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Response of a telescope proton recoil spectrometer based on a YAP: Ce scintillator to 5–80 MeV protons for applications to measurements of the fast neutron spectrum at the ChipIr irradiation facility

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ABSTRACT

A telescope proton recoil spectrometer consisting of a 500 μm thick silicon detector and a 2.54 cm × 2.54 cm YAP:Ce inorganic scintillator has been developed to measure the neutron spectrum at ChipIr, a fast neutron beam line that has recently started operations at the ISIS neutron source in the UK. The spectrometer has been tested with protons in the range 5–80 MeV at the INFN-LNS cyclotron accelerator. The light yield of the YAP scintillator to protons has been characterized relative to gamma-rays of same energies and found to scale linearly with the proton energy in the whole range. Background rejection using a ΔE-E technique by combining data from the silicon and YAP:Ce detectors has also been tested successfully.

1. Introduction

The new beam-line ChipIr has been built at the ISIS neutron source of the Rutherford Appleton Laboratory (UK) for neutron irradiation of electronic and avionic devices and systems [1]. ChipIr is designed to provide a fast neutron spectrum that mimics the atmospheric one with approximately 10^8 – 10^9 times higher intensity at ground level [2]. The neutron energy spectrum and the flux spatial distribution of fast neutron beam-lines (e.g. ChipIr) are determined on the basis of Monte Carlo calculations that try to reproduce the complexity of nuclear and intra-nuclear interactions up to 800 MeV. Direct measurements of these quantities are needed for the characterization of the neutron flux, to benchmark the simulations, and for a better understanding of the underlying physics of this type of facilities.

A Telescope Proton Recoil spectrometer (TPR) has been developed for measuring the fast neutron spectrum in the energy range 10 MeV $< E_n < 120$ MeV [3]. The TPR system is composed by a plastic scatterer to convert neutrons into recoil protons and a high resolution proton spectrometer. The latter is based on a YAP:Ce fast inorganic scintillator with an energy resolution in the range 5%–10% at 0.6 MeV and a fast decay time (< 50 ns) to minimize pileup for operations at high background counting rates (say, 100 kHz - 1 MHz background induced by environmental γ-rays) [4]. The scintillator is used in coincidence with a silicon (Si) detector (ΔE measurement) for background reduction and particle discrimination [5]. In order to characterize the performance of YAP:Ce scintillator as a proton spectrometer, measurements of its light yield to protons have been previously performed [4] at the Uppsala tandem accelerator in the energy range 4–8 MeV and at the Legnaro Tandem ALPI-PIAVE accelerator in 9–20 MeV energy range [6]. In those tests, a 2.54 cm × 0.2 cm thick YAP crystal was used and the whole detector concept was latter assessed for the first time at the VESUVIO beam line [3,7].

In this work, we extend the characterization of the light yield of a 2.54 cm × 2.54 cm (diameter × height) YAP:Ce scintillator to protons with energies up to 80 MeV, such as those needed to determine the neutron spectrum up to 150 MeV at ChipIr. In particular, we determine the linearity of the light yield in this energy range and discuss the results in view of applications at ChipIr.

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2. Experimental setup

The TPR neutron spectrometer consists of a 2.54 cm × 2.54 cm YAP:Ce scintillator and a Si detector (2.54 cm × 0.5 mm). The entrance of the YAP scintillator was covered by a 30 μm thick Al foil for the optimization of light collection. The Si detector was also covered by a layer of 30 μm thick Al foil on two sides to shield from light and electromagnetic noise.

The YAP scintillator was coupled to a Hamamatsu R9420–100–10mod Photo-multiplier-tube (PMT) and operated with negative voltage at 650 V so to cover the whole proton energy range. The Si detector was equipped with a low-noise current preamplifier (CIVIDEC C2). The detector is reverse biased at +170 V. All signals were fed directly into a 500 MSamples/s digitizer (CAEN DT5730) and were saved by triggering the signals on YAP scintillator. The waveforms are then analyzed off-line for coincidence and pulse height analysis.

The measurements have been performed with 62 MeV and 80 MeV proton beams using the cyclotron accelerator at INFN-LNS. Aluminum foils of different thicknesses have been used to reduce the energy of protons impinging on the TPR spectrometer and obtain measurement points in the 5–80 MeV range. As the flux of the direct proton beam would be too intense to measure, a Rutherford scattering configuration has been used to reduce the flux on detectors. This was obtained by using a 0.25 mm thick polyethylene target as a scatterer to produce recoil protons from the primary beam. The TPR spectrometer was then placed at a distance of 30.8 cm from the target with an angle of 27° with respect to the incident proton beam. The angle was chosen to be large enough so that the detectors and their supporting structures did not intercept the beam but, at the same time, so to ensure a high enough signal on the detector.

