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Development of a Solid-State Detector with a ^{6}Li/Ti Multilayer Converter for Ultracold Neutrons

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ABSTRACT

A new type of solid-state detector for ultracold neutrons has been developed and confirmed to be applicable at $4.2K$. ^{6}Li/Ti multilayers, in which the effective potential is compensated, were formed as a neutron converter by vacuum evaporation on the surface of a silicon-surface-barrier detector. The detector was tested using a cold-neutron beam, and the reaction products in $^6\mathrm{Li}+n \rightarrow \alpha+t$ were clearly observed in the pulse-height spectrum with a detection efficiency of 0.28% for 4Å neutrons. This is consistent with the estimated value, and implies that ultracold neutrons can be detected with an efficiency of greater than 60%. The detector enables us to study the characteristics of ultracold neutrons in liquid helium, which is necessary to discuss the feasibility of an intense ultracold neutron source based on the superthermal method.

The interaction between matter and very slow neutrons whose wavelengths are much longer than the distance of atoms in matter can be described by an effective potential which is the nuclear potential averaged over the matter volume [1]. The effective potential is given as

$$U = \frac{2\pi\hbar^2}{m} bN, \tag{1}$$

where m is the neutron mass, b the bound neutron scattering length and N is the number density of nuclei in the matter. Neutrons which are totally reflected at any glancing angle by the effective potential are called ultracold neutrons (UCN). UCN can be confined in a bottle for several hundreds of seconds. Measurements of the neutron properties using stored UCN have provided the most reliable and precise values of the neutron lifetime [2] as well as the upper limit of the neutron electric dipole moment [3,4]. The advantage of using UCNs is that they can be confined in a material bottle to achieve a remarkably long measurement time. Increasing the UCN intensity is essentially important for further improvements in measuring neutron properties. The possibility of an intense UCN source by a superthermal method was pointed out by Golub [5]. In the superthermal method, cold neutrons are decelerated by emitting single phonons in superfluid helium. UCN production by the superthermal method has been confirmed, as reported in Ref. [6] and [7]. A quantitative study of UCN absorption on the wall of a container and at the matter window to extract UCN is necessary in order to discuss the feasibility of a superthermal UCN source. A UCN detector which can be operated in superfluid helium would enable us to study the characteristics of UCN directly in superfluid helium.

The common method to efficiently detect low-energy neutrons is to detect charged particles produced in neutron-capture reactions. We adopted a surface-barrier silicon semiconductor for the detection of reaction products, since it can be applied at liquid-helium temperature.

^{6}Li is a suitable neutron converter, since all of the reaction products in the reaction

$$n +^6 Li \rightarrow \alpha + t + 4.78MeV \tag{2}$$

are charged particles, and the reaction cross section is $940b$ for thermal neutrons, which amounts to $0.3Mb$ for UCN when assuming the $1/v$-law. Reaction products α and t emerge at almost opposite directions with kinetic energies of 2.06 and $2.73MeV$, respectively. ^{6}LiF is commonly used as a neutron converter, since lithium is very unstable under humidity. Improvements of solid-state neutron detectors with a ^{6}LiF neutron converter were reported in Ref. [8]. However, the neutron converter must satisfy a special requirement: it must absorb UCN efficiently, while its surface is transparent to UCN. The effective potential should have a small real part and a large imaginary part. ^{6}LiF has an effective potential of $U = (120 - 4.2i)neV$, and reflects neutrons with $E \leq 120neV$. The use of ^{6}Li metal is advantageous, since $U = (26.4 - 3.2i)neV$. To overcome the instability of lithium under humidity, we formed a multilayer of ^{6}Li and titanium by vacuum evaporation. Furthermore, the real part of the effective potential of ^{6}Li layers was canceled out by the negative effective potential of titanium layers.

We report on a result concerning a performance test at $4.2K$ of the UCN detector with a ^{6}Li/Ti multilayer neutron converter.

