Neutron beam filter system for fast neutron cross-section measurement at the ANNRI beamline of MLF/J-PARC

2021 Nuclear Data Section Encouragement Award

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Accuracy improvement of nuclear data for MAs

Recent research trends are focused on the development of **Transmutation Facilities** for the treatment of **Nuclear Waste**. Convert the long-term component of Nuclear Waste (**Minor Actinides**) into **stable nuclei**.

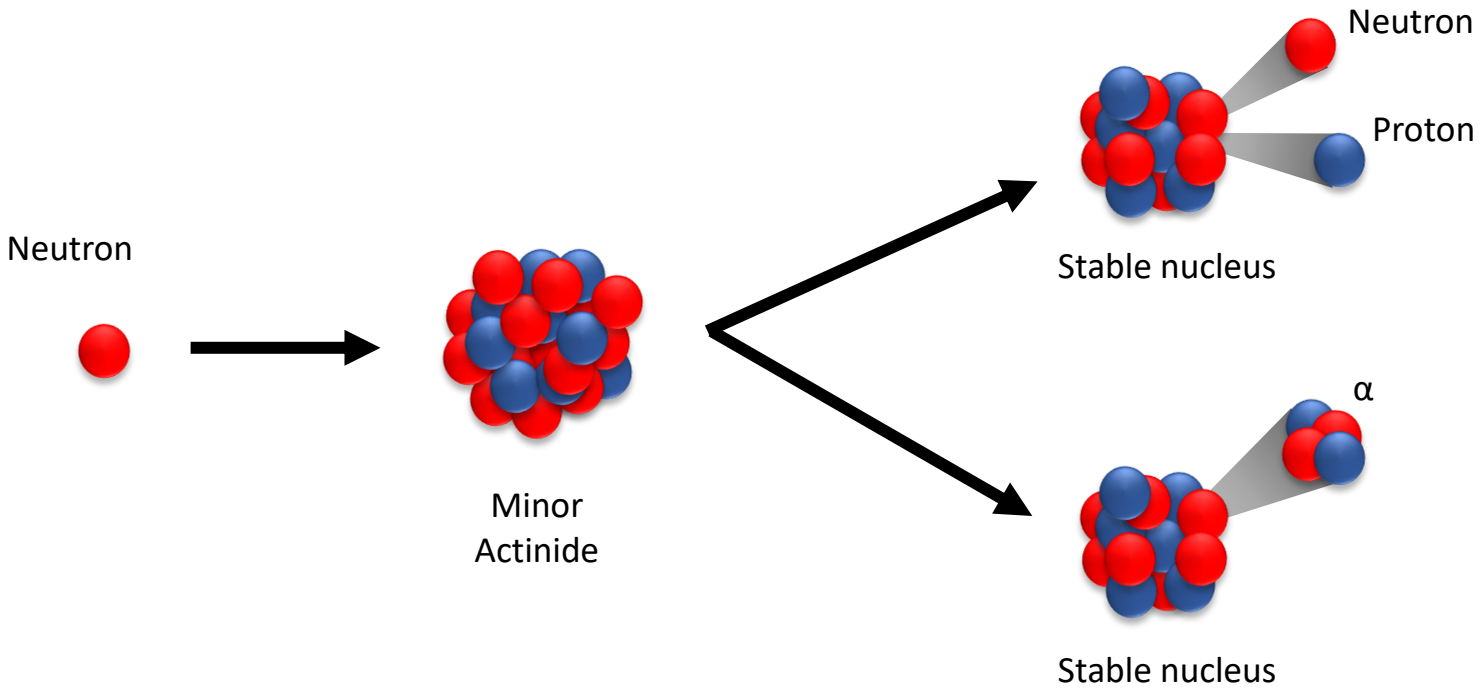


Fig. 1 Diagram of the nuclear transmutation process for minor actinides.

Accuracy improvement of nuclear data for MAs

Minor Actinides are usually **unstable radionuclides**, hence, it is **difficult** to measure nuclear reaction probabilities for such nuclei.

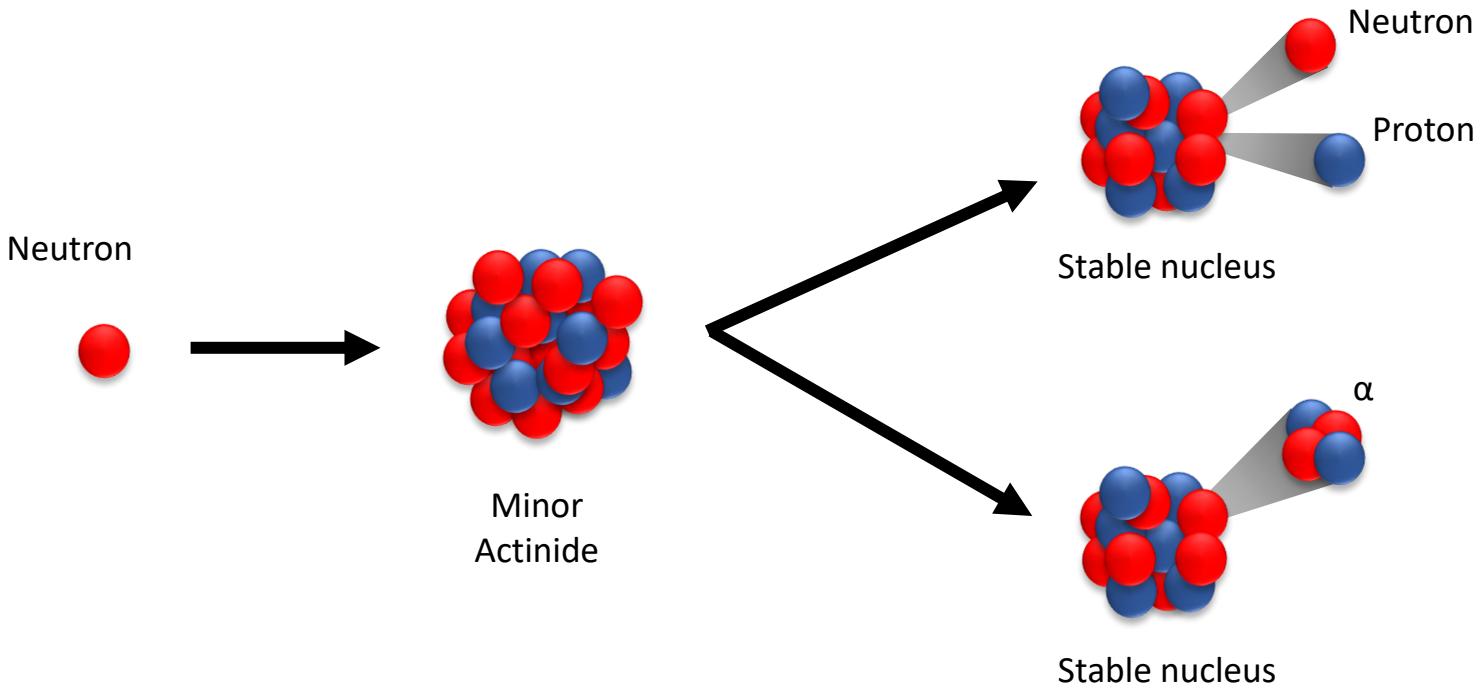


Fig. 1 Diagram of the nuclear transmutation process for minor actinides.

Accuracy improvement of nuclear data for MAs

Accelerator-Driven System (ADS) is a proposed sub-critical facility to perform the **nuclear transmutations** of **MAs**

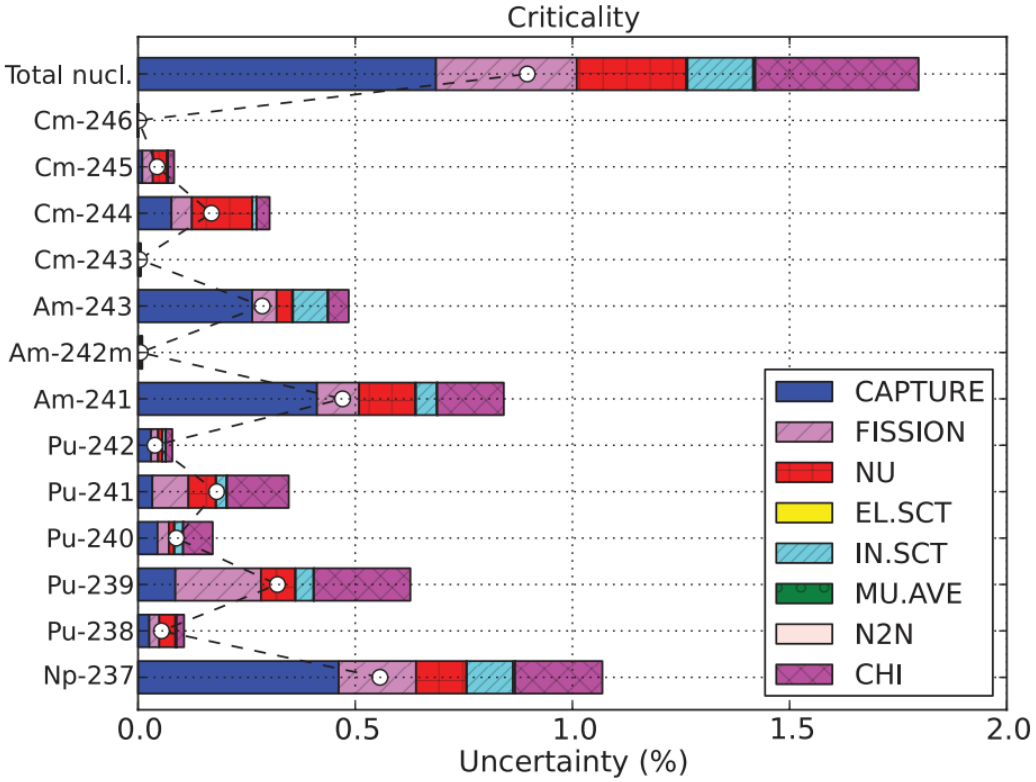


Fig. 2 Uncertainties by reaction and nuclide of ADS criticality*

*H.Iwamoto et al. J. Nucl Sci. Technol., 2013; 50(8):856-862.

- Although achieved through **fission**, **other reaction channels** also need to be considered
- **Accurate data** for the **neutron capture cross section** of **MAs** is important for the **ADS** design
- **Improvement** required for **keV-neutron** data

Accuracy improvement of nuclear data for MAs

An accuracy improvement of the current **nuclear data** for the **neutron capture cross section of MAs** in the **keV-region** is needed.

More accurate experiments for
Minor Actinides are required

Accura MAs

Experiments with **keV-neutrons** at **ANNRI** are currently **impractical** due to the **double-bunch** structure of the neutron beam

An accura **neutron capture cross section of MAs** in the **keV-region** is needed.

The **double-bunch** problem in the ANNRI beamline has to be **resolved** in order to perform further accurate neutron capture experiments with **keV-neutrons**

More accurate experiments for

“Study on accuracy improvement of fast-neutron capture reaction data of long-lived MAs for development of nuclear transmutation systems” project

Project Overview

Joint collaboration project by **JAEA**, **Tokyo Tech** and **Kyoto Univ.**

Focused on improving the accuracy of **nuclear data** for minor actinides in the **keV** region for **^{237}Np**, **^{241}Am** and **^{243}Am**

Divided in 4 parts:

- Neutron Beam Filter Develop.
  - JAEA
- Sample Characteristic Assay
  - Kyoto Univ.
- Neutron Capture Measurement
  - Tokyo Tech
  - **^{237}Np**, **^{241}Am** and **^{243}Am**
- Theoretical Reaction Model Study
  - JAEA

MLF Facility

In the MLF facility, **pulsed neutrons** are generated by **pulsed protons shot** to a **Hg** target via **spallation reactions.** In previous years, the **J-PARC** accelerator was operated in **single bunch mode**.

