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ABSTRACT: Neutron detectors are an essential tool for the development of many research fields, as nuclear, particle and astroparticle physics as well as radiotherapy and radiation safety. Since neutrons cannot directly ionize, their detection is only possible via nuclear reactions. Consequently, neutron-based experimental techniques are related to the detection of charged particle or electromagnetic radiation originating from neutron-induced reactions. The study of fast neutrons is often based on the neutron-proton elastic scattering reaction. In this case, the ionization induced by the recoil protons in a hydrogenous material constitutes the basic information for the design and development of neutron detectors. Although experimental techniques have continuously improved and refined, so far, proton-recoil track imaging is still weak in laboratory rate environments because of the extremely small detection efficiency. To address this deficiency, we propose a novel recoil-proton track imaging system in which the light deriving from a fast scintillation signal is used to perform a complete reconstruction in space and time of the event. In particular, we report the idea of RIPTIDE (RecoIl Proton Track Imaging DEtector): an innovative system which combines a plastic scintillator coupled to imaging devices, based on CMOS technology, or Micro Channel Plate sensors. The proposed apparatus aims at providing neutron spectrometry capability by stereoscopically imaging the recoil-protons tracks, correlating the spatial information with the time information. RIPTIDE intrinsically enable the online analysis of the ionization track, thus retrieving the neutron direction and energy, without spoiling the overall efficiency of the detection system. Finally, the spatial and topological event reconstruction enables particle discrimination – a crucial requirement for neutron detection - by deducing the specific energy loss along the track.

KEYWORDS: fast neutron detection; imaging; scintillators.

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# Contents

# 1. Introduction

It is well known that the first experiment leading to the discovery of the neutron already contained the two basic components of a neutron detector: a converter (paraffin layer) and a charged particle detector (Ionization Chamber). Nowadays the converter can be external (radiator) or embedded in the charged particle detector, see ref. [1] for an extensive and up-to-date review. Typically, neutron detectors are classified into slow (including thermal-energy) and fast neutron detectors (neutron kinetic energy $E_n > 10$ keV). In both cases the detection efficiency depends on the product between the probability of neutron interaction into the conversion layer and the escape probability of the reaction products. For this reason, a continuous effort is being spent by the international agencies such as the International Atomic Energy Agency (IAEA) and the Cross Section Evaluation Working Group (responsible for the production of the U.S. Evaluated Nuclear Data File ENDF/B) in order to establish a series of suitable cross sections, referred to as Neutron Cross section Standards [2] to be used as reference in neutron experiments. These Neutron Data Standards are reported in Fig. 1 as a function of neutron energy in the laboratory system. The involved cross sections of 7 different nuclear reactions cover a wide energy range, from thermal energy up to 200 MeV. Moreover, beside these standards, other reactions are commonly used as reference, for instance $^3$He(n,p), $^{157}$Gd(n,$\gamma$) and the H(n,n)H and the $^{235}$U(n,f) reaction above the energy range where they are considered as standard, up to 350 MeV and 1 GeV, respectively. More in detail, $^3$He, $^6$Li and $^{10}$B are widely used as slow neutron detection converters (*e.g.,* $^3$He proportional counters) and recently $^6$Li, $^{10}$B and U in advanced neutron-beam monitoring in the full neutron-energy range (see for instance refs. [3 - 5]).

Though such converters are extensively used for environmental dosimetry (neutron counters), neutron-beam flux and energy measurements and beam profiling, they are not able to provide neutron tracking, *i.e.* complete momentum reconstruction of the detected neutrons. On the other hand, when fast neutrons are involved, kinematical properties of two-particle reaction make neutron tracking possible. In this context, the neutron-proton (*n-p*) elastic scattering represents the simplest and promising interaction to be applied, as widely reported in the literature. Consequently, several state-of-the-art approaches have been recently proposed with the aim of tracking

