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He-II Spallation UCN source

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Abstract: A new ultra cold neutron (UCN) production in a spallation neutron source is discussed. The new method uses phonon excitation in He-II, where we can use large phonon phase-space for neutron cooling. The new method is free from the Liouville's theorem which limits the turbine UCN source at Grenoble. The spallation neutron source reduces the phonon up-scattering which depends on temperature, because of small γ heating compared with the reactor. The phonon up-scattering rate limits the UCN storage time. As a result, higher neutron flux can be applied to He-II, and therefore, an enhancement of 10^3 in the UCN production is expected compared with the turbine UCN-source which is the most intensive at present.

Ultra cold neutrons (UCN) have been used for various kinds of experiments, for example, neutron electric dipole moment (EDM) measurements, neutron β decay experiments, quantum mechanical tests and surface physics experiments. The measurement of the neutron EDM is one of the most stringent tests of T violation. Many CP-violation theories have been tested with the neutron EDM. Recent topic of the CP violation is a comparison with a baryon asymmetry, which is an asymmetry in abundance between matter and anti-matter in the universe. The existence of *CP*-violation processes is believed to be indispensable for the formation of matter after the big bang. The standard model, which predicts a neutron EDM of 10^{-31} cm can not explain the observed baryon asymmetry, while the baryon asymmetry suggests a much larger EDM of $10^{-26\sim-27}$ cm in a super symmetric model. [1] The present experimental value of the neutron EDM is less than 10^{-25} cm. We have no significant improvement of the accuracy in these 10 years. One of the main reasons for this saturation is the limit of an available UCN density. A breakthrough in the UCN density will improve the accuracy of the neutron EDM, and also open new opportunities for neutron β-decay experiments. Nuclear β-decay coupling constants, G_A and G_V are obtained by the neutron β-decay without the uncertainty of the nuclear structure. According to the CVC theory, G_V dose not change upon the renormalization of the strong interaction, and therefore, is represented by $G_F\ V_{UD}$. G_F is the Fermi coupling constant whose value is obtained precisely in the muon decay. V_{UD}, which is represented as $\cos\theta_C$ is the largest Kobayashi-Maskawa matrix element. θ_C is the Cabbibo angle. The value of V_{UD} has been obtained from nuclear β decays for super-allowed Fermi transitions. However, the value from the β decays contradicts the value obtained from the unitarity relation of Kobayashi-Maskawa matrix elements. Precision experiments of neutron β-decay asymmetry are expected to resolve this discrepancy. The neutron experiments are free from nuclear uncertainty. The accuracy of the neutron polarization is indispensable for the precision experiment. Almost 100% polarization is obtained for UCN, because the temperature of the UCN is very low. An intense UCN source is also indispensable for the precision experiment.

At present, UCNs are obtained upon very cold neutron deceleration by a turbine at the reactor. Here, the UCN density is limited by the Liouville's theorem. The UCN density does not increase upon the deceleration, since the phase-space volume is invariant for this system. A break through is a "superthermal" UCN production in He-II. Neutrons are cooled by phonon excitation in He-II, where large phonon phase-space is used. As a result the new UCN-production method will greatly improve the UCN intensity. The point of neutron cooling is in energy-momentum relations for the neutron and interacting particle. If the interacting particle has the same energy-momentum dispersion curves as the neutron, the energy and momentum is effectively transfer from the neutron to the interacting particle. The transfer efficiency is well explained by a parameter called lethargy ξ, which is approximated by

$$\xi = 2/(M/m + 2/3). \tag{1}$$

M and m are the target-nucleus and neutron mass, respectively. The lethargy is a logarithm of an average energy loss rate for one collision. Free protons or deuterons in 300-K thermal and 20-K cold moderator are used for neutron moderation from MeV to meV regions. Below 20 K, almost all materials freeze and therefore, no free-particle excitation by meV neutrons except phonon excitation. It means the mass M becomes too large to cool down the neutron. Below the cold neutron region, phonon excitation is used for the neutron cooling. The phonon dispersion curve of He-II intersects at the cold neutron region with the neutron dispersion curve. As a result, cold neutrons can be further cooled down to a UCN region through the intersection point. A UCN-production rate, P is obtained by the UCN-production cross section and neutron flux at the intersection point as [2]

$$P = (2/3)\Phi(E_c/k_BT_o)^{3/2}(E_o^*/k_BT_o)^{1/2}\exp(-E_o^*/k_BT_o)[2N\sigma_c\alpha S(k^*)]. \qquad (2)$$

