Mass distribution in the 50-, 60-, and 70-MeV bremsstrahlung-induced fission of ^{232}Th

ISINN-20
Alushta, Ukraine, May 21-26, 2012
19th International Seminar on Interaction of Neutrons with Nuclei:
«Fundamental Interactions & Neutrons, Nuclear Structure, Ultracold Neutrons, Related Topics»

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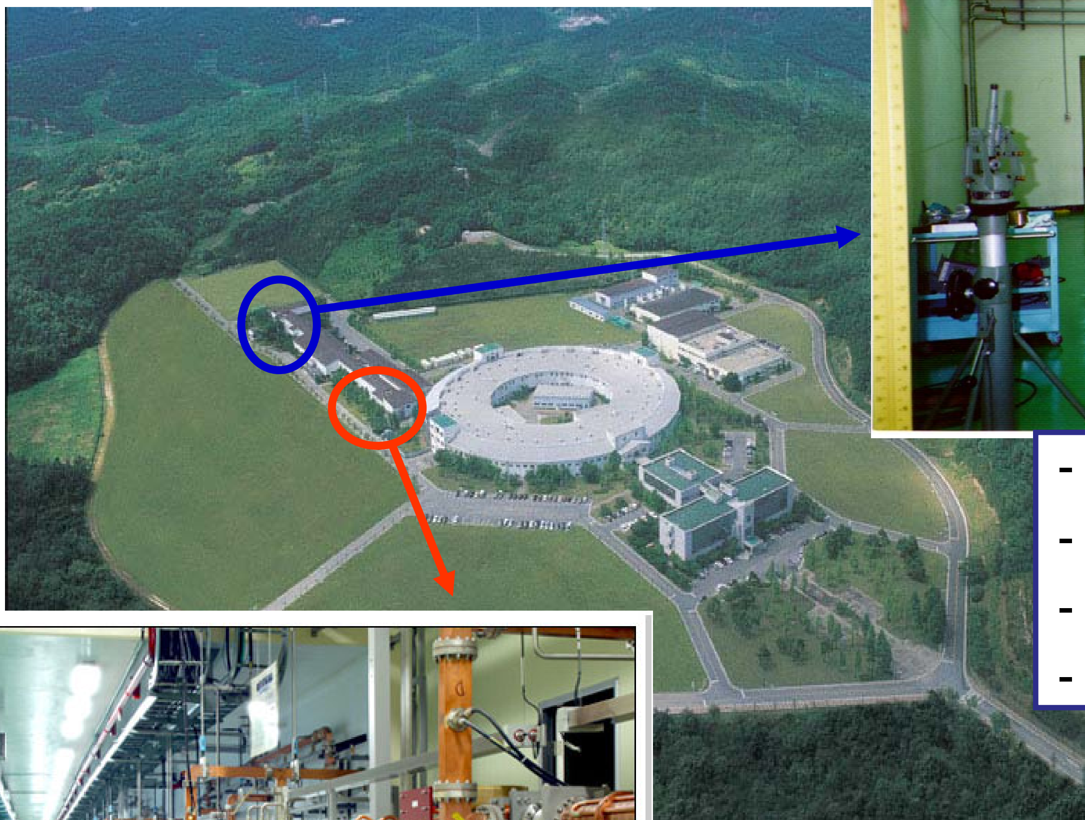
See “PHYSICAL REVIEW C **85**, 024623 (2012)”

Abstract

The post-neutron yields of various fission products in the mass region of 77-153 have been determined for the first time in the 50-, 60- and 70-MeV bremsstrahlung-induced fission of ^{232}Th by using a recoil catcher and an off-line γ-ray spectrometric technique in the electron linac at Pohang Accelerator Laboratory, Korea. The mass-yield distributions were obtained from the fission products yield data using charge distribution corrections. The fission yields of the present work and the existing data from the ^{232}Th(γ,f) reaction at various energies are compared with those from the ^{232}Th(n,f), the ^{238}U(n,f), and the ^{238}U(γ,f) reactions. We observed that the yields of fission products for A=133-134, A=138-139, A=143-144, and their complementary products in the above fissioning systems are higher than other fission products, which is explained based on the nuclear structure effect. However, we observed that the yields of fission products for A=133-134 are lower than those for A=143-144 in the ^{232}Th(γ,f) reaction compared to those of the ^{232}Th(n,f), the ^{238}U(n,f), and the ^{238}U(γ,f) reactions. The yields of fission products for A=133-134 increase but those for A=143-144 decrease with an increasing the excitation energy in the ^{232}Th(γ,f) and the ^{232}Th(n,f) reactions, however those trends are reversed in the ^{238}U(γ,f) and the ^{238}U(n,f) reactions. The increasing or the decreasing trends for the yields of fission products for A=133-134 and A=143-144 with the excitation energy in the ^{232}Th(γ,f), the ^{232}Th(n,f), the ^{238}U(n,f), and the ^{238}U(γ,f) reactions are explained from the shell effect of the complementary products based on the static scission point model and the standard I and II channel of bimodal fission. The peak-to-valley (P/V) ratio for the above fissioning systems was also obtained from the mass-yield distribution. The peak-to-valley ratio for the ^{232}Th(γ,f) and the ^{238}U(γ,f) reactions at different energies from the present data and the existing literature data are interpreted to examine the role of excitation energy.

Electron accelerators for bremsstrahlung production

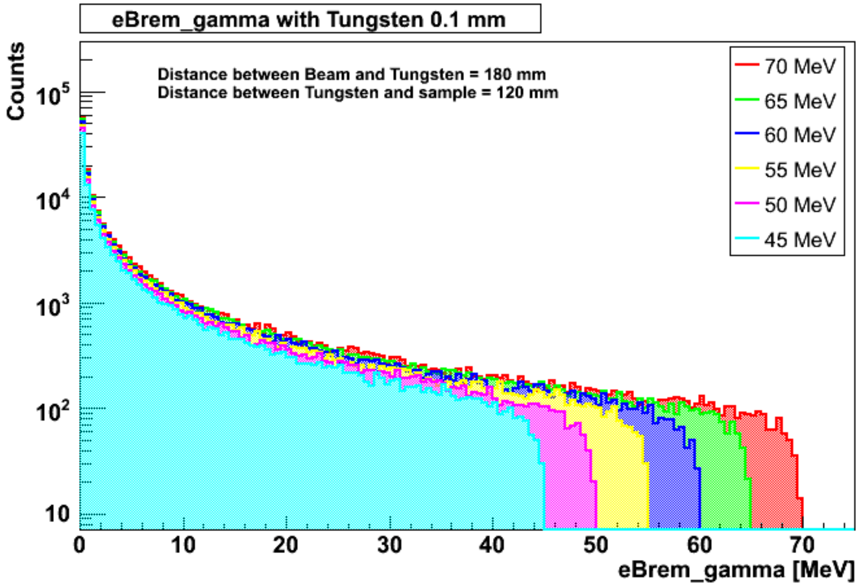
Pohang Accelerator Laboratory

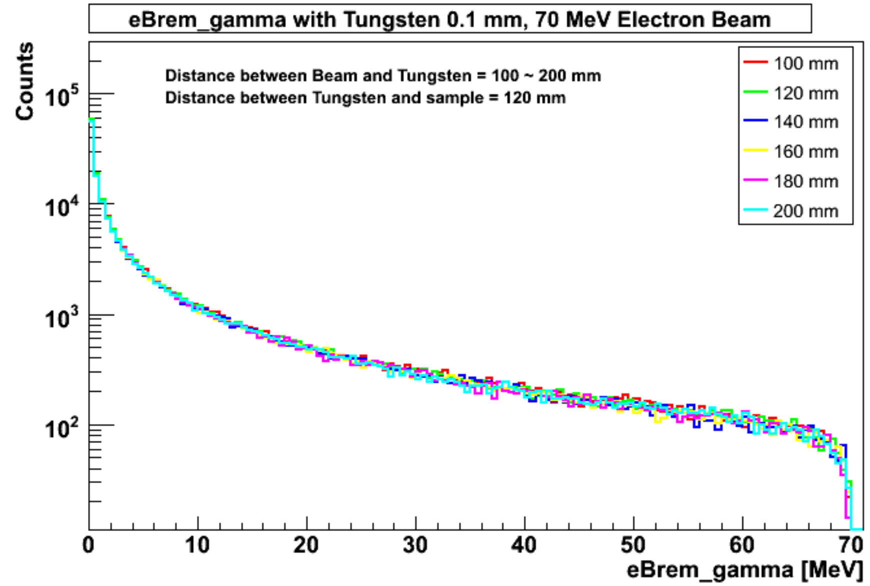


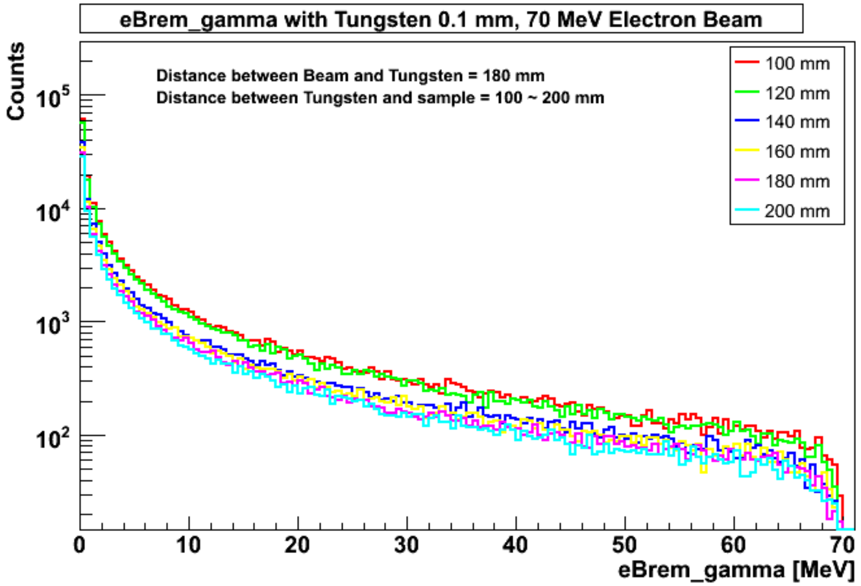
- Beam Energy : 50-70 MeV
- Beam Current : 100 mA
- Pulse Width : 1.0 μs ~2.0 μs
- Repetition Rate : 10 Hz ~ 12 Hz

