JAERI-Research
2003-004

A SYSTEMATICS OF FISSION PRODUCT MASS YIELDS WITH 5 GAUSSIAN FUNCTIONS

March 2003

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編集兼発行　日本原子力研究所

A Systematics of Fission Product Mass Yields with 5 Gaussian Functions

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(Received January 29, 2003)

A systematics of fission product mass yields is proposed. The systematics is based on Moriyama-Ohnishi systematics developed about 30 years ago. The parameter set of the systematics is newly determined by examining measured data taken after Moriyama-Ohnishi systematics was released. The systematics using the newly determined parameter set is employed to calculate mass distributions of various kinds of fission and compare them with measured data. The comparison shows rather good agreement between them from spontaneous fission to high energy particle induced fission.

Keywords: Fission Yields, Mass Distribution, Fissioning Nuclide, Fission Product, Systematics

5つのガウス関数による核分裂収率システマティックスの検討

日本原子力研究所東海研究所エネルギーシステム研究部

片倉　純一

(2003 年 1 月 29 日受理)

核分裂生成物の核分裂収率を予測するシステマティックを検討し、新たなシステマティックスを提案した。このシステマティックスは 30 年程前に提案された森山-大西システマティックスに基づいている。森山-大西システマティックスの後に測定されたデータを基にパラメータの見直しを行い、新たな関数型によるパラメータを決定した。このパラメータを用いて核分裂収率を計算し、測定データと比較した。様々な核分裂による収率について自発核分裂から高エネルギー粒子による核分裂まで広い範囲で測定との良い一致を得た。

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1 Introduction

It is an important problem for nuclear technology to reduce the nuclear waste produced in nuclear reactors. Several concepts for transmutation of nuclear waste [1] have been proposed, using classical thermal or fast fission reactors as incinerators or using accelerator driven systems. These concepts are being extensively studied with regard to their feasibility, neutron economics, environmental safety, and so on.

For these studies, nuclear data including fission yields are required. For the requirement, Nuclear Data Section, International Atomic Energy Agency, organized a coordinated research program (CRP) titled "Fission Product Yield Data Required for Transmutation of Minor Actinide Nuclear Waste". In the task of the CRP, it is recognized that it is necessary to develop fission yield systematics to estimate the yields over a wide range of fissioning nuclides and the energy range from thermal to 150 MeV.

There are some evaluated fission yields data which are compiled as Evaluated Nuclear Data File such as JENDL [2], ENDF [3], JEF [4] and so on. As these evaluated data, however, are for traditional nuclear reactors, the evaluated yields are categorized for thermal neutron fission, fast neutron (neutron emitted by fission) fission and high energy (14 MeV) neutron fission. Although these evaluated yields data are applicable to the traditional reactor technology covering the above energy range, they are not able to apply to the higher energy region required for the CRP. The reliable evaluated fission yields data by such high energy neutrons has not been compiled yet. Even measured data have been limited to those for some fissioning nuclides. Then the systematics of the fission yields data of so-called minor actinides is needed to predict the fission yields data by such high energy neutron fission.

There are several systematics of fission yields. Of such systematics, Wahl's systematics [5] is widely recognized and shows good agreement with existent yields data by low energy neutrons. It is, however, uncertain that the systematics can be extended to the energy region more than 100 MeV and how is the uncertainty of the systematics in such a high energy region. Therefore it will be worthwhile to make another systematics.

In Japan Moriyama-Ohnishi (hereafter MO) proposed a systematics about 30 years ago [6]. The systematics succeeded to reproduce the mass distributions of the fission products experimentally available at that time. The systematics, however, fails to reproduce the recently measured mass distributions by high energy neutron and proton induced fission. Then new systematics is needed to get the mass yields by higher energy neutron or proton fission. We examined the parameters in the MO systematics based on newly measured data and obtained a new set of the parameters which are applicable to the higher energy fission than 100 MeV.

First the outline of the MO systematics and the problem using the MO systematics are given in Chapter 2. In Chapter 3 the parameter search for new systematics is given. The calculations using the newly determined parameters and comparisons with measured data are described in Chapter 4. Summary is given in Chapter 5.

2 Moriyama-Ohnishi Systematics

2.1 Outline of the Moriyama-Ohnishi Systematics

In the MO systematics, the mass distribution $\psi(A, E^*)$ of fission products just after prompt neutron emission is described as sum of symmetric component $\psi_s(A, E^*)$ and asymmetric component $\psi_a(A, E^*)$. In these expression A is a mass of fission fragment and E^* is an excitation energy of of the fissioning nuclide. The asymmetric component is then divided into heavy fragment component $\psi_h(A, E^*)$ and light fragment component $\psi_l(A, E^*)$. And each of these components is formed of two curves (curve 1 and 2). Then the mass distribution $\psi(A, E^*)$ is expressed as follows:

$$\begin{aligned}\psi(A, E^*) &= N_s\psi_s(A, E^*) + N_a\psi_a(A, E^*) \\ &= N_s\psi_s(A, E^*) + N_a\left[\psi_{h1}(A, E^*) + \psi_{l1}(A, E^*) + F\left\{\psi_{h2}(A, E^*) + \psi_{l2}(A, E^*)\right\}\right],\end{aligned} \tag{2.1}$$

where N_s, N_a and F are normalization factors and determined by systematics.

The five components in the above equation are assumed to be Gaussian distribution:

$$\psi_s(A, E^*) = \frac{1}{\sqrt{2\pi}\sigma_s}\exp\left\{-(A - A_s)^2/2\sigma_s^2\right\}, \tag{2.2}$$

$$\psi_{h1}(A, E^*) = \frac{1}{\sqrt{2\pi}\sigma_{h1}}\exp\left\{-(A - A_{h1})^2/2\sigma_{h1}^2\right\}, \tag{2.3}$$

$$\psi_{h2}(A, E^*) = \frac{1}{\sqrt{2\pi}\sigma_{h2}}\exp\left\{-(A - A_{h2})^2/2\sigma_{h2}^2\right\}, \tag{2.4}$$

and the other two functions $\psi_{l1}(A, E^*)$ and $\psi_{l2}(A, E^*)$ for the light fragment are given by reflecting $\psi_{h1}(A, E^*)$ and $\psi_{h2}(A, E^*)$ about the symmetric axis $A_s = (A_f - \bar{\nu})/2$. Here A_s, A_{h1} and A_{h2} are the mass numbers corresponding to the peak positions of the Gaussian distribution curves, and σ_s^2, σ_{h1}^2 and σ_{h2}^2 are the dispersions of these distributions. A_f denotes the mass number of the fissioning nuclide. The quantity $\bar{\nu}$ is the average number of prompt neutrons emitted per fission, and is given by

$$\bar{\nu} = \begin{cases} 0.107A_f - 23.37 + 0.085E^*, & E^* \le 7.967\ \text{MeV}, \\ 0.107A_f - 23.968 + 0.16E^*, & E^* > 7.967\ \text{MeV}. \end{cases} \tag{2.5}$$

