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Production of Ultra Cold Neutrons by a Doppler Shifter with Pulsed Neutrons at J-PARC


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Abstract. Ultracold neutrons (UCNs) are neutrons whose kinetic energy is around a few hundred nanoelectronvolts. Neutrons with such small kinetic energy can be trapped in a material vessel or magnetic fields. Because of these unique characteristics, UCNs are used for some important experiments of fundamental physics. The Doppler shifter is a device to produce UCN by slowing them down by the reflection on a mirror moving with half of the velocity of incoming neutrons. A Doppler shifter using a quadruple-stack of monochromatic supermirrors that reflects neutrons with a velocity around 68m/s [1, Hino et al.(2010)] was fabricated, and operated with a pulsed neutron source of J-PARC. An important feature of the Doppler shifter is the use of a pulsed neutron beam. Unlike in continuous neutron beams, the neutron velocity can be selected by choosing a time slice in a pulsed neutron bunch. Thus the UCN production improves by ~80 times in the case of J-PARC. We successfully produced the UCNs by the Doppler shifter: the measured UCN production rate is consistent with the simulations.
1. Introduction

Ultracold neutrons (UCNs) are neutrons whose kinetic energy is around a few hundred nanoelectronvolts. Neutrons with such small kinetic energy can be trapped in a material vessel, or potential well of magnetic and gravitational fields. Because of these unique characteristics, UCNs are used for numbers of important experiment of fundamental physics.

A Doppler shifter is a device to produce UCNs by reflecting neutrons by moving materials [2–5]. If the reflector is moving in the same direction as the beam with half of the velocity of the neutron, the velocity in a laboratory system can be slowed down to be zero. Slowing down of neutrons by a Doppler shifter doesn’t change the phase space density of neutron beam because the interaction is a conservative force (the Liouville's theorem) unlike by moderators. Thus, an intrinsic UCN density produced by a Doppler shifter is the same as in the initial neutron beam (in the case of perfect conversion). The phase space density, \( n(\nu) \), for a continues beam with the Boltzmann distribution is described as

\[
    n(\nu) = \phi \frac{1}{2\nu_T^2} e^{-\frac{\nu}{\nu_T^2}}^2 \tag{1}
\]

where \( \phi \) is neutron flux on a surface of a moderator, \( \nu_T \) is a mean velocity corresponding to the neutron temperature, \( T \). In the case of J-PARC, \( \phi = 2.1 \times 10^{13} \text{ cm}^{-2}\text{s}^{-1} \) for 1MW proton beam power [6,7], \( T = 57 \text{ K} \), which means that \( \nu_T = 969 \text{ m/s} \). Thus, its time averaged neutron density is 0.033 cm\(^{-3}\)(m/s\(^{-3}\)).

The phase space density of a neutron beam at a pulsed neutron source is concentrated in time. Thus the density in phase space is increased \( 1/f \Delta \tau \) times compared with a continues neutron source, where \( f \) is the frequency of pulses and the \( \Delta \tau \) is the effective pulse width [3]. The phase space density of the neutron beam at J-PARC (\( f=25 \text{ Hz}, \Delta \tau =500 \mu\text{sec} \) for neutrons with velocity of 136 m/s) is 2.6 cm\(^{-3}\)(m/s\(^{-3}\)), which is 80 times greater than at a continuous neutron beam with the same flux. The phase space density can be converted to the UCN density, \( \rho_{\text{UCN}} \), as

\[
    \rho_{\text{UCN}} = n_{\nu}^4 \pi v_{\text{UCN}}^3 = 3.5 \times 10^{-3} \frac{\text{UCN}}{\text{cm}^3} \tag{2}
\]

where \( v_{\text{UCN}} \) is the critical velocity of UCN and taken as 6.8 m/s in this paper. Thus, a Doppler shifter at an intense, pulsed neutron source has a possibility to produce pulsed UCNs with very high phase space density.

