A Proton Recoil Telescope for Neutron Spectroscopy

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Abstract. The N2P research program funded by the INFN committee for Experimental Nuclear Physics (CSNIII) has among its goals the construction of a Proton Recoil Telescope (PRT), a detector to measure neutron energy spectra. The interest in such a detector is primarily related to the SPES project for rare beams production at the Laboratori Nazionali di Legnaro. For the SPES project it is, in fact, of fundamental importance to have reliable information about energy spectra and yield for neutrons produced by d or p projectiles on thick light targets to model the “conversion target” in which the p or d are converted in neutrons. These neutrons, in a second stage, will induce the Uranium fission in the “production target”. The fission products are subsequently extracted, selected and re-accelerated to produce the exotic beam. The neutron spectra and angular distribution are important parameters to define the final production of fission fragments. In addition, this detector can be used to measure neutron spectra in the field of cancer therapy (this topic is nowadays of particular interest to INFN, for the National Centre for Hadron therapy (CNAO) in Pavia) and space applications.

1. Introduction

Recently, new interest in various applications of medium and high-energy neutron beams has developed. For example, 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 hundred 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 hundred MeV [3]. 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. Radiation exposure of aircraft crews and staff of high-energy accelerator facilities occurs to a large extent through neutrons in this energy range [4,5]. The development of dosimetric methods in these fields
requires precisely specified quasi-monoenergetic neutron beams. 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.

1.1. Neutron beams for rare beam production

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 context, SPES (Study for Production of Exotic Species) [6] has been initiated at the Laboratori Nazionali di Legnaro to investigate the feasibility and define a technical concept of a radioactive beams facility, as a first step toward the planned European facility EURISOL. A primary deuteron beam from a linac driver will be used for radioactive beam production. The beam power dissipation, essentially due to electronic stopping power, occurs in a massive target called converter, in which beam and reaction products are stopped and do not diffuse out owing to the relatively low temperature. The only escaping radiations are thus gamma-rays and neutrons. The energetic neutrons are used to induce fission in an Uranium carbide (UCx) target placed downstream of the converter.

The neutron energy spectrum impinging on the uranium target influences the mass distribution of fission products. Slow neutrons lead to an asymmetric mass distribution with a deep valley in the region of equal mass splits. Faster neutrons increase the fission cross section and open new channels. The symmetrical region is nearly filled and the mass distribution extends further out of the light (A=80) and heavy (A=160) regions.

The fast neutron spectrum has to be studied for various projectiles, beam energies and types of converter material. In addition, physical and chemical properties of converters must be considered. Berilliyum (Be) has been identified as the best neutron emitter in terms of the n/projectile ratio, but its physical properties (low melting point, toxicity) could be problematic for an actual converter that works in a hot and radiative environment. For this reason other materials such as , $^{13}$C have been proposed. Calculations show that its neutron emission is globally lower by 30 % than the one of Be but is less reduced in the forward direction which is the one of more practical interest. Recently, $^{12}$C has been made available in form of graphite and some data are available in the literature [7]

2. Proton Recoil Telescope project

Liquid scintillators are commonly used for neutron spectra measurements. They are chosen since they are able to discriminate neutrons from gamma-rays. The method used is pulse-shape discrimination (PSD). It exploits the different rise time of the pulses generated by neutrons (the n,p scattering) and by photons (Compton scattering). The neutron energy is determined 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 (beam current of about 10$^5$ particle/second) to avoid random coincidences and the overlap of arrival of slow and fast neutrons created by neighbouring accelerator pulses.

The 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) and the possibility to use the full intensity delivered by the accelerator. In this way the lower intrinsic efficiency with respect to liquid scintillators should be compensate. It will become possible to measure detailed angular and energy neutron distributions, at various projectile energies, with beam time requests acceptable with the schedule of accelerators.
2.1. Working principle

The PRT 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: 

$$E_n = \frac{E_p}{\cos^2(\theta)}$$

where $\theta$ is the angle between the incident and the recoil directions. The simultaneous measurement of both proton energy and recoil angle allows to determine the initial neutron energy. For such a kind of detectors the initial neutron direction has to be fixed, then different technical solutions can be chosen. The simplest one is also to fix the recoil angle and measure the energy of the scattered proton in a narrow cone around this direction by a small area detector [8]. A more sophisticated solution is to consider position sensitive detectors to track the scattered proton path. In this case a plastic scintillator as active target for the (n, p) scattering could be considered [9].

2.2. The N2P detector project

The PRT under construction 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.

