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A multilayer surface detector for ultracold neutrons

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ABSTRACT

A multilayer surface detector for ultracold neutrons (UCNs) is described. The top ^{10}B layer is exposed to vacuum and directly captures UCNs. The ZnS:Ag layer beneath the ^{10}B layer is a few microns thick, which is sufficient to detect the charged particles from the ^{10}B(n,α)^{7}Li neutron-capture reaction, while thin enough that ample light due to α and ^{7}Li escapes for detection by photomultiplier tubes. A 100-nm thick ^{10}B layer gives high UCN detection efficiency, as determined by the mean UCN kinetic energy, detector materials, and other parameters. Low background, including negligible sensitivity to ambient neutrons, has also been verified through pulse-shape analysis and comparison with other existing ^{3}He and ^{10}B detectors. This type of detector has been configured in different ways for UCN flux monitoring, development of UCN guides and neutron lifetime research.

1. Introduction

Detection of ultracold neutrons (UCNs), or neutrons with kinetic energies less than about 300 neV ($1\,\text{neV}=10^{-9}\,\text{eV}$), is much like detection of thermal neutrons. That is, the same neutron-capture reactions, such as ^{3}He(n, p)^{3}H, ^{6}Li(n,α)^{3}H, ^{10}B(n,α)^{7}Li and ^{157}Gd(n,γ)^{158}Gd, are used to turn neutrons into charged particles or γ-rays [1–6]. The charged particles and γ-rays released from the capture reactions have kinetic energies ranging from hundreds of keV to a few MeV and can be readily detected using gas ionization chambers or scintillators.

Detection of UCNs, unlike detection of thermal neutrons, is sensitive to the surface conditions, gravity, magnetic fields and ambient gas conditions. All of these factors can modify UCN velocities and therefore alter inelastic scatterings of UCNs as well as UCN capture or absorption. Sensitivity of UCNs to gravity, magnetic fields, material structures and phases of matter provides opportunities to probe these forces or material structures with a precision that is inaccessible to methods using charged particles. On the other hand, it is a common UCN detection challenge to reduce non-UCN background in all of the measurements. Two reasons are: (a) UCN counting rates are typically low and the UCN signals are similar to background signals, in particular background neutron signals that can come from upscattered UCNs, thermal and higher energy neutrons and (b) production of UCNs using either nuclear reactors or accelerators also generates higher energy neutrons and γ-rays that easily outnumber the UCN population.

The UCN absorption mean free path (λ_a) is given by [7–9]

$$\lambda_a = \tau_a v_n \tag{1}$$

where the neutron absorption time (τ_a) in solid ^{10}B is independent of the neutron velocity (v_n) and can be calculated from thermal

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thermal neutron absorption cross-section, $\sigma_{th} =$ 3842 barn for the (n,α) process, $\tau_a = (n_0 \sigma_{th} v_{th})^{-1} = 9.0$ ns. Here n_0 is the solid density of ^{10}B and v_{th} the neutron thermal velocity. For UCNs at 4.4 m/s, $\lambda_a = 40$ nm. The de Broglie wavelength of UCN (λ_n) is longer than λ_a [10]:

$$\lambda_n = \frac{904.5}{\sqrt{E_n}} = \frac{395.6}{v_n} \tag{2}$$

where λ_n is in nm, the kinetic energy of the neutron (E_n) in neV and the velocity of the neutron (v_n) in m/s. For a UCN with a kinetic energy of 100 neV or a velocity of 4.4 m/s, $\lambda_n = 90$ nm.

We describe a multilayer surface detector for UCNs based on ^{10}B thin-film capture of neutrons. The top ^{10}B layer is exposed to vacuum and directly captures UCNs. The ZnS:Ag luminescent layer is beneath the ^{10}B layer. The effective ZnS layer thickness measured using a ^{148}Gd α source is a few microns thick, which is sufficient to stop the charges from the ^{10}B(n,α)^{7}Li neutron-capture reaction while thin enough that light due to α and ^{7}Li escapes for detection by photomultiplier tubes. The average ^{10}B film thickness does not exceed 300 nm.

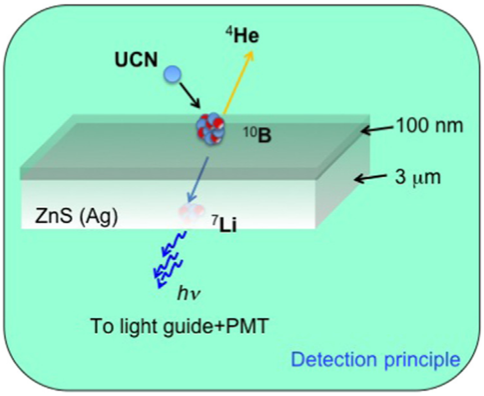

Fig. 1. The multilayer ^{10}B surface detector for UCNs consists of a thin ^{10}B top layer supported by a luminescent layer of ZnS:Ag. At least one of the charged particles α or ^{7}Li generated from the neutron capture slows down or stops in the ZnS:Ag layer and emits light. A light-guide or a transparent window is used to transmit the light to a photomultiplier tube (PMT). A ^{10}B thickness of 100 nm and a ZnS:Ag thickness of a few microns are sufficient.

