First ultracold neutrons produced at TRIUMF

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We installed a source for ultracold neutrons at a new, dedicated spallation target at TRIUMF. The source was originally developed in Japan and uses a superfluid-helium converter cooled to 0.9 K. During an extensive test campaign in November 2017, we extracted up to 325,000 ultracold neutrons after a one-minute irradiation of the target, over three times more than previously achieved with this source. The corresponding ultracold-neutron density in the whole production and guide volume is 5.3 cm$^{-3}$. The storage lifetime of ultracold neutrons in the source was initially 38 s and dropped to 25 s during the eighteen days of operation. During continuous irradiation of the spallation target, we were able to detect a sustained ultracold-neutron rate of up to 1500 s$^{-1}$.

Simulations of UCN production, UCN transport, temperature-dependent UCN yield, and temperature-dependent storage lifetime show excellent agreement with the experimental data and confirm that the ultracold-neutron-upscattering rate in superfluid helium is proportional to $T^7$.

Keywords: Ultracold neutrons, spallation, superfluid helium

I. INTRODUCTION

Ultracold neutrons (UCNs) with energies of a few hundred nanoelectronvolts can be trapped by material bottles, magnetic fields, and gravity for hundreds of seconds. That makes them an ideal tool to precisely measure fundamental properties of the neutron, e.g. its electric dipole moment [1, 2], lifetime [3, 4], decay correlations [5], interaction with gravitational forces [6], and charge [7].

However, the precision of such experiments is limited by the low UCN densities that can be delivered by current sources. Typically, less than two dozen UCNs per cm$^3$ are detected after filling an experiment [8, 9]. The UCN source that has been operating the longest, but still is one of the most intense ones, is installed at Institute Laue-Langevin, Grenoble, France. It reflects cold neutrons on moving blades mounted on a “UCN turbine”, slowing them to ultracold velocities [10]. All newer sources rely on a superthermal process: cold neutrons scattering on a cold converter can induce solid-state excitations and lose almost all of their energy [11]. The low temperature of the converter suppresses the inverse process of upscattering.

So far, superthermal sources have been realized with two converter materials: solid deuterium at temperatures around 5 K and superfluid helium (He-II) at temperatures below 1 K. Solid deuterium offers a rich spectrum of solid-state excitations, offering a high UCN-production cross section, but also high absorption cross sections [12]. Conversely, superfluid helium has a lower UCN-production cross section, but can have much lower absorption.

Several superthermal sources with deuterium converters are currently operational, at Los Alamos National
Laboratory [9], Paul Scherrer Institut [13] (both using spallation neutron sources), and at University of Mainz [14] (using a reactor neutron source).

A superfluid-helium converter is used at Institut Laue-Langevin [15] (using a cold-neutron beam from a reactor source) and has been used at the Research Center for Nuclear Physics [16] (RCNP, using a spallation neutron source). The latter source has been moved to TRIUMF in 2016 and installed at a new, dedicated spallation neutron source [17].

II. PRODUCTION AND LOSSES OF ULTRACOLD NEUTRONS IN SUPERFLUID HELIUM

The dispersion relations of free neutrons and of phonons in superfluid helium cross at an energy \( E \) of 1 meV, allowing a neutron with that energy to excite a single phonon and lose virtually all of its energy and momentum. Detailed measurements of the scattering function of superfluid helium show that multi-phonon scattering allows the same process at slightly higher energies [18, 19]. The UCN-production rate \( P \) in the superfluid is given by the cold-neutron flux \( \Phi(E) \) and the total scattering cross section \( \sigma(E) \) given by these processes:

\[
P = \int \Phi(E)\sigma(E)dE. \tag{1}
\]

The UCN-loss rate \( \tau^{-1} \) in the superfluid, defined as the inverse of the storage lifetime \( \tau \), is given by the rates of upscattering in superfluid helium \( \tau_{up}^{-1} \), absorption in helium \( \tau_{abs}^{-1} \), wall loss \( \tau_{wall}^{-1} \), and beta decay \( \tau_{\beta}^{-1} \):

\[
\tau^{-1} = \tau_{wall}^{-1} + \tau_{up}^{-1} + \tau_{abs}^{-1} + \tau_{\beta}^{-1}. \tag{2}
\]

The wall-storage lifetime is determined by the material, cleanliness, and roughness of the walls and is typically on the order of tens to hundreds of seconds.

