Spallation UCN production for nEDM

Yasuhiro Masuda\textsuperscript{a,*}, Kichiji Hatanaka\textsuperscript{b}, Sun-Chan Jeong\textsuperscript{a}, Shinsuke Kawasaki\textsuperscript{a}, Ryohei Matsumiya\textsuperscript{b}, Kensaku Matsuta\textsuperscript{c}, Mototsugu Mihara\textsuperscript{c}, and Yutaka Watanabe\textsuperscript{a}

\textsuperscript{a}High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
\textsuperscript{b}RCNP, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
\textsuperscript{c}Graduate School of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan

**Abstract**

A new superthermal UCN production in He-II, which is placed in a spallation neutron source, is discussed. In the new UCN source, the production rate is expected to be 200 UCN/cm$^3$/s at a proton beam power of 500 MeV$\times$40 $\mu$A and the UCN maximum energy of $E_c = 210$ neV. The $\gamma$ heating in the He-II can be removed by means of $^3$He pumping according to calculations. For an EDM measurement, UCN are extracted from a He-II bottle through an aluminum window by using a superconducting magnet. The possibility of a $^{129}$Xe magnetometer for the EDM measurement is also discussed.

**Keywords:** UCN; EDM; superfluid helium.

1. Introduction

Ultracold neutrons (UCN) are applied to various kinds of experiments such as neutron EDM (nEDM) measurements. The nEDM has been measured for many years. With the improvements of these measurements, many CP violation theories have been checked and then excluded. The super symmetric theory, which predicts nEDM in the region of $10^{-27}$ e cm, is the target of next generation nEDM measurements. The nEDM measurement
at Grenoble in 2006 is state of the art, which shows an upper limit of $3 \times 10^{-26}$ e cm [1]. The precision is dominated by the statistical error, namely the number of UCN in an EDM measurement cell, which is represented in terms of UCN density. The main systematic error arises from a geometric phase effect (GPE). Many institutes have been developing new generation of UCN sources for increasing the UCN density, and new magnetometers for decreasing the GPE. Here we discuss our approach.

2. Spallation UCN production in He-II

2.1. Advantage of He-II spallation UCN source

We have placed superfluid helium (He-II) in a cold neutron source for UCN production as shown in Fig. 1 (a). Cold neutrons become UCN upon phonon excitation. The UCN production rate $P$ is represented in terms of the cold neutron flux and the cross section. The cold neutron flux is much higher in the cold source than in a cold neutron guide as shown in Fig. 1 (b), where the flux is limited by the solid angle of the guide. The number of UCN in a UCN bottle increases with a time constant $\tau$, which is the UCN lifetime, as shown in Fig. 2. The UCN density $\rho$ in the bottle asymptotically approaches $P \tau$. Solid deuterium can be also used for UCN production as shown in Fig. 1 (c). He-II has a smaller UCN production cross section than solid deuterium, but a longer lifetime. The UCN are extracted from the He-II and then diffuse to an experimental bottle through a UCN guide. The UCN density in the bottle also depends on an additional factor $\varepsilon$, which is related to extraction and dilution. He-II has advantage in the factor $\varepsilon$: UCN can be extracted without loss from deep points in He-II, because UCN have a very long mean free path in He-II. We can increase the UCN production volume so that the dilution effect becomes small upon UCN diffusion to the experimental bottle.

2.2. Geometry of He-II in spallation neutron source

We constructed a prototype UCN source of He-II in a spallation neutron source at RCNP as shown in Fig. 3 [2, 3]. A He-II bottle was vertically inserted into a cold moderator of 10 K D$_2$O, which was surrounded by a thermal moderator of 300 K D$_2$O. UCN was produced upon a proton beam impingement of 390 MeV $\times$ 1 $\mu$A, which diffused through vertical and horizontal UCN guides to a UCN detector.
valve. After a build-up time, this valve was opened for UCN detection. UCN were accelerated in gravity to pass an aluminum window at the detector. We have estimated the UCN density at the valve by using the UCN count rate. We obtained a density of 26 UCN/cm³ at a UCN maximum energy of $E_c = 90$ neV [3]. We obtained a UCN lifetime of 81 s. The production rate was estimated to be 4 UCN/cm³/s at $E_c = 210$ neV.

We are constructing the second-generation UCN source of He-II as shown in Fig. 4. A He-II bottle is horizontally inserted into the spallation neutron source so that the number of UCN produced upon the proton beam impingement increases. In this horizontal arrangement, we need a cryogenic window or a ramped UCN guide to confine the He-II in the UCN source volume. We have placed a UCN valve so that UCN are confined in the source volume during UCN production. After UCN production this UCN valve is opened so that UCN go to an experimental bottle, for example an EDM cell, through the cryogenic window. The magnetic field of a superconducting coil compensates the Fermi potential of the window material. UCN of one spin state pass the window. UCN of the other spin state are completely repelled. Polarized UCN diffuse to the EDM cell through a rotary valve. After Ramsey resonance, UCN are directed to a polarization analyzer by this rotary valve.

