

1 The ultracold neutron source - UCN, neutrons for particle physics.

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Abstract Ultracold neutrons provide a unique tool to study the property of the neutron. We give an overview of the ultracold neutron source (UCN) at PSI which provides highest UCN intensities to fundamental physics experiments by exploiting PSI's high intensity proton beam and the high UCN production in solid deuterium at a temperature of 5 K.

1.1 Introduction

Ultracold neutrons (UCN) are neutrons at the ultralow end of the energy spectrum, with kinetic energies below about 300 neV, corresponding to velocities below 8 m/s or to temperatures below 4 mK, hence they are termed "ultracold". This energy is on the same level as the neutron optical potential of certain materials which hence can be used to store UCN in material bottles. This energy also corresponds to the potential difference of a neutron when lifted 3 meters in the earth gravitational field, and also to the potential difference in a 5 Tesla magnetic field gradient acting on the neutron magnetic moment. Hence, UCN can be easily confined and manipulated, and therefore provide a unique tool to study the particle properties of the neutron itself. Highest intensities of UCNs are badly needed to reach the interesting highest sensitivity range in fundamental physics experiments, with the most prominent experiment being the search for a permanent electric dipole moment of the neutron (nEDM) [1, 2].

The intention to build a UCN source at PSI was formulated in the late 1990'ies. The UCN project was initiated and realized under the lead of Manfred Daum. The technical design presented in 2000 [3] was based on preceding studies in Russia [4, 5, 6] and a successful operation of a solid-deuterium based UCN source at the Los Alamos National Laboratory [7]. The scientific goal was a new high sensitivity nEDM search. Several pioneering experiments by the PSI UCN group determining e.g. UCN production in solid deuterium [8, 9] and UCN loss cross-sections [10, 11] paved the way to the final design. The UCN source was then installed as the second neutron target station of PSI's high intensity proton facility (HIPA). After a short test beam in 2010, the UCN source started regular operation in 2011 [12, 13, 14] providing UCN to experiments at three beamports.

1.2 UCN Source Setup

The UCN source is operated in the following way: PSI's 590 MeV, 2.4 mA proton beam is diverted by a kicker magnet [15] for up to 8 s onto the lead spallation target (Label 2 in Fig.1) [16]. The neutrons, about 8 per initial proton [17] are thermalized in the surrounding heavy water (label 4). The central moderator vessel (label 5) contains solid deuterium (sD₂) at a temperature of 5 K which first serves as cold moderator and finally as UCN production medium. The cryo-system necessary for manipulation, cooling and freezing of the deuterium [18] is sketched in Fig. 2. UCN exit the moderator vessel through a lid (label 6) into a vertical guide where the energy boost from the sD₂ [19] is lost. The flapper valve (label 8) of the 1.6 m³ large storage vessel is closed at the end of the proton

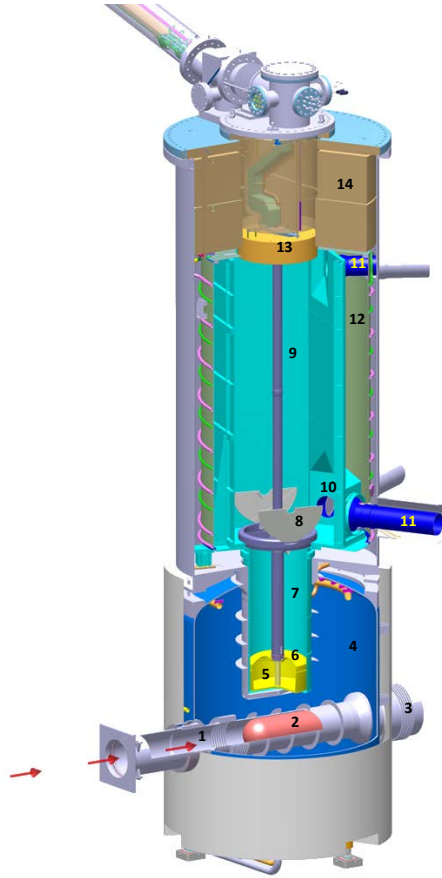


Figure 1: CAD image of the UCN tank with indicated parts relevant to UCN production and transport. 1 - proton beam tube, 2 - lead spallation target, 3 - target shielding, 4 - heavy water moderator tank, 5 - D₂ moderator vessel, 6 - lid, 7 - vertical guide, 8 - flapper valve, 9 - storage vessel, 10 - UCN guide shutter, 11 - UCN guide section, 12 - thermal shield, 13 - cryo-pump, at 5 K, 14 - stainless steel shielding.

pulse. UCN are delivered via about 8 m long neutron guides (label 11) to three beamports. Strong emphasis on quality was put into all parts and extensive tests were done before installations, e.g. the cryo-performance of several parts, most importantly the flapper valves (label 8) and UCN guide shutters (label 11). Also the UCN transport performance of all installed UCN guides [20] was measured. The overall neutron optics performance was later analyzed and understood in terms of a detailed simulation of the entire UCN source [21].