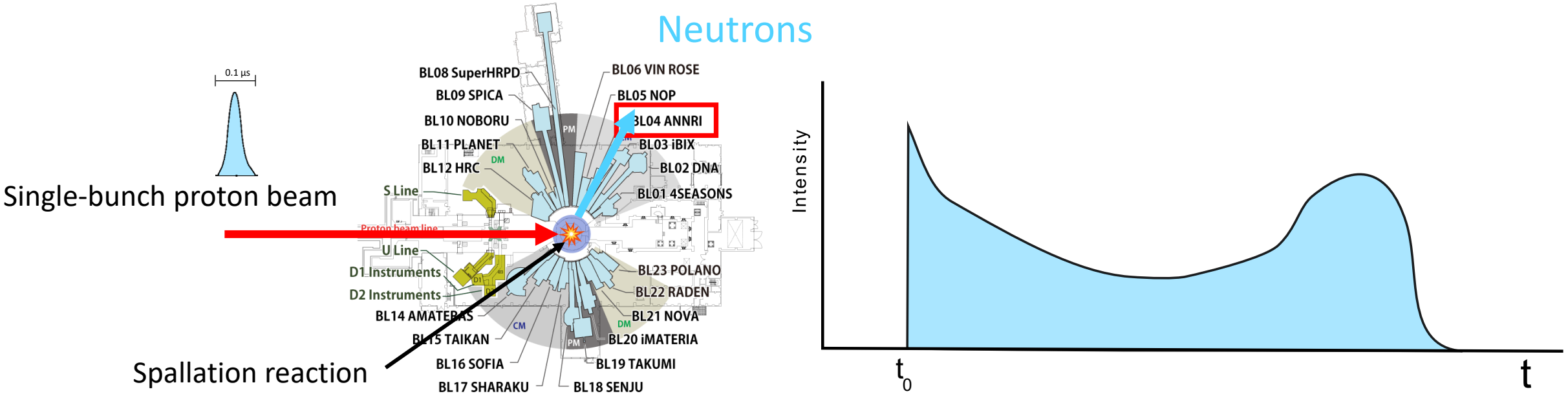


Fig. 3 Schematic of the MLF facility and the single-bunch neutron generation process.
*https://mlfinfo.jp/ja/blmap.html

Double-bunch mode of J-PARC

Recently, the **J-PARC** accelerator was switched onto **double-bunch mode** where two proton bunches are shot with a time difference of **0.6 μs** to generate neutrons every 40 ms (25 Hz).

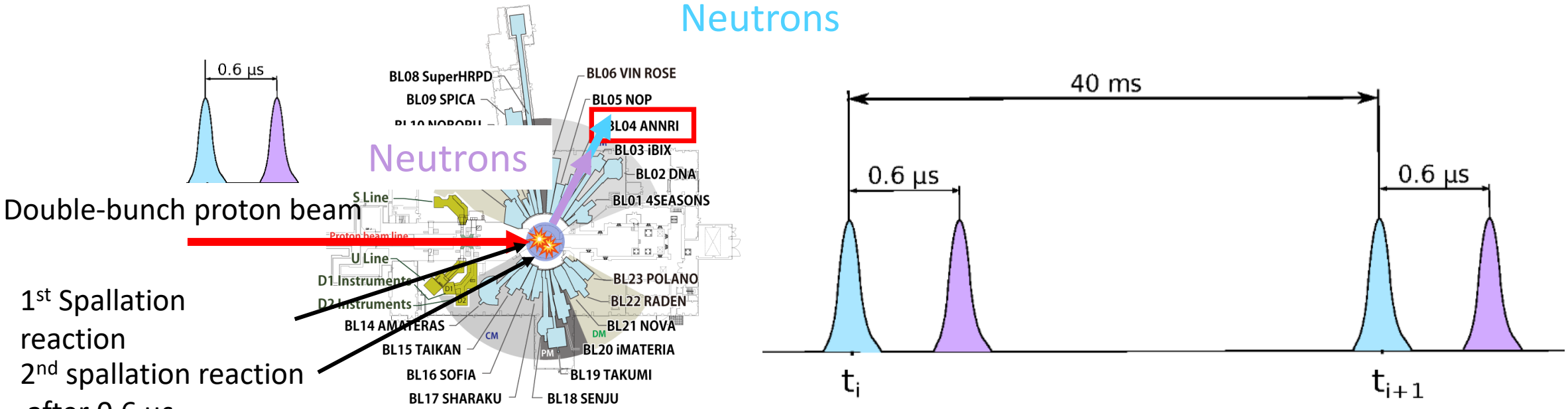


Fig. 4 Schematic of the MLF facility and the double-bunch neutron generation process.
*https://mlfinfo.jp/ja/blmap.html

Double-bunch mode of J-PARC

In time-of-flight (TOF) experiments, the energy of the neutrons is determined from **timing measurements**.

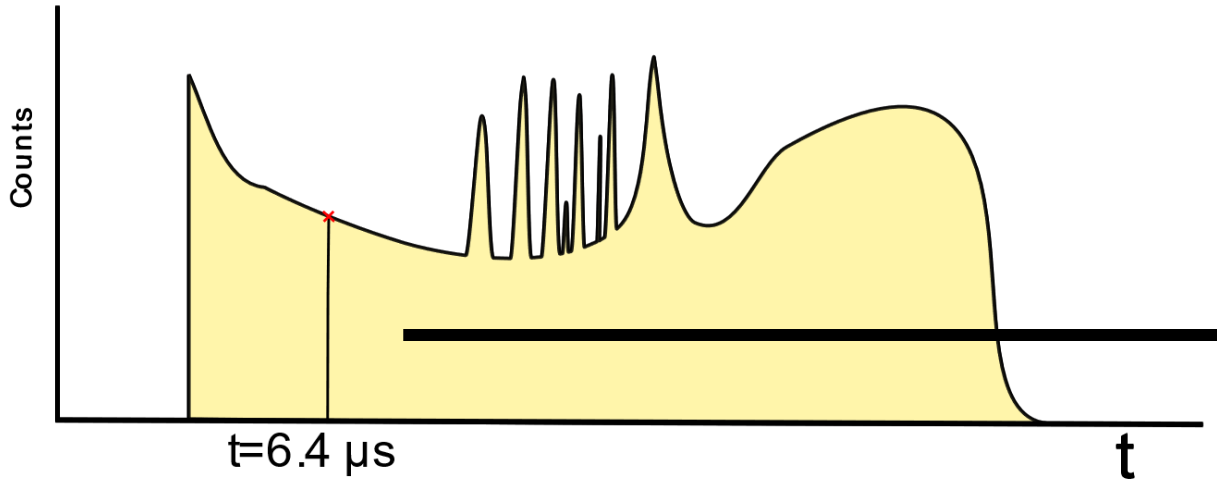


Fig. 5 Example of raw events detected in a capture experiment at ANNRI with the NaI(Tl) spectrometer in single-bunch mode

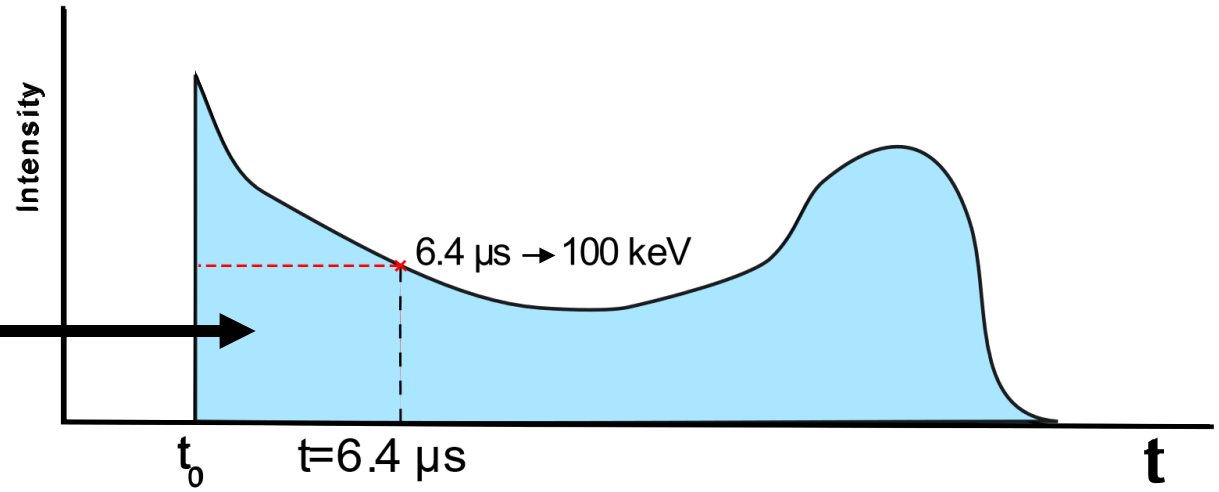


Fig. 6 Schematic of the neutron flux generated in the single-bunch mode

Double-bunch mode of J-PARC

In time-of-flight (TOF) experiments, the energy of the neutrons is determined from **timing** **ities** for **keV-neutrons** in **d**

It is **impossible** to determine the **originating proton pulse** of the detected neutron events for **keV neutrons**

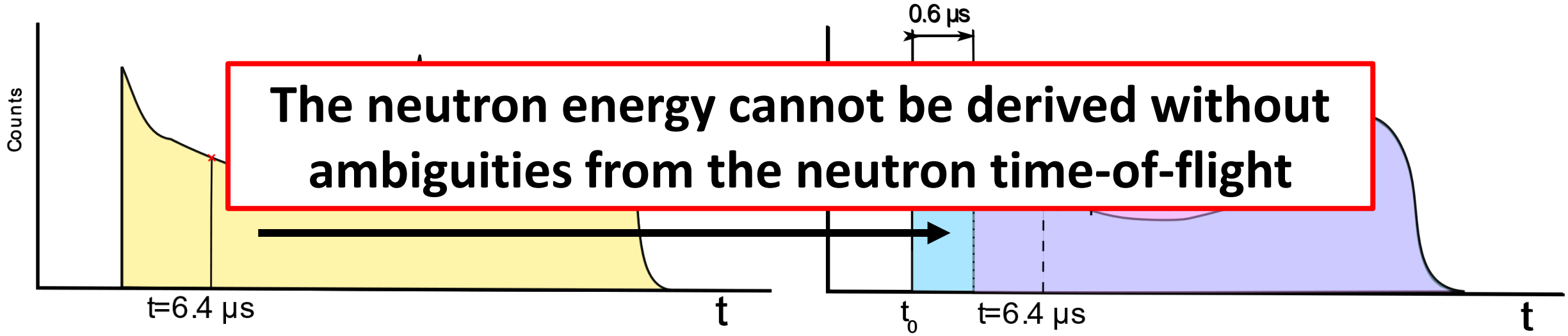
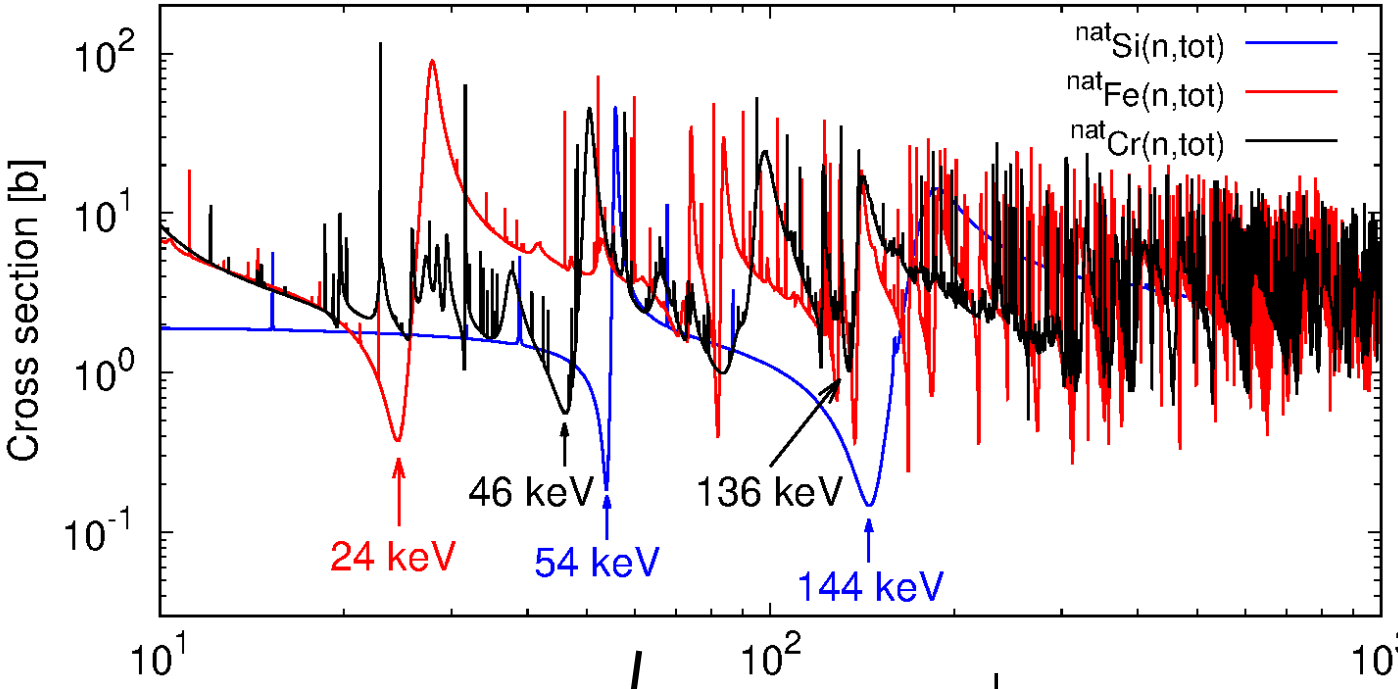


Fig. 7 Example of raw events detected in a capture experiment at ANNRI with the NaI(Tl) spectrometer in double-bunch mode

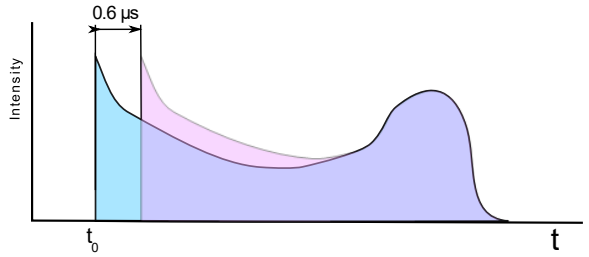
Fig. 8 Schematic of the neutron flux generated in the double-bunch mode. For example, events detected with time-of-flight (t=6.4 μs) can have two different neutron energies of 100 or 120 keV depending on the originating proton pulse.

