Ultracold Neutrons—Physics and Production

Introduction

Free neutrons are the most fundamental ones of the easily accessible, electrically neutral spin-1/2 systems. They take part in all the four known interactions: they strongly interact with nucleons and nuclear matter, they undergo weak β-decay, they have magnetic moments and gravitational mass. Although the neutron itself is a composite system, and thus, strictly speaking, not a fundamental particle, it is one of the finest probes for fundamental physics. Neutrons can be and are used to study all interactions, to search for new interactions, to test fundamental quantum mechanics and symmetries of nature. Over the past five decades the field of slow neutron precision physics developed and could usually make major advancements when new and more powerful neutron sources became available.

Very often experiments benefit from using slower neutrons and, thus, longer de Broglie wavelengths $\lambda = 2\pi\hbar/(m \cdot v)$, for example, thermal neutrons at about 2,200 m/s average velocity have wavelengths of the typical atomic scale of about 1 Å. Fermi and Zinn [1] found that neutrons can be totally reflected from material surfaces under grazing angles of incidence. To each material a critical (maximum) angle for total reflection of thermal neutrons exists that becomes larger for smaller neutron velocities. Consequently, sufficiently slow neutrons will be reflected under all angles of incidence. These neutrons are called "ultracold neutrons" (UCN). Due to their specific properties ($\lambda \geq 600$ Å) they have opened a new door for the field of fundamental physics.

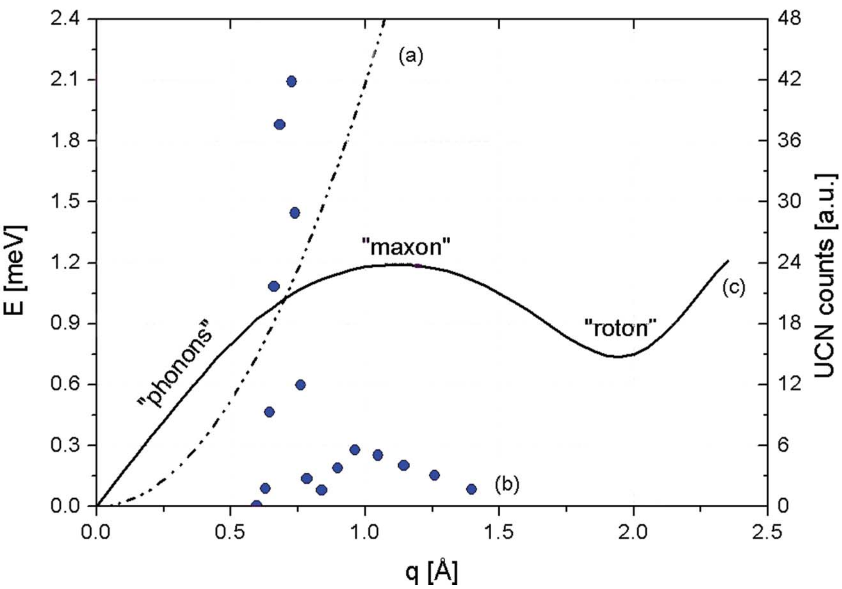


Figure 1. *Dispersion relation of superfluid helium (c) and free neutron (a). Neutrons with $E \approx 1 meV$ can excite a single phonon $q \approx 0.7 Å^{-1}$ with same energy and are thus down-scattered to the UCN energy range. The UCN production rate (b) (circles) [16] shows the dominance of this single phonon process with respect to multiphonon processes.*

Besides numerous reviews, two text books have been written on UCN [2, 3]. For an update on the status of the field, readers are referred to two recent workshops [4, 5]. In this article we briefly review the peculiarities of ultracold neutrons, including their generation and mentioning some of their applications.

