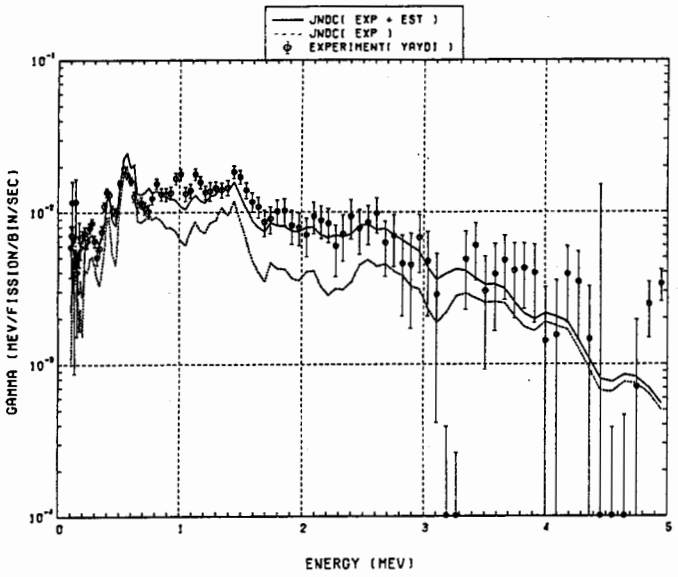

Fig.1 Comparison of gamma-ray energy spectrum at 19 sec after a fission burst of ^{235}U by fast neutron.
Solid line is a calculation complemented by the estimated spectra and dotted line a calculation excluding them.
The measurements were performed at the University of Tokyo/7/.

Exponential fit of energy spectrum

The calculation of the gamma-ray spectrum mentioned in the previous section needs a detailed procedure. And it is inconvenient. Therefore, it is useful to provide a simple formula with the same accuracy as the detailed calculation. For this purpose, the exponential fit was performed.

In order to make exponential fits, the calculated gamma-ray energy spectrum was rebined into 20 energy groups. The energy group structure is listed in Table 1.

Table 1 Energy group structure

Energy group	Upper energy (MeV)	Energy group	Upper energy (MeV)
1	0.1	11	2.0
2	0.2	12	2.2
3	0.4	13	2.4
4	0.6	14	2.6
5	0.8	15	3.0
6	1.0	16	4.0
7	1.2	17	5.0
8	1.4	18	6.0
9	1.6	19	7.0
10	1.8	20	8.0

The ratios of the calculated energy release rates of ^{235}U fission by fast neutron to the measured ones are shown in Fig.2 for the 6th energy group(0.8-1.0 MeV) as a function of cooling time after a fission burst. The C/E ratios remain within 10 % for a cooling time region when the measurements exist, if the estimated spectra are introduced. So, if the fitting was performed successfully, it is able to give the spectrum with the accuracy of about 10 % at this energy region.

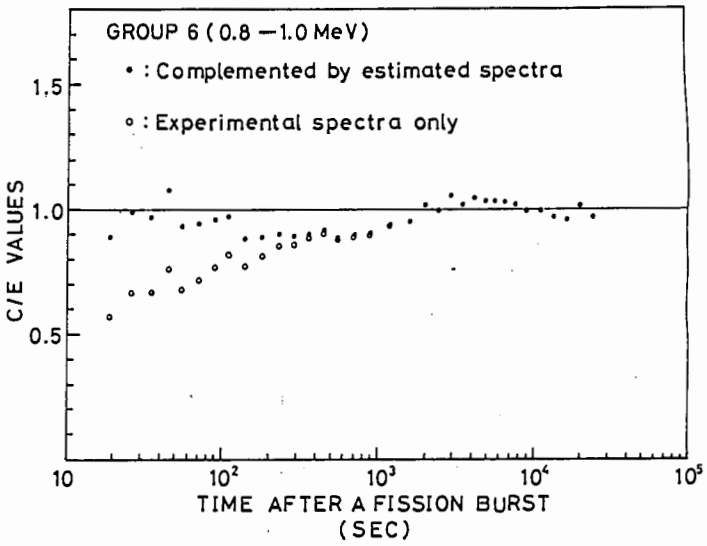

Fig.2 The ratios of the calculated energy release rates to the measured ones.

The time dependence of the energy release rate, $f_g(t)$, of each energy group was fitted to a sum of exponentials,

$$f_g(t) = \sum \alpha_i \exp(-\lambda_i t) \ (\mathrm{MeV/fission/sec/bin}),$$

where α_i and λ_i are the fitted parameters. In this procedure, the number of exponentials was set to be 31 and the values of the parameters λ_i were fixed for all energy groups. The exponential fit of total energy release rate was performed previously/3/ and gave the fitting error lower than 1 % for a wide range of cooling time. Then, the same values as the previous ones were used for the first attempt in order to keep the consistency.