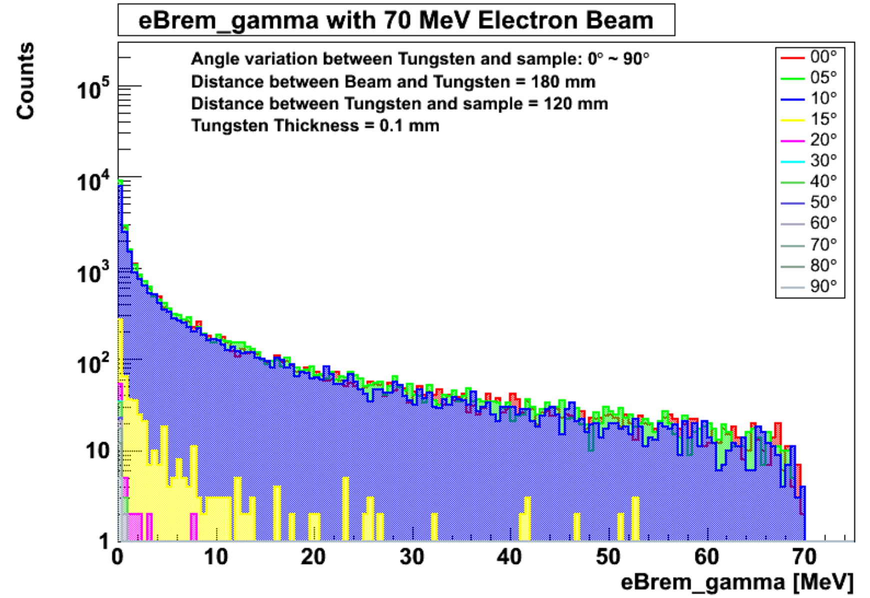
- Beam Energy : 2.5 GeV
- Beam Current : 100 mA
- Pulse Width : 1.0 ns
- Repetition Rate : 10 Hz

Bremsstrahlung spectrum for 0.1mm W converter -GEANT4 Calculation -

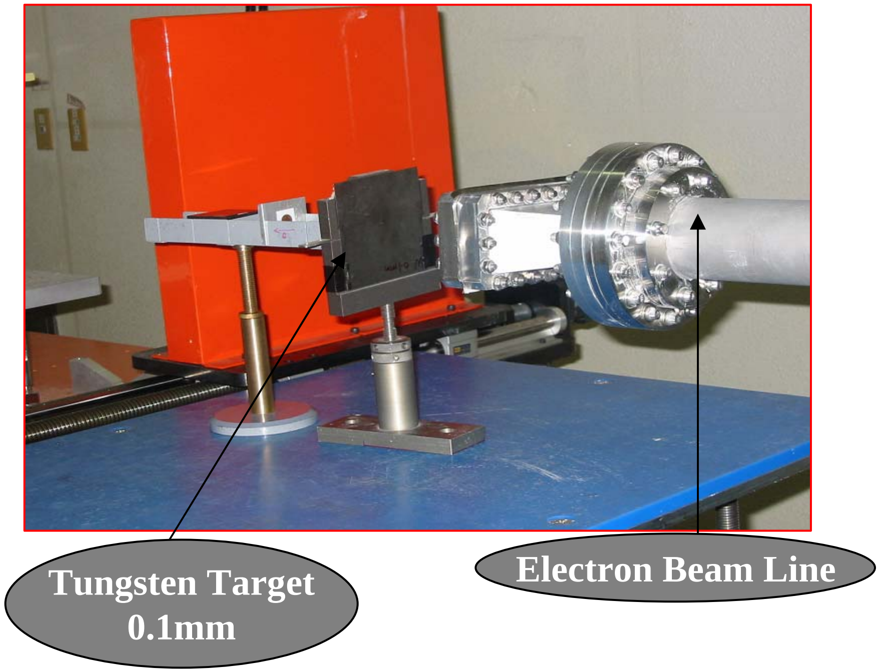


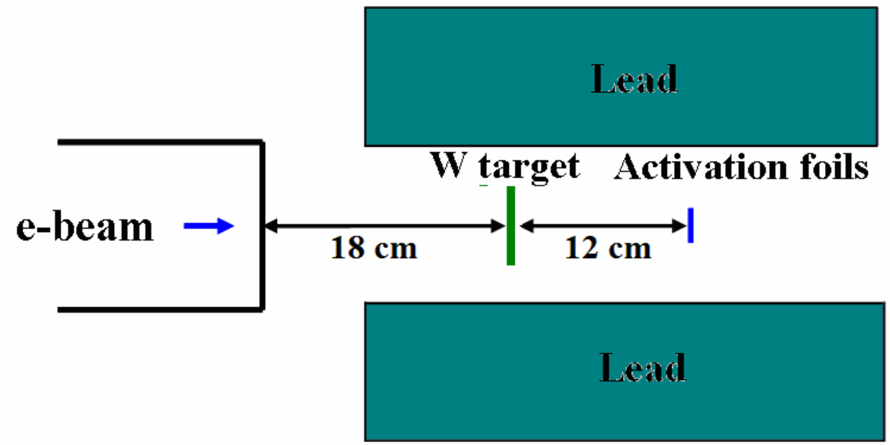


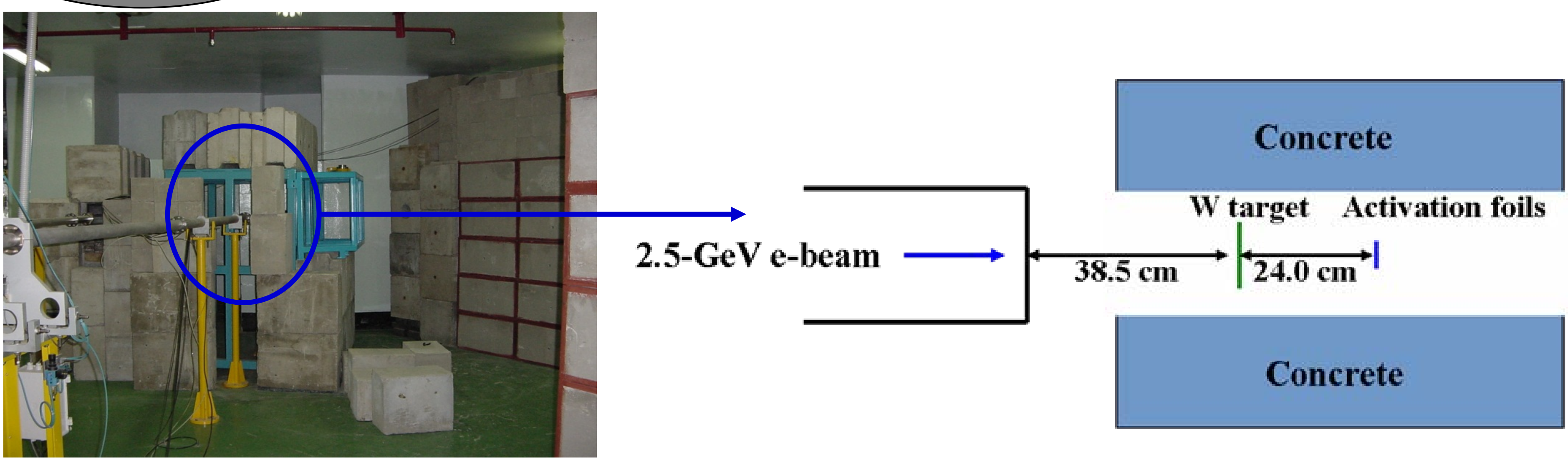




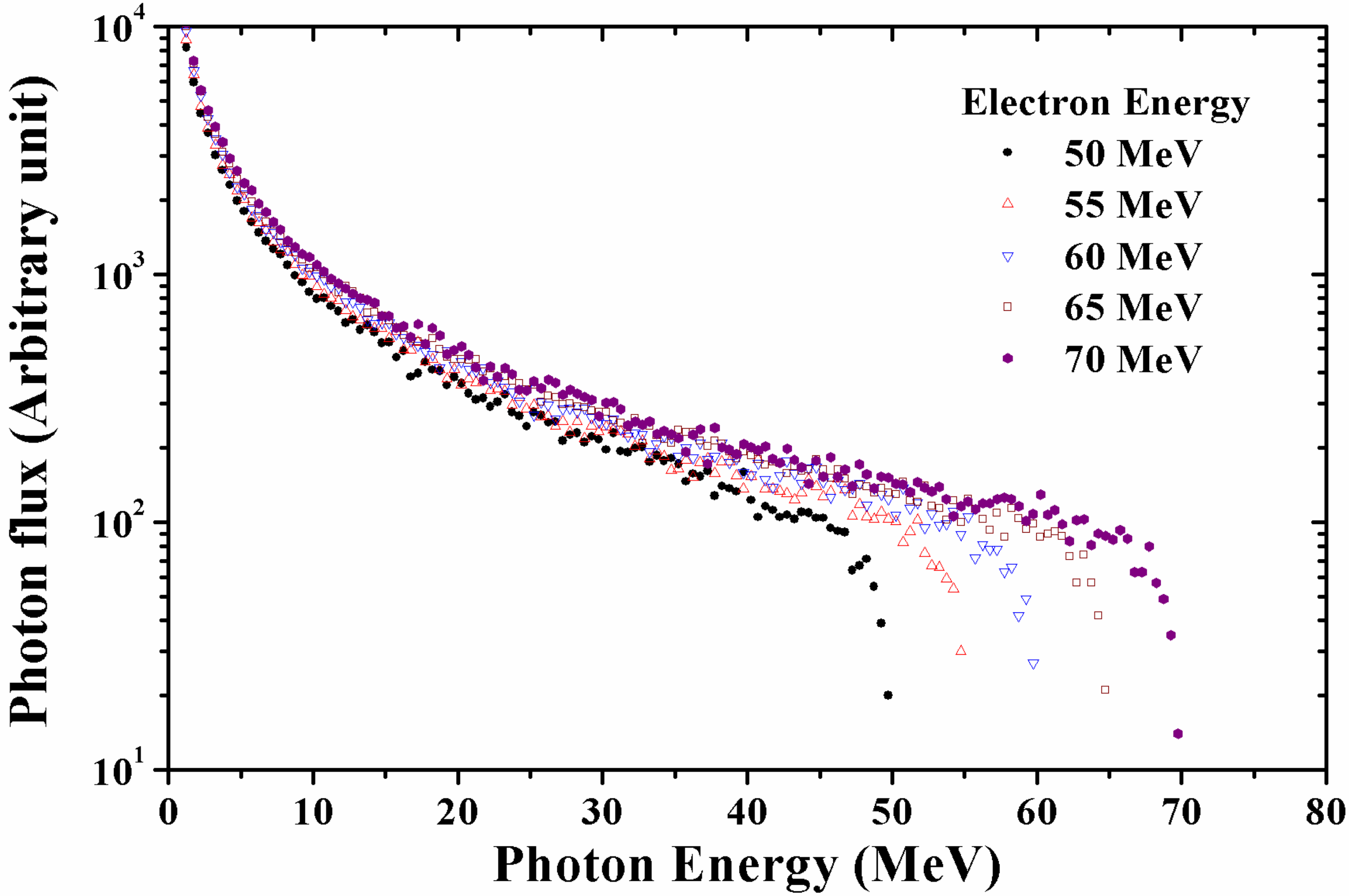
Bremsstrahlung production and Sample Irradiation







