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Optimization of He-II UCN Source with Spallation Neutron Source

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Abstract

A spallation neutron source was designed for super thermal UCN production in He-II. The configuration of neutron production target, moderator and He-II bottle was optimized in order to obtain high neutron flux with low γ heating in He-II. In the optimization the advantage of the spallation neutron source is used: The spallation neutron source has high n/γ ratio and freedom in target moderator configuration in comparison with the reactor. As a result, a great improvement in UCN density is expected compared with the present most intense UCN source at the Grenoble reactor.

Introduction

Ultra cold neutrons (UCNs) have been used for the measurements of β-decay lifetime, neutron electric dipole moment (EDM) and so on. UCNs have also a promising role in neutron β-decay asymmetry experiments. The experimental accuracy and possibility in these experiments are limited by UCN density. The motivation of the present work is to realize high intensity UCN source far beyond the Grenoble UCN source that is the most intense UCN source at present.

A super thermal UCN source will make a breakthrough for the UCN production [1]. The super thermal source applies phonon excitation to neutron cooling. Cold neutrons are down scattered into a UCN region at the intersection point of the energy-momentum dispersion curves of the neutron and phonon. The number of UCNs builds up during a UCN storage time in a UCN bottle. The storage time is limited by a UCN up-scattering, absorption and the β-decay. The up-scattering is a reverse process to the down-scattering. An up-scattering rate depends on the temperature of phonon medium, while a down-scattering rate is independent of the temperature.

Constituent nuclei in the phonon medium should have small neutron-absorption cross-section. We use He-II as the material of phonon medium, since the ^{4}He has no absorption cross section. Solid deuterium is also good material, but the deuteron has small absorption cross-section. UCN has a finite lifetime because of the absorption, 200 ms in deuterium, which is very short compared with the β-decay lifetime.

A spallation neutron source is quite suitable for the super thermal UCN production [2]. In order to obtain high UCN density, we need cold neutron flux as high as possible in He-II, where temperature should be kept below 1 K so that the up-scattering rate becomes comparable to the β-decay rate. The dominant heat deposit in the He-II comes from the γ rays of the spallation neutron source. The spallation neutron source has 12 times higher neutron/γ ratio than the reactor. In the spallation source, a γ-ray shield can be placed near the neutron-production target that is a dominant γ ray source. These properties are quite suitable for the super thermal UCN production. We designed a spallation neutron source for the UCN production in He-II. We optimized the target moderator configuration in order to obtain higher neutron flux in He-II with lower γ heating. We used a Monte Carlo simulation code, LCS code of Los Alamos for the optimization.

Optimization

A schematic view of the UCN source is shown in Fig. 1. A cylindrical He-II bottle is vertically placed above a neutron production target. The target is covered with a lead γ ray shield. For neutron moderation, cylindrical 20-K heavy water and 300-K heavy water surround the He-II bottle. The 300-K heavy water is surrounded by a graphite neutron reflector and a polyethylene neutron shield. A heat deposit on He-II is removed by a ^{3}He cryostat (or ^{4}He cryostat). The proton beam power for the production of the spallation neutrons is assumed to be 400W (400MeV × 1 μA), which is available at RCNP, Osaka University.

The optimization of the UCN source was carried out in the following way. Firstly, two kinds of target materials, lead and tungsten are compared in the point of cold neutron flux and γ-ray heat deposit in He-II (①). Secondly, optimal thickness of the lead γ shield (②), the 300-K heavy water and 20-K heavy water (③,④) were searched for. Finally, the cold neutron flux and the heat deposit were calculated for three He-II bottles of zirconium, stainless steel and aluminum (⑤).

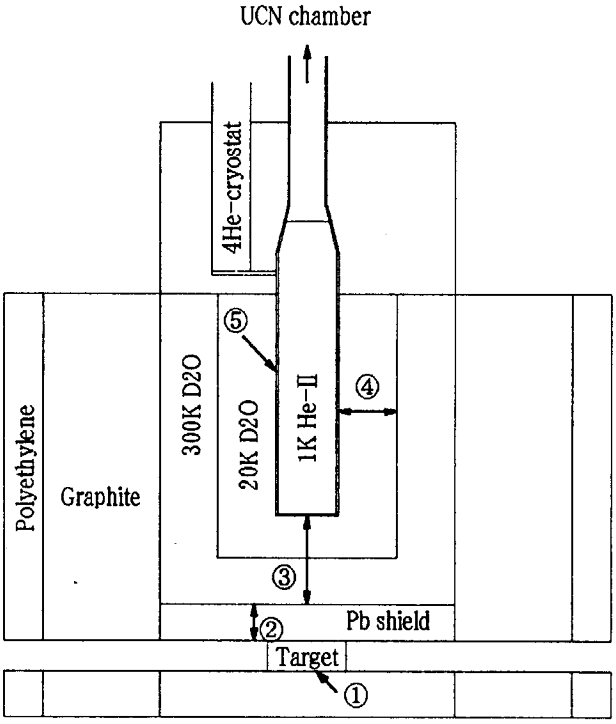

Fig.1 Basic configuration of UCN source.
The numbers enclosed by circles indicates parameters for optimization.