The values of the parameters λ_i are listed in Table 2. Only the parameters α_i were fitted by a least-squares method. For this procedure, the gamma-ray spectra were prepared for 93 points of cooling time from 0.0 to 10^{13} sec after a fission burst. The fittings were performed by SALS code/8/.

The results of the fitting and the error are shown in Fig.3 for the case of the 6th group of the spectrum after a fission burst of ^{235}U by fast neutron. In this case, the fitting error is lower than 5 % before 10^9 sec after the fission. After 10^9 sec, the error becomes larger than 5 %. The errors of other energy groups were still remained within 10 % before 10^9 sec except for the higher

energy groups. For the higher energy groups, it became difficult to fit the spectrum to the given exponentials with fixed parameters in Table 2, since the nuclides contributing to this energy region become small and the fixed parameters may not agree with their half-lives.

Table 2 Fixed parameter values

λ_i		λ_i		λ_i	
λ_1	3.290	λ_{12}	1.357-3	λ_{23}	1.277-7
λ_2	2.210 *)	λ_{13}	5.645-4	λ_{24}	2.714-8
λ_3	1.001-1	λ_{14}	1.850-4	λ_{25}	2.251-8
λ_4	5.157-1	λ_{15}	5.435-5	λ_{26}	8.985-9
λ_5	2.951-1	λ_{16}	4.918-5	λ_{27}	4.366-9
λ_6	1.951-1	λ_{17}	1.922-5	λ_{28}	7.707-10
λ_7	1.037-1	λ_{18}	8.422-6	λ_{29}	7.280-10
λ_8	3.488-2	λ_{19}	2.443-6	λ_{30}	2.430-10
λ_9	1.330-2	λ_{20}	6.925-7	λ_{31}	9.550-15
λ_{10}	5.004-3	λ_{21}	6.202-7		
λ_{11}	3.591-3	λ_{22}	1.503-7		

*) Read as 1.001×10^{-1}

The energy spectra by the fitting are shown in Figs.4 and 5 comparing the calculated ones. Figure 4 shows the spectra at 0 sec, that is, just after the fission of ^{235}U by fast neutron. The difference between the calculated and the fitted results is very small and is not seen in this scale except for the high energy part. Figure 5 shows the spectra at 20000 sec after the fission. The difference becomes greater than that at 0 sec, but it remaines within 10 %. As seen in these figure, the contribution of the higher energy parts to the spectrum is small comparing with other energy region.

Conclusion

Gamma-ray energy spectra from aggregate fission product nuclides were calculated with the spectrum data which were complemented by the estimated spectra. The calculation showed an improvement of the spectrum prediction. By using the results, the exponential fits were performed. The fitting error remained within 10 % for most of the energy groups at a cooling time region before 10^9 sec after the burst fission of ^{235}U by fast neutrons. In high energy parts, the error became over 10 %. These errors are larger than the result of the total energy release rate. In the case of the total energy release rate, however, the number of the nuclides contributing to it is large and the their characters are not appeared. In the present case, the situation is different. So, the error within 10 % may be acceptable. However, the error over 10 % appeared in high energy parts is rather large for the application, for example, to radiation source. In that case, high energy gamma rays play an important role. In order to decrease the error, it may be needed to change the parameters fixed in the fitting procedure.

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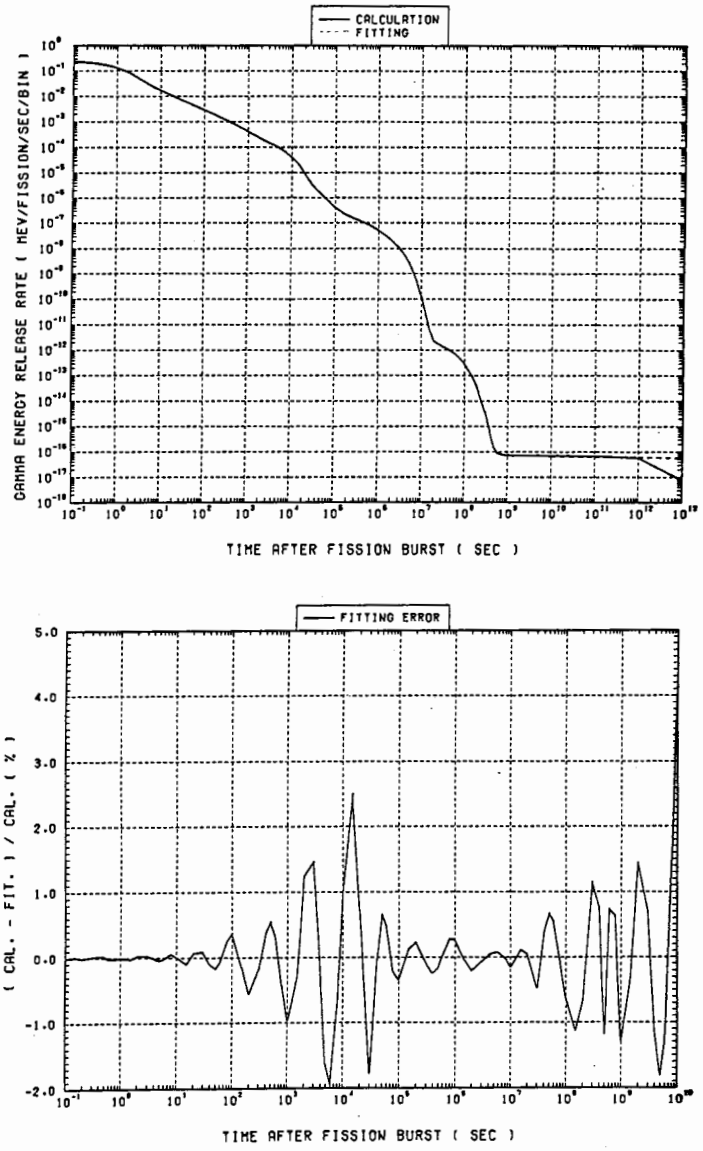

