Activities for Nuclear Data Measurements in Korea

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Guinyun Kim

Kyungpook National University

Abstract

G. N. Kim[1,*], M. W. Lee[1], K. S. Kim[1], K. Kim[1], S. C. Yang[1], T. I. Ro[2], Y. R. Kang[2], H. S. Kang[3], H.S. Lee[3], M. H. Cho[3], I. S. Ko[3], and W. Namkung[3]

[1]*Department of Physics, Kyungpook National University, Daegu 702-701, Korea*
[2]*Department of Physics, Dong-A University, Busan 604-714, Korea*
[3]*Pohang Accelerator Laboratory, Pohang University of Science and Technology, Pohang 790-784, Korea*
**email:gnkim@knu.ac.kr*

We report the activities by using the pulsed neutron facility in Pohang Accelerator Laboratory, which consists of an electron linear accelerator, a water-cooled Ta target with a water moderator, and a 12 m time-of-flight path. It can be possible to measure the neutron total cross-sections in the neutron energy range from 0.01 eV to few hundreds eV by using the neutron time-of-flight method. A ^{6}LiZnS(Ag) glass scintillator was used as a neutron detector. We measured neutron total cross-sections for various samples with the time-of-flight method. We also report the nuclear data production experiments by using the activation methods with neutron and bremsstrahlung beams from the electron linac. We also report the measurements of production cross sections of various radioisotopes from the charged particle induced reactions at MC50 cyclotron of the Korea Institute of Radiological and Medical Sciences.

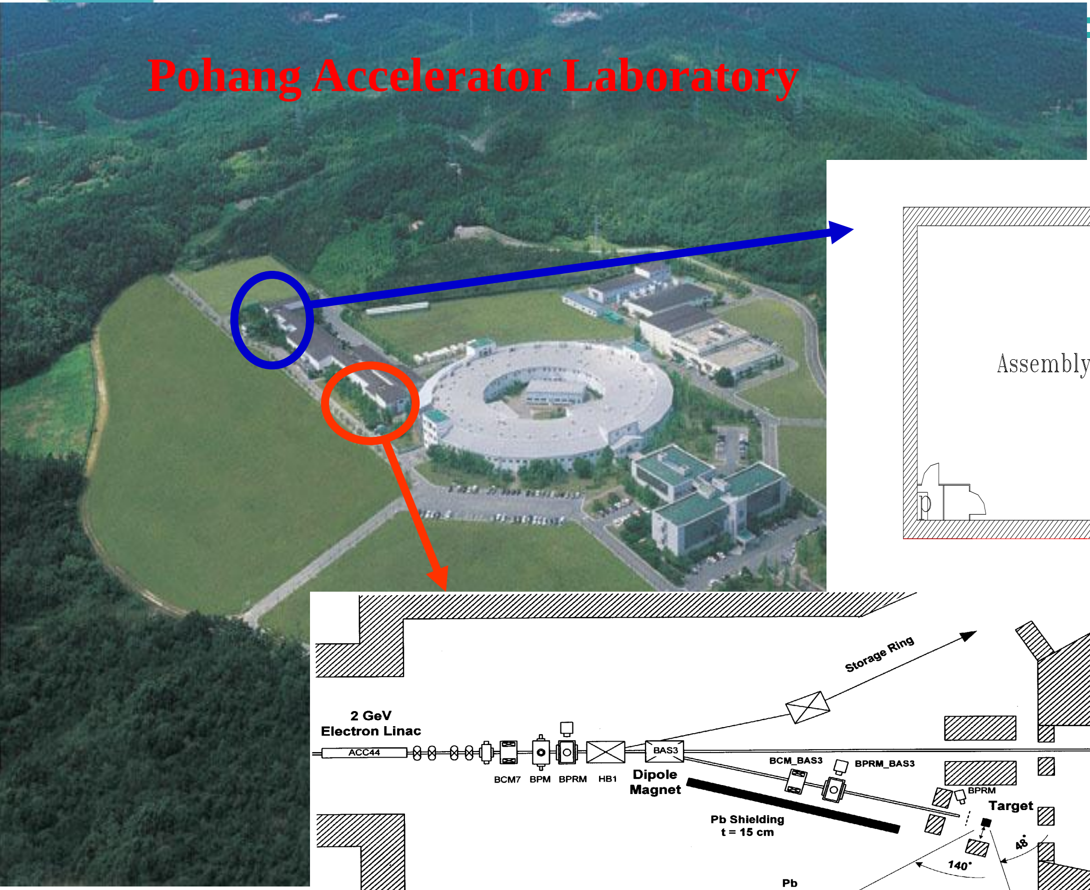
Activities for Nuclear Data Measurements

- **Activities on Nuclear Data Measurements in Korea**
  - **Neutron Total Cross-section measurements at PAL**
  - **Photo-nuclear reactions with Bremsstrahlung beam**
  - **Proton-induced reaction cross-section measurements at KIRAM**
- **Activities on Nuclear Data Measurements in Abroad**
  - **keV-neutron capture cross-sections at Titech**
  - **Proton-induced reaction cross-section measurement at CYRIC (Tohoku Univ.)**
  - **Neutron capture cross-section measurements at RPI, USA**
- **Other Collaborating Institute**
  - **FLNP, Russia**
  - **BARC, India**
  - **VAST, Viet Nam**
  - **CIAE, China**

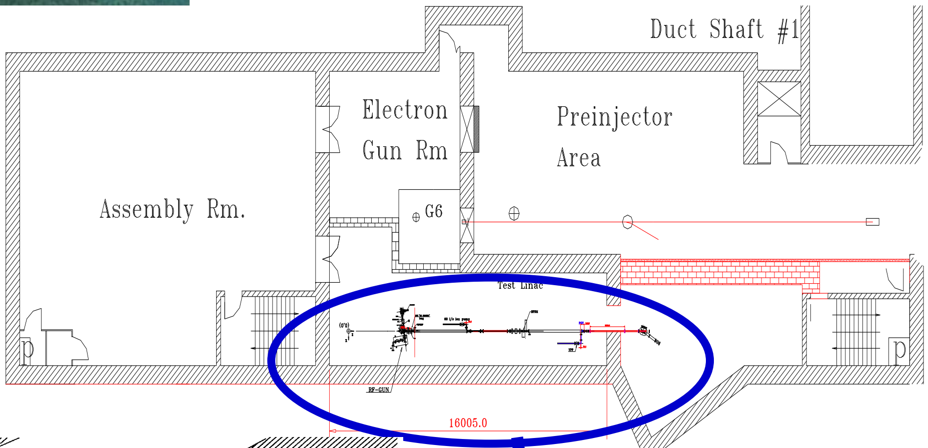
Activities on Nuclear Data Measurement in Korea

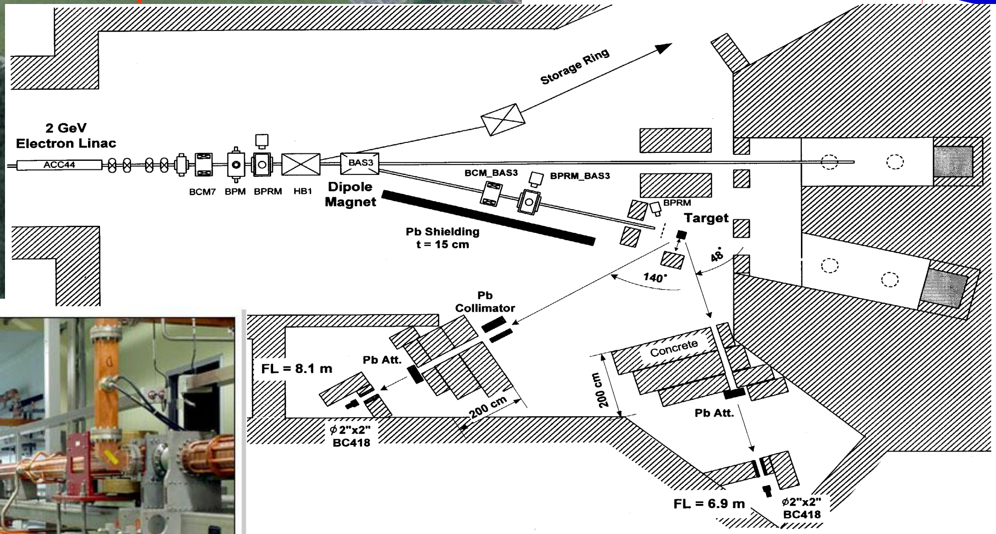
- Neutron Total Cross-section measurements at PAL
- Photo-nuclear reactions with Bremsstrahlung beam at PAL
- Charged ion-induced nuclear reactions at KIRAM

Experimental Facility at Pohang Accelerator Laboratory



Pohang Neutron Facility based on 100-MeV e-linac





Pohang High Energy Radiation Facility with 2.5 GeV e-linac

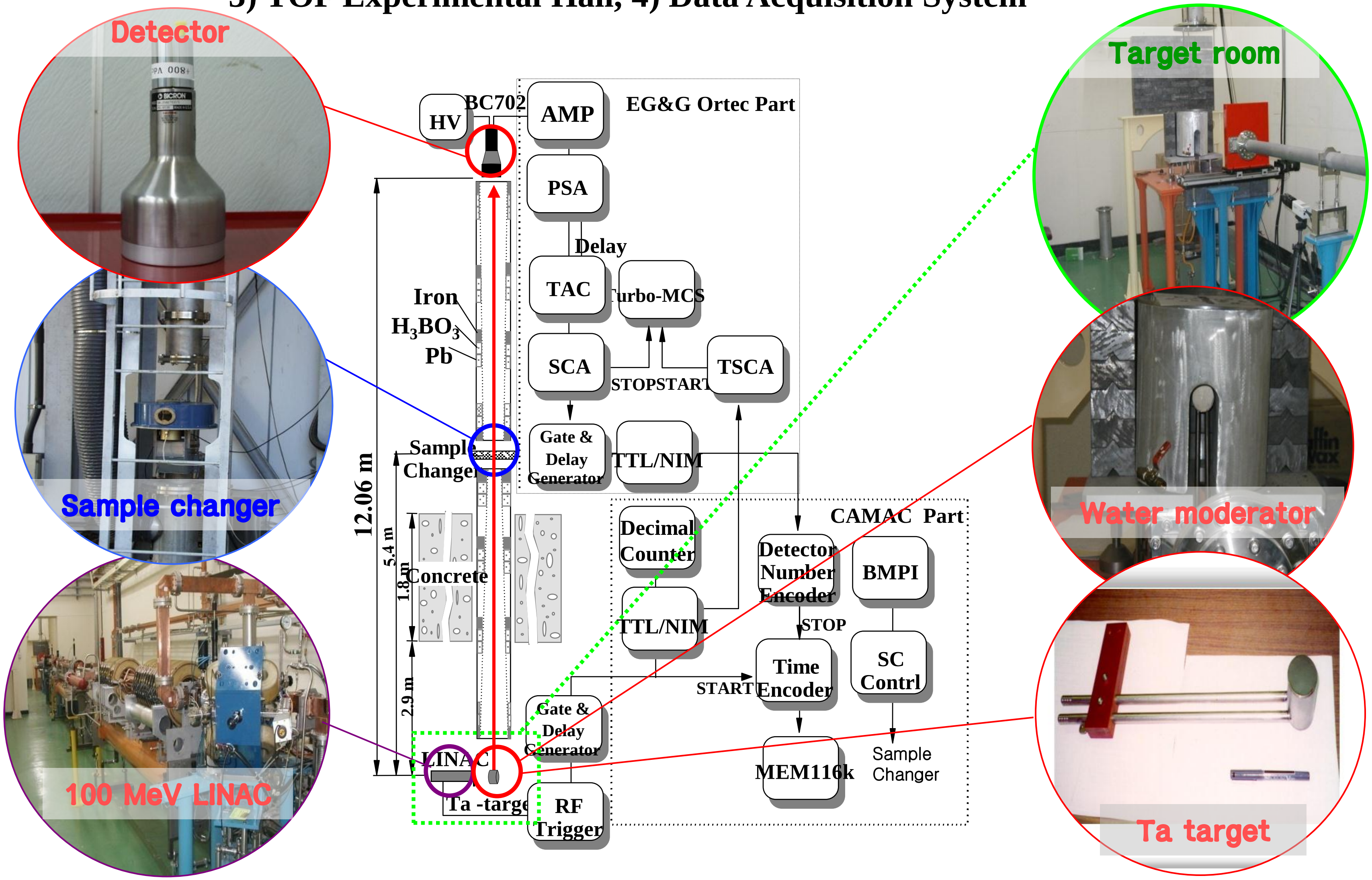
1. **Neutron Total Cross-section measurements by neutron TOF method**
2. **Measurement of Thermal Neutron Cross-sections and Resonance Integrals by Neutron Activation Method**

1. Neutron Total Cross-section measurements by neutron TOF method

Pohang Pulsed Neutron Facility (PNF)

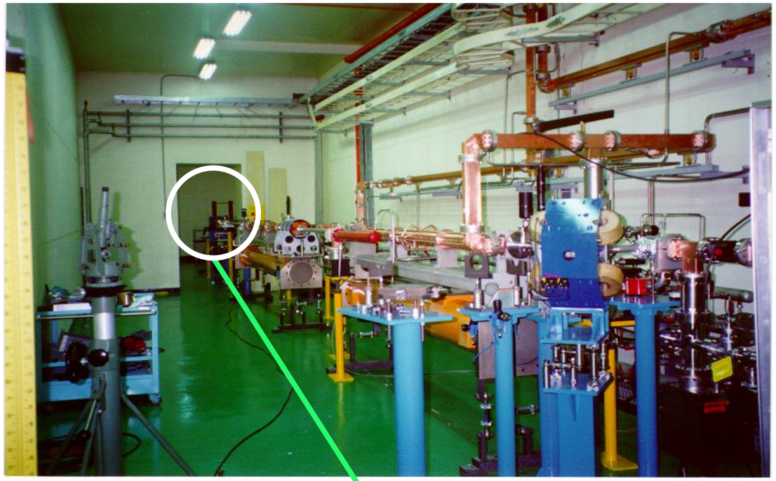
1) Electron Linear Accelerator, 2) Target System

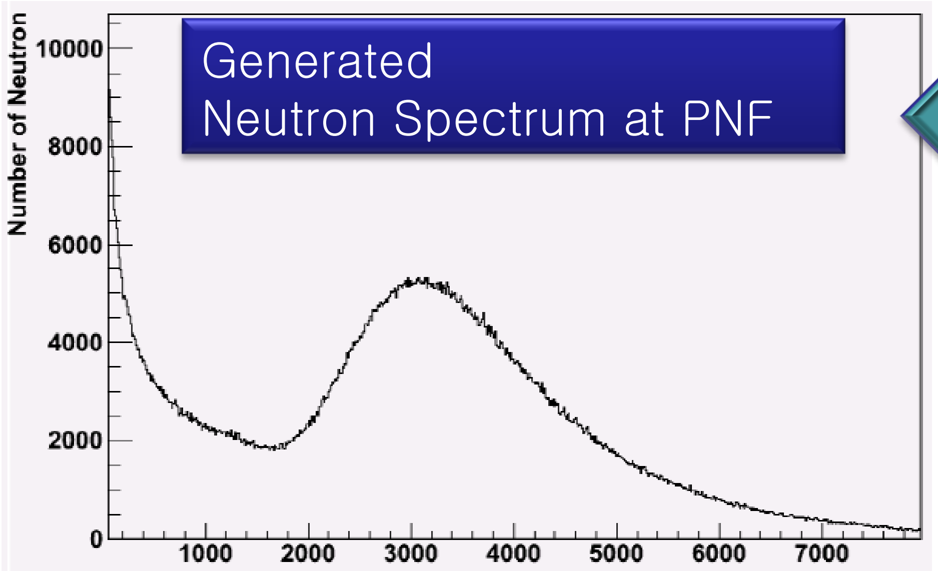
3) TOF Experimental Hall, 4) Data Acquisition System



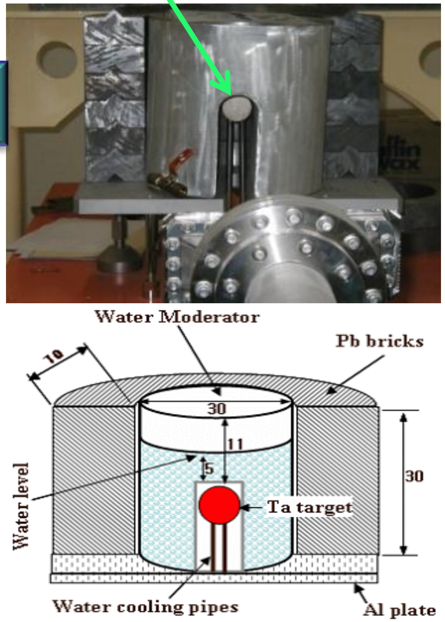
Pohang Pulsed Neutron Facility (PNF)

- Electron accelerator based Time of Flight system
  - ✓ electron energy = 50 ~ 70 MeV
  - ✓ repetition rate = Below 30Hz
  - ✓ pulse width = 1 ~ 2 μs
  - ✓ peak beam current = 30 ~ 60 mA
  - ✓ TOF flight length = 11.5~12m
  - ✓
- Target + water moderator : to produce neutron pulse
  - ✓ Ta plates + cooling system



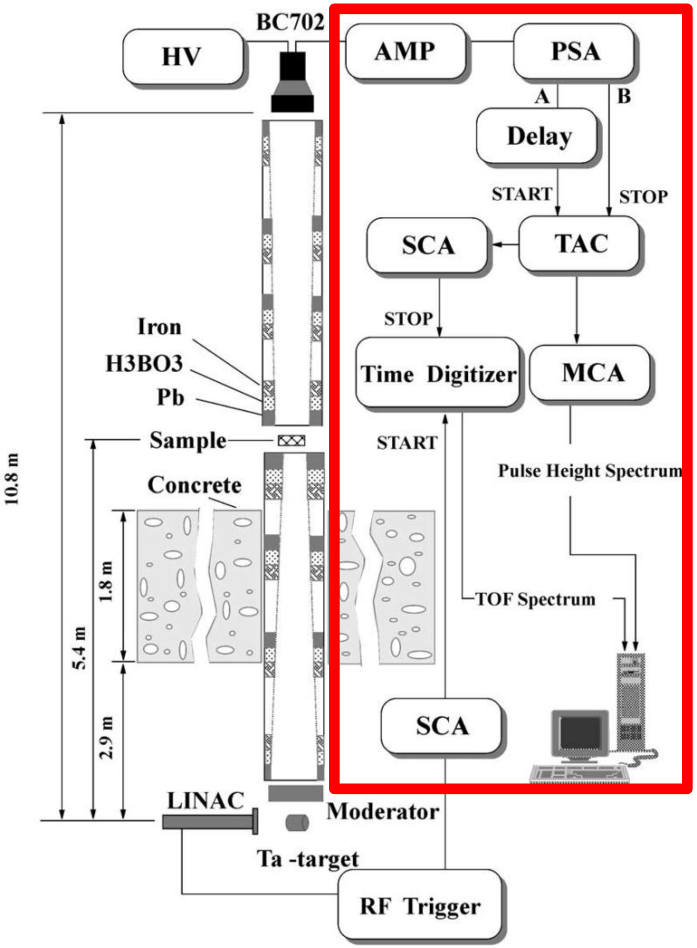


Neutron Arrival Time (μs)



Data Acquisition System

Current DAQ

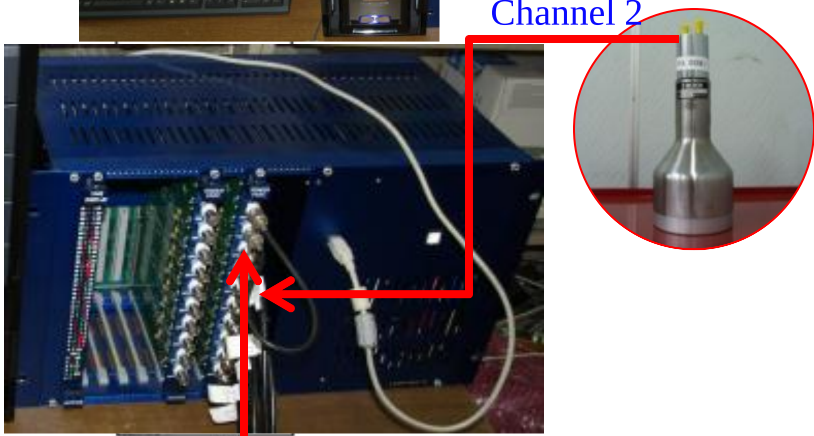


DAQ Computer

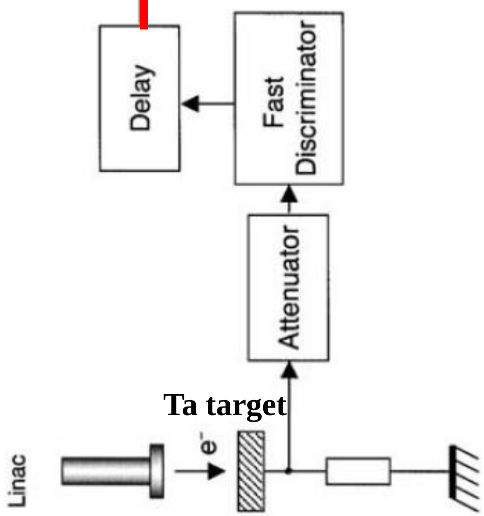
FADC DAQ

One 100 MHz 10-bit
8 channel FADC
Module in VME crate

Neutron Signal
Channel 2



Gate Channel 1



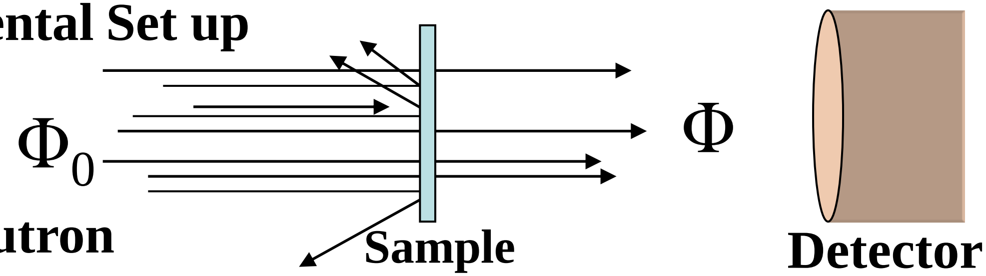
Measurement of Neutron Total Cross Section