The upscattering lifetime is strongly dependent on the temperature \( T \) of the superfluid and roughly follows

\[
\tau_{up}^{-1} \approx B \cdot \left( \frac{T}{1K} \right)^7, \tag{3}
\]

with \( B \) between 0.008 s\(^{-1}\) and 0.016 s\(^{-1}\) [20]. So, to suppress the upscattering rate to a similar level as the wall-loss rate, the superfluid helium has to be cooled to a temperature around 1 K.

The absorption lifetime is dominated by the high neutron-absorption cross section of \(^3\)He. In natural helium—with a \(^3\)He abundance of \(10^{-6}\)—the absorption lifetime would be less than 100 ms. Isotopically purified helium—available with \(^3\)He abundances below \(10^{-12}\) [21]—can increase the absorption lifetime to several thousand seconds.

The ultimate limit of storage lifetime is given by the lifetime of free neutrons of \( \tau_\beta = (880.2\pm 1.0) \text{ s} \) [22].

III. DESCRIPTION OF THE SOURCE

The UCN source developed at RCNP uses 8 L of isotopically purified superfluid helium, cooled to about 0.9 K with a \(^3\)He cooling circuit. Cold neutrons are provided by two-stage moderation in liquid heavy water at room temperature and solid heavy water cooled to 20 K. For a more detailed description refer to [10].

In 2016, we moved the source to TRIUMF and installed it at a new, dedicated spallation neutron source. TRIUMF’s cyclotron provides a 483 MeV proton beam of which up to 40 \(\mu\)A of beam current can be diverted onto a tungsten spallation target surrounded by lead blocks [17]. The UCN source is placed above the target and surrounded by graphite blocks serving as additional neutron reflectors. To conform to Canadian safety standards we had to add pressure relief stands and add more radiation shielding, requiring a 4.5 m longer UCN guide than at RCNP, see Fig. [1].

The UCN-production volume filled with superfluid helium has a cylindrical shape and is attached to a vertical UCN guide, connecting the production volume to a \(^3\)He-cooled heat exchanger, see Fig. [2]. The temperature of the superfluid helium is measured by four Cernox sensors placed in the superfluid between the UCN guide and the heat exchanger.

The combined height of UCN-production volume and vertical UCN guide is 1.25 m, with the lower 0.62 m filled with superfluid helium. Right above the liquid surface, a short, narrower section of the vertical guide blocks superfluid film flow to reduce heat load. Above the cryostat, the UCN guide continues horizontally in a vacuum jacket to transition from cryogenic to room temperature. It ends with a burst disk for pressure relief and a gate valve (VAT 17.2 series) with a protective ring improving UCN transmission in the open state.

Downstream of the valve, the UCN guide follows a horizontal 45\(^\circ\) kink to avoid radiation leaking through a direct line of sight to the experimental area. Finally, it penetrates through 3 m of additional shielding and drops down to allow the UCNs to penetrate a 0.1 mm-thick aluminium foil and to enter the main detector. The total volume of the production and guide volume is 60.8 L. The foil separates the helium-filled UCN guide from the detector vacuum to reduce contamination of the source. The main detector uses photomultiplier tubes to detect scintillation light produced by UCN captured in \(^6\)Li-enriched glass [22]. A secondary \(^3\)He proportional counter with its own aluminium window is mounted to a 5 mm pinhole in the guide, see Fig. [1] and serves as a monitor detector for measurements of transmission through additional guides that will be presented in a separate publication.
FIG. 1. UCN source and guide geometry at TRIUMF. When the target is irradiated, spallation neutrons are moderated and converted to ultracold neutrons in the cryostat, see Fig. 2. After a period of accumulating UCNs in the source, the UCN valve is opened and UCNs can reach the detectors. The radiation shielding encasing the cryostat and pumps is not shown.