① Target material

The cold neutron flux and the heat deposit in the He-II obtained by the Monte Carlo calculation for the two targets are shown in Table 1. Here, a UCN production rate, which is obtained from the estimated cold neutron flux following the equation of Golub [1], is shown. The result shows that the two materials are comparable to each other. The heat deposits are much lower than the cooling power of the helium cryostat at ~1K. In the following calculation, we fix the target material as lead.

Table.1 UCN production rate and heat deposit as a function of target materials

Material	UCN production rate [n/cm^3/sec]	Heat deposit [mW]
Pb	16.6	43
W	15.9	41

② Thickness of Pb shield

The thickness of the lead γ shield was treated as a variable in the calculation of the cold neutron flux and the heat deposit. The target distance from the He-II bottle was also changed along with the shield thickness, but other parameters were not changed. The both cold neutron flux and heat deposit increase as the target approaches to the He-II bottle. The ratio of the two variables was almost constant. The result suggests the effect of target γ ray is small. A shorter target distance is desirable, because we can obtain a higher neutron flux with a smaller proton beam current. In the following calculation, we fixed the lead-shield thickness at 5 cm.

③ Moderator thickness at the bottom

Here, we assumed 20-K heavy water to be the 20-K ideal gas that has the same density as solid heavy water at 20-K. We assumed the both 20-K and 300K moderators to have the same thickness at the bottom. Here, the variable is the total thickness of 300-K and 20-K heavy water.

The UCN production as a function of the total moderator thickness is shown in Fig. 3. The UCN production rate increases as the total thickness decreases. The heat deposit has similar behavior, except it varies more rapidly in the region of the total thickness less than 15cm. The result suggests that scattering between high-energy neutron and He nucleus induced the rapid heat increase at small distance. We fixed the total thickness at 15cm. 300-K and 20-K moderator thickness are fixed 10 and 5 cm, respectively, since the radiation damage induced by neutron collision is more serious for solid. The cold neutron flux has no significant dependence on the ratio of the 300-K moderator thickness to the 20-K moderator thickness.

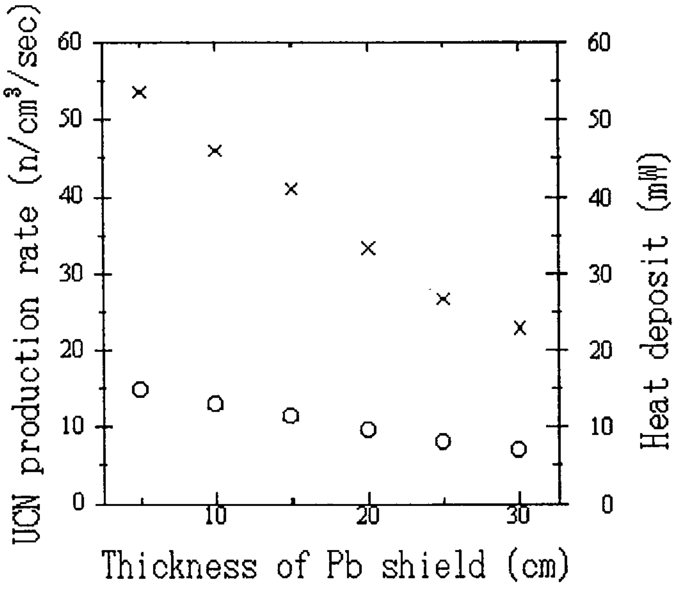

Fig. 2 UCN production rate and heat deposit as functions of target position. Open circles and crosses show the production rate of UCN and heat deposit, respectively.

