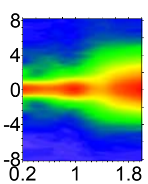
Neutron detectors, application and future possibilities

Francesco Sacchetti

Università degli studi di Perugia

IOM CNR, Unità di Perugia

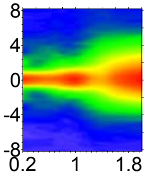


Catania Novembre 2014

Neutron sources

The neutrons must be normally extracted from nuclei at the high energetic cost of about 8 MeV/n. There exist three major processes which produce neutrons, that is fusion, fission and spallation. Neutron can be produced also using electron beams, but with lower efficiency. A much smaller efficiency is obtained using radioactive means.

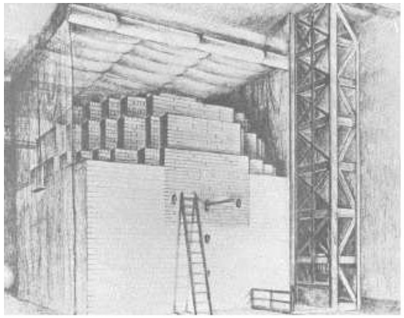
1) Natural sources: very rare because the major processes producing neutrons are not common in nature. Fission, at present time, is no more possible with natural U (essentially a mixture of ^{235}U and ^{238}U with a too low ^{235}U content). Fusion needs special energetic conditions which cannot be obtained in nature on the Earth, spallation needs the acceleration of particles, e.g. protons, to rather high energy (>500 MeV), again not spontaneously possible on the Earth.



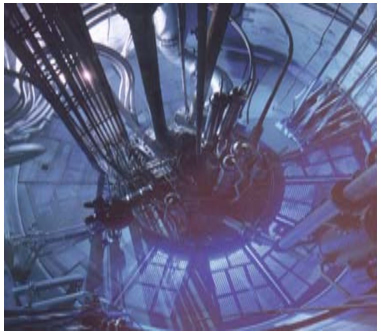
2) Artificial sources are based on the three basic processes. The most flexible one is the ***fission*** which has intrinsic limits due to the high heat release of this reaction.

$$^{235}U + n = FP + \nu n + \gamma$$

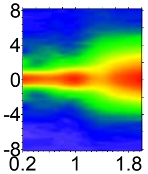
where ν is 2.5 on the average, FP are (two) Fission Products (highly radioactive, medium life time, extremely dangerous) and there is an average energy release of about 200 MeV (2 MeV neutrons, 10 MeV γ plus kinetic energy).



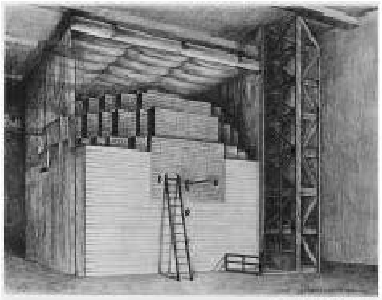
CP-1, 1942



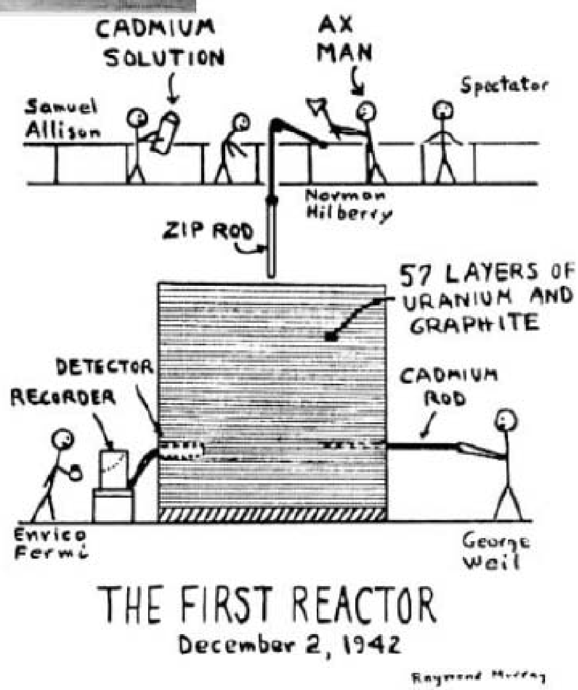
ILL, 1972



Chicago Pile – 1 was the ***first fission reactor*** which went critical in 1942 under the leadership of Enrico Fermi



Chicago Pile-1



1942, from a telephone call of Compton: the Italian navigator has landed in the New World…

