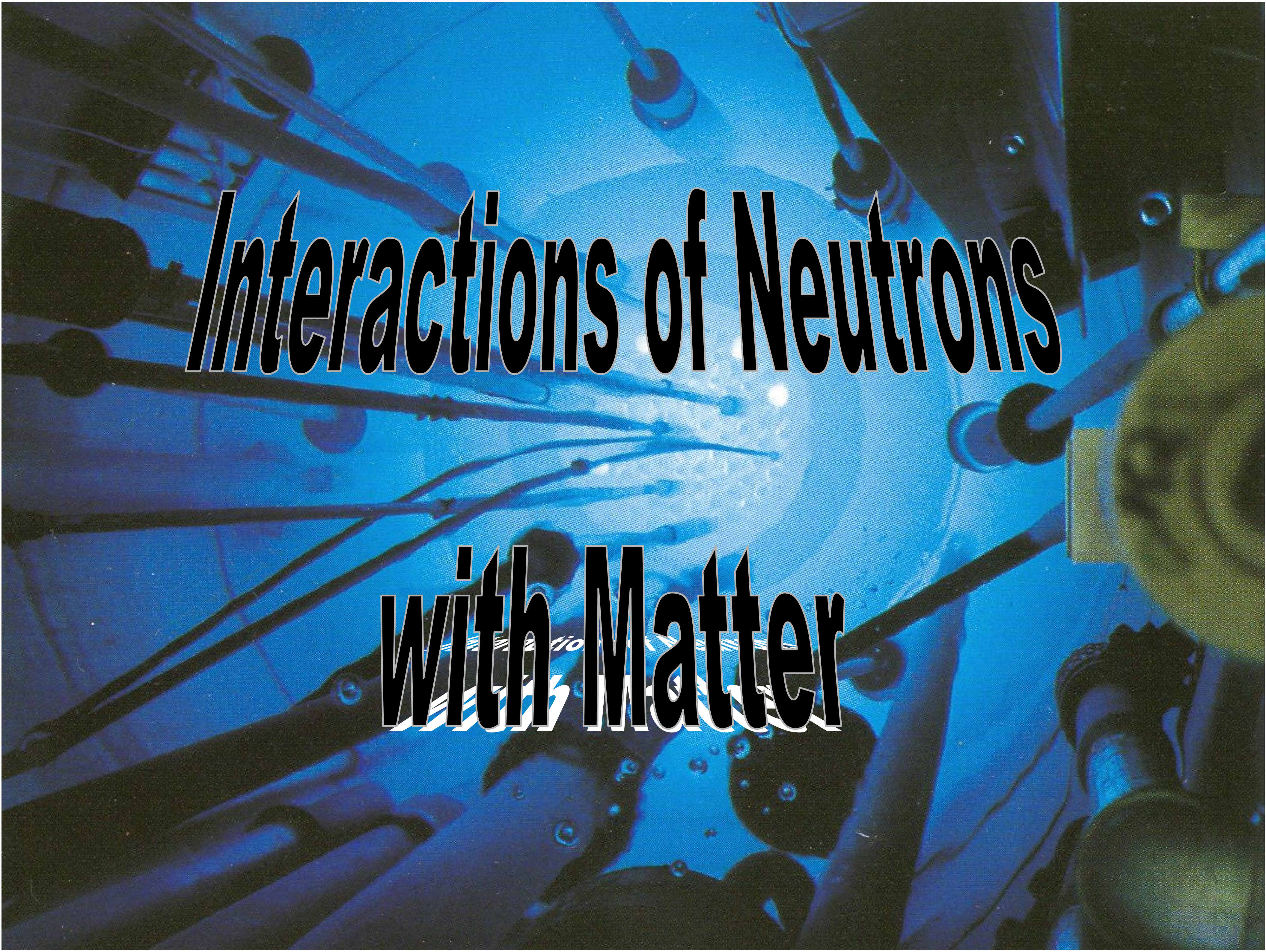

Interactions of Neutrons
with Matter

Commercial Neutron Generator ING-03

Neutrons can be produced in a variety of reactions, e.g., in nuclear fission reactors or by the $D(d,n)^3He$ or $T(d,n)^4He$ reactions

Specs: $< 3 \cdot 10^{10}$ $D(d,n)^3He$ neutrons/s Total yield $2 \cdot 10^{16}$ neutrons

Pulse frequency 1-100Hz Pulse width >0.8 μs, Power 500 W

Alternative option:
$T(d,n)^4He$, $E_n \approx 15$ MeV

Source: All-Russian Research Institute of Automatics **VNIIA**

Nuclear Interactions of Neutrons

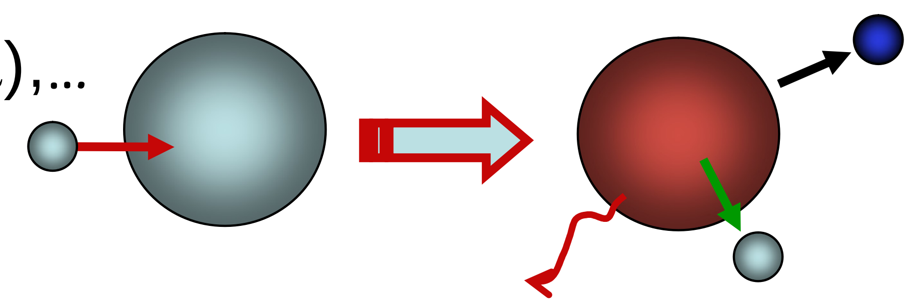
No electric charge → no direct atomic ionization → only collisions and reactions with nuclei → 10^{-6} x weaker absorption than charged particles

Processes depend on available n energy E_n:

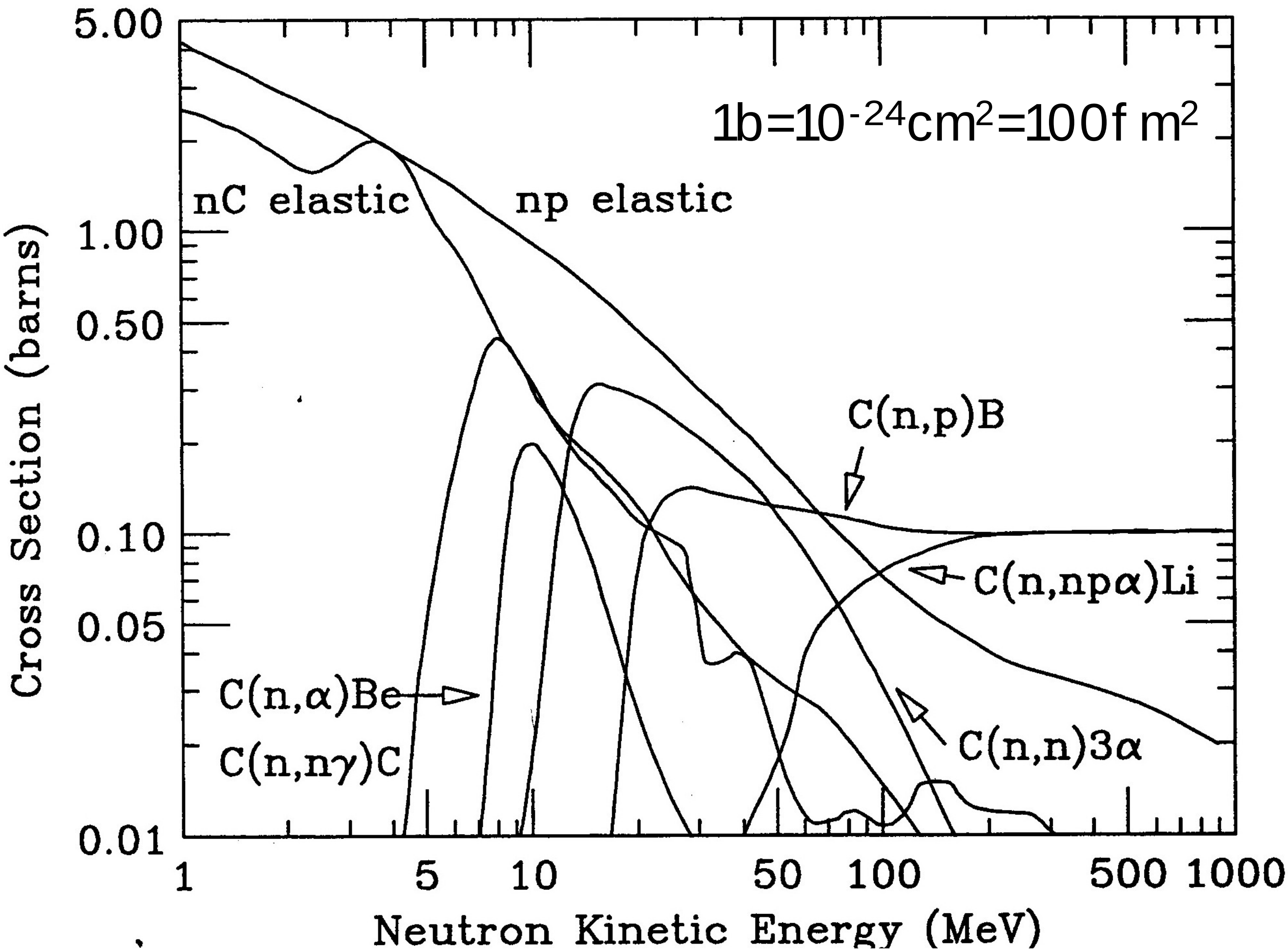
$E_n \sim 1/40$ eV		$(= k_B T)$ Slow diffusion, capture by nuclei
E_n <	10 MeV	Elastic scattering, capture, nucl. excitation
E_n >	10 MeV	Elastic+inel. scattering, various nuclear reactions, secondary charged reaction products

Characteristic secondary nuclear radiation/products:

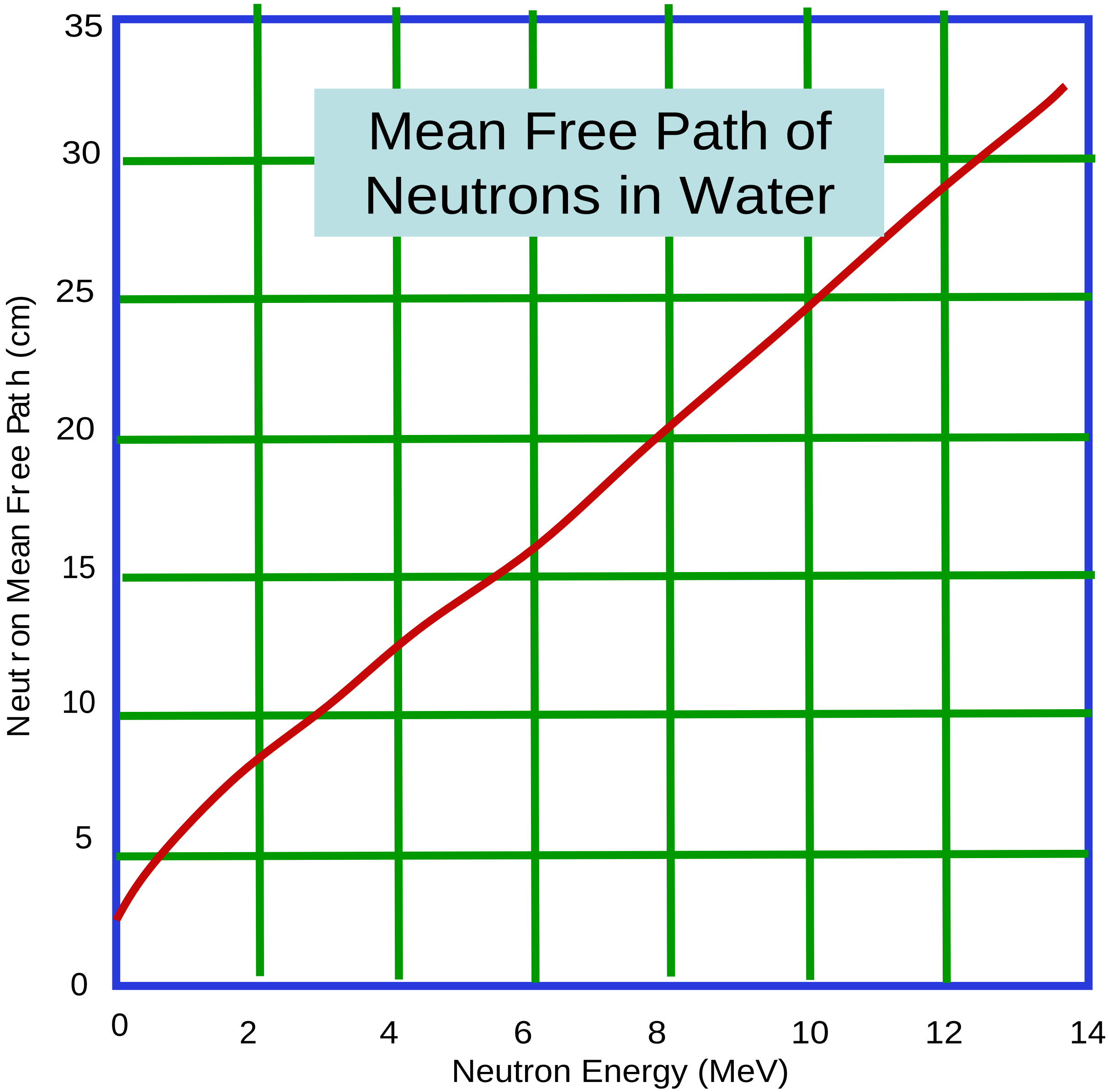
1. γ-rays (n, γ)
2. charged particles (n,p), (n, α),...
3. neutrons (n,n'), (n,2n'),...
4. fission fragments (n,f)