neutrons by using *n-p* single and double scattering (see for instance refs. [6 - 9]). Hereafter this kind of detectors are referred to as Recoil Proton Track Imaging (RPTI) systems and are presented in the next section.
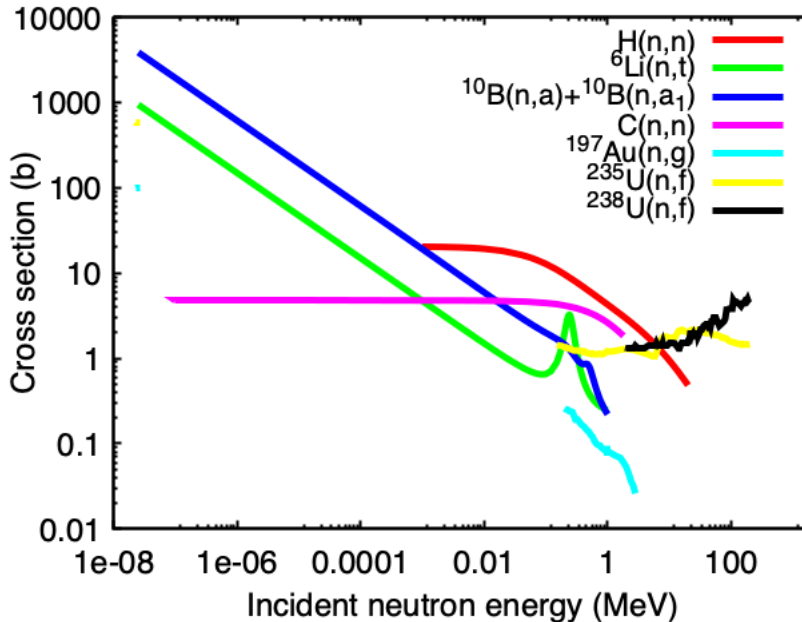


Figure 1. IAEA-ENDF/B-VII Neutron Cross-section Standards [2], retrieved from the IAEA web page.

## 1.1 RPTI neutron detectors

The basic tool for neutron momentum reconstruction in RPTI detectors is the two-body kinematics. In fact, in the *n-p* elastic scattering the neutron energy $E_n$ is related to the proton recoil angle and energy ($\theta_p$ and $E_p$) by the classical formula $E_n = E_p/\cos^2(\theta_p)$. Proposed RPTI detectors in literature exploiting this relationship can face limitations in terms of detection efficiency, complexity, cost, and final implementation. For instance, ref. [6] reports the feasibility study of an RPTI system to be used for neutron spectrometry measurements, consisting of a gas scintillator ($CF_4$) combined to a real-time imaging device. More in detail, the experimental setup is constrained in a fixed angle scattering geometry, thus exhibiting a poor detection efficiency (approximately $10^{-7}$-$10^{-6}$ %). Moreover, because the scintillation yield is weak, several amplification stages are required for a reliable proton track reconstruction by the image-intensified CCD camera (1024x1024 pixels). Apart for this limitation, impressive tracks of the recoil protons were obtained (as shown in ref. [6]), leading to a good energy resolution by proton range measurement in $CF_4$ (2.33% at $E_n$ = 14 MeV). The obtained result is strictly related to the density of the gaseous scintillator, magnifying proton ranges.

On the other hand, a more complex approach has been proposed for the *MONDO* tracker [7,8,10], whose basic principle was suggested in 2013 by Wang and Morris [11]. The detection principle relies on single and sequential *n-p* elastic scattering, *Mondo* being developed for tracking ultrafast neutrons produced in Particle Therapy treatments (neutron dosimetry). More in details, the information on recoiling protons is provided by a matrix of plastic scintillating fibers and the produced light is amplified using a triple GEM-based image intensifier or by CMOS