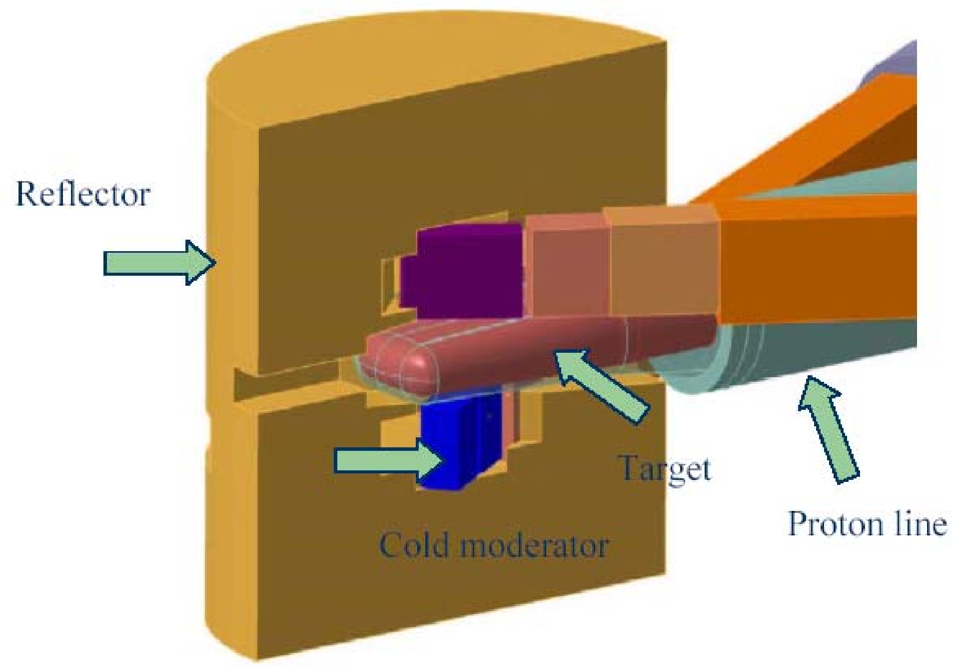
SCRAM=Safety Control Rod Axe Man

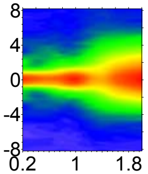
Fusion is in principle very good for neutron production but it is difficult to achieve for practical purposes apart from the study of fusion itself. ***Spallation*** is much better suited to the production of high brillance neutron beams.

$$p + A = SP + \nu n + \gamma + pp$$

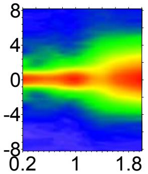
where ν is up to 30 on the average, SP are Spallation Products and there is an average energy release depending on the energy transferred to the neutrons. The pp are particle pairs.

SNS target scheme

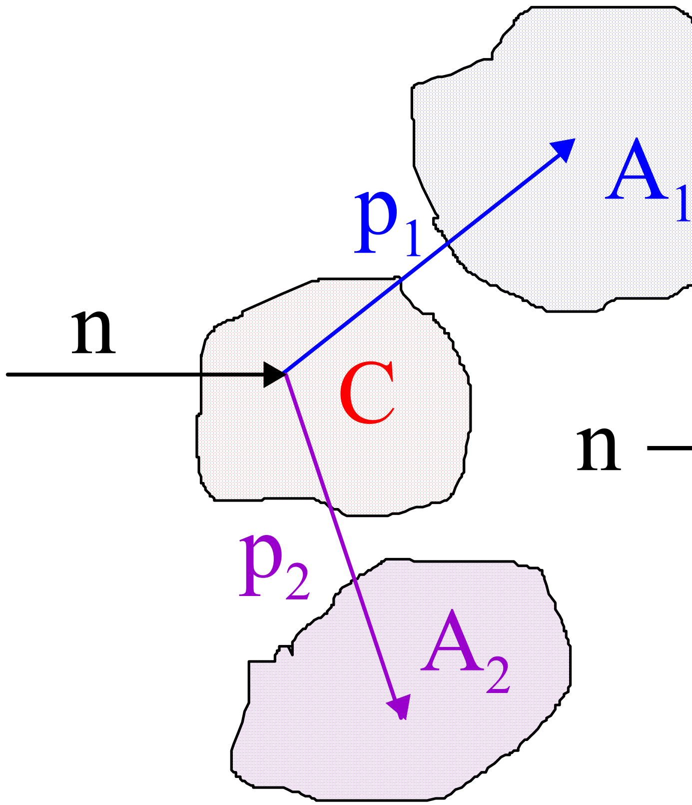




The actual SNS mercury target container (2005). In 2010, serious but controlled damages have been observed.

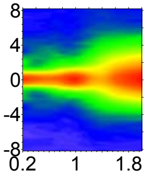


Principle of neutral particle detection



$$n \rightarrow p_1 + p_2$$

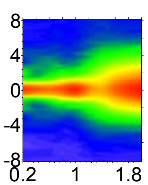
A primary reaction in a converter (C) must be employed to produce charged particles which can release energy in a proper apparatus (A_1 and A_2)



Contrary to the case of photon in which case all materials are potentially absorbing and the only relevant parameter is the atomic number, there exist only specific isotopes which can ***convert*** neutrons into charged particles.

The utility of a neutron ***converter*** depends strongly on the neutron energy as the capture cross section shows a complex behaviour as a function of the neutron energy.

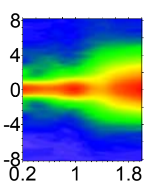
Relevant processes are: neutron capture through (n,γ), (n,α) and (n,p) reactions, these reactions show often several resonances, and fission (only with fissile isotopes, mainly ^{235}U and ^{238}U, bat also ^{239}Pu), again showing resonances.



In the case of ***photon*** it is normally rather easy to use the ***converter*** also to collect energy from the charged particles (often electrons) produced by the primary absorption, this is not easy in the case of neutrons apart from gaseous absorbing media.