1. Neutron Energy E in eV corresponding to channel I in TOF

$$E[eV] = \left(\frac{72.3 \times L[m]}{(I - I_0) \times W[\mu s]} \right)^2$$

L: flight path length
W: channel width

2. **Experimental Set up**



3. **Neutron Transmission rate**

$$T(E_i) = \frac{[In(E_i) - In^B(E_i)] / M_{In}}{[Out(E_i) - Out^B(E_i)] / M_{Out}}$$

4. **Total Cross Section**

$$\sigma(E_i) = -\frac{1}{N} \ln T(E_i)$$

N: atomic density

5. Total Cross Section after Purity Correction

$$\sigma_T = \frac{\sigma - M_T \cdot \sum_j P_j \sigma_j M_j^{-1} \times 10^{-6}}{1 - \sum_j P_j \times 10^{-6}}$$

σ: measured total cross section

M_T: total weight of sample

M_j: weight of impurity sample

P_j : impurity in ppm

Recent Measurement of Neutron Total Cross Section

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Contents lists available at ScienceDirect

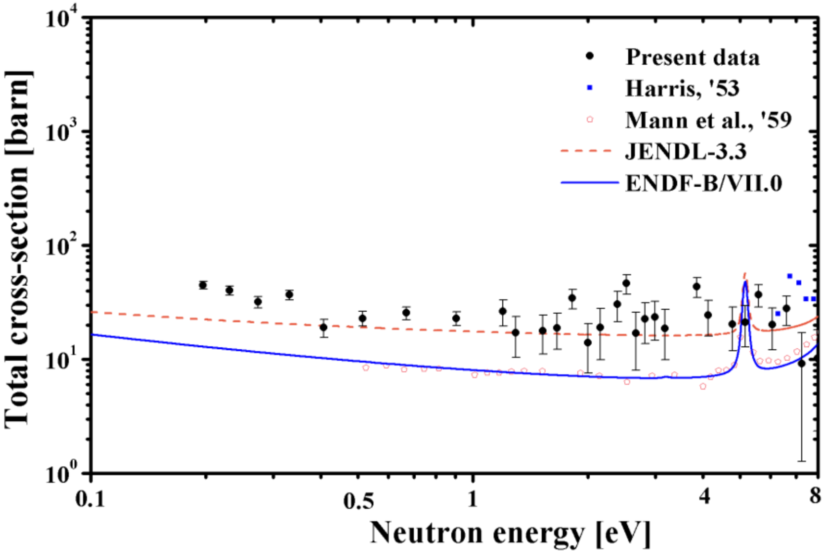
Nuclear Instruments and Methods in Physics Research B

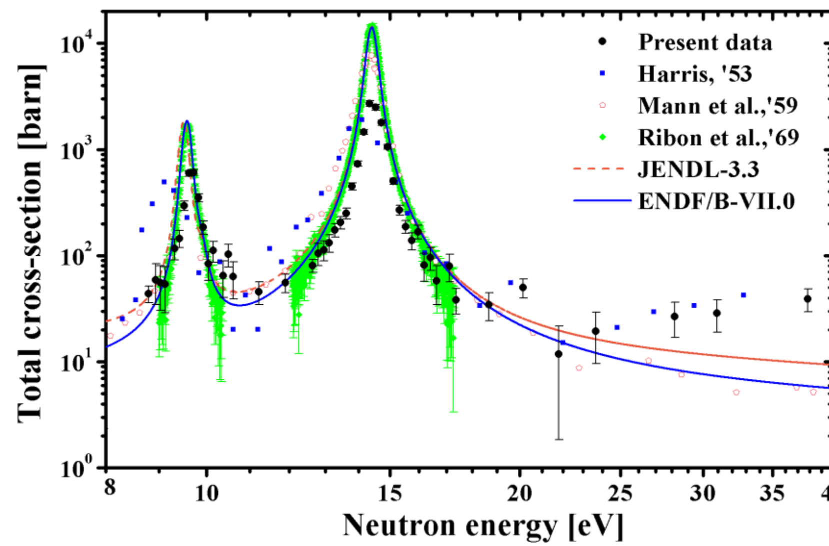
journal homepage: www.elsevier.com/locate/nimb

Measurement of neutron total cross-section and resonance parameters of xenon

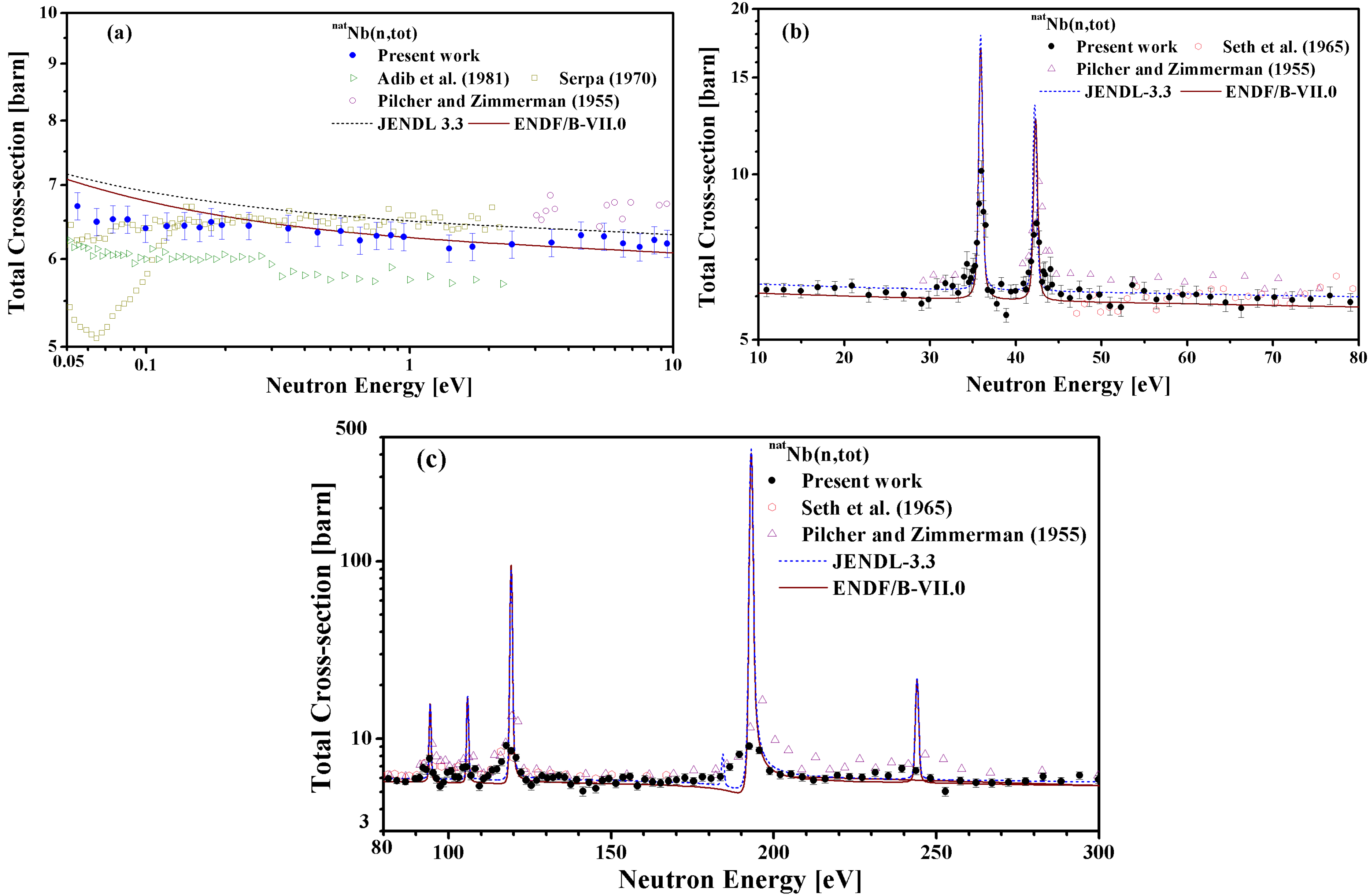
V.R. Skoy [a,b], T.F. Wang [a], G.N. Kim [a,*], Y.D. Oh [c], M.H. Cho [c], I.S. Ko [c], W. Namkung [c]

[a] Department of Physics, Kyungpook National University, Daegu 702-701, Republic of Korea
[b] Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia
[c] Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea

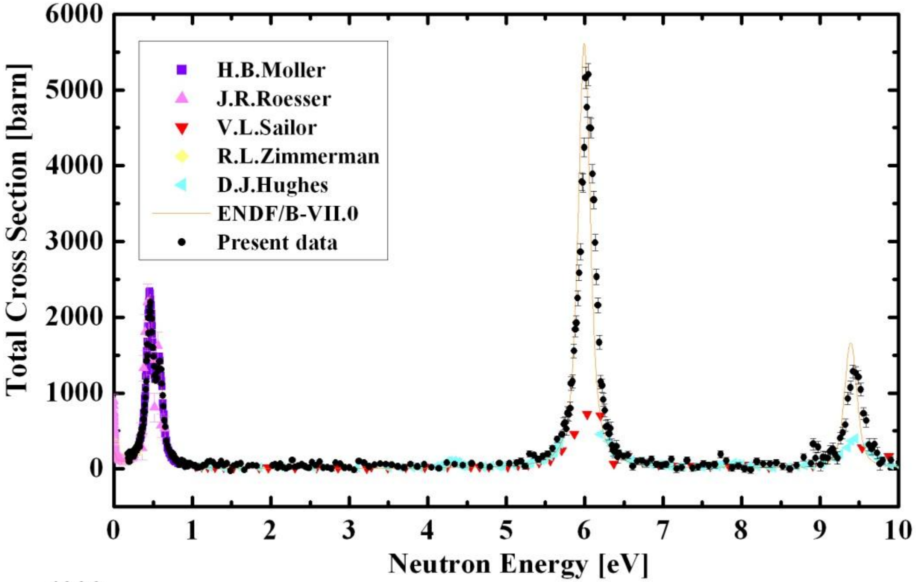


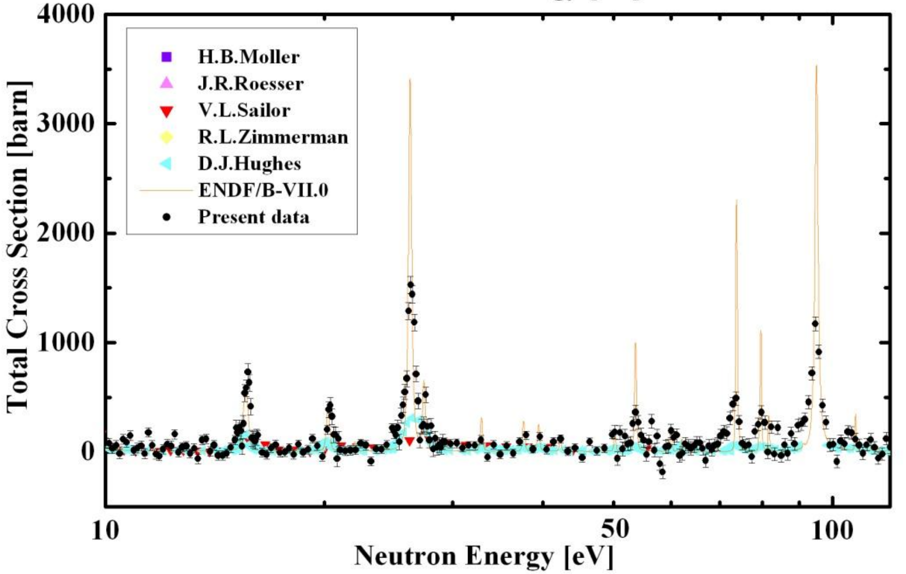


Measurement of the total neutron cross-section and resonance parameters of niobium at the Pohang pulsed neutron facility



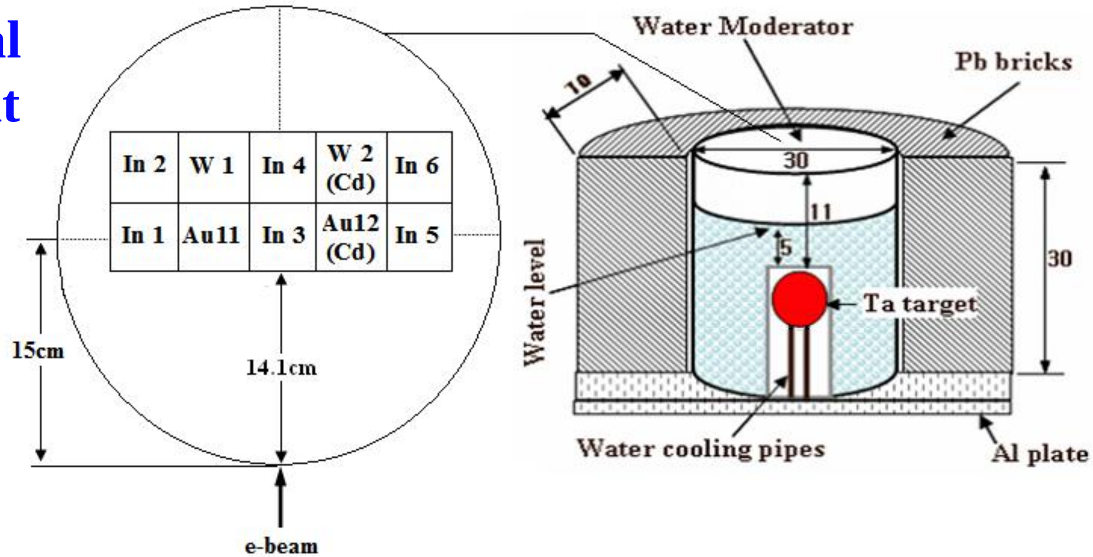
Measurements of neutron total cross-sections and resonance parameters of erbium at the Pohang Neutron Facility





2. Measurement of Thermal Neutron Cross-sections and Resonance Integrals by Neutron Activation Method

Experimental Arrangement



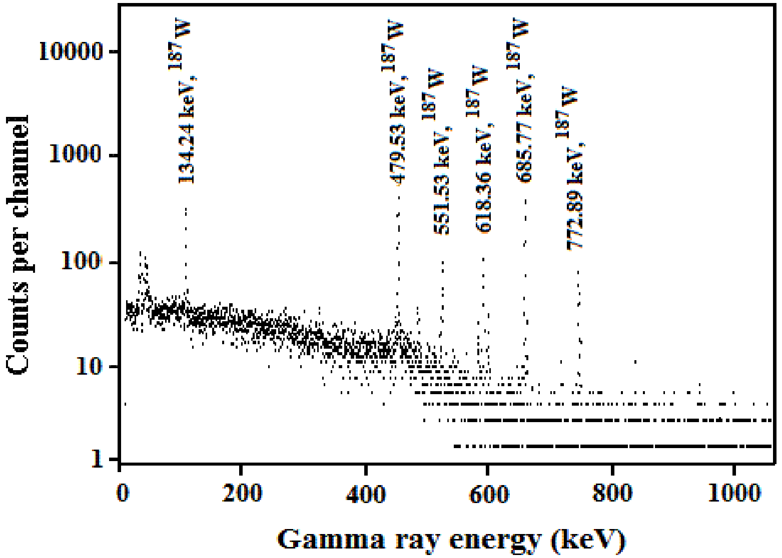
Foil	Size (mm)	Weight (g)	Thickness (mm)	Purity (%)
Au 11	18×18	0.1863±0.0005	0.03	99.95
Au 12	18×18	0.1885±0.0005	0.03	99.95
W 1	18×18	1.2636±0.0008	0.2	99.95
W 2	18×18	1.2891±0.0008	0.2	99.95
In 1	18×18	0.1276±0.0004	0.05	99.99
In 2	18×18	0.1217±0.0004	0.05	99.99
In 3	18×18	0.1214±0.0004	0.05	99.99
In 4	18×18	0.1220±0.0004	0.05	99.99
In 5	18×18	0.1271±0.0004	0.05	99.99
In 6	18×18	0.1245±0.0004	0.05	99.99

Data Analysis

$$\sigma_{0,W} = \sigma_{0,Au} \times \frac{R_W - F_{W,Cd} R_{W,Cd}}{R_{Au} - F_{Au,Cd} R_{Au,Cd}} \times \frac{G_{th,Au}}{G_{th,W}} \times \frac{g_{Au}}{g_W}$$

$$R_{W(Au)} \quad or \quad R_{W(Au),Cd} = \frac{N_{obs}\lambda(1-e^{-\lambda T})}{n_o \varepsilon I_\gamma (1-e^{-\lambda\tau})(1-e^{-\lambda t_i})e^{-\lambda t_w}(1-e^{-\lambda t_c})}$$

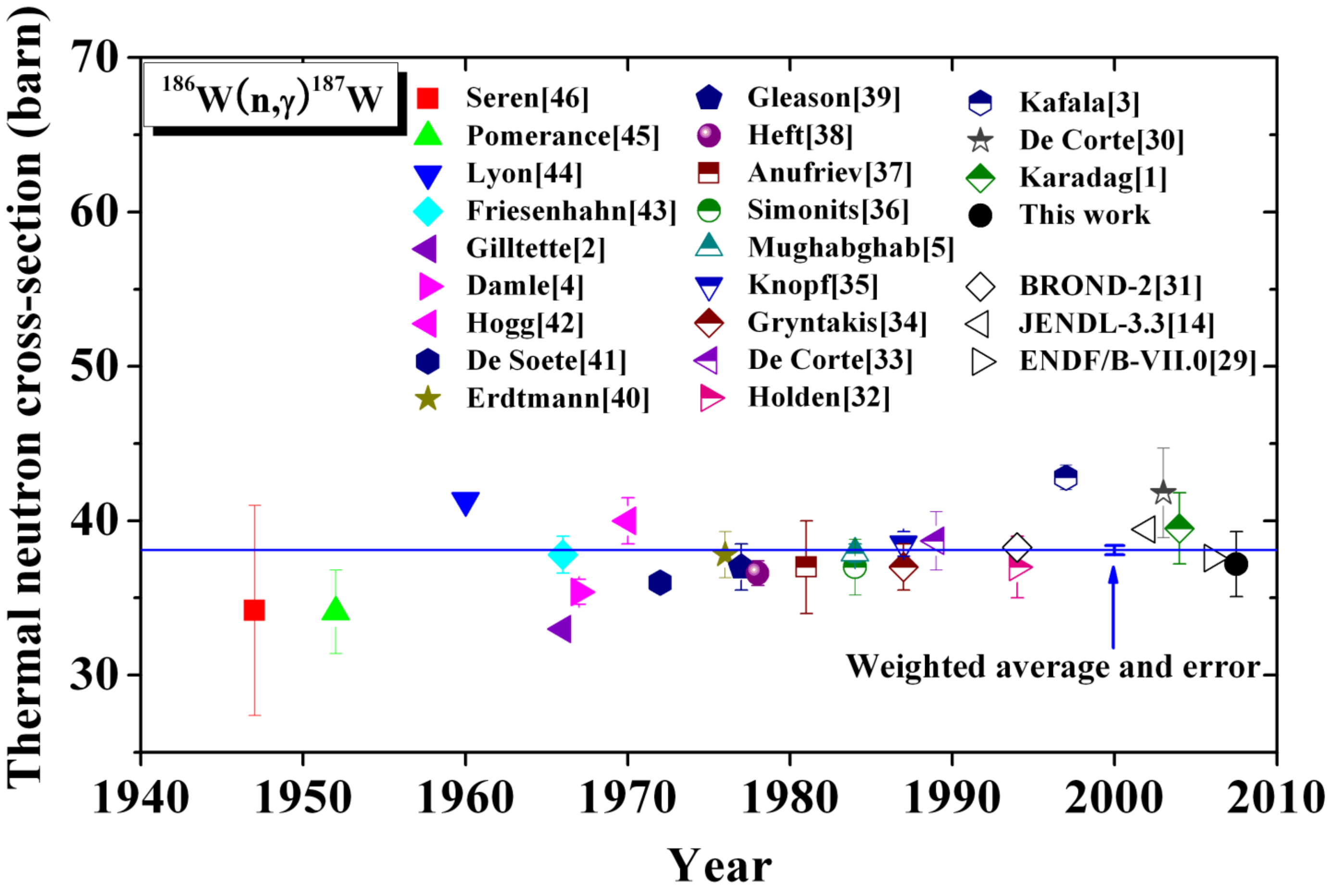
$$I_{0,W}(\alpha) = I_{0,Au}(\alpha) \times \frac{g_W \sigma_{0,W}}{g_{Au}\sigma_{0,Au}} \times \frac{CR_{Au} - F_{Au,Cd}}{CR_W - F_{W,Cd}} \times \frac{G_{epi,Au}}{G_{th,Au}} \times \frac{G_{th,W}}{G_{epi,W}}$$



