MASTER DI II LIVELLO IN RADIOPROTEZIONE

Neutron detection

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Data 17/04/2015

UNIVERSITA' CAMPUS BIO-MEDICO DI ROMA

Neutron detection

Neutrons are generally detected through nuclear reactions that result in prompt charged particles such as protons, alpha particles, and so on. Virtually every type of neutron detector involves the combination of a target material designed to carry out the conversion together with one of the conventional radiation detectors .

Because the cross section for neutron interactions in most materials is a strong function of neutron energy, rather different techniques have been developed for neutron different energy regions.

We start discussing those methods that are of primary importance for the detection of neutrons whose energy is below the cadmium cut-off about 0.5 eV.

This is conventionally called the slow neutron region and is distinguished from intermediate and fast neutrons with energies above this value.

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NUCLEAR REACTIONS OF INTEREST IN NEUTRON DETECTION

In searching for nuclear reactions that might be useful in neutron detection, It must be considered

1) the cross section for the reaction that must be as large as that efficient detectors can be built with small size. This is particularly important for detectors in which the target material is incorporated as a gas.

2) the target nuclide should either be of high isotopic abundance in the natural element, or alternatively, an economic source of artificial enriched samples should be available for detector fabrication. In many applications, intense field of gamma rays are also found with neutrons and the choice of reaction bears on the ability to discriminate against gamma rays.

3) The Q-value of the reaction that determines the energy liberated in the following neutron capture is important . The higher the Q-value, the greater is the energy given to the reaction products, and the easier is the task of discriminating against gamma-ray simple amplitude discrimination.

It is important to point out that all the common reactions used to detect slow neutrons result in heavy charged particles.

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Possible reaction products are listed below:

Target nucleus+neutron

- Recoil nucleus
- Proton
- Fission Fragments
- Alfa particles

All the conversion reactions are sufficiently exothermic so that the kinetic reaction products is determined solely by the Q-value of the reaction and does not reflect the very small incoming energy of the slow neutron.

The distance traveled by the reaction products following their formation has important consequences in detector design.

If we are to capture the full kinetic energy of these products, the detector must be designed with an active volume that is large enough to fully stop the particles. If the detection medium is a solid, this requirement is easily achieved because the range of any of the reaction products shown does not exceed a few tenths of a millimeter in any solid material.

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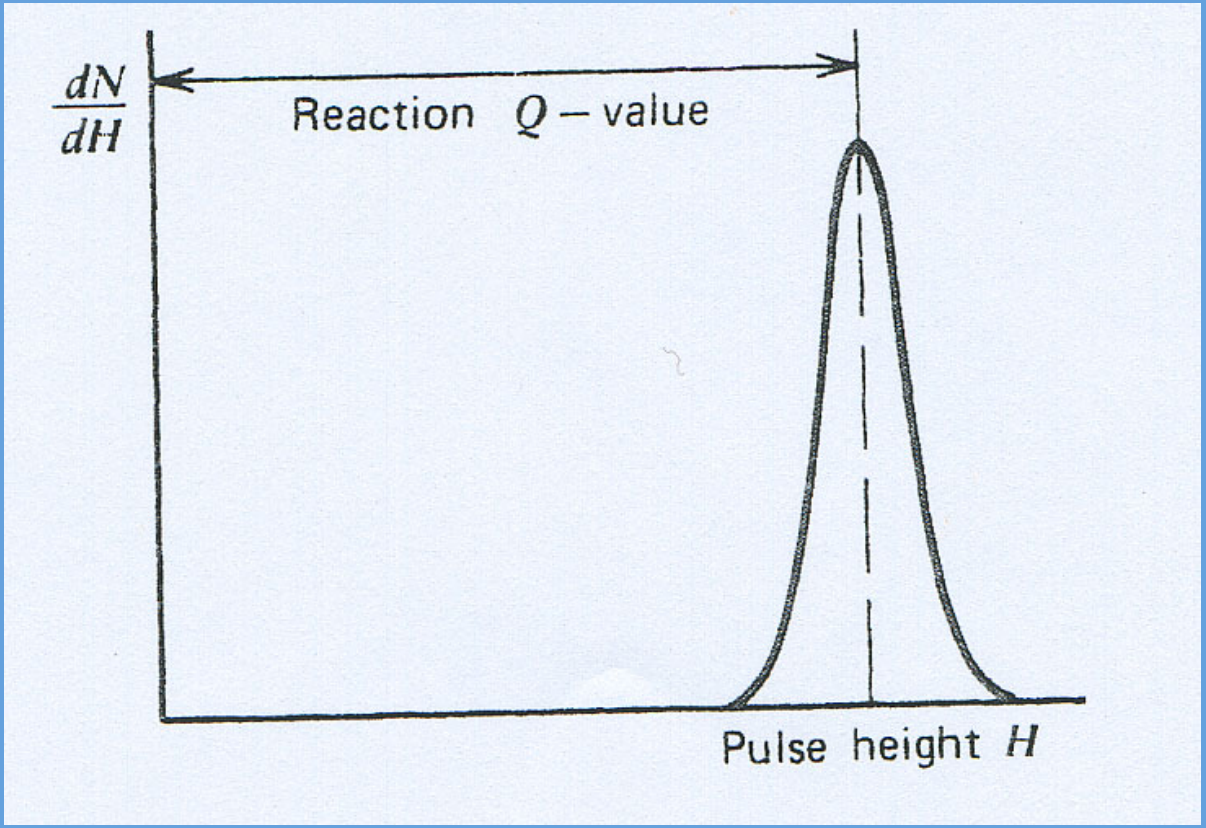
If the detection medium is a gas, ranges of the reaction products (typically several centimeters) can be significant compared with detector dimensions and some may not deposit all their energy. If the detector is large enough so that these losses can be neglected, the response function will be consisting only of a single full-energy peak as shown in the picture.

Under these circumstances the detector would exhibit a very flat counting plateau and the ability to discriminate against low-amplitude events (such as gamma ray induced processes) would be maximized.



If a significant number induced events do not deposit the full energy, a low-energy continuum is added to the pulse height spectra.

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The most used reaction for the conversion of slow neutrons into directly detectable particles is the $^{10}B(n, \alpha)$ reaction. The reaction may be written

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}\alpha$$

6% + 2.792 MeV Ground state

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li^{*} + ^{4}_{2}\alpha$$

94% +2.310 MeV Excited state

where the branching indicates that the reaction product ^{7}Li may be left either in its ground state or in its first excited state. When thermal neutrons (0.025 eV) are used to induce the reaction, about 94% of all reactions lead to the excited state and only 6% directly to the ground state.

In either case, the Q-value of the reaction is very large (2.310 or 2.792 MeV) compared with the incoming energy of the slow neutron, so that the energy imparted to the reaction products (^{7}Li and α) is essentially just the Q-value itself.

Thus, the incoming kinetic energy of the neutron is submerged in the much larger reaction energy, and it is impossible to extract any information about its original value.

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Also, because the incoming linear momentum is very small, the reaction products must also show a net momentum of essentially zero. Consequently, the two reaction products must be emitted in exactly opposite directions, and the energy of the reaction will always be shared in the same manner between them. Individual energies of the alpha particle and lithium nucleus can be calculated simply by conservation of energy and momentum as follows:

$m_{Li} \bullet v_{Li} = m_\alpha v_\alpha$

$$E_{Li} + E_\alpha = 2.31 MeV = Q$$

$(m_{Li} \bullet v_{Li})^2 = (m_\alpha \bullet v)^2_\alpha$

but

$$V_{Li} = \sqrt{2\frac{E_{Li}}{m_{Li}}}$$

and than

$$\sqrt{2E_{Li}m_{Li}} = \sqrt{2E_\alpha m_\alpha}$$

$$E_\alpha = 1.47 MeV \qquad E_{Li} = 0.84 MeV$$

where the calculation has been carried out for the case of populating the excited state of ^7Li. A similar calculation would yield larger values by 21% for reactions leading to the ground state.

