SIMULATION OF CAPTURE-GATED FAST NEUTRON SPECTROMETER WITH HIGHLY SEGMENTED ORGANIC MEDIA

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Abstract

We present a GEANT4 Monte Carlo based calculation of the response function of segmented fast neutron spectrometer. A pilot version of the device consists of 16 quartz 80 ml tubes each filled with liquid organic scintillator and viewed by 2 PMTs. Of specific interest, the spectrometer is expected to have good pulse height resolution, estimated to lie in the range (10–15)% for 14 MeV neutrons if doped with ^{10}B/^{6}Li or surrounded with ^{3}He proportional counters. High pulse height resolution is achieved by compensation of the nonlinear light-yield of the scintillator due to separate detection of each recoil protons in different segments. Here we demonstrate a response function of the device in different possible modes of operation. Such a device may definitely be applied to low-background experiments in fundamental physics research, characterizations of neutron fluence in space, and the health physics community.

1 Introduction

In organic medium a several MeV neutron deposits almost all initial energy mainly in a few scattering events. This consideration provides one with the basis for designing full-absorption fast neutron detectors. A method that has gained wide acceptance in recent decades is based on full absorption of neutrons in organic scintillators doped with isotopes with a large neutron capture cross section, e. g., ^{6}Li and ^{10}B [1, 2], or surrounded with ^{3}He counters [3].

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Detection of fast scintillations due to recoil protons in a medium, followed by registration of moderated-neutron capture, guarantees that the energy deposited by recoil protons corresponds to full absorption of a neutron. Detectors of this type are called capture-gated spectrometers.

As it was shown in previous report [4] the most significant obstacle in attaining high energy resolution in such a detector is a poor pulse height resolution: the response of a capture detector to monoenergetic neutrons is conventionally composed of two easily distinguishable peaks [8]. Moreover, the relative intensities of these peaks vary with energy of incident neutrons. Such a response shape results from the nonlinear dependence of the light yield in the scintillator on the proton energy and the multiplicity of recoil protons produced during moderation.

A technique for correct measurements of the total neutron energy based on properly segmented organic medium was proposed in [9]. A pilot model of sectioned fast neutron spectrometer has been built and tested [10]. This work is intended to investigate main features of the detector response with Monte Carlo simulations.

2 Sectioned spectrometer design

2.1 The key principle

For the nonlinearity of the light yield to be compensated, it is necessary that individual contributions of recoil protons to the total signal be distinguished. A few MeV neutron in an organic scintillator deposits 90% of its energy through 3–4 collisions producing thus several hot recoil protons. To be able to detect those recoils the scintillator volume is divided into optically separated sections small enough to guarantee the low (<10%) probability of two or more recoils in one section. Measuring the light intensity in each hit section say with PMT and using light-yield function $I(E_p)$, one can unambiguously reconstruct energy of each individual recoil proton. The initial energy of a neutron in the case of its capture is simply a sum of restored recoil energies, if one neglects collisions with carbon.

2.2 Operating principle

The operating principle is as follows. The spectrometer is a capture gated detector that measures the scintillation signals produced by recoil protons in optically separated sections filled with an organic scintillator. The data acquisition system can be triggered by multiple operation of detector sections in a short (20–30 ns) time interval, provided that the majority threshold ($MALU$, see [11] for detail) can be tuned. To guarantee a full absorption of the neutron the trigger must be confirmed with consequent capture event.

There are two main operating modes of the spectrometer. The first one is, when the majority threshold is set to unity ($MALU = 1$), the system is triggered by any single event from any individual section without following capture confirmation. In this case, total device response corresponds to response of a single isolated section. Irradiating the detector with monoenergetic neutrons one should obtain a step-like response in $MALU = 1$ mode due to flat recoil proton energy distribution after single collision. This mode is a calibrating one used to adjust individual sections.

The second main mode is the system is triggered when at least 3 sections are hit over several tens of ns ($MALU = 3$). The trigger is confirmed if a capture appeared in a few μs thus suppressing significantly a γ-ray background. In this mode, the neutron energy is the sum of the recoil proton energies. These energies are calculated from the individual values in the QDC channels from each activated section with a correction for the electron energy scale and the light yield function. This mode is the main operating mode for the measurement of fast neutron flux.

