Measurement of the Ionizing Energy Depositions after Fast Neutron Interactions in Silicon

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Outline

- ❑ Introduction
- ❑ Experimental setup and methods of data evaluation
- ❑ Results

INTRODUCTION

Measurement of ionizing energy losses after monoenergetic neutron impact

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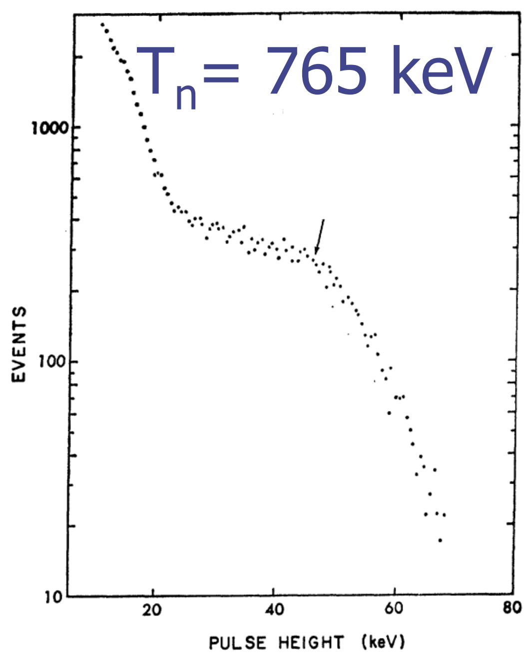
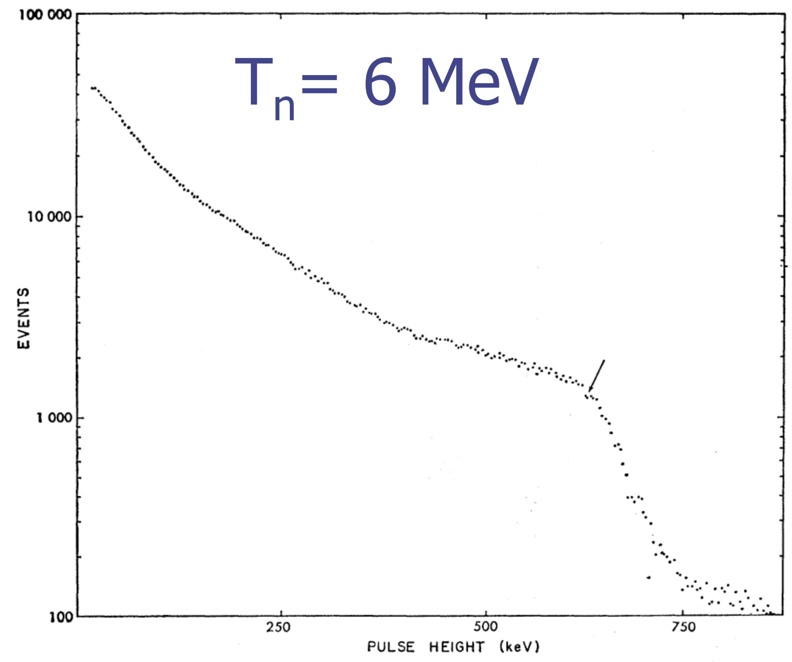
- Sattler, 1965:
  "Ionization produced by energetic silicon atoms within a silicon lattice"
  (Phys. Rev. Vol 138, Vol. 6 A)





Radiation damage in silicon

- Radiation damage affects performance of detectors and/or electronic curcuits
- Permanent damage (changes in sensor material):
  - Displacement of silicon atoms within the lattice (non-ionizing energy depositions)
  - → Increases leakage current
  - → Decreases charge collection efficiencies
- Single Event Effects (changes in logic state of device):
  - High local charge deposition (ionizing energy losses)
  - → Examples: SEU, MBU, ...

