All neutron detection relies on observing a neutron-induced nuclear reaction.

The capture cross sections for fast-neutron induced reactions are small compared to those at low energies (in the limit: geometric with resonances).

Two approaches to detect fast neutrons:
– thermalized & capture which only provides a “count”

– Elastic scatter from protons at high energy – observe recoils for ToF techniques.

Fig. 15.9 Knoll, 3rd Ed.
Bonner Spheres – “Counter”

\[ n + ^3\text{He} \rightarrow (^4\text{He})^* \rightarrow p + ^3\text{H} \text{, } Q=0.765 \text{ MeV} \]

Moderate neutrons in spheres of different sizes and then detect the neutrons in a proportional counter in the center. Add metal for highest energy neutrons … unfold response to get distribution.

STS-102 Space Shuttle, six spheres, 3He, 6atm
Fast neutron detection: Long Counter

\[ \text{n} + ^{10}\text{B} \rightarrow (^{11}\text{B})^* \rightarrow ^{7}\text{Li}^* + ^4\text{He} , \text{Q}=2.31 \text{ MeV}, \text{Branch}=94\% , \text{target abundance} = 19.9\% \]

\[ \rightarrow ^{7}\text{Li} + ^4\text{He} , \text{Q}=2.79 \text{ MeV}, \text{Branch}=6\% \]

NSCL Bucket neutron detectors use BF\textsubscript{3} (1” diameter, 4” long, 400Torr) in a parafin filled container.

Fig. 15.6 Knoll, 3\textsuperscript{rd} Ed.
Gd-loaded Liquid Scintillator – “Counter”

\[ n + ^{157}\text{Gd} \rightarrow (^{158}\text{Gd})^* \rightarrow ^{158}\text{Gd} + \gamma, \ Q \sim 8 \text{ MeV}, \ \text{target abundance} = 15.6\% \ (255k \text{ barns}) \]

“ORION” detector at GANIL, similar to “superBall” at NSCL (both decommissioned)
Fast Neutron Detection: Scattering

\[ \frac{E_R}{E_n} = \frac{4A}{(1 + A)^2} \cos^2 \theta_{lab} \quad \text{max at } \theta_{lab} = 0^\circ \]

<table>
<thead>
<tr>
<th>Tgt</th>
<th>A</th>
<th>$4A/(1+A)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$^2\text{H}$</td>
<td>2</td>
<td>8/9=0.889</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>4</td>
<td>16/25=0.64</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>12</td>
<td>48/169=0.284</td>
</tr>
</tbody>
</table>

Fig. 15.15 Knoll, 3rd Ed.
Proton-radiator telescope: Target allows protons to escape. Target thickness has to be consistent with the $\Delta E/\Delta \Theta$ of the recoil angular distribution.

20 MeV n .. Scatters and gives protons 
10 MeV p in CH$_2$ .. dE/dx $\sim$30MeV/ g/cm$^2$

$$Ep = En \cos^2 \theta$$
$$\Delta Ep = Ep(\theta) - Ep(0)$$
$$\Delta Ep = En[1-\cos^2 \theta]$$
$$\Delta Ep = En \sin^2 \theta \quad (\sim3\% \text{ for } 0-10^\circ)$$

Energy loss must be less than change with angle

$$\Delta x \sim \Delta Ep / (dE/dx) = 0.03 \times 20\text{MeV} / 30 \text{MeV/ g/cm}^2$$
$$\Delta x \sim 0.02 \text{ g/cm}^2$$

Efficiency is set by thickness

$$n \Delta x \sim (2\times6\times10^{23} / 14) \times 0.02 = 1.7\times10^{21} / \text{cm}^2$$
$$\sigma(E=20 \text{ MeV}) = 0.4 \text{ b}$$
$$\varepsilon = 1 - e^{-n \Delta x \sigma} = 7\times10^{-4}$$

Give up! Use a thick plastic scintillator .. 10 cm $\varepsilon\sim0.2$
Fast Neutron Detection: Scattering Pulse Height

$^{12}\text{C}(n,n')$ cross section has a modest angular distribution. Small energy dependence on recoil angle. The $^1\text{H}(n,n')$ distribution is flat.

Combine and fold with scintillator light output

2.6 MeV neutron 1”x1” stilbene

NE213 into 1.9cm x10cm

Set threshold
Fast Neutron Detection: Arrays

MoNA plastic scintillator
Ten layers – plastic scint.

Add Iron converter layers

NSCL “neutron wall”
One layer of liquid scint.

\[ E = \frac{m}{2} v^2 = \frac{m}{2} \left( \frac{L}{t} \right)^2 \]

\[ \frac{dE}{dt} = -\frac{mL^2}{t^3} \rightarrow \frac{dE}{dt} = -\frac{2E}{t} \rightarrow \frac{dE}{E} = \frac{-2dt}{t} \]
Estimate the number of photons reaching the end of a MoNA slat from the interaction of a cosmic ray muon passing through the midpoint of the slat. The attenuation length of the slats was found to be 4.2m, the slats are 200x10x10 cm$^3$, are made from BC-408 scintillator and are readout on the long ends.