3 Simulation

3.1 Detector model for simulation

The pilot model of the spectrometer consists of 16 identical sections, each of which is a quartz tube with dimensions of $\varnothing 30\times 150$ mm and 2 mm thick walls. The same design is accepted as a base of simulation. To simplify calculations each optical section is described as a simple 80 ml cylinder of both organic liquid (H/C=1.8) or plastic (H/C=1.0) scintillator. The density of medium is suggested to be 0.85 g/cm^3. The light yield has been chosen to be same as of NE-213 [11], and it is supposed that all light is collected at PMT during scintillation. After moderation a neutron can be captured with ^{6}Li, ^{10}B or ^{3}He. The concentration of ^{6}Li and ^{10}B is assumed to be 1 g/l of scintillator. Again, to simplify the model the ^{3}He is uniformly distributed in the scintillator with 1 g/l density and 1.3 g in total. The same amount of ^{3}He can be easily provided with 20–25 proportional counters with 5–7 bar pressure surrounding the scintillator. The main kind of interactions considered during moderation of fast neutron in organics are elastic scattering on ^{1}H and both elastic and inelastic one on ^{12}C. The capture is detected mainly through $n(^6\text{Li},\alpha)^3\text{H}$, $n(^{10}\text{B},\alpha)^7\text{Li}$ and $n(^3\text{He},^3\text{H})p$ reactions. The detector is placed in empty space during simulation.

The Monte Carlo simulation of this neutron spectrometer response function has been carried out using Geant 4.8.2 package with neutron cross section set G4NDL 3.10 [5], and simulation results were analysed by using ROOT 5.14 package [6]. The interactions which a neutron undergoes in the detector are defined by the physics list of a GEANT4 toolkit. The GEANT4 physics list used in our program was optimized to handle low energy interactions of electrons, gammas and neutrons. The interactions of neutrons at low energies include radiative capture, elastic scattering, fission and inelastic scattering. All data are derived from evaluated data libraries obtained from ENDF/B-VI data [7].

For this version of GEANT4 the currently supported final states for inelastic scattering $nA \to$ are $n\gamma$s, np, nd, nt, n^3He, $n\alpha$, $nd\alpha$, $nt\alpha$, $nt2\alpha$, $n\alpha p$, $n3\alpha$, $2n$, $2np$, $2nd$, $2n2\alpha$, $3n$, $3np$, $3n\alpha$, $4n$, $4np$, $4n\alpha$, $d\alpha$, $d2\alpha$, dt.

Two main modes of operation described above were simulated there. Four different neutron energies (2, 5, 10 and 14 MeV) were used to irradiate the detector. In $MALU = 1$ mode the distribution of a recoil proton energy was recorded in every individual sections. In addition in $MALU = 3$ mode in case of capture the energy of every recoil proton deposited in each hit section was calculated into a light flash intensity with consequent summation of light over each single section. Than assuming only single recoil proton to appear in a hit section an energy of that recoil recalculated from light. Finally an initial energy of neutron was reconstructed as a simple sum of energies of recoils. In both modes an efficiency of each process was recorded.

4 Results

4.1 Response

The histograms of recoil energy distributions in $MALU = 1$ mode for different neutron energies and N/C ratios are presented in Fig. 1–4. Every point there is a sum of energies of all recoil protons in a single hit section. First of all one may note that the response has a well expressed step-like shape at the energies 5, 10 and 14 MeV. It is because mainly single recoil proton appear in a single hit section at these energies. At 2 MeV energy the probability of neutron to scatter twice or more increases and two or more recoils may appear in a single section. Therefore the step shape of the response is distorted there. Second, at higher energies narrow peaks appear in the response due to an energy loss in inelastic scattering on carbon exciting of 4.4 and 10.2 MeV levels of ^{12}C.

Figures 5–8 represent the response of the detector with H/C=1.8 in the $MALU = 3$ mode gated by a capture on ^{3}He. In order to make the effect of compensation of nonlinear light-yield more expressive we also present there the response of the detector with the same volume but with non-segmented medium. It consists of the distribution of light flash intensity (grey curve) and has a well known double-peak feature. Histograms of corresponding recoil energies restored from this light (black thin curve) are presented there also. In contrast, the black thick line there represents the distribution of recoil energies restored properly from separate lights in separate sections in the segmented detector. It looks like a single line energy spectrum of incident neutrons with no double-peak behavior.