There is also a general rule: the neutron cross section is decreasing as a function of energy and in the very low energy limit it is often approximated by the one over velocity function.

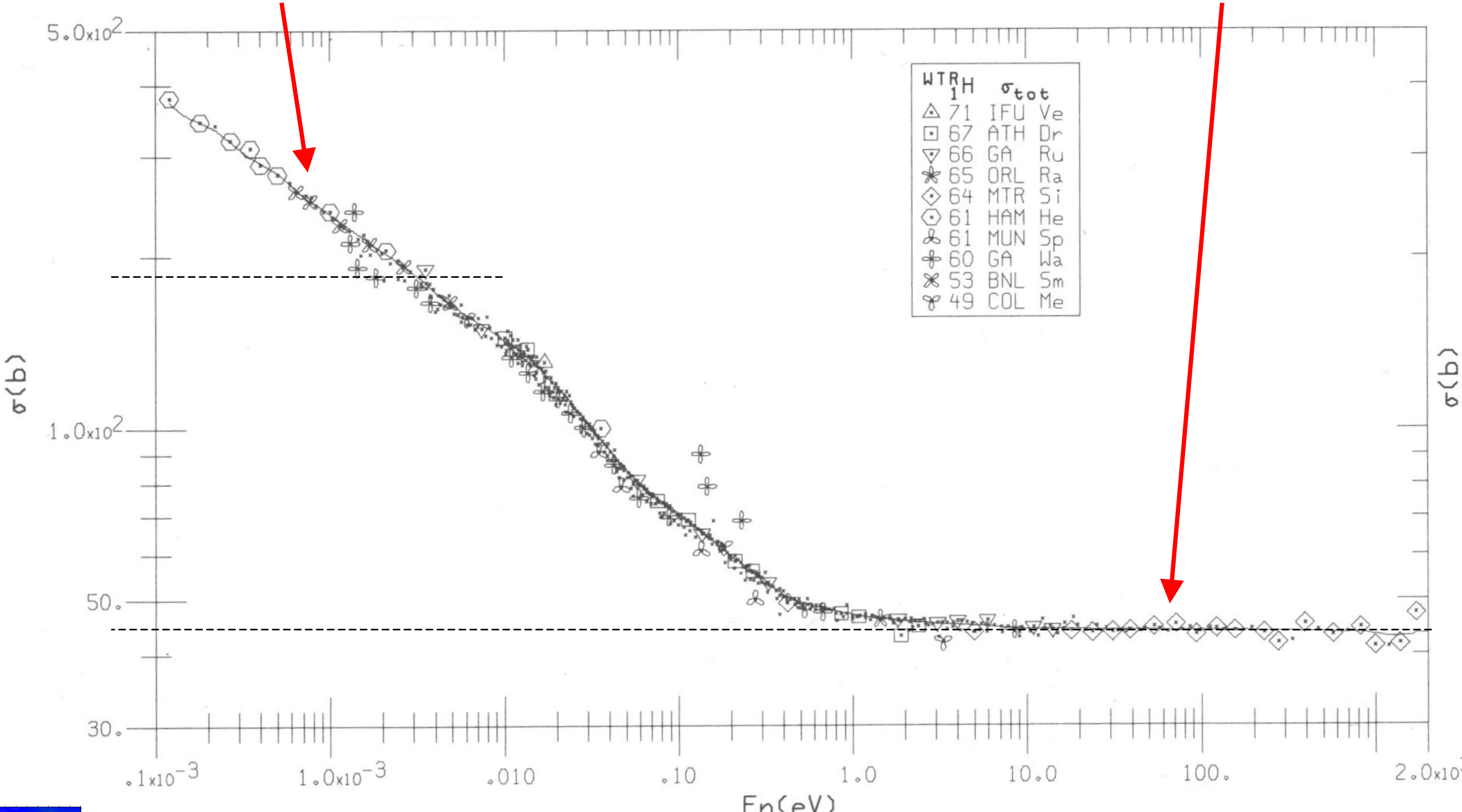
Considering that a neutron beam and the environment are always contaminated by γ-ray a good discrimination level for this radiation in mandatory.