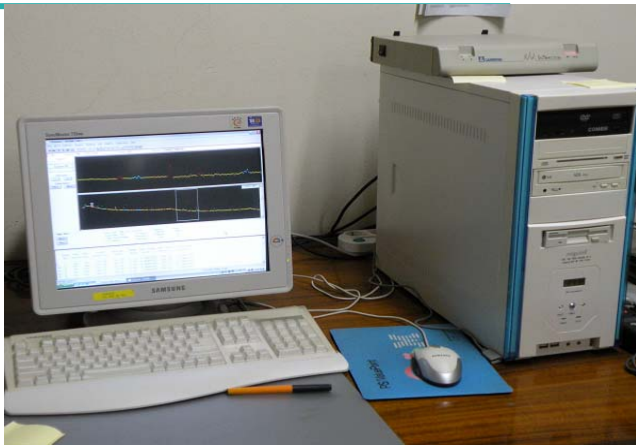
Bremsstrahlung spectrum for 0.1mm W converter
-GEANT4 Calculation -



Low-background gamma-ray spectrometry

- Coaxial CANBERRA high-purity germanium (HPGe) of diameter 60.5 mm and length of 31 mm.

- The detection efficiency was 20% at 1332.5 keV relative to a 3″ diameter × 3″ length NaI(Tl)

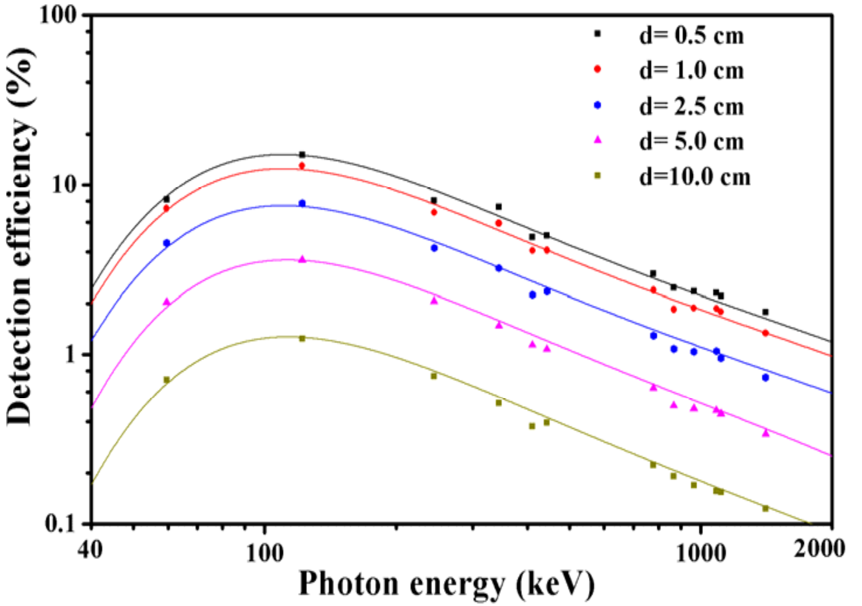


Detection Efficiency:

$$\varepsilon(E_\gamma) = \frac{N(E)}{I_\gamma(\%)} \frac{1}{A_{ref} . e^{-\lambda . t_d}}$$

Fifth order polynomial fitting: $\ln \varepsilon = \sum_{i=0}^{5} a_i (\ln E)^i$

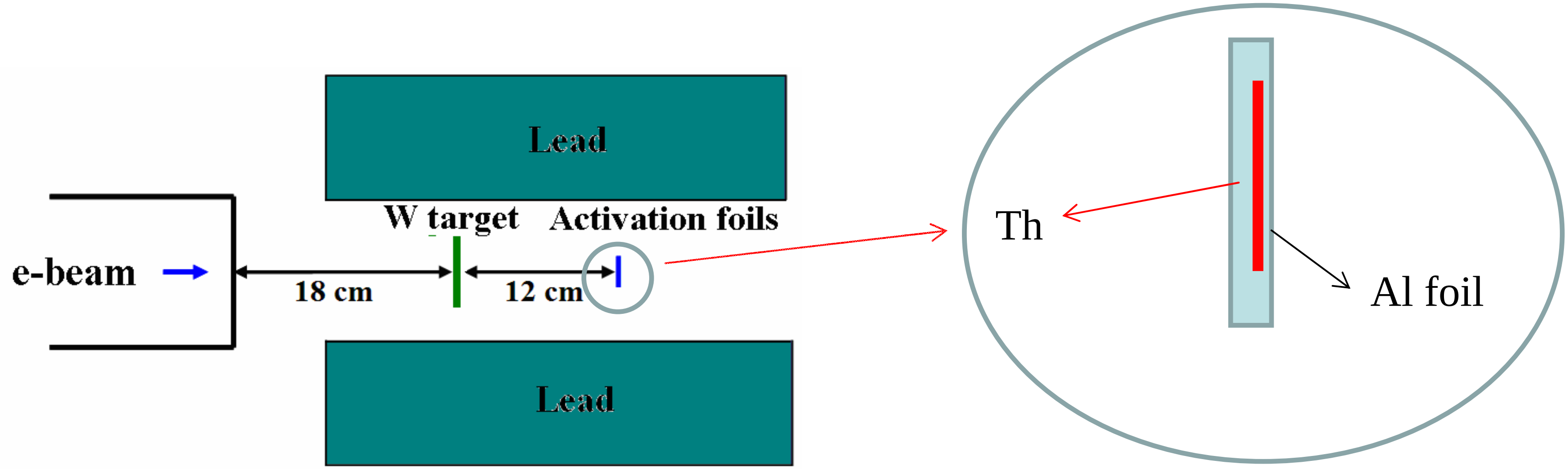
Nuclide	Half life (Yrs.)	No. of γ-rays	E_γ(keV)	I_γ(%)
^{241}Am	432.2	1	59.5412	35.9
^{152}Eu	13.537	11	121.78	28.58
			244.70	7.58
			344.28	26.50
			411.12	2.23
			443.97	3.15
			778.91	12.94
			867.38	4.25
			964.08	14.61
			1085.87	10.21
			1112.07	13.64
			1408.00	21.01



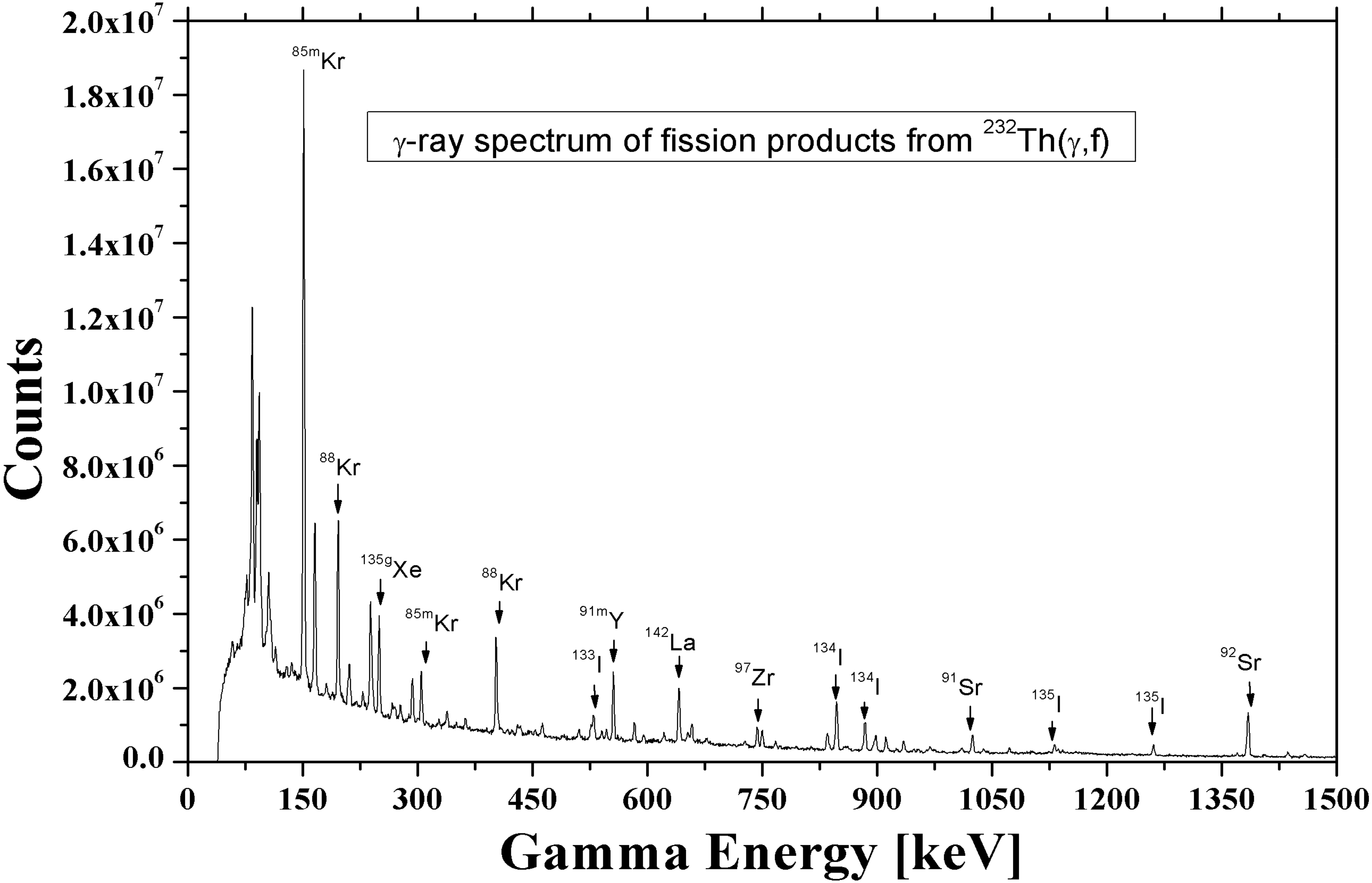
Specification of Samples

	Chemical Purity	Enrichment	Thickness	Size
^{232}Th	99.999	Natural	0.025 mm	0.25 cm^2
Al	99.99	Natural	0.025 mm	

- The ^{232}Th metal target (76.8-114.0 mg) was wrapped with a 0.025 mm thick Al foil with purity more than 99.99%.



