**Application Details**

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**Requested Beam Time Units (1 BTU = 8h)**

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**Special Requirements or Comments**

Targets: plastic (C2H4). Experiment will be performed in air to allow for frequent changes of scattering angles. A quartz and a camera will be needed to centre the beam on the target.
Characterization of YAP(Ce) crystal for a Telescope Proton Recoil neutron spectrometer. (Proposal to the LNS-PAC – September 2016)

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ABSTRACT
We submit a proposal for measurements at INFN-LNS to test the response of a Telescope Proton Recoil based on YAP(Ce) scintillator to protons in the 20-80 MeV energy range. The detectors that will be tested at the INFN-LNS are of relevance for a Telescope Proton Recoil neutron spectrometer (TPR) for application to spallation sources. In particular, a TPR is being designed for the new ChipIR beamline at the ISIS spallation source in UK. Here the YAP crystals (1” and 0.1” thick) will be used in coincidence with silicon detectors in ΔE-E configuration.
A previous experiment was performed in January 2016 at LNS-PAC. This demonstrated the feasibility of the method based on the use of the YAP(Ce) crystal as proton spectrometer. However, the detector showed problems of long term pulse height stability. We improved the design of the spectrometer mainly by adding a reference light source and we propose to repeat the same irradiation, i.e. 2 BTU of cyclotron beam at 62 and 80 MeV proton energy.

INTRODUCTION
The new beam-line ChipIr has been built at the ISIS neutron source of the Rutherford Appleton Laboratory (UK) [1] for neutron irradiation experiments on electronic and avionic devices and systems. ChipIr is designed to feature 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 kind of facilities.
A Telescope Proton Recoil spectrometer (TPR) was developed for measurement of the fast neutron spectrum with particular interest in the energy range 10 MeV < E_n < 120 MeV.
The TPR system is composed by a thin plastic foil to convert neutrons into recoil protons and a high resolution proton spectrometer.
A prototype TPR spectrometer was first tested on the VESUVIO beam line, and results are reported in Ref.[3-4]. A silicon detector was used for the transmission measurements (ΔE measurement), together with a 2.54 cm thick YAP crystal used as proton spectrometer (E measurement).

MOTIVATIONS
The requirements on the proton energy resolution can be achieved using fast inorganic scintillators, in coincidence to silicon detectors.
In particular, YAP(Ce) are the proposed scintillator crystals for the TPR of ChipIR. The fast scintillation time constants of these crystals (<30 ns) would enable their use at high count rates up to few MHz.

Characterization of the spectrometer based on a 1”×1” YAP(Ce) crystal to protons up to 80 MeV was performed with the Cyclotron accelerator at INFN-LNS in January 2016. Two energies were chosen at 62 MeV and 80 MeV from the Cyclotron accelerator, a plastic target was used for Rutherford scattering, and some aluminum foils were placed in front of the TPR spectrometer to select the proton energy on the YAP crystal. MCNP code and Pstar database were used to calculate the proton energy incident on the YAP crystal. The pulse height spectrum measured by the YAP crystal showed structures due to elastic scattering on C and H and inelastic reactions (see Fig. 1). Interaction with air and other materials (e.g. the collimator) contribute to the background. The capability of the system to discriminate charged products using the ΔE-E technique has been demonstrated (see Fig. 2).

The crystal has been calibrated with $^{137}$Cs and $^{60}$Co γ-ray sources. The relative light yield of protons with respect to gammas has been measured and is here reported to be in the range of 51.3%-83.5%. However, an instability in the PMT gain (causing systematic shifts in the measurements) was present. This is the reason why the accuracy on the light yield measurement was compromised and it is one of the main issues to be addressed in the new experiment.

Here we propose to repeat the measurements after a change in the design of the proton spectrometer. In particular we propose to add a light source to monitor the behaviour of the detector (see figure 3). The source is a small YAP crystal coupled to a Am-241 alpha source (5.5 MeV alphas). The source is designed for the characterization of PMTs. The activity is very low (only $40 \pm 8$ Bq), which gives $(20 \pm 4)$ counts/sec on the PMT. The counts are concentrated in a peak at 5000-6000 photoelectrons for a bialkali photocathode. Due to the very low count rate the source will not visible during proton irradiation, because overwhelmed by the protons with degraded energy and other radiation. Anyway it can be used after each run, when the beam is off, since it can be discriminated from the activation by pulse height.