EXPERIMENTAL SETUP AND METHODS OF DATA EVALUATION

Timepix Detectors

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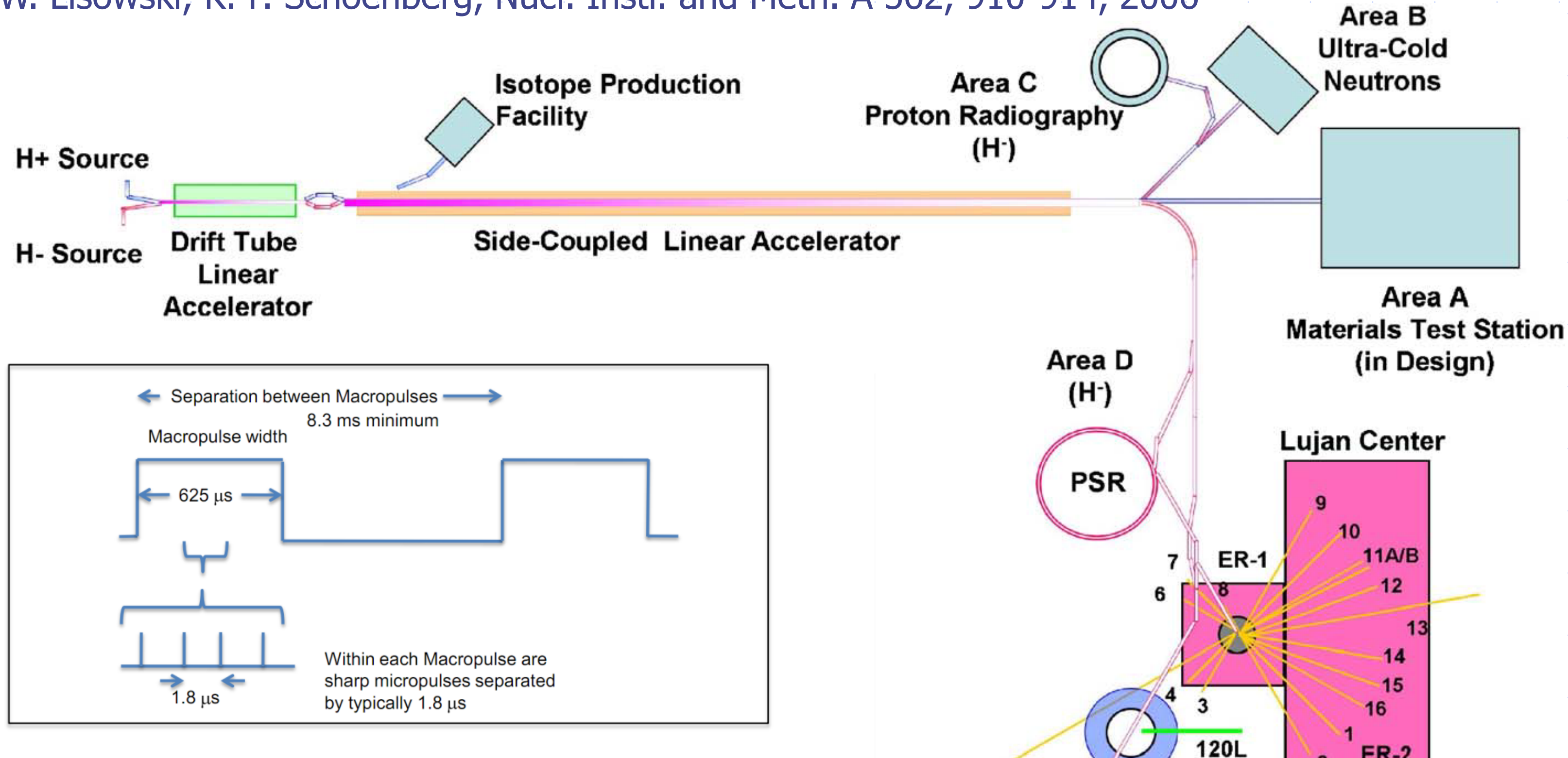
- Timepix detectors
  - Hybrid pixel detectors
  - Developed at CERN
  - 256 x 256 pixels
  - Pixel pitch: 55µm
  - Silicon sensor layer flip-chip bump bonded to the ASIC