Typical γ-ray spectrum of fission products in the 70-MeV bremsstrahlung induced reaction from ^{232}Th



Determination of Yields for Fission Products

- From the observed number of γ-rays (N_{obs}) under the photo-peak of each individual fission product, their **cumulative yields (Y_R)** relative to ^{135}I were determined by :

$$N_{obs}(CL/LT) = n\sigma_F(E)\Phi I_\gamma \varepsilon Y_R (1-e^{-\lambda t_{irr}})e^{-\lambda t_{cool}}(1-e^{-\lambda CL})/\lambda$$

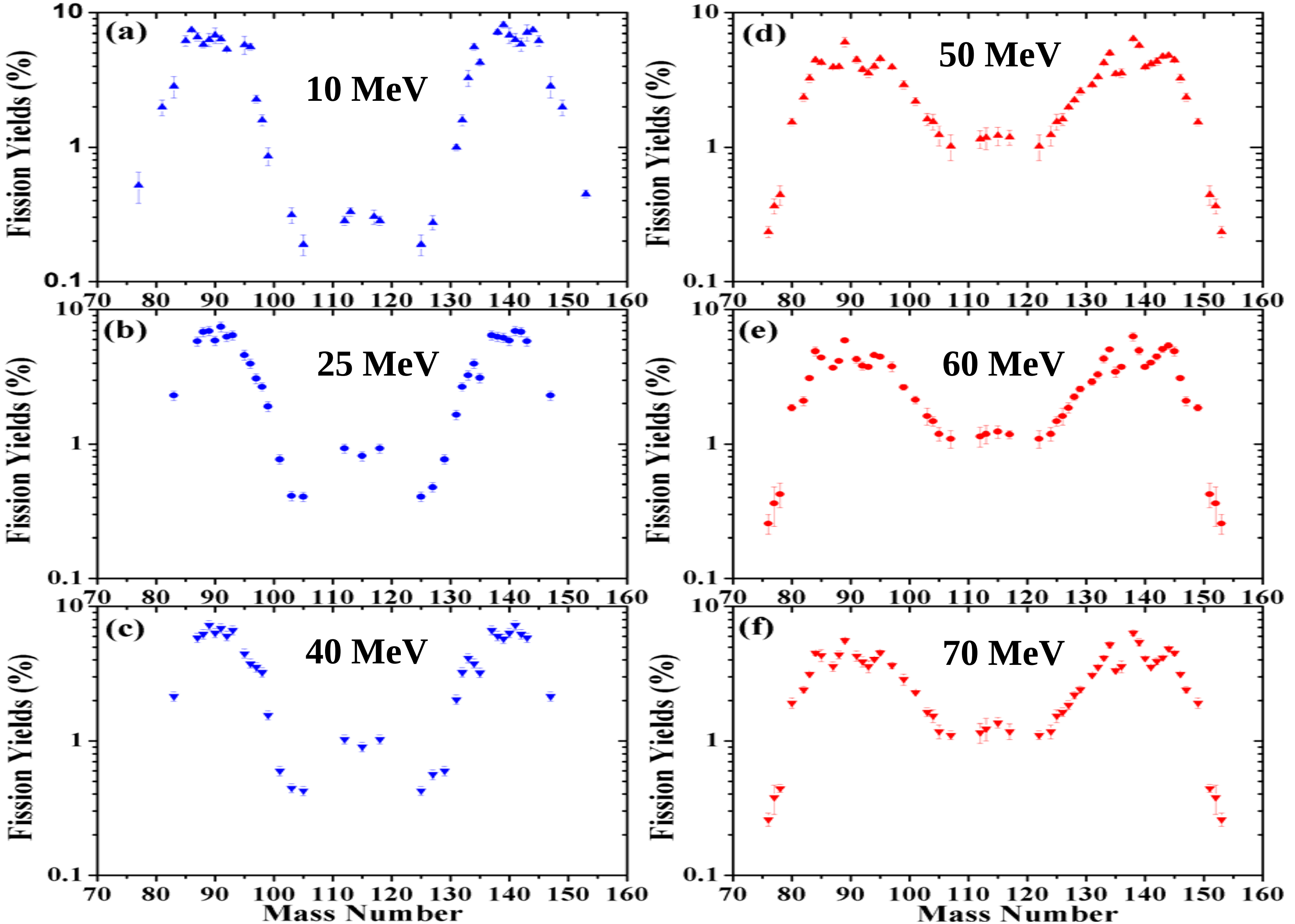
where n is the number of target atoms $\sigma_F(E)$ is the photo-fission cross-section of the target nuclei and $\Phi = \int_{E_b}^{E_e} \phi dE$ is the integrated photon flux from the reaction threshold (E_b) to the end-point energy (E_e) for the photon flux (ϕ) at the photon energy E. The t_{irr} and t_{cool} are the irradiation and the cooling time, and CL and LT are the real and the live times of counting, respectively. λ is the decay constant of the isotope of interest and ε is the detection efficiency of the γ-rays in the detector system. I_γ is the abundance or the branching intensity of the chosen γ-rays of the reaction products.

- From the relative **cumulative yields (Y_R)** of the fission products, their relative mass-chain yields (Y_A) were determined by :

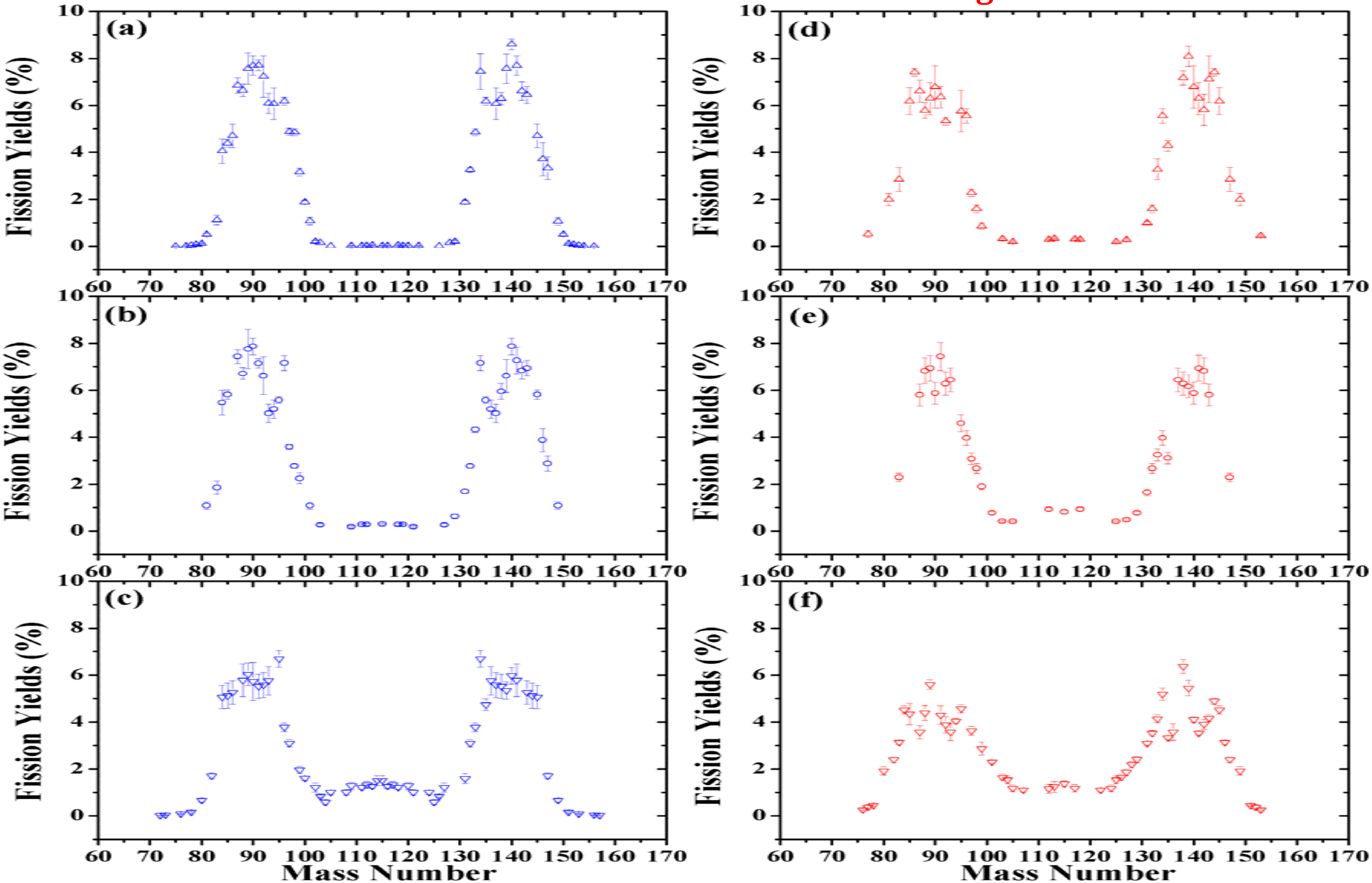
$$Y_A = Y_R / FCY, \quad FCY = \frac{EOF^{a(Z)}}{\sqrt{2\pi\sigma_z^2}} \int_{-\infty}^{Z+0.5} \exp\left[-(Z-Z_P)^2/2\sigma_z^2\right] dZ$$

where Z_P is the most probable charge and σ_z is the width parameter of an isobaric yield distribution. $EOF^{a(Z)}$ is the even-odd effect with $a(Z)$ = +1 for even Z nuclides and -1 for odd-Z nuclides.