As several times already in the past, we are today at a point at which fundamental physics applications require larger UCN intensities in order to further advance. Especially the importance of the search for a finite value of the electric dipole moment of the neutron pushes the development of new and more powerful UCN sources. We describe the new schemes for the production of UCN that have been studied in detail recently and are presently being realized at various laboratories around the world. In particular, the UCN source project currently commissioning at the Paul Scherrer Institut (PSI) in Villigen, Switzerland will allow for a next generation of more sensitive fundamental physics studies.

Ultracold Neutrons

Ultracold neutrons are free (unbound) neutrons defined via their most important property: they can be stored! They have very low kinetic energies below about 300 neV corresponding to ~3.5 mK, hence their

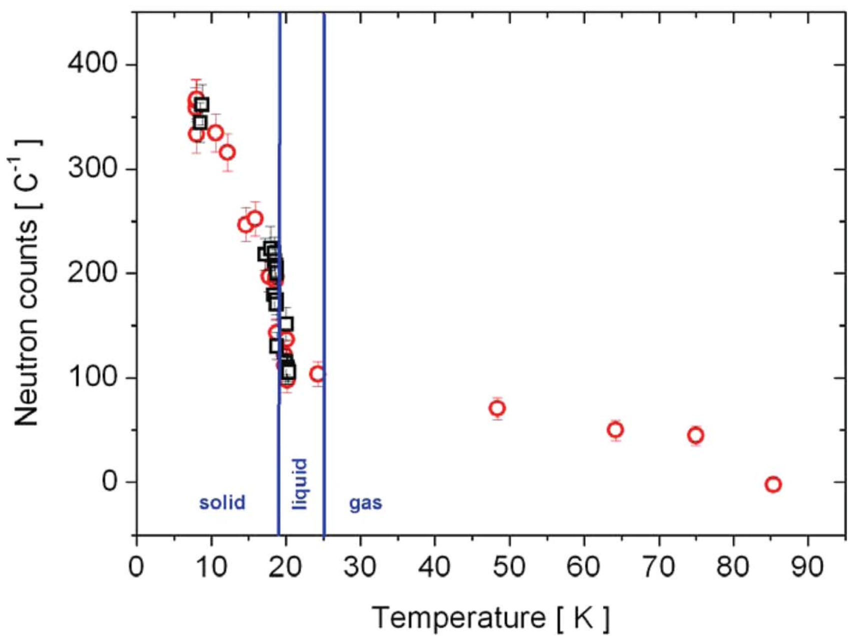


Figure 2. *Experimentally determined temperature dependence of UCN production in deuterium [22]. The sharp increase with solidification is obvious.*

name: ultracold. They can be confined by the strong interaction (total reflection at any angle of incidence from surfaces of certain materials like Ni, Be, stainless steel), the magnetic moment interaction (repulsion of one spin component from field gradients due to the neutron magnetic moment) and due to gravitation (limited vertical reach).

UCN reflection on walls via the strong interaction can be well described by a potential step model solving the Schrödinger equation with a step height equal to the so-called Fermi (optical) potential: $V_F = (2\pi\hbar^2/m) \cdot Na$; where N is the number density in the material assumed to be homogeneous, a is the coherent scattering length, and m is the mass of the neutron. For example $V_F(\text{Ni}) = 252\,\text{neV}$, $V_F(\text{diamond}) = 304\,\text{neV}$. For kinetic energies below this threshold energy total reflection occurs at any angle.

In inhomogeneous magnetic fields, the kinetic energy change of the neutrons can be expressed as $\Delta E_{kin} = \pm 60 \cdot \text{neV/T}\ \Delta|\boldsymbol{B}|$, taking the positive sign if the spin component is antiparallel to the field $\boldsymbol{B}$.

Also the gravitational interaction is on the same scale for UCN, $\Delta E_{kin} = \Delta h \cdot 103\,\text{neV/m}$, where Δh is the height difference.

The effects of all three interactions can be combined and used for UCN traps. The energy spectrum of stored UCN depends on peculiarities of the trap and is a function of height with a material or magnetic field dependent cut-off, typically below about $\Delta h = 3\,\text{m}$.

