

# Detecting sub-MeV neutrons in solid plastic scintillator with gamma-ray discrimination

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**Abstract**—We report on recent efforts to design a solid plastic scintillation hodoscope to measure neutron production cross sections at low energies. Our program includes not only the development of the detector itself, but also a set of auxiliary measurements which will help characterize its low-energy response.

A novel scintillation counter has been developed to detect sub-MeV neutrons while rejecting gamma-ray backgrounds with good efficiency. The detector uses multiple layers of thin solid scintillator, with optical isolation between the adjacent layers. Incident low-energy neutrons produce ionizing recoil particles which remain within just one of the scintillator layers, while background gamma rays create electrons which most often cross the boundary between layers. By observing the trigger pattern within the layers, most gamma-ray backgrounds can be distinguished from the low-energy neutrons of interest. We report on the results of our Monte Carlo studies of this design, as well as on the operation of a prototype detector unit.

We also have undertaken a new measurement of the neutron-proton total cross section below 1 MeV. Calculations of the efficiency for detecting low energy neutrons in plastic scintillator rely on accurate low energy n-p cross sections, yet surprisingly few such data currently exist. New measurements which span the region from 150 to 800 keV neutron (lab) energy are reported and discussed.

Additionally, we have measured the light response of BC 418 scintillator for recoil proton energies as low as 100 keV. Recoil protons are produced at a known energy in the scintillator by placing it in a neutron beam and detecting in coincidence the elastically scattered neutrons at fixed angle. Our new results extend the energy range of previous measurements of the light response of solid organic scintillators, and may indicate a significantly modified response at the lowest observed energies.

**Index Terms**—scintillation detector, neutron detector, scintillation light, neutron-proton scattering

## I. INTRODUCTION

THE organic (plastic) scintillator is a nearly ideal material for detecting fast neutrons. The scintillation light produced by an interacting neutron is generated promptly, allowing the time of the neutron interaction to be accurately determined. For a relatively thin scintillation detector, and in cases where a prompt time-start signal is available, one can then measure the neutron velocity and determine its energy. In the neutron energy range from a few keV to

several MeV, the dominant neutron interaction in plastic is due to elastic neutron-proton scattering, and because of the generally large value of this cross section, organic scintillators have a relatively high neutron detection efficiency. Moreover, the efficiency of detectors made of organic scintillators can be readily determined by Monte Carlo techniques, given a knowledge of the n-p cross section and of the light production properties of the material. Solid plastics are easily machined and polished, and this allows for a very wide variety of detector geometries. Also, liquid scintillators can be produced with a light decay time constant which is different for the fast electron recoils created by the interaction of gamma rays as compared with the relatively slow proton recoils produced by neutron-proton interactions. Various pulse-shape-discrimination (PSD) schemes have been developed to use this time difference to discriminate between neutrons and gamma rays in organic liquid scintillators.

One application of the use of organic scintillators is a measurement of the yield of fast neutrons following neutron-induced fission. At the Los Alamos Neutron Science Center (LANSCE), we are collaborating on the FIGARO project, which determines the fission neutron yield for a number of actinide targets at beam energies from a few MeV to several tens of MeV. Presently, liquid scintillator detectors are used for these experiments because they allow one to reject most gamma-ray backgrounds. However, because the technique of PSD is limited to neutron energies above about 1 MeV, the FIGARO project cannot now determine the neutron yield below this threshold energy. It is estimated that  $\sim 30\%$  of the total fission yield occurs below 1 MeV, so it is useful to develop alternate techniques by which these low energy measurements can be made.

## II. THE LAYERED NEUTRON DETECTOR

Our goal is to produce a scintillator with high detection efficiency and large solid angle acceptance. The detector should be capable of time-of-flight (TOF) measurements for neutrons spanning the energy range from a few hundred keV to several MeV. These requirements are easily met by solid organic scintillators. But we also want our detector to be capable of suppressing gamma-ray backgrounds at these low energies. Unfortunately, neither solid nor liquid scintillators are capable of PSD in our energy region of interest. We have therefore investigated an alternative method for using solid organic scintillator to discriminate between neutron- and gamma-induced events.

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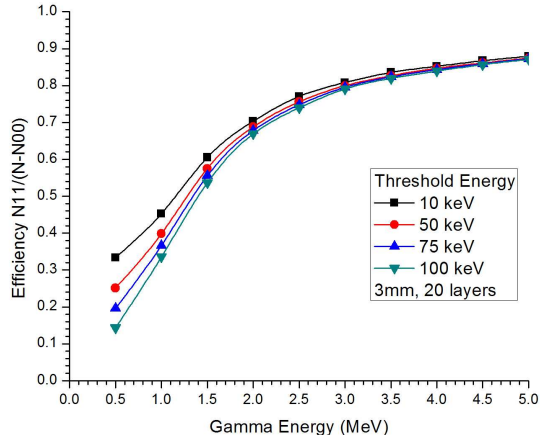


Fig. 1. GEANT4 simulation of the efficiency for rejecting incident interacting gamma rays in a detector composed of 20 layers of plastic scintillator, each of 3 mm thickness. The various thresholds are given in electron-equivalent energy.