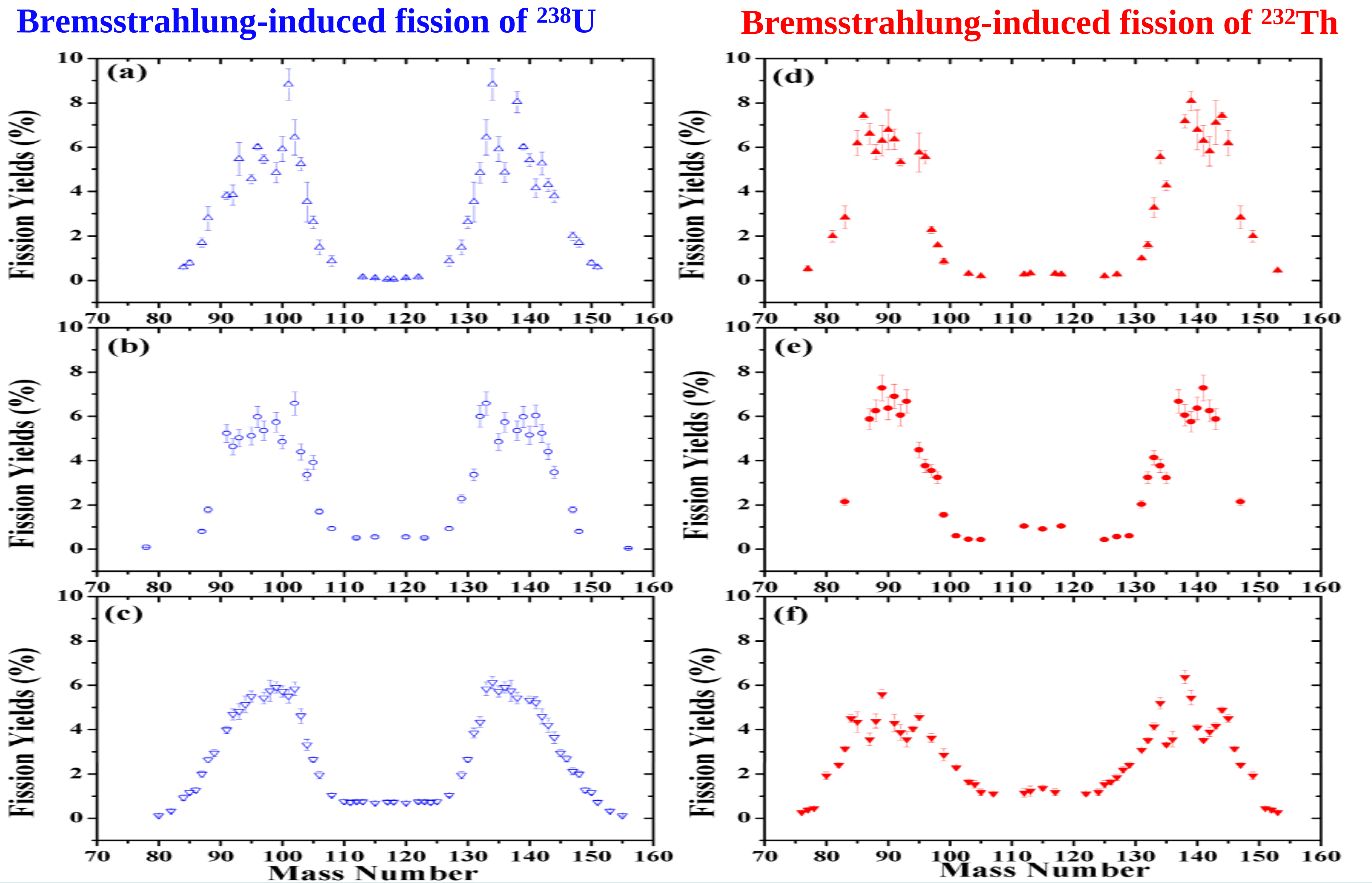
[Fig. 1] Yields of Fission Products (%) for bremsstrahlung-induced fission of ^{232}Th



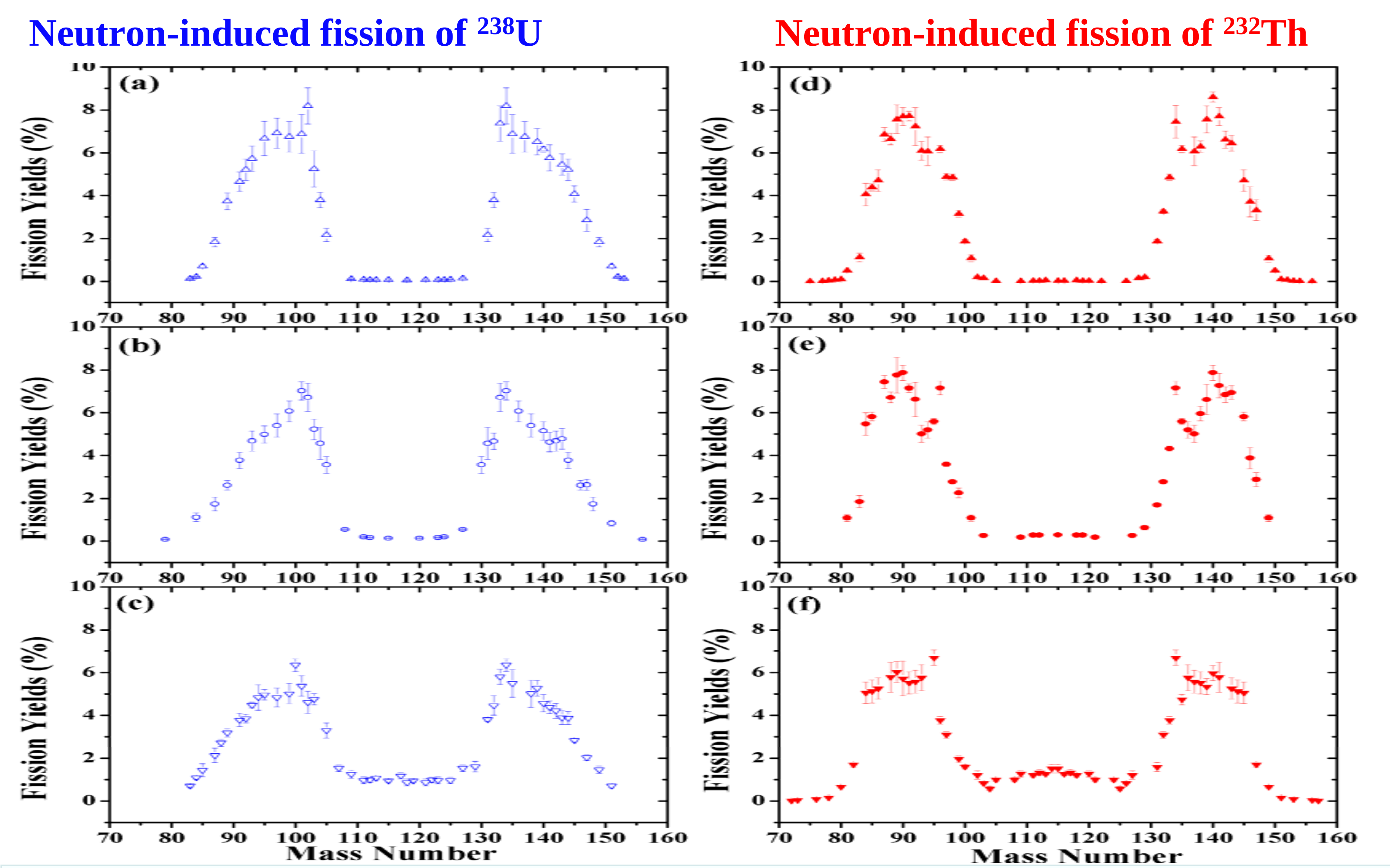
Neutron-induced fission of ^{232}Th **Bremsstrahlung-induced fission of ^{232}Th**



[Fig. 2] Yields of fission products (%) as a function of mass number in the neutron-induced fission of ^{232}Th at (a) 7.61-MeV, (b) 12.61-MeV, and (c) 19.41-MeV excitation energies and in the bremsstrahlung-induced fission of ^{232}Th at (d) 7.35-MeV, (e) 13.22-MeV, and (f) 21.25-MeV excitation



[Fig. 3] Yields of fission products (%) as a function of mass number in (a) 10-MeV, (b) 40-MeV, and (c) 70-MeV bremsstrahlung-induced fission of ^{238}U and in (d) 10-MeV, (e) 40-MeV, and (f) 70-MeV bremsstrahlung-induced fission of ^{232}Th.

