Measurement of Reaction Cross-sections for ^{89}Y at Average Neutron Energies of 7-36 MeV

M. Zaman, G. N. Kim*, H. Naik, K. Kim
Department of Physics, Kyungpook National University, Daegu 702-701, Korea

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ABSTRACT

We measured neutron-induced reaction cross-sections for $^{89}Y(n,2n)^{88}Y$, $^{89}Y(n,3n)^{87}Y$, $^{89}Y(n,4n)^{86}Y$, $^{89}Y(n,\gamma)^{90m}Y$ and $^{89}Y(n,\alpha)^{86}Rb$ reactions with the average neutron energy region from 7.45 to 36.29 MeV by an activation and an off-line γ-ray spectrometric technique. High energy neutrons were produced from the $^{9}Be(p,n)$ reaction with 25-, 35- and 45-MeV proton beam from the MC-50 Cyclotron at Korea Institute of Radiological and Medical Sciences (KIRAMS). The neutron-induced reaction cross-sections of ^{89}Y as a function of neutron energy were calculated using the TALYS 1.4 with the mono-energetic neutron. The present results for $^{89}Y(n,xn;x=2\text{-}4)$, $^{89}Y(n,\gamma)^{90m}Y$ and $^{89}Y(n,\alpha)^{86}Rb$ reactions are compared with the literature data and those from the TALYS 1.4. We observed that the individual reaction cross-section increases sharply from its reaction threshold to the energy where other reaction channel is opened. Then it remains constant for a while until the next reaction channel reaches its maximum.

Outline

- Introduction
- Experimental setup at KIRAMS
- Monte Carlo Simulation of neutron spectrum
- Yttrium cross-section measurement
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  - Cross section measurement specific formula
- Uncertainties
- Results
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Introduction

Neutron-induced reaction cross-sections are important:

1. **Fundamental researches:**
   - Nuclear physics
   - Reactor physics
   - Astrophysics

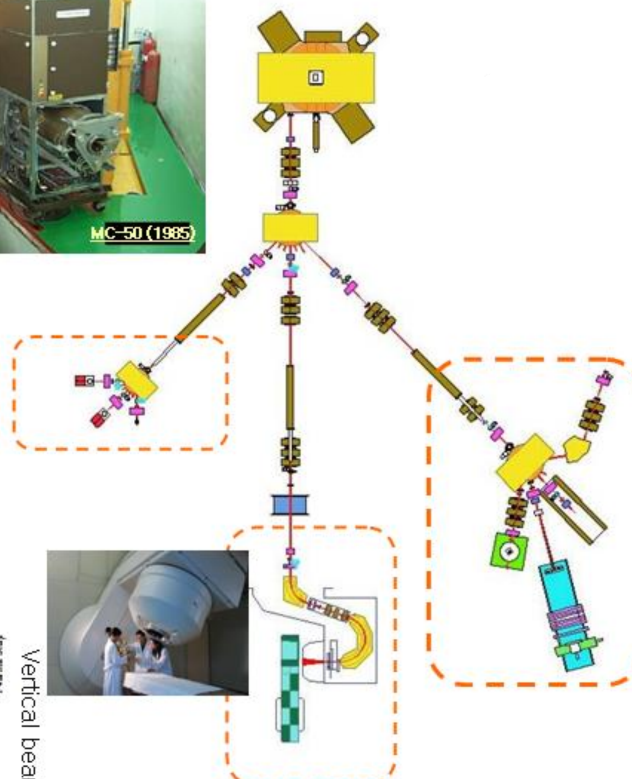
2. **Practical applications:**
   - Nuclear technology
   - Dosimetery
   - Radiation safety
   - Development of radiation detector
   - Improving nuclear data libraries

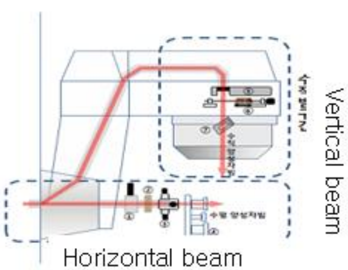
3. **In a wide range of energies are important for applications:**
   - Design of radiation shielding
   - Calculation of absorbed dose in the human body during radiotherapy
   - Activation analysis
   - Physics and technology of fusion and fission reactors.

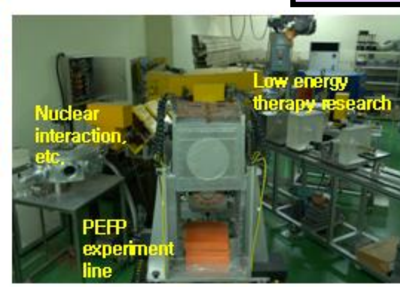
Introduction(cont…)

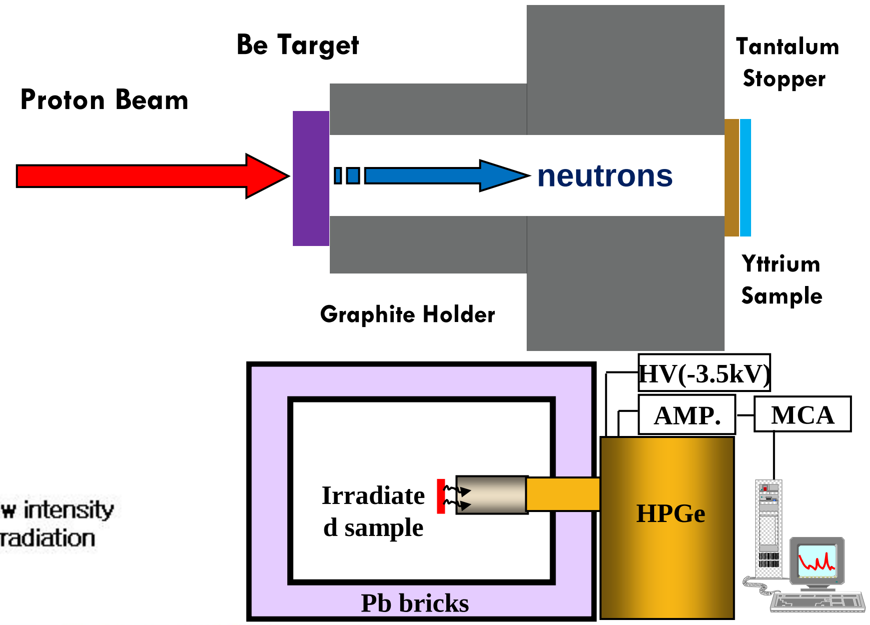
- **The $^{89}Y(n,2n)$ reaction cross-sections in the neutron energy range from threshold to 20 MeV were reported with various mono-energetic neutron beam .**
- **In this work neutron-induced reaction cross-sections of yttrium are determined for neutron energies of 7-36 MeV by activation and off-line γ-spectrometry technique.**
- **Theoretical calculations for mono-energetic neutron beam was done by using the TALYS 1.4 code.**
- **The neutron spectrum for $^{9}Be(p,n)$ reaction was calculated with the MCNPX.**
- **The flux-weighted average cross-sections were calculated from the experimental literature data and the theoretical data with the TALYS 1.4 code.**
- **The present results are compared with the flux-weighted average cross-sections from the literature and those from the theoretical values of TALYS 1.4 code.**

