MASS AND CHARGE STUDIES IN NEUTRON AND PHOTON (BREMSSTRAHLUNG) INDUCED FISSION OF ACTINIDES AND PRE-ACTINIDES

BY

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MAIN TOPIC OF THE TALK

(A) MEASUREMENTS OF FISSION PRODUCTS YIELDS IN LOW ENERGY AND 14.7 MEV NEUTRON INDUCED FISSION OFACTINIDES USING

REACTOR APSARA AND CIRUS AT BARC, MUMBAI AND

#14.7 NEUTRON GENERATOR AT DEPARTMENT. OF PHYSICS, PUNE UNIVERSITY.

(B) MEASUREMENTS OF FISSION PRODUCTS YIELDS IN PHOTON (i.e. BREMSSTRAHLUNG) INDUCED FISSION OF ACTINIDES AND PRE-ACTINIDES USING

#8-10 MEV MICROTRON AT MANGALORE AND ELECTRON LINAC AT KHARGHAR.

#2.5 GEV, 100 MEV ELECTRON LINAC AT POHANG, SOUTH KOREA.

NEUTRON INDUCED FISSION

HISTORICAL

- Discovery of neutron by Chadwick in 1932
- Discovery of artificial radioactivity by Curie and Joliot in 1934
- Transmutation of element by Fermi and coworkers in 1934. Uranium as target to get trans-uranium element.
- Hahn and Strassmann as well as Curie and Savitch in 1937 independently took special interest to separate the radioactive element.
- Ba as carrier they separate the isotope believed to be radium from 238U(n,2α) reaction and their decay.

*Fractional crystallization indicates the activity is isotope of Ba not the isotope of Ra.

*This finding leads to discovery of fission in 1939.

- Meitner and Frisch in 1939 name the new type nuclear reaction as nuclear fission similar to cell division.

PROCESS OF NUCLEAR FISSION

*Heavy nuclei A>200 (actinides) elements are deformed in their ground state due to inherent Columbic instability

*Repulsive Coulomb force destabilizes the nucleus

*Attractive nuclear force (analogous to surface tension) opposes

- Interplay of of these two forces causes spontaneous fission
- Or fission of compound nucleus after neutron absorption
- In the fission about 200 MeV energy is released.
- In 1939 Frich proved the energy release by the large pulse height in ionization chamber experiment.
- Bohr in 1939 theoretically calculated the energy release of 200 MeV considering nucleus as liquid drop.

$$^{235}U + n \rightarrow {}^{236}U^{*} \rightarrow \text{Two Fission Products}$$

Energy Release in Fission $=\Delta mc^2$, $\Delta m = M(^{236}U) - M(2\ \text{Products})$

200 MeV = 168 MeV (K.E.) + 8 MeV (prompt neutron)+

+ 7 MeV (prompt gamma) + 8 MeV (beta)

+ 12 MeV (neutrino) +7 MeV (gamma)

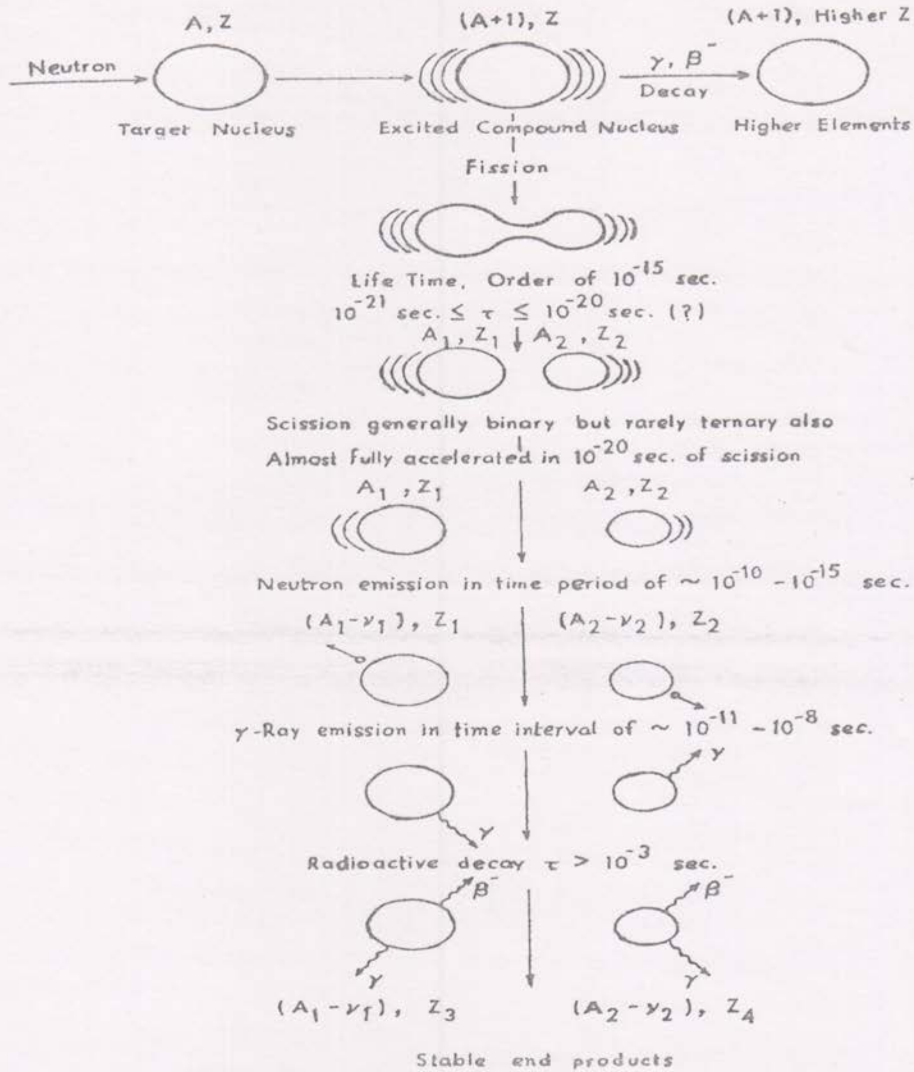


FIG.-1. SCHEMATIC DIAGRAM OF FISSION PROCESS (REF.10)

NUCLEAR FISSION OF ACTINIDES OR PRE-ACTINIDES
IS POSSIBLE BY THE BOMBARDMENT OF TARGET

ACTINIDES - (227Ac, 232Th, 231Pa, 232,238U, 238,240Pu, 241,243Am)
(227,229Th, 233,235U, 238Np, 239,241Pu, 242Am, 245Cm, 249,251Cf, 255Fm)

PHOTON (BREMSSTRAHLUNG) ENERGY ABOVE 6 MeV –NO BARRIER

LOW AND HIGH ENERGY NEUTRON – NO BARRIER

PRE-ACTINIDES (197Au, nat-Pb, 209Bi – Fission barrier ~20-25 MeV

$ CHARGE PARTICLE (^{1}H, α (^{4}He), charge particle (e.g. ^{14}N, ^{16}O etc.)
FACED COULOMB BARRIER (E_c)

$E_c = Z_1 Z_2 e^2 / r_0 (A_1^{1/3} + A_2^{1/3})$, $^{238}U + {}^{1}H$, E_c =12.5 MeV, $^{238}U + \alpha$, E_c = 25 MeV

$ HIGH ENERGY ELECTRON (GeV)

ALTERNATELY
SPONTANEOUS FISSION OF HIGH-Z ACTINIDES (244-Cm, 252-Cf, 256-Fm)
DUE TO INHERRENT COULOMB INSTABILITY.

NUCLEAR DATA AND ITS IMPORTANCE

*Nuclear data such as neutron capture cross sections, fission cross section, fission yields and decay data including half-lives, decay energy, branching ratios etc. are required for many reactor calculations e.g. reactor design, handling and safety point of view.

*Some of the data on capture cross-section and fission cross section are available in literature.

*Major fission yields data are available in thermal neutron fission of actinides.

- Fission yields data in fast neutron fission for minor actinides are less available due to the rare availability of such actinides.

IMPORTANCE OF FISSION & YIELDS OF FISSION PRODUCTS

•In fission large amount of energy (~ 200 MeV) and large number (~2000) of fission products are produced.

• Peaceful use of the energy

•Conventional power reactor to produce electricity
BWR, PHWR (235U, 239Pu +238U), AHWR (233U +232Th)
ADS (Spallation source nat-Pb, 209Bi, 232Th, 238U,
Incinerating long-lived minor actinides 237Np, 240Pu,
241Am, 243Am, 244Cm and 245Cm)

*Research reactor to produce radioisotopes for medical, industrial and agricultural applications.

•Yields of short-lived fission products are important for decay heat calculation, which are needed for design of reactor.

•To explain the fission mechanism and physics of nuclear fission by studying kinetic energy, mass, charge, fragment angular momentum and angular distribution of fission products.

*Fission Yields (FY) data are necessary for modern reactor design and fuel handling.

*FY of $^{229,232}Th$, $^{231,233}Pa$ & $^{232,233}U$ for AHWR, KAMINI

*FY of $^{235,238}U$, ^{237}Np & $^{238,239,240,241}Pu$ for PHWR, BWR, and CANDU.

*Waste management and burning of minor actinides ^{237}Np, $^{238,240}Pu$, $^{241,243}Am$, $^{244,245}Cm$ using ADS.

*Fission Yields data are important for mass/charge and fragment angular momentum studies. Such studies provide information on:

(i) effect of nuclear structure such as shell closure proximity and odd-even effect.

(ii) dynamics of descent from the saddle to point of neck formation and from the latter to the scission point.

NEED OF FY IN ^{229,232}Th (n,f) AND ^{232,233}U (n,f)

FP   FP   FP

$(n_f,f)\uparrow 0.64$ b   β   β $(n_{th},f)\uparrow 530$ b   α $(n_{th},f)\uparrow 30$ b

^{232}Th (n_{th},γ) → ^{233}Th → ^{233}Pa → ^{233}U --- → ^{229}Th →

1.405×10^{10} y   22.3 m   26.967 d 1.592×10^{5} y   7340 y

↓ (n,2n)   β   ↓(n,2n)   α

^{231}Th → ^{231}Pa (n_{th},γ) → ^{232}Pa → ^{232}U ----- → ^{228}Th →

25.52 h   32760 y   1.31 d   68.9 y   1.9116 y

$(n_f,f)\downarrow 4.61$b $(n_{th},f)\downarrow 74$b

FP   FP

FP =Fission Products formed in neutron induced fission of Th and U.

NEED OF FY IN $^{235,238}U(n,f)$ AND $^{238,239}Pu\ (n,f)$

FP　　　　　　　　FP　　　　　　　　FP

$(n_f\ ,f)\uparrow 2.02$ b　　　　$(n_{th}\ ,f)\uparrow 746$ b　　$(n_{th}\ ,f)\uparrow 584$ b

$^{238}U\ (n_{th},\gamma) \rightarrow\ ^{239}U \rightarrow\ ^{239}Np \rightarrow\ ^{239}Pu \rightarrow\ ^{235}U \rightarrow$

$4.468\text{x}10^{10}$ y　23.45 m　2.3565 d　24110 y　$7.038\text{x}10^{6}$ y

$\downarrow$ (n,2n)　　　　　　$\downarrow$ (n,2n)

$^{237}U \rightarrow\ ^{237}Np \rightarrow\ ^{237}Pu\ (n_{th},\gamma) \rightarrow\ ^{238}Pu \rightarrow\ ^{234}U \rightarrow$

6.75 d　$2.144\text{x}10^{5}$ y　45.2 d　87.7 y　$2.455\text{x}10^{5}$ y

$(n_f,f)\downarrow 6.36$b　　　　$(n_{th},f)\downarrow 17.9$b

FP　　　　　　　　FP

FP=Fission Products formed in neutron induced fission of U and Pu.

THEORETICAL MODEL (LIQUID DROP MODEL)

*Bohr and Wheeler – Nucleus as charge liquid drop

*Existence of potential energy surface based on

*Changes in the Coulomb and surface energy as a function of deformation (α) of the fissioning nucleus

$$R(\theta) = R_0 / \lambda\, [1+ \alpha_n P_n (\cos\theta)\,]$$

$$Es = Es(0)\, [\, 1 + 2/5\, \alpha_2^2\,]$$
$$Ec = Ec(0)\, [\, 1 - 1/5\, \alpha_2^2\,]$$

$$Es(0) = 17.94\, [1-1.7826\{(A-2Z)/A\}^2]A^{2/3}\ \text{MeV}$$
$$Ec(0) = 0.71\, Z^2 /A^{1/3}\ \text{MeV}$$

$$x = \frac{\Delta C}{\Delta S} = \frac{Ec-Ec(0)}{Es - Es(0)} = \frac{1/5\alpha_2^2\, Ec(0)}{2/5\, \alpha_2^2\, Es(0)} = \frac{Z^2 /A}{50.88\, [-1.7826\{\{A-2Z)/A\}^2]}$$

x ->1.0 then fission occurs

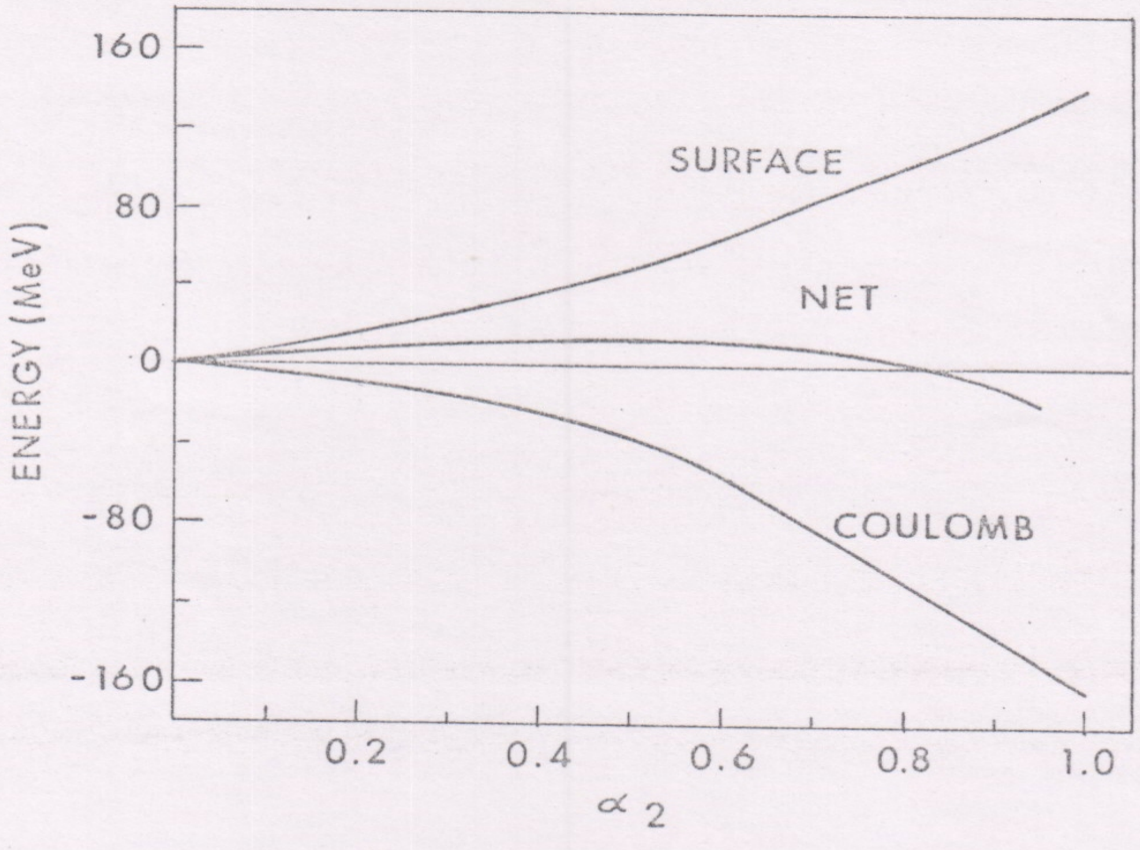


FIG.-2 SURFACE, COULOMB AND NET DEFORMATION ENERGIES AS A FUNCTION OF α_2. (REF. 13)

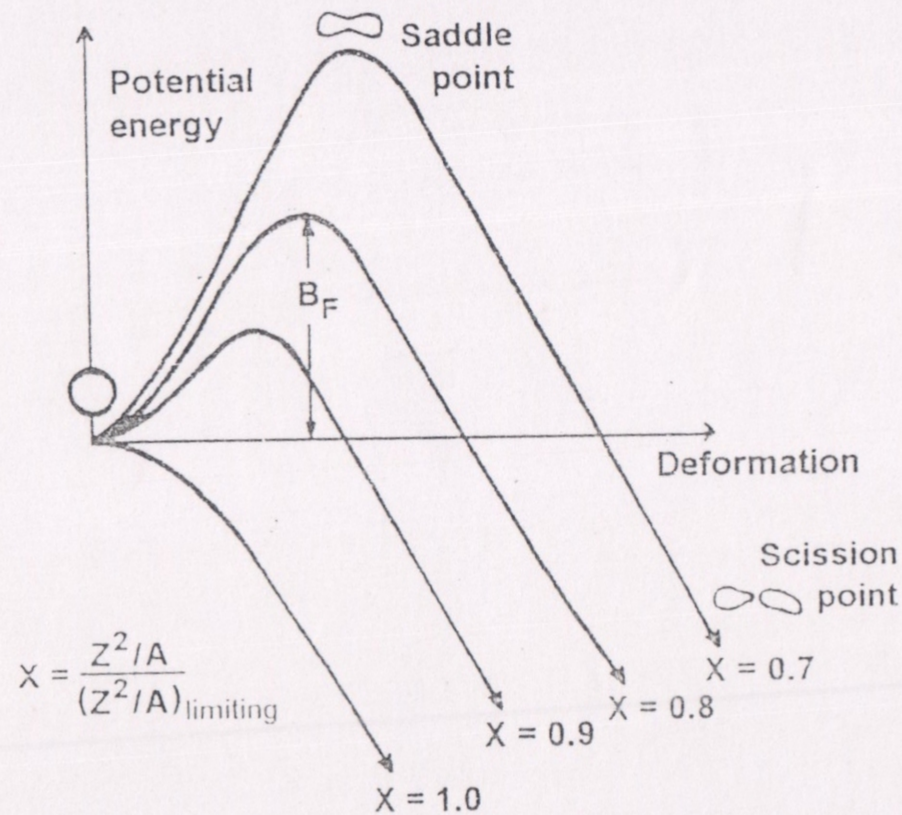
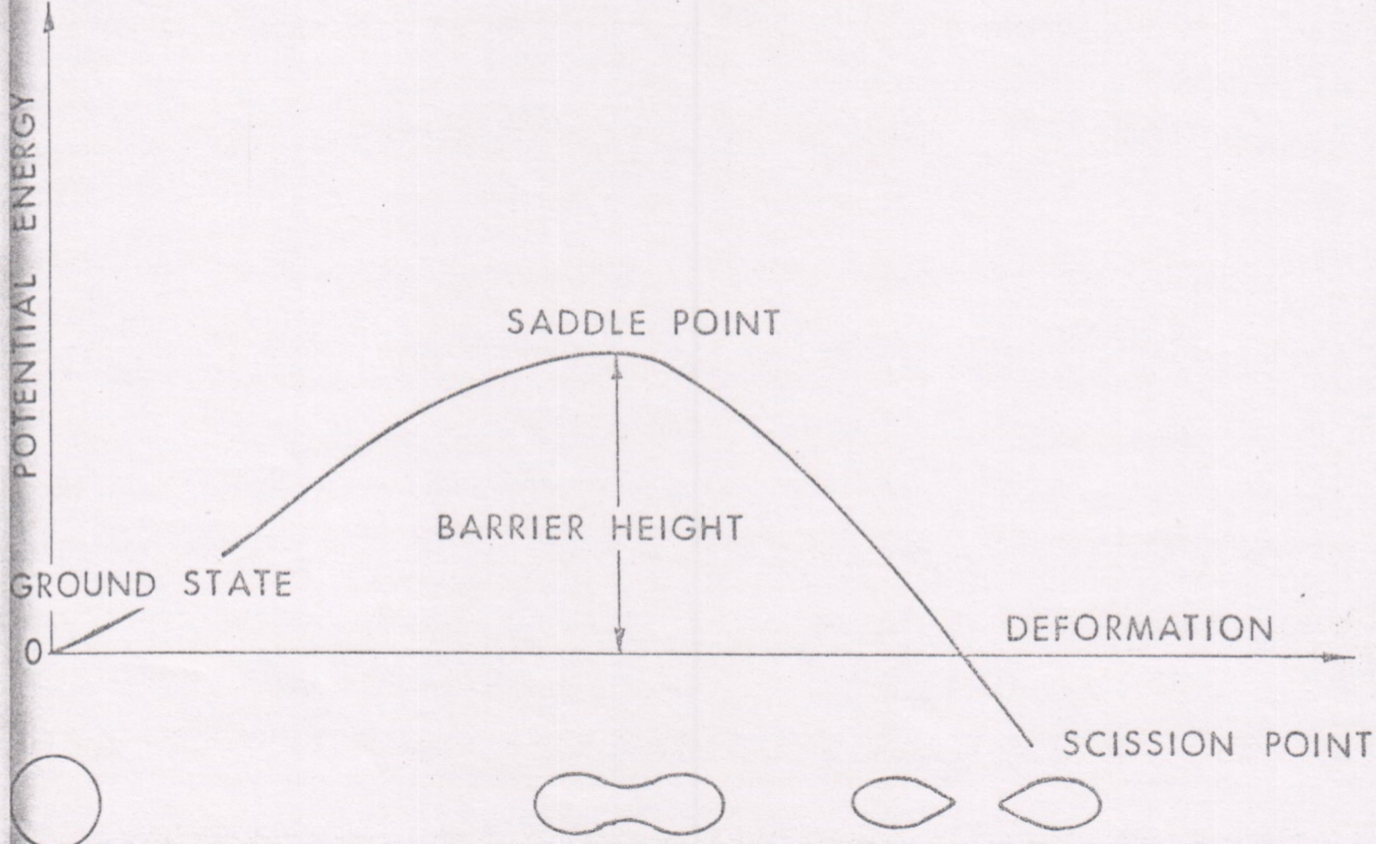


Fig. 1. Liquid drop model barriers for different fissility parameters (X)



G.-3. LIQUID DROP POTENTIAL ENERGY AS A FUNTION OF DEFORMATION.

STRUTINSKY HYBRID MODEL AND WILKINS STATIC MODEL AT SCISSION

•Hybrid of LDM +Single particle model
•Shell effect –deviation of uniform single particle level distribution
*Paring effect - similar as above

$$V = V_{LDM} + \Sigma(\delta U = \delta P)$$

δP = Pairing energy correction calculated based on BCS theory
I.e. Barden, Cooper and Schrieffer theory
δU = Shell energy correction

$$\delta U = U - \hat{U} = \Sigma 2\varepsilon_v n_v - 2\int \varepsilon\, g(\varepsilon)\, d\varepsilon$$

ε_v = single particle energy, n_v = occupation number
$g(\varepsilon)$ = uniform level density.

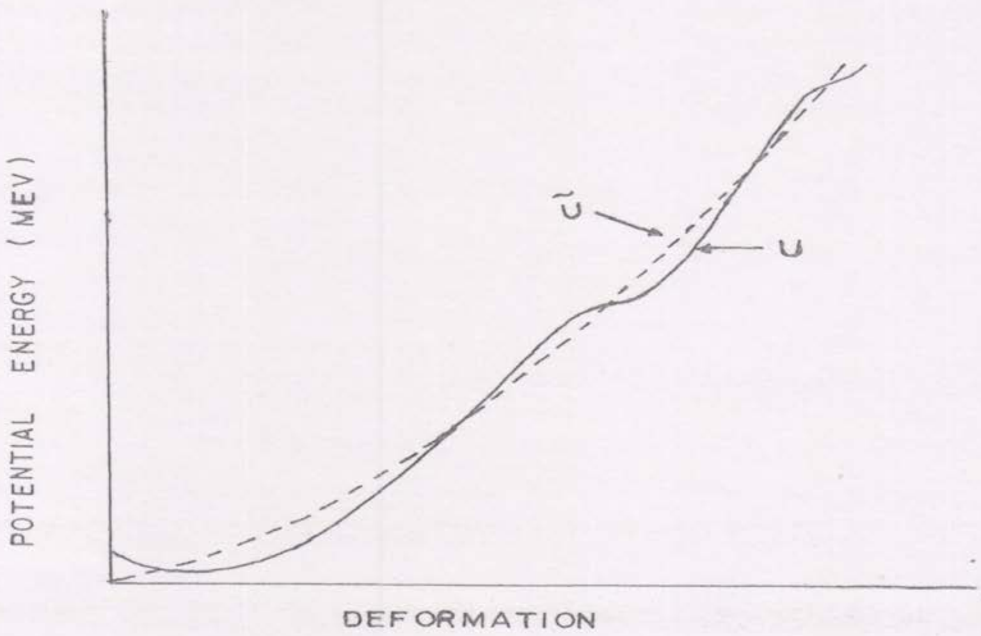


FIG.-5a SINGLE PARTICLE NUCLEAR ENERGY AS A FUNCTION OF DEFORMATION (REF. 32)

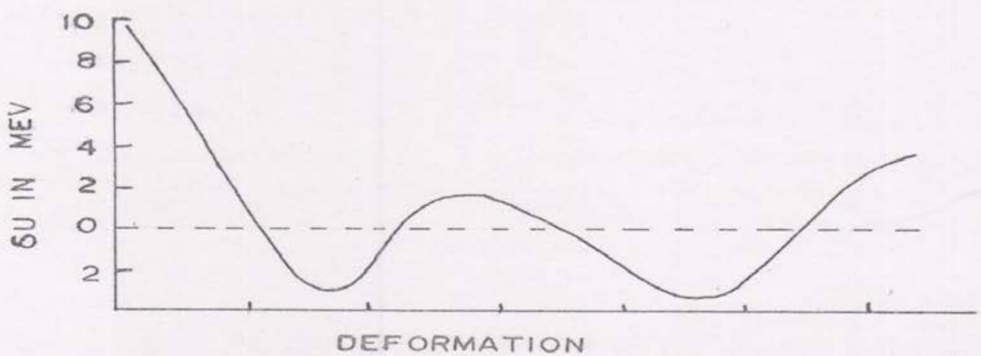


FIG.-5b SINGLE PARTICLE SHELL CORRECTION ENERGY (δU) FOR NEUTRONS=146 (REF. 33)

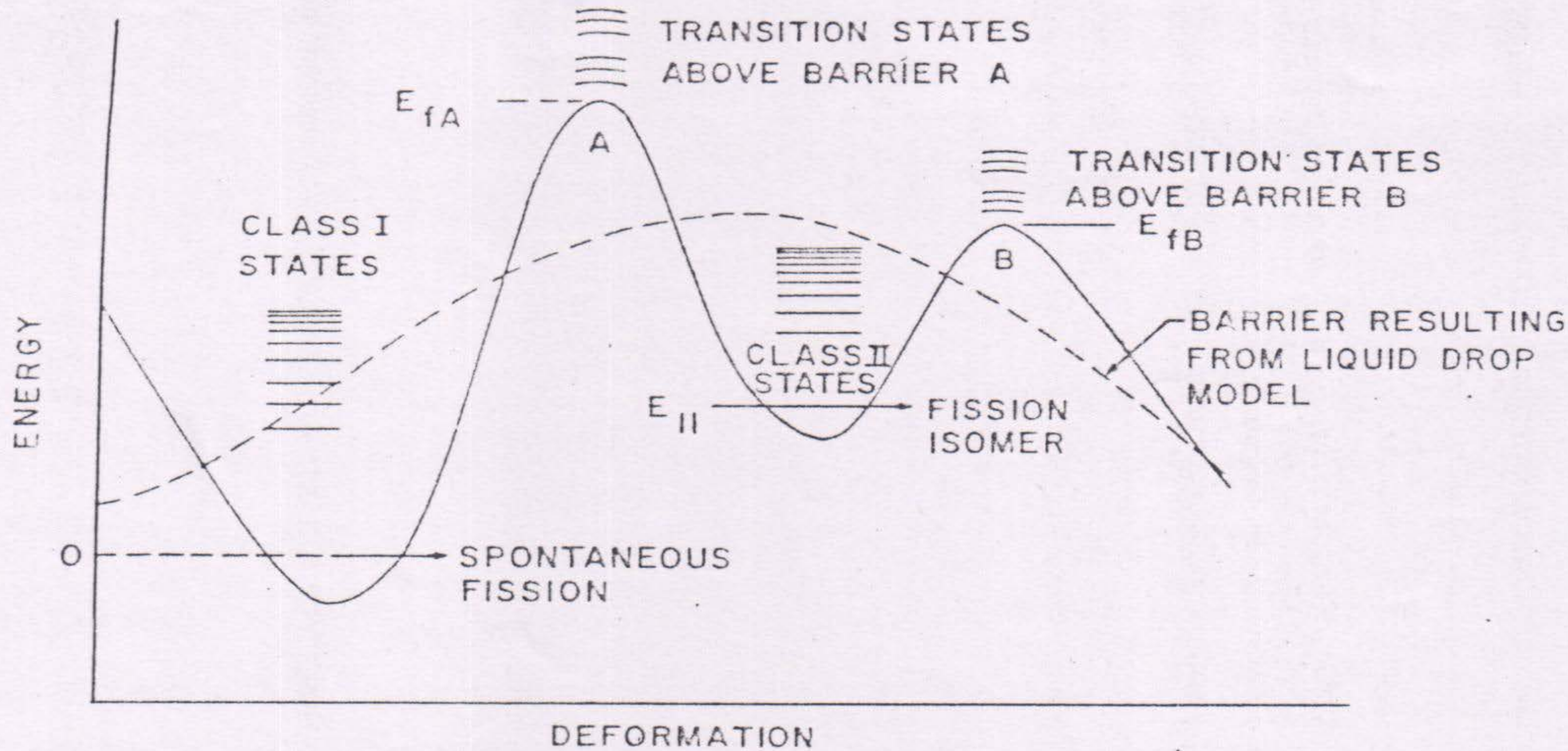


FIG.-6 . DOUBLE HUMPED FISSION BARRIER

FISSION STUDIES

*Neutron emission curve – saw-tooth nature
*Gamma and x-ray emission curve – saw- tooth nature
*Kinetic energy distribution
*Mass and charge distribution –symmetric or asymmetric
*Fragment angular momentum
*Angular distribution of fission products

MASS AND CHARGE DISTRIBUTION FROM FISSION YIELD

- Division of nucleus (fission) is not always same in terms of A and Z of the resultant of fission products.
- 2000 fission products of A= 72-172 and Z= 31- 62.

*Mass distribution –asymmetric for actinides (Ac-Cf) fission
-symmetric for pre-actinide (Pb &Bi) and higher actinides (Fm)

*Charge distribution –even-odd effect for even-Z systems
-No even-odd effect for odd-Z systems

TYPES OF FISSION YIELDS

*Independent Yield (IY)- Percentage of yield of any fission product formed from the fiissioning nuclei.

*Cumulative Yield (Y_C)- Summation of the independent yield percentage of all fission products up to the nuclide of interest in a given mass chain formed from the fiissioning nuclei.

*Mass chain Yield (Y_A)- Summation of the independent yield percentage of all fission products in a given mass chain formed from the fiissioning nuclei.

*Charge chain Yield (Y_Z)- Summation of the independent yield percentage of all fission products for different masses of an element formed from the fiissioning nuclei.

* FCY=$Y_C/Y_{A,}$,   FIY=IY/Y_A,   IYR=$Y_h/(Y_h+Y_l)$

DECAY SCHME OF FISSION PRODUCTS

131mTe (30.0 h)
↓ ¥
131Sn → 131Sb → 131gTe → 131I → 131Xe
23.03 m 25.0 m 8.02 d stable

132Sbm (2.8m) 132Im (83.6 m)
↓ ↓ ¥
132Sn → 132Sbg → 132Te → 132Ig → 132Xe
40.0 s 4.15 m 78.2 h 2.7 h stable

133mTe (55.4m) 133mXe
↓ ¥ ↓ ¥
133Sn → 133Sb → 133gTe → 133I → 133Xe → Cs
2.35 m 12.4 m 20.8 h stable

134Im (3.7 m)
↓ ¥
134Sb → 134Te → 134I → 134Xe
10.22 s 41.8 m 52.6m stable

135Xem (15.6 m)
↓ ¥
135Te → 135I → 135Xe → 135Cs
1.68 s 6.61 h 9.09 h stable

IMPORTANT FACTORS IN FISSION

- Bohr shows that fission of uranium nucleus by thermal neutron was due to 235-U but not from 238-U.

