中子及中子探测
Neutron and Neutron Detection

周荣 Rong ZHOU
四川大学 核科学与工程技术学院
College of Nuclear Science & Engineering, SCU
zhourong@scu.edu.cn

Outline

- Characteristics of Neutron
- Neutron Source
- Interaction of Neutron with Matter
- Neutron Detection
  - Neutron detector
  - energy spectrum measurement
  - flux measurement

CHARACTERISTICS OF NEUTRON

Classification of Neutron by Energy

- Cold neutron:
- Thermal neutron: E=0.0253eV
- Epithermal neutron
- Slow neutron: E<1keV
- Moderate Energy neutron: E=1~100keV
- Fast neutron: E=0.1~20MeV

Characteristics of Neutron

- Uncharged
- m_n = 1.67492716 ×10-24g = 1.00865u = 939.565330MeV
- S=1/2, μ_n=-1.9130428μ_N
- β^- decay , T1/2=10.6min

$$n \rightarrow p + \beta^- + \tilde{\nu}_e$$

NEUTRON SOURCE

Isotopic Neutron Source

- Using (α, n) or (γ, n) reaction to produce neutron
- Using spontaneous fission to produce neutron

(α, n) type neutron source

$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + \mathrm{n} + Q$$

- Q: reaction energy, 5.702MeV
- ^{12}C could be on ground state or excited state.
- γ ray would be emitted when ^{12m}C de-excite.
- neutron energy spectrum is continuous

(α, n) Type Neutron Source

- ^{226}Ra-Be
- ^{210}Po-Be
- ^{241}Am-Be
  - average energy of neutron: 5.0 MeV,
  - ^{241}Am $T_{1/2}$=433a, stable neutron yield
  - low γ base
- ^{239}Pu-Be
  - not very common

(γ, n) Type Neutron Source

$$\gamma + {}^{9}\mathrm{Be} \rightarrow {}^{8}\mathrm{Be} + \mathrm{n} - 1.665\mathrm{MeV}$$

$$\gamma + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} - 2.224\mathrm{MeV}$$

- mono-energetic (Why?)
- low and non-stable neutron yield
- large volume

(γ, n) Type Neutron Source

Source	Half time	Neutron energy (MeV)	Neutron Yield ($10^6 s^{-1} Ci^{-1}$)
^{124}Sb-Be	60.20d	0.024	3.6
^{72}Ga-$^{2}H_2O$	14.10d	0.16	0.64
^{24}Na-$^{2}H_2O$	15.02h	0.22	2.7
^{140}La-Be	40.3h	0.62	0.04
^{24}Na-Be	15.02h	0.83	2.4

Spontaneous Fission Neutron Source

- ^{244}Cm, ^{249}Bk, ^{252}Cf, ^{254}Es, ^{255}Fm
- 1g ^{252}Cf emits 2.31×10^{12} n/s
- Very expensive, tens of gram of ^{252}Cf could be produced in two years in a 100MW reactor.

Accelerator Neutron Source

$$^{2}H + d \rightarrow {}^{3}He + n + 3.269MeV$$

$$^{3}H + d \rightarrow {}^{4}He + n + 15.59MeV$$

- Accelerate p/d/α particles to bombard target nuclei.
- Could produce mono-energetic neutrons of suitable intensity

Reactor Neutron Source

- Produce neutrons by chain reaction in reactor

INTERACTION OF NEUTRON WITH MATTER

Interaction of Neutron with Matter

- Neutron is uncharged, so it can NOT interact with electrons
- Interaction with nucleus
- Secondary charged particle interact with matter: ionization

Absorption of Neutron

- Radioactive Capture (n, γ)
- Nuclear Reaction (n, α), (n, p)
- Fission (n, f)
- Multi-particle Emission (n, 2n), (n, np)

Radioactive Capture

$$n + {}^{235}U \rightarrow {}^{236}U + \gamma$$

$$n + {}^{115}In \rightarrow {}^{116}In + \gamma$$

$${}^{116}In \xrightarrow{T_{1/2}=14.1s} {}^{116}Sn + \beta^{-} + \tilde{\nu}_e$$

1: Neutron Activation Analysis
2: Measure neutron flux

(n, α/p) nuclear reaction

$$\mathrm{n}+{}^{10}\mathrm{B}\rightarrow\begin{cases}\alpha+{}^{7}\mathrm{Li}+Q(2.792\mathrm{MeV},6.1\%)\\ \alpha+{}^{7}\mathrm{Li}+Q(2.310\mathrm{MeV},93.9\%)\end{cases}\qquad \sigma_0=3837\pm9\mathrm{b}$$

$$\mathrm{n}+{}^{6}\mathrm{Li}\rightarrow\alpha+{}^{3}\mathrm{H}+4.786\mathrm{MeV}\qquad \sigma_0=940\pm4\mathrm{b}$$

$$\mathrm{n}+{}^{3}\mathrm{He}\rightarrow\mathrm{p}+{}^{3}\mathrm{H}+0.765\mathrm{MeV}\qquad \sigma_0=5333\pm7\mathrm{b}$$

$$\sigma=\frac{\sigma_0 v_0}{v}\propto\frac{1}{v}\propto\frac{1}{\sqrt{T_n}}$$

cross section of thermal neutron

Fission (n, f)

Thermal neutron:

$$^{233}\mathrm{U}\ \ \sigma_0 = 531.1 \pm 1.3\mathrm{b}$$

$$^{235}\mathrm{U}\ \ \sigma_0 = 582.2 \pm 1.3\mathrm{b}$$

$$^{239}\mathrm{Pu}\ \ \sigma_0 = 742.5 \pm 3.0\mathrm{b}$$

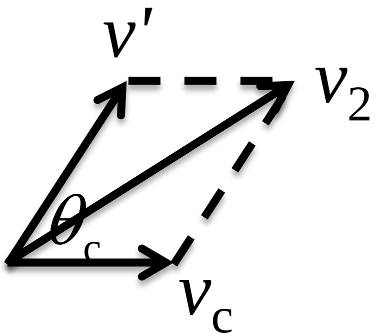
Fast neutron: ^{238}U

Multi-particle Emission (n, 2n), (n, np)