Timepix3 CERN chip board

- Timepix 3:
  - Thickness: 300µm
  - Depletion voltage: 90V
  - Data driven readout (Maximal count rate 40 Mpix/s)
  - Measurement of energy **and** time, simultaneously (time resolution 1.56 ns)
  - Threshold set to 5 keV (down to ~2 keV possible)

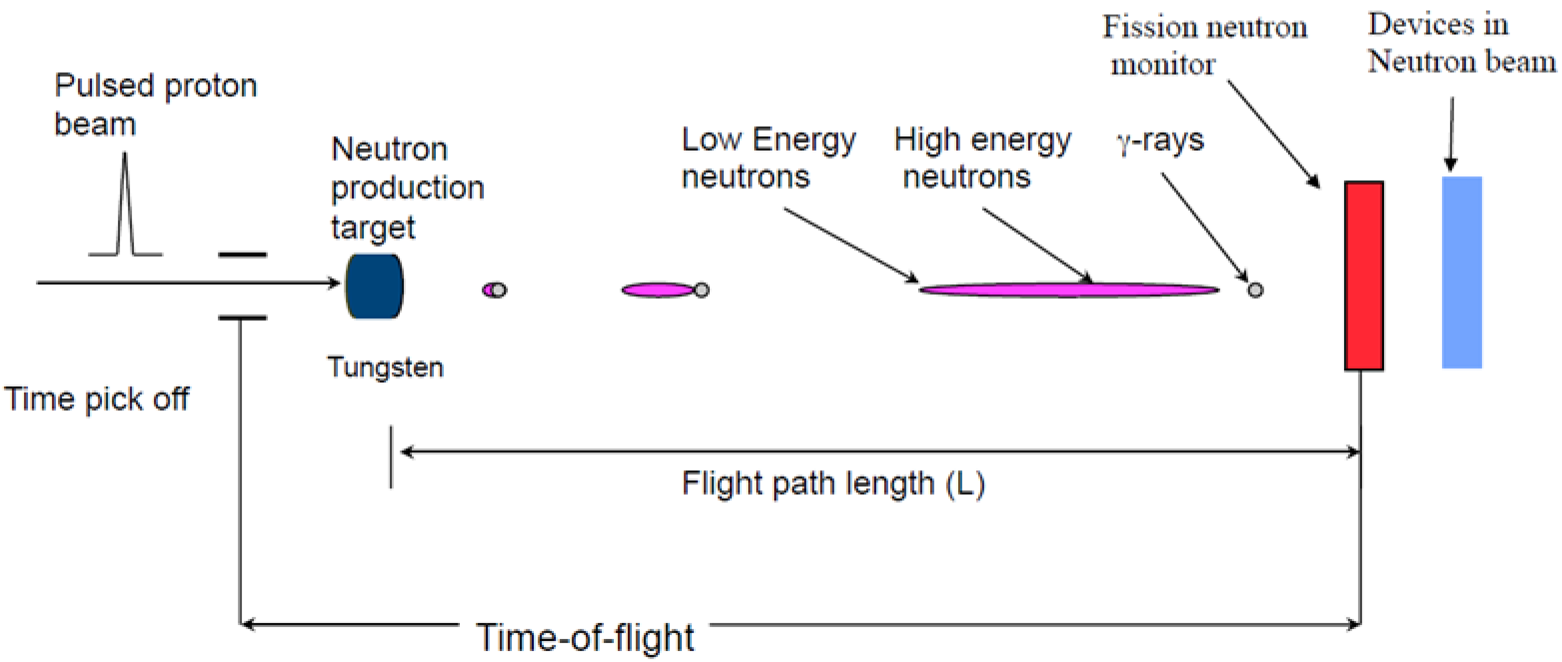
Los Alamos Neutron Science CEnter (LANSCE)

P. W. Lisowski, K. F. Schoenberg, Nucl. Instr. and Meth. A 562, 910-914, 2006



- Neutron spallation source: 800 MeV protons on tungsten target
- ‘white‘ neutron spectrum with kinetic neutron energies up to 600 MeV

Time-of-Flight technique



Neutron TOF = $\frac{72.3\,L}{\sqrt{E_n}}$ (non-relativistic)