The storage time of UCN is fundamentally limited by the time constant of neutron β-decay of almost 15 minutes. Practically, also loss factors like nuclear absorption, inelastic up-scattering and imperfections of realistic storage containers (e.g., holes or slits) contribute considerably.

UCN in Fundamental Physics

The possibility to store UCN for relatively long observation times makes them unique and highly sensitive probes, testing our understanding of fundamental physics [2, 3, 6]. Most of these experiments today are statistically limited and further advancements strongly depend on new high-intensity sources for UCN. A key experiment is the search for a permanent electric dipole moment of the neutron (nEDM). A finite nEDM violates time-reversal invariance and, therefore, might help to understand the matter–antimatter asymmetry in our universe. It is tightly linked to some of the open problems in modern physics, the so-called "strong CP-problem" and the "SUSY CP-problem." Its observation would be a clear indication for physics beyond the electro-weak Standard Model of particle physics [7–9]. Other important studies with UCN include determination of the neutron lifetime and decay parameters, strongly influencing our understanding of weak interactions and big bang nucleosynthesis [6]. UCN are also being used to study fundamental quantum mechanics, search for exotic interactions, test baryon number conservation, and measure properties of the neutron itself, such as the search for a tiny but finite charge of the neutron.

The Production of UCN

The typical kinetic energy of UCN (~100 neV) is orders of magnitude below the typical neutron energy in a thermal moderator (~25 meV) of a neutron source, such as a nuclear reactor. The energy distribution of the thermalized neutron gas is often

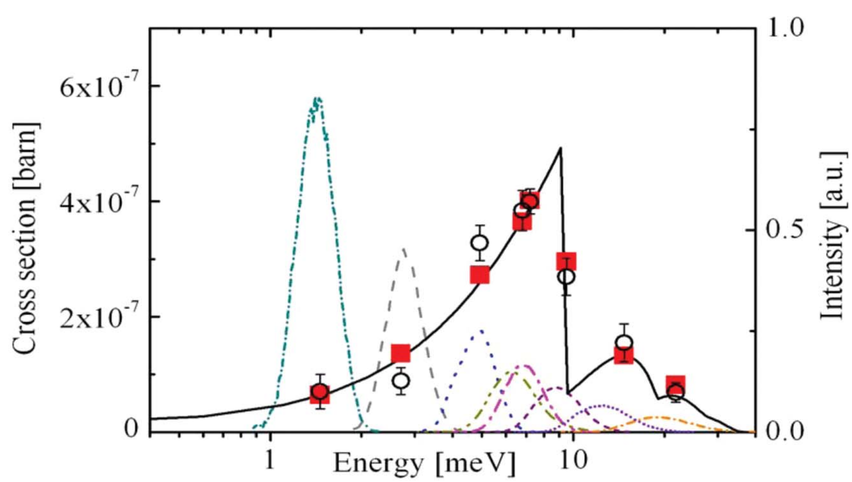


Figure 3. *UCN production as function of incoming neutron energy [20]. The dashed, colored curves display individual cold neutron energy distributions (intensity: vertical right scale) prepared from the "white" cold neutron beam using a neutron velocity selector and measured by time-of-flight. The measured UCN production cross-section (left vertical scale) for the individual energies is displayed as open circles. The red squares are the cross-sections calculated for the energy distributions, the solid black line is calculated as continuous function of energy. The cut-off at around 9 meV comes from cut-off of the phonon density of states in the simple Debye model at the Debye temperature. Above this energy, multiple phonon excitations still permit UCN production.*