Neutron Cross Sections



Neutron Mean Free Path



$$N(x) = N(0)e^{-x/\lambda}$$

$$\lambda = \frac{1}{\mu} = \frac{1}{\rho\sigma} \quad mfp$$

ρ: atomic density
σ: cross section

λ = average path length in medium between 2 collisions

$$\Gamma_{FWHM} = 2.35 \cdot \sigma$$

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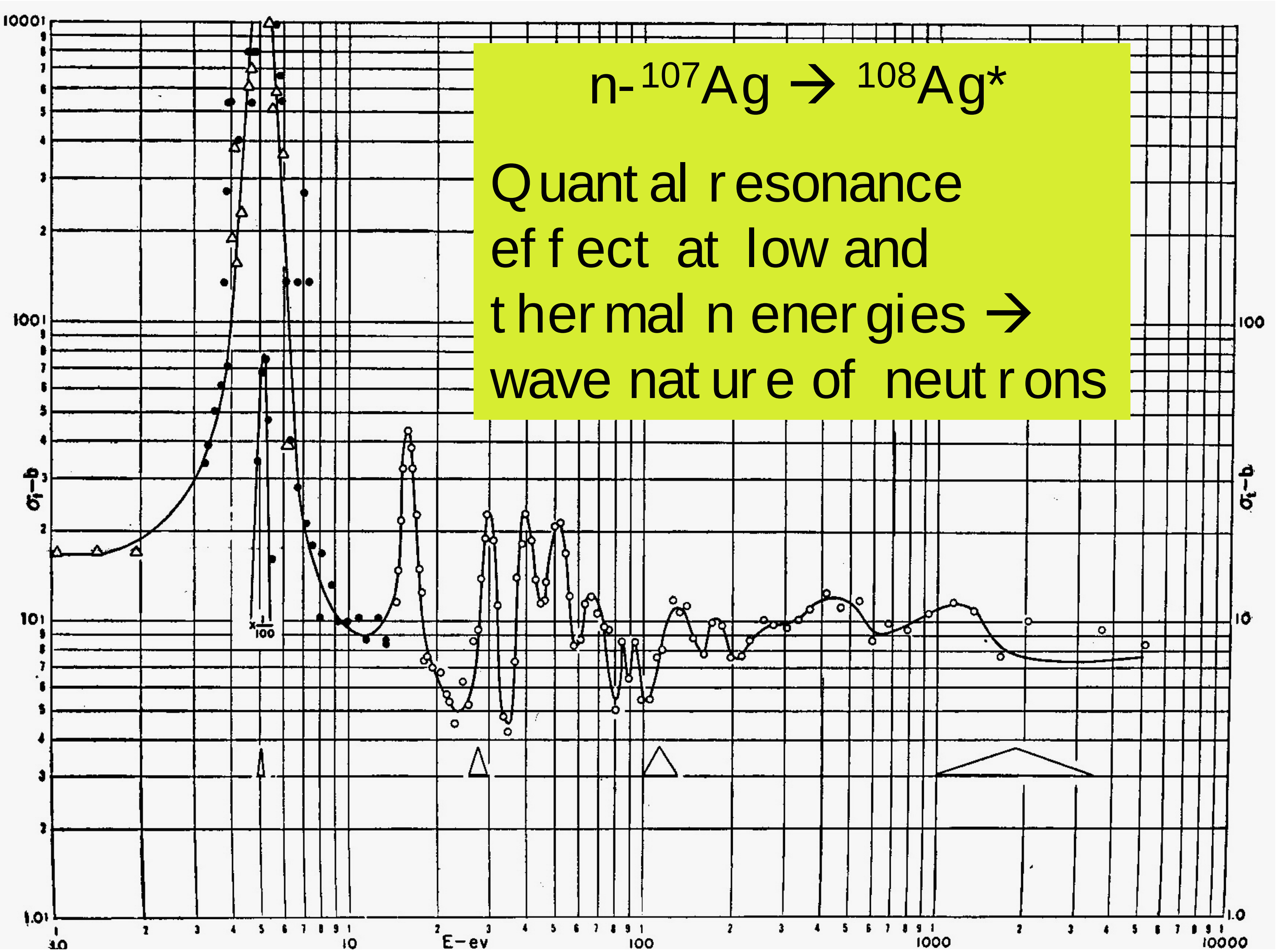
Neutron Resonance Capture



n-^{107}Ag → ^{108}Ag*

Quantal resonance effect at low and thermal n energies → wave nature of neutrons

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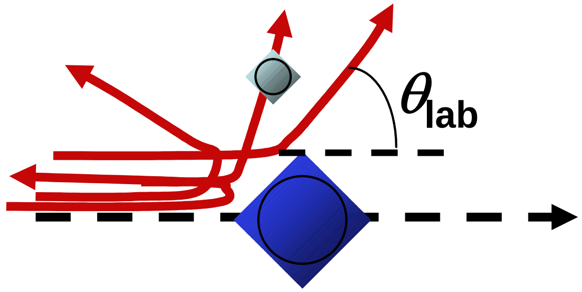
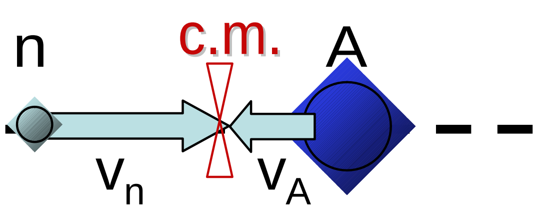
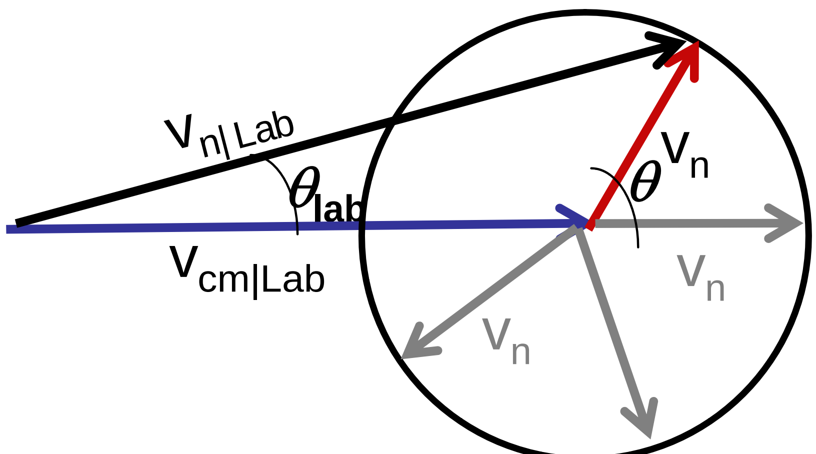
Energy Transfer in Elastic Scattering