Fig. 1 Pulse height spectra from the thick YAP TPR spectrometer measured at LNS.

Fig. 2. ΔE-E discrimination at 62 MeV measured at LNS. The individual stripes shown in the figure identify different particles as labelled.
EXPERIMENTAL SETUP

The experimental setup will consist of two telescopes. Each of them is made by a YAP(Ce) crystal (1” thick) and a silicon detector placed in front of it and working in transmission mode. The crystals are coupled to Hamamatsu PMTs, operating with negative High Voltage in the range 600-700V. The signals from the PMTs are fed directly into a 1 Gsample/s – 10 bit digitizer (CAEN-DT5751). Silicon detectors are equipped with a CIVIDEC C2 preamplifier, and signals are recorded by the same CAEN digitizer.

The proton beam will impinge on thin CH$_2$ targets, in order to reduce the proton flux reaching the detectors, which will be mounted at selected angles around the target in a Rutherford scattering setup.

We propose an elastic scattering experiment of the primary 62 and 80 MeV protons on the thin CH$_2$ target. Aluminum attenuators with calibrated thickness will be placed in front of our spectrometers and used to decrease the energy of protons reaching the YAP(Ce) crystal. This will allow us to collect information on the spectrometer response function in the whole energy range 10 – 80 MeV.

Summary of Request of Beam-time

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Special requirements

Targets: plastic (C$_2$H$_4$). Experiment will be performed in air to allow for frequent changes of scattering angles. A quartz and a Camera will be needed to centre the beam on the target.

References

Status Report

Characterization of a Telescope Proton Recoil Spectrometer based on a YAP(Ce) scintillator to protons up to 80MeV

Abstract: In order to measure the response function of the telescope proton recoil (TPR) spectrometer for ChipIr, characterization of the spectrometer based on a 1”×1” YAP(Ce) crystal to protons up to 80MeV was performed with the Cyclotron accelerator at INFN-LNS. Two energies were chosen at 62MeV and 80MeV from the Cyclotron accelerator, a plastic target was used for Rutherford scattering, and some aluminum foils were placed in front of the TPR spectrometer to select the proton energy on the YAP crystal. MCNP code and Pstar database were used to calculate the proton energy incident on the YAP crystal. It was shown that features of the spectrum include elastic scattering on C and H and inelastic reactions. Interaction with air and other materials (e.g. the collimator) contribute to the background. The capability of the system to discriminate charged products using the ΔE-E technique has been demonstrated.

The crystal has been calibrated with $^{137}$Cs and $^{60}$Co γ-ray sources. The relative light yield of protons with respect to gammas has been measured and is here reported to be in the range of 51.3%-83.5%. However, an instability in the PMT gain (causing systematic shifts in the measurements) was present. This is the reason why the accuracy on the light yield measurement was compromised and it is one of the main issues to be addressed anticipating the installation of the TPR on ChipIR.

Keywords: Neutron spectroscopy, Telescope proton recoil, Fusion, Spallation sources, YAP
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1. Introduction

The new beam-line ChipIr [1] has been built at the ISIS neutron source of the Rutherford Appleton Laboratory (UK) for neutron irradiation experiments on electronic and avionic devices and systems. ChipIr is designed to feature 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 kind of facilities.

A Telescope Proton Recoil spectrometer (TPR) was developed for measuring the fast neutron spectrum with particular interest in the energy range $10 \text{ MeV} < E_n < 120 \text{ MeV}$. The TPR system is composed by a thin plastic foil to convert neutrons into recoil protons and a high resolution proton spectrometer [3]. The requirements on the proton energy resolution can be achieved using fast inorganic scintillators (E measurement), in coincidence to silicon detectors ($\Delta E$ measurement). A prototype TPR spectrometer was first tested on the VESUVIO beam line, and results are reported in Ref.[4][5]. In particular, YAP(Ce) are the proposed scintillator crystals for the TPR of ChipIr. The fast scintillation time constants of these crystals (<30 ns) would enable their use at high count rates up to few MHz.