Φ is the thermal-neutron flux. The incident flux is assumed to be in a thermal equilibrium. T_o is a neutron temperature. k_B is the Boltzmann constant. E_o^* and k^* are energy and momentum at the intersection point, respectively. E_c is an average Fermi potential of the bottle. N is a helium nuclear number density. σ_c is the coherent-scattering cross section of ^{4}He. α is $v_n^*/(v_n^* - v_g)$. (v_n^* is the neutron velocity at the intersection point. v_g is the phonon group velocity.) $S(k^*)$ is a He-II form factor, which is obtained by experiments.[3] A steady-state UCN density is obtained by the product of the UCN-production rate and an UCN storage time, τ_s in the bottle. The phonons excited by the cold neutrons defuse away in the He-II. Phonons are also excited by thermal energy. These phonons can excite UCNs to usual neutrons. The process is called up-scattering. The number of phonon is greatly suppressed at low temperature. The phonon up-scattering rate becomes comparable to the neutron β-decay rate at a temperature of 1 K. The UCN has also finite life because of absorption by the nucleus. The absorption rate is obtained as

$$1/\tau_{abs} = N_a\, \sigma_a\, v_n. \qquad (3)$$

N_a is a nuclear-number density and σ_a is an absorption cross section. The UCN storage time is obtained by the reciprocal of the sum of the up-scattering rate and absorption rate. The absorption rate in liquid ^{4}He is zero.

The operation of the superthermal source should be carried out very low temperature to reduce the up-scattering rate, that contradicts the requirement to realize a high intensity UCN source. We need high cold neutron flux near the neutron source center where γ heating is large. In this point of view, the spallation neutron source has great advantage, since it has a lower γ to neutron ratio than the reactor. In the reactor, the configuration of the fuel element and neutron moderator is designed to keep the chain reaction. A large number of neutrons are consumed in the chain reaction. On the other hand, the configuration of the neutron production target and moderator in the spallation source is designed only for neutron source performance. The neutron absorption in the spallation target is small. As a result, a 5 MW spallation source is comparable to the 60-MW research-reactor at Grenoble in the point of the thermal neutron flux. [4, 5] Since γ production is expected to be proportional to the source power, a γ to neutron ratio is small in the spallation neutron source. In addition to this advantage, the γ heating is greatly reduced by placing a γ ray shield, since the spallation source has freedom in the configuration.

The spallation neutron source has another advantage for the UCN production. Neutrons are emitted upon proton beam irradiation. A pulsed operation is rather easy, which will greatly improve background problems. Almost all kinds of radiation promptly emitted from the source upon the proton beam irradiation quickly disappear after switching off the proton beam. The pulsed operation is fairly suitable for high precision experiments, since the background subtraction is essentially important for high precision experiments.

The He-II UCN production was experimentally observed by ILL, KEK and NIST. [6, 7, 8]. The idea of spallation UCN source has been developed for the experiments of the neutron EDM and β decay. [5, 9] A horizontal He-II bottle was proposed for an EDM experiment in liquid helium. A vertical He-II bottle was also proposed for neutron β-decay and other UCN experiments. [10] In the vertical bottle, gaseous phase is separated from liquid phase where UCNs are produced. The He-II bottle is connected to a UCN experimental chamber through a UCN guide as shown in Fig. 1. The three parts work as a UCN bottle. There is no cryogenic window between the UCN production area and experimental chamber, therefore, no UCN extraction loss. A UCN storage time is limited by up-scatterings by impurities at a bottle wall, phonons in liquid helium and helium nuclei in gas. The latter two up-scatterings depend on phonon density and helium atomic flux, respectively, and therefore depend on the He-II temperature. Below 0.8 K, the two up-scattering rates are much smaller than the up-scattering rate at the wall and comparable to the β-decay rate of the neutron.