FIG. 2. Detailed simulation model of the source. Spallation neutrons produced by irradiating the target with protons are moderated in heavy water and converted to ultracold neutrons in the superfluid helium. Red dots indicate the temperature sensors used to determine the temperature of the superfluid.

IV. ULTRACOLD-NEUTRON YIELD

A typical measurement of UCN yield starts with an irradiation of the target with a certain proton-beam current and for a certain duration \( t_i \), with the UCN valve closed. During this time, UCNs accumulate in the source, reaching a number

\[
N = P \tau_1 \left[ 1 - \exp \left( - \frac{t_i}{\tau_1} \right) \right],
\]

(4)
determined by the production rate \( P \) and the loss rate in the source \( \tau_1^{-1} \). The loss rate

\[
\tau_1^{-1} = f_1 \tau_{He}^{-1} + (1 - f_1) \tau_{vapor}^{-1} + \tau_{wall,1}^{-1} + \tau_\beta^{-1}
\]

(5)
is the sum of losses in liquid helium \( f_1 \tau_{He}^{-1} \), in helium vapor \( (1 - f_1) \tau_{vapor}^{-1} \), on the guide walls \( \tau_{wall,1}^{-1} \), and due to decay \( \tau_\beta \). Since the source is only partially filled with superfluid helium, the loss rate is corrected by the fraction of time \( f_1 \) that detectable UCN spend in the superfluid. These components are difficult to disentangle in experiment, instead we estimated them in simulation, see section [V].

Once the irradiation period ends the valve opens and the accumulated UCNs can reach the detector. The rate in the detector quickly peaks after a few seconds, see Fig. 3, and then drops exponentially with a time constant

\[
\tau_2^{-1} = f_2 \tau_{He}^{-1} + (1 - f_2) \tau_{vapor}^{-1} + \tau_{wall,2}^{-1} + \tau_d^{-1} + \tau_\beta^{-1}
\]

(6)

With the valve open, the loss rate to the detector \( \tau_d^{-1} \) has to be included. The fraction of time UCNs spend in the superfluid \( f_2 \) and the wall losses \( \tau_{wall,2} \) are now different compared to equation (5). The valve stays open for two to three minutes and then the cycle repeats.

We determined the total number of detected UCNs by integrating the rate in the detector while the valve was open and subtracting the background rate, which we estimated before the irradiation started while the valve was closed. During irradiation, the background rate in the detector increased proportionally to the beam current by \((2.5 \pm 0.5) \text{s}^{-1} \mu\text{A}^{-1}\). More detailed studies of cross-talk and pile-up in the detector showed that those effects distort the measured rate by less than 1%. For details refer to [24]. To check that the detected neutrons are indeed ultracold neutrons we performed an experiment with a
Irradiation
Valve closed
Valve open

FIG. 3. Rate in the detector during two typical measurement cycles with a beam current of 1 µA, an irradiation time of 60 s, and with the valve opened for 120 s. The dashed lines indicate the start of irradiation and the valve actuation times in the first cycle. The red line is a fit as explained in section VI.

FIG. 4. Number of UCNs extracted from the source after irradiating the target for 60 s with different beam currents. At currents below 1 µA, the UCN yield is proportional with current (dashed line). At higher currents, the yield drops due to the increased heat load; the labels indicate the peak helium temperatures reached during irradiation.

nickel foil replacing the aluminium foil. In this configuration, the rate in the main detector did not increase above the background, confirming that the vast majority of detected neutrons had energies below 245 neV, the Fermi potential of nickel.

