Superthermal Source of Ultracold Neutrons for Fundamental Physics Experiments

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Ultracold neutrons (UCNs) play an important role for precise measurements of the properties of the neutron and its interactions. During the past 25 years, a neutron turbine coupled to a liquid deuterium cold neutron source at a high-flux reactor has defined the state of the art for UCN production, despite a long history of efforts towards a new generation of UCN sources. This Letter reports a world-best UCN density available for users, achieved with a new source based on conversion of cold neutrons in superfluid helium. A conversion volume of 5 liters provides at least 274 000 UCN in a single accumulation run. Cyclically repeated operation of the source has been demonstrated, as well.

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Ultracold neutrons (UCN) move so slowly that they can populate traps made of matter or magnetic mirrors and sometimes also employing gravity, where one can store and manipulate them for several hundreds of seconds. Because of this property, trapped neutrons have become a valuable tool for precise measurements in fundamental physics complementary to experiments at high-energy accelerators [1–3]. For instance, studies of quantum states of the neutron in the Earth's gravitational field attract much current interest as a tool to search for deviations from Newton's gravity law at the micrometer length scale [4,5]. Such investigations take advantage of the neutron being a neutral, massive probe without atomic structure and therefore no disturbing van der Waals or Casimir forces. On the other hand, with its internal quark structure, the neutron offers access to many different physics phenomena. These are investigated with cold and ultracold neutrons by a growing community of researchers. High-precision studies of the static and decay properties of the neutron and its interactions provide important data for particle physics and cosmology. In addition, they enable sensitive searches for new physics. Among recent new topics addressed with UCN feature searches for "mirror matter" as a viable candidate for dark matter [6,7], a sensitive test of Lorentz invariance [8], searches for a new fundamental force mediated by axionlike particles [9,10], and a demonstration of the effect of accelerated matter on the neutron wave [11]. More long-standing are efforts to improve the accuracy of the weak axial-vector and vector coupling constants of the nucleon derived from precise values of the neutron lifetime [12,13] and the beta asymmetry, i.e., the asymmetry of electron emission with respect to the spin of the decaying neutron [14,15]. These values crucially enter the calculation of reaction rates in big-bang nucleosynthesis and stellar fusion [16]. They are also applied to calculate various processes in particle physics such as for the calibration of antineutrino detectors, which is currently scrutinized in view of a "reactor antineutrino anomaly" hinting at the existence of sterile neutrinos [17,18]. Similarly long-standing is the search for a nonvanishing neutron electric dipole moment (EDM), which would violate the combined symmetries of charge conjugation (C) and parity (P) and was proposed already in 1950 by Purcell and Ramsey [19]. This search provides a prominent route to investigate new mechanisms of CP violation beyond the standard model complex phase of the mixing matrix for three quark generations, needed to explain the matter-antimatter asymmetry in the Universe [20]. At the present best level of sensitivity, which has become severely limited by counting statistics, still no EDM was observed [21].

As most other experiments with UCNs, the EDM search [21] has been performed using a long-serving source [22] at the high-flux reactor of the Institut Laue Langevin (ILL) in Grenoble, France. It employs a neutron turbine for a phase-space transformation of very cold neutrons from a liquid deuterium moderator down to the energy range of UCN, whose high-energy limit is set by the neutron optical potential of the material selected for a UCN trap (such as 252 neV for beryllium) or by the magnetic potential provided by field gradients in a magnetic bottle (60 neV/T). With UCN densities in the order of 10 per cm^3 made available for experiments in a typical configuration of the UCN extraction from the turbine [23], the ILL source has defined the state of the art for more than 25 years. However, notably, the prospect to make an important discovery in refining the neutron EDM search has strongly motivated many research groups to invest into developments of "next generation" UCN sources [24–29]. Some of these aim to improve available UCN densities by more than 2 orders of magnitude. The physical basis is "superthermal" UCN production [30]. In this process proposed long ago, neutrons incident on a cold converter made of solid deuterium or superfluid ^{4}He loose nearly their entire energy in single scattering events, producing elementary excitations in the converter which are cooled away by a refrigerator. At low temperature, the scarcity of low-energy excitations on speaking terms with the trapped UCNs suppresses scattering back to higher energies due to the Boltzmann factor. The UCNs thus become energetically trapped, enabling buildup of a high UCN density prior to their extraction to an experiment.

In our UCN source project, we employ superfluid ^{4}He with temperatures below 1 K as converter medium. It has the unique properties to have neither any cross section for nuclear absorption nor any excitations with energies below 1 meV that are able to up-scatter UCN. Accumulation of UCNs in a converter installed at a neutron beam may thus lead to higher UCN densities than ordinary moderation close to a reactor core [30]. However, in an early attempt to bring this technique to life, the UCN output was a factor 50 lower than expected [31]. In the sequel, several research groups at NIST [32], the ILL [33], and at the SNS [34] decided to perform experiments *in situ* within the helium bath. While this avoids UCN extraction from the converter, it excludes common user experiments which involve equipment at room temperature and need to be fed by an external UCN source. To make such a source available, we have developed a simple and efficient method for UCN accumulation and extraction from the converter, as demonstrated recently using a prototype apparatus at the Munich research reactor FRM II [35,36]. Key elements of the apparatus (see Fig. 1) are a short vertical section of neutron guide and a cold UCN valve situated above the helium bath. In contrast to the horizontal UCN extraction scheme, as employed in [31], no UCN loss creating foil for separation of the extraction guide and the conversion medium is needed here. With a bent section and careful thermal anchoring of the guide, the helium converter can be coupled to a UCN guide at room temperature, without excessive heat load on the source.

