Minicourse on Experimental techniques at the NSCL **Neutron detection & spectroscopy**

Thomas Baumann

National Superconducting Cyclotron Laboratory
Michigan State University
e-mail: baumann@nscl.msu.edu

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1 Introduction

Neutron detection techniques play an important role in the investigation of rare isotopes, of which the majority are neutron rich nuclei. Some of these system are very loosely bound and exhibit unusual nuclear structures like neutron halos or skins. The investigation of these nuclei often involves coincidence measurements between charged breakup fragments and neutrons. On the other hand, neutron rich nuclei are interesting because the remnants of the r-process in super nova explosions beta-decay through this part of the nuclear chart. Some parameters of these nuclei are essential in determining the abundance of elements. Beta-delayed neutron emissions can be studied using highly efficient detectors for neutrons of intermediate energies.

In this lecture I will focus on neutron detection techniques that are used in our laboratory, and point to some examples of experimental applications.

2 Neutron detection techniques

The name-giving feature of neutrons is also the most problematic if it comes to their detection: they have no charge. Due to this fact, neutrons can not be detected directly. Neutrons are always detected through nuclear reactions that create charged particles which can in turn be detected by radiation detectors.

2.1 Slow neutron detection

Neutrons are called slow if their energy is below the cadmium cutoff[1] of about 0.5 eV. Neutrons of these energies are detected via nuclear conversion reactions, for example (n,α) or (n,p) reactions. All common techniques used to detect slow neutrons result in heavy charged particles:

$$\text{target nucleus} + \text{neutron} \longrightarrow \begin{cases} \text{recoil nucleus} \\ \text{proton} \\ \text{alpha particle} \\ \text{fission fragment} \end{cases}$$

Because the energy of the detected neutron is small compared to the Q-values of these reactions, the reaction products carry away an energy corresponding to the Q-value. This means that the information on the neutron energy is lost in these reactions. The three conversion reactions commonly used in detectors are:

			Q-value:
^{10}B + n	$\longrightarrow$	^{7}Li* + α	2.310 MeV (excited state, 94%)
		^{7}Li + α	2.792 MeV (ground state, 6%)
^{6}Li + n	$\longrightarrow$	^{3}H + α	4.78 MeV
^{3}He + n	$\longrightarrow$	^{3}H + p	0.764 MeV

The energy from the reaction is shared by the two reaction products, the alpha particle (or proton) and the recoil nucleus, according to conservation of momentum and energy.

The ^{10}B(n,α) reaction is employed in BF_3 proportional tubes where boron trifluoride is used as a proportional gas. The BF_3 gas is usually enriched in ^{10}B, and it has to be used at lower absolute pressures between 0.5 and 1.0 atm in order to get a good performance as a proportional gas.

In a similar way, ^{3}He is used as a conversion target and proportional gas in the ^{3}He proportional counter. Due to the lower Q-value of the ^{3}He(n,p) reaction, the discrimination of gamma rays is more difficult than with BF_3 counters, since secondary electrons only deposit a small amount of energy in the gas,.

Both types of proportional counters show the *wall effect* in their pulse height spectra (see Fig. 1), which occurs when the neutron capture happens close enough to the detector wall for one of the reaction products to strike

[1] *cadmium cutoff:* In neutron irradiations, the energy value which, for a given experimental configuration, is determined by the condition that if a cadmium cover surrounding a detector were replaced by a fictitious cover black to neutrons below this value and transparent to neutrons with energy above this value, the observed detector response would be unchanged [1].