In previous work, a Thermica crystal was used to reflect neutrons with velocity of 400 m/s [3,4]. However, there were some difficulties in the fabrication of the crystal reflector as the mosaic spread of the crystals was too small. In another work [5] intercalated graphite (iHOPG) was used for the reflection crystal which is not for UCN production, but for UCN up-scattering. The reflectivity of the crystal was more than 80% and the mosaic spread of the intercalated graphite was 5.5°. In this paper, we report about UCN production by a new Doppler shifter with a pulsed neutron source in J-PARC.

We adopted a stack of monochromatic supermirrors with a large reflection momentum which was newly developed at KURRI [1]. Neutrons reflected from the supermirror have directions perpendicular to the mirror surface unlike the randomized directions produced by mosaic crystals. It is an advantage to convert a monochromatic beam with a small divergence to UCNs.

In this experiment, we used the monochromatic supermirror with a large reflection momentum of 2.2 nm\(^{-1}\), this is the largest reflection momentum available from any supermirror in the world at present. The mirror reflects neutrons with velocity of around 68 m/s at rest, thus incoming neutrons with the velocity of 136 m/s (called very cold neutrons (VCN)), can be used for the slowing down. Because of the relatively slow neutron velocity, the Doppler shifter can be designed as compact and removable.

2. Experimental setup and apparatus

The experiment has been performed at beamline BL05 in J-PARC/MLF [8,9]. The beam line is used for fundamental studies and has three beam branches. The Doppler shifter was set up on the
unpolarized beam branch because that produces the most intense neutron beam. The scheme of the experimental setup is shown in Figure 1. The branch is inclined upward 2.8°. 4 monochromatic supermirrors (VCN mirrors hereafter) are set to extract only the VCN component in order to reduce background. The reflecting momentum of the VCN mirrors is 0.65 nm\(^{-1}\) with a width of ~10% \cite{10}. The set of VCN mirrors is tilted by angle of 10° from the incident beam, so that the VCNs are reflected downward by 18.6°. The set of mirrors is shielded by surrounding B\(_4\)C resin to reduce the background of neutrons and gammas. The Doppler shifter is placed 1.0 m downstream of the VCN mirrors, i.e. 17.1 m from the moderator. The VCN beam passes through the Doppler shifter and is recorded by a position sensitive detector \cite{11} at 17.8 m, which is shown as a VCN detector in Figure 1. A UCN detector is mounted on the top of the Doppler shifter. The distance from the center of the Doppler reflector to the window of the UCN detector is 241 mm, so that the longitudinal velocity of Doppler shifted neutrons can be measured by the time-of-flight (TOF) method. The cross section of the UCN beam is 82 mm for the VCN beam direction and 57 mm for the horizontal direction. Parameters of the apparatus are summarized in Table 1.

![Figure 1. A drawing of the experimental setup of the Doppler shifter and other devices.](image)

2.1. Neutron beam

2.1.1. Cold neutrons and VCNs from J-PARC/MLF BL05

The pulsed neutron source of J-PARC/MLF has three cold moderators; BL05 sees the coupled moderator. The neutron beam from the moderator is divided into three branches by supermirror benders and transported to the exit of the unpolarized beam branch passing through vacuum guide covered by the neutron absorber of 4 m in length. Neutron spectra measured at the exit of this branch are shown in Figure 2. A spectrum was measured to longer wavelengths by using intervals between neutron pulses due to operation for Main Ring of J-PARC. The spectra can be fitted by the Boltzmann distribution with attenuation proportional to the wavelength, described as

\[
\phi(\lambda) = \frac{4h^3}{m^3\lambda^4} \left( \frac{m}{2\kappa b^2} \right)^{\frac{3}{2}} \exp \left( -\frac{h^2}{2m\kappa b^2} - a\lambda \right),
\]

where
where $h$ is the Planck constant, $m$ is the neutron mass, $k_B$ is the Boltzmann constant, $T$ is the temperature, $\lambda$ is the neutron wavelength, and $a$ is an attenuation coefficient. $T = 57.3$ K, which was a calculated value by a simulation of the moderator [6,7], is used here. The attenuation coefficient, $a$, was defined as 0.80 nm$^{-1}$ by fitting, which means that the phase space density is reduced by 45% for 1 nm in wavelength.