Neutron

The **Neutron** double-bunch **reactors**. Qua that present a



he effects of the pplied to **nuclear** d using materials tion.



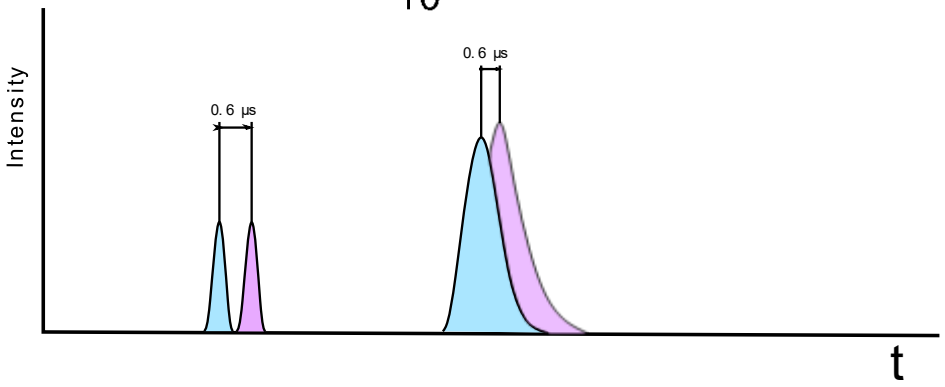


Fig. 9 Neutrons with the energy of the **sharp minimum** of the filter material can **pass through** to create **quasi-monoenergetic neutron peaks**

Neutron Filtering System Setup

Filter materials (Fe, Si and Cr) were introduced in the **rotary collimator** of the ANNRI beamline. Configurations of **20 cm** of **Fe** and **Si**; **15 cm** of **Cr** were tested.

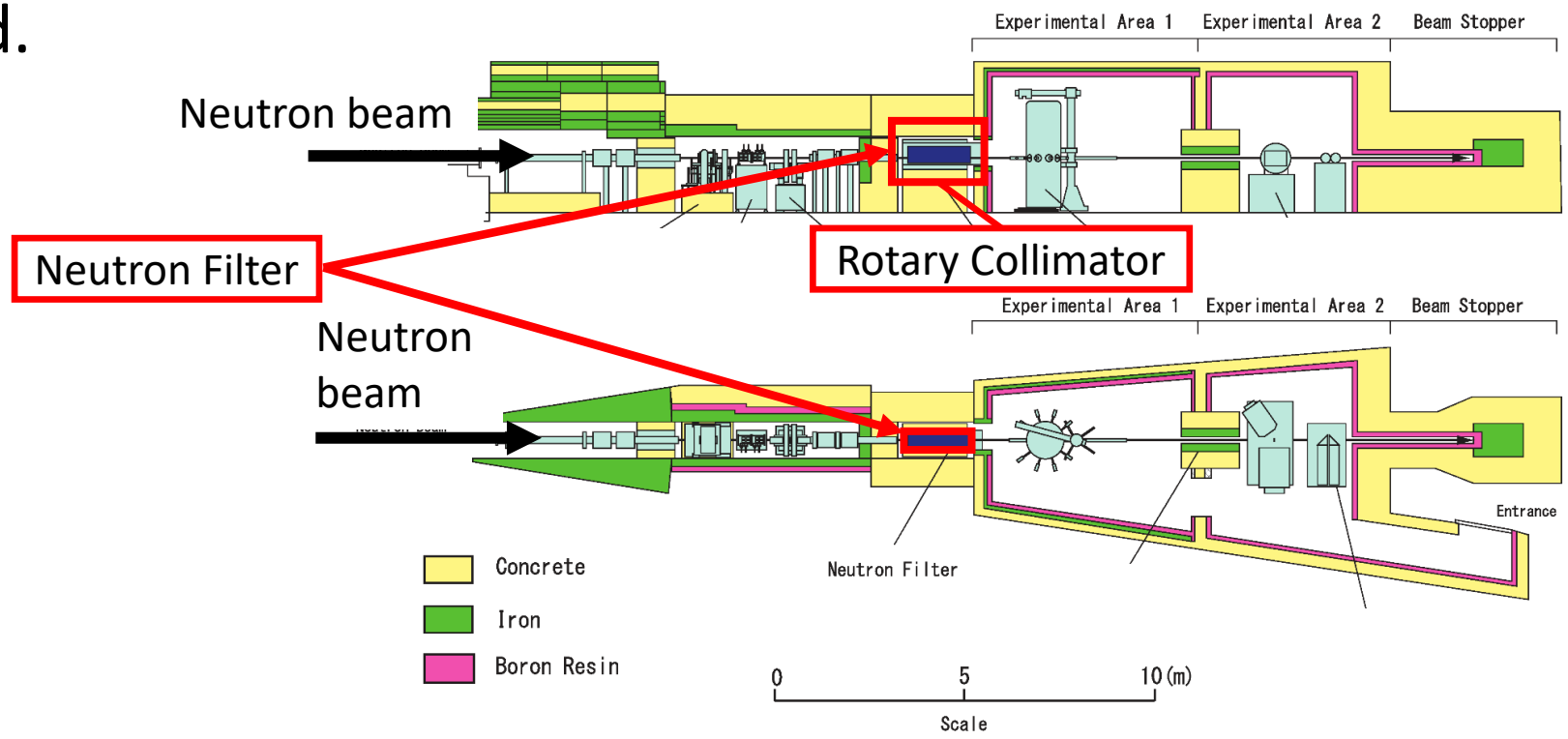


Fig. 10 Overview of the **ANNRI** beamline. The **filter material** was inserted into the **rotary collimator**.

Experimental Setup

The time distribution of the filtered neutron flux was obtained by using both **Li-glass detectors** and a **NaI(Tl) spectrometer**. **Standard Au neutron capture cross-section** measurement to assess the **filter performance**.

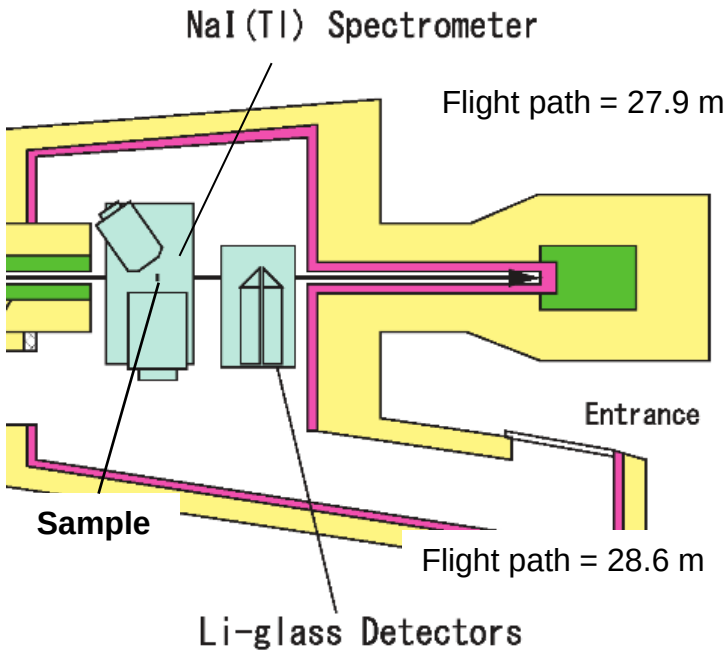


Fig. 11 Overview of the **NaI(Tl) spectrometer** and **Li-glass detectors** in the ANNRI beamline.

FILTERED NEUTRON FLUX DETERMINATION

NaI(Tl) spectrometer

- **Boron sample**
- **$^{10}B(n,\alpha\gamma)^{7}Li$** reaction

Li-glass detectors

- Direct neutron flux measurement

PERFORMANCE ASSESSMENT IN CAPTURE EXPERIMENTS

NaI(Tl) spectrometer

- **Au sample**
- Neutron capture **γ-ray** measurement
- **Au neutron capture cross-section** used as **standard cross-section** for verification. It has been **measured extensively** in the past and its evaluated (JENDL-4.0) results are deemed **highly reliable**.

Experimental Results

The **neutron flux** derived from experiments with **Li-glass detectors** and a **NaI(Tl) spectrometer** present **very good agreement**. The difference in time is due to the different detector position.

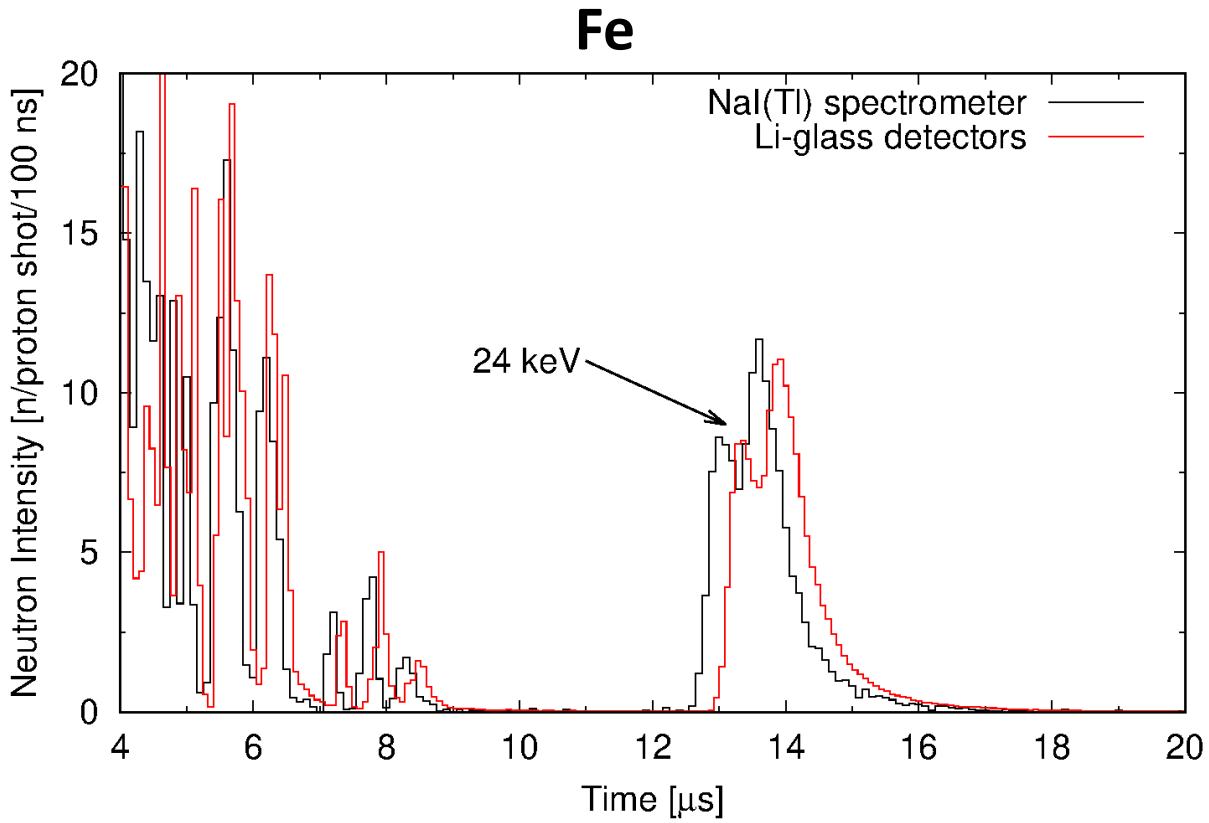


Fig. 12 Filtered neutron beam through **20 cm of Fe** measured by **Li-glass detectors** and a **NaI(Tl) spectrometer**

Experimental Results

The **neutron flux** derived from experiments with **Li-glass detectors** and a **NaI(Tl) spectrometer** present **very good agreement**. The difference in time is due to the different detector position.