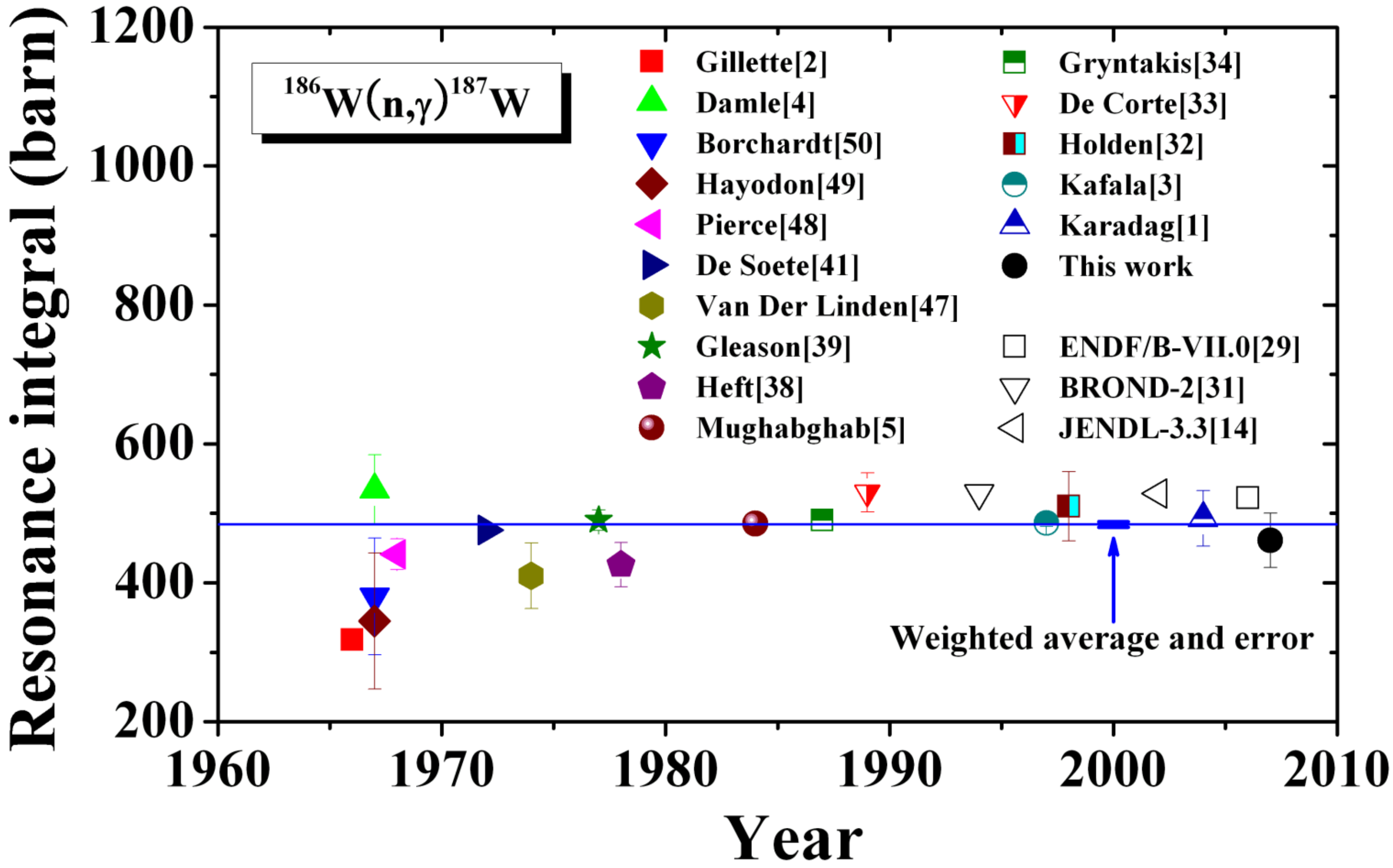
Reaction	Main resonance energy [eV]	Half-life	Main γ- rays		Isotopic abundance [%]
			Energy [keV]	Intensity [%]	
$^{186}W(n,\gamma)^{187}W$	18.8	23.72 h (6)	479.550 (22)*	21.8 (7)	28.6 (2)
			551.52 (4)	5.08 (17)	
			618.26(4)	6.28 (21)	
			685.73 (4)*	27.3 (9)	
$^{197}Au(n,\gamma)^{198}Au$	4.9	2.69517 d (21)	411.80205 (17)*	95.58	100
			675.8836 (7)	0.084 (3)	

* Gamma rays used in calculations

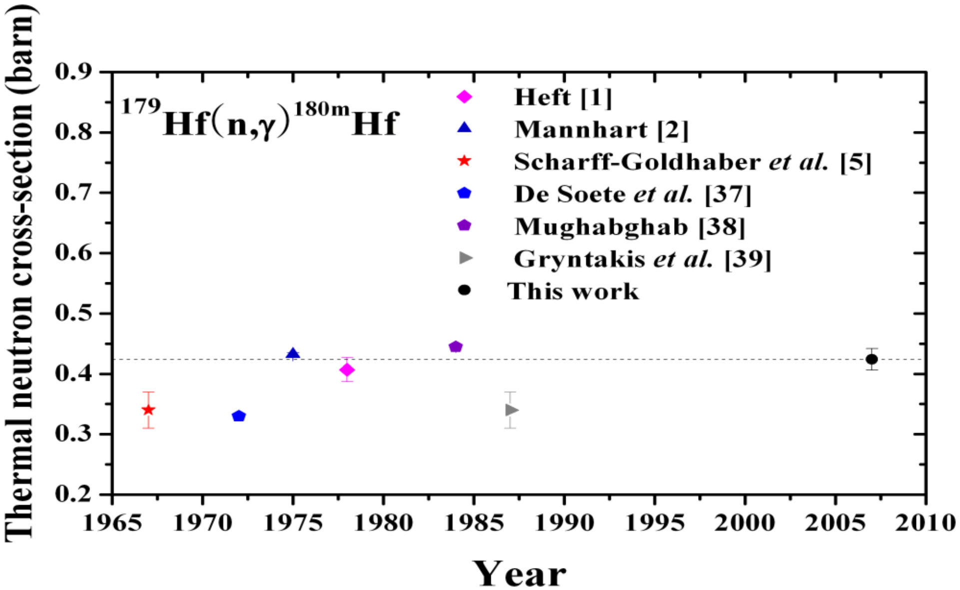
Thermal Neutron Cross-sections of the $^{186}W(n,\gamma)^{187}W$ reaction

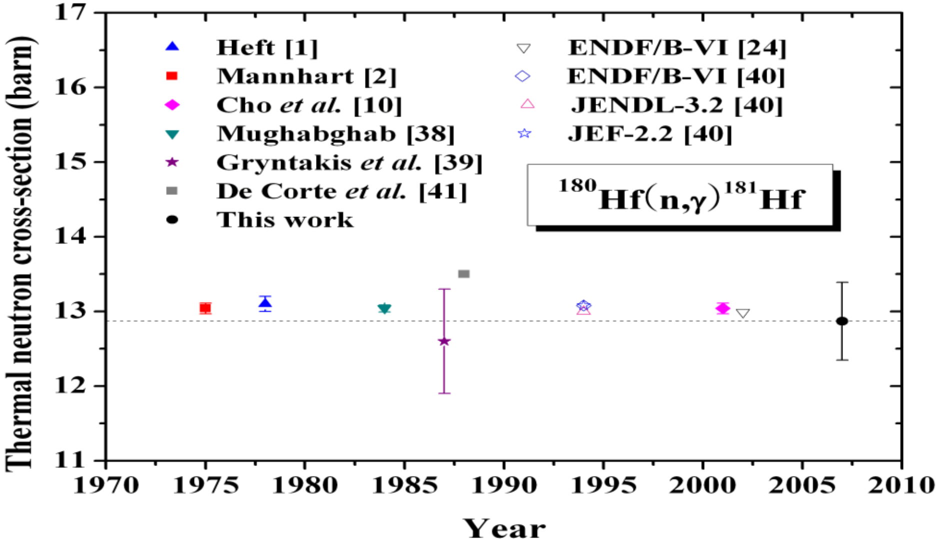


Resonance Integrals of the $^{186}W(n,\gamma)^{187}W$ reaction

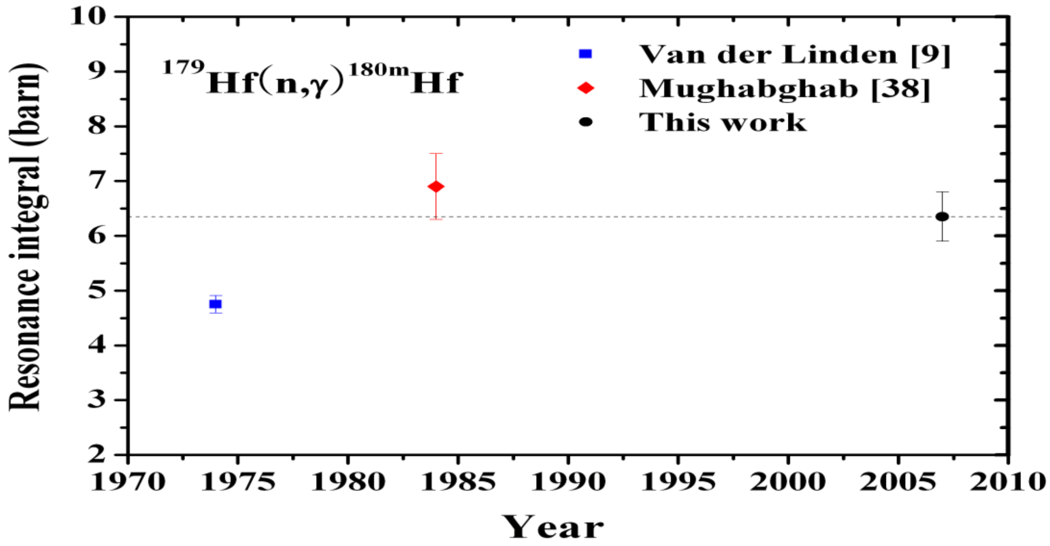


Thermal Neutron Cross-sections of the $^{179}Hf(n,\gamma)^{180m}Hf$ and $^{180}Hf(n,\gamma)^{181}Hf$ reactions





Resonance Integrals of the $^{179}Hf(n,\gamma)^{180m}Hf$ and $^{180}Hf(n,\gamma)^{181}Hf$ reactions



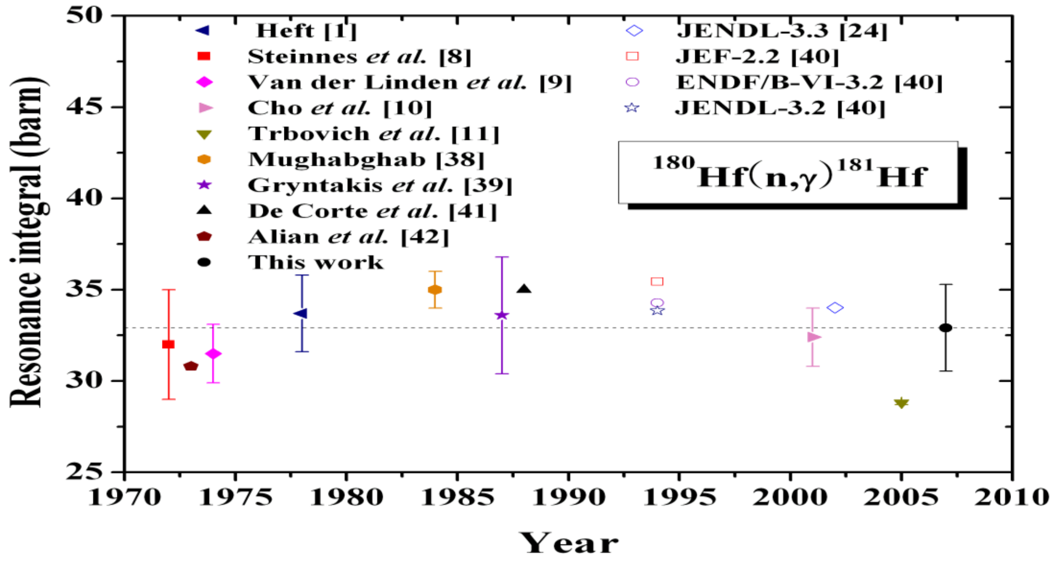


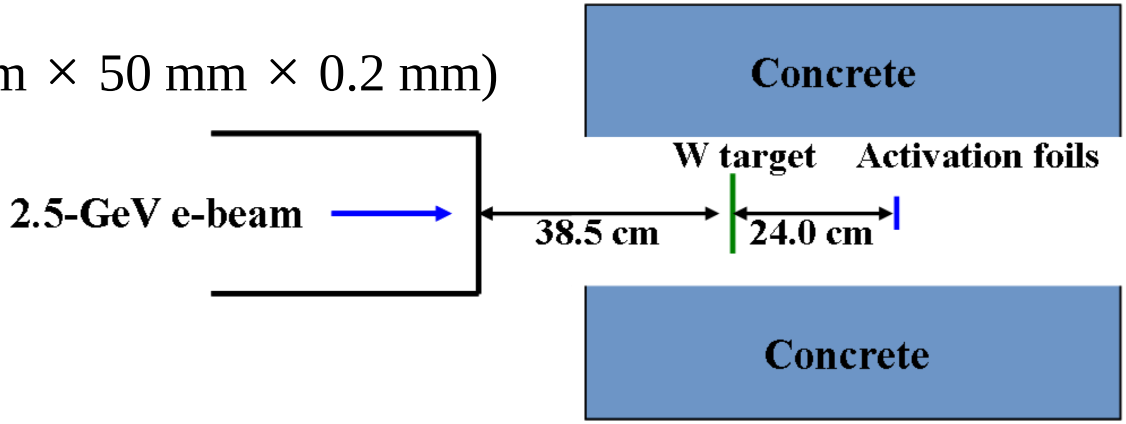
Photo-nuclear reactions with Bremsstrahlung beam at PAL

1. **Isomeric Yield Ratio Measurement**
2. **Photo-fission Reaction (See Naik’s talk)**

1. Isomeric Yield Ratio Measurement

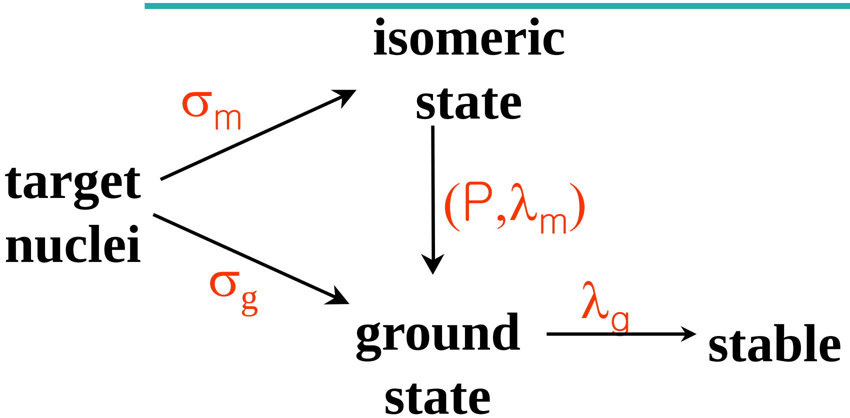
Experimental Arrangement

- Electron energy : 2.5 GeV
- Beam current : 2.19 × 10^{14} electron
- Repetition rate : 10 Hz
- Pulse width : 1.0 nsec
- Target : thin W (50 mm × 50 mm × 0.2 mm)



Sample	Purity (%)	Diameter (inch)	Thickness (inch)
Sc	99.81	0.5	0.005
Ti	99.63	0.5	0.004
Fe	99.559	0.5	0.005
Cu	99.96	0.5	0.004

Methodology



$$\frac{dN_m}{dt} = Y_m - \lambda_m N_m$$

$$\frac{dN_g}{dt} = Y_g - \lambda_g N_g + P\lambda_m N_m$$

where: N_m, N_g are the numbers of nuclei for m, g state, λ_m and λ_g are the decay constants of these states, and P is the branching ratio for the decay of metastable to ground state. Y_m and Y_g are the reaction yields .

- ***The reaction yield, Y_i, can be expressed as***

$$Y_i = N_0 \int_{E_{th}}^{E_{\gamma\max}} \sigma_i(E)\,\Phi(E)\,dE$$

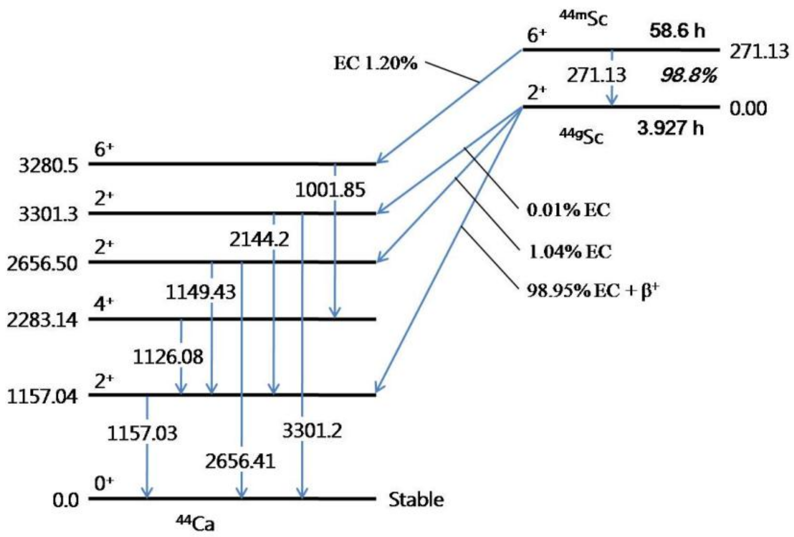
The reaction cross-section, σ_i, can be expressed as

$$\sigma_i = \frac{S\lambda(1-e^{-\lambda T})}{\Phi N_0 \varepsilon I_\gamma (1-e^{-\lambda\tau})(1-e^{-\lambda t_i})e^{-\lambda t_w}(1-e^{-\lambda t_c})}$$

- Isomeric Ratio: $$IR = \frac{\sigma_m}{\sigma_g} = \left[\left(\frac{C_g}{C_m}\times\frac{\varepsilon_m I_{\gamma m}}{\varepsilon_g I_{\gamma g}} - \frac{P\lambda_g}{\lambda_g-\lambda_m}\right)\times\frac{A_m B_m C_m D_m}{A_g B_g C_g D_g} + \frac{P\lambda_m}{\lambda_g-\lambda_m}\right]^{-1}$$

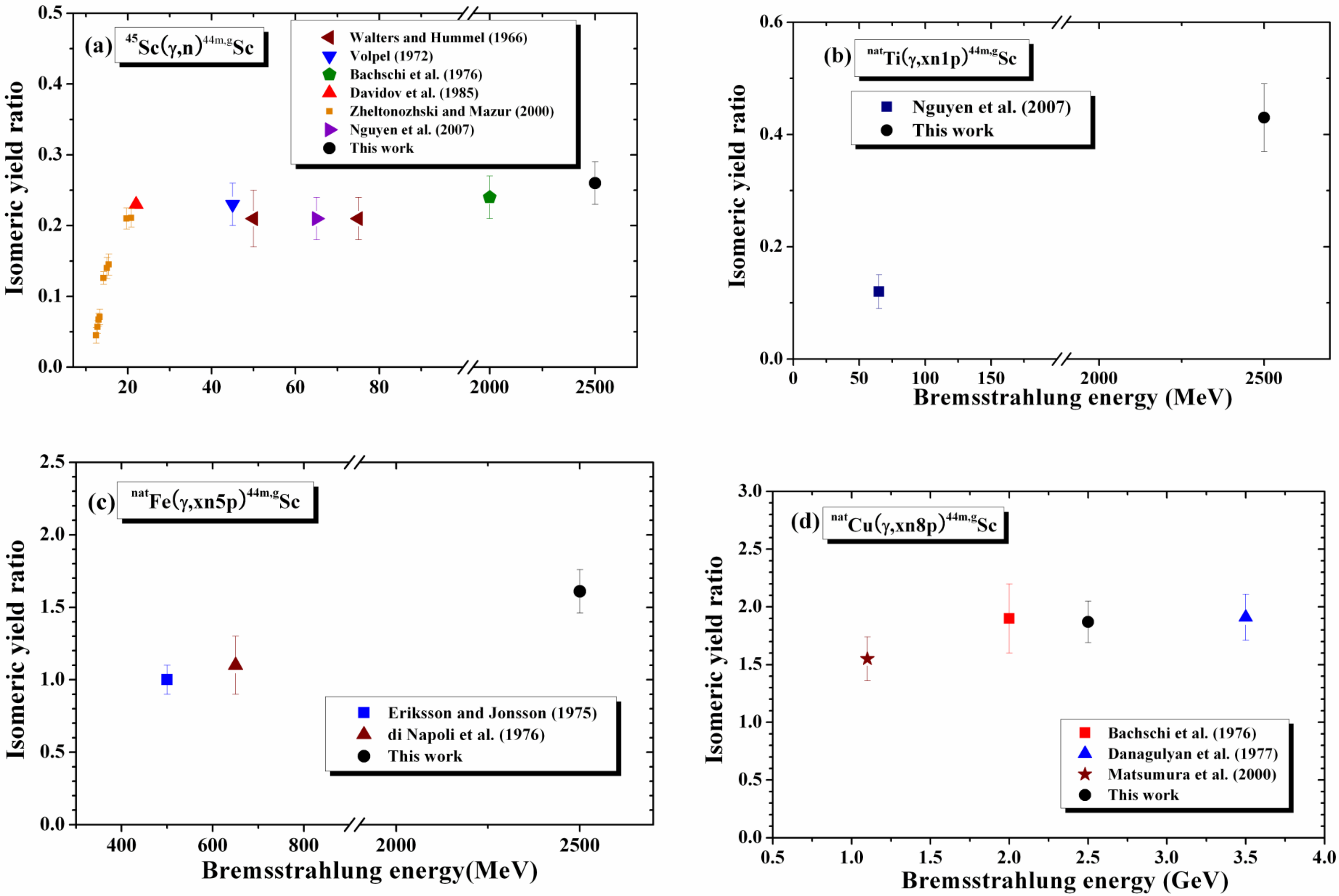
where: $A_{m(g)} = \frac{1-e^{-\lambda_{m(g)}\tau}}{1-e^{-\lambda_{m(g)}T}} e^{-\lambda_{m(g)}(T-\tau)}$ $B_{m(g)} = \frac{1-e^{-\lambda_{m(g)}t_i}}{\lambda_{m(g)}}$ $C_{m(g)} = e^{-\lambda_{m(g)}t_w}$ $D_{m(g)} = 1-e^{-\lambda_{m(g)}t_c}$

