Nuclear Instruments and Methods in Physics Research A 751 (2014) 19–22

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Thin YAP:Ce and $LaBr_3$:Ce scintillators as proton detectors of a thin-film proton recoil neutron spectrometer for fusion and spallation sources applications

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ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form
28 February 2014
Accepted 7 March 2014
Available online 16 March 2014

Keywords:
Scintillators
Neutron spectroscopy
Fusion plasmas

ABSTRACT

Two thin inorganic scintillators based on YAP and $LaBr_3$ crystals (1 in. diameter × 0.1 in. height) have been used for proton measurements at the Uppsala tandem accelerator in the energy range 4–8 MeV. Measurements show a comparable good energy resolution for the two detectors, better than 2% (FWHM) for 8 MeV protons, which compares to 3.8% (LaBr3) and 3.7% (YAP) obtained at the 1.3 MeV peak of a ^{60}Co γ-ray source. The main advantages of these crystals are a fast scintillation time (less than 30 ns), an excellent light yield and the capability to operate in large neutron background, which make them ideal candidates as proton detectors of a thin-film proton recoil neutron spectrometer for application on fusion experiments and fast neutron spallation sources.

1. Introduction

Neutron spectrometers for measurements in the MeV range have played important roles in spallation sources and fusion plasma devices in recent years [1–7]. The instrumentation used in both cases is of dedicated design that depends on the specific diagnostic needs of each experiment. For example, in fusion plasma applications at JET, a Magnetic Proton Recoil (MPR) spectrometer has been used for 14 MeV neutron measurements at 5% resolution, providing information of unprecedented detail on neutron emission from the plasma [8–10]. The significant dimensions (several tens of meters) and weight (about 80 t) of the instrument, however, do not make the MPR technique particularly suitable for applications where there are space limitations, such as arrays of neutron detectors arranged in a camera system. In this context, a Thin-film Proton Recoil (TPR) spectrometer could be an interesting alternative. The TPR detection principle is based on neutron-to-proton conversion via elastic scattering on hydrogen nuclei at a given angle in a plastic thin foil. The scattered proton energy can be easily measured and converted back to the incoming neutron energy, provided that the recoil angle is known [11]. A preliminary design of a non-magnetic TPR detector for fusion plasma diagnostics has been presented in Ref. [12]. Here it is shown through calculations that TPR could attain an energy resolution close to that of the MPR, combined with an increased efficiency of 2.9 10^{-4} n cm^2 and compact dimensions. The design in Ref. [12] used silicon detectors as proton spectrometers, given their excellent energy resolution and fast signals. In particular, a proton energy resolution better than 2% would be ideal for a TPR system, so that the overall energy resolution of the spectrometer, that gains contributions also from the finite aperture of the recoil solid angle and the thickness of the scattering foil, could still be about 5%.

In this paper we demonstrate that such requirement for the proton energy resolution could be also achieved using fast inorganic scintillators as alternatives to silicon detectors. Their main advantages are the resistance to neutron irradiation and cost effectiveness. In particular $LaBr_3$(Ce) and YAP(Ce) are the proposed scintillator crystals, the latter being the most cost effective one. Besides, the fast scintillation time constants of these crystals would enable their use at high count rates up to few MHz. A prototype of a TPR spectrometer of such design was tested at the ISIS neutron source of the Rutherford-Appleton Laboratory (UK) in a proof-of-principle measurement using YAP scintillators, presented in Ref.[13]. In this experiment neutron spectroscopy in the energy range 30 to 80 MeV was demonstrated and advantage was taken from the fast scintillation time of the crystal, which is needed to cope with the high instantaneous count rate provided

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http://dx.doi.org/10.1016/j.nima.2014.03.012
0168-9002/

by the pulsed nature of the ISIS neutron source. However, for this application no strict requirement was set on the overall energy resolution.

In this paper, we report on measurements aimed at the determination of the energy resolution of YAP and $LaBr_3$ to protons in the energy range 4 to 8 MeV. The experiment, performed at the Uppsala Tandem accelerator at low counting rates (a few kHz), is presented in the next section. The results on the energy resolution are then illustrated and compared to laboratory calibrations using γ-ray sources.

2. Experimental setup

Two thin inorganic scintillators based on YAP and $LaBr_3$ crystals (1 in. diameter × 0.1 in. height) have been coupled to two eight dynode Photo Multiplier Tubes (PMTs), model R6231 by Hamamatsu [14]. Special care was taken in the case of $LaBr_3$ which, being hygroscopic, was encapsulated on all sides, with a thin (125 μm) Be entrance window. This is where the proton beam was impinging in the experiment and was needed to minimize energy loss, which would otherwise not be tolerable in the thick encapsulating material. The ^{9}Be window was not needed for YAP, as this crystal is not hygroscopic. In this case, a thin (20 μm) aluminum layer was used for the purpose of light collection optimization only.