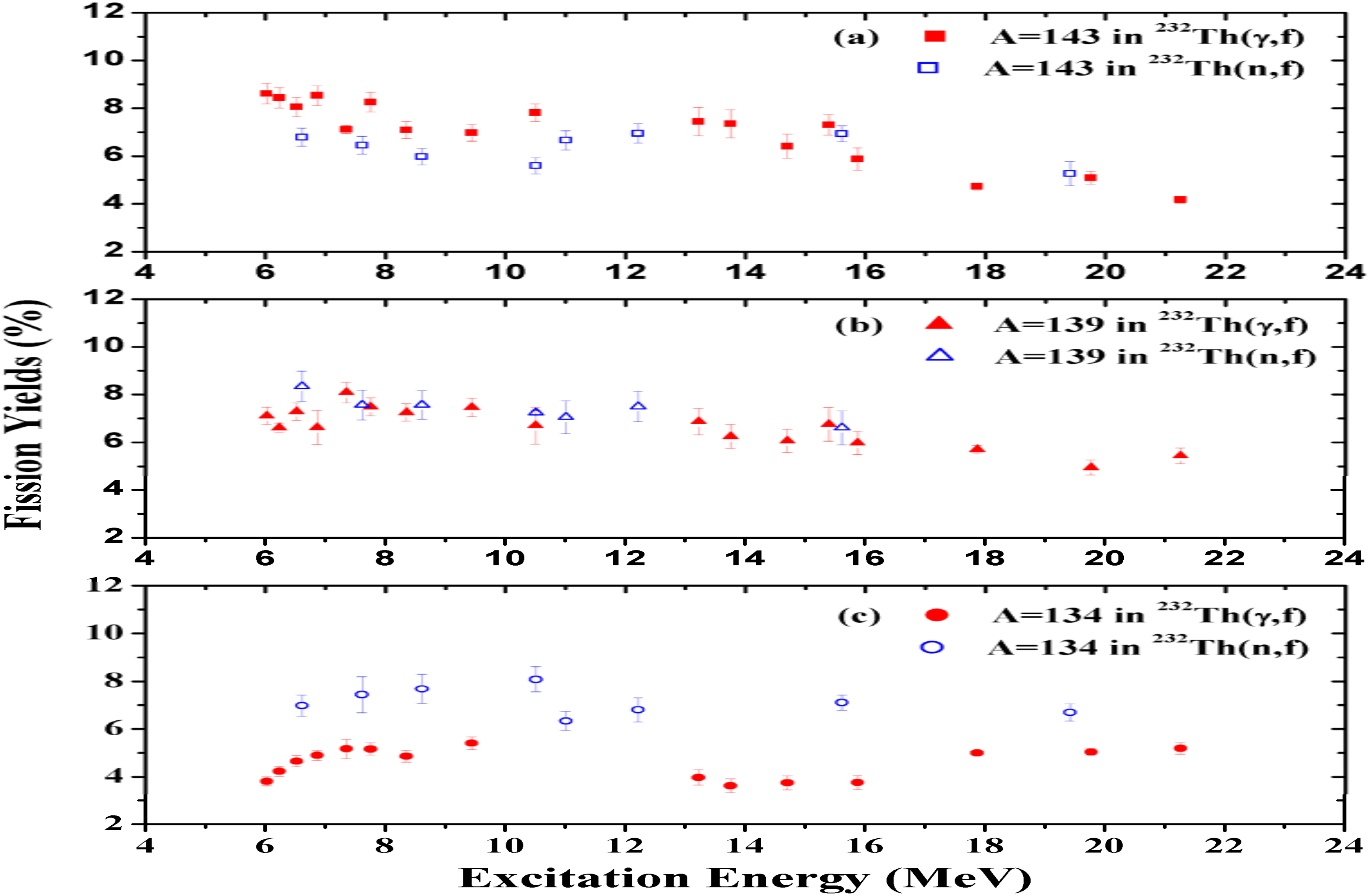


[Fig. 4] Yields of fission products (%) as a function of mass number in the neutron-induced fission of ^{238}U at (a) 7.35-MeV, (b) 12.45-MeV, and (c) 19.15-MeV excitation energies and in the neutron-induced fission of ^{232}Th at (d) 7.61-MeV, (e) 12.61-MeV, and (f) 19.41-MeV excitation energies.

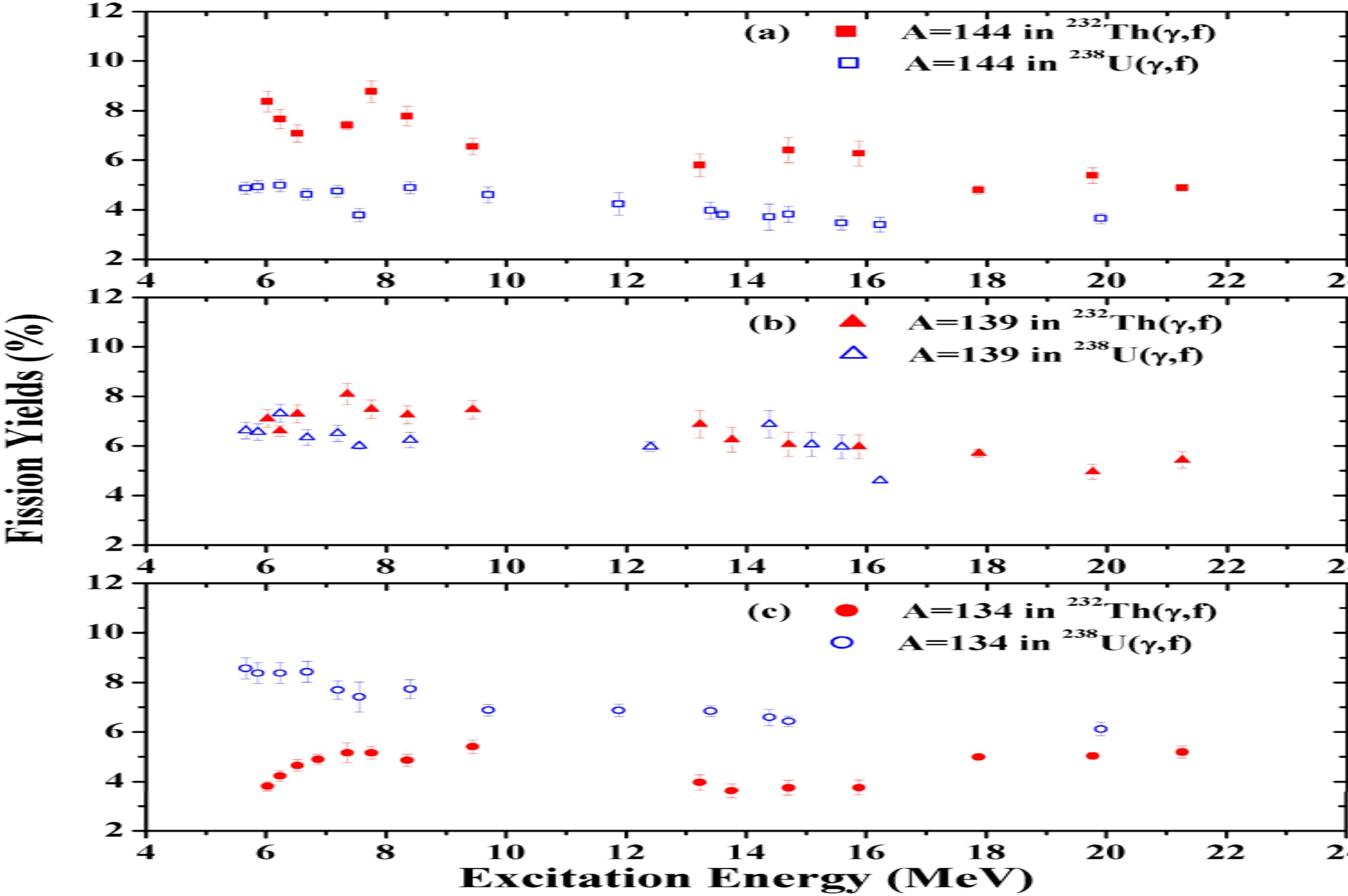
Summary for Yields of Fission Products

- From Figs. 1 and 2 that there is a well-known third peak around the symmetric mass region in the mass-yield distribution of ^{232}Th(γ,f) and ^{232}Th(n,f) reactions, which is absent in the case of ^{238}U(γ,f) (Fig. 3) and ^{238}U(n,f) (Fig. 4). This is due to the fact that the type of potential barrier for ^{232}Th differs from that for ^{238}U, as shown by Moller, who calculated the saddle point configurations against the mass asymmetric deformation.
- From Figs. 1 and 2, the yields of fission products for A=133-134, 138-139, 143-144, and their complementary products in the bremsstrahlung- and the neutron-induced fission of ^{232}Th are higher than those of the other fission products. Similar observation was shown by us in the neutron-induced fission of various actinides and also in the 10-MeV bremsstrahlung-induced fission of ^{232}Th, ^{238}U, and ^{240}Pu.
- From Figs. 1-4, the yields of fission products for A=133-134 are lower than those for A=143-144 in ^{232}Th(γ,f), whereas those are reversed in ^{232}Th(n,f), ^{238}U(n,f), and ^{238}U(γ,f).

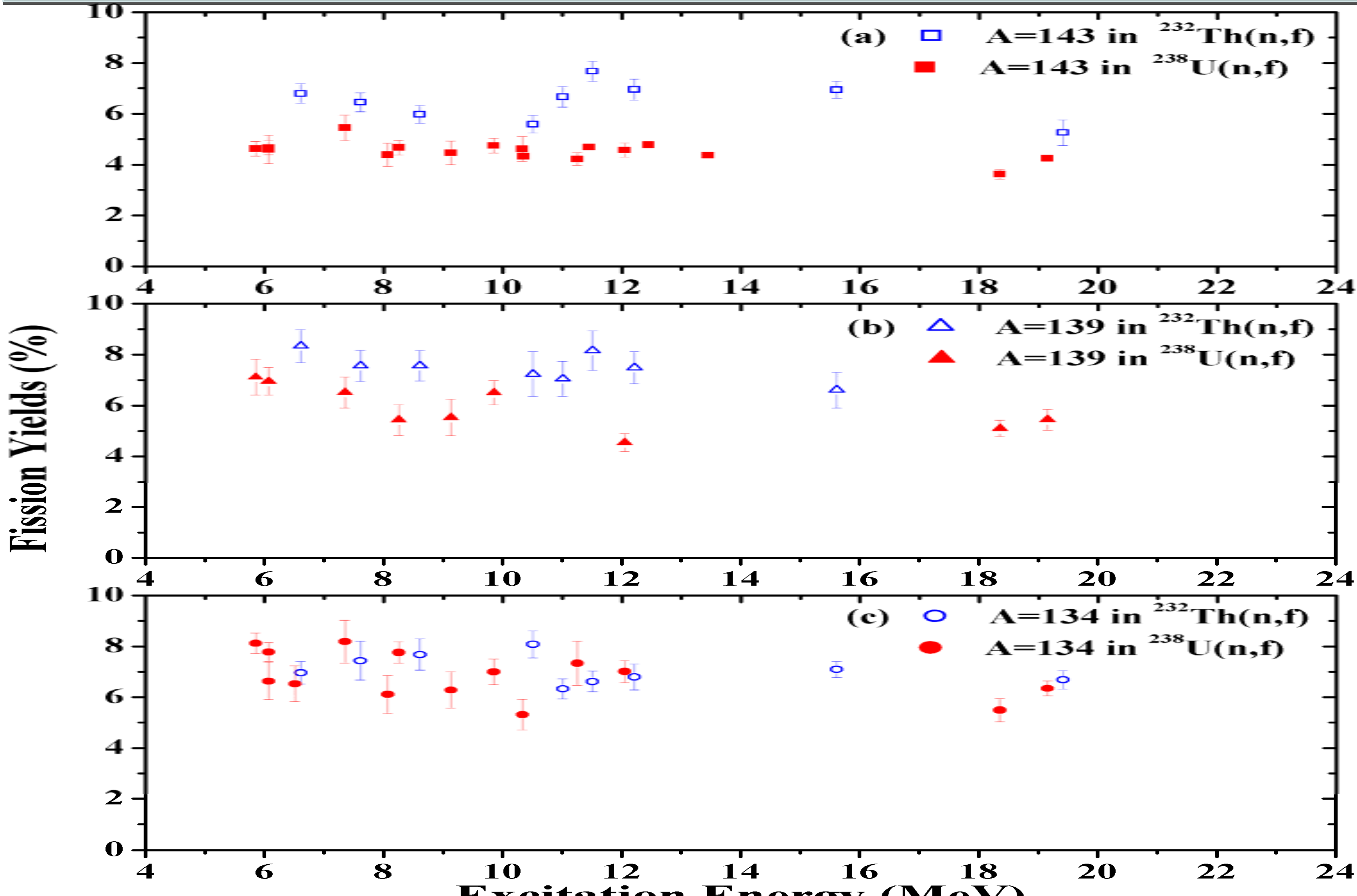
[Fig. 5] Yields of fission products (%) as a function of excitation energy for (a) A=143, (b) A=139, and (c) A=134 in the bremsstrahlung- and the neutron-induced fission of ^{232}Th.