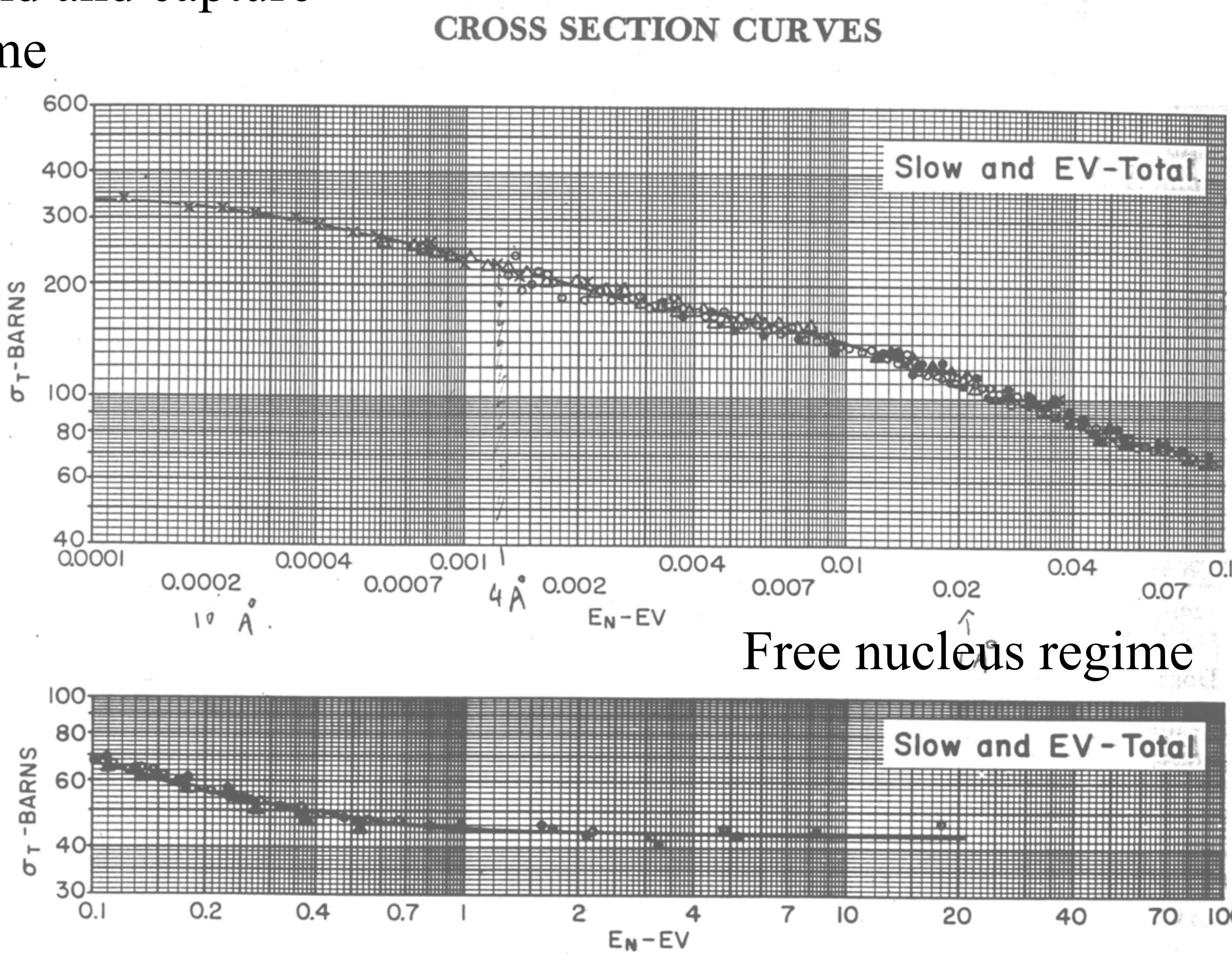
H_2 total cross section

Bound and capture regime

Free nucleus regime

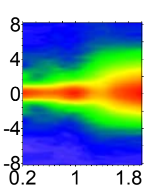


Bound and capture regime

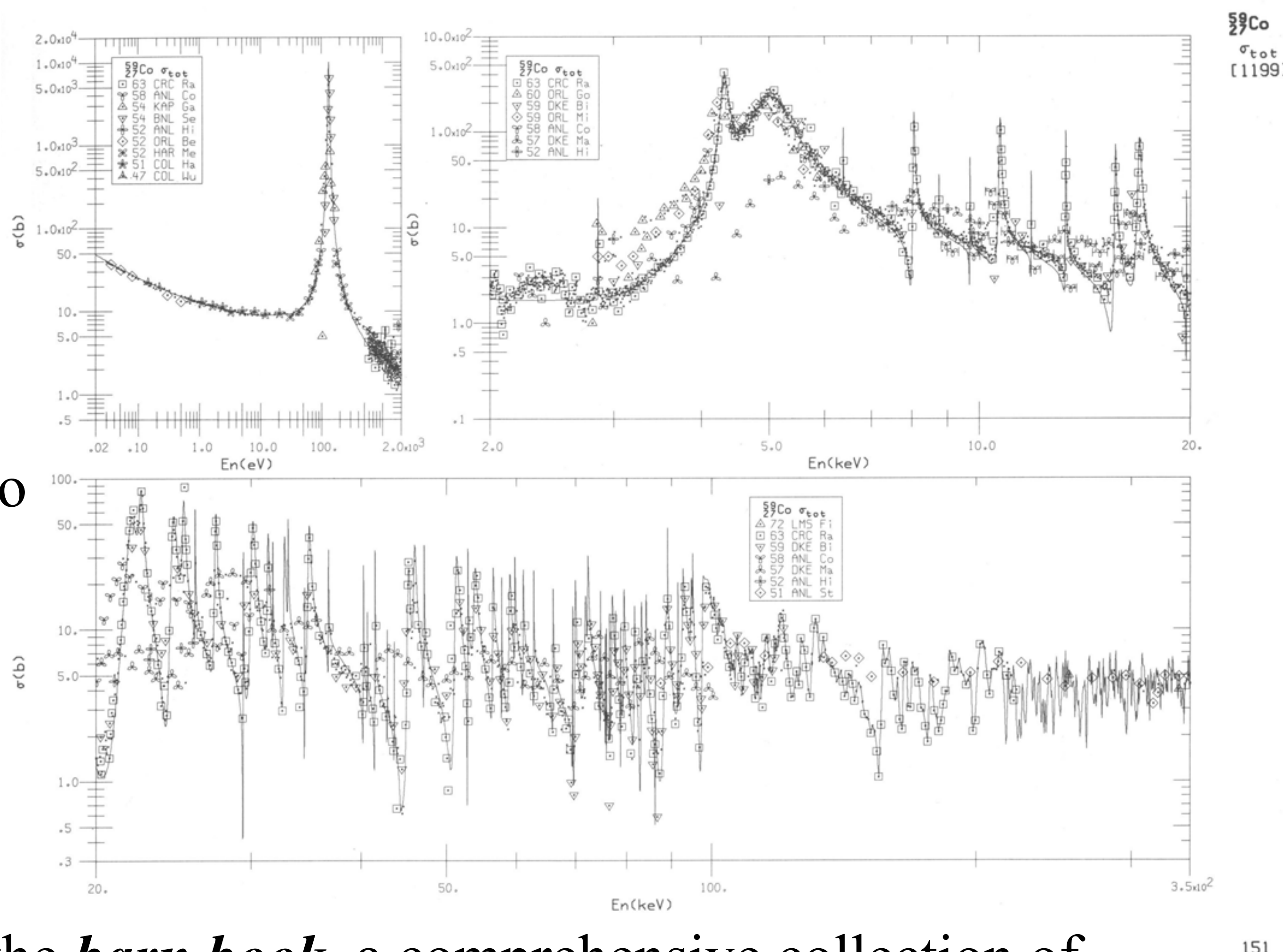


Free nucleus regime

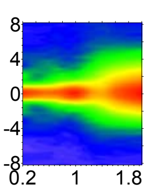
Cross section of light water, it is dominated by hydrogen



Capture resonances in ^{59}Co