3. TPR coincidence measurements

3.1. Background rejection and particle discrimination

Two events, recorded by the Si detector (ΔE) and by the YAP:Ce scintillator (E) with a same trigger, are considered to be coincident if the time interval Δt between them falls within an acceptance window. The center of this time window T_c was determined by observing the peak which stands out from a continuum of random coincidences in a histogram of Δt vs coincidence events. We obtained $T_c = 27.6$ ns and 30.4 ns for measurements at proton energies of 62 MeV and 80 MeV, respectively, with corresponding widths of 10 ns and 12 ns.

The energies deposited by charged particles on the two detectors allow to produce identification (ID) maps mathematically described by the Bethe formula [8,9], where the bending radius of each ID depends on the charge and mass of the ion species. This makes particle identification possible, such as shown by the ΔE–E contour plot in Fig. 1. Here we can easily distinguish protons as main contributors to the most intense ID, which stands out from a structure-less background due to γ-rays. Above the proton signature, there are then other particles which are separated by the different charge and mass: deuterons, tritons, ^{3}He and α. The intensity of these signatures is however less pronounced than protons, as the lower interaction cross section compared to nuclear elastic scattering and higher stopping power in air, Al foils, and Si detector.

3.2. Measured pulse height spectra

Pulse height spectra (PHS) on the YAP scintillator were obtained after coincidence analysis. Fig. 2 shows the PHS with incoming protons at 62 MeV and 80 MeV without Al foils in front of the spectrometer. The most important feature of the PHS is the peak at the maximum pulse height position, that is the contribution of proton elastic scattering on carbon (Peak_C). The contribution of scattering on hydrogen (Peak_H) and inelastic scattering on carbon can also be observed. As Peak_C has the highest energy and best resolution, we decided to use the position of this peak to determine the relative light yield of the YAP:Ce detector as a function of the incident proton energy (see Section 4.3). We can further notice that the shape of the peak is not Gaussian, as one would expect for a well collimated beam [6]. Detailed analysis reveals that it could be resulted by protons scattering on air (see Section 4.2). The statistical error on the PHS position Peak_C is about 0.5%–2.3%.

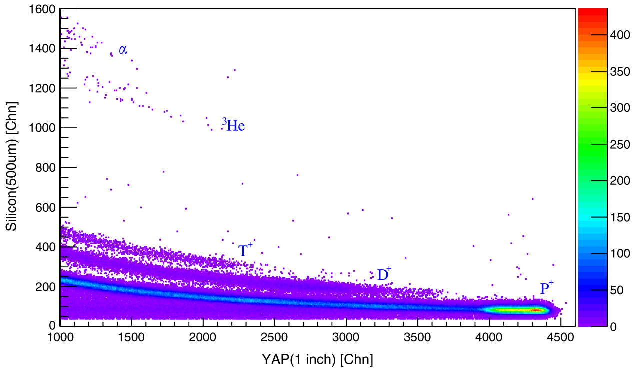

Fig. 1. $\Delta E - E$ contour plot of coincidence events measured by the TPR. Elongated structures ("bananas") due to particles produced from the interaction of protons with the polyethylene target can be clearly seen.

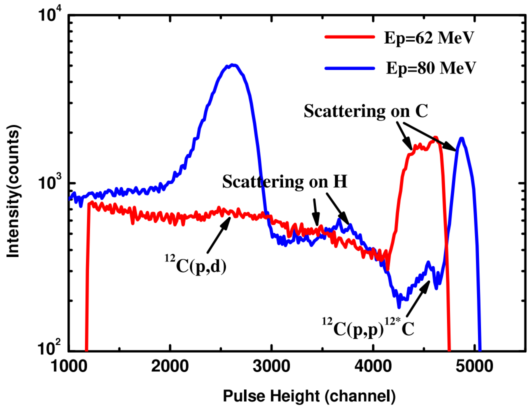

Fig. 2. Measured PHS on the YAP scintillator with 62 MeV and 80 MeV proton beams.

4. Analysis and results

4.1. Calculations of incident proton energy

Al foils of different thicknesses were placed in front of the TPR system to obtain a range of different proton energies on the TPR from the two beam energies (62 and 80 MeV) available with the cyclotron accelerator. The proton energy on the YAP scintillator after the Al foils was calculated with two independent methods that were found to be consistent. The first method was the simulation using the MCNPX code [10] with the la150h library [11]. This determines the transport of protons including scattering on the target and struggling in the Al energy degrader and air. With the second method, the energy of the scattered protons on carbon (on polyethylene) was derived analytically based on the kinematical scattering model. Proton energies lost in air, target, Al foils and silicon detector were determined based on the Pstar library [12]. The two methods provided consistent results within 1%.