The quantities N_s, N_a, A_s, σ_s, A_{h1}, A_{h2}, σ_{h1} and σ_{h2} are obtained by least-squares method and are given by

$$N_s = 200/(1 + 2R), \tag{2.6}$$

$$N_a = 200R/\left\{(1 + F)(1 + 2R)\right\}, \tag{2.7}$$

$$\sigma_s = 0.1759A_f - 41.71 + 0.2056E^{*0.25}(S + 31.908), \tag{2.8}$$

$$A_{h1} = 0.5190(A_f - \bar{\nu}) + 0.02840A_f(40.2 - Z_f^2/A_f)^{1/2}, \tag{2.9}$$

$$A_{h2} = 0.5673(A_f - \bar{\nu}) + 0.02151A_f(40.2 - Z_f^2/A_f)^{1/2}, \tag{2.10}$$

$$\sigma_{h1} = 0.07327A_f - 14.50 + 0.01783E^{*0.25}(S + 31.908), \tag{2.11}$$

$$\sigma_{h2} = 0.08089A_f - 15.87 + 0.006847E^{*0.25}(S + 31.908). \tag{2.12}$$

The quantities R and F are given by

$$R = \exp\{2.262S + 0.0682A_f - 11.542 + \alpha + \exp(\beta)\}, \quad (2.13)$$

$$F = \sigma_{h2}/\sigma_{h1}\exp(-0.08349A_f + 19.43), \quad (2.14)$$

where

$$\alpha = \begin{cases} +7.75(A_f)^{-1/2}, & \text{for even } Z_f \text{ - even } N_f, \\ -7.75(A_f)^{-1/2}, & \text{for odd } Z_f \text{ - odd } N_f, \\ 0, & \text{for odd } A_f, \end{cases} \quad (2.15)$$

and

$$\beta = \begin{cases} 2.531 - 0.10546E^*, & \text{for even } A_f, \\ 2.118 - 0.07990E^*, & \text{for odd } A_f. \end{cases} \quad (2.16)$$

These α and β represent the pairing effect of the fissioning nuclide (Z_f,A_f). The S factor appearing in the above equations represents the nuclear shell effect of both fissioning nuclide and fission fragments. The latter is included because of the importance of the shells of the fission fragments which is comparable to that of the fissioning nuclide. Moriyama and Ohnishi employ the shell energy formula $S(N_f, Z_f)$ given by Meyers and Swiatecki [7)] for the S factor adopting the magic number of $N = 126$, 164 and 184 for neutrons and $Z = 82$, 100 and 114 for protons. The numbers $N = 164$ and $Z = 100$ are introduced to take into account the shell effect of fission fragment. The S factor is represented as follows by Meyers and Swiatecki:

$$S(N,Z) = 5.8s(N,Z), \quad (2.17)$$

$$s(N,Z) = \frac{F(N)+F(Z)}{(\frac{1}{2}A)^{\frac{2}{3}}} - 0.26A^{\frac{1}{3}}. \quad (2.18)$$

$$F(N) = q_i(N - M_{i-1}) - \frac{3}{5}(N^{\frac{5}{3}} - M_{i-1}^{\frac{5}{3}}), \qquad \text{for } M_{i-1} < N < M_i \quad (2.19)$$

$$q_i = \frac{3}{5}\frac{M_i^{\frac{5}{3}} - M_{i-1}^{\frac{5}{3}}}{M_i - M_{i-1}}, \quad (2.20)$$

where M_i is the magic number mentioned above.

2.2 Problems of the Moriyama-Ohnishi Systematics

The calculated mass yields curves using the MO systematics were compared with the measured data of mass distributions for various kinds of fission available at that time. They showed rather good agreement with the measured data. The measured data available at the time, however, were restricted to a limited number. When we make comparison with recently measured distribution, some discrepancies between the calculated distribution and the measured one are seen. An example of the discrepancy is shown in Fig. 2.1, where mass distributions of ^{248}Cm fission by 20 MeV protons are compared between the calculated results using MO systematics and the measured data [8]. The measured mass yields show obvious asymmetric components even though each data point shows scattering behavior, but the MO systematics shows only symmetrical distribution and fails to reproduce the asymmetric behavior the measured data show. This failure seems to imply that the way taking the shell effect into the ratio of the symmetric component to the asymmetric one in the MO systematics is not suitable and should be revised for the application to such kind of fission as ^{248}Cm.

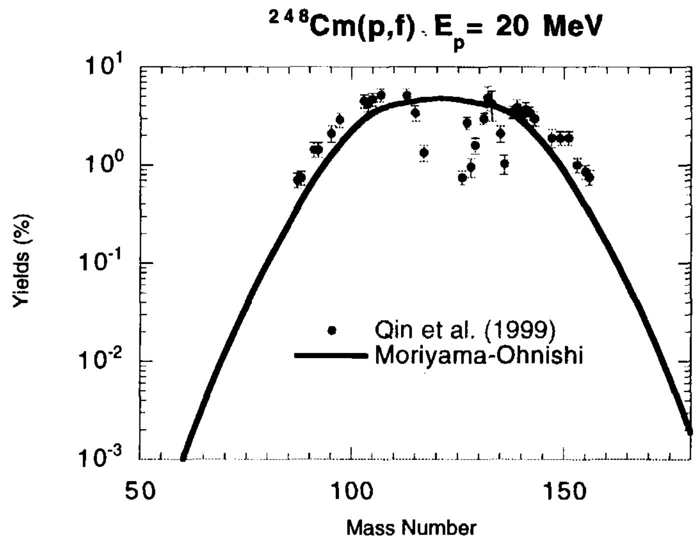

Fig. 2.1 Mass Yield Curve of ^{248}Cm + 20.0 MeV protons

Another example is shown in Fig. 2.2, where mass distributions of ^{238}U fission by 160 MeV neutrons are compared between the calculation using the MO systematics and the measurement [9]. This figure shows that the MO systematics shifts the distribution to lower mass side than the measured data. And the width of the tail seems to be too wide. Asymmetric property is still seen in the MO systematics, although it is not apparently seen in the measured distribution. These failures of the MO systematics at high energy region seems to indicate that the energy dependence of the parameters such as width of the symmetric part, the number of emitted neutrons and the ratio of the symmetric part to the asymmetric part in the MO systematics is not suitable for this kind of fission.