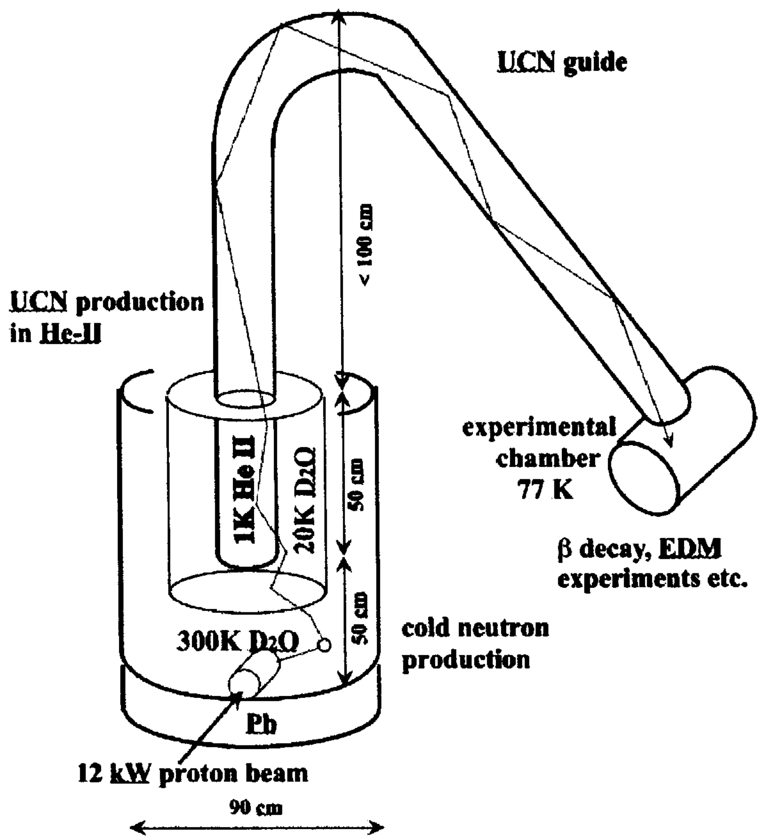

Fig. 1 Vertical He-II bottle for UCN production

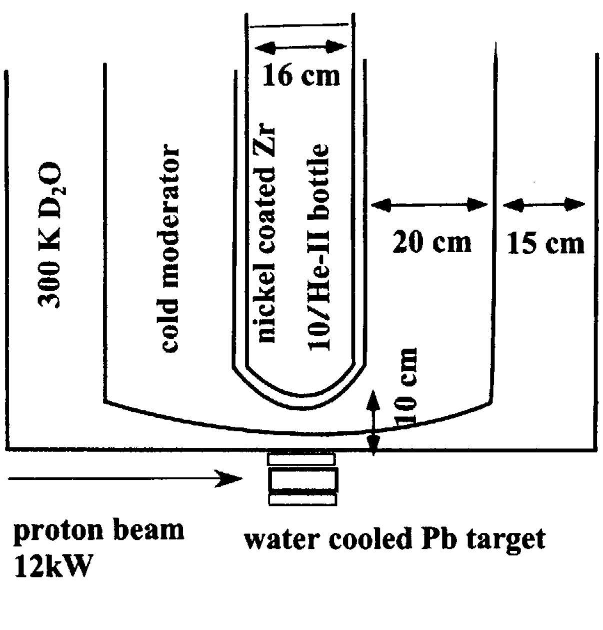

Fig. 2 Target moderator configuration for He-II UCN production.

The configuration of target and moderator is optimized so that large cold neutron flux is obtained in He-II with low γ heating. [11, 12] In Fig. 2, the result of the optimization is shown. Neutron flux at the intersection point is estimated by using the LSC-code which is the Monte Carlo simulation code of Los Alamos. Here cold moderator is assumed to be the 20-K ideal gas which comprises deuteron and oxygen with a nuclear number density ratio of 2 to 1. A UCN production rate is calculated with the neutron flux following the equation of Golub and Pendlebury. [2] The result of the production rate is $10^3/\mathrm{cm}^3$ s in the whole He-II bottle. The volume of the He-II is 10 l. Here, we assume the proton beam power is 12 kW (400 MeV $\times$ 30 μA). If we assume the UCN storage time in the bottle is 100 s, the UCN density becomes $10^5/\mathrm{cm}^5$. The result of the γ heating is 3 W in the He-II bottle. At 20 K, heavy water freezes,