Neutron with lab velocity v, energy E, scatters randomly off target nucleus of mass number A at rest in lab.





$$\max : v_{n|Lab} = v$$

$$\min \;: v_{n|Lab} = v\,\frac{A-1}{A+1}$$

$$c.m.: \; p_n = -p_A \qquad p_n + p_A = 0$$

$$v_n = v\,\frac{A}{A+1} \qquad v_A = -v\,\frac{1}{A+1}$$

$$v_{cm|Lab} = v\,\frac{1}{A+1}$$ lab velocity of center of gravity

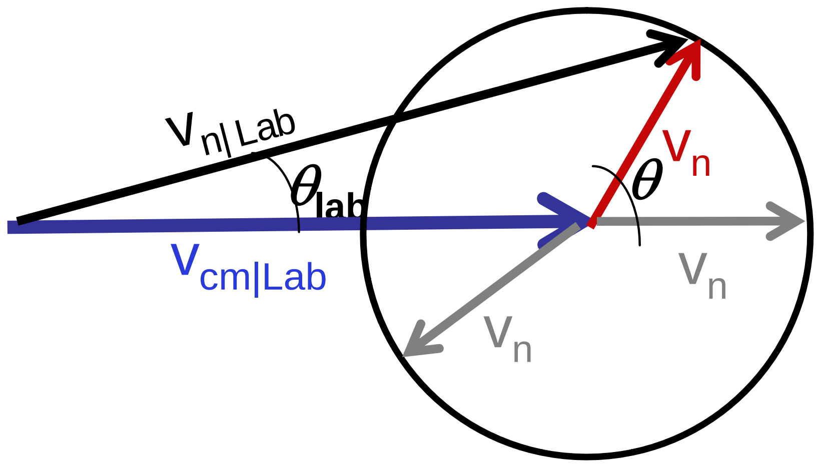
$$\max, \min : v_{n|Lab} = v_{cm|Lab} \pm v_n$$

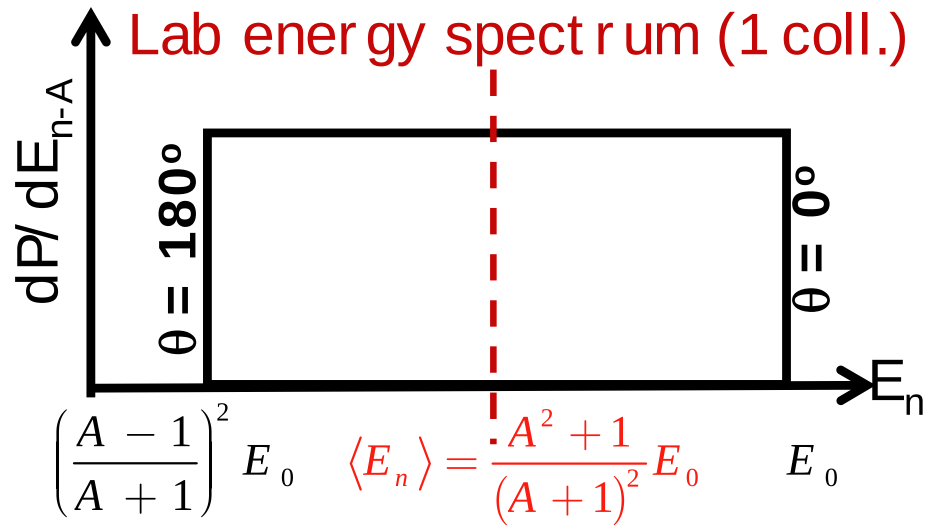
$$\max : \; E_{n|Lab} = E$$

$$\min \; : \; E_{n|Lab} = E\,\frac{(A-1)^2}{(A+1)^2}$$

Neutron Energy Spectrum

Neutron with energy E_0 scatters off target nucleus A at rest in lab.





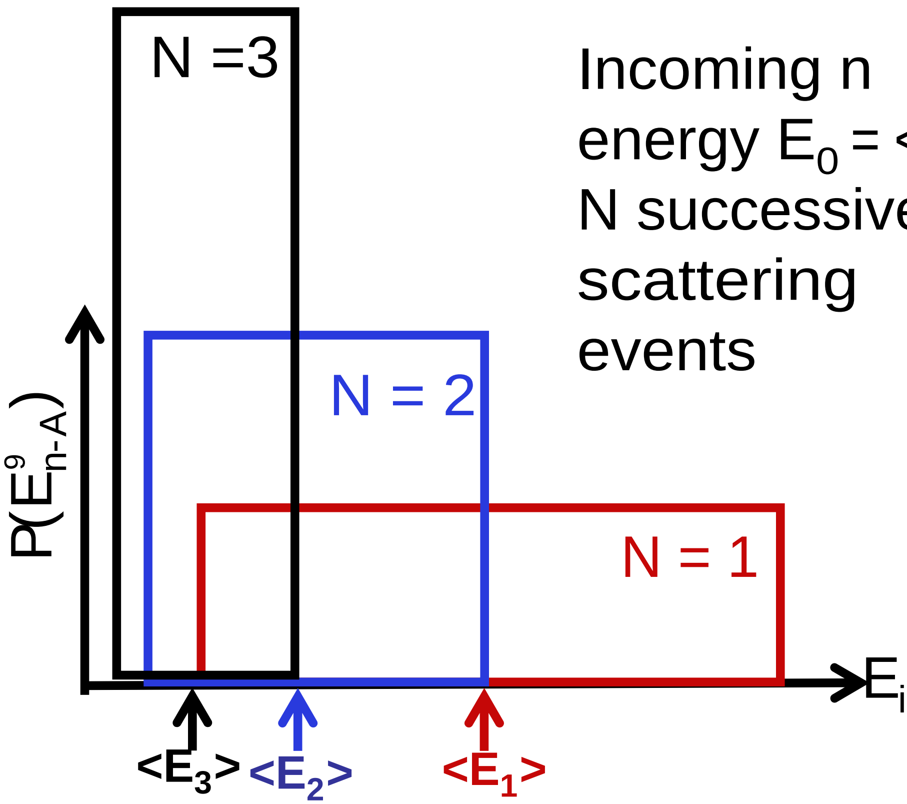
$$E_{n|Lab} \propto v^2_{n|Lab} = \left(\vec{v} + \vec{v}_{cm|Lab}\right)^2 = \ldots\ldots\ 2v^2 \frac{A}{(A+1)^2} \cos\theta$$

$$\frac{dE_{n|Lab}}{d\theta} \propto \sin\theta \rightarrow \frac{dE_{n|Lab}}{d\Omega} \propto \frac{dE_{n|Lab}}{\sin\theta\, d\theta} = const.$$

$$\Rightarrow \frac{d\sigma_{n-A}(\theta)}{d\Omega} \propto \frac{d\sigma_{n-A}\left(E_{n|Lab}\right)}{dE_{n|Lab}} \propto \frac{dP_{n-A}\left(E_{n|Lab}\right)}{dE_{n|Lab}}$$

The laboratory energy spectrum of scattered n reflects the center-of-mass scattering angular distribution !