Table 1
Maximum ion ranges (R^i) of the charged products from the ^{10}B(n, α)^{7}Li neutron capture process in ^{10}B solid films and ZnS.

Ion (probability, w^i)	Energy (E_0^i, MeV)	Range in ^{10}B (R^i, μm)	Range in ZnS (R^i, μm)
α (47%)	1.47	3.5	4.2
α (3%)	1.78	4.4	5.1
^{7}Li (47%)	0.84	1.8	2.3
^{7}Li (3%)	1.02	2.1	2.5

Below we first present the working principle of the detector and some relevant material properties, followed by some details of the detector design and construction. Next, we describe detector operation and detector performance, and correlate the detector performance with ^{10}B-film characterization. The efficiency limitations are discussed towards the end, leaving room for further efficiency improvement through better understanding of the surface texture.

2. Detection principle and material properties

The working principle of the detector is illustrated in Fig. 1. The detector design takes several lengths into account: UCN capture length (λ_a), α and ^{7}Li ion ranges (R^i) in solid ^{10}B and ZnS, and light attenuation in ZnS and the light-guide. Compared with gas-based detectors, using only solid components in the detector removes the need for a material window. Compared with bulk ^{7}Li- or ^{10}B-doped scintillators for thermal neutrons, a 100-nm thin-film coating is sufficient since λ_a is only 40 nm for UCNs at 4.4 m/s. An ideal UCN detection efficiency up to 95% is expected for a film thickness of $3\lambda_a$ [11] or about 120 nm. When the UCN reflection from the ^{10}B coated ZnS:Ag surface is taken into account, the efficiency can be reduced further by more than 20% due to reflection, as shown below.

The ion ranges (R^i) in ^{10}B and ZnS are calculated using the Stopping and Range of Ions in Matter (SRIM) code [12] and summarized in Table 1. Since the ion ranges are many times the ^{10}B film thickness $\sim 3\lambda_a$, the charged particle energy losses in the ^{10}B are small, except for ions that move at large angles with respect to the surface normal. For the 0.84 MeV ^{7}Li, the full ion stopping in ^{10}B only occurs when the angle is greater than $\theta_c = \cos^{-1}(3\lambda_a/R^i)$ or about 86° for $\lambda_a = 40$ nm. The corresponding loss of detection efficiency is about 3% due to the 0.84 MeV ^{7}Li loss alone. The total efficiency loss for the two branching ratios and both α and ^{7}Li in the ^{10}B layer is

$$\epsilon_{loss}(^{10}B) = \sum_i w^i \frac{T_0}{R^i} \tag{3}$$

for a flat uniform ^{10}B layer thickness T_0. The values of w^i are given in Table 1. For $T_0 = 120$ nm, $\epsilon_{loss}(^{10}B) = 5\%$.

ZnS:Ag coated acrylic acetate sheets (around 120 μm thick) were obtained commercially [13] and used as the substrates for ^{10}B thin-film coating. According to the vendor, a transparent thermosetting adhesive is applied to the acetate surface for ZnS:Ag bonding, so the ZnS:Ag facing the ^{10}B is not coated with any adhesive. The ZnS:Ag powder size is 16 μm on average. Scanning

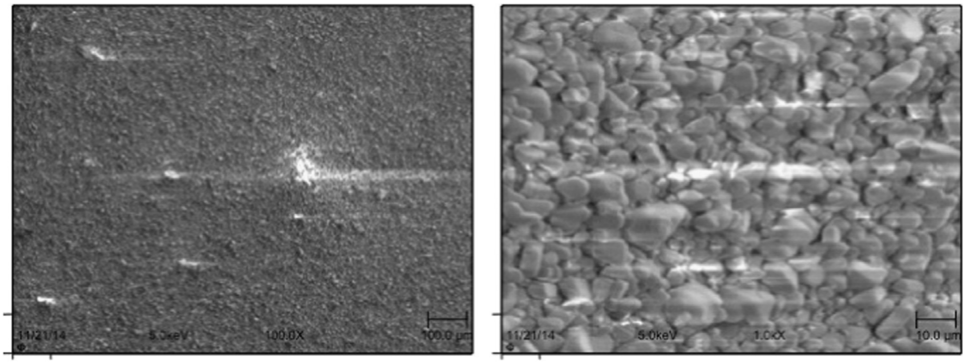

Fig. 2. (Left) The 100-μm resolution image of a ^{10}B-coated ZnS surface using a scanning electron microscope (SEM). (Right) The 10-μm resolution of the same film. The bright spots in both images are due to electrostatic charging of the surface.