- Ultrafast neutron (>8~10Mev) could cause this kind of interaction

Elastic Scattering

$$v' = v_1 - v_c = v_1 - \frac{m}{M+m} v_1 = \frac{M}{M+m} v_1$$



$$v_2^2 = v_c^2 + v'^2 + 2 v_c v' \cos\theta_c$$

$$= \frac{v_1^2}{(M+m)^2} (m^2 + M^2 + 2mM\cos\theta_c)$$

$$\frac{E_2}{E_1} = \frac{1}{(M+m)^2} (m^2 + M^2 + 2mM\cos\theta_c)$$

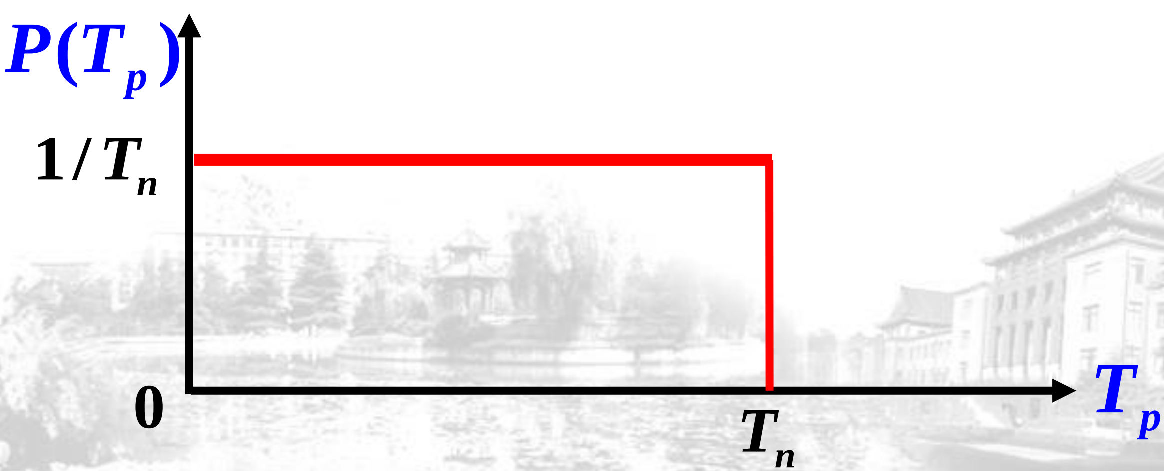
$$= \frac{1}{2}[(1+\alpha) + (1-\alpha)\cos\theta_c] \quad \alpha = \left[\frac{M-m}{M+m}\right]^2 \approx \left[\frac{A-1}{A+1}\right]^2$$

Elastic Scattering

$$\Delta E = E_1 - E_2 = \frac{E_1}{2}(1-\alpha)(1-\cos\theta_c)$$

When target is ^1H

$$T_p = \Delta E = E_1 - E_2 = \frac{E_1}{2}(1-\cos\theta_c)$$



NEUTRON DETECTON

How to detect neutron?

- By nuclear reaction
- By recoil nucleus
- By nuclear fission
- By neutron activation

Detect Neutron by Nuclear Reaction

- $^{10}B(n, \alpha)^{7}Li$ reaction
  - BF_3(gas), B_2O_3(solid), B_4C (solid)
  - ^{10}B natural abundance 19.8%, concentrated to 96%
- $^{6}Li(n, \alpha)^{3}H$ reaction
  - High reaction energy, easy to identify γ and neutron
  - ^{6}Li natural abundance 7.5%, expansive to concentrate
- $^{3}He(n, p)^{3}H$ reaction
  - Large cross section,
  - low natural abundance(1.38×10^{-4}%), expansive
- for slow neutron detection,
- hard to measurement the energy, for Q>>En
- suitable for flux measurement

Detect Neutron by Recoiled Nucleus

$$E_p = E\cos^2\phi$$

- $\Phi=0^\circ$,$E_p=E$
- $\Phi=10^\circ$,$E_p=0.97E$
- For fast neutron detection

Detect Neutron by Fission

- detect fisson fragment to record neutron
- ^{235}U, ^{239}Pu, ^{233}U for thermal neutron
- ^{232}Th, ^{238}U etc. for fast neutron "threshold detector"
- E_f~200MeV >> $E_{n,}$ So hard to measure neutron's energy

Detect Neutron by Activation

- Activate materials by (n, γ) reaction
- Measure the radioactivity of the activated material

Summarize

Method	Interaction	Material	Cross Section (10^{-24} cm^2)	Usage
Nuclear Reaction	(n, α) (n, p)	^{10}B, ^{6}Li, ^{3}He	~1000	thermal/slow neutron's flux
Recoiled Nucleus	(n,n)	H	~1	fast neutron's energy
Nuclear Fission	(n,f)	^{235}U, ^{239}Pu ^{238}U,	~500 ~1	flux
Activiation	(n,γ)	In, Au, Dy, etc.	thermal neutron ~100 response neutron ~1000 fast neutron ~1	flux

NEUTRON DETECTOR

Neutron Detector

- Gas-filled detector
- Scintillation detector
- Semiconductor detector
- self-powered detector

BF_3 Proportional Tube

$$n+{}^{10}B \rightarrow \begin{cases} \alpha + {}^{7}Li + Q(2.792\,MeV, 6.1\%) \\ \alpha + {}^{7}Li + Q(2.310\,MeV, 93.9\%) \end{cases} \qquad \sigma_0 = 3837 \pm 9\,b$$

- A proportional tube employing BF_3 as operating gas
- Mainly for thermal and slow neutron detection
- Neutron energy E<<Q, only for flux measurement