2.2. Doppler shifter

2.2.1. The reflection mirrors of Doppler shifter
Monochromatic supermirrors, which can reflect around 2.2nm$^{-1}$ (68 m/s), are used for the reflector of the Doppler shifter. The mirrors were made by an ion-sputter at KURRI on Si substrate of 0.3 mm thickness. The reflectivity for a single mirror is ~20% with width of 10%, which is 2 times larger than the Thermica crystal [3]. Stacking a number of such mirrors can increase the total reflectivity, because the VCNs that cannot be reflected and transmitted by just a single mirror, can be reflected by other mirrors. We use a quadruple stack of the mirrors, whose reflectivity is 40% [1]. The reflectivity spectrum of the reflector is shown in Figure 3.

Figure 2. Neutron spectra of the unpolarized beam branch of BL05 at J-PARC/MLF.

Figure 3. The reflectivity of a quadruple stack of monochromatic supermirrors used for the reflector of the Doppler shifter.

2.2.2. The Rotor of the Doppler Shifter
The reflector is mounted on an edge of an aluminium blade. Its radius to the mirror center is 325 mm. The blade is kept in a vacuum chamber in order to avoid air resistance and UCN losses, and rotated by a servomotor placed outside of the vacuum chamber through a magnetic-fluid seal. The chamber is evacuated to less than 40 Pa during the operation. The rotation speed can be set to between 0 and 3000 rpm. In the present experiment, the rotor was operated with 2000 rpm (30 msec cycle), so that the reflector velocity in the laboratory system was about 68 m/s, which is same as the reflection velocity of the reflector. The pulsed beam frequency is 25 Hz, thus the phases of the beam and the rotor are matching every 120 msec. The phase of the rotor was adjusted to the beam timing by using a resolver of the servomotor, and the deviation of the phase was 0.15° peak to peak, which corresponds to 0.8 mm in the position of the reflector.

2.3. Detectors and DAQ
A proportional gas counter (UCN DUNia-10 FLNP, JINR) was used for the UCN detector. The detector is filled with 1.3 kPa of $^3$He, 1.1 kPa of CH$_4$, and 110 kPa of Ar. A window of the UCN detector is made of Al of 100 µm thickness, whose critical potential is 54 neV [12]. Thus, the detector
is insensitive to UCNs with velocity less 3.2 m/s. The detection efficiency is the product of the transmission efficiency of Al window and the reaction efficiency of the detector, described as

\[ e = \exp(-N_A \sigma_{Al}(L_{Al}))(1 - \exp[-N_{3He} \sigma_{3He} L_{3He}]) \]  

where \( N_s \) is the atomic number density, \( \sigma_s \) is the cross section, and \( L_s \) is the length for each subscript. The reaction efficiency of \(^3\text{He}\), which is known to follow the 1/\( v \) law, was measured by comparing counting rates for cold neutrons with a “thick” \(^3\text{He}\) gas detector. By fitting the ratio of counting rates of two detectors from 0.2 nm to 0.8 nm, we obtained the detection coefficient of the UCN detector as a function of wavelength \( \lambda \):

\[ N_{3He} \sigma_{3He} L_{3He} = N \sigma_{3He} (\lambda_0) \frac{\lambda}{\lambda_0} = (3.11 \pm 0.04) \cdot 10^{-2} \text{ [nm]} \]  

We used transmission efficiency of Al foil measured by A.Steyerl and H.Vonach [13]. The cross section of Al for 10 m/s neutrons consists of absorption cross section of 50.0 \( \pm \) 1.5 barn and inelastic cross section of 9.2 \( \pm \) 1.8 barn. The wavelength dependence was calculated using equation (1) in [13]. Using Eq.(4) the detection efficiency was calculated to be 78 \( \pm \)1% for 6.8 m/s neutrons (58 nm). Its detection area is I.D. 90 mm, so that all neutrons from the Doppler shifter can be accepted. Note that gamma-rays had been discriminated by the pulse heights.