*Thermal neutron (En= 0.025 eV) fission
227,229Th, 233,235U, 238Np, 239,241Pu, 242Am 245Cm, 249Cf, 255Fm

*Fast neutron (En> 500 keV) induced fission
232Th, 231Pa, 238U, 237Np, 240Pu, 243Am, 244Cm

*Thermal and fast neutron neutron induced fission
232U, 238Pu, 241Am.

*Spontaneous fission (e.g. 242,244Cm, 250,252Cf, 256Fm)

- Half-life of actinides and Purity of samples

*Height of outer barrier (V_B)

*Excitation energy (E^*)

*Fission cross section (σ_f)

*Activation cross section (σ_a)

*Decay scheme of fission products

Nuclide	Half-life	V_B (MeV)	E_{th}-V_B MeV	σ_{th} (barns)	σ_f (barns)	σ_a (barns)
229-Th	7340 y	6.5	0.294	30.81	444.1	61
232-Th	1.404×10^{10} y	6.65	-1.864	<.0000025	0.636	7.37
231-Pa	32760 y	6.25	-0.697	0.0197	4.605	200.6
232-U	68.9 y	5.8	0.05	76.8	344.1	74.9
233-U	1.592×10^5 y	5.5	1.343	529.9	772.2	45.5
235-U	7.038×10^6 y	5.53	1.01	584.0	274.9	98.3
238-U	4.468×10^9 y	6.16	-1.36	.000001	2.02	2.68
237-Np	2.144×10^6 y	5.9	-0.41	0.0192	6.36	175.9
238-Pu	87.7 y	5.7	-0.05	17.89	52.7	540
239-Pu	24110 y	5.07	1.46	746.7	299.1	263.9
240-Pu	6564 y	5.5	-0.26	0.588	8.938	289.4
241-Pu	14.29 y	5.1	1.21	1015	590.4	358.2
241-Am	432.2 y	5.7	-0.21	3.018	13.87	600.4
243-Am	7370 y	5.6	-0.33	0.0012	7.586	3.8
244-Cm	18.1 y	5.0	0.52	1.037	13.22	15.1
245-Cm	8500 y	4.3	2.16	2001	800.7	2.63
252-Cf	2.65 y	3.6	0	-	-	-

NEUTRON SOURCES (Few examples) & NEUTRON SPECTRUM

a. neutron induced fission of actinides - in reactor

APSARA – neutron flux = 1.2×10^{12} n s^{-1} cm^{-2}

CIRUS – neutron flux = 5.0×10^{12} n s^{-1} cm^{-2}

DHRUVA – neutron flux = 1.0×10^{13} n s^{-1} cm^{-2}

b. spontaneous fission of actinides e.g.

^{252}Cf ($T_{1/2}$ = 2.65 y) – neutron flux = 2.30×10^{12} n s^{-1} g^{-1}

c. photo neutron induced fission and reactions

reaction	Q-value (MeV)
Actinides ((γ,f)	-3.6 to -6.7
$^{9}Be(\gamma,n)$	-1.666
$^{2}H(\gamma,n)$	-2.226

γ from ^{24}Na, ^{28}Al, ^{38}Cl, ^{56}Mn, ^{72}Ga, ^{76}As, ^{88}Y, ^{116m}In,^{124}Sb, ^{140}La, ^{144}Pr

from electron LINAC or MICROTRON.

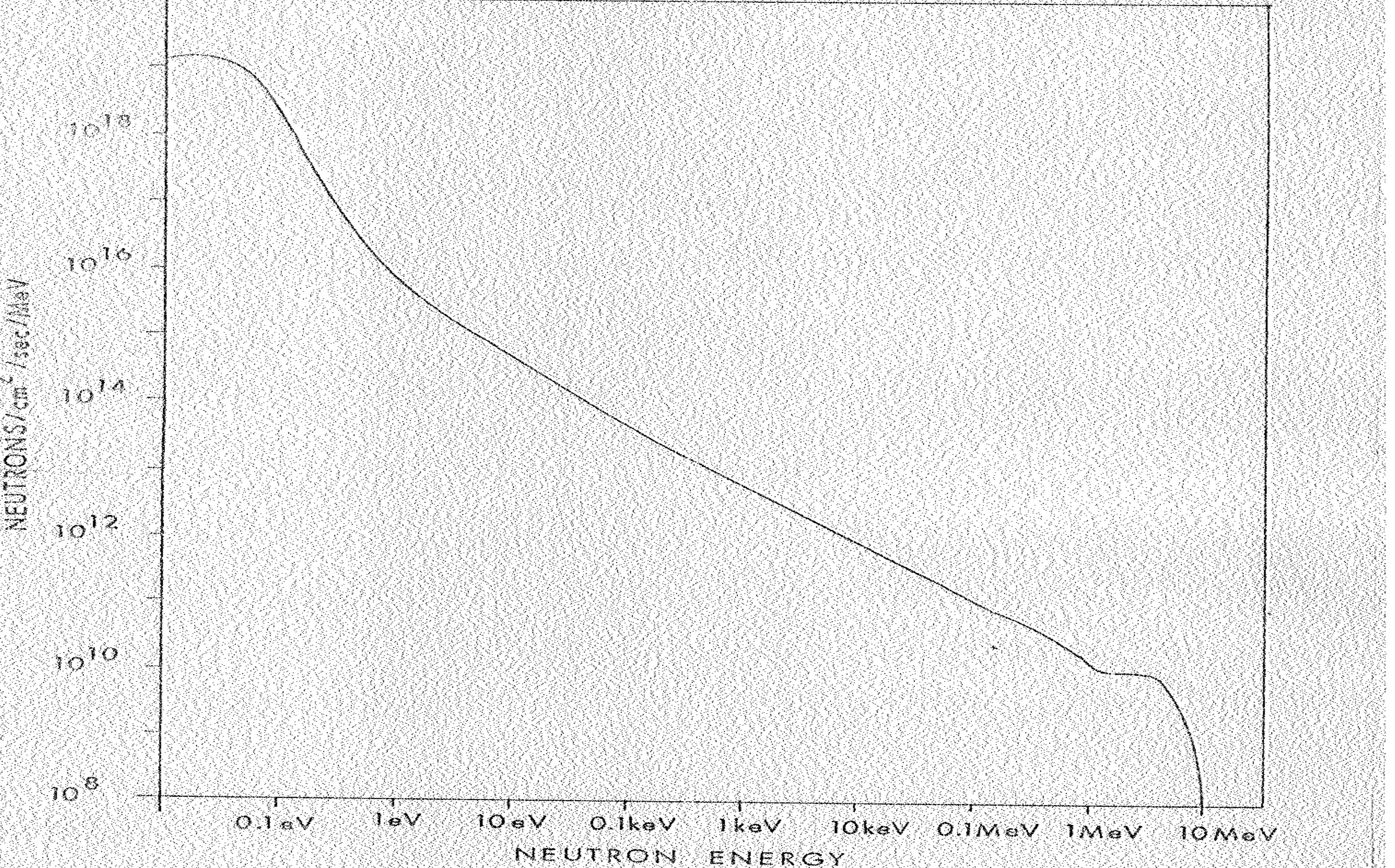
d. $^{9}Be(\alpha,n)$ – α source – ^{210}Po, ^{226}Ra, ^{227}Ac, $^{238,239}Pu$, ^{241}Am, $^{242,244}Cm$,

$^{241}Am/Be$ ($T_{1/2}$= 433 y), Eα= 5.48 MeV, 70 neutrons per 10^{6} α particle

15-23 % neutron yield with E_n <1.5 MeV

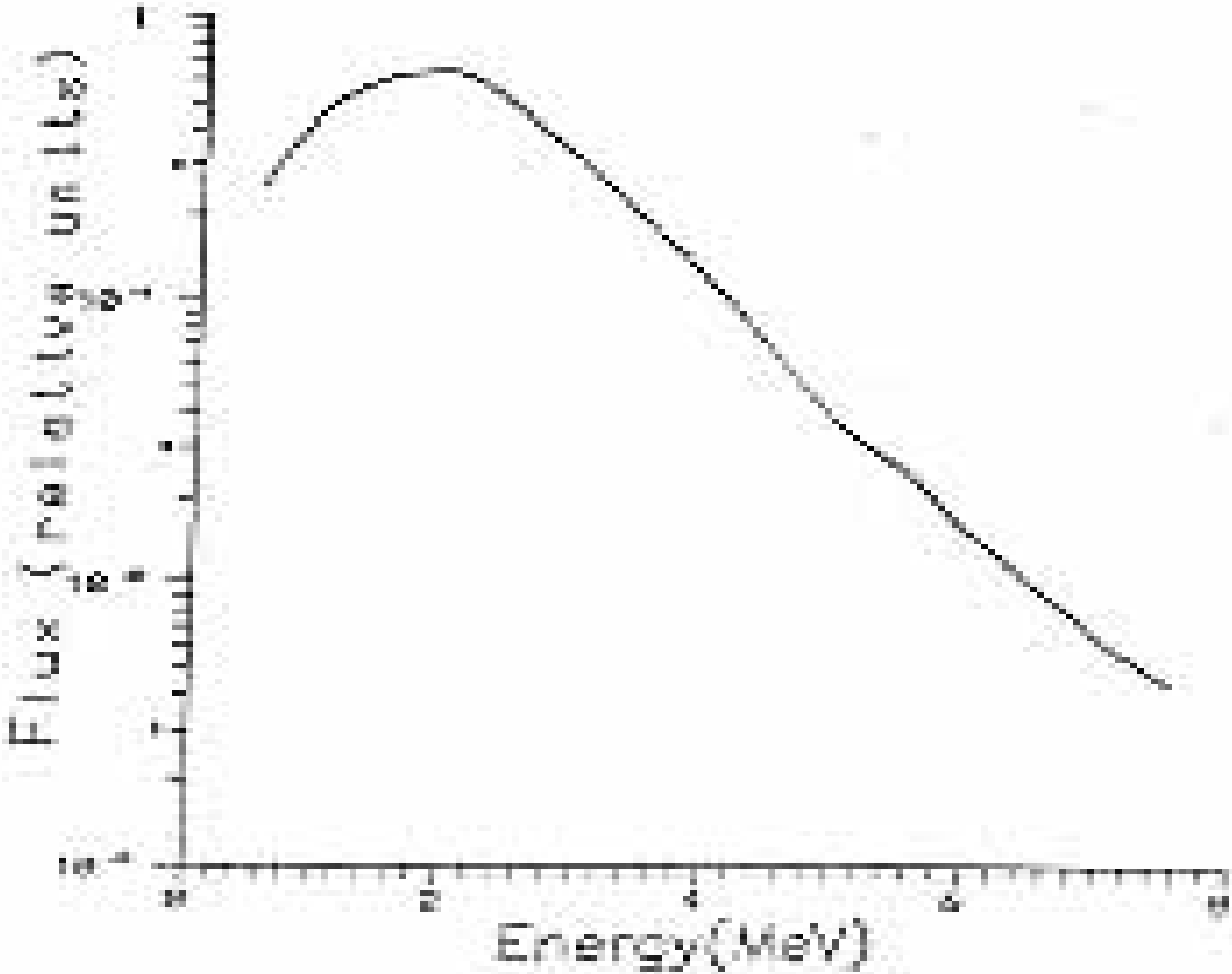
e. Reaction from accelerated charged particle e.g ^{3}H,, ^{7}L (p,n) or $^{9}Be(d,n)$

reaction	Q-value (MeV)	neutron energy	neutron per 1 mA of D
$^{2}H(^{2}H,n)$	+3.26	3 MeV	10^{9} n/s from D
$^{3}H(^{2}H,n)$	+17.6	14.7 MeV	10^{11} n/s from T



NEUTRONS/cm²/sec/MeV
10^20
10^18
10^16
10^14
10^12
10^10
10^8
0.1eV
1eV
10eV
0.1keV
1keV
10keV
0.1MeV
1MeV
10MeV
NEUTRON ENERGY

Fig. 1



Flux (relative units)
Energy(MeV)

EXPERIMENTAL

(I) ASSEMENT OF PURITY OF ACTINIDES

ALPHA SPECTROMETRY

(II) TARGET PREPARATION

(A) FOR COMPARISON METHOD

(B) FOR MASS SPECTROMETRIC METHOD

(C) FOR ABSOLUTE METHOD

(III) IRRADIATION

IN REACTOR APSARA OR CIRUS

(IV) FISSION PRODUCTS ANALYSIS

(a) DIRECT GAMMA RAY SPECTROMETRIC ANALYSIS

RADIOCHEMICAL SEPARATION FOLLOWED BY BETA OR GAMMA RAY COUNTING

(b) MASS SPECTROMETRIC METHOD

(c) TRACK-ETCH CUM GAMMA RAY SPECTROMETRIC METHOD

(I) ASSESSEMENT OF PURITY AND AMOUNT OF TARGETS

*Most of the actinides are alpha active.

- So assessment of purity and amount and isotopic composition of target by alpha spectrometry or mass spectrometry.

*Typical example of 240-Pu, 243-Am & 244-Cm are given below

Actinides	Isotopic composition	Composition (%)
240-Pu	240-Pu	99.48
	239-Pu	0.39
	241-Pu	0.13
	242-Pu	0.003
243-Am	243-Am	99.998
	241-Am	0.0016
	242m-Am	0.00021
244-Cm	244-Cm	99.43
	245-Cm	0.0065
	246-Cm	0.48
	247-Cm	0.006
	248-Cm	0.015

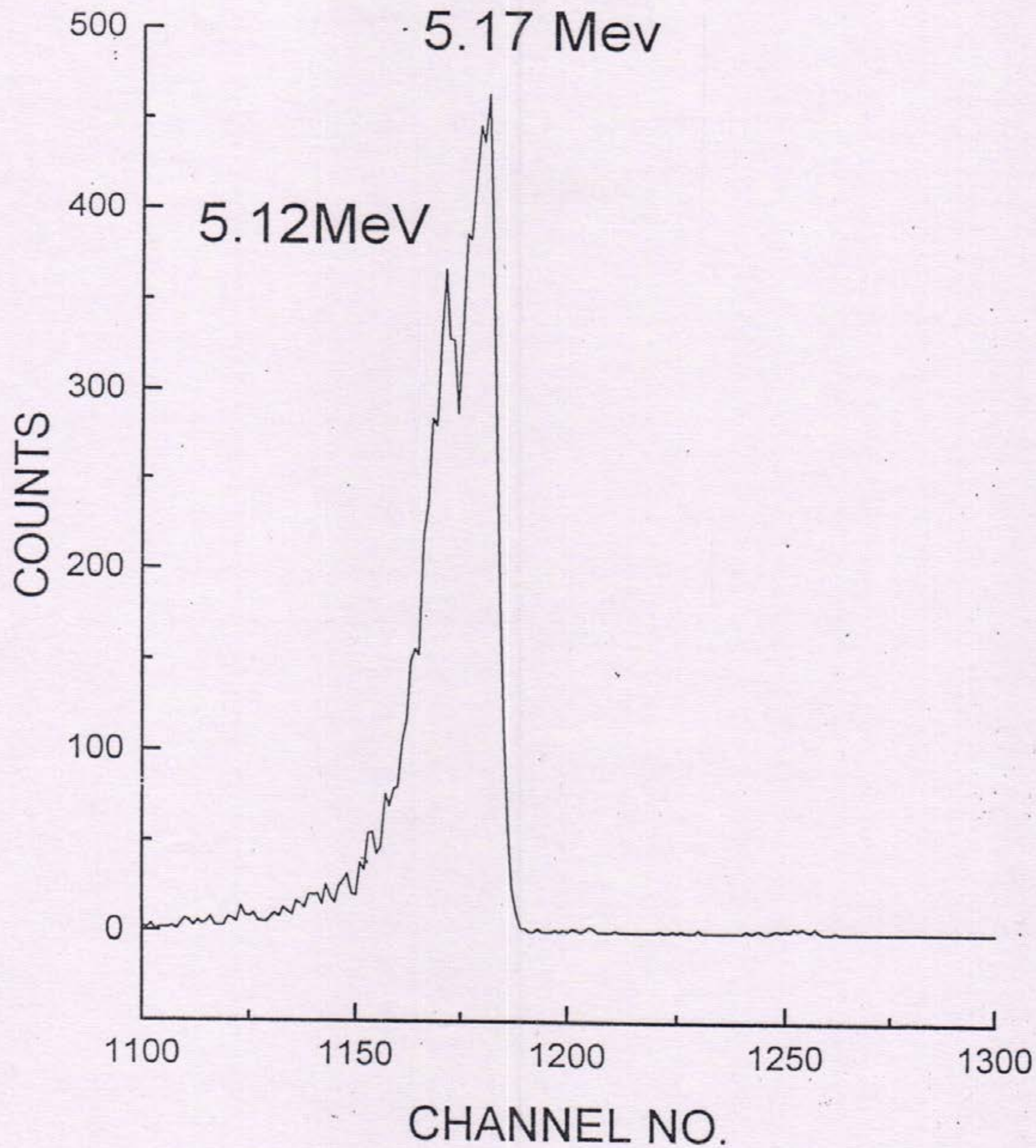


Fig5. Alpha spectrum of ^{240}Pu

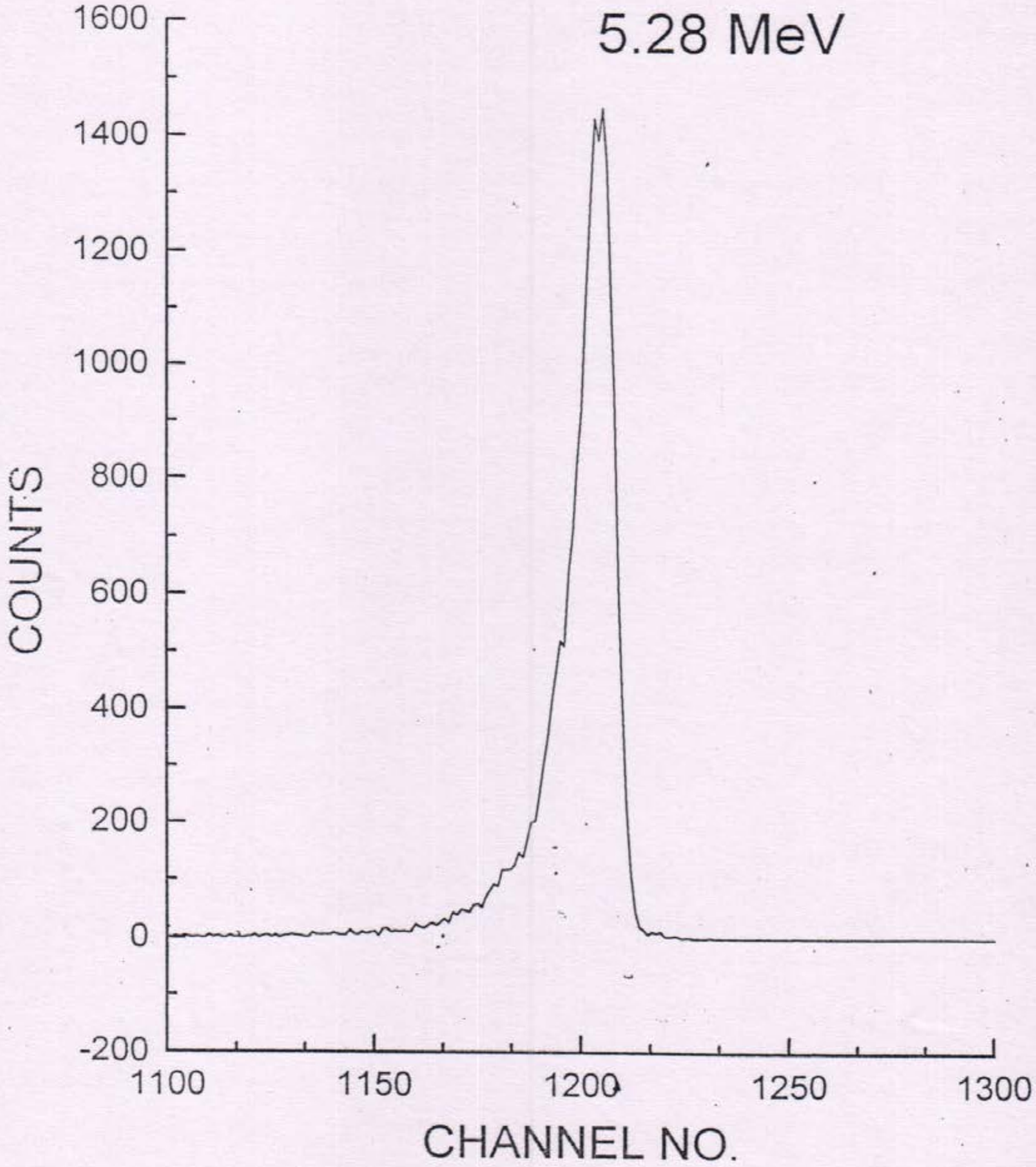


Fig.7. Alpha spectrum of ^{243}Am

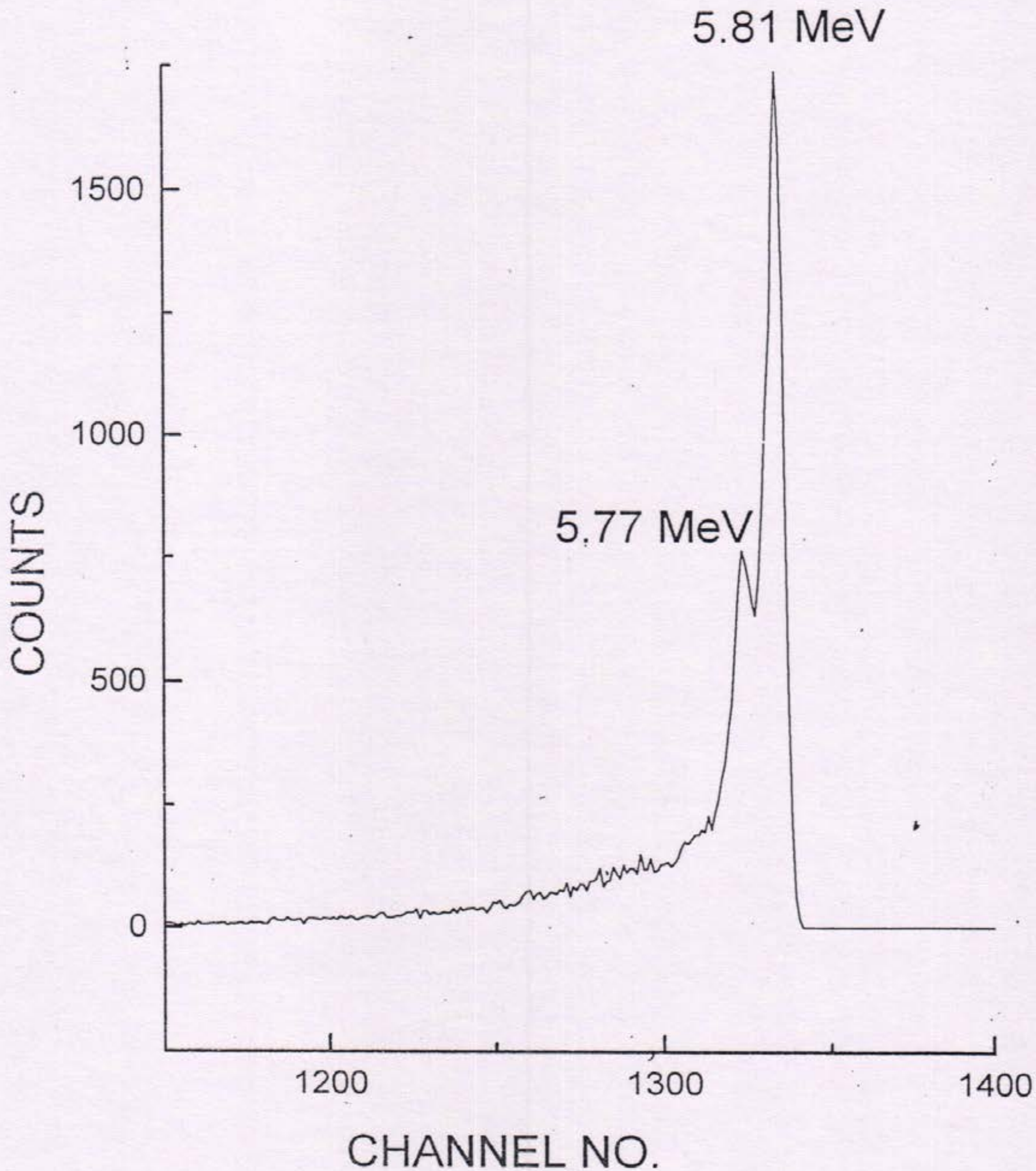


FIG. 8. ALPHA SPECTRUM OF ^{244}Cm

(II) TARGET PREPARATION

(A) FOR COMPARISON METHOD

*Fission rate monitor- Nitrate solution of 235-U (1-5 μg) dried on 0.0025 cm thick Al foil and sealed in alkathene bags

*Chosen actinides targets – metal foil or metal oxide or nitrate solution or electrodeposited targets enclosed or dried on Al foil or quartz ampoule and sealed in alkathene bags.

-Metal or Oxide powder in quartz ampoule -232-Th (5-10 mg)

-Electrodeposited targets of 227-Ac (~100 μg), 229-Th(~30 μg), 232-U (~10 μg), 233-U (~10-50 μg), 239-Pu (~10-50 μg), 245-Cm (~2 μg) covered with 0.0025 cm thick Al foil..

- Nitrate solution dried on quartz ampoule -231-Pa (~1 mg), 237-Np (~2 mg)

(B) FOR MASS SPECTROMETRIC METHOD

-Oxide power sealed inside quartz ampoule –238U (5-10 mg)

-Nitrate solution dried and sealed inside quartz ampoule 233-U, 235-U, 239-Pu, 241-Pu - each targets 0.5 - 1 mg

(C) FOR ABSOLUTE METHOD

*Chosen actinides targets
-Metal oxide 238-U (5-10 mg)
-Nitrate solution dried on silica capsule- 237-Np (0.2-10 mg), 238-Pu(3-10 μg), 239-Pu (3-10 μg), 241-Pu (3-10 μg), 241Am (100-900 μg), 245-Cm (2-4 μg)
-Electrodeposited targets of 237Np (100-200 μg), 238-Pu (20 μg) 239-Pu (10-25 μg), 241-Pu (10-25 μg), 241-Am (50-100 μg), 243-Am (90 μg), 244-Cm (80-96 μg).

*Fission rate monitor – Along with the actinides targets, 100-200 μgl of dilute nitrate solution and Lexan or mica track detector taken in polypropylene tube of 4 cm long and 3 mm diameter.
238-U (1.42 mg/ml), 237-Np (24.56 μg/ml), 238-Pu (0.5 μg/ml), 240-Pu (5.07 μg/ml), 243-Am (26.85 μg/ml), 244-Cm (0.202μg/ml)

(III) IRRADIATION AND FISSION PRODUCTS COLLECTION

*FOR THERMAL AND 14.7 MeV NEUTRON IRRADIATION

- Targets along with fission rate monitors wrapped with0.0025 cm thick Al foil and sealed in alkathene bags.

*FOR EPI-CADMIUM NEUTRON IRRADIATION

-Targets along with fission rate monitors covered with 0.0025 cm thick Al foil and wrapped with 1 mm thick Cd foil

* IRRADIATION AND FISSION PRODUCTS COLLECTION

- 5 min to 7 hrs irradiation of the sample by low energy neutron in reactor APSARA or 14 MeV neutron from neutron generator at department of Physics, Pune university.

- 1- 5 min irradiation in the reactor CIRUS using pneumatic carrier facility or for 15-90 days in irradiation position of the reactor

- Fission production collection by recoil catcher technique

- Cooling of irradiated target for 5 min to months depending upon the half live of nuclides of interest and technique of assessment.

ANALYSIS OF FISSION PRODUCTS

*Direct analysis of fission products

*Off-line gamma ray spectrometric technique of fission products by using HPGe detector coupled to a PC based

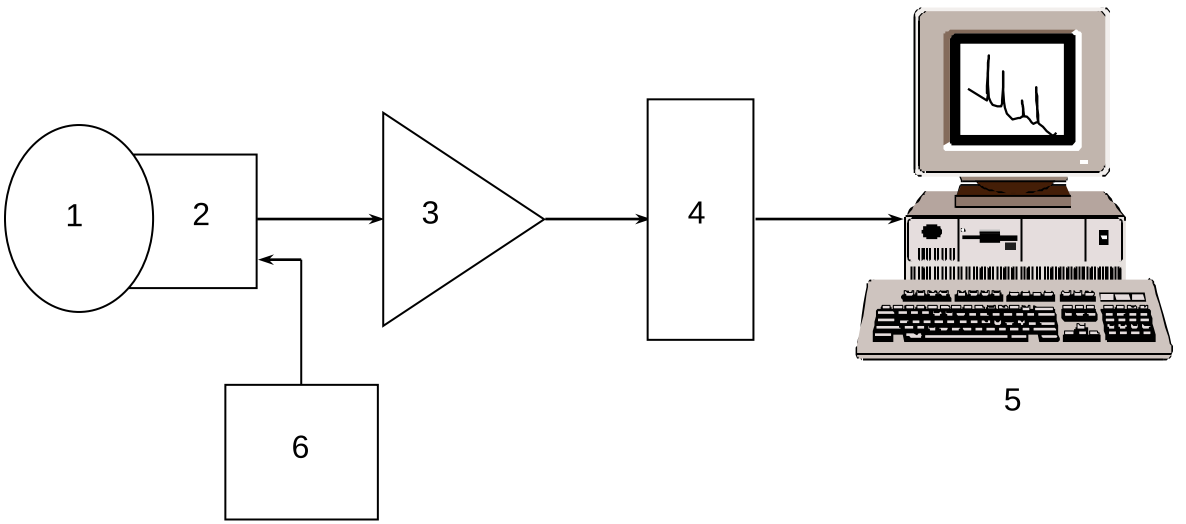
4K- channel analyzer.

•Radiochemical separation of fission products and beta or gamma ray counting of the fission products or

*Mass spectrometric analysis of the fission products.

*Etching of Lexan or mica track detector and counting of fission track. Some times gamma ray counting (for short lived fission products) and then etching of the track detector.

