Pulse Discrimination
between Recoil Protons and Secondary Electrons
for a Silicon Diode Based Neutron Spectrometer

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Outline

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• Silicon diode based neutron detector
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Motivation

Characterization of the low-energy (few MeV) neutron fields generated by low-energy ion-accelerators:
• Biological cultures irradiations
• Electronic circuit radiation damage studies
• Shielding calculation for radiation protection

Offer an alternative to organic scintillator / PMT spectrometers, based on silicon diodes with comparable spatial and energy resolution
Recoil proton spectrometer for neutrons

Polyethylene radiator (1 mm)

Si PIN Diode (300 µm)

Spectroscopy Chain

Recoil-proton spectrum

Unfolding Procedure

Analytical Response Matrix

Neutron spectrum
Distribution of the recoil proton energy $p(E_p)$

The collision between $n$ and $p$ in the center of mass reference system is isotropic and elastic in the MeV energy range.

In the laboratory system $\theta$ is the angle between the incoming $n$ and the recoil $p$:

$$V_p = V_{in} \cos \theta, \quad E_p = E_{in} \cos^2 \theta$$

and differentiating $dE_p = - E_{in} 2 \cos \theta \sin \theta \, d\theta$.

Integrating the differential cross section (Lab) in the solid angle between $\theta$ and $\theta + d\theta$

$$p(\theta) \, d\theta = 2 \cos \theta \sin \theta \, d\theta \quad \text{maximum for } \theta = \pi/4$$

$$p(E_p) \, dE_p = p(\theta) \, d\theta$$

Substituting there is a cancellation and

$$p(E_p) = 1/E_n \quad \text{with} \quad 0 < E_p < E_n \quad \text{CONSTANT}$$
Distribution of the deposited energy by the recoil protons in the silicon $p(Ed)$

Model equations:

\[ p(E_p) = \frac{1}{E_n} \quad \text{in the interval } (0 - E_n) \]

\[ R_p = R_0 \cdot E_p^\beta \quad \text{range-energy power law} \]

\[ R_{\text{total}} = R_{\text{radiator}} + R_{\text{detector}} \]

\[ E_d = \left[ \left( E_n \cdot \cos^2 \theta \right)^\beta - \frac{h}{(R_0 \cdot \cos \theta)} \right]^{1/\beta} \]

\[ p(E_d) = \frac{2}{3} \cdot \beta \cdot \left( \frac{E_d}{E_n} \right)^{\beta-1} \cdot \frac{1}{E_n} \cdot \left[ 1 - \left( \frac{E_d}{E_n} \right)^{3/2} \right] \]
Experimental and analytical response functions

![Graph showing experimental and analytical response functions for different energies.](image-url)
Analytical, simulated and experimental spectrum
Spectra for monoenergetic neutrons (0.8–4.7 MeV)

 Deposited energy (keV) vs. Response (cm²)

- $E_n = 0.787$ MeV
- $E_n = 0.892$ MeV
- $E_n = 0.996$ MeV
- $E_n = 1.100$ MeV
- $E_n = 1.203$ MeV
- $E_n = 1.306$ MeV
- $E_n = 1.511$ MeV
- $E_n = 1.715$ MeV
- $E_n = 1.918$ MeV
- $E_n = 2.121$ MeV
- $E_n = 2.323$ MeV
- $E_n = 2.525$ MeV
- $E_n = 2.727$ MeV
- $E_n = 2.929$ MeV
- $E_n = 3.130$ MeV
- $E_n = 3.332$ MeV
- $E_n = 3.533$ MeV
- $E_n = 3.734$ MeV
- $E_n = 3.935$ MeV
- $E_n = 4.136$ MeV
- $E_n = 4.336$ MeV
- $E_n = 4.537$ MeV
- $E_n = 4.738$ MeV
P-i-N diode simulation . . .