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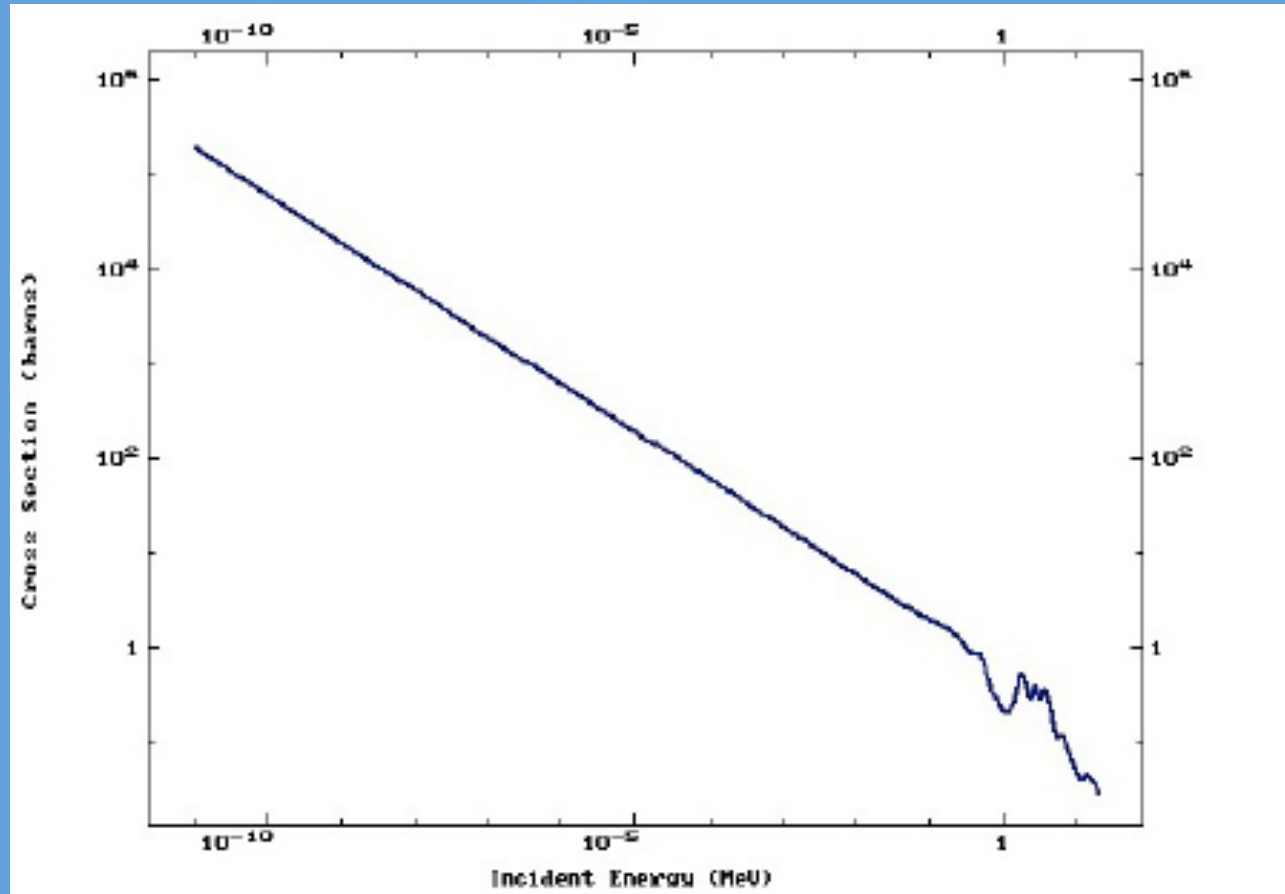
The figure is a plot of cross sections versus neutron energy the $^{10}B(n, \alpha)Li$ reaction

The thermal neutron cross section for the $^{10}B(n, \alpha)$ reaction is 3840 barn. The cross-section value drops rapidly with increasing neutron energy and is proportional to 1/v (the reciprocal of the neutron velocity) over much of the range.



Cross section of $^{10}B(n, \alpha)Li$ reaction

The utility of this reaction stems from its rather large and structure-less cross section and from the fact that boron, highly enriched in its ^{10}B concentration, is readily available.
The natural isotopic abundance of ^{10}B is 19.8%.

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The $^{6}Li(n, \alpha)$ Reaction

Another reaction used for the detection of slow neutrons is the (n, α) reaction in ^{6}Li.
Here the reaction proceeds only to the ground state of the product and is written simply as

$$^{6}_{3}Li + ^{1}_{0}n = ^{3}_{1}H + ^{4}_{2}\alpha \quad 4.78\ \text{MeV}$$

The excited lithium nucleus quickly returns (half-life of ~10^{13} s) to its ground state with the emission of a 0.48 MeV gamma ray. We assume that this photon always escapes and does not contribute to the response of the detector.

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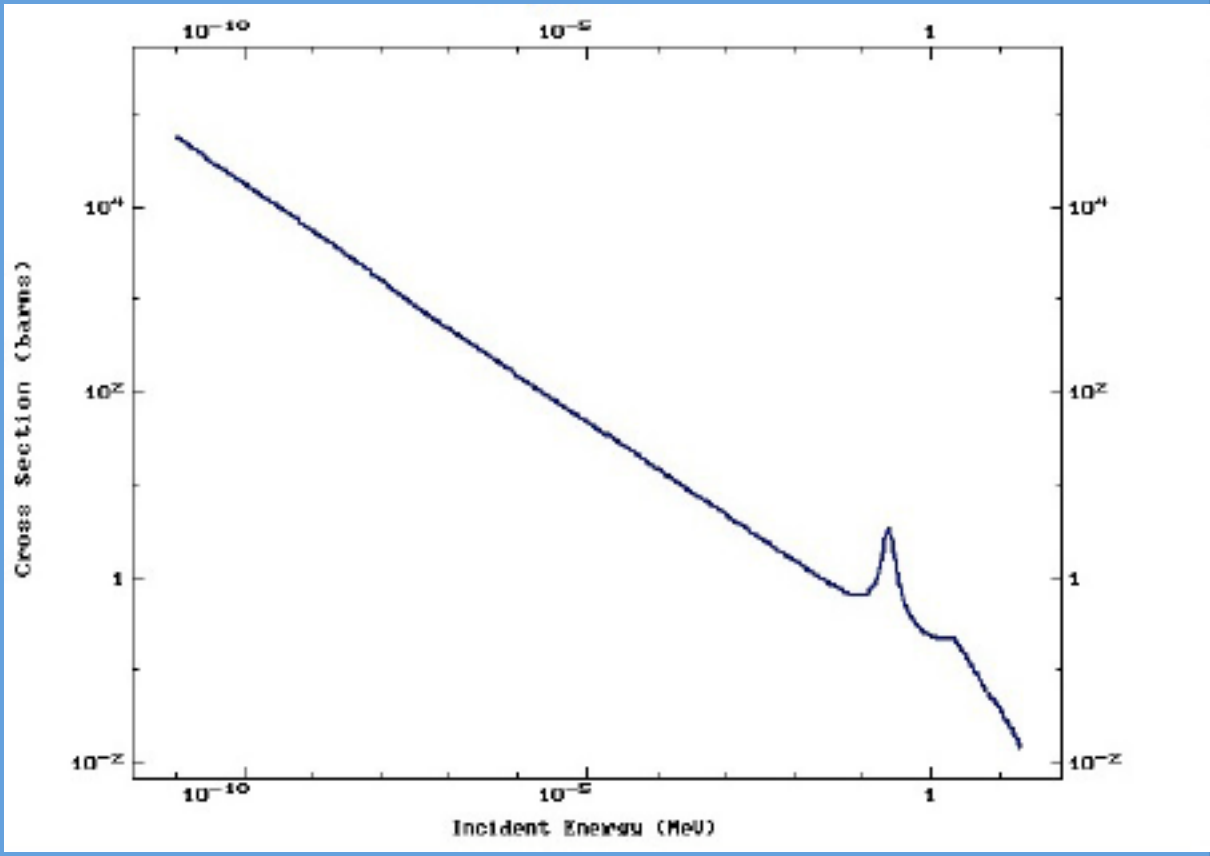
Calculation of the reaction product energies for negligible incoming neutron energy yields the following:

$E_{^3H}$ = 2.73 MeV and E_α = 2.05 MeV

The alpha particle and triton produced in the reaction must be oppositely directed when the incoming neutron energy is low.