HPGe detector with PC based 4K channel analyzer



For gamma ray spectrometric technique

1: High-Purity Coaxial Germanium detector (HPGe),
(ORTEC, Model GEM-20180-p, Serial No. 39-TP21360A);
2: Preamplifier (ORTEC, Model 257 P, Serial No. 501);
3: Amplifier (ORTEC-572);
4: 4-Input Multichannel Buffer, Spectrum Master-919, (ORTEC);
5: Computer (Maestro, GammaVision)
6: Bias supply (High Voltage: +2000 v) (ORTEC - 659)

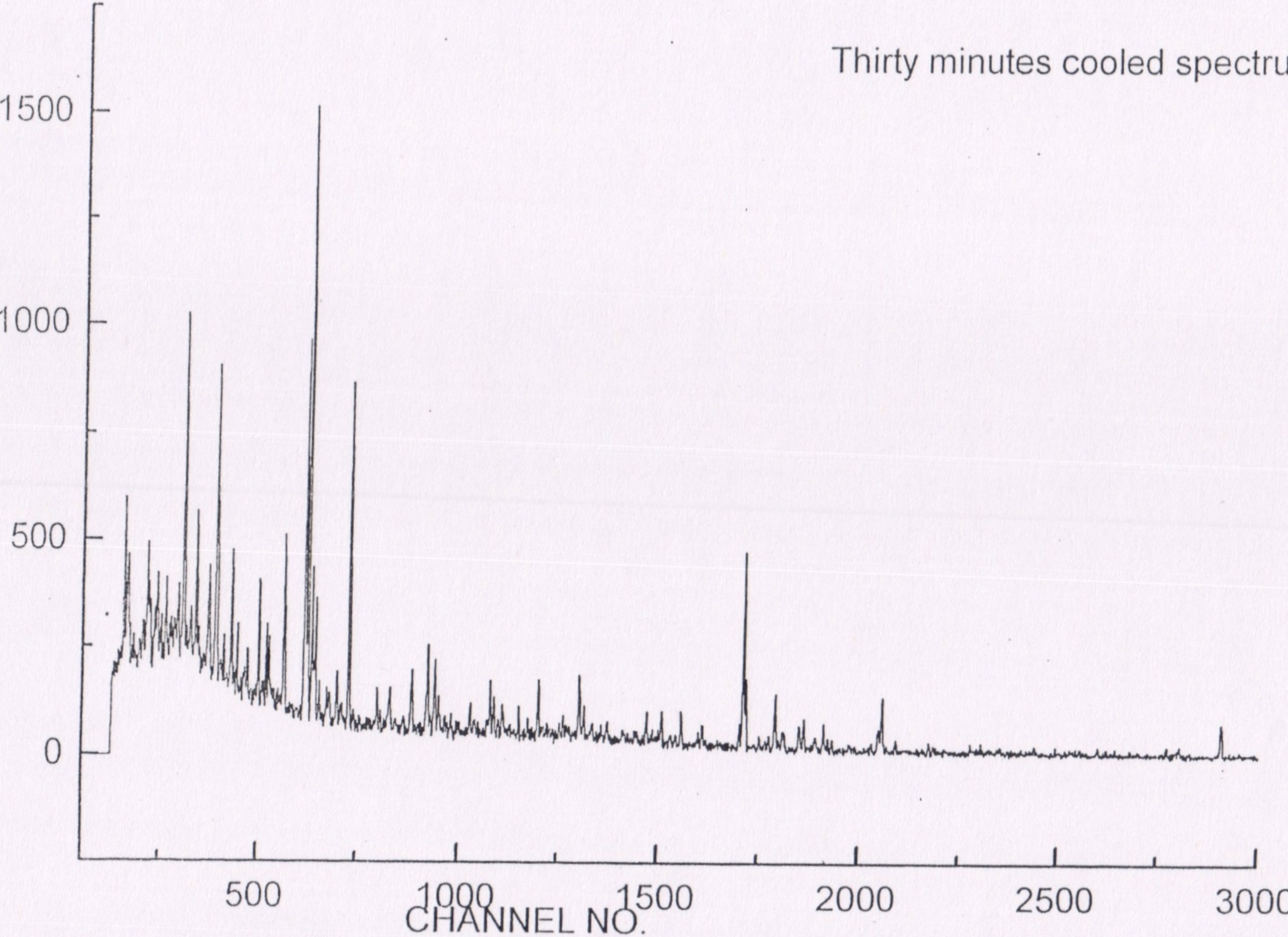


Fig.12. Gamma ray spectrum of fission products from nuetron irradiated ^{243}Am collected on lexan catcher foil showing the absence of gamma lines of ^{239}Np

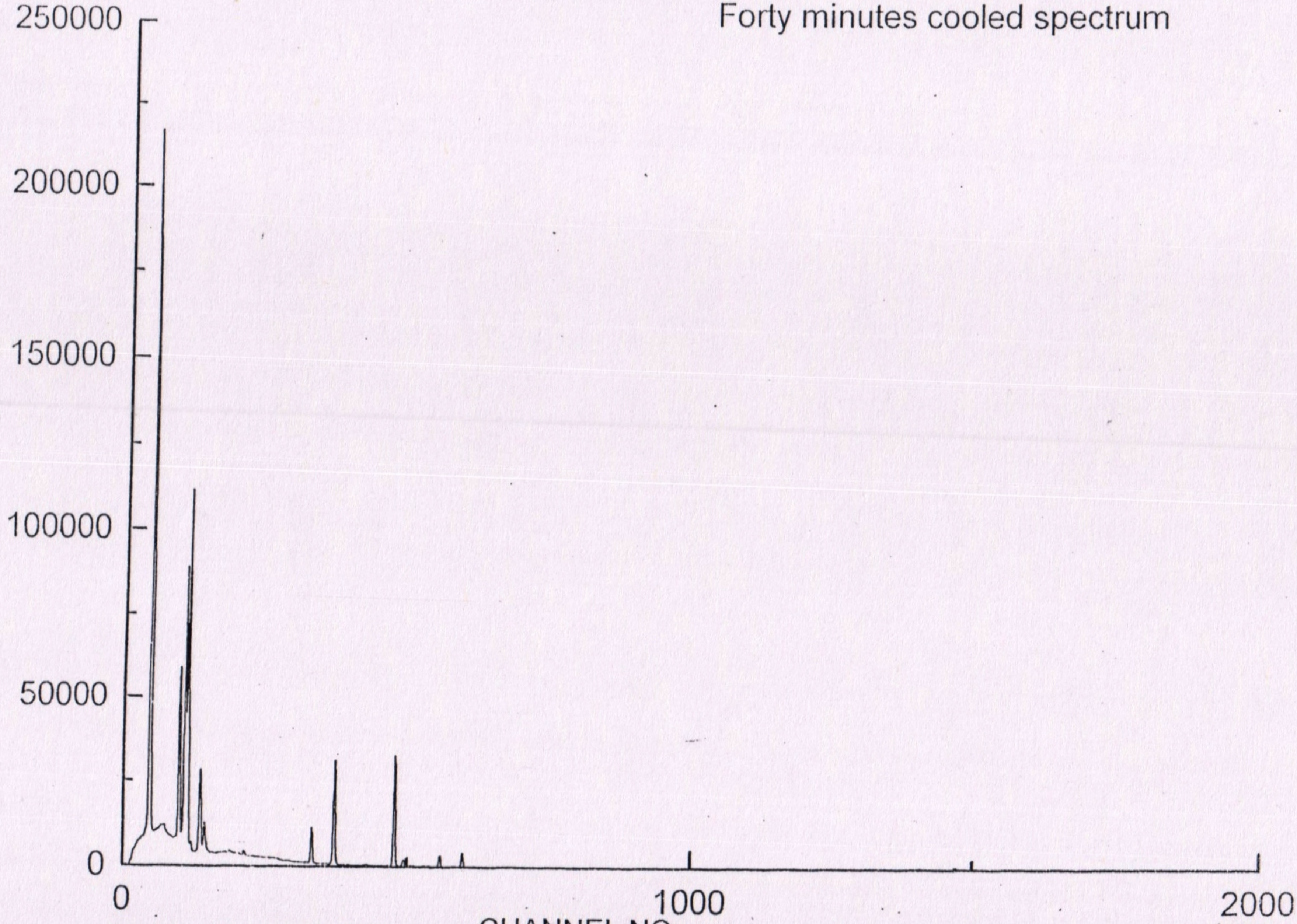


Fig.13. Gamma ray spectrum of fission products from neutron

DECAY SCHME OF FISSION PRODUCTS

$^{134}I^{m}$

3.7m ¥

↓ ¥

^{134}Sb → ^{134}Te → ^{134}I → ^{134}Xe

10.22 s 41.8 m 52.6m stable

$^{135}Xe^{m}$

15.6 m ¥

↓ ¥

^{135}Te → ^{135}I → ^{135}Xe → ^{135}Cs

1.68 s 6.61 h 9.09 h stable

CALCULATIONS OF FISSION PRODUCTS YIELD

(A) COMPARISON METHOD

- From the photo-peak activities $(A_i)_x$ of the gamma lines of the fission products (i) in the fissioning system (X), its fission yields

$$(Y_i)_x = R \frac{(Y_s)_x}{(Y_s)_u} (Y_i)_u, \quad R = \frac{(A_i)_x / (A_s)_x}{(A_i)_u / (A_s)_u}$$

$(A_s)_x$, $(A_s)_u$, $(A_i)_x$ and $(A_i)_u$ are peak areas of gamma lines of standards and fission products in fissioning system of interest and in 235-U.

$(Y_s)_x$, $(Y_s)_u$, $(Y_i)_x$ and $(Y_i)_u$ are yields of standards and fission products in fissioning system of interest and in 235-U.

(B) MASS SPECTROMETRIC METHOD
(Comparison or Absolute method)

(i) In comparison method

* Isotopic ratio (IR) of fission products elements were determined.
* Yields of fission product (Y) was obtained by multiplying the IR with yield of reference nuclide from literature.

(ii) In absolute method

- Absolute number of atoms of each nuclides were determined by isotope dilution technique and
- Total number fission by using a flux monitor.
- As for example 10-B/11-B ratio in BF_3 flux monitor irradiated simultaneously in the same neutron flux along with the fissioning system of interest

(C) ABSOLUTE METHOD by Track cum Gamma ray spectrometric technique

*Total number of fission (F) = $n\sigma\varphi t = T_d\ W / K_{wet}\ C$

• Gamma ray activity (A_i) = $N\sigma\Phi Y a\varepsilon\ [1-\exp(-\lambda t)\ \exp(-\lambda T)$

N = Number of target atoms, W = weight of target material (g)

σ = fission cross section (cm^2) , Φ = neutron flux ($cm^{-2}\ s^{-1}$)

a = gamma ray abundance, ε = efficiency of the detector

t=irradiation time (s), T=Cooling time (s), T_d=Track density(#/cm^2)

K_{wet} = track registration efficiency in solution (cm)

C = conc. of the target material (g cm^{-3}) used for track registration

$$\text{Yield (Y)} = \frac{Ai}{a\varepsilon\ [1-\exp(-\lambda t)\ \exp(-\lambda T)} \quad \frac{C.K_{wet}}{W.T_d}$$

ERROR ANALYSIS

NATURE	SOURCE OF ERROR	% OF ERROR
(a) Random	(I) Counting statistics	3-4
	(ii) Irradiation time	1-1.5
	(iii) Rate of fission ($R=n\sigma\varphi$)	5-7
	(iv) Least sqare analysis)	5-7
	Total (σ_R)	7.8-10.8
(b) Systematic	(i) Half-lives	1
	(ii) Gamma ray abundance	2
	(iii) Branching ratio (abundance)	2-5
	(iv) Detector efficiency	5
	(v) Precursor yields	4-5
	Total (σ_S)	7-9

Upper limit (σ_t) of error in single measurement is given as

σ_T = Square root of ($\sigma_R^2 + \sigma_S^2$) =10.5-15 %

Probable error (σ_P) in single measurement = 0.6745σ_T = 7.4 - 9%

Pre-cissional error in (σ_0) in replicate (n) measurement = 8 – 13%

Standard error(σ_M) of mean value = σ_0/ square root of n = 5-8 %

Quoted error on yields value within 68 % confidence limit =

= Square root of ($\sigma_T^2 + \sigma_M^2$) = 8.6 – 12.4 %

* In all the cases σ^2 are the variance.

RESULTS on Cumulative yields with errors bar are given before.

RESULTS:- Absolute yields of fission products in $^{238}U(n_{1.9MeV},f)$

S. No.	Nuclide	Half life	γ-ray energy (keV)	γ-ray abunda-nce (%)	Fission product yield (%) Present work	Fission product yield (%) ENDF-VI
1.	83-Br	2.39 h	529.5	1.3	0.187	0.393±0.024
2.	85m-Kr	4.48 h	304.9	13.7	0.635±0.206	0.740±0.01
3	87-Kr	76.3 m	402.6	49.6	1.206±0.121	1.617±0.91
4.	88-Kr	2.84 h	196.3	26.3	2.098±0.083	2.036±0.04
5.	89-Rb	15.2 m	1032.1	58.0	3.052±0.385	2.813±0.07
			1248.1	42.6	2.888±0.093	2.813±0.07
6.	91-Sr	9.52 h	1024.3	33.4	4.335±0.135	4.084±0.11
7.	92-Sr	2.71 h	1384.1	90.0	4.410±0.130	4.278±0.11
8.	93-Sr	7.42 m	875.9	23.9	4.560±0.091	4.933±0.29
9.	93-Y	10.25 h	266.9	6.8	5.134±0.348	4.936±0.15
10.	94-Y	18.7 m	918.7	56.0	4.340±0.257	4.639±0.18
11.	95-Y	10.3 m	954.1	13.4	5.032±0.061	5.150±0.10
12.	95-Zr	64.02 d	756.7	54.5	4.701±0.214	5.151±0.05

S. No.	Nuclide	Half life	γ-ray energy (keV)	γ-ray abundance (%)	Fission product yield (%) Present work	ENDF-VI
13.	97-Zr	4.48 h	304.9	13.7	6.408±0.147	5.564±0.078
14.	99-Mo	2.748 d	140.5	90.7	6.282±0.269	6.188±0.087
			739.4	12.1	7.365±0.590	6.188±0.087
15.	101-Mo	14.6 m	590.9	16.4	4.799±0.276	6.197±0.372
16.	103-Ru	39.254 d	497.1	88.7	6.124±0.282	6.261±0.063
17.	104-Tc	18.3 m	358.0	89.0	5.237±0.211	5.029±0.100
18.	105-Ru	4.44 h	724.3	46.7	5.104±0.314	4.058±0.114
19.	107-Rh	21.7 m	302.8	66.0	0.993±0.183	

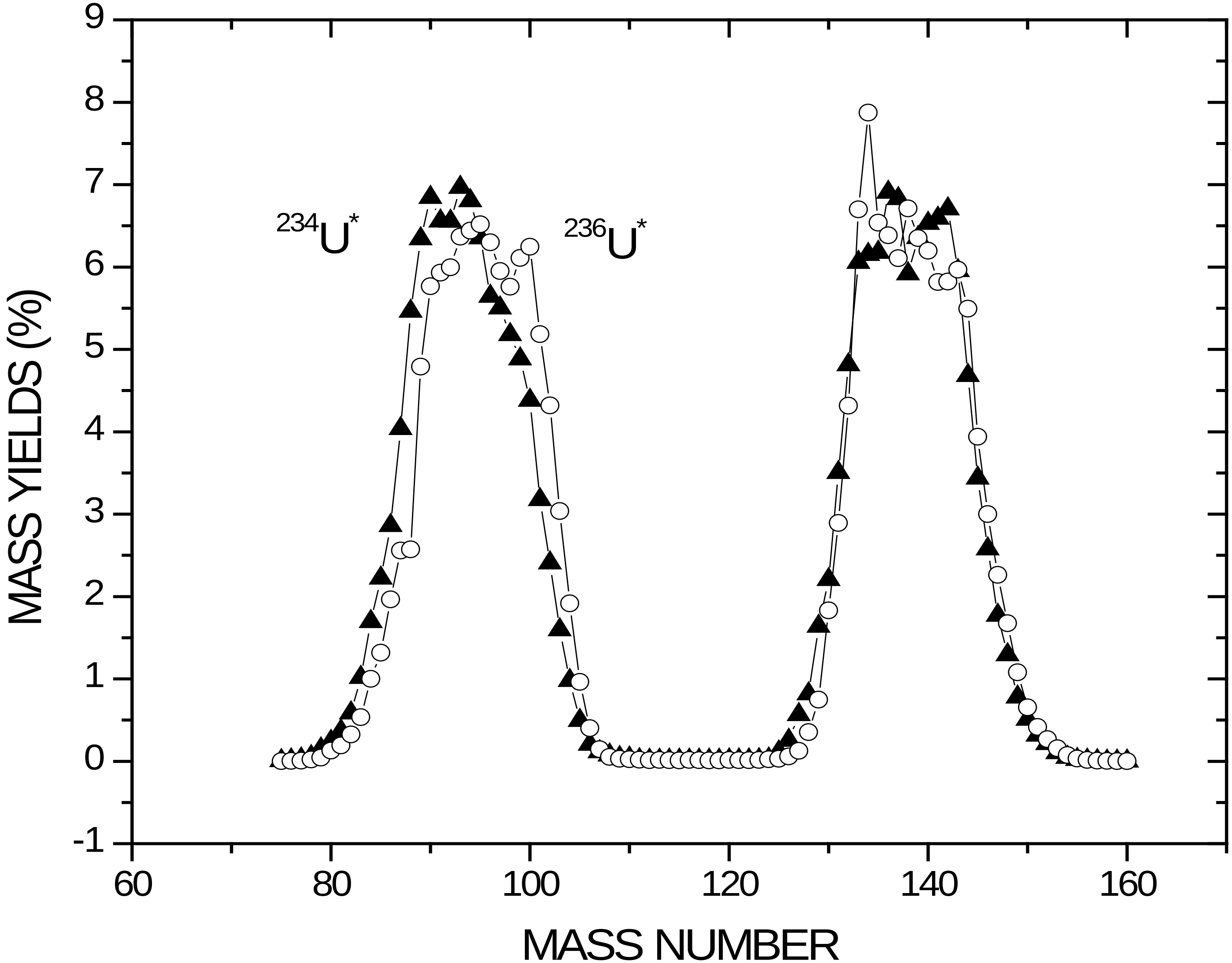
S. No.	Nuclide	Half life	γ-ray energy (keV)	γ-ray abundance (%)	Fission product yield (%) Present work	ENDF-VI
21.	115g-Cd	2.23 d	527.1	27.5	0.055±0.004	0.034±0.001
22.	117g-Cd	2.49 h	273.4	28.0	0.038±0.006	0.028±0.013
23.	117m-Cd	3.36 h	1066.0	23.1	0.007±0.002	0.009±0.004
24.	127-Sb	3.85 d	685.7	35.3	0.135±0.015	0.135±0.008
25.	128-Sn	59.1 m	482.3	59.0	0.278±0.002	0.460±0.074
26.	129-Sb	4.32 h	812.4	43.0	0.985±0.130	0.945±0.076
27.	131-Sb	23.03 m	943.0	44.0	3.089±0.175	3.245±0.195
28.	131-I	8.04 d	364.5	81.2	3.313±0.110	3.282±0.042
29.	133-I	20.8 h	529.9	87.0	6.755±0.216	

S. No.	Nuclide	Half life	γ-ray energy (keV)	γ-ray abundance (%)	Fission product yield (%) Present work	ENDF-VI
31.	135-I	6.55 h	1260.4	28.6	8.422±0.118	6.965±0.139
					(8.460±0.380)	
			1131.5	22.5	7.649±0.280	6.965±0.139
					(7.420±0.380)	
32.	137-Xe	3.818 m	455.5	31.2	8.650±0.027	6.011±0.120
33.	138-Xe	14.08 m	434.5	20.3	8.924±0.721	5.675±0.159
34.	138-Cs	32.2 m	1435.8	76.3	11.669±0.246	5.728±0.160

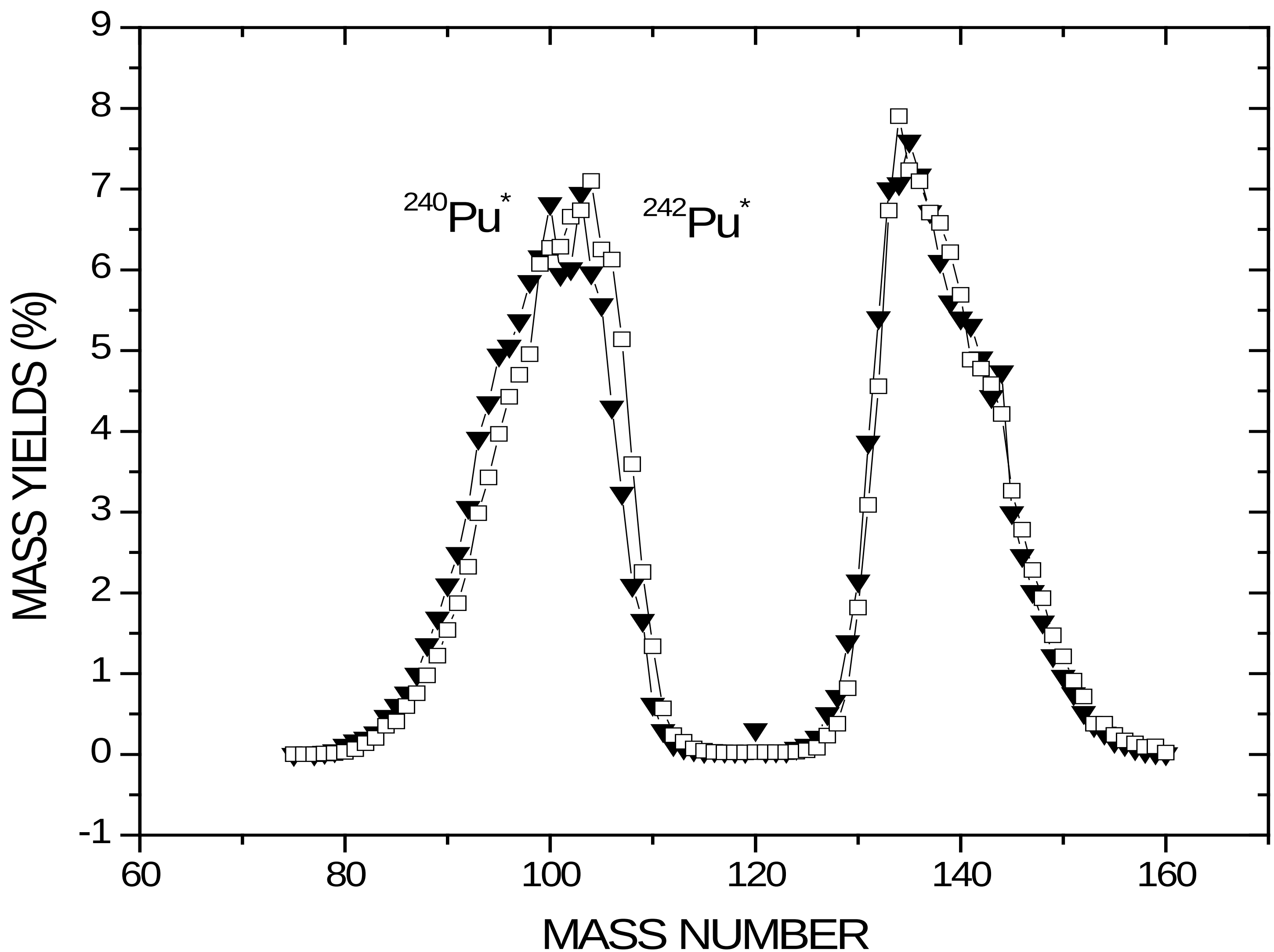
S. No.	Nuclide	Half life	γ-ray energy (keV)	γ-ray abundance (%)	Fission products yield (%) Present work	ENDF-VI Data
36.	140-Ba	12.75 d	537.3	24.4	5.646±0.154	5.846±0.058
37.	141-Ba	18.27 m	190.3	46.3	5.448±0.048	5.379±0.323
38.	141-Ce	32.5 d	145.4	48.4	5.107±0.619	5.379±0.108
39.	142-Ba	10.6 m	255.2	20.6	3.899±0.179	4.577±0.183
40.	142 La	1.542 h	641.3	47.0	6.057±0.159	4.580±0.092
41.	143Ce	1.375 d	293.3	42.0	4.952±0.122	4.597±0.064
42.	144-Ce	284.4 d	133.5	11.1	4.568±0.464	4.550±0.064
43.	146-Ce	13.52 m	316.7	51.0	3.572±0.225	3.426±0.096
44.	147-Nd	10.98 d	531.0	13.0	2.555±0.185	2.572±0.051
45.	149-Pm	15.08 h	286.0	2.85	1.679	1.618±0.032
46.	151-Pm	28.4 h	340.0	22.0	0.723±0.018	0.795±0.016
47.	153-Sm	46.7 h	103.2	28.3	0.332	0.411±0.012

MASS YIELDS OF FISSION PRODUCTS IN NEUTRON INDUCED FISSION OF ACTINIDES DETERMINED IN RLG (OLD RADIOCHEMISTRY DIVISION)

ACTINIDES	TECHNIQUE	AUTHORS
232-Th (n, f)	Beta, γ-ray counting	R.H. Iyer et al.
227-Ac, 231Pa, 237Np (n, f)	Beta, γ- ray counting	R. S. Iyer et al.
229-Th(n, f)	γ-ray spectrometry	R. J. Singh et al.
232-U (n, f)	γ-ray spectrometry	S. B. Manohar et al.
233,235-U, 239,241-Pu (n,f)	Mass Spectrometry	S.A. Chitamber et al.
241-Pu, 245-Cm (n,f)	γ-ray Spectrometry	A. Ramaswami et al.
238-U, 237-Np, 238,240-Pu 243-Am, 244-Cm	Track etch cum γ-ray Spectrometry	H. Naik et al. R.H. Iyer et al.



MASS YIELDS (%)
9
8
7
6
5
4
3
2
1
0
-1
60
80
100
120
140
160
MASS NUMBER
234U*
236U*



9
8
7
6
5
4
3
2
1
0
-1
MASS YIELDS (%)
60
80
100
120
140
160
MASS NUMBER
$^{240}Pu^*$
$^{242}Pu^*$

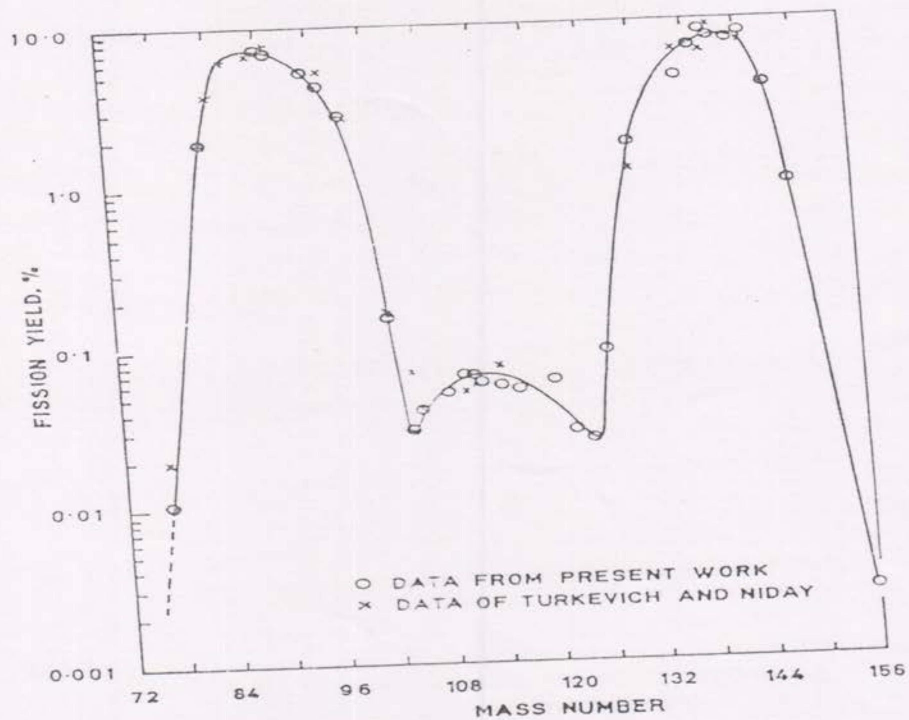

10·0
1·0
0·1
0·01
0·001
FISSION YIELD, %
72
84
96
108
120
132
144
156
MASS NUMBER
○ DATA FROM PRESENT WORK
× DATA OF TURKEVICH AND NIDAY

FIG. 1

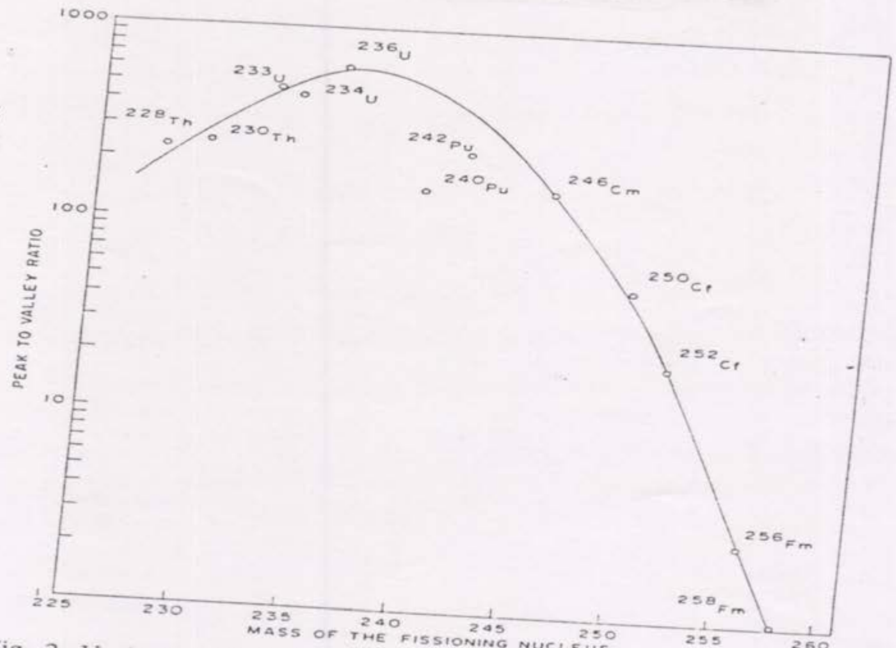


Fig. 2. Variation of Peak to Valley ratio as a function of mass of the fissioning nucleus in thermal neutron induced fission.

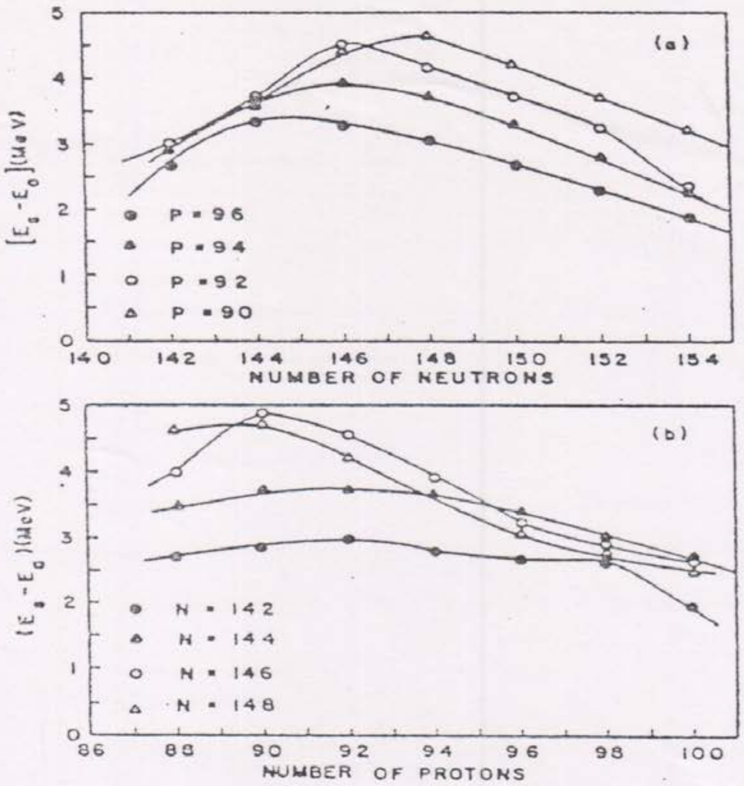


FIG. 2. Variation of $(E_s - E_a)$ as a function of (a) neutron and (b) proton number of the fissioning nucleus.

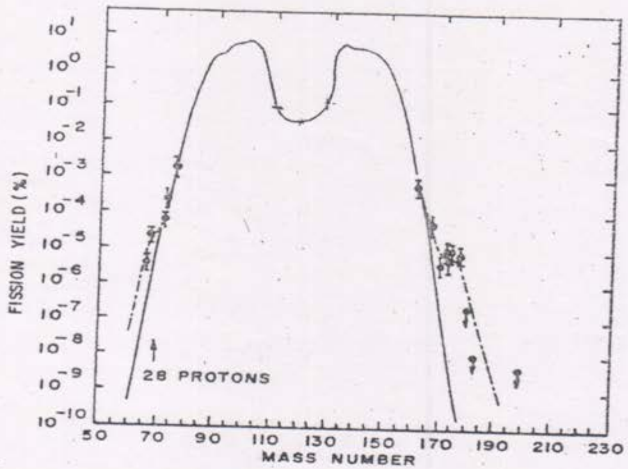


FIG. 3. Mass distribution in the fission of ^{238}U by reactor neutrons. The curve has been extrapolated using the available data (Ref. 6) to the mass numbers $A = 60$ on the lighter side and $A = 180$ on the heavier side by means of Eq. (3) referred to in the text. Dotted portion is drawn using the present experimental data in Table I.