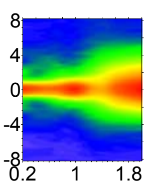


From the ***barn book***, a comprehensive collection of neutron cross sections in the energy range from 0.1 meV up to 10 MeV for different isotopes

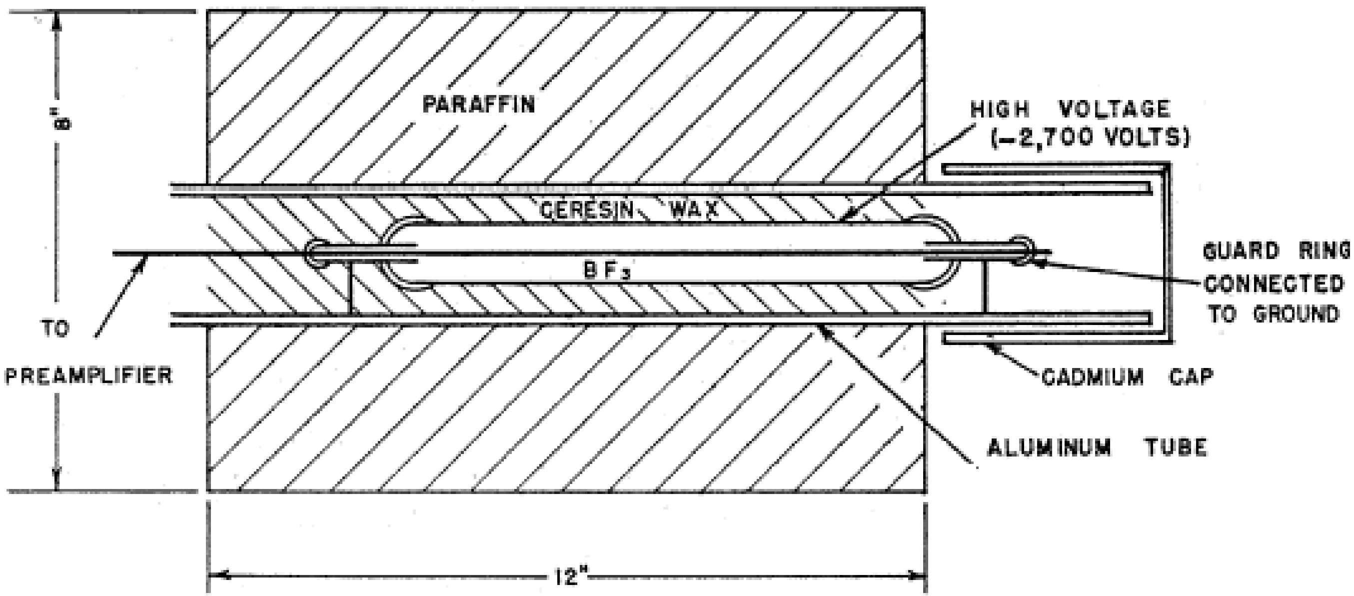


The detectors to detect neutral particles are characterized by the detection efficiency and the Detection Quantum Efficiency (DQE).

