# Time-of-Flight Measurement of Fast Neutron Interactions in Silicon by Means of Timepix Detectors

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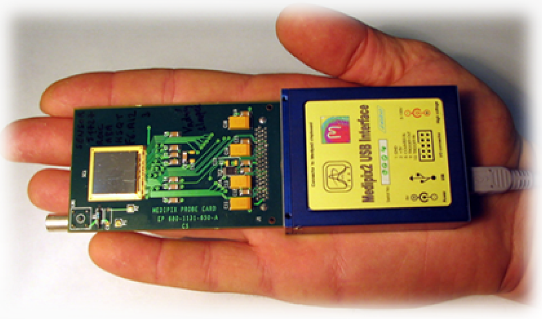
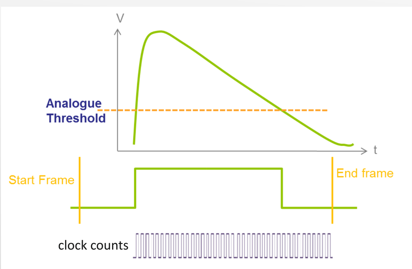
## Timepix Detectors for Neutron Measurements

The Timepix detectors are hybrid semiconductor pixelated X-ray imaging detectors, based on the technology of the Medipix2. They were developed in the Medipix collaboration together with CERN.



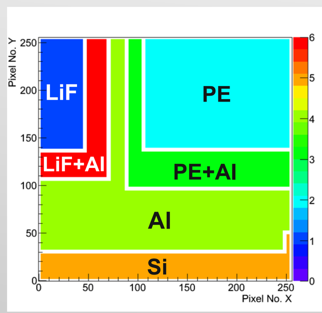
**Specifications:**
Pixel array: 256 x 256, pixel size: 55 x 55 μm$^2$
Total sensitive area: 1.982 cm$^2$ (87% of chip)
Silicon sensor layer (thickness: 300μm)

Electronics in each pixel cell:
- amplifier and discriminator
- 14-bit counter (range of 11810 counts)
- 8-bit configuration register (masking, individual adj.)



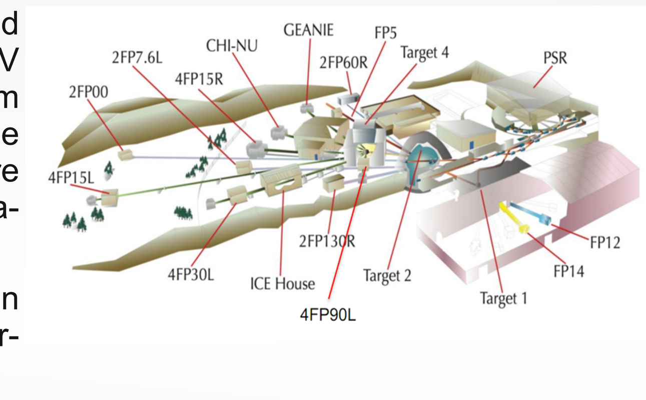

Particles crossing the sensor layer create electron hole pairs, that drift through the Silicon sensor layer due to an applied electrical field, and thus induce charge in the electrodes of each pixel. The induced voltage pulse is shaped by a charge sensitive amplifier. Depending on the mode this signal is used in different ways. In the Time-of-Arrival (ToA) mode the number of clock pulses of a reference clock is measured from the first time this pulse crosses an adjustable analog threshold level to the end of the frame.

In order to enhance the detector response to neutrons of different energies, converter foils were attached to the top of the Silicon sensor layer, i.e. polyethylene (PE), PE+Al, $^6$LiF, $^6$LiF+Al, Al (PE: thickness 120mg cm$^{-2}$, LiF: 5mg cm$^{-2}$, 89% of $^6$Li).
Thermal neutrons are detected reliably with a detection efficiency of 1% by measuring alpha particles and tritons from the $^6$Li(n,α)$^3$H-reaction below $^6$LiF.
The detector responses and efficiencies to fast neutrons, that create recoiled protons in the polyethylene (PE) foil and, from given thresholds in nuclear interactions with the Silicon itself, are presented.