Output of BF_3 Detector

- Let m_1 and m_2 be the mass of α and ^{7}Li, and ignore neutron's energy, so

$$m_1 v_1 + m_2 v_2 = 0$$

$$\frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 = Q$$

Energy of α： $7Q/11$, 1.47MeV(93.9%),
Energy of ^{7}Li: $4Q/11$, 0.84MeV(93.9%),

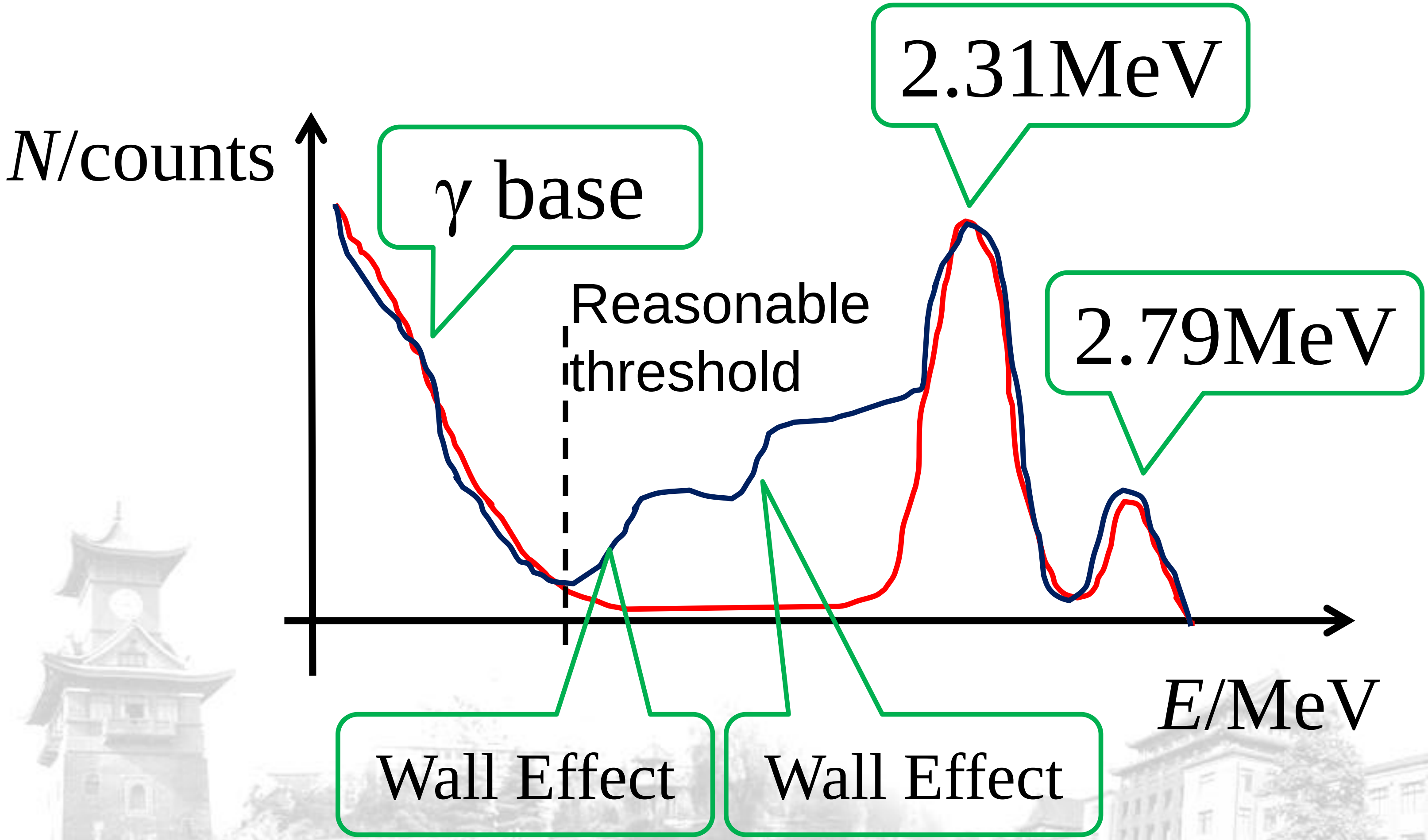
Output of BF_3 Detector

$$w = 30eV, N_p = 2.31MeV / w = 77000$$

Suppose C_d=4 pf, A=10,

$$v = \frac{77000 \times 1.6 \times 10^{-19} \times 10}{4 \times 10^{-12}} = 30(mV)$$

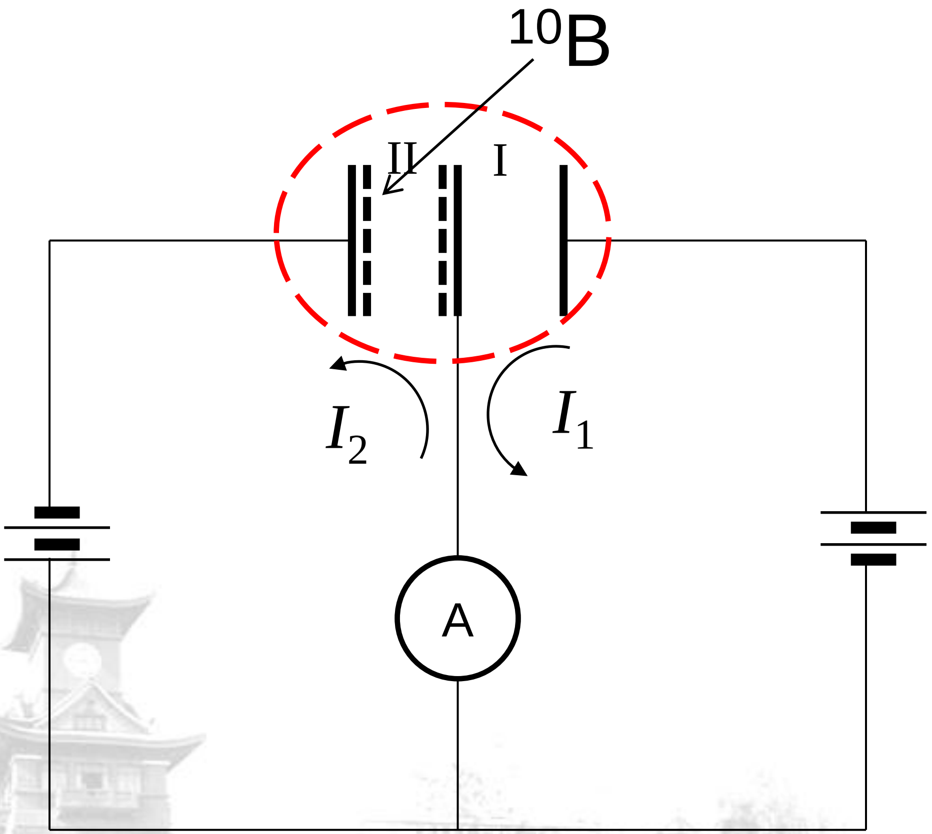
Spectrum output by BF_3



Other Characteristic of BF_3

- Plateau curve
- Efficiency = Number of neutron reacting with ^{10}B / Number of incident neutron
  - ε≈5% for thermal neutron when using natural Boron.
- Question: What factors determine the efficiency of BF_3 detectors?

Compensated Boron Chamber



$$I_1 = I_\gamma$$

$$I_2 = I_\gamma + I_n$$

$$I = I_2 - I_1 = I_n$$

Range:
$10^5 \sim 10^{10}/cm^2 \cdot s$

Fission Chamber

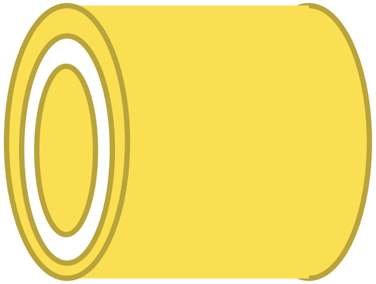
- Add a layer of ^{235}U (with thickness of ~2mg/cm^2) on the node of chamber
- Because of large energy emitted in fission, γ signals could be easily wiped out by threshold.
- Flux sensitivity ~ 0.5s^{-1}
- Maximum ~$10^5 s^{-1}$

Scintillation Detector

- ZnS(Ag) fast neutron scintillation screen
- ZnS(Ag) slow neutron scintillation screen
- Lithium scintillator
- Organic scintillator

ZnS Fast Neutron Scintillation Screen

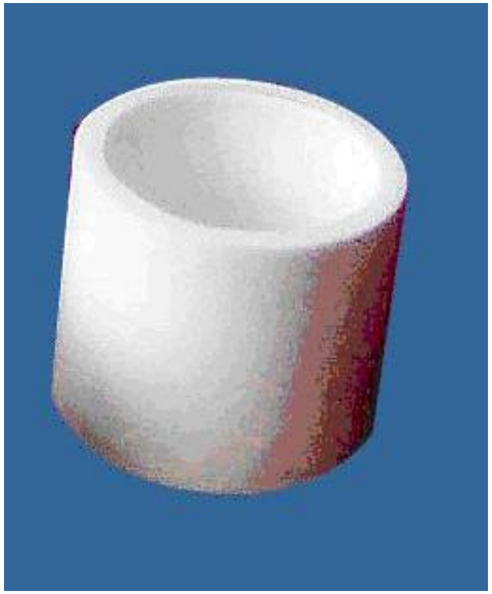
- ZnS + organic glass
- Elastic collision occurred between fast neutron and H in organic glass
- ZnS(Ag) interact with recoiled proton and scintillate