**Table 1. Parameters for the experimental apparatus**

<table>
<thead>
<tr>
<th>Parameters for the neutron beam</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beamline</td>
<td>J-PARC/MLF BL05, Unpolarized branch</td>
</tr>
<tr>
<td>Beam power</td>
<td>120 kW</td>
</tr>
<tr>
<td>Repetition</td>
<td>25 Hz</td>
</tr>
<tr>
<td>Neutron flux</td>
<td>( 1.1 \times 10^7 \text{ cm}^{-2}\text{s}^{-1} )</td>
</tr>
<tr>
<td>Neutron flux in 2.74–3.34nm</td>
<td>( 2.4 \times 10^3 \text{ cm}^{-2}\text{s}^{-1} )</td>
</tr>
<tr>
<td>Beam size (vertical)</td>
<td>55 mm</td>
</tr>
<tr>
<td>Beam size (horizontal)</td>
<td>45 mm</td>
</tr>
<tr>
<td>Beam divergence (vertical)</td>
<td>13.1 mrad</td>
</tr>
<tr>
<td>Beam divergence (horizontal)</td>
<td>10.7 mrad</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Parameters for the rotor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius to mirror center</td>
<td>325 mm</td>
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<tr>
<td>Rotation speed</td>
<td>2000 rpm</td>
</tr>
<tr>
<td>Mirror size</td>
<td>35 mm (horizontal) ( \times ) 30 mm (vertical)</td>
</tr>
<tr>
<td>Mirror speed</td>
<td>64.9 m/s(inner), 68.1 m/s(center), 71.2 m/s(outer)</td>
</tr>
<tr>
<td>Phase stability</td>
<td>0.15° (peak to peak)</td>
</tr>
<tr>
<td>Distance from the source to the reflector</td>
<td>17.10 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters for the reflector</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflector type</td>
<td>Monochromatic supermirror</td>
</tr>
<tr>
<td>Number of mirrors in a stack</td>
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</tr>
<tr>
<td>Reflecting momentum in rest system</td>
<td>2.16 nm(^{-1})</td>
</tr>
<tr>
<td>Reflecting velocity in rest system</td>
<td>136 m/s</td>
</tr>
<tr>
<td>Reflectivity by a stacked mirror</td>
<td>40%</td>
</tr>
<tr>
<td>FWHM of reflection peak</td>
<td>10%</td>
</tr>
</tbody>
</table>
A position sensitive detector [11] with ZnS:Ag/LiF scintillator [14] was used to measure VCNs transmitted through the Doppler shifter. It was used to adjust the tilting angle of VCN mirrors and the rotation phase of the Doppler shifter. The efficiency of VCN detector was estimated 85% for VCN of 3.0 nm.

Data from the detectors were taken by an ADC/TDC module with proton timing pulses which were used for TOF analysis. The time resolution of the DAQ was 1 µsec. Large pulse height events were observed simultaneously with proton pulses - these events were omitted from the analysis.

3. Experimental results

3.1. Transmitted VCN

The TOF spectra at the VCN detector are shown in Figure 4. The velocity of VNCs is 136 m/s so that VCNs are expected to be detected 131 msec after the proton pulse, which corresponds to 11 msec in the 4th frame of the neutron pulses of 25 Hz (40 msec). A dip measured at 10-11 msec was caused by the reflection of the Doppler mirror. The phase of the rotor was adjusted to make the dip to be a certain position in the TOF spectrum to reflect VCNs with 136 m/s. The reduction rate of the dip was ~40%, which was consistent with the reflectivity of the Doppler mirror. The phase of the beam pulse and the rotor matched every 120 msec. Three spectra with phase differences of 0°, 120°, and 240° are shown in Figure 4. Other dips were observed in every 10 msec due to phase differences. The total neutron count on the VCN detector was 13 kcps at 120 kW.