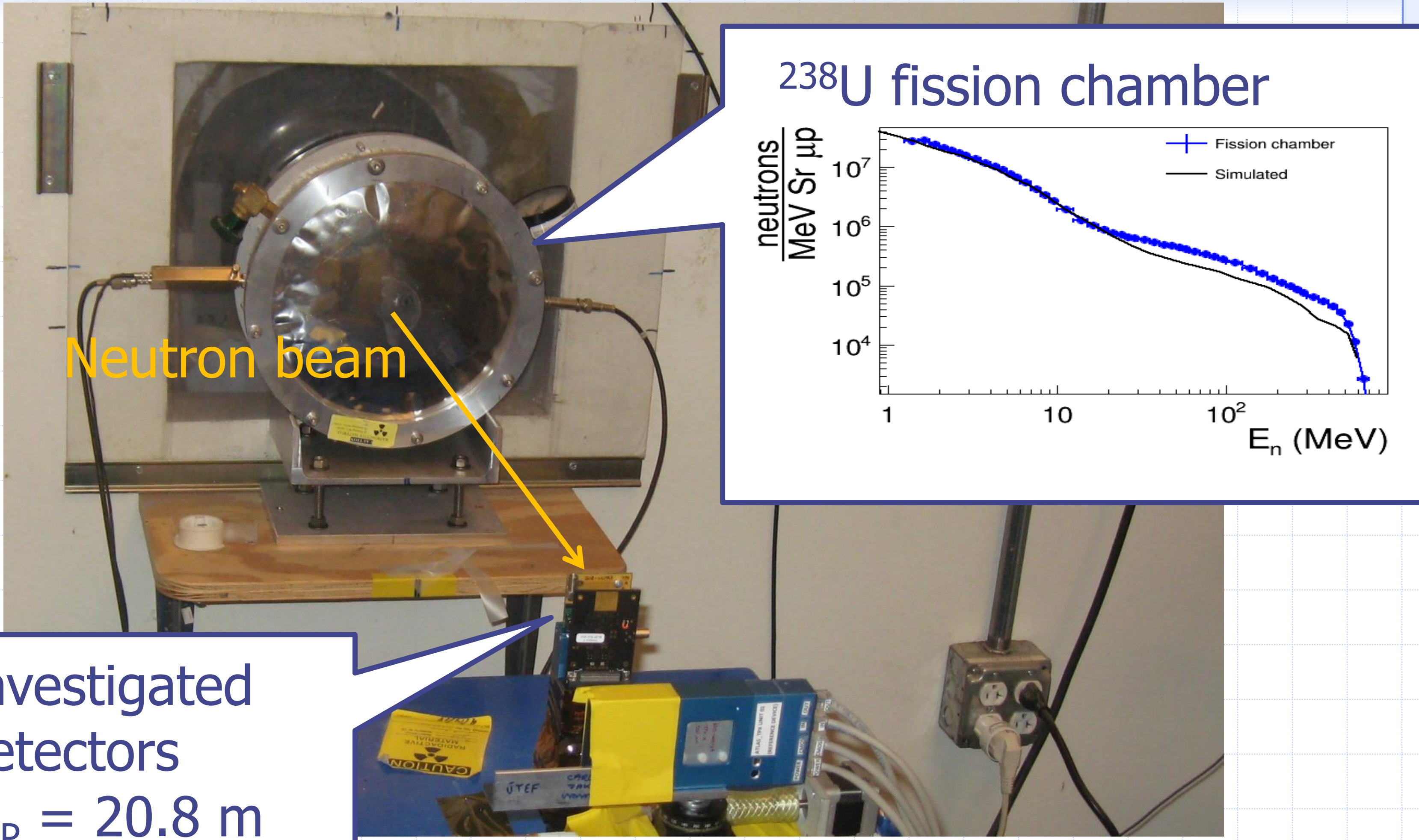
γ-ray TOF = $\frac{L}{c}$ c is velocity of light