The core of the UCN source is the solid deuterium moderator which serves also as UCN converter at a temperature of 5 K. This 30 liter large solid D₂ crystal requires very careful preparation in order to achieve optimal UCN output. A schematic view of the involved subsystem is shown in Fig. 2. Preparation starts from the ultrapure and isotopically pure D₂ gas stored in 30 m³ large tanks at STP which is slowly transferred via freezing into the 'condensation' vessel. The D₂ is then liquefied and transferred into the 'conversion' vessel at about 20 K where an about 97% high ortho-D₂ concentration is accumulated via spin-flip on Oxisorb®[®], a chromium-oxide-based catalyzer material in about 1 day of

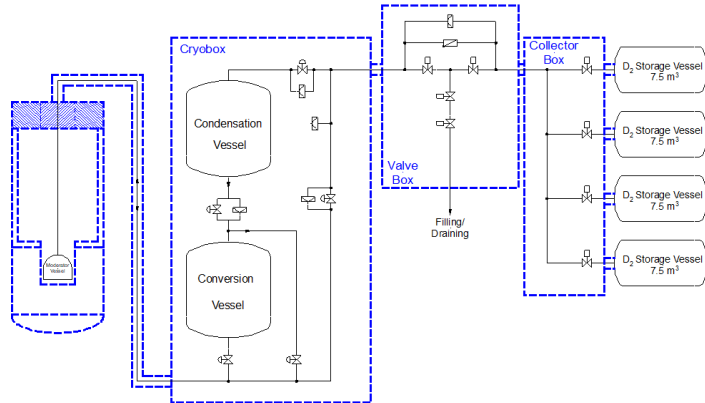


Figure 2: Schematic view of the subsystems needed for preparation of the solid ortho-deuterium (see text).

boiling. Raman spectroscopy is used to check the ortho- D_2 concentration [22, 23] typically above 99% during longer operation periods. Further-on, the 10 m long transfer line to the moderator vessel is passed in liquid form. The liquid D_2 is then slowly solidified in the moderator vessel over several days in order to achieve a high UCN output. The moderator vessel shown in Fig. 3a is entirely made from AlMg3 with special coolant channels for the supercritical He cooling agent at 4.7 K. These channels enter in the center of the vessel and allow the He stream to the outside wall up and back in 8 separated sections, as schematically depicted in Fig. 3b.

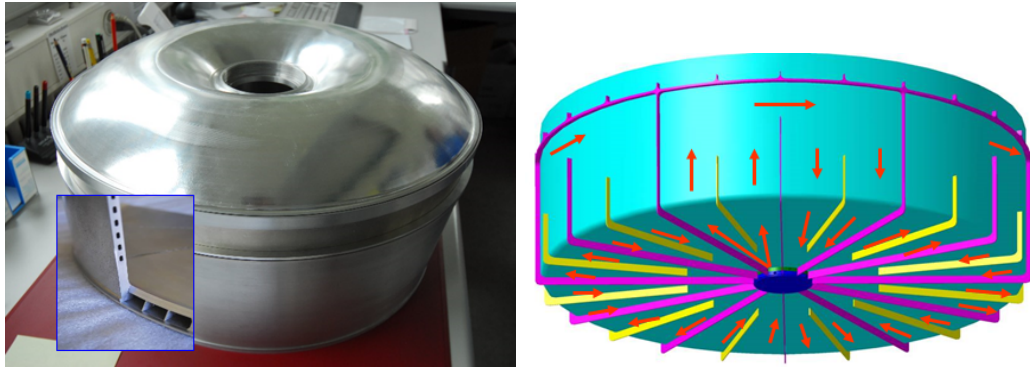


Figure 3: a) View of the moderator vessel with a cut insert view from a test vessel wall. b) Schematic view of the He coolant flow in the vessel demonstrating the sectional cooling.