The UCN-production rate is expected to be proportional to the beam current. Consequently, for lower beam currents the UCN yield increases linearly with current. However, at higher beam currents the increased heat load on the superfluid raises its temperature and UCN-upscattering rate, reducing the UCN yield, see Fig. 4.

The highest number of extracted UCN was 325 000 after irradiating the target for 60 s with 10 µA. Dividing this number by the total guide volume of 60.8 L yields a UCN density of 5.3 cm⁻³. At the nominal beam current of 1 µA the yield was 47 500, corresponding to a UCN density of 0.78 cm⁻³.

The saturating number of UCNs in the source can be directly observed by measuring the UCN yield after different irradiation times, see Fig. 5. The saturation time constant decreases at higher beam currents, again due to the increasing temperature and upscattering rate of the superfluid. For currents above 1.5 µA and irradiation times above 60 s the yield starts to drop again due to the further increasing temperature.

Furthermore, instead of operating the source in “batch mode”, with the valve opening after the irradiation period, we can also continuously irradiate the target while leaving the valve open. At beam currents of 1 µA or less, such a configuration will lead to a constant stream of 1500 UCN s⁻¹ µA⁻¹ reaching the detector. During irradiation with higher beam currents, the temperature of the superfluid slowly increases and we observe a decreasing rate.

V. STORAGE LIFETIME

The number of UCNs that can be accumulated directly depends on their storage lifetime in the source τ₁ (equation 4), making it a crucial performance parameter. To determine the storage lifetime, we ran cycles where we opened the valve with different delays after the irradiation ended. A typical storage-lifetime measurement consisted of nine cycles with valve delay times of 0 s, 170 s, 20 s, 120 s, 50 s, 80 s, 30 s, 20 s and 5 s; an exponential
To simulate UCN storage and transport, we built a detailed model of the production volume and UCN guides for the Monte Carlo simulation PENTrack [25], including the burst disk, actual shape of the UCN valve in open and closed state, pinhole, foil, and main detector. PENTrack uses Fermi potentials to model interaction of UCNs with materials; the imaginary part of the potential determines the loss of UCNs. We set the losses in the foil according to measurements performed by [26]. We modeled the main detector with its two scintillator layers [23] and their corresponding Fermi potentials and absorption cross sections, as stated in [27].

We assumed that the spectrum of produced UCN is proportional to \( \sqrt{E} \) and that the upscattering rate in superfluid helium follows \( \tau_{\text{He}}^{-1} = B \cdot (T_{\text{He}}^{-7.7}) \), with \( B \) between 0.008 s\(^{-1}\) and 0.016 s\(^{-1}\) as measured by [20]. By tuning the imaginary Fermi potentials of guides and production volume, see table I, we matched the simulated UCN transport more accurately to measured data, we fit both the simulated and measured rate of UCN in the detector after opening the

**TABLE I. Fermi potentials and diffuse-reflection probabilities used for materials in the PENTrack simulation.**

| Material                        | Fermi potential (neV) | Diffusivity |
|---------------------------------|-----------------------|-------------|
| He-II                           | 18.8 \( -0.5hBT^2 \)  | 0.16        |
| He vapor                        | \(-0.5h\tau_{\text{vapor}}^{-1}\) | 0.16        |
| Production volume (NiP)         | 213 \( -0.12\nu \)   | 0.05        |
| Guides (stainless steel)        | 183 \( -0.14\nu \)   | 0.03        |
| Foil (aluminium)                | 54.1 \( -0.0028\nu \) | 0.20        |
| GS30 scintillator               | 83.1 \( -0.00012\nu \)| 0.16        |
| GS20 scintillator               | 103 \( -1.2\nu \)    | 0.16        |

**VI. COMPARISON WITH SIMULATIONS**

Since the source volume is connected to a long UCN guide sealed with O-rings, we expected residual gas to contaminate the source every time we open the UCN valve. To determine the impact of this contamination, we regularly measured the storage lifetime over a period of eighteen days, see Fig. 7. The drop in storage lifetime also directly impacted the UCN yield as expected from equation 4.
Fig. 8. Comparison of fall time $\tau_2$ (top) and rise time $\tau_{\text{rise}}$ (bottom) in experimental data and simulations with different diffuse-reflection probabilities. The boxes indicate the second and third quartile of the experimental data, the empty circle its average. The best match is found with a diffuse-reflection probability of 3%.