As seen in those figures, the MO systematics fails to reproduce the recently measured particle

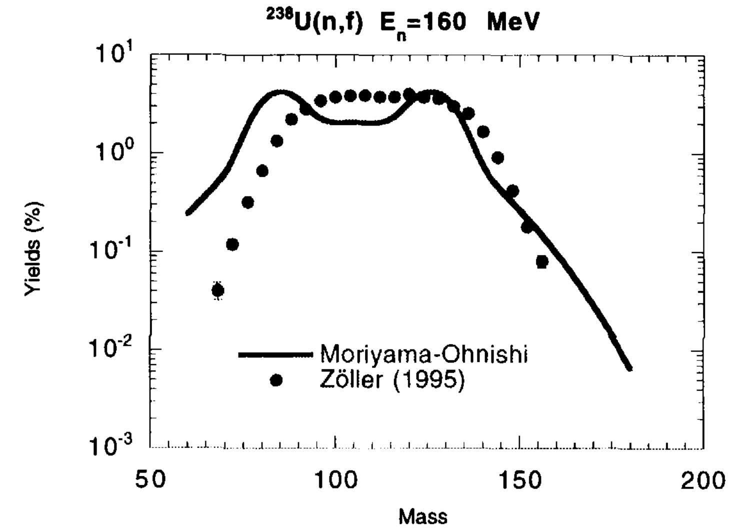

Fig. 2.2 Mass Yield Curve of ^{238}U + 160 MeV neutrons

induced fission with high incident energy. Then new parameter set is needed to get the systematics which is applicable to these kinds of high energy fission.

3 Parameter Search for New Systematics

The basis of the MO systematics is 5 Gaussian functions as mentioned in the previous chapter. Recently multimodal fission analysis suggests that there is the mode named standard III [10]. In this case 7 Gaussian functions are needed to reproduce the measured mass distribution. But in most of the fissions, 5 Gaussian functions seem to be enough to reproduce the mass distribution. Then 5 Gaussian functions are kept in our search of new parameter set for the systematics.

There are several measured mass distributions available. The measured mass distributions were decomposed into 5 Gaussian functions by least squares fit. From the fitted Gaussian functions, the parameters of the systematics were calculated and examined for various kinds of fission. After the examination, the 8 parameters in 5 Gaussian distributions were determined. As for $\bar{\nu}$ value, the expression by Wahl [11] was used:

$$\bar{\nu} = 1.404 + 0.1067(A_F - 236) + [14.986 - 0.1067(A_F - 236)] \cdot [1.0 - \exp(-0.00858E^*)], \quad (3.1)$$

where E^* is the excitation energy, that is, the sum of the incident energy (E) and the binding energy (BN) of the incident particle. The other 7 parameters were determined as follows:

$$\begin{aligned}
R &= [112.0 + 41.24\sin(3.675S)] \cdot \frac{1.0}{BN^{0.331} + 0.2067} \cdot \frac{1.0}{E^{0.993} + 0.0951}, && (3.2)\\
F &= 10.4 - 1.44S, && (3.3)\\
\sigma_s &= 12.6, && (3.4)\\
\sigma_{h1} &= (-25.27 + 0.0345A_f + 0.216Z_f)(0.438 + E + 0.333BN^{0.333})^{0.0864}, && (3.5)\\
\sigma_{h2} &= (-30.73 + 0.0394A_f + 0.285Z_f)(0.438 + E + 0.333BN^{0.333})^{0.0864}, && (3.6)\\
A_{h1} &= 0.5393(A_f - \bar{\nu}) + 0.01542A_f(40.2 - Z_f^2/A_f)^{1/2}, && (3.7)\\
A_{h2} &= 0.5612(A_f - \bar{\nu}) + 0.01910A_f(40.2 - Z_f^2/A_f)^{1/2}. && (3.8)
\end{aligned}$$

where S is the shell factor defined in Eq. (2.17) but the magic numbers, N=164 and Z=100 introduced by Moriyama and Ohnishi to consider the shell effect of fission fragment are removed here.

The energy dependence of the R parameter was examined from the Zöller's measured data [9]. The measurement were performed using ^{238}U(n,f) reaction by incident neutron energy from 1 MeV to 500 MeV. Such wide energy region is suitable to get energy dependence in the same A and Z values. The Zöller's data were fitted with 5 Gaussian functions and the obtained parameters in the 5 Gaussian functions were used to derive the R values. According to the Eqs. (2.1), (2.6) and (2.7), the R value is defined as:

$$\begin{aligned}
R &= \frac{\text{fragment yield given by two asymmetric components}}{\text{fragment yield given by the symmetric component}}\\
&= \frac{Y_{h1} + Y_{h2} + Y_{l1} + Y_{l2}}{Y_s}\\
&= \frac{2(Y_{h1} + Y_{h2})}{Y_s} && (3.9)
\end{aligned}$$

where Y_{h1}, Y_{h2}, Y_{l1} and Y_{l2} are the yields of the asymmetric components and Y_s the yield of the symmetric component. Using the above equation, the R values of each incident energy were obtained and the energy dependence was determined. The obtained energy dependence is shown in Fig. 3.1.

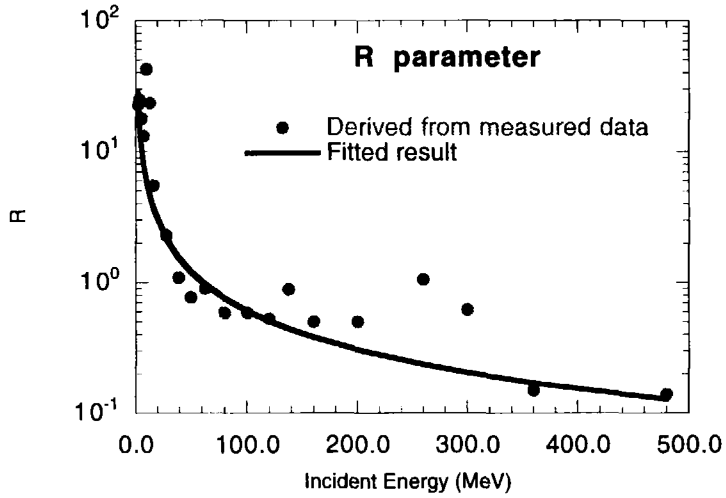

Fig. 3.1 Energy dependence of R parameter

The A, Z and S dependence of the R parameter were also examined using the measured mass distributions of various kinds of fissioning nuclides. In this case the mass distribution of nearly same incident energy of the same particle is suitable. For this purpose the data by Dickens [12)] were used, because he gave the parameters of 5 Gaussian functions of mass distributions by fast neutron fission for various kinds of fissioning nuclides from ^{232}Th to ^{248}Cm. From the examination the S dependence of the R value was seemed to show a sinuous behavior. Then a sine curve was assumed for the S dependence. Figure 3.2 shows the S dependence of the R parameter with the fitted sine curve. Combining the energy dependence and the S dependence of the R parameter, Eq. (3.2) was determined.