[Fig. 6] Yields of fission products (%) as a function of excitation energy for (a) A=144, (b) A=139, and (c) A=134 in the bremsstrahlung- induced fission of ^{232}Th and ^{238}U.



[Fig. 7] Yields of fission products (%) as a function of excitation energy for (a) A=143, (b) A=139, and (c) A=134 in the neutron-induced fission of ^{232}Th and ^{238}U.



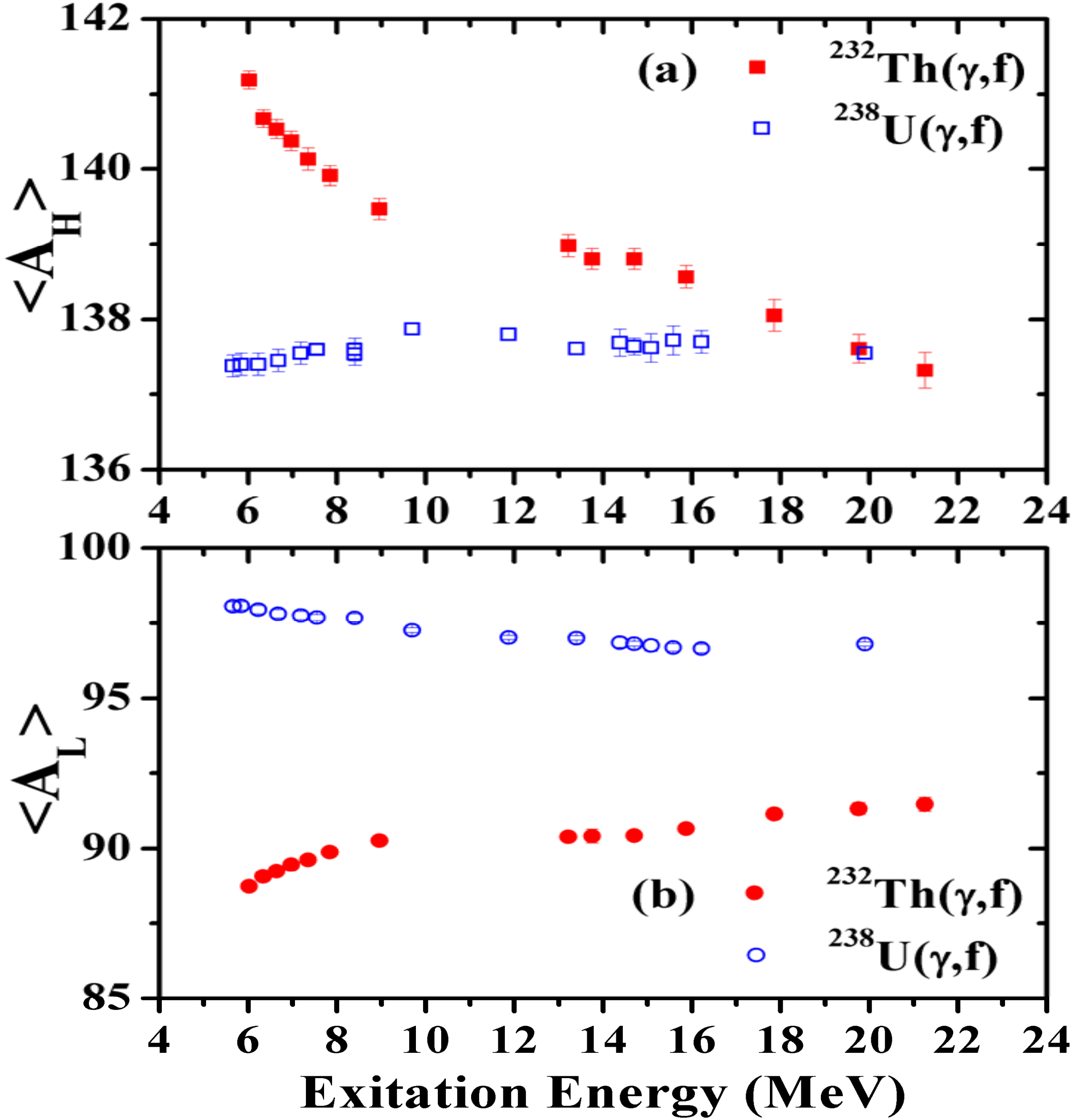
Summary for Yield of Fission Products with different mass number

- The yields of fission products for A=133-134 in the $^{232}Th(\gamma,f)$ reaction at lower excitation energy are lower than those in the $^{232}Th(n,f)$, $^{238}U(n,f)$, and $^{238}U(\gamma,f)$ reactions, whereas those for A=143-144 are reversed. The yield of fission products for A=133-134 increases but that of fission products for A=143-144 in $^{232}Th(\gamma,f)$ decreases with increasing the excitation energy.
- On the other hand, the yields of fission products for A=133-134, 138-139, and 143-144 in the $^{232}Th(n,f)$, the $^{238}U(n,f)$, and the $^{238}U(\gamma,f)$ reactions decrease with increasing the excitation energy.
- The increasing or the decreasing trends of fission product yields in the above fissioning systems with increasing the excitation energy are due to the different shell combinations in the complementary products, which changed with increasing the number of neutron evaporation.

[Fig. 8] (a) Average values of light mass (<A_L>) and (b) average values of heavy mass (<A_H>) as a function of excitation energy in the bremsstrahlung-induced fission of ^{232}Th and ^{238}U.

$$\langle A_H \rangle = \sum (Y\ A_H) / \sum Y$$

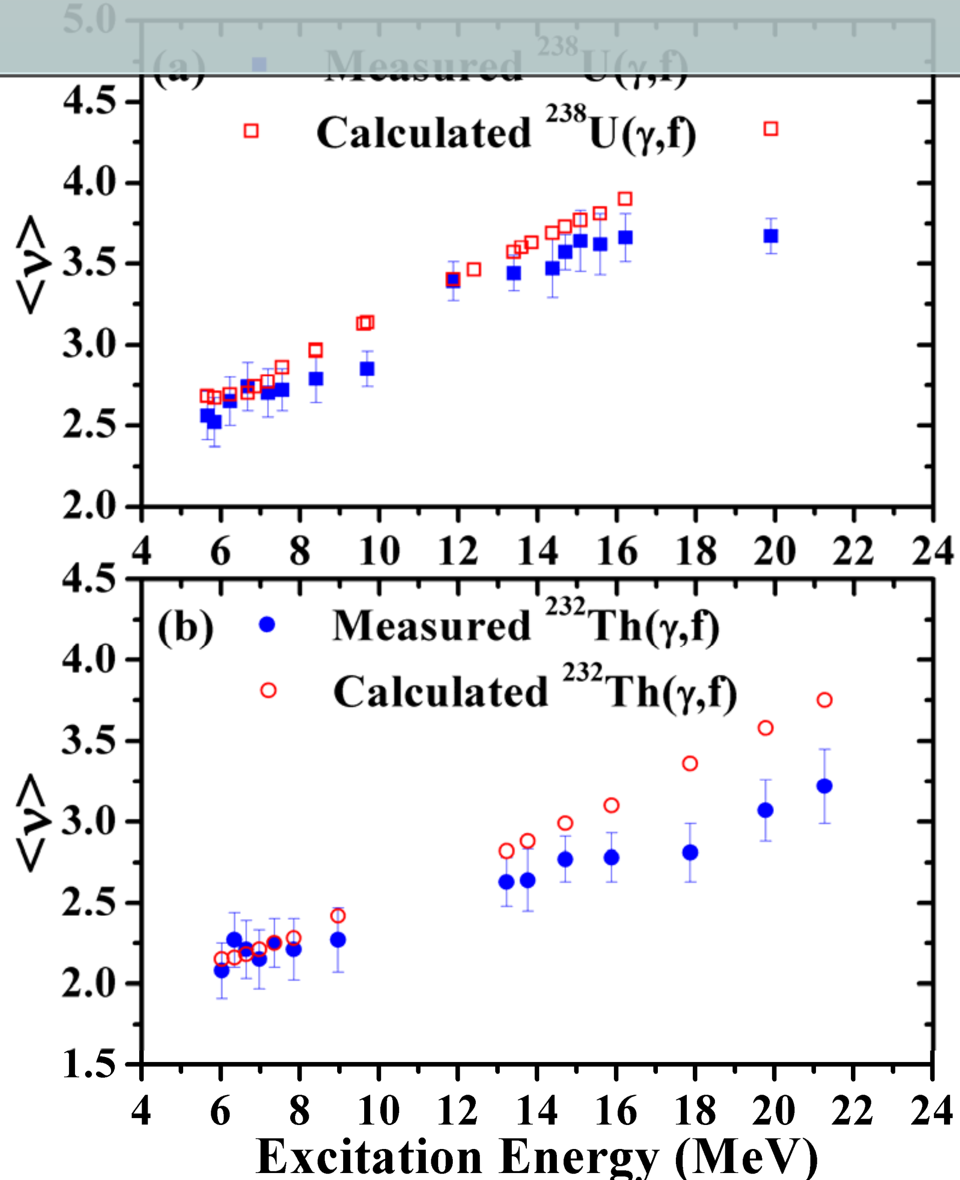
$$\langle A_L \rangle = \sum (Y\ A_L) / \sum Y$$