The thermal neutron cross section for this reaction is 940 barn . The cross section remains below that for the ^{10}B reaction until the resonance (> 100 keV). The lower cross section is generally a disadvantage but is partially offset by the higher Q-value and resulting greater energy given to the reaction products. with a natural isotopic abundance of 7.4% and is also widely available in separated form.

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The ^{3}He(n, p) Reaction

The gas ^{3}He is also widely used as a detection medium for neutrons through the reaction

$$^{3}_{2}He + ^{1}_{0}n = ^{3}_{1}H + ^{1}_{1}p \qquad 0.764\ \mathrm{MeV}$$

For reactions induced by slow neutrons, the Q-value of 0.764 MeV leads to opposite ed reaction products with energies

E_p=0.573 MeV and $E_{^3H}$ = 0.191 MeV

The thermal neutron cross section for this reaction is 5330 barn, higher than that for the boron reaction, and its value also falls off with a 1/v energy dependence (see next figure).

Although ^{3}He is commercially available, its relatively high cost is factor in some applications.

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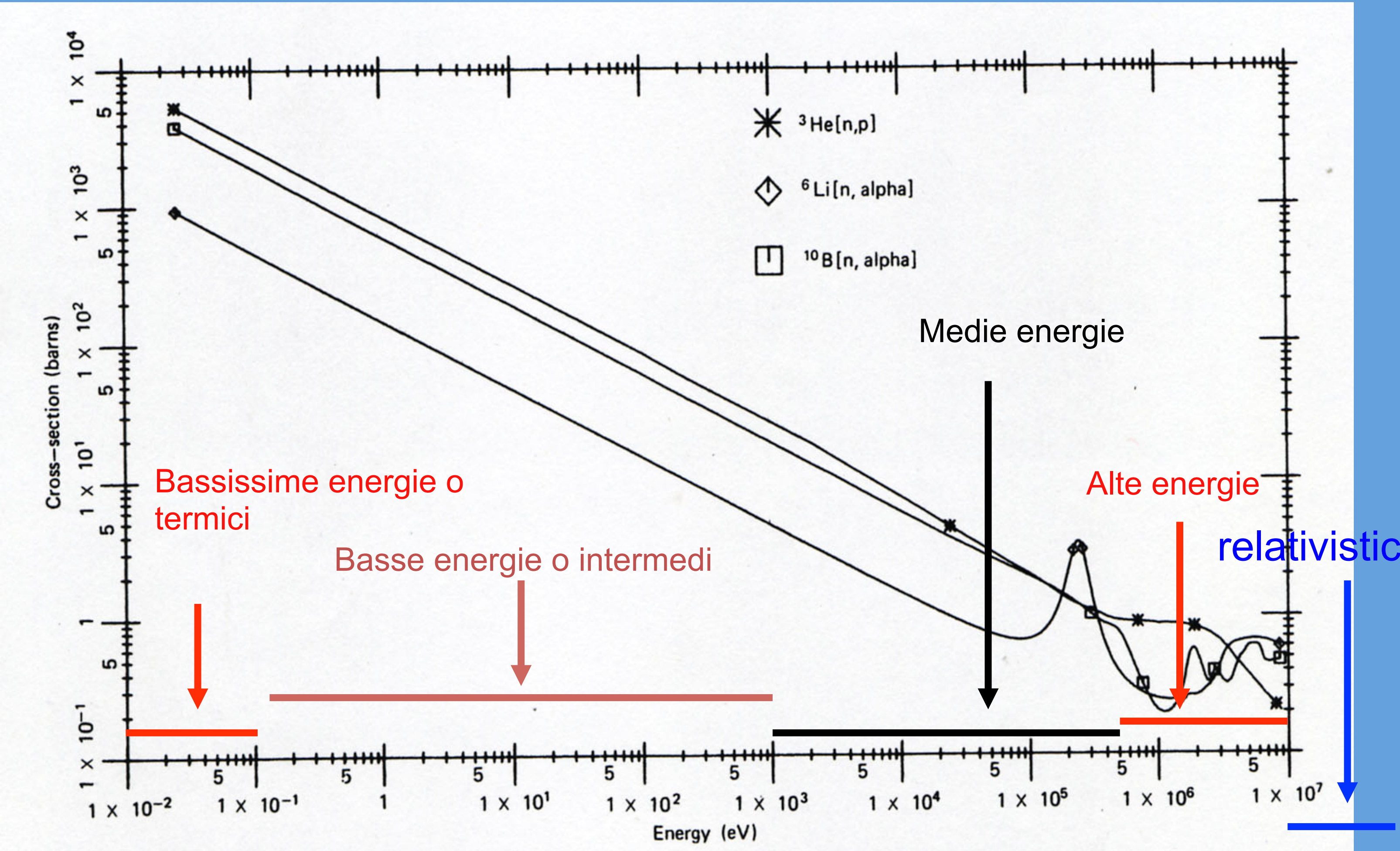

Cross section versus neutron energy for some reactions of interest in neutron detection.

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Processi esoenergetici utilizzati per la rivelazione di neutroni

Reaction	Q(MeV)	σ (barn)
$^{10}B + n \rightarrow {}^{7}Li + \alpha$	2.792	3840
$^{3}He + n \rightarrow {}^{3}H + p$	0.764	5330
$^{6}Li + n \rightarrow {}^{3}H + \alpha$	4.78	940

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DETECTORS BASED ON THE BORON REACTION

A widely used detector for slow neutrons is the BF_3 proportional tube.

In this device, boron trifluoride serves both as the target for slow neutron conversion into secondary particle well as a proportional gas.

A number of other boron-containing gases have been evaluated, BF_3 is the near-universal choice because of its superior properties as a proportional gas, as well as its high concentration of boron.

In nearly all commercial detectors, the gas is highly enriched in ^{10}B, resulting in an efficiency some five times greater than if the gas contained natural occurring boron.

Because the performance of BF_3 as a proportional gas is poor when operated at higher pressures, its absolute pressure in typical tubes is limited to about 0.5—1.0 atm.

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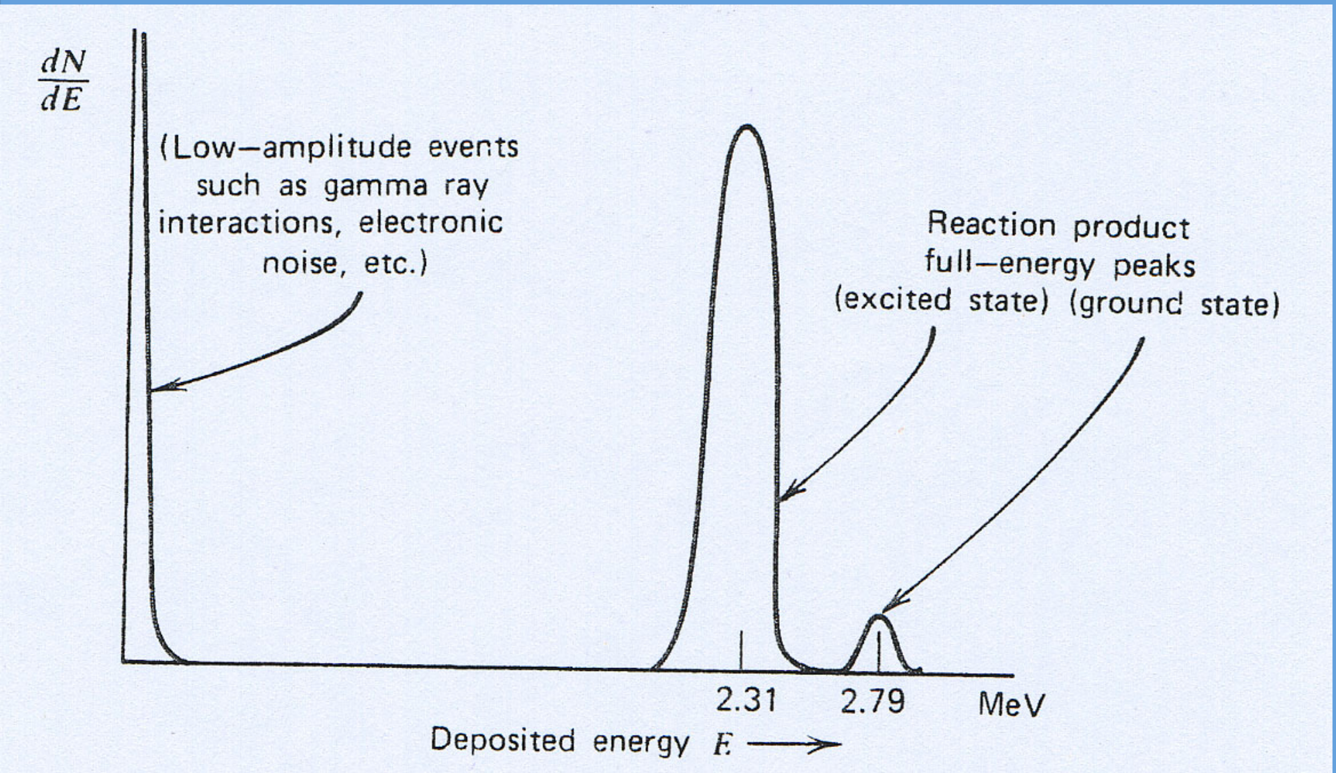

