Measurements of Thermal-Neutron Capture Cross-Sections for Radioactive Nuclides

EFNUDAT Workshop . BUDAPEST 23-25/SEP/2009

Shoji NAKAMURA
Japan Atomic Energy Agency

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1. Motivation

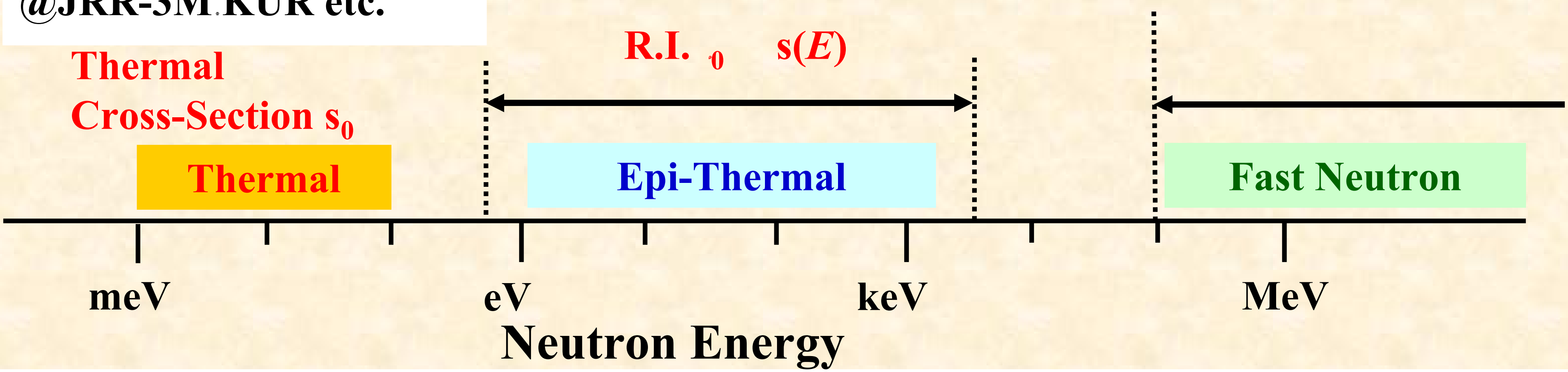
Nuclear Cross-Section Data → **Evaluated Data File**
ex. **JENDL**

- **Transmutation study, Fuel Burn-up, Fission Products, *etc.***
- **Fast Breeder Reactor, ADS Reactor, Innovative Reactor, *etc.***

^{90}Sr ^{137}Cs ^{99}Tc ^{129}I
^{134,135}Cs ^{166m}Ho
^{237}Np ^{238}Np
^{241}Am ^{243}Am …
^{244}Cm ^{242}Cm …
^{107}Pd ^{93}Zr …
@JRR-3M.KUR etc.

^{237}Np .KUR LINAC

^{99}Tc, ^{237}Np, ^{129}I
Fast Neutron Capture Cross-Sections
.TokyoUniv. “YAYOI”



Problems in Cross-Section Data for FP & MA

A very few reliable data

1. **Discrepancies among reported data**

   ^{90}Sr. 0.8 to 0.015 (b)

   ^{137}Cs. 0.11 to 0.25 (b)

2. **Relatively large errors**

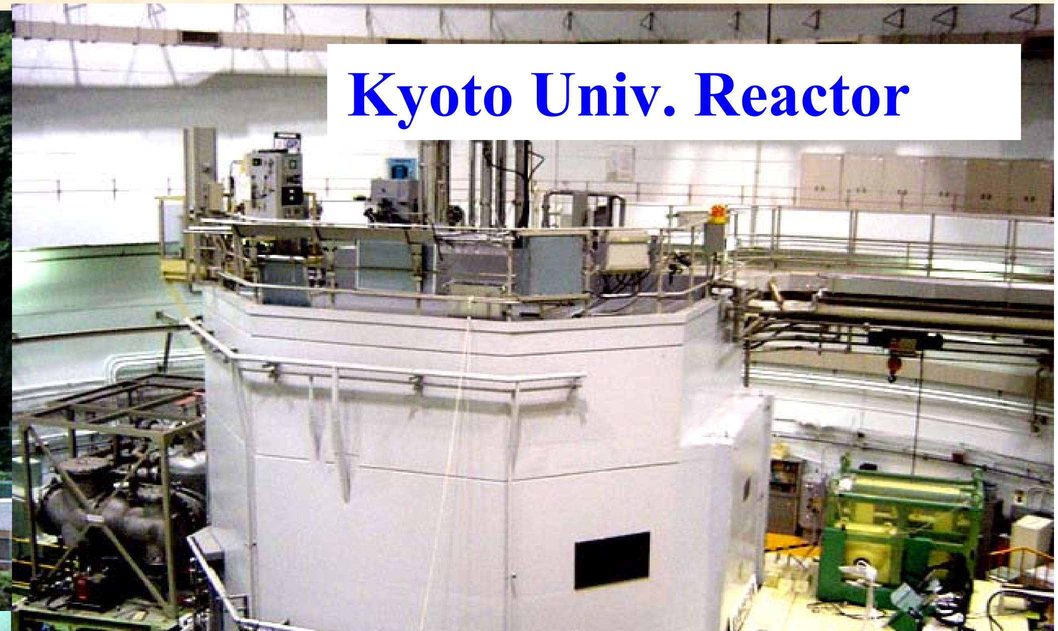
   ^{241}Am. 780 ± 50, 636 ± 46, 602 (b)

3. **A few of exp. Data ^{135}Cs, ^{107}Pd, ^{93}Zr *etc*.**

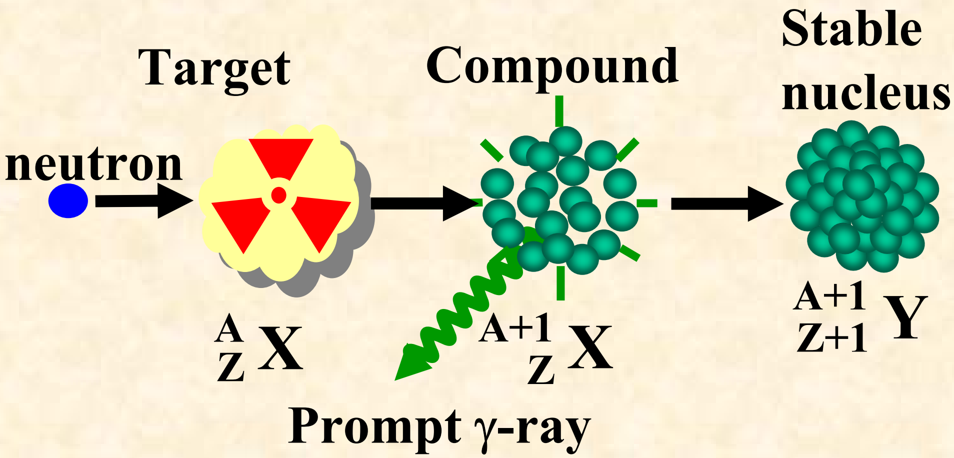
4. **No Data ^{238}Np**

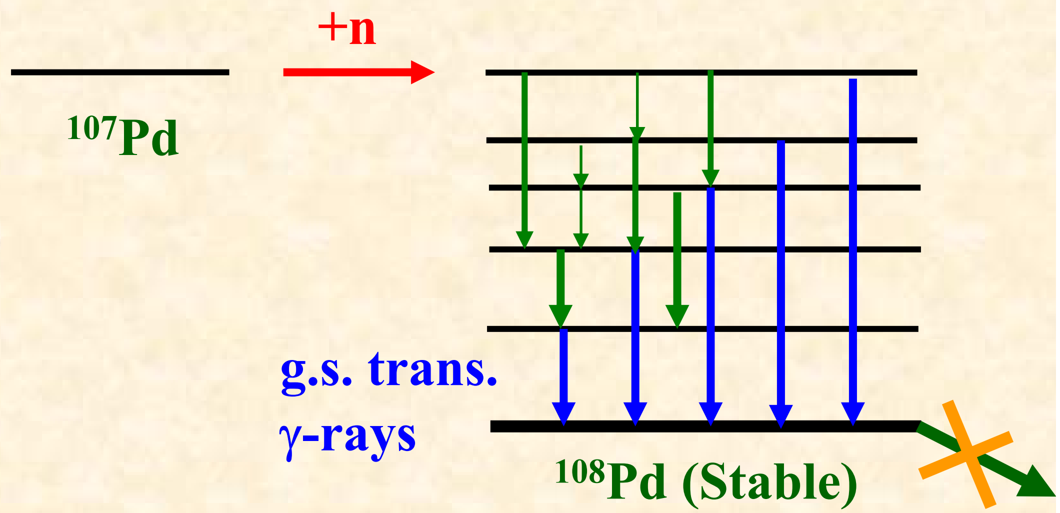
Aimed to re-measurement the cross-sections for important FP's and MA's