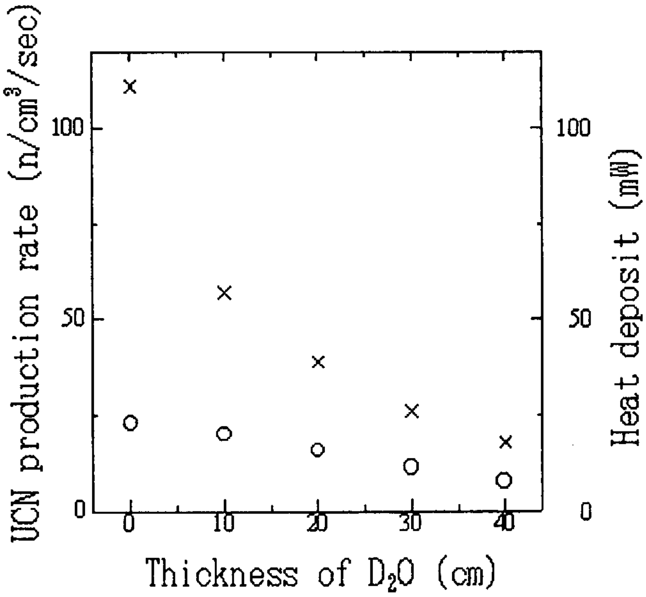

Fig.3 UCN production rate (circle) and heat deposit (cross) as functions of total moderator thickness.

④ Radial width of solid D_2O

The UCN production rate and the heat deposit as functions of a radial width of the 20-K heavy water are shown in Fig. 4. The cold neutron flux increases as the radial thickness increases, and saturates at 15-cm thickness, while the heat deposit is almost constant. We fixed the radial thickness at 20 cm.

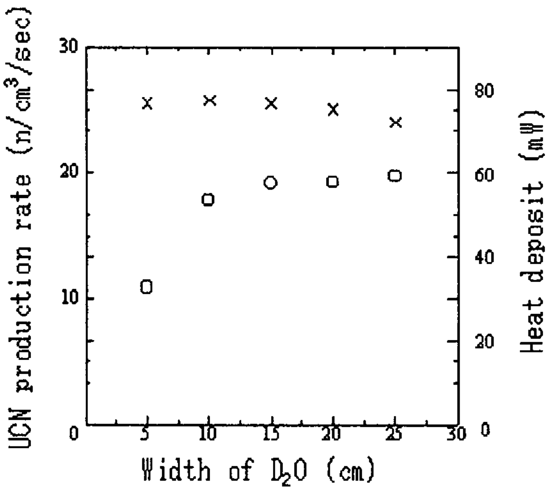

Fig.4 UCN production rate (circle) and heat deposit (cross) as functions of radial width of the moderator

⑤ Material of He bottle

The results of the Monte Carlo calculation for a 0.5-mm thick stainless steel, a 0.5-mm thick zirconium and a 2-mm thick aluminum He-bottle are shown in table 2. The stainless steel is common as a cryogenic material, but it has the large neutron radiative-capture cross-section that results in neutron attenuation and γ heating. In this point of view, zirconium is one of the best materials, since it has very small neutron cross-sections and is a good material for cryogenics [3]. Aluminum has also similar properties as zirconium, but mechanical strength is rather weak compared with zirconium. We need thicker bottle wall for aluminum. For the first UCN production, we will use aluminum because of easy fabrication.

Table.2 Table.1 UCN production rate and heat deposit
as a function of He-Ⅱ bottle materials

Material	Thickness [mm]	UCN production rate [n/cm^3/sec]	Heat deposit [mW]
SUS	0.5	11.9	39
Zr	0.5	16.3	16
Al	2.0	14.6	26

Conclusion

The result of the optimization is summarized in Table 3. In the table, other important parameters, a volume of He-II, the UCN storage time are listed. The storage time is obtained from the up-scattering rates in He-II, in helium gas in a UCN bottle and at the bottle wall. The former two up-scattering rates depend on He-II temperature, which is assumed to be 0.92 K. The up-scattering rate at the wall is assumed to be 1/100 s^{-1}. The heat deposit of 75 mW is easily removed by a usual ^{3}He cryostat.

Table.3 Optimized values

UCN production	20.2 (n/cm^3/sec)
Neutron flux at He-Ⅱ bottle	1.5×10^{10}(n/cm^2/sec)
He-Ⅱ volume	1.1×10^4 (cm^3)
Heat deposit at He-Ⅱ bottle	75 (mW)
Temperature of He bottle	0.92 (K)
Storage time	85 (sec)
Density (Tn=20K)	425 (n/cm^3)
Density (Tn=80K)	57 (n/cm^3)

At 20-K, heavy water freezes, therefore we can not treat nuclei in heavy water as free particles for low energy neutrons. The neutron temperature should be higher than the moderator temperature, which results in decrease of the cold neutron flux from the present value. If we assume the neutron temperature rises from 20 to 80 K, [4] we should take a reduction factor of 1/8 into account. The study of the form factor of the neutron scattering is under preparation for accurate calculation.

The UCN density of 425 UCNs/cm^3 in an experimental chamber expected by the present calculation is much larger than the best UCN density in an experimental chamber, 1 UCNs/cm3, at Grenoble [5]

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