The pulse height spectra shows the ideal pulse height spectrum expected from a BF_3 tube of very large dimensions. For a large tube, nearly all the reactions occur sufficiently far from the walls of the detector to deposit the full energy of the products within the proportional gas.

In that event, all the energy of the reaction is deposited in the detector and the only variation is a result of the branching of the reaction between the excited state and ground state of the ^{7}Li product nucleus. The branching ratio for thermal neutrons is such that about 6% of the reactions lead to the ground state and 94% to the first excited state. Therefore, the areas under the peaks as shown in figure should be in the ratio 94:6 as illustrated.

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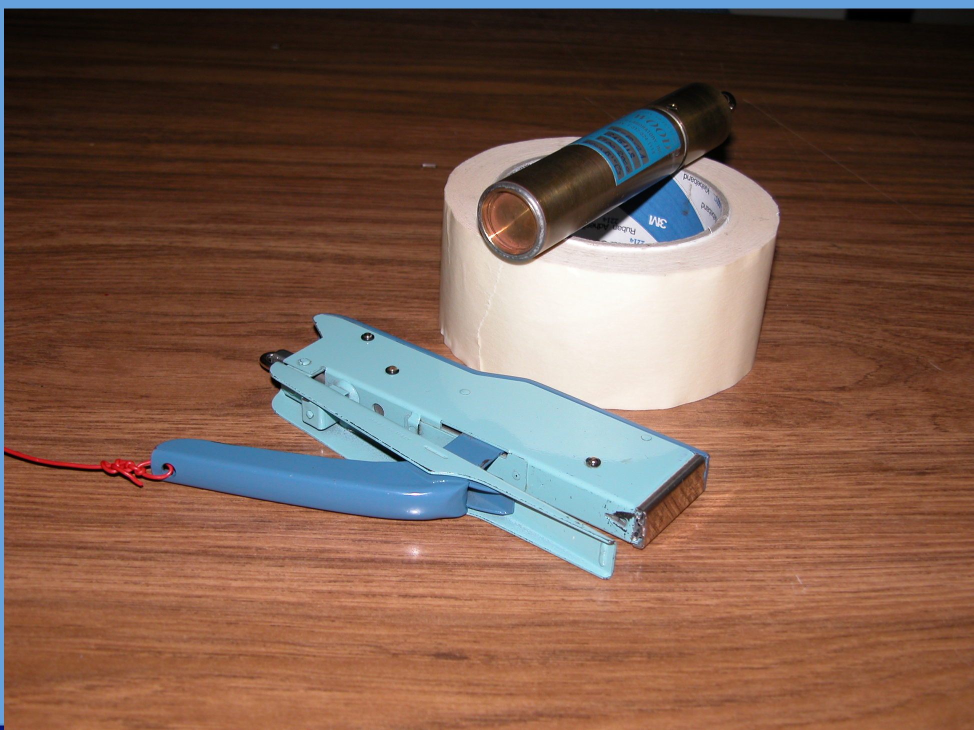
Once the size of the tube is no longer large compared with the range of the alpha particle and recoil lithium nucleus produced in the reaction, some events no longer deposit the full reaction energy in the gas. If either particle strikes the chamber wall, a smaller pulse is produced. The cumulative effect of this type of process is known as the wall effect in gas counters. Because the range of the alpha particle produced in the reaction is on the order of 1 cm for typical BF_3 gas pressures, almost all practical tubes are small enough in diameter so that the wall effect is significant.



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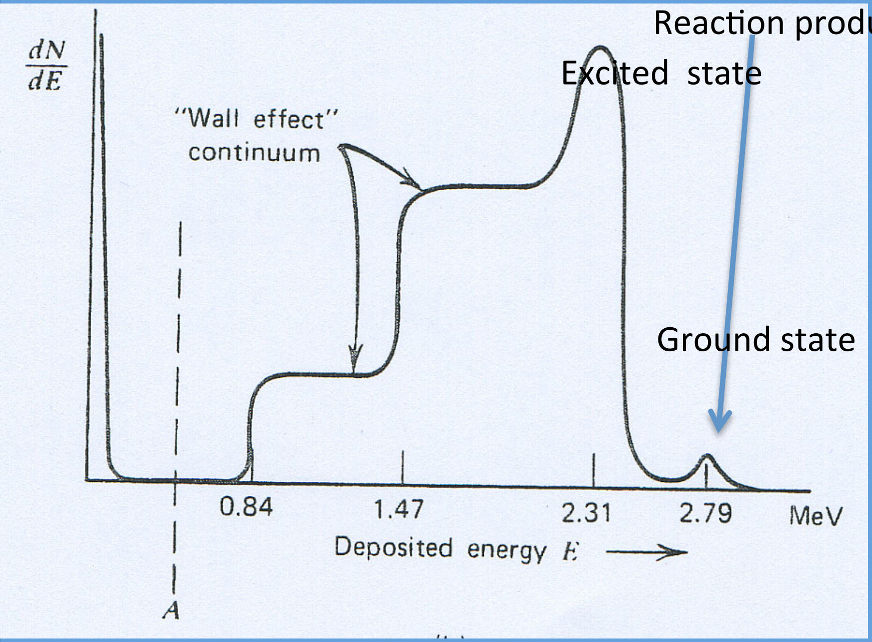
The following figure shows the differential pulse height spectrum expected from a tube in which the wall effect is important. The primary change from the spectrum previously shown is the addition of a continuum to the left of the peaks corresponding to partial energy deposition in the gas of the tube.

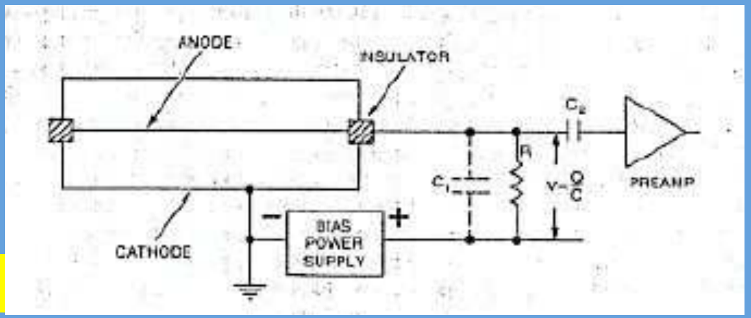


The two steps or discontinuities in the continuum are an interesting feature of the spectrum and can be explained through the following argument.