![Figure 4](image)

**Figure 4.** TOF spectra of VCN transmitted the Doppler shifter.

3.2 Doppler shifted neutrons

The TOF spectrum of the Doppler shifted neutrons is shown in Figure 5, where the distance from the reflector center to the detector surface was 241 mm. The zero point of the TOF was set to a moment when VCN and the Doppler mirror were crossing. The solid and dashed lines show spectra with the mirror rotating and with the mirror stopping on the VCN path to estimate the background, respectively. A significant peak was observed from 10 to 60 msec in the TOF caused by the rotation. A small peak observed around 45 msec was caused by reflection of the “next” rotation of the mirror.

A spectrum of the Doppler shifted neutrons in a unit of wavelength is shown in Figure 6 with a Monte Carlo simulation [10], where events with the static mirror in Figure 5 were subtracted as background. The total count rate on the UCN detector was 1.07 ± 0.05 cps at 120 kW. We adopted an error of 5% as count rate caused by fluctuation of proton beam power. The expected neutron count by the simulation...
was 1.2 cps so that the observation and the simulation agree to within 11%. According to the simulation, the content of UCNs in the spectrum which have longer wavelength than 58 nm (6.8 m/s) was 28%. It means that the UCN count rate on the detector was 0.30 cps.

4. Discussion and outlook

4.1. UCN density from the phase space

The UCN intensity reaches 0.30 cps with 120 kW of beam power. We can calculate the UCN density in the same manner as reference [4]. By correcting for the detection efficiency for UCNs of 78%, the UCN intensity was 0.046 UCN/pulse. The solid angle of detected UCNs was $8.0 \times 10^{-2}$ str. This yields that 0.27 UCN exist in the swept volume if the phase space was totally filled by neutrons. The swept volume was estimated as 32 cm$^3$ by multiplying the reflector size of $3 \times 3$ cm$^2$ and effective sweeping length of 3.6 cm, which was deduced by the FWHM of the interacting time of 0.4 ms as a result of the simulation. Finally, the UCN density of the Doppler shifter calculated from the phase space density was 0.22 UCN/cm$^3$ with 120 kW of the proton beam power. The phase space density of VCN at 120 kW was 9.7 UCN/cm$^3$ calculated by eq.(2), (3), the transporting efficiency of beam line, and reflectivity of VCN mirrors. Thus, UCN conversion efficiency in phase space by the Doppler shifter was 2.2%.

4.2. Future upgrade

The VCN intensity after the Doppler shifter is 13 kcps. The divergent VCN beam is collimated by a vacuum guide with neutron absorber located at 12 to 16 m from the moderator. The vertical and horizontal divergences of the VCN beam are 13.1 and 10.7 mrad, which correspond to transverse velocities of 1.8 and 1.5 m/s, respectively. Because the horizontal velocity is conserved, the phase space of the UCN has a room to be filled up to 6.8 m/s. Thus, UCN intensity can be increased by increasing the VCN divergence. Simulations show that by installing a supermirror guide instead of the vacuum guide in the beam branch one can increase VCN and UCN intensities by factor of about 30.

5. Conclusions

A Doppler shifter with supermirrors having large reflection momentum was fabricated. A quadruple-stack of the monochromatic supermirrors with reflectivity of 40% and width of 10% for reflection momentum of about 2.2 nm$^{-1}$ was used as the reflector. The result of the UCN production experiment

![Figure 5](image1.png) **Figure 5.** The TOF spectra of the reflected neutrons detected by the UCN detector: The reflector rotating (solid); the reflector at rest on the VCN path (dashed).

![Figure 6](image2.png) **Figure 6.** Wave length spectra of longitudinal component of the Doppler shifter neutrons (solid) and Monte Carlo calculation (dashed).
at BL05 beamline in J-PARC/MLF was a measured intensity of the Doppler shifted neutrons of 1.07±0.05 cps at 120 kW that within 11% is consistent with the Monte-Carlo simulations.

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