Multiple n- A Scattering



Incoming n energy $E_0 = \langle E_0 \rangle$, N successive scattering events

$$\langle E_1 \rangle = \left[\frac{A^2+1}{(A+1)^2} \right]^1 E_0 = a^1 \langle E_0 \rangle$$

$$\langle E_2 \rangle = a \langle E_1 \rangle = a^2 \langle E_0 \rangle$$

....

$$\langle E_N \rangle = a \langle E_{N-1} \rangle = a^N \langle E_0 \rangle$$

$$\Rightarrow \boxed{P(E_1) = \frac{1}{(1-a)E_0}}$$

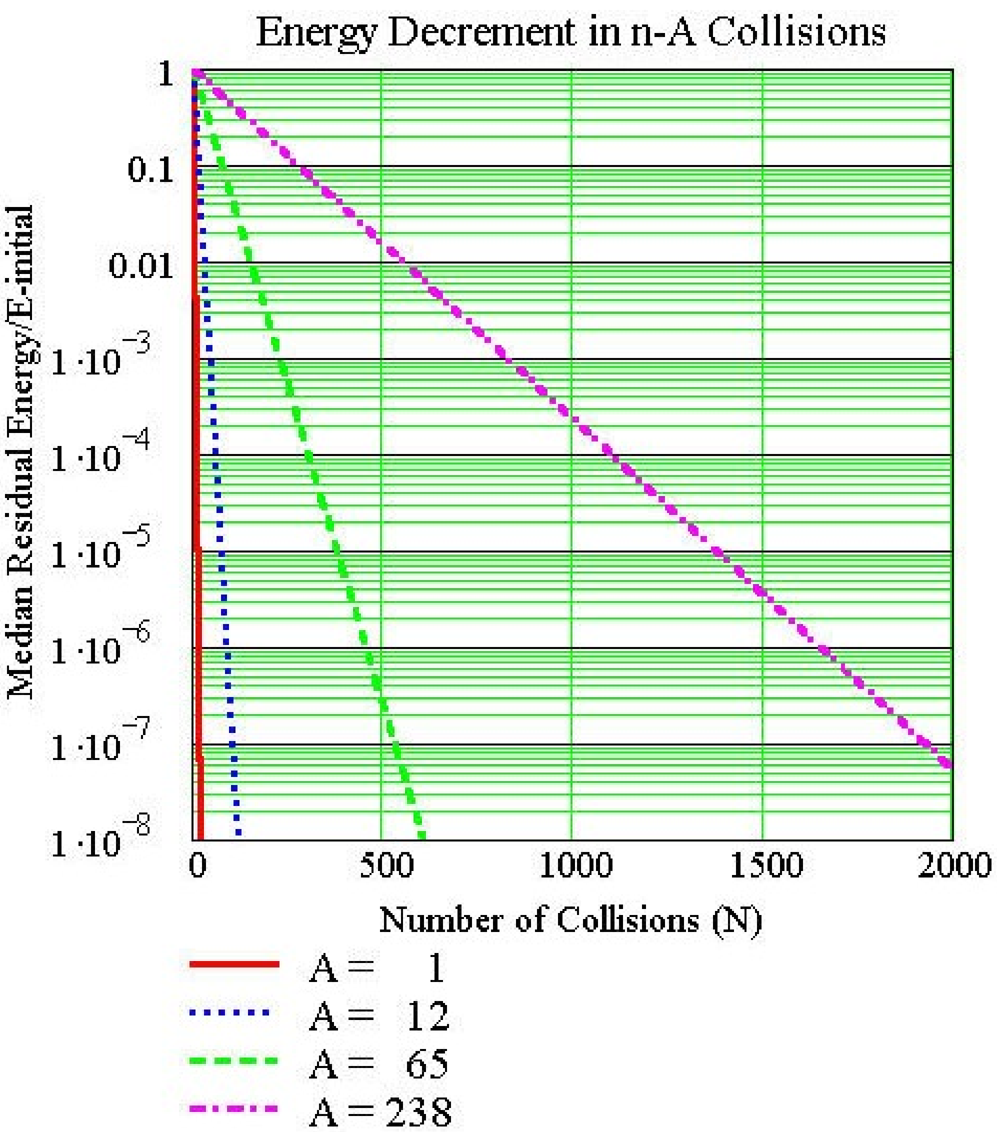
$$\underline{\underline{x}} := \left\langle \ln\left(E_0/E_1\right) \right\rangle = \int_{aE_0}^{E_0} dE \, \ln\left(\frac{E_0}{E}\right) P(E) = \frac{1}{(1-a)} \int_1^a dE \, \ln E =$$

"Logarithmic Decrement" ξ

$$= \frac{\left[x \ln x - x\right]_1^a}{(1-a)} = 1 + \frac{a \ln a}{(1-a)} = 1 + \frac{A^2+1}{2A} \ln\left(\frac{A^2+1}{(A+1)^2}\right) \xrightarrow[A>10]{} \underline{\underline{\frac{2}{A+2/3}}} \neq f(E_0)$$

$$\langle \ln E_N \rangle = \langle \ln E_0 \rangle - N\xi$$

Thermalization Through Scattering



$$\langle \ln E_N \rangle = \langle \ln E_0 \rangle - n x$$

$$Define\ \tilde{E}\ as\ median\,(<mean)$$

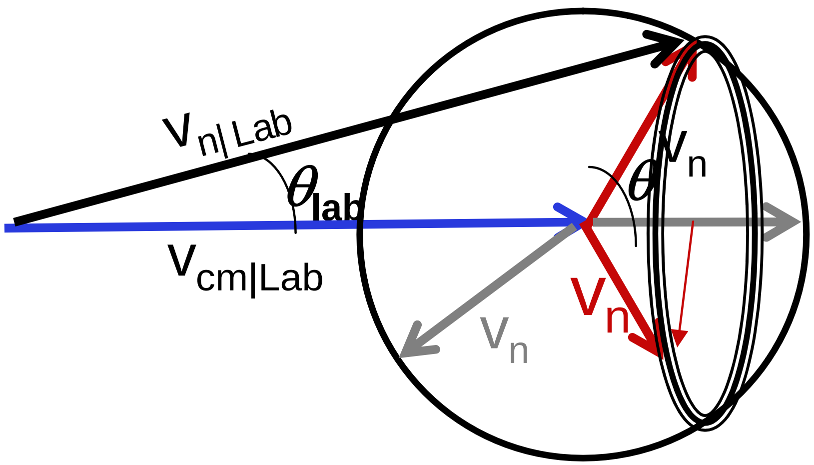
$$\ln \tilde{E} := \langle \ln E_N \rangle = \langle \ln E_0 \rangle - N x$$