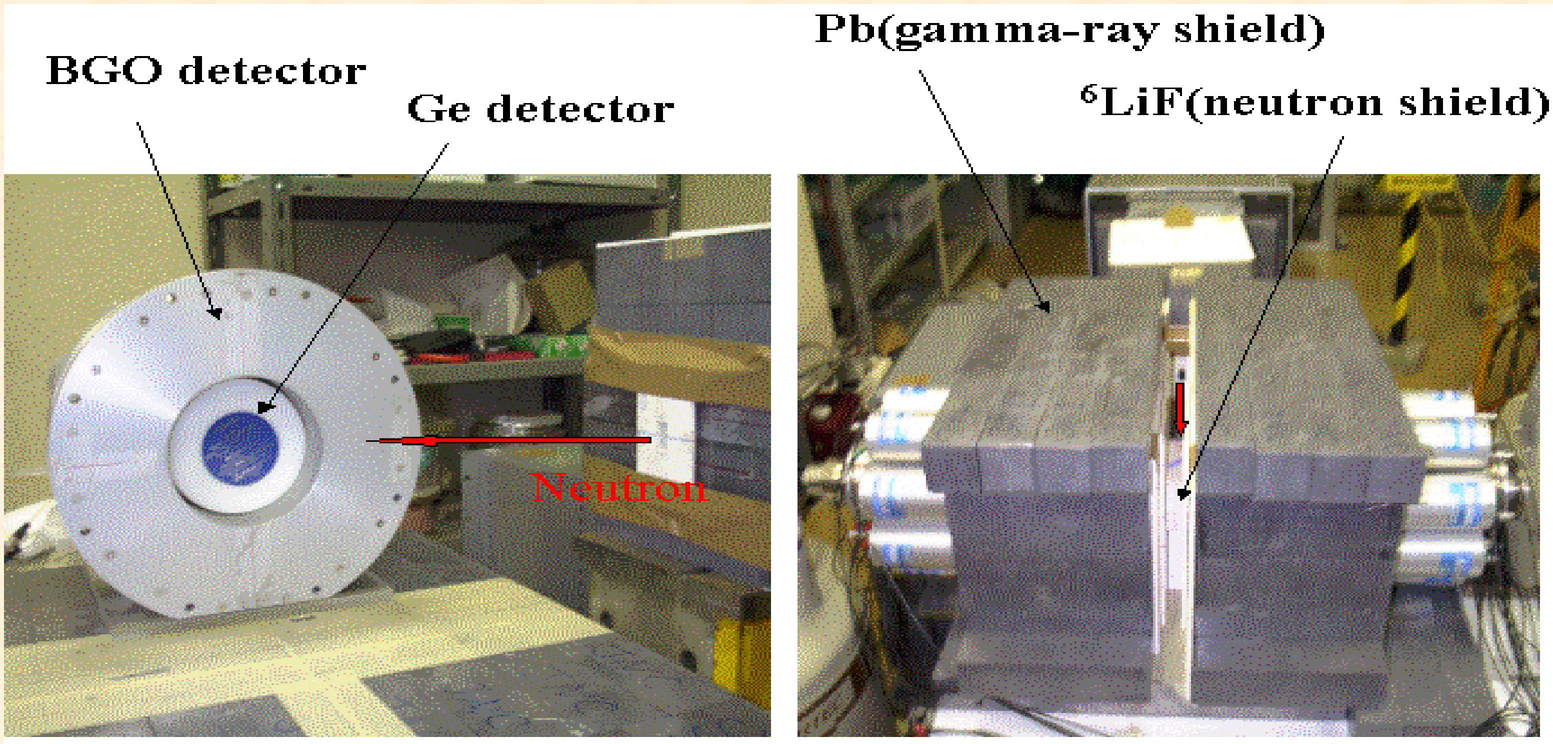
2.Methods -Neutron Activation Analysis-



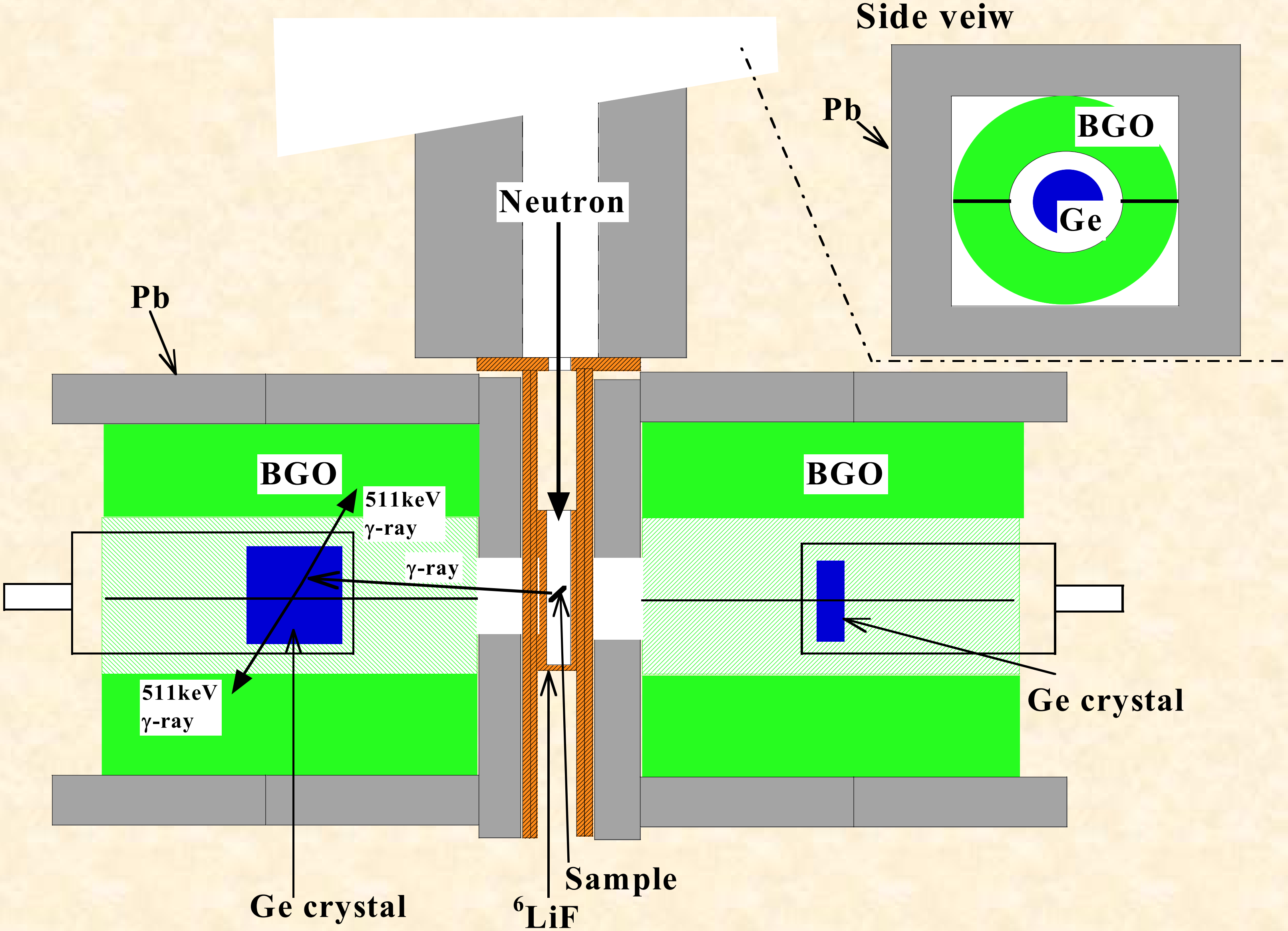
-Prompt γ-ray Spectroscopic Analysis-



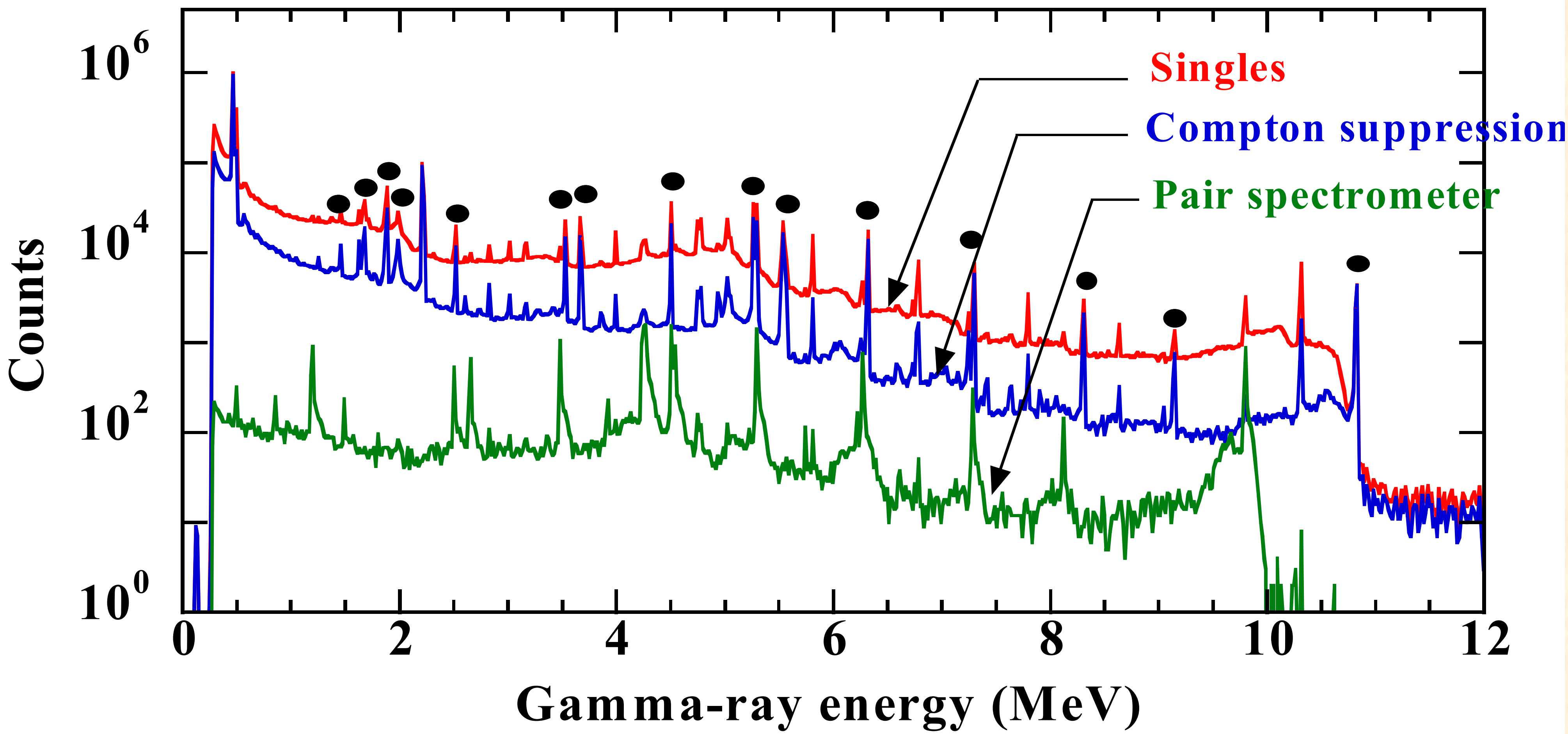




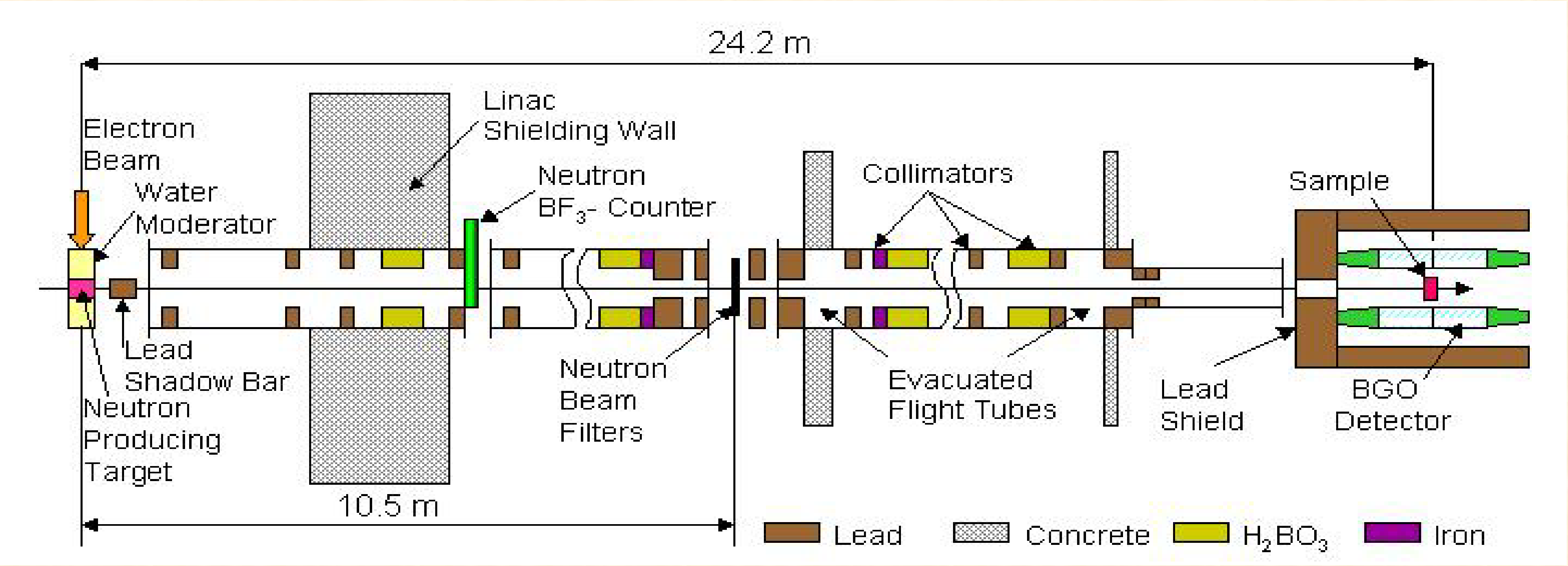
Ge & BGO Detector Geometry

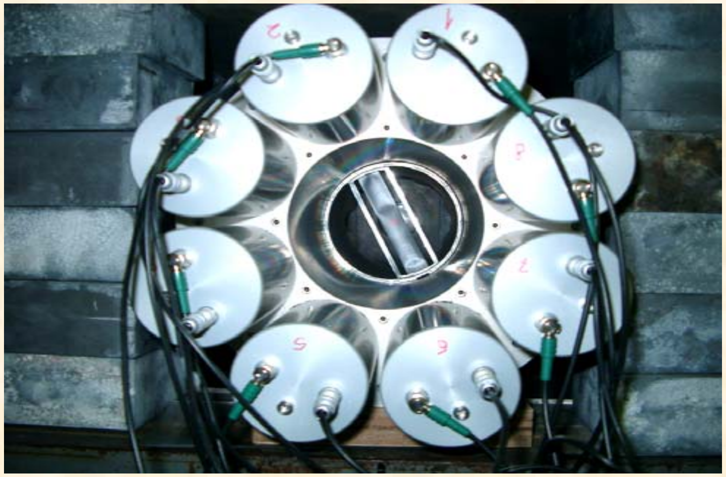


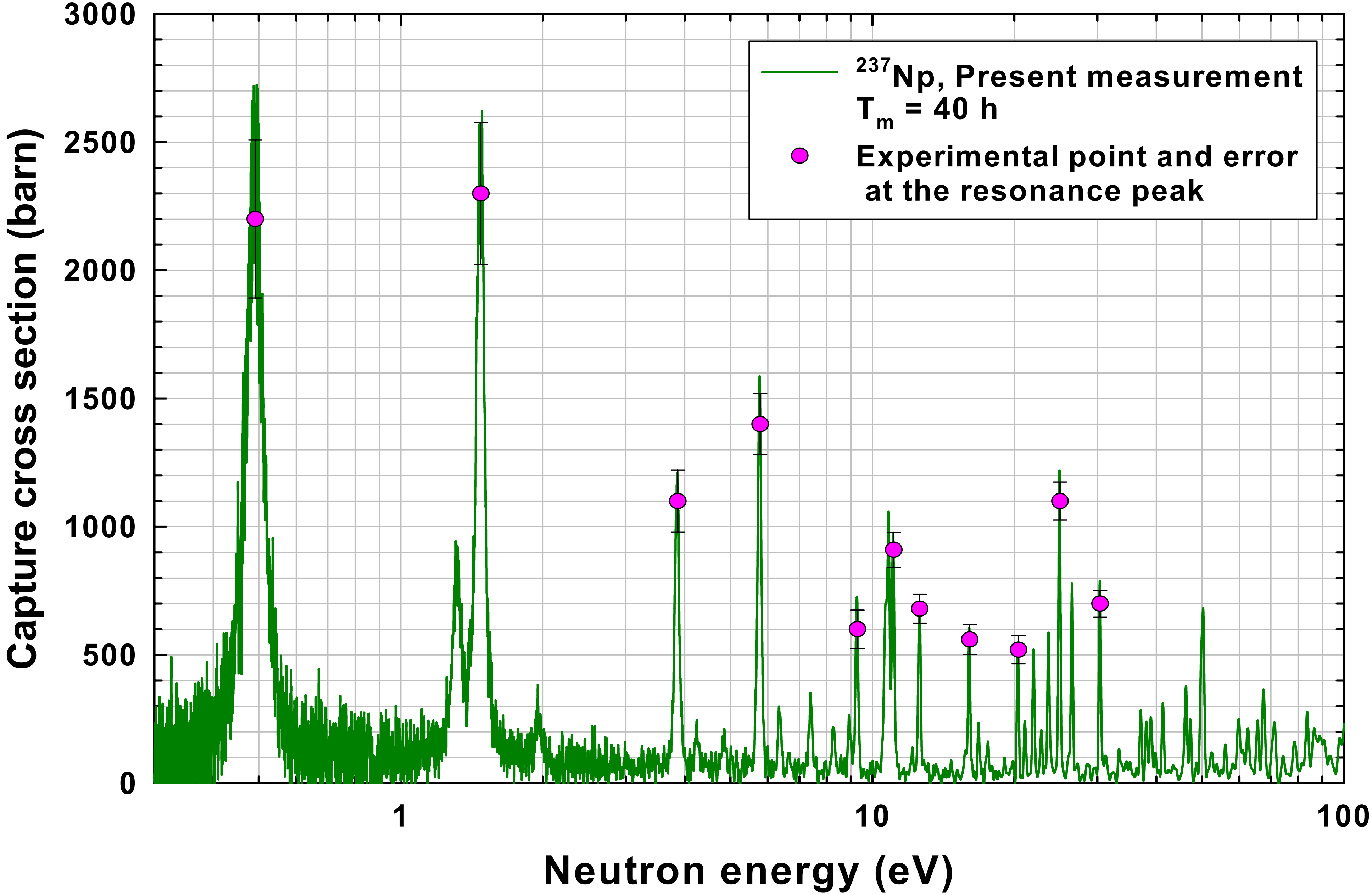
An Example of γ-ray spectrum



-Time-Of-Flight Analysis-







^{237}Np, Present measurement
T_m = 40 h
Experimental point and error at the resonance peak
Capture cross section (barn)
Neutron energy (eV)
0
500
1000
1500
2000
2500
3000
1
10
100

3. Experiment Ex.1 $^{90}Sr(n,\gamma)^{91}Sr$ reaction

Only upper limits of I_0

$\sigma_0 = 15.3^{+1.3}_{-4.2}$ (mb)

$I_0 < 160$ (mb)

(1994 .JRR-4)

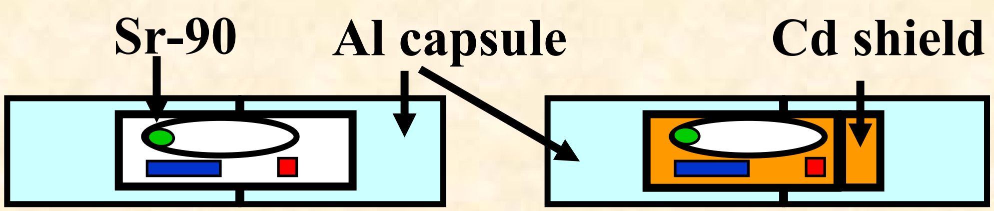
Al capsules for confinement of samples

Al capsule also play the role as a heat sink

Modified Cadmium-ratio Method

Muli-flux monitors

Extract σ_0 from the reaction rate R



bare	**With Cd shield**
(σ_0+I_0)	(I_0)
Reaction rate:R	**R’**

Kyoto Univ. Reactor : KUR @ Hydraulic Facility

Neutron Flux : 1×10^{14} n/cm^{2}sec

Irradiation: 10 hours

Ex.1 $^{90}Sr(n,\gamma)^{91}Sr$ reaction -Results-

Author	Thermal Cross Section, σ_0 (mb)	Resonance Integral, I_0 (mb)
Present Work	10.1 ± 1.3	104 ± 16
Harada *et al*. [1994]	$15.3^{+1.3}_{-4.2}$	<160

S.Nakamura *et al*. : *J. Nucl. Sci. Technol*., 38, No.12, 1029(2001).

Measured σ_0 and I_0 separately
First data for I_0
Error of σ_0 was improved to 1/2
Adopted as a part of JENDL-4

Ex.2 $^{241}Am(n,\gamma)^{242g}Am$ reaction

$^{241}Am(n,\gamma)^{242g}Am$ reaction cross-section

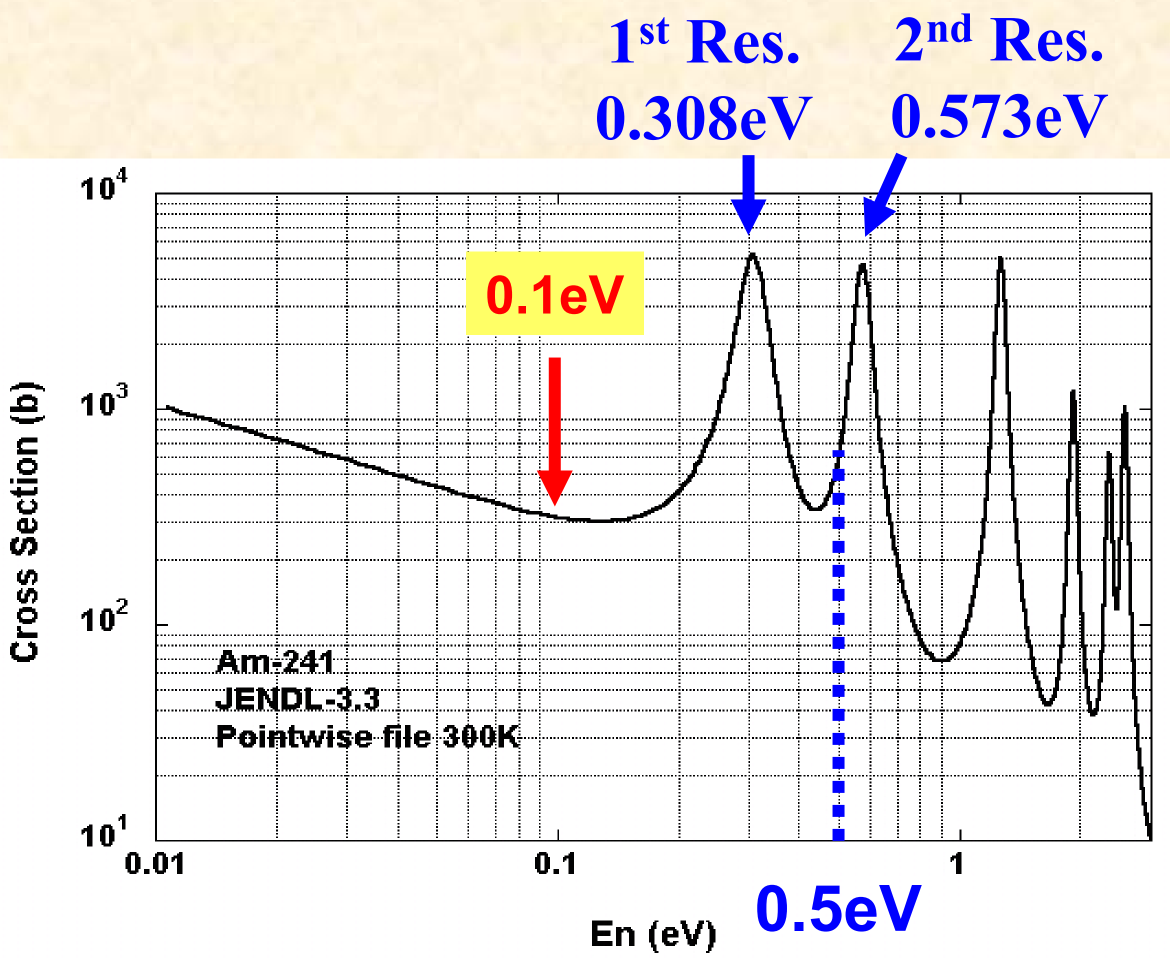
Differences between the reported data: 600 to 800 (b)

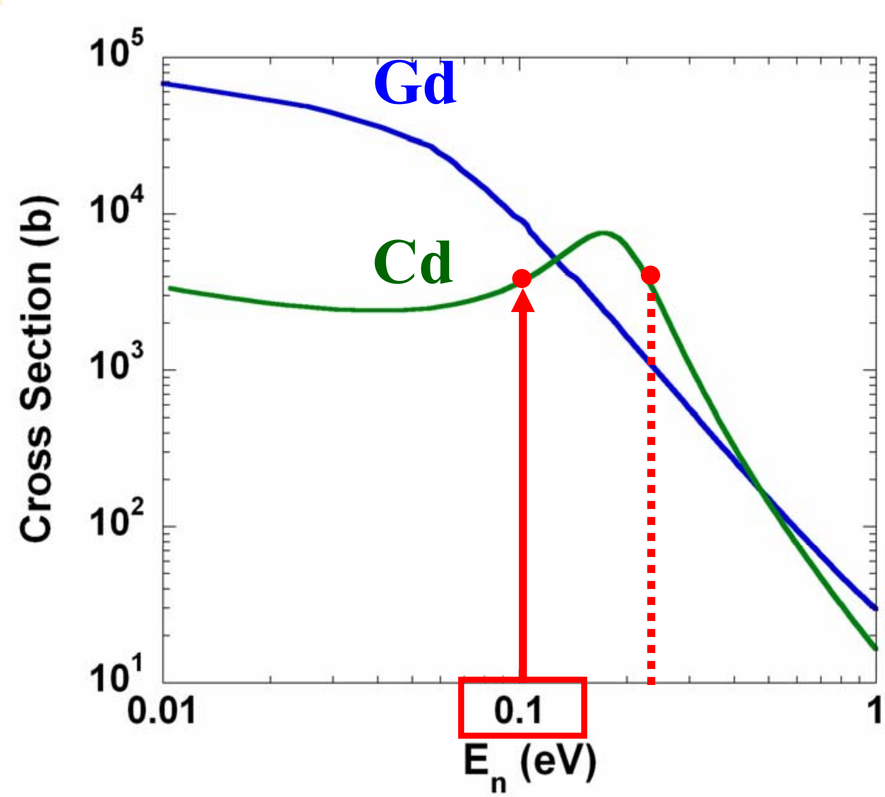
Cd shield

Difficult to set the cut-off into the low energy

Gd shield

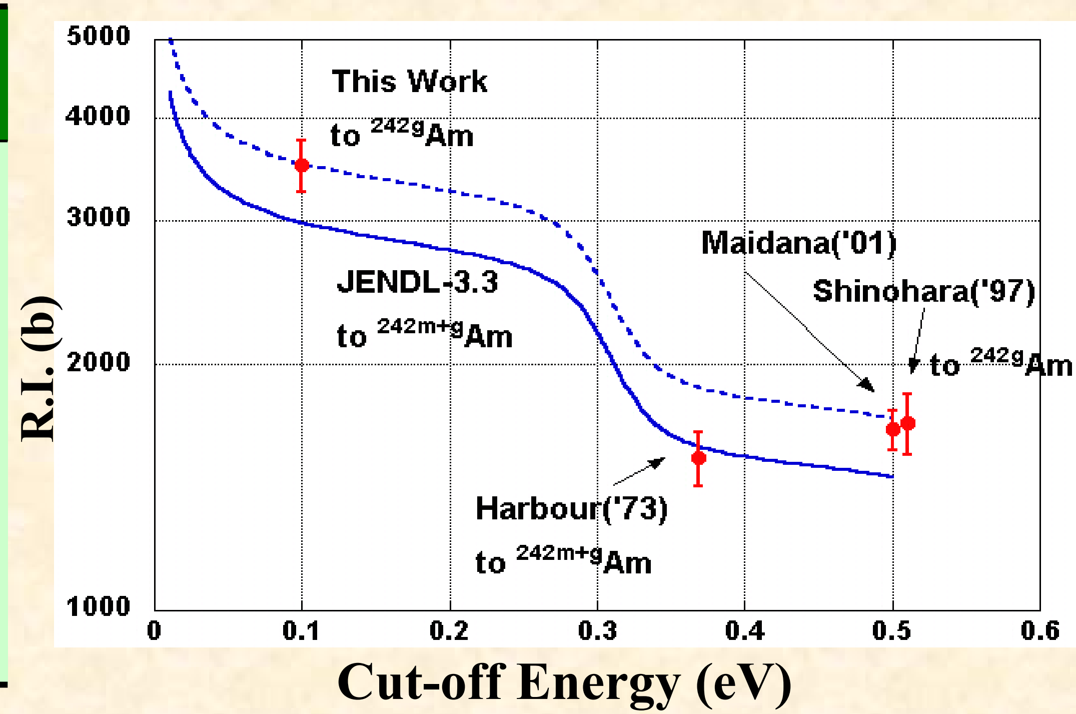
Set the cut-off to 0.1eV





Ex.2 ^{241}Am(n,γ)^{242g}Am reaction -Results-

Authors	σ_{0g} (b)	I_{0g} (b)	Cut-off (eV)
This Work	628±22	3.5±0.3 k	0.107
Fioni	636±46	---	----
Shinohara.	768±58	1694±146	0.5
Gavrulov	780±50	---	---
Harbour	748±20	1330±117	0.369
Bak	670±60	2100	
Deal	770	---	----

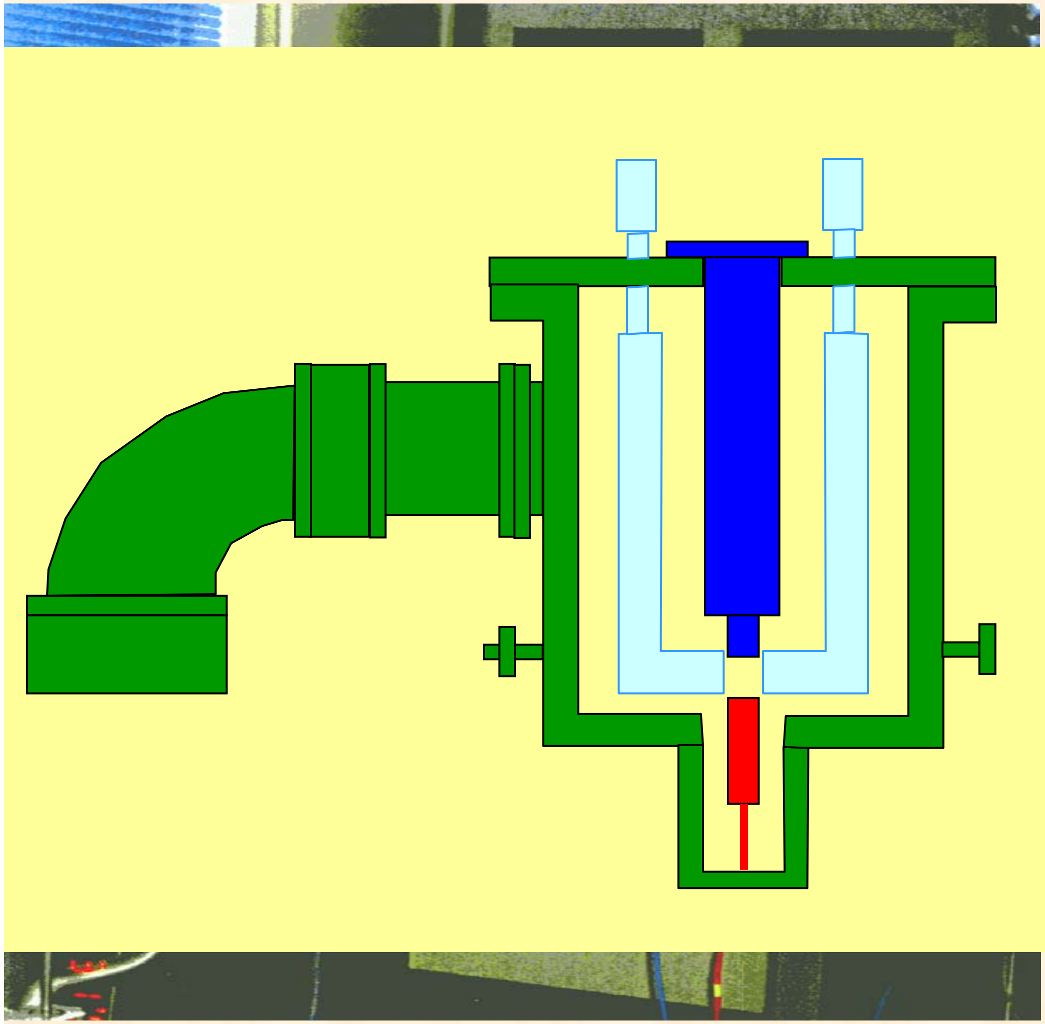


The differences among past data was caused by the treatment of the first resonance peak (0.308eV).