Measurements on the light response of these crystals to protons were performed in the 4-8 MeV energy range at the Uppsala tandem accelerator [6] and in the 9-20 MeV energy range at the Legnaro Tandem ALPI-PIAVE accelerator [7] with a 0.1” thickness YAP crystal. A relative light yield close to 98% was found. In this work, the characterization of a thick YAP (1” in thickness) was tested up to 80 MeV.

2. Experimental

Measurements have been performed in the 5-75 MeV energy range with the Cyclotron accelerator at INFN-LNS. The Cyclotron accelerator provide 62 and 80 MeV protons and some Al foils with a step of 1 mm in thickness were placed in front of the spectrometer to change the protons energy incident on the YAP crystal. Three spectrometers at different positions were tested at the same time as shown in Fig. 1.

![Fig. 1 The schematic diagram of the experiment](image)

The TPR spectrometer mainly consists of a thick cylindrical YAP(Ce) crystal (2.54 cm in diameter and 2.54 cm in thickness) and an Au-Si barrier detector (2.54 cm in diameter and 0.5 mm in thickness). The silicon detector is sensitive to light and was covered with two thin Al foils (30µm thickness) on the two sides in the experiment. The YAP(Ce) crystal was covered with a thin Al foil (30µm thickness) for the optimization of the light collection as well.
Protons from the Cyclotron accelerator passed through a gold target (100µg/cm²) and a polyethylene target (0.25 mm in thickness). The distance between the two targets is about 4 m. The TPR spectrometer was placed at the angle of 27° with respect to the incident proton beam with a distance of 30.8 cm from the polyethylene target to measure the scattering protons from the polyethylene target. The thick YAP crystal was coupled with a Hamamatsu PMT and operated with negative high voltage at 650V. The signals from the PMT were fed directly into a 1 GS/s-10 bit digitizer (CAEN-DT5751). The silicon detector was equipped with a CIVIDEC C2 preamplifier, and signals were recorded by using the same CAEN digitizer.

### 3. Pulse Height Spectra

Pulse height spectra (PHS) have been measured for the TPR spectrometer after coincidence with the signals from the YAP crystal and the silicon detector. PHS on the thick YAP crystal at 62 and 80 MeV are shown in Fig. 2. A non-Gaussian shape was systematically found for the proton peak and it looks like consisting with two peaks. The peak was interpreted as due to a poor collimation of the incident proton beam in Ref[7], which broadens the peaks, and did not allow us to evaluate the resolution of the two detectors at the proton peak for energies above 8 MeV.

![Figure 2](image)

**Fig. 2** Measured pulse height spectrum from the thick YAP TPR spectrometer

#### 3.1 Proton peak analysis

There should be only two clear proton peaks on the spectra: scattering on C and scattering on H. The big peak at lower channel position as shown in Fig. 2(b) is an additional one. To understand how did the peak come from, four samples with different thickness Al foils were chosen to compare as shown in Fig. 3. The intensity was normalized to one second and named by count rate. The peak at lower channel position only appeared when the initial proton energy equals to 80 MeV. The channel of the peak decreased when the thickness of the Al foils increased, and disappeared until 9mm thickness Al foils were placed.
3.2 Count rate and background

For checking the operation status of the digitizer, the current of the proton beam line was changed from 300 pA to 70 pA at 80 MeV. The count rate was calculated for the three situations and shown in Fig. 4. The count rate run at 150 pA is almost twice than the run at 70 pA but higher than the run at 300 pA. The result revealed that the digitizer could be too “busy” when the current of the beam was 300 pA.
Fig. 4 Pulse height spectra at 80MeV with a current of 300, 150 and 70 pA. At 300 pA the count rate could be compromised by the dead time in data-transfer from the digitizer.

In order to measure the background, the experiments without plastic target at different initial energies were performed. The PHS obtained using 62 MeV initial protons with and without the plastic target were compared and shown in Fig. 5.