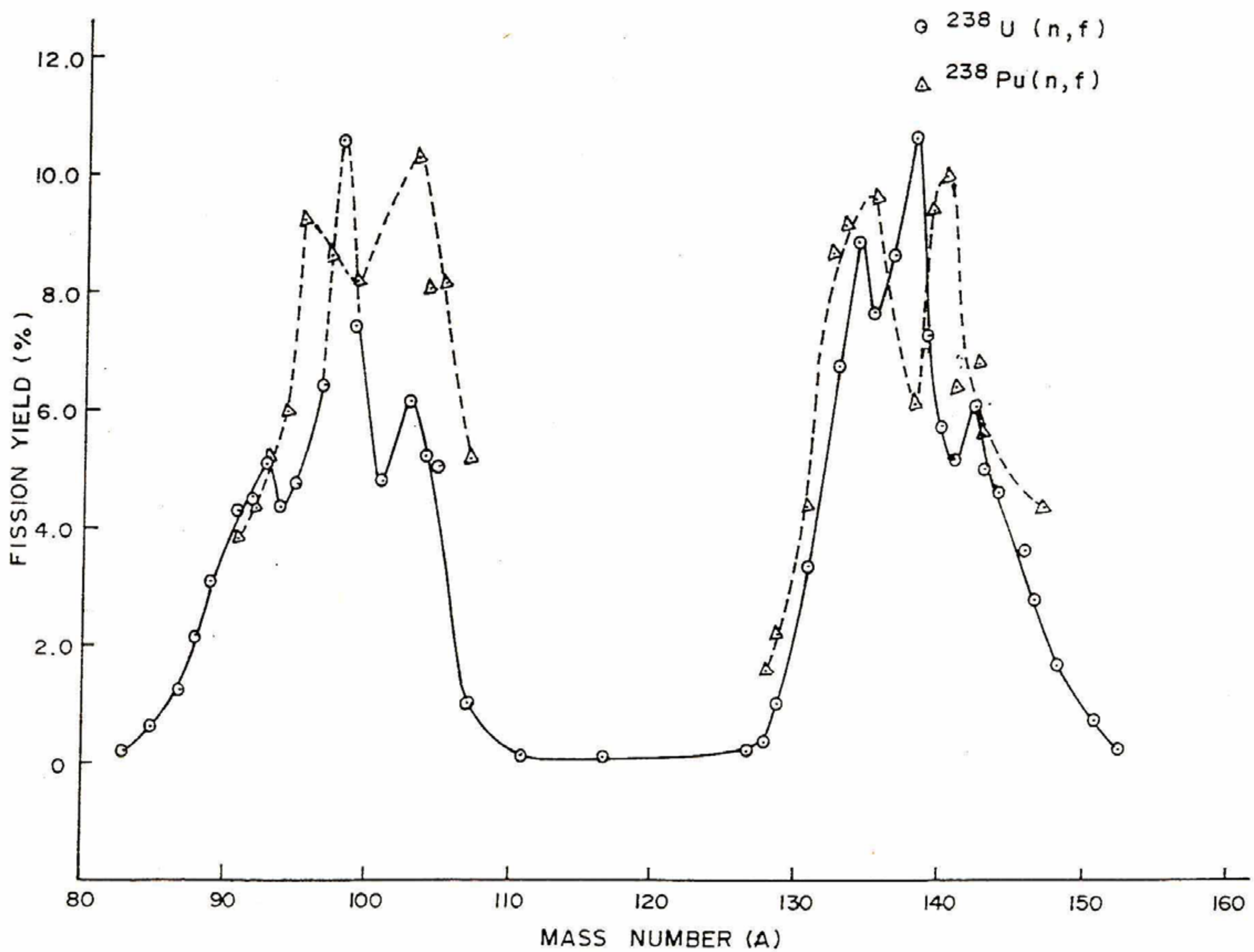


FIG.1. POST NEUTRON MASS YIELD DISTRIBUTIONS OF 238-U(n,f) AND 238-Pu(n,f).

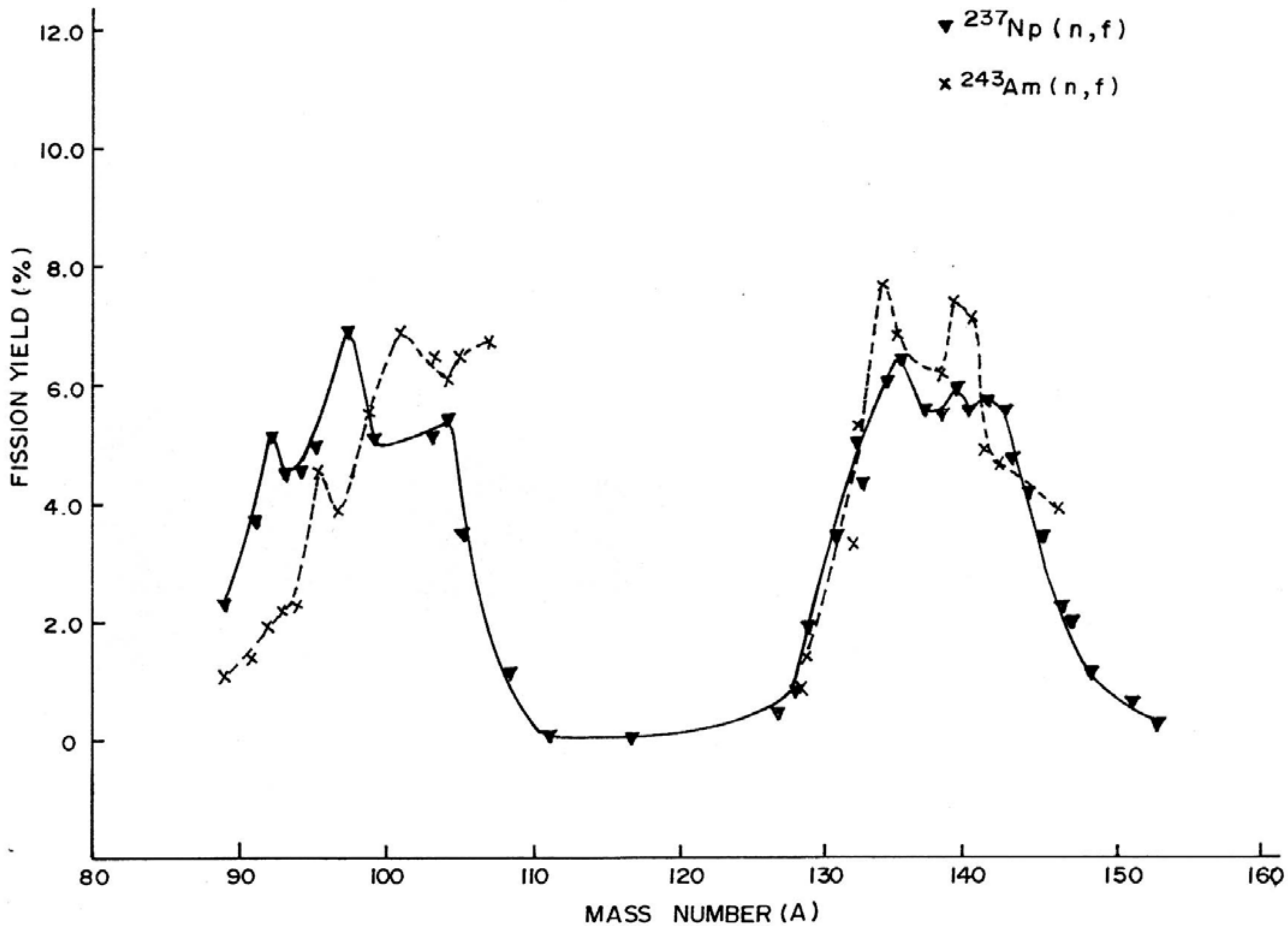


FIG. 2. POST NEUTRON MASS YIELD DISTRIBUTIONS ON 237-Np(n,f) AND 243-Am(n,f).

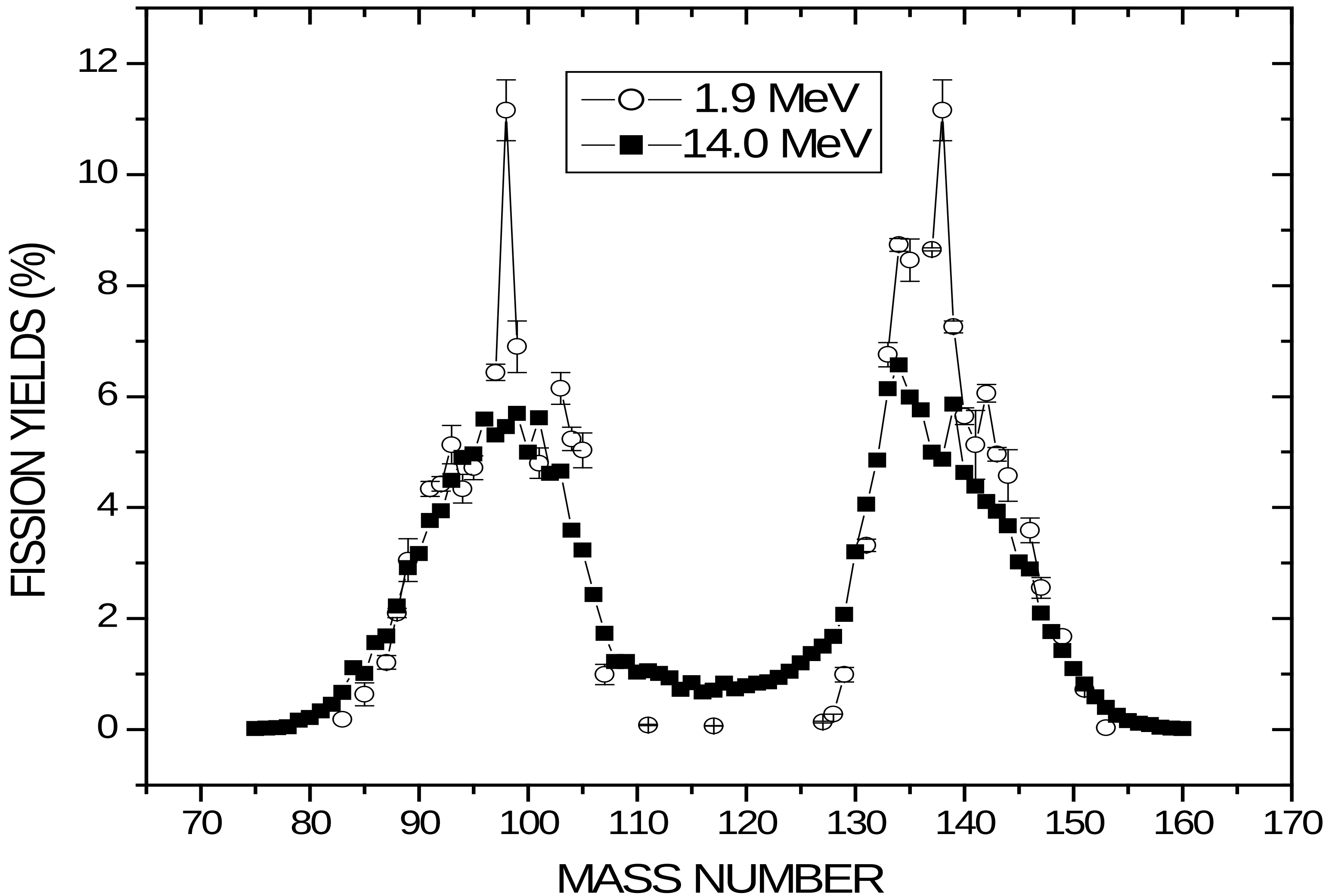


Fig.2. Plot of mass chain yields vs. their mass number in $^{238}U(n,f)$.

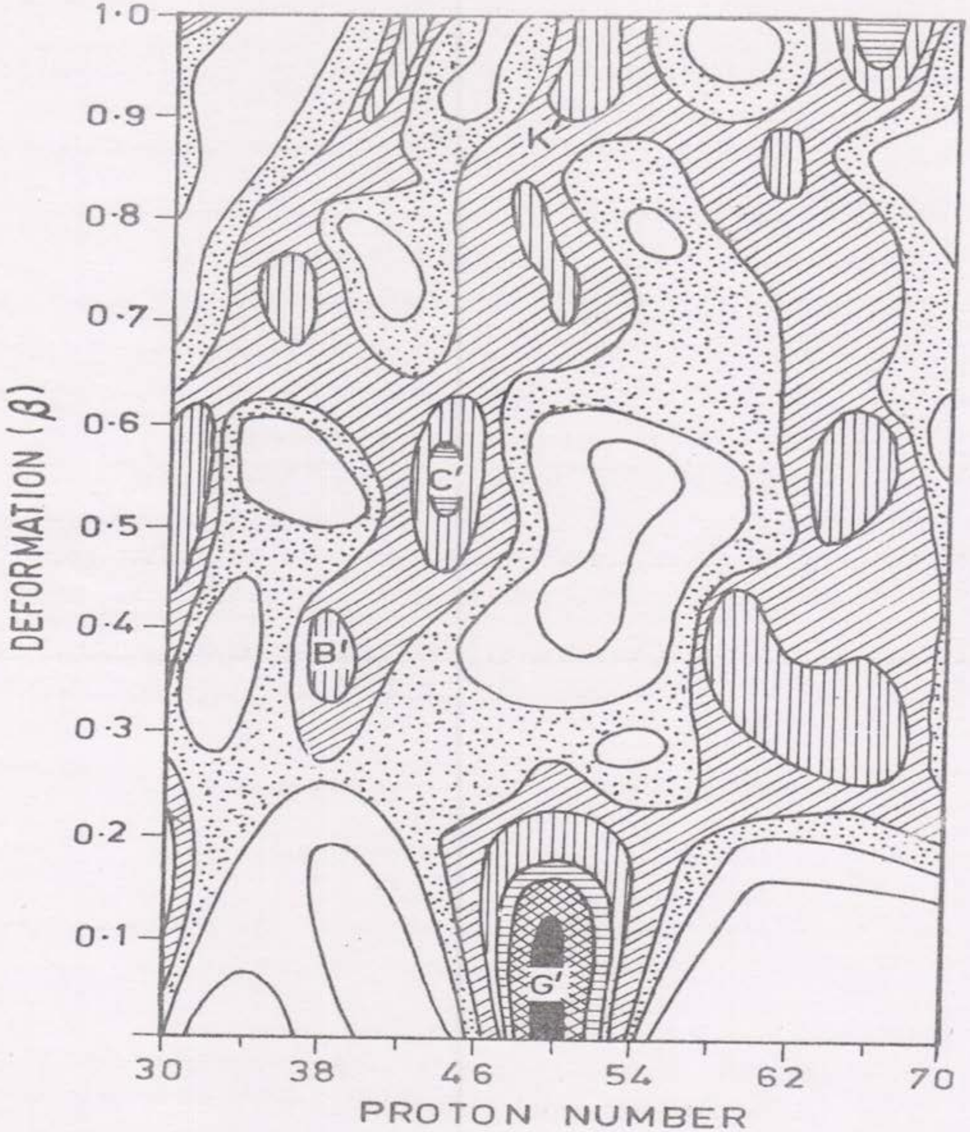


FIG.-9. DEFORMED SHELLS FOR PROTONS (REF.48)

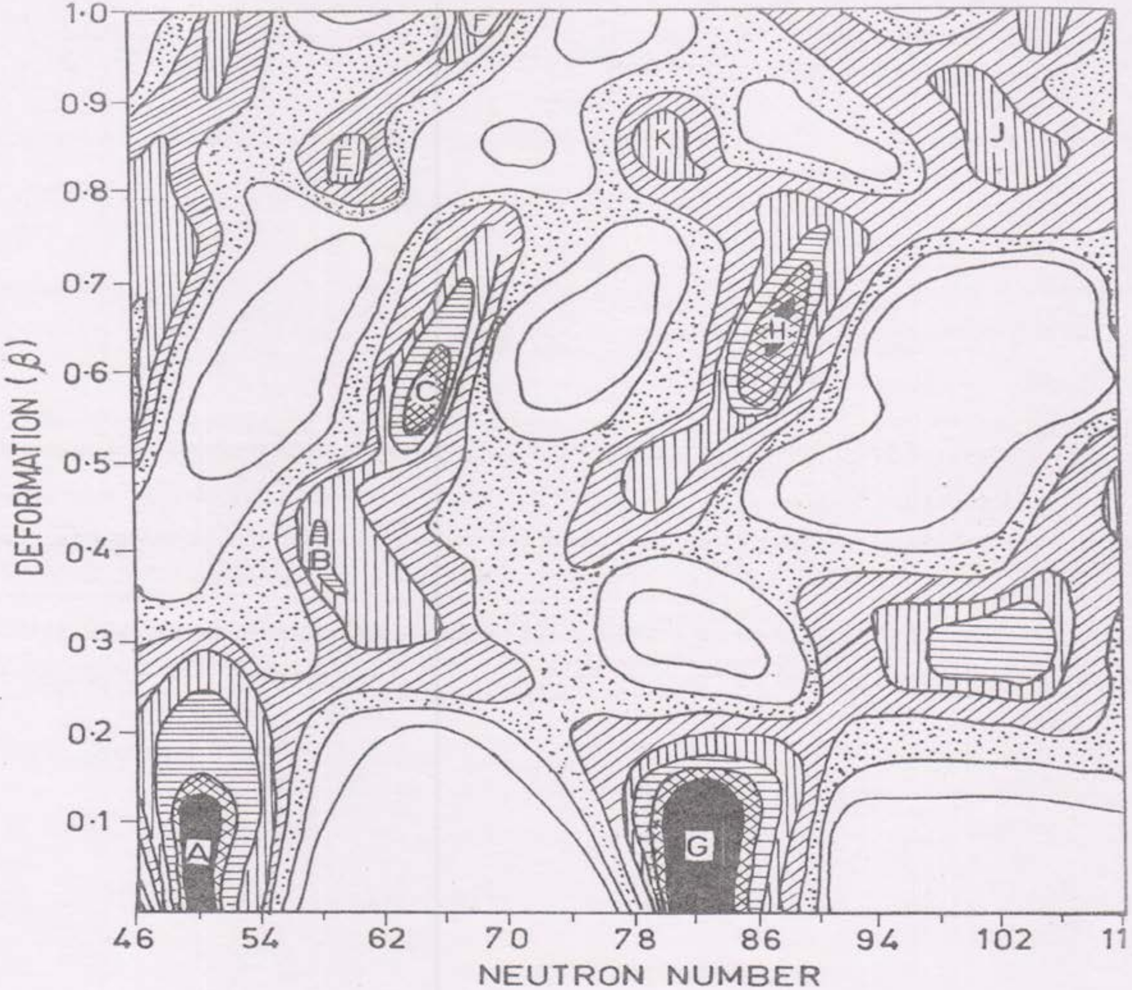


FIG.-10 . DEFORMED SHELLS FOR NEUTRONS (REF. 48)

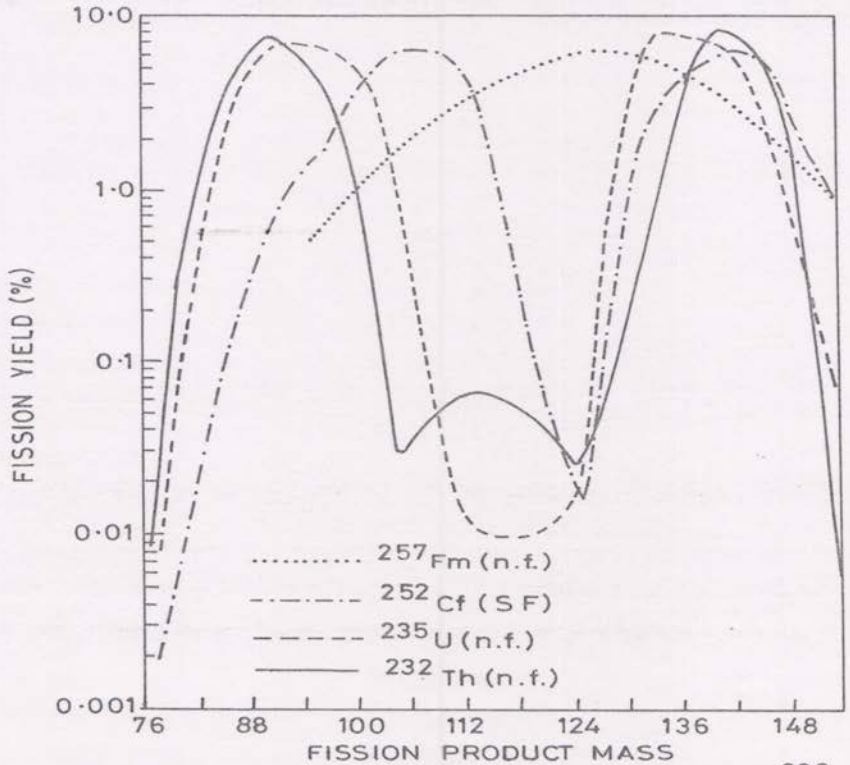


FIG. 25 MASS DISTRIBUTIONS IN FISSION OF ^{232}Th. ^{235}U, ^{252}Cf AND ^{257}Fm. (REFERENCE 36)

CHARGE DISTRIBUTION

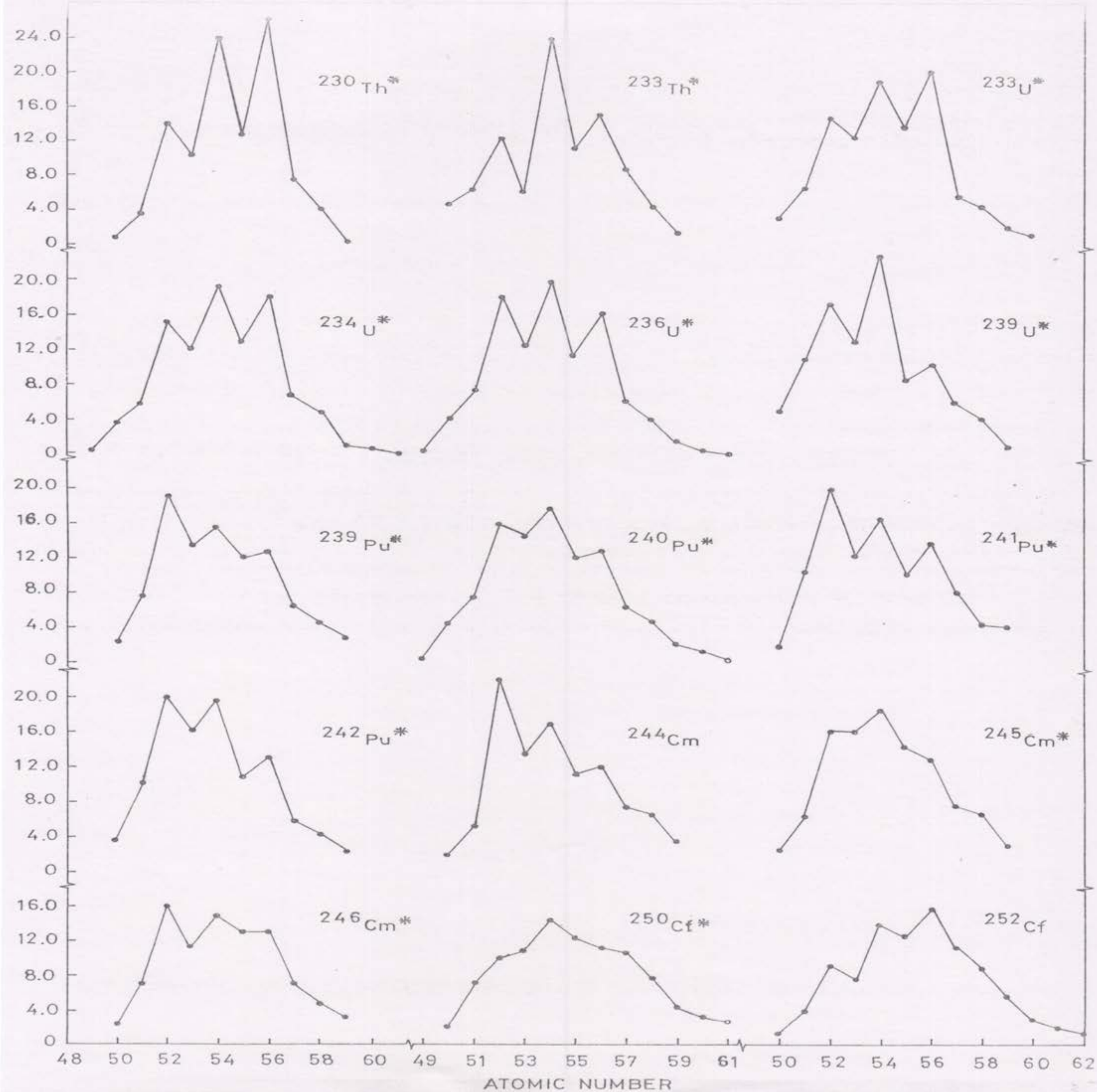
(a) Isotopic – Z fixed A changes
(b) Isobaric – A fixed Z changes

$$FCY = \frac{EOF^{a(X)}}{\sqrt{2\pi\sigma^2}} \int_{-\infty}^{X+0.5} \exp\left[- (X-X_P)^2 / 2\sigma^2 \right] dX$$

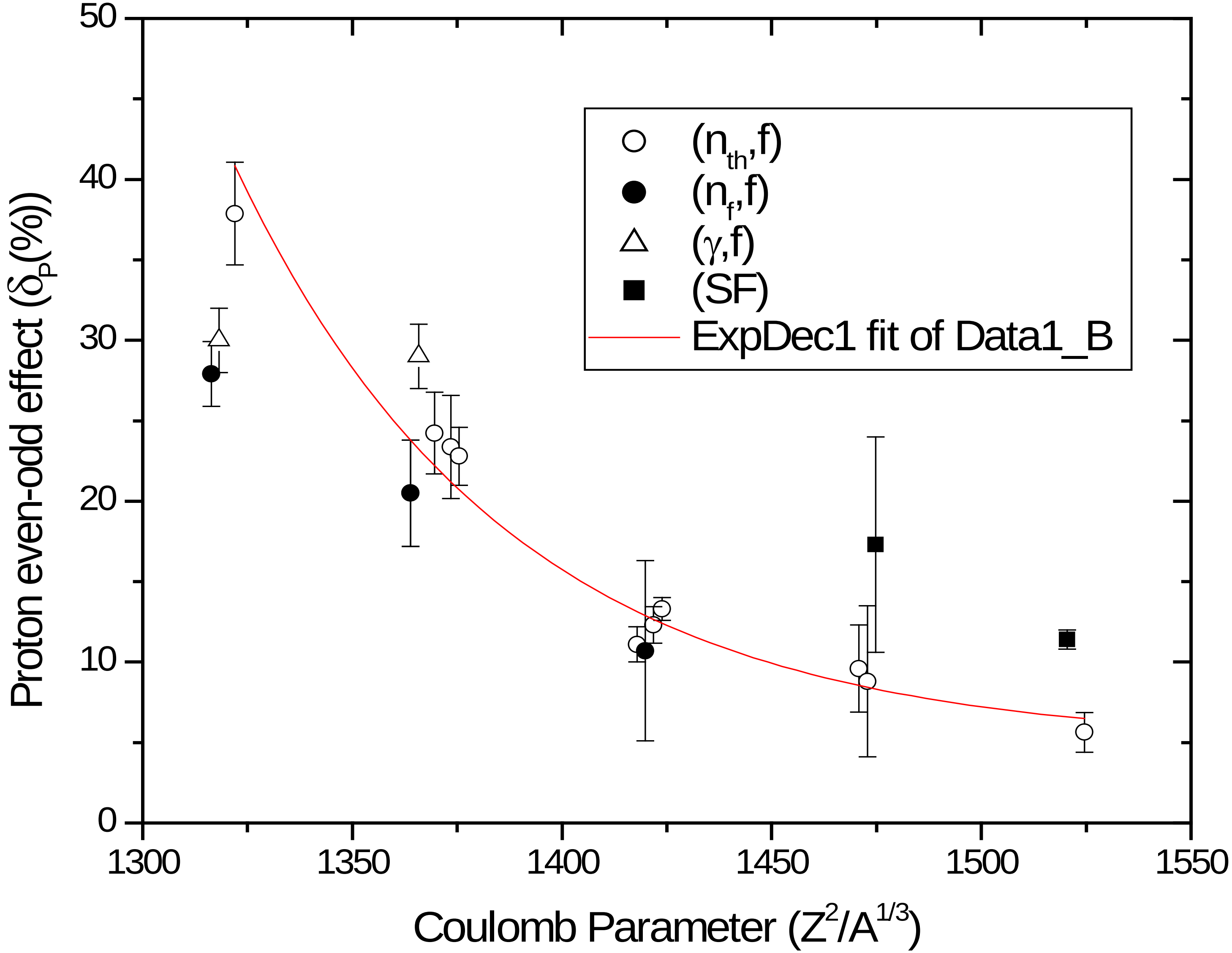
Charge polarization (ΔZ) = $Z_P - Z_{UCD}$)

$$I\,Y = \frac{EOFa(X)}{\sqrt{2\pi\sigma^2}} \int_{X-0.5}^{X+0.5} \exp\left[- (X-X_P)^2 / 2\sigma^2 \right] dX$$

$$\text{Even-Odd factor } (\delta_P(\%)) = \frac{\sum Y_e - \sum Y_O}{\sum Y_e + \sum Y_O} \times 100$$



24.0
20.0
16.0
12.0
8.0
4.0
0
230Th*
233Th*
233U*
234U*
236U*
239U*
239Pu*
240Pu*
241Pu*
242Pu*
244Cm
245Cm*
246Cm*
250Cf*
252Cf
48 50 52 54 56 58 60
49 51 53 55 57 59 61
50 52 54 56 58 60 62
ATOMIC NUMBER



Proton even-odd effect (δ_p(%))
Coulomb Parameter ($Z^2/A^{1/3}$)
(n_{th},f)
(n_f,f)
(γ,f)
(SF)
ExpDec1 fit of Data1_B
0
10
20
30
40
50
1300
1350
1400
1450
1500
1550

SUMMARY

1. Mass yields distribution is asymmetric with third peak for lighter actinides.

2. In low energy neutron fission, fine structure in the interval of 5 mass units due to proton pairing (even-odd) effect. It decreases with increase of Coulomb parameter and neutron energy.

3. Higher yields for A=133-135, 138-140 and 143-145 mass chains and their complementary is due to shell combination of 82n, 86-88n, 64-66n, 50n,p, 44p, 38p and 28p etc. Effect of shell closure proximity decreases with increase of neutron energy and Coulomb parameter.

4. Average A_H of 139$\pm$1 is fixed for all actinides. However, average A_L increases from lighter to heavier actinides.

4. A_H of 139$\pm$1 is due to average effect of spherical 82n (134$\pm$1) and deformed 88n (144$\pm$1). This is also favorable from N/Z point of view. A_H of 134$\pm$1 due to spherical 82n shell is not favorable from N/Z point of view.

5. In neutron induced fission of 238-U P/V decreases from 180 at 1.9 MeV to 8-10 at 14 MeV. Decrease of P/V ratio, shell and even-odd effect from low to 14 MeV neutron fission indicates effect of excitation energy.

PHOTON (BREMSSTRAHLUNG) INDUCED FISSION
(ROLE OF EXCITATION ENERGY)

MEASUREMENTS OF YIELDS OF FISSION PRODUCTS IN 2.5 GeV, 50-70 MeV AND 8-10 MeV BREMSSTRAHLUNG (PHOTON) INDUCED FISSION OF

1. PRE-ACTINIDES (^{nat}Pb, ^{209}Bi) AND
2. ACTINIDES (^{232}Th, ^{238}U AND ^{240}Pu).

EXPT WITH 2500 & 50-70 MEV BREMSSTRAHLUNG WAS DONE USING 2.5 GEV AND 100 MEV ELECTRON LINAC AT POHANG ACCELERATOR LABORATORY (PAL), KOREA.

EXPERIMENT WITH 8-10 MeV BREMSSTRAHLUNG WAS DONE USING

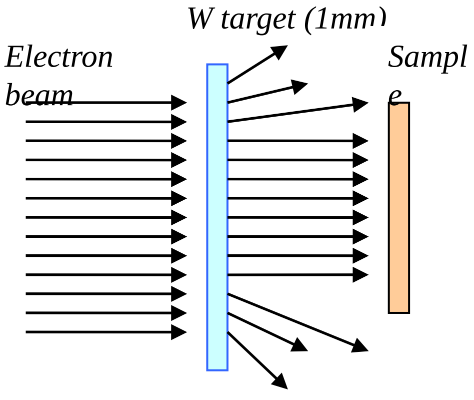
a. 8 MeV ELETRON MICROTRON AT MANGALORE AND
b. 10 MEV ELECTRON LINAC OF EBC CENTER AT KHARGHAR, MUMBAI.