approximated by a Maxwell-Boltzmann distribution and the amount of neutrons in the very low energy tail is therefore rather small. Lower energy neutrons become further suppressed because of longer travel times in the moderator medium before extraction and the temperature of the extracted neutron gas is accordingly shifted to higher values. Historically it was therefore not even clear that a sizeable amount of ultracold neutrons could be extracted from a moderator, having in mind also additional material that the neutrons must transmit, such as enclosures of the moderator medium and safety windows. While such considerations might have been somewhat discouraging, UCN have the distinct advantage that they can be detected with very high efficiency. The ability to control the background count rate of UCN detectors on a level of a few counts per 1000 s allowed at that time to detect similar UCN rates. Curved neutron guides were used to filter out faster neutrons that could not fulfill the necessary conditions for total reflection. Shapiro's group in Dubna succeeded in detecting UCN this way in 1968 [10]. Steyerl (Munich) in 1969 [11] reported, independently, measured neutron cross-sections for neutron velocities as low as 5 m/s (E = 130 neV). In this case, vertical extraction of the neutrons out of the reactor was used, which helps to mitigate some of the extraction loss problems: the neutrons are still faster when penetrating window materials (loss cross-sections are usually inversely proportional to velocity) and then get slowed down when climbing the gravitational potential.

Various developments have allowed one to increase the intensity of UCN considerably over the years. Clearly, the extracted intensity is proportional to the initial one, thus high initial neutron flux helps and could be increased by more than 4 orders of magnitude as compared to the first experiments. Also, the intensity in the tail of the Maxwell-Boltzmann distribution increases significantly when the temperature of the neutron gas is lowered, thus extracting UCN from a cold moderator of liquid hydrogen or deuterium gained almost another 2 orders of magnitude. Improvements were made on UCN guide quality by developing high Fermi potential, very low roughness surfaces, allowing a low-loss transport of UCN over many meters.

Today's highest UCN intensity is obtained at the instrument PF2, which has been in operation for more than 20 years at the high flux reactor of the Institute Laue-Langevin (ILL) in Grenoble. Vertical extraction over 17 m height through a curved replica guide system is used for initial deceleration and background suppression. Then a mechanical decelerator, the "neutron turbine," transforms very cold neutrons of approximately 40 m/s into the UCN energy range. The neutron turbine (developed by A. Steyerl since 1975) consists of a set of curved blades moving with a peripheral velocity 20 m/s in the same direction as the neutrons. The neutrons are thus decelerated by several total reflections from the moving curved blades. Up to 50 UCN/cm^3 have been observed in a storage setup directly at the turbine exit [12]. In specific experiments, the achievable density is usually somewhat lower, for example, about 2 polarized UCN/cm^3 in the nEDM experiment [13].

While many ideas for more intense UCN sources have been discussed over the past 4 decades, only over the past 10 years has there been a major effort to realize those. The obvious reason is that most UCN experiments nowadays are again statistically limited. In order to obtain higher UCN intensities and densities the trend is to build so-called "superthermal sources."

Superthermal UCN Sources

In "conventional" UCN sources neutrons are extracted from a distribution almost in thermal equilibrium with a moderation system. The concept of "superthermal" sources is different: Thermal or cold neutrons are inelastically scattered and transfer their kinetic energy to an excitation of the scattering medium (e.g., to a phonon). The loss in kinetic energy is called down-scattering. By detailed balance, the reversed process of up-scattering is suppressed by a Boltzmann factor, $\exp(-\Delta E/k_B T)$.

If the medium is sufficiently cold and the excitation energy introduced by the neutrons can be cooled away, up-scattering becomes negligible. Then, the UCN production becomes insensitive to a further temperature decrease of the medium.

The UCN production rate Q can be expressed as:

$$\begin{aligned} Q(E_{\mathrm{UCN}}) &= VP(E_{\mathrm{UCN}}) \\ &= V\int \mathrm{d}E_0 \Phi_0 \Sigma(E_0 \rightarrow E_{\mathrm{UCN}}) \end{aligned} \quad (1)$$

where V = UCN production volume, E_{UCN} = neutron energy in the UCN range, E_0 = incoming neutron energy, Φ_0 = incoming neutron flux, Σ = macroscopic cross-section for down-scattering, P = UCN production rate per unit volume.