The most significant result of simulation is a resolution of the response. The FWHM of the restored neutron energy peak at 14 MeV (Fig. 8) is less than 5%. One may compare it with 10% of dispersion of different sections in the pilot model of the detector.

4.2 Efficiencies

One of main results of simulation is an efficiency of neutron capture after moderation in the detector medium. It is defined as a number of captures divided by number of neutrons that was being inside the detector at least once. Obviously it depends of initial neutron energy and should decrease with the energy increasing. These efficiencies for every isotope are presented in the Table 1 as a function of energy of incident neutron. Statistical uncertainty of each value is less then 5%. An H/C ratio of the medium is 1.8 here. These results are in good agreement with known cross sections of capture of thermal neutron for those isotopes.

As mentioned in the subsection 3.1 the data connected with the neutron cross sections in GEANT4 are derived from evaluated data libraries obtained from ENDF/B-VI data [7].

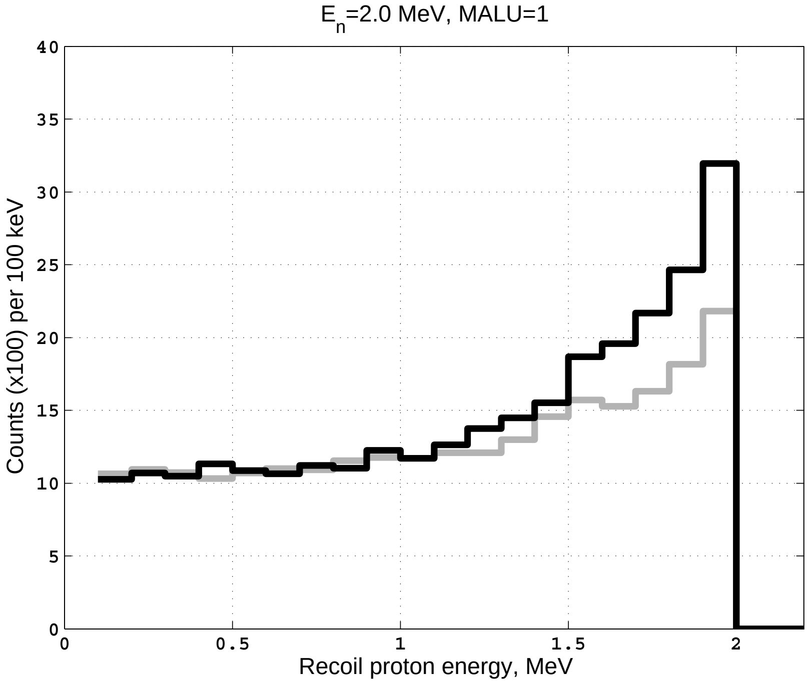

Figure 1: The response of the detector in the $MALU = 1$ mode. $E_n = 2$ MeV, black curve corresponds to H/C=1.8, grey curve — H/C=1.0.

Table 1: Efficiency of capture as a function of initial neutron energy

E_0, MeV	^{3}He	^{6}Li	^{10}B
2	7.9	0.18	2.2
5	3.4	0.11	0.9
10	1.4	0.08	0.4
14	1.2	0.06	0.3

5 Conclusions

The simulation demonstrated that the technique of compensation of nonlinear light-yield of organic scintillators results in narrow single peak response instead of wide double-peak one in usual nonsegmented spectrometer. In case of sectioned device the real pulse height resolution will be determined mostly by statistics of photoelectrons and in principle may lie in 10–15% range at 14 MeV neutron energy. A detailed simulation is now undergo to investigate it more precisely.

Another conclusion is that different kinds of design are possible. For example, in low-background deep underground experiments one may choose a liquid organics with H/C=1.8 and ^{3}He in proportional counters as a capturer to provide one with higher efficiency though it looks to be more complicated. In case of space research a device consisting of simple plastic cylinders doped with ^{10}B looks to be more convenient with slightly poorer efficiency and resolution.