Single Photon Avalanche Diode arrays (SPAD). So far, the detection properties have been investigated by Monte Carlo simulations, reporting an overall neutron detection efficiency in the range 0.1-1% for 10 - 400 MeV neutrons. It is worth noticing that the dramatic efficiency cut-off for the low energy range (10-100 MeV) is inherently due to the detector structure (matrix of scintillation fibers), while the high energy cut-off is related to the finite detection volume (capability to completely contain two subsequent recoiled proton trajectories). Finally, the use of the recoil proton technique for neutron detection in Particle Therapy has been reported also in refs. [12] and [13]. In particular, the proposed detectors are a Recoil Proton Telescope combined to a hydrogenated converter with a stack of CMOS tracking sensors and a FaNS-2 capture-gated detector (an advanced spectrometer for neutron flux and energy reconstruction, conceived as a segmented fast neutron detector based on $^3$He proportional counters and plastic scintillators), respectively. It is worth mentioning that to our knowledge, no RPTI detector is currently in data-taking phase, though several systems are under study.

## 2. RIPTIDE, a novel approach

As discussed in the following section, current limitations of RPTI systems can be largely mitigated by the detection system here proposed: a RecoIl Proton Track Imaging Detector (RIPTIDE). The system is based on a detection concept joining, at the same time, a simple and scalable layout with a low-cost technical implementation. However, before going into details of the proposed system, we recall the required technical specifications to achieve scientific advances in the field of Nuclear Physics, Astrophysics, particle therapy and other applications. In particular, the detection efficiency should be higher than 10% while enabling real-time neutron tracking; the detector readout should implement fast single-event readout with time resolution of the order of a few ns; the achievable angular resolution should be of the order of a few degrees. Finally, γ-rays and charged particles should be easily discriminated and rejected by the system.

### 2.1 Working principle

With no doubt, the *n-p* elastic scattering reaction is the most used reaction in fast neutron detectors and neutron metrology. This is not surprising since, as mentioned above, the differential cross section is considered as a standard up to 20 MeV and a primary reference up to 350 MeV (and it is well-known up to 1.6 GeV [14]). Clearly, the good knowledge of *n-p* elastic total and differential cross sections are crucial ingredients for a reliable efficiency determination by Monte Carlo simulations and several publications can be found in the literature for its correct implementation (see for instance refs. [15,16]) in Monte Carlo codes such as Geant4 [17,18].

A detector sketch describing the RIPTIDE working principle is shown in Fig. 3. More in detail, the basic idea relies on recording a snapshot of the scintillation light produced by protons originated from *n-p* elastic (single or multiple) scattering in a plastic scintillator. The three-dimensional proton-recoil track reconstruction is obtained by 2D projections on orthogonal planes. Therefore, the central plastic scintillator (active volume) is surrounded by three (or more) optical systems coupled either to CMOS or Micro Channels Plates (MCP) imaging devices. From the geometrical point of view, the neutron momentum can be reconstructed in the 3D active volume of RIPTIDE in two cases:
- single *n-p* scattering, by knowing the primary vertex of neutron trajectory (*e. g.* point-like target in Nuclear Physics applications);
- double or multiple *n-p* scattering in the detector active volume.

