A Proton Recoil Telescope for neutron spectroscopy

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A compact and versatile Proton Recoil Telescope (PRT) detector has been realized to measure neutron energy spectra in the range from few to about 170 MeV. The PRT is a position sensitive detector made by: an active multilayer segmented plastic scintillator as neutron to proton converter, two silicon strip detectors for proton energy and position measurement and a final thick CsI(Tl) scintillator to measure the residual proton energy. The detector has been tested with the $^{13}$C(d,n) reaction at the Laboratori Nazionali del Sud of INFN using a 40 MeV deuteron beam.

1 Introduction

Future nuclear energy production will rely on generally well accepted ways of waste disposal and a solution to the inherent safety problem of critical reactor design. New concepts have been proposed for these problems, such as accelerator driven sub-critical fission reactors or transmutation of radioactive waste [1, 2]. These concepts require new neutron interaction data in the range between 20 and several hundreds MeV. Moreover, cancer therapy with neutron, proton and ion beams, the so-called hadron therapy, will require precise dosimetric methods for energies up to several hundreds MeV [3]. This topic is nowadays of particular interest to INFN in view of the commissioning of the National Centre for Hadron therapy (CNAO) in Pavia. Finally, projects like SPIRAL2 [4] or EURISOL [5] plan to produce intense radioactive beams from the fission on Uranium induced by fast neutrons. The fast neutrons will be generated in thick targets (C, Be or Hg) bombarded by a primary beam of deuterons or protons. A detailed knowledge of neutron spectra and angular distribution for the (p,n) and (d,n) reactions are thus needed up to several hundreds MeV. In fact, the energy distribution of the converted neutrons influences the mass distribution of the Uranium fission fragments and consequently the radioactive ion beams produced.

2 Proton Recoil Telescope description

A compact and versatile neutron detector adapted for all the above described applications is the Proton Recoil Telescope (PRT) that is based on the detection of the recoil proton in the elastic scattering of a neutron on a thin (1-2 mm) hydrogenated target. The energy of the recoil proton ($E_p$) is related to the incident neutron energy ($E_n$) by the relationship: $E_n = E_p / \cos^2(\theta)$, where $\theta$ is the angle between the incident and the recoil directions. The simultaneous measurement of both proton energy and recoil angle allows the initial neutron energy to be determined.

In Figure 1 a schematic drawing of our PRT is reported. It is a position sensitive detector made by: an active multilayer segmented plastic scintillator as neutron to proton converter, two silicon strip detectors for proton energy and position measurement and a final 3”×3” CsI(Tl) scintillator coupled to a photomultiplier tube to measure the residual proton energy.

The conversion target consists of 5 planes, each made by 4 active plastic scintillator (EJ 212 from Scionix) strips, 12 mm wide, 50 mm long and 0.40 mm thick. Each strip is connected to a photomultiplier tube by a cylindrical plexiglass light guide. For the inner plane the y impact position is given by the
Fig. 1: Schematic drawing of the PRT detector. n indicates the incident neutron, p the recoil proton. $\theta$ is the recoil angle. (a) is the multilayer active converter, (b1) and (b2) the silicon strip detectors and (c) the thick CsI(Tl) scintillator. The distance between detectors is not in scale. In the figure an ideal case with a proton hitting all detectors is illustrated. For each detection plane the tracked ($x$, $y$ or both) coordinates of the hit are reported. For details see the text.

hit strip, while the $x$ position is given by the analysis of the light signals collected at both sides of the single strip. For the other 4 planes we determine only the $x$ or $y$ position. This is achieved mounting the strips alternatively in the $y$ or $x$ directions. The silicon detectors are two double-sided totally depleted DC microstrips commercially available from Micron Semiconductors. They have a thickness of 300 $\mu$m, a total active area of 5 cm $\times$ 5 cm divided into 16 strips (each 3 mm wide) in the junction (front) side and 16 strips (orthogonally oriented with respect to the front, each 3 mm wide) in the ohmic (rear) side. An energy range from few to about 170 MeV will be covered. Detection efficiency, threshold and energy resolution have been tuned by Monte Carlo (MC) simulations performed with the GEANT3 [6] code. The MICAP [7] code is used for the calculation of conversion efficiency. The whole detector efficiency is a function of the incident neutron energy and its average value is of the order of $10^{-5}$.