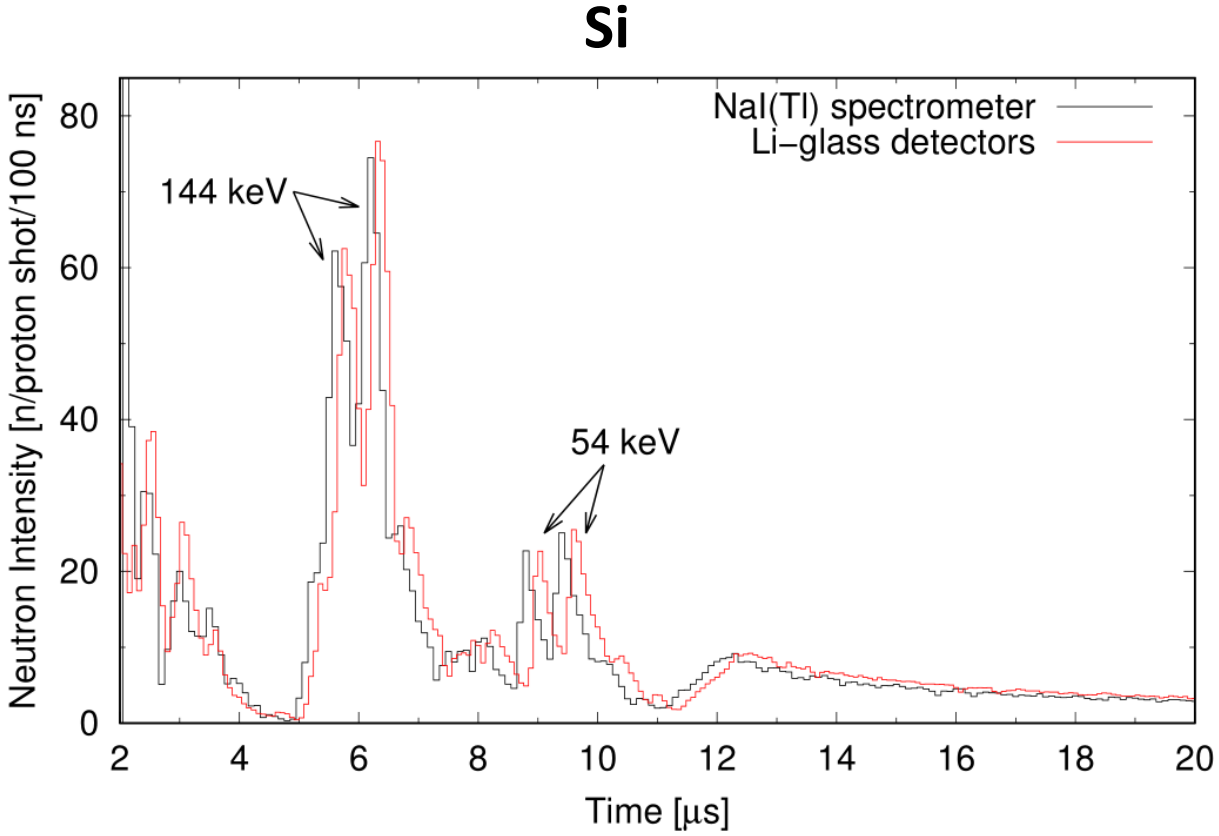
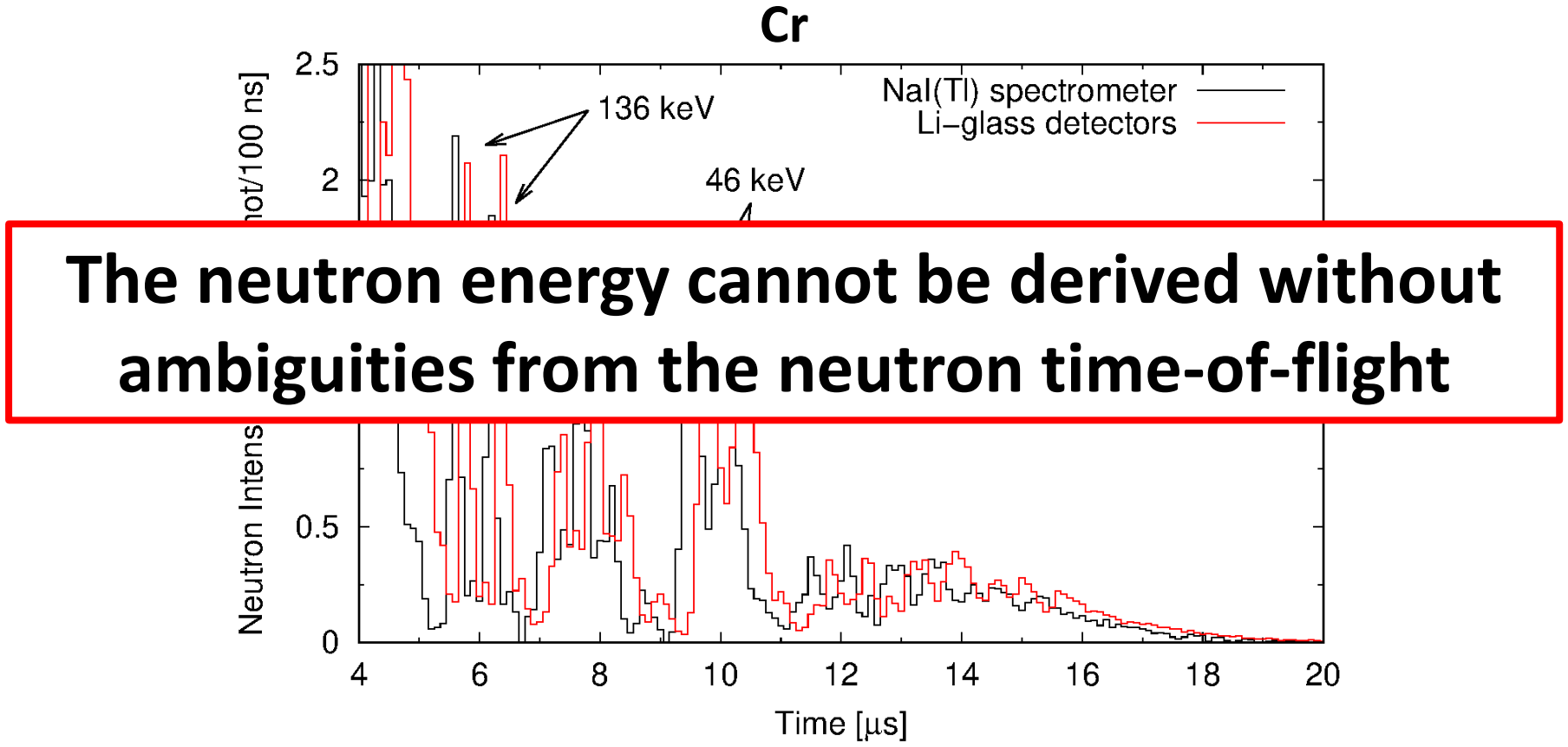


Fig. 13 Filtered neutron beam through **20 cm of Si** measured by **Li-glass detectors** and a **NaI(Tl) spectrometer**

Experimental Results

The peaks at the energies of **24, 46, 54, 136 and 144 keV** are clearly **isolated**. **Time** to **energy** conversion is presents **ambiguities.**



The neutron energy cannot be derived without ambiguities from the neutron time-of-flight

Fig. 14 Filtered neutron beam through **15 cm of Cr** measured by **Li-glass detectors** and a **NaI(Tl) spectrometer**

Monte-Carlo Simulation

The **neutron energy distribution** within the filtered peaks can be derived through Monte-Carlo simulations with **PHITS**, unfolded with the **resolution function** of the ANNRI beamline

Experimental results were **simulated** for the filter materials (**Fe, Si** and **Cr**)

In PHITS, **simultaneous** calculations of neutron time and energy are performed

The simulation **precision** was evaluated by comparing the **simulated** neutron time distribution to the **experimental** neutron time distribution for each filter

Monte-Carlo Simulation

Two-dimensional results for the neutron **time** and **energy** distributions were obtained with **PHITS**. Simulation results were assessed by comparing the **simulated** neutron time distribution with the **experimental** results.

Fe

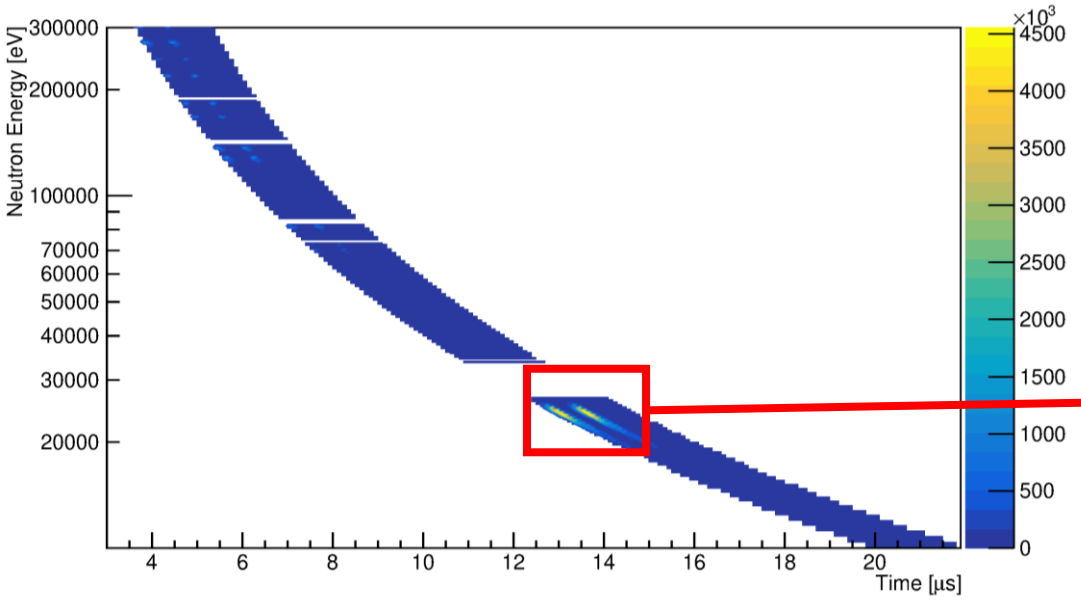


Fig. 15 Two-dimensional simulation results with **20 cm of Fe**

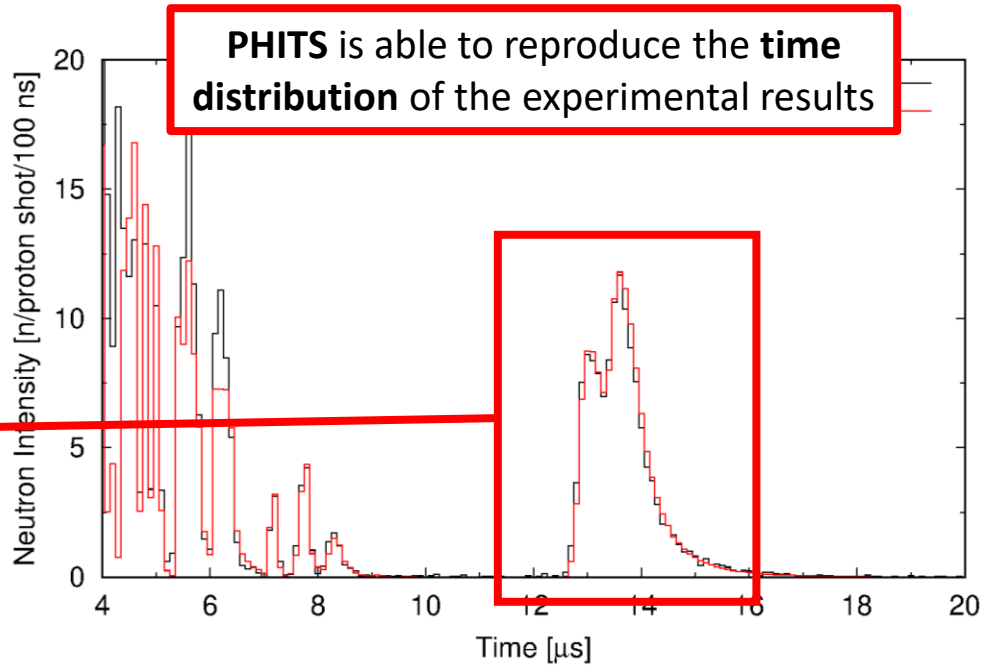
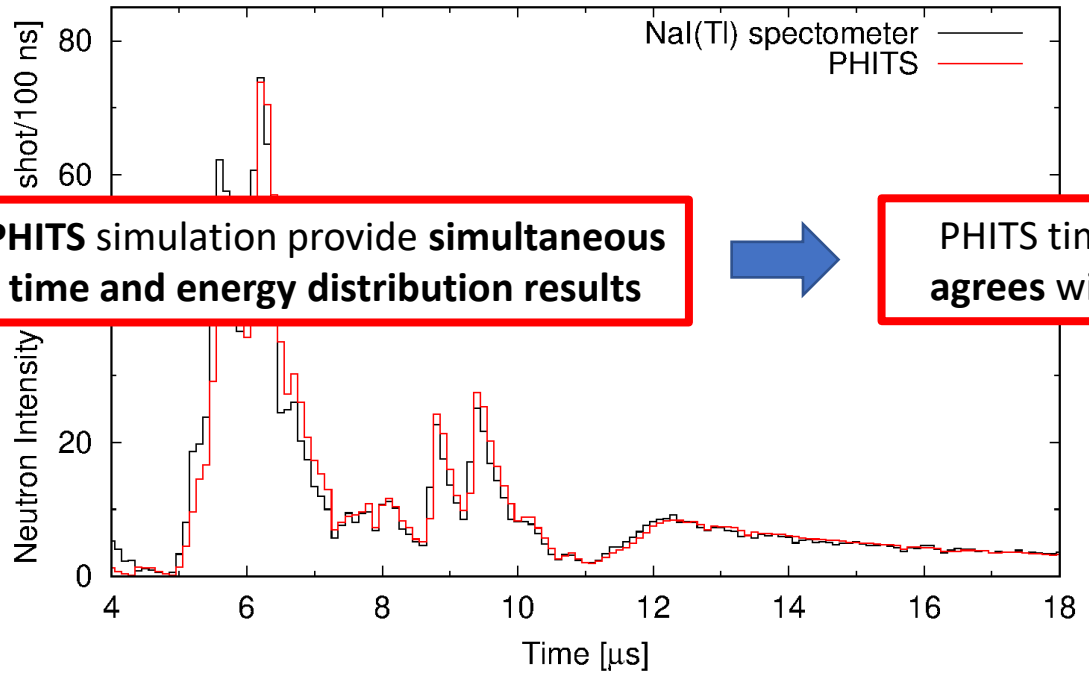