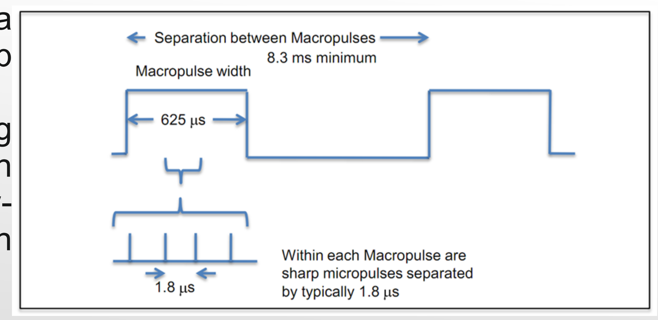

## Los Alamos Neutron Science Center (LANSCE)

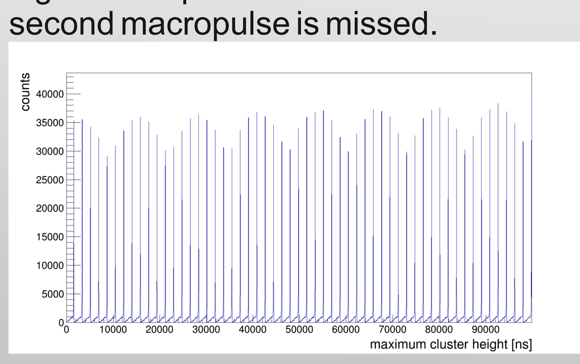
At the Weapons Neutron Research facility at LANSCE a pulsed neutron beam with an energy range from a few hundreds of keV up to 800MeV is produced by using the 800MeV proton beam from the LANSCE linac with a tungsten target (Target 4). In the spallation process around 20 neutrons per incident proton are generated at the interaction point. Charged particles are separated from the beam by a magnetic field.




The Timepix device was set up at ICE House II (4FP30R) in 14.885m distance from the interaction point and irradiated perpendicularly.

The proton beam is divided into 625μs long macropulses with a repetition rate of 8.3ms. Each macropulse contains sharp micropulses separated by 1.8μs.
A triggered measurement has been performed. The 100μs long frames have been opened on the first micropulse of each macropulse. Each frame thus contains particles from the following 55 micropulses. As the dead time of the read out is 11ms each second macropulse is missed.




By means of this stable trigger (10ns jitter) the measured timestamps can be integrated over the whole set of measured frames without losing the information of the relative time of the interacting particle with respect to the beginning of the corresponding micropulse. The clock frequency of the measurement was 48MHz. Thus, 1 clock count corresponds to 20.8ns. The first and the last micropulse per frame were excluded in the evaluation.

## Time-of-Flight Technique

The beginning of each micropulse is indicated by the gamma flash from the interaction point that arrives 49.6ns (time a particle at the speed of light needs to travel from the interaction point to the detector) after the interaction. By identifying the corresponding ToA value ($ToA_{max}$), the Time-of-Flight for each cluster can be calculated as:

$$t_{Flight} = [(ToA_{max} - ToA) \cdot 20.8 + 49.6]\ ns$$

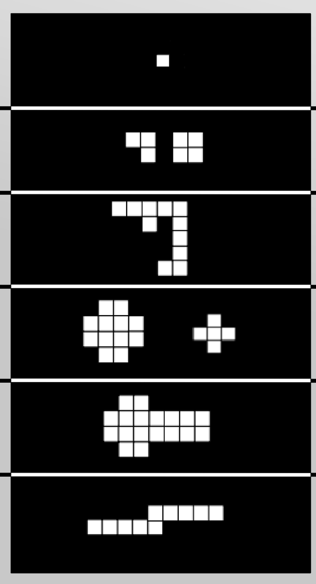
Different Times-of-Flight correspond to different velocities and thus different kinetic neutron energies. Using the laws of special relativity, the following equation is found:

$$T = E - M = (\gamma - 1) \cdot M$$

$\gamma = (1-\beta^2)^{-0.5}$; $\beta = v/c = d/(c \cdot t_{Flight})$;
$M = 957.59\,MeV$ (1); $c = 2.9997 \cdot 10^8\, m/s$ (1); $d = 14.885\,m$

## Pattern Recognition

A pattern recognition tool identifies different cluster shapes that indicate different kinds of reactions in the Silicon, and assigns them to the six basic categories:

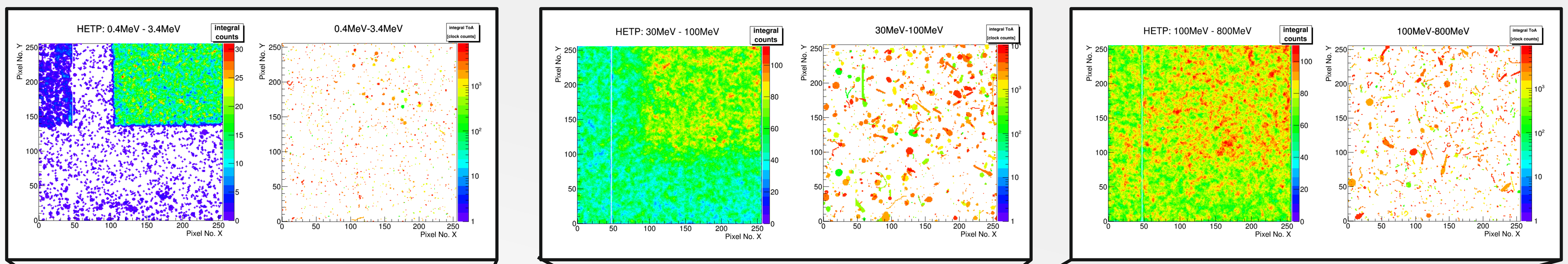


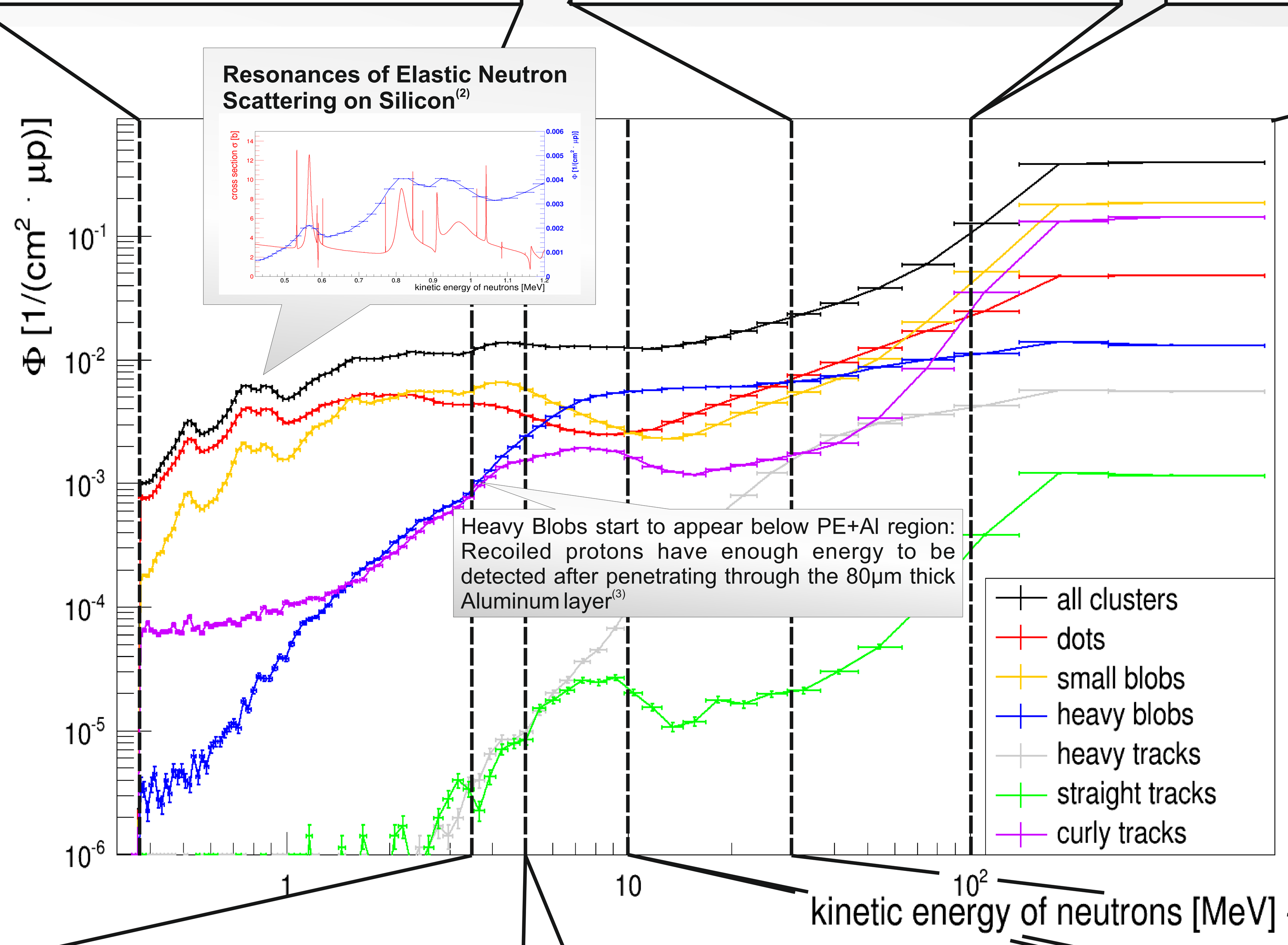
| | |
|---|---|
| Dot | Photons and electrons (10keV) |
| Small Blob | Photons and electrons |
| Curly Track | Electrons (MeV range) |
| Heavy Blob | Heavy ionizing particles with low range (alpha particles,…) |
| Heavy Track | Heavy ionizing particles (protons,…) |
| Straight Track | Energetic light charged particles (MIP, Muons,…) |