Decay scheme and Nuclear reactions leading to $^{44m,g}Sc$ isomeric pairs

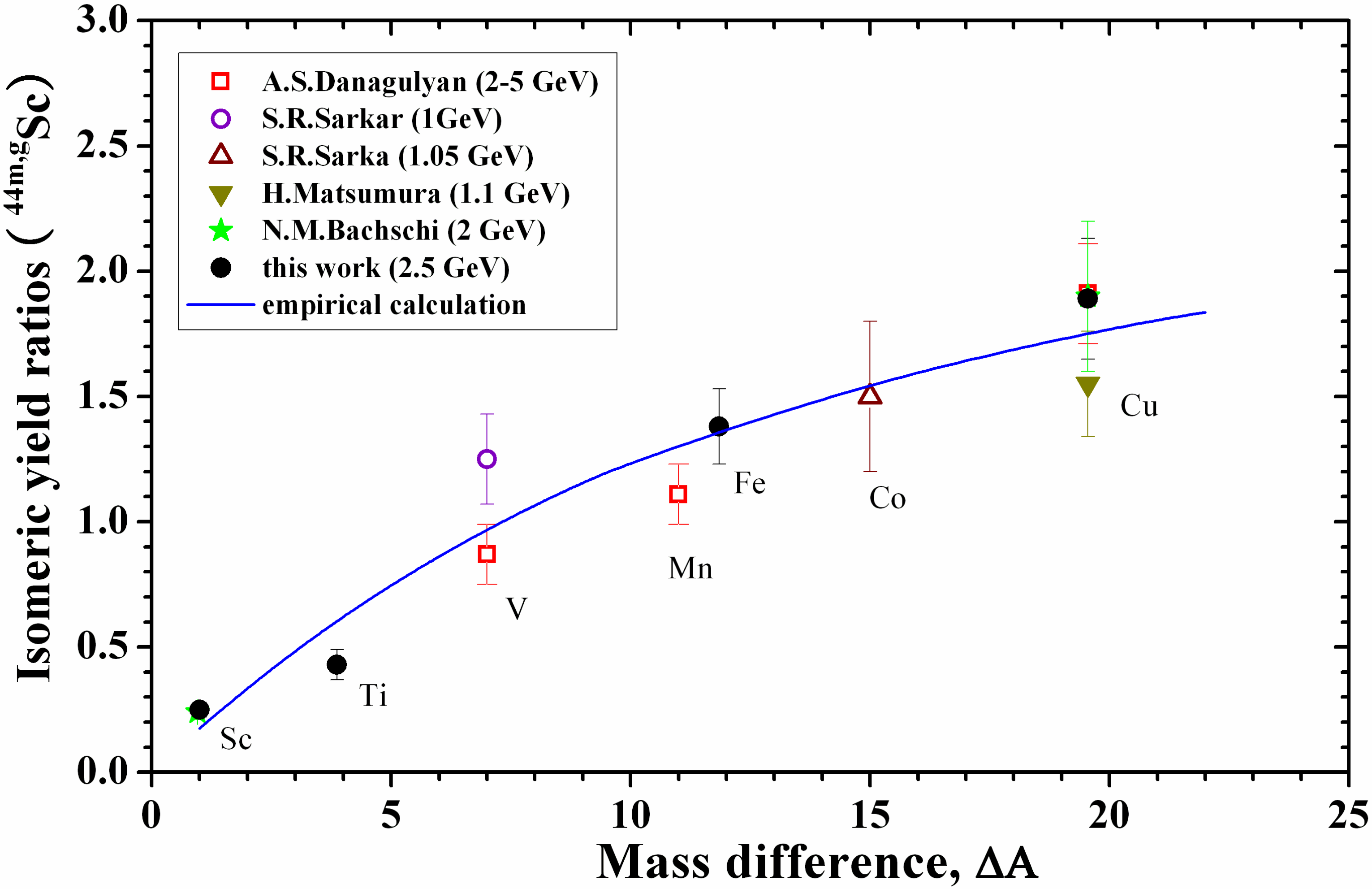


Nuclear reaction	Threshold energy (MeV)	Half-life, $T_{1/2}$	Main γ-ray energy, E_γ (keV)	γ-ray intensity, Iγ (%)
$^{45}Sc(\gamma,n)^{44g}Sc$ $^{45}Sc(\gamma,n)^{44m}Sc$	11.32 11.60	3.927 h 58.6 h	1157.03 271.13	99.9 86.7
$^{nat}Ti(\gamma,xn1p)^{44g}Sc$ $^{nat}Ti(\gamma,xn1p)^{44m}Sc$	41.18 41.45	3.927 h 58.6 h	1157.03 271.13	99.9 86.7
$^{nat}Fe(\gamma,xn5p)^{44g}Sc$ $^{nat}Fe(\gamma,xn5p)^{44m}Sc$	114.89 115.16	3.927 h 58.6 h	1157.03 271.13	99.9 86.7
$^{nat}Cu(\gamma,xn8p)^{44g}Sc$ $^{nat}Cu(\gamma,xn8p)^{44m}Sc$	180.63 180.90	3.927 h 58.6 h	1157.03 271.13	99.9 86.7

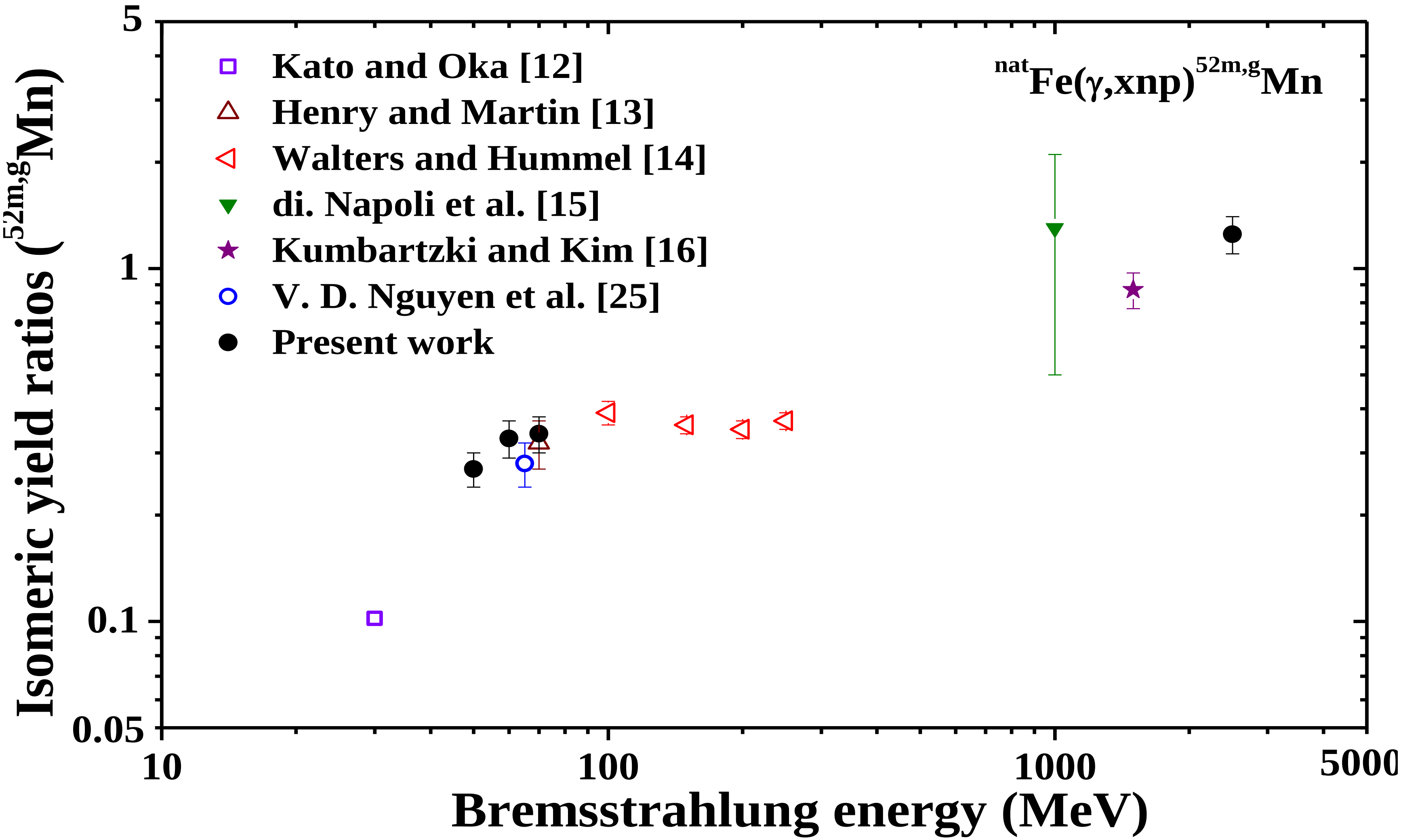
The experimental isomeric ratios



Isomeric yield ratios of $^{44m,g}Sc$ formed in different targets: Sc, Ti, V, Mn, Fe, Co and Cu with bremsstrahlung in the energy range 1-5 GeV as a function of mass difference, ΔA.

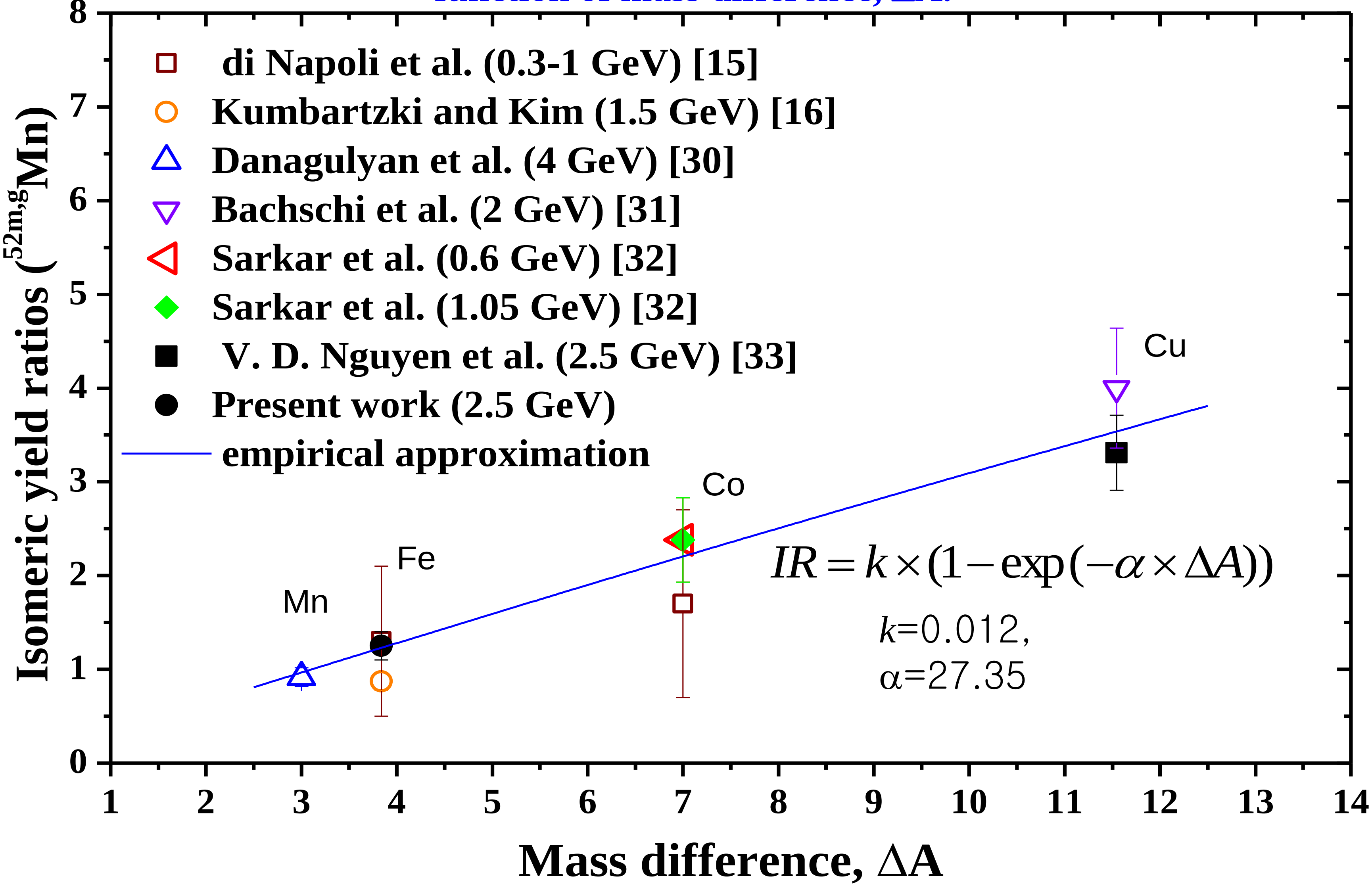


Isomeric yield ratios of $^{nat}Fe(\gamma,xnp)^{52m,g}Mn$



Isomeric yield ratios of ^{52m,g}Mn formed in different targets

Mn, Fe, Co and Cu with bremsstrahlung in the energy range 1-5 GeV as a function of mass difference, ΔA.



2. Photo-fission Reaction (See H. Naik's talk)

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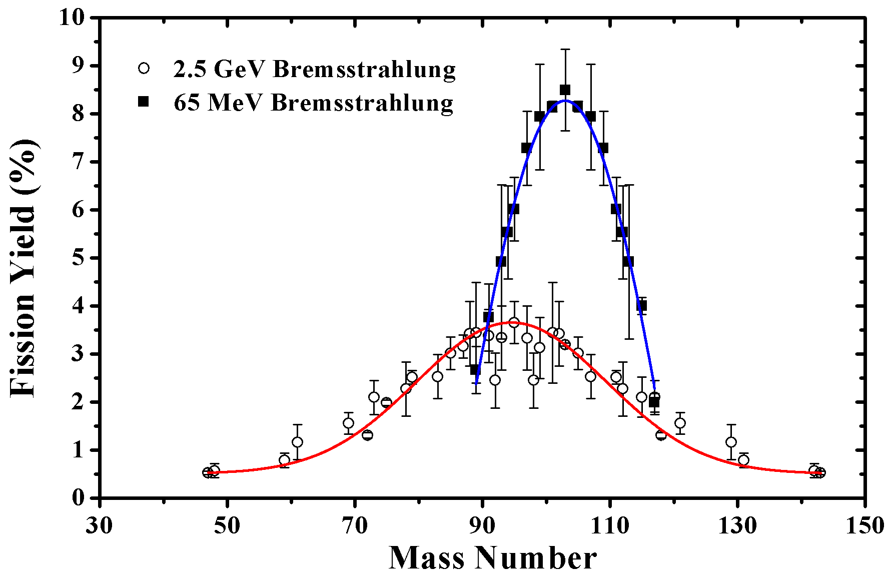
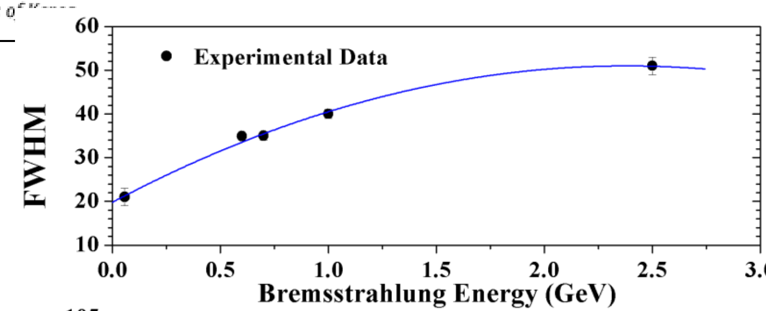
BEAM INTERACTIONS WITH MATERIALS AND ATOMS

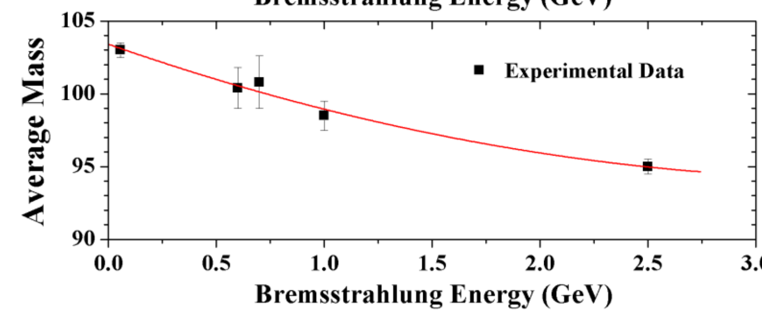
Product yields for the photo-fission of ^{209}Bi with 2.5 GeV bremsstrahlung

Haladhara Naik [a], Sarbjit Singh [a], Annareddy Venkat Raman Reddy [a], Vijay Kumar Manchanda [a], Guinyun Kim [b,*], Kyung Sook Kim [b], Man-Woo Lee [b], Srinivasan Ganesan [c], Devesh Raj [c], Hee-Seock Lee [d], Young Do Oh [d], Moo-Hyun Cho [d], In Soo Ko [d], Won Namkung [d]

[a] *Radiochemistry Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India*
[b] *Department of Physics, Kyungpook National University, Daegu 702-701, Republic of Korea*
[c] *Reactor Physics Design Division, BARC, Trombay, Mumbai 400085, India*
[d] *Pohang Accelerator Laboratory, Pohang University of Science and Technology, Pohang 790-784, Republic o*







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DOI 10.1140/epja/i2009-10812-8

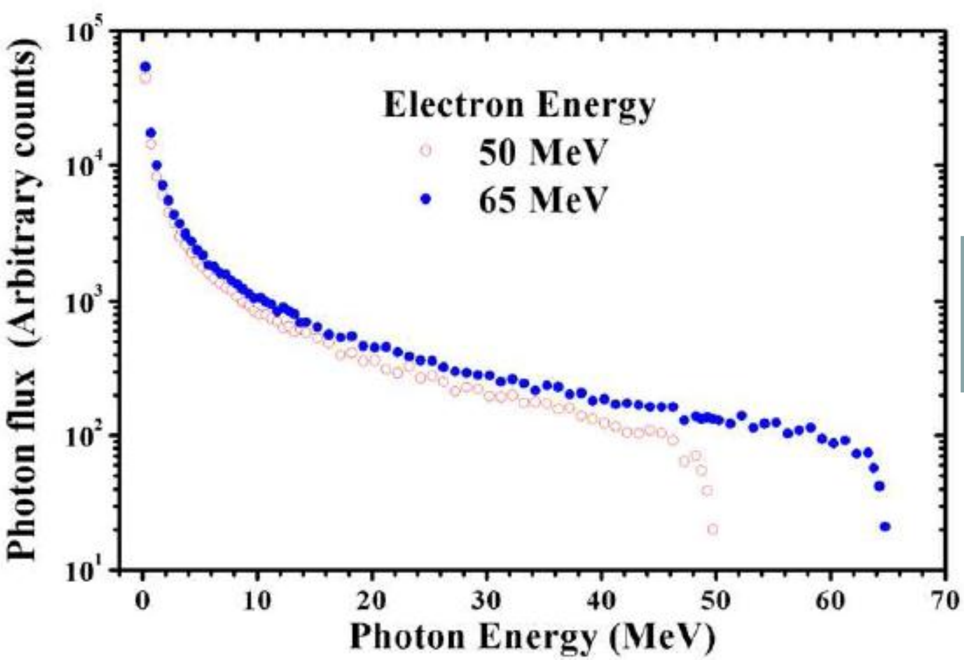
THE EUROPEAN PHYSICAL JOURNAL A

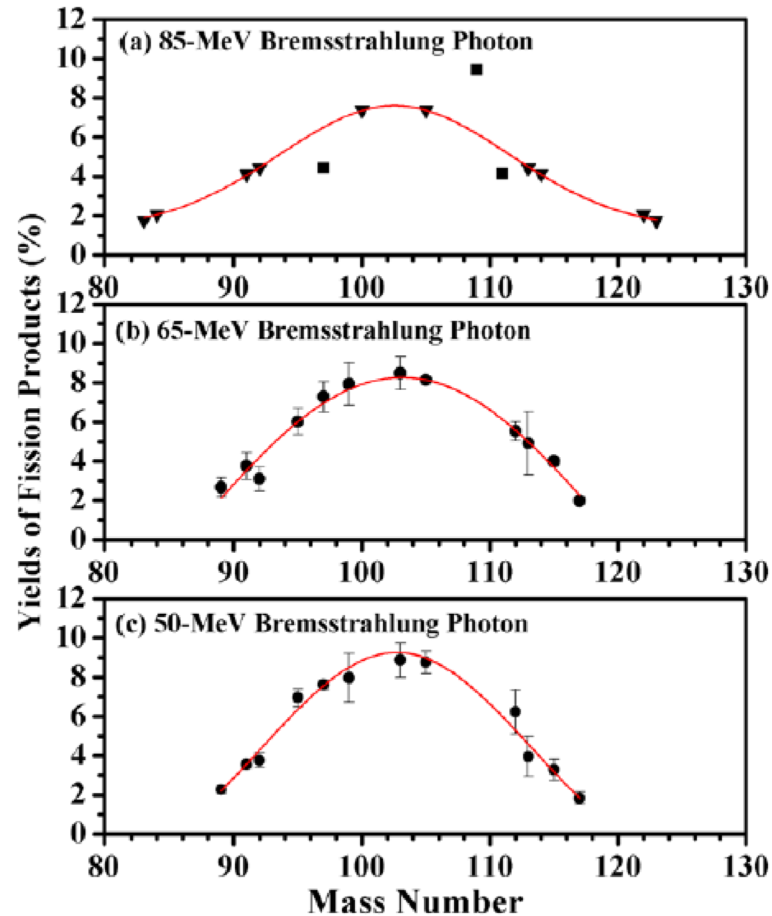
Regular Article – Experimental Physics

Measurement of photo-fission yields and photo-neutron cross-sections in ^{209}Bi with 50 and 65 MeV bremsstrahlung