Another nuclides

Difficult and/or impossible to supply samples: ***ex.*** **^{135}Cs (2.3x10^{6}yr)**

Use ^{135}Cs contained in ^{137}Cs std. sol. as an impurity



Mass Analyzer for *NAA*

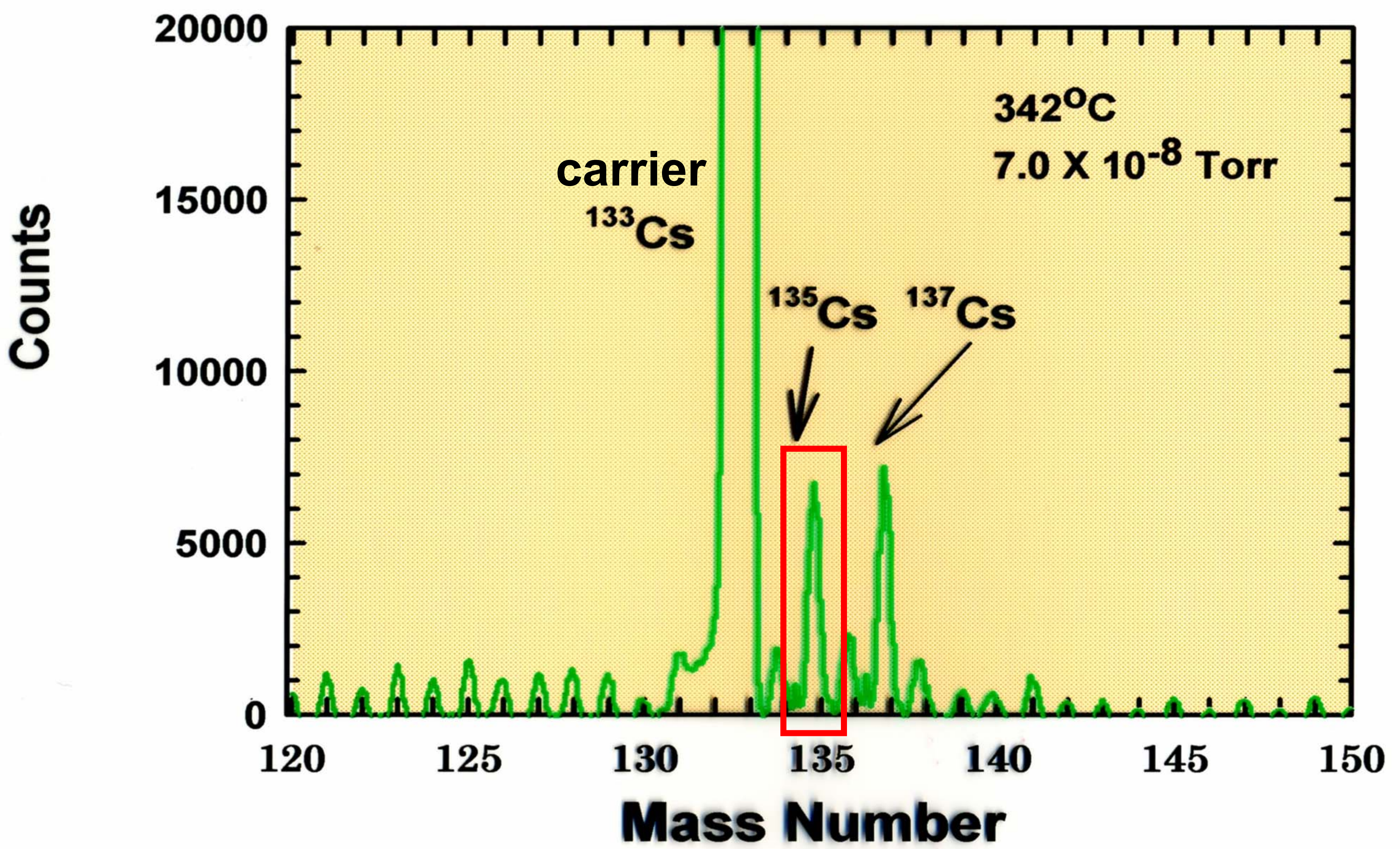
Quadrupole Mass Filter

Liq. N Cooling Trap

High Vacuum : 10^{-10} Torr

Detection limit : 300 ng

Isotope Ratio $^{135}Cs/^{137}Cs$



4. Highlight Data

FP's & MA's cross-section data by JAEA

Nuclide	Past Data □Author, Year□	JAEA Data
^{90}Sr	σ_{eff}□0.8±0.5□ (Zeisel 1966)	σ_0□10.1±1.3m□ I_0□104±16m□ (2001)
^{99}Tc	σ_0□20±2□ I_0'□186±16□ □Lucas 1977□	σ_0□22.9±1.3□ I_0□398±38□ □1995□
^{129}I	σ_0□27±2□ I_0□36±4□ □Eastwood 1958□	σ_0□30.3±1.2□ I_0□33.8±1.4□ □1996□
^{127}I	σ_0□4.7±0.2□ I_0□109±5□ □Friedmann 1983 □	σ_0□6.40±0.29 I_0□162±8□ □1999□
^{135}Cs	σ_0□8.7±0.5□ I_0□61.7±2.3□ □Baerg 1958□	σ_0□8.3±0.3□ I_0□38.1±2.6□ □1997□
^{134}Cs	σ_{eff}□134±12□ (Bayly 1958)	σ_{eff}□141±9□ (1999)
^{133}Cs	σ_0□30.4±0.8□ I_0□461±25□ □Baerg 1960□	σ_0□29.0±1.0□ I_0□298±16□ □1999□

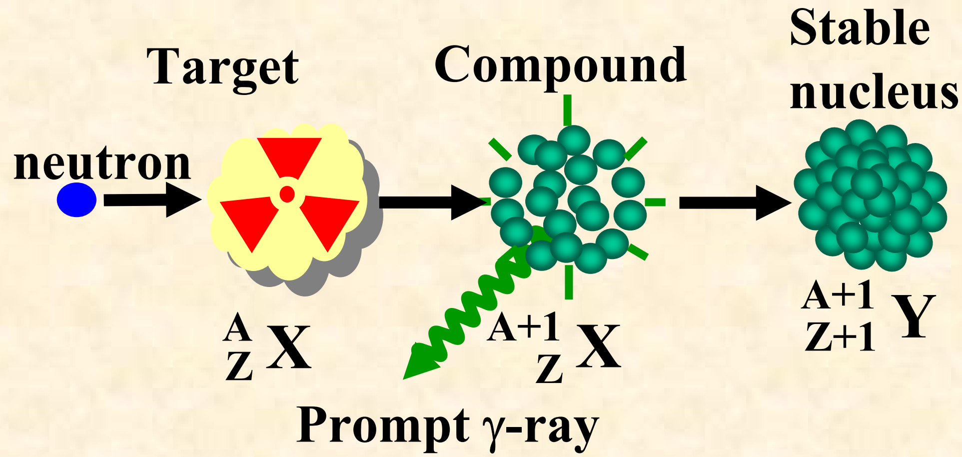
Nuclide	Past Data □Author, Year□	JAEA Data
^{166m}Ho	σ_0□9140±650□ I_0□1140±90□ □Masyanov 1993□	σ_{eff}□3±1 k□□2000□ σ_0□3.11±0.82k□ I_0□10.0±2.7k□ (2002)
^{237}Np	σ_0□158±3□ I_0□652±24□ □Kobayashi1994□	σ_0□141.7±5.4□ I_0□ 862±51□ (2003□ σ_0□169±6□ (2006)
^{238}Np	No Data	σ_{eff}□479±24□ (2004)
^{241}Am	$\sigma_{0□}$□ 768±58□ $I_{0□}$□1694±146□ □Shinohara 1997 □	$\sigma_{0□}$□628±22□ $I_{0□}$□3.5±0.3k□ (2007)
^{243}Am	σ_{0m}□80□, σ_{0g}□4.3 σ_{0m+g}□84.3□ □Ice 1966□	σ_{eff}□174.0±5.3□ (2006)

Limit of application by NAA

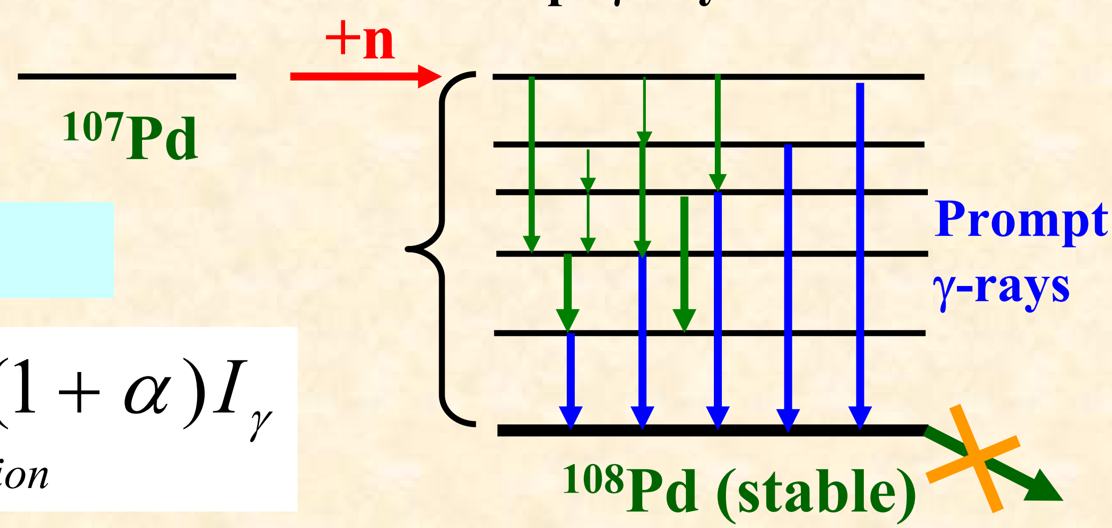
Impossible to measure the cross-sections by NAA !!

ex. **^{107}Pd .6.5x10^{6}y)**

^{93}Zr.1.53x10^{6}.)



Prompt γ-ray spectroscopy



g.s. Trans. Method

$$\sigma = \sum_{g.s.transition} (1+\alpha) I_\gamma$$

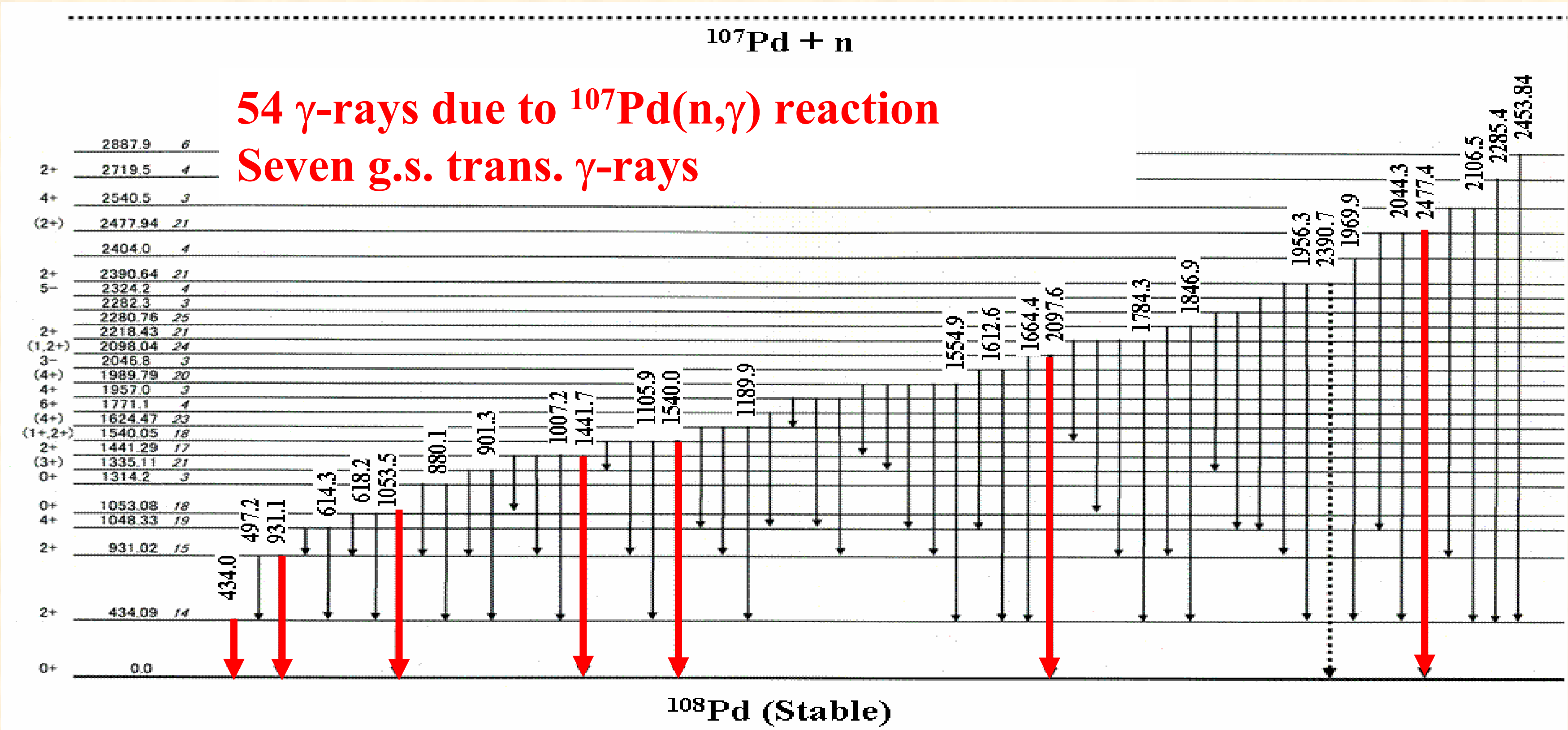
α : Internal Conversion Coefficient

I_γ : γ-ray intensity feeding to g.s. (unit.barn)

Stand. Cross-section 332 (mb) of H(*n*,γ)

8-MW Los Alamos Omega West Reactor (OWR) (Shutdown in 1994)

Application to cross-section measurement for ^{107}Pd



Author	Cross Section σ_0(b)
Present Work	9.16±0.27
JENDL-3.3	2.0071
T.O.I. 8ed	1.8±0.2
Mughabghab	1.8±0.2

Obtained ^{107}Pd cross-section experimentally !
About 5 times larger than eval. data! !!

Calc. values by res. parameters

Result of thermal-neutron capture cross-section for $^{93}Zr(n_{th},\gamma)$ and $^{91}Zr(n_{th},\gamma)$ reactions

References		σ_0 for ^{91}Zr (b)	σ_0 for ^{93}Zr (b)
H.Pomerance[a)]	1952	1.52 ± 0.12	$1.3 < \sigma_0 < 4$
Garrison *et al.*[b)]	1962	1.2 ± 0.32	1.1 ± 0.4
Clayton[c)]	1972	1.579	1.996
Mughabghab *et al.*	1981	1.24 ± 0.25	$1.3 < \sigma_0 < 4$
Table of Isotopes *8ed*	1998	1.24 ± 0.25	2.7 ± 1.4
JENDL-3.3	2002	1.247	2.239
This Work		1.30 ± 0.04	0.63 ± 0.02

a) Measurements with ORNL pile oscillator
b) Statistical model estimates
c) Calculation by the resonance parameters from BNL-325

Thank you

for your kind attention

Supplement A:

Analysis of Prompt γ rays emitted from ^{107}Pd(n_{th},γ) Reaction

Analysis of Prompt γ ray from ^{107}Pd(n_{th},γ) Reaction

Reported Data

^{107}Pd. $T_{1/2}$=6.5×10^{6} yr

Refs.	σ_0 (b)	I_0 (b)
JENDL-3.3	2.0071	112.2
Macklin ('85)		108.1 ± 4.3*1
Holden ('81) ENSDF of U.S.NNDC	1.8 ± 0.2(b)	86.6
Singh ('78)	1.8*2	87*2

*1 Cal. val. with 130 resonances up to 3.5keV

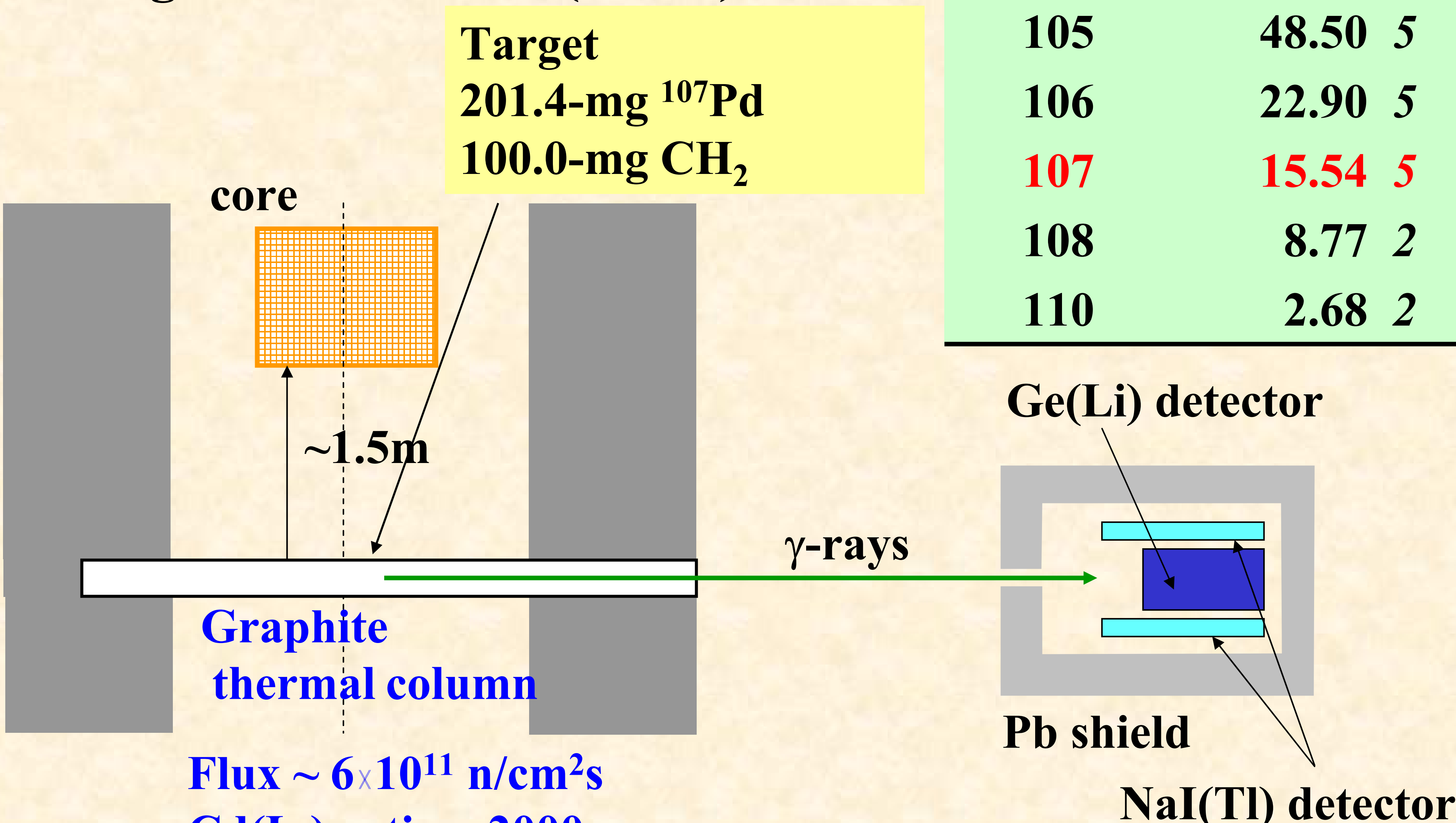
*2 Cal. Val. with 34 ^{107}Pd resonances below 700eV

8-MW Los Alamos
Omega West Reactor (OWR)

8-MW Los Alamos Omega West Reactor (OWR)

Exp. in 1988

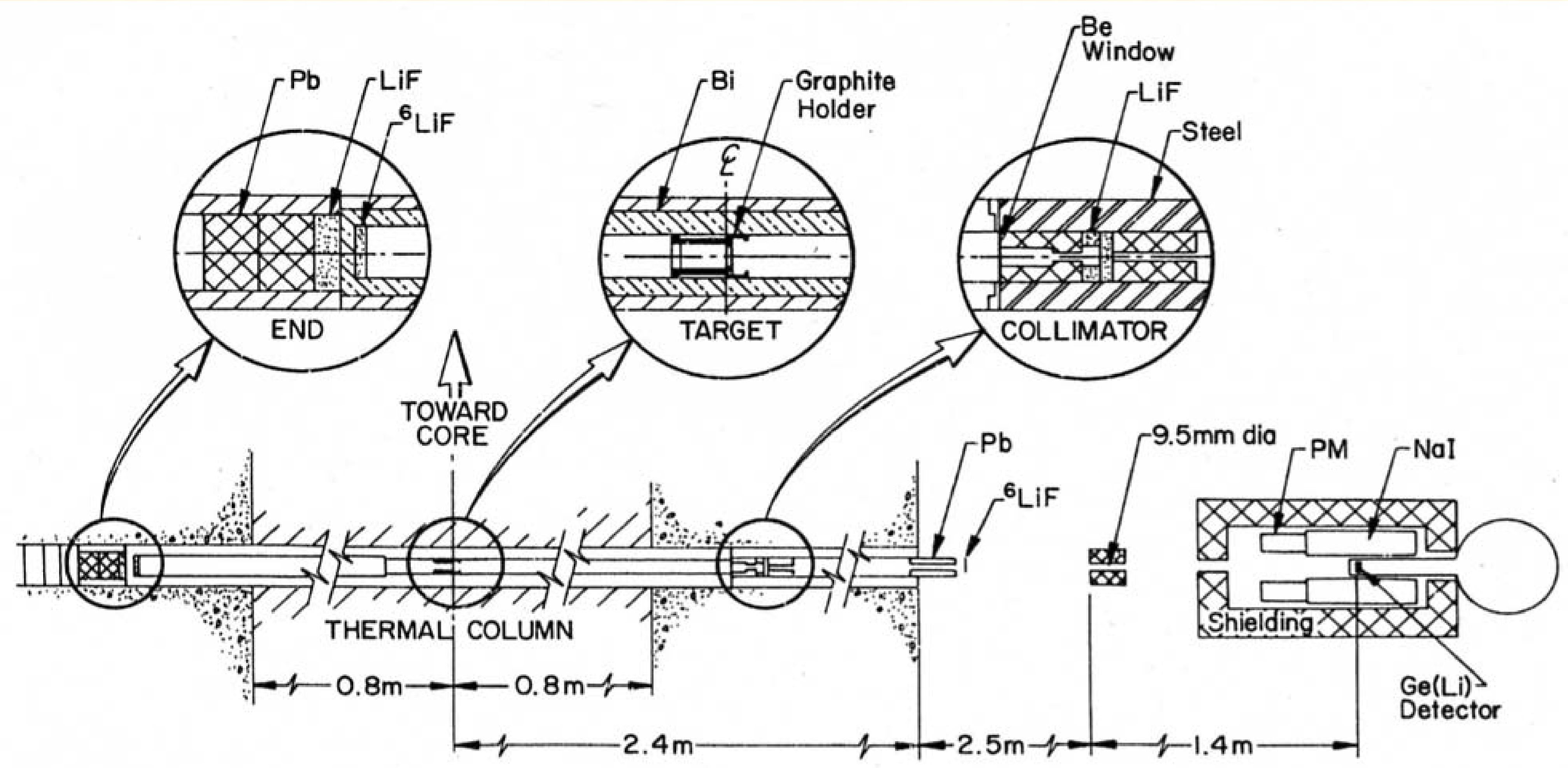
Mass	Abundance(%)
104	1.61 *2*
105	48.50 *5*
106	22.90 *5*
107	15.54 *5*
108	8.77 *2*
110	2.68 *2*