Roll Scintillator

ZnS Slow Neutron Scintillation Screen

$ZnS + {}^{10}B$



Neutron Cup

Lithium Scintillator

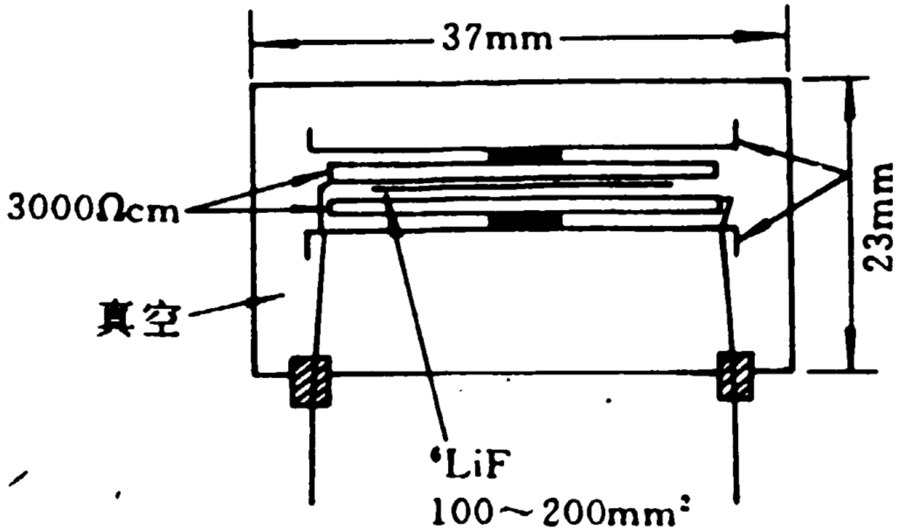
- $^{6}Li(n,\alpha)^{3}H$
- LiI(Eu)
  - Hygroscopic
  - ~100% efficiency for thermal neutron
  - Time resolution : ~0.3μs
- $LiO_2 \cdot 2SiO_2(Ce)$

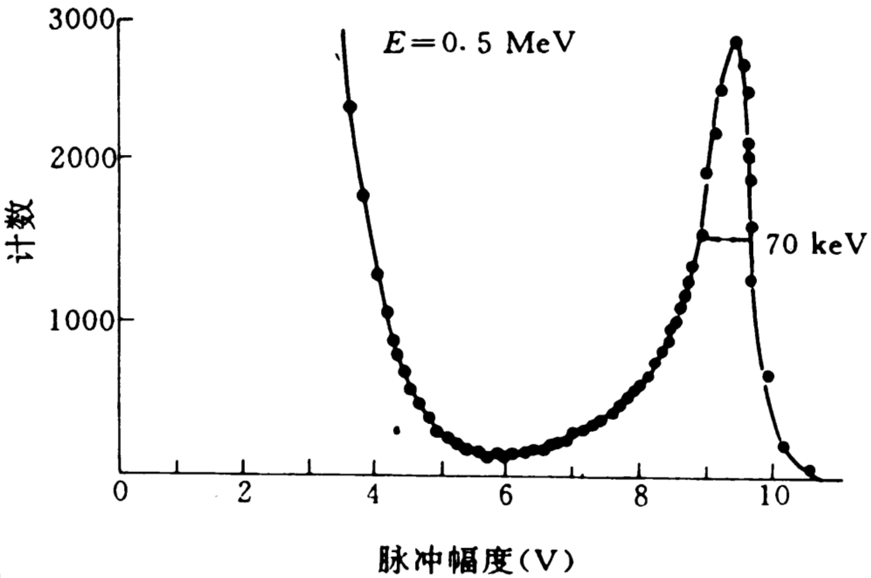
Organic Scintillator

- Organic scintillator is rich in Hydrogen
- Detect neutron by recording recoiled proton
- Anthracene crystal
- Stilbene crystal
- Plastic scintillator
- Liquid scintillator
  - Very short decay time
  - Discriminate n/γ by pulse shape

Semiconductor Detector

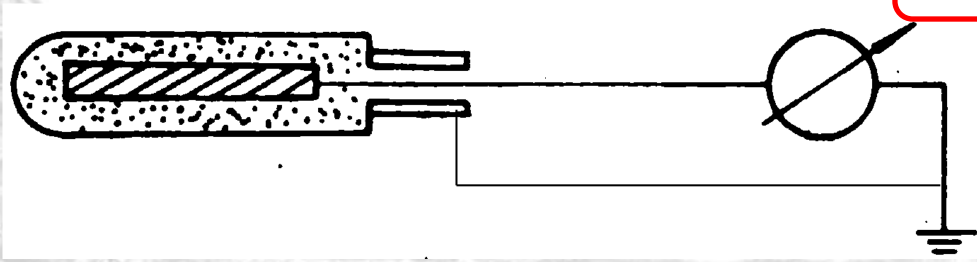
- ^{6}LiF+Au-Si Surface barrier detector
  - Not sensitive for γ
- For flux and energy spectrum measurement of fast neutron

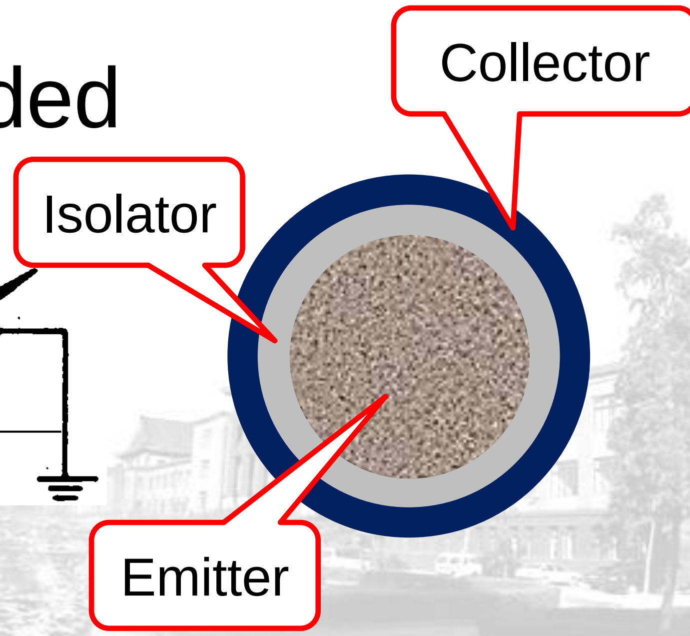




Self-powered detector

- Neutron activation (using ^{103}Rh or ^{51}V)
- β^- decay
- Measure the current of β^- particles to obtain the neutron flux
- No external power needed