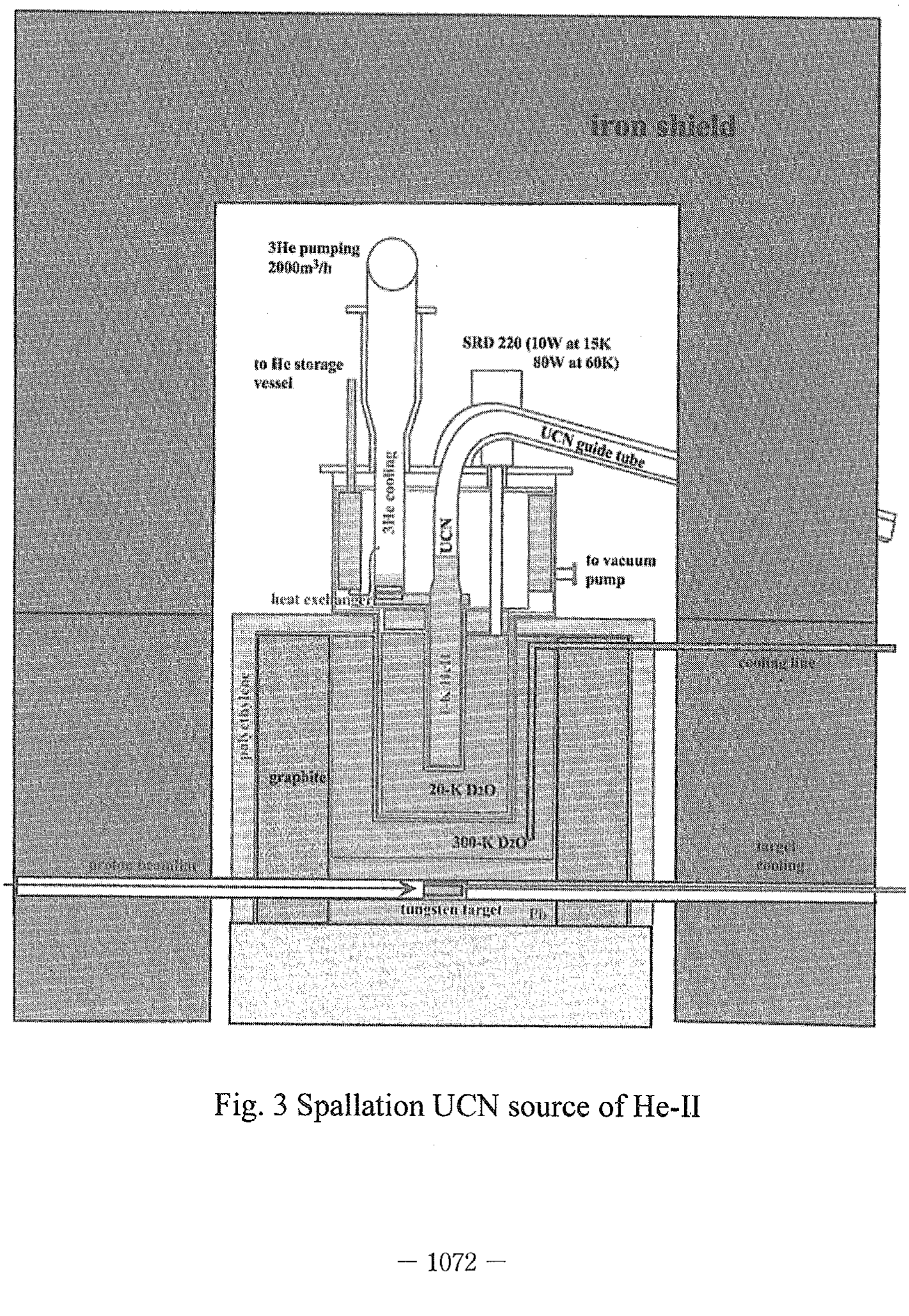

Fig. 3 Spallation UCN source of He-II

therefore, neutron temperature dose not reach the heavy water temperature. If we assume the neutron temperature is 80 K, [13] we should take a reduction factor of 1/8 into account.

The γ heating of 3 W is removed by a usual ^{3}He cryostat through a heat exchanger of fine copper-fins. The heat exchanger was developed for a polarized proton filter for neutron polarization. Liquid ^{4}He was used as coolant for polarizing material, which was cooled by liquid ^{3}He through the heat exchanger. [14] Liquid ^{3}He was removed from a neutron beam line, since the ^{3}He nucleus has strong neutron absorption cross section. A same kind of heat exchanger is used for He-II bottle cooling. A cooling power of 3 W is possible at 0.8 K by usual ^{3}He pumping.

A spallation UCN source configuration is shown in Fig. 3. A UCN production experiment will be carried out in a 400-W-proton (400 MeV $\times$ 1 μA) beam-line at RCNP, Osaka University and then the UCN source will be placed in JAERI-KEK joint project for high intensity proton accelerators.

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