Fig. 16 Time distribution simulation results with **20 cm of Fe** compared to experimental results.

Monte-Carlo Simulation

Two-dimensional results for the neutron **time** and **energy** distributions were obtained with **PHITS**. Simulation results were assessed by comparing the **simulated** neutron time distribution with the **experimental** results.

Si

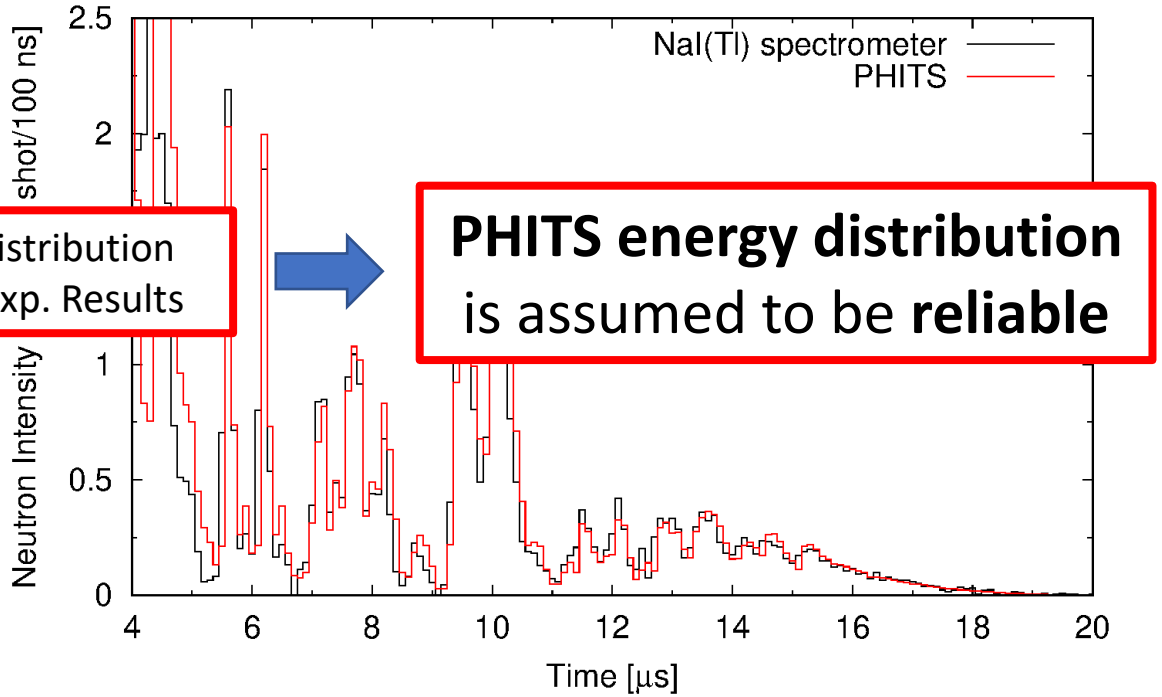


PHITS simulation provide **simultaneous time and energy distribution results**

PHITS time distribution **agrees** with Exp. Results

Fig. 17 Time distribution simulation results with **20 cm of Si** compared to experimental results.

Cr



PHITS energy distribution is assumed to be **reliable**

Fig. 18 Time distribution simulation results with **15 cm of Cr** compared to experimental results.

Monte-Carlo Simulation – Energy distribution

Only **events** from the **gated areas** were analyzed to obtain the **neutron energy distribution** at the peak position without the influence neutrons filtered at other energies.

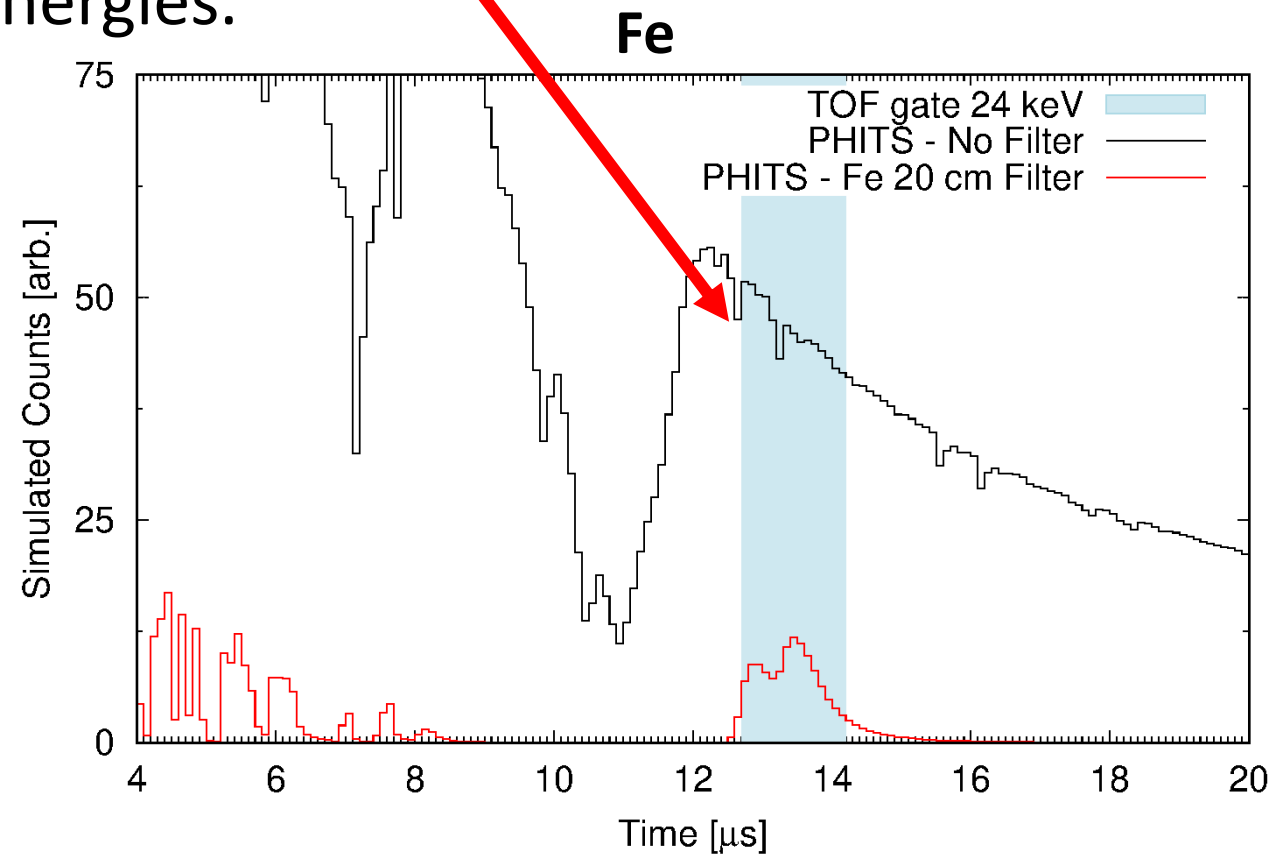


Fig. 19 TOF gate to wrap the **24 keV** filtered neutron peak with the **Fe filter**

Monte-Carlo Simulation – Energy distribution

Only **events** from the **gated areas** were analyzed to obtain the **neutron energy distribution** at the peak position without the influence neutrons filtered at other energies.

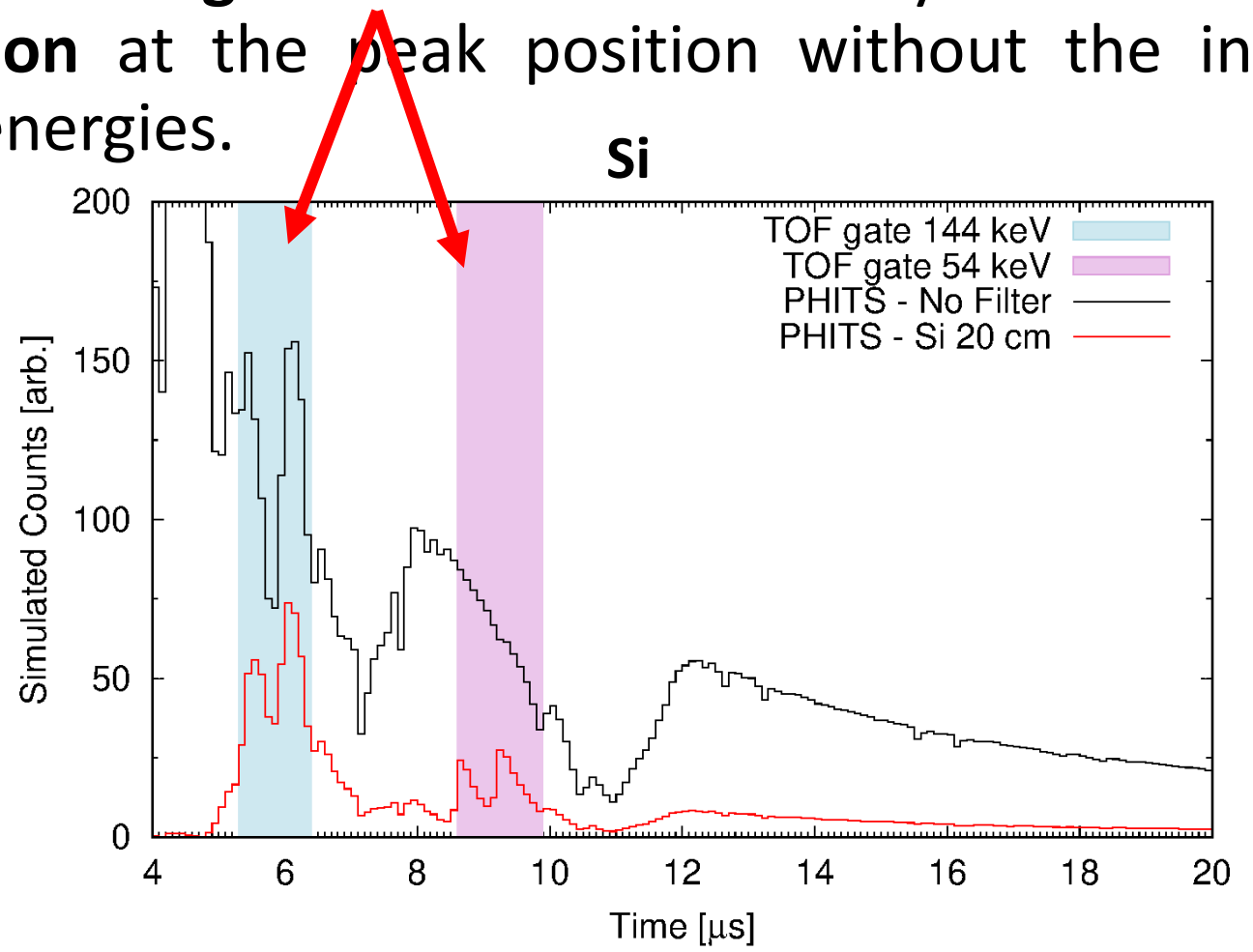


Fig. 20 TOF gates to wrap the **54 and 144 keV** filtered neutron peaks with the **Si filter**

Monte-Carlo Simulation – Energy distribution

Only **events** from the **gated areas** were analyzed to obtain the **neutron energy distribution** at the peak position without the influence neutrons filtered at other energies.

