Nuclear Instruments and Methods in Physics Research B 333 (2014) 6–11

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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

Design and demonstration of a quasi-monoenergetic neutron source

T.H. Joshi[a,b,*], S. Sangiorgio[b], V. Mozin[b], E.B. Norman[a,b], P. Sorensen[b], M. Foxe[c,b,1], G. Bench[b], A. Bernstein[b]

[a] Department of Nuclear Engineering, University of California, Berkeley, CA 94720, USA
[b] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[c] Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA 16802, USA

ARTICLE INFO

Article history:
Received 5 March 2014
Received in revised form 8 April 2014
Accepted 18 April 2014
Available online 16 May 2014

Keywords:
Neutron source
Neutron filter
^{7}Li (p,n)^{7}Be reaction
Nuclear recoil

ABSTRACT

The design of a neutron source capable of producing 24 and 70 keV neutron beams with narrow energy spread is presented. The source exploits near-threshold kinematics of the ^{7}Li (p,n)^{7}Be reaction while taking advantage of the interference 'notches' found in the scattering cross-sections of iron. The design was implemented and characterized at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory. Alternative filters such as vanadium and manganese are also explored and the possibility of studying the response of different materials to low-energy nuclear recoils using the resultant neutron beams is discussed.

1. Introduction

Characterizing the response of radiation detector media to low-energy $\mathcal{O}$(keV) recoiling atoms, often referred to in the literature as nuclear recoils, is necessary to accurately understand the sensitivity of radiation detectors to light weakly interacting massive particles (WIMPS) [1,2] and coherent elastic neutrino-nucleus scattering (CENNS) [3–7]. To produce nuclear recoils of known energy, several different types of experiments have been proposed; the use of monoenergetic neutron sources and tagging the scattered neutron [8–10], exploiting time of flight and neutron tagging with a pulsed neutron source [11], end-point measurements using a monoenergetic neutron source [12,13], use of broad spectrum neutron sources and comparison with monte carlo simulations [14], and tagged resonant photo-nuclear scatter [15]. With the exception of the proposal to use resonant photo-nuclear scatter, these experimental designs have all been employed, however successful characterization of sub-keV nuclear recoils has been limited to several results in germanium [7,12,16]. A quasi-monoenergetic $\mathcal{O}$(10 keV) neutron source that can be easily constructed at small proton accelerators would enable further characterization of low-energy nuclear recoils in candidate detector materials. More generally, such a source would be useful for characterizing the response of detector materials to $\mathcal{O}$(10 keV) neutrons.

In this article we present the design of a neutron source capable of producing such a beam. The design employs the near-threshold kinematics of the ^{7}Li (p,n)^{7}Be reaction to target resonance interference notches present in the neutron scattering cross-section of certain isotopes. The use of resonance interference notches as neutron filters, only transmitting neutrons within a narrow energy range, has been successfully demonstrated for many years using nuclear reactors [17,18], however the availability of research reactors instrumented and available for this type of work is limited. Using a nuclear reaction as the source of neutrons allows production of neutron beams with narrow energy spread at proton accelerator beam-lines capable of producing 2 MeV beams.

A prototype neutron source was constructed at the target station of the microprobe beam line at the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory (LLNL) [19]. In Section 2 we discuss the characteristics of near-threshold ^{7}Li (p,n)^{7}Be. In Section 3 we discuss the use of interference notches in iron, vanadium, or manganese as neutron filters. The results from characterization of the neutron source using an iron filter are described in Section 4 and a discussion of possible low-energy nuclear recoils measurements that may be performed with such a neutron source is included in Section 5.

2. Near-threshold ^{7}Li (p,n)^{7}Be

The ^{7}Li (p,n)^{7}Be reaction has been extensively studied and used as an accelerator based neutron source thanks to the low Q-value (1.88 MeV) [20]. In the near-threshold regime of the ^{7}Li (p,n)^{7}Be

---

[*] Corresponding author at: Department of Nuclear Engineering, University of California, Berkeley, CA 94720, USA..

E-mail address: thjoshi@berkeley.edu (T.H. Joshi).

[1] Current address: Pacific Northwest National Laboratory, USA.

http://dx.doi.org/10.1016/j.nimb.2014.04.008
0168-583X/© 2014 Elsevier B.V. All rights reserved.

reaction, the incident energy of the proton beam (E_p) establishes a kinematically constrained maximum neutron energy that varies with polar angle (φ) with respect to the incident proton beam. This behavior is evident in the proton energy contours shown in Fig. 1. Though solution of the non-relativistic kinematics equations to understand kinematic constraints of neutron production is straight-forward, calculation of the differential neutron yield is non-trivial. In this study we employ the prescription given in [21] for calculation of near-threshold differential neutron yield for protons traversing a Li-loaded target. This methodology was validated in [22]. We make the following reasonable assumptions throughout the article: proton energy loss is constant within the thin targets considered, the incident proton beam is mono-energetic, and target composition is uniform.

