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# Measurement and simulation of the neutron response of the Nordball liquid scintillator array

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## Abstract

The response of the liquid scintillator array Nordball to neutrons in the energy range $1.5 < T_n < 10$ MeV has been measured by time of flight using a $^{252}$Cf fission source. Fission fragments were detected by means of a thin-film plastic scintillator. The measured differential and integral neutron detection efficiencies agree well with predictions of a Monte Carlo simulation of the detector which models geometry accurately and incorporates the measured, non-linear proton light output as a function of energy. The ability of the model to provide systematic corrections to photoneutron cross-sections, measured by Nordball at low energy, is tested in a measurement of the two-body deuteron photodisintegration cross-section in the range $E_\gamma = 14-18$ MeV. After correction the present $^2$H($\gamma$, n)p measurements agree well with a published evaluation of the large body of $^2$H($\gamma$, p)n data.

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## 1. Introduction

Recently, photoneutron production cross-sections on a range of nuclei [1] have been measured in the energy region 11–30 MeV at the high-duty-factor, tagged-photon facility of MAX-lab [2] in Lund, Sweden. The purpose is to test calculations of neutron dose received during the course of bremsstrahlung radiotherapy [3]. In these time-of-flight (TOF) experiments, at relatively low kinetic energy ($T_n$), the neutron signal is obscured by an accelerator-induced room background and a high rate of random-coincidence events produced by untagged photons incident on the experimental target. The bulk of this background arises from detected photons, so that good particle identification is required to access $T_n \sim 1$ MeV, where both the photoproduction cross-section and the biological effectiveness of neutrons are at a maximum. The MAX-lab liquid scintillator array Nordball [4], with good n/$\gamma$ pulse-shape discrimination (PSD) properties and $\sim$1 ns (FWHM) time resolution, was used for these measurements. This paper presents Nordball calibration procedures and a computer model used to evaluate systematic effects which distort the measured neutron yield.

At low energies neutron attenuation and multiple scattering effects on measured neutron yields are large. Thus a simulation of the experiment based on GEANT-3 [5], which models neutron interactions in all materials in the vicinity of the detector array, has been developed to correct for these effects. The non-linear pulse-height

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response of the scintillators to low-energy recoil protons has a critical bearing on these calculations, especially close to threshold, and so this was measured with a white $^{252}$Cf neutron source. This is a calibration standard since the neutron yield from spontaneous fission (decay branching ratio 3.1%) is high and both the absolute numbers and energy spectrum of prompt neutrons per fission are well known [6,7]. Neutron detector response may be obtained in a TOF measurement if fission events are tagged by detection of at least one heavy fragment, which provides a time reference. Although fission chambers [8] are possibly the optimal detectors for fragment detection, a simple thin-film organic scintillator presented a viable, available alternative at the time of the measurement. This type of detector has several desirable properties:

1. Insensitivity to $\gamma$-rays or neutrons as the plastic is extremely thin.
2. Fast response with a similar time resolution to Nordball, which also gives high counting rate capability.
3. Fast, cheap production.

Here, we compare the measured and simulated fission-neutron response of the Nordball array and describe a test of the simulation by measurement of the well known $^{2}$H$(\gamma, n)$p cross-section. Here, the simulations have been used to compute the large attenuation and multiple scattering corrections, as well as the neutron detection efficiency. Section 2 gives an overview of the experimental set-up, the measured Nordball response is presented in Section 3, the Monte Carlo (MC) simulation is described in Section 4, measurements and simulations are compared in Section 5, and a short summary is given in Section 6.

## 2. The TOF experiment

### 2.1. The Nordball array

The Nordball detector (Fig. 1) consists of 16 liquid scintillators, type Bicron BC-501, with PSD capability. Ten detectors are of hexagonal cross-section and six detectors of pentagonal cross-section. Their respective volumes are 3.3 l and 2.6 l at a common thickness of 16 cm. The liquid is contained within a 2 mm thick, stainless steel cannister, coated on its inner surface with $TiO_2$ reflective paint. This is connected to a 5 in. XP2041 photomultiplier tube (PMT) via a Pyrex glass window. A cylinder of $\mu$-metal shields the PMT from stray magnetic fields and an outer plastic housing encases tube and voltage-divider circuit, which provides a negative anode signal.

All detectors were mounted on aluminium frames and placed on a 32 cm thick layer of borated paraffin, supported by an iron table. The configuration of Fig. 1 consisted of five detector columns, positioned in 15° steps, at a distance of 150 cm from the central position where the experimental target or the fission detector was located. The bigger hexagonal detectors were placed in the two bottom rows, five pentagonal detectors in the third, and the last one on top of the central column. Paraffin towers to both sides of the iron table partially shielded the array against regions of strong neutron background. For the deuteron photodisintegration experiment a $40 \times 40 \times 1.8$ cm plastic-scintillator sheet was inserted between the target and Nordball to identify charged particle events.

### 2.2. Fission detector

The thin-film scintillator was prepared following Ref. [9]. A solution of plastic scintillator in xylene was spread uniformly over the glass window of a 2 in. PMT (Philips XP2262B) which was placed upright in a vacuum chamber. Slow evacuation of the chamber causes solvents to evaporate and a thin layer of scintillating material remains on the glass. Its thickness was tuned, by varying the amount of plastic in the solution, to optimise discrimination between fission fragments and the 30 times more numerous $\alpha$ particles.

The fission source [10] consists of a platinum-clad, nickel disk, on to which $Cf_2O_3$ was electro-deposited. The active area (0.2 cm$^2$) is covered by a 50 $\mu$g/cm$^2$ layer of gold allowing the passage of fission fragments with relatively small energy loss. The source was placed on the centre of the scintillating film and the PMT was sealed with a plastic cap, lined with aluminised mylar foil, to exclude external light and provide some reflection of scintillation light. The fission detector was positioned so that the source sat at the target-centre position (Fig. 1) at the same height as the middle of the second Nordball row and the photon beam axis.

The axis of the PMT was offset ~10° from vertical. Apart from the bottom row of the array, this offset avoided fission neutrons having to pass through the glass of the PMT on the way to the Nordball detectors. Placing the PMT horizontally would have displaced the loose source from the active area of the PMT face. As a consequence of attenuation in glass, the detected neutron yield in the bottom detectors was found to be about 15% smaller at low energies where the interaction cross-section is highest. These losses are consistent with the predictions of a computer model of the experiment (Section 4.2) which approximated the PMT by a 2 mm thick glass cylinder and calculated for tilting angles in the range of $5-15°$. However, the angle was not sufficiently well determined to enable quantitative comparisons and hence the bottom detectors were excluded from the analysis of differential and absolute neutron detection efficiencies presented in Section 5.

No suppression of bottom-row neutron yield was observed in the deuteron photodisintegration measurement, which used a cylindrical $D_2O$ target, supporting the assumption of increased neutron attenuation in glass during the $^{252}$Cf measurement.

Fig. 2 shows the fragment pulse-height distribution obtained from the $^{252}$Cf source, which produced a counting