PRODUCTION OF GAMMA PHOTON (BREMSSTRAHLUNG) FROM ELECTRON BEAM (MICROTRON OR ELECTRON LINAC)

-Thermo ionic source Lithium hexaborate

-Beam specification

-Electron linac	100 MeV	2.5 GeV
energy range	50-70MeV	2.5 GeV
Beam current	100 (10-50) mA	100-200 mA
Pulse width	1-2 (1.5) μs	1 ns
Repetition rate	10-12 (3.75) Hz	10 Hz



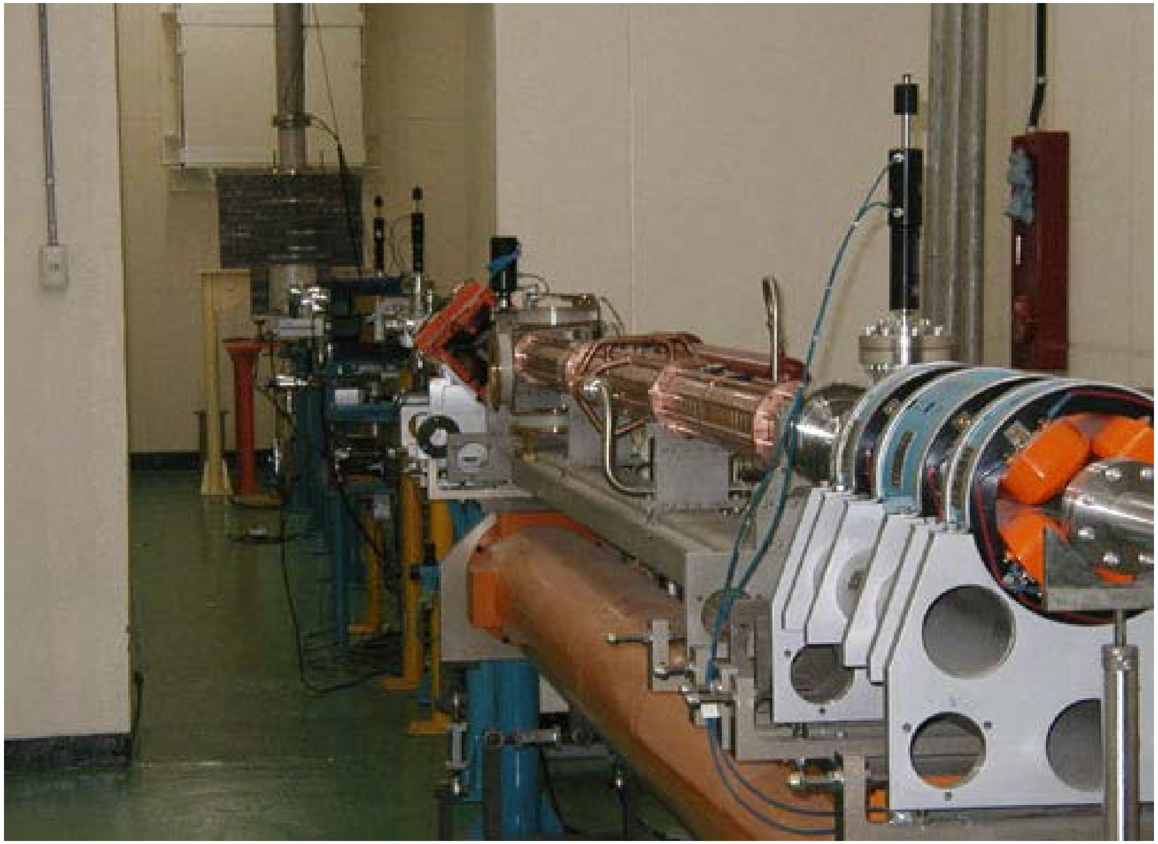
ADVANTAGE OF PHOTO-FISSION OVER NEUTRON INDUCED FISSION

Photon (bremsstrahlung) can be produced from electron LINAC.
Neutron beam of good flux is available primarily from reactor.

ELECTRON LINAC	REACTOR
Making is easy and cheap	costly and difficult to make
Does not need high security	Need tide security arrangement
Does not need any actinides as target and thus any country can make Electron LINAC	Needs actinides as fuel and thus all country can not make a reactor.
In photo fission of actinides production of heavier actinides is not possible no alpha activity problem	Neutron induced fission of actinides also causes neutron activation and beta decay to produce heavy actinides with high alpha activity.
Medical isotopes from photo-fission of actinides are free from alpha contamination	There is chance of alpha contamination for medical isotopes obtained from neutron induced fission of actinides.

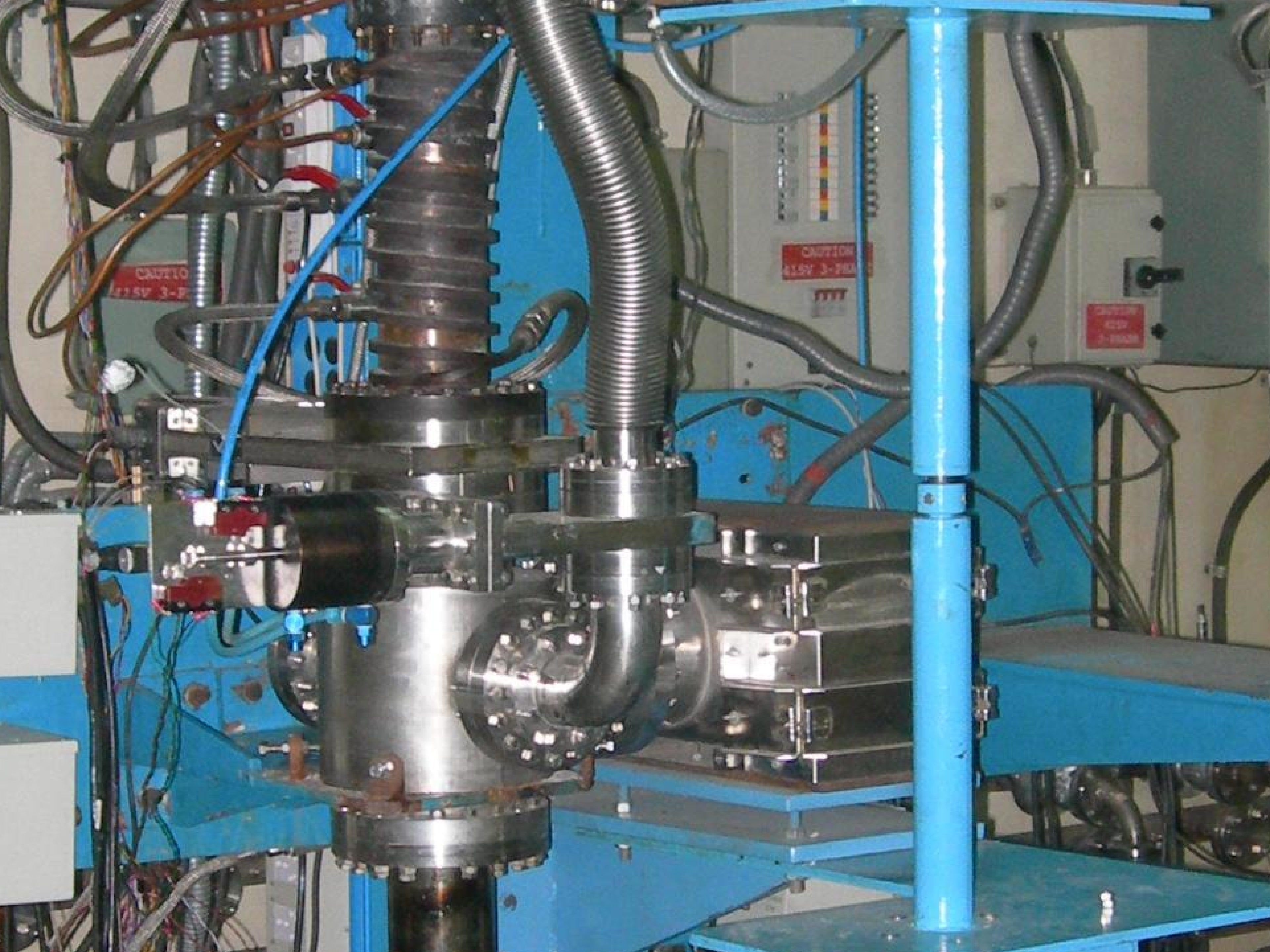
POHANG ACCELATOR LABORATORY


Observatory
Guest House
Power Substation
Utility Building
Technical Building II
Linear Accelerator Building
Storage Ring Building
Experimental Hall (Beamlines)
Technical Building I
Administration Building
Main Entrance



Pohang 65 MeV electron linear accelerator

Pohang 2.5 GeV electron linear accelerator

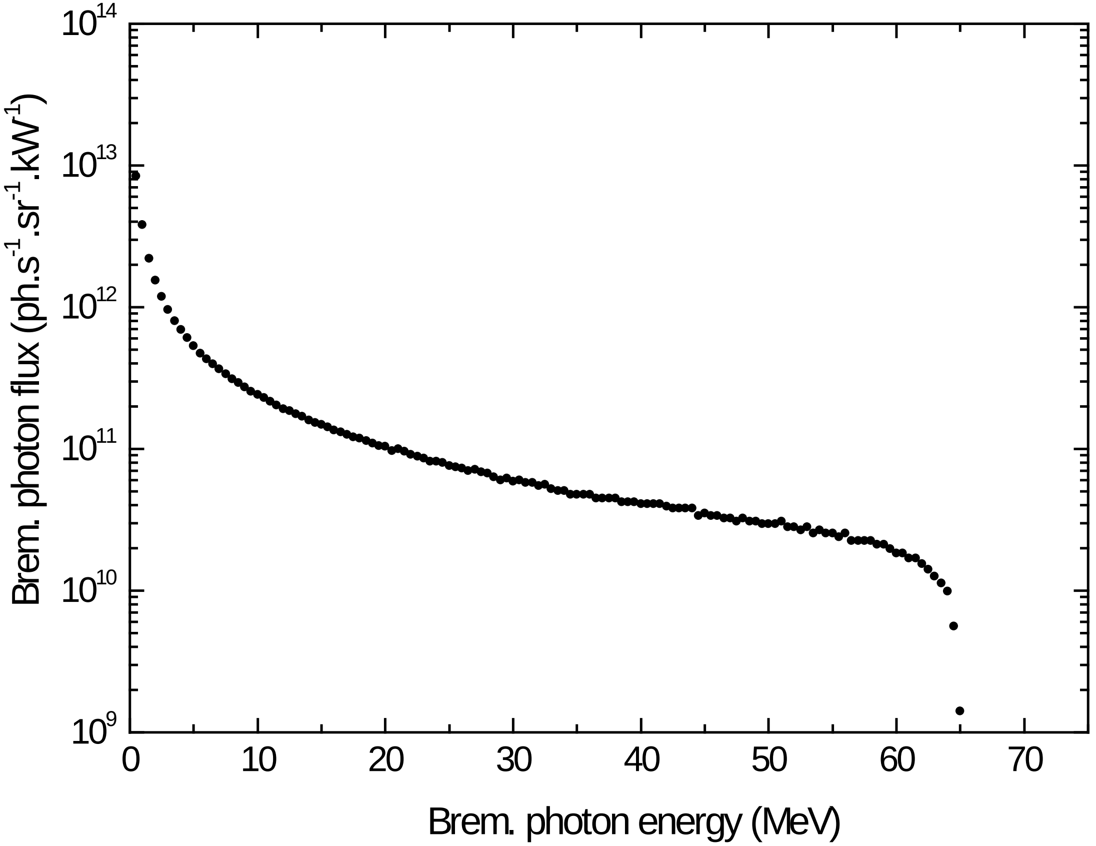

CAUTION
CAUTION

- **2.5 GeV LINAC used for the production of Synchrotron radiation and experiments related to that.**

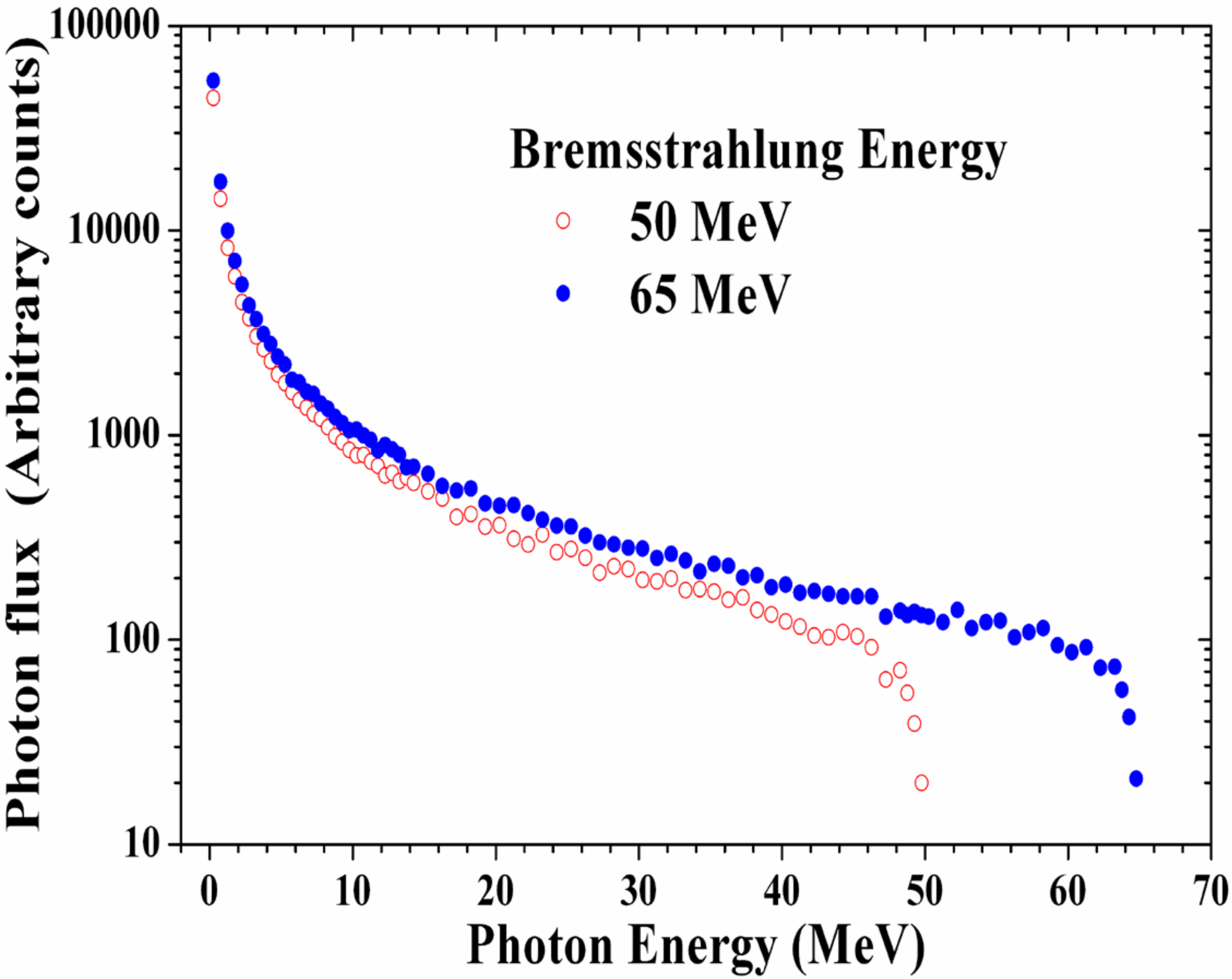
- **Synchrotron radiation** is electromagnetic radiation, similar to cyclotron radiation, but generated by the acceleration of ultrarelativistic (i.e., moving near the speed of light) electrons through magnetic fields. This may be achieved artificially by storage rings in a synchrotron, or naturally by fast moving electrons moving through magnetic fields in space. The radiation typically includes infrared, optical, ultraviolet, x-rays.

* 65 MeV LINAC used for production of Bremsstrahlung and neutrons

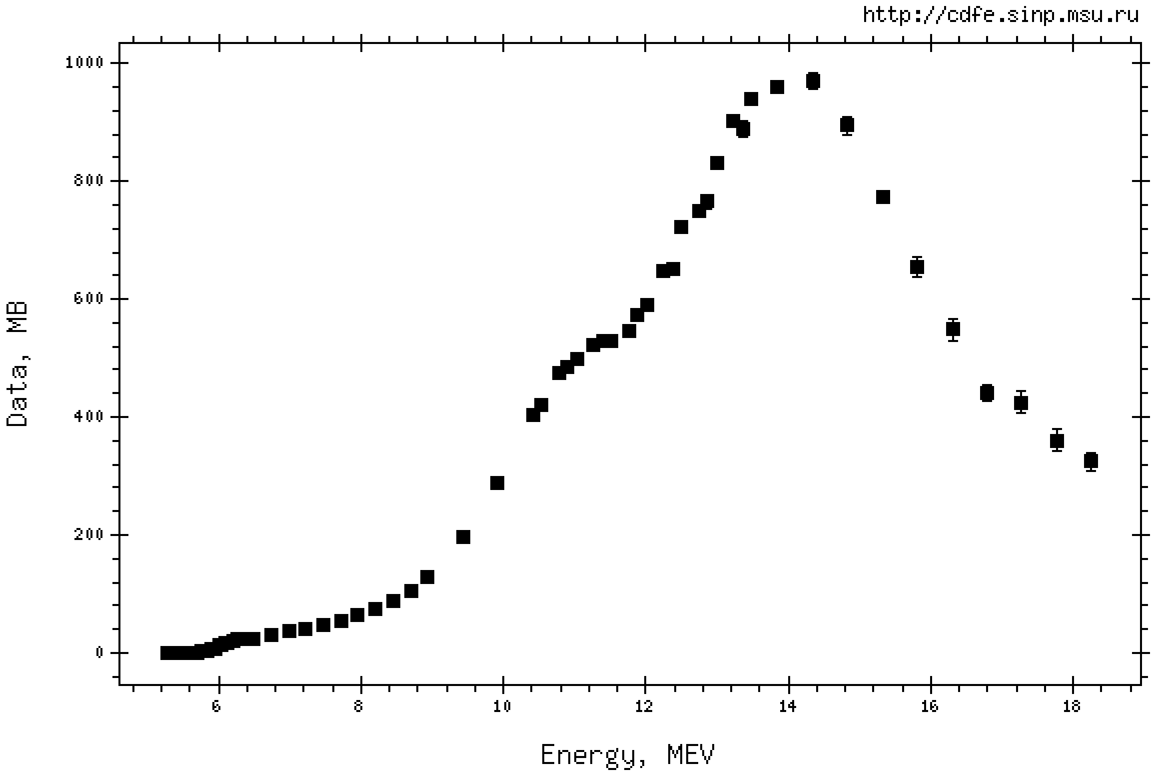
- Bremsstrahlung In a narrow sense, the electromagnetic radiation emitted by electrons when they pass through (Coulombic field) of matter. Charged particles radiate when accelerated, and in this case the electric fields of the atomic nuclei provide the force which accelerates the electrons. The continuous spectrum of x-rays from an x-ray tube is that of the bremsstrahlung; in addition, there is a characteristic x-ray spectrum due to excitation of the target atoms by the incident electron beam. The major energy loss of high-energy (relativistic) electrons (energy greater than about 10 MeV, depending somewhat upon material) occurs from the emission of bremsstrahlung, and this is the major source of gamma rays in a high-energy cosmic-ray shower. *See also* Cosmic rays; Electromagnetic radiation.
- In a broader sense, bremsstrahlung is the radiation emitted when any charged particle is accelerated by any force. To a great extent, as a source of photons in the ultraviolet and soft x-ray region for the investigation of atomic structure (particularly in solids), bremsstrahlung from x-ray tubes has been replaced by synchrotron radiation. Synchrotron radiation is an analog to bremsstrahlung, differing in that the force which accelerates the electron is a macroscopic (large-scale) magnetic field.



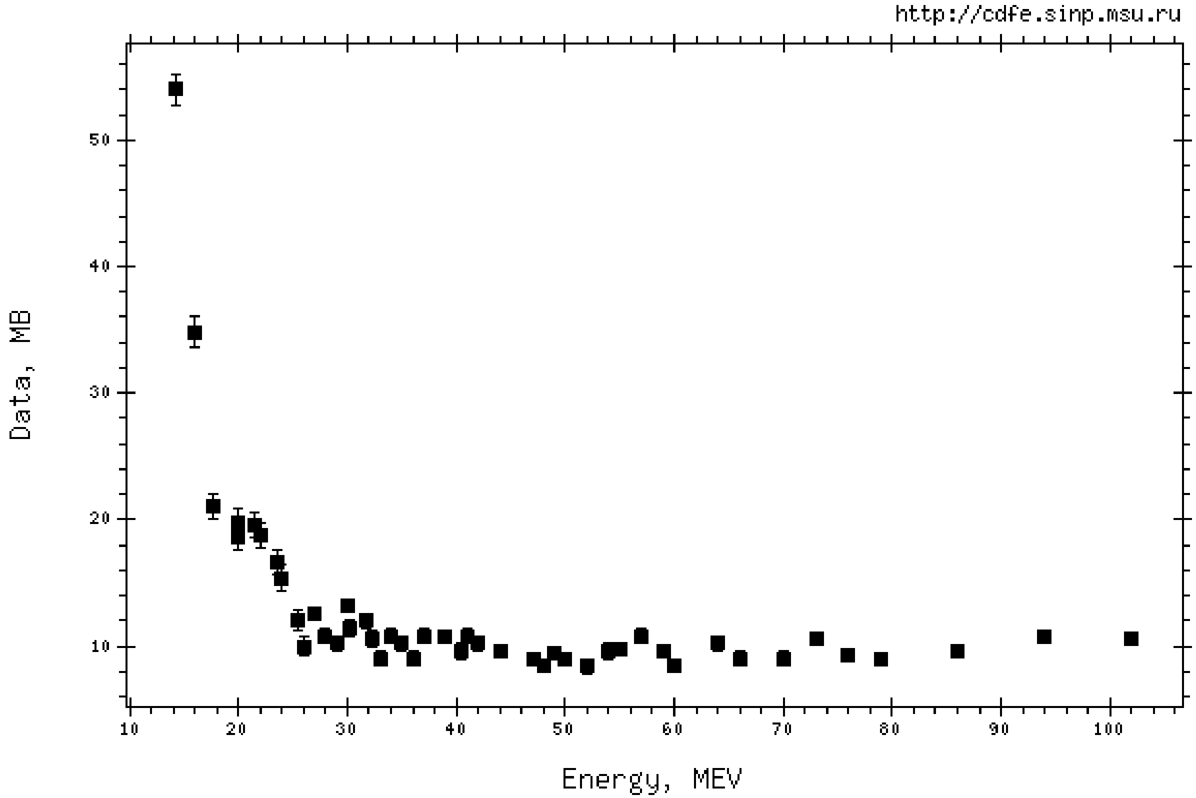
A spectrum of Bremsstrahlung with maximum energy of 65 MeV



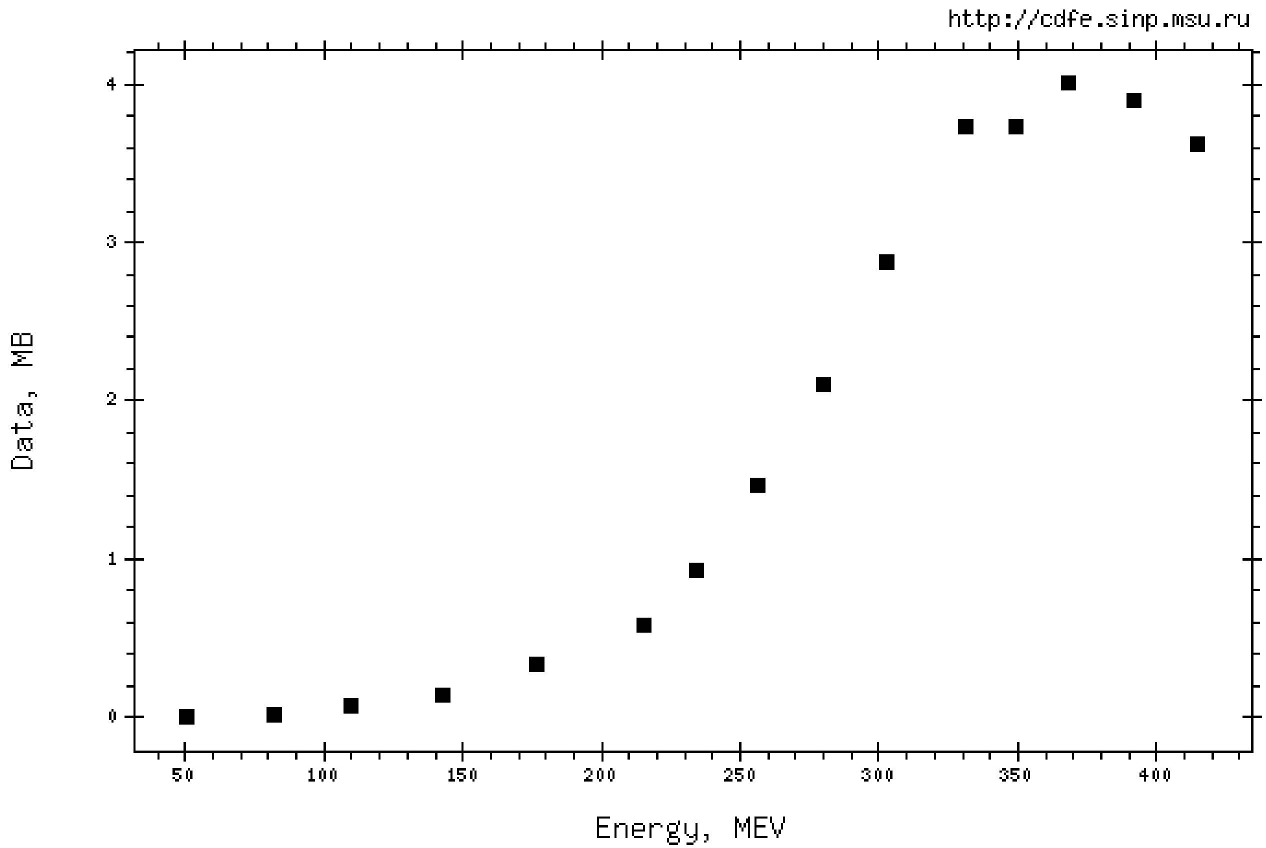
Bremsstrahlung Energy
50 MeV
65 MeV
Photon flux (Arbitrary counts)
100000
10000
1000
100
10
0
10
20
30
40
50
60
70
Photon Energy (MeV)



Photofission cross section of ^{232}Th(γ,f)

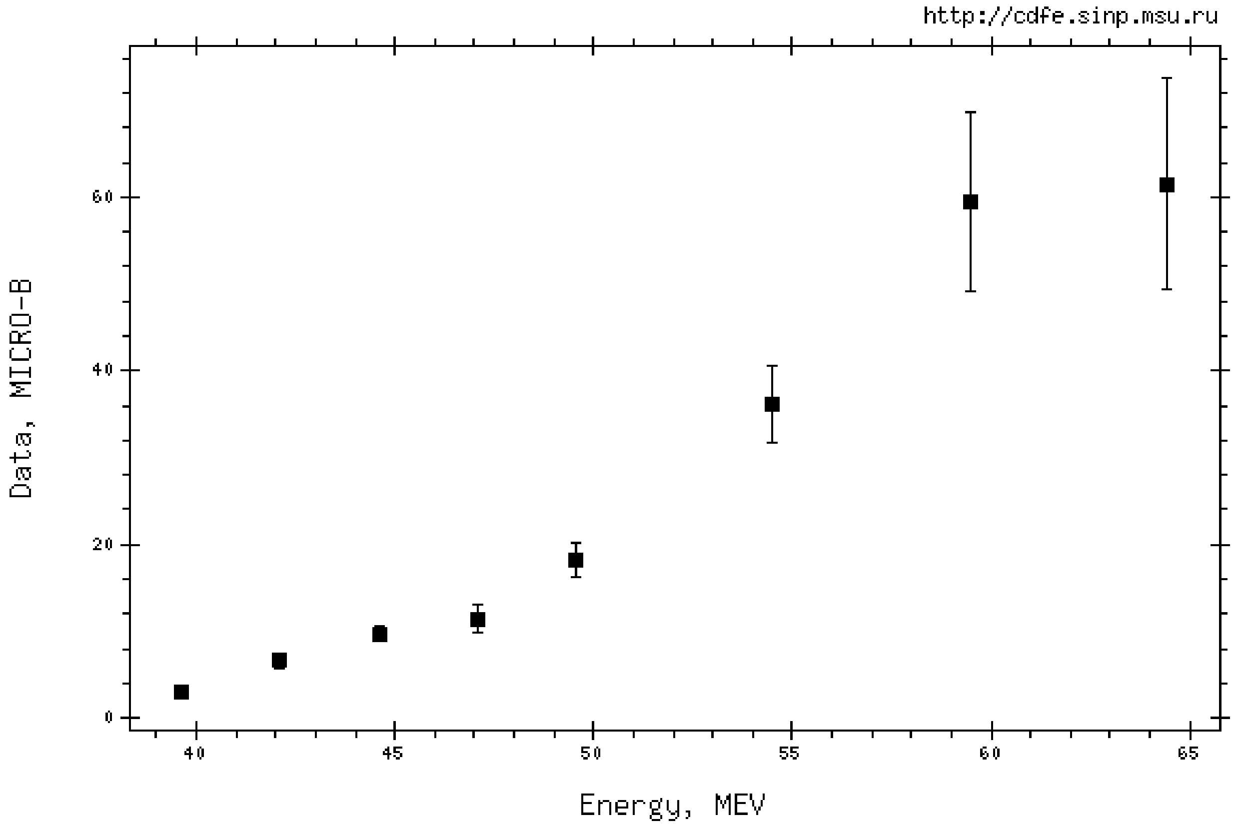


Photofission cross section of ^{232}Th(γ,f)



Photofission cross section of ^{209}Bi(γ,f)

Phys. Rev. Vol.179 (1969)1176



Photofission cross section of ^{209}Bi(γ,f)

Nucl. Phys. Vol. 342 (1980) 37

EXPERIMENTAL

#For 2.5 GeV and 50-70 MeV bremsstrahlung radiation at PAL, Korea

-Bremsstrahlung was produced by impinging 2.5 MeV or 50-70 MeV electron beam on 1.0 mm or 0.1 mm thick W placed at a distance of 18 cm.

-74 g of 209-Bi or 12 g of nat-Pb metal foil (size 5cm x 5cm) wrapped with 0.025 mm thick Al foil and sample was placed at 12 cm distance from W.

-Irradiation was done for 3-5 hours with photon from pulsed electron beam and then cooled for 1 hour..

#For 8-10 MeV bremsstrahlung radiation from Microtron at Mangalore and electron LINAC at EBC, Kharghar, Navi-Mumbai, India.

- Bremsstrahlung was produced by impinging 8-10 MeV electron beam on1 mm thick Ta metal foil.

-2-5 g of ^{232}Th or ^{238}U metal foil of 0.025 mm thick (size 1.5 cm x 1.5cm) wrapped with 0.025 mm thick Al foil.

- 50 μg of ^{240}Pu in the nitrate form was dried on similar Al foil..

-The target was kept below the tantalum foil on a suitable stand.and irradiated for 4 hour with photon from 8-10 MeV electron beam. Then cooled for 1.5 hours.

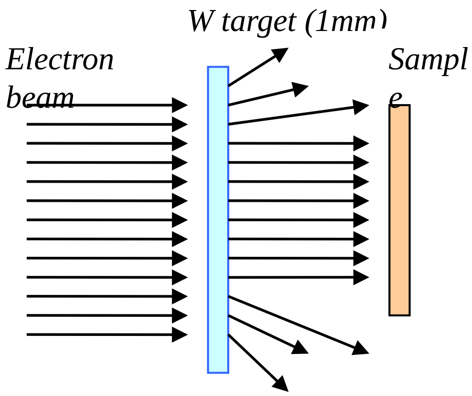
-Gamma ray counting of the fission products was done using precalibrated HPGe detector coupled to a PC based 4096 channel analyzer.

-Resolution of the detector system was 2.0 KeV at 1332.0 keV of ^{60}Co.