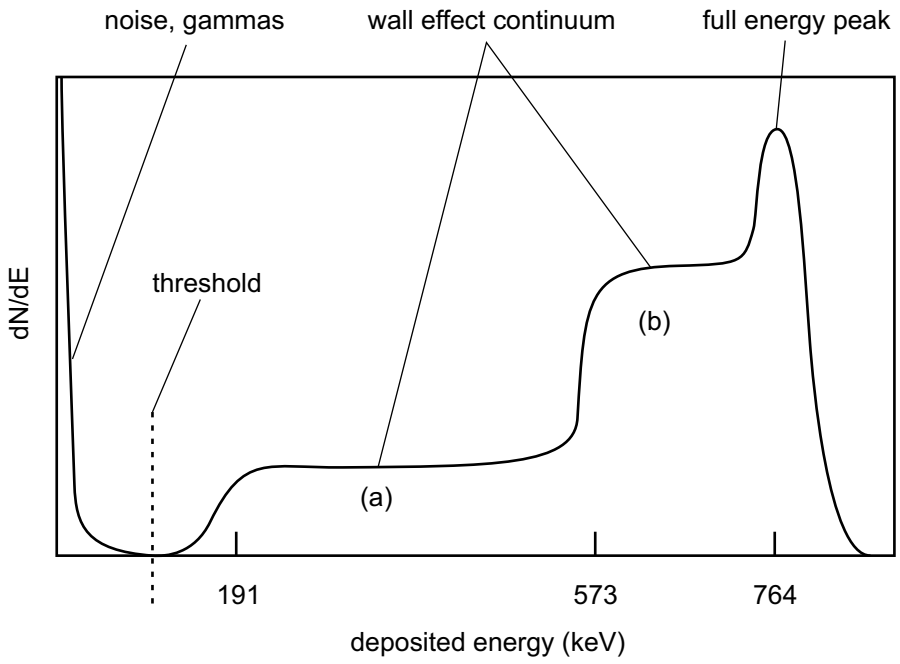

Figure 1: Expected pulse height spectrum from a ^{3}He tube. The two steps in the spectrum are caused by one of the reaction products hitting the detector wall. In area (a), the triton energy is fully deposited, but the proton only deposited a fraction of its energy, and vise versa in area (b).

it. In this case, only a fraction of its energy is deposited in the gas. Since the neutron does not bring in any significant momentum when it is captured, the two reaction products are emitted opposite to each other. Consequently, only one of them can strike the wall at a time, yielding to a characteristic pulse height spectrum with two steps. The wall effect is larger for small detectors.

The ^{6}Li(n,α) reaction is usually used in scintillators. One possibility is lithium iodide, which is chemically similar to sodium iodide. Due to the density of enriched ^{6}LiI(Eu) crystals, a 10 mm thick detector is almost 100% efficient for neutrons ranging from thermal energies up to about 0.5 eV. Lithium is also incorporated in scintillating glass matrices. Lithium glass scintillators are used in time-of-flight measurements due to their relatively fast time response of less that 100 ns. This type of detector, however, is more commonly used in the detection of neutrons with intermediate energies.

A more detailed description of slow neutron detection can be found in Ref. 2.

2.2 Intermediate energy neutrons

The cross sections of the neutron capture reactions described in the previous section decrease rapidly with neutron energy. Therefore the detectors mentioned earlier are very inefficient if they are used directly for neutrons of intermediate energies (also called fast neutrons). But the slow neutron detectors can be surrounded by a hydrogen-containing material that moderates the neutrons down to energies where the detection efficiency is high. This moderation is done by elastic scattering, and the neutron can be slowed down most effectively by hydrogen nuclei [3]. Polyethylene and paraffin are the most common moderators.

The detection efficiency of a moderator-detector combination will depend on the neutron energy and the thickness of the moderator. This fact lead to a very practical application in neutron dosimetry. If a LiI scintillator is placed in the center of a 12 inch polyethylene sphere, the energy dependence of the detection efficiency coincidentally matches the curve of dose equivalent delivered into a biological medium as a function of energy. The neutron count of such a detector will automatically include the energy dependent weighting factors for the dose equivalent. These *Bonner spheres* can be found all over this laboratory measuring the neutron dose.

The low energy neutron detector that is being built at the NSCL will incorporate BF_3 and ^{3}He proportional tubes embedded in a polyethylene moderator in order to detect beta-delayed neutrons that range in energy up to 6 MeV (see Fig. 2).