The coupled system ***converter*** plus charged particle collector has always a finite efficiency which is the combination of the neutron capture probability and the capability of the charged particle collector of detecting the capture products. A high neutron capture cross section is important to detect all the neutrons and a good collection system for the charged capture products is essential to produce a good signal well above the noise level.



Old style BF_3 detector

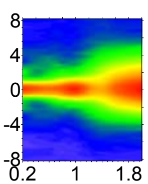


PHYSICAL REVIEW VOLUME 72, NUMBER 8 OCTOBER 15, 1947

A Neutron Detector Having Uniform Sensitivity from 10 Kev to 3 Mev

A. O. HANSON* AND J. L. MCKIBBEN
Los Alamos Scientific Laboratory, Santa Fe, New Mexico

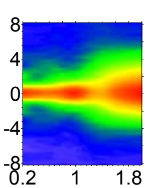
(Received July 10, 1947)



The DQE is the effective fluctuation of the detector rate as compared to that expected in the ideal case of Poisson distribution. The DQE is equal to unity in the case of a capture process with a single channel in the final state.

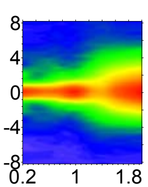
$$DQE = \frac{\sigma^2_{pois}}{\sigma^2_{out}}$$

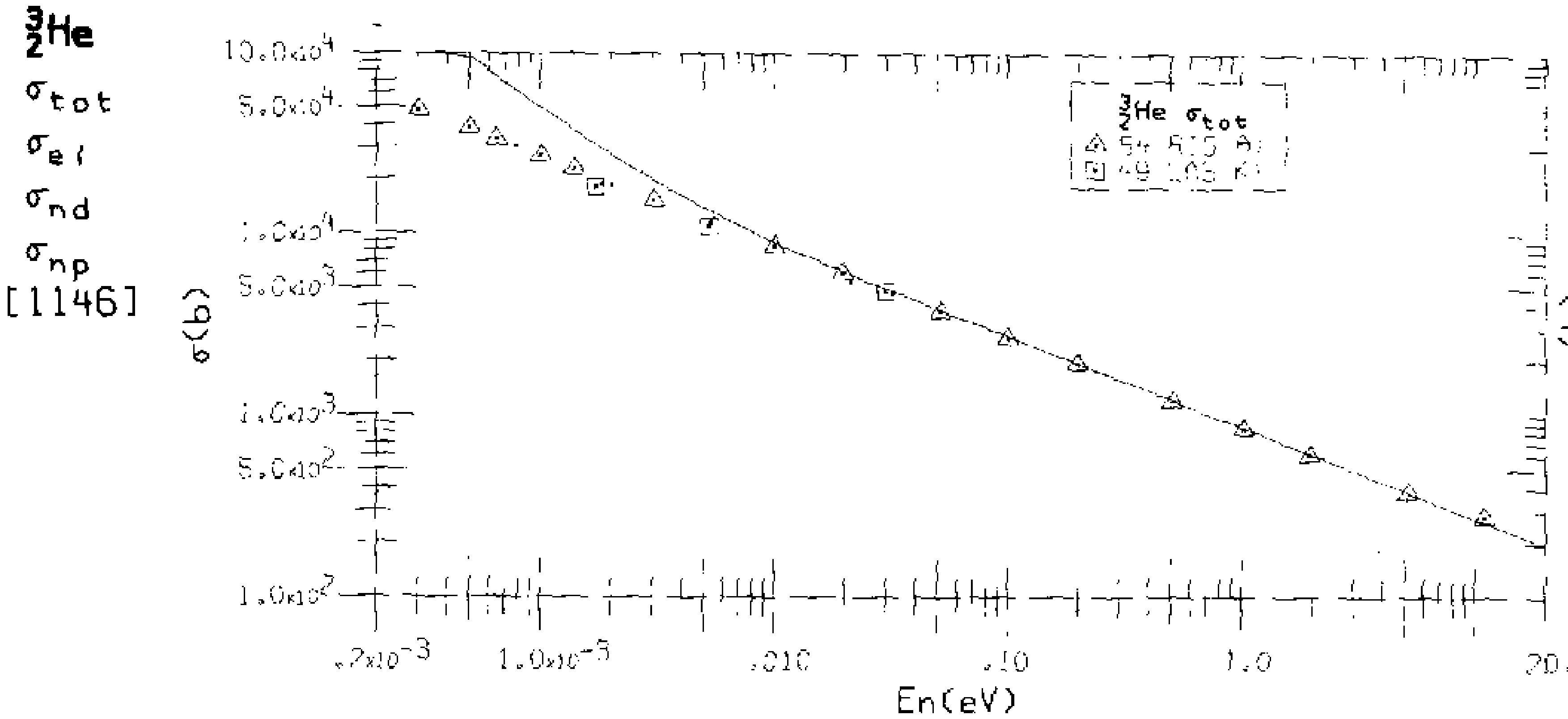
This property is important to avoid an increased error of the observed rate as compared to that expected for the usual Poisson distribution.