The energy resolution of the PRT is evaluated by considering the quadratic deviation of the distribution $(E_n - E_r)$, where $E_n$ is the incident neutron energy and $E_r$ is the reconstructed neutron energy. The effects to be taken into account are the converter thickness, the reconstruction of the scattering angle $\theta$ and the energy resolution of the detectors (i.e. Silicon and CsI). The track reconstruction is performed by a linear fit in the planes $x$-$z$ and $y$-$z$ by using the coordinates obtained by the hit strips of the detectors. From the two projected straight lines, a three-dimensional direction is reconstructed and the angle $\theta$ is obtained. With such a method the resolution coming from the angular reconstruction should be less than 1%. The 5 different thin layers of active scintillator are a compromise between the optimization of the energy resolution contribution due to the conversion target and the conversion efficiency. In this way, a total energy resolution of 6% below 10 MeV and 2% above this value has been estimated.

3 First in-beam measurement with the $^{13}$C(d,n) reaction at 40 MeV

The PRT has been tested in November 2006 at the Laboratori Nazionali del Sud (LNS) in Catania. We collected data for one day with a 26 MeV proton beam from the TANDEM to debug the apparatus and for three days with a 40 MeV deuteron beam delivered by the Superconducting Cyclotron for the main experiment. We placed the PRT detector at 30 $\mu$m, 1/2 with respect to the proton/deuteron beam direction and at 200 cm from the target. We used a pressed graphite powder (density: $\rho = 0.58$ g/cm$^3$) 82% enriched in $^{13}$C housed in the chamber described in ref. [8]. The target was thick enough to stop completely the beam. The present geometry allows the direction of the neutron entering the PRT to be defined with a collimation spread of less than 1°. The main reaction $^{13}$C(d,n) was chosen to complete the characterization of $^{13}$C as
neutron converter for rare beam production [8]. The data collected amount to 150,000 events with protons and 1,500,000 with deuterons.

As an example of the collected data, in Fig. 2 we report the energy lost by the recoil protons in the first silicon strip detector versus the energy lost in the second one.

The typical pattern due the proton energy deposition in two subsequent material layers is evidenced. To process the data for reconstructing the neutron energy, the silicon strips and the CsI detector were calibrated in energy. A dedicated calibration run was performed for the silicon detectors by using a pulser and a 3 peaks $\alpha$-source (Pu, Am, Cm) and the calibration was obtained pixel by pixel.

For the CsI calibration, the scatter plot of the energy deposited in the second Si detector and in the CsI(Tl) one was analyzed (Fig. 3) and the energy calibration for CsI(Tl) scintillator was deduced.

In Fig. 3 the accumulation band is due to protons crossing the second silicon detector and releasing their residual energy in the CsI(Tl). The accumulation region in the lower left corner is noise generated by noncorrelated photons. In the accumulation band, corresponding to protons of different energies, as the energy increases, the loss in the silicon detector decreases and the energy released in the CsI grows up.

By using the MC program SRIM, the energy lost in each of the active converter layers has been calculated and tabulated as a function of the proton residual energy and of the thickness crossed by the proton: in this way the initial total energy of the proton can be measured at the conversion point. The proton angle is reconstructed with the technique described in the previous section: using both the measured angle and the measured energy of the proton the initial energy of the neutron can be reconstructed. In Fig. 4 example of a reconstructed proton track from the event display program.

As a preliminary conclusion, the PRT has been tested successfully in-beam showing good performances, the analysis program has been tested and implemented with a full energy and track reconstruction of the detected proton. Data analysis is still in progress and we plan to complete the work in the next few months.
Fig. 3: Correlation between the energy loss in the second silicon detector and the response of the CsI detector. The accumulation band is due to protons crossing to the true signal. The region in the lower left corner corresponds to protons crossing the second silicon detector and releasing their residual energy in the CsI(Tl). The accumulation region in the lower left corner is noise generated by noncorrelated photons.

Fig. 4: Example of proton track reconstruction for a good event in the x-z (top) and y-z (bottom) planes. The 3D track is determined combining the two fits.

References