Efficient extraction of a collimated ultra-cold neutron beam using diffusive channels

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Abstract

We present a first experimental demonstration of a new method to extract a well-collimated beam of ultra-cold neutrons (UCN) from a storage vessel. Neutrons with too large divergence are not removed from the beam by an absorbing collimation, but a diffuse or semidiffuse channel with high Fermi potential reflects them back into the vessel. This avoids unnecessary losses and keeps the storage time high, which may be beneficial when the vessel is part of a UCN source with long buildup time of a high UCN density.

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Many next-generation ultra-cold neutron sources employ conversion of cold neutrons in solid deuterium or superfluid helium down to the ultra-cold regime $E_{\text{UCN}} \leq 250$ neV (see, e.g., refs. [1, 2, 3, 4] and the book [5]). In a superthermal source UCN are accumulated in a storage vessel to build up a high UCN density, from where they are extracted continuously or periodically, depending on the specific experiment. The saturated UCN density is given by

$$\rho_{\text{UCN}} = P \tau_{\text{tot}}, \quad (1)$$
where $P$ is the production rate per unit volume and $\tau_{\text{tot}}$ the storage lifetime of the vessel. Any aperture reduces the storage time $\tau_{\text{tot}}$ and thus the maximum density, which in turn reduces the extracted flux. If an experiment requires only a UCN beam with narrow divergence, extraction without loosing unwanted neutrons would be advantageous. This can be realised using a channel made of rough walls of high Fermi potential. Neutrons scattered from the rough surface will start a diffuse motion inside the channel and, for a sufficiently long channel, be scattered back into the primary volume, unless they decay. For definition of a beam in one dimension, we employ a channel made from two parallel surfaces, either both rough or one rough the other specular (called diffuse and semidiffuse). 

A diffuse channel of height $h$ and length $l$ will transmit a beam with a divergence of $p_\perp \leq p_{||} \cdot h/l$. In a horizontal configuration of same height with a specular lower surface the angle of divergence is doubled, and neutrons with $E_\perp \leq mgh$ will also be transmitted. Such a semidiffuse horizontal channel might be ideal for the spectrometer GRANIT [6], currently being developed to measure transitions between gravitationally bound quantum states of UCN above a mirror. Losses may appear inside the channel and due to outward diffusion of neutrons.

The storage time $\tau_{\text{tot}}$ of UCN in a vessel with an extraction channel can be described by

$$ 1/\tau_{\text{tot}} = 1/\tau_{\text{vol}} + 1/\tau_{\text{ch}}, \quad (2) $$

where $\tau_{\text{vol}}$ is the storage time of the vessel without extraction channel. The loss rate $1/\tau_{\text{ch}}$ depends on the probability $r$ that a UCN entering the channel becomes reflected back into the vessel (in the following $r$ is simply called "reflectivity") and the cross section $A_{\text{ch}}$ of the channel,

$$ 1/\tau_{\text{ch}} = (1 - r) \bar{v}_{\text{UCN}} A_{\text{ch}} / 4V, \quad (3) $$

$V$ is the storage volume and $\bar{v}_{\text{UCN}}$ the mean UCN velocity. The reflectivity $r$ can be deduced experimentally from comparison of the semidiffuse (or diffuse) configuration with the specular at same height. It can not be directly deduced from the transmission because of unknown losses due to wall absorption and up-scattering. A first experiment was carried out at the ultra-cold neutron installation PF2 [7] of the Institut Laue Langevin, Grenoble.
Figure 1: Experimental set-up (not to scale): UCN pass through the beam guide (a) and a switch (b), which is used to either fill the storage volume (V) or empty it into the "storage" detector (f). An UCN tight shutter (c) is used to lock off the storage volume. The extraction channel (d) is made of two rectangular pieces of sapphire (w: 80 mm, l: 30 mm, h: 8 mm), polished on one and rough on the other side. They are externally connected to the Fomblin coated storage volume. The "transmission" detector (e) is fixed to the volume via an aluminium tube (t) (ø 90 mm, length: 80 mm) which is covered with a PET foil to eliminate randomly scattered UCN.

The set-up is shown in Fig. 1.