An example is shown in Fig. 3. Then, we tuned the probability that a UCN is diffusely reflected by the guide walls (following Lambert’s law) to match the rise time $\tau_{\text{rise}}$ and the fall time $\tau_2$ to the experimental data, see Fig. 8. The delay between opening the valve and the first UCN being detected in the detector, $\Delta t$, is constant in all scenarios. The parameter $R_B$ is the background rate in the experimental data and zero in the simulated data.

FIG. 9. UCN yield (top) and storage lifetime (bottom) at different temperatures after irradiating the target with $1 \mu$A for 60 s (filled circles). The simulated data (empty squares and triangles) fits the experimental data (see text). The lines are interpolations of simulated data to guide the eye.

To estimate UCN production, we built detailed target, moderator, and UCN-converter geometries for the Monte Carlo software MCNP6.1 [31], taking into account material impurities determined from assays and fill levels of moderator vessels, see Fig. 2. With this model, we simulated the complete source: the proton beam hitting the target; secondary neutrons, protons, photons, and electrons; and neutron moderation in graphite and heavy water. In contrast to liquid heavy water, there is no detailed data on thermal-neutron scattering in solid heavy water available. Instead, we relied on a free-gas model with an effective temperature of 80 K, as this seems to be the minimum effective neutron temperature achieved with solid-heavy-water moderators [32]. From the simulated cold-neutron flux in the UCN-production volume and equation (1) we determined a production rate of $(20 600 \pm 200) \text{s}^{-1} \mu\text{A}^{-1}$ for UCNs with energies up to 233.5 neV.

Figure 9 shows the yield and storage lifetime at dif-
different temperatures determined by the four temperature sensors in the superfluid. In the yield measurement the higher temperatures were reached during an interruption of cooling, in the storage-lifetime measurement by using heaters. Especially at lower temperatures, the four temperature sensors showed large discrepancies and stabilizing the temperature proved difficult, leading to large uncertainties. The horizontal error bars in Fig. 9 correspond to the full range of temperatures measured between the end of irradiation and the valve closing again after detecting the produced UCNs.

Nevertheless, simulations with a liquid-helium-upscattering parameter $B$ of 0.016 s$^{-1}$ (lower solid line and squares) match the measured data well. When setting $B$ to 0.008 s$^{-1}$ (upper solid line and squares), the yield at higher temperatures is slightly overestimated. Simulations without vapor upscattering (dotted lines and triangles) show significant differences at higher liquid temperatures—at 1.5 K the simulated storage lifetime in vapor, $(1 - f_1)\tau_{\text{vapor}}$, is reduced to roughly 50 s while it has no significant effect at 0.9 K.

Fig. 10 shows the UCN rate in the detector while we continuously irradiated the target with different beam currents with the UCN valve open. At beam currents above 1 µA the temperature of the superfluid increases slowly, reducing the UCN rate. The simulated data with a liquid-helium-upscattering parameter $B$ of 0.016 s$^{-1}$ (lower solid line) slightly overestimates the drop in rate with temperature; with $B = 0.008$ s$^{-1}$ (upper solid line) it slightly overestimates the UCN rate, but better matches the drop with temperature.

Unfortunately, the discrepancies between the temperature sensors in the superfluid prevent a more accurate determination of the upscattering parameter. Measurements of heat transport in superfluid helium also agreed with the expected trends in the temperature sensors, once correcting for offsets, and sensor calibration dominated the uncertainty [33].