Using this prescription we are able to calculate the expected differential neutron yield for any combination of proton beam energy, lithium-loaded target composition, and target thickness. Fig. 2 illustrates thin target behavior for 53 $\mu g/cm^2$ metallic lithium, 115 $\mu g/cm^2$ lithium oxide, 199 $\mu g/cm^2$ lithium fluoride, 285 $\mu g/cm^2$ lithium carbonate targets computed in 0.250 keV and 0.5° intervals with $E_p = 1.930$ MeV. The areal densities were selected such that lithium areal number density is the same for the four example targets. Lithium carbonate, though not a traditional target material, is selected because, as discussed in Section 4, the metallic lithium target used to characterize the neutron source was inadvertently mishandled, resulting in a composition of lithium carbonate. Integrating the differential neutron yield over discrete angles allows comparison of an ideally collimated source with different target characteristics. Fig. 2 compares resultant neutron spectra from these thin targets when collimated at 45°. Thin targets have several benefits for production of highly tuned neutron sources. As illustrated in Fig. 2, well collimated thin lithium targets may be used to produce neutron beams with small energy spreads by varying collimation angle and/or proton beam energy. As a result, thin targets allow kinematic selection of neutron energies and avoid production of extraneous neutrons (those not produced in the desired energy and angular range), thus limiting the experimental backgrounds associated with neutrons (e.g. elastic and inelastic scatter of neutrons and capture gammas). Additionally, the 478 keV gamma yield from inelastic proton scatter within the lithium-loaded target, ^{7}Li(p,p$'$)^{7}Li, is significantly reduced when using thin targets.

For these reasons very thin targets may be quite attractive for some applications, however production, handling, and lifetime of very thin metallic Li targets pose experimental challenges. Very thin targets of lithium oxide or lithium fluoride may be used to ease these concerns, but come at the sacrifice of total neutron rate and increased target stopping power (for equivalent lithium areal number density) which broadens the energy of a collimated beam (Fig. 2). It should also be noted that the neutron energy in sources of this type are entirely defined by reaction kinematics and, as a result, are very sensitive to uncertainties in proton energy and angular alignment.

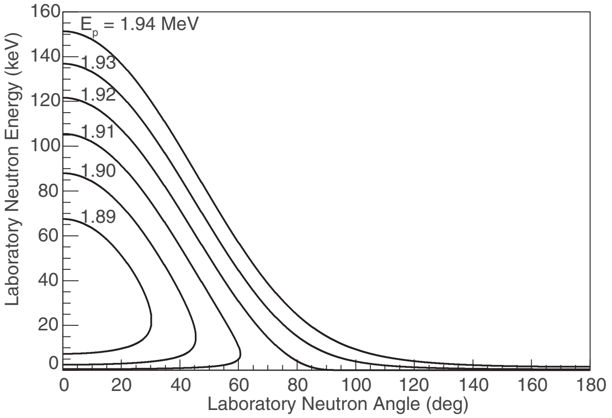

Fig. 1. Proton energy contours for the ^{7}Li (p,n)^{7}Be reaction near threshold.

3. Filtered neutron beams

One approach to utilize the benefits of near-threshold kinematics for production of beams with narrow energy spread (~10% FWHM), while minimizing sensitivity to uncertainties in proton beam energy and angular location, is the exploitation of narrow resonance interference notches in the neutron scattering cross-section of some isotopes. Interference notches selectively transmit neutrons of a particular energy (Fig. 3), allowing some materials to serve as a neutron filter. A material endowed with an interference notch at a desirable energy may be used as a neutron filter in combination with a collimated ^{7}Li (p,n)^{7}Be source. Placement of the filter within the collimator aperture and tuning the kinematics of a near-threshold ^{7}Li (p,n)^{7}Be source to target the notch effectively produces a neutron beam with narrow energy spread. The width of the energy spread is dependent upon the properties of the interference notch and the thickness of the filter. The presence of the filter within the collimator also effectively attenuates the 478 keV gammas produced via inelastic scatter in the target, resulting in a quasi-monoenergetic neutron beam with limited gamma contamination.

The sharp maximum neutron energy dictated by reaction kinematics can be used to target specific interference notches. Depending on the presence of lower-energy notches within the filter cross-section, and the thickness of the Li-loaded target, the resulting neutron beam may sometimes be composed of more than one spectral components. To avoid the situation where lower energy notches are filled when targeting higher energies, thin lithium loaded targets may be employed. Alternatively, an additional material may sometimes be identified that effectively out-scatters the lower energy component while allowing some transmission of the higher energy neutrons, and thus be used as a pre-filter.

The 24 keV notch in iron has been characterized for production of neutron beams at nuclear reactors [17]. The 24, 70 and 82 keV notches (Fig. 3) in natural iron may be targeted using the approach described here. If targeting the 70 or 82 keV notches with a thick Li-loaded target, a titanium filter may be used in combination with the iron to effectively out-scatter the 24 keV neutrons. Fig. 4 illustrates the ideally collimated neutron spectra (before and after filtering) when targeting these candidate notches in iron. A lithium carbonate differential neutron yield is used in Fig. 4 when illustrating the 24 and 70 keV notches because it was the configuration used to experimentally characterize the neutron source as discussed in Section 4. Targeting of the 82 keV notch is illustrated with a lithium oxide target.

While iron is an effective neutron filter with several notches, the many naturally occurring isotopes with competing cross-sections limit its performance. An enriched 5^6Fe filter would perform significantly better than one made with natural iron. Despite this drawback natural iron was selected for experimental demonstration of this work due to availability. Several other materials, such as vanadium and manganese, are also endowed with interference notches that may be targeted with the neutron source described and are both composed of single naturally occurring isotopes. Fig. 4 shows several examples of configurations where these filters may be employed to provide narrow neutron beams with a lithium oxide target.