[Fig. 9] Measured Average Neutron number (<ν>$_{expt}$) and theoretical average neutron number (<ν>$_{cal}$) as a function of excitation energy in the bremsstrahlung-induced fission of (a) ^{238}U and (b) ^{232}Th.

$$\langle \nu \rangle_{\mathrm{expt}} = A_C - \left(\langle A_L \rangle + \langle A_H \rangle \right)$$

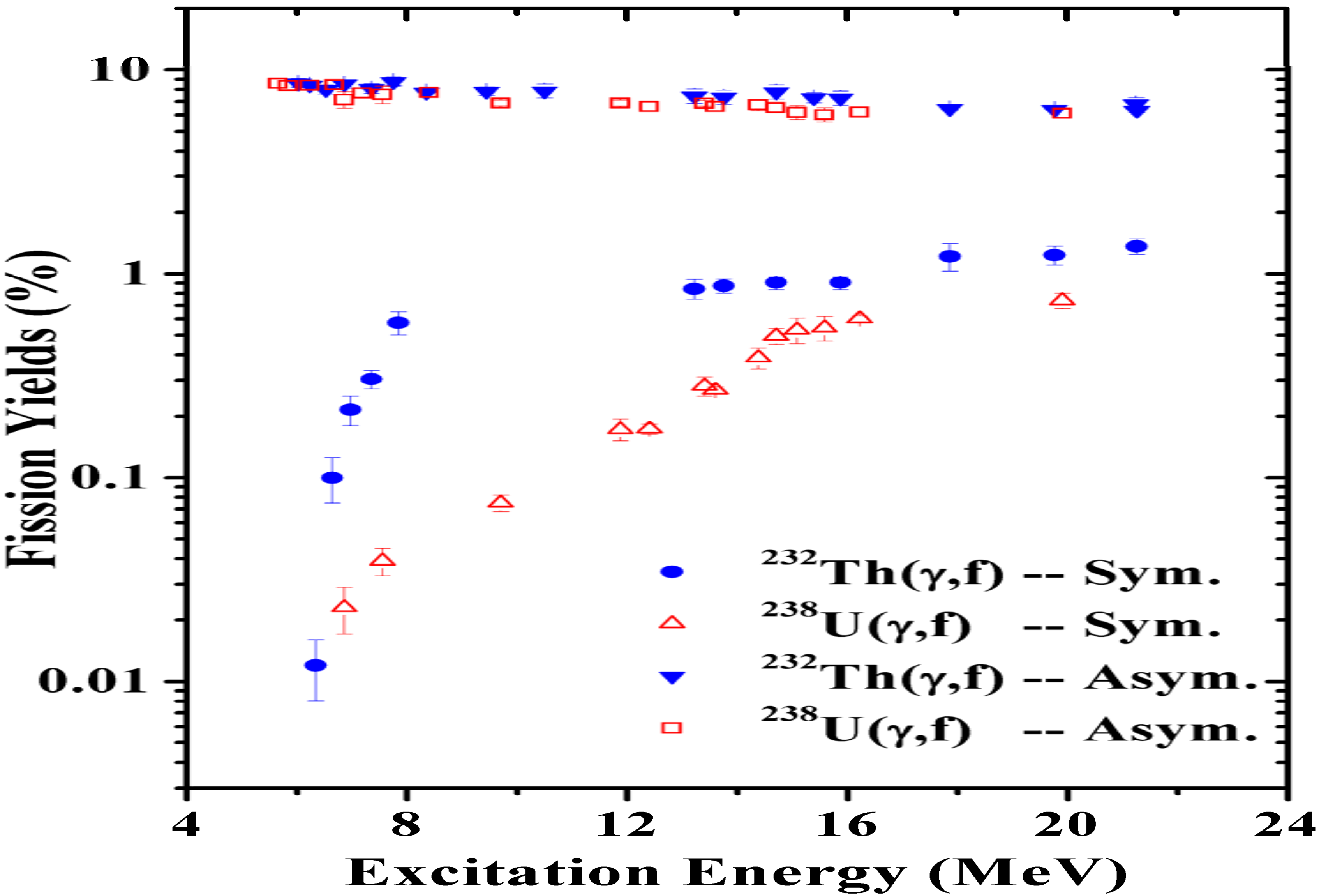
A_C is the compound nucleus mass



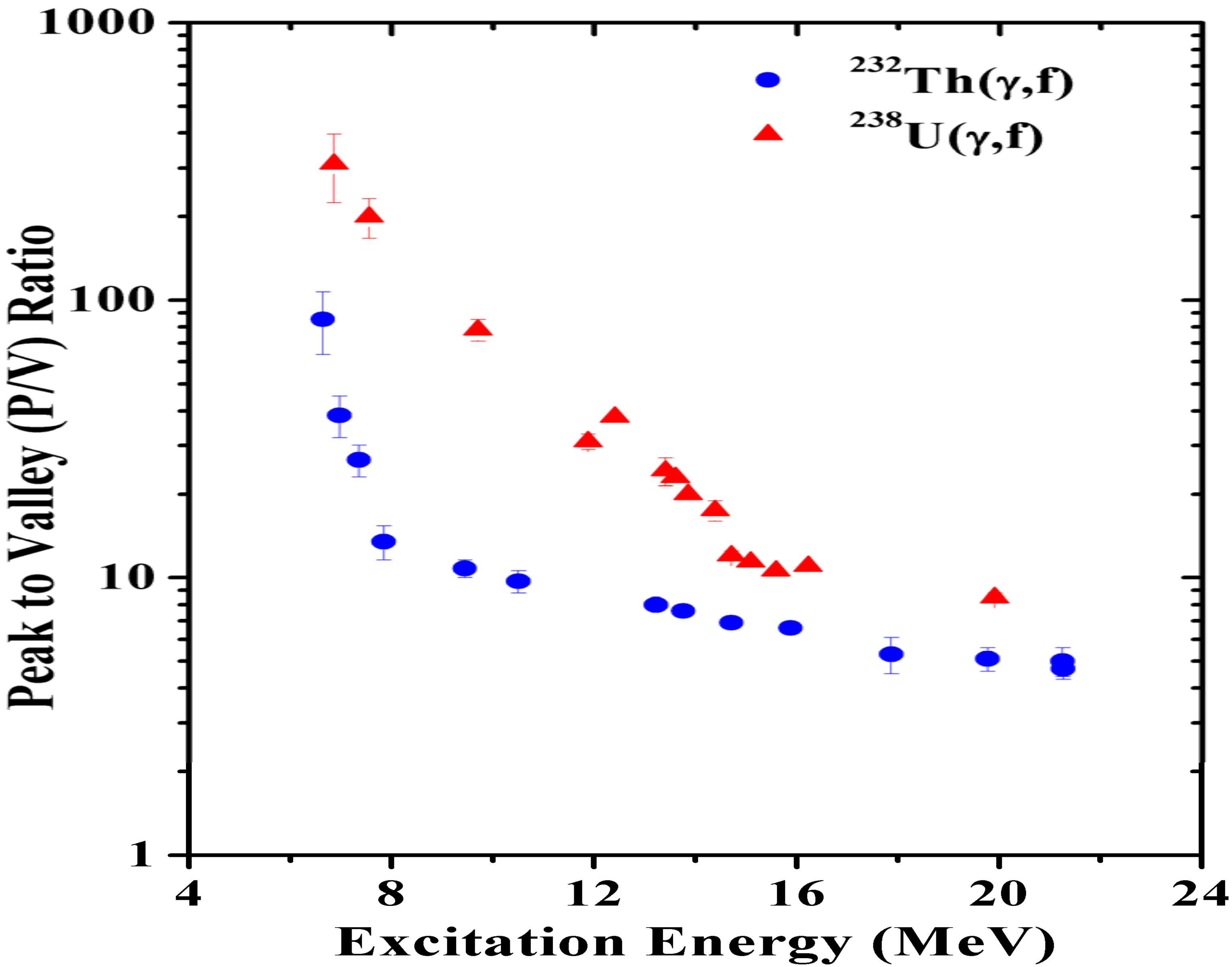
Summary for <A_L> , <A_H>, and number of neutrons

- It can be seen from Fig. 8 that the **<A_L>** value for the ^{232}Th(γ,f) reaction increases with the excitation energy, whereas that for the ^{238}U(γ,f) reaction decreases with the excitation energy.
- The **<A_H>** value for the ^{232}Th(γ,f) reaction decreases with the excitation energy, whereas that for the ^{238}U(γ,f) reaction increases with the excitation energy.
- It can be seen from Fig. 9 that both the <ν>$_{\mathbf{expt}}$ and the <ν>$_{\mathbf{cal}}$ values for the ^{232}Th(γ,f) and the ^{238}U(γ,f) reactions increases with the excitation energy. These observations indicate the role of excitation energy.
- It can be seen from Fig. 8 that the increase trend of the **<A_L>** value and the decrease trend of the **<A_H>** value for the ^{232}Th(γ,f) reaction with the excitation energy are sharper at the lower excitation energy. This may be higher-fission barrier or a different type of potential barrier in ^{232}Th compared to those in ^{238}U.

[Fig. 10] Yields of symmetric and asymmetric fission products (%) in the bremsstrahlung-induced fission of ^{232}Th and ^{238}U as a function of excitation energy.



[Fig. 11] The peak-to-valley (P/V) ratio as a function of excitation energy in the bremsstrahlung-induced fission of ^{232}Th and ^{238}U.



Summary for Yield of symmetric and asymmetric fission products as well as the P/V ratios

- In the bremsstrahlung- and the neutron-induced fission of ^{232}Th and ^{238}U, the yields of asymmetric products marginally decreased with an excitation energy. For symmetric products it increased sharply up to the excitation energy of 8 MeV and thereafter it varied slowly due to the increasing of the pre-fission neutron emission and the multi-chance fission probability. However, the increase trend of the fission product yield for symmetric products in the ^{232}Th(γ,f) and the ^{232}Th(n,f) reactions are more sharp than that in the ^{238}U(γ,f) and the ^{238}U(n,f) reactions. We observed the decrease trend of the P/V ratio with an increasing the excitation energy.
- The peak to valley (P/V) ratio at all excitation energies is always lower in the ^{232}Th(γ,f) and the ^{232}Th(n,f) reactions than that in the ^{238}U(γ,f) and the ^{238}U(n,f) reactions due to the presence of a third peak in the symmetric mass region. This is due to the different type of potential barrier for ^{232}Th than ^{238}U.