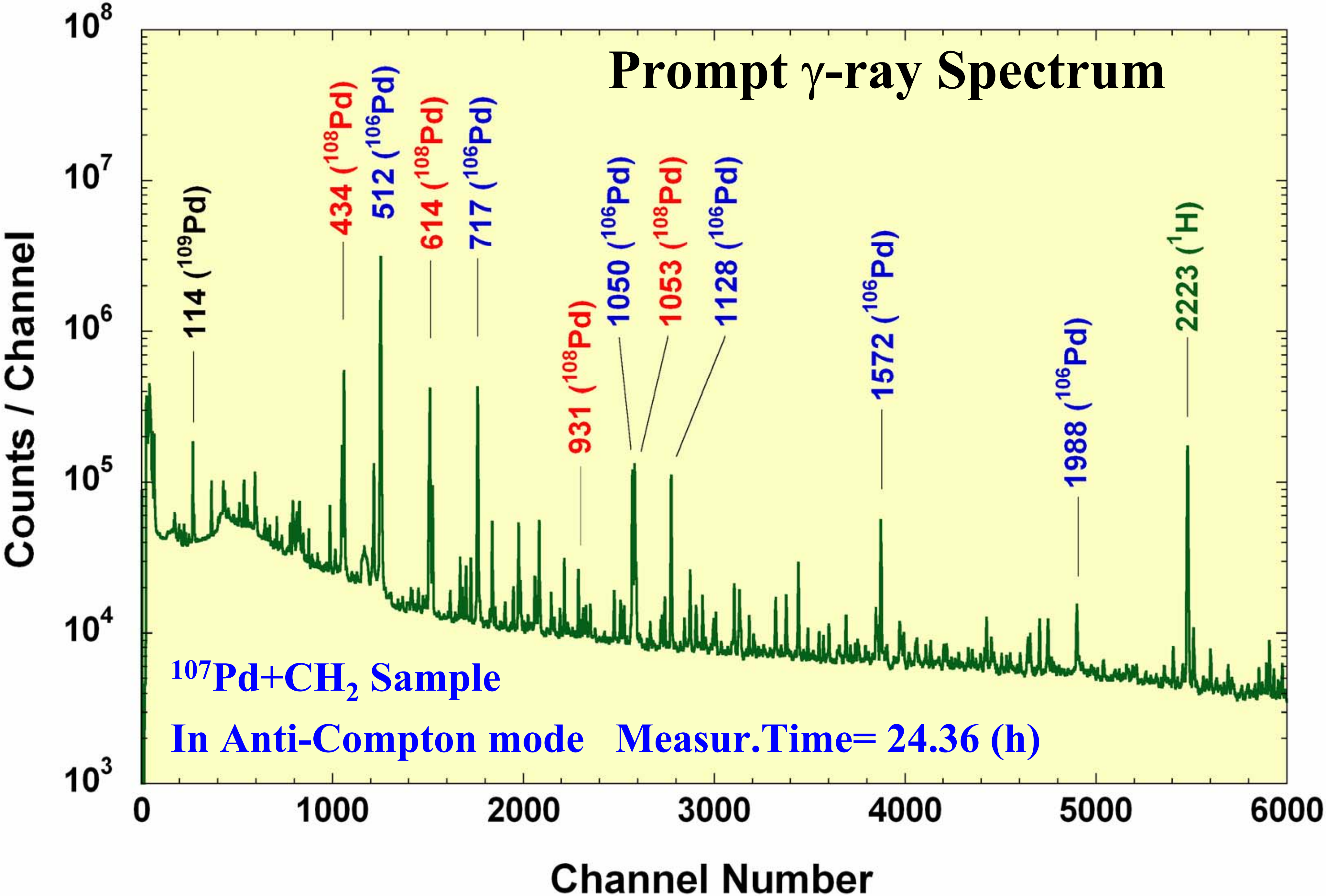


Flux ~ 6×10^{11} n/cm^{2}s
Cd(In) ratio ~ 2000
Maxwell distribution

Experimental arrangement of the target, collimator, and detector at the Los Alamos Omega West Reactor

Phys.Rev.C, 32,18,1985. S.Raman *et al.*





Prompt γ-ray Spectrum
114 (109Pd)
434 (108Pd)
512 (106Pd)
614 (108Pd)
717 (106Pd)
931 (108Pd)
1050 (106Pd)
1053 (108Pd)
1128 (106Pd)
1572 (106Pd)
1988 (106Pd)
2223 (1H)
107Pd+CH2 Sample
In Anti-Compton mode   Measur.Time= 24.36 (h)
Counts / Channel
Channel Number
10^8
10^7
10^6
10^5
10^4
10^3
0
1000
2000
3000
4000
5000
6000

Analysis Process

^{107}Pd+100mg CH_2
Anti-Compton Spectrometer Data
Low Energy region: 0.3.3 MeV
663 peaks

Select prompt γ-rays with known levels

Test of selected g-rays with Gtol Code

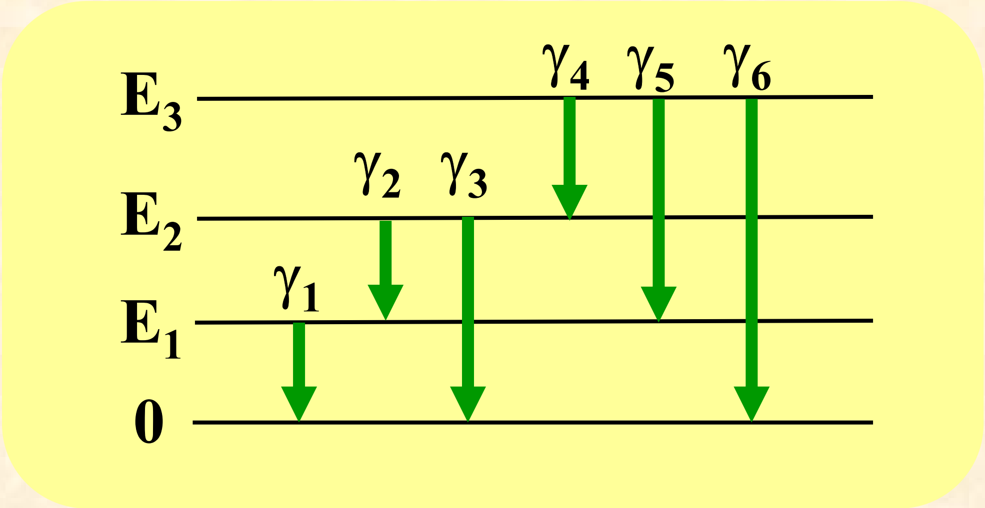
Efficiency correction calibration by ^{1}H+n cross section 332.6±0.7(mb)

Emission Intensity (I_γ) for γ-rays from ^{107}Pd(n,γ) reaction

Lower limit of cross section $\sum_{g.s.} I_\gamma$

Authorization by Gtol Code

Program that calculates optimized energy levels by least-squares method with the information on γ-ray energies



U.S. National Nuclear Data Center

ENSDF Analysis and Utility Programs

Version 6.4b [Dec.3,2003]

ENSDF data set

Emission Intensity: I_γ

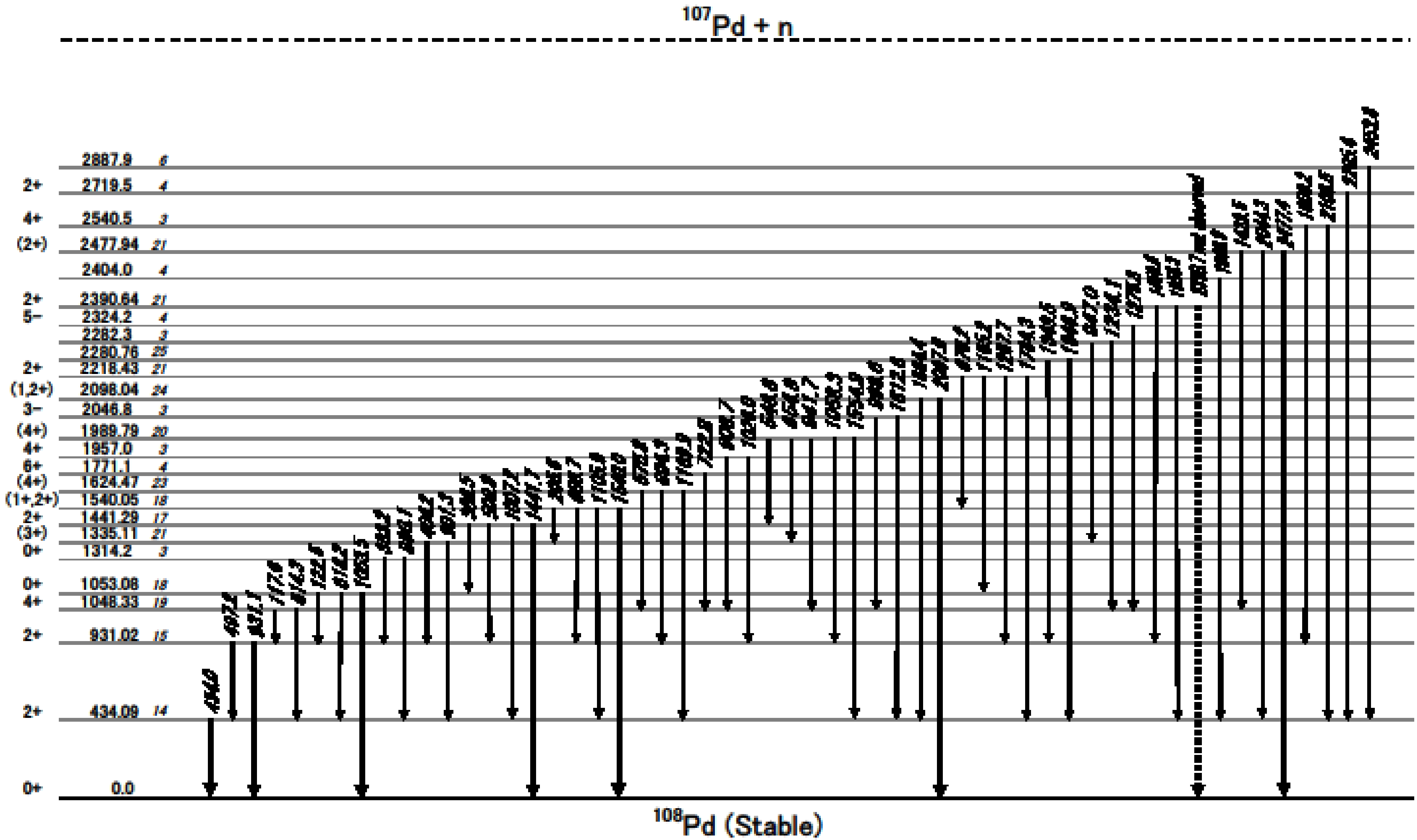
Intensity I_γ of prompt r ray from $^{107}Pd(n,\gamma)$ reaction are given by following equation:

$$I_\gamma = \frac{\varepsilon_H n_H \sigma_H}{n_{pd} Y_H} \cdot \frac{Y_{Pd}}{\varepsilon_{pd}}$$

where

- n_H, n_{Pd} : **Target amounts of H and ^{107}Pd**
- ε_H : **Detection efficiency fo 2.2-MeV γ ray**
- ε_{Pd} : **Detection efficiency fo 2.2-MeV γ ray ^{108}Pd**
- σ_H : **^{1}H cross-section 332.6 ± 0.7(mb)**
- Y_H : **Yield of 2.2-MeV γ ray**
- Y_{Pd} : **Yield of prompt γ ray from ^{108}Pd**

Extraction of prompt γ rays



Results of authorization

Level (keV)		J_π	Deexciting γ rays	Level (keV)		J_π	Deexciting γ rays
0.0		0^+		2046.2	*3*	3^-	998.0, 1612.3
434.01	*15*	2^+	433.1	2097.87	*23*	$(1,2^+)$	1664.2, 2097.5
930.54	*17*	2^+	496.4, 930.5	2217.74	*21*	2^+	677.5, 1164.6, 1287.3, 1784.1
1047.87	*20*	4^+	613.5	2281.1	*3*		1351.0, 1846.7
1053.11	*21*	0^+	619.1, 1053.1	2282.49	*12*		946.4, 1233.6
1313.4	*3*	0^+	382.3, 879.5	2325.3	*7*	5^-	1277.4
1334.73	*25*	(3^+)	900.6	2390.36	*21*	2^+	1459.4, 1956.2, 2390.7
1440.90	*21*	2^+	1006.6, 1441.3	2403.8	*4*		1969.8
1539.75	*20*	$(1^+,2^+)$	1105.3, 1539.7	2477.65	*20*	(2^+)	1429.2, 2044.2, 2477.6
1623.7	*3*	(4^+)	693.5, 1189.4	2540.1	*3*	4^+	1608.9, 2106.4
1956.0	*3*	4^+	908.1, 1025.4	2719.4	*4*	2^+	2285.4
1988.79	*21*	(4^+)	548.0, 654.1, 941.1, 1057.8, 1554.6				

Lower limit of thermal-neutron capture cross-section

Emission Intensities: I_g of γ-rays feeding to the ground state of ^{108}Pd

Observed γ rays (keV)	Intensity I_γ (mb)
434.0	7588 ± 255
931.1	606 ± 19
1053.5	488 ± 73
1441.7	214 ± 8
1540.0	104 ± 6
2097.6	83 ± 6
2477.4	72 ± 7

$$\sum_{g.s.} I_\gamma \cdot (1+\alpha_T) = 9.16 \pm 0.27 \quad (b)$$

Gamma-ray intensity balance for the 434keV level

	E_γ(keV)	I_γ (mb)	E_γ (keV)	I_γ (mb)
OUT	434.0	7588±255		
IN	497.2	1940±63	1664.4	34±4
	614.3	2168±81	1784.3	117±7
	618.2	454±30	1946.9	133±6
	880.1	93±4	1956.3	45±5
	901.3	713±23	1969.9	33±4
	1007.2	399±13	2044.3	133±8
	1105.9	169±9	2106.5	103±7
	1189.9	39±5	2285.4	82±8
	1554.9	42±8	2453.8	27±6
	1612.6	374±18		

IN : 7.10±0.11 (b)   OUT : 7.59±0.26 (b)

Result of thermal-neutron capture cross-section for $^{107}Pd(n_{th},\gamma)^{108}Pd$ reaction

Refs.	σ_0 (b)	I_0 (b)
This Work	9.16 ± 0.27	
JENDL-3.3	2.0071	112.2
Macklin ('85)		108.1 ± 4.3 *1
Holden ('81) ENSDF of U.S.NNDC	1.8 ± 0.2(b)	86.6
Singh ('78)	1.8 *2	87 *2

*1 Cal. val. with 130 resonances up to 3.5keV

*2 Cal. Val. with 34 ^{107}Pd resonances below 700eV

Result of thermal-neutron capture cross-section for $^{105}Pd(n_{th},\gamma)^{106}Pd$ reaction

References		σ_0 (b)
Table of Isotopes 8th	1998	20.0 ± 3.0
JENDL-3.3	2002	20.25
Mughabghab *et al.*	2003	21.0 ± 1.5
Firestone *et al.*	2005	21.1 ± 1.5*
This Work		19.1 ± 0.5*

* Prompt g-ray analysis

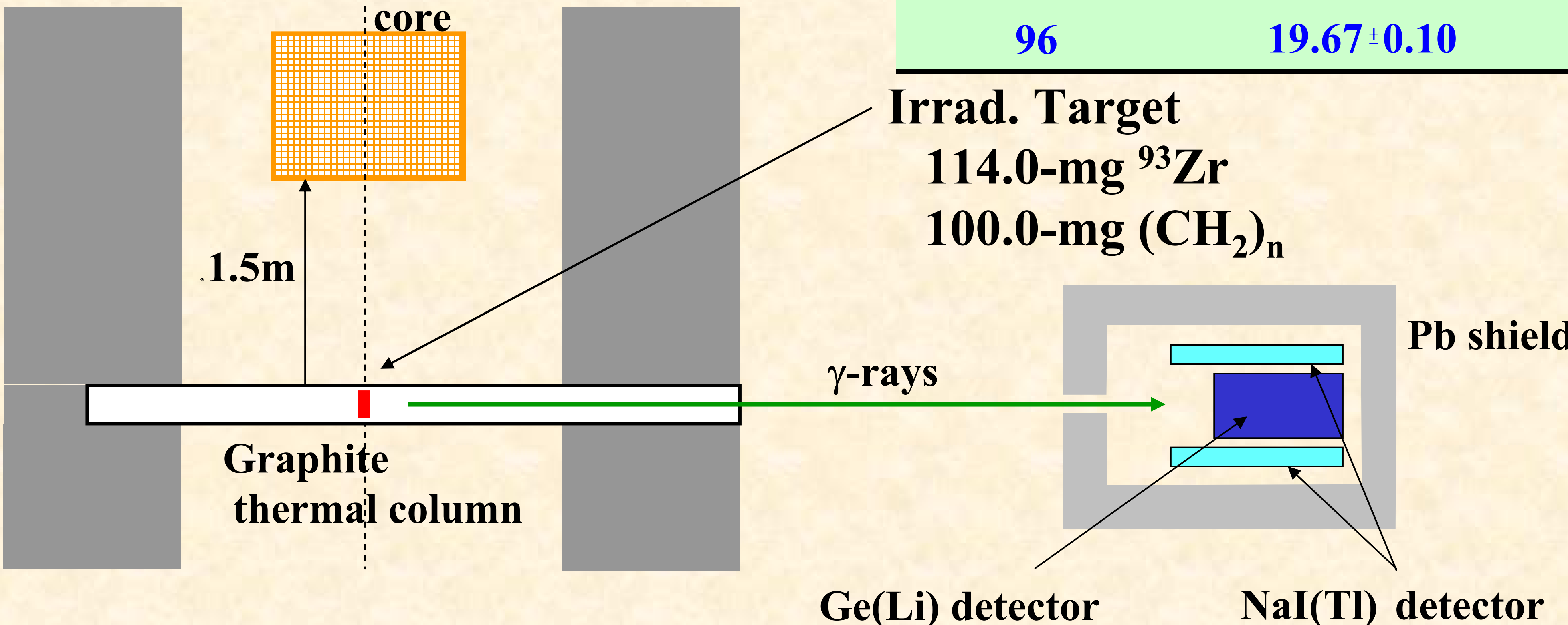
Supplement B:

Analysis of Prompt γ rays emitted from $^{93}Zr(n_{th},\gamma)$ Reaction

Experiment

8MW Los Alamos
Omega West Reactor

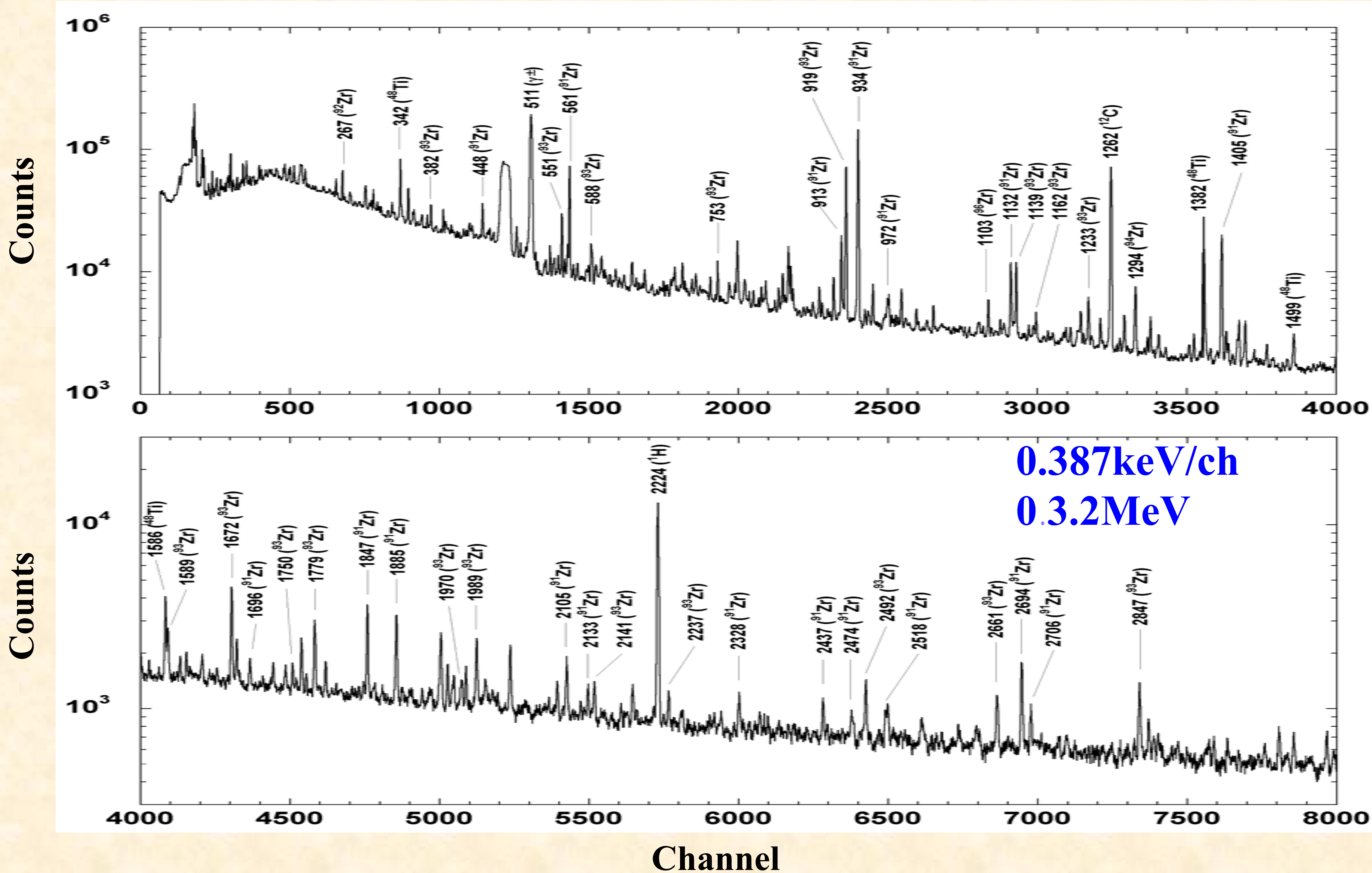
Mass	Abundance(%)
90	2.29 ± 0.05
91	18.61 ± 0.10
92	18.95 ± 0.10
93	19.98 ± 0.10
94	20.50 ± 0.10
96	19.67 ± 0.10