2.3 High energy neutrons

For neutrons of even higher energies the use of a moderator is unpractical, furthermore, moderator based detectors are slow and can not be used for time measurements. The most common method to detect fast neutrons is based on elastic scattering of neutrons on light nuclei, resulting in a recoil nucleus. This is also the principle of proton recoil scintillators. Fast neutrons incident on a hydrogen-containing scintillator will scatter elastically and give rise to recoil protons ranging in energy up to the full neutron energy. The energy of the recoil protons is then deposited in the scintillator and converted to fluorescence.

A large variety of hydrogen-containing scintillators is available: organic crystals (anthracene, stilbene), liquid scintillators (organic scintillant in in an organic solvent), and plastic scintillators (organic scintillant in in a polymerized hydrocarbon). Anthracene has the highest light output of them all, but organic crystals are difficult to get in large sizes and are expensive. In addition, they can easily be damaged by mechanical or thermal shock, and the light output depends on the relative orientation of particle movement and crystal axis. Therefore, liquid and plastic scintillators, which are relatively

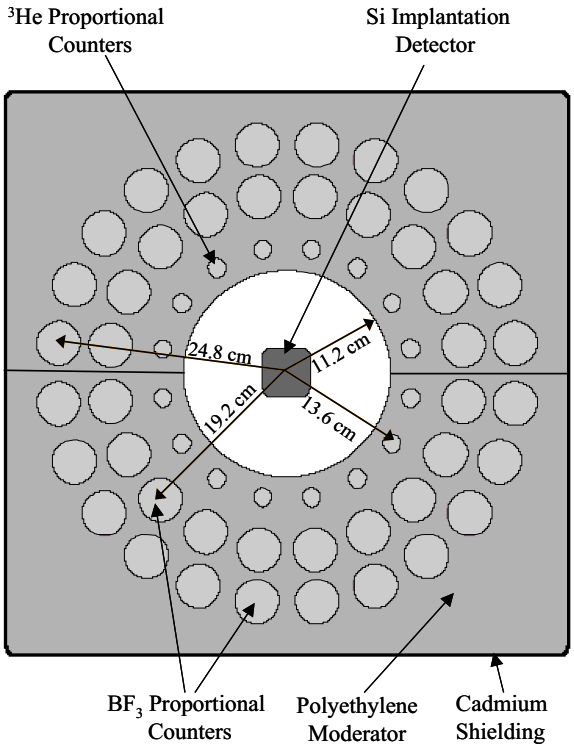

Figure 2: Cross section of the low energy neutron detector at the NSCL surrounding the beta decay station.

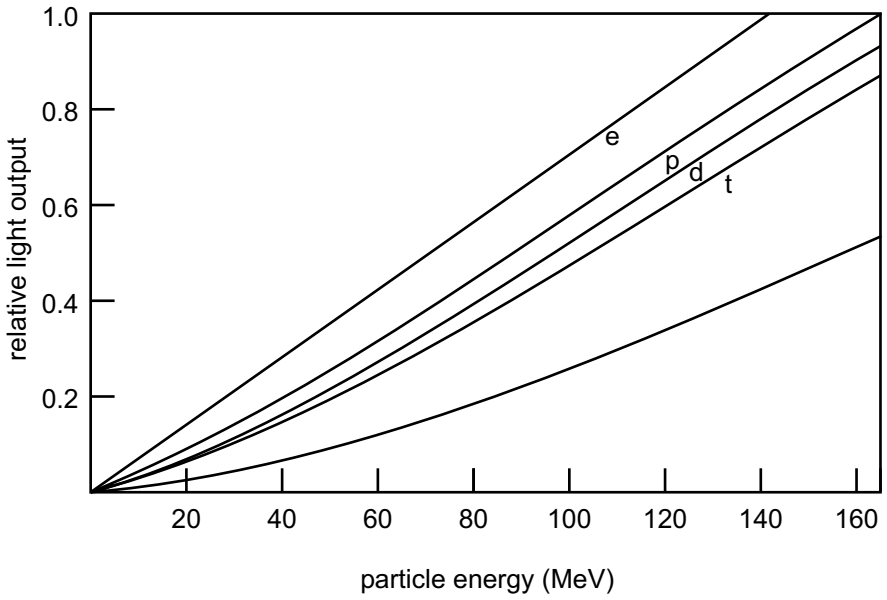

Figure 3: Relative light output versus particle energy for different charged particles. These curves are typical for plastic scintillators.

inexpensive and easy to handle, are most commonly used in fast neutron detection.