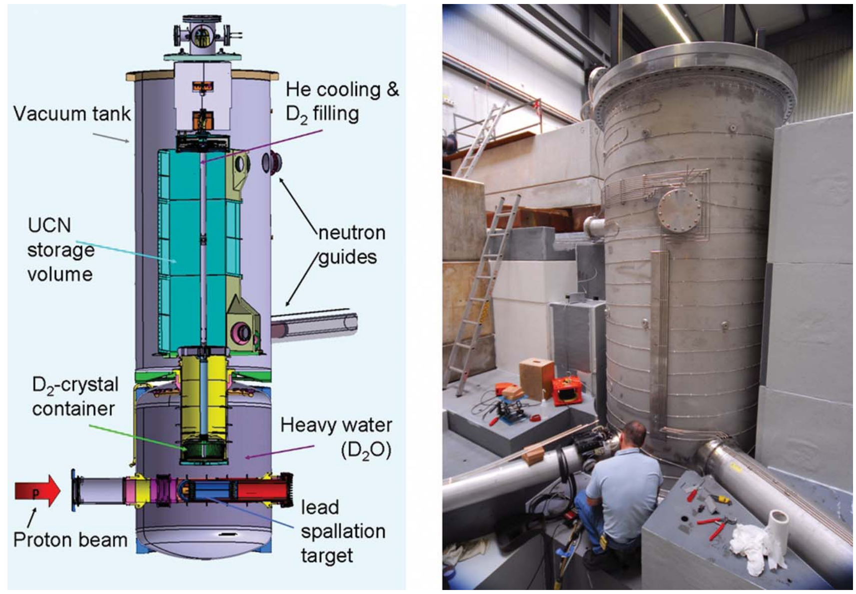


Figure 4. *a) Schematic view of the main components of the ultracold neutron source at PSI contained in a large moderator and vacuum tank system. b) Picture of the UCN vacuum tank taken during construction in spring 2009, showing the main neutron guides' vacuum tubes being prepared for welding.*

In fact, the achievable UCN density can be much larger than the one that would correspond to the thermal equilibrium density at the given moderator temperature. Therefore, and because the process is a one-step conversion of cold neutrons to UCN rather than a moderation, the medium is often called a "superthermal converter."

The maximum achievable UCN density is given as the product of production rate per volume P times the UCN average storage time τ in the system, which depends on the rates for neutron decay ($1/\tau_\beta$), up-scattering in the medium ($1/\tau_{up}$), absorption on the nuclei of the medium or contaminants ($1/\tau_{abs}$), and, for a containment, also according losses during wall collisions ($1/\tau_{wall}$):

$$\tau = \left(\frac{1}{\tau_\beta} + \frac{1}{\tau_{\mathrm{up}}} + \frac{1}{\tau_{\mathrm{abs}}} + \frac{1}{\tau_{\mathrm{wall}}} \right)^{-1} \quad (2)$$

The two factors, production rate P and average storage time τ, can be very different for different media. The research and development effort of the past few years concentrated mostly on two possible choices, superfluid helium and solid deuterium. Qualitatively, helium can provide a very long storage time but has a comparatively low production rate, while deuterium has a high production rate but a rather limited τ. Below, we give some more detail on the status of research with both these materials. As a matter of fact, UCN sources have been constructed already for both materials, and the next generation of powerful sources will use these media. Research on other promising materials (e.g., solid oxygen, solid heavy methane, and nanoparticles), is ongoing but much less advanced [4, 5].

Superfluid Helium as Ultracold Neutron Converter

Already in 1977, Golub and Pendlebury [14] developed ideas to use superfluid helium as a converter for UCN. The characteristic phonon dispersion curve of He-II is an ideal two-level system for superthermal cooling (see Figure 1). As explained before, an incident neutron can excite a quasi-particle by transfer of energy and momentum while the inverse process is suppressed by a Boltzmann factor. In superfluid helium, up-scattering becomes negligible below $T \approx 0.7$ K. The dominant process, shown in Figure 1, is the excitation of a single phonon at the crossing of the free neutron and phonon dispersion curves, with a momentum transfer $q \approx 0.7$ Å^{-1} and $E \approx 1$ meV, corresponding to a neutron wavelength of 8.9 Å. The availability of 8.9 Å cold neutrons is crucial and their flux must be maximized. An advantage of this narrow useful initial neutron energy distribution is that the input beam into the UCN source can be tailored to provide exactly the required neutrons. Reflecting these neutrons out of a white beam permits one to use the rest of the spectrum for other applications and at the same time minimizes the activation of source equipment with useless neutrons that would only contribute to backgrounds in most experiments.