Fig.3 Results of exponential fit and the fitting error for the 6th energy group.

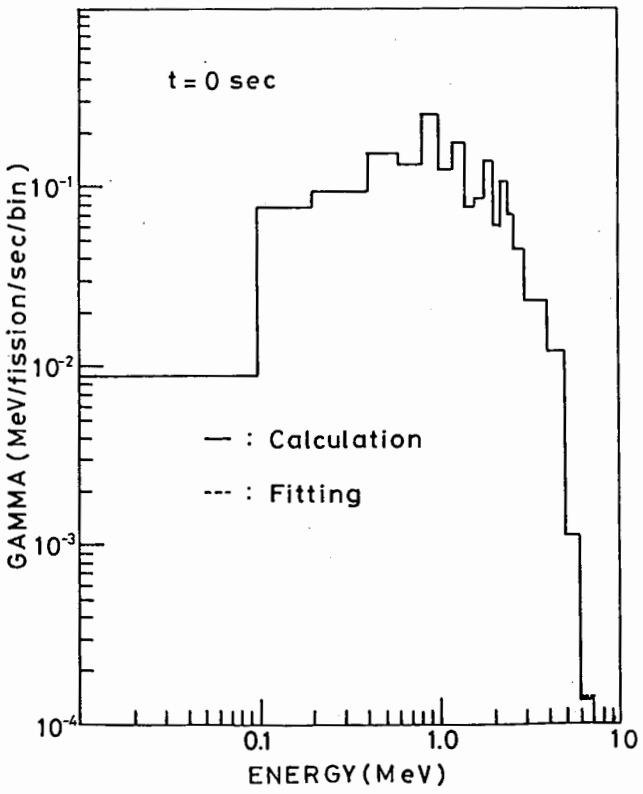

Fig.4 Comparison of gamma-ray energy spectrum between the calculated and the fitted results. (t = 0 sec)

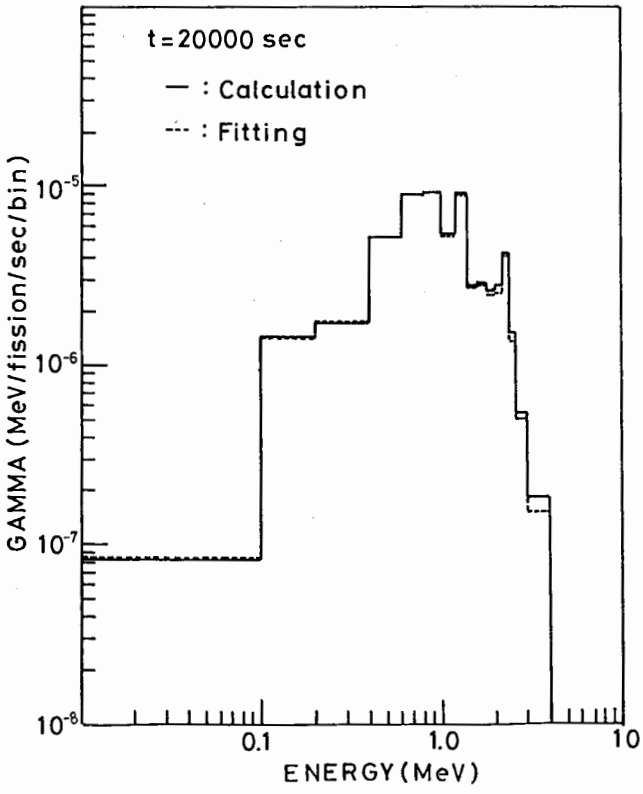

Fig.5 Comparison of gamma-ray energy spectrum between the calculated and the fitted results. (t = 20000 sec)