Example: L= 20m

E_n= 1 MeV
TOF_n= 1.5 μs
TOF_γ = 67 ns

E_n = 100 MeV
TOF_n= 150 ns

Experimental setup and neutron energy spectrum

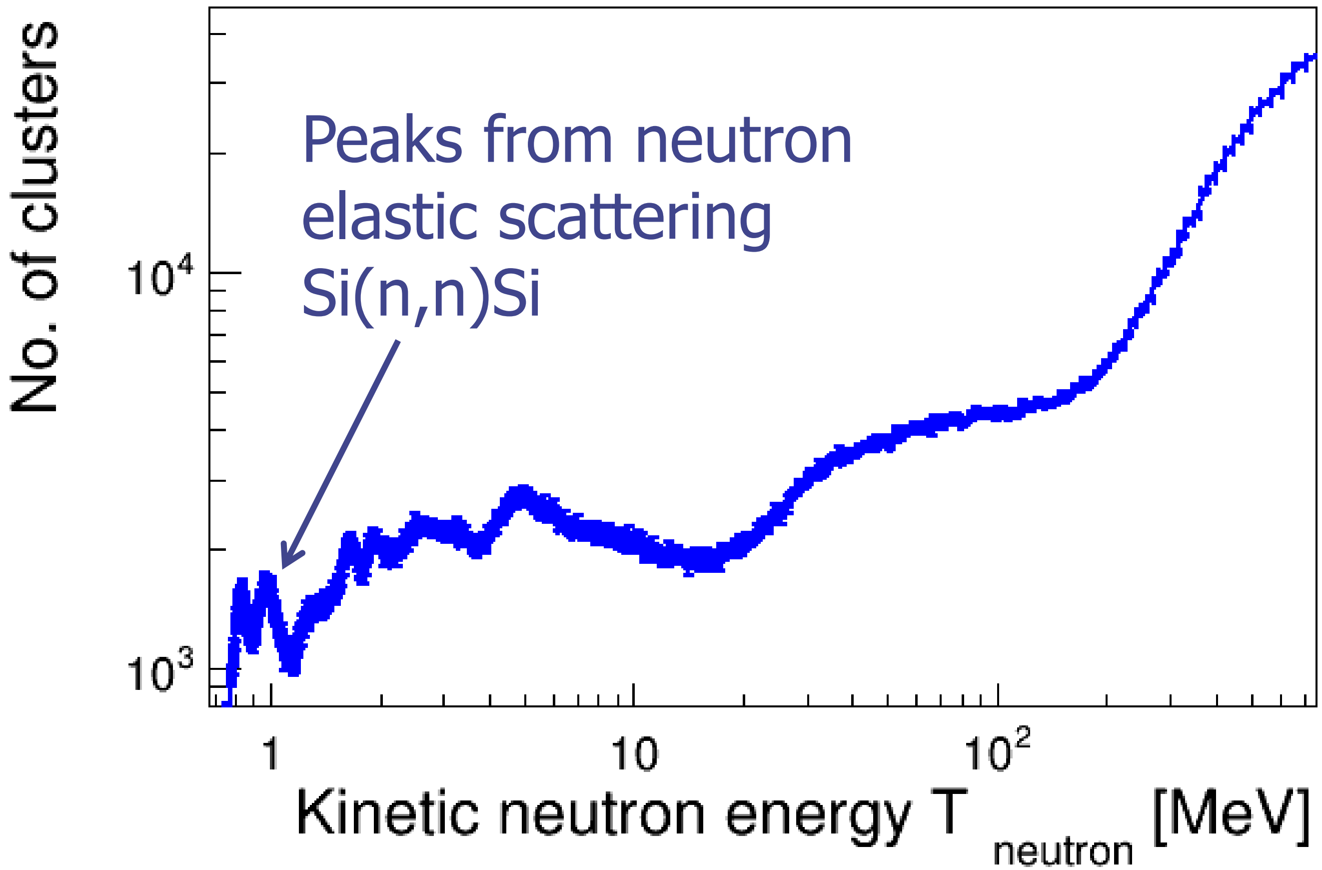


Investigated detectors

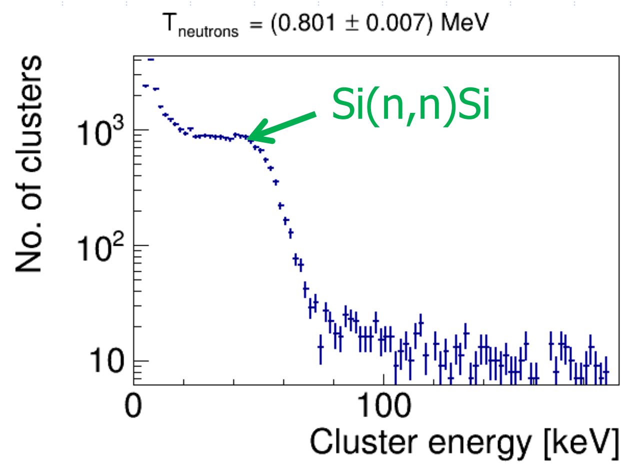
d_{IP} = 20.8 m

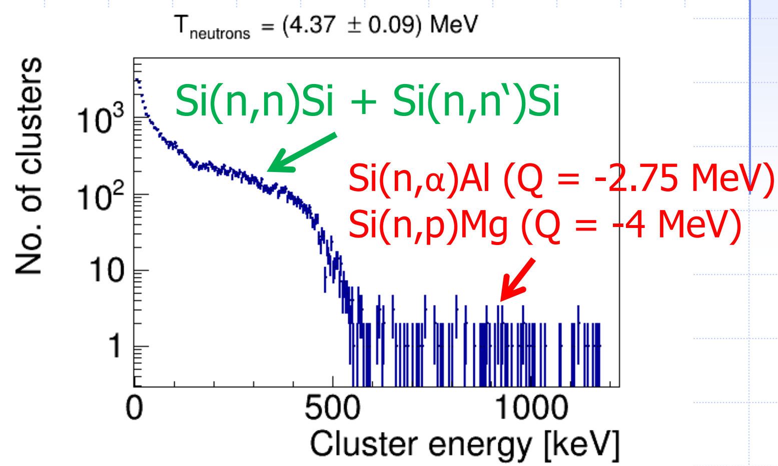
RESULTS