H. Naik[1], S. Singh[1], A.V.R. Reddy[1], V.K. Manchanda[1], S. Ganesan[2], D. Raj[2], Md. Shakilur Rahman[3], K.S. Kim[3], M.W. Lee[3], G. Kim[3,a], Y.D. Oh[4], H.-S. Lee[4], M.-H. Cho[4], I.S. Ko[4], and W. Namkung[4]

[1] Radiochemistry Division, Bhabha Atomic Research Centre, Trombay, Mumbai
[2] Reactor Physics Design Division, BARC, Trombay, Mumbai, 400085, India
[3] Department of Physics, Kyungpook National University, Daegu 702-701, Repu
[4] Pohang Accelerator Laboratory, Pohang University of Science and Technology,





J Radioanal Nucl Chem (2010) 283:439–445
DOI 10.1007/s10967-009-0383-1

Mass–yield distributions of fission products from photo-fission of ^{nat}Pb induced by 50–70 MeV bremsstrahlung

Haladhara Naik · Guinyun Kim · Ashok Goswami · Sarbjit Singh · Vijay Kumar Manchanda · Devesh Raj · Srinivasan Ganesan · Young Do Oh · Hee-Seock Lee · Kyung Sook Kim · Man-Woo Lee · Moo-Hyun Cho · In Soo Ko · Won Namkung

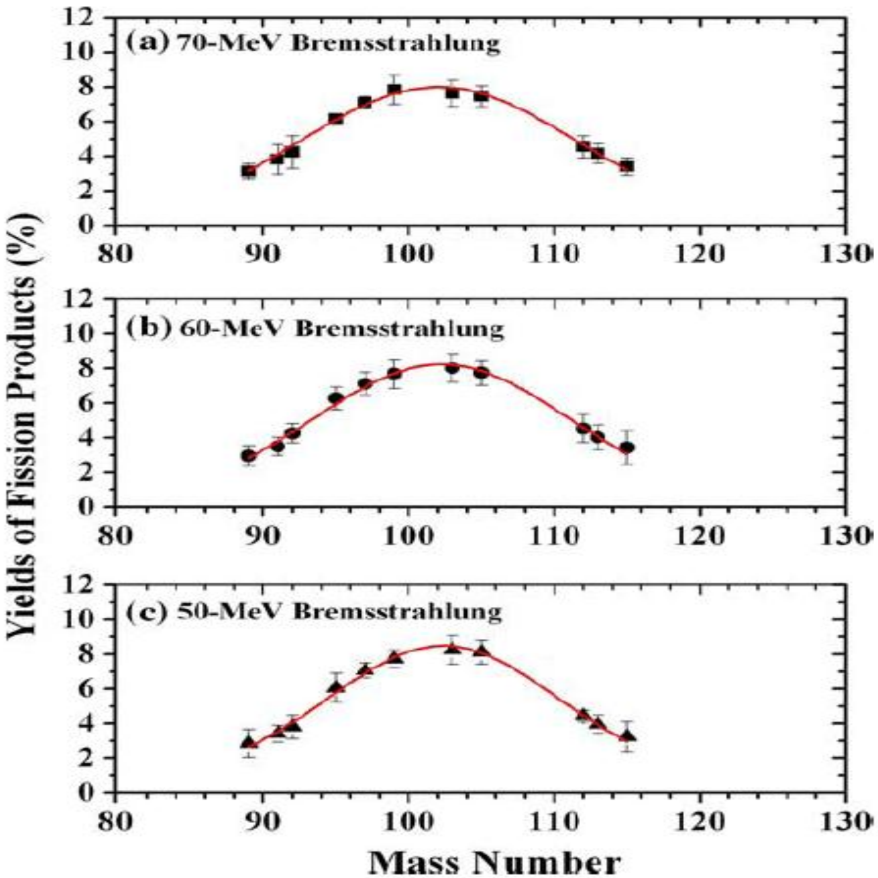


Table 2 Average mass and FWHM of mass distribution in the bremsstrahlung induced fission of ^{nat}Pb and ^{209}Bi

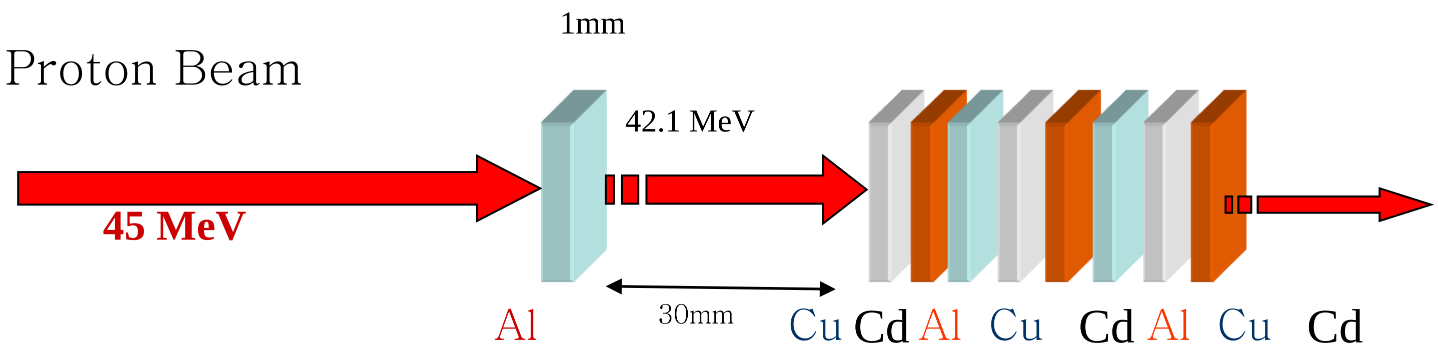
Fissioning system	Bremsstrahlung energy (MeV)	Average mass (A_H)	FWHM mass units	Reference
^{nat}Pb	50	102.34	21	A
	60	102.25	22	A
	70	102.03	23	A
^{209}Bi	28–40	103.5	19.0	[50]
	50	103.1	20.5	[54]
	65	102.7	22.0	[53]
	85	102.5	23.0	[49]

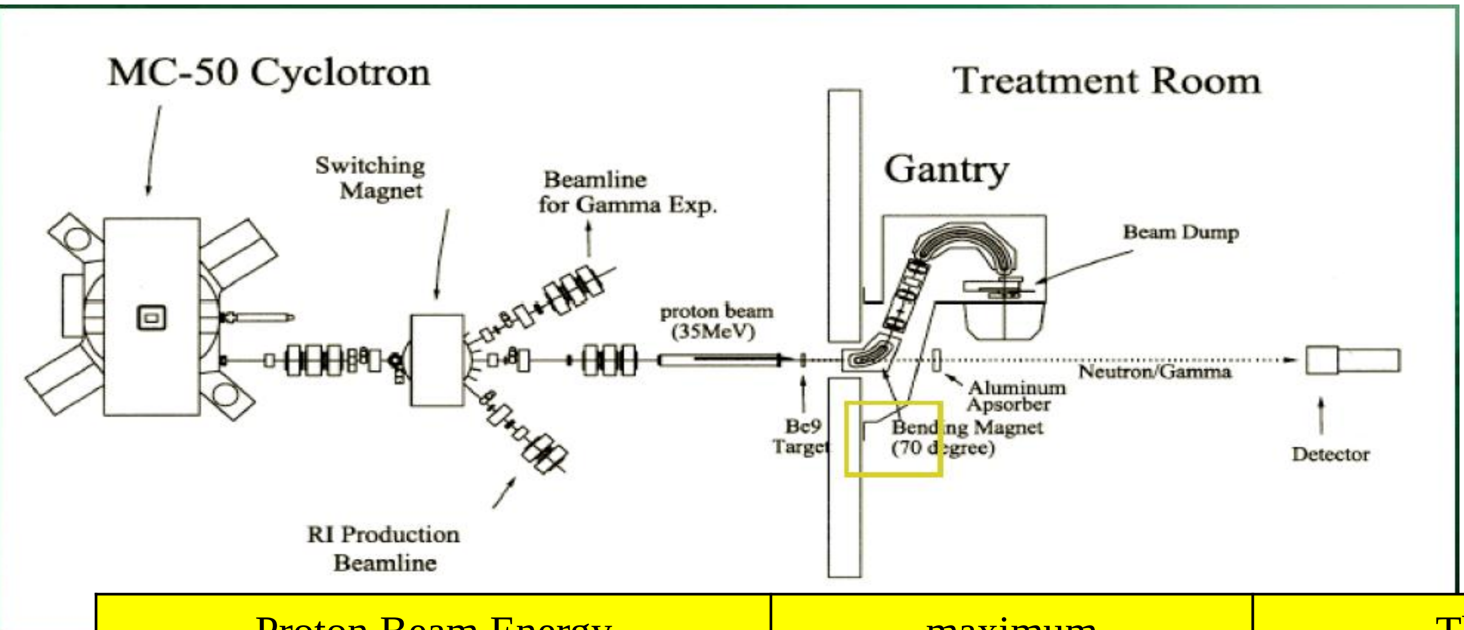
A present work

Measurement of Proton-induced Cross-sections at KIRAM

(part of K.S. Kim)