The delivered UCN intensity reflects the quality of the achieved solid deuterium, likely a mosaic crystal with many defects and cracks, as was shown in the pioneering UCN experiments [8, 9, 10, 11]. A slow freezing is crucial in the preparation process of the source. Figure 4 displays the typical UCN intensity behavior (green line) during such a slow freezing process. The vapor pressure (blue line) which is a direct measure of the D_2 (surface) temperature decreases from above 400 mbar (liquid D_2) to the triple point at about 171 mbar, where it solidifies. After solidification the pressure rapidly decreases below 10^{-2} mbar. The UCN output shows the opposite behavior. UCN loss processes

dominate at higher temperatures, especially in the liquid D_2 and the high-density vapor above the D_2 . Once 5 K are reached, thermal losses are minimized and the UCN output is largest, and in addition increasing with growing ortho- D_2 concentration and improved crystal quality, i.e. less cracks or cavities which can trap UCN.

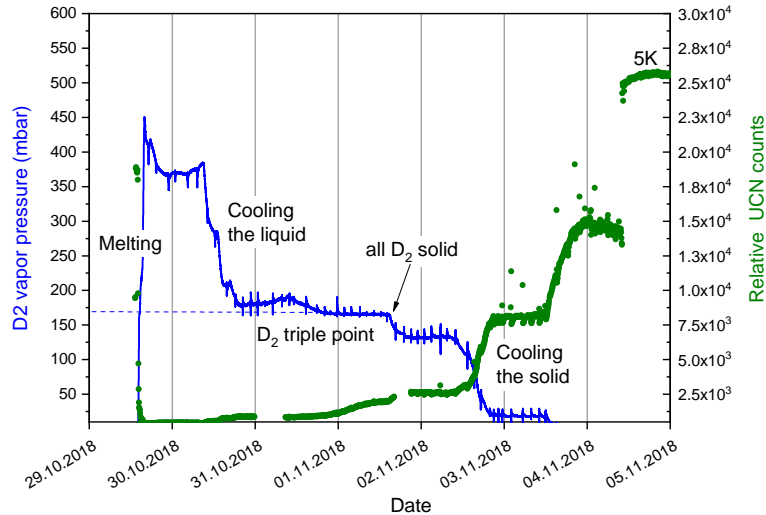


Figure 4: Observed behavior during slow freezing of the deuterium. The vapor pressure of the D_2 (blue line) indicates the D_2 temperature. The D_2 was fully melted. When reached about 400 mbar pressure cooling started and the D_2 slowly approached the triple point at 171 mbar (horizontal dashed line). The D_2 solidifies and the solid is further cooled, indicating a sub 10^{-2} mbar pressure when reaching 5 K. The large increase in UCN output shown in the green bullets demonstrates the strong reduction in UCN losses within the D_2 .

1.3 UCN Source Performance

One important performance parameter is the number of UCNs delivered at a beamport in a given time interval as this determines the available number of UCNs in an experiment. The typical time structure of UCNs for a proton beam pulse is shown in Fig. 5. The flaps of the storage vessel open before the proton beam hits the spallation target and their closing time is optimized with respect to the end of the proton pulse to provide the maximum number of UCNs to the experiments.

The measured exponential decay of the UCN count rate at the West-1 beamport, Fig. 5a), has a time constant of about 30 s, reflecting the emptying time of the central storage vessel through the West-1 guide into the UCN detector. The UCN rate at beamport South behaves identically. If all shutters to the UCN guides remain closed on the storage vessel, the storage time constant is about 90 s. At the end of a period, standard operating period is 300 s long, the flaps are re-opened to be ready for the next proton beam pulse.

Fig. 5b) shows the UCN rate observed at the West-2 beamport located 230 cm above the bottom of the storage vessel [21]. The faster exponential decay demonstrates that the UCNs with high enough energies to reach up to 230 cm are quickly drained through that

port. The total number of UCNs delivered at the West-1 or South beamport was has been up to 45 Mio. at the best operating conditions. The total number of delivered UCNs depends on the status of the solid deuterium and was constantly increased over the years due to improvement of operating conditions.