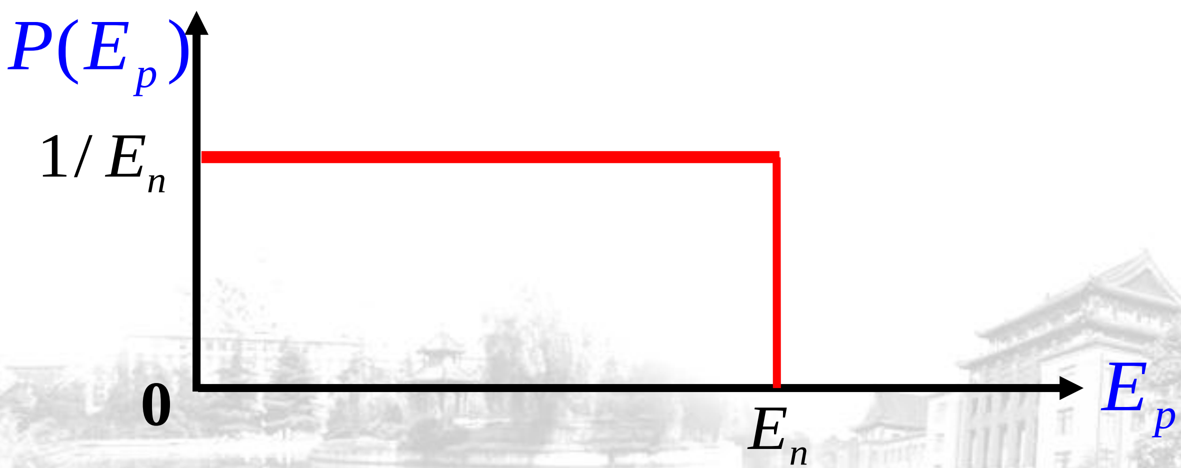


NEUTRON ENERGY SPECTRUM MEASUREMENT

By Recoiled Hydrogen

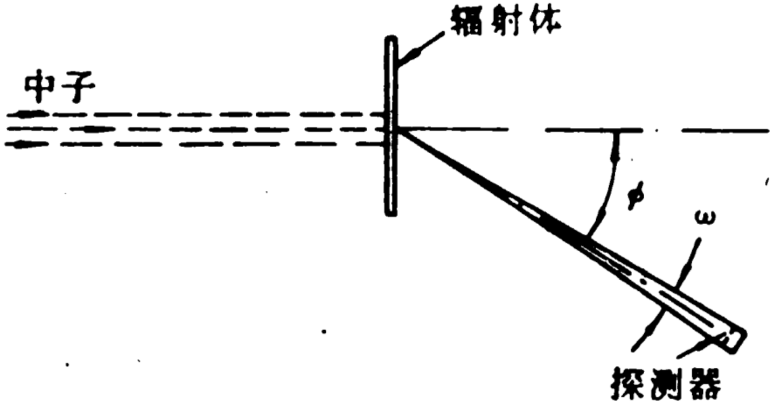
$$E_p = E_n \cos^2 \phi$$

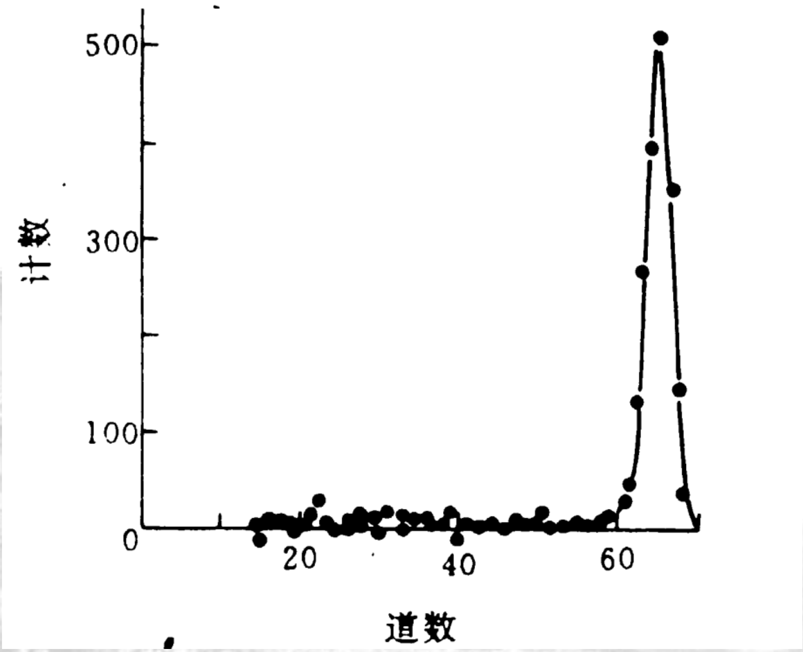
- Differential Measurement
- Integrating Measurement

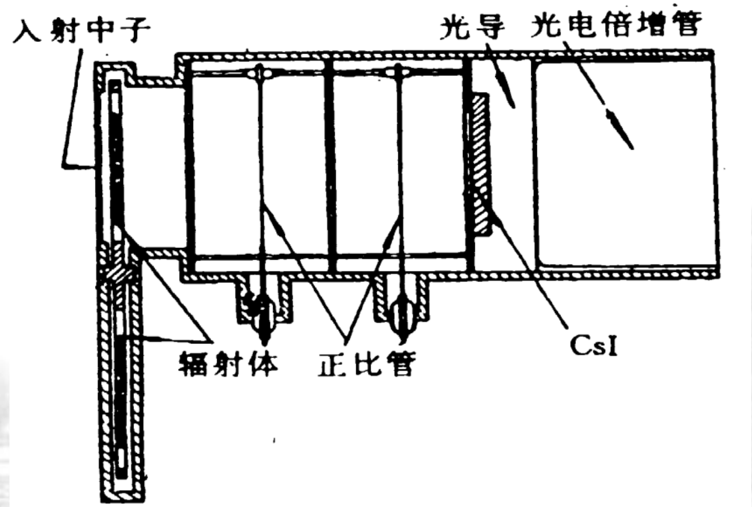


Differential Measurement

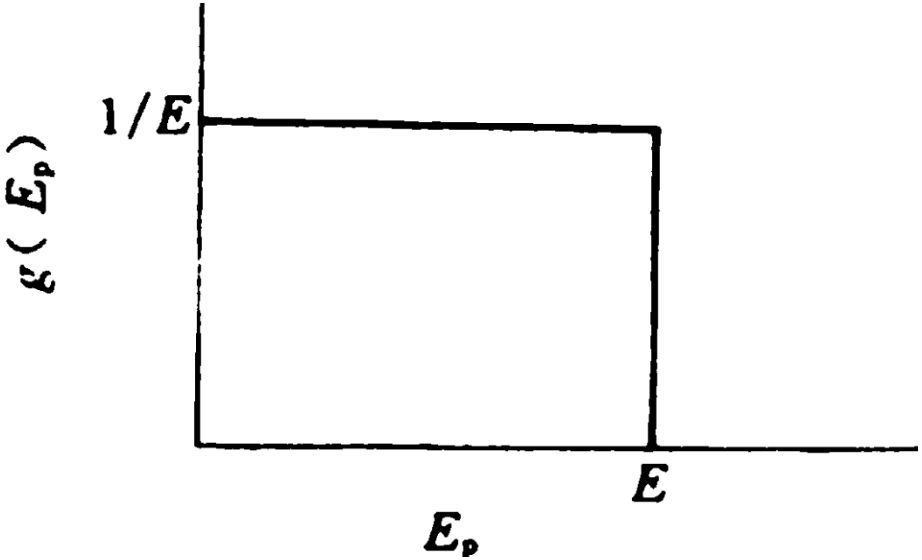
- $J(E_p) \sim \Phi(E) n \sigma(E) \omega / 4\pi$