Experimental Setup at KIRAMS





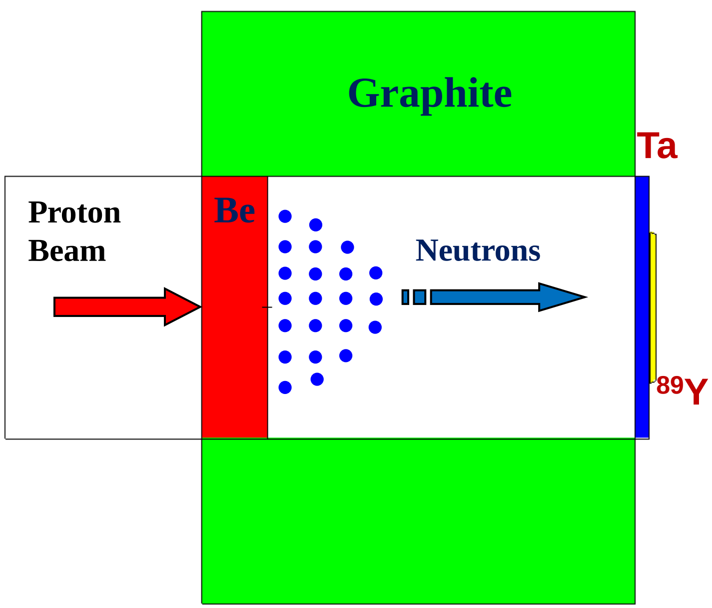




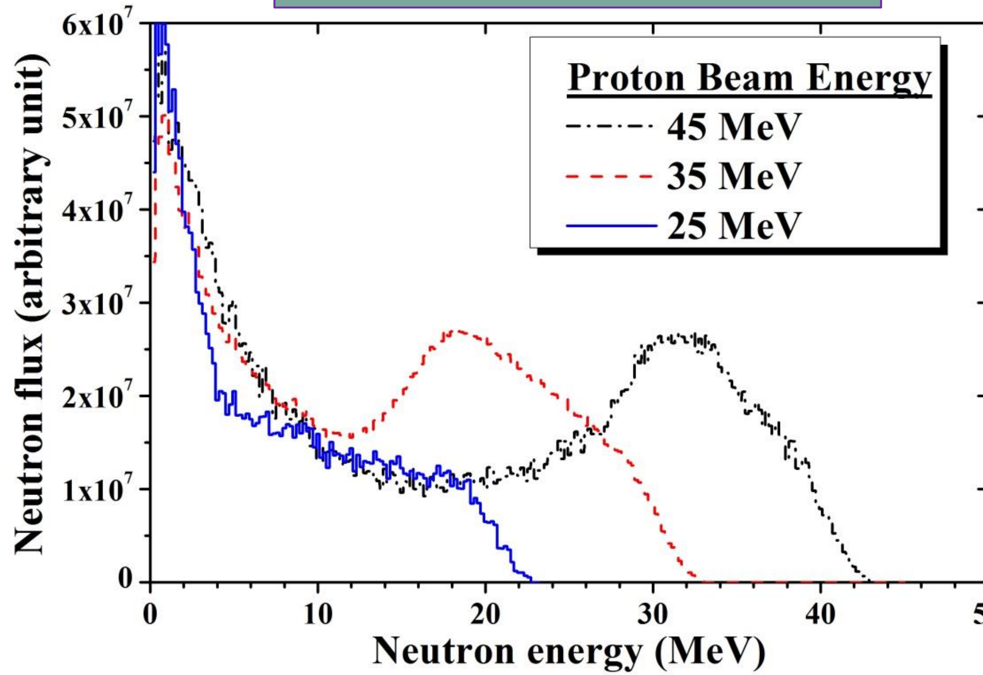
MCNPX Simulation of ^{9}Be(p,n) neutron spectrum at MC50 Cyclotron, KIRAMS

- High energy neutrons are produced in ^{9}Be(p,n) reaction
- Irradiation of 5 mm ^{9}Be target followed by beam stopper (Ta disk)

MCNPX Modelling



P+Be/Ta neutron spectrum



Yttrium Cross Section Measurement

- The ^{9}Be(p,n) reaction on ^{9}Be target is utilized for activation cross sections measurement
- Only reactions (n,2n), (n,3n), (n,4n), (n,γ) and (n,α) of yttrium were measured

- Products of (n,xn), (n,γ) and (n,α) reactions on yttrium are well identifiable
- Half-lives of the products have good length of *γ*-spectrometry
- *γ* transitions are intensive for detection and good separation from each other

- The available experimental microscopic cross-sections for ^{89}Y(n,2n)^{88}Y, ^{89}Y(n,3n)^{87}Y, ^{89}Y(n,γ)^{90m}Y and ^{89}Y(n,α)^{86}Rb reactions are from EXFOR.
- Since the nuclear data libraries are poor we have used TALYS code for calculation of (n,xn) reaction cross-sections

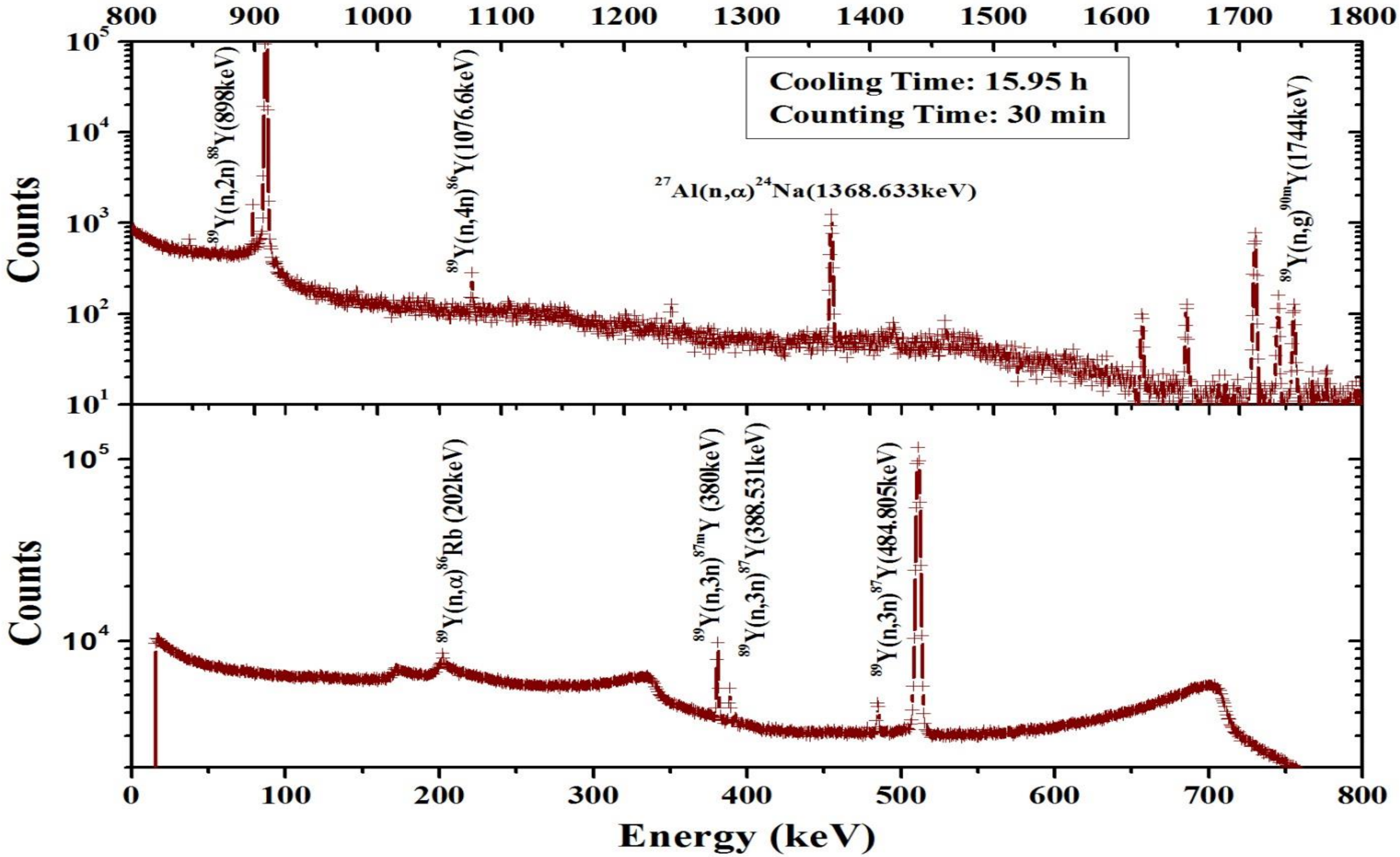
Experimental Procedure

- The experiment was performed by using the MC-50 Cyclotron at KIRAMS, Korea.
- The neutron beam was produced from the $^{9}Be(p,n)$ reaction when proton beam hits a 5 mm thick Be target.
- Protons beam passing through the beryllium target was stopped on the tantalum.
- ^{89}Y foil (8 mm × 8 mm) wrapped with Al foil and positioned at zero degree with respect to the proton beam direction and placed a 2.8 cm from the Be target.
- The Al wrapper is used as a neutron flux monitors.