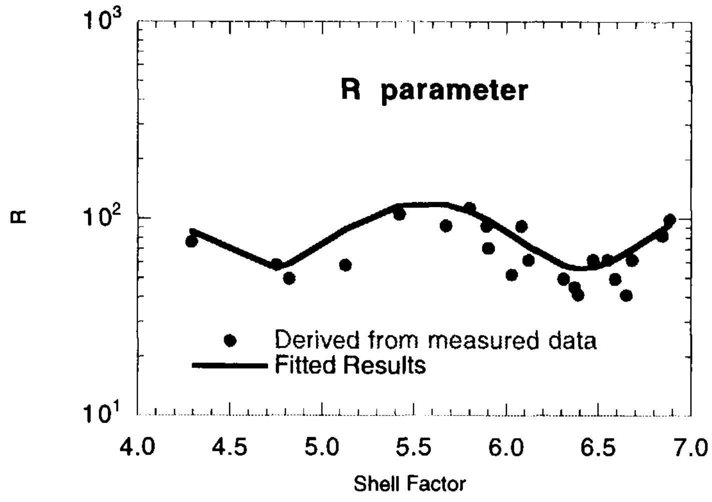

Fig. 3.2 Shell energy dependence of R parameter

The Dickens' data were also used to examine the A, Z and S dependences of the F parameters. After several trial, it was found to be reasonable to assume that the F parameter linearly depends on only the S parameter and Eq. (3.3) was obtained. Figure 3.3 shows the S dependence of the F parameter with the fitted line.

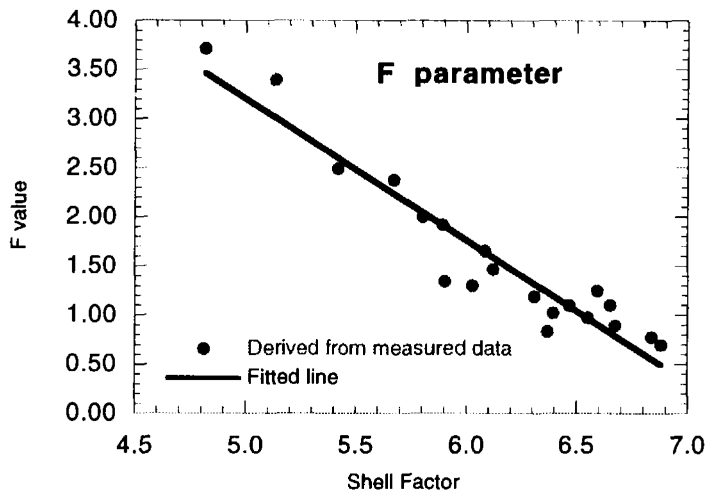

Fig. 3.3 Shell energy dependence of F parameter

As for parameters A_{h1} and A_{h2} the original form of the A and Z dependences were kept as the same as the MO systematics but the coefficients were newly obtained by re-fitting measured data including newer data than those Moriyama and Ohnishi used. Then Eqs. (3.7) and (3.8) were obtained.

The width of the symmetric part, σ_s, seemed to have no apparent energy dependence when the Zöller's measured data were examined. Both Wahl [5] and Dickens [12] give a constant width for the symmetric part even though their values are different from each other. The σ_s values derived from this work based on the Zöller's measured data are seemed to be consistent with constant width and the value is nearly same as that of Dickens. Then we adopted Dickens' value of 12.6.

The parameters of σ_{h1} and σ_{h2} seemed to have no clear energy dependence but slightly increase tendency with energy when these values derived from the Zöller's measured mass distribution were examined. They seemed to have no clear A, Z and S dependence too. Then it was simply assumed that they have a linear dependence on A and Z and slight energy dependence. From these examinations the equations seen in Eqs. (3.5) and (3.6) were derived.

4 Calculation Using New Parameters Set

Using the new parameter set, mass distributions of various kinds of fission were calculated and compared with measured data and those of the MO systematics. The comparisons of ^{248}Cm fission by 20 MeV proton and ^{238}U fission by 160 MeV neutron, which are indicated in Section 2.2 as problem of the MO systematics, are shown in Figs. 4.1 and 4.2. As seen in these figures the present calculations overcome the problems of the MO systematics. For ^{248}Cm fission by 20 MeV proton, the present calculation can reproduce the valley of the mass distribution although the MO systematics fails to make the asymmetric distribution. In the case of ^{238}U fission by 160 MeV neutron, the present calculation can reproduce the measured distribution rather well comparing with the MO systematics.

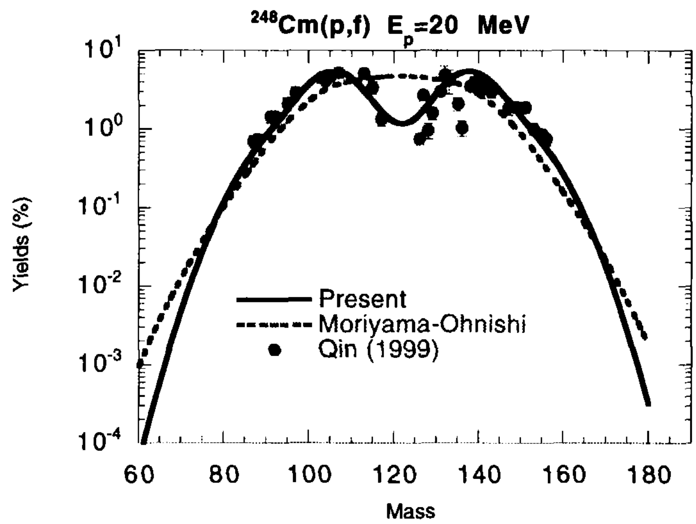

Fig. 4.1 Comparison of ^{248}Cm fission by 20 MeV protons

The comparisons of other results are summarized in Figs. 4.3 through 4.5. In these figures, the mass distributions in log scale (lefthand side) and linear scale (righthand side) are shown.