Particles that locally deposit a huge amount of energy in the Silicon sensor layer are further referred to as "**H**igh **E**nergy **T**ransfer **P**articles" (HETP). Their signatures are Heavy Tracks and Heavy Blobs.
In terms of neutron detection, this HETP-signatures are created by the recoiled protons below PE and nuclear interactions of neutrons in the Silicon itself.

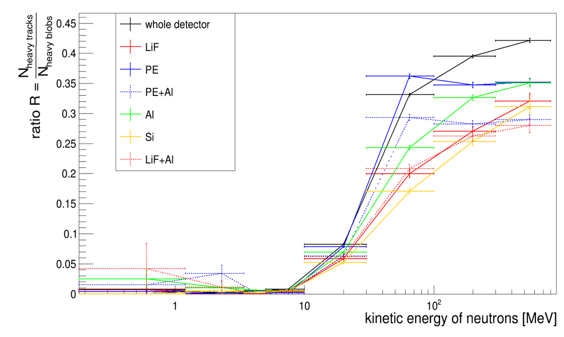
(1) *Review of Particle Physics, K. Nakamura (Particle Data Group), JP G37, 075021*
(2) *The cross sections for elastic scattering were taken from JANIS-database: http://www.oecd-nea.org/janis/book/. The measured data was corrected by 60 ns for the inaccuracy in timing due to the time walk effect.*
(3) *Recoiled protons with energies up to 2.96MeV are completely slowed down to thermal energies within the 80μm (CSDA range) thick Aluminum layer.*