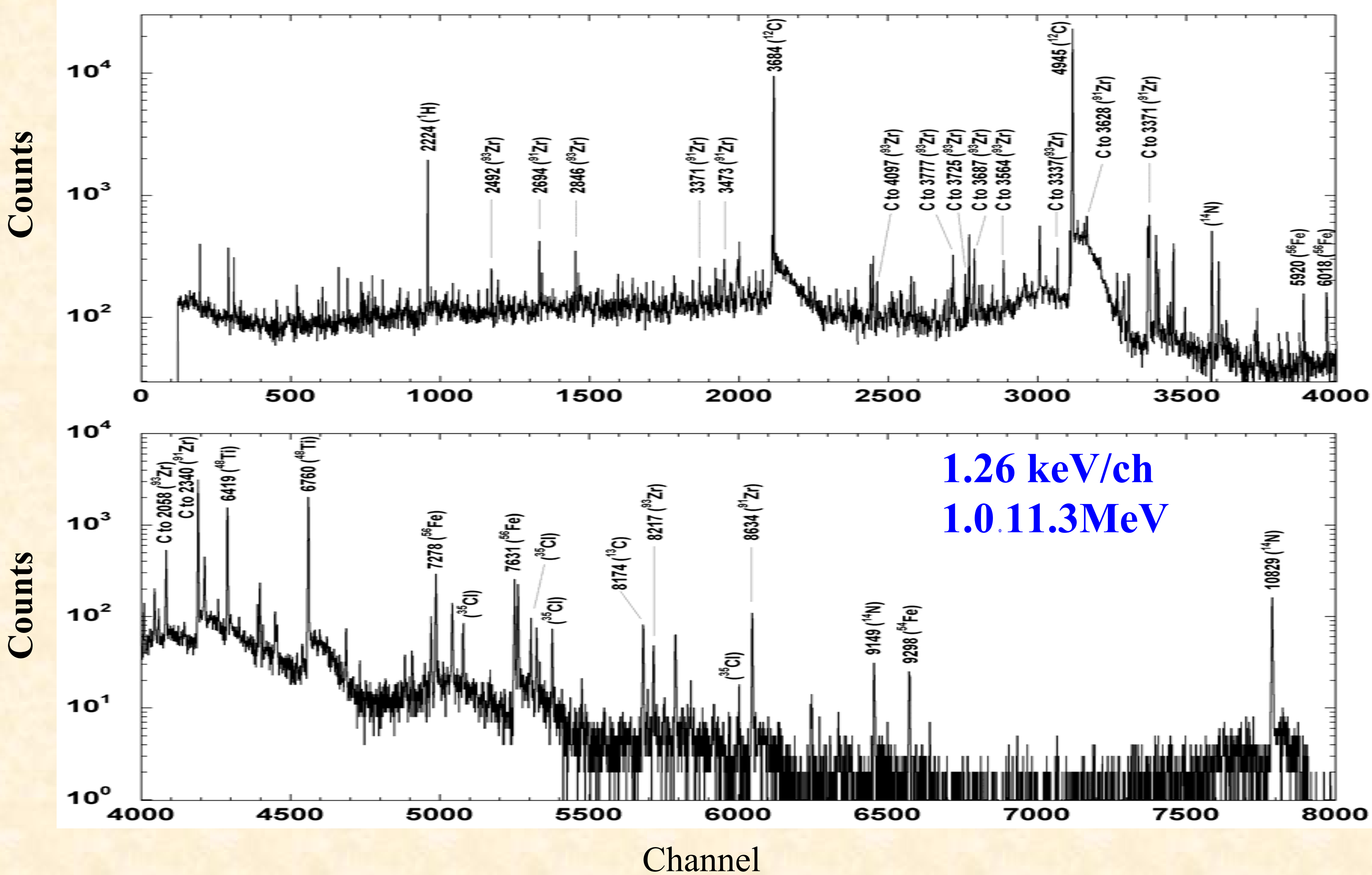
Flux .6×10^{11} n/cm^{2}s
Cd(In) ratio . 2000
Maxwell distribution

- **Anti-Compton mode**
- **Pair-spectrometer mode**

Measured Spectra (Anti-Compton mode)



Measured Spectra (Pair-spectrometer mode)



Analysis Process

Zr + 100 mg $(CH_2)_n$
Anti-Compton mode
3.176 MeV
219 peaks

Efficiency correction calibration by ^{1}H+n
σ = 332.6 ± 0.7(mb)

$$I_\gamma = \frac{\varepsilon_H n_H \sigma_H}{n_{Zr} Y_H} \cdot \frac{Y_{Zr}}{\varepsilon_{Zr}}$$

Intensity for 918 keV γ-ray

Zr
Anti-Compton mode
3.176 MeV
530 peaks

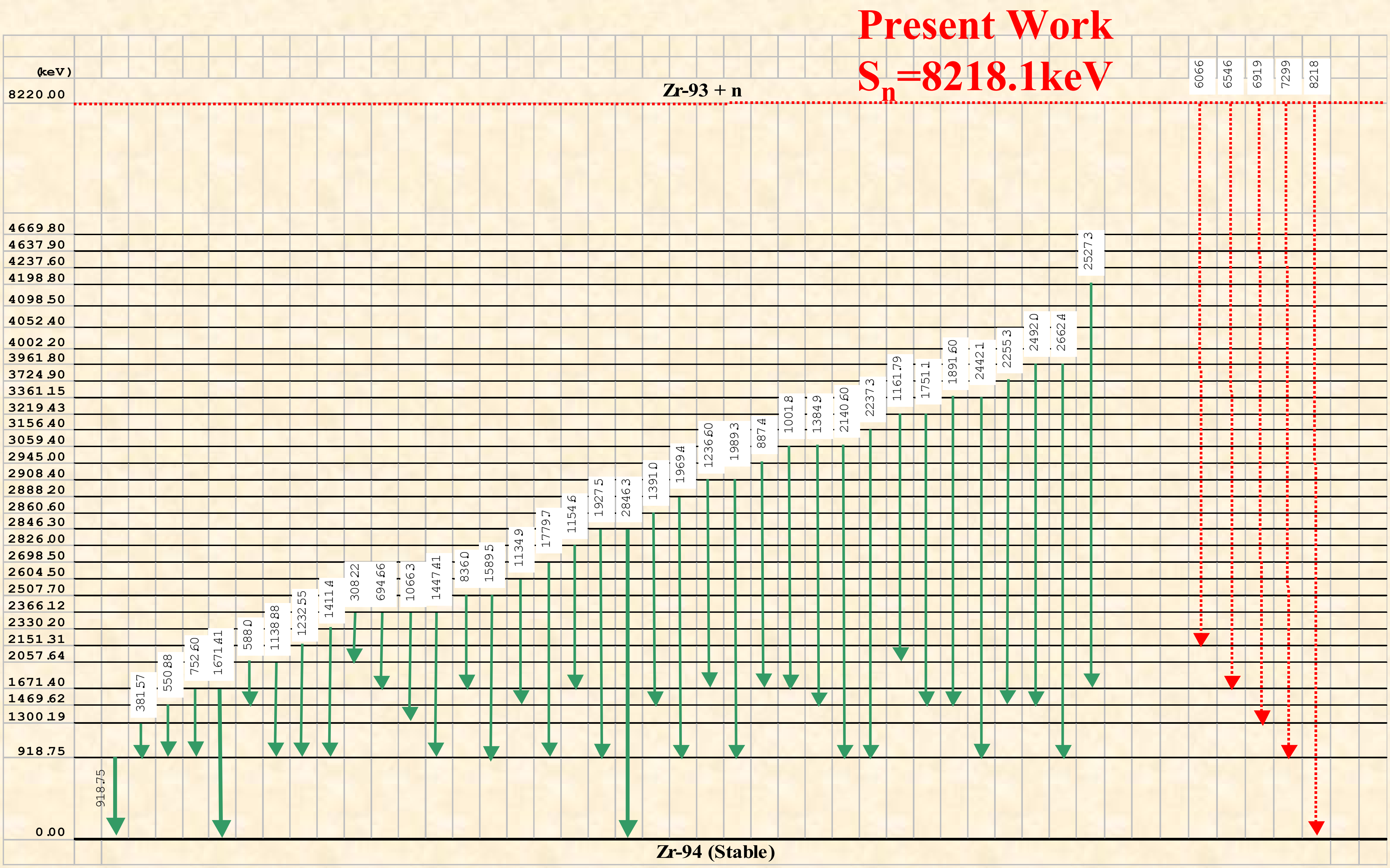
Zr
Pair Spectrometer mode
1.0 11.3 MeV
162 peaks

Gtol Code

Intensities I_γ (mb)

lower limit of cross sections
Σ Iγ g.s.

Prompt γ rays due to ^{93}Zr(n_{th},γ) reaction



Lower limit of thermal-neutron capture cross-section

Emission Intensities: I_γ of γ-rays feeding to the ground state of ^{94}Zr

Observed γ rays (keV)	Intensity I_γ (mb)
918.8	543.5 ± 3.7
1671.5	53.1 ± 1.1
2846.5	27.1 ± 0.7
8217.7	4.6 ± 0.4

$$\sum_{g.s.} I_\gamma = 0.63 \pm 0.02 \;\; (b)$$

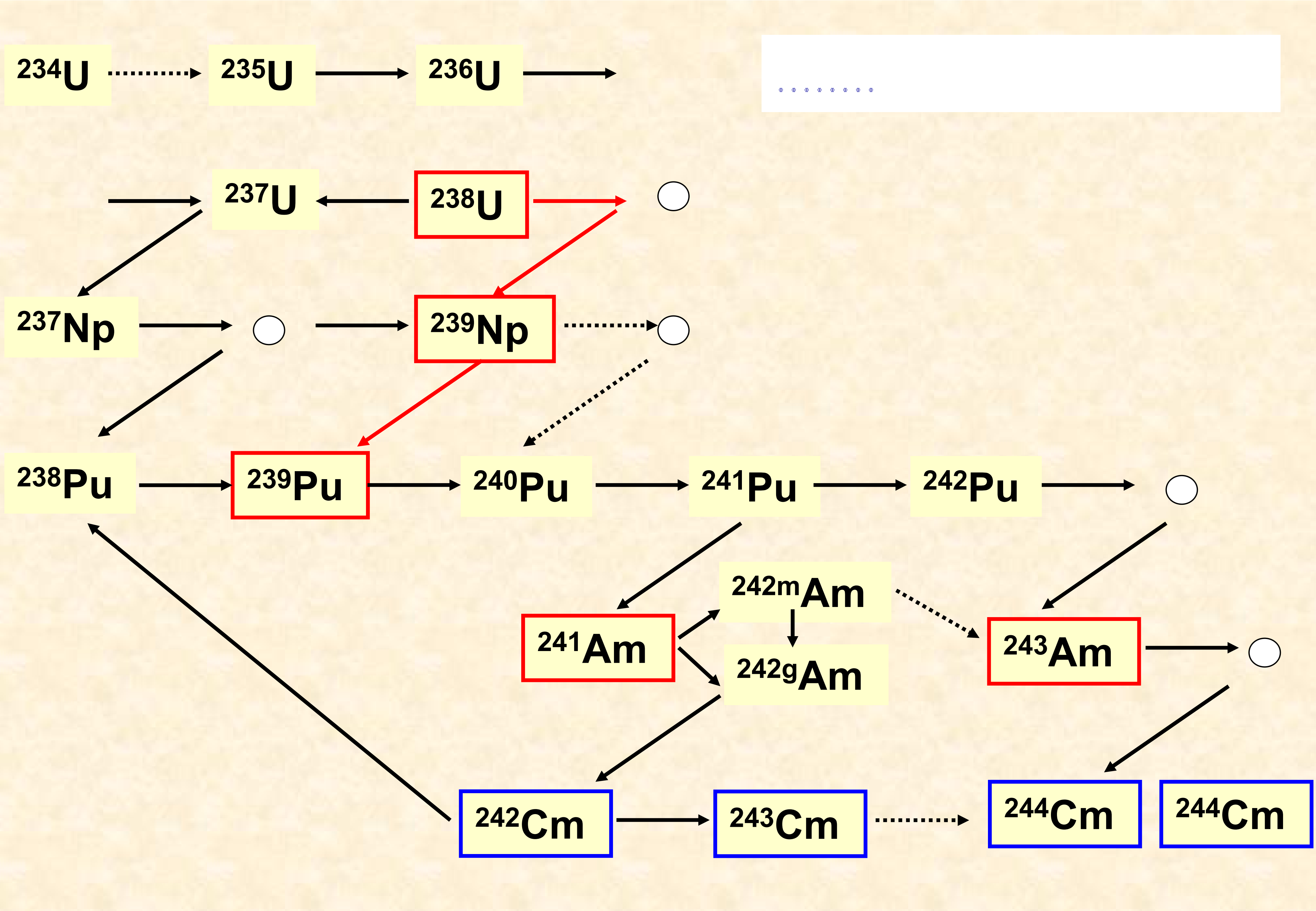
Result of thermal-neutron capture cross-section for $^{93}Zr(n_{th},\gamma)$ and $^{91}Zr(n_{th},\gamma)$ reactions

References		σ_0 for ^{91}Zr (b)	σ_0 for ^{93}Zr (b)
H.Pomerance[a)]	1952	1.52 ± 0.12	$1.3 < \sigma_0 < 4$
Garrison *et al.*[b)]	1962	1.2 ± 0.32	1.1 ± 0.4
Clayton[c)]	1972	1.579	1.996
Mughabghab *et al.*	1981	1.24 ± 0.25	$1.3 < \sigma_0 < 4$
Table of Isotopes *8ed*	1998	1.24 ± 0.25	2.7 ± 1.4
JENDL-3.3	2002	1.247	2.239
This Work (lower limit)		1.30 ± 0.04	0.63 ± 0.02

a) Measurements with ORNL pile oscillator
b) Statistical model estimates
c) Calculation by the resonance parameters from BNL-325

Supplement C:

Thermal-Neutron Capture Cross-Section And Resonance Integral of $^{241}Am(n,\gamma)^{242g}Am$ Reaction



^{234}U
^{235}U
^{236}U
^{237}U
^{238}U
^{237}Np
^{239}Np
^{238}Pu
^{239}Pu
^{240}Pu
^{241}Pu
^{242}Pu
^{241}Am
^{242m}Am
^{242g}Am
^{243}Am
^{242}Cm
^{243}Cm
^{244}Cm
^{244}Cm

Motivation

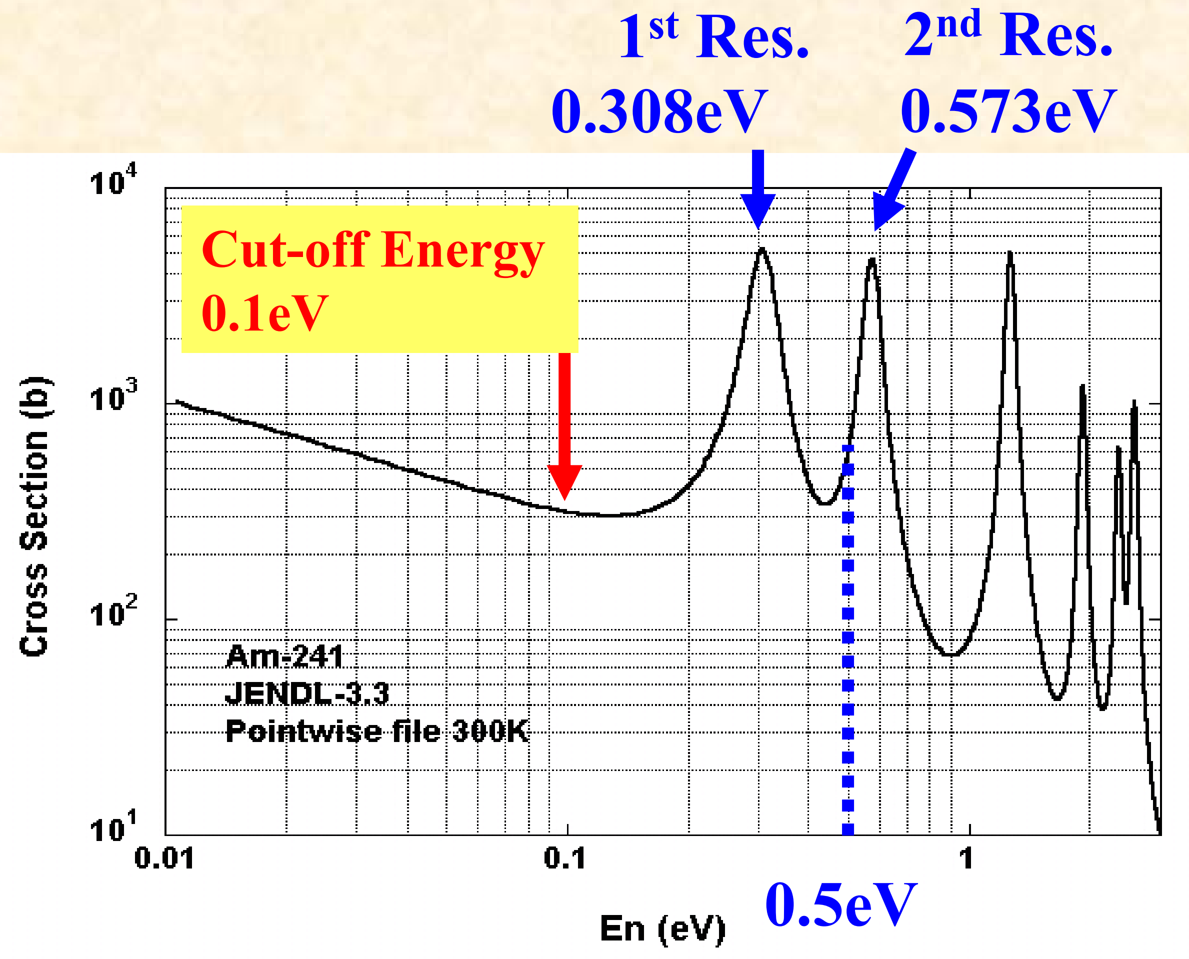
^{241}Am 432 yr → ^{242m}Am 141yr, ^{242g}Am 16h → ^{242}Cm 163d → ^{243,244,245}Cm

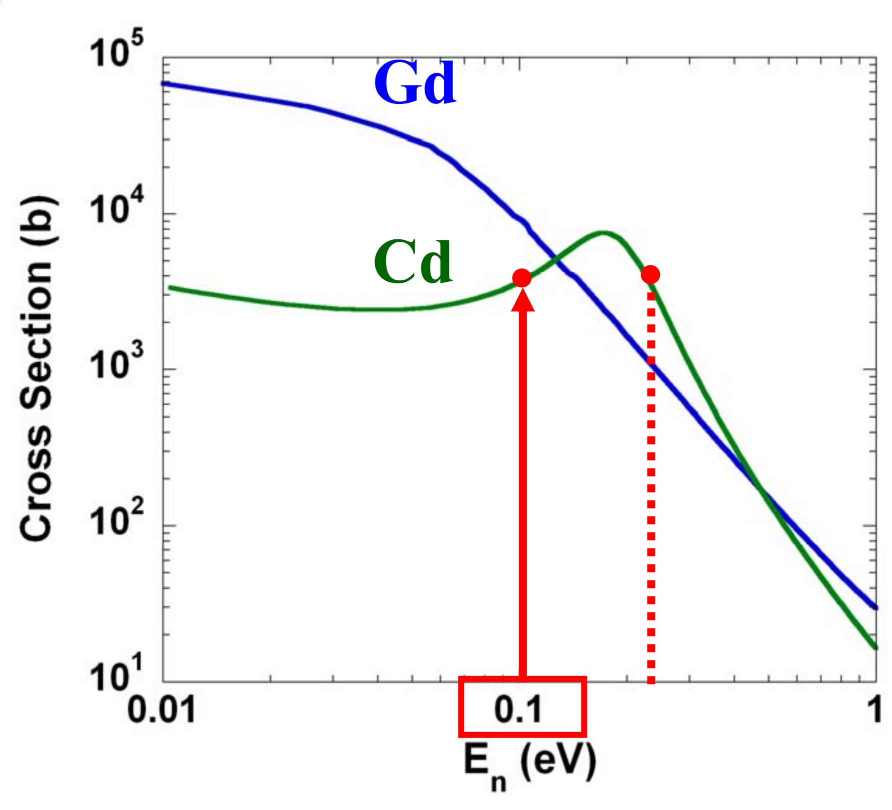
^{242}Cm → ^{238}Pu

- Problem of **decay heat** ^{242}Cm (163 day)
- Production of **long-lived Cm isotopes**
- Discrepancies among the reported data: σ_0 about **20%**