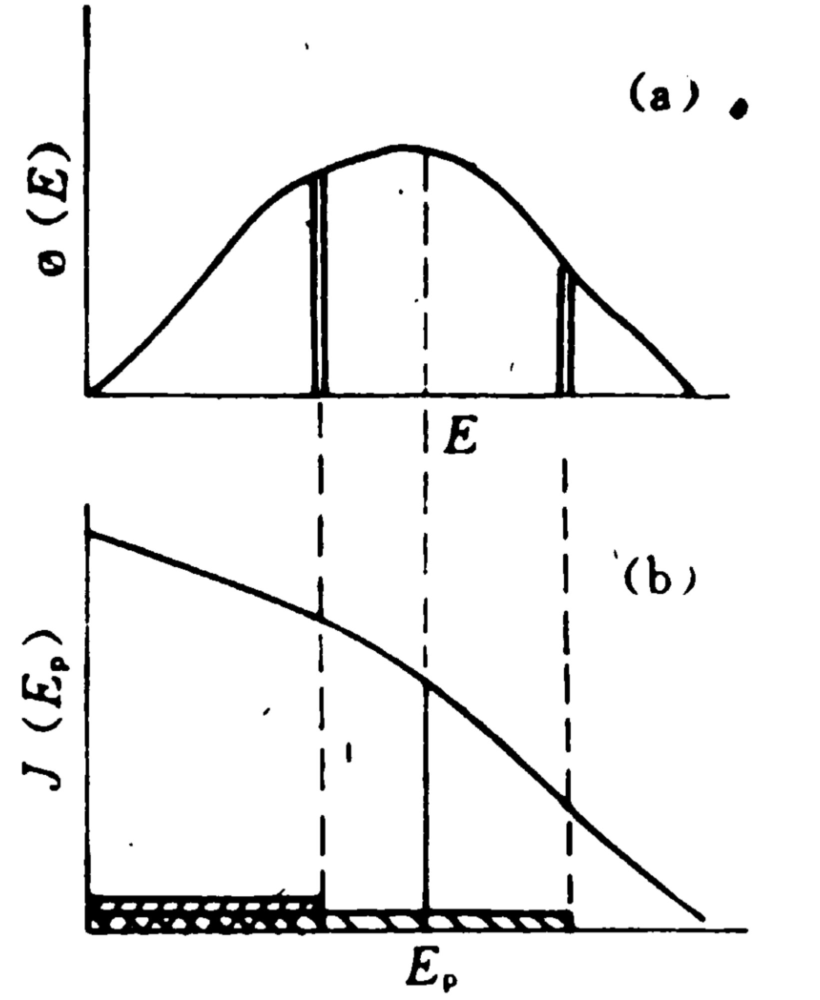


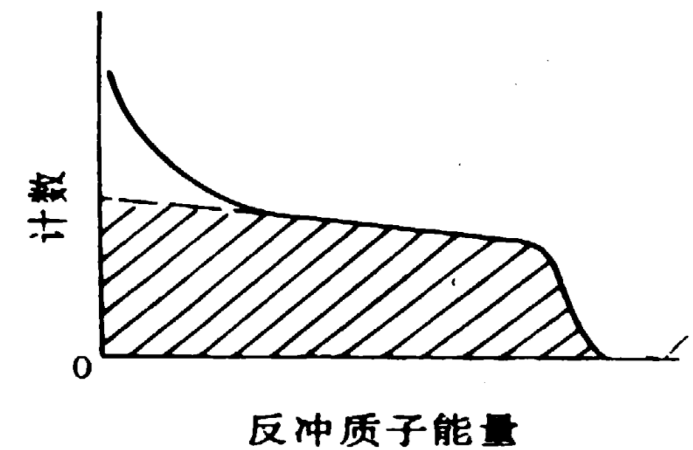




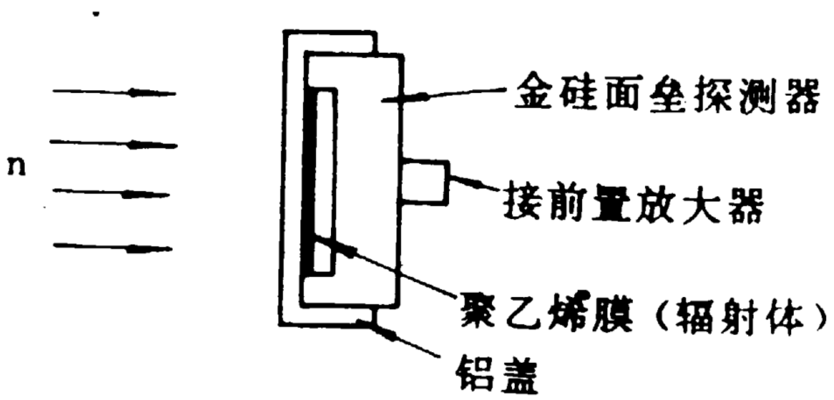
Integrating Measurement

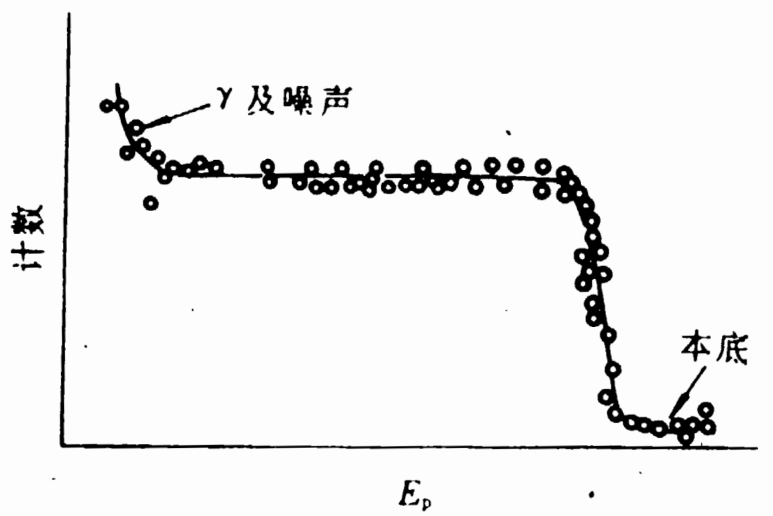


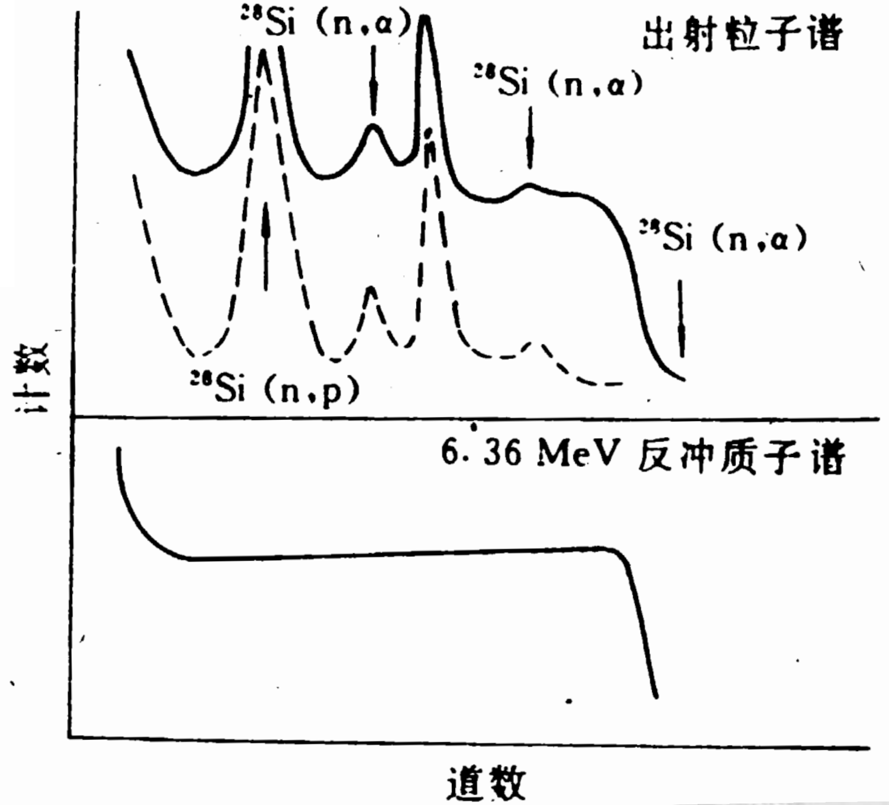




Flat Film Semiconductor Neutron Detector





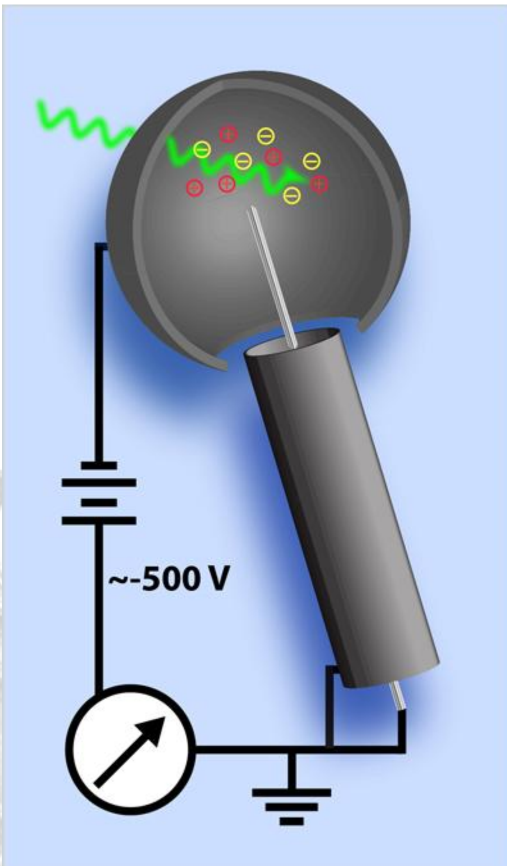


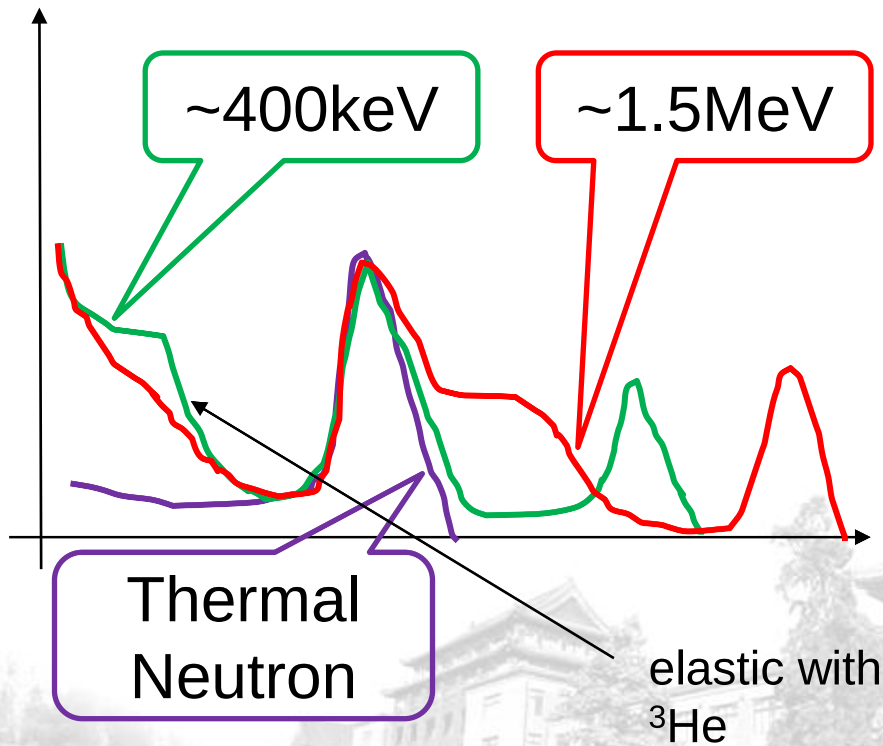
^{6}Li Spectrometer

- ^{6}LiI(Eu) Scintillation Detector
  - Only for spectrum measurement of neutron of energy above ~MeV, because of its limited energy resolution
- ^{6}LiF Sandwich Semiconductor Detector
  - could detect neutron of energy around 10keV or higher
  - Good energy resolution: 14.3keV@100keV, 3.75keV@6keV

^{3}He Spectrometer

$$n + {}^{3}\mathrm{He} \rightarrow p + {}^{3}\mathrm{H} + 0.765\,\mathrm{MeV} \qquad \sigma_0 = 5333 \pm 7\,\mathrm{b}$$





Only for neuron of energy less than 1Mev, with energy resolution 80keV

Time of Flight (TOF)

$$E = \frac{1}{2}mv^2, v = \frac{l}{t}$$

$$E = \frac{ml^2}{2t^2} = \frac{5226l^2}{t^2} \quad E\text{:eV}, \; l\text{:m}, \; t\text{:μs}$$