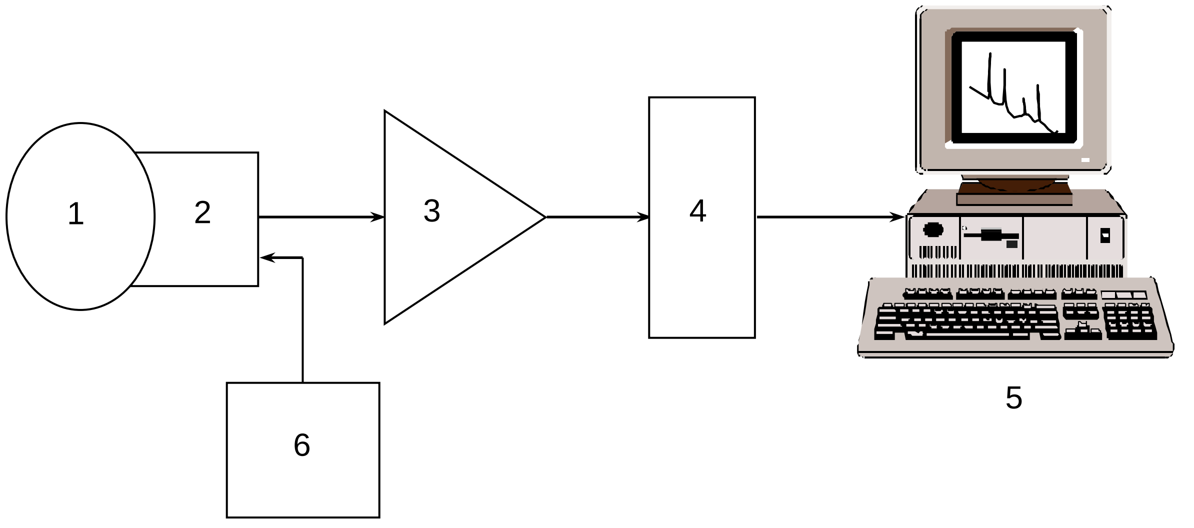
ELECTRON BEAM

-Thermo ionic source Lithium hexaborate
-Beam specification

-Electron linac	100 MeV	2.5 GeV
energy range	50-70MeV	2.5 GeV
Beam current	100 (10-50) mA	100-200 mA
Pulse width	1-2 (1.5) μs	1 ns
Repetition rate	10-12 (3.75) Hz	10 Hz

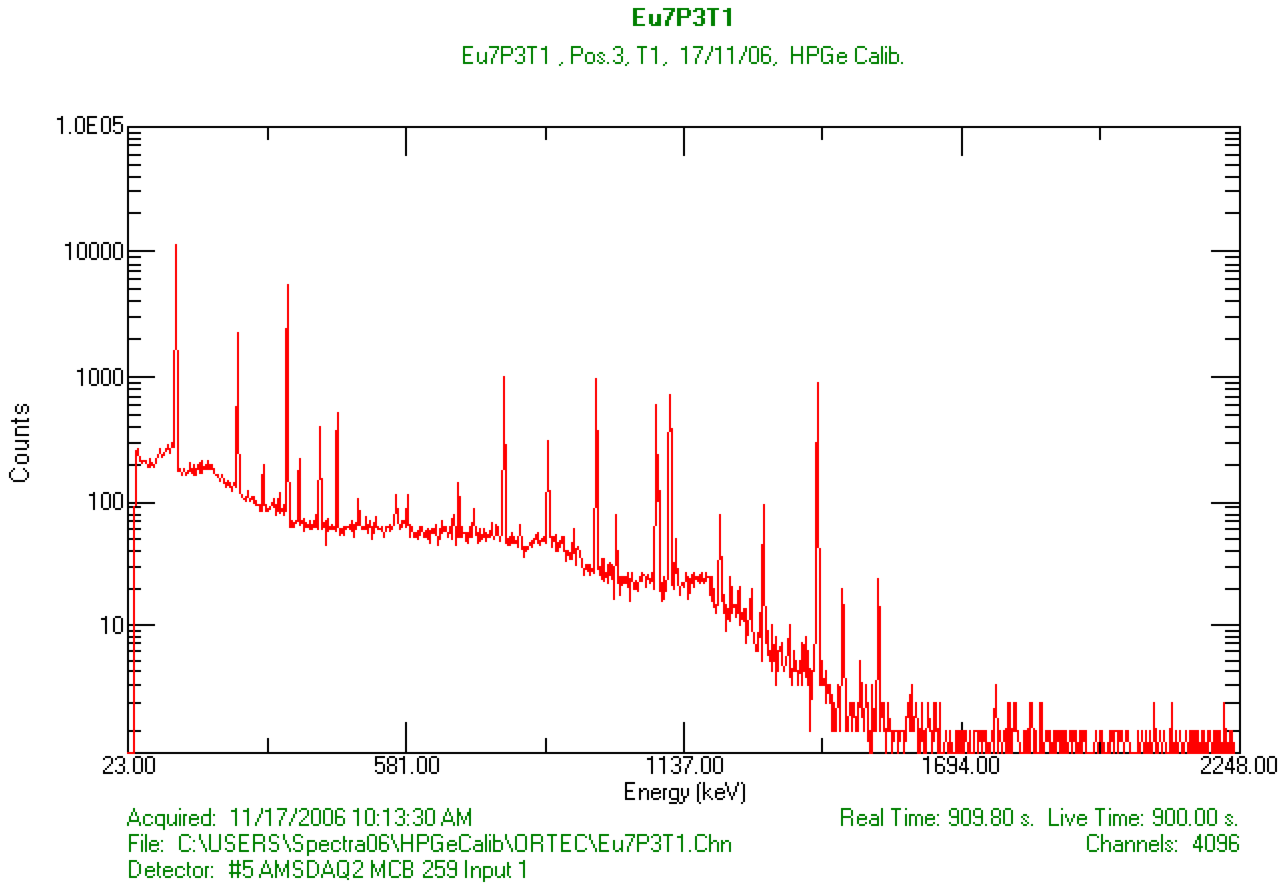


HPGe gamma ray spectrometry at Pohang Neutron Facility



The HPGe gamma ray spectrometry at PNF

1: High-Purity Coaxial Germanium detector (HPGe),
(ORTEC, Model GEM-20180-p, Serial No. 39-TP21360A);
2: Preamplifier (ORTEC, Model 257 P, Serial No. 501);
3: Amplifier (ORTEC-572);
4: 4-Input Multichannel Buffer, Spectrum Master-919, (ORTEC);
5: Computer (Maestro, GammaVision)
6: Bias supply (High Voltage: +2000 v) (ORTEC - 659)



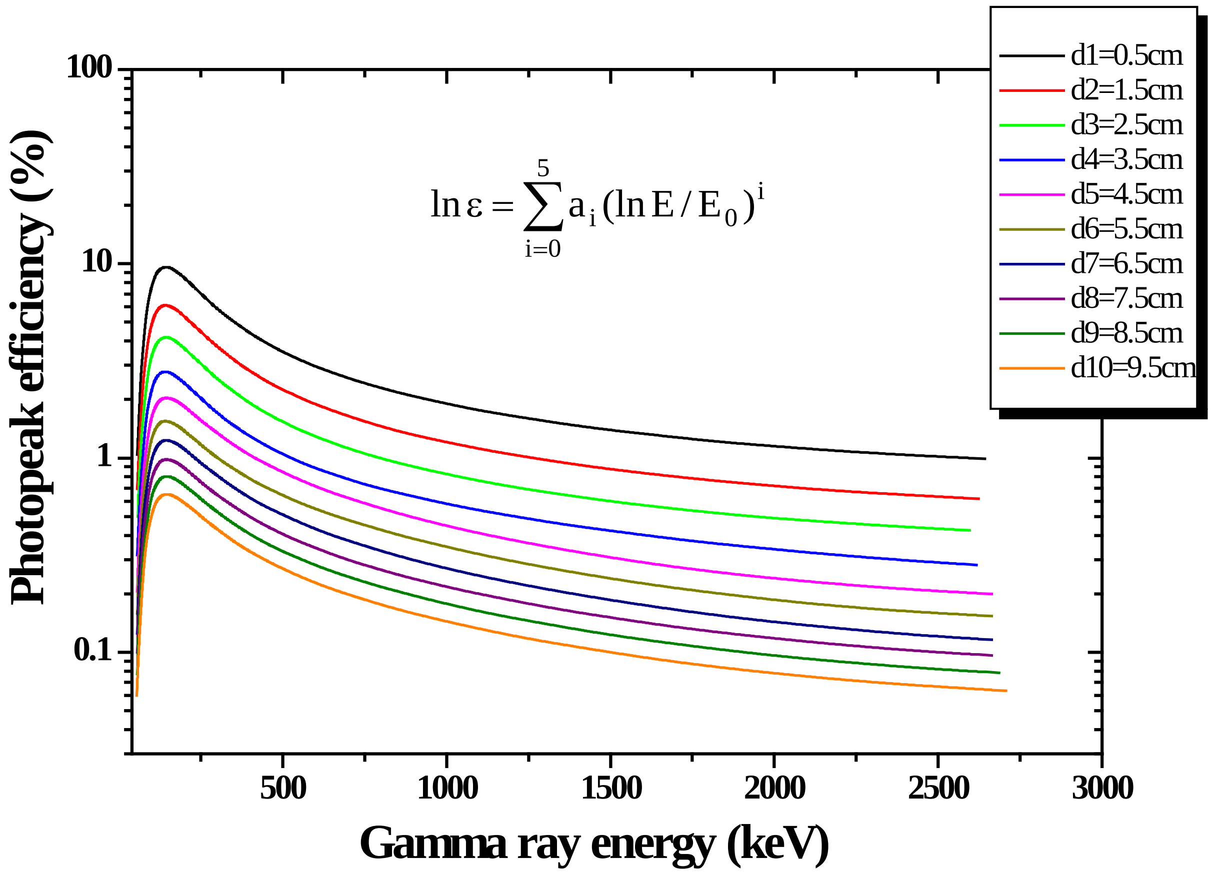
Gamma ray spectrum of Eu -152 standard source

Fitted function:

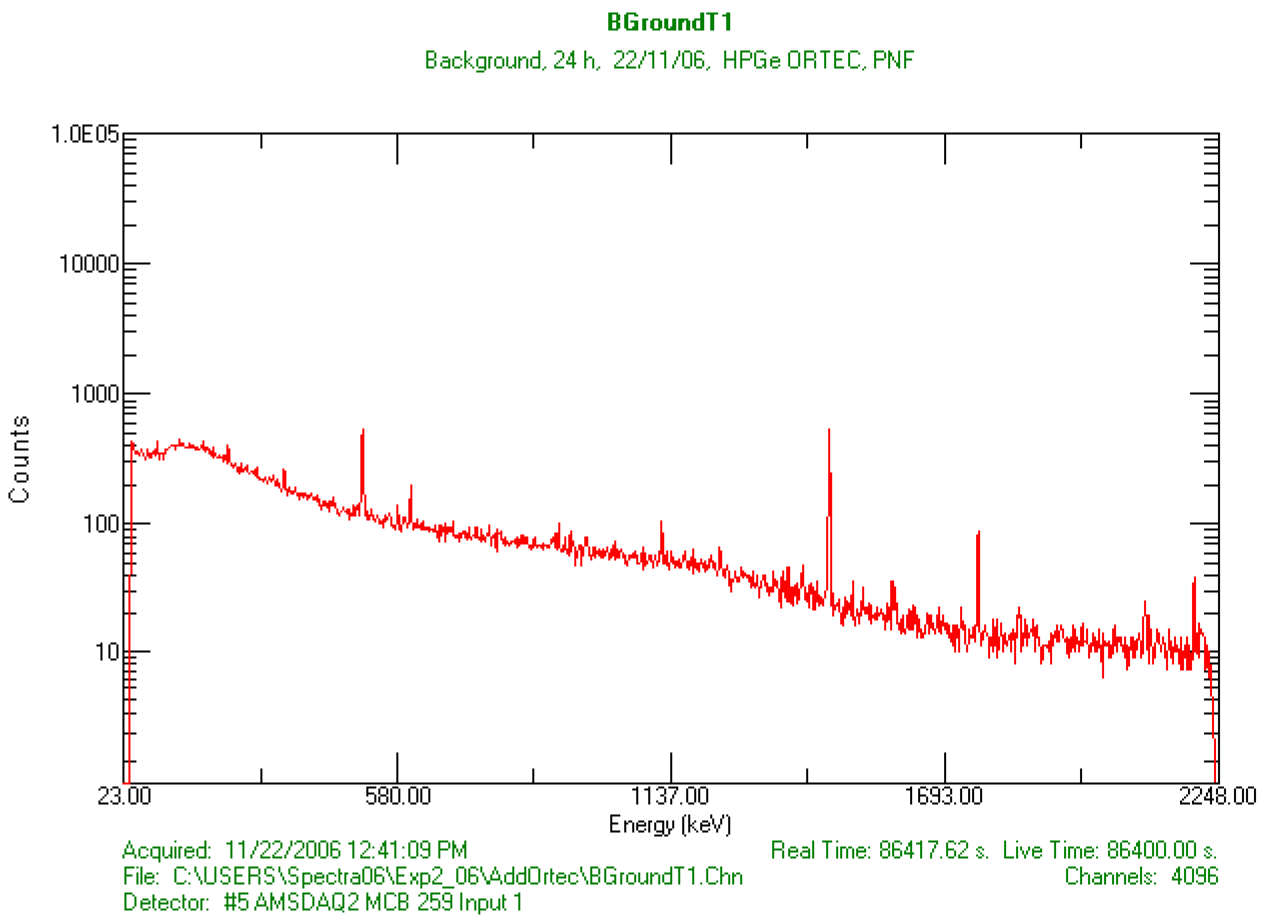
$$\ln \varepsilon = \sum_{i=0}^{5} a_i (\ln E / E_0)^i$$

where: ε is the photopeak efficiency, E is the energy of gamma rays , E_0 =1 keV, a_i are the fitted parameters (table).

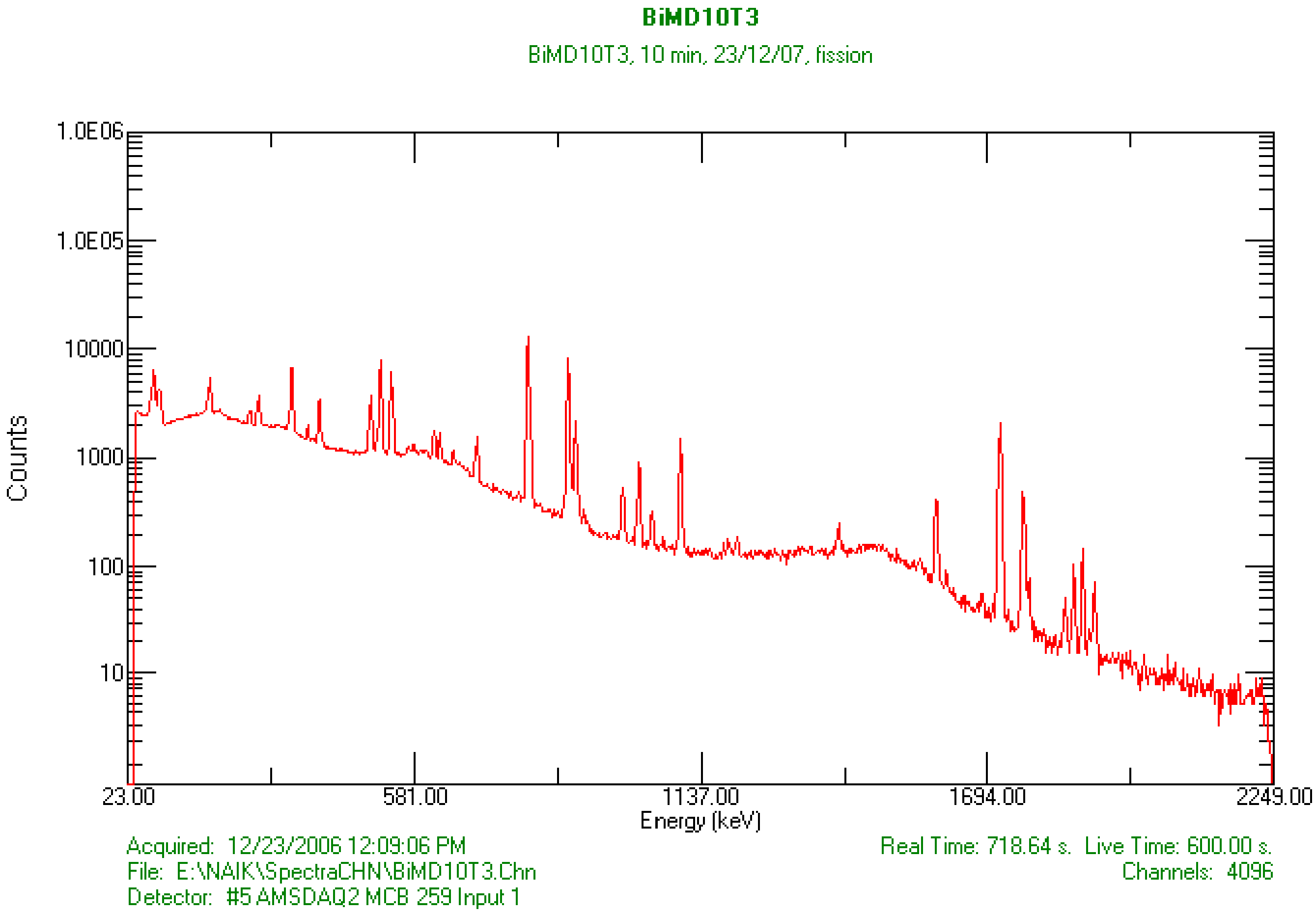
	a_0	a_1	a_2	a_3	a_4	a_5
d.1	-411.37319	315.22548	-95.08567	14.24046	-1.06305	0.03168
d.2	-417.57234	320.37942	-96.90733	14.55737	-1.09020	0.0326
d.3	-417.96005	320.38679	-96.90982	14.55779	-1.09024	0.0326
d.4	-435.20896	334.39162	-101.42241	15.25921	-1.14251	0.03408
d.5	-455.08566	354.59551	-109.53849	16.84068	-1.29183	0.03955
d.6	-488.13482	382.91111	-119.1308	18.4348	-1.42196	0.04373
d.7	-447.77322	347.36001	-106.88759	16.36013	-1.24873	0.03802
d.8	-442.22509	342.2072	-105.07934	16.04863	-1.22243	0.03715
d.9	-442.45108	342.22748	-105.086	16.04976	-1.22254	0.03716
d.10	-442.64593	342.2153	-105.0821	16.0491	-1.22251	0.03716



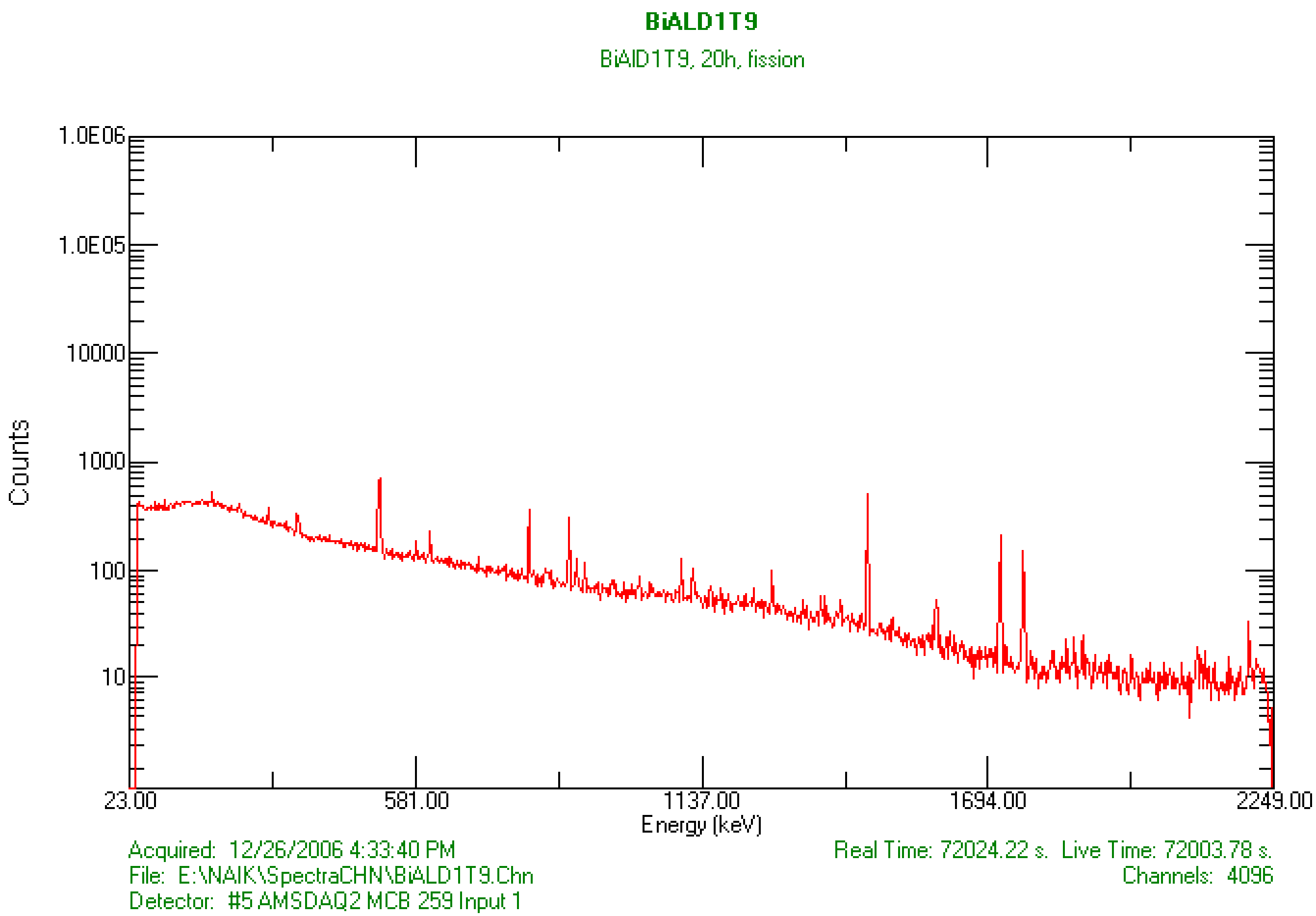
Photopeak efficiency of HPGe detector (ORTEC) at Pohang (dia. 3 mm)



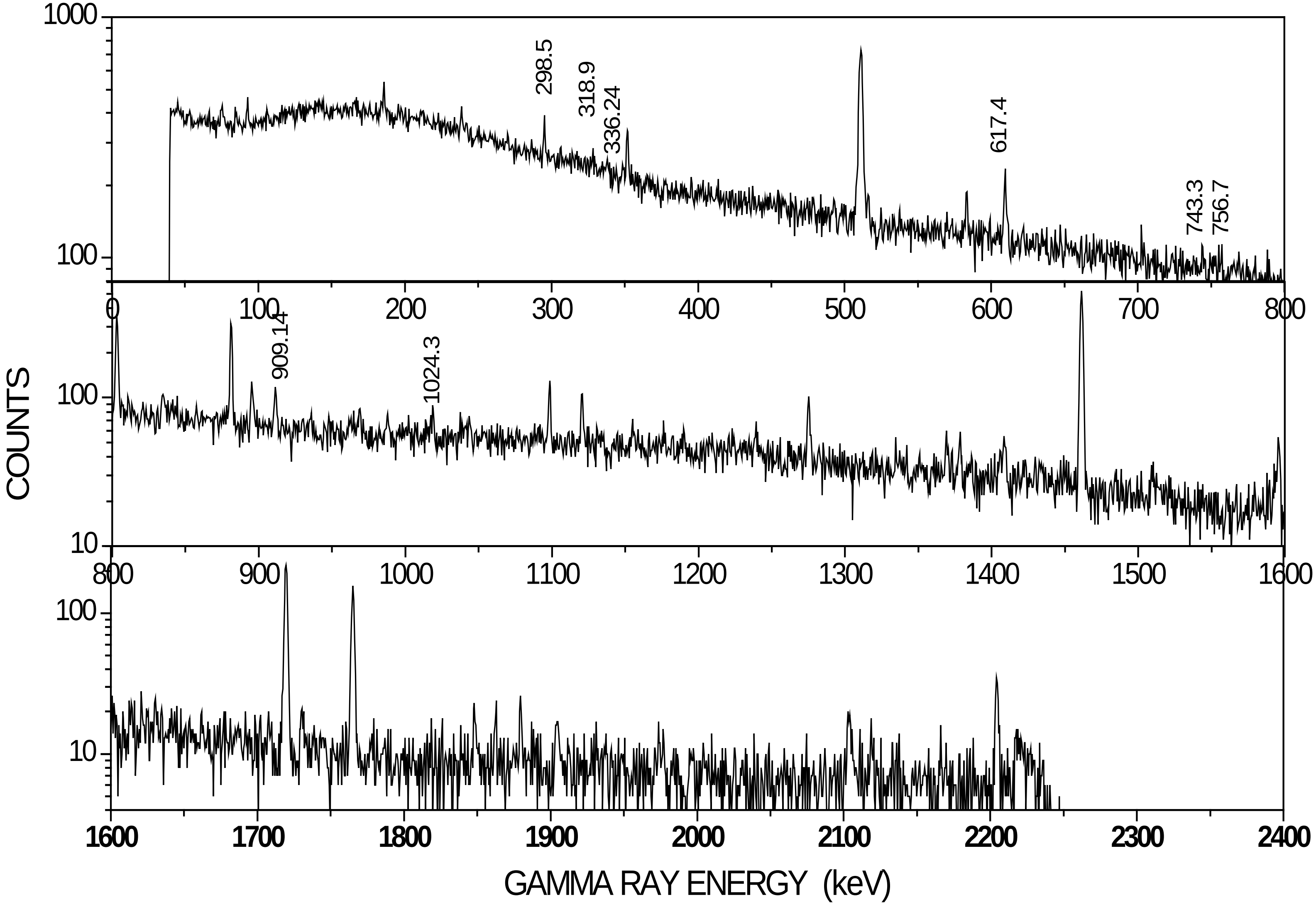
Gamma ray spectrum of background (counting time: 24 h)



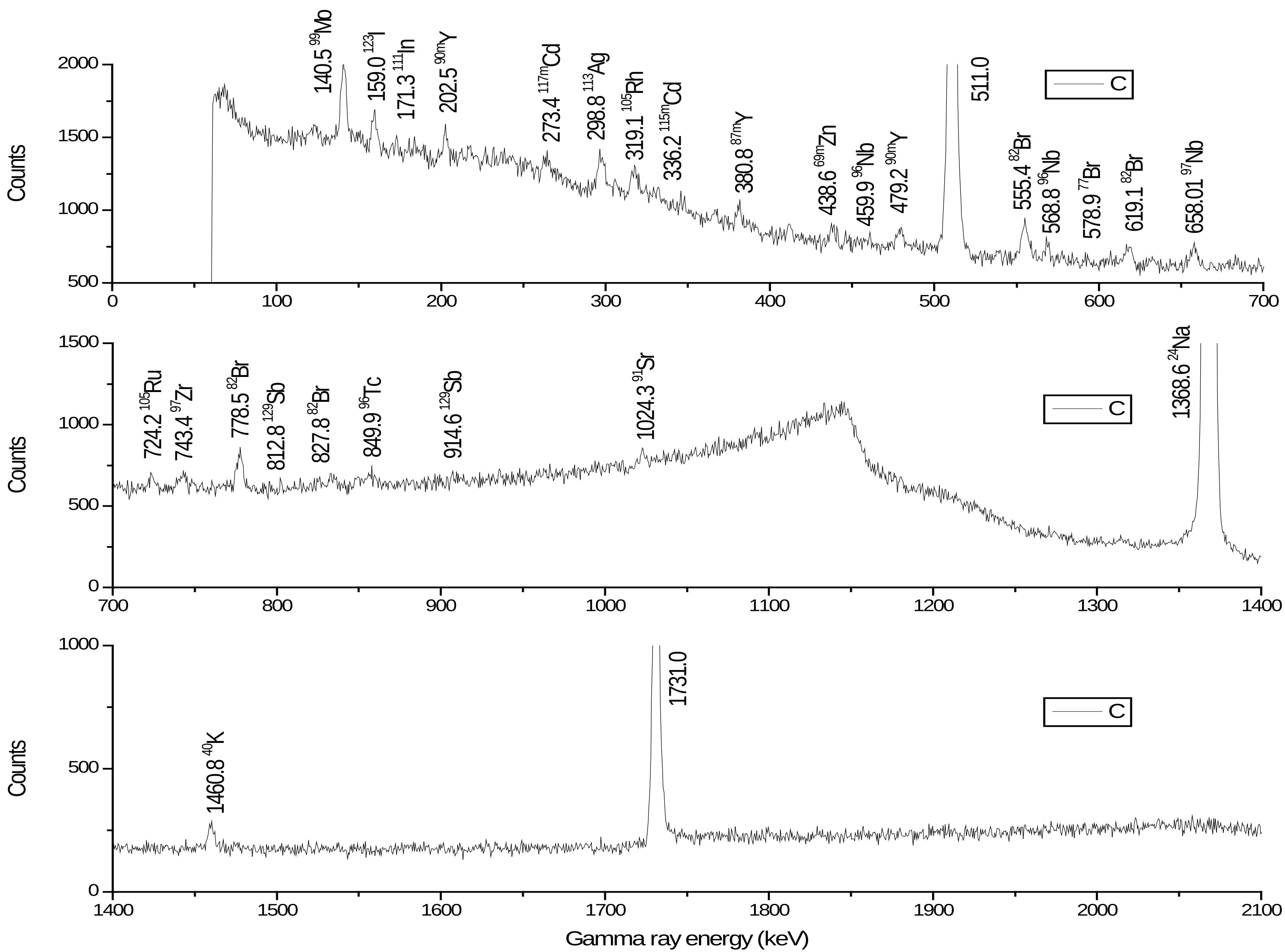
Gamma ray spectrum of irradiated Bi sample



Gamma ray spectrum from Al catcher



COUNTS
GAMMA RAY ENERGY (keV)
1000
100
10
298.5
318.9
336.24
617.4
743.3
756.7
909.14
1024.3
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400


Counts
0
100
200
300
400
500
600
700
500
1000
1500
2000
140.5 ^{99}Mo
159.0 ^{123}I
171.3 ^{111}In
202.5 ^{90m}Y
273.4 ^{117m}Cd
298.8 ^{113}Ag
319.1 ^{105}Rh
336.2 ^{115m}Cd
380.8 ^{87m}Y
438.6 ^{69m}Zn
459.9 ^{96}Nb
479.2 ^{90m}Y
511.0
555.4 ^{82}Br
568.8 ^{96}Nb
578.9 ^{77}Br
619.1 ^{82}Br
658.01 ^{97}Nb
C
Counts
700
800
900
1000
1100
1200
1300
1400
0
500
1000
1500
724.2 ^{105}Ru
743.4 ^{97}Zr
778.5 ^{82}Br
812.8 ^{129}Sb
827.8 ^{82}Br
849.9 ^{96}Tc
914.6 ^{129}Sb
1024.3 ^{91}Sr
1368.6 ^{24}Na
C
Counts
1400
1500
1600
1700
1800
1900
2000
2100
0
500
1000
1460.8 ^{40}K
1731.0
C
Gamma ray energy (keV)

CALCULATIONS OF FISSION PRODUCTS YIELDS

- From the photo-peak activities of the gamma lines, Yields of fission products (Y) were obtained using decay equation

$$A_i = N\sigma\Phi Y a\varepsilon\ [1- \exp(-\lambda t) \exp(-\lambda T)$$

N = Number of target atoms
σ = fission cross section 1.0×10^{-4}
Φ = photon flux
a = gamma ray abundance
E = efficiency of the detector
t = irradiation time
T = Cooling ttime

-Yields of fission products (Y) relative to fission products ^{103}Ru
-Absolute yields of fission products obtained after normalizing the total yield to 200 %

CALCULATION OF EXCITATION ENERGY

-The average excitation energy (E_{exc}) of compound nucleus corresponding with end point energy (E_e)

$$E_{exc}(E_e) = \frac{\int E\, N(E_e, E)\, \sigma(E)\, dE}{\int N(E_e, E)\, \sigma(E)\, dE}$$

$N(E_e, E)$ = bremsstrahlung spectra

σ_f = photo-fission cross section

E_e (MeV) =	8.0	10.0	12.0	15.0	20.0	30.0	70.0
E_{exc} (MeV) =	6.53	7.6	9.4	11.3	12.6	13.3	20.63

NUCLEAR SPECTROSCOPY DATA OF FISSION PRODUCTS AND THEIR CUMULATIVE YIELDS IN 65 MeV (γ,F) OF 209-Bi

Nuclide	Half life	γ ray energy keV	abundance (%)	Cumulative Yields (%)
^{89}Zr	78.41 h	909.1	99.87	0.314 ± 0.058
^{91}Sr	9.5 h	1024.3	33.4	0.443 ± 0.082
^{95}Zr	64.02 d	724.2	44.17	0.723 ± 0.069
		756.7	54.46	0.693 ± 0.087
^{97}Zr	16.9 h	743.3	92.8	0.857 ± 0.091
^{99}Mo	2.748 d	140.3	90.7	-
		739.4	12.1	0.934 ± 0.129
^{103}Ru	39.254 d	497.1	88.7	1.0
^{105}Rh	35.36 h	318.9	19.2	0.969 ± 0.013
^{112}Ag	3.13 h	606.7	3.096	0.675 ± 0.156
		617.4	43.0	0.627 ± 0.172
^{113}Ag	5.37 h	298.5	10.0	0.879 ± 0.189
$^{115}Cd^{g}$	53.46 h	336.2	45.9	0.471 ± 0.021
$^{117}Cd^{m}$	3.36 h	1066.0	23.056	0.090 ± 0.017
$^{117}Cd^{g}$	2.49 h	273.4	27.7	0.144 ± 0.015

Nuclear spectroscopic data and yields of fission products in the 65 MeV bremsstrahlung induced fission of ^{209}Bi.