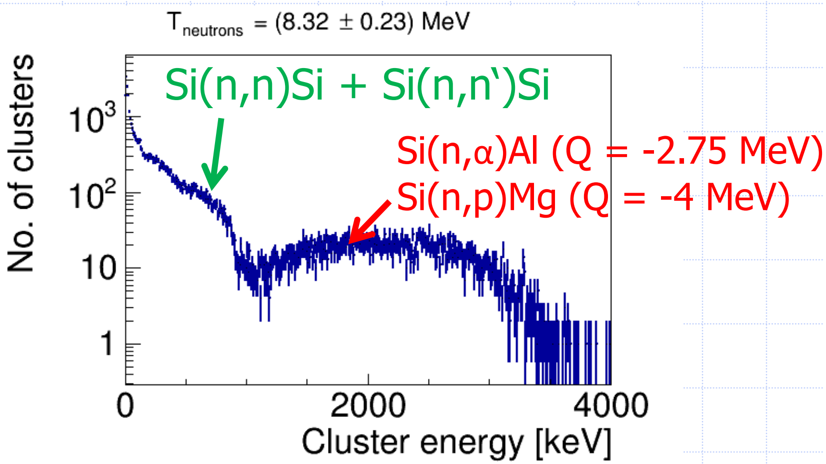
Measured neutron kinetic energy spectrum

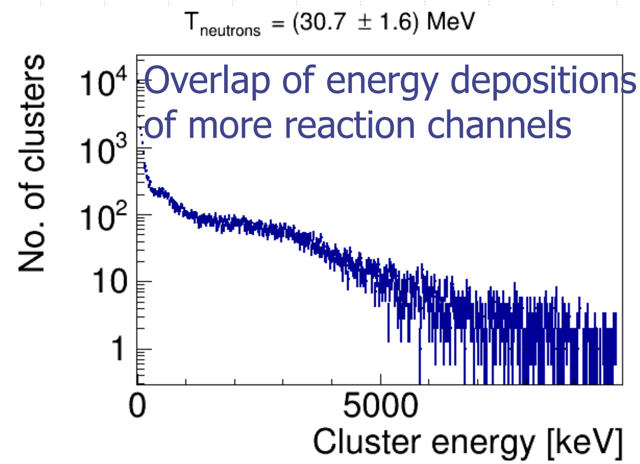


Examples of energy deposition spectra for selected neutron energy intervals









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Edges of energy depositions of silicon recoils from neutron elastic scattering

