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A telescope detection system for direct and high resolution spectrometry of intense neutron fields

S. Agosteo [a, b], A. Fazzi [a, b], M.V. Introini [a, b], M. Lorenzoli [a, b], A. Pola [a, b, *]

[a] *Politecnico di Milano, Dipartimento di Energia, Sezione di Ingegneria Nucleare, Via Lambruschini 4, 20156 Milano, Italy*
[b] *INFN, Sezione di Milano, Via Celoria 16, 20133 Milano, Italy*

HIGHLIGHTS

- An innovative neutron spectrometer based on a monolithic telescope is proposed.
- The device exploits an active-converter.
- The geometrical configuration allows to have a high resolution (<250 keV-FWHM).
- The system demonstrates to perform a direct measurement of neutron spectra.

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ABSTRACT

A high energy- and spatial-resolution telescope detector was designed and constructed for neutron spectrometry of intense neutron fields. The detector is constituted by a plastic scintillator coupled to a monolithic silicon telescope (MST), in turn consisting of a ΔE and an E stage. The scintillator behaves as an "active" recoil-proton converter, since it measures the deposited energy of the recoil-protons generated across. The MST measures the residual energy of recoil-protons downstream of the converter and also discriminates recoil-protons from photons associated to the neutron field. The lay-out of the scintillator/MST system was optimized through an analytical model for selecting the angular range of the scattered protons. The use of unfolding techniques for reconstructing the neutron energy distribution was thus avoided with reasonable uncertainty (about 1.6% in neutron energy) and efficiency (of the order of 10^{-6} counts per unit neutron fluence). A semi-empirical procedure was also developed for correcting the non-linearity in light emission from the organic scintillator. The spectrometer was characterized with quasi-monoenergetic and continuous fields of neutrons generated at the CN Van De Graaff accelerator of the INFN-Legnaro National Laboratory, Italy, showing satisfactory agreement with literature data.

1. Introduction

Neutron spectrometers (Brooks and Klein, 2002) can be classified against the principle exploited for assessing the energy distribution of a neutron field, i.e.: i) measurement of the energy of charged particles released in neutron-induced nuclear reactions; ii) measurement of the neutron velocity; iii) threshold-reactions, in which a minimum neutron energy is indicated by the appearance of a neutron-induced effect such as radioactivity, a specific gamma-ray energy or a phase transition; iv) experimental data unfolding from a set of detectors showing a different response to neutron energy; v) measurement of the energy of recoil nuclei from neutron elastic scattering.

Neutron energy is assessed with the time-of-flight technique by measuring the neutron flight time over a known distance. A first method requires the neutron is scattered in a start detector, e.g., an organic scintillator, and the time-of-flight to a downstream detector placed at a known distance and angle is measured (Elevant et al., 1995; Manduchi et al., 1995; Kurosawa et al., 1999; Meigo et al., 1999; Elevant, 2002). A second method uses a start signal provided by an associated particle or quantum that is emitted from the neutron source at the same time as the neutron is (Böttger et al., 1990; Colonna and Tagliente, 1998).

The Bonner sphere spectrometer (BSS, Bramblett et al., 1960) consists of a set of moderating spheres of different diameter

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* Corresponding author. Politecnico di Milano, Dipartimento di Energia, Sezione di Ingegneria Nucleare, Via Lambruschini 4, 20156 Milano, Italy.
E-mail address: andrea.pola@polimi.it (A. Pola).

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housing a thermal neutron detector at their center. The spherical shape of the moderator allows approaching an isotropic angular response. Fast neutrons irradiating the spheres are slowed-down to thermal energies with a different effectiveness, depending on the moderator dimensions and on the neutron energy. For a sphere of a given diameter, the response represents the number of events acquired by the thermal neutron detector per unit fluence of neutrons of a given energy impinging on the moderator. The response variation versus neutron energy is the response function of a sphere of a given dimension. The set of response functions of all the spheres of a BSS constitutes its response matrix. Recently, a novel active neutron spectrometer condensing the functionality of Bonner spheres in a single moderator was also proposed (Bedogni et al., 2014).

Recoil spectrometers are either detectors in which recoils at all angles to the incident neutron direction are accepted for measurement, or recoil telescopes, in which recoils at a particular angle (preferably 0°) are selected for analysis. The spectrometer response function (pulse height spectrum of secondary particles resulting from monoenergetic neutron irradiation) is typically a broad continuum for the former category and a narrow function for the latter one. Recoil spectrometers based on proportional counters are widely used in the energy range 50 keV to a few MeV (Ing et al., 1997; Rosenstock et al., 1997; Pichenot et al., 2002).