Experimental conditions and characteristics of samples

Experiment No.	Proton Beam		Irradiation Time (min)	Yttrium Mass (g)	Aluminum Mass (g)	Tantalum Thickness (mm)
	Energy (MeV)	Current (nA)				
1	45	200	30	0.0400	0.0298	1.05
2	35	200	60	0.0423	0.0394	0.45
3	25	200	60	0.0409	0.0435	0.00

Typical γ-ray spectrum of irradiated ^{89}Y wrapped with ^{27}Al foil



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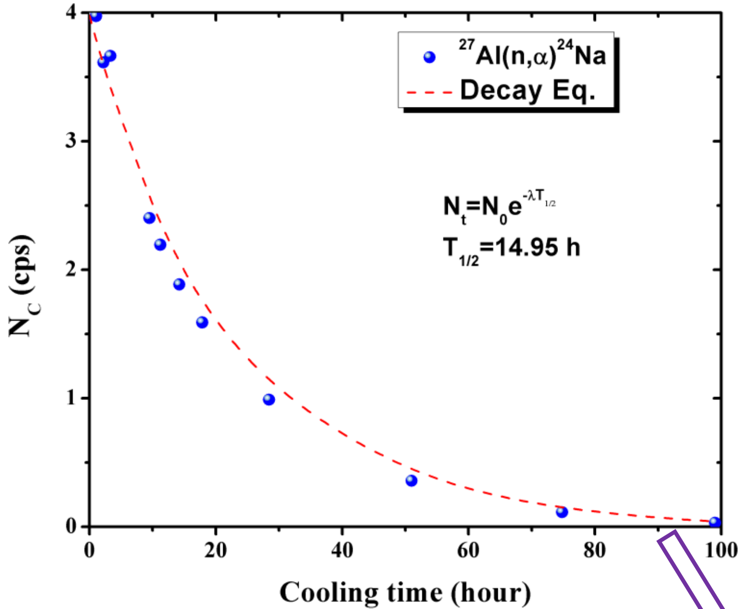
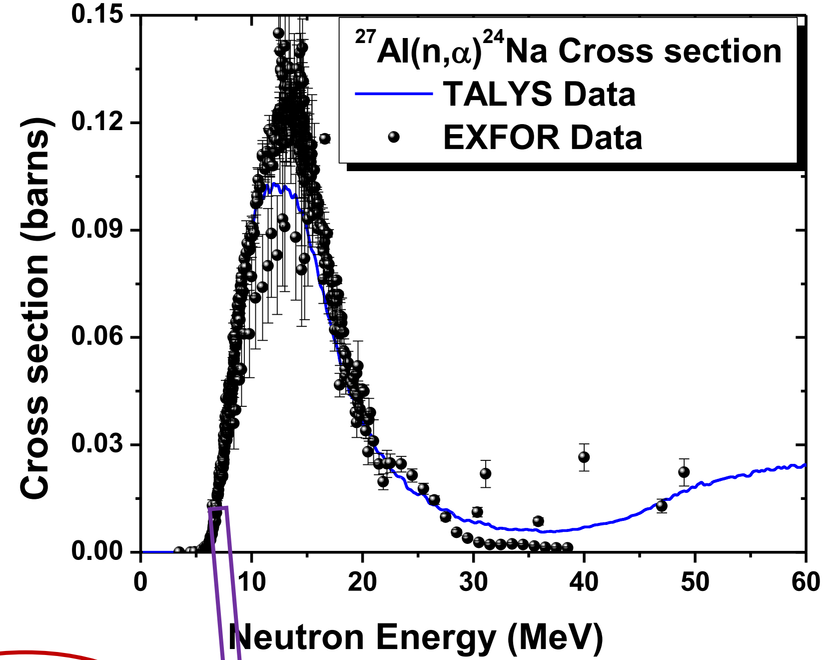
Neutron Flux Monitoring: Al Foils

Reactions	Half-life	Spin-Jπ	E_γ (keV)	I_γ(%)	Decay mode	E_{th}(MeV)
^{27}Al(n, α)^{24}Na	14.95 h	4^+	1368.63	100.0	β^-	3.25



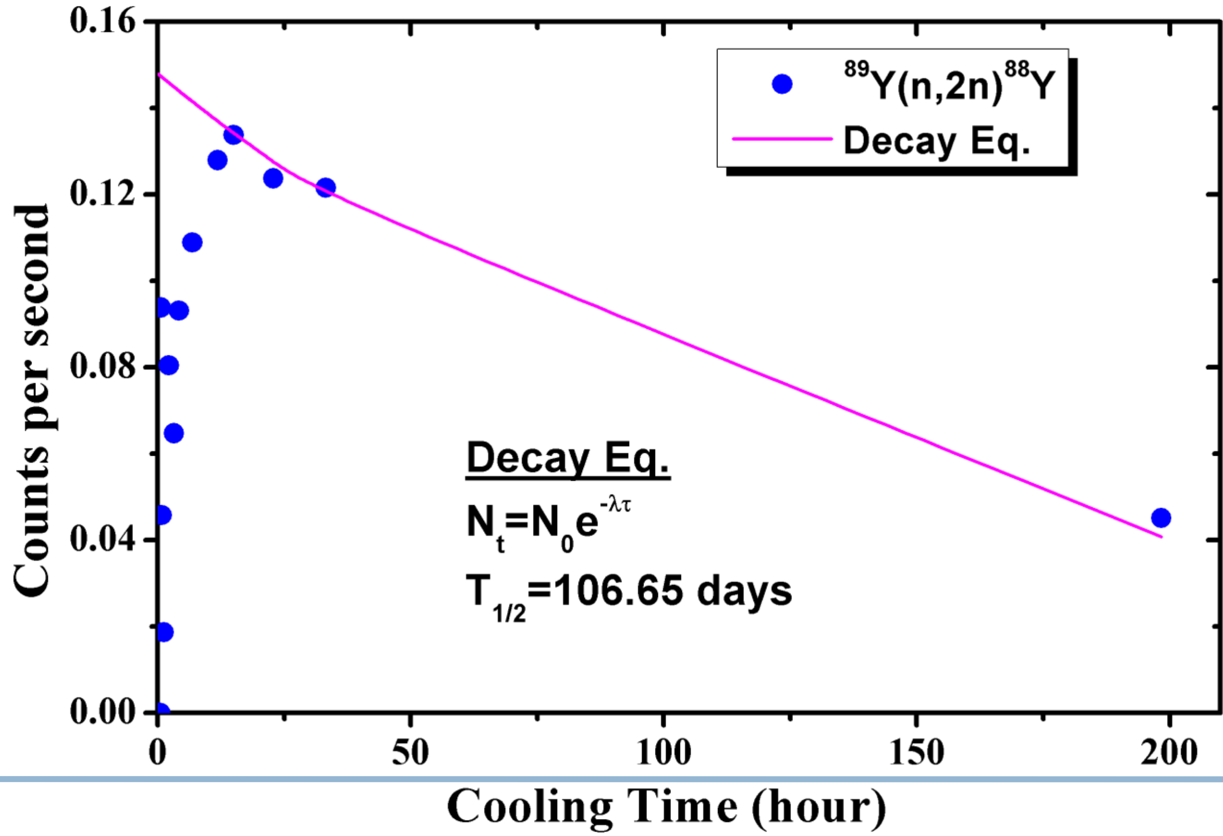


N_{obs}: number of observed γ-rays
n: number of target atom
I_γ :branching intensity of the γ-rays
E: detection efficiency
***λ*:** decay constant
T_I*, *T_C*, *CL*,** and ***LT are the irradiation time, cooling time, real time, and the counting time