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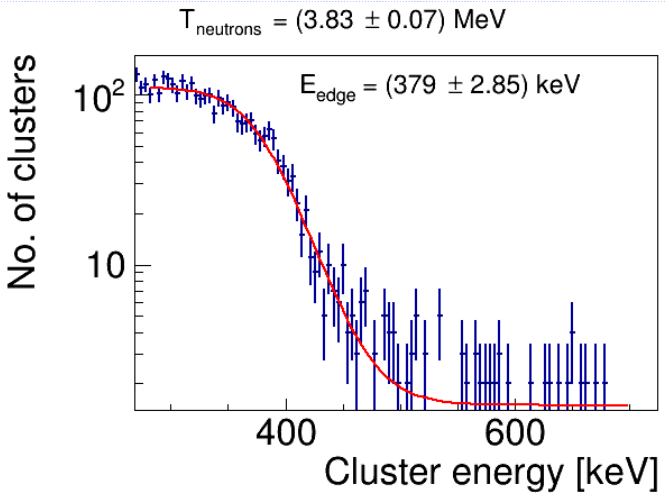
- Energy determination by fitting:

$$f(E) = \frac{A}{\exp\left(\frac{E-E_{edge}}{D}\right)+1} + B + C \cdot E$$

- Max. energy transfer to the silicon in elastic scattering:

$$T_{Si,max} = \frac{4M_{Si}m_n}{(M_{Si}+m_n)^2}T_n = 0.133 \cdot T_n$$

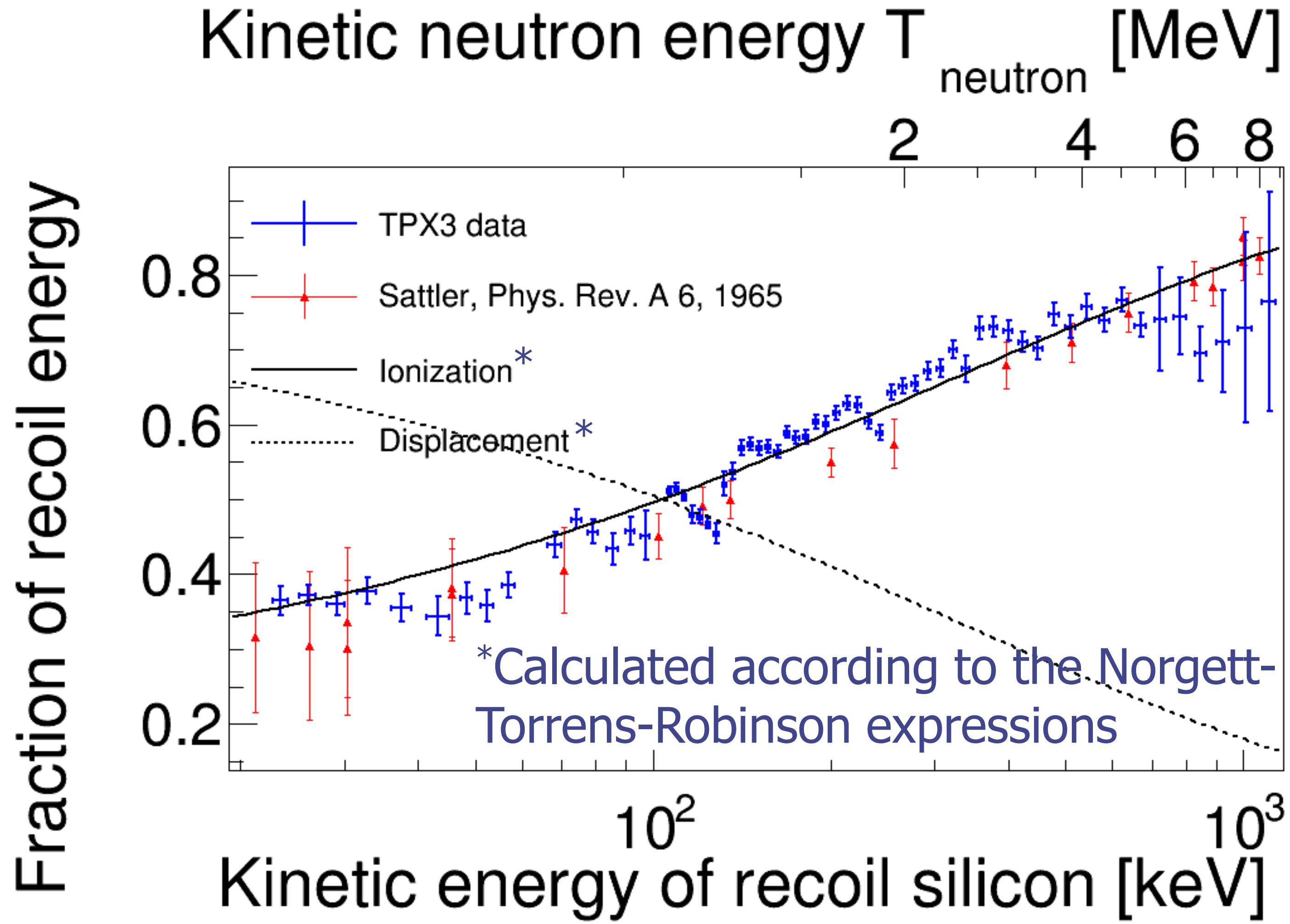
→ Energy goes partly into displacement E_{NIEL} (NIEL) and ionization E_{ion}.