![Fig. 5 Pulse height spectra with and without the plastic target at 62 MeV](image)

The PHS obtained using 80 MeV initial protons with and without the plastic target are shown in Fig. 6. The current of proton beams was 70 pA and was assumed as the same in the two experiments.

![Fig. 6 Pulse height spectra with and without the plastic target at 80 MeV](image)

Fig. 6 shows that the peak at low channel position was totally contributed by the background. The curve of the net count rate has a fluctuation at that position. It was caused by the channel position drift when the experiments performed with and without target. This is also the uncertainty of the channel position that should be considered.
4. Data analysis

4.1 Energy range of the proton peak

Fig. 2 shows that the proton peak from scattering on H has a large FWHM than the peak from scattering on C. The proton energy from scattering on H, $E'_p$, can be derived with the equation (1) [3]:

$$E'_p = E_p \cdot \cos^2 \theta = K_1 \cdot E_p$$  \hspace{1cm} (1)

Where $E_p$ is the initial proton energy and $\theta$ is the scattering angle respected to the initial incident protons on the target, as shown in Fig. 7. $K_1$ is set as the coefficient.

The proton energy from scattering on Carbon atom, $E'_c$, can be derived with the equation (2) without considering the relativistic effect:

$$E'_c = \frac{1 + A^2 + 2\sqrt{A^2 - s(n^2 - 2s/n^2)}}{(1 + A)^2} E_p = K_2 \cdot E_p$$  \hspace{1cm} (2)

where $A$ is the atomic mass of the recoil particle, $A=12$ for Carbon.

In order to calculate the energy range of the protons from the center of the target, the extreme positions on the YAP detector in horizontal direction were chosen and named by A and B. The coefficients for scattering protons from H and C in the experiments were calculated as shown in Table 1. The coefficient for protons from target on A to B was changed 0.7% for scattering protons on Carbon and 8.3% for scattering protons on H.

<table>
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<th>Coefficient on C, $K_2$</th>
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<tr>
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</tr>
<tr>
<td>B</td>
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The position of the peak of scattering on H can be calculated by the position of the peak scattering on C with the data in Table 1. However, the distance between the two peaks measured in experiment is a little larger than the calculation based on the data in table 1. The reason is that the proton energy scattering from H is lower and deposited more energy in the air and the Al foils placed before the detector.

4.2 Delta-E particle discrimination

Particles were discriminated with ToF method and the relationship between the energy deposited on $\Delta E$ detector and E detector at 62 MeV was shown in Fig. 8. There are some deuterium particles and a few other kinds of particles on the PHS. The deuterium particles contributed a smooth peak at the position as
shown in Fig. 2. The energy resolution of the deuterium peak is bad and can't be used to measure the response of the detector. The peak scattering on C as shown in Fig. 2 was only contributed by protons and has a good energy resolution. It was used to calibrate the proton energy response of the detector in this work.

4.3 Calculation of the proton peak energy

Considering the energy loss in the entrance window of the detector and the Al foils before the detector, and the energy changes after protons scattering from the polyethylene target, a calculation has been performed with MCNP6 code and the ENDF/B-VII.1 library. At the same time, a calculation with the Pstar database [8] and the iterative method was also performed to compare with it. The calculations with Pstar database fit the ones using MCNP6 well. Fig. 9 shows the relationship between the proton energy on the thick YAP and the thickness of Al foils before it.

However, the precisely of the calculation was decided by the detailed model described in MCNP or Pstar database, especially for the materials description which placed before the detector. YAP crystal was
written as YAlO₃ (Ce: 10%) and the density (g/cm³) of air, Au-Si detector and collimator (Plexiglass: C₅H₈O₂) were 0.00129, 2.33 and 1.4 in MCNP model. In order to evaluate the influence of the wall and the density of the air, the comparisons of some calculations, with and without the wall, different density values of the air, were shown in Fig. 10.