Nuclide	Half life	γ-ray energy (keV)	γ-ray abundance (%)	Yield of fission product (%)	
				Relative	Absolute
^{89}Zr	78.41 h	909.14	99.87	0.314 ± 0.058	2.668 ± 0.493
^{91}Sr	9.63 h	1024.3	33.4	0.443 ± 0.082	3.764 ± 0.697
$^{92}Sr^{*}$	2.71 h	1383.93	90.0	0.365 ± 0.073	3.096 ± 0.619
^{95}Zr	64.02 d	724.2	44.17	0.723 ± 0.069	6.143 ± 0.586
		756.7	54.46	0.693 ± 0.087	5.888 ± 0.739
^{97}Zr	16.91 h	743.3	93.06	0.857 ± 0.091	7.281 ± 0.773
^{99}Mo	65.94 h	739.5	12.13	0.934 ± 0.129	7.935 ± 1.096
^{103}Ru	39.26 d	497.08	91.0	1.0 ± 0.01	8.496 ± 0.850
$^{105}Ru^{*}$	4.44 h	724.3	47.3	0.889 ± 0.196	7.548 ± 1.662
^{105}Rh	35.36 h	318.9	19.2	0.959 ± 0.013	8.148 ± 0.110
^{112}Ag	3.13 h	606.7	3.096	0.675 ± 0.056	5.735 ± 0.476
		617.4	43.0	0.627 ± 0.172	5.327 ± 1.461
^{113}Ag	5.37 h	298.6	10.0	0.579 ± 0.189	4.919 ± 0.606
^{115g}Cd	53.46 h	336.24	45.9	0.471 ± 0.021	4.002 ± 0.178
^{117m}Cd	3.36 h	1065.98	23.056	0.090 ± 0.017	0.765 ± 0.144
^{117g}Cd	2.49 h	273.35	27.9	0.144 ± 0.015	1.223 ± 0.127

Table 2. Nuclear spectroscopic data and cumulative yields of fission products in the 2.5 GeV bremsstrahlung induced fission of 209Bi.

S. No.	Nuclide	Half life	γ-ray energy (keV)	γ-ray abundance (%)	Yield of fission product (%) Relative	Absolute
1.	47Sc	3.349 d	159.38	68.3	0.164 ±0.012	0.524 ±0.038
2.	48V	15.974 d	983.52	99.98	0.148 ±0.010	0.473 ±0.032
3.	59Fe	44.503 d	1099.25	56.52	0.247 ±0.047	0.790 ±0.150
4.	69Znm	13.76 h	438.63	94.72	0.192 ±0.034	0.614 ±0.109
5.	72Zn	46.5 h	191.96	9.37	0.410 ±0.018	1.311 ±0.058
6.	75Se	119.779 d	264.66	58.3	0.628 ±0.019	2.008 ±0.061
7.	77Br	57.036 h	578.85	2.96	0.536 ±0.011	1.714 ±0.035
8.	83Rb	86.2 d	529.635	29.3	0.791 ±0.143	2.529 ±0.457
9.	85Krm	24.48 h	304.87	14.0	0.514 ±0.021	1.643 ±0.067
10.	87Y	79.8 h	388.53	82.0	0.744 ±0.011	2.379 ±0.035
11.	87Ym	13.37 h	380.79	78.0	0.244 ±0.073	0.780 ±0.233
12.	88Kr	2.84 h	196.3	25.98	1.070 ±0.210	3.421 ±0.671
13.	88Zr	83.4 d	392.87	97.0	0.821 ±0.102	2.625 ±0.326
14.	89Zr	89.41 h	908.96	100.0	1.077 ±0.328	3.443 ±1.049
15.	91Sr	9.63 h	1024.3	33.4	1.081 ±0.184	3.456 ±0.588
			749.8	23.61	1.018 ±0.158	3.255 ±0.505
16.	92Sr	2.71 h	1383.93	90.3	0.767 ±0.180	2.452 ±0.575
17.	95Zr	64.02 d	756.7	64.46	1.261 ±0.213	4.031 ±0.681
			724.2	44.17	1.015 ±0.058	3.245 ±0.185
18.	95Tcm	161 d	582.08	29.96	0.219 ±0.044	0.700 ±0.141
19.	97Zr	16.91 h	743.36	92.8	1.044 ±0.209	3.338 ±0.668
20.	99Mo	2.458 d	140.14	89.43	1.022 ±0.176	3.267 ±0.563
			739.34	12.17	0.934 ±0.219	2.986 ±0.700

Table 2. continued

S. No.	Nuclide	Half life	γ-ray energy (keV)	γ-ray abundance (%)	Yield of fission product (%) Relative	Absolute
21.	101mRh	4.34 d	306.86	81.0	0.265 ±0.034	0.847 ±0.109
22.	103Ru	39.254 d	497.08	90.9	1.0 ± 0.01	3.197 ±0.032
23.	105Ru	4.44 h	724.21	47.0	0.853 ±0.176	2.727 ±0.563
			676.56	15.7	0.787 ±0.044	2.516 ±0.141
24.	105Rh	35.36 h	319.14	19.2	0.933 ±0.105	2.983 ±0.336
25.	105Ag	41.29 d	344.52	41.0	0.270 ±0.071	0.863 ±0.227
26.	111Ag	7.45 d	342.17	7.0	0.787 ±0.044	2.516 ±0.141
27.	111In	2.805 d	171.28	90.0	0.139 ±0.026	0.444 ±0.083
28.	112Ag	3.13 h	617.4	43.6	0.711 ±0.177	2.273 ±0.566
29.	115gCd	53.46 h	336.24	45.9	0.651 ±0.168	2.081 ±0.537
			527.9	27.45	0.664 ±0.093	2.122 ±0.297
30.	117mCd	3.36 h	1065.98	23.056	0.248 ±0.050	0.793 ±0.160
31.	117gCd	2.49 h	273.35	27.7	0.398 ±0.102	1.272 ±0.326
32.	121mTe	154 d	212.9	81.0	0.342 ±0.068	1.093 ±0.217
33.	121Te	116.78 d	573.13	80.3	0.145 ±0.015	0.464 ±0.048
34.	123gTe	40.06 m	160.33	86.0	0.509 ±0.102	1.627 ±0.326
35.	129Sb	4.32 h	812.8	43.0	0.364 ±0.114	1.164 ±0.364

Table 3. Nuclear data and cumulative yields of fission products in the 10 MeV bremsstrahlung induced fission of ^{240}Pu.

S. No.	Nuclide	Half life	γ-ray energy (keV)	γ-ray abundance (%)	Yield of fission product (%) Relative	Absolute
1.	$^{85}Kr^{m}$	4.48 h	304.87	14.0	0.200 ±0.050	0.858 ±0.215
2.	^{87}Kr	76.3 m	402.59	49.6	0.324 ±0.036	1.390 ±0.154
3.	^{88}Kr	2.84 h	196.3	25.98	0.451 ±0.111	1.935 ±0.476
4.	^{91}Sr	9.63 h	749.8	23.61	0.660 ±0.083	2.832 ±0.356
			1024.3	33.4	0.654 ±0.093	2.806 ±0.399
5.	^{92}Sr	2.71 h	1383.93	90.3	0.656 ±0.089	2.815 ±0.382
6.	^{95}Zr	64.02 d	756.7	64.46	0.851 ±0.026	3.652 ±0.112
7.	^{97}Zr	16.91 h	743.36	92.8	1.035 ±0.134	4.441 ±0.575
8.	^{99}Mo	2.458 d	140.51	89.43	1.719 ±0.229	7.375 ±0.982
			739.5	12.13	1.888 ±0.347	7.375 ±1.489
9.	^{103}Ru	39.254 d	497.08	90.9	1.964 ±0.385	8.428 ±1.652
10.	^{105}Ru	4.44 h	724.2	47.0	0.882 ±0.025	3.784 ±0.107
11.	^{105}Rh	35.36 h	319.14	19.0	1.034 ±0.228	4.437 ±0.978
12.	^{112}Ag	3.13 h	617.4	43.6	0.130 ±0.020	0.558 ±0.086
13.	$^{115}Cd^{g}$	53.46 h	336.24	45.9	0.056 ±0.007	0.240 ±0.030
14.	$^{117}Cd^{m}$	3.36 h	1065.98	23.1	0.030 ±0.005	0.129 ±0.021
15.	$^{117}Cd^{g}$	2.49 h	273.35	28.0	0.015 ±0.005	0.064 ±0.021

Table 3.continued

S. No.	Nuclide	Half life	γ-ray energy (keV)	γ-ray abundance (%)	Yield of fission product (%) Relative	Absolute
16.	^{127}Sb	3.85 d	685.7	37.0	0.276 ±0.029	1.184 ±0.124
17.	^{128}Sn	59.07 m	482.3	59.0	0.340 ±0.026	1.459 ±0.112
18.	^{129}Sb	4.32 h	812.8	43.0	0.412 ±0.072	1.768 ±0.309
19.	^{131}I	8.04 d	364.49	81.7	0.770 ±0.154	3.304 ±0.661
20.	^{132}Te	76.896 h	228.16	88.0	0.897 ±0.030	3.849 ±0.129
21.	^{133}I	20.8 h	529.87	87.0	1.269 ±0.108	5.445 ±0.463
22.	^{134}Te	41.8 m	566.0	18.6	1.890 ±0.187	8.108 ±0.802
			767.2	29.5	1.706 ±0.184	7.319 ±0.789
23.	^{134}I	52.5 m	847.3	95.4	2.441 ±0.360	10.472±1.544
			884.09	64.9	2.369 ±0.574	10.163±2.462
24.	^{135}I	6.57 h	1260.41	28.9	1.336 ±0.049	5.733 ±0.210
25.	^{138}Cs	33.41m	1435.8	76.3	1.769 ±0.052	7.591 ±0.223
26.	^{139}Ba	1.384 h	165.86	23.7	1.386 ±0.199	5.947 ±0.854
27.	^{142}La	1.518 h	641.29	47.0	0.851 ±0.026	3.652 ±0.112
28.	^{143}Ce	33.039 h	293.27	42.8	0.764 ±0.175	3.278 ±0.751

ERROR ANALYSIS

NATURE	SOURCE OF ERROR	% OF ERROR
(a) Random	(I) Counting statistics	3-4
	(ii) Irradiation time	1-1.5
	(iii) Rate of fission ($R=n\sigma\varphi$)	5-7
	(iv) Least sqare analysis)	5-7
	Total (σ_R)	7.8-10.8
(b) Systematics	(i) Half-lives	1
	(ii) Gamma ray abundance	2
	(iii) Branching ratio (abundance)	2-5
	(iv) Detector efficiency	5
	(v) Precursor yields	4-5
	Total (σ_S)	7-9

Upper limit (σ_t) of error in single measurement is given as

σ_T = Square root of ($\sigma_R^2 + \sigma_S^2$) =10.5-15 %

Probable error (σ_P) in single measurement = 0.6745σ_T = 7.4 - 9%

Precissional error in (σ_0) in replicate (n) measurement = 8 – 13%

Standard error(σ_M) of mean value = σ_0/ square root of n = 5-8 %

Quoted error on yields value within 68 % confidence limit =

= Square root of ($\sigma_T^2 + \sigma_M^2$) = 8.6 – 12.4 %

* In all the cases σ^2 are the variance.

RESULTS on Cumulative yields with errors bar are given before.

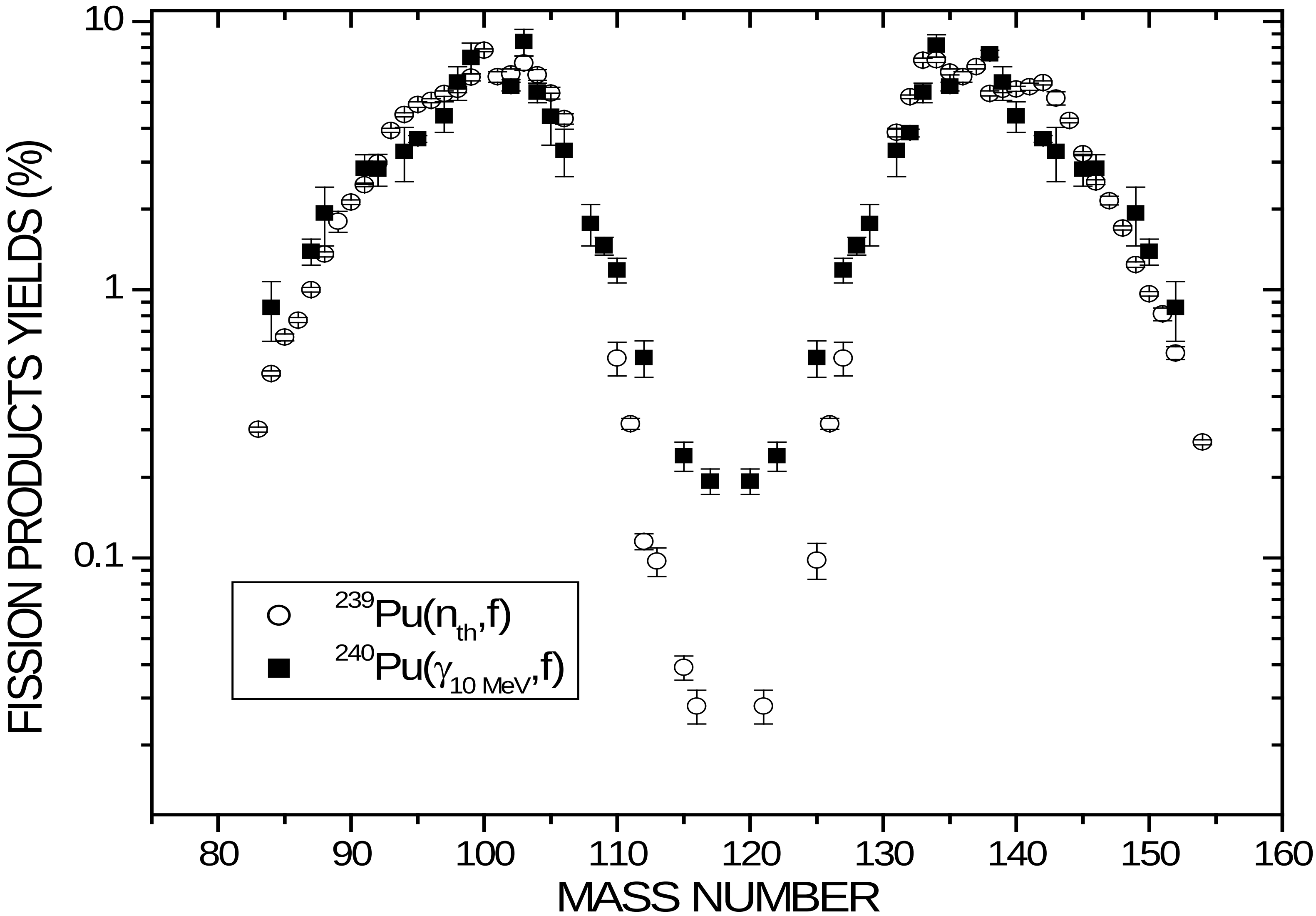
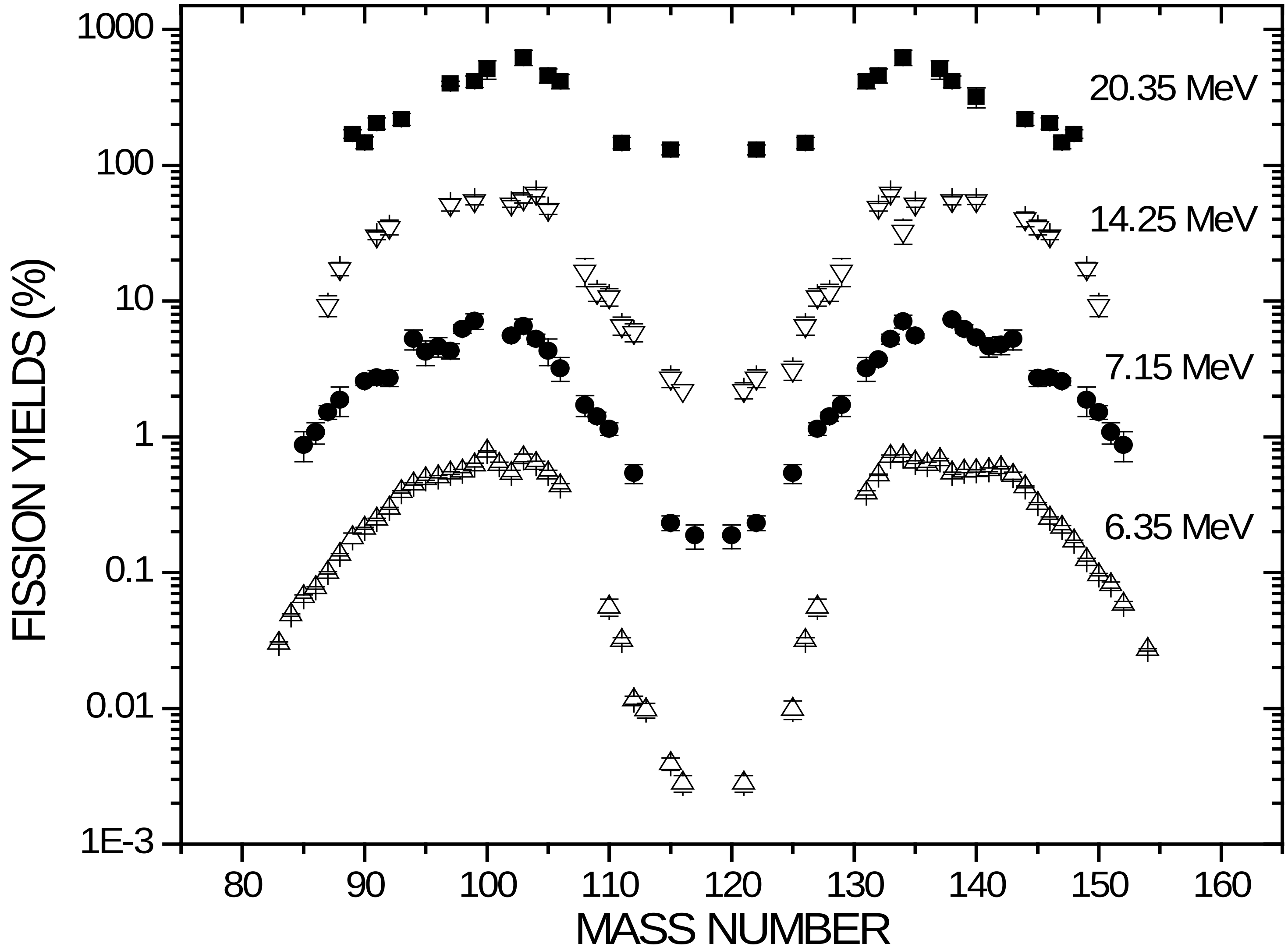
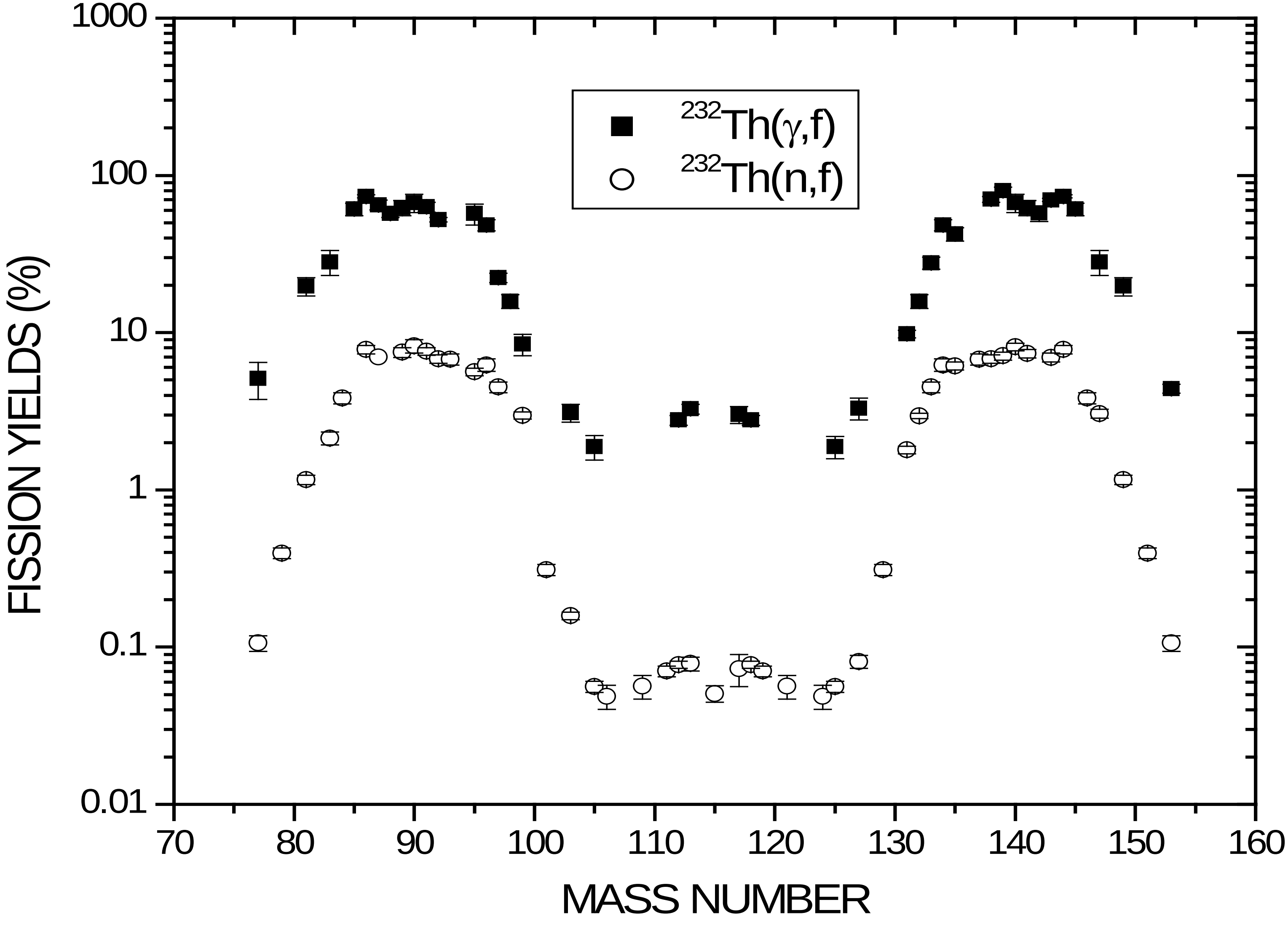


Fig.2. Yields of fission products (%) vs. their mass number



Yields of fission products vs. their mass number in $^{239}Pu(n,f)$ & $^{240}Pu(\gamma,f)$



FISSION YIELDS (%)
1000
100
10
1
0.1
0.01
70
80
90
100
110
120
130
140
150
160
MASS NUMBER
232Th(γ,f)
232Th(n,f)

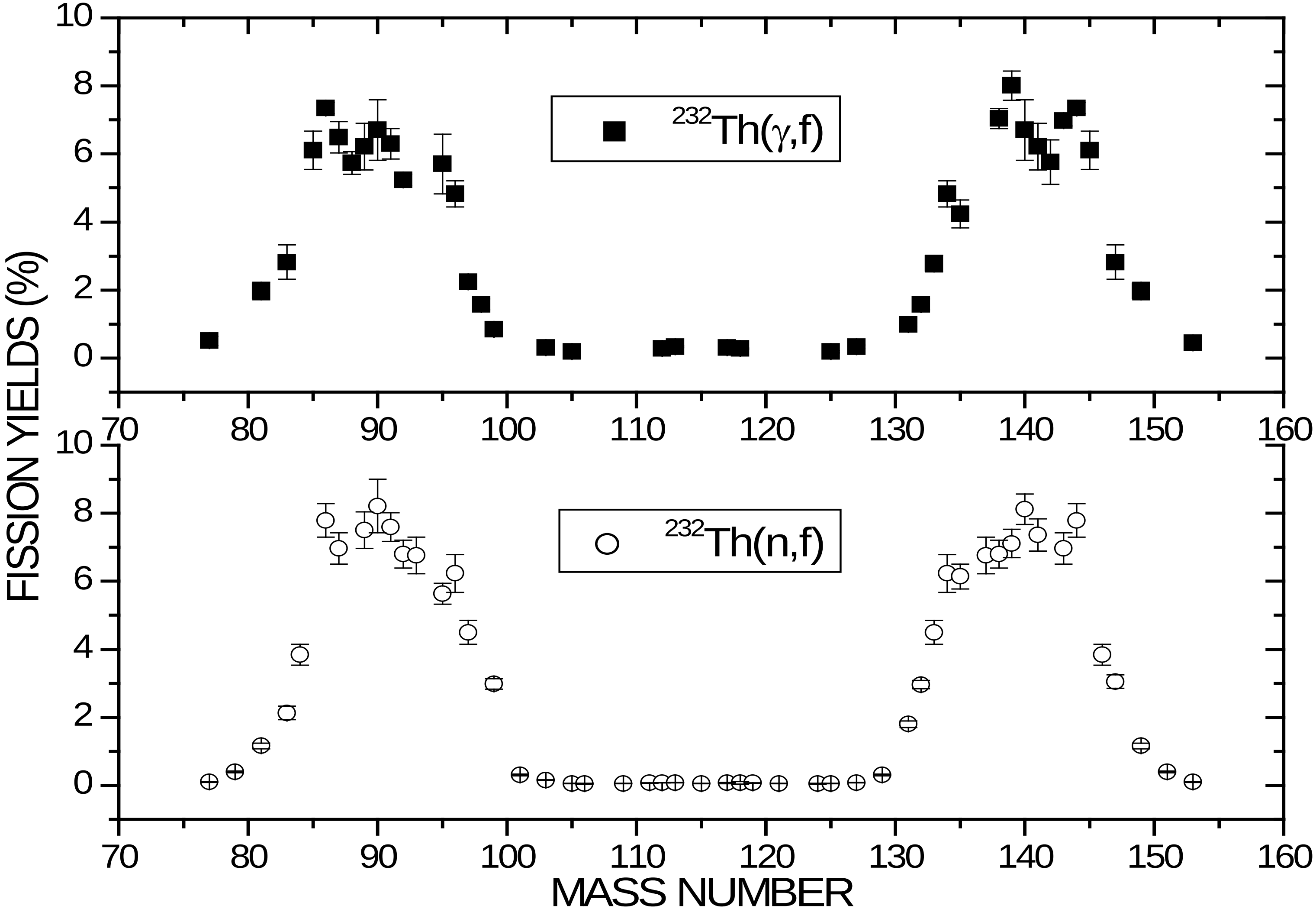
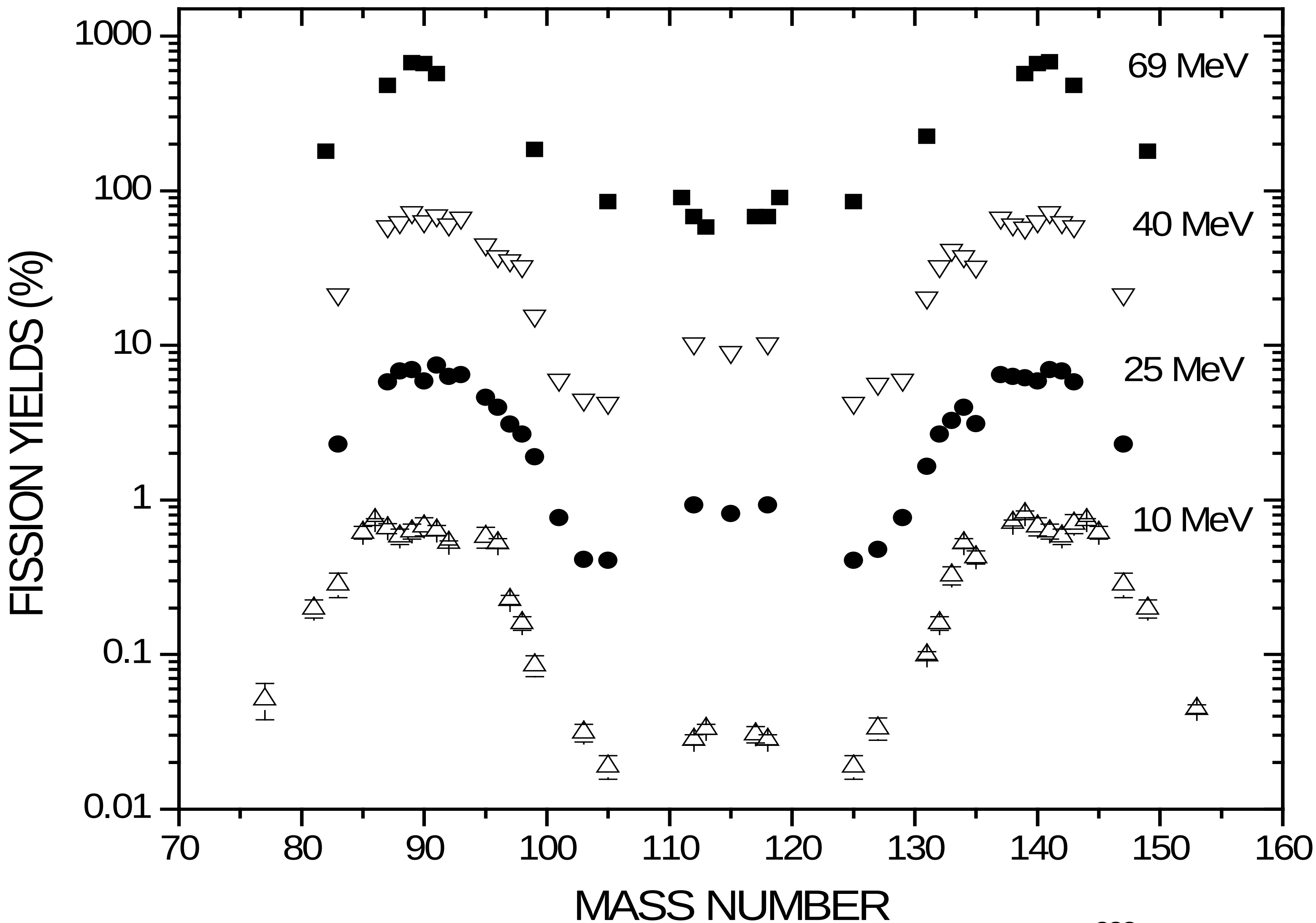
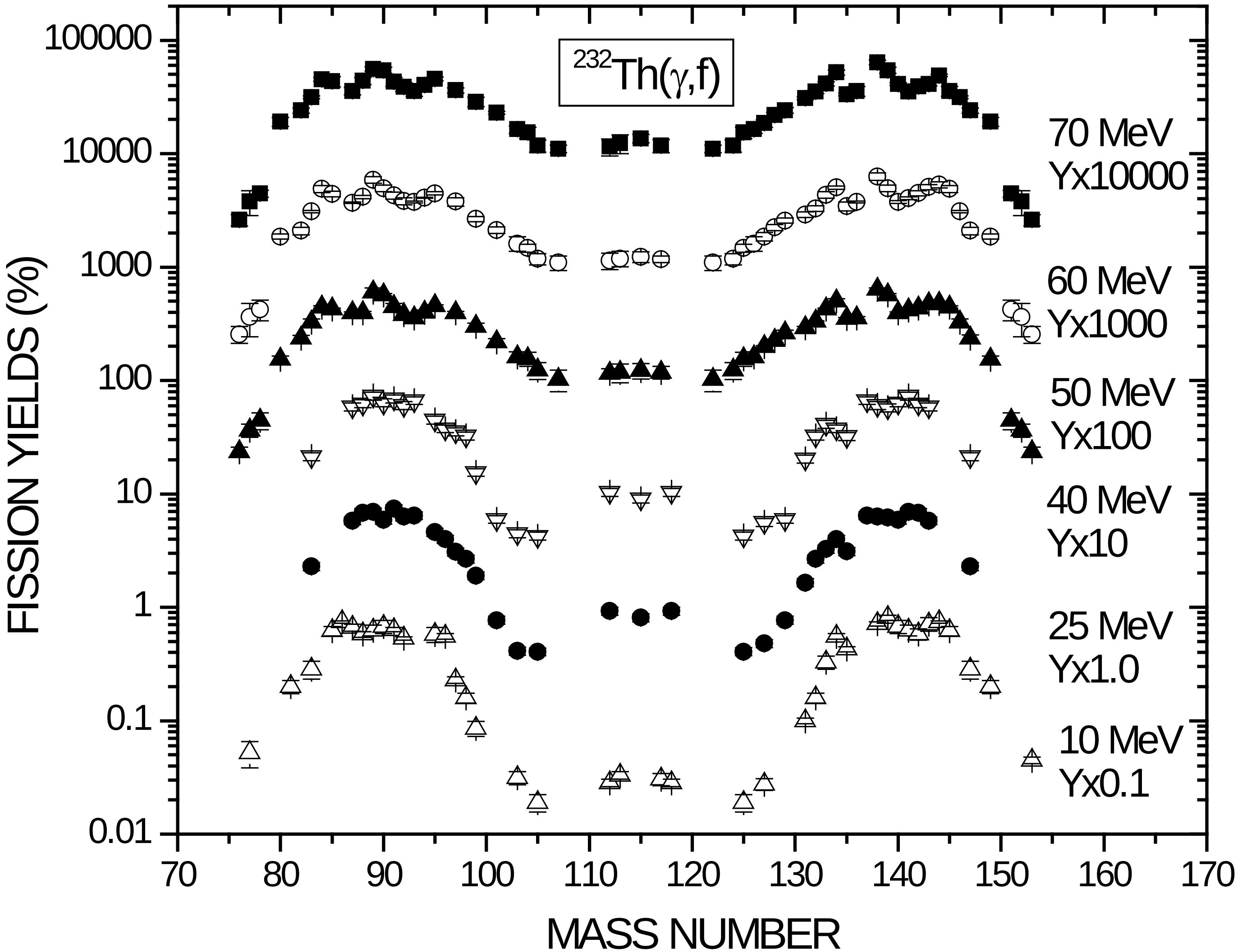