A silicon surface barrier-type semiconductor with a sensitive area of $100mm^2$ (ORTEC BR-16-15-100) was used as a detector of the reaction products. The surface of the silicon was coated by aluminum of $50\mu g/cm^2$. A multilayer neutron converter was formed on the surface of the semiconductor by vacuum evaporation. The configuration of the multilayer neutron converter is shown in Fig. 1 and Table 1. A $14\mu g/cm^2$ titanium layer was formed on the aluminum coating so as to obtain an adhesive surface. (I) A nickel layer of $78\mu g/cm^2$ was formed on the titanium layer to increase the UCN detection efficiency due to total reflection as discussed later. (II) 35 bilayers of $0.23\mu g/cm^2$ ^{6}Li and $1.4\mu g/cm^2$ titanium and (III) 25 bilayers of $0.23\mu g/cm^2$ ^{6}Li and $1.8\mu g/cm^2$ titanium were evaporated on the nickel layer. (IV) The surface of the neutron converter was coated by a $82\mu g/cm^2$ titanium layer, which prevents lithium from reacting with water in the atmosphere.

Region	U [neV]	thickness		
		[$\mu g/cm^2$]	[Å]	
(I)	240	78	880	Ni (UCN reflector)
(II)	$-2.2 - 2.0i$	$35 \times \left\{ \begin{array}{c} 0.23 \\ 1.4 \end{array} \right.$	$35 \times \left\{ \begin{array}{c} 50 \\ 30 \end{array} \right.$	^{6}Li (UCN converter) Ti
(III)	$-7.4 - 1.8i$	$25 \times \left\{ \begin{array}{c} 0.23 \\ 1.8 \end{array} \right.$	$25 \times \left\{ \begin{array}{c} 50 \\ 40 \end{array} \right.$	^{6}Li (UCN converter) Ti
(IV)	-50	82	1800	Ti

Table.1 Effective potential and thickness of layers formed on the detector.

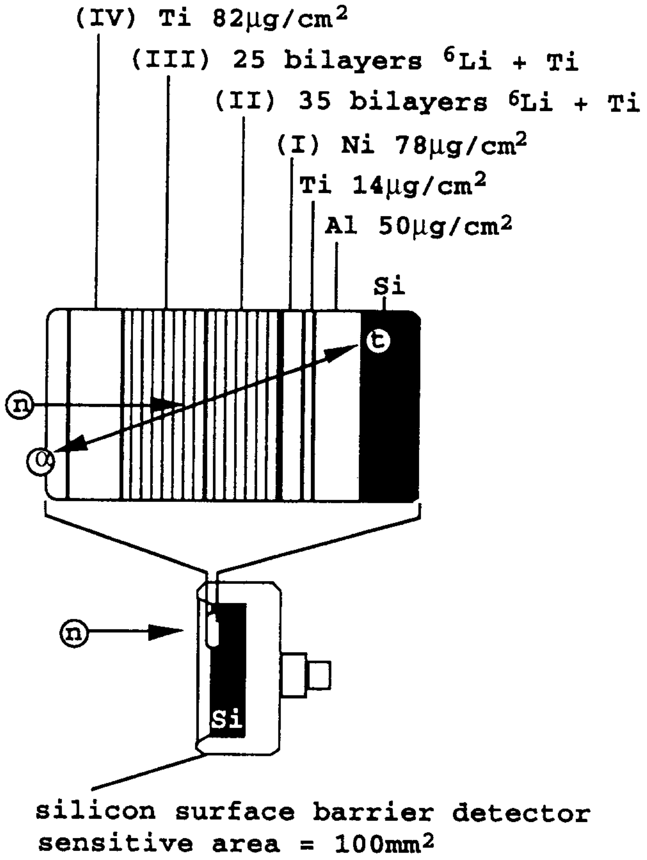

Fig.1 Detector configuration.

In regions (II), (III) and (IV), the real part of the effective potential is almost zero, or negative, and neutrons are absorbed in regions (II) and (III). Due to the large effective potential in region (I), UCNs are totally reflected and reflected UCNs are absorbed in regions (II) and (III). Fig. 2 shows the calculated neutron absorption probability of the neutron converter as a function of the neutron energy. This figure demonstrates the effect of the nickel layer as a reflector. The absorption efficiency is increased by a factor of ~ 2 for UCN with the energy around the effective potential of nickel.

The performance test of the UCN detector was carried out using a cold-neutron beam from the cold-neutron guide at the KEK spallation neutron source. The experimental arrangement is shown in Fig. 3. A ^3He proportional counter (LND type 2628) was placed at $28.69m$ from the neutron source to monitor the beam intensity. The gas inside the counter was ^{4}He-^{3}He-CO$_2$ with a pressure of $800Torr$ in total, and the partial pressure of ^3He was $40Torr$. The thickness of the ^{3}He was $21.6mm$, which corresponds to a 3.3% detection efficiency for 4Å neutrons.