4.2. PHS analysis

The PHS has been analyzed by fitting the highest energy peak with Gaussian functions. Fig. 3 shows an example of a fit for a measurement

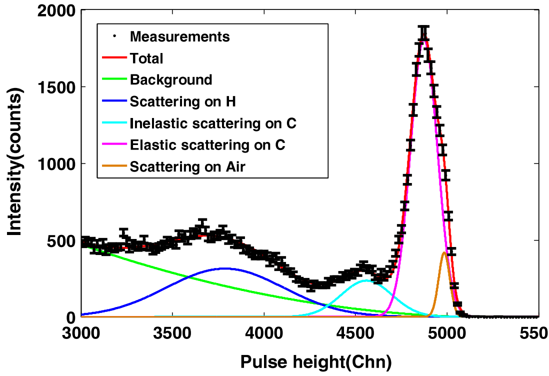

Fig. 3. Fit of the experimental data with different components that contribute to the measured spectrum, as indicated in the legend. An empirical polynomial fit is used to described the background.

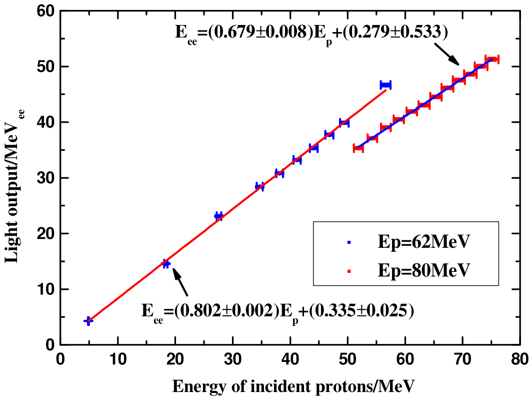

Fig. 4. ΔE–E contour plot of coincidence events measured by the TPR.

with 80 MeV protons. In the analysis of each PHS we considered components due to: (a) elastic scattering on carbon and on hydrogen; (b) inelastic scattering on carbon; (c) scattering on air and (d) a continuous background that is empirically described by a polynomial. The position of the ^{12}C elastic scattering peak is the most important parameter as it is used to determine the relative light yield (see Section 4.3). At an energy lower by 4.44 MeV with respect to the ^{12}C elastic scattering peak we then found a further peak from inelastic scattering on carbon, where the energy difference corresponds to the first excited state of the ^{12}C nucleus. As oxygen and nitrogen have higher masses than ^{12}C, scattering by air determines a barely visible peak at even higher energies than scattering on carbon.

Concerning the peak broadening, kinematics predicts wider peaks when scattering occurs on lighter elements. This is why the elastic scattering peak on hydrogen is significantly larger than that on ^{12}C.

4.3. Calibrations and light output

In order to obtain the relation between proton energy and relative light yield, we must provide the PHS with an energy scale. In our experiment we decided to adopt the equivalent electron energy (MeV$_{ee}$) scale, so that the light yield for protons at an energy E_p is expressed relative to γ-rays of same energy $E_\gamma = E_p$. To this end, we have calibrated the PHS with ^{137}Cs (0.662 MeV) and ^{60}Co (1.17 and 1.33 MeV) γ-ray sources prior to the proton measurements. A linear relation between pulse height in channels (Chn) and the electron equivalent energy (E_{ee}) $E_{ee} = 1.0523 \times 10^{-2} Chn - 0.02$, as determined by the γ-ray calibration, has been used to calibrate the PHS.

With this input, from the position of the ^{12}C elastic peak in the PHS and in MeV$_{ee}$ units, we were able to determine the curve of the relative light yield of the YAP scintillator as a function of the proton energy, as shown in Fig. 4. We find that the relative yield is linear for the set of data obtained with beam energies of both 62 MeV ($R^2 = 0.9988$) and 80 MeV($R^2 = 0.9989$).

Even though the slopes differ for the two data sets, measurements obtained with a proton beam of 62 MeV show a relative light output of $(80.2 \pm 0.2)\%$, while measurements obtained with a proton beam of 80 MeV provide a relatively reduced light output of $(67.9 \pm 0.8)\%$. After an analysis of the possible causes we concluded that the problem was a shift of the PMT gain from the first to the second set of measurements, that were performed on different days. The calibrations with gamma sources were done on the same day as the first set of measurements, so it is reasonable to assume that the relative yield determined with these data is the most accurate. As changes of the PMT gain are important and have been already observed in the measurements reported in this paper, we have now implemented a LED source driven by an external pulser in the detector to monitor the long term stability of the PMTs for applications at ChipIr.

5. Conclusion

A YAP:Ce scintillator based TPR spectrometer has been tested using protons in the energy range 5 to 80 MeV by means of the cyclotron accelerator at INFN-LNS. Background rejection and particle discrimination capabilities have been successfully demonstrated using time coincidence and ΔE–E measurements. The relative light yield of the YAP scintillator was measured to be about 80% (with 10% uncertainty) with respect to γ-rays of same energy. Most importantly, the light yield scales linearly with the proton energy in the whole range we have tested. This demonstrates the possibility to use a YAP:Ce scintillator as the proton spectrometer in a TPR detector concept for measurements of the neutron spectrum up to 150 MeV at ChipIr.

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