![Graph](image1)

Fig. 10 The comparison of the calculation with and without some structure in MCNP model. On the left the effect of the lab hall is shown to be negligible. The right figure shows the effect of air density on the peak position

There was no CH₂ target in the MCNP model and no difference between the calculations with and without the wall were shown, even the YAP detector was just described as a crystal. The protons scattered back from the wall can be ignored in calculations to save the time. The relative uncertainty of proton energy with changing densities is about 0.6%. The uncertainties of the Al foils in thickness and density, the density of the air, and the position of the detector should be considered into the total uncertainty of the calculated proton energy on YAP, 1.5% uncertainty was assumed here.

4.4 Analysis of the proton peak at lower energy position

The thickness of the collimator is 5cm, the material is PAMA (C₅H₈O₂) and the density is 1.18g/cm³. In order to analyze the influence of the collimator, two models with the collimator and with a killed collimator (imp: p=0) were used to calculate the flux distribution of protons as shown in Fig. 11.

![Graph](image2)
Fig. 11 The 2-D flux distribution of protons with the collimator and with a killed collimator

The flux of scattering protons at the back of the collimator position is higher than the situation that the collimator was killed. The Pulse height spectra of protons on the thick YAP detector were also calculated as shown in Fig. 12. The higher proton flux contributed all the protons for the lower channel peak on the pulse height spectrum. The proton peaks at about 75MeV energy on the spectra, with and with a killed collimator, were the same. The proton peak at lower channel position for 80MeV measurements was contributed by the leakage protons from the collimator. The proton peak, at the position of the proton peak scattering on C on the background spectrum, was contributed by the scattering protons from the tube on the collimator.

Fig. 12 The flux distribution of scattering protons and the PHS on YAP with and without collimator

4.5 Analysis of the proton peak scattering on C

There was a clear proton peak on the background pulse height spectrum at the position of the peak from scattering on C in calculation. The energy of the proton peak measured without target is a little higher
than the proton peak measured with the target, as shown in Fig. 13. If the proton peak scattering from C on the measured pulse height spectrum was set as consisting with two Gauss peaks, the fitness R-square will be more than 0.95. It’s better than fitted by one gauss peak with a R-square less than 0.8.

The background contributed some in the proton peak but not too much. The ratio of the area of the peak from the background to the area of the peak obtained with target is about 0.149 in calculation. However, the ratio in experimental is about 0.206 for 62MeV measurements and 0.413 for 80MeV measurements. The difference could be caused by the movement of the detector at the two groups of measurements. The proton peak at 62MeV was fitted with 2 Gauss peaks as shown in Fig. 14 as an example.

In order to find out where did the peak come from on background spectrum, the position of the detector and the material of the collimator were changed to show the difference on the PHS, as shown in Fig. 15.
Move the position of the detector

- 3 cm forward
- Original
- 3 cm backward

Intensity/source$^{-1}$

Energy/MeV

Fig. 15 The comparison of the PHS in calculation with changing some conditions in MCNP model

When the detector was moved 3 cm forward, the angle respect to the proton beam increased and the protons energy decreased correspondingly. On the other hand, if the detector was moved 3 cm backward, the protons energy incident on the YAP detector would be higher. The flux distribution of the protons at the surface perpendicular to proton beam line depends on the protons' scattering with air. The farther from the target, the more scatted protons were incident on the detector. In measurements, the detector was not collimated to the center of the plastic target with a laser collimator. During the two groups of measurements at 62MeV and 80MeV, the detector was moved for calibrating. The detector can't be sure that it was placed at the same position and with same direction for the two situations. This could be a main reason to explain the different shape of the proton peaks at 62MeV and 80MeV measurements.

Fig. 16 The channels and energies between the two peaks, which were fitted for the proton peak scattering on C
Channels between the two fitted peaks for the proton peak from scattering on C in measurements were calculated and shown in Fig. 16(a). The channels between the two peaks are not equal to a const. When the initial proton energy equals to 62 MeV, the channels between the two peaks decreased while adding the Al foils before the detector. However, when the proton energy equals to 80 MeV, the channels between the two peaks increased while adding the Al foils before the detector.