The polarized UCN density in the EDM cell can be estimated by means of a formula, $\rho = P \tau \varepsilon$. By using comparison between dilution factors in Fig. 3 and Fig. 4 geometries, and the UCN density obtained in the prototype source, the polarized UCN density in the EDM cell is estimated to be 26 UCN/cm³. Here the UCN lifetime is increased by a factor 2. If we use the phonon limited UCN lifetime at a temperature of 0.8 K [4] and the UCN lifetime in a baked UCN bottle [5], the UCN lifetime in the production volume becomes 170 s.

2.3. Proton beam power and heating in He-II

The UCN production rate $P$ is proportional to the proton beam power, which is limited by $\gamma$ heating in the He-II bottle. We have estimated the $\gamma$ heating by means of a Monte
Carlos simulation code, PHITS. We will increase the proton beam power up to 390 MeV×10 µA or 500 MeV×40 µA, where the γ heating becomes 1 W or 5.2 W. If we include β heating, the value will be 1.3 W or 6.8 W. The heat in the He-II can be removed upon 3He evaporation in a 3He cryostat via a heat exchanger. The cooling power of the 3He cryostat is estimated to be 8 W in terms of the latent heat of 3He vaporization (33 J/mol at 0.7 K), the 3He vapor pressure (1.5 Torr), the 3He pumping power (10000 m³/h), the gas constant and the temperature at the pump.

The UCN production rate at the power of 500 MeV×40 µA is estimated to be 200 UCN/cm³/s at \(E_c = 210\) neV.

The statistical error can be reduced by a factor of much more than 10.

3. Geometric phase effect

The systematic error at the Grenoble measurement was dominated by a geometric phase effect (GPE) for the \(^{199}\)Hg magnetometer. The GPE arises from the motion of the \(^{199}\)Hg atom in the EDM cell which is used as a magnetometer [6, 7]. The \(^{199}\)Hg spin sees transverse magnetic fields, \((\partial B_0/\partial z)r/2\) and \(E \times v/c^2\), which rotate upon the motion. The effect of these rotations is represented in terms of time dependent perturbations, namely Dyson series [8].

The position-velocity correlation in the \(E\) dependent term is suppressed during random walks, if we increase the atomic number density. This will be possible for \(^{129}\)Xe atoms, because its neutron cross section is small. The suppression factor is represented in terms of the ratio of the diffusion rate to the Larmor frequency as \([v_{xy}\lambda/(2\pi\omega_L)^2]/(\omega_L/2\pi)^2\) [6], which becomes \([8\ Hz/120\ Hz]^2\) at a \(^{129}\)Xe pressure of 3 mTorr, an EDM cell radius of 25 cm, and a magnetic field of 10 µT. The mean free path \(\lambda\) is obtained from a data book [9]. At the 3 mTorr, we can apply an electric field of 10 kV/cm for a 10 cm gap distance assuming the extrapolation of the Pachen curve in Ref. [10]. The GPE is reduced to \(4\times10^{-28}\) e cm at a magnetic field gradient of 1 nT/m. This small field gradient is realized, if we use the neutron to \(^{129}\)Xe NMR frequency ratio.

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References

[1] C. Baker, D. Doyle, P. Geltenbort, K. Green, M. van der Grinten, P. Harris, P. Iaydjiev, S.N. Ivanov, D.J.R. May, J.M. Pendlebury, J. Richardson, D. Shiers, and K. Smith, Phys. Rev. Lett. 97, 131801 (2006).
[2] Y. Masuda, T. Kitagaki, K. Hatanaka, M. Higuchi, S. Ishimoto, Y. Kiyanagi, K. Morimoto, S. Muto, and M. Yoshimura, Phys. Rev. Lett. 89, 284801 (2002).
[3] Y. Masuda, K Hatanaka, S.C. Jeong, S. Kawasaki, R. Matsumiya, K. Matsuta, M. Mihara, and Y. Watanabe, Phys. Rev. Lett. 108, 134801 (2012).
[4] R. Golub, C. Jewell, P. Ageron, W. Mampe, B. Heckel, and I. Kilvington, Z. Phys. B 51, 187 (1983).
[5] P. Ageron, W. Mampe and A.I. Kilvington, Z. Phys. B 59, 261 (1985).
[6] J. Pendlebury, W. Heil, Y. Sobolev, P. Harris, J. Richardson, R. Baskin, D. Doyle, P. Geltenbort, K. Green, M. van der Grinten, P. Iaydjiev, S. Ivanov, D. May, and K. Smith, Phys. Rev. A 70, 032102 (2004).
[7] S. Lamoreaux and R. Golub, Phys. Rev. A 71, 032104 (2005).
[8] Y. Masuda, K. Asahi, K. Hatanaka, S.C. Jeong, S. Kawasaki, R. Matsumiya, K. Matsuta, M. Mihara, and Y. Watanabe, Phys. Lett. A 376, 1347 (2012).
[9] W.M. Haynes, 2010. CRC Handbook of Chemistry and Physics, 91st Edition. CRC Press/Taylor and Francis, Boca Raton, pp. 6-56.
[10] IEEE Trans. PAS-88 (1969) 100.