VII. CONCLUSIONS

We successfully operated a superfluid-helium source for ultracold neutrons at a new spallation source at TRIUMF. Although we were able to extract three times more UCNs than ever before, thanks to an increased beam current on the spallation target, we achieved only half of the previously best storage lifetime, most likely due to contamination of the source while it was moved, the burst disk added to the UCN guide, and the new UCN valve not optimized for UCN storage.

Simulations including the temperature-dependent upscattering in superfluid helium and helium vapor confirm that the former follows $\tau_{\text{He}}^{-1} = B \cdot (\frac{T}{T_\text{f}})^7$, matching the experimental UCN yield and storage lifetime best with $B$ between 0.008 s$^{-1}$ and 0.016 s$^{-1}$. Upscattering in helium vapor plays a significant role at liquid temperatures above 1 K.

This research provides the prerequisites for future developments: a next-generation source with cooling power and ultracold-neutron flux increased by two orders of magnitude, and an experiment to measure the electric dipole moment of the neutron with a sensitivity of $10^{-27}$ e cm. The excellent match of simulations and experiment makes us confident that we can predict the performance of this future source and experiment very well.

Further operation of the current prototype source will focus on tests of components for these future installations, e.g., UCN guides, valves, polarizers, storage volumes, and vacuum windows to mitigate degradation due to contamination.

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[27] G. Ban, G. Bison, K. Bodek, Z. Chowdhuri, P. Geltenbort, W. C. Griffith, V. Hélaine, R. Henneck, M. Kasprzak, Y. Kermaidic, K. Kirch, S. Komposch, P. A. Koss, A. Kozela, J. Krempel, B. Lauss, T. Lefort, Y. Lemière, A. Mtchedlishvili, M. Musgrave, O. Naviliat-Cuncic, F. M. Piegsa, E. Pierre, G. Pignol, G. Quéméner, M. Rawlik, D. Ries, D. Rebreyend, S. Roccia, G. Rogel, P. Schmidt-Wellenburg, N. Severijns, E. Wursten, J. Zejna, and G. Zsigmond, *The European Physical Journal A* **52**, 326 (2016).

[28] M. Daum, B. Franke, P. Geltenbort, E. Gutsmiedl, S. Ivanov, J. Karch, M. Kasprzak, K. Kirch, A. Kraft, T. Lauer, B. Lauss, A. Müller, S. Paul, P. Schmidt-Wellenburg, T. Zechlau, and G. Zsigmond, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **741**, 71 (2014).

[29] S. Wlokka, P. Fierlinger, A. Frei, P. Geltenbort, S. Paul, T. Pschl, F. Schmid, W. Schreyer, and D. Steffen, (2017), arXiv:1701.07431 [physics.ins-det].

[30] F. Atchison, M. Daum, R. Henneck, S. Heule, M. Horisberger, M. Kasprzak, K. Kirch, A. Knecht, M. Kuźniak, B. Lauss, A. Mtchedlishvili, M. Meier, G. Peltzoldt, C. Plonka-Spehr, R. Schelldorfer, U. Straumann, and G. Zsigmond, *The European Physical Journal A* **44**, 23 (2010).

[31] T. Goorley, M. James, T. Booth, F. Brown, J. Bull, L. J. Cox, J. Durkee, J. Elson, M. Fensin, R. A. Forster, J. Hendricks, H. G. Hughes, R. Johns, B. Kiedrowski, R. Martz, S. Mashnik, G. McKinney, D. Pelowitz, R. Prael, J. Sweezy, L. Waters, T. Wilcox, and T. Zukaitis, *Nuclear Technology* **180**, 298 (2012).

[32] J. J. Rush, D. W. Connor, and R. S. Carter, *Nuclear Science and Engineering* **25**, 383 (1966).

[33] F. Rehm, *Heat conductivity in superfluid helium and ultra cold neutron source cryogenics*, Bachelor’s thesis, University of Coburg (2018).