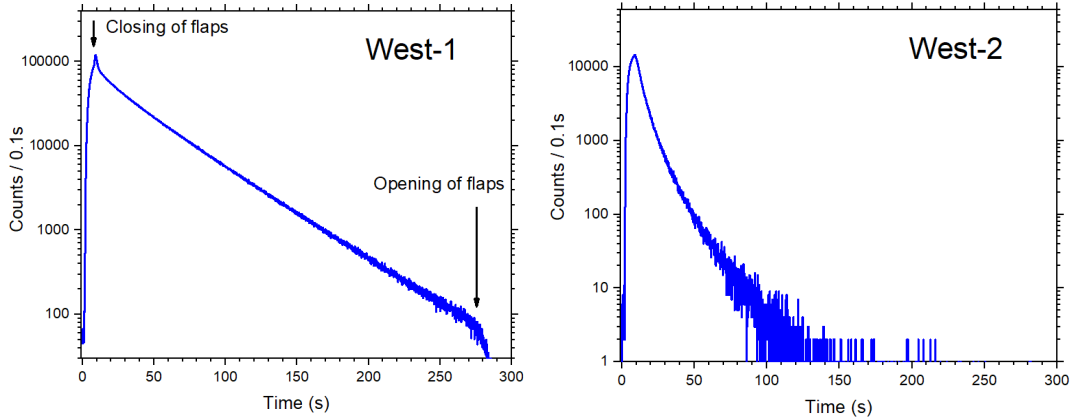


Figure 5: a) UCN counts after one proton beam pulse at the West-1 beamport. Closing and opening of the flaps refers to the central flapper valves. b) Same as a) but at the West-2 beamport.

Several studies to understand all aspects of the UCN source have been conducted since inauguration. The proton beam current and position is constantly monitored online with beam monitors. Neutron production and thermalization was measured via neutron activation and well matched in detailed MCNP simulations [17].

Neutron moderation was studied via tritium production in the solid D_2 moderator [23]. The high ortho D_2 concentration and the high isotopic purity of the D_2 was confirmed [23].

The transport of UCNs from production in the solid deuterium to a beamport has been carefully studied in various measurements detailed in the thesis works [24, 25]. Many geometry details were put into a full simulation model and the simulation results then well matched observations [21].

The measured integral UCN intensity per beam pulse also shows a time dependence on the scale of several hours to days, which decreases the average UCN output considerably. After different studies a temperature-cycling procedure named “conditioning” was developed which allows us to get fully rid of the accumulated losses and regain full UCN intensity. This UCN count rate behavior is shown in Fig. 1.3a, where the times when the conditioning procedure was applied are labeled with “C”. Fig. 1.3b depicts the measured deuterium vapor pressure in the moderator vessel during such a conditioning process over approximately 2 hours. The rise in vapor pressure during a proton beam pulse, depicted with the blue arrow, is miniscule. The rise during temperature cycling is up to about 50 Pa, depending on the total operation time since the latest conditioning. This is far below the triple-point pressure of ~ 170 mbar and hence only sublimation, movement and resublimation of surface molecules occurs during conditioning. Nevertheless, full rate recovery occurs.

One of the key characteristic numbers describing a UCN source is the UCN density which can be achieved in a given storage vessel. We have built a stainless steel ‘standard UCN storage vessel’ with a volume of 20 liters [26]. This bottle was used to characterize

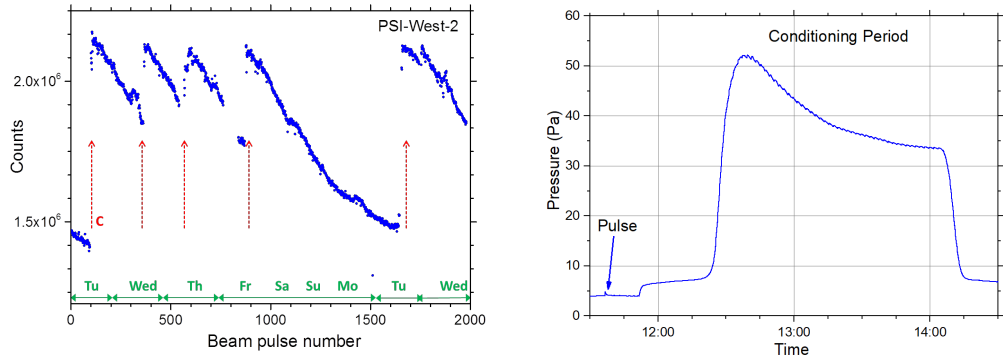


Figure 6: a) UCN count rate behavior as observed over a 9 days operating period. The drop is interpreted as frost effect. The count rate increases to the original level when the conditioning procedure is applied at the given times labeled “C”. Picture from Ref. [21] with kind permission of The European Physical Journal (EPJ). b) vapor pressure of the solid deuterium surface in the moderator vessel during a full conditioning cycle.

the height-dependent UCN density at beamport West-1 [25]. It peaks around 50 cm above beamport as shown in Fig. 7. This standard bottle was then used to characterize UCN densities of all operating UCN sources around the world in a standardized and hence comparable way [25, 27, 28]. As a result was shown that the PSI source provides world-leading performance to UCN storage experiments.