An electronic chain devoted to energy resolution measurements and consisting of an ORTEC 570 amplifier and an ORTEC Multichannel Analyzer was prepared [15]. The scintillators were first irradiated with calibration γ-ray ^{137}Cs and ^{60}Co sources at the IFP-CNR spectroscopy laboratory in Milano and then with 4 to 8 MeV protons from a tandem accelerator at Uppsala University. The accelerator features an accelerating voltage up to 5 MV and can produce beams of protons as well as heavy ions. Fig. 1 shows the setup of the experiment in Uppsala inside the proton interaction chamber, i.e. a metal cylinder with a diameter of about 0.5 m. The proton beam enters from the aperture on one side of the chamber, along a diameter and perpendicularly to the chamber s plane. The experiment was performed using a Rutherford scattering configuration [16] on a gold foil target (~3 μm), which was necessary to significantly reduce the proton current in the detector, which would otherwise result in counting rates well beyond the MHz range that can be coped with the device. A proton scattering angle on the gold foil of about 45° with respect to the proton beam was chosen. PMTs were operated with a negative high voltage of 750 V and energy calibration was repeated in situ with ^{137}Cs and ^{60}Co sources.

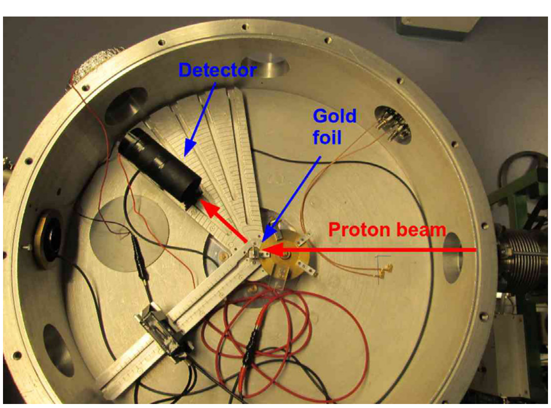

Fig. 1. Experimental setup at the Uppsala tandem accelerator. The position of the detector and target (a gold-foil) for the Rutherford scattering experiment are indicated, together with the proton beam direction.

The spectroscopic chain described above is the reference for energy resolution measurements, but it cannot be used at high rates (MHz), since the shaped signals after the amplifier have a too long time constant (μs). High rate measurements can however still be performed by direct digitization of the signal from the PMT anode using a digital acquisition system (see the experimental setup in Ref. [13]). Count rates up to a few MHz can be handled thanks to the fast scintillation time of YAP and $LaBr_3$ crystals, which is 27 and 16 ns, respectively, with only a moderate degradation in the energy resolution, as demonstrated in Refs. [17,18]. The shapes of YAP and $LaBr_3$ signals after the PMT anode are compared in Fig. 2. In particular, we can notice a clear difference in the falling edges of the two signals, which is due to the different time constant of the crystals. The rising edge is instead similar, as this part of the signal is dominated by the PMT response, which is the same for both scintillators.

3. Detector characterization with laboratory gamma-ray sources

The thickness of the two crystals is optimized to stop protons up to 20 MeV. For this reason the detectors have low efficiency to γ-rays, which are the main background sources during the measurement. Nevertheless, the high density and high effective *Z* of the crystal allow distinguishing full-energy-peaks when the crystal is irradiated with laboratory γ-ray sources. These measurements are useful to determine the energy resolution of the two crystals to γ-rays in the MeV range, obtained from the FWHM of the full-energy peaks. ^{137}Cs and ^{60}Co sources were used for this scope with the results summarized in Table 1 for YAP and $LaBr_3$. Here we note that the energy resolution found in the two cases does not differ significantly, especially above 1 MeV, where it is practically identical and has a value of 3.8%. This number can be compared to the expected light yield of 63,000 photons-per-MeV

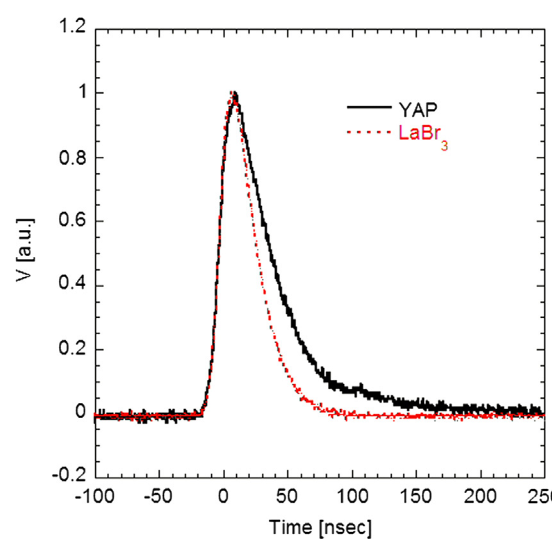

Fig. 2. Measured YAP and $LaBr_3$ signals from the PMT anode.

Table 1
Energy resolution values (FWHM/E) measured with γ-ray sources for the thin $LaBr_3$ and YAP scintillators used in the proton experiment.

Source	Peak energy(MeV)	$LaBr_3$ resolution(%)	YAP resolution (%)
^{137}Cs	0.66	4.2	5.5
^{60}Co	1.17	3.5	3.8
^{60}Co	1.33	3.7	3.8