Nuclear Inst. and Methods in Physics Research, A 883 (2018) 115–135

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Model-based design evaluation of a compact, high-efficiency neutron scatter camera

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A R T I C L E I N F O

Keywords:
Neutron
Scatter camera
Scintillator
Photodetector
Imaging

A B S T R A C T

This paper presents the model-based design and evaluation of an instrument that estimates incident neutron direction using the kinematics of neutron scattering by hydrogen-1 nuclei in an organic scintillator. The instrument design uses a single, nearly contiguous volume of organic scintillator that is internally subdivided only as necessary to create optically isolated pillars, i.e., long, narrow parallelepipeds of organic scintillator. Scintillation light emitted in a given pillar is confined to that pillar by a combination of total internal reflection and a specular reflector applied to the four sides of the pillar transverse to its long axis. The scintillation light is collected at each end of the pillar using a photodetector, e.g., a microchannel plate photomultiplier (MCP-PM) or a silicon photomultiplier (SiPM). In this optically segmented design, the (x, y) position of scintillation light emission (where the x and y coordinates are transverse to the long axis of the pillars) is estimated as the pillar's (x, y) position in the scintillator "block", and the z-position (the position along the pillar's long axis) is estimated from the amplitude and relative timing of the signals produced by the photodetectors at each end of the pillar. The neutron's incident direction and energy is estimated from the (x, y, z)-positions of two sequential neutron–proton scattering interactions in the scintillator block using elastic scatter kinematics. For proton recoils greater than 1 MeV, we show that the (x, y, z)-position of neutron–proton scattering can be estimated with < 1 cm root-mean-squared [RMS] error and the proton recoil energy can be estimated with < 50 keV RMS error by fitting the photodetectors' response time history to models of optical photon transport within the scintillator pillars. Finally, we evaluate several alternative designs of this proposed single-volume scatter camera made of pillars of plastic scintillator (SVSC-PiPS), studying the effect of pillar dimensions, scintillator material (EJ-204, EJ-232Q and stilbene), and photodetector (MCP-PM vs. SiPM) response vs. time. We demonstrate that the most precise estimates of incident neutron direction and energy can be obtained using a combination of scintillator material with high luminosity and a photodetector with a narrow impulse response. Specifically, we conclude that an SVSC-PiPS constructed using EJ-204 (a high luminosity plastic scintillator) and an MCP-PM will produce the most precise estimates of incident neutron direction and energy.

1. Introduction

This paper will start with a brief overview of the operational principles of neutron scatter cameras. Then we will discuss previous neutron scatter camera designs and the advantages of our proposed design. Next, we will discuss the reconstruction method used to estimate scintillation position, proton recoil energy and scintillation time. Subsequently, we will detail the factors used in our expected response, such as the scintillator, photodetector and pillar impulse response. We will then detail the methodology of simulating observed responses to compare to expected responses. Using the observed and expected responses, we will show the precision of scintillation position, proton recoil energy and scintillation time estimation. This paper will conclude by illustrating back-projected image resolution of a compact, high-efficiency neutron scatter camera.

1.1. Operational principles

Neutron scatter imagers estimate incident neutron direction using the kinematics of neutron scattering off hydrogen-1 in an organic scintillator. A neutron must scatter twice within the active volume of

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https://doi.org/10.1016/j.nima.2017.11.025
Received 17 July 2017; Received in revised form 17 October 2017; Accepted 7 November 2017
Available online 22 November 2017

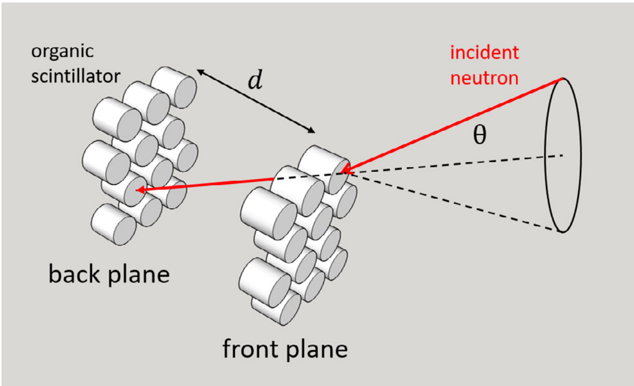

Fig. 1. Neutron Scatter camera operational principles. Incident neutron cone angles are created using the time of flight of the neutron between the two planes and the scintillation brightness from neutron elastic scatter in the front plane.

the detector to estimate incident neutron direction. The location of both scatters, the time between scatters and the energy deposited in the first scatter may be used to describe a cone of possible incident neutron directions whose axis is aligned with the vector connecting the two scatters. A graphic illustrating this method is shown in Fig. 1.