In Figs. 4.3 and 4.4, the comparisons of neutron induced fission are shown. The neutron energy covers from thermal to 160 MeV. For thermal neutron induced fission, the mass distributions of ^{233}U, ^{235}U and ^{245}Cm fission are shown. These comparisons of thermal neutron fission show that the present calculations reproduce the measured data [13, 14, 15, 16, 17] rather well than the MO systematics do. For medium energy neutron fission, ^{235}U fission by 8.1 MeV neutron, ^{239}Pu fission by 7.9 MeV neutron and ^{237}Np fission by 5 MeV neutron are shown in these figures. The agreement with the measurements [18, 19, 20] seems to be good although slight deviation is seen at the valley part of the ^{235}U fission by 8.1 MeV neutron and at the high mass wing of the ^{237}Np fission by 5 MeV neutron. As examples of higher energy fission, mass distributions of ^{242}Pu fission by 15.1 MeV neutron and ^{238}U fission by 160 MeV neutron are shown together with the measured data [21, 9]. In these comparisons the improvement of the present

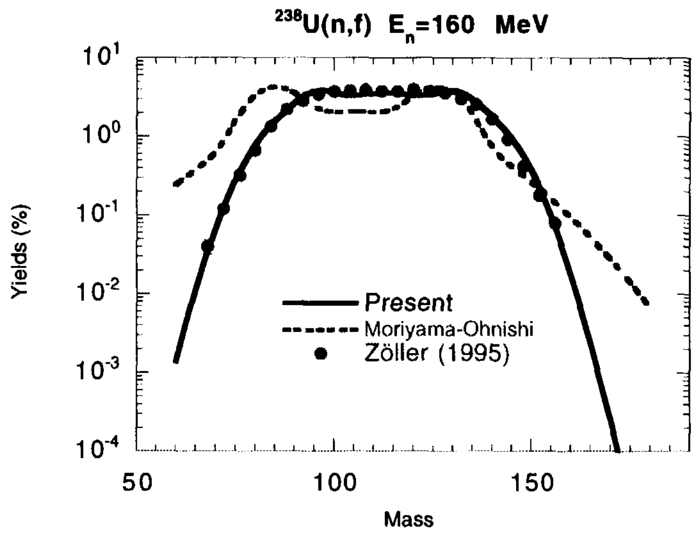

Fig. 4.2 Comparison of ^{238}U fission by 160 MeV neutrons

calculations is easily seen. For ^{242}Pu fission, the valley part is well reproduced by the present calculation but Moriyama-Ohnishi systematics fails to reproduce the valley part. For ^{238}U fission, the mass distribution of the MO systematics shifts to light mass region too much and the valley to peak ratio is not suitable comparing with the measured data. The present calculation, however, improves the discrepancy and reproduce the measured data rather well, although the slight discrepancy is still seen at the peak mass region.

In Fig. 4.5, the mass distributions of proton induced fission are shown. This figure shows the mass distributions of ^{241}Am, ^{243}Am, ^{248}Cm and ^{238}U fission by protons whose energy values are 16 MeV, 15.6 MeV, 20 MeV and 340 MeV respectively. From all of these comparisons it is easily seen that the present calculations improve the agreement with the measured data [22, 8, 23] comparing with the MO systematics. As stated in the previous chapter, the present calculation can reproduce the asymmetric mass distribution of ^{248}Cm fission rather well. In the case of ^{238}U fission by 340 MeV protons, the present calculation shows symmetric distribution and is in good agreement with the measured data. The present systematics, then, seems to be applicable to the fission by such high energy protons as 340 MeV.

The proposed systematics can make calculation of mass distribution for even spontaneous fission. The calculated mass distributions of spontaneous fission are shown in Figs. 4.6 and 4.7 comparing with the evaluated data of ENDF/B-VI file [24]. These figures also show that the present calculations are better than Moriyama-Ohnishi systematics.