Because the incoming neutron carries no appreciable momentum, the two reaction products must be oppositely directed.

$$ {}^{10}_{5}B + {}^{1}_{0}n \rightarrow {}^{7}_{3}Li + {}^{4}_{2}\alpha $$

6%	+ 2.792 MeV	Ground state
94%	+2.310 MeV	Excited state



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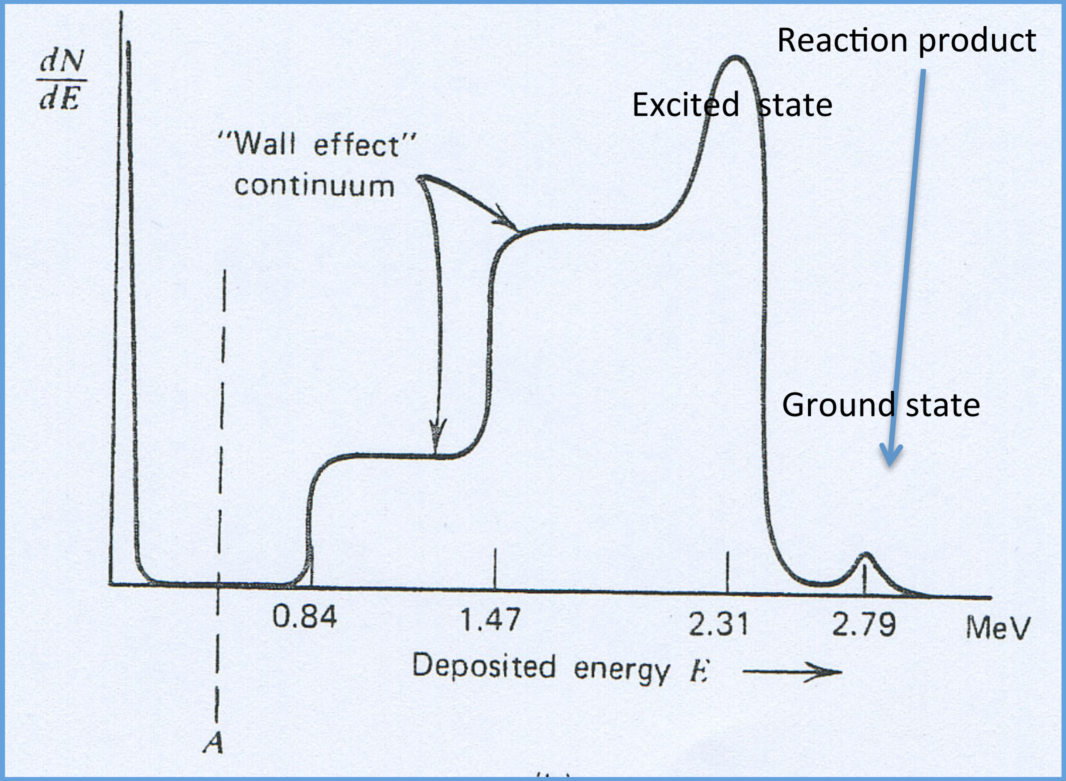

If the alpha particle strikes the wall, the ^{7}Li recoil is therefore directed away from the wall and is very likely to deposit its full energy within the gas.

Conversely, if the ^{7}Li recoil strikes a wall, the entire energy of the alpha particles from that same reaction is usually fully absorbed.

Thus, we expect to see wall losses for only one reaction product at a time.
There are two possibilities: the alpha particle hits a wall after depositing some fraction of its energy in the fill gas, whereas the ^{7}Li recoil is fully absorbed in the gas, or the ^{7}Li recoil hits a wall after depositing part of its energy and the alpha particle is fully absorbed.

The neutron detection efficiency can be increased and the wall effect suppressed by making tube larger in dimension. Similar improvements can be achieved by raising the pressure of BF_3 fill gas.

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BF_3 Tube Construction

The neutron detection efficiency can be increased and the wall effect suppressed by making tube larger in dimension. Similar improvements can be achieved by raising the pressure of BF_3 fill gas. Pressures in the range 200—300 torr (approximately 27—40 kPa) gave best resolution in this work, whereas the full-energy peaks in the spectrum broadened considerably at higher pressure due to recombination and negative ion formation. In many counting situations, the poorer resolution is of no real consequence, and tubes with the higher gas pressure would be quite acceptable as long as a distinct counting plateau is maintained.

In common with most proportional counters, BF_3 tubes are universally constructed using cylindrical outer cathodes and small-diameter central wire anodes. Aluminum often the material of choice for the cathodes because of its low neutron interaction cross section. BF_3 tubes of typical construction are normally limited to operating temperatures up about 100 ˚C, but tubes of special design can extend the operating range to as high as 150 ˚C.

However, the pulse amplitude decreases and the pulse height resolution decreases.

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Gamma-Ray Discrimination

A very important consideration in many applications of BF_3 tubes is their ability to discriminate against gamma rays, which often are found together with the neutron flux to be measured measured.

Gamma rays interact primarily in the wall of the counter and create secondary electrons that may produce ionization in the gas. Because the stopping power for electrons in gases is quite low, a typical electron will deposit only a small fraction of its initial energy within the gas before reaching the opposite wall of the counter.

Thus, we should most gamma-ray interactions will result in low-amplitude pulses that will lie in the tail to the left in previous figure. Simple amplitude discrimination can then easily eliminate these gamma rays without sacrificing neutron detection efficiency.

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- **If the gamma-ray flux is sufficiently high, however, several complications can reduce the effectiveness of this amplitude discrimination.**
-
- **At high rates, pulse pile-up can result in apparent peak amplitudes for gamma rays which are considerably larger than any individual pulse.**

- **A compromise must then be struck in choosing the pulse-shaping time constant in the detector electronics. Short time constants is desirable in order to reduce the gamma-ray pile-up but may lead to reduction in the neutron-induced amplitude due to incomplete charge integration.**

- **At very high gamma rates, there is evidence that chemical changes occur in the BF_3 gas caused by molecular disassociation leading to degraded pulse height spectra from neutron-induced events.**

- **If this degradation is sufficiently severe, it may no longer be possible to separate gamma- and neutron events. In extreme cases, the radiation-induced chemical changes can result in damage to the tube. Conventional BF_3 tube are able to discriminate gamma ray signal up to 2 Gy/h**

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BF_3 fromCentronic

Neutron flux is defined in terms of $n.cm^{-2}.s^{-1}$ where n is a unit-less number meaning ‘neutrons’.

In the past the neutron flux has always been considered as the number of neutrons contained within 1 cubic centimetre multiplied by the average neutron speed in centimetres per second. It is designated ‘nv’. Whilst the numeric value obtained is the same as in the above definition of the paragraph, the ‘n’ of ‘nv’ is not unit-less but represents the number of neutrons per cm^3. Velocity is represented by v in $cm.s^{-1}$.

BF_3 Neutron Proportional Counters

Boron trifluoride (BF_3) Neutron Proportional Counters are sensitive to thermal neutrons, but are less sensitive to gamma radiation than Helium-3 (^3He) counters. Centronic BF_3 Neutron Proportional Counters are typically used for thermal neutron diffraction, spectroscopy, industrial gauging, mixed waste monitoring and soil moisture detection.

Selection from product range – summary of parameters

CENTRONIC PART NUMBER		BF3 GAS PRESSURE, SENSITIVITY AND OPERATING VOLTAGE					
		20cm Hg (XX=20)		40cm Hg (XX=40)		70cm Hg (XX=70)	
Replace the XX in each part number with the number specified under BF3 Gas Pressure	**ACTIVE LENGTH (mm)**	**SENSITIVITY (cps/nv)**	**OPERATING VOLTAGE (Volts)**	**SENSITIVITY (cps/nv)**	**OPERATING VOLTAGE (Volts)**	**SENSITIVITY (cps/nv)**	**OPERATING VOLTAGE (Volts)**
13mm Diameter Tubes							
5EB/XX/13M	50	0.15	1200	0.3	1300	0.53	1800
25mm Diameter Tubes							
13.5EB/XX/25M	135	1.5	1300	3.0	1800	5.0	2400
15EB/XX/25M	150	1.8	1300	3.5	1800	5.9	2400
31EB/XX/25M	310	3.9	1300	7.4	1800	12.5	2400
50EB/XX/25M	500	6.0	1300	12	1800	20	2400
100EB/XX/25M	1000	12	1300	23	1800	39	2400
125EB/XX25M	1250	15	1300	29	1800	49	2400
50mm Diameter Tubes							
15EB/XX/50M	150	7	1900	13	2800	22	3600
25EB/XX/50M	250	12	1900	22	2800	36	3600
50EB/XX/50M	500	23	1900	44	2800	72	3600
107EB/XX/50M	1070	53	1900	102	2800	169	3600

All detectors available in Aluminium, Copper or Stainless Steel construction. HN connectors are fitted as standard. Other connectors are available.