## Detector Responses to Different Kinetic Neutron Energies

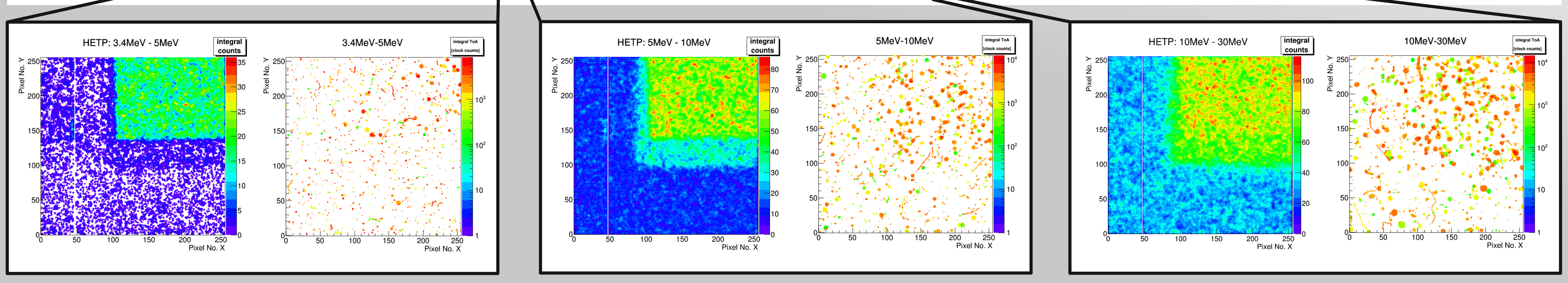



The measured fluences of different cluster types over energy, detector responses in form of HETP (Integrated over all measured frames) and representative frames for defined energy ranges (1000 events per frame) are shown.
In the low energy range different thresholds can be defined for the assignment of neutron energies, i.e. the enhanced response in form of HETP below LiF up to 3.4MeV and the threshold for the detection of recoiled protons below the additional Aluminum layer.




Going to higher energies nuclear reactions of neutrons with Silicon gain importance and begin to dominate the signal above 50MeV. Here the ratio of the number of Heavy Blobs to Heavy Tracks to the number of Heavy Blobs can be used to identify the neutron energy.

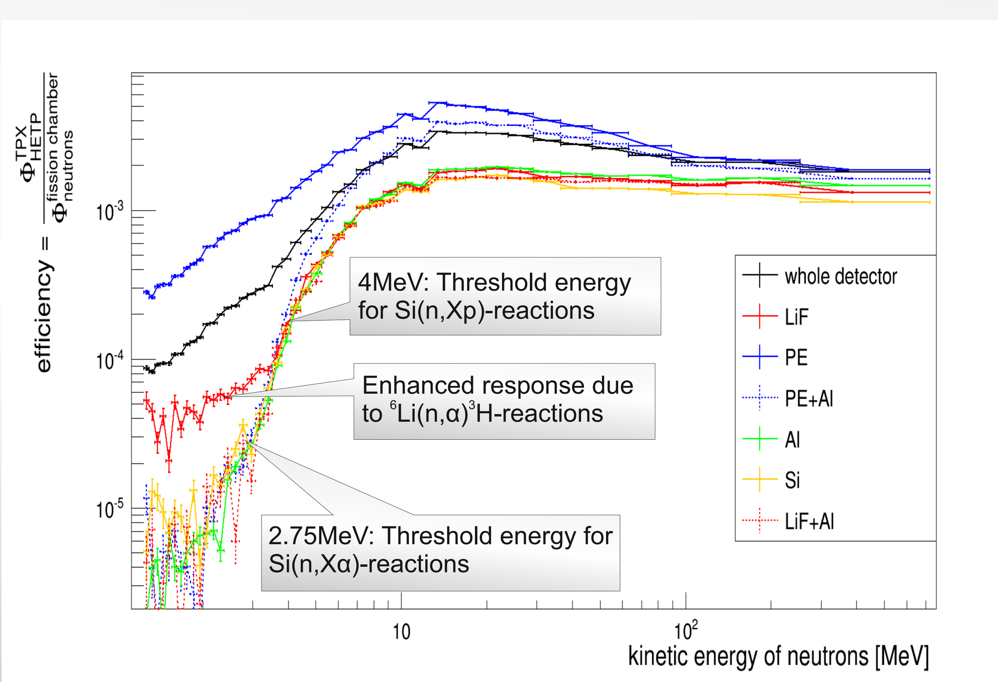



## Detection Efficiencies of Different Converter Foils

The detection efficiency is obtained by scaling the measured fluence of HETP by the reference neutron fluence provided by a fission chamber situated 1m closer to the interaction point than the Timepix device.

This is done seperately for each region and the whole detector.

Again, the thresholds for the enhanced response below the LiF- (up to ~3.4MeV) and PE+Al-region (above ~4MeV) can be seen. Over the whole energy range the most sensitive area is the one below PE, with the maximal efficiency of 0.525% at approximately 13MeV.




## Comparison with Simulations

In the simulation a detailed model of the TPX detector with the convertor foils was created using the MCNPX code in version v2.7e, a general-purpose Monte Carlo code developed at Los Alamos National Laboratory (LANL, USA).
Neutron detection efficiencies were obtained using parallel neutron beams perpendicularly impinging on the detector. The limited energy resolution of the measurement was taken into account by simulating quasimonoenergetic neutron beams. The simulated quantity was the number of neutrons that created charged particles depositing more than 230keV in Silicon.