The transmitted neutrons were incident into the UCN detector, which was placed $29.48m$ from the neutron source. The UCN detector was cooled down to $4.2K$ in a cryostat. The beam windows were made of aluminum, and the thickness was $2mm$ in total. The temperature of the detector was measured using a germanium thermometer. A bias of $-100V$ was applied to the detector. The output pulse was processed by a preamplifier (ORTEC142) and an amplifier (ORTEC570). The pulse-height spectrum obtained using a pulse-height analyzer (CANBERRA 35 PLUS) is shown in Fig. 4. Two peaks corresponding to t and α are clearly separated. The asymmetric peak shape can be explained as being the result of the energy spread of t and α according to the variation in the energy loss while traveling through the layers of the neutron converter.

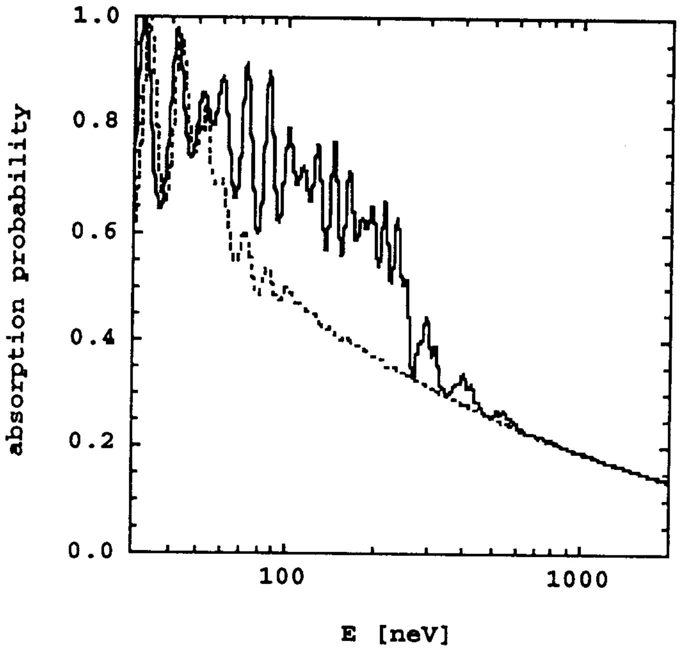

Fig.2 Absorption probability of neutrons versus the incident energy. The solid line is the absorption probability with the nickel layer as a UCN reflector, and the dotted line that without the nickel layer. The silicon is assumed to be infinitely thick.

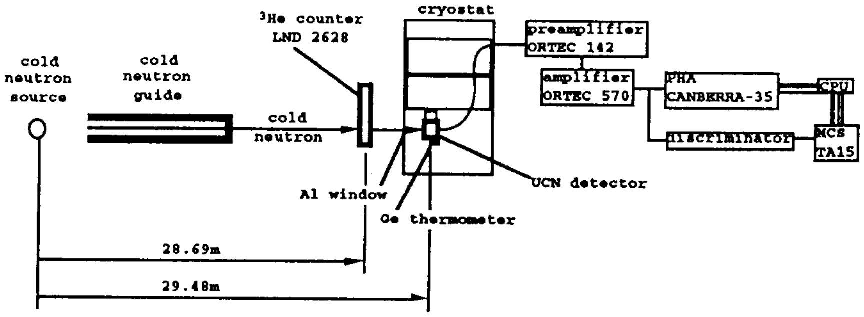

Fig.3 Schematic view of the experimental arrangement of the performance test of the UCN detector using a cold-neutron beam at the KEK spallation neutron source.

The counting rate versus the neutron time-of-flight was measured using a multichannel scaler (TA15) [9]. The discrimination level was set at channel 130 in the pulse height spectrum. The counting rates of the ^{3}He beam monitor and the UCN detector are expected to have the same energy dependence, since both of the neutron absorption cross sections of ^{3}He and ^{6}Li obey the $1/v$-law. The ratio of the counting rate of the UCN detector and that of the ^{3}He beam monitor is shown in Fig. 5 as a function of neutron time-of-flight. The ratio is independent of the incident neutron energy within the experimental errors, and the averaged ratio was determined to be $(8.5 \pm 0.1)\%$. The detection efficiency of the UCN detector was calculated to be 0.28% at 4Å from the detection efficiency of the ^{3}He beam monitor. This value is consistent with the calculated detection efficiency, which is 0.29%.