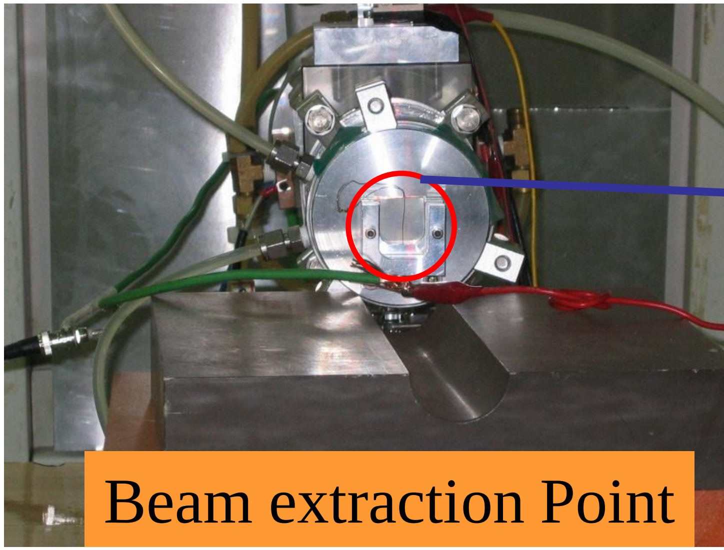
Experimental Set up at MC-50 facility



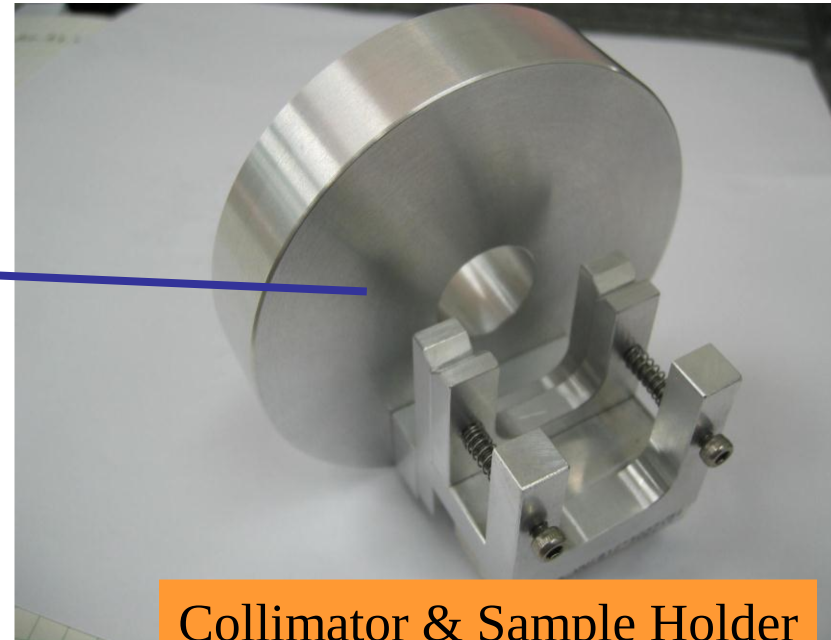


Proton Beam Energy	maximum	This work
	50 MeV	45 MeV
Current	60µA	100 nA

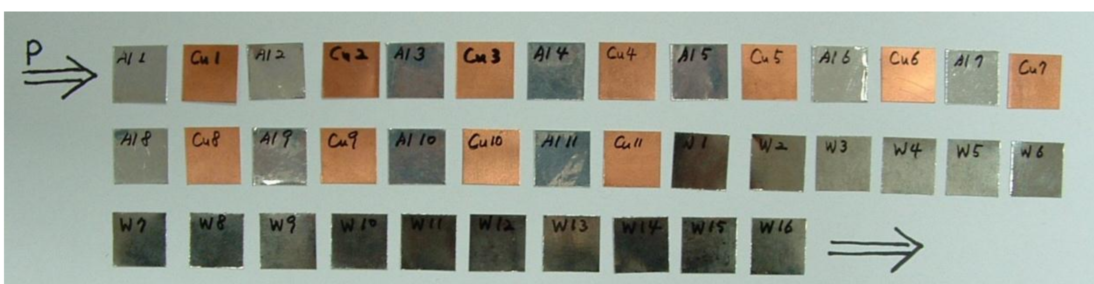
Sample Holder and Samples



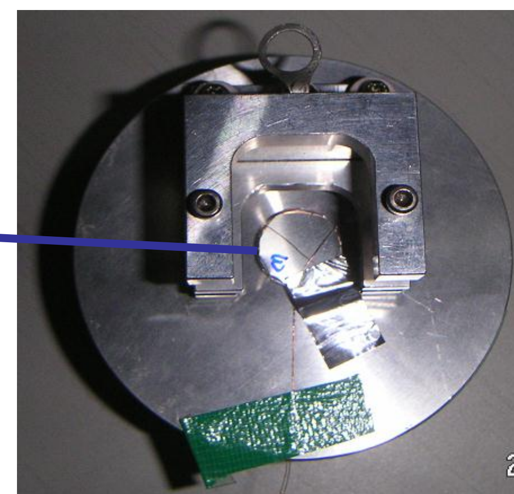
Beam extraction Point



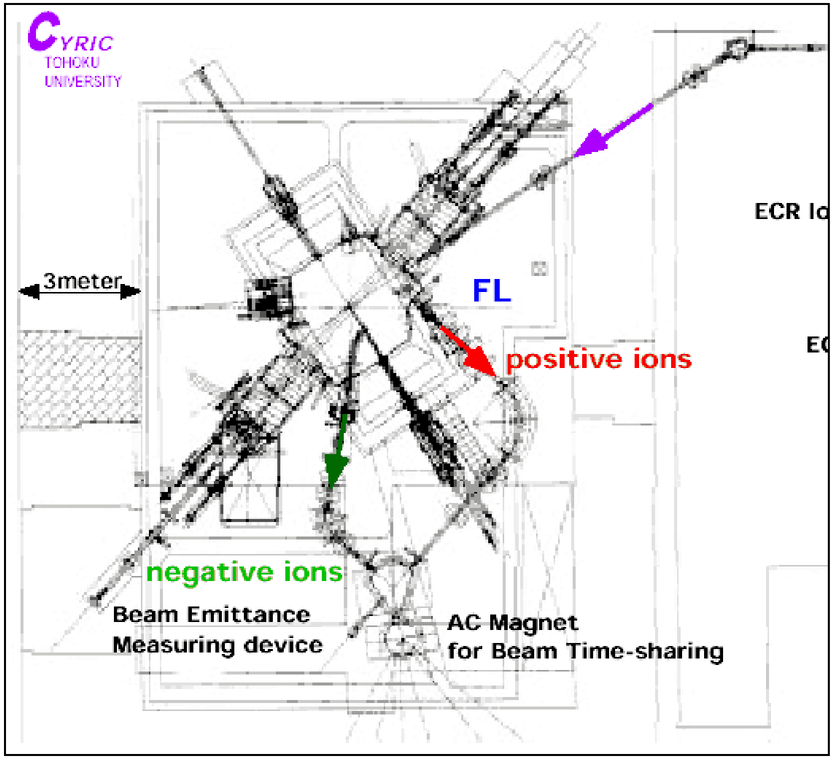
Collimator & Sample Holder

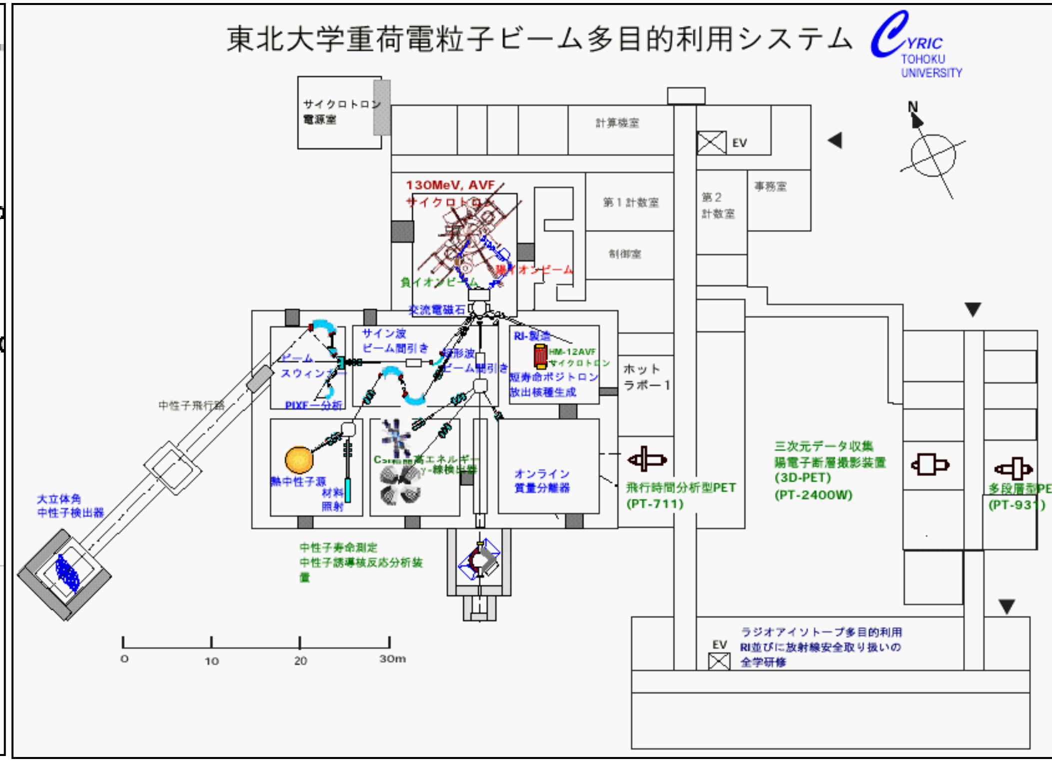


Targets & Monitor samples



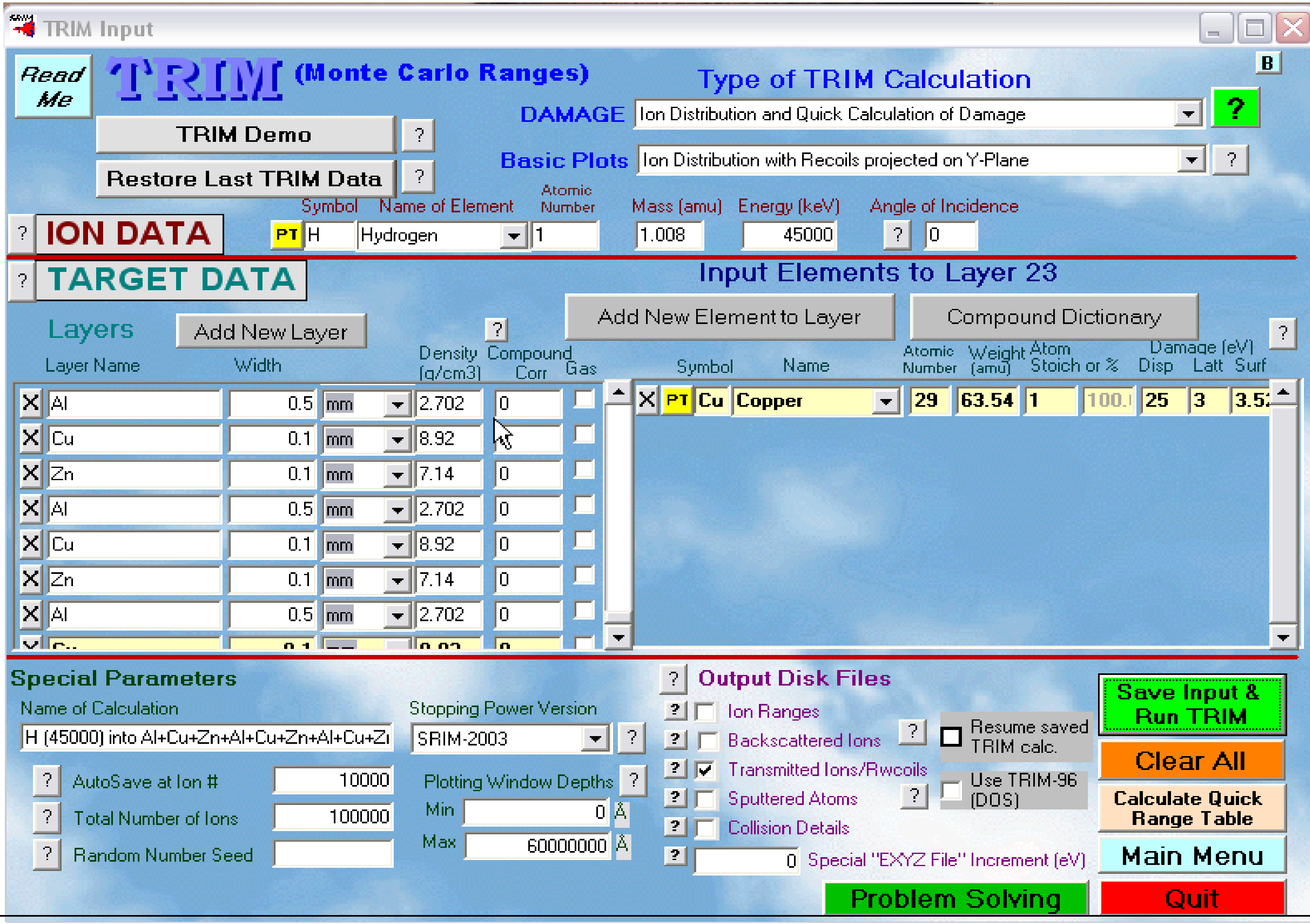
AVF Cyclotron in CYRIC





Deuteron Beam Energy	maximum	This work
	65 MeV	40 MeV
Current	50μA	100nA

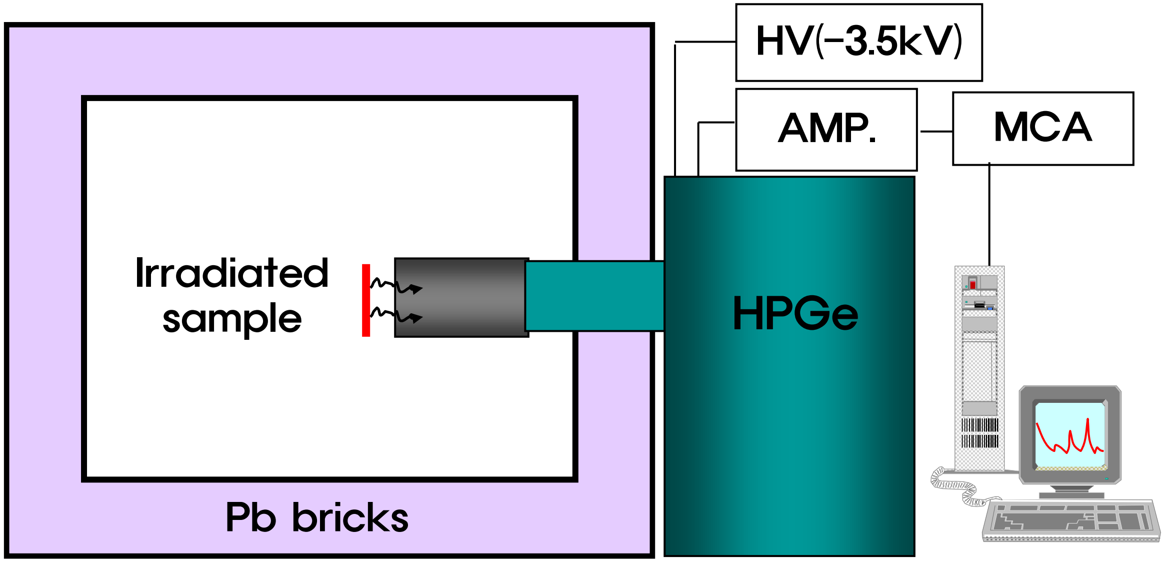
Calculation of proton beam energy degradation

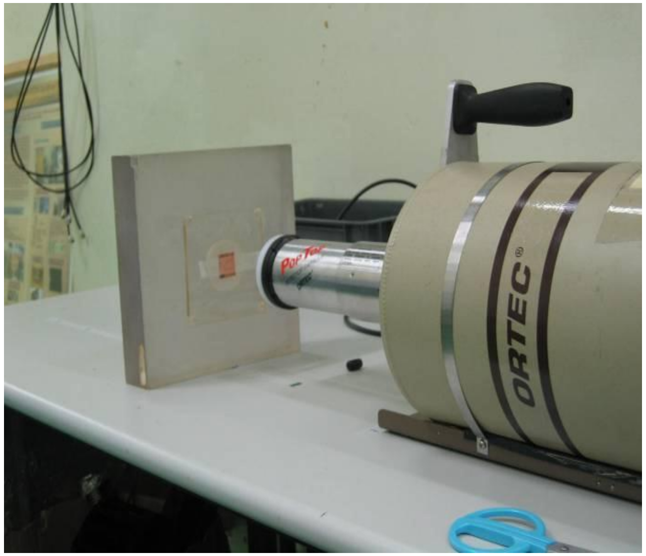


Gamma-ray spectrometry and Standard Sources

Nuclide	Half-life	Energy	Activity
^{109}Cd	462.6d	88.0336 keV	123.7 kBq
^{57}Co	271.79d	122.06065 / 136.47350 keV	53.2 kBq
^{137}Cs	30.07y	661.657 keV	370.2 kBq
^{54}Mn	312.1 d	834.841 keV	6.9 kBq
^{60}Co	5.27 y	1173.228 / 1332.490 keV	266.3 kBq
^{22}Na	2.6019 y	1274.537 keV	219.1 kBq

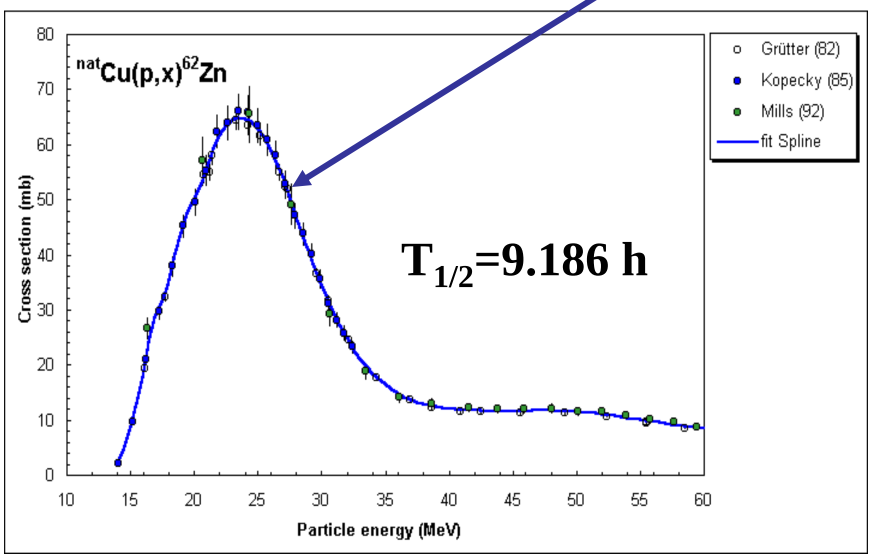
The gamma-ray spectrometry

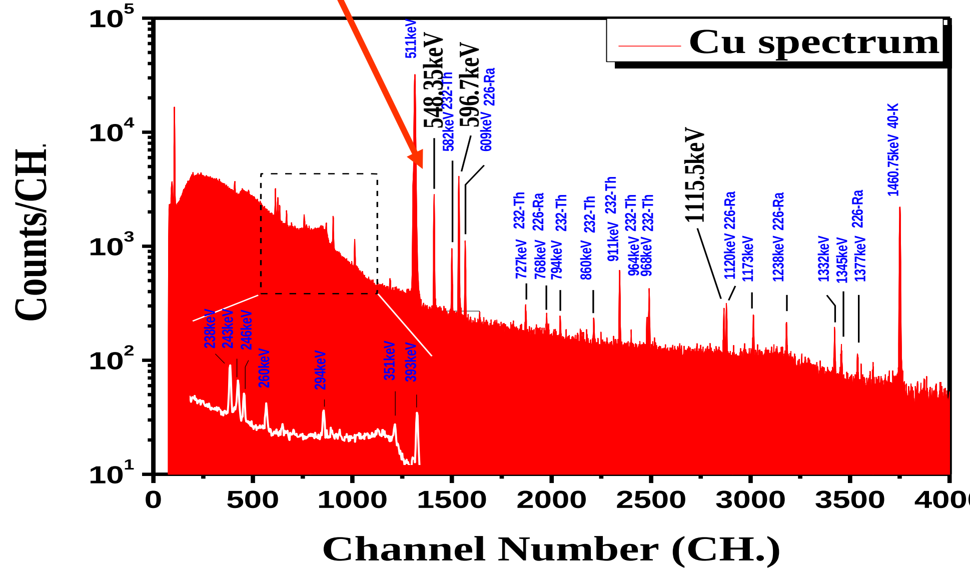




Determination of beam flux

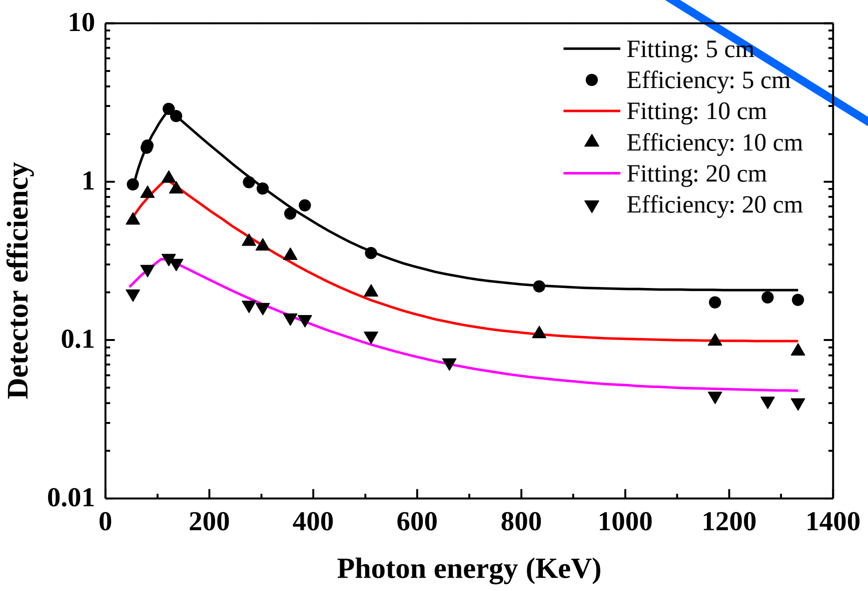
$$\phi = \frac{\lambda C}{\varepsilon \times I_{\gamma} \times N_{d} \times t \times \sigma (1 - e^{-\lambda t_m}) e^{-\lambda t_c} (1 - e^{-\lambda t_i})}$$

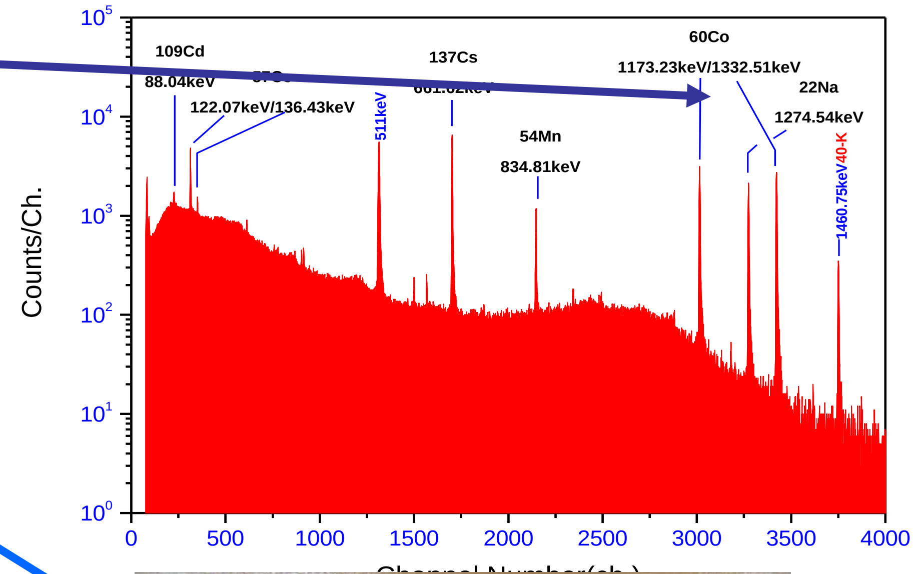




Determination of Detector Efficiency

$$\varepsilon = \frac{CPS}{A_0 e^{-\lambda t} \times I_\gamma}$$





Formula of Cross sections calculations

Reaction Rate

$$R = \frac{\lambda C}{\varepsilon I_\gamma NQ(1-e^{-\lambda t_m})e^{-\lambda t_c}(1-e^{-\lambda t_i})}$$

R = Reaction rate
λ = decay constant, s^{-1}
C = total counts of gamma-ray peak area
N = number of target atoms, atom
ε = peak efficiency
I_γ = branching ratio of gamma-ray
t_c, t_m, t_{irr} = cooling time, measuring time, irradiation time (s)
Q = proton beam current, coulomb.

Cross-Sections

$$\sigma = \frac{RQN}{\phi N_d l}$$

σ = cross section, cm^{-2}
N_d = atomic density, $atom/cm^3$
l = foil thickness, cm
ϕ = beam intensity, $p/cm^2/sec$

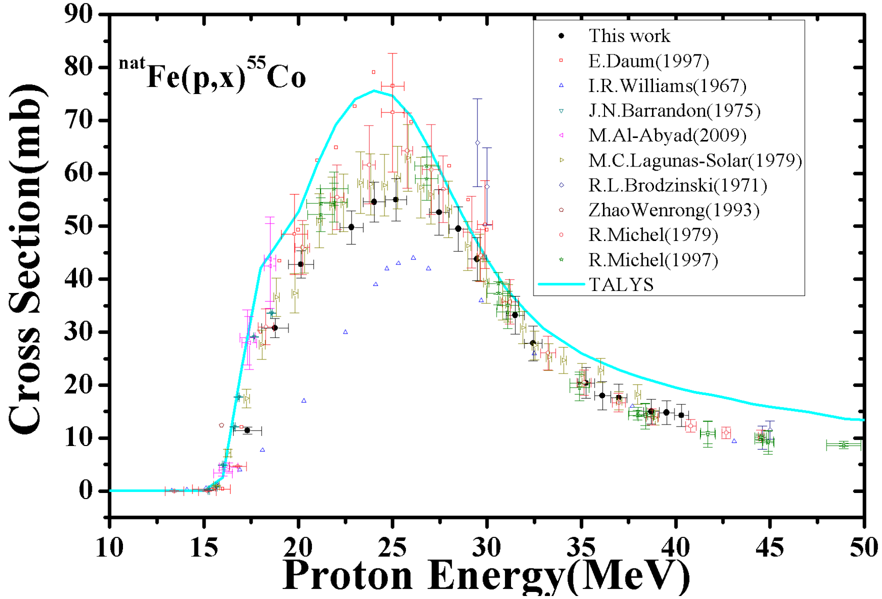
$$\sigma = \frac{\lambda C}{\varepsilon \times I_\gamma \times N_d \times t \times \phi(1-e^{-\lambda t_m})e^{-\lambda t_c}(1-e^{-\lambda t_i})}$$

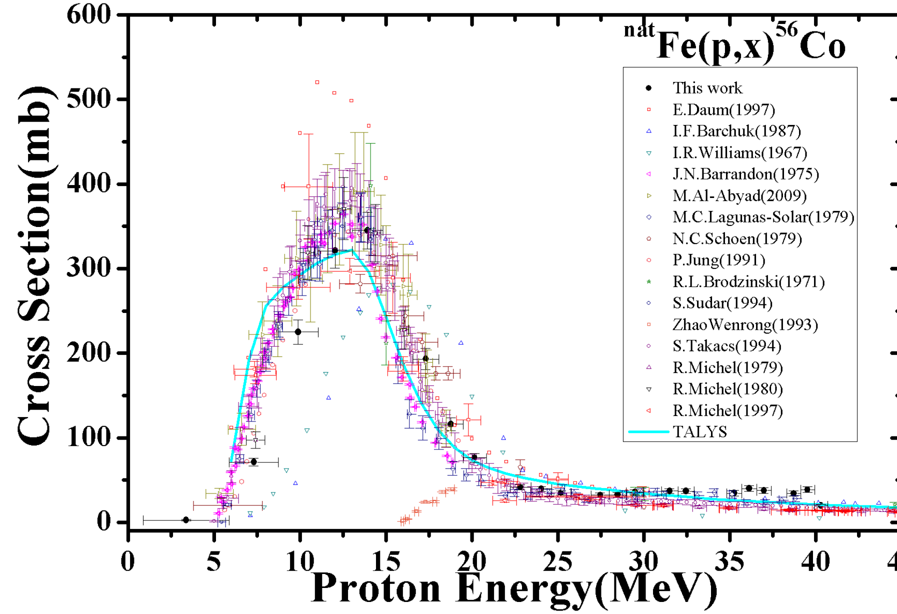
Deduction of Integral Yield

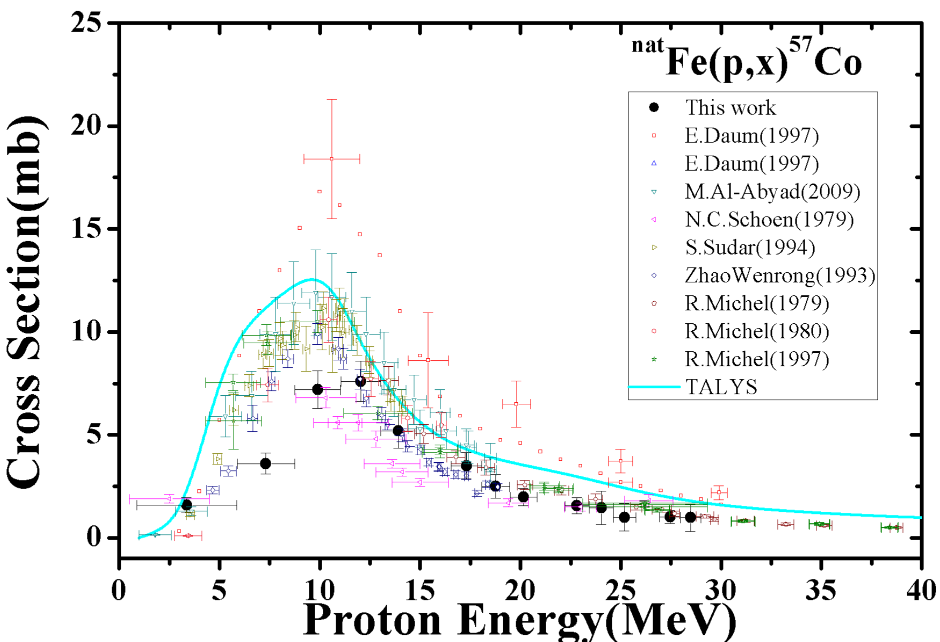
$$Y = I_p . N_d . \int_0^E \frac{\sigma(E)}{\left(dE/dx\right)_E} . dE \times \lambda$$

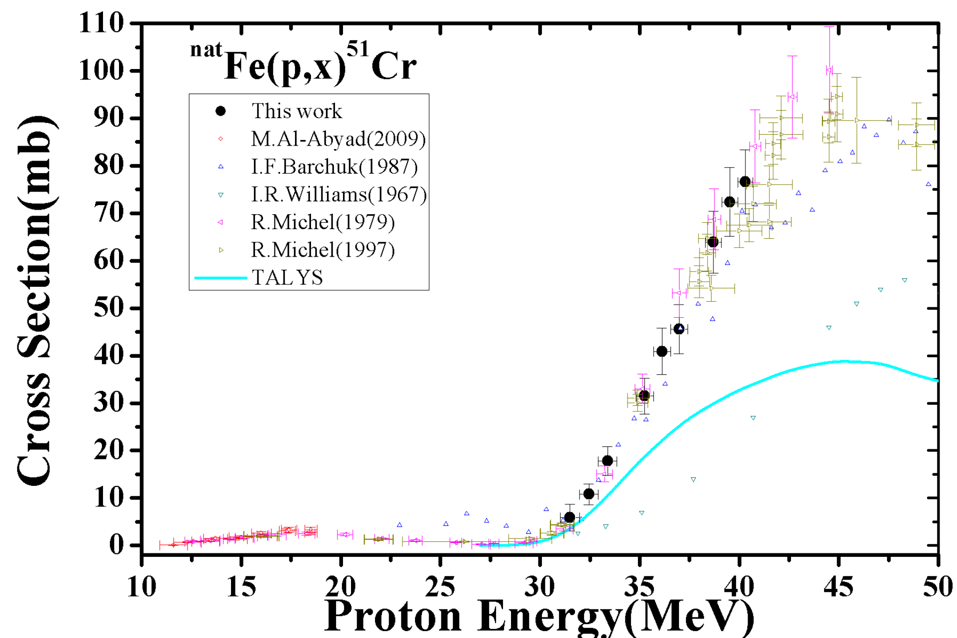
I_p = Proton flux (p/cm2-sec)
N_d = Number density (atoms/cm3)
$\sigma(E)$ = Cross-sections (cm2)
$(dE/dx)_E$ = Stopping power (MeV/cm)
dE = E_{in}-E_{out}: energy difference
λ = Decay constant