Properties of different scintillators that need to be considered are:

- light output (this is usually quoted in % of anthracene)
- decay constant (can the detector be used for timing?)
- wavelength of light emission (has to match the photo multiplier's sensitivity)
- H/C ration (carbon recoils only give a small light output)
- attenuation length (important for large detectors)
- puls-shape discrimination capability

Light output

Because the light response from electrons above roughly 125 keV is linear for most scintillators, the light output of different charged particles is commonly given in equivalent electron energy, or MeVee. The light output for heavy charged particles is always less than that for electrons of the same energy

and non-linear (see Fig. 3). This quenching of light output is described by Birks' saturation law:

$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx} + C\left(\frac{dE}{dx}\right)^2}$$

This is actually the formula with the extension by Craun & Smith [5]. dL/dx is the light energy emitted per unit path length, dE/dx is the specific energy loss for the charged particle, and S is the scintillation efficiency. The two empirical parameters kB and C can be looked up in the literature for specific scintillator materials [5].

Time response

Organic scintillators have a fast time response and are well suited for time measurements. The rise time, i.e. the time it takes to populate the prompt fluorescence levels, is of the order of 0.5–1.0 ns for most organic scintillators, and decay times range from 2 to 4 ns.

Some scintillators have a slower decay component in addition, and the population of these slower decaying levels depends on the particle type (see Fig. 4). These scintillators offer the possibility of *pulse-shape discrimination*, which can be used to distinguish between neutrons and events from gammas.

See Ref. 4 for more on scintillation detectors.

The tasks that detectors for fast neutrons need to fulfill might be quite different. Most detectors need a high detection efficiency. If you only want to count neutrons, that and the possibility to discriminate against background events might be all you need. If you want to measure the energy of the neutrons, you have to make sure that the complete energy of the incident neutrons is deposited in the detector volume, and a good energy resolution is needed. This might be quite difficult to achieve for high energy neutrons. An easier way to determine the neutron energy is the time of flight measurement. In this case, it does not matter if not the full energy of the neutron is deposited inside the detector, however, timing becomes important. Position information for neutrons can be gained by using a detector array with a sufficient granularity or by measuring the time difference of the light signals arriving on opposite ends of the detector. A good position resolution in general can not be achieved together with a very high detection efficiency. The high detection efficiency would require a large detector thickness, which gives rise to multiple neutron scattering. For most applications, a compromise has to be found.

2.4 Neutron shielding

In order to improve the signal-to-background ratio, neutron detectors need to be shielded from external sources of neutrons. To shield neutrons, they have

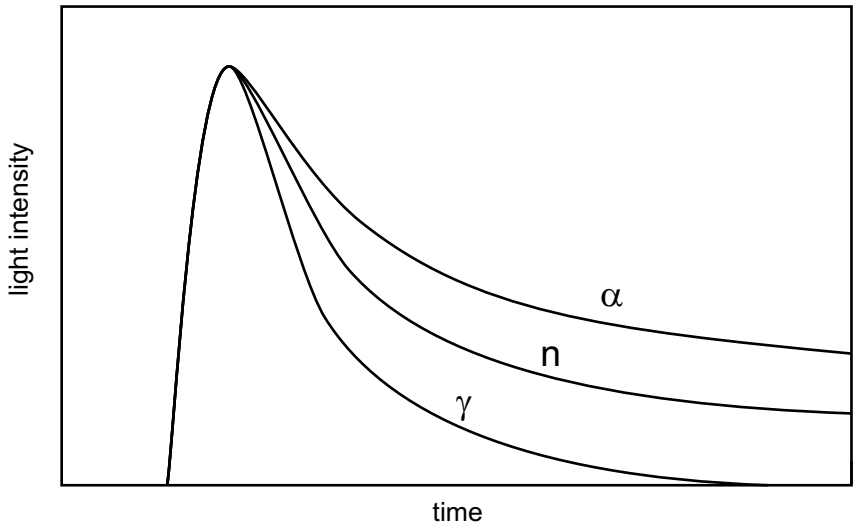

Figure 4: Decay times for scintillation light in a scintillator with pulse-shape discrimination capabilities (qualitative diagram).