$$\boxed{\tilde{E}(N) = E_0 \cdot e^{-N x}}$$

N-therm: E_0=2 MeV → 0.025eV

A	ξ	N- therm
1	1.0000	18
12	0.1578	115
65	0.0305	597
238	0.0084	2172

n Angular Distribution



$$v_n = \frac{v}{A+1}A \qquad v_{cm|Lab} = \frac{v}{A+1}$$

$$\vec{v}^{\,2}_{n|Lab} = \left(\vec{v}_n + \vec{v}_{cm|Lab}\right)^2 = \frac{v^2}{(A+1)^2}\left[A^2 + 1 + 2A\cos q\right]$$

$$v_n^2 = v_{n|Lab}^2 + v_{cm|Lab}^2 - 2v_{n|Lab}v_{cm|Lab}\cos q_{Lab} \qquad |: v^2\big/(A+1)^2$$

$$A^2 = \left[A^2 + 1 + 2A\cos q\right] + 1 - 2\sqrt{A^2 + 1 + 2A\cos q}\,\cos q_{Lab}$$

$$\boxed{\cos q_{Lab} = \frac{1 + A\cos q}{\sqrt{A^2 + 1 + 2A\cos q}}}$$

$$\left\langle \cos q_{Lab} \right\rangle = \frac{1}{2}\int_{-1}^{+1} d\cos q\,\frac{1 + A\cos q}{\sqrt{A^2 + 1 + 2A\cos q}} = \frac{2}{3A} \left\{ \begin{array}{l} >0 \;\rightarrow \\ \text{forward} \\ \text{scattering} \end{array} \right.$$

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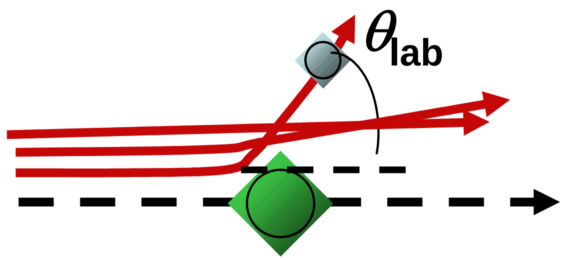
A Dependence of Angular Distribution

Properties of n scattering depends on the sample mass number A

➔ Measure time-correlated flux of transmitted or reflected neutrons

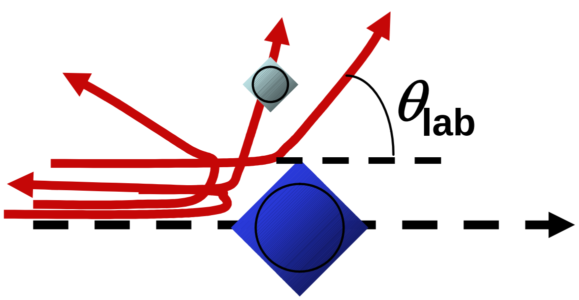
Light Nucleus



$$\langle \cos q_{lab} \rangle = 2/(3A) \propto A^{-1} \ average$$

$$\langle q_{lab} \rangle \sim \frac{p}{2} - \frac{2}{3A}$$

Heavy Nucleus



$$\tilde{E}(N) \approx E_0 \cdot \exp\left\{ \frac{-2N}{(A + 2/3)} \right\}$$

$$(After\ \ N\ \ collisions)$$

Light nuclei: slowing-down and diffusion of neutron flux

Heavy nuclei: neutrons lose less energy, high reflection/transmission

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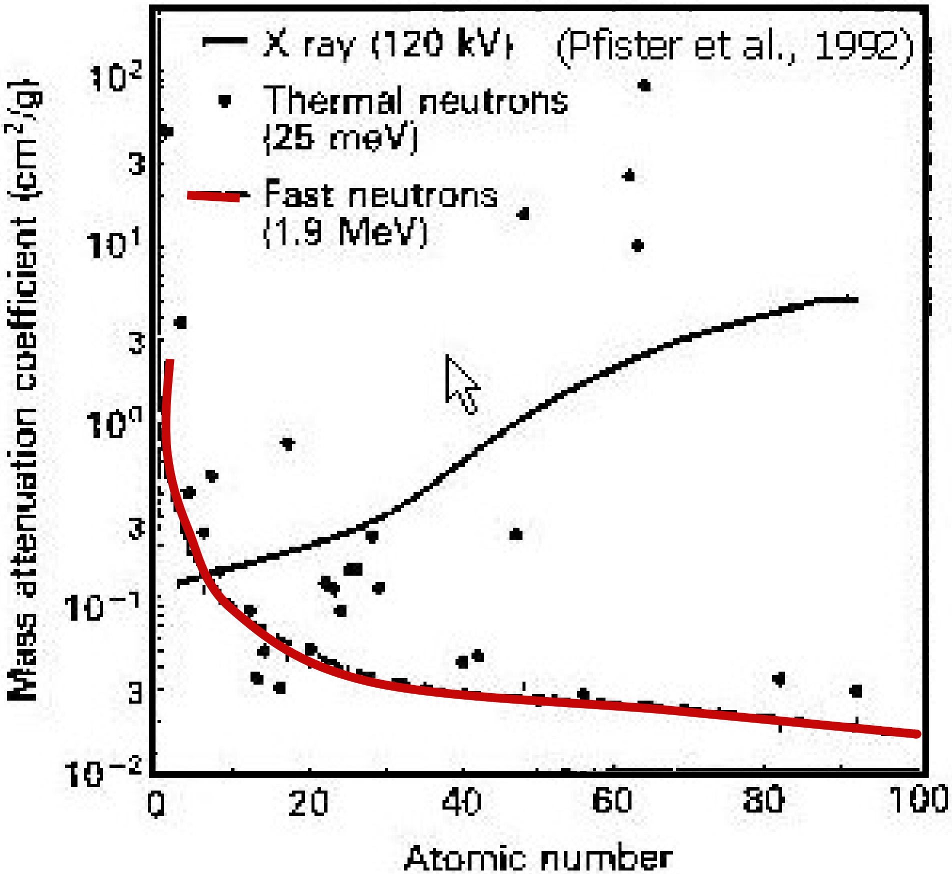
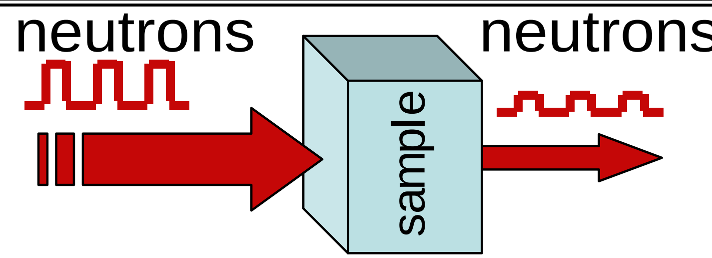
Principle of Fast-Neutron Imaging (2)



Transmission decreases exponentially (reflectivity increases) with thickness and density of sample, for most materials.