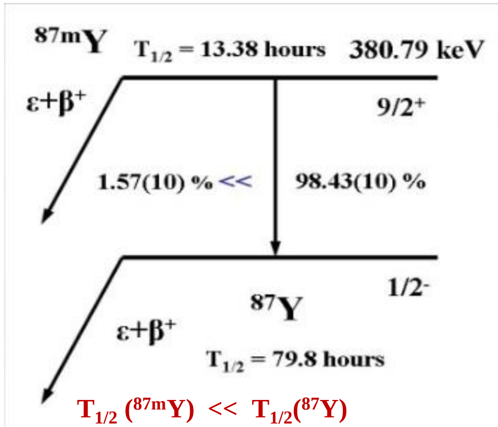
$$\phi_n = \frac{N_{obs}(CL/LT)\lambda}{n\sigma_R(E_n)\ I_\gamma\ \varepsilon\left(1-e^{-\lambda T_I}\right)e^{-\lambda T_C}\left(1-e^{-\lambda CL}\right)}$$

$^{89}Y(n,2n)^{88}Y$ Reactions

Reactions	Half-life	Spin-Jπ	E_{γ} (keV)	I_{γ}(%)	Decay mode	E_{th} (MeV)
$^{89}Y(n,2n)^{88}Y$	106.65 d	4^-	898.042 1836.06	93.7 99.2	β^+	11.61



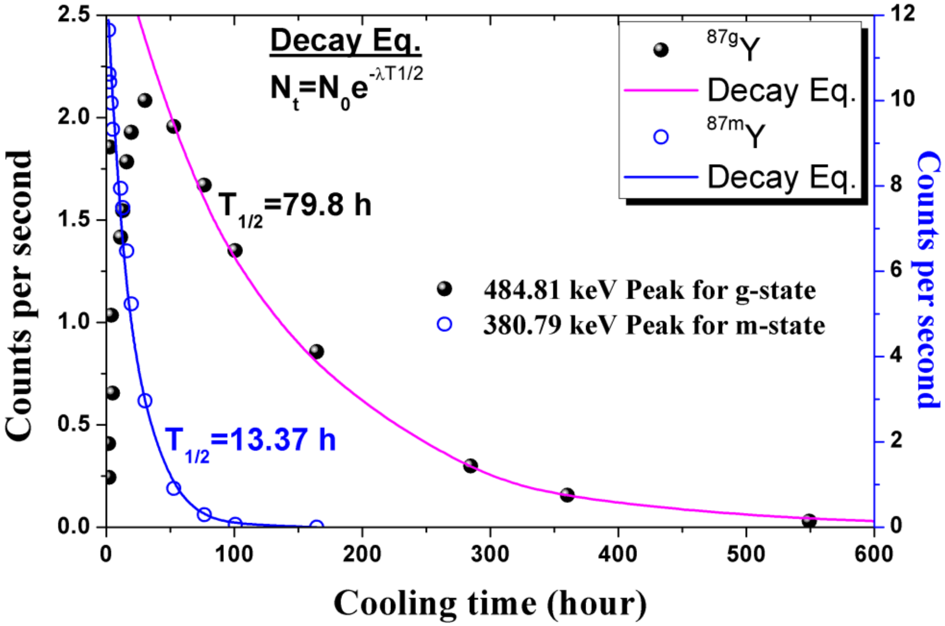
$^{89}Y(n,3n)^{87m,g}Y$ and $^{89}Y(n,4n)^{86m,g}Y$ Reactions

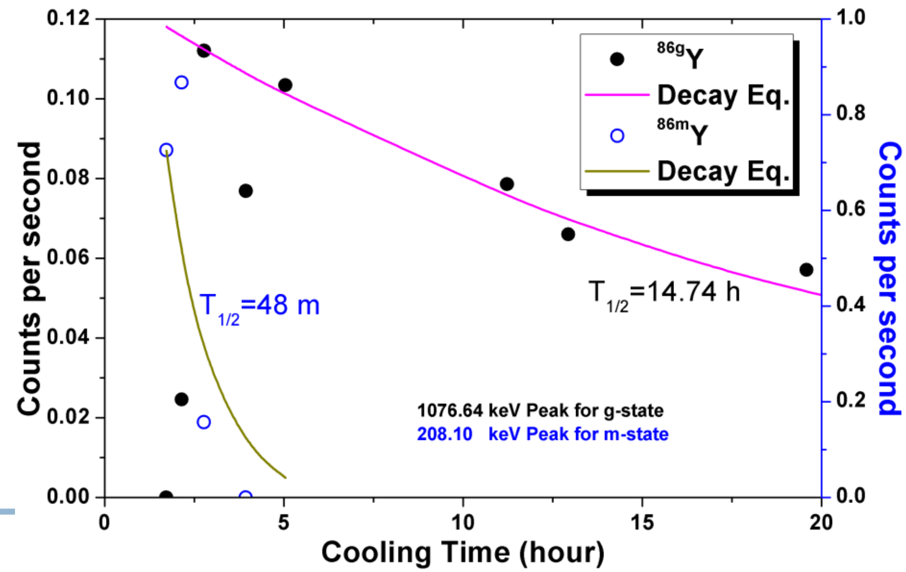


Reactions	Half-life	Spin-Jπ	E_γ (keV)	I_γ(%)	Decay mode	E_{th}(MeV)
$^{89}Y(n,3n)\,^{87m,g}Y$	79.8 h 13.37 h	1/2- 9/2+	484.80 380.79	89.7 78.0	β^+ IT	21.06
$^{89}Y(n,4n)\,^{86m,g}Y$	14.74 h 48.0 m	4- 8+	1076.64 208.10	83.0 94.0	β^+ IT	33.01

$^{87m}Y/^{86m}Y$ $$N_1 = N_{01} e^{-\lambda_1 \cdot t}$$

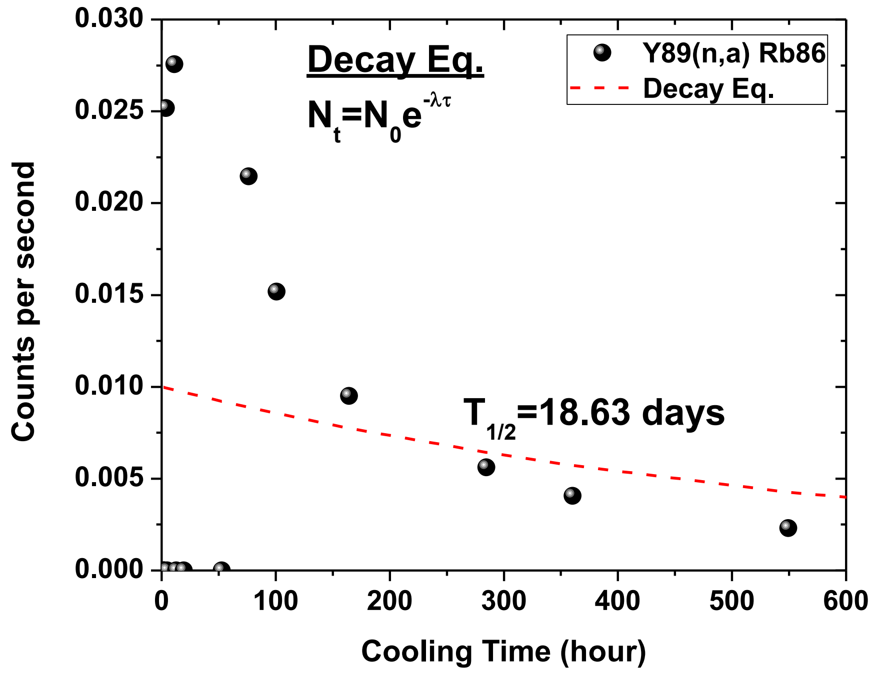
$^{87}Y/^{86}Y$ $$N = \left(N_{02} + \frac{\lambda_1}{\lambda_1 - \lambda_2} \cdot N_{01} \right) e^{-\lambda_2 \cdot t}$$