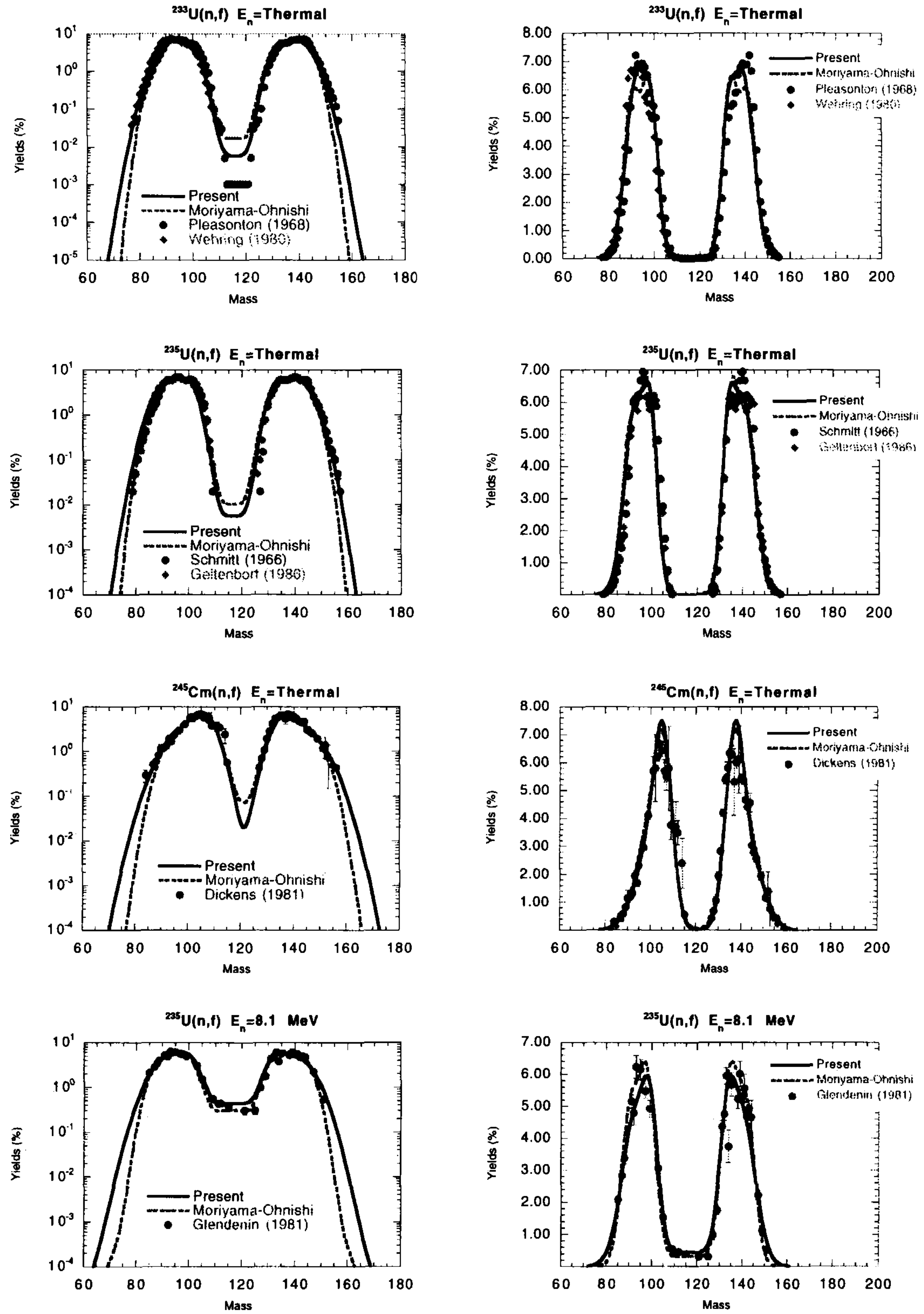

Fig. 4.3 Comparison of neutron induced fission (I)

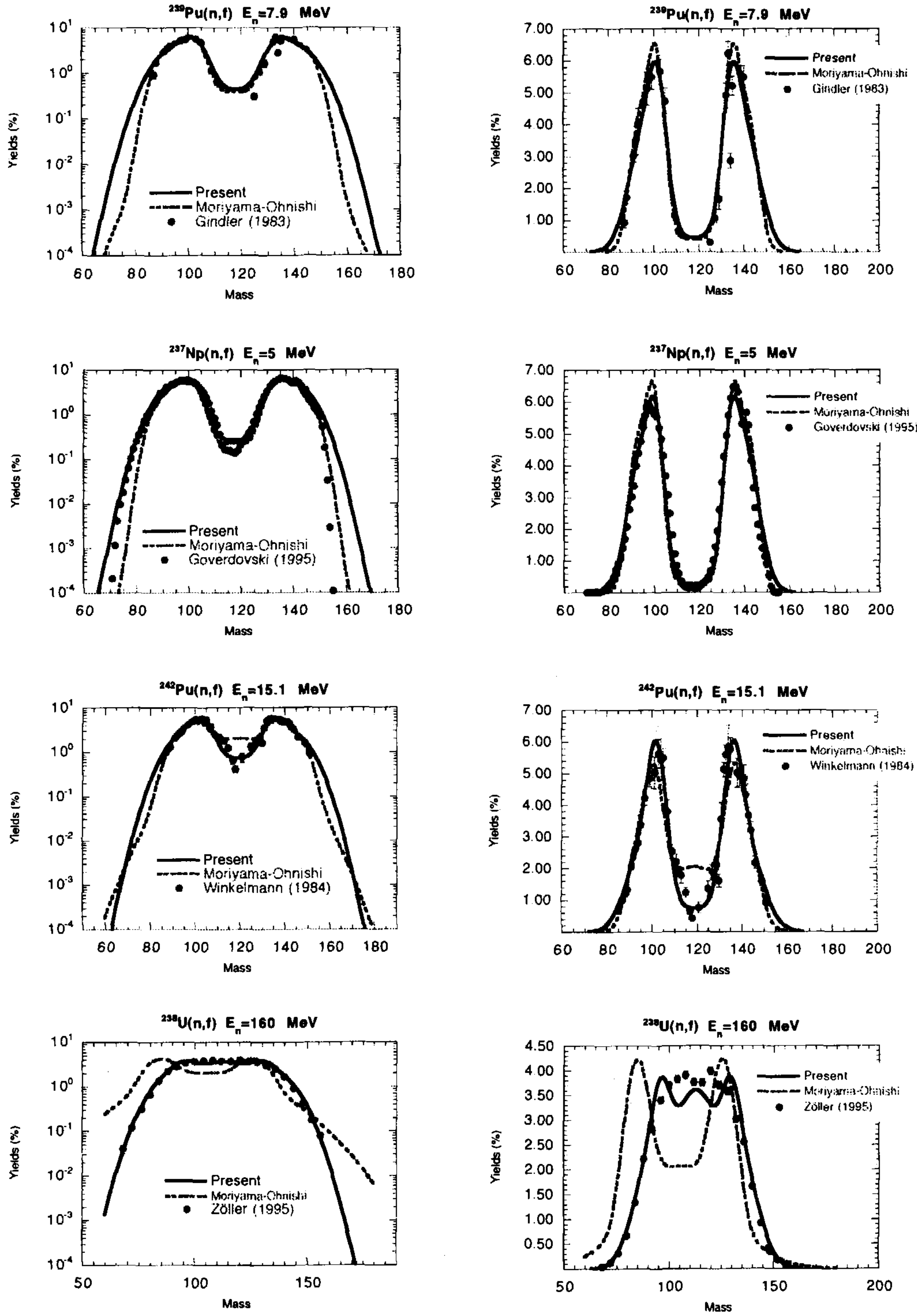

Fig. 4.4 Comparison of neutron induced fission (II)