to be moderated to energies where the absorption cross sections are high. Hydrogen-containing moderators that are cheap are for instance water, concrete, and paraffin. The neutron capture in hydrogen leads to a 2.22 MeV gamma ray, therefore boron (0.48 MeV gamma) or lithium (no gamma emission) are preferred as absorbers. These elements can be mixed with the moderator material or added in a thin layer where the neutrons are moderated. Common two-component neutron shields are paraffin-boron, polyethylene-boron, and polyethylene-lithium. Cadmium sheets are an excellent shield to thermal neutrons [6].

Cosmic radiation is also detected by neutron detectors, however, it is difficult to shield, even with the thickest concrete ceilings. If cosmic radiation or charged particles from the reaction target need to be shielded, an *anti-coincidence shield* can be used. In this active shielding method, only events where the anti-coincidence detector did not fire are accepted. In principle any charged particle detector can be used as a veto detector, commonly large plastic or liquid scintillators are used.

3 Experimental techniques

Here I will give just a few examples of experimental techniques that involve rare isotope beams and rely on the detection of neutrons. A large number

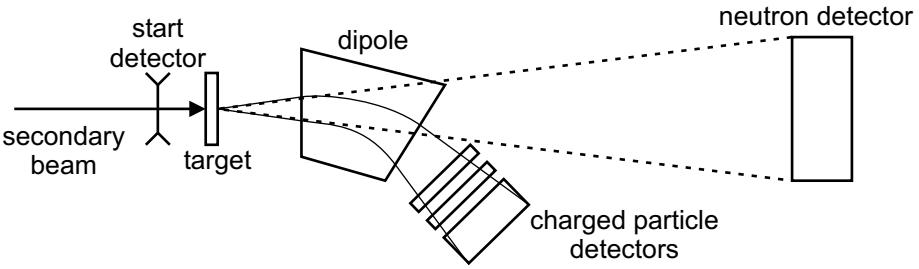

Figure 5: Schematic drawing of a setup for a kinematically complete measurement of breakup reactions. The incoming secondary beam needs to be identified, in addition, the incoming angles need to be known. The time of flight is measured between start detector and neutron detector. The neutron detector also records the position of the neutrons. The charged particle detectors provide ΔE-E information and the position/angles of charged fragments.

of neutron-rich isotopes can be studied through their breakup in charged particle core and valence neutrons. This method is especially useful to study loosely bound systems, like neutron halo nuclei, or even neutron-unbound systems.

3.1 Invariant mass analysis

The invariant mass analysis requires the kinematically complete measurement of all reaction products stemming from a breakup reaction. If the four-momenta of all fragments are known, the invariant mass can be calculated and the state of the system before breakup can be reconstructed. The invariant mass analysis is very useful in the investigation of unbound states and the correlation of breakup fragments. The final result is an invariant mass spectrum (also called relative energy spectrum), which shows a peak in case the reaction proceeded via a resonance. To determine the momenta and energies of all fragments, the neutrons need to be measured as well. This method puts a high demand on the neutron detection system, since the kinetic energy and the direction of the individual neutrons has to be determined. Figure 5 shows a schematic setup of such an experiment [7].

Problems with the invariant mass analysis arise if reaction products are in excited states and de-excite by gamma emission that is not detected. In this case, the escaped energy is missing in the analysis. Another cause of errors is the straggling of the reaction products in the target and other matter along their path. This will alter their momentum vector and introduce an error.