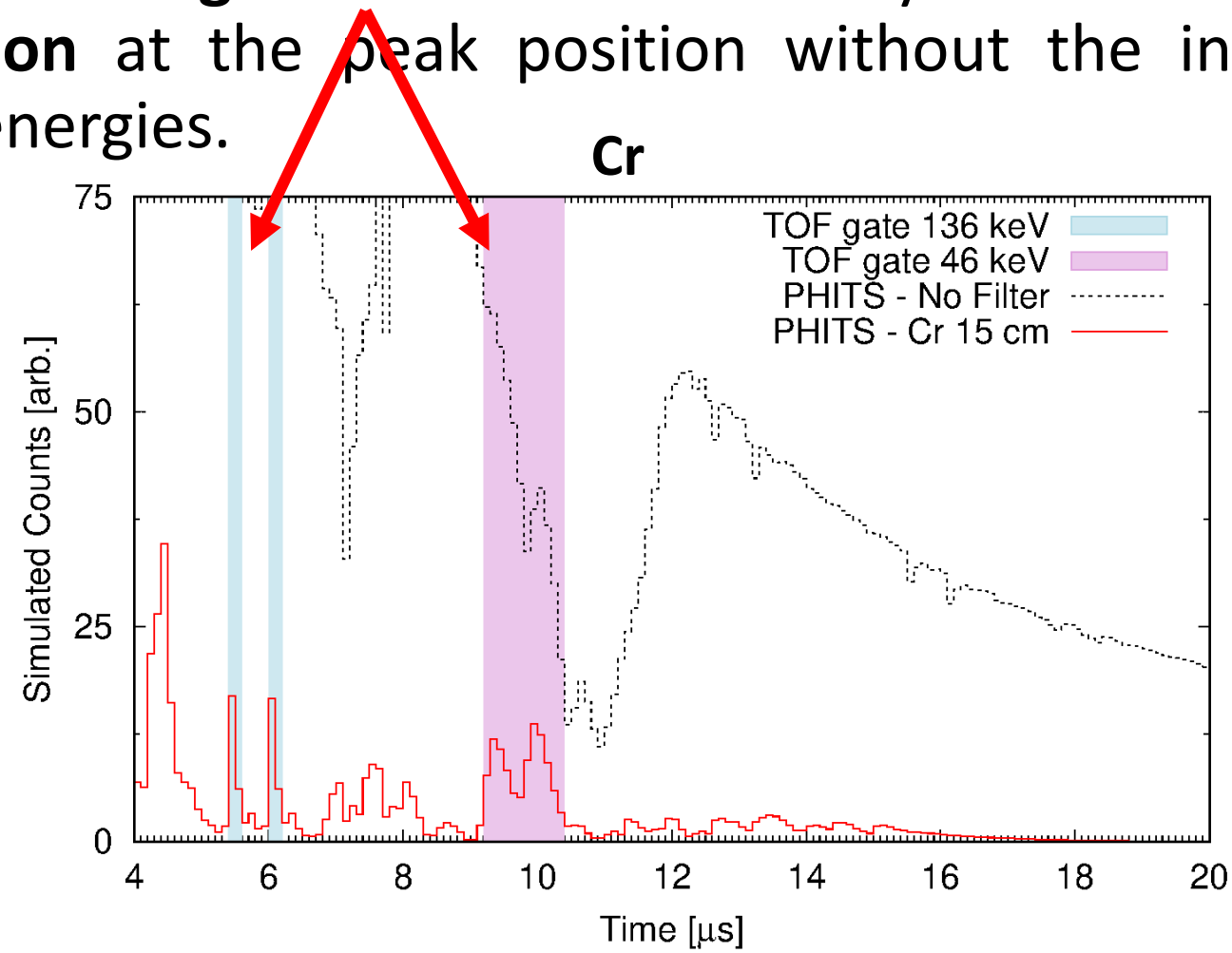


Fig. 21 TOF gates to wrap the **46 and 136 keV** filtered neutron peaks with the **Cr filter**

Monte-Carlo Simulation – Energy distribution

The **neutron energy distribution** was obtained by gating the PHITS results at each filtered peak.

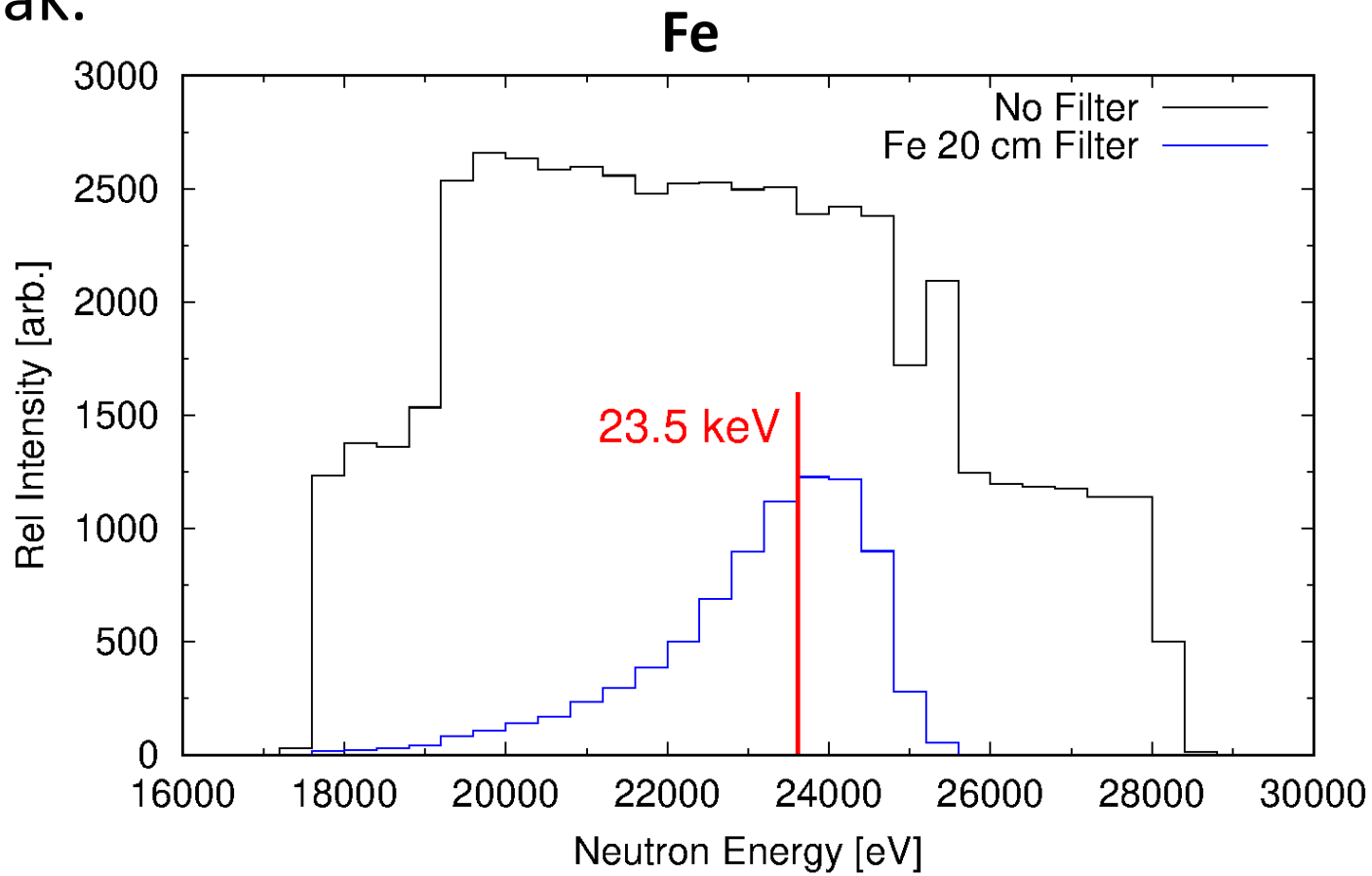


Fig. 22 **Energy distribution** of the **filtered neutron beam (blue)** and its **energy centroid (red)** compared to the **energy distribution without filter (black)**

Monte-Carlo Simulation – Energy distribution

The **neutron energy distribution** was obtained by gating the PHITS results at each filtered peak

Si

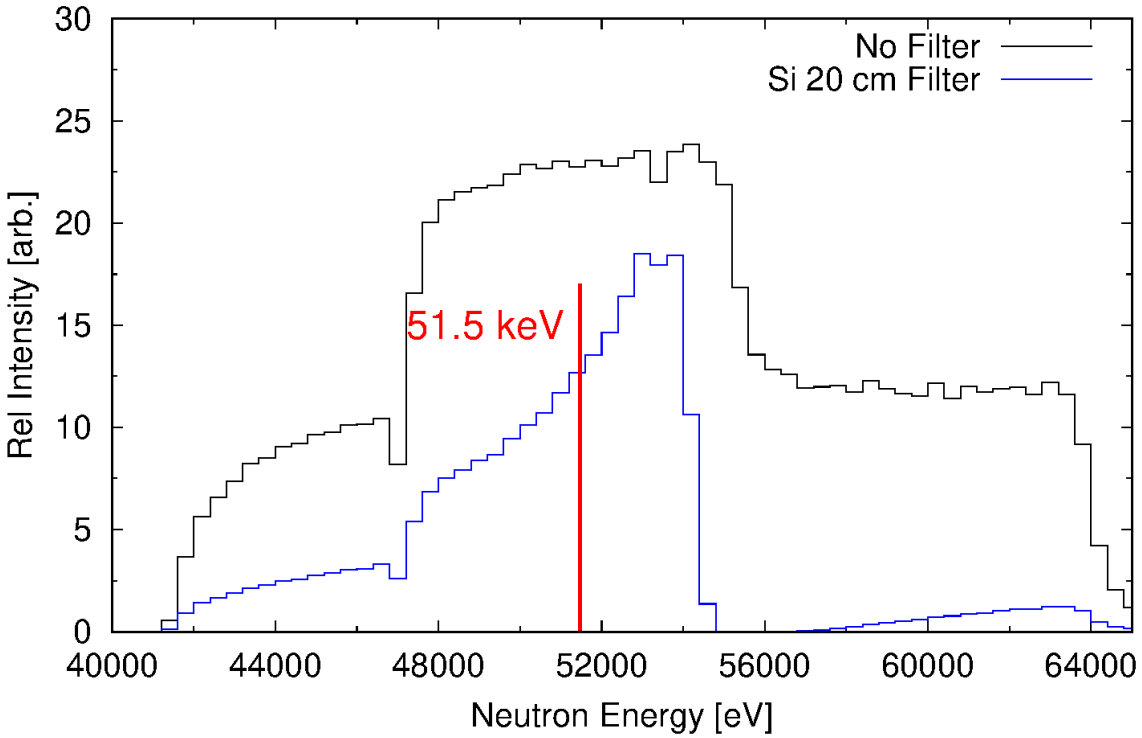


Fig. 23 **Energy distribution** of the **54 keV filtered neutron beam (blue)** and its **energy centroid (red)** compared to the **energy distribution without filter (black)**