Although ^{4}He recoil devices can extend the energy range up to about 15 MeV, organic scintillators are usually the preferred detectors for spectrometry at higher energies (Harvey and Hill, 1979; Klein and Neumann, 2002), in particular stilbene crystals and liquid scintillators, due to their capability of discriminating between neutron and photon events by pulse-shape analysis. The response functions of these detectors are dominated by n–p elastic scattering in this energy range. Since the n–p cross-section is well-known, response matrices and detection efficiencies can be computed accurately and neutron spectra can be reliably unfolded from measured pulse height spectra. Charged particles produced in the scintillator by neutron interactions with carbon nuclei make significant contributions to the response functions of organic scintillators at incident neutron energies above about 8 MeV, but are adequately accounted for in simulated response functions for energies up to about 15 MeV (Klein and Neumann, 2002).

Recoil telescope spectrometers strive to achieve a simple response function, ideally a single sharp peak at a pulse height uniquely related to the neutron energy. A wide variety of detection systems have been designed for approaching this requirement. Recoil telescopes can provide simple response functions but usually with low neutron detection efficiency, typically <0.01%. Another approach that is used to achieve a simple response function is the capture-gated neutron spectrometer (Aleksan et al., 1989; Kamykowski, 1992; Aoyama et al., 1993; Bart Czirr, 1994; Bertin et al., 1994). This is a recoil detector spectrometer, usually a liquid or plastic scintillator, which selects events in which neutrons transfer all of their energy by elastic and inelastic scattering within the scintillator. A delayed coincidence between the summed pulse height signal and the subsequent (0.2–50 ms) signal due to capture of the neutron after moderation to a low energy (<10 eV) is required. Neutron capture is detected by doping the organic scintillator (liquid or plastic) with ^{10}B or ^{6}Li, or by incorporating a separate low-energy neutron detector in the system. The neutron energy is obtained from the summed pulse height signals which in general generate a broad distribution (FWHM ~50%). However, detection efficiencies of about 10% can be achieved.

A monolithic silicon telescope coupled to a polyethylene converter was studied by Agosteo et al., 2007, 2011, as a recoil-proton spectrometer for low-energy neutron fields (below about 8 MeV), with an efficiency of the order of 10^{-4} counts per unit neutron fluence. The device consists of a surface ΔE stage, about 2 μm in thickness, and an E stage, 500 μm in thickness, made out of a single silicon wafer. The sensitive area of the detector is about 1 mm^2. The two stages share a deep p$^+$ electrode obtained through an high-energy boron implantation (Tudisco et al., 1999).

The neutron spectrometer is assembled by placing a 1 mm thick polyethylene layer adjacent to the ΔE stage of the monolithic silicon telescope. This device accomplishes the role of detecting the recoil-protons generated in the converter by neutrons impinging on hydrogen nuclei. The spectra acquired by the silicon detector correspond to the distribution of energy deposited within the sensitive volume by recoil-protons only (apart from the secondary electrons generated by background photons interacting with the detector assembly).

Since the ΔE stage measures a LET-related quantity, the acquisition of the time-correlated distribution of events which deposit an energy ΔE in the ΔE stage and a total energy E_{MST} in the whole detector (the so called ΔE- E_{MST} scatter plot) allows a particle-related event discrimination.

The energy distributions of the neutron yield are reconstructed with an unfolding algorithm based on a non-linear least-squares method. The response matrix was calculated by using an analytical model developed by Agosteo and Pola, 2008.

The aim of the present work is to develop a compact device capable of performing real-time direct neutron spectrometry with high energy resolution. It should be noted that the instruments described above do not meet this requirement, apart from TOF detectors, which are based on very complex detection systems. On the other hand, the experimental data acquired with multisphere and recoil nuclei devices must be unfolded through dedicated algorithms which: i) limit the simplicity of the systems, ii) deteriorate their energy resolution and iii) prevent the possibility of a real-time measurement of neutron spectra.

The spectrometer proposed in the present work is composed by a plastic scintillator coupled to a photomultiplier and a residual energy stage constituted by a monolithic silicon telescope (MST). The scintillator behaves as an “active” recoil-proton converter, while the silicon telescope measures the residual energy of recoil-protons downstream of the converter. Moreover, the MST discriminates the recoil-protons from photons associated to the neutron field.

2. Spectrometer design

As discussed in the Introduction, the spectrometer proposed herein consists of a monolithic silicon telescope (MST) coupled to a plastic scintillator acting as an active recoil-proton converter. Agosteo et al., 2007, 2011 used the same MST, coupled adjacently to a “passive” recoil-proton converter (a polyethylene layer 1 mm in thickness), for measuring the energy distribution of neutrons from low energy charged particles. A scheme of that device (polyethylene converter telescope, PCT in the following) is shown in Fig. 1. The MST is characterized by a dead layer of titanium (about 0.24 μm in thickness), a ΔE and a E stage about 2 μm and 500 μm in thickness, respectively.

The energy E_p transferred to a recoil-proton by a neutron of energy E_n through an elastic collision is:

$$E_p = E_n \cdot \cos^2(\theta) \quad (1)$$

where θ is the recoil-proton scattering angle.

In the PCT configuration, the distribution of the residual energy of recoil-protons generated at all scattering angles in the polyethylene converter is measured by the MST. Therefore, any information about E_p and θ, and therefore E_n, is completely lost and the