A key issue for a long UCN lifetime in superfluid helium, besides the low temperature, is a low contamination with ^{3}He (^{3}He/^{4}He $\leq 10^{-12}$), which requires ^{4}He purification. In principle, the lifetime (see Eq. 2) is only limited by neutron decay; in practice, however, also non-negligible wall losses contribute and may lead to lifetimes on the order of ~200 s. This still rather long lifetime can be used most efficiently by accumulating UCN inside the source for a comparable time in order to approach equilibrium density. This more than compensates for a low production rate and allows for UCN densities of 10^3–10^4 cm^{-3} at existing cold neutron beam lines. Two types of UCN sources based on superfluid helium are being operated and further developed:

- ***Integral sources***: These are sources where experiment and source are combined in one apparatus and the measurement is performed *in-situ* inside the superfluid helium. Experiments to measure the electric dipole moment of the neutron (ILL, SNS) or the neutron lifetime (NIST) are being pursued.
- ***Multipurpose sources***: The source is an apparatus on its own and delivers neutrons to any experiment connected to it by UCN guides. Such sources had problems in the past to extract UCN through cryogenic windows being prone to growing deposits of absorbing contaminants. However, such problems have been overcome as UCN accumulation and window-less extraction from the superfluid has been realized [15].

Solid Deuterium as Ultracold Neutron Converter

The potential of solid deuterium as a good cold neutron (CN) moderator and UCN converter was also recognized almost 30 years ago, experimentally in Gatchina [17] and theoretically by Golub and Böning [18]. It has been repeatedly demonstrated in test experiments over the past years. A suitable deuterium UCN converter has low temperature to avoid thermal up-scattering and high ortho-deuterium concentration in order to avoid up-scattering on para-deuterium. The loss cross-section for UCN is not negligible as in ^{4}He. The UCN lifetime in solid deuterium it is ultimately limited to $\tau \sim 150$ ms by neutron absorption on deuterons. In practice $\tau \sim 30$ ms has been demonstrated and up to 70 ms may be achievable. In contrast to superfluid helium, integral sources make no sense; the issue is rather to extract the UCN from the converter system as fast as possible [19]. Advantages of solid deuterium over helium are the fact that it can be operated at temperatures of 4–8 K and it provides a larger UCN production cross-section. The higher operating temperature allows one to operate at higher heat loads (i.e., in a higher flux closer to the actual neutron source). Concepts have been developed that allow one to obtain densities of 10^3–10^4 cm^{-3}. The physics of solid deuterium UCN sources has been experimentally studied in quite some detail over the past 10 years. The relevant total slow neutron cross-sections of gaseous, liquid, and solid deuterium have been measured, as well as the integral UCN production cross-section from a cold neutron beam on a deuterium target. The most recent experiments delivered the UCN production as a function of incoming neutron velocity [20] and the generalized density of states with inelastic neutron scattering [4, 21]. All observations, as the temperature dependence of UCN lifetimes, the total scattering and UCN production cross-sections as well as the velocity dependent production cross-sections could so far be well described by a simple theoretical model [18] in which the down-scattering via phonon creation is calculated using a simple Debye model for solid deuterium. Multi-phonon excitations in the calculation are needed and have been included to obtain agreement [20, 22].