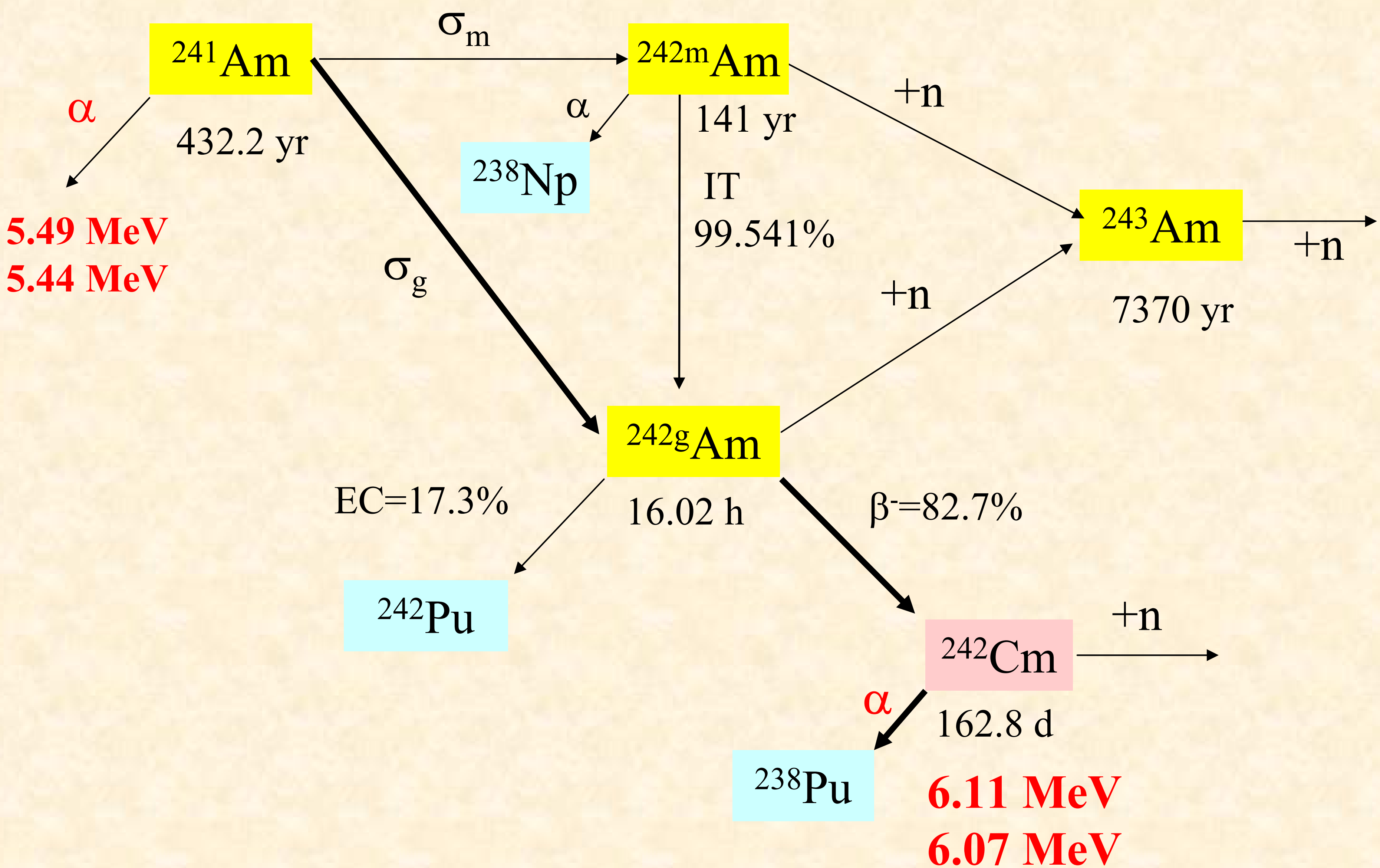
Authors Year		$\sigma_{0,g}$ (b)	$I_{0,g}$ (b)
Maidana et al.	(2001)	602±9	1665±91
Fioni et al.	(2001)	636±46	------
Shinohara et al.	(1997)	768±58	1694±146
Gavrulov et al.	(1977)	780±50	------
Harbour et al.	(1973)	748±20	1330±117
Bak et al.	(1967)	670±60	2100
Deal et al.	(1964)	770	------

Cross Section Curve of $^{241}Am(n,\gamma)$ reaction





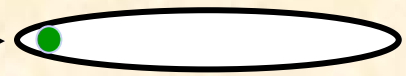
Partial Decay Scheme



Irradiation of samples

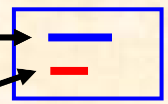
Purity ^{241}Am : 99.93 %
^{243}Am : 0.0647%
Other : 0.0002%

Am-241
100Bq

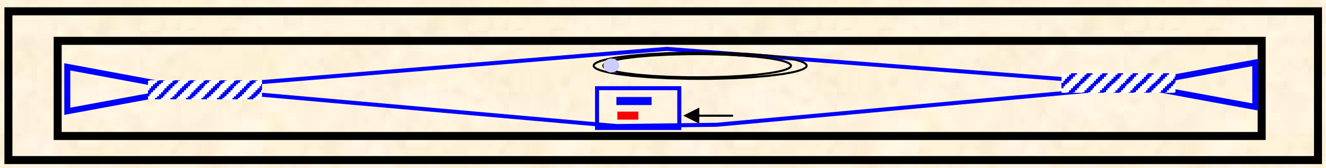


Co/Al 1 mm

Au/Al 0.5 mm



High purity quartz tube
8mmf, 50mm in length



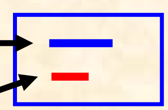
KUR @Long-Irradiation Plug
Irradiation for 68Hours

Am-241
500Bq

20mm

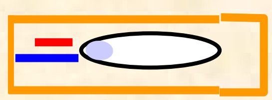
Co/Al 1 mm

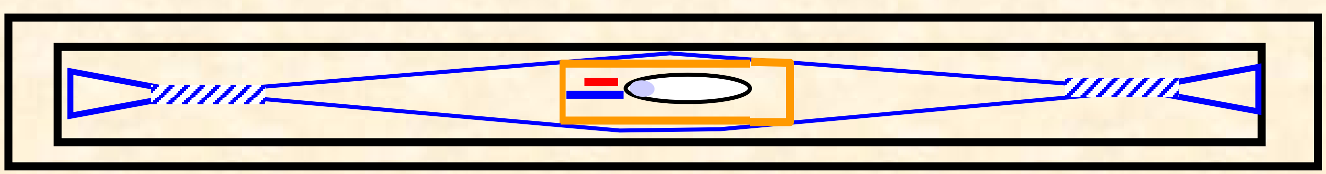
Au/Al 0.5 mm



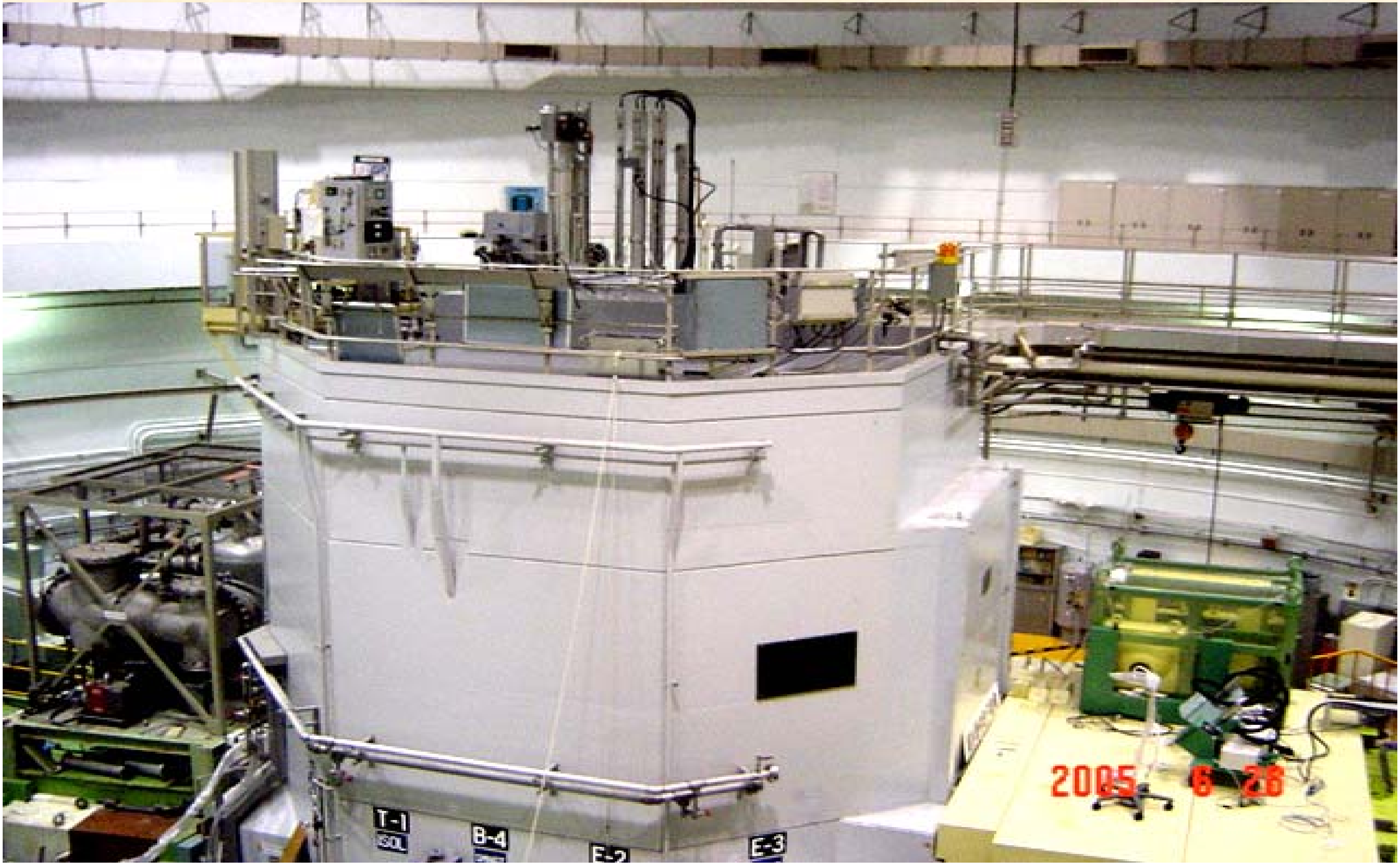
Cut-off Energy
0.107eV

Gd covered capsule



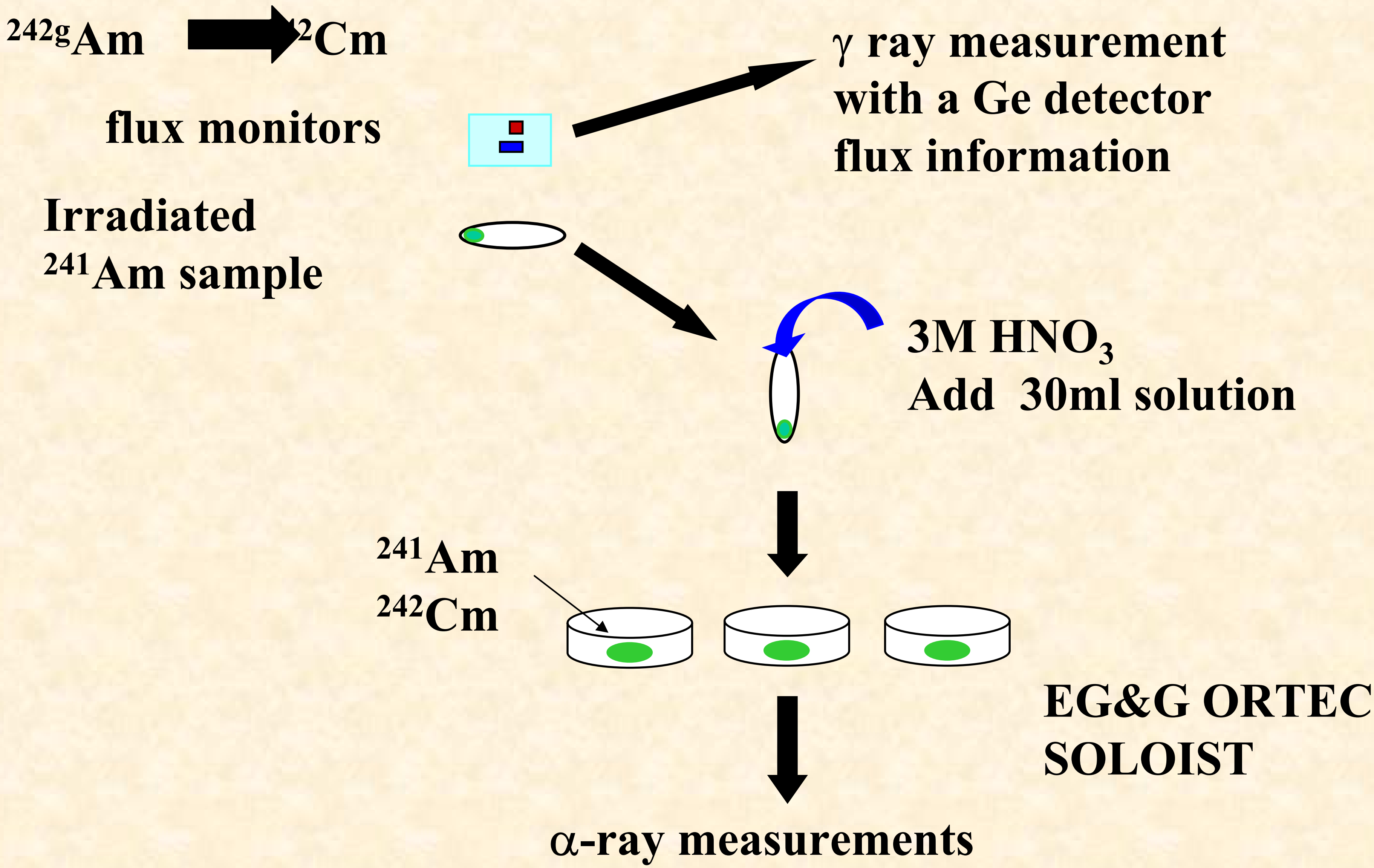


Kyoto University Reactor: KUR @KURRI

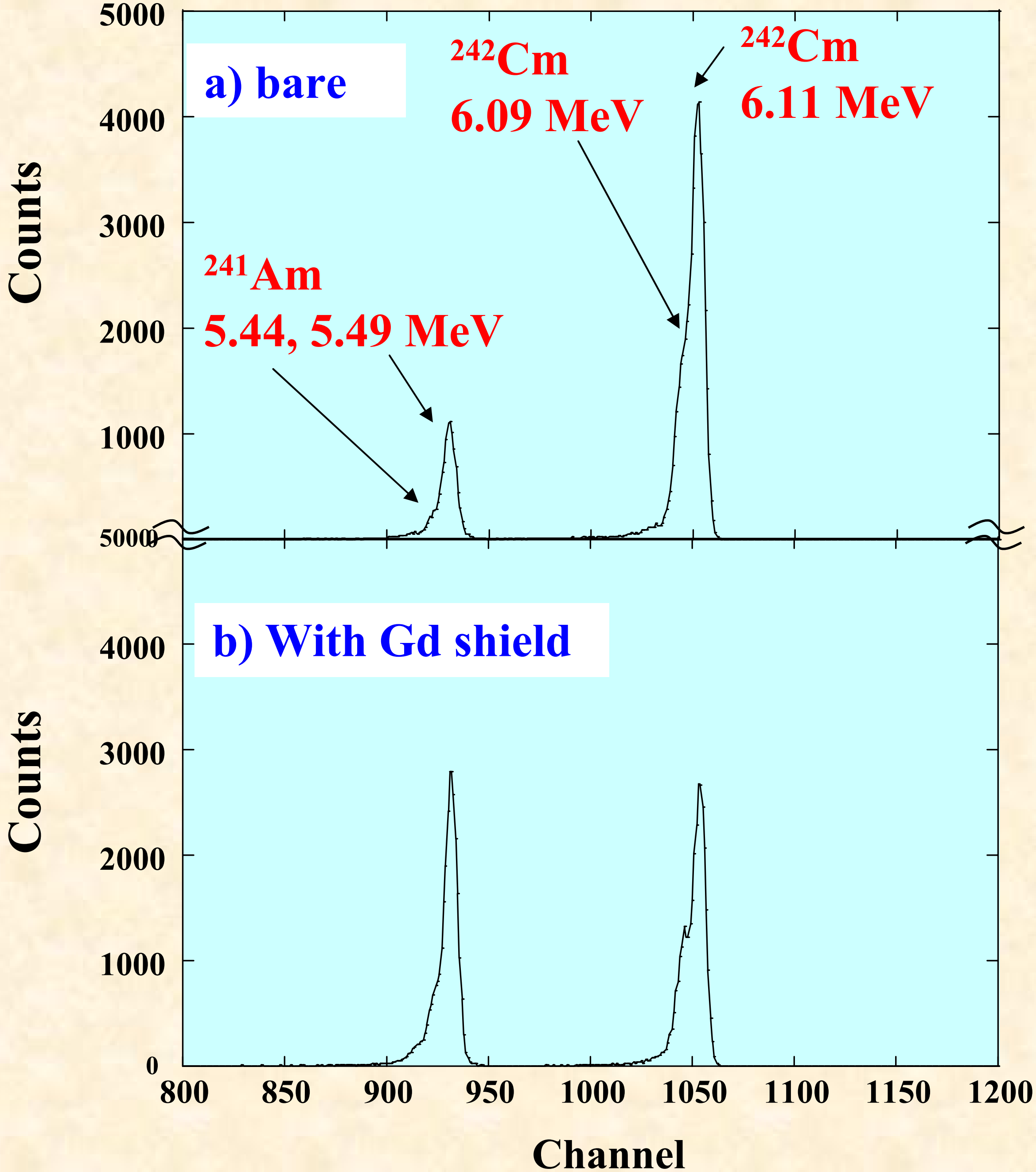


Measurements of Samples

20 Days Cooling after Irradiation



α-ray spectra of irradiated ^{241}Am sample



Energy Resolution 45keV

^{241}Am : 11421 ± 107 Cnts.
^{242}Cm : 47259 ± 217 Cnts.

^{241}Am : 28510 ± 169 Cnts.
^{242}Cm : 30736 ± 175 Cnts.

Analysis - the Westcott's convention-

$$\frac{R}{\sigma_0} = gG_{th}\phi_1 + \phi_2 \cdot s_0 G_{epi}$$

for irradiation without a Gd shield,

$$\frac{R'}{\sigma_0} = g\ G_{th}\phi'_1 + \phi'_2 \cdot s_0 G_{epi}$$

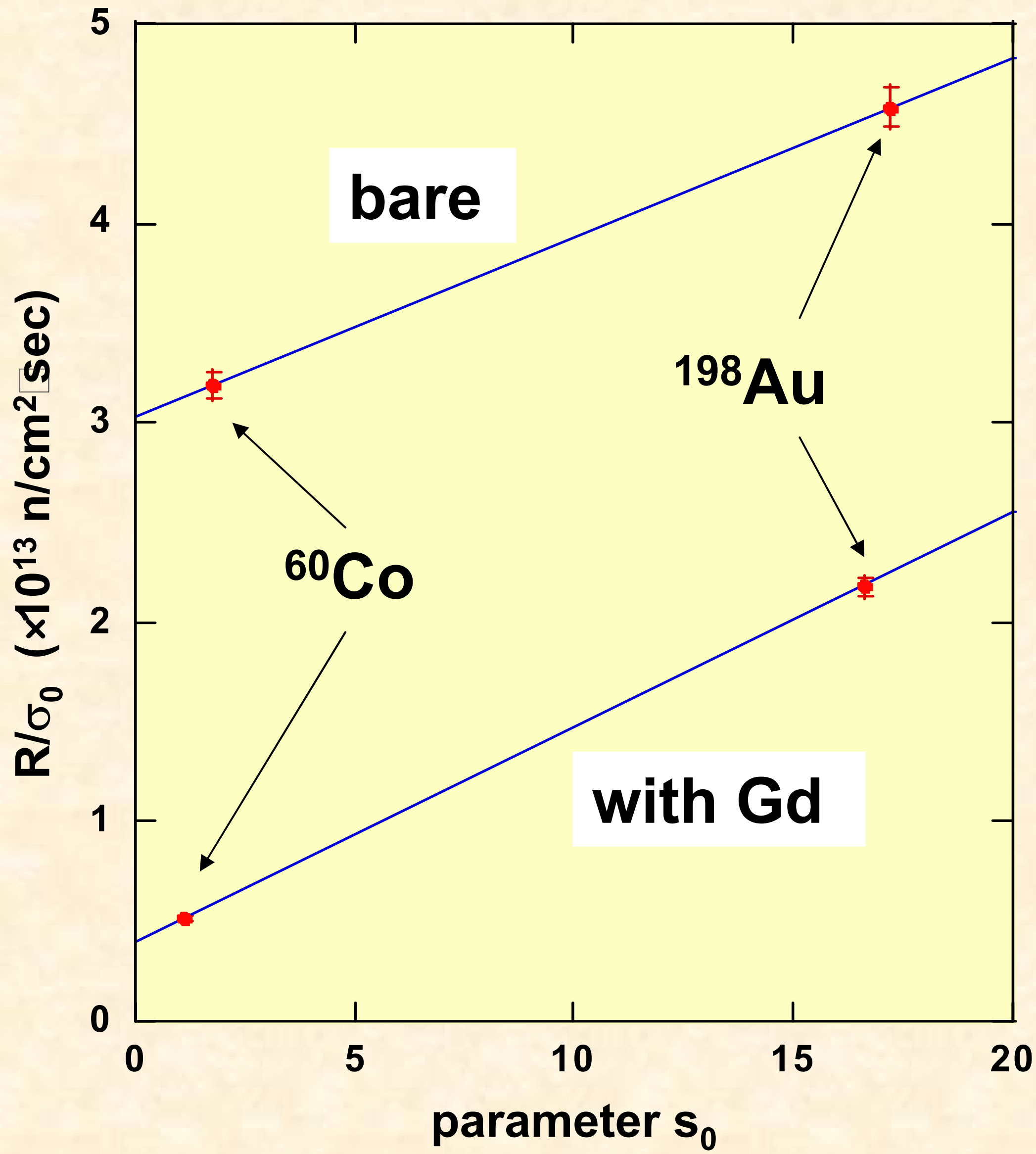
for irradiation with a Gd shield.
where

$$s_0 = \sqrt{\frac{4}{\pi}} \cdot \frac{I'_0}{\sigma_0}$$

I_0' is the resonance integral
after subtracting the 1/υ component
g : 1.051 for ^{241}Am
Resonance Integral I_0