Measured Cross sections of $^{nat}Fe(p,x)$

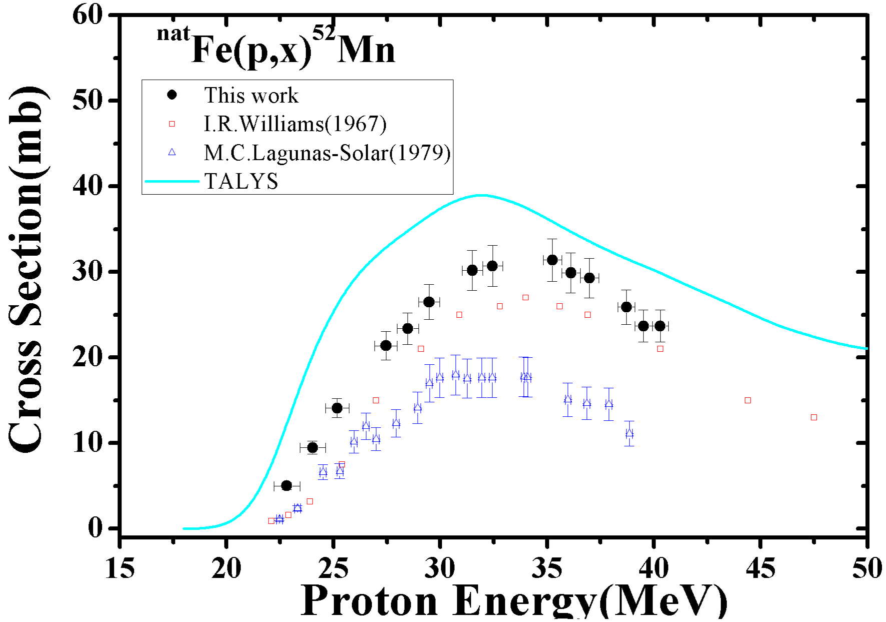


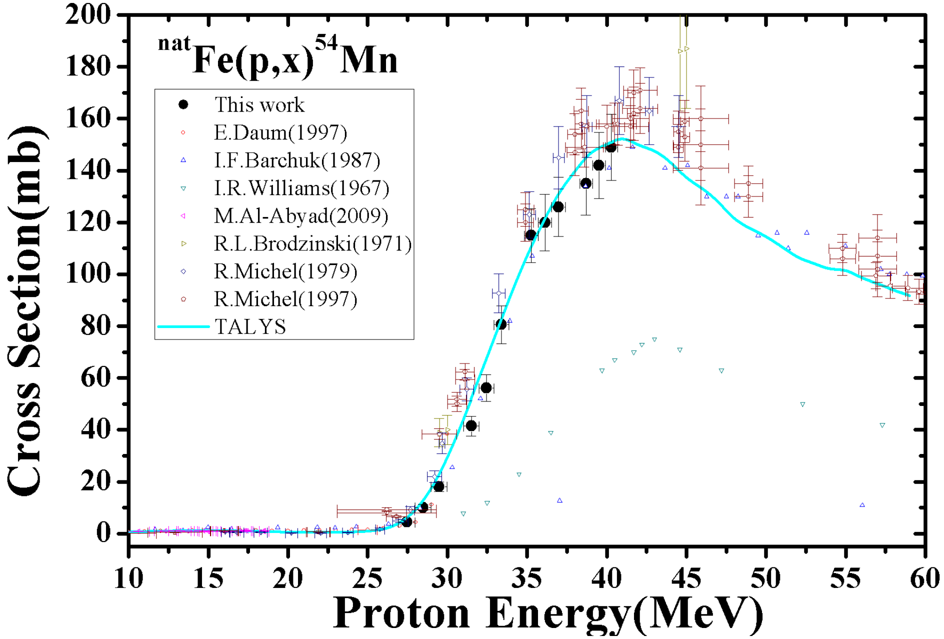




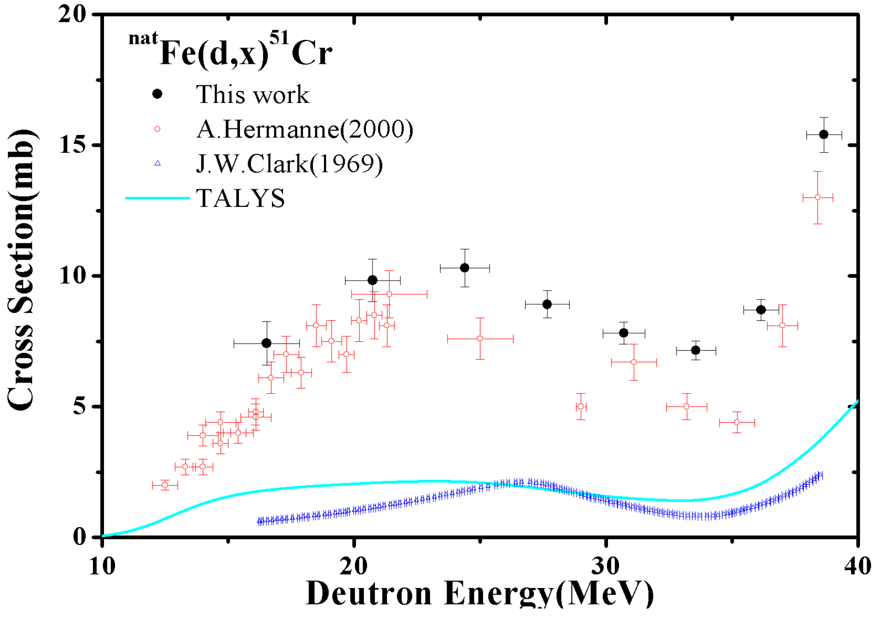


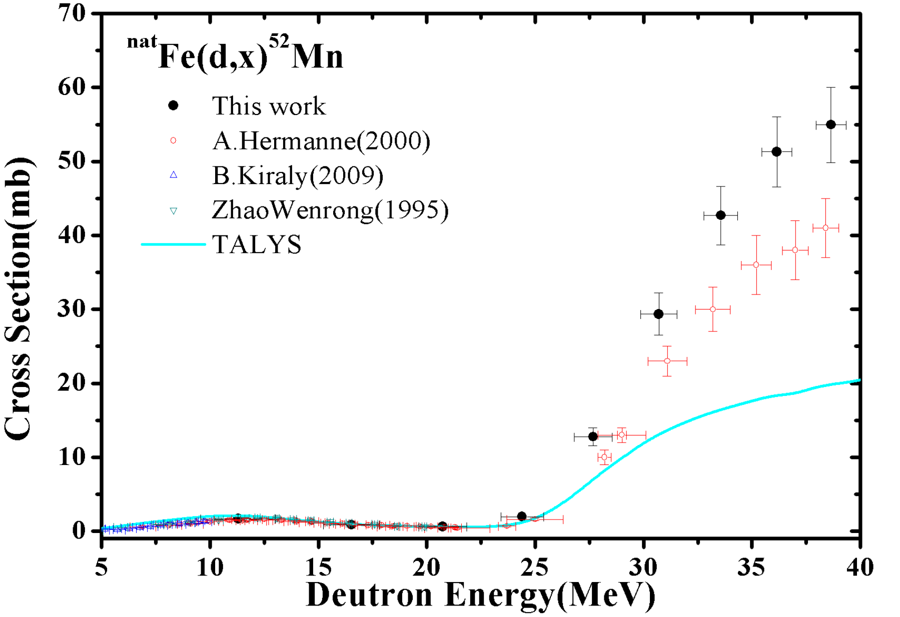
Measured Cross sections of $^{nat}Fe(p,x)$

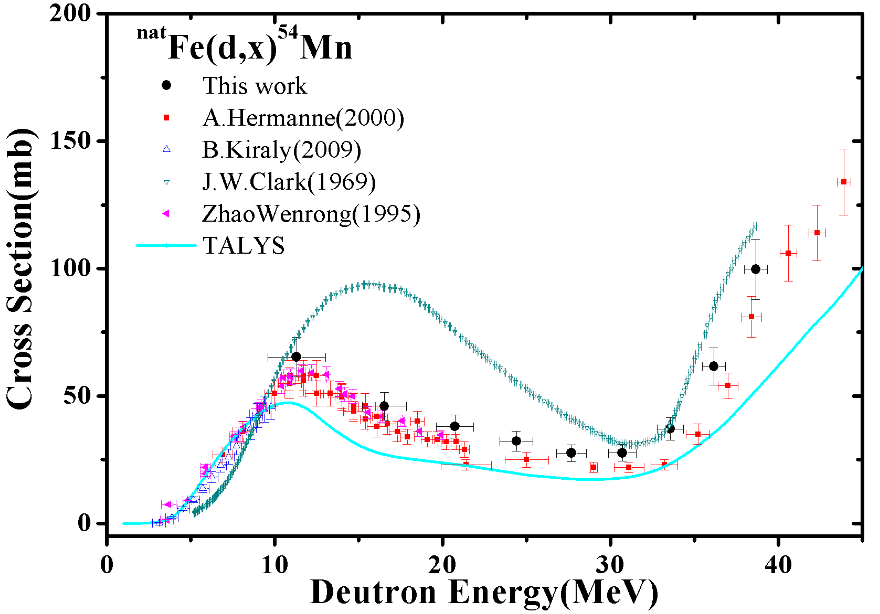


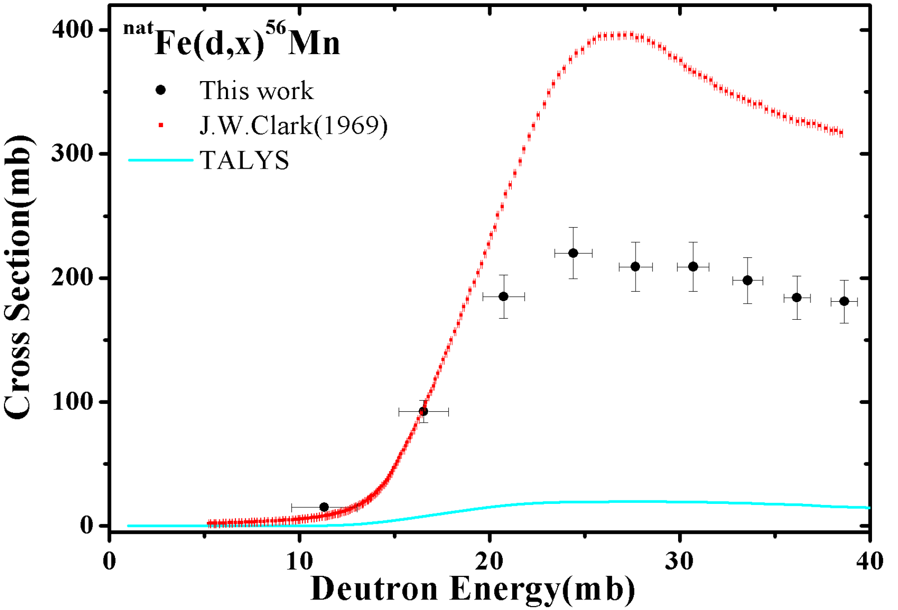


Measured Cross sections of $^{nat}Fe(d,x)$

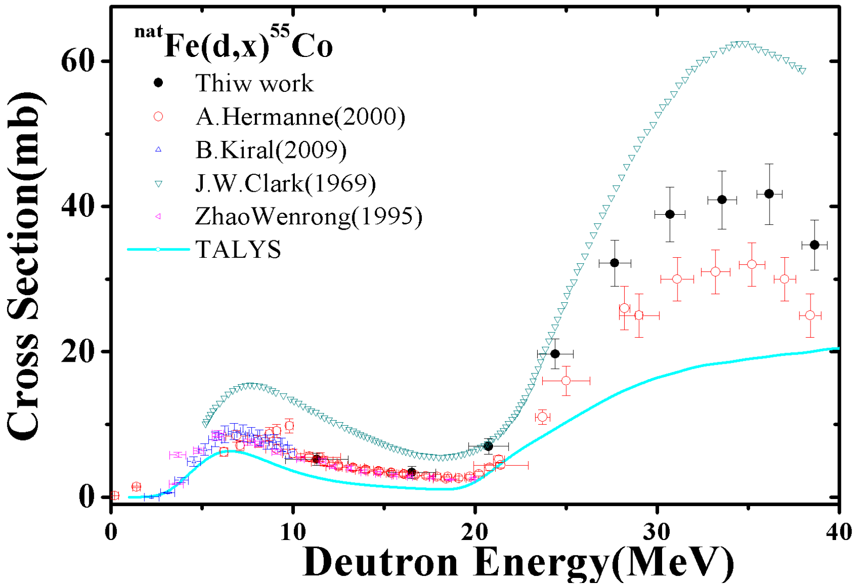


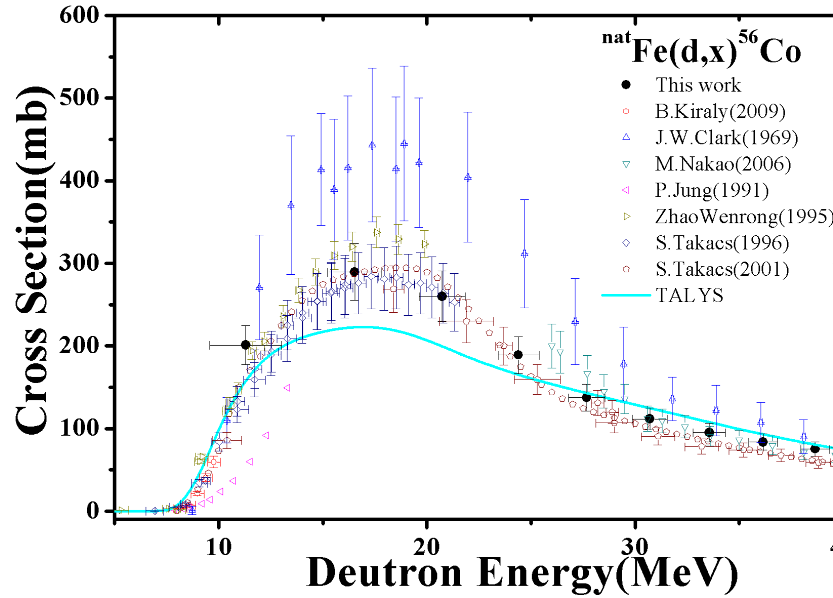


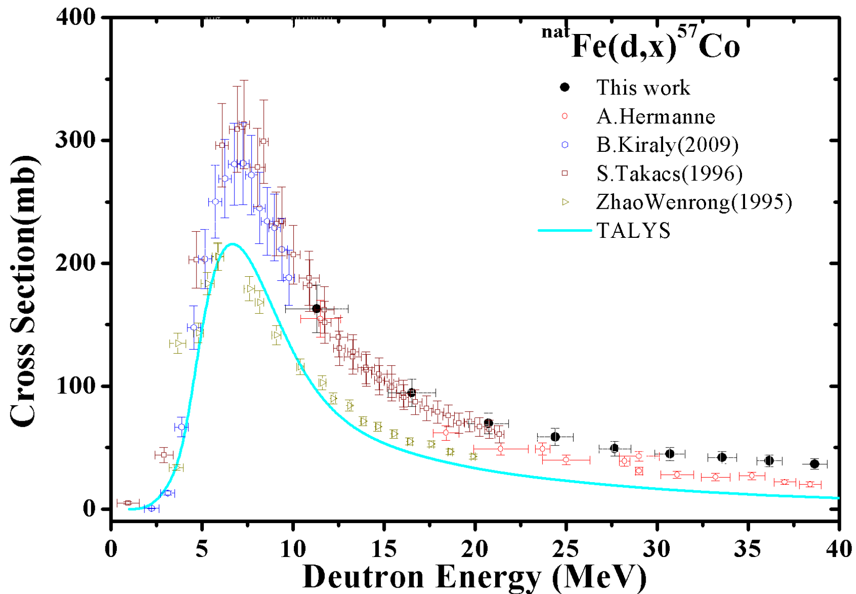


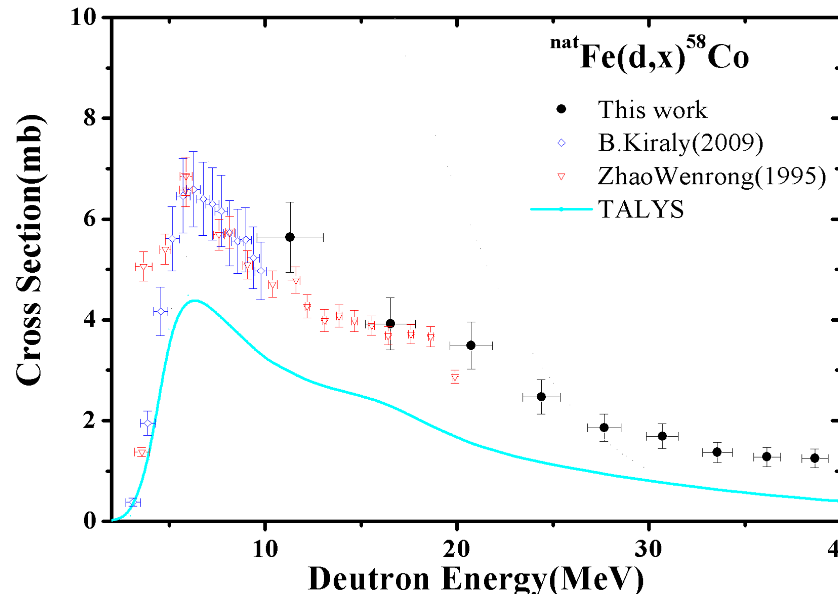


Measured Cross sections of $^{nat}Fe(d,x)$









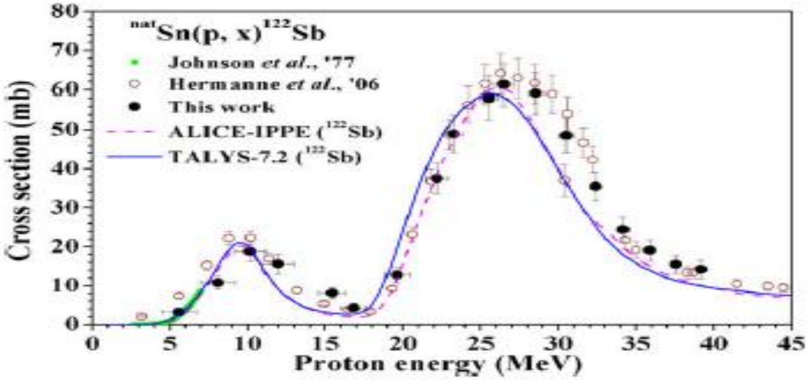


Fig. 2. Excitation function for the $^{nat}Sn(p,x)^{122}Sb$ processes.

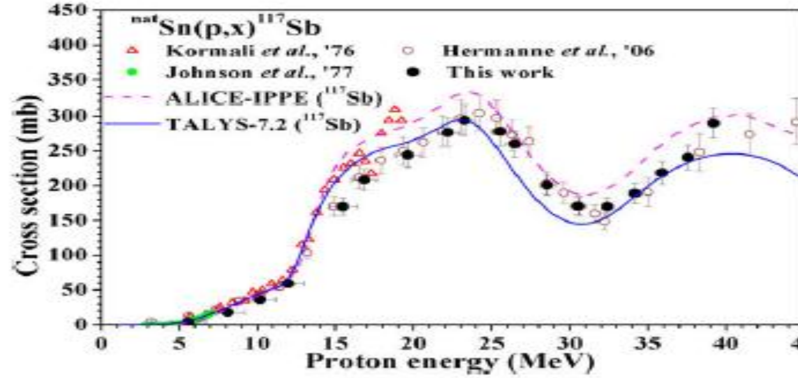


Fig. 5. Excitation function for the $^{nat}Sn(p,x)^{117}Sb$ processes.

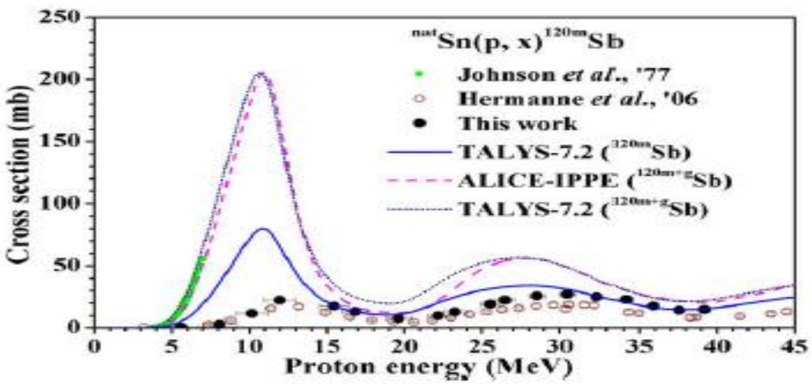


Fig. 3. Excitation function for the $^{nat}Sn(p,x)^{120m}Sb$ processes.