Figures 2 and 3 show results from experiments [20, 22] at the cold neutron beam line FUNSPIN at the Paul Scherrer Institut. The cold neutrons interacted with deuterium in a cryogenic target cell. Ultracold neutrons leaving the target were separated from the cold neutron beam and detected with low background. Because these measurements could be calibrated by UCN production from deuterium gas, which can be calculated, absolute cross-sections could be extracted. Figure 2 shows the number of detected UCN as a function of target temperature. The empty target at 85 K indicates the background level, temperatures above 24 K are for gas, below that for liquid and below 18.7 K for solid deuterium. The yield of UCN from the solid increases with lowering the temperature because of suppressing the up-scattering of UCN before extraction. Figure 3 shows the results for velocity dependent UCN production on solid ortho-deuterium at 8 K. A velocity selector was used providing the indicated energy distributions. The measured data is displayed as open circles. The red squares indicate calculated results using the measured velocity distribution for the specific point as input, and the black line is the result of the calculation as a continuous function of energy. The simple Debye model results in the steep cut-off at the Debye temperature of solid deuterium of about 110 K corresponding to an energy of about 9 meV. This explains the importance of including multi-phonon processes in the calculation in order to describe the data at larger neutron energies.

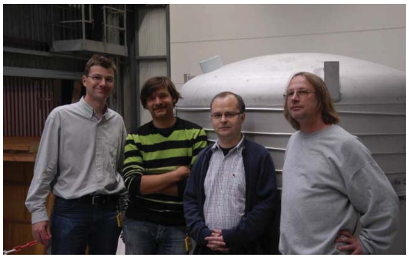
Very recently, the simple Debye model could be replaced by the measured phonon density of states, delivering an equally good description of the measured data points [4, 21].

The UCN Source at PSI—The First High Intensity Source Based on Solid Deuterium

The UCN source at the Paul Scherrer Institut (see ucn.web.psi.ch) is a pulsed spallation source and uses solid deuterium for the generation of ultracold neutrons [23]. It takes full advantage of the large production cross-section and circumvents problems with the finite lifetime of UCN inside the converter by decoupling the production region from the storage region [19]. Figure 4a sketches the important components of the UCN source. Neutrons are produced by spallation when the proton beam from the PSI ring cyclotron hits a lead target. The basic principle is to use the full beam (proton kinetic energy: 590 MeV, dc-beam current >2 mA, beam power >1.2 MW) in macropulses of a few seconds at 1% duty cycle. Almost 10 neutrons (average energy of a few MeV) per incident proton are generated and thermalized in the 3.5 m^3 heavy water moderator. The typical lifetime of the neutrons inside the D_2O moderator is ~5 ms. The neutrons are further cooled in 30 liters of solid deuterium (sD_2) at 5–8 K, in which neutron lifetimes of 30–40 ms can be achieved. In the crystal some of the cold neutrons are converted to UCN and can leave the deuterium converter vessel upward into vacuum. On top of a short (1.2 m) vertical guide a storage volume of about 2 m^3 gets filled with UCN. The walls of the storage volume are coated with diamond-like carbon, providing a high Fermi potential and low UCN losses. The 1.2 m ascent balances the boost effect UCN experience due to the Fermi potential of solid deuterium when leaving the solid. After a few seconds of production, the density of the UCN gas reaches equilibrium and bombarding the spallation target further does not help. At this instant a large shutter at the bottom of the storage volume is closed and the proton beam is switched back to the other users of the facility (pion and muon production targets, spallation neutron source SINQ). Two main (south, west) and one R&D guide made from NiMo (85%/15%) coated glass tubes are selectable with UCN shutters at the storage volume and can be used to deliver the neutrons on demand to experiments in two experimental areas. It is expected that a typical experiment of up to a few hundred liters of volume at the height of the beamline can be filled with a UCN density of about 1000 cm^{-3}, which is almost two orders of magnitude more than possible today. A superconducting 5 T magnet at the end of the south beamline is used to provide polarized UCN. Figure 4b shows the source hall during construction. Commissioning has started in fall 2009. An international collaboration (see nedm.web. psi.ch), is simultaneously setting up an experiment to search for the electric dipole moment of the neutron and plans on data taking, starting in 2010.