$\phi(0)$ → δ ← $\phi(\delta)$

incoming transmitted

$$\phi(\delta) = \phi(0) \cdot T(\delta)$$

$$T(\delta) = e^{-\Sigma \cdot d} \;\; Transmission$$

$$\Sigma = \mu \cdot \rho = N_A \cdot \sigma_A \cdot \rho$$

$$\mu = atten.coeff$$

$$\rho = material\ density$$

Neutron Diffusion

Multiple scattering = statistical process

Heavy materials (A>>1): random scattering

$$N = \frac{1}{x}\ln\left(\frac{E_0}{E_1}\right)$$ Number of collisions $E_0 \rightarrow E_1$

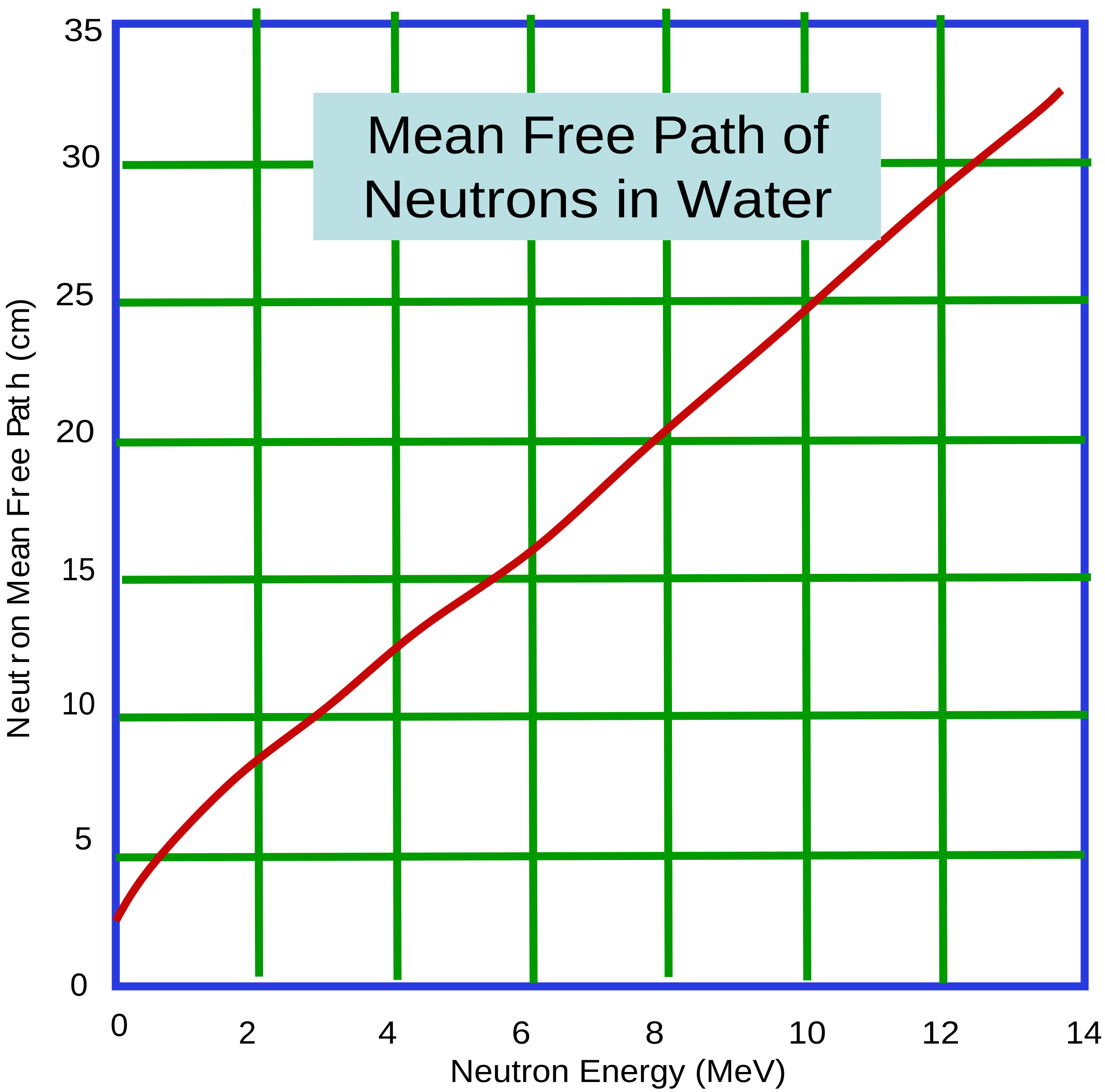
Probability for no collision along path length x: P(x)

$$P(x) = \frac{1}{\lambda}\cdot e^{-\frac{x}{l}}$$ for λ = const.

$$Mean - square\ displacement$$

$$\left\langle x^2 \right\rangle_N = N\left\langle \lambda^2 \right\rangle = \int_0^\infty dx\, x^2 e^{-x/l} \Big/ \int_0^\infty dx\, e^{-x/l} = 2\lambda^2$$