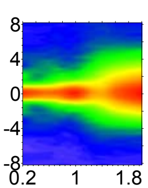
Principal capture reactions useful at low energy

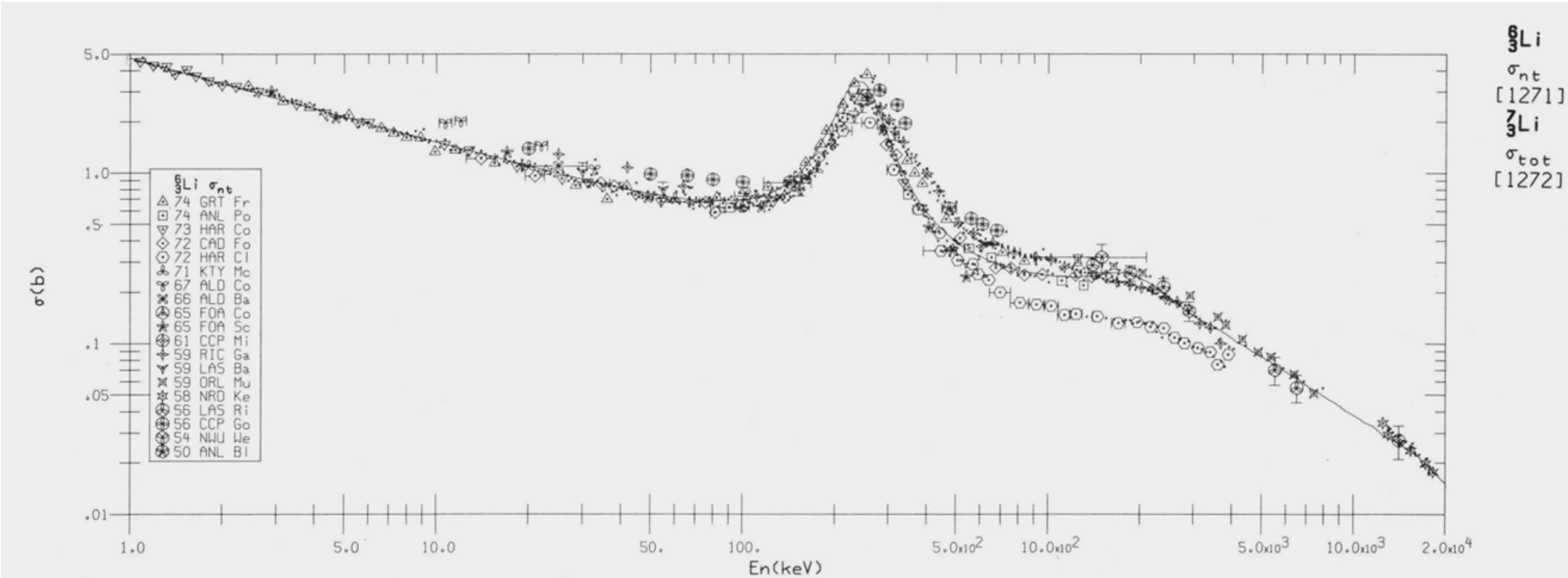
	σ thermal (25 meV)
$^{3}He + n = {}^{3}H + p + 0.77$ MeV	5333 b
$^{6}Li + n = {}^{3}H + {}^{4}He + 1.79$ MeV	940 b
$^{10}B + n = {}^{7}Li + {}^{4}He + \gamma(0.48$ MeV$) + 2.3$ MeV (93%)	3835 b
$^{10}B + n = {}^{7}Li + {}^{4}He + 2.78$ MeV (7%)	
$^{155}Gd + n = \gamma + e + 2$ MeV $\quad$ $^{157}Gd + n = \gamma + e + 2$ MeV	259000 b
	DQE~0.8



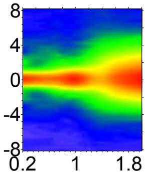


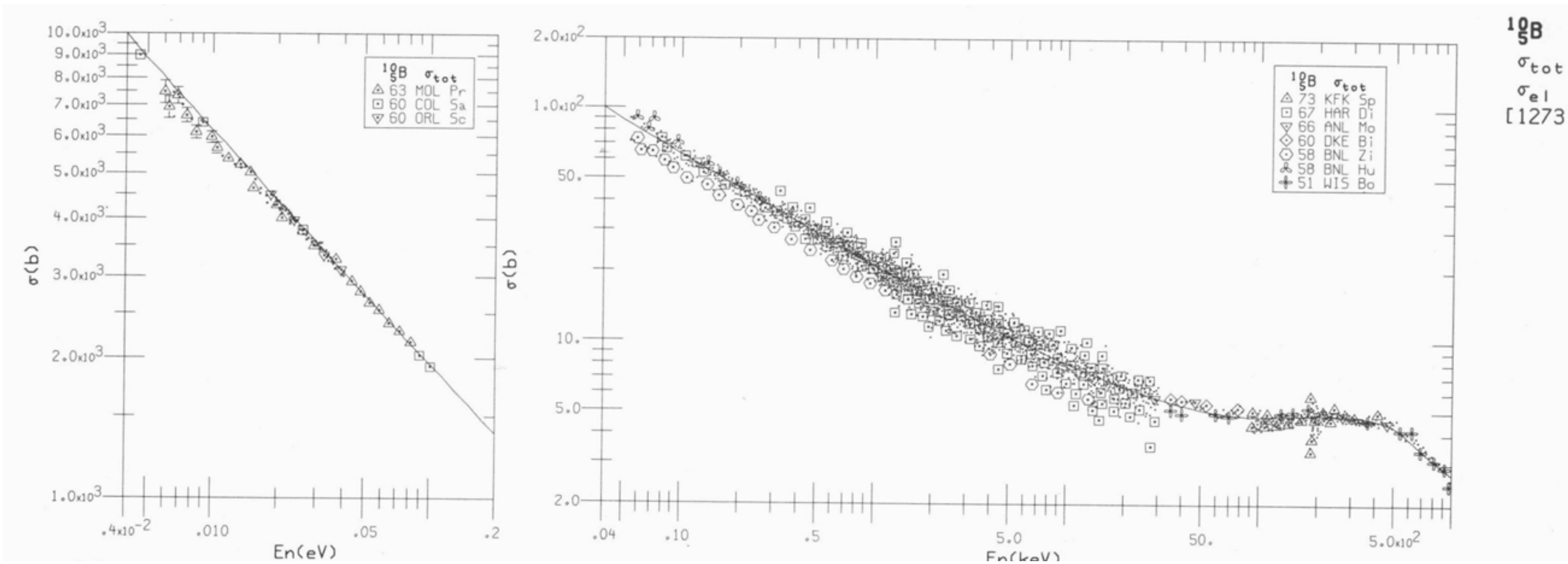
From the ***barn book***, a comprehensive collection of neutron cross sections in the energy range from 0.1 meV up to 10 MeV for different isotopes