In summary, by stereoscopically imaging the recoil-proton tracks and correlating the spatial information with the time information, the proposed apparatus can provide neutron spectrometry capability and, at the same time, enable specific energy loss analysis along the track. Consequently, the proposed system makes it possible to retrieve the neutron direction and energy, without spoiling the intrinsic efficiency of the detection volume (plastic scintillator). In addition, particle discrimination can be obtained by spatial and topological event reconstruction, which is a crucial feature in neutron detection. Note that large efficiencies can be achieved by a full-scale detector, once the scalability of the here-proposed demonstrator will be proved.
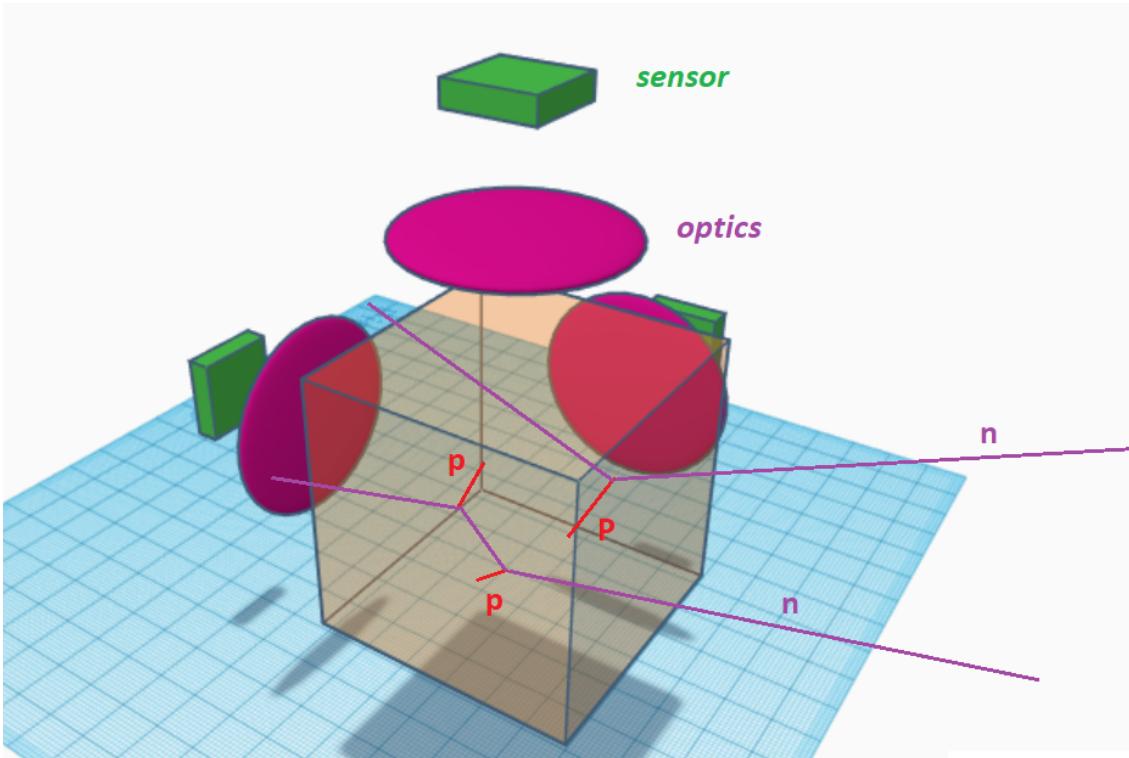


**Figure 2**: RIPTIDE working principle: the scintillation light produced by protons from *n-p* elastic scattering in a plastic scintillator (yellow cube) is used to traceback the spatial and topological reconstruction of the event.

## 2.2 A first prototype

As a preliminary design for the RIPTIDE demonstrator, we have selected a cubic active volume whose dimension results from a compromise between detection efficiency (> 10% at $E_n = 10$ MeV) and the geometrical constraints given by the wide-angle optics. In this first configuration, proton track lengths in the range from 0.2 to 30 mm (corresponding to protons of 3.5 – 60 MeV) can be identified. These estimations were obtained considering the stopping power and range of protons in vinyltoluene-based plastic scintillators (such as BC-400/EJ-200) reported in Fig. 3 and retrieved from ref. [19]. Therefore, considering a scintillating active volume of around 200 cm$^3$ and a neutron range $5 < E_n < 20$ MeV, we estimated, by means of Geant4 MC simulations, an efficiency in the order of 10-20% (assuming a detection threshold of 1 MeV electron energy equivalent, thus excluding *n-C* scattering events). Moreover, an absolute detection efficiency of

approximately 25% (considering single and double scattering) and 16% (considering only single scattering) for monoenergetic neutron at $E_n$ = 10 MeV was deduced. The simulated proton-recoil energy spectrum of RIPTIDE is shown in Fig 4.