Neutron Mean Free Path



$$N(x) = N(0)e^{-x/\lambda}$$

$$\lambda = \frac{1}{\mu} = \frac{1}{\rho\sigma} \quad mfp$$

ρ: atomic density
σ: cross section

λ = average path length in medium between 2 collisions

$$\Gamma_{FWHM} = 2.35 \cdot \sigma$$

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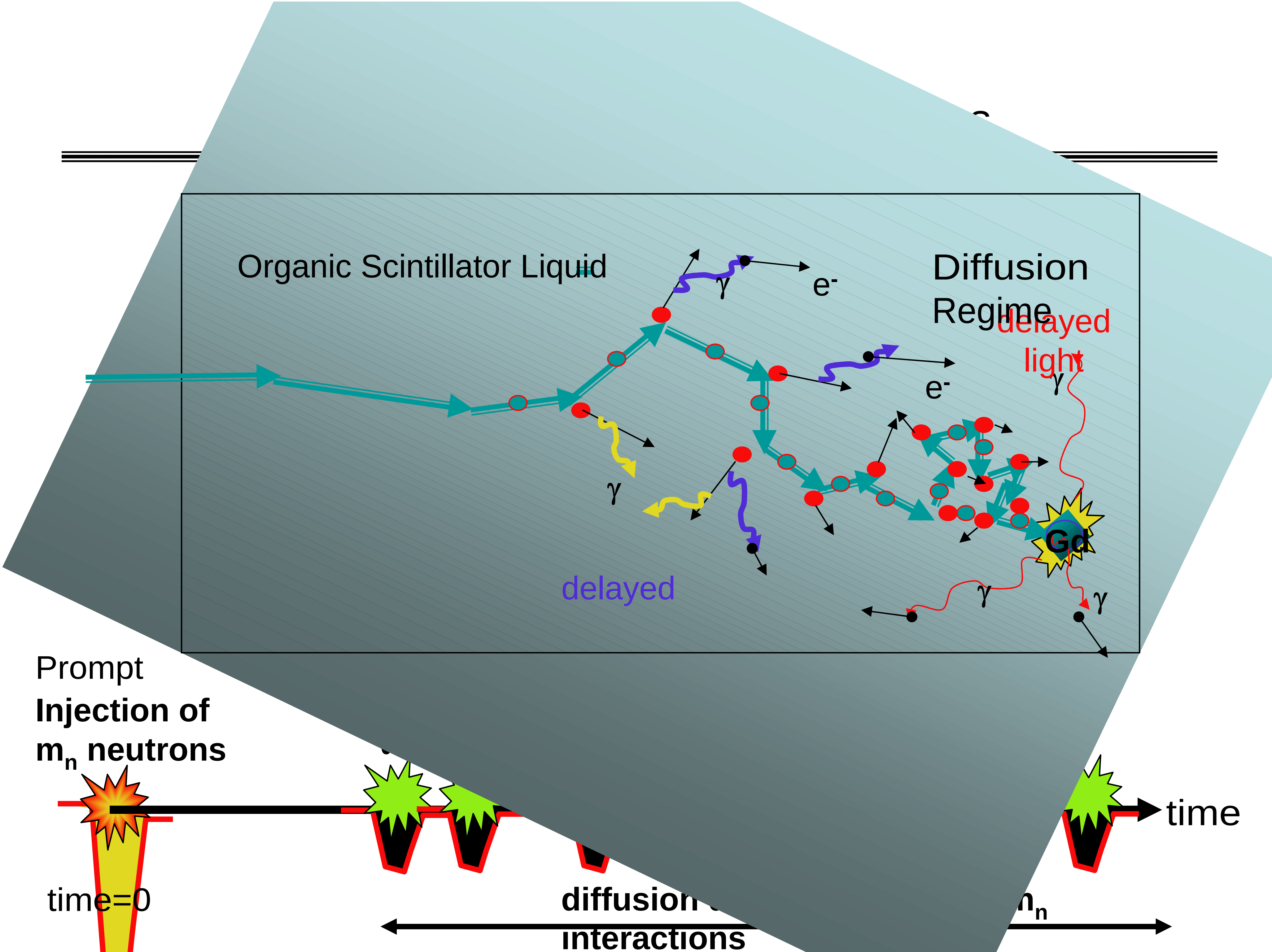
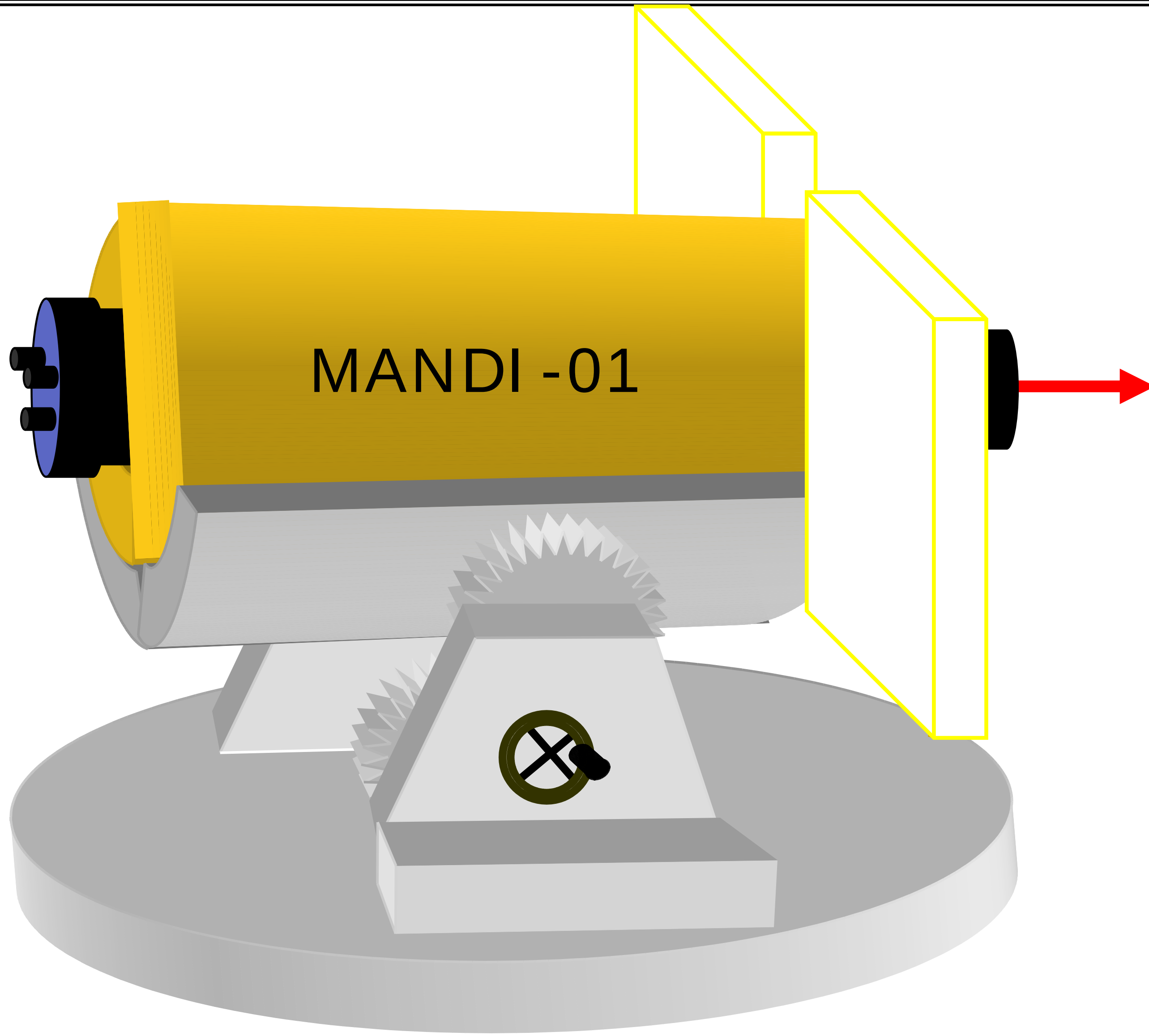

Organic Scintillator Liquid
Diffusion Regime
delayed light
γ
e-
e-
delayed
Gd
Prompt
Injection of
m_n neutrons
time
time=0
diffusion
interactions

A Mobile Accelerator-Based Neutron Diagnostic Imager



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