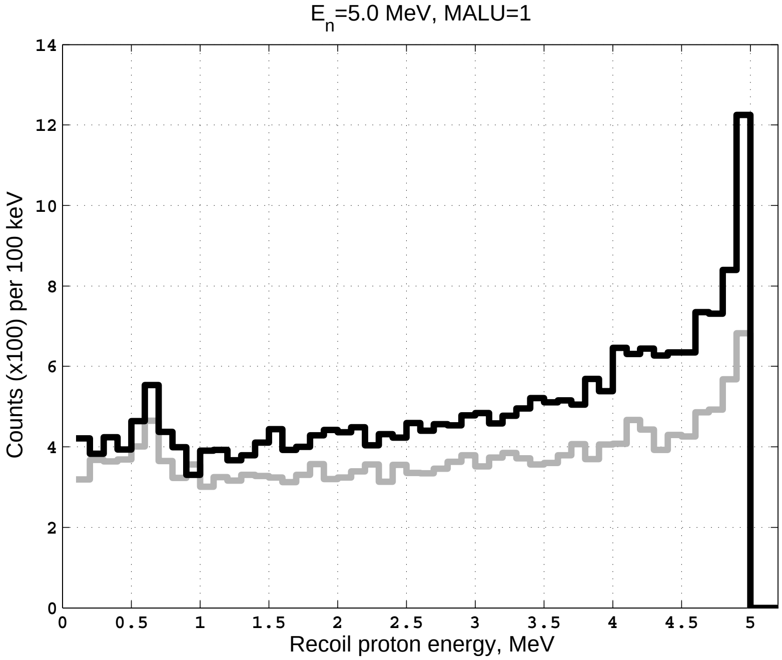

Figure 2: The response of the detector in the $MALU = 1$ mode. $E_n = 5$ MeV, black curve corresponds to H/C=1.8, grey curve — H/C=1.0.

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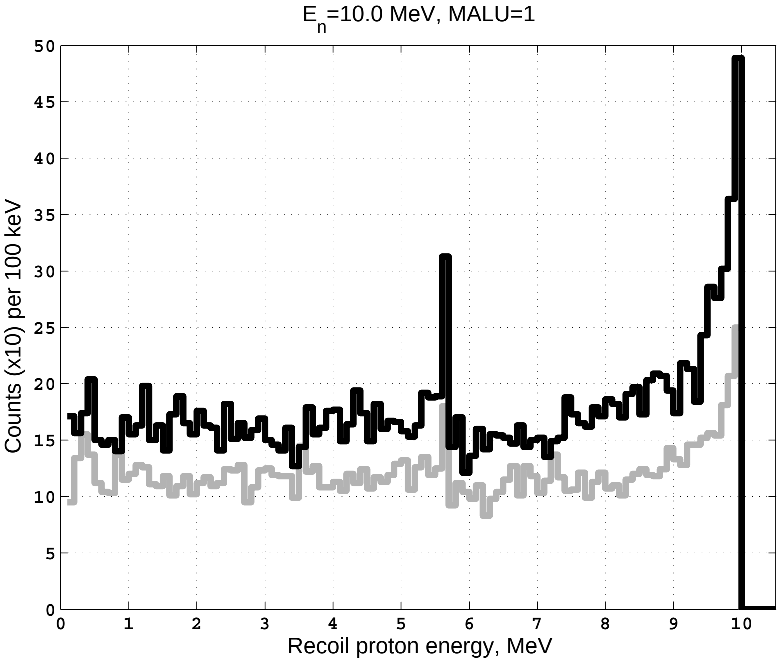

Figure 3: The response of the detector in the $MALU = 1$ mode. $E_n = 10$ MeV, black curve corresponds to H/C=1.8, grey curve — H/C=1.0.