One can argue that among the concurring neutron scattering interactions in plastic scintillators the $^{12}$C(n,n') reaction is the most prominent. Neutron elastic scattering from C nuclei (and some inelastic scattering channels as well) produces light below typical detection threshold, anyhow, these kinds of events can occur with high rates in the active volume: for instance, a 90-MeV neutron in the detector volume is three times more likely to elastically scatter from C compared to scattering from H [20]. As already mentioned, neutron-particle scattering (as well as γ-rays signals) will be disentangled by *dE/dx* track analysis. Nevertheless, we are working on MC simulations to better estimate this effect.
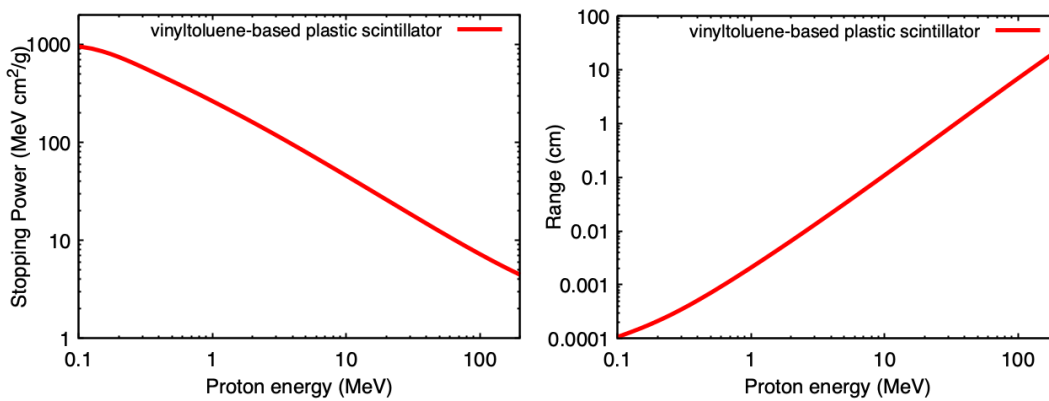
**Figure 3**: Stopping power (left panel) and range of protons in BC-400/EJ-200 plastic scintillator. Data retrieved from NIST-PSTAR [19].
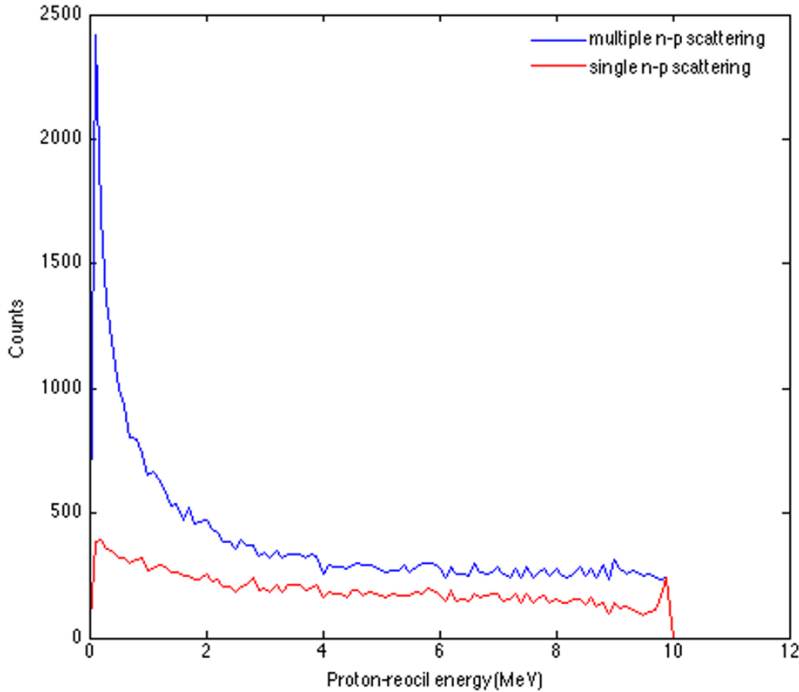
**Figure 4**: Geant4 MC energy-loss simulations of recoiling protons after *n-p* elastic scattering in BC-408 plastic scintillator induced by neutrons of 10 MeV kinetic energy.