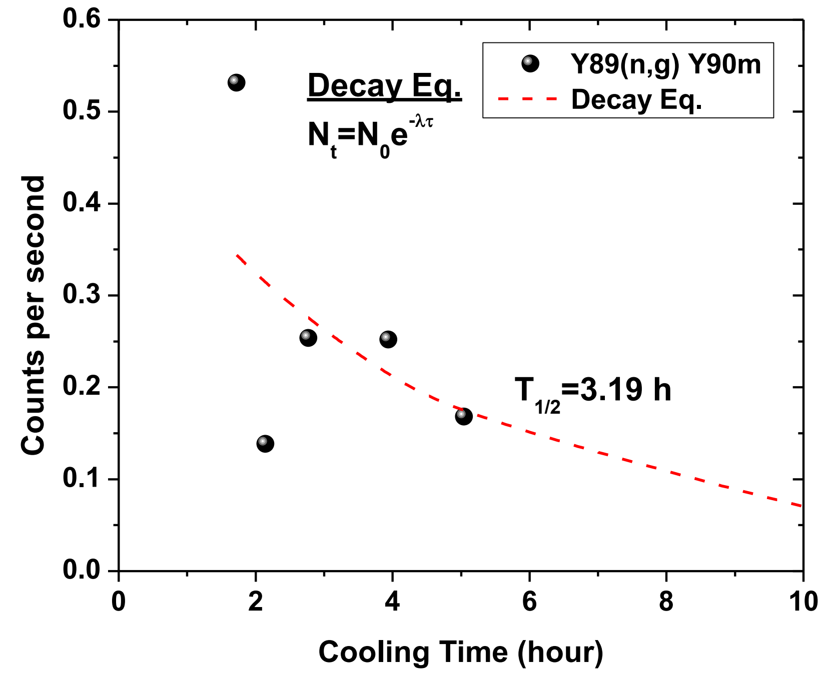




$^{89}Y(n, \gamma)^{90m}Y$ and $^{89}Y(n, \alpha)^{86}Rb$ Reactions

Reactions	Half-life	Spin-Jπ	E_γ (keV)	I_γ(%)	Decay mode	E_{th} (MeV)
$^{89}Y(n,g)Y^{90m}$	3.19 h	7^+	479.17	90.74	IT	No threshold
$^{89}Y(n,a)Rb^{86}$	18.63 d	2^-	1744.01	91.36	β^-	No threshold





Determination of ^{89}Y(n,xn) reaction Cross Section

Cross section formula based on gamma activity and irradiation data

Cross section

$$\langle \sigma \rangle = \frac{N_{obs}(CL/LT)\lambda}{n\phi_n\, I_\gamma\, \varepsilon \left(1-e^{-\lambda T_I}\right) e^{-\lambda T_C} \left(1-e^{-\lambda CL}\right)}$$

ϕ_n: From Aluminum Monitor

Integrated n's flux

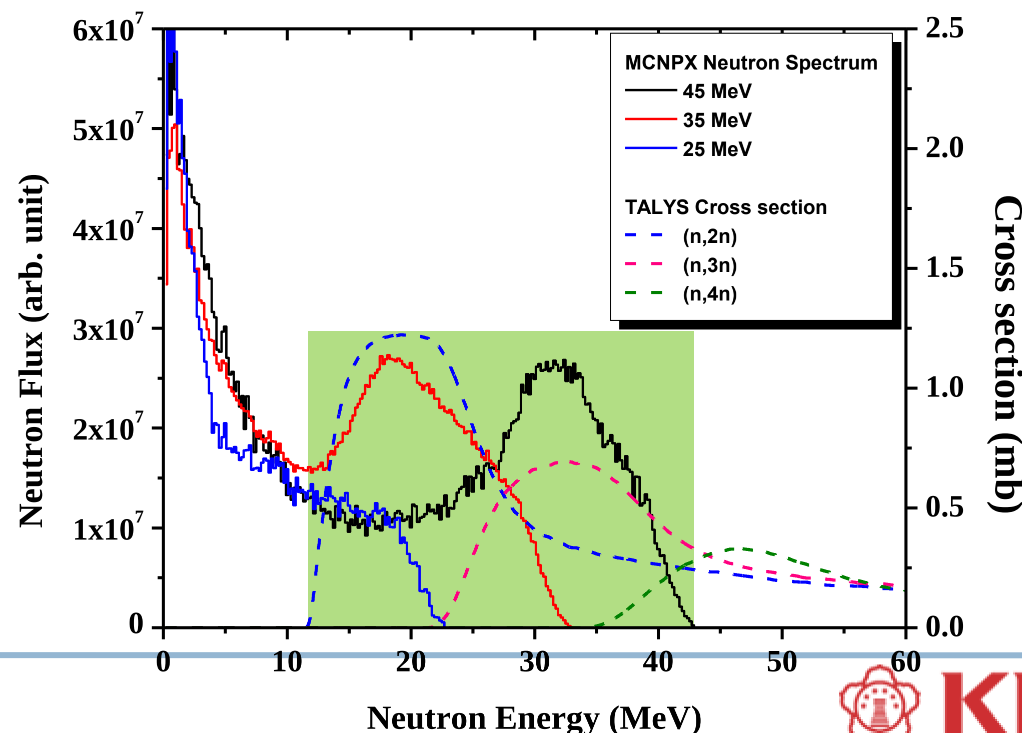
$$\phi_n \left(= \int_{E_{th}}^{E_{\max}} \phi(E_n)\, dE_n\right)$$

Average Energy

$$\langle E_n \rangle = \int_{E_{th}}^{E_{\max}} E_n \phi(E_n)\, dE_n \Big/ \int_{E_{th}}^{E_{\max}} \phi(E_n)\, dE_n$$

Theoretical Calculations Using TALYS

$$\langle \sigma \rangle = \frac{\int_{E_{th}}^{E_{\max}} \sigma(E_n)\phi(E_n)\, dE_n}{\int_{E_{th}}^{E_{\max}} \phi(E_n)\, dE_n}$$



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Uncertainties

The overall uncertainty is the quadratic sum of both statistical and systematic errors.

The statistical error in the observed activity due to counting statistics is estimated to be 5-10%, which can be determined by accumulating the data for an optimum time period that depends on the half-life of the nuclides of interest.