![Schematic drawing of the PRT detector.](image)

Detection threshold and energy resolution have been tuned by Monte Carlo (MC) simulations performed with the GEANT3 [10] code. Improved simulations with MICAP [11] are in the starting phase to introduce ($n$, p) elastic scattering cross section for the determination of the detector efficiency as a function of the incident neutron energy. A rough estimate of this efficiency is about 0.9% (0.3%) for 10 (30) MeV neutron and 2 mm of plastic converter.

The assumptions made for the MC simulations are the following: 1) the incident flux is perpendicular to the converter surface, 2) each incident neutron produce a scattered proton at a depth randomly chosen within the converter thickness, 3) $E_p(\theta)$ is calculated with relativistic kinematics. The scattering probability in the ($\theta$, $\phi$) direction is determined by the differential cross-section. The detector geometry is included in the simulations. In particular we can vary the pitch of the Si strips, the thickness of the active converter, the distance between detectors. The energy resolution of the PRT is evaluated by considering the quadratic deviation of the distribution ($E_n - E_r$) where $E_r$ 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(Tl)). In a first set of MC calculation a simplified geometry was
considered in which a unique 5 cm x 5 cm area conversion target was used. In this case the proton tracking was made only by two 5 cm x 5 cm strip silicon detectors. Distances in the range 10-30 cm were considered for the two tracking detectors. The total active area of the detectors was chosen as the maximum area of a commercially available actual silicon detectors. In Fig. 2 the different contributions to the energy resolution are reported as a function of the incident neutron energy.

![Graph showing contributions to energy resolution](image)

Fig. 2 Contributions to the overall energy resolution of the PRT. RADI is the converter contribution, ANG the recoil angle determination, RIS the intrinsic energy resolution of the detectors.

The main contribution comes from the converter. Furthermore, this contribution is the prominent one for energies below 50 MeV. This is due to the fact that the depth at which the (n, p) scattering takes place is known only within the converter thickness implying a relatively big error of the energy loss correction of the proton in the target medium. Reducing the converter thickness we obtain a better resolution while worsening the efficiency. Resolution due to the angular reconstruction should be maintained at a constant value less than 1% considering a distance of 25 cm between the silicon strip detectors and a detector pitch of about 0.5 cm (about 1° angular uncertainty). 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.

A detection threshold of about 5 MeV should be achieved for a 300 \( \mu m \) thick silicon. This threshold correspond roughly to the maximum energy of a proton that completely stops in the first silicon detector. The detection threshold could be further reduced if an active position sensitive converter is used.

The above results suggest us to design a multilayer, segmented active conversion target to improve energy resolution and lower the detection threshold. In Fig. 3 a schematic drawing of the converter is sketched. The conversion target consists of 5 planes, each made by 4 active plastic scintillator strips (EJ212 from SCIONIX), 12 mm wide, 50 mm long and 0.4 mm thick. Each strip is connected to a HAMAMATSU photomultiplier tube by a cylindrical plexiglas 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.
This more sophisticated concept of the conversion target has the advantage to reduce the uncertainty of the depth at which the (n, p) scattering takes place by a factor of 5 (0.4 mm with respect to 2 mm) thus improving the energy resolution at lower neutron energy as documented in Fig. 4.

A further 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 we use are two double-sided totally depleted DC microstrip commercially available from MICRON Semiconductors. They have a thickness of 300 μm, a total active area of 5 cm x 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.

For the residual proton energy measure, we use a cylindrical 3” x 3” CsI(Tl) scintillator coupled by an HAMAMATSU photomultiplier tube.

We are now in the assembly phase of the PRT detector. The plastic scintillator strips have been tested with an alpha source and have been glued in the entrance flange. In fig. 5 we report a picture of the mounted plastic strips.
The mechanics of the Silicon strip detector is under construction. We plan to have the complete detector ready in January 2006. Test with neutron sources are planned at the beginning of 2006. The measurement campaign for the SPES project is planned in the second half of next year. A letter of intent has been already sent to the Program Advisory Committee of the Laboratori Nazionali del Sud (LNS) in Catania. Proton and deuteron beams up to 60 MeV are, in fact, available from the Superconducting cyclotron in operation at LNS.

3. Conclusions
We presented here a project of a Proton Recoil Telescope for neutron spectroscopy. The performance of the detector have been presented as resulting from MC GEANT-based calculations. The assembly phase is now at the latest stages. The experimental campaign is planned at LNS next year. In the next year is also planned a study for the use of such a detector in other fields like space, dosimetry and beam monitoring.

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