$$t = \frac{72.3l}{\sqrt{E}}$$

From time spectrum to energy spectrum

$$\phi(E)\varepsilon(E)dE = \varphi(t)dt$$

energy distribution of incident neutrons

detection efficiency

time of flight distribution

TOF Instrument

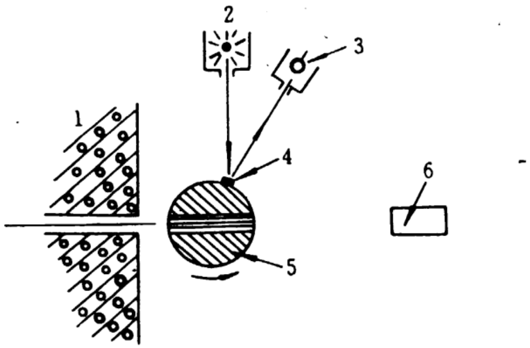


图11.32　机械选择器中子能谱仪
1——反应堆；2——光源；3——光电管；
4——镜子；5——转子；6——中子探测器。

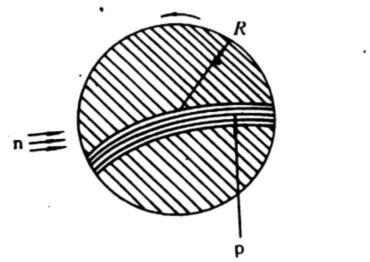
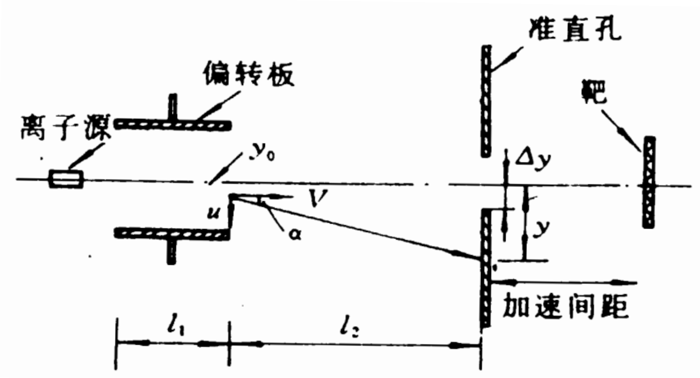


图11.33　狭缝是有曲率的转子



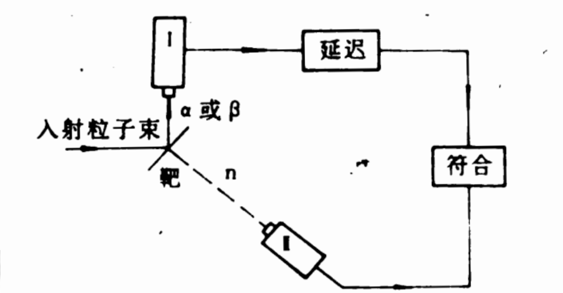
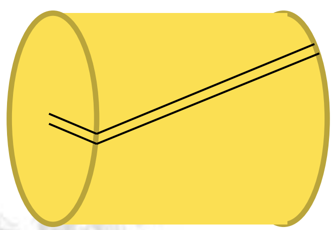


图11.30　伴随粒子法飞行时间谱仪原理图



Crystal Diffraction

$$2d\sin\theta = n\lambda$$

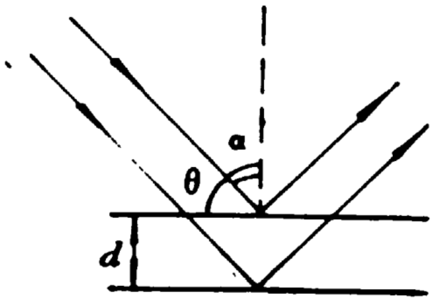


图11.36　中子波在晶体上的反射

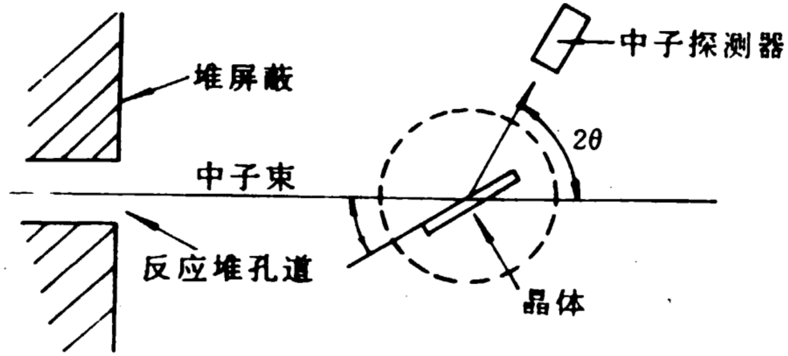


图11.37　中子晶体衍射谱仪示意图

FLUX MEASUREMENT

What is flux

$$\Phi = \int v n(v) dv$$

- v: velocity of neutron
- $n(v)$: density of neutrons with velocity in (v, $v+dv$)
- Φ: neutron flux, is a scalar

Flux Measurement

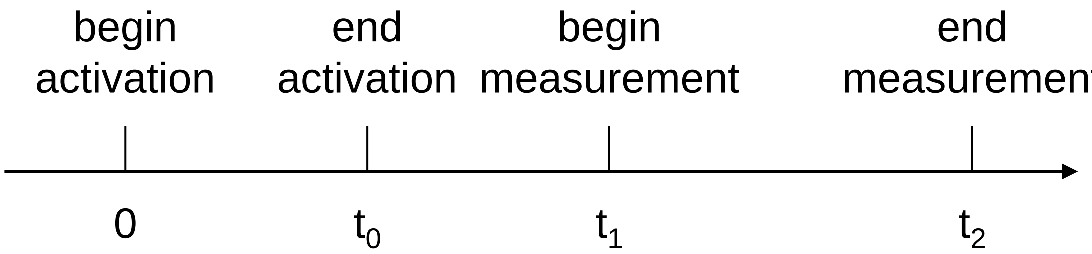
- (n,n) recoiled proton
- (n,γ) neutron activation
- (n,α), (n,p) nuclear reaction
- accompanying events measurement

By recoiled proton

$$n_p = \Phi \sigma P$$

- *Φ*: neutron flux
- σ: micro cross section
- *P*: number of hydrogen atoms
- n_p: count rate recorded by detector

By activation

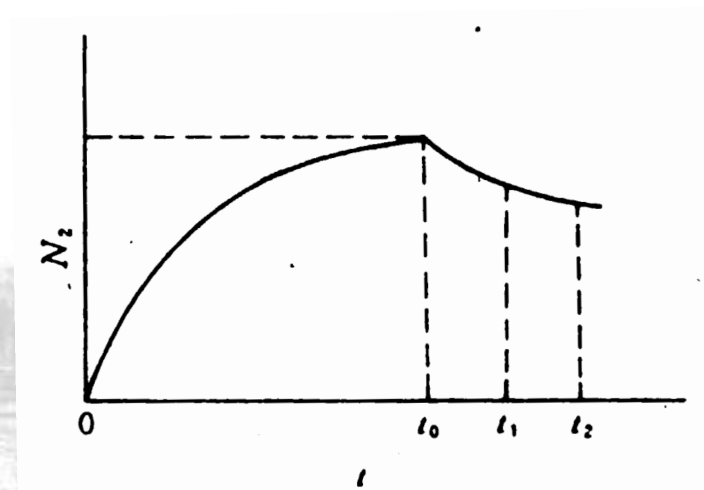


$$\frac{dN_2}{dt} = \sigma N_1 \Phi - \lambda_2 N_2$$

$$N_2(0) = 0$$

$$\Rightarrow \quad N_2(t) = \frac{N_1 \sigma \phi}{\lambda_2}(1 - e^{-\lambda_2 t})$$

$$N_2(t) = N_2(t_0) e^{-\lambda_2 (t_1 - t_0)}$$



Other measurement

- $MnSO_4$ bath method
- Accompanying particle method

Homework

- 2,3,4,5