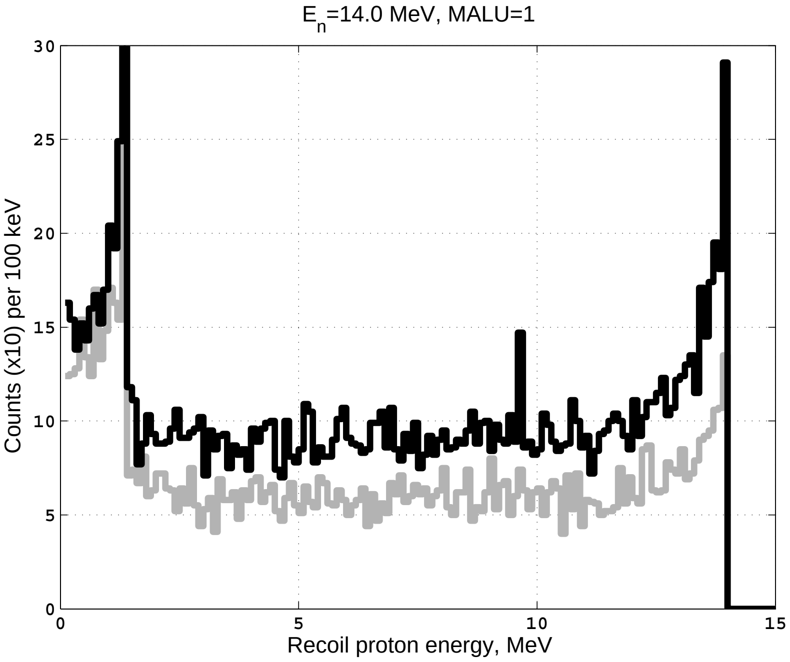

Figure 4: The response of the detector in the $MALU = 1$ mode. $E_n = 14$ MeV, black curve corresponds to H/C=1.8, grey curve — H/C=1.0.

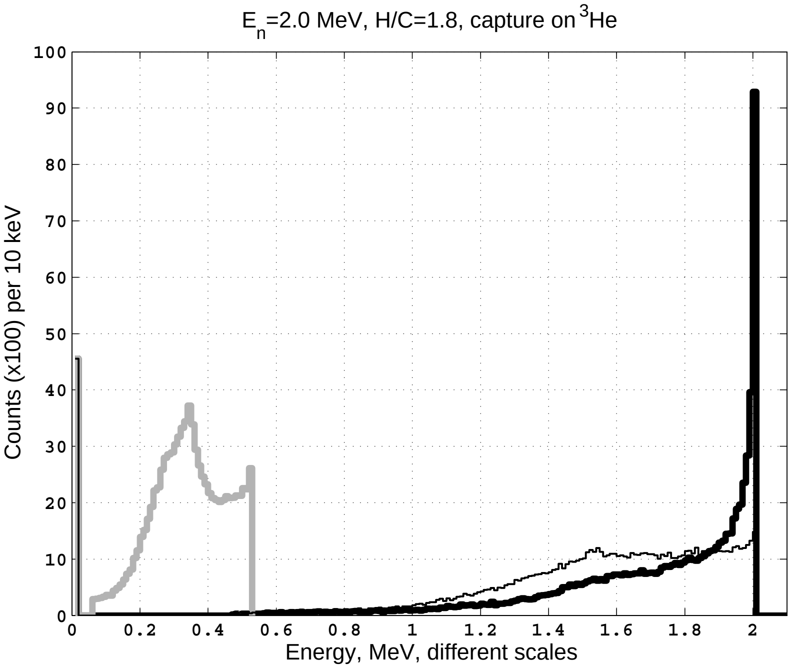

Figure 5: The response of the detector with H/C=1.8 in the $MALU = 3$ mode gated by a capture on ^{3}He. Black thick line is a restored neutron energy distribution, see text for other details.

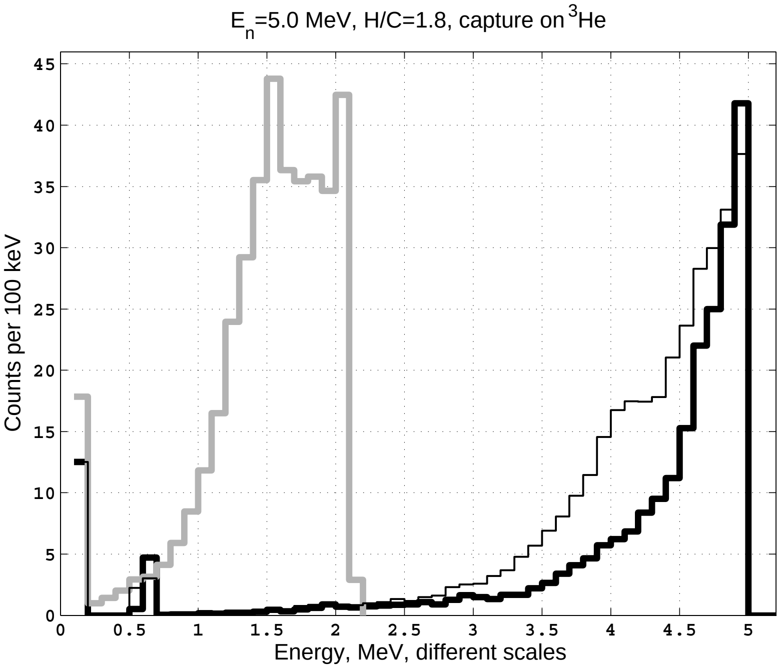

Figure 6: The response of the detector with H/C=1.8 in the $MALU = 3$ mode gated by a capture on ^{3}He. Black thick line is a restored neutron energy distribution, see text for other details.