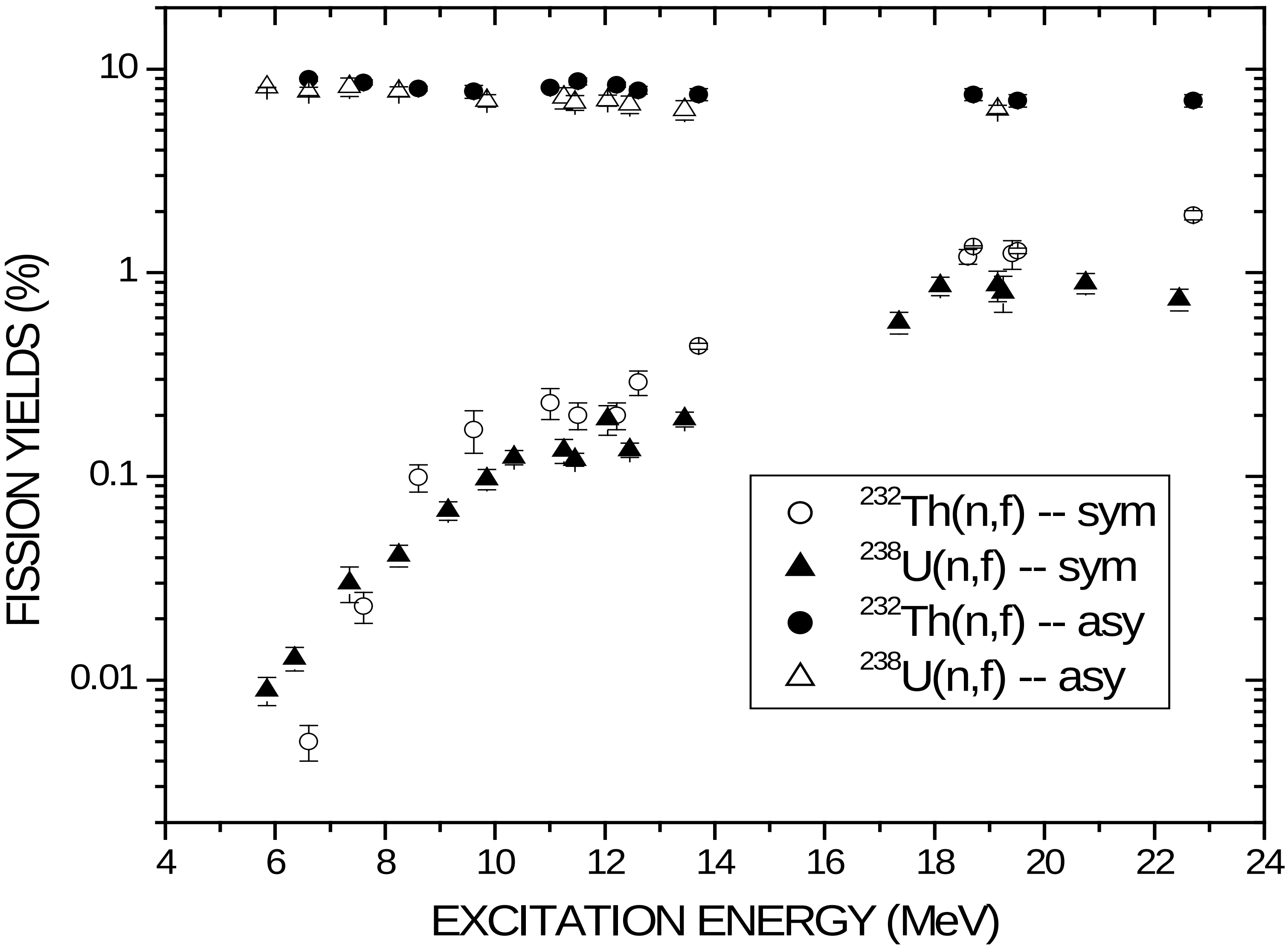
Fig.2. Mass yield distribution in $^{232}Th(\gamma,f)$ and $^{232}Th(n,f)$.



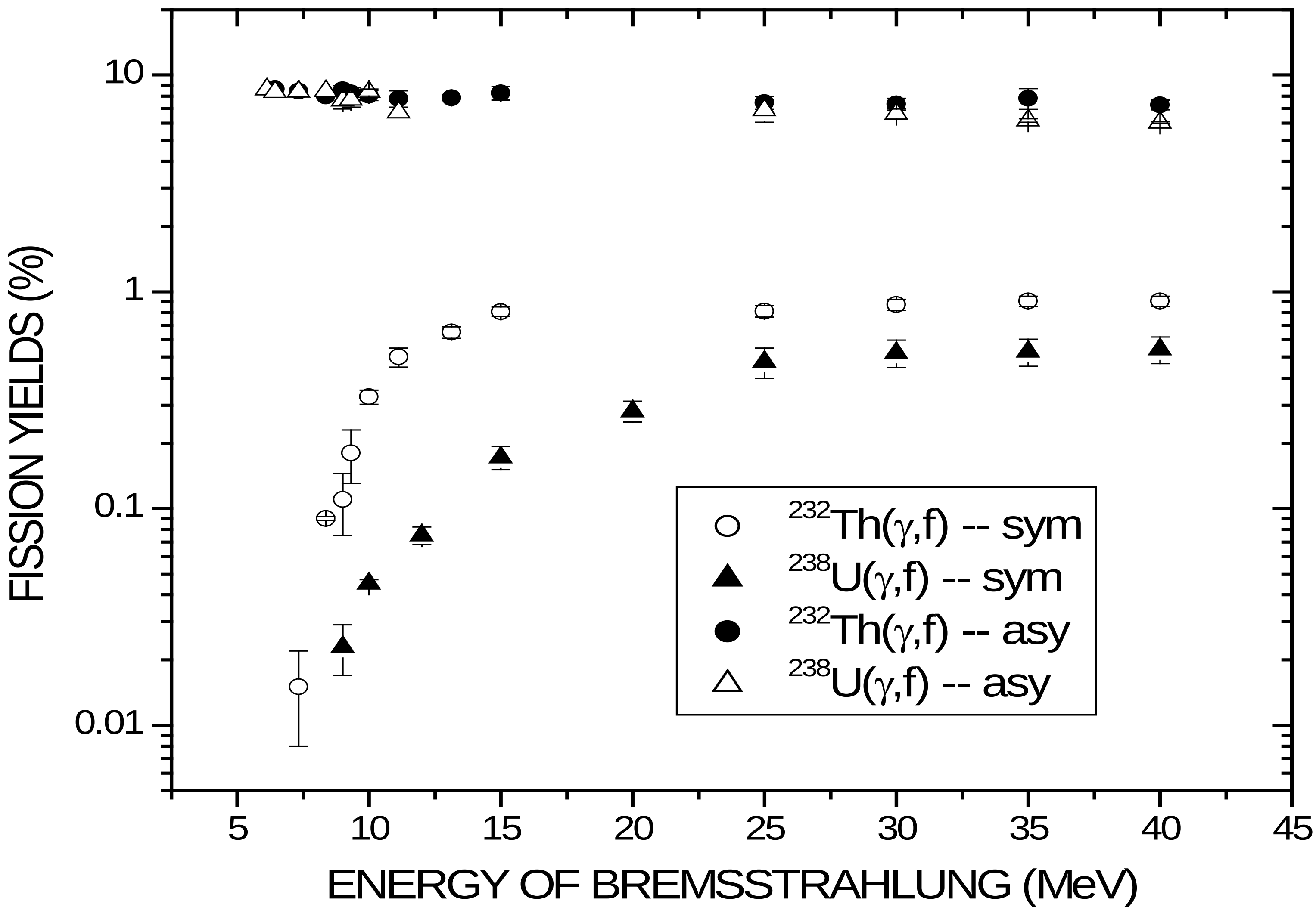
Yields of fission products (%) vs. their mass number in $^{232}Th(\gamma,f)$



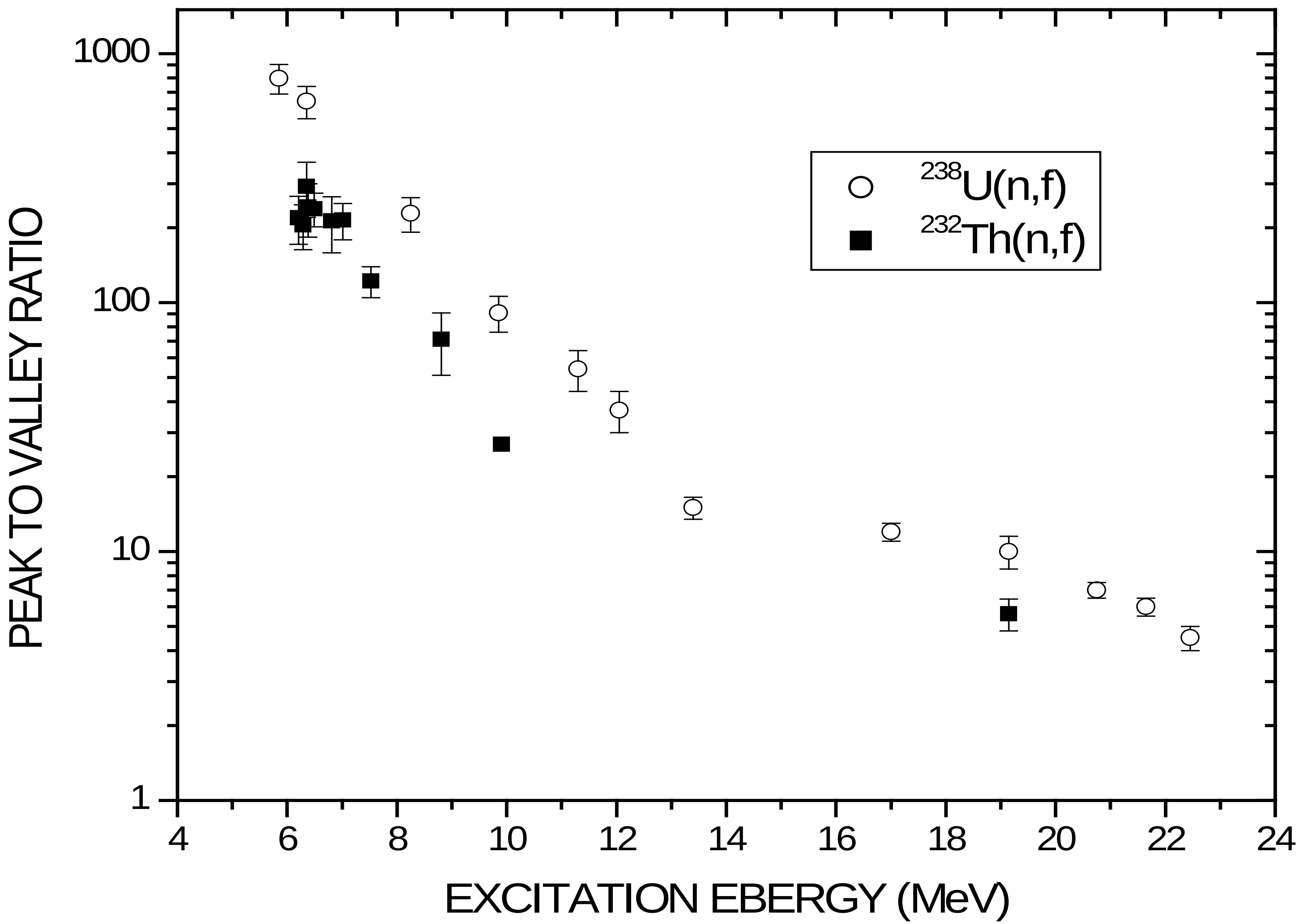
Yields of fission products (%) vs. their mass number in ^{232}Th(γ,f)



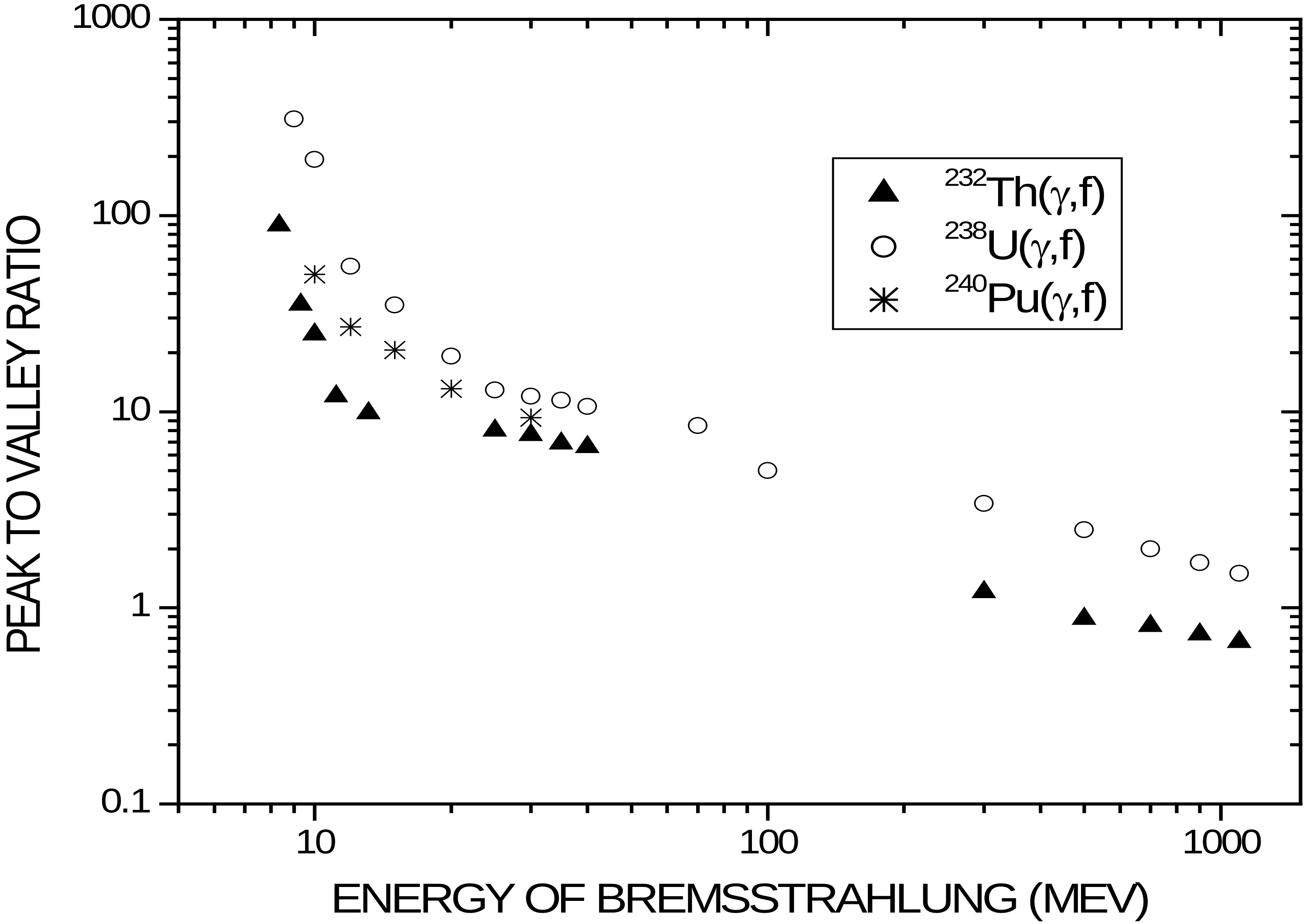
FISSION YIELDS (%)
10
1
0.1
0.01
4
6
8
10
12
14
16
18
20
22
24
EXCITATION ENERGY (MeV)
232Th(n,f) -- sym
238U(n,f) -- sym
232Th(n,f) -- asy
238U(n,f) -- asy



10
1
0.1
0.01
FISSION YIELDS (%)
5
10
15
20
25
30
35
40
45
ENERGY OF BREMSSTRAHLUNG (MeV)
232Th(γ,f) -- sym
238U(γ,f) -- sym
232Th(γ,f) -- asy
238U(γ,f) -- asy



PEAK TO VALLEY RATIO
1000
100
10
1
4
6
8
10
12
14
16
18
20
22
24
EXCITATION EBERGY (MeV)
^{238}U(n,f)
^{232}Th(n,f)


1000
100
10
1
0.1
PEAK TO VALLEY RATIO
10
100
1000
ENERGY OF BREMSSTRAHLUNG (MEV)
$^{232}Th(\gamma,f)$
$^{238}U(\gamma,f)$
$^{240}Pu(\gamma,f)$

DISCUSSION AND CONCLUSION

Yields of 28-35 fission products have been determined in the 10 MeV bremsstrahlung induced fission off ^{232}Th, ^{238}U and ^{240}Pu. The mass distributions are asymmetric in nature as in the case of neutron induced fission.

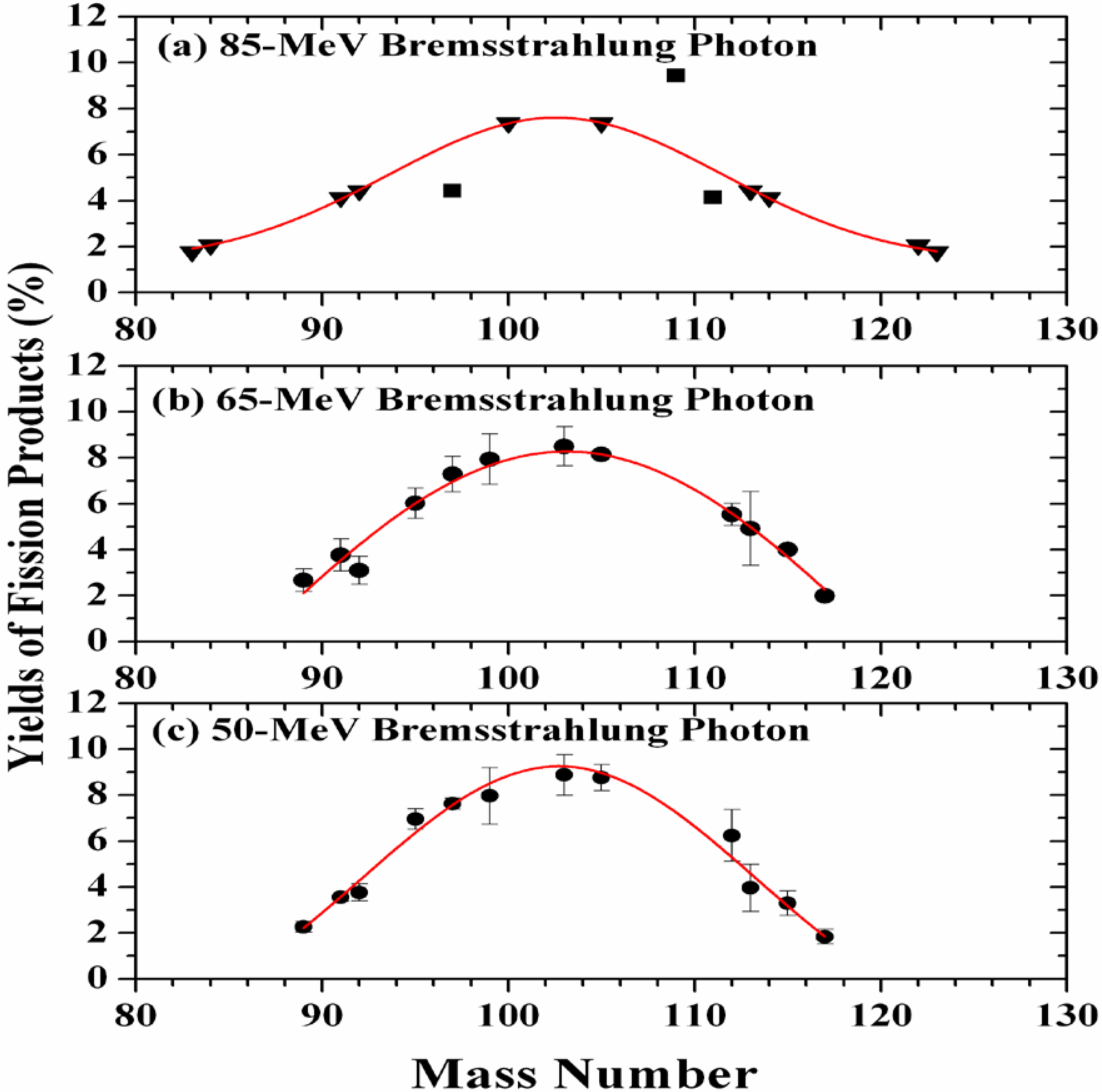
In the case of ^{232}Th, there is third peak around symmetric region as in the case of neutron induced fission of ^{229,232}Th. This is due to the second dip in the outer symmetric barrier, which is called Thorium anomaly.

#The average heavy mass number is 139±1 due to preference of deformed 88n shell, which is favorable from N/Z point of view compared to spherical 82n shell.

#The yields of fission products around mass number 133-135,138-140 and 143-146 and their complementary are higher than expected. This is due to the presence of spherical 82n shell and deformed 88n shell at mass number 133-135 and 143-145 respectively, which indicates the effect of shell closure proximity.

#-Higher yields of fission products in the interval of five mass units due even-odd effect, which also indicates the role of nuclear structure effect.

#The peak to valley ratio (P/V) decreases with decrease of bremsstrahlung energy, which indicates the role of excitation energy.



(a) 85-MeV Bremsstrahlung Photon
(b) 65-MeV Bremsstrahlung Photon
(c) 50-MeV Bremsstrahlung Photon
Yields of Fission Products (%)
Mass Number
0
2
4
6
8
10
12
80
90
100
110
120
130

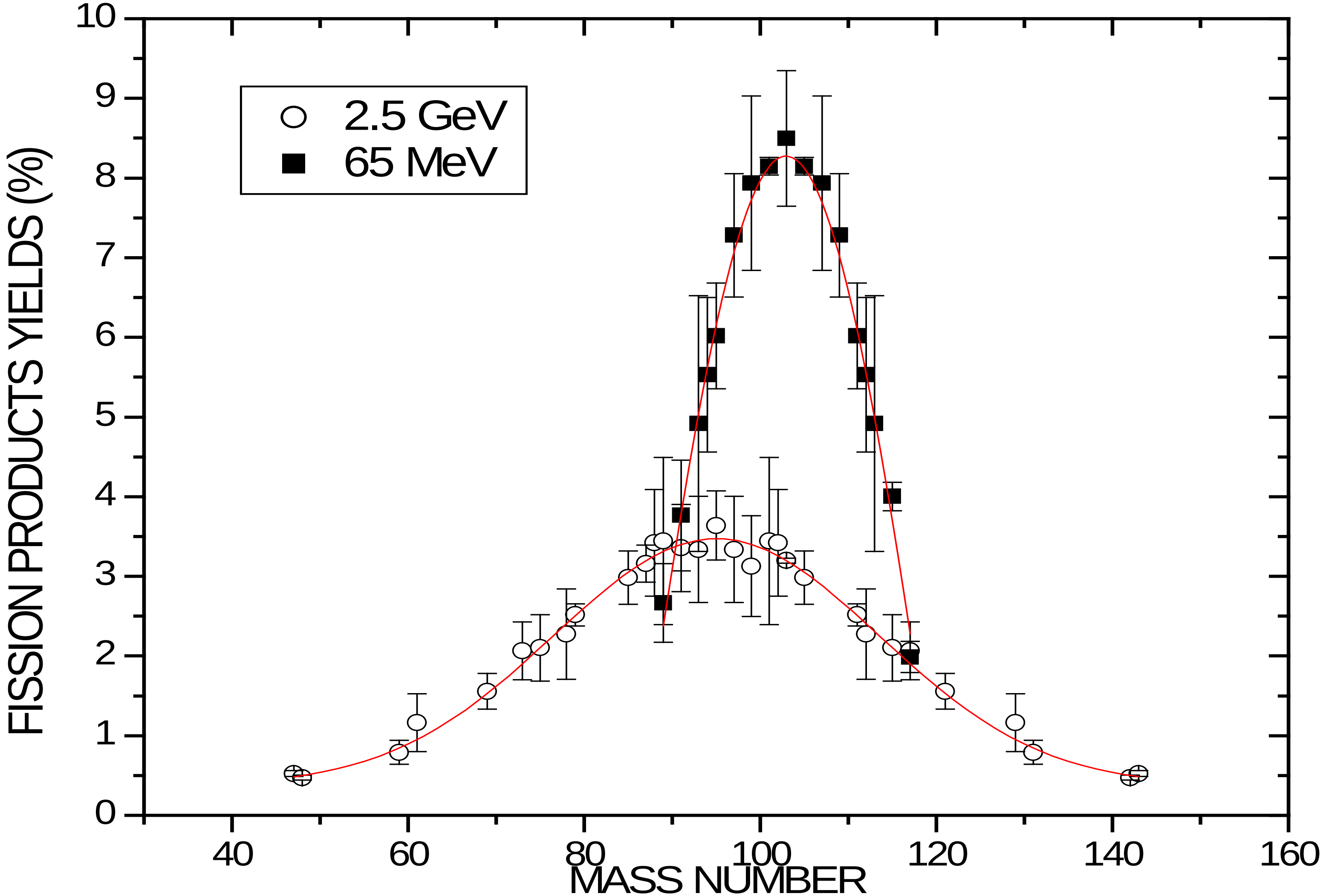


Fig.2. Plot of fission products yields vs. their mass number in the 65 MeV and 2.5 GeV bremsstrahlung induced fission of ^{209}Bi

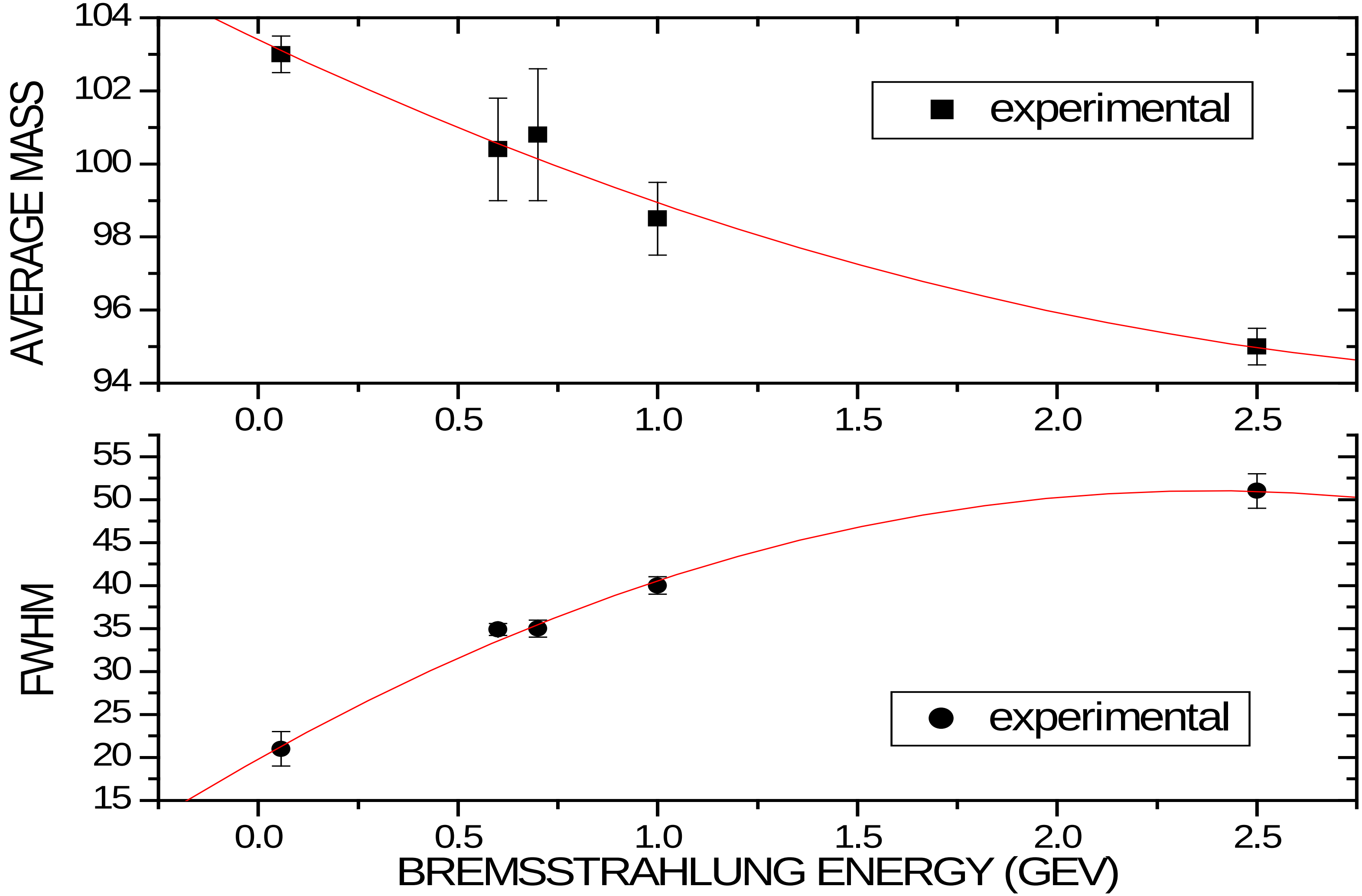


Fig.3. Plot of average mass and FWHM of mass distribution vs. Eγ in the bremsstrahlung induced fission of ^{209}Bi

DISCUSSION AND SUMMARY

#Yields of 11-35 fission products have been determined.

#Yield of 109Pd in 85 MeV and 112Pd at 28-50 MeV are higher than expected, which is due to the presence of deformed 66n shell (nuclear structure effect).

#-Mass distribution of 28-85 MeV, 0.6-2.5 GeV bremsstrahlung induced fission of ^{209}Bi is symmetric in nature, which indicates the liquid drop fission barrier.

#1. FWHM increases with increase of energy of bremsstrahlung i.e. 19-23 mass units at 28-85 MeV. 35-40 mass units at 0.6-1.0 GeV and 51 mass units in 2.5 GeV.

#2. Average mass decreases from mass number 103-102 at 28-85 MeV to 100-98 at 0.6-1.0 GeV & 95 mass at 2.5 GeV.

The above two observations is due to increase of multi-nucleon emission and multi-chance fission probabilities with increase of excitation energy.

#The nuclear structure effect observed at low energy vanishes at high energy, which also indicates the role of excitation energy.

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