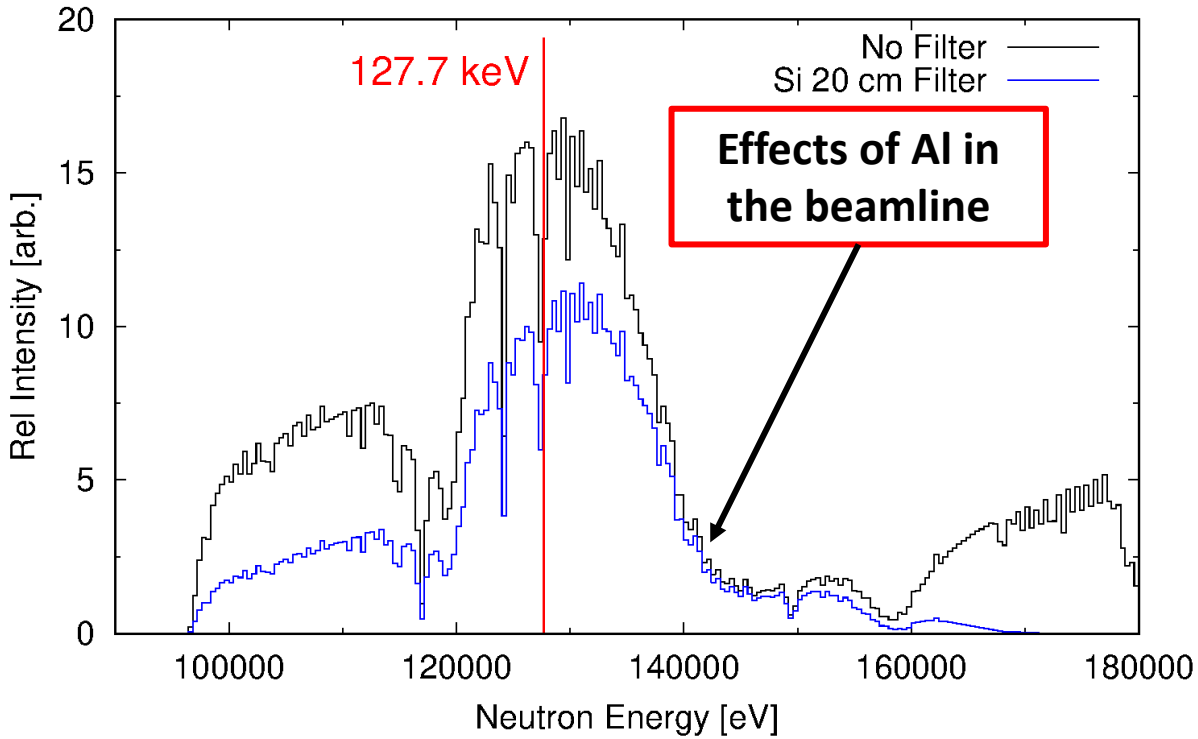


Fig. 24 **Energy distribution** of the **144 keV filtered neutron beam (blue)** and its **energy centroid (red)** compared to the **energy distribution without filter (black)**

Monte-Carlo Simulation – Energy distribution

The **neutron energy distribution** was obtained by gating the PHITS results at each filtered peak

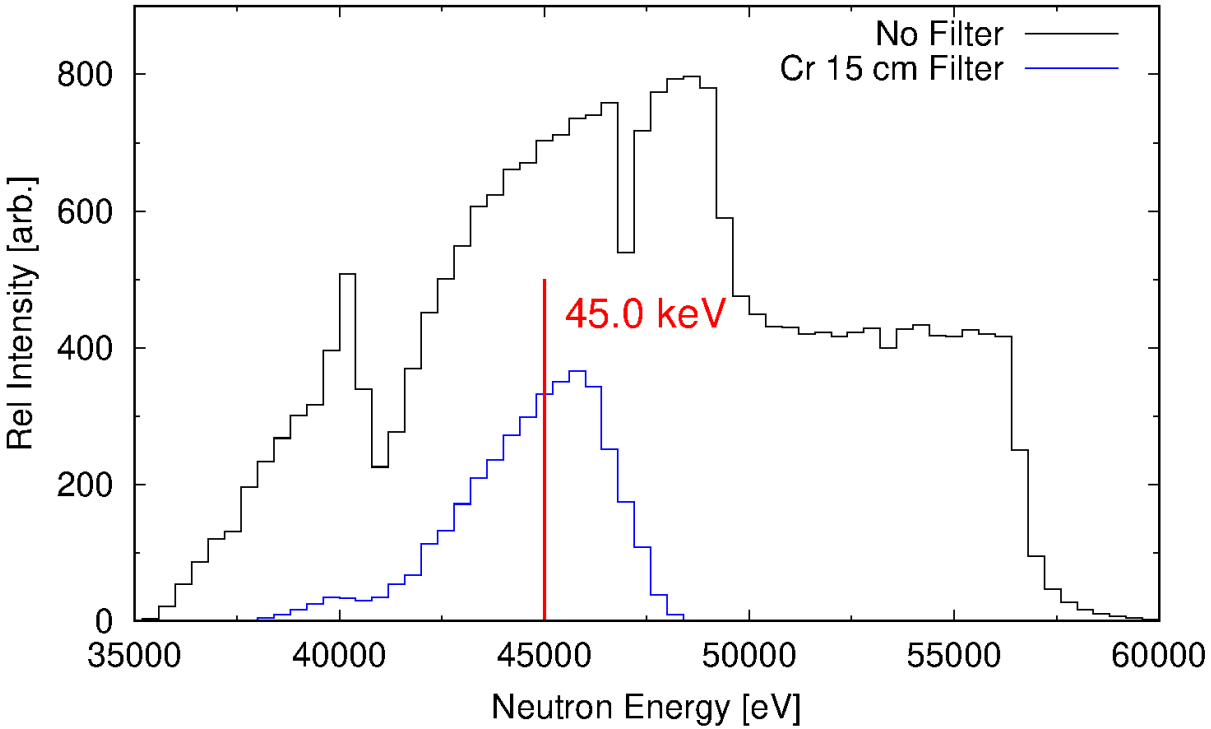


Fig. 25 **Energy distribution** of the **46 keV filtered neutron beam (blue)** and its **energy centroid (red)** compared to the **energy distribution without filter (black)**

Cr

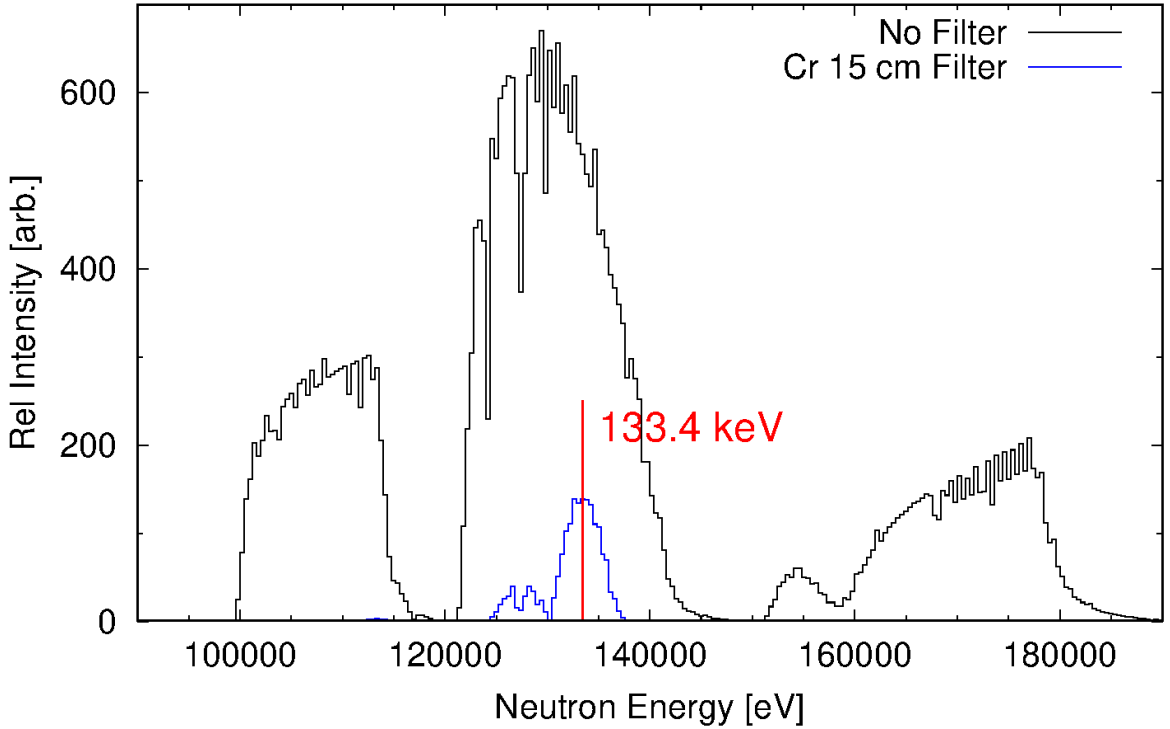


Fig. 26 **Energy distribution** of the **136 keV filtered neutron beam (blue)** and its **energy centroid (red)** compared to the **energy distribution without filter (black)**

Standard Cross Section Results

The **^{197}Au(n,γ) cross-section** was determined using the **Fe**, **Si** and **Cr** filtered peaks. Results contain **total uncertainties below 5%**.

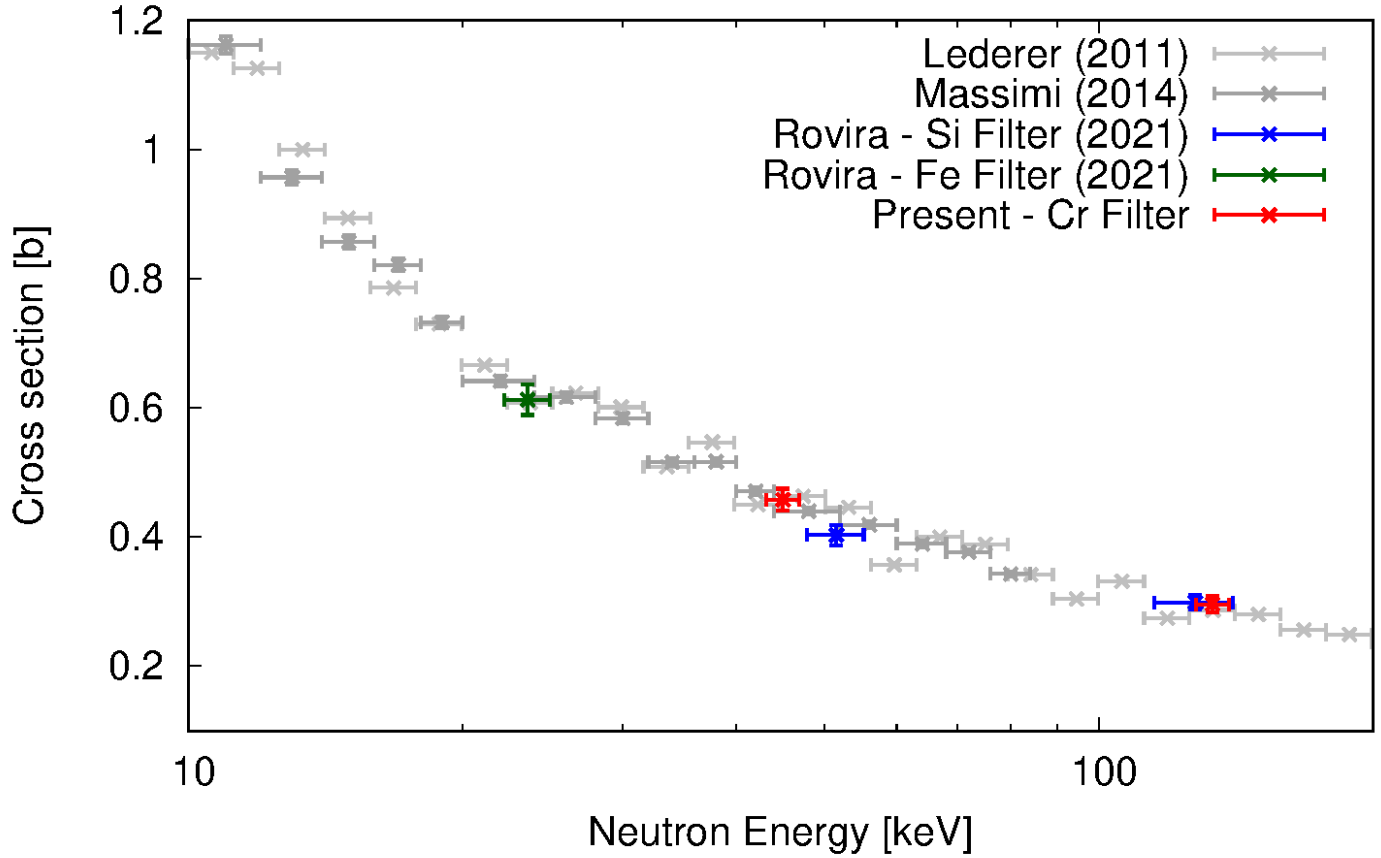


Fig. 27 Cross section results for **^{197}Au** using the **Fe filter (green)**, **Si filter (blue) and Cr filter (red)** compared with the latest **TOF experimental results**.