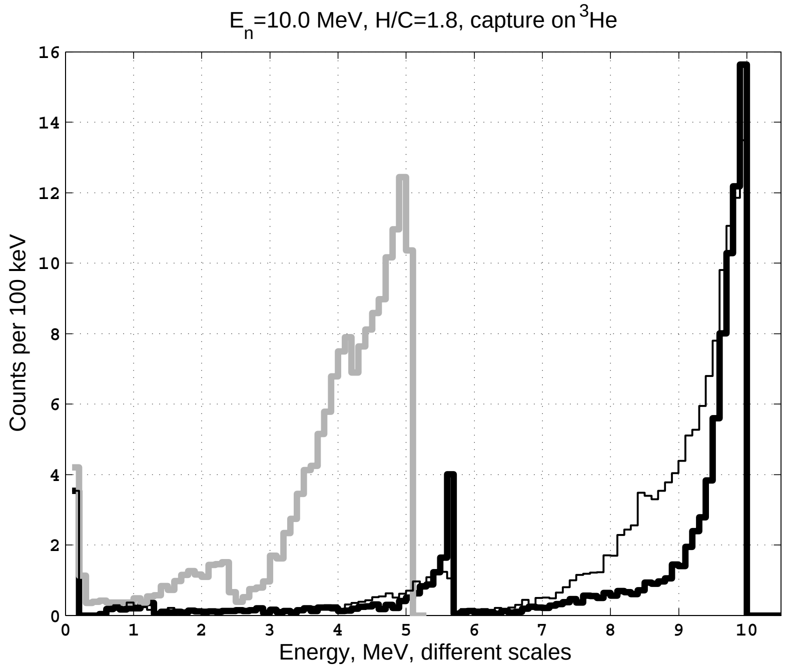

Figure 7: The response of the detector with H/C=1.8 in the $MALU = 3$ mode gated by a capture on ^{3}He. Black thick line is a restored neutron energy distribution, see text for other details.

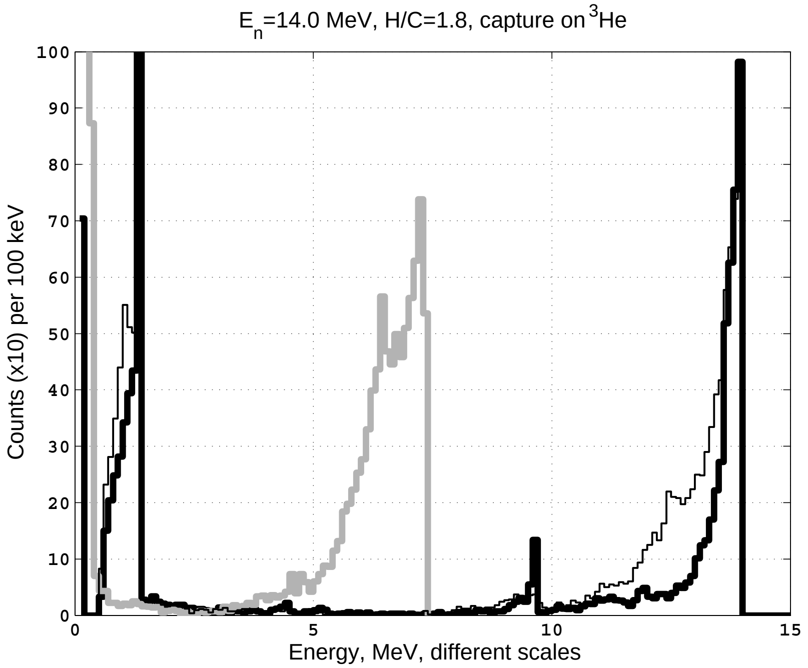

Figure 8: The response of the detector with H/C=1.8 in the $MALU = 3$ mode gated by a capture on ^{3}He. Black thick line is a restored neutron energy distribution, see text for other details.