- Energy measured: $E_{edge} = E_{ion.}$ (ionizing energy deposition)

→ Fraction of ionizing energy losses: $f_{meas,ion} = \frac{E_{edge}}{T_{Si,\max}} = \frac{E_{edge}}{0.133 \cdot T_n}$

Neutron scattering: Losses by ionization vs. losses due to displacement



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Conclusion

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- Example spectra of ionzing energy depositions of charged products after fast neutron impact were presented
- By spectrum analysis the competition of ionizing versus non ionizing energy losses was studied
- The results closely agreed with the calculations of Norgett-Torrens-Robinson and a previous measurement by Sattler

Impact:

- Knowledge of ionizing energy depositions essential for single event effect estimation/simulations
- Knowledge of non ionizing energy depositions necessary for understanding permanent radiation damage

Thank you for your attention!

ARDENT

Advanced Radiation Dosimetry European Network Training

Primary knock-on atoms and cascades of defects

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1. Creation of primary knock-on silicon atom (PKA) in neutron elastic scattering
   - Recoil silicon energy: $T_{Si} = \frac{4M_{Si}M_n}{(M_{Si}+M_n)^2} \cdot (1 - \cos(\theta)) \cdot T_n$

2. PKA loses its energy by
   - displacement of atoms from their lattice sites (NIEL) – cascade of displaced atoms, displacement damage
   - ionization of atoms in the lattice (IEL)

- Competition of NIEL vs. IEL losses theoretically described by

$$f_{\mathrm{NIEL}} = \frac{E_{\mathrm{de}}}{E_{\mathrm{Si}}} = \frac{1}{1+k\cdot g(\epsilon)} \quad \text{and} \quad f_{\mathrm{ion}} = \frac{k\cdot g(\epsilon)}{1+k\cdot g(\epsilon)}$$

With $k = 0.1462$, $\epsilon = 1.014 \cdot 10^{-2} Z_{\mathrm{Si}}^{1/7} \cdot E_{\mathrm{Si}} = 2.147 \cdot 10^{-5} E_{\mathrm{Si}}$ and $g(\epsilon) = 3.4008 \cdot \epsilon^{1/6} + 0.40244 \cdot \epsilon^{3/4} + \epsilon$

(Quasi-)monochromatic neutrons by means of ToF assigment

- Relative energy resolution as a a fuction of neutron kinetic energy (assuming time resolution of 25 ns)