When a low energy gamma ray interacts in plastic, a recoil electron is produced with an energy that can vary from near zero to the energy of the incident photon. Typically, though, the electron carries a large fraction of the initial gamma-ray energy. The range of a 1 MeV electron in organic scintillator, for example, is approximately 4.4 mm. In a similar way, a fast neutron which scatters from hydrogen produces a recoil proton with energy spanning the range from zero to the full energy of the incident neutron. But the distance over which the recoiling proton travels is very much smaller than an electron of the same energy. For neutrons limited to a few MeV, this range is at most 100 microns in plastic scintillator.

We have developed a prototype detector which exploits this electron-proton range difference to distinguish neutrons from gamma rays. Multiple layers of thin scintillator are stacked together, with the particles incident along the “thin” direction of the layers. The recoil protons from neutron interactions create light in just one layer of the stack, while electrons from gamma-ray interactions produce scintillation light which most often occurs in a pair of adjacent layers. By recording the pattern of light produced in all the layers, a separation of neutrons and gamma rays can be accomplished on an event-by-event basis. The efficiency of the layered detector for incident neutrons is not strongly affected by the segmentation; its value is nearly the same as it would be for a solid scintillator of the same overall dimensions. But by rejecting events in which adjacent planes have been triggered, a large fraction of the gamma-ray backgrounds can be eliminated.

Monte Carlo techniques have been used to optimize the gamma-ray rejection efficiency with respect to the thickness of the individual scintillator layers. Since this rejection depends on the gamma-ray energy, we have done these calculations at energies typical of our experimental environment. Also, the rejection was studied as a function of the detection threshold in the scintillator. In Figure 1 we show the results of these calculations for a stack composed of 20 layers of scintillator,

each with a thickness of 3 mm. We plot the fraction of interacting gamma rays for which the energy deposited in each member of a pair of adjacent layers is found to cross a given threshold. This is our rejection efficiency. As expected, the rejection is improved at lower threshold, and it reaches its largest value as the photon energy is increased. The saturation effect observed at high energy is due to electrons recoiling within a single plane of scintillator. The efficiency continues to grow, however, as the fraction of pair-production interactions increases at high energy. Overall, we find that above about 2 MeV, roughly 2/3 of the gammas are rejected, while about 1/3 of gamma rays at 0.5 MeV can be distinguished using the 3 mm layer geometry.

Optical isolation between adjacent layers in our prototype detector is maintained by wrapping the scintillator with a thin opaque material. The scintillators are then inserted into UVT acrylic light guides such that light from alternate layers is combined and viewed by a common pair of photomultiplier tubes (PMTs): the odd-numbered layers of the stack trigger one pair of PMTs, and the even-numbered layers trigger a separate PMT pair. Since our goal is to operate the detector at the lowest possible neutron energy, our thresholds are set near the noise level produced by single photoelectrons in the PMTs. By viewing each group of layers with a pair of PMTs and imposing a coincidence requirement for accepted events, these random noise triggers can be eliminated. A detector with higher thresholds, set well above the noise level, would not require a pair of PMTs on each group of layers.

A prototype detector with 10 layers of 3 mm BC 408 scintillator has been constructed. Each scintillator plane is approximately 10 cm  $\times$  10 cm, and light from each group of 5 planes is combined in a pair of light guides and collected in Hamamatsu R1250 PMTs. The PMT pairs on each group of layers are operated in coincidence, and thresholds are set near 10 keV. Both ADC and TDC data were collected from the detector when illuminated with low energy gamma-ray sources. From these data we have determined the gamma-ray rejection efficiency, and find that it matches closely the Monte Carlo predictions. We also have operated the detector directly in the attenuated beam produced by the pulsed neutron spallation source at LANSCE. These data have been used to measure the response at neutron energies ranging from 500 keV to over 100 MeV. Again, these results are found to follow the Monte Carlo predictions. Presently, a layered detector in a 1-m long “bar” geometry is being assembled for testing at LANSCE later this year.

### III. NEUTRON-PROTON SCATTERING BELOW 1 MEV

At energies up to 2 MeV, the dominant interaction of neutrons in organic scintillator is via elastic neutron-proton scattering. Therefore, in order to calculate the efficiency of a neutron detector using an analytical or Monte Carlo method, one must know the n-p cross section with good accuracy in this energy region. A look at all of the relevant data collected during the past 50 years shows almost no measurements in the interesting region from 100 to 500 keV, and only a small number of experiments which have reported results somewhat above this energy.