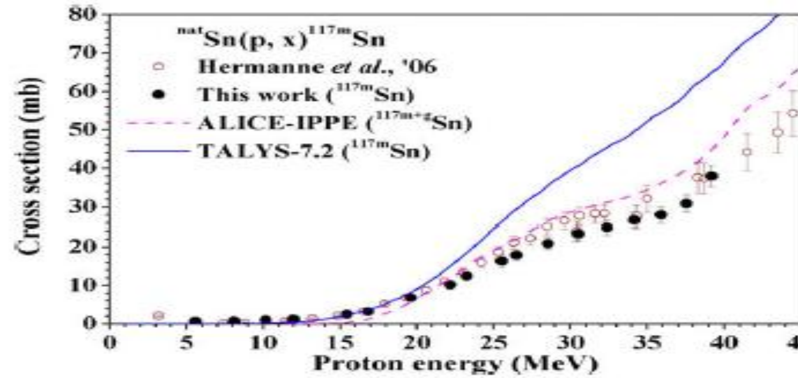


Fig. 6. Excitation function for the $^{nat}Sn(p,x)^{117m}Sn$ processes.

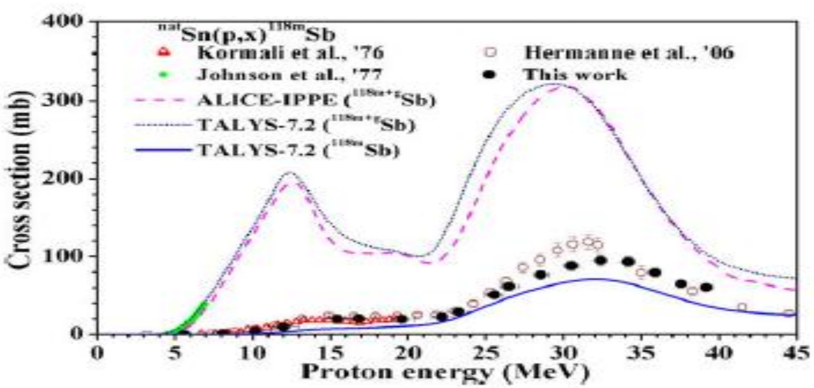


Fig. 4. Excitation function for the $^{nat}Sn(p,x)^{118m}Sb$ processes.

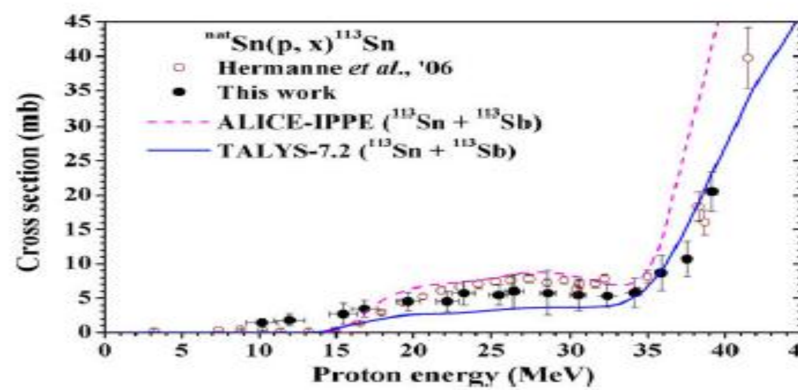


Fig. 7. Excitation function for the $^{nat}Sn(p,x)^{113}Sn$ processes.

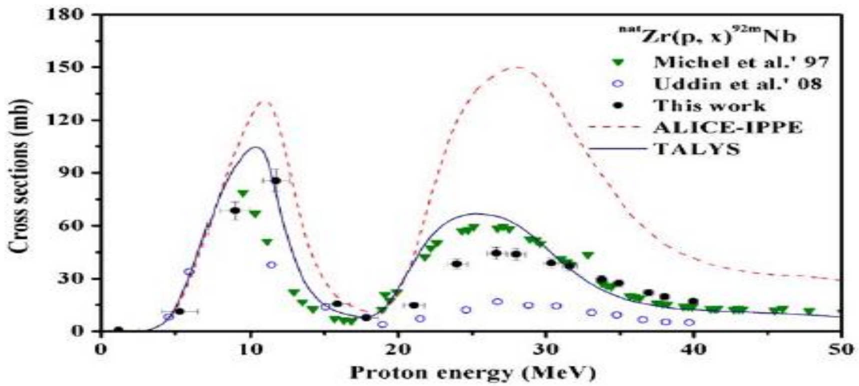


Fig. 2. Excitation function of the $^{nat}Zr(p,x)^{92m}Nb$ reaction.

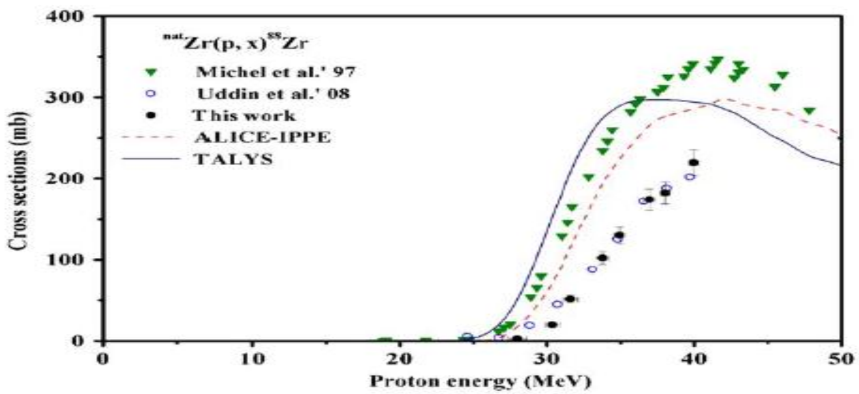


Fig. 3. Excitation function of the $^{nat}Zr(p,x)^{88}Zr$ reaction.

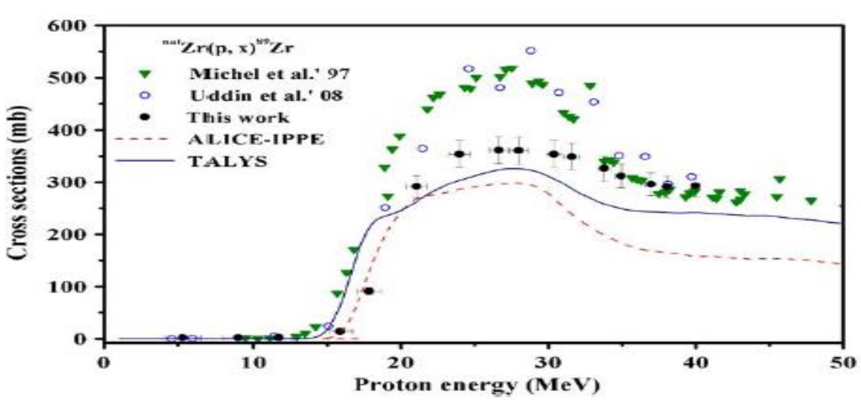


Fig. 4. Excitation function of the $^{nat}Zr(p,x)^{89}Zr$ reaction.

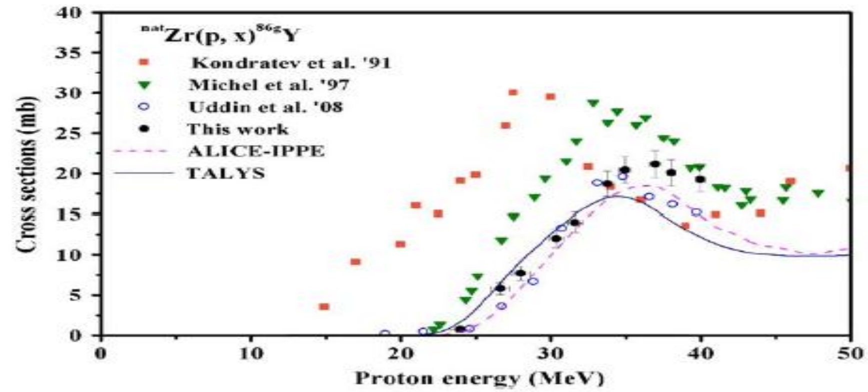


Fig. 5. Excitation function of the $^{nat}Zr(p,x)^{86}Y$ reaction.

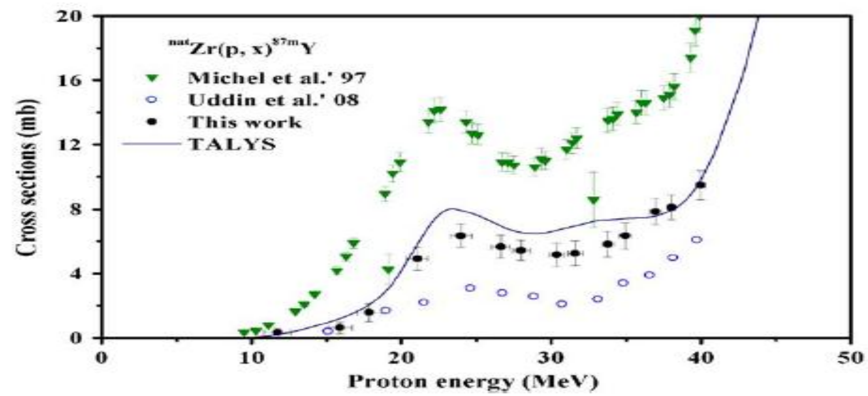


Fig. 6. Excitation function of the $^{nat}Zr(p,x)^{87m}Y$ reaction.

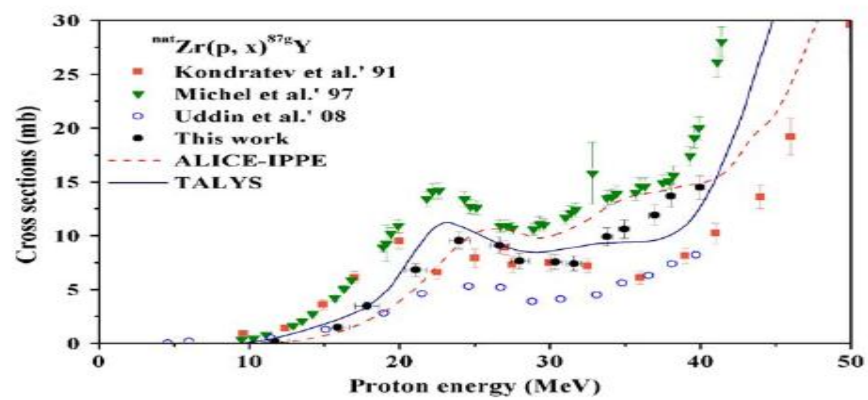


Fig. 7. Excitation function of the $^{nat}Zr(p,x)^{87g}Y$ reaction.

Summary and Discussion

- **Reported the recent activities on LENP :**

➢ **Neutron Cross Section Measurement using Pohang Neutron Facility**

- 12 m TOF path length
- New DAQ system based on FADC was developed
- Resonance parameter determination with SAMMY code
- 4π Gamma detector by using 12 BGO crystals for neutron capture cross section

➢ **Neutron Activation measurements with thermal neutrons of PNF**

➢ **Photo-nuclear Reaction Measurements with 50-70 MeV and 2.5 GeV Bremsstrahlung**

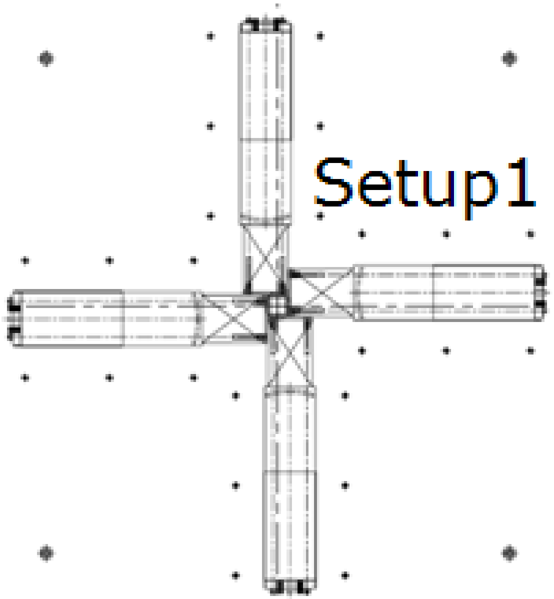
➢ **Charged particle induced reaction Measurements with MC 50 cyclotron**

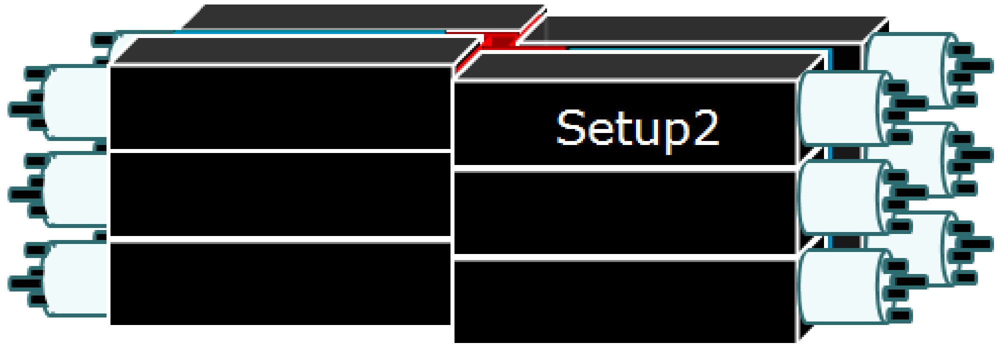
➢ **Collaboration with Domestic and Foreign Users**

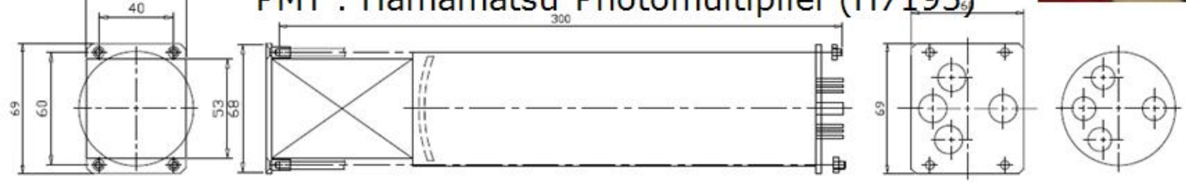
- Vietnam, China, India, Poland, Russia, Mongol

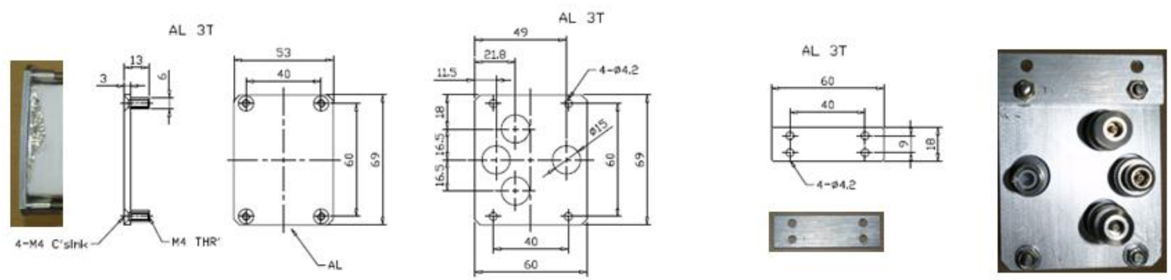
4π Gamma detector by using 12 BGO crystals

- Coverage : 98.25% (setup1), 98.21% (setup2)

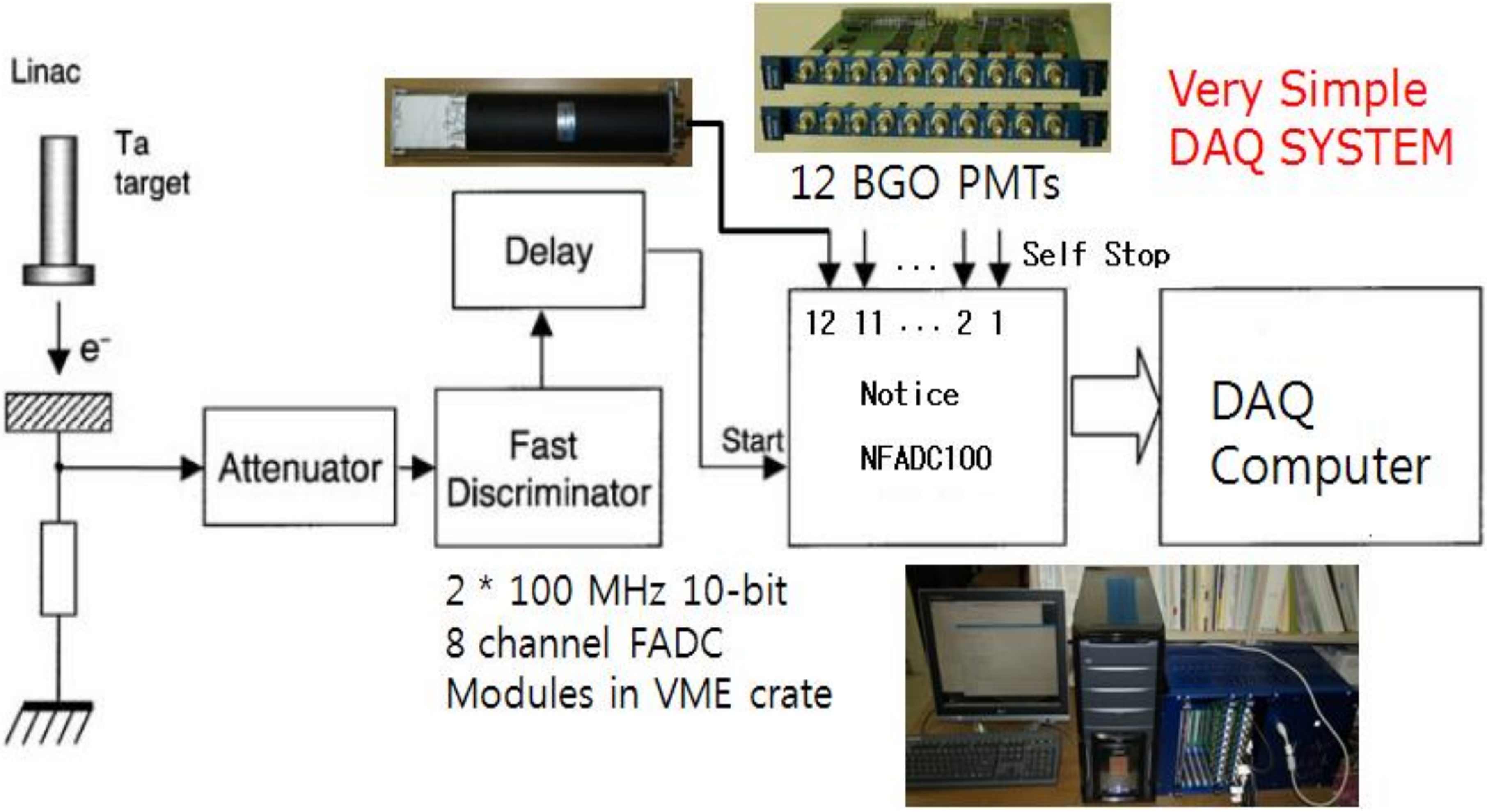








Data Acquisition System based on FADC



Papers in 2010

1. Measurements of neutron total cross-sections and resonance parameters of erbium at the Pohang Neutron Facility, Nucl. Instr. Meth. B 268 (2010) 106-113.
2. Measurement of neutron cross sections and resonance parameters of ^{169}Tm below 100 eV, Chinese Phys. C 34 (2010) 1-5.
3. Measurement of isomeric yield ratios in ^{nat}In and ^{nat}Sn with 50, 60, and 70 MeV bremsstrahlung photons, Nucl. Instr. Meth. B 268 (2010) 13-19.
4. Measurement of keV-neutron capture cross-sections and capture g-ray spectra of ^{56}Fe and ^{57}Fe, Nucl. Instr. Meth. B 268 (2010) 440-449.
5. Cyclotron production of the ^{105,106m}Ag, ^{100,101}Pd, ^{100,101m,105}Rh radionuclides by ^{nat}Pd(p,x) nuclear processes, Nucl. Instr. Meth. B 268 (2010) 2303-2311.
6. Isomeric yield ratios in the photoproduction of ^{52m,g}Mn from natural iron using 50-, 60-, 70-MeV, and 2.5-GeV bremsstrahlung, J. Radioanal Nucl. Chem. 283 (2010) 683-690.
7. Measurement of isomeric-yield ratios for the ^{197}Au(γ,*n*)^{196m,g}*Au* reactions induced by bremsstrahlung, J. Radioanal Nucl. Chem. 283 (2010) 519-525.
8. Mass–yield distributions of fission products from photo-fission of ^{nat}Pb induced by 50–70 MeV bremsstrahlung, J. Radioanal Nucl. Chem. 283 (2010) 439-445.
9. Multicrystal Scintillation Detector for Investigation of Angular Correlations in (n,γ) Reactions, IEEE Trans. Nucl. Sci., 57 (2010) 1391-1395.
10. Measurement of isomeric yield ratios for ^{93}Nb(γ,4n)^{89m,g}Nb and ^{nat}Mo(γ,xn1p)^{95m,g}Nb reactions with 50-, 60-, and 70-MeV Bremsstrahlung, J. Radioanal Nucl. Chem. DOI 10.1007/s10967-010-0839-3.
11. Measurement of isomeric yield ratios for the ^{44m,g}Sc isomeric pairs produced from ^{45}Sc and ^{nat}Ti targets at 50-, 60-, and 70-MeV Bremsstrahlung, J. Radioanal Nucl. Chem. DOI 10.1007/s10967-010-0831-y
12. Measurement of thermal neutron cross-section and resonance integral for the ^{165}Ho(n, γ)^{166g}Ho reaction using electron linac-based neutron source, accepted in NIMB.
13. Mass-yield distribution of fission products from photo-fission of natPb induced by 2.5 GeV bremsstrahlung, minor correction in European Physical Journal A