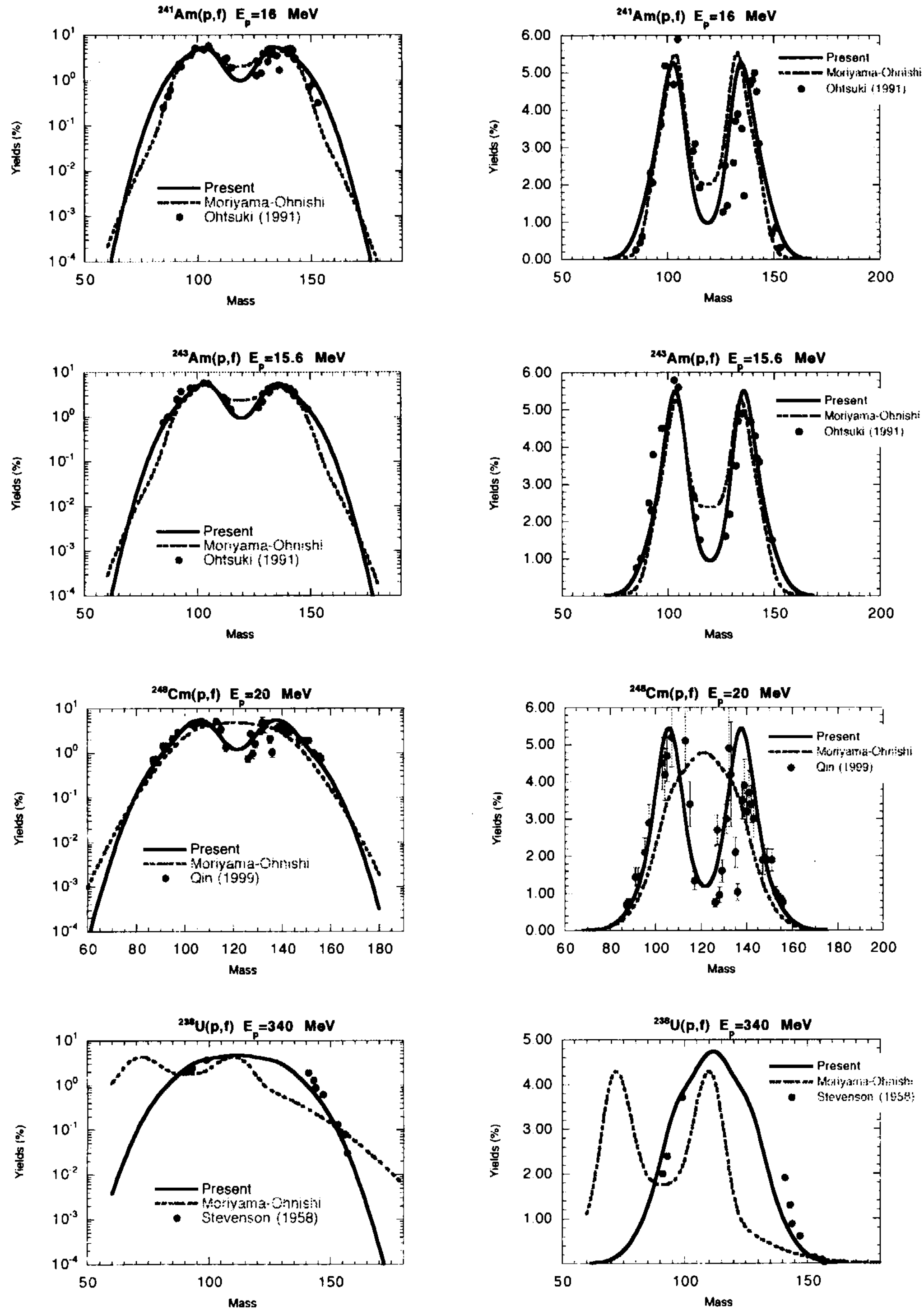

Fig. 4.5 Comparison of proton induced fission

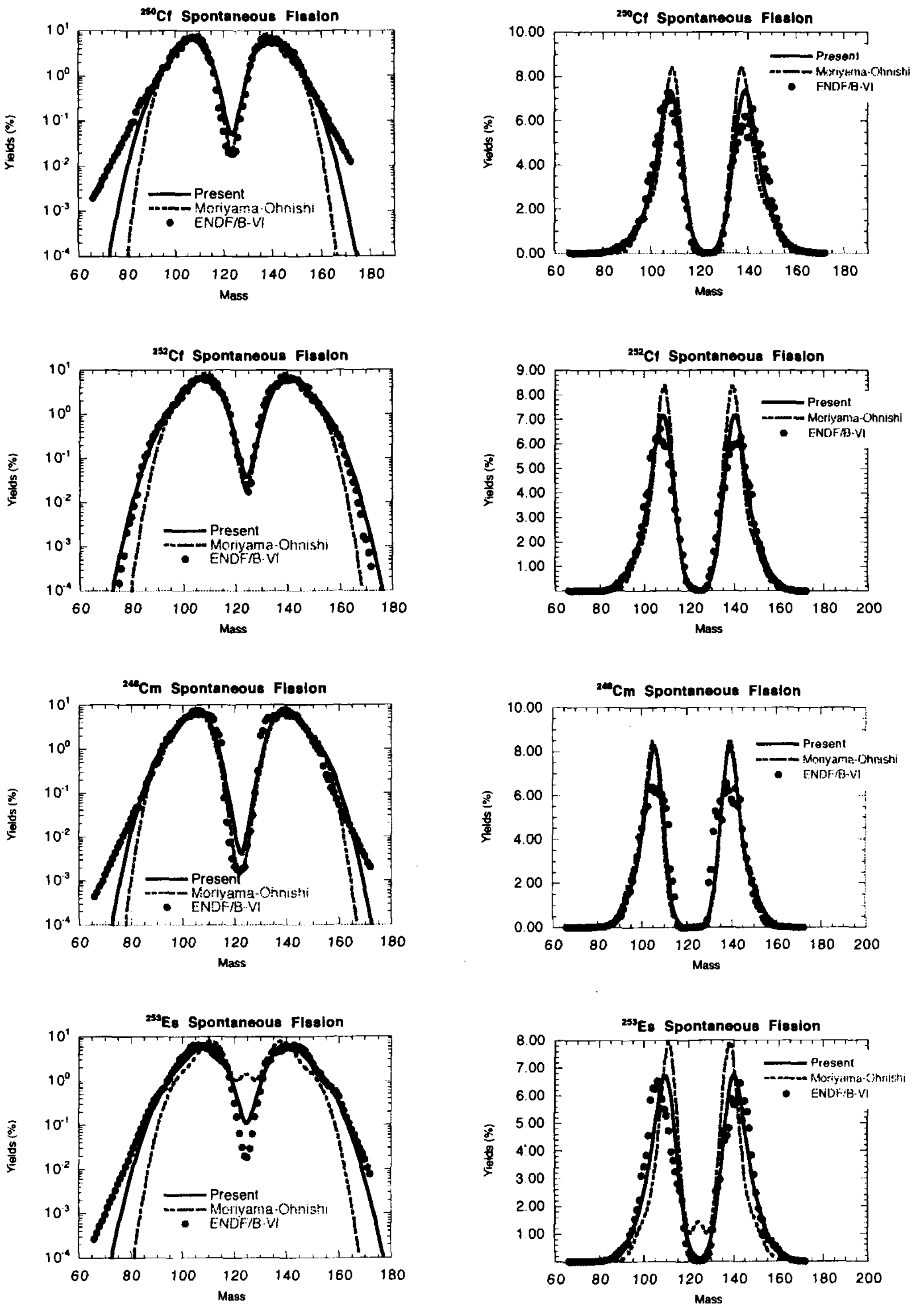

Fig. 4.6 Comparison of spontaneous fission (I)