$I_0 = I_0' + 0.9725\sigma_0$

for cut-off energy of 0.107 eV

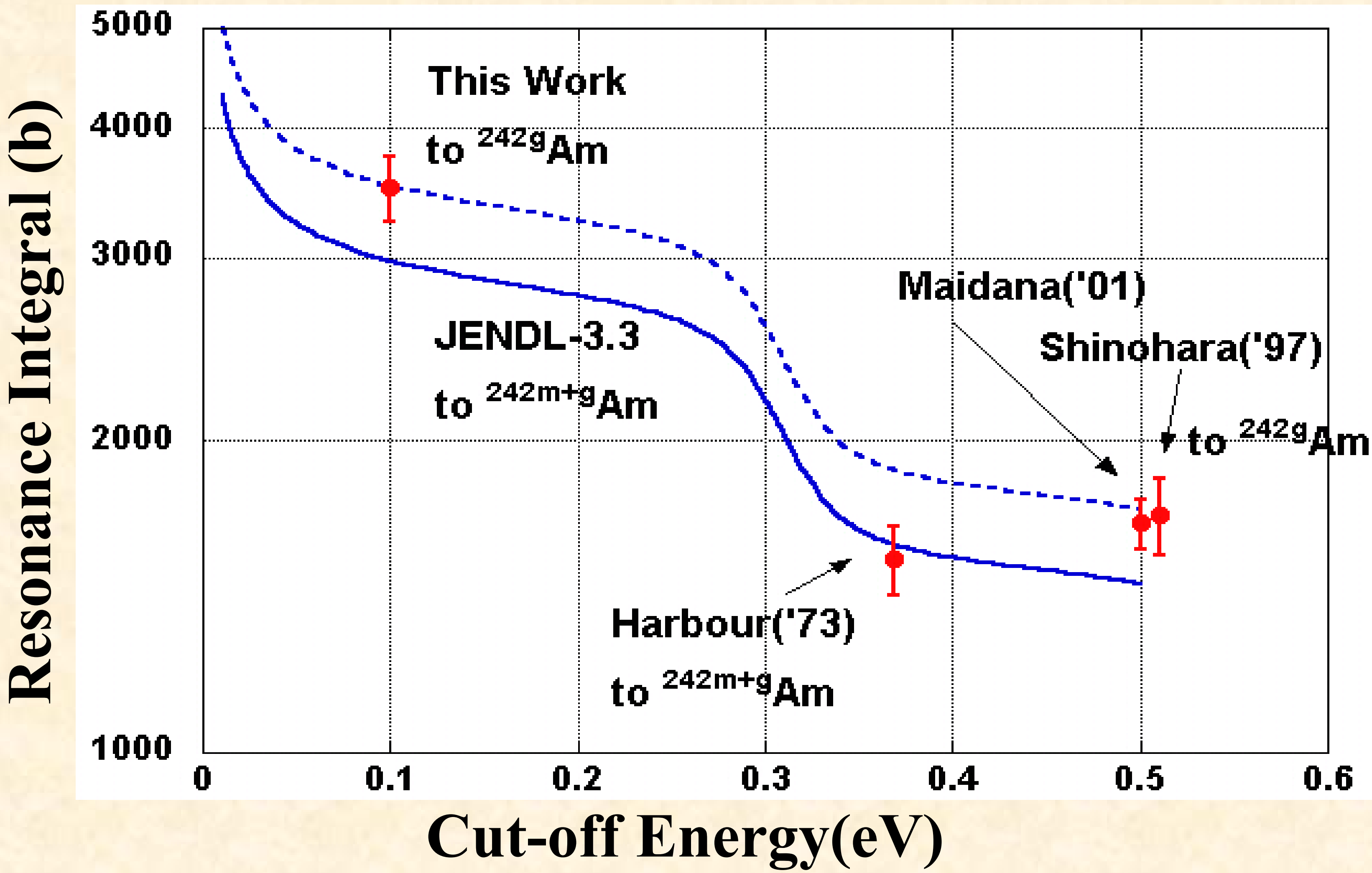


Results of σ_0 and I_0 for the $^{241}Am(n,\gamma)^{242g}Am$ reaction

Authors & Year	σ_{0g} (b)	I_g (b)	Cut-off Energy(eV)
This Work	628±17	3.5±0.3 k	0.107
JENDL-3.3 (2002)	639.4*	1456 *	
Maidana et al. (2001)	602±9	1665±91	0.5
Fioni et al. (2001)	636±46	----	----
Shinohara et al. (1997)	768±58	1694±146	0.5
Gavrulov et al. (1977)	780±50	---	---
Harbour et al. (1973)	748±20	1330±117	0.369
Bak et al. (1967)	670±60	2100	
Deal et al. (1964)	770	----	----

. ^{241}Am to $^{242m+g}Am$

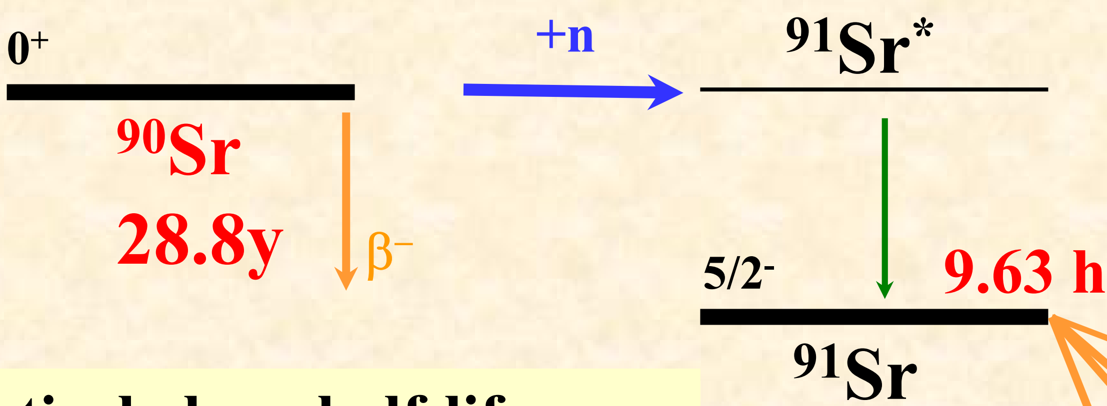
Result of I_0 for the $^{241}Am(n,\gamma)^{242g}Am$ reaction

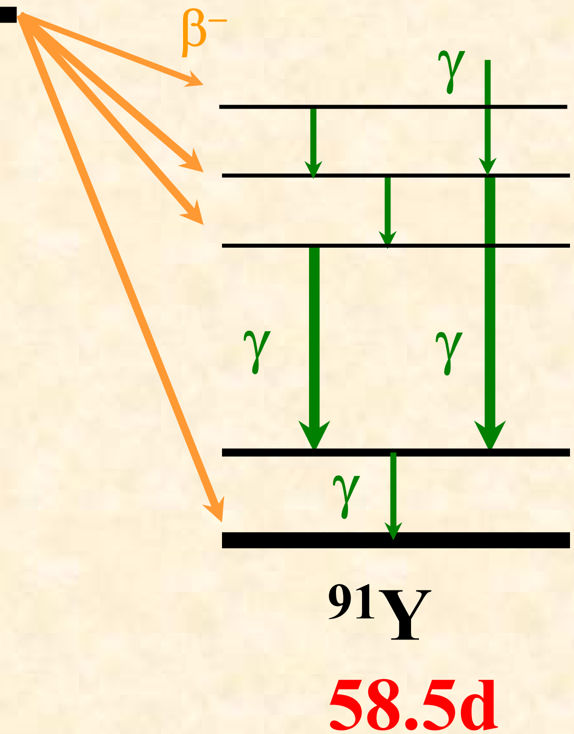


Supplement D:

Thermal-Neutron Capture Cross-Section and Resonance Integral of $^{90}Sr(n,\gamma)^{91}Sr$ Reaction

$^{90}Sr(n,\gamma)^{91}Sr$ reaction Cross-Section





- **relatively long half-life**
- **β-ray emitter**
- **Decay heat**

Past Measurement **1994.JRR-4**

$\sigma_0 = 15.3\ ^{+1.3}_{-4.2}$ **(mb)**

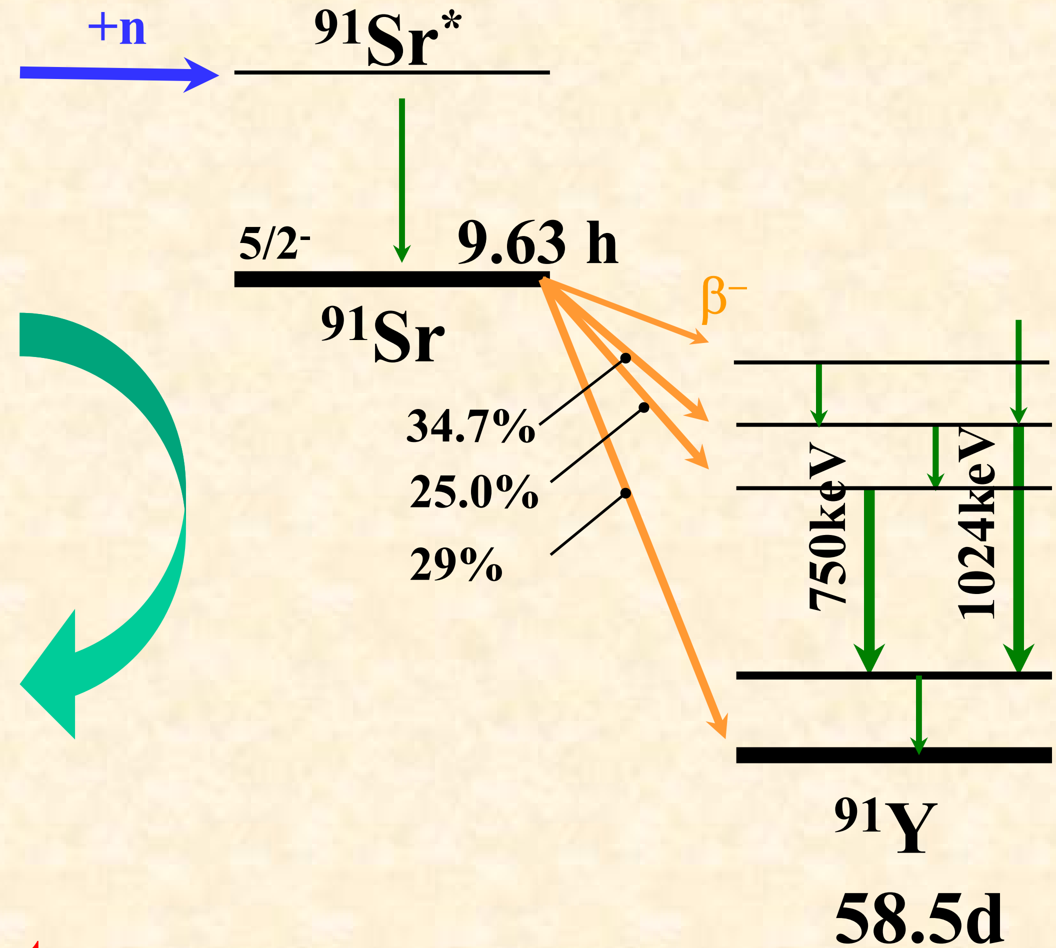
I_0 **160 (mb)**

- **upper limit just for I_0**

Experiment Procedure

0^+

^{90}Sr



Irradiation Sample

^{90}Sr Stand.Sol. ^{85}Sr sol. (as tracer)

Au, Co neutron flux monitors

Irradiation KUR Hyd.

Irrad. With Cd shield capsule

Chemical Treatment

huge γ-ray B.G. due to ^{24}Na(15h)

1369keV 2754keV

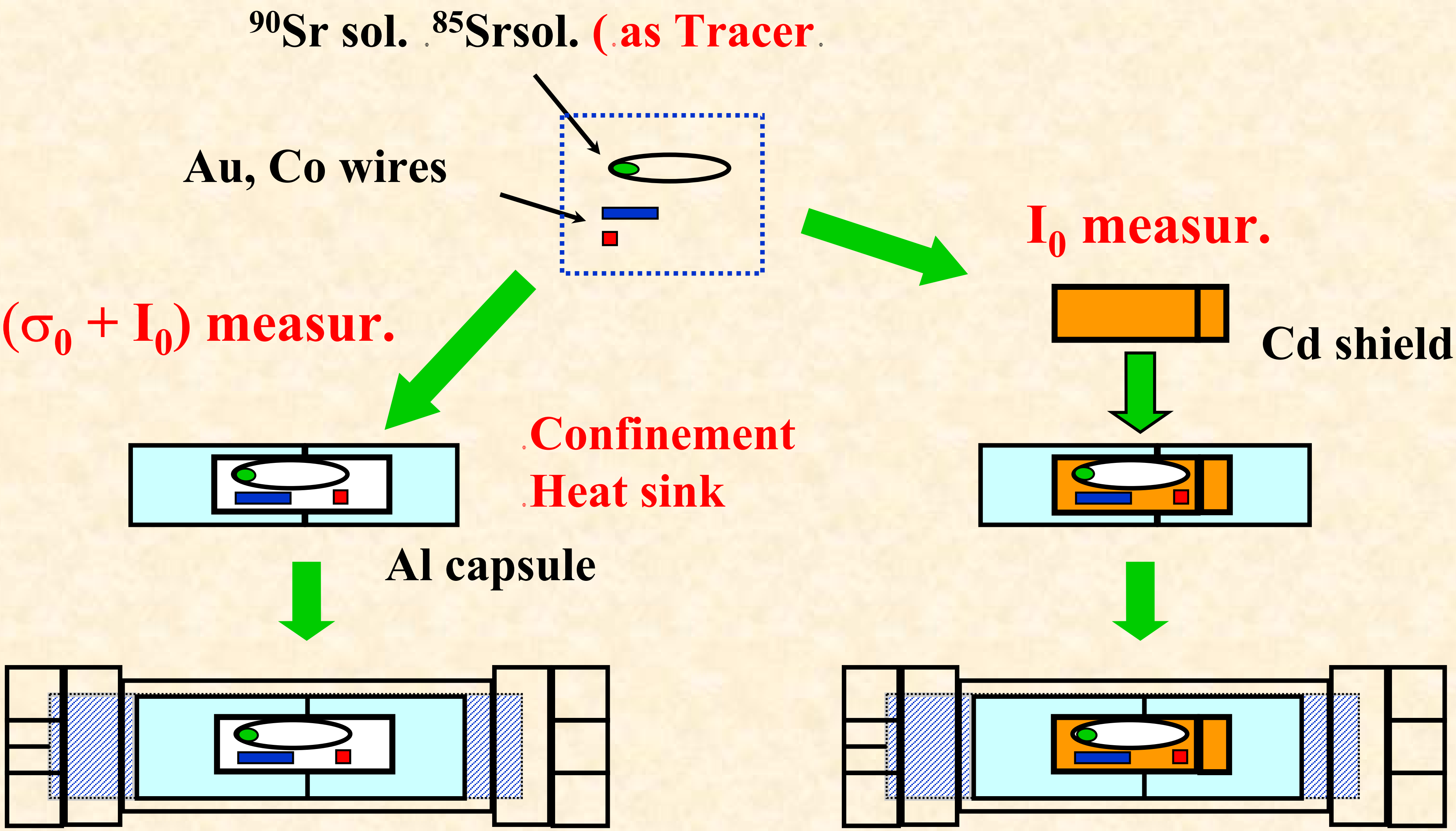
Singles Measurement with Ge detector

Yield of ^{91}Sr → Reaction rate

Induce Activities of Monitors → Neutron Fluxes

Derivation of σ_0 and I_0

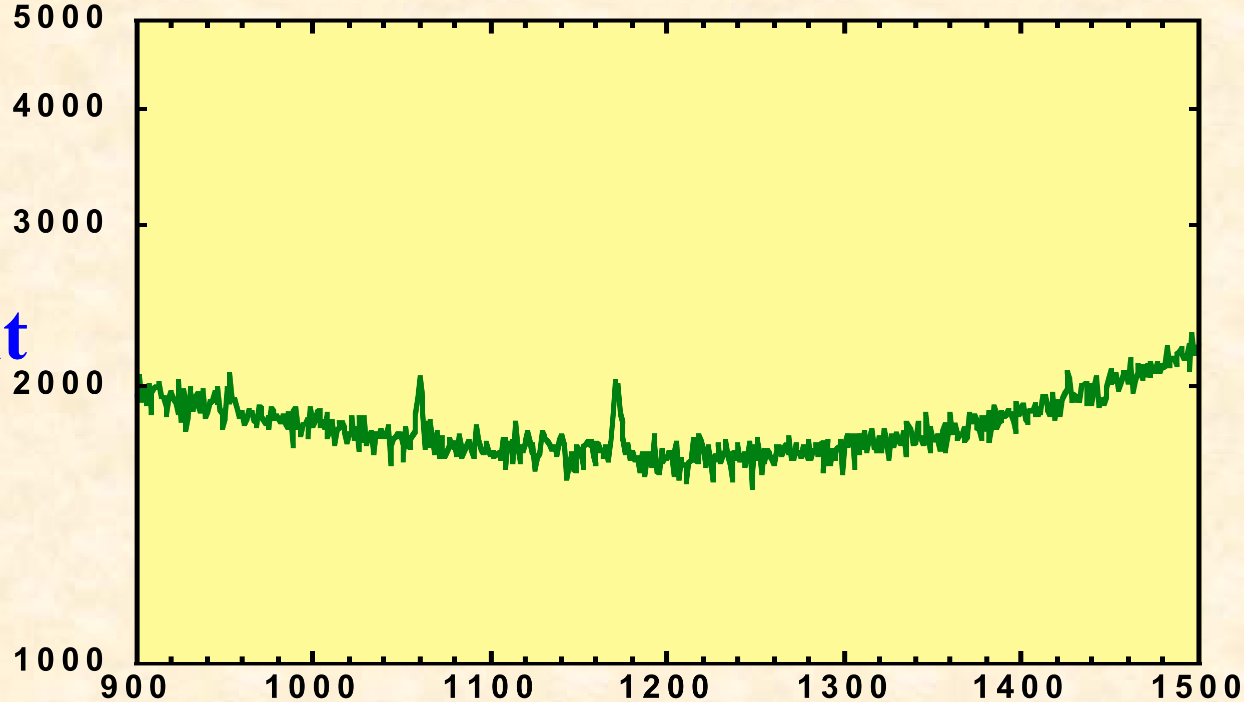
Irradiation Targets



Irrad. Capsules for Hydraulic Irrad.
KUR Hyd 1×10^{14} n/cm^{2}sec

γ-ray Spectra

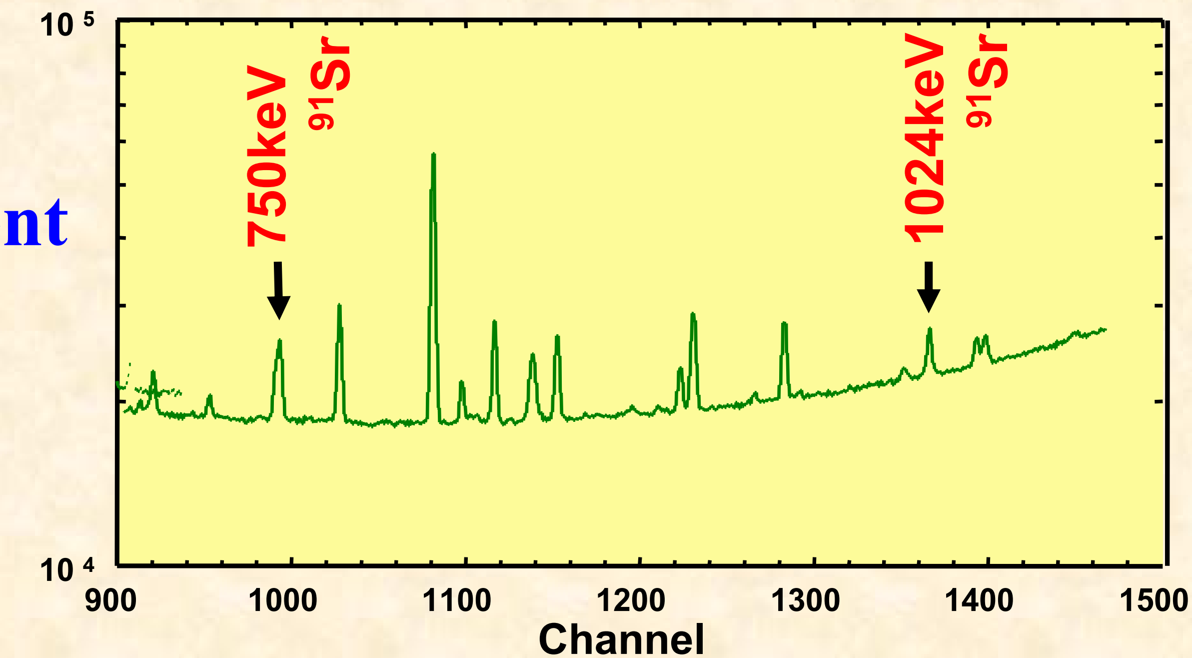
Before
Chemical Treatment

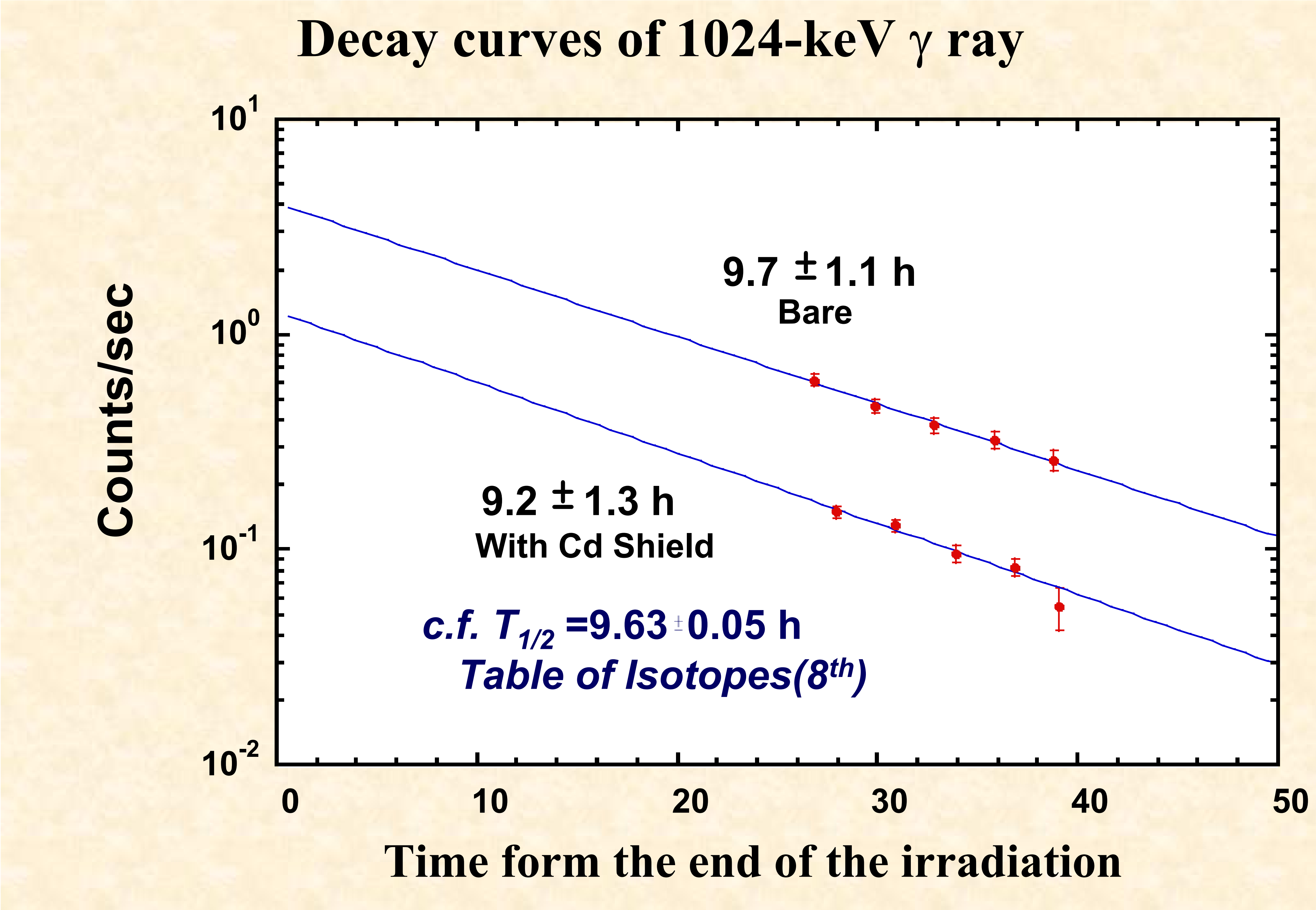


Technique of solvent extract

Reduction of ^{24}Na!