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Detection Efficiency of a BF_3 Tube

The detection efficiency for neutrons incident along the axis of a BF_3 tube is given by
$\varepsilon(E) = 1 — \exp [-\Sigma_a(E)L)]$

Where
Σ_a= macroscopic cross section of ^{10}B at neutron energy E
L = active length of the tube

A BF_3 tube exposed to neutrons with mixed energies will respond principally to the slow neutron component.
The above equation slightly overestimates the neutron counting efficiency because there usually are regions near the end of the tube in which charge collection is inefficient, resulting in reduced neutron response.
The influence of these dead spaces is most severe for detectors whose length is small and has been the subject of experimental investigations that lead to a more precise prediction of detector efficiency.

Most practical BF_3 counters are filled with pure boron trifluoride enriched to about 96% in ^{10}B. However, because BF_3 is not ideal as a proportional counter gas, counters are sometimes manufactured using BF_3 with an admixture of a more suitable gas such as argon.

This dilution causes a decrease in detection efficiency, but the pulse height spectrum from the tube generally shows sharper peaks and consequently a more stable counting plateau than tubes filled with pure BF_3.

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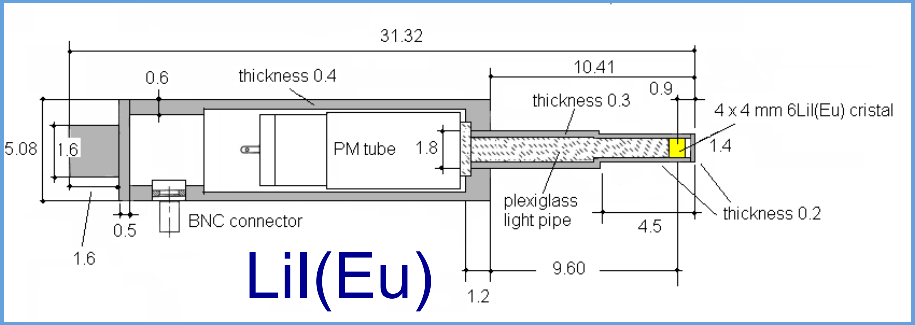
Cristals of LiI are generally large compared with the ranges of the reaction products from a neutron interaction. Therefore the pulse height response will be free of wall effects and should be a single peak for all slow neutron interaction.



Usually , neutrons associated with gammas,

both will interact with most scintillators but :

Neutron + ^{6}Li → alpha + Triton (4.78 MeV total)

(particles !) → Peak at > 4 MeV

Two methods exist for recording the pulses from the LiI(Eu) scintillator.

The first method is the use of a single channel analyzer (SCA). This system counts pulses from the detector that fall into the SCA energy "window". Here gross counts can be recorded. By subtracting the background count rate in a purely gamma environment, net counts can be produced as a function of time in the neutron gamma field.

A second method uses a multi-channel analyzer in which pulses are binned according to their pulse height in volts. A multi-channel analyzer (MCA) was used to record the pulses. This allows for a finer background subtraction of gamma ray noise in the residual spectrum than the SCA energy window method. As gamma rays interact in the crystal, they produce recoil electrons. These recoil electrons typically have ranges larger than the crystal. This is the reason the crystals are kept quite small.

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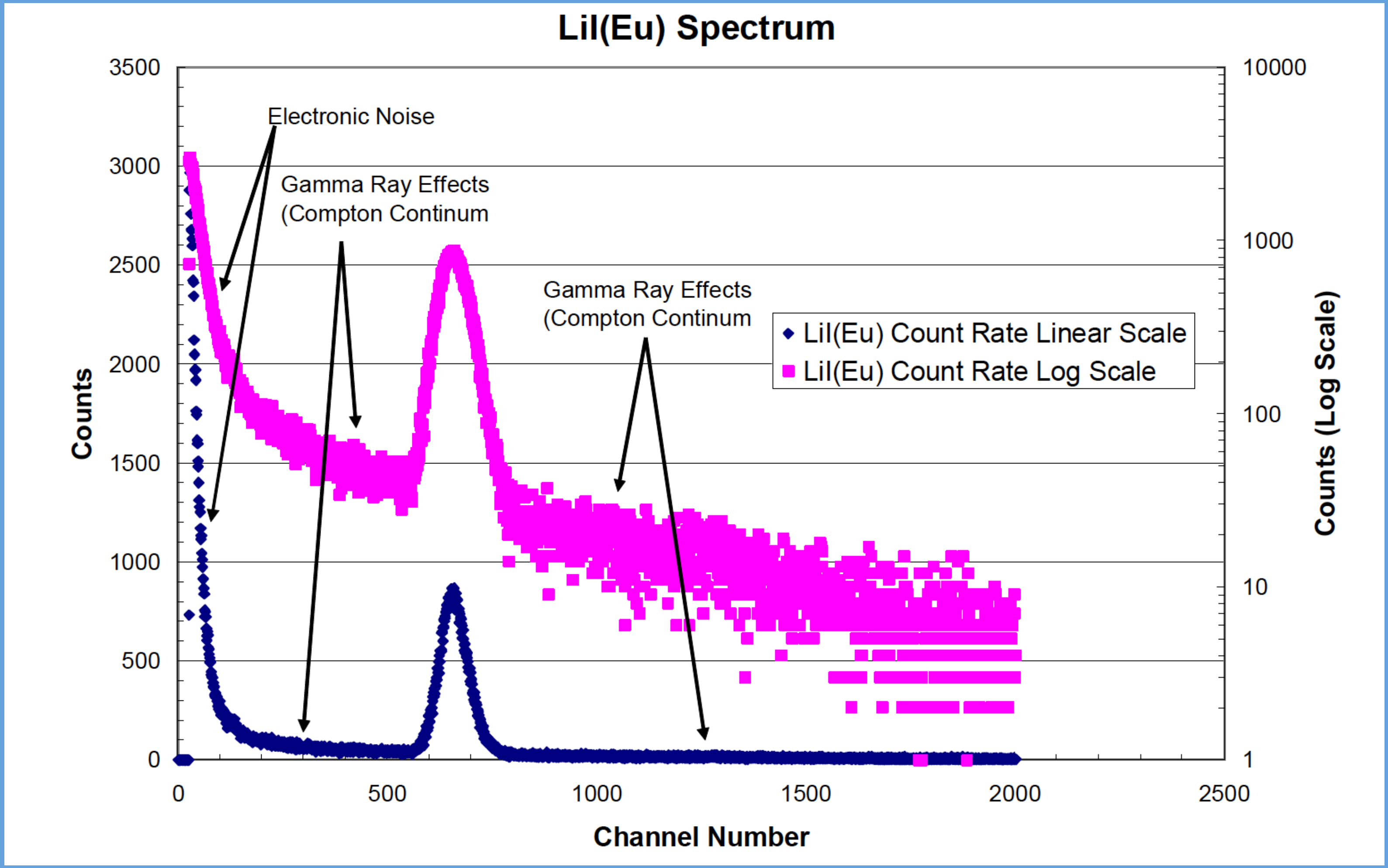
Since the electrons don't fully deposit their energy, they produce a Compton recoil electron spectrum. Even though the crystal has a very small diameter, there is still considerable gamma ray background that is present in the measurements