Standard Cross Section Results

The peak

The **present** cross section results with the **Fe**, **Si** and **Cr** filters **agree** within uncertainties with both **experimental** and **evaluated** nuclear data

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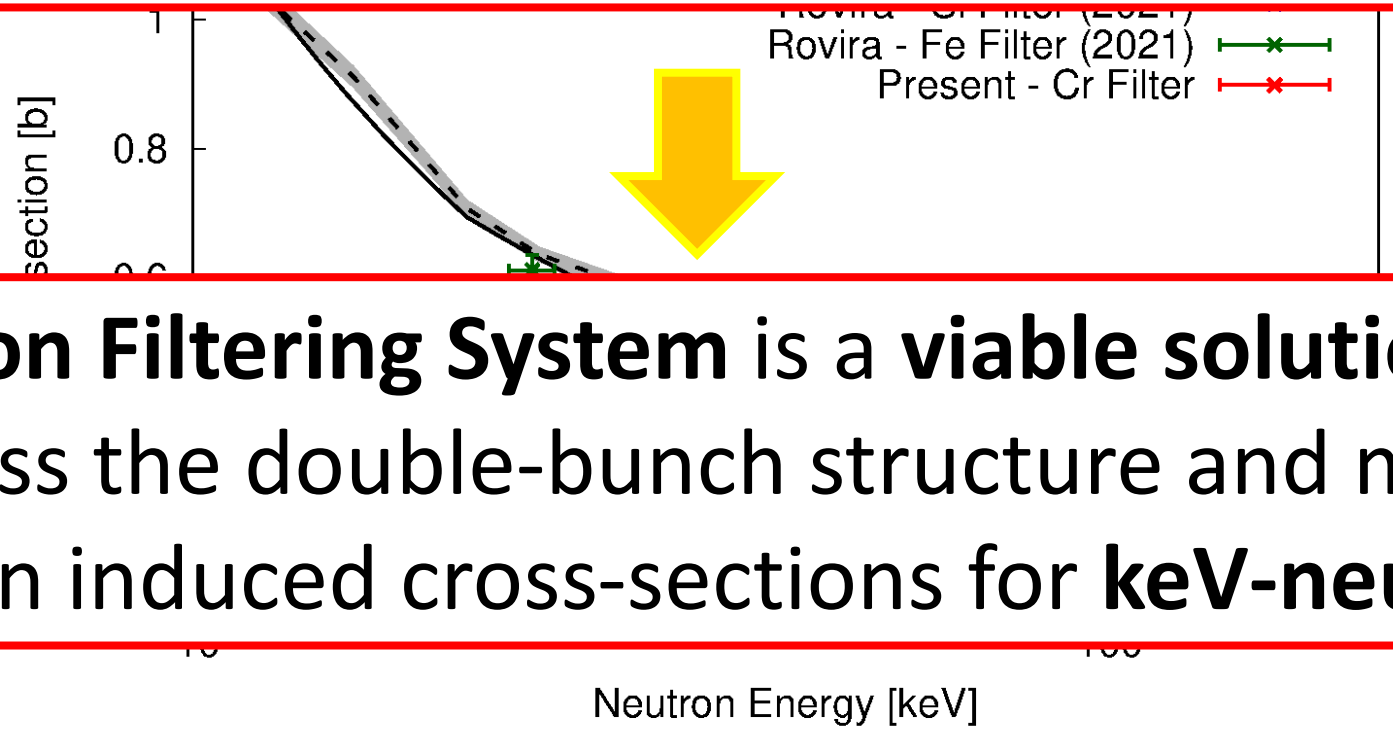

The **Neutron Filtering System** is a **viable solution** in order to bypass the double-bunch structure and measure neutron induced cross-sections for **keV-neutrons.**

Fig. 28 Cross section results for **^{197}Au** using the **Fe filter (green)**, **Si filter (blue) and Cr filter (red)** compared with the evaluated data from **JENDl-4.0** and the **IAEA Standard** libraries.

Minor Actinides Cross Section Results

The **first** cross section results have already been published in the work of **Kodama* et al**. The neutron capture cross section of **^{243}Am** was measured at the energy of **23.5 keV** with the **Fe** filter.

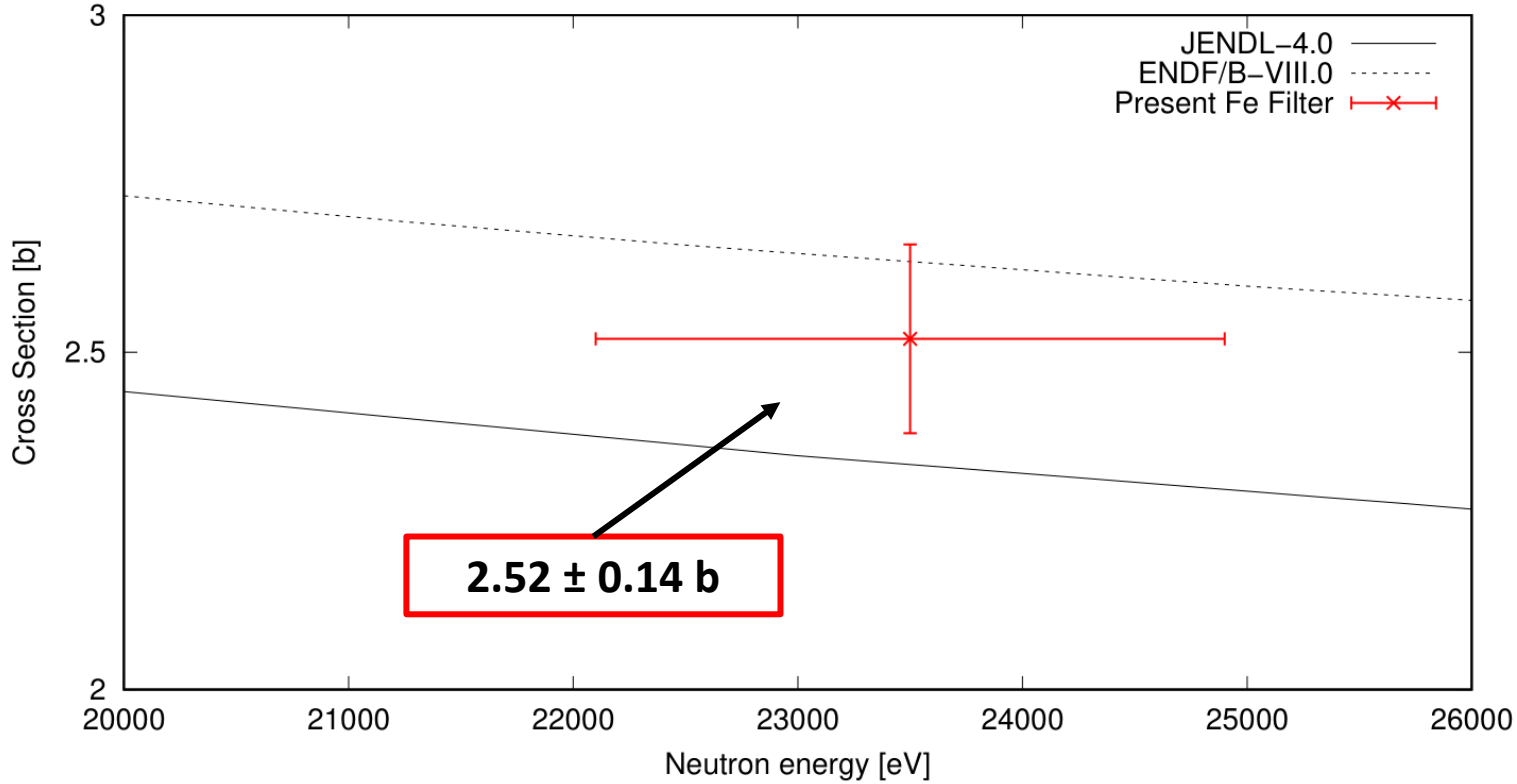

Fig. 29 Cross section results for ^{243}Am at **23.5 keV** with the **Fe** filter from the work of **Kodama* et al.** compared with evaluated results from **JENDL-4.0** and **ENDF/B-VIII.0**

*Kodama et al. J. Nucl. Sci and Technol. Rapid Communication, 2021.

Minor Actinides Cross Section Results

Preliminary neutron capture cross section of **^{241}Am** measured at the energy of **23.5 keV** with the **Fe** filter.

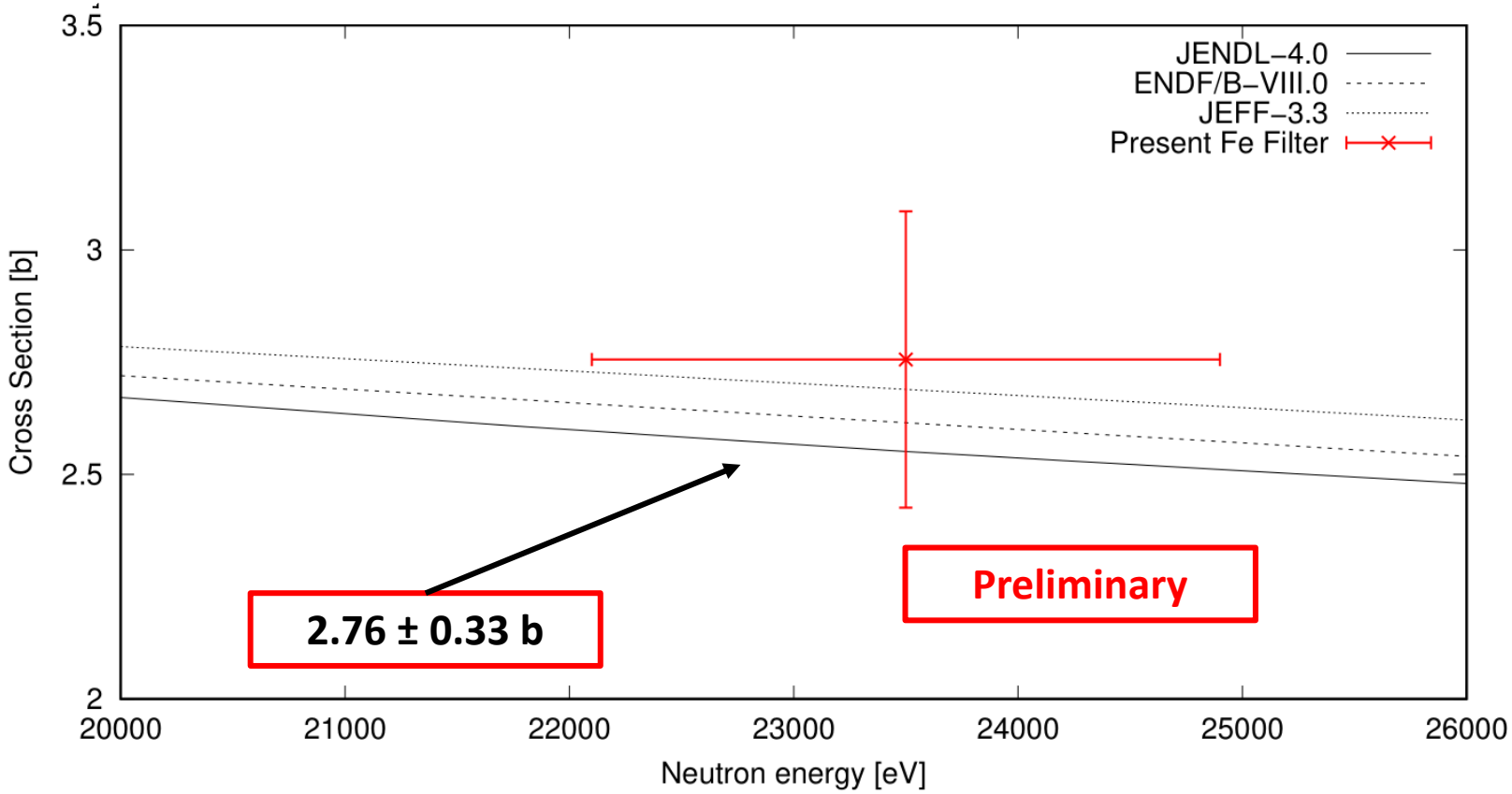

Fig. 30 Preliminary cross section results for ^{241}Am at **23.5 keV** with the **Fe** filter compared with evaluated data libraries

Conclusions

- **Developed a Neutron Filtering System to bypass the effects of the double-bunch mode**
  - Filtering system is able to **tailor quasi-monoenergetic neutron peaks** with **Fe, Si and Cr** with **peaks of 23.5, 45.0, 51.5, 127.7 and 133.4 keV**
  - The **time distribution** of the filtered neutron flux was accurately determined by experiments with both **Li-glass detectors** and a **NaI(Tl) spectrometer**
  - **Monte-Carlo simulations** are able to **reproduce** the experimental results
  - **Neutron energy distributions** of the filtered peaks determined from simulations
  - **Performance** in **neutron-induced cross-section** measurements **verified** by the good agreement with **experimental** and **evaluated** data for ^{197}**Au**.
- **Cross-section measurements with fast neutrons can be performed using the Neutron Filtering System at ANNRI**
  - First cross section results for minor actinides (^{243}**Am**) already published

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