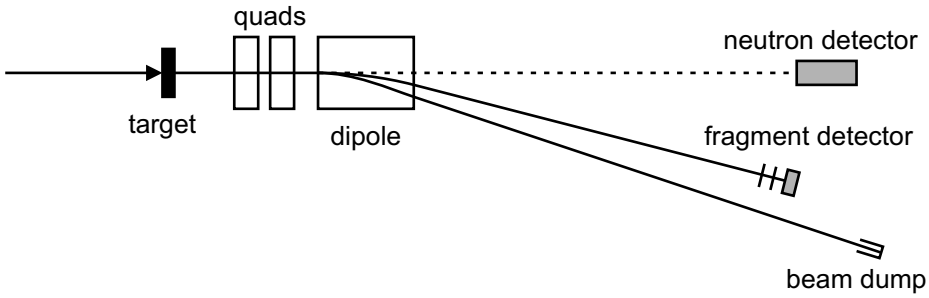

Figure 6: Schematic setup of SNDS. An unbound neutron state is created by projectile fragmentation in the target. The relative velocity of the charged fragments and the neutron is measured by time-of-flight at zero degree. Non-reaction beam particles are collected in a shielded location.

3.2 Sequential neutron decay spectroscopy

In contrast to the kinematically complete measurement, the sequential neutron decay spectroscopy (SNDS) limits the detected reaction products to a collinear geometry (see Fig. 6). The flight times of charged fragments as well as neutrons which are emitted in a narrow cone in forward direction are measured. The relative velocity spectrum yields the same information as the invariant mass spectrum and is directly related to the decay energy.

3.3 The NSCL neutron walls

The NSCL has the large-area position sensitive neutron detector displayed in Fig. 7. The detector consists of two walls covering an area of 2 by 2 m^2 each [9]. The detection material is liquid scintillator (NE-213) that is filled in 2-m-long Pyrex cells with a rectangular cross section. Photo-multipliers on each end of the cell detect the scintillator light. The time difference of left and right signal enables a position determination with a resolution of better than 10 cm. The liquid scintillator offers pulse shape discrimination of gamma rays.

3.4 The sweeper magnet

The sweeper magnet is a compact superconducting 4 T dipole magnet to deflect charged reaction fragments from the direction of the neutron detector. The sweeper magnet will be situated in the N4 vault as shown in Fig. 8, but can also be placed in front of the S800 spectrograph.

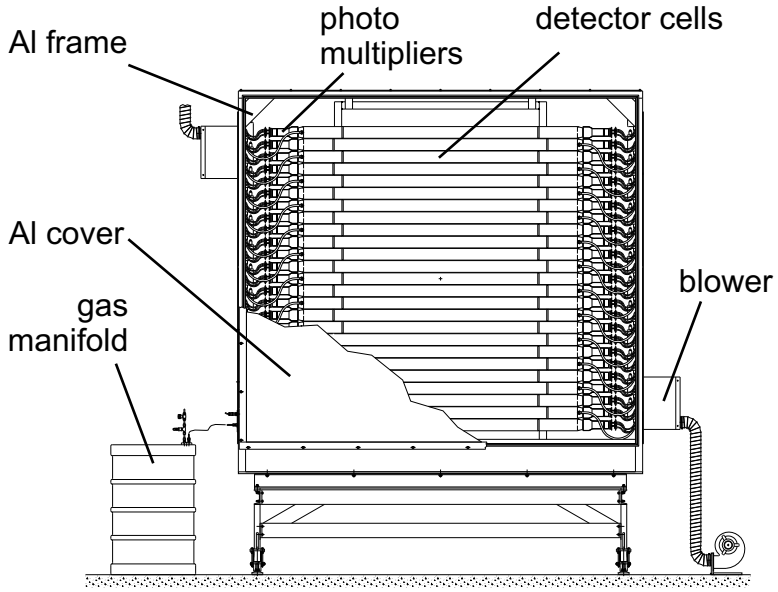

Figure 7: Cut-away drawing of one wall of the Neutron Wall Array.