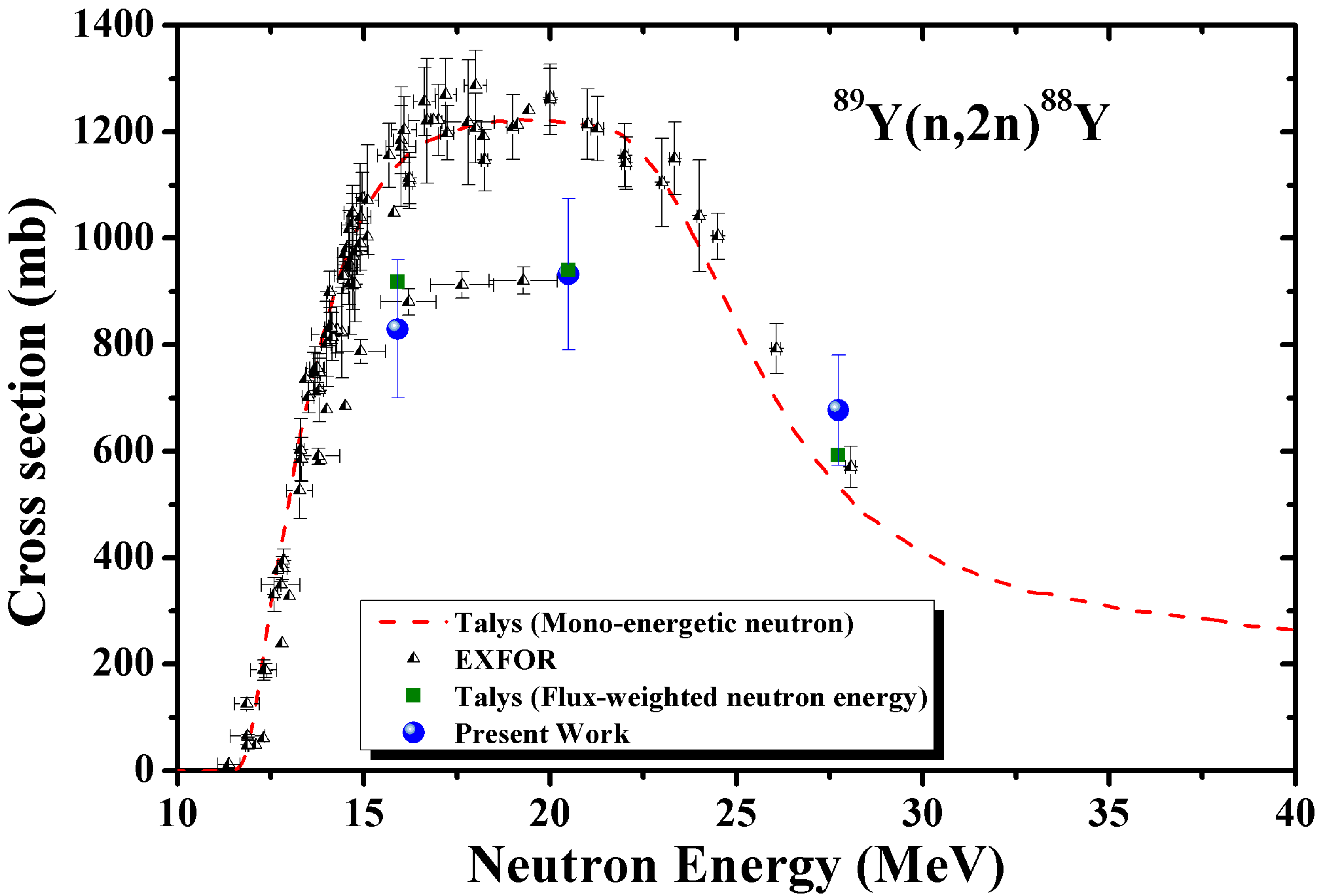
The systematic errors are due to uncertainties:

- Irradiation time (~0.5%)
- Detection efficiency calibration (~4%)
- Neutron flux (5-12%)
- Half-life of nuclides of interest (~2)
- γ-ray abundance (~1%)

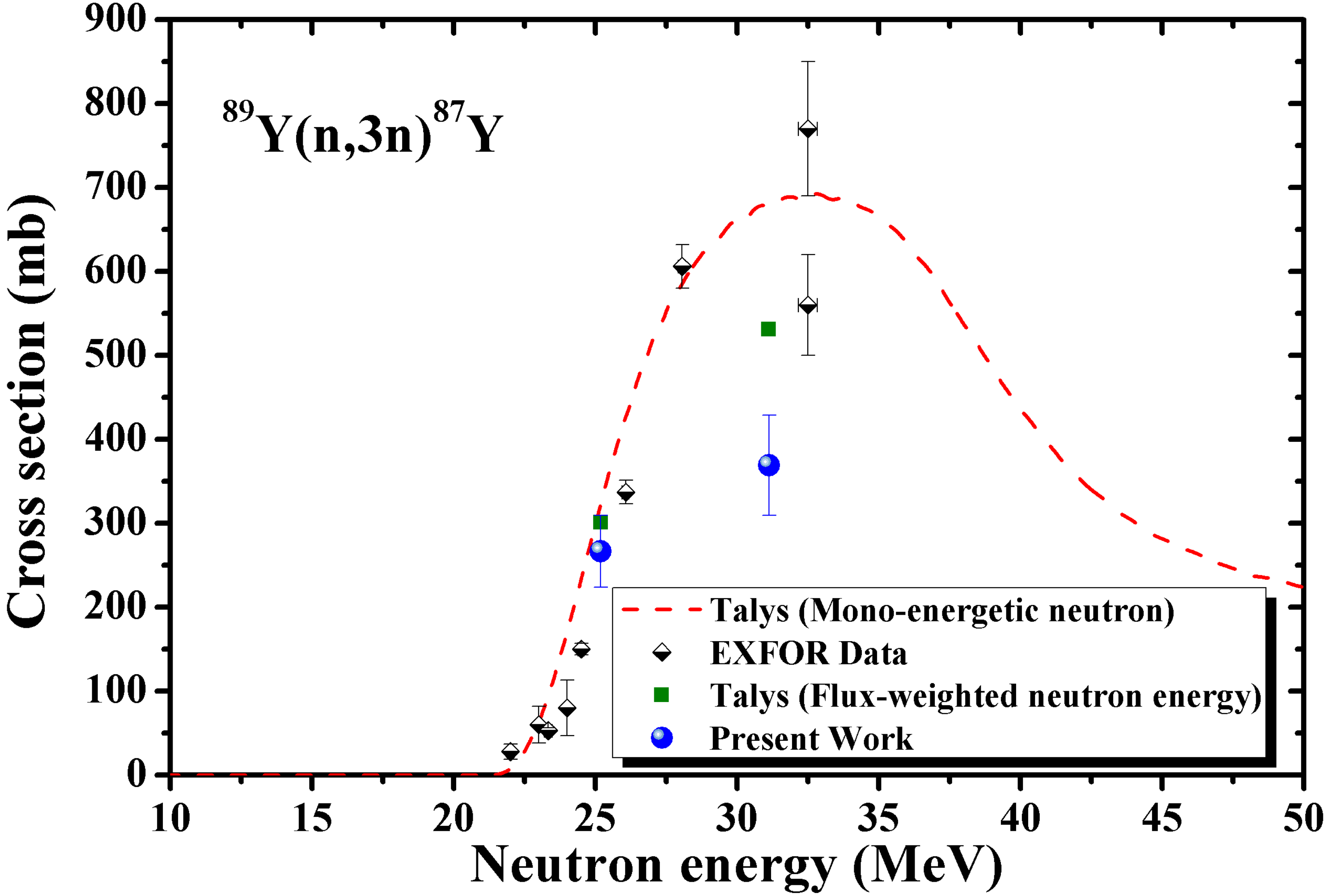
The total systematic error is about 7-13%

The overall uncertainties for the (n,xn) reaction cross sections are in between 8 and 16%.