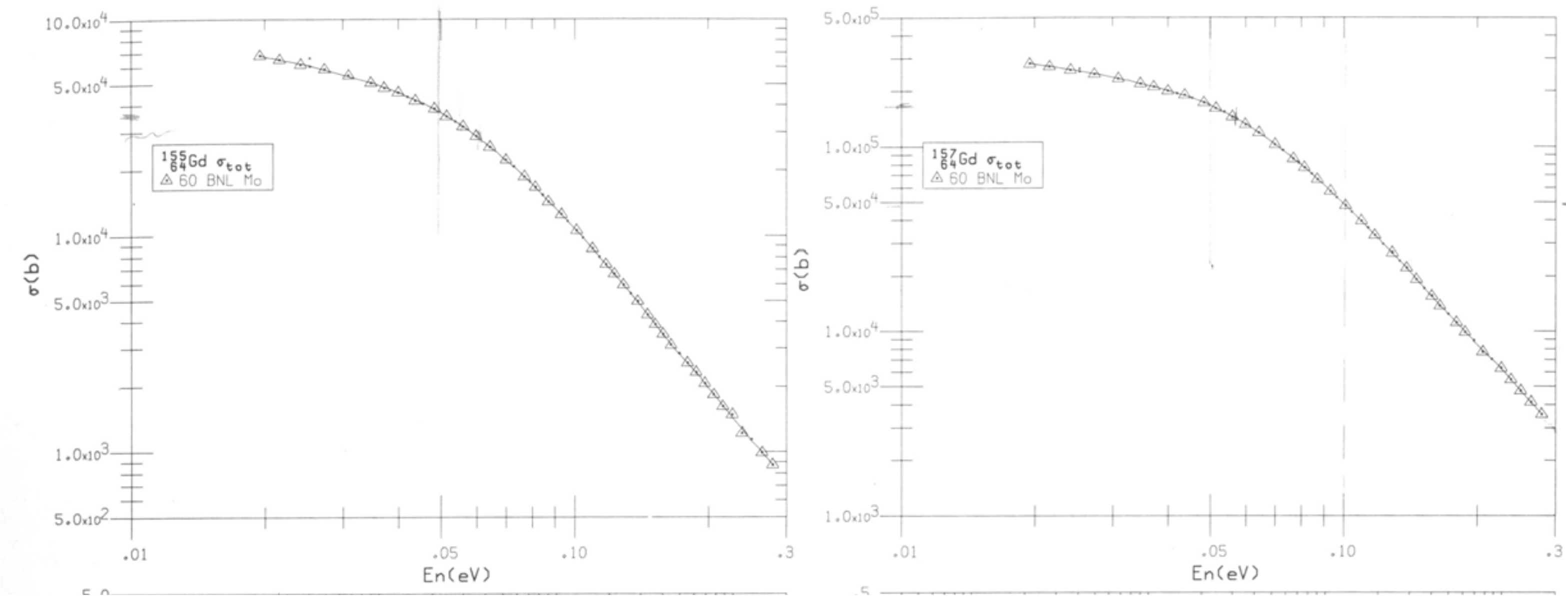


Medium energy cross section in ^{6}Li showing a resonance at 250 keV





Total cross section of ^{10}B in the 4 meV-1 MeV range

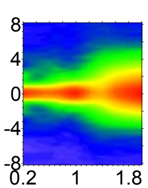


$^{155}_{64}$Gd

σ_{tot}

$^{157}_{64}$Gd

Total cross section of ^{155}Gd and ^{157}Gd at low energy, the resonance at about 50 meV is fairly broad, many other resonances are present at high energy.



There are different basic designs for neutron detection:

Gas detectors

Scintillators

Solid state

Imaging systems

Special detectors

Dose/dose-rate monitors (control monitors, personal monitors)