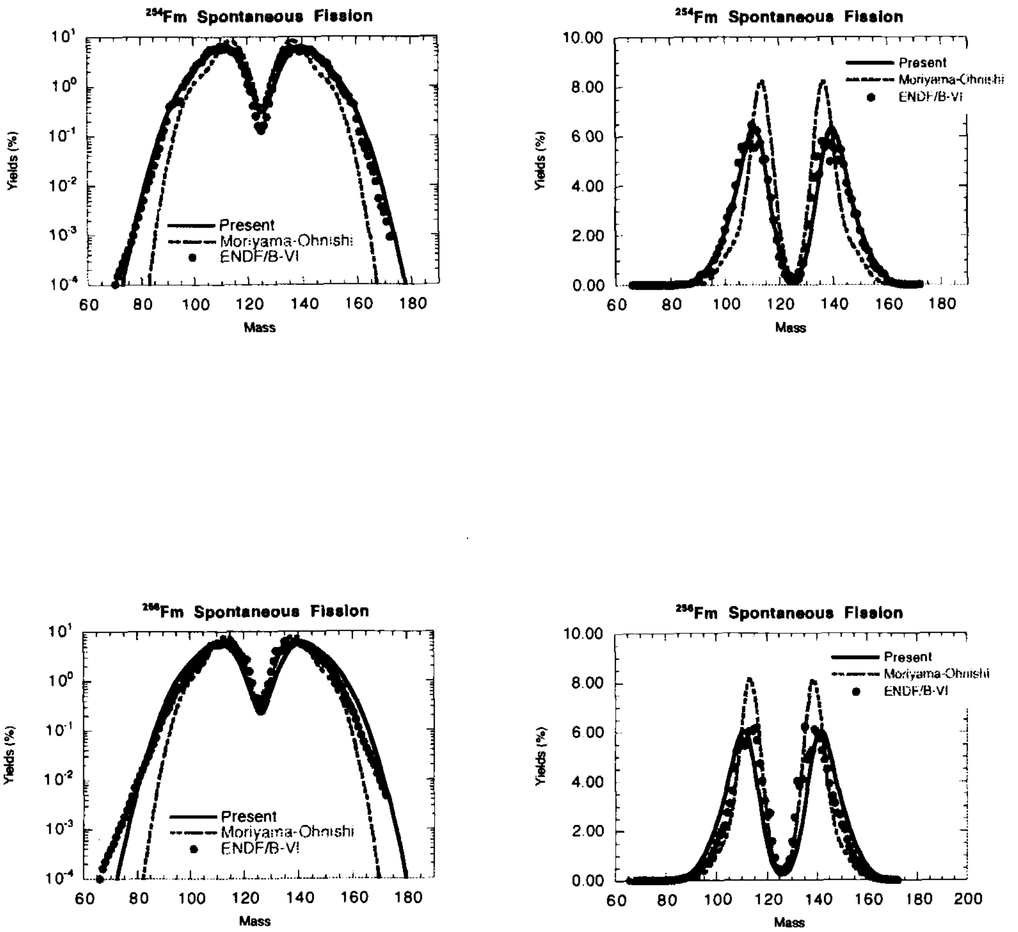

Fig. 4.7 Comparison of spontaneous fission (II)

5 Summary

Parameters of 5 Gaussian-type fission yields systematics were proposed. The calculations using the systematics were performed for various kinds of fission. The results of the calculations were compared with the measured data. The comparisons showed rather good agreement for the mass yields of fission by proton and neutron of energy from thermal to higher than 100 MeV. The systematics seems to be applicable to even spontaneous fission.

In the framework of the IAEA CRP, several systematicses and theoretical models were proposed and inter comparisons among them were performed. The present systematics gives a useful tool to such comparisons. The results of the comparisons will be published in a CRP report. In the report, present status of fission yields prediction will be given.

Acknowledgements

The author expresses thanks to the head of Nuclear Data Center, Dr. Hasegawa, for his support to this work. Thanks are also due to the members of Working Group of Fission Yield, Nuclear Data Committee for helpful discussion.

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国際単位系 (SI) と換算表

表 1　SI 基本単位および補助単位

量	名　称	記　号
長　さ	メートル	m
質　量	キログラム	kg
時　間	秒	s
電　流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光　度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 3　固有の名称をもつ SI 組立単位

量	名　称	記号	他の SI 単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー, 仕事, 熱量	ジュール	J	$N \cdot m$
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	$A \cdot s$
電位, 電圧, 起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	$V \cdot s$
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	$cd \cdot sr$
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 2　SI と併用される単位

名　称	記　号
分，時，日	min, h, d
度，分，秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ eV = 1.60218 \times 10^{-19}\ J$

$1\ u = 1.66054 \times 10^{-27}\ kg$

表 4　SI と共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ Å = 0.1\ nm = 10^{-10}\ m$

$1\ b = 100\ fm^2 = 10^{-28}\ m^2$

$1\ bar = 0.1\ MPa = 10^5\ Pa$

$1\ Gal = 1\ cm/s^2 = 10^{-2}\ m/s^2$

$1\ Ci = 3.7 \times 10^{10}\ Bq$

$1\ R = 2.58 \times 10^{-4}\ C/kg$

$1\ rad = 1\ cGy = 10^{-2}\ Gy$

$1\ rem = 1\ cSv = 10^{-2}\ Sv$

表 5　SI 接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

（注）

1. 表 1 ― 5 は「国際単位系」第 5 版，国際度量衡局 1985 年刊行による。ただし，1 eV および 1 u の値は CODATA の 1986 年推奨値によった。
2. 表 4 には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は，JIS では流体の圧力を表わす場合に限り表 2 のカテゴリーに分類されている。
4. EC 閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表 2 のカテゴリーに入れている。

換　算　表

力	$N(=10^5 dyn)$	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　$1\ Pa \cdot s(N \cdot s/m^2) = 10\ P$（ポアズ）$(g/(cm \cdot s))$

動粘度　$1\ m^2/s = 10^4 St$（ストークス）(cm^2/s)

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	$J(=10^7 erg)$	kgf・m	kW・h	cal（計量法）	Btu	ft・lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J（計量法）
　= 4.184 J　（熱化学）
　= 4.1855 J（15 °C）
　= 4.1868 J（国際蒸気表）

仕事率　1 PS（仏馬力）
　= 75 kgf・m/s
　= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86 年 12 月 26 日現在）

A Systematics of Fission Product Mass Yields with 5 Gaussian Functions