4.6 Uncertainty analysis

When the proton energy was fixed at 62 and 80 MeV, and no Al foils was placed at the front of the YAP detector, the position of the proton peak on YAP was observed moving, as shown in Fig. 17. The movement at 62 MeV is large but is small at 80 MeV. The threshold was changed from event Run 15. PHS of Run 5 was compared with Run 20 at Ep=62 MeV, and almost 400 channels movement was found. The maximum movement of the channel was set as the system uncertainty. The relative uncertainty was defined as about 9.8% for 62 MeV measurements and about 4.3% for 80 MeV measurements. As the shift can't be defined, the worst scenario 9.8% that was observed so far was used for all measurements.

4.7 The relationship between pulse height and proton energy

If the proton peak scattering on C was contributed by the true signals and background signals, and the fitted proton peak at higher channel position was contributed by background. Then the relationship between pulse height and proton energy can be obtained by calculating the proton energy on YAP with MCNP, as shown in Fig. 18.
Fig. 18 The peak channel as a function of the proton energy on the thick YAP detector. A fit to both datasets with a line from the origin is also shown.

There is almost 100-200 channels between the two fitted peaks as shown in Fig. 16(a). If the linear relationship as shown in Fig. 18 at 80MeV was used to calculate the proton energy between the two peaks, then the energy should be 1-2.5MeV as shown in Fig. 16(b). It’s a big difference to compared with the energy loss from $^{12}\text{C}$ 1st excited state by emitting 4.438MeV $\gamma$ rays, which is the inelastic reaction.

When the initial proton energy was 80MeV, a small proton peak, which has a little lower energy to the proton peak scattering on C, was found on the PHS as shown in Fig. 6. If the proton energy between the peak and the lower energy peak as shown in Fig. 14 was calculated with the linear relationship as shown in Fig. 18, then the energies were 4.79-6.64MeV as shown in Fig. 19. As the thickness of the Al foils before the detector increasing, the energy between the peak increasing. It was caused by the more energy deposited for the lower energy protons.

Fig. 19 The energy between the proton peak from elastic and inelastic scattering on C
Actually, the proton energy from inelastic reaction on C can be derived with equation (3).

\[
E'_p = \left( \frac{\cos \theta \sqrt{E_p}}{A+1} + \sqrt{\left( \frac{A-1}{A+1} + \left( \frac{\cos \theta}{A+1} \right)^2 \right) E_p + \frac{A}{A+1} Q} \right)^2
\]

(3)

Where \( Q \) is the reaction energy, \( Q = -4.438 \text{MeV} \) for \(^{12}\text{C}(p, \text{inl})^{12}\text{C} \) reaction as \(^{12}\text{C} \) on the 1st excited state. \( E_p \) is the proton energy on the target. \( A \) is the atomic energy, \( A = 12 \) for C.

As the detector was placed at 26.9 degree with respect to the proton beam, the proton energy after scattering on C between elastic and inelastic reaction is 4.406MeV, a little lower than 4.438MeV. If the channel uncertainty was concerned, the little peak can be deduced that it was contributed by the inelastic protons on C.

As the threshold was changed after event Run 15, the gain of the PMT could be changed correspondingly and a channel shift exit on PHS. If the movement of the proton peak's channel between Run15 and Run20 as shown in Fig. 17 was set as the systemic uncertainty. The relative uncertainty was about 2.85%. As the shift can't be defined, the worst scenario 4.3% for 80MeV measurements was used for 62MeV measurements. If the peak movement from Run5 to Run 16 was set as the channel shift, then the channel shift factor would be 299 channels or 7.2% movement. The channel position of 62MeV measurements were subtracted 299 channels or multiply 0.9326 in channels. The relationship between the measurements at 62MeV and 80MeV are shown in Fig. 20.

![Fig. 20](image)

Fig. 20 The peak channel as a function of the proton energy on the thick YAP detector after subtracting and multiplying channel position for 62MeV measurements

If the channel was shifted by subtracting a fixed channel value, the slope of the curve for 62MeV measurements is the same as shown in Fig. 18, but more closer to 80MeV measurements by multiplying a coefficient. The energy on the YAP at zero channel should be zero as well. The adjustment of the channel position by multiplying a coefficient seems more reasonable.
5. Discussion

5.1 Overload analysis of the digitizer

The digitizer was suspected operating in a overload situation through the analysis of the count rate with different proton currents as shown in Fig. 4. However, the count rate can't be used to compare the status of the digitizer's operation directly, it should be corrected with the dead time of the digitizer and normalized to the source protons. In order to check the operation was overload or not, each data file was analyzed based on the events on YAP (after coincident with the silicon detector) and the time recorded. Fig. 21 shows the operation of a run event at 62 MeV with a current of 300 pA in different time bin.

