A Proton Recoil Telescope for Neutron Spectroscopy

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INTRODUCTION

Recently, new interest in various applications of medium and high-energy neutron beams has developed, for example: waste disposal and a solution to the inherent safety problem of critical reactor design for nuclear energy production [1,2]; cancer therapy with neutron, proton and ion beams, the hadron therapy, that require precise dosimetric methods for energies up to several hundred MeV (this topic is nowadays of particular interest to INFN, after the project for the National Centre for Hadron therapy (CNAO) to be built in Pavia has been approved) [3]; radiation exposure of aircraft crews and staff of high-energy accelerator facilities [4,5]; finally, projects related to the production of radioactive beams for fundamental and applied physics would also greatly benefit from the knowledge of cross sections for neutron production.

For all the above mentioned points, the specification of neutron beams involves several dedicated measurements of the beam characteristics including the total fluence, measured with respect to known standard cross-sections, the energy spectrum and angular distribution of the emitted neutrons. The production of radioactive beams for fundamental nuclear physics experiments is a priority of the scientific community. In particular, special emphasis has been set on the availability of neutron-rich beams from few MeV/A up to 20 MeV/A. This will open new possibilities for experimental studies of neutron-rich nuclei using different reaction mechanisms such as Coulomb excitation, inelastic scattering, single and multiple nucleon transfer, fusion reactions, etc. Such reactions will provide valuable nuclear structure information and will allow to explore new nuclei very far from the stability valley. Beams of neutron-rich nuclei will also offer better chances to synthesize heavy elements because the fused system will be closer to the stability line with higher surviving probability. In this contest it is planned the EURISOL project in which energetic neutrons, produced by a deuteron beam that impinges on a converter, are used to induce fission in an Uranium carbide (UCx) target placed downstream of the converter [6].

PROTON RECOIL TELESCOPE PROJECT

Liquid scintillators are commonly used for neutron spectra measurements, in fact they are able to discriminate neutrons from gamma-rays using the pulse-shape discrimination (PSD) and to determine neutrons energy by its time of flight (TOF) measure. The energy accuracy scales like the inverse of the distance from the target point reducing the global efficiency due to the solid angle coverage. Moreover, the tolerable reaction rate has to be kept low enough to avoid random coincidences and the overlap of arrival of slow and fast neutrons created by neighbouring accelerator pulses.

Activation method should be also used as a backup method to allow an independent crosschecking of the results. Only gross properties of the neutron spectrum can be determined with this method, that is useful to obtain integrated quantities such as the number of neutrons in energy and angular bins. The measurement is simple and the equipment is very cheap . The drawback is the need for Ge detectors to be available for off-line counting the decays, often longer than a month to collect reasonable statistics. Details can be found e.g. in ref. [7].

The Proton Recoil Telescope (PRT) detector described in the following shall reduce the required beam time due to a larger solid angle coverage (shorter distance from the target point) with respect to the liquid scintilators and the possibility to use the full intensity delivered by the accelerator: in this way the lower intrinsic efficiency should be compensate. The PRT is based on the detection of the recoil proton in the elastic scattering of a neutron on a thin 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 θ is the angle between the incident and the recoil directions. The simultaneous measurement of both proton energy and recoil angle allows to determine the initial neutron energy, when the initial neutron direction is fixed.

The PRT realized at LNL 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. In this way we will cover an energy range from few to hundreds MeV. In Figure 1 a schematic drawing of the detector is reported.

Detection efficiency, threshold and energy resolution have been tuned by Monte Carlo (MC) simulations performed with the GEANT3 [8] code. The MICAP [9] code is used for the calculation of (n , p) elastic scattering cross section. The estimated intrinsic detector efficiency is a function of the incident neutron energy and is about 0.3% (0.15%) for 10 (40) MeV neutron and 2 mm of plastic converter.

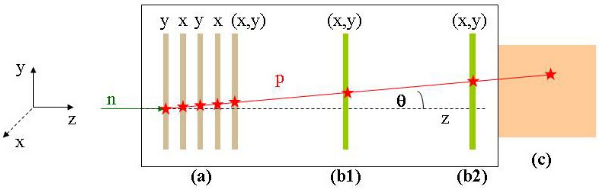

FIG. 1: *Schematic drawing of the PRT detector. n indicates the incident neutron, p the recoil proton. θ is the recoil angle. (a) is the multilayer active converter, (b1) and (b2) the silicon strip detectors and (c) the thick CsI(tl) scintillator. The distance between detectors is not in scale. In the figure an ideal case with a proton hit in all detectors is illustrated. For each detection plane the tracked (x, y or both) directions are reported. For details see the text.*

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 θ 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 θ 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, total energy resolution of 6% below 10 MeV and 2% above this value has been estimated.

Our conversion target consists of 5 planes, each made by 4 active plastic scintillator strips 12 mm wide, 50 mm long and 0.4 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 hit strip, while the x position is given by the analysis of the light signal collected at both side 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. A second advantage in segmenting the single planes is to have a further point for the tracking procedure of the recoil proton with the possibility to reconstruct also the events that stops in the first silicon detector, thus lowering the minimum threshold for the proton detection.

The silicon detectors have a thickness of 300 μm, a total active area of 5 cm x 5 cm divided into 16 strips in both sides but orthogonally oriented. For the residual proton energy measure, we use a cylindrical 3” x 3” CsI(Tl) scintillator coupled by a photomultiplier tube.

In the last November 2006, an experiment was performed with our apparatus at the Laboratori Nazionali del Sud (LNS) in Catania. We measured for 1 days with a 26 MeV proton beam from the TANDEM to debug in-beam the apparatus and for 3 days with a deuteron beam of a 40 MeV delivered by the superconducting cyclotron for the main experiment. We placed the PRT detector at 30 degrees with respect to the beam direction at 200 cm from the thick carbon target 82% enriched in ^{13}C (density: ρ=0.67 g/cm3) [10]. The data collected amount to ~150.000 events with protons and ~1.500.000 with deuterons. From very preliminary analysis, we have ~700 good (i.e. fully reconstructed) neutron events with the proton beam and ~50.000 in the deuteron case. As an example, we report in Fig. 2 the 2D correlation matrix of the energy signal due to the detected recoil protons in the two Silicon strip detectors for the (d,^{13}C) reaction case. The typical curve due the proton energy deposition in two subsequent material layers is evidenced.

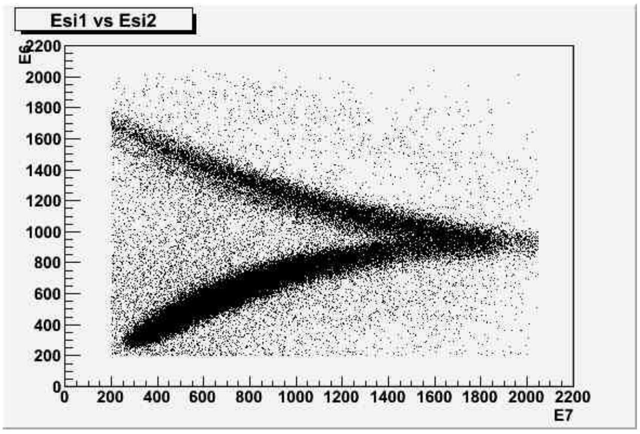

FIG. 2: *2D correlation matrix relative to the two Si detector signals in the case of the (d,^{13}C) reaction. The typical curve due to the proton energy deposition is evidenced.*

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