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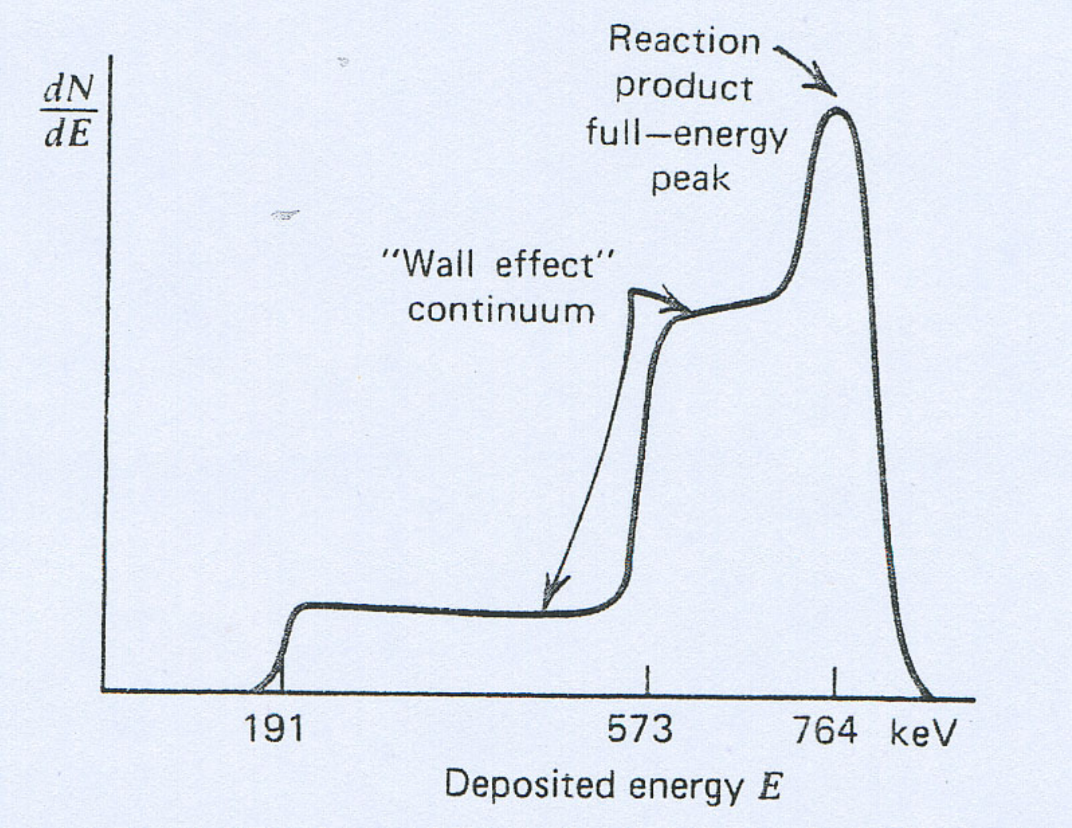
^{3}He Proportional Counter

With a cross section even higher than that of the boron reaction, the ^{3}He(n,p) reaction is an alternative for slow neutron detection. Unfortunately, because ^{3}He is a noble gas, no solid compounds can be fabricated and the material must be used in gaseous form.

^{3}He of sufficient purity will act as an acceptable proportional gas, and detectors based on this approach have come into common use. In a large detector, one would expect each thermal neutron reaction to deposit 764 keV in the form of kinetic energy of the triton and proton reaction products.

Because the range of these reaction products is not always small compared with the dimensions of the proportional tube, however, the wall effect discussed BF_3 tube can also be important for ^{3}He proportional counters. The expected spectrum for a tube of typical size is illustrated.



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$$ {}_{2}^{3}He + {}_{0}^{1}n = {}_{1}^{3}H + {}_{1}^{1}p \quad 0.764 \text{ MeV} $$

Only a single full energy peak should be expected for neutron energies that are small compared with 764 keV. The step structure to the left of the peak is similar to that shown in for a BF_3 that the discontinuities will occur at energies corresponding to that of the proton (573 keV) and triton (191 keV).

The continuum in the pulse height spectrum due to the wall effect is detrimental for several standpoints. The voltage range over which an acceptable counting plateau will be observed is reduced, and the smaller pulse height for some neutron events will reduce the separation expected from low-amplitude, gamma-induced pulses.

Consequently consideration is often given in the design of ^{3}He tubes to minimize the wall effect. One is to build the counter with a diameter as large as possible so that most neutron interactions occur far away from the wall. Another is to increase the pressure of the ^{3}He to reduce the range of the charged particle reaction products.

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Compared with BF_3 tubes, ^3He counters can be operated at much higher pressure with acceptable gas multiplication behavior and are therefore preferred for those applications in which maximum detection efficiency is important.

The lower Q-values for the ^3He reaction, however, makes gamma-ray discrimination more difficult than for an equivalent BF_3 tube. When the gamma irradiation rate is high, the pile-up of the resulting pulses can raise their amplitudes to the point that a clean separation from the neutron-induced pulses is no longer possible.

The acceptable operating temperature for ^3He tubes has been shown to extend as high as 200-250°C. In general, the pulse amplitude increases and the pulse height resolution decreases with increasing temperature, while the pulse rise time shows temperature dependence.

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^{3}He proportional counters from Centronic

^{3}He proportional counters are constructed using metal walls and specially manufactured metal-ceramic insulators. In the interest of long counter life and good resolution particular attention is paid to the removal of impurities from filling gases and other materials. Tubular counters of 25 and 50 mm diameter are standard as are spherical ^{3}He counters for applications where omni-directional response is required.

The gas filling comprises a mixture of ^{3}He and other gases, typically krypton or carbon dioxide. This mixture can be selected to optimise specific aspects of performance, e.g. krypton gives best results for use in neutron spectroscopy, whereas carbon dioxide gives lower sensitivity to gamma radiation when counting thermal neutrons only. Fillings of up to 10 atmospheres are available as standard.

The sensitivity of the counter is dependant upon both the filling pressure and the energy of the neutrons being detected.

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Type	Advantages	Disadvantages
BF_3	Excellent photon rejection Low cost	Typical filling pressure only 67 to 80 kPa, energy resolution suffers beyond this point
^3He	Filling pressure up to 1 MPa More sensitive and more stable than BF_3 Good photon rejection	Expensive
$^6LiI(Eu)$	High sensitivity (solid) Compact size (typically $4 \times 4 \times 1$ mm^3) helps to reduce response anisotropy	Photon rejection weaker than gas counters Light-guide and photomultiplier tube partially reduce the advantage of compact size