After treatment




Decay curves of 1024-keV γ ray
Counts/sec
10^1
10^0
10^-1
10^-2
0
10
20
30
40
50
Time form the end of the irradiation
9.7 ± 1.1 h
Bare
9.2 ± 1.3 h
With Cd Shield
c.f. T1/2 =9.63 ± 0.05 h
Table of Isotopes(8th)

Analysis **Westcott's convention**

$$\frac{R}{\sigma_0} = gG_{th}\phi_1 + \phi_2 \cdot s_0 G_{epi}$$

for irradiation without a Gd shield,

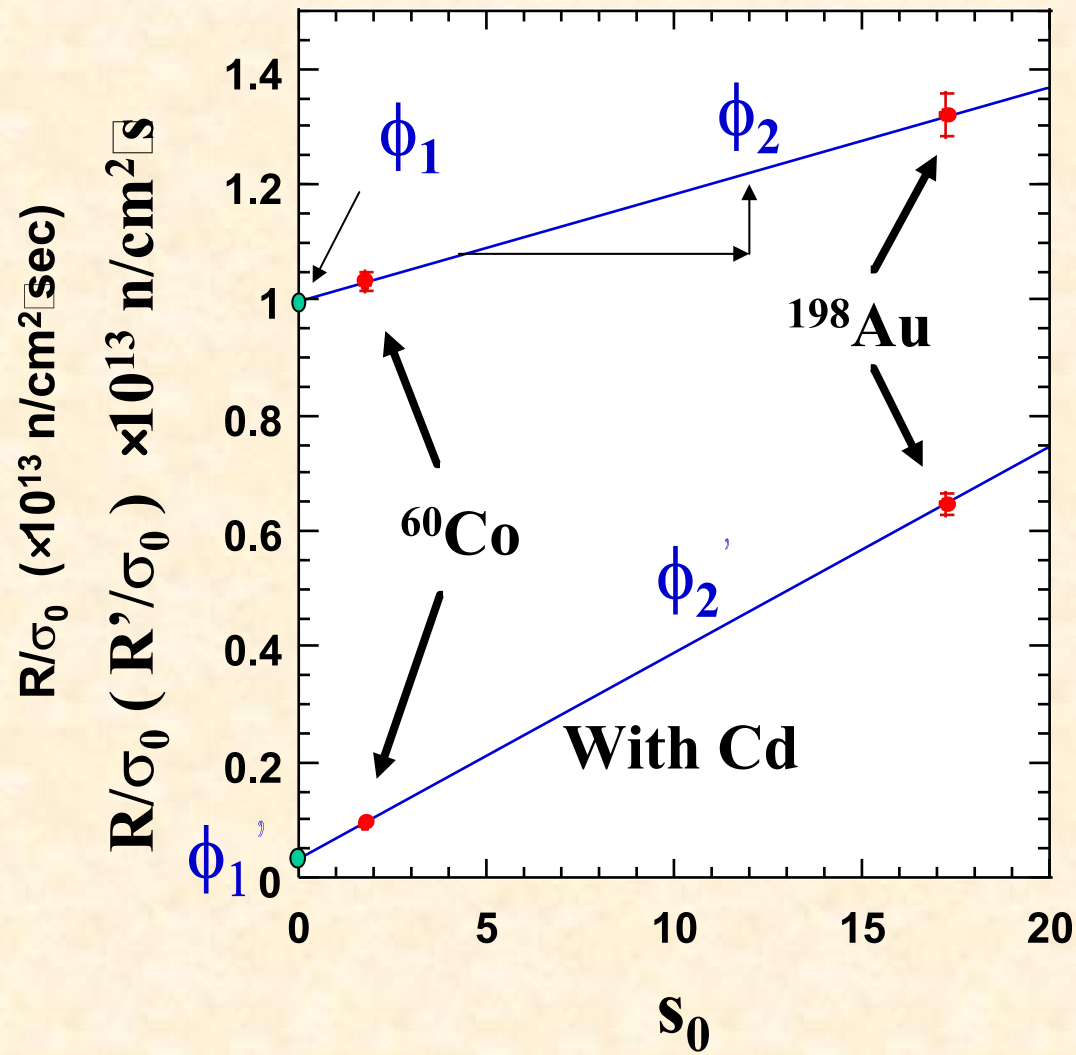
$$\frac{R'}{\sigma_0} = g\ G_{th}\phi'_1 + \phi'_2 \cdot s_0 G_{epi}$$

for irradiation with a Gd shield.
where

$$s_0 = \sqrt{\frac{4}{\pi}} \cdot \frac{I'_0}{\sigma_0}$$

I_0' is the resonance integral
after subtracting the 1/υ component
g : deviation form 1/υ low

Resonance Integral I_0
$I_0 = I_0' + \mathbf{0.45}\sigma_0$
for cut-off energy of 0.5 eV

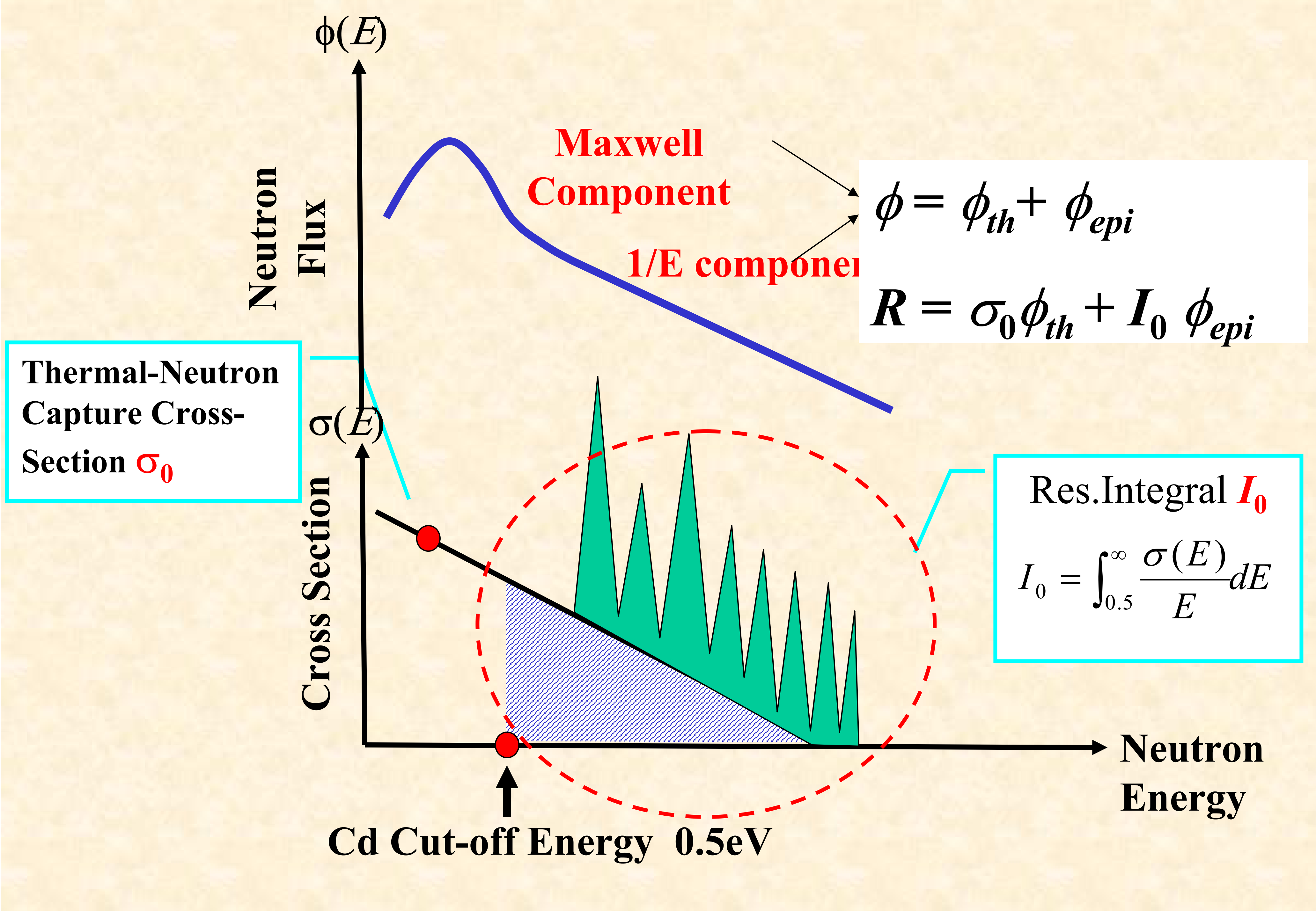


Results

Author		Thermal Cross Section, σ_0 (mb)	Resonance Integral, I_0 (mb)
Zeisel	[66]	800 ± 500	----------
McVey *et al.*	[83]	14.0 ± 2.4	----------
Lone *et al.*	[93]	9.7 ± 0.7	----------
Harada *et al.*	[94]	$15.3^{+1.3}_{-4.2}$	160
Present Work		10.1 ± 1.3	104 ± 16

Supplement E:

Brief Outline of Analysis In the Basis of Westcott's Convention



φ(E)
Neutron Flux
Maxwell Component
1/E componen
$\phi = \phi_{th} + \phi_{epi}$
$R = \sigma_0 \phi_{th} + I_0 \phi_{epi}$
Thermal-Neutron Capture Cross-Section σ_0
σ(E)
Cross Section
Res.Integral I_0
$I_0 = \int_{0.5}^{\infty} \frac{\sigma(E)}{E} dE$
Neutron Energy
Cd Cut-off Energy 0.5eV

Cadmium Ratio Method

$$R = \sigma_0 \cdot \phi_{th} + RI \cdot \phi_{epi}$$

$$R' = RI \cdot \phi_{epi}$$

Cadmium ratio R_{cd}

$$R_{Cd} = \frac{\sigma_0 \cdot \phi_{th} + RI \cdot \phi_{epi}}{RI \cdot \phi_{epi}} = \frac{\phi_{th}}{\phi_{epi}} \cdot \frac{\sigma_0}{RI} + 1$$

$$R_{Cd,x} = \frac{\phi_{th}}{\phi_{epi}} \cdot \frac{\sigma_{0,x}}{RI_x} + 1$$

$$R_{Cd,Co} = \frac{\phi_{th}}{\phi_{epi}} \cdot \frac{\sigma_{0,Co}}{RI_{Co}} + 1$$

$$RI_x = RI_{Co} \frac{(R_{Cd,Co} - 1)}{(R_{Cd,x} - 1)} \cdot \frac{\sigma_{0,x}}{\sigma_{0,Co}}$$

Modified Cadmium Ratio Method

$$R = n\upsilon_0\hat{\sigma} = n\upsilon_0\sigma_0(gG_{th} + r(T/T_0)^{1/2}s_0G_{epi})$$

Westcott's Convention

Siple Neutron-Flux notaions

Bare: $$R/\sigma_0 = \phi_1 \cdot G_{th} + \phi_2 \cdot s_0 \cdot G_{epi}$$

with Cd: $$R'/\sigma_0 = \phi_1' \cdot G_{th} + \phi_2' \cdot s_0 \cdot G_{epi}$$

Nuclide: x

$$\begin{cases} R_x / \sigma_{0,x} = \phi_1 \cdot G_{th,x} + \phi_2 \cdot s_{0,x} \cdot G_{epi,x} \\ R'_x / \sigma_{0,x} = \phi'_1 \cdot G_{th,x} + \phi'_2 \cdot s_{0,x} \cdot G_{epi,x} \end{cases}$$

Neutron flux components $\phi_{1,2}$ $\phi'_{1,2}$

Multi-flux Monitor Method

$$R_x / \sigma_{0,Au} = \phi_1 \cdot G_{th,Au} + \phi_2 \cdot s_{0,Au} \cdot G_{epi,Au}$$

$$R'_{Au} / \sigma_{0,Au} = \phi'_1 \cdot G_{th,Au} + \phi'_2 \cdot s_{0,Au} \cdot G_{epi,Au}$$

$$R_{Co} / \sigma_{0,Co} = \phi_1 \cdot G_{th,Co} + \phi_2 \cdot s_{0,Co} \cdot G_{epi,Co}$$

$$R'_{Co} / \sigma_{0,Co} = \phi'_1 \cdot G_{th,Co} + \phi'_2 \cdot s_{0,Co} \cdot G_{epi,Co}$$

Analysis on the basis of the Westcott's convention

$$\frac{R}{\sigma_0} = gG_{th}\phi_1 + \phi_2 \cdot s_0 G_{epi}$$

for irradiation without a Gd shield,

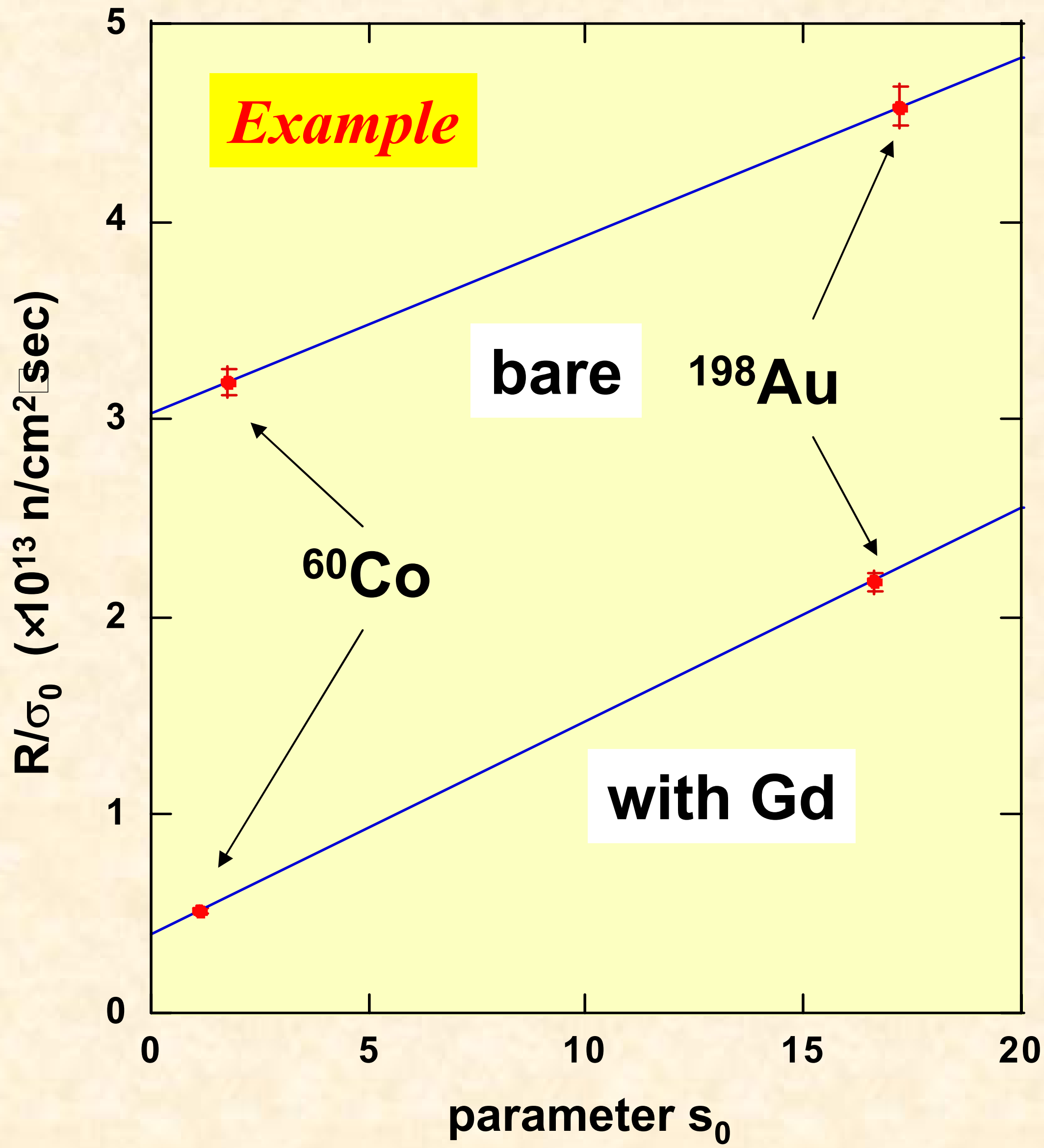
$$\frac{R'}{\sigma_0} = g\ G_{th}\phi'_1 + \phi'_2 \cdot s_0 G_{epi}$$

for irradiation with a Gd shield.
where

$$s_0 = \sqrt{\frac{4}{\pi}} \cdot \frac{I'_0}{\sigma_0}$$

I_0' is the resonance integral
after subtracting the 1/υ component
g : deviation form 1/υ low

Resonance Integral I_0
$I_0 = I_0' + \mathbf{0.45}\sigma_0$
for cut-off energy of 0.5 eV

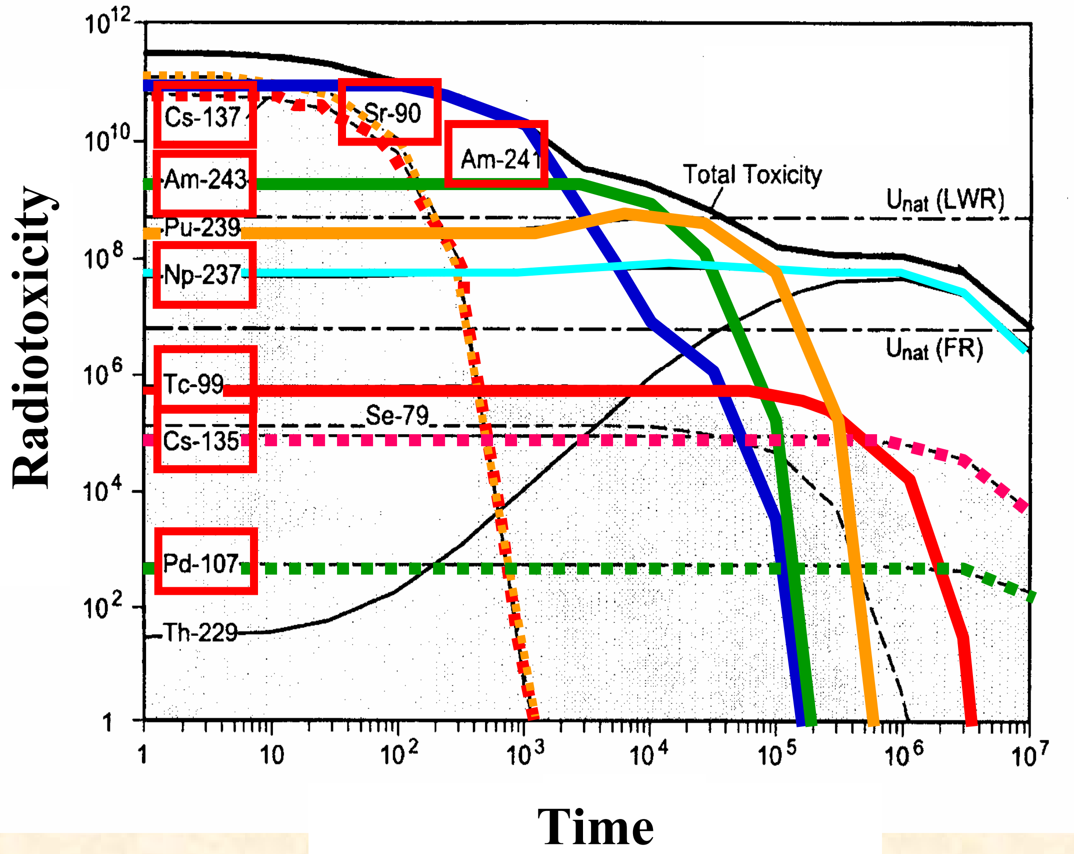


Supplement F:

Others

Motivation

High Level Nuclear Wastes
Log-Lived Fission Products.FP's)
Minor Actinides.MA's)



Reduction of
.Disposal Managements
.Load to Environment

Nuclear Transmutation

Cross-Section Data
to Evaluate Reaction Rates
WRENDA: World Request List for Nuclear Data

Important FP's.Me's
Selection of Nuclides
High Priority Request List

Transmutability of long-lived fission products

Fission product	Decay $T_{1/2}$ (y)	Trans $T_{1/2}$ (y)	Isotopic separation	Transmutable (yes/no)
^{129}I	$1.6x10^7$	51	no	yes
^{135}Cs	$2.3x10^6$	170	yes	no
^{99}Tc	$2.1x10^5$	51	no	yes
^{126}Sn	$1.0x10^5$	$4.4x10^3$	yes	no
^{79}Se	$6.5x10^4$	$2.2.10^3$	yes	no

Reference. NEA2002 Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles

Example of LSD for the reaction rate of ^{99}Tc