1.2. Theory

Neutrons transfer some or all of their energy to the detection medium during elastic scatter [1]. The amount of energy transferred is dependent upon recoil nucleus mass and the angle of scatter given by

$$E_{n'} = \frac{(1+\alpha) + (1-\alpha)\cos\theta_{CM}}{2} E_n \tag{1}$$

where $\alpha = \left(\frac{A-1}{A+1}\right)^2$, A is the mass of the target nucleus, E_n is the incident energy of the neutron, $E_{n'}$ is the energy of the neutron after elastic scatter and θ_{CM} is the scatter angle in the center-of-mass (CM) coordinate frame. Scattering by light nuclei is isotropic in the center-of-mass coordinate frame. Neutrons transfer all of their energy to a proton ($A = 1$) in a head on collision when $\theta_{CM} = 180°$. The center-of-mass scattering angle is related to angle in the lab frame by

$$\tan\theta_L = \frac{\sin\theta_{CM}}{\frac{1}{A} + \cos\theta_{CM}} \tag{2}$$

where θ_L is the lab frame scattering angle. We can simplify Eq. (1) to calculate the scattered neutron angle in the lab frame. If we use only scatters on hydrogen ($A = 1$), $\alpha = 0$ and Eq. (1) simplifies to

$$E_p = E_n \sin^2\theta_L \tag{3}$$

where θ_L is the angle between the incident neutron and the scattered neutron directions in the lab frame. We cannot directly measure the incident energy of the neutron; however, we can reconstruct it by summing the proton recoil energy in the first scatter and the energy of the scattered neutron shown in Eq. (4)

$$E_n = E_p + E_{n'} \tag{4}$$

where E_p is the proton recoil energy. We can estimate the scattered neutron energy $E_{n'}$ using neutron time of flight between two scatters using

$$E_{n'} = \frac{1}{2} m_n v^2 = \frac{1}{2} m_n \left(\frac{d}{\Delta t}\right)^2 \tag{5}$$

where m_n is the mass of a neutron, v is the speed of the scattered neutron, d is the distance between the first and second neutron elastic scatter, and Δt is the time between the two scatters. A second neutron scatter must

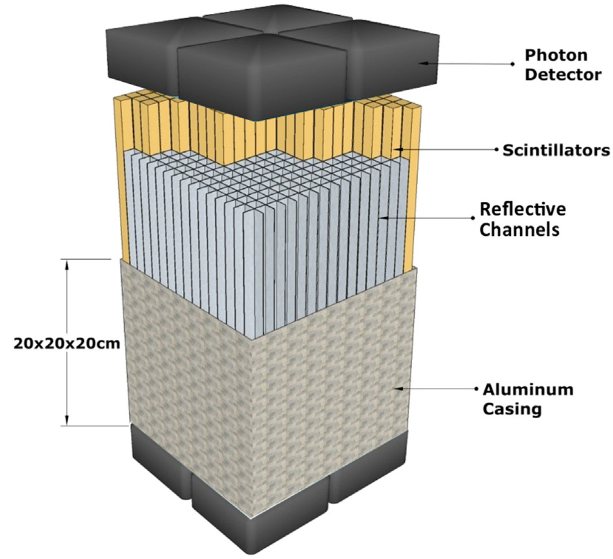

Fig. 2. Compact neutron scatter camera made of optically segmented pillars of scintillator and reflective channels.

occur, otherwise scattered neutron energy cannot be estimated and cone back-projection is impossible.

For the proposed design, we estimated the proton recoil energy using the intensity of light emitted in the first neutron elastic scatter. Concurrently, we estimated the scintillation position along the pillar using photodetectors' signal amplitude and relative timing. A neutron must interact in different pillars to reconstruct the scintillation position for both scatter events. We have all the information needed to back-project a cone of incident neutron angles using Eq. (6).

$$\theta_L = tan^{-1}\left(\sqrt{\frac{E_p}{E_{n'}}}\right). \tag{6}$$

1.3. Imager design

In this paper, we propose a high efficiency imager design to localize neutron emitting material. The instrument design uses a semi-contiguous volume of organic scintillator that is subdivided into optically isolated pillars. Each scintillator pillar is surrounded by a 1 mm air gap; this air gap allows scintillation light to undergo total internal reflection (TIR) to increase light collection efficiency. Each channel is lined with a reflective film/paint to reflect photons escaping back into the pillar. Orthogonal to each pillar and attached to opposing ends are photodetectors. Opposing photodetectors enable two waveforms to be recorded for each neutron elastic scatter. The device consists of a scintillating volume of approximately 8000 cm^3. A depiction of a single volume scatter camera made of pillars of plastic scintillator (SVSC-PiPS) is shown in Fig. 2.

2. Previous work

One of the first known neutron scatter telescopes was proposed in 1968[2]. The device was used to measure solar neutrons and the resulting albedo neutrons from earth at an altitude of 120,000 ft [3–5]. The device consisted of two large planes of mineral oil liquid scintillator, optically separated into eight cells per plane, located 1 m apart. In 1986, a double scatter fast neutron detector measured the neutron energy spectrum from a thermonuclear plasma source by utilizing the time of flight of neutrons between successive scatters [6]. In 1992, researchers measured the energy spectrum (15 to 100 MeV) and