“Front-side injection”

“Rear-side injection”

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Pulse Discrimination between............
............ Neutron Spectrometer
… and measurements

![Graph showing pulse discrimination between electron and proton]

Preamplifier output signal (mV)

Time (ns)

- **Electron**
- **Proton**

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Pulse Discrimination between...........

......... Neutron Spectrometer
Electronics for pulse shape analysis
Custom low noise preamplifier

![Graph showing ENC (electrons) vs. Shaping time (ns)]
Energy-time scatter plot for monoenergetic neutrons

Deposited energy $E$

Start-stop time interval $T_{ss}$

Window for discrimination

$E_n = 3.3$ MeV

Protons

$T_{ss}$ threshold

Electrons
Pulse width vs. energy scatter plots

En = 3.3 MeV

En = 1.3 MeV

\[ V_{\text{BIAS}} = V_{\text{dep}} + 10 \text{ V} \]
n-γ discrimination on timing spectrum

Counts per unit neutron fluence (cm$^2$)

Start-stop interval (ns)

- diode with polyethylene
- diode without polyethylene

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Pulse Discrimination between..........     ............ Neutron Spectrometer
Timing spectra vs. diode bias voltage  \( \text{En} = 1.3 \text{ MeV} \)

![Graph showing timing spectra vs. diode bias voltage for different reversed voltages.](image)

- **Counts per unit charge (\( \mu \text{C}^{-1} \))**
- **T\(_{\text{start-stop}}\) (ns)**

Reversed voltage
- 29 V
- 30 V
- 31 V
- 32 V
- 33 V
- 34 V
Energy spectrum with electron (γ) anticoincidence
Energy spectra with discrimination (0.8 - 3.5 MeV)

Counts per unit neutron fluence (cm$^2$)

Deposited energy (keV)

(a) $E_n = 0.787$ MeV
(b) $E_n = 0.892$ MeV
(c) $E_n = 1.100$ MeV
(d) $E_n = 1.306$ MeV
(e) $E_n = 1.715$ MeV
(f) $E_n = 1.918$ MeV
(g) $E_n = 2.323$ MeV
(h) $E_n = 2.727$ MeV
(i) $E_n = 3.138$ MeV
(l) $E_n = 3.533$ MeV

(d1) $E_n = 1.306$ MeV without discrimination
Energy spectra for low-energy neutrons

![Graph showing energy spectra for different neutron energies](image)

- Red line: $E_n = 0.787$ MeV
- Green line: $E_n = 1.100$ MeV
- Blue line: $E_n = 1.306$ MeV

Graph notes:
- $E_n = 1.306$ MeV (without electrons anticoincidence)
Timing spectra for low-energy neutrons

Counts per unit neutron fluence (cm$^2$)

$E_n = 0.892$ MeV
$E_n = 0.996$ MeV
$E_n = 1.100$ MeV
$E_n = 1.203$ MeV
$E_n = 1.306$ MeV

Rise time (ns)
Unfolding check on monoenergetic neutrons

![Graph showing neutron spectra]

- $E_n = 2.53$ MeV
- $E_n = 3.13$ MeV
- $E_n = 3.73$ MeV

Neutrons fluence per unit charge ($\text{cm}^{-2} \mu\text{C}^{-1}$)

Energy (MeV)
Neutron continuous spectrum
0° by 5 MeV protons striking a thick beryllium target

Conclusions and perspectives

• A recoil-proton spectrometer for neutrons based on silicon diode operating in the 1-6 MeV range has been realized and tested

• $n-\gamma$ discrimination is feasible and effective to lower the detection limit. Partial failure below 1.2 MeV will be investigated

• A thicker diode will increase the upper detection limit to 10 MeV

• A thinner dead-layer will decrease the lower limit

• An intercomparison with other types of n-spectrometer is planned

• Simpler and better (digital?) discrimination will be investigated

References: Proc. 2003 IEEE NSS (Portland), N26-75
S. Agosteo et al., "Neutron spectrometry with a recoil radiator-solicon detector device," NIM, in press