Details on the optical system, readout modules and frontend electronic will be given in a dedicated article, as we are now testing different solutions. Here, for the sake of completeness, we recall that the scintillation signal induced by a proton in plastic scintillators can be relatively large, typically $10^3$ photons per MeV. For instance, a 3.5 MeV recoil proton produces approximately $10^4$ photons distributed along a 0.2 mm track. Consequently, a suitable wide-field optical readout system can be used, implementing the best trade-off among aperture and depth of field, scintillator emission spectra and lens transmittance.

## 3. Possible applications

Neutron detectors with tracking capability will play a relevant role in nuclear and subnuclear physics as well as in applications in the next years. For instance, the n_TOF (Neutron Time Of Flight) [21] collaboration at CERN is planning to perform the measurement of the neutron-neutron scattering length. The idea is based on the interaction of the two neutrons in the final state of the neutron-induced deuteron breakup reaction $^2$H(n,p)nn. By exploiting the unique features of the updated n_TOF facility, the measurement could be carried out at EAR2 experimental area in a wide energy range (namely between 10 and 100 MeV). Therefore, for the first time, the dependence on the energy of the neutron-neutron scattering length could be investigated, thus making a relevant step beyond the present knowledge on the topic. So far, such a measurement was hindered by the possibility of using a neutron detector able to reconstruct the momentum of the two neutrons impinging on its active volume. Clearly, the prerequisite for this experiment is

the possibility to use a technique to optically record the tracks of recoil protons in plastic scintillator by using real-time imaging devices, like foreseen by the full-scale RIPTIDE design.

On the other hand, the FOOT (FragmentatiOn Of Target) [22] collaboration aims to improve the tumor treatments in hadrotherapy by studying the interaction of heavy-ion beams with human tissues. Typical beams of protons or carbon ions impinge to the nuclei constituting the human body, thus leading to nuclear fragmentation with significative secondary neutrons production. While nuclear fragments are an important source of biological damage (both for cancer cells and for nearby healthy tissues) secondary neutrons are an unavoidable drawback of hadrotherapy. Therefore, the accurate knowledge of the nuclear fragmentation process is mandatory to plan the most effective and safe medical treatment.

So far, FOOT has focused its research program on charged particle productions in nuclear fragmentation induced by medium-light ions (most abundant in our organism). However, the most missing information concerns neutron production: data in the literature are scarce and reported with few details, moreover, they are sometime affected by systematic errors. Therefore, the collaboration is planning a dedicated measurement campaign. Clearly, the feasibility of these challenging experiments depends on the availability of a neutron detector, like full-scale RIPTIDE, with particle discrimination capability, and able to reconstruct the neutron trajectory in an experimental environment highly contaminated by the presence of neutron background. It is also worth mentioning that these neutron data are also interesting for other applications fields, as for instance radioprotection in space. NASA and other space agencies have started since several years risk assessment evaluation for astronauts, in view of long duration space missions, such for instance the travel to Mars. In addition to other risks, both galactic cosmic rays and particles from the unpredictable Solar Particle Events must be considered. The design and optimization of spacecraft shielding requires a detailed knowledge of neutron production in fragmentation processes.

## Conclusions

Available or proposed fast-neutron detectors with imaging capabilities provide promising perspective in the field of nuclear and particle physics and related applications. However, proton-recoil track imaging is still far from being considered a well-established technique. To face this deficiency, we are designing a prototype to demonstrate the possibility to reconstruct with sufficient precision the tracks and the vertices of neutron interactions with the hydrogen contained in a plastic scintillator. The technological challenge imposed by a suitable optical readout joins with the requirements to get high data transfer rate capability from the imaging devices and the associated electronics. At the present stage we have been optimizing the detector design in terms of efficiency and particle tracking by tuning and cross-checking Monte Carlo Simulations.
In summary, RIPTIDE aims at establishing a novel neutron detection technique towards a new class of detectors with an unprecedented efficiency and timing properties, together with track-reconstruction capabilities, if successful, this innovative approach can represent a cutting-edge technology for several scientific, medical, and industrial applications.

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