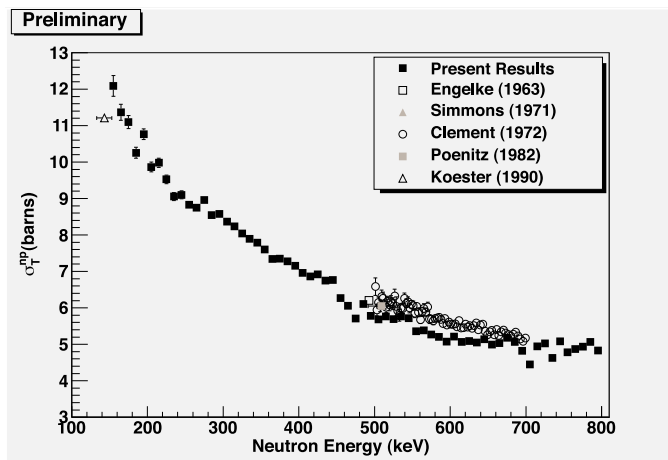


Fig. 2. The currently archived “modern” n-p total cross section measurements, and the preliminary results obtained from our transmission experiments.

We have begun a series of experiments aimed at measuring the n-p cross section at energies from 150 to 800 keV. A neutron beam spanning a 50 keV energy range is created using pulsed protons on a thin LiF target. The forward-produced neutrons are collimated with extensive copper, lead and borated-paraffin shielding into a 2-cm diameter beam. We then use a transmission geometry to determine the fraction of this beam which is removed after passing through a sample of polyethylene with known areal density. Transmitted neutrons are detected in a thin, heavily-shielded BC501A detector, which produces nearly background-free measured neutron TOF distributions. Using the measured neutron TOF, the transmission, and therefore the n-p cross section, is determined in 10 keV beam energy bins. The energy of the proton beam is varied in 50 keV steps to cover the overall neutron energy range of interest.

In Figure 2 we present our recent results. The error bars shown are statistical only, and are generally smaller than the size of the plotting symbol. All other n-p total cross section measurements published within the past 50 years are also shown for comparison. Our analysis of these data is ongoing.

#### IV. SCINTILLATION LIGHT RESPONSE IN BC 418

The pulse-height spectra of organic scintillators, when used as neutron detectors, are most often calibrated with gamma-ray sources. This results in an energy scale which is given in units of keV electron-equivalent (keVee). A recoiling proton created by a scattered neutron produces less scintillation light than an electron of the same energy. Thus, one must know the relation between proton energy and electron-equivalent energy in order to accurately set detector thresholds and determine the detection efficiency.

A large number of experiments have been done over many years to determine the response of a variety of scintillation materials. Most of these have been limited to proton energies above 1 MeV. An exception is the work of Smith, et al, [1], in which the response of the common organic scintillator NE102 was measured for proton energies as low as 350 keV. These

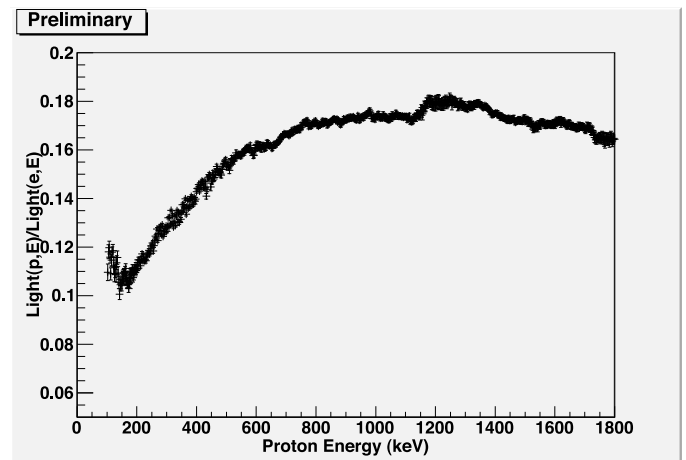


Fig. 3. The ratio of measured mean light outputs for equal-energy protons and electrons in BC418 scintillator.

data have been analyzed [2] to determine best-fit parameters of the Birks formula [3] relating light production in scintillators to energy loss for heavy charged particles. The NE102 data, like those for another organic scintillator, Pilot B, may suggest a deviation from the usual Birks relation at proton energies below about 1 MeV.

We have begun a study of the scintillator BC418, measuring the light response for recoil protons in the energy range from 100 to 1800 keV. The recoil protons were created in the scintillator by elastically scattering neutrons of known energy, and detecting them at a scattering angle of  $45^\circ$ . Since in our energy region there are no open inelastic n-C channels, and since carbon recoils do not produce enough light to be detectable in our apparatus, two-body kinematics can be used to assign the energy of the recoil proton, event-by-event.

Neutrons were produced from pulsed proton bombardment of a very thin ( $\sim 5$  keV) LiF target. The 3 mm BC418 scintillator was positioned 26 cm from the LiF target, and was aligned colinear with the proton beam. The 5 cm  $\times$  5 cm scintillator was viewed by a pair of fast 5 cm  $\phi$  PMTs. Scattered neutrons were detected with a well-shielded BC501A scintillator at a flight path of 149 cm. TOF and pulse-height spectra were collected from both the “active target,” and from the neutron detector. Correlations amongst these measured parameters were imposed so as to reduce the number of accepted background events to a very small level.

In Figure 3 we show our preliminary measurements of the relative light output between recoil protons and electrons of the same energy. Above about 800 keV the ratio is relatively flat, but at lower energy the relative light output of protons shows a significant decrease. Our data near the lowest measured recoil energy, 100 keV, may also indicate additional structure in this curve.

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