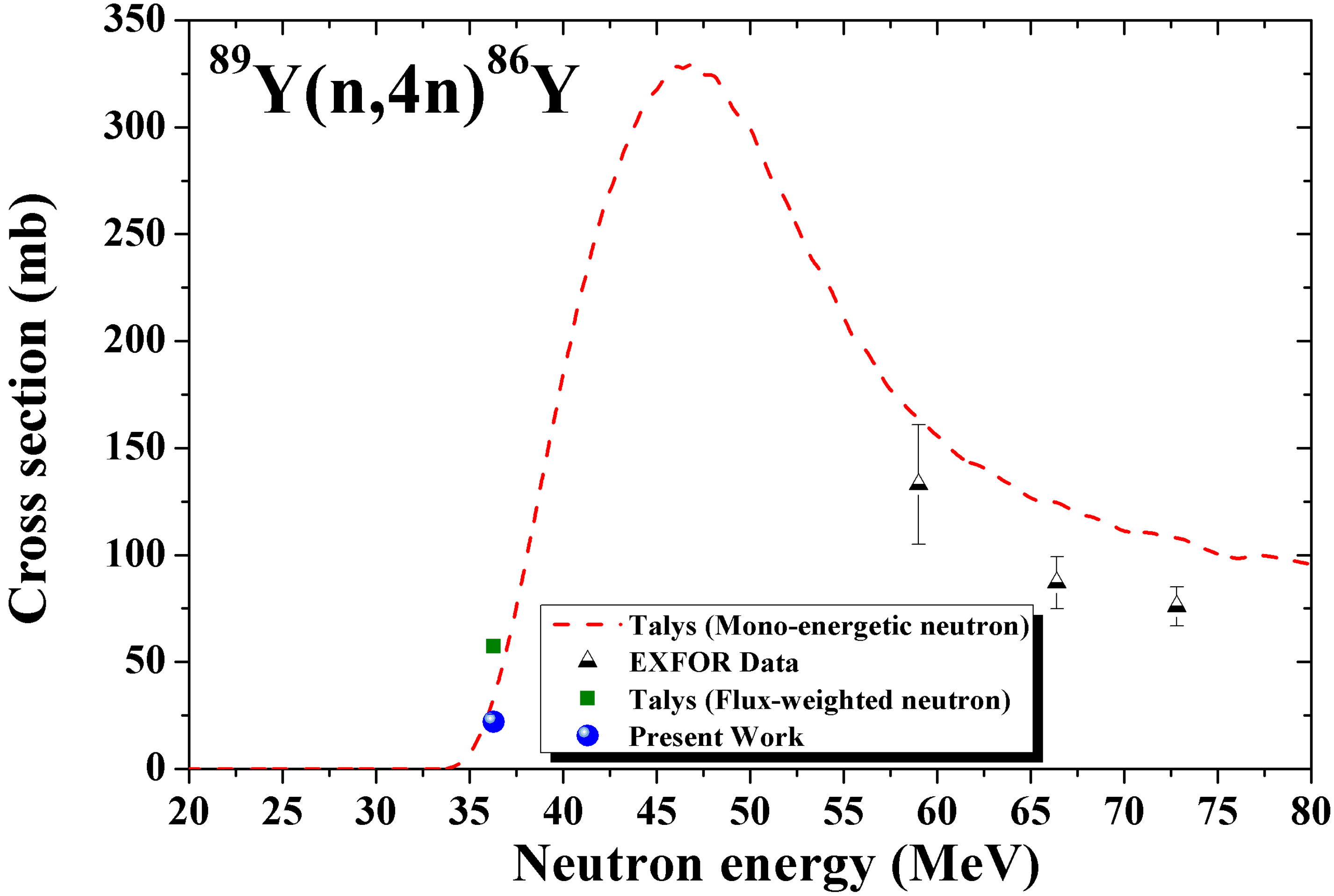
Cross sections for $^{89}Y(n,2n)^{88}Y$ reaction



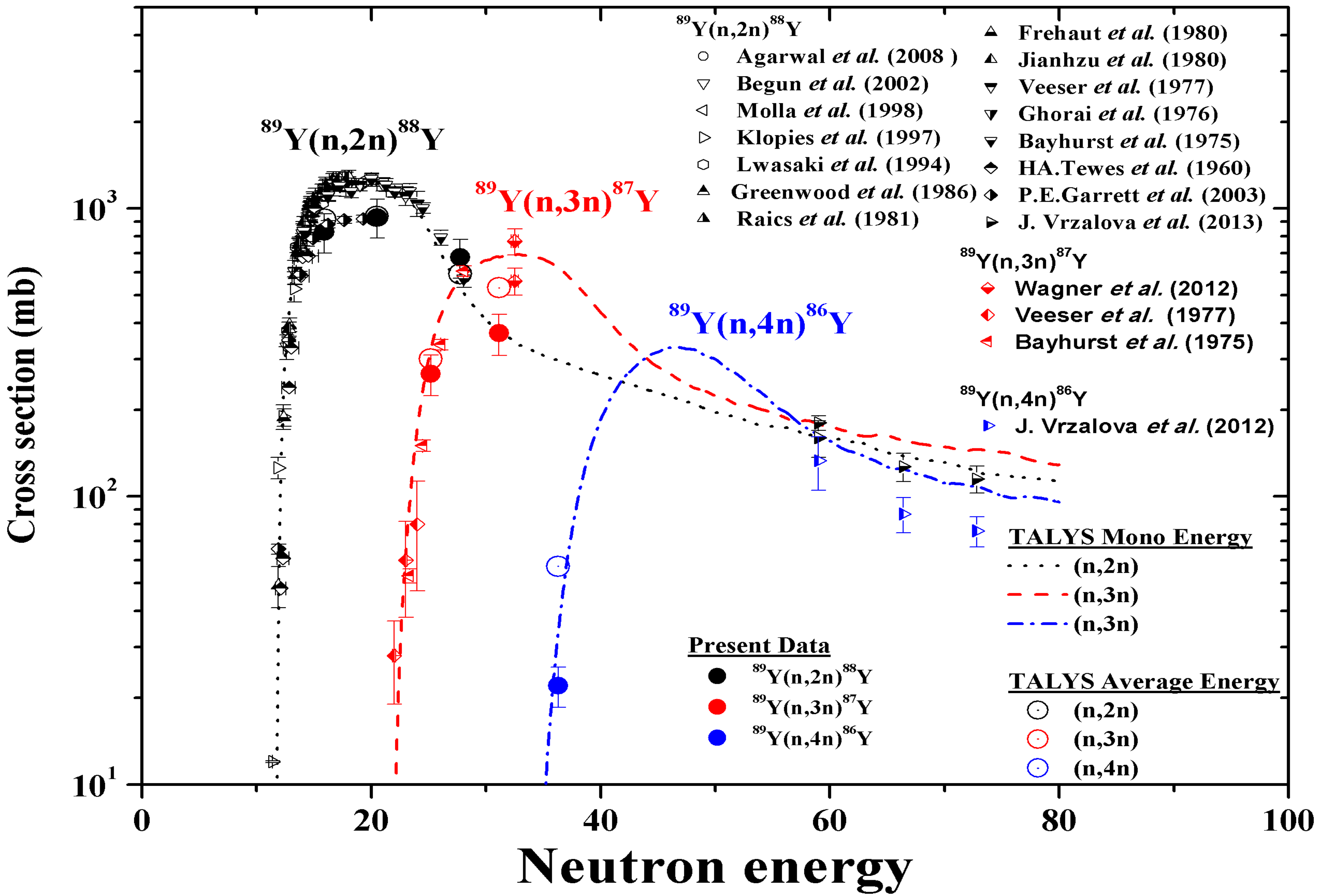
Cross sections of $^{89}Y(n,3n)^{87}Y$ reaction