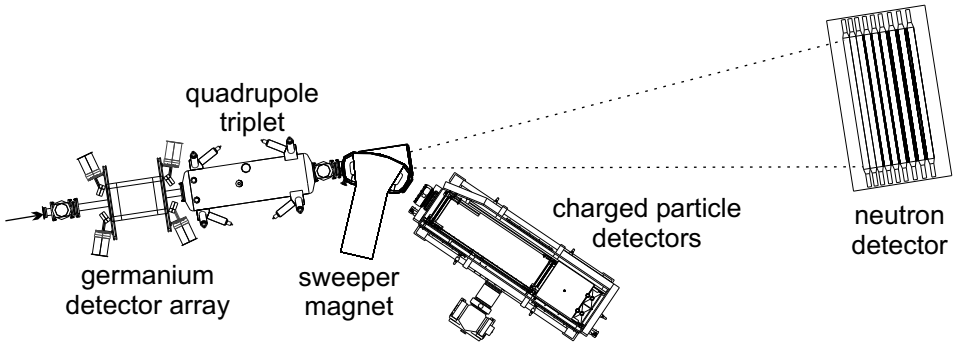

Figure 8: Setup of sweeper magnet and neutron detector in the N4 vault.

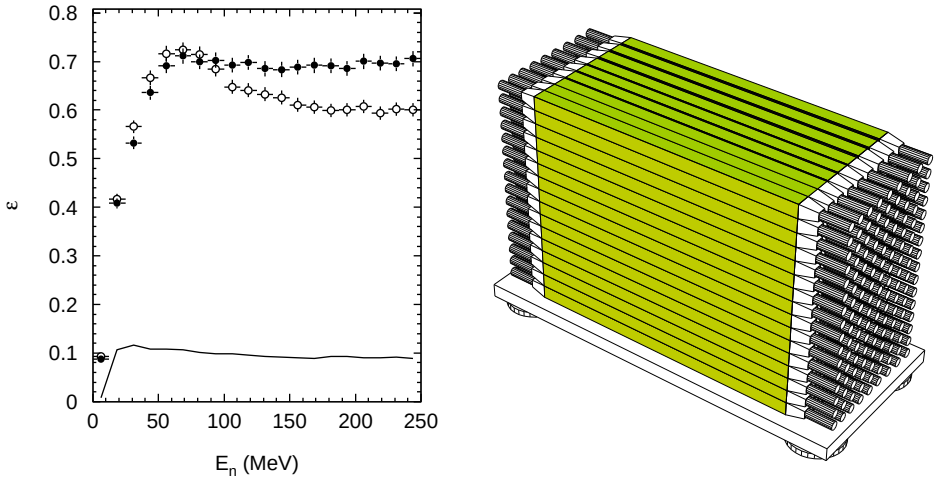

Figure 9: The figure on the left shows the calculated efficiency curve for a detector consisting of 144 pure scintillator blocks (9 layers of 16 blocks) each measuring 200 $\times$ 10 $\times$ 10 cm^3 and additional three layers of 1.0 cm iron converter and three layers of 2.0 cm iron converter (filled circles). The open circles represent the efficiency curve for a detector with the same configuration of plastic scintillator but without passive iron converters. For reasons of comparison, the calculated efficiency of the existing neutron walls is plotted as a solid line. A perspective front view of the simulated detector, showing the plastic scintillator blocks fitted with light guides and photo-multipliers, and the iron plates is depicted on the right.

3.5 The modular neutron array

The modular neutron array (MoNA) is a large-area neutron detector to be used in connection with the new sweeper magnet and its focal plane detection system or with the combination of sweeper magnet and the S800 magnetic spectrograph. It will cover an area of 2.0 m wide by 1.6 m high (see Fig. 9). The active part of it consists of nine layers with sixteen two-meter long horizontal blocks of plastic scintillator stacked vertically in each layer. The individual detector blocks are fitted with photo-multiplier tubes on each end. Except for the first three layers, passive iron converters are placed in front of the plastic scintillators in order to enhance the detection efficiency for neutrons with energies of 100 MeV and above.

The detector will operate as a time-of-flight wall, i.e. the neutron energy is deduced from the time it takes the neutron to travel the distance from a start detector to the detector block where it is detected. This method is advantageous since it is difficult to collect the complete neutron energy in a limited volume, and the time of flight can be determined with a much better precision if a sufficiently long flight path is available.

References

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