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

- Sattler, 1965:
  
  “Ionization produced by energetic silicon atoms within a silicon lattice”

\[ T_n = 765 \text{ keV} \]

\[ T_n = 6 \text{ MeV} \]
Radiation damage in silicon

- Radiation damage affects performance of detectors and/or electronic circuits

- 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, ...
Timepix Detectors

- 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

- 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)


- Neutron spallation source: 800 MeV protons on tungsten target
- 'white' neutron spectrum with kinetic neutron energies up to 600 MeV
Time-of-Flight technique

\[ \text{Neutron TOF} = \frac{72.3 L}{\sqrt{E_n}} \quad \text{(non-relativistic)} \]

\[ \text{\( \gamma \)-ray TOF} = \frac{L}{c} \quad c \text{ is velocity of light} \]

Example:
- \( L = 20 \text{m} \)
- \( E_n = 1 \text{ MeV} \)
- \( \text{TOF}_n = 1.5 \mu\text{s} \)
- \( \text{TOF}_\gamma = 67 \text{ ns} \)
- \( E_n = 100 \text{ MeV} \)
- \( \text{TOF}_n = 150 \text{ ns} \)
Experimental setup and neutron energy spectrum

Neutron beam

238U fission chamber

Investigated detectors

\[ d_{\text{IP}} = 20.8 \text{ m} \]
RESULTS
Measured neutron kinetic energy spectrum

Peaks from neutron elastic scattering Si(n,n)Si
Examples of energy deposition spectra for selected neutron energy intervals

1. $T_{\text{neutrons}} = (0.801 \pm 0.007) \text{ MeV}$
   - $\text{Si}(n,n)\text{Si}$

2. $T_{\text{neutrons}} = (4.37 \pm 0.09) \text{ MeV}$
   - $\text{Si}(n,n)\text{Si} + \text{Si}(n,n')\text{Si}$
     - $\text{Si}(n,\alpha)\text{Al} (Q = -2.75 \text{ MeV})$
     - $\text{Si}(n,p)\text{Mg} (Q = -4 \text{ MeV})$

3. $T_{\text{neutrons}} = (8.32 \pm 0.23) \text{ MeV}$
   - $\text{Si}(n,n)\text{Si} + \text{Si}(n,n')\text{Si}$
     - $\text{Si}(n,\alpha)\text{Al} (Q = -2.75 \text{ MeV})$
     - $\text{Si}(n,p)\text{Mg} (Q = -4 \text{ MeV})$

4. $T_{\text{neutrons}} = (30.7 \pm 1.6) \text{ MeV}$
   - Overlap of energy depositions of more reaction channels

Cluster energy [keV]
Edges of energy depositions of silicon recoils from neutron elastic scattering

- Energy determination by fitting:
  \[ f(E) = \frac{A}{\exp\left(\frac{E - E_{\text{edge}}}{D}\right) + 1} + B + C \cdot E \]

- 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 \( E_{\text{NIEL}} \) (NIEL) and ionization \( E_{\text{ion}} \).

- Energy measured: \( E_{\text{edge}} = E_{\text{ion}} \). (ionizing energy deposition)
  → Fraction of ionizing energy losses:
  \[ f_{\text{meas,ion}} = \frac{E_{\text{edge}}}{T_{Si,max}} = \frac{E_{\text{edge}}}{0.133 \cdot T_n} \]
Neutron scattering: Losses by ionization vs. losses due to displacement

Kinetic neutron energy $T_{\text{neutron}}$ [MeV]

Fraction of recoil energy

Kinetic energy of recoil silicon [keV]

TPX3 data
Sattler, Phys. Rev. A 6, 1965
Ionization*
Displacement*

*Calculated according to the Norgett-Torrens-Robinson expressions
Conclusion

- Example spectra of ionizing 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!
Primary knock-on atoms and cascades of defects

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

\[
\begin{align*}
  f_{\text{NIEL}} &= \frac{E_{de}}{E_{Si}} = \frac{1}{1+k \cdot g(\epsilon)} \quad \text{and} \quad f_{\text{ion}} = \frac{k \cdot g(\epsilon)}{1+k \cdot g(\epsilon)}
\end{align*}
\]

With \( k = 0.1462, \epsilon = 1.014 \cdot 10^{-2}Z_{Si}^{1/7} \cdot E_{Si} = 2.147 \cdot 10^{-5}E_{Si} \) and \( g(\epsilon) = 3.4008 \cdot \epsilon^{1/6} + 0.40244 \cdot \epsilon^{3/4} + \epsilon \)
(Quasi-)monochromatic neutrons by means of ToF assignment

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

Time-of-Flight technique used to select quasi-monoenergetic neutrons:
- \( \Delta T_n/T_n \) up to \( \sim 3\% \) (\( T_n < 10 \text{ MeV} \))
- \( \Delta T_n/T_n \sim 5\% \) (\( T_n \sim 30 \text{ MeV} \))

Compare to neutrons from van-de-Graaff:
- \( \Delta T_n/T_n \sim 50\% \) (\( T_n \sim 200 \text{ keV} \))
- \( \Delta T_n/T_n \sim 4\% \) (\( T_n \sim 1 \text{ MeV} \))
- \( \Delta T_n/T_n \sim 2\% \) (\( T_n > 15 \text{ MeV} \))