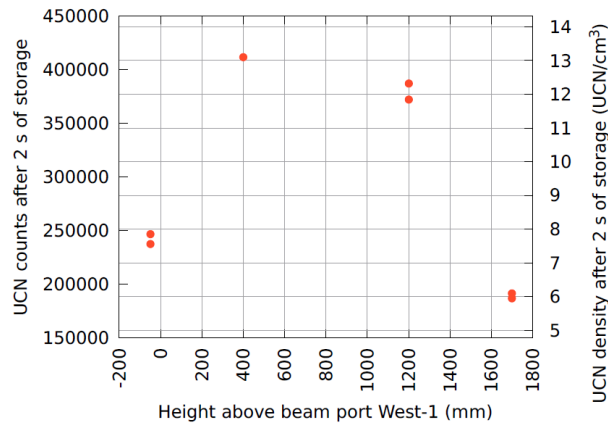


Figure 7: UCN density measured at different heights with respect to beamport West-1. Picture from Ref. [25].

The PSI UCN source has been operating since 2011 on a regular schedule, mainly providing UCN to the nEDM experiment. The yearly operation can be characterized via the annual proton beam current onto the UCN spallation target and the number of proton beam pulses per year, both are shown in Fig. 8. The peak in 2016 was driven by the main data taking period of the nEDM experiment. The lower numbers in the subsequent years are due to longer periods of solid deuterium studies for UCN source improvements, which needed longer times with fewer proton beam pulses for performance checks.

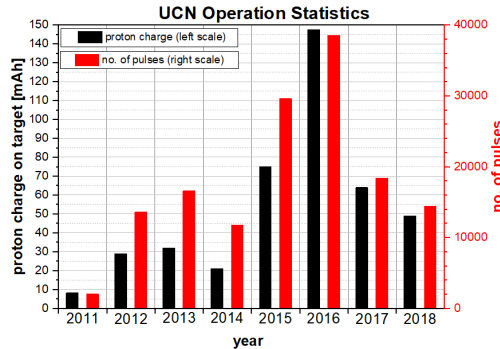


Figure 8: Annual statistics of the first operating years of the UCN source showing total accumulated beam current on target and number of beam pulses onto the UCN spallation target.

1.4 Physics results at the UCN source

The driving experiment for the construction of the UCN source at PSI was the experiment to search for an electric dipole moment of the neutron which delivered a new nEDM limit in 2020 [2]. In addition, significant physics results were achieved:

- a precision measurement of the mercury to neutron magnetic moment ratio [29];
- observation of gravitationally induced vertical striation of polarized ultracold neutrons by spin-echo spectroscopy [30]
- measurement of gravitational depolarization of ultracold neutrons [31]
- a new limit for spin-dependent forces mediated by axion-like particles [32];
- a first laboratory limit for oscillating electric dipole moments [33];
- new limits for mirror neutron oscillations in mirror magnetic fields [34].

Some of these results are treated in additional contributions to this volume.

1.5 Particle physics at the SINQ

The UCN source was conceived and built for research in fundamental neutron physics. However, the first neutron source built at PSI is the SINQ facility (cite ??). While dedicated to neutron scattering instruments it has been employing a polarized cold-neutron beamline also dedicated to fundamental neutron physics; namely the 'FUNSPIN' beamline [35] providing 6×10^8 neutrons $\text{cm}^{-2}\text{s}^{-1}\text{mA}^{-1}$ with 95% polarization [36]. Following some recent modifications it was renamed to 'BOA'.

The main physics results came from the nTRV collaboration's series of measurements to determine neutron decay parameters. A precise determination of electron-neutron correlation coefficients R and N allowed for a precise test of the Standard Model and to search for exotic scalar and tensor interactions in neutron decay [37, 38, 39, 40].

An experiment provided a new measurement of the spin-dependent doublet neutron-deuteron scattering length [41, 42]. Another Ramsey-type experiment provided an upper limit on the strength of an axial coupling constant for a new light spin 1 boson in the millimeter range [43].

Finally, we want to note again the importance of the FUNSPIN beamline for many measurements conducted in preparation of the UCN source where many parameters of

UCN production and loss were determined [8, 9, 10, 11, 44, 45, 46].

1.6 Summary

A high-intensity source for ultracold neutrons, designed and built at PSI, has been operating since 2011. We report on its operation and its performance. Some of our findings with respect to the solid deuterium converter and its surface conditions are presented. We conclude with a list of physics results in fundamental neutron physics achieved the UCN source and complement it with the ones where measurements were done at the SINQ.

1.7 Acknowledgments

The UCN source at PSI could only be built due to the dedicated long-term support by many individuals and support groups at PSI which worked for several years together within the UCN source team. Especially we acknowledge the invaluable contributions of all former and present members of the BSQ group and the UCN physics group.

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