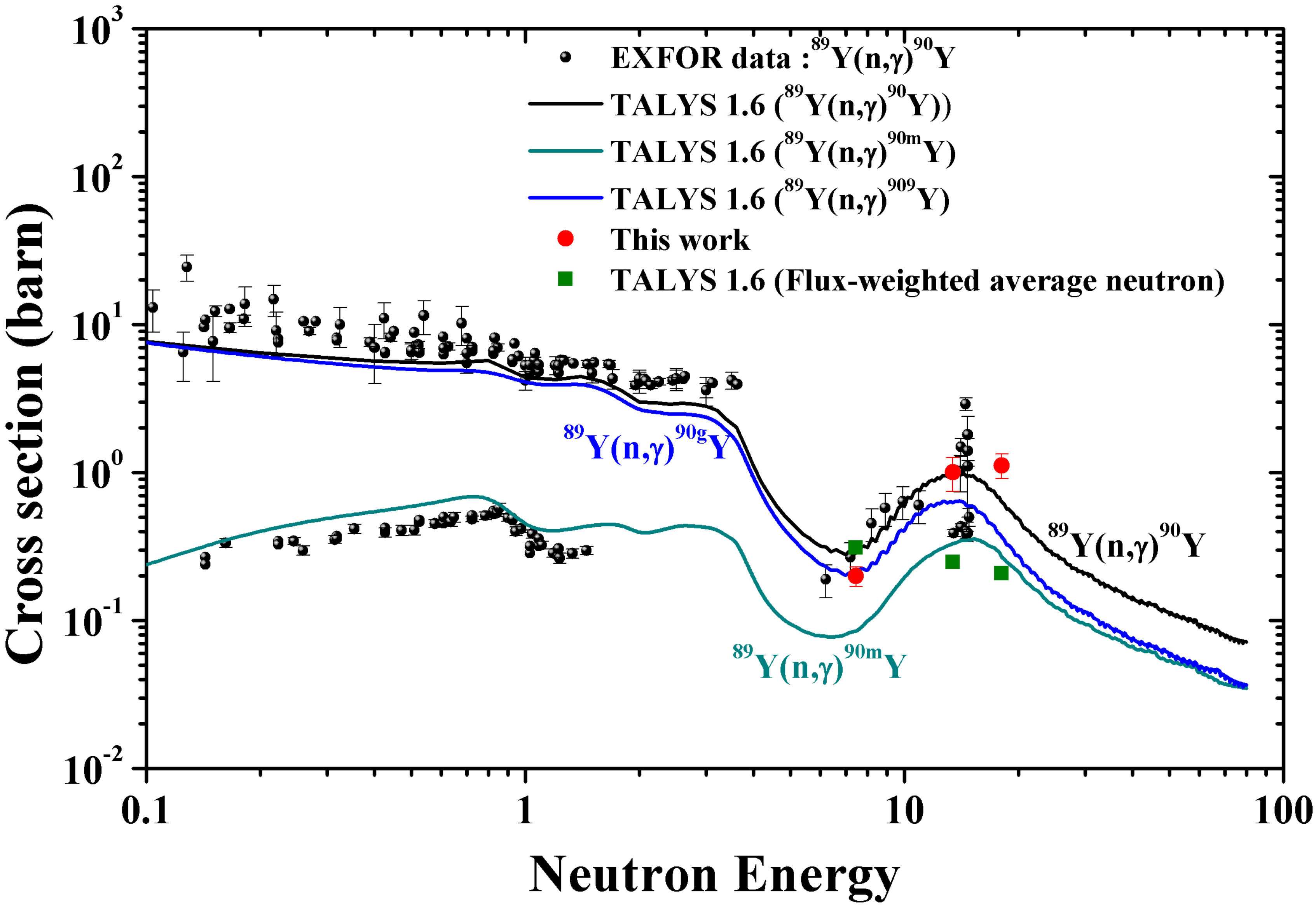
Cross sections of $^{89}Y(n,4n)^{86}Y$ reaction



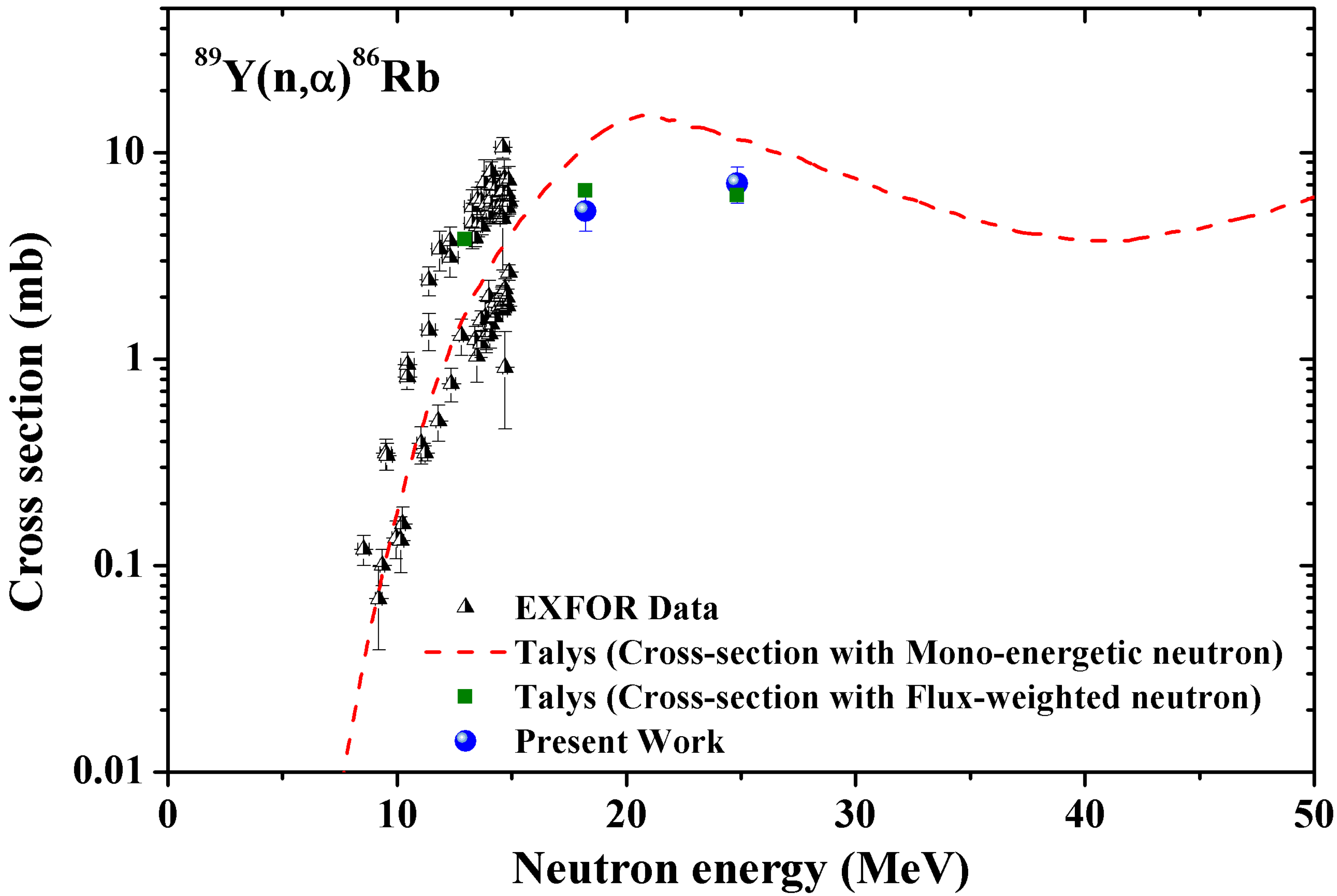
Cross sections of $^{89}Y(n,xn)^{88,87,86}Y$ reaction



Cross Sections of $^{89}Y(n,\gamma)^{90m}Y$ Reaction



Cross sections of $^{89}Y(n,\alpha)^{86}Rb$ Reaction



Conclusion

- The quasi-mono energetic neutron sources are good tool for neutron cross-sections measurements.
- The cross-sections of the $^{89}Y(n,xn,\ x=2\text{-}4)$, $^{89}Y(n,\gamma)Y^{90m}$, and $^{89}Y(n,\alpha)Rb^{86}$ reactions at the average neutron energies of 15.9, 20.5, 25.2, 27.7, 31.1, and 36.3 MeV have been determined using off-line γ-ray spectrometric technique.
- The present results are in general agreed with the flux-weighted values calculated by the TALYS 1.4 code and those obtained from literature data of the mono-energetic neutrons.
- The experimental and theoretical cross-sections of the $^{89}Y(n,xn,\ x=2\text{-}4)$ reactions increase sharply from the threshold to a certain energy, where the next reaction channel opens up. Then it remains constant up to the point, where the next reaction channel increases. Thereafter it slightly decreases due to the opening of higher reaction channels. These observations indicate the partition of excitation energy in different reaction channels.