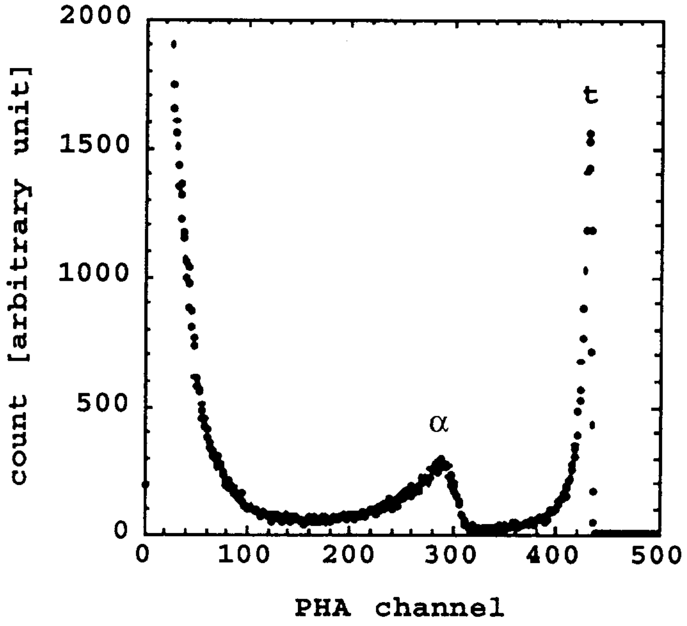

Fig.4 Pulse-height spectrum at liquid-helium temperature.

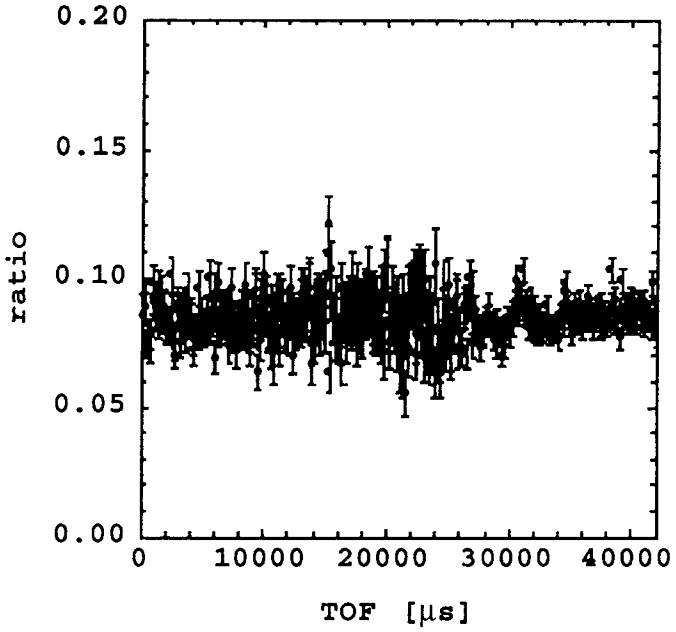

Fig.5 Ratio of the counting rates of the UCN detector and the ^{3}He beam monitor counter versus the neutron time-of-flight.

We reported on a new type of UCN detector which can be used at liquid-helium temperature. The choice of material is important for a UCN converter, because UCN can be reflected by the effective potential of the material. We overcame this problem by forming a ^{6}Li/Ti multilayer converter in which the effective potential is canceled out. The reaction products were clearly observed in the pulse-height spectrum, and the detection efficiency was 0.28% at 4Å, which is consistent with the calculated value. We formed a nickel layer as a UCN reflector in order to increase the detection efficiency of UCN. The calculated UCN detection efficiency is more than 60%, which is sufficiently large to study the UCN characteristics in superfluid helium.

This type of detector could be improved so as to be sensitive to the incident UCN energy by stacking several detectors having different reflectors. Higher energy UCN can penetrate the reflector materials, while UCN with a kinetic energy lower than the threshold energy of the reflector material is reflected by the reflector. A position-sensitive UCN detector can be made by forming the UCN converter on a position-sensitive semiconductor detector.

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