The channel was made from sapphire plates which have a Fermi potential larger than that of the Fomblin grease coating of the storage vessel. Each of the plates has a rough and a specular surface. Thus it is possible to measure with two rough (double diffuse, dd) or two specular (sp) surfaces, or with the semidiffuse (sd) configuration with a rough upper and a specular lower surface. Channel heights 100 µm, 500 µm and 1000 µm, defined by spacers, were used in the sd and sp configurations, the height of 1000 µm also in the dd configuration. A position sensitive CASCADE-U detector [8] detected the UCN transmitted through the channel. Its readout structure consists of 30 horizontal stripes covering a height of 90 mm. The stripes were merged to six larger zones with 30, 9, 9, 9, 9, and 24 mm height, respectively. The channel setup could be manually changed by opening the vacuum on the side of the transmission detector. The horizontal alignment
was checked with a precision spirit level. Thereafter the whole setup was evacuated below $5 \times 10^{-4}$ mbar.

| channel height [µm] | storage time $\tau_{\text{tot}}$ [s] | channel type | reflectivity |
|---------------------|----------------------------------|--------------|--------------|
| 100                 | 110.2 ± 2.2                     | sd           | 0.98$^{+0.02}_{-0.16}$ |
| 100                 | 94.7 ± 1.7                      | sp           | 0.39 ± 0.06  |
| 500                 | 90.1 ± 0.8                      | sd           | 0.35 ± 0.05  |
| 500                 | 80.5 ± 1.6                      | sp           |              |
| 1000                | 80.9 ± 1.3                      | sd           |              |
| 1000                | 70.8 ± 1.2                      | sp           |              |
| 1000                | 92.4 ± 1.8                      | dd           | 0.65 ± 0.05  |
| 0                   | 110.9 ± 2.3                     |              |              |

**Table 1**: Storage times of the Fomblin coated volume for different measured channel heights and types: semidiffuse (sd), specular (sp), and double diffuse (dd). The reflectivity is given relative to the specular channel of same height.

For each configuration, we measured during an emptying time of 200 s the number of UCN remaining in the vessel, having stored them with the shutter C closed for a holding time of 50, 100, 150, 200, 250, or 300 s. After correcting each data point for losses during counting, the storage time was obtained from a fit of a single exponential decay to the data. The results for the different configurations are listed in Table 1. The channel height 0µm corresponds to the closed volume (the two plates are placed on top of each other without spacer). This yields the unperturbed storage time $\tau_{\text{vol}}$. From equations (2) and (4), replacing $\tau_{\text{ch}}$ by $\tau_{\text{sp}}$ for the specular, and by $\tau_{\text{sd}}$ for the semidiffuse channel, the reflectivity is given as

$$r = 1 - \frac{\tau_{\text{sp}}}{\tau_{\text{sd}}},$$

where we have assumed $r = 0$ for the specular channel. For all channel heights we observed an increase of the storage lifetime of the semidiffuse configuration with respect to the specular one. For a channel height of 100 µm the reflectivity amounts to $r \geq 80\%$. This channel does not reduce the storage time of our vessel any more.

Figure 2 shows the vertical distribution of transmitted UCN. For the same channel height, the total transmission decreases with addition of roughness to the surfaces. Furthermore, the intensity distribution shows an attenuation of UCN with larger vertical momentum if the surfaces are changed from specular to semidiffuse, and to completely diffuse
Figure 2: Vertical distribution of transmitted neutrons for the 1000 µm channel 50 mm behind channel exit. The channel exit window was in between detection zone 2 and 3. Zone 1 is on the top, whereas zone 6 is on the bottom. Furthermore, zone 1 and 6 had larger active areas (see text). The resolution is not sufficient to resolve the collimated beam.
configuration. The observed spatial distribution demonstrates the collimating properties of the semidiffuse and diffuse channels.

In summary, we have shown that one may continuously extract, by a semidiffuse or diffuse channel, a well-collimated beam of ultra-cold neutrons from a vessel without significantly diminishing its storage time. We measured UCN reflectivities from the channel opening better than 80% in this first experimental test of a new method to be explored further in future experiments.

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