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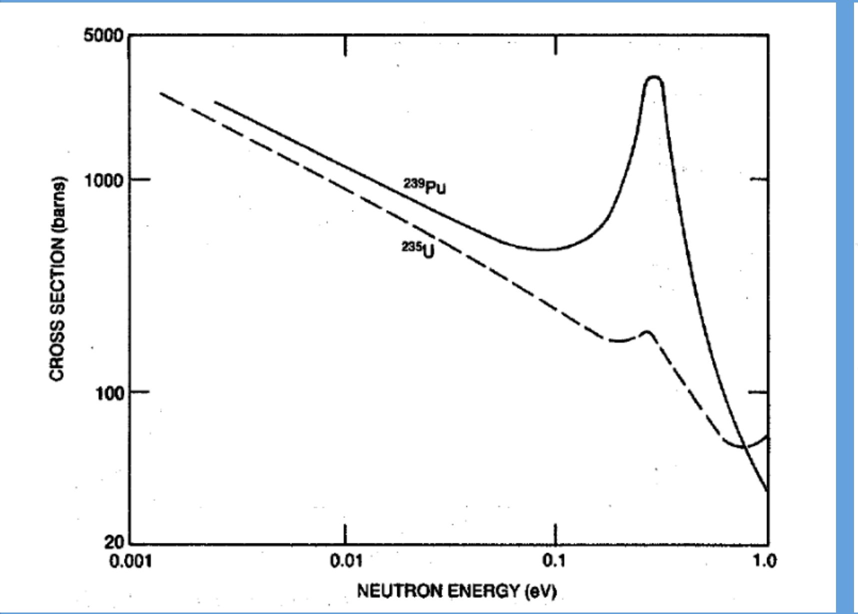
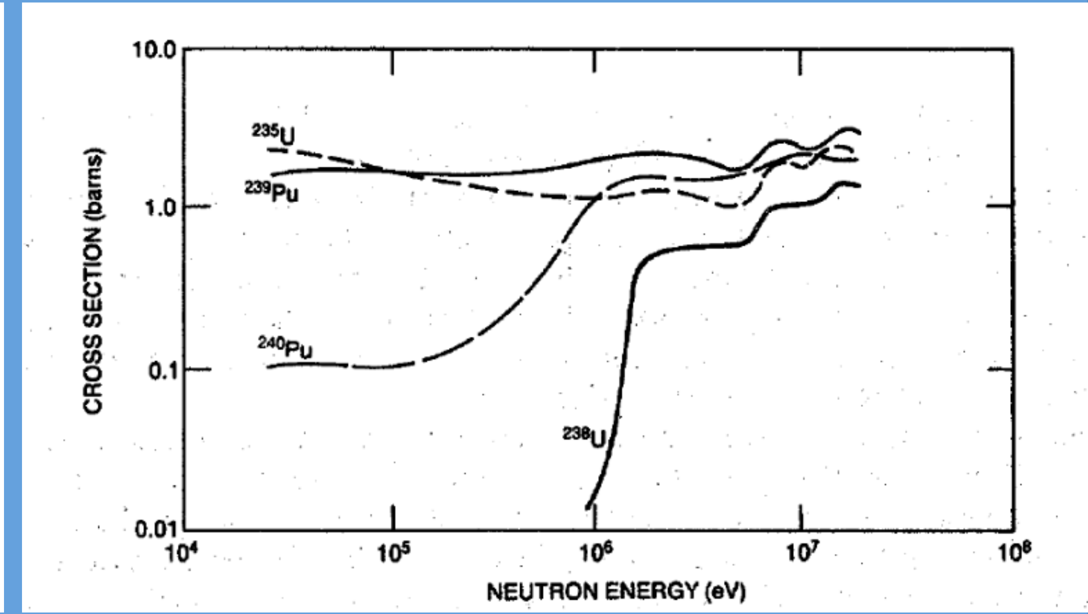
The neutron induced fission reaction can serve as a means of converting slow neutron into ionizing reaction products that can be detected by conventional means.

The main remarkable characteristic of the fission reaction is the large amount of energy 200 MeV liberated in the reaction, about of 165 MeV of which appears as kinetic energy of fission fragments.

$^{235}U + n \rightarrow$ fission fragments+ 2or 3 n+ 200MeV





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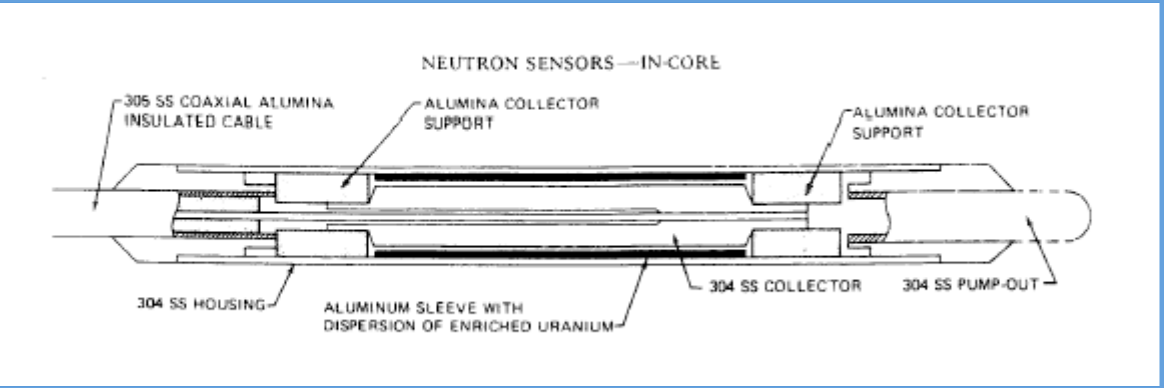
For this reason the neutron induced fission reaction can be expected to be of larger magnitude in most detectors than any other competing reaction or background or counter contamination.
So extremely low counting rate can be achieved

The most popular shape of fission detector is an ionizing chamber that has its inner surfaces coated with a fissile deposit



1 barn= 10^{-24} cm^2

Nuclide	Cross section (barn)	Threshold MeV	Cross section @ 3 MeV	Hal life
^{231}Pa	10 mbarn	0.5	1.1	
^{233}U	530	-	1.9	
^{235}U	580	-	1.3	
^{237}Np	19mbarn	0.4	1.5	
^{239}Pu	750	-	2	

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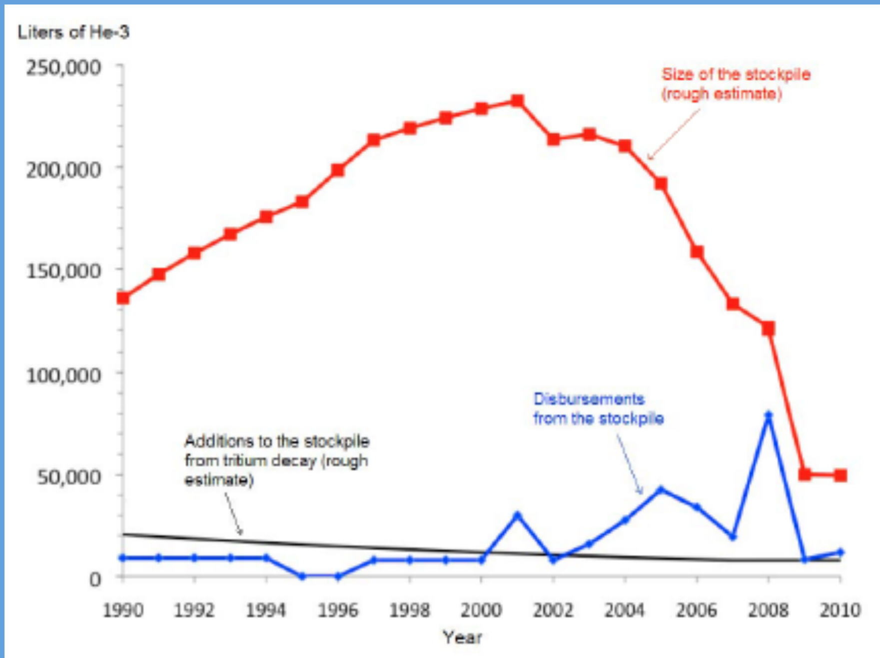
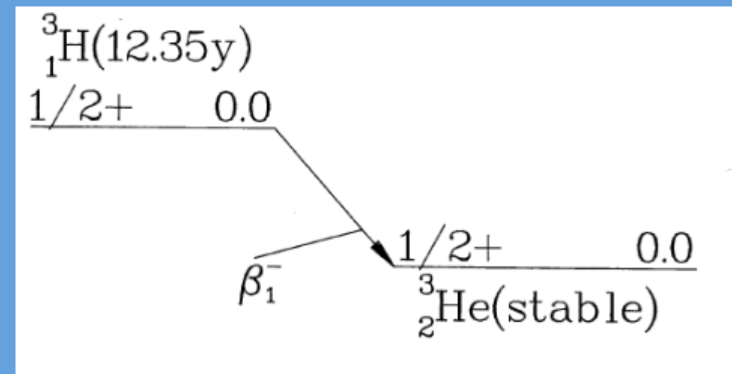
The world is experiencing a shortage of helium-3



Tritium is produced by irradiating lithium in a light-water nuclear reactor.



From the perspective of the weapons program, the extracted helium-3 is a byproduct of maintaining the purity of the tritium supply. This means that the tritium needs of the weapons program, not the demand for helium-3 itself, determine the amount of helium-3 produced.

At present, helium-3 is only produced as a byproduct of the manufacture and purification of tritium for use in nuclear weapons. The supply of helium-3 therefore derives mostly, perhaps entirely, from two sources: the U.S. and Russian governments.

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