UCN Research and Source Projects Worldwide

Besides the effort at PSI in Switzerland, there are activities for improved UCN sources proposed, planned, or under way at the ILL Grenoble, at Los Alamos National Laboratory (LANSCE), at the Mainz TRIGA reactor, at the Technical University of Munich for the FRM-II, at PNPI Gatchina for the WWR-M reactor, at Indiana University for LENS, at the North Carolina PULSTAR



Klaus Kirch, Philipp Schmidt-Wellenburg, Geza Zsigmond, and Bernhard Lauss.

reactor, at RCNP Osaka, TRIUMF, and J-PARC.

Over the past few years a considerable number of institutions have entered the field of ultracold neutron physics, for the development of new sources as well as for their exploitation in fundamental physics. We are now at the point that new sources will come online and new precision experiments will provide results with much improved sensitivities within the next few years. Major improvements in technology have often produced unexpected and spectacular results. We are eagerly waiting to see the development in the field of UCN physics over the next decade.

References

1. E. Fermi and W. H. Zinn, *Phys. Rev.* 70 (1946) 103.
2. V. K. Ignatovich, *Ultracold Neutrons (Clarendon Press, Oxford, 1990)*.
3. R. Golub, D. J. Richardson, S. K. Lamoreaux, *Ultra-cold Neutrons (Adam Hilger, Bristol, 1991)*.
4. Proceedings of International Workshop on Particle Physics with Slow Neutrons, 29–31 May 2008, Grenoble, *Nucl. Instr. Meth. A* 611(2–3) (2008).
5. 7th International UCN workshop, 8–14 June 2009, St. Peterburg, http://cns.pnpi.spb.ru/ucn/index.html
6. J. S. Nico and W. M. Snow, *Annu. Rev. Nucl. Part. Sci*. 55 (2005) 27; H. Abele, *Prog. Nucl. Part. Phys*. 60 (2008) 1.
7. N. F. Ramsey, *Ann. Rev. Nucl. Part. Sci*. 32 (1982) 211.
8. M. Pospelov and A. Ritz, *Ann. Phys*. 318 (2005) 119.
9. M. Raidal et al., *Eur. Phys. J.* C57 (2008) 13.
10. V. I. Lushchikov, Y. N. Pokotilovsky, A. V. Strelkov, and F. L. Shapiro, *Sov. Phys. JETP Lett*. 9 (1969) 23.
11. A. Steyerl, *Phys. Lett*. 29B (1969) 33.
12. A. Steyerl and S. S. Malik, *Nucl. Instr. Meth*. 284 (1989) 200.
13. C. A. Baker et al., *Phys. Rev. Lett*. 97 (2006) 131801.
14. R. Golub and J. M. Pendlebury, *Phys. Lett*. 62A (1977) 337.
15. O. Zimmer et al., *Phys. Rev. Lett*. 99 (2007) 104801.
16. C. A. Baker et al., *Phys. Lett*. A 308 (2003) 67.
17. I. S. Altarev et al., *Phys. Lett*. 80A (1980) 413.
18. R. Golub and K. Böning, *Z. Phys*. B51 (1983) 95.
19. Y. Pokotilovski, *Nucl. Instr. Meth*. A 356 (1995) 412.
20. F. Atchison et al., *Phys. Rev. Lett*. 99 (2007) 262502.
21. A. Frei et al., *Phys. Rev*. B 80 (2009) 064301.
22. F. Atchison et al., *Phys. Rev*. C 71 (2005) 054601.
23. A. P. Serebrov et al., *JETP Lett*. 66 (1997) 802.

K. Kirch
Paul Scherrer Institut,
Villigen PSI, Switzerland
ETH Zürich, Zürich, Switzerland

B. Lauss,
P. Schmidt-Wellenburg,
and G. Zsigmond
Paul Scherrer Institut, CH-5232
Villigen PSI, Switzerland