![Fig. 21 Recorded events as a function of the running time](image)

The relationship between the intensity and running time can present the current was stable or not, as shown in Fig. 21 (left). If no proton was recorded in a small time bin, the digitizer could be busy at that
time. The strength of the intensity with 0 count can present the status, as shown in Fig. 21 (right). For most measurements, the digitizer was operated in a normal status. The dead time correction of the digitizer didn’t affect the peak channel.

5.2 Calibration
In order to extend the light output of the YAP crystal for protons up to 80 MeV, the electron equivalent energy scales (in units of MeVee, MeV electron equivalent) of the spectra were obtained by calibrating with $^{137}$Cs (0.662MeV) and $^{60}$Co (1.17 and 1.33MeV) $\gamma$-ray sources. Examples of measured pulse height spectra were shown as Fig. 22, where one can notice that the full energy peaks used for calibration are clearly visible. A linear relation between the measured pulse height in channels and the MeVee was found for the thick YAP crystal, as presented in the calibration curve at Fig. 23.

![Fig. 22 Pulse height spectra of the calibration with $^{60}$Co and $^{137}$Cs](image1)

![Fig. 23 Measured calibration lines for YAP:Ce scintillator using $\gamma$-rays from $^{137}$Cs and $^{60}$Co sources at different voltages](image2)
5.3 Light output

The resulting plot of the relative light yield of the YAP scintillator is shown in Fig. 24, where the pulse height amplitudes are expressed in electron equivalent energy (MeVee) as a function of the incoming proton energy calculated by MCNP code. The relative light output of YAP:Ce scintillator versus the incoming proton energy (Ep) is linear for initial proton energy at 62MeV (R^2=0.9988) and 80MeV (R^2=0.9989). The best fits for the three curves are given with the formulas shown in Fig. 24.

\[ E_{\text{ee}} = (0.80203 \pm 0.03342) E_p + (0.33535 \pm 0.50051) \]

The thick YAP crystal was found with a smaller light output ability than the 0.1” thickness one which was tested before. One of the reason is that the self-absorption of light in the thick YAP crystal is higher than that in thin YAP crystal.

6. Conclusion and outlook

Proton Telescope measurements have been performed with a thick YAP:Ce (25.4 mm) in coincidence with a silicon detector using the Cyclotron accelerator at INFN-LNS. Two energies were chosen at 62MeV and 80MeV and some aluminum foils were placed in front of the TPR spectrometer to select the proton energy incident on the YAP crystal. The energy incident on the YAP crystal was about 5MeV to 75 MeV with MCNP calculation. The YAP crystal shows a linear response in this energy range as well as a low light yield to protons. The relative light yield of the YAP:Ce crystal was measured to be in the range of (67.9±16.6)% to (80.2±3.3)%%. This is lower than the value measured for the thin YAP:Ce crystal (2.5mm thickness), which was measured to be (95.6±0.3)%, and is also lower than the value measured with a thick YAP:Ce (2.5mm thickness) in Legnaro with protons in the 10-30MeV energy range. However, the observed long term instability of the PMT gain does not allow for an accurate measurements of this value, and in fact jeopardizes the precision of the calibration to be used on ChipIR. We suggest a revision of the TPR design, which could consist of changing the PMT or adding a monitor light source to correct for long term shifts. On the other hand, the scintillator crystal is confirmed to be a
good candidate component for a TPR neutron spectrometer based on inorganic crystals in fusion and spallation source applications, given their large light yield and fast scintillation time constants.

Concerning the use for measurements of the neutron spectrum from spallation sources, the linearity of the response to protons has to be investigated also at higher energies. In the future a Geant4 model will be developed, allowing a higher flexibility in the selection of high proton energy data bases and the modified nuclei model for data files.

Reference