Figure 1 shows the setup of the converter vessel which acts as a trap for UCN accumulation. It is placed in a superfluid helium tight container from aluminum. The trap is a 1 m long rectangular channel with cross section 7×7 cm^2, matching the size of the incident beam. It is made of beryllium oxide ceramics, closed at both ends, with 1 mm thick windows from metallic beryllium for entrance and exit of the neutron beam. These materials have neutron optical potentials of about 250 neV (corresponding to a maximum neutron velocity of 7 m/s) and low neutron absorption cross sections. The vertical section for UCN extraction is a 10 cm long thin-walled tube with inner diameter 23 mm made from electropolished stainless steel to provide guiding of UCNs and small heat conduction into the helium bath. A cold gate valve on top of this ‘‘UCN chimney’’ allows for building up a high density of UCN in the converter before releasing them to an experiment. The valve consists of a 0.5 mm thick foil from stainless steel with a hole with diameter 23 mm, which can be moved within a slit in the UCN guide to allow for complete (or any partial) opening. Another important detail of the apparatus is a ‘‘superleak’’ for purification of the helium supplied to the converter from traces of the strongly neutron absorbing isotope ^{3}He. It consists of a tube filled with fine compressed powder [36]. For characterization of the source, UCNs are guided to a standard ^{3}He gas filled UCN detector at room temperature, in which the neutron

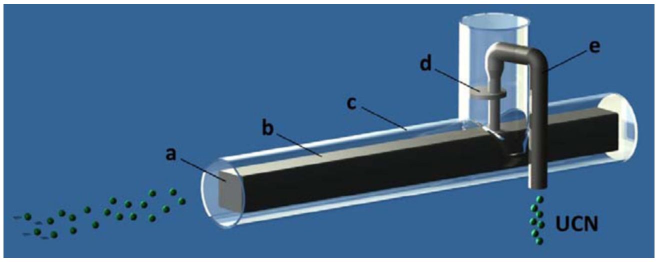

FIG. 1 (color online). Schematics of the apparatus. (a) Beryllium entrance window of the UCN converter vessel. (b) UCN converter vessel for UCN accumulation, filled with superfluid helium. A beam of cold neutrons from a guide with same cross sectional dimensions as the vessel enters from the left. (c) Shield to protect the cold converter vessel from thermal radiation (a second, outer shield and the vessel for the isolation vacuum are not shown). (d) UCN valve. (e) UCN extraction guide towards a detector (not shown).

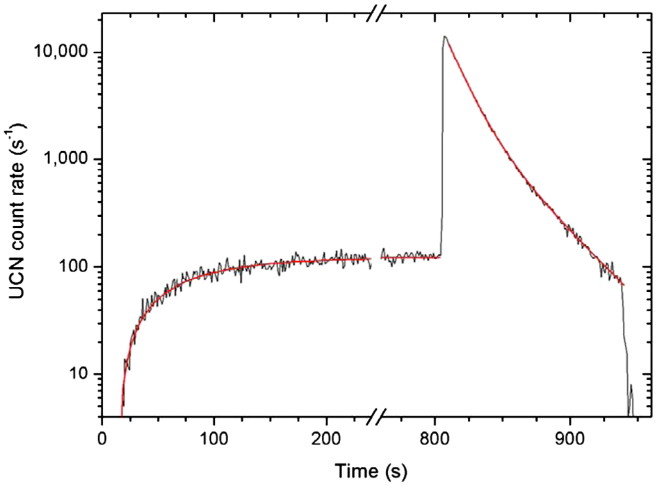

FIG. 2 (color online). UCN count rate as a function of time in an accumulation experiment. The UCN valve stayed closed during about 800 s of irradiation with the cold beam. Then, the beam was shut and the UCN valve opened to release the accumulated UCNs to the detector. 134 s later, the UCN valve was closed again. While the UCN buildup in the converter is well-described by a single exponential fit with time constant $\tau = (67 \pm 2)$ s, the fit to the UCN extraction peak on the right employs a sum of two exponential decays with two time constants $\tau_1 = (13 \pm 1)$ s and $\tau_2 = (35 \pm 3)$ s, with 83% of the measured intensity in the faster component. The reduced χ^2 of 2.2 indicates that a fit involving two time constants provides already a good approximation to the facts that UCNs are generated with a broad spectrum and that UCNs with different velocities leave the converter with different time constants.

capture reaction $n(^3\mathrm{He}, p)t$ provides an electrical signal due to ionization of the gas by the emitted charged particles. The cryostat of the UCN source (not shown in Fig. 1) allows us to cool the converter down to 0.7 K as determined with a calibrated resistor thermometer fixed to the outside of the aluminum vessel. The time needed to prepare the source starting from room temperature is about five days.

The apparatus has been installed at a monochromatic neutron beam with a flux density of $9 \times 10^8\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{nm}^{-1}$ at a neutron wavelength of 0.89 nm, for which UCNs are produced through creation of a single elementary excitation (phonon) in the superfluid ^{4}He. A converter with a volume of 5 liters has been exposed to the beam. We have performed various experiments to characterize the new source. The first addresses the question of how many UCNs can be extracted from the converter vessel after a saturating irradiation with the neutron beam. Figure 2 shows the corresponding UCN count rate as a function of time. Leakage of UCNs through the closed UCN valve allowed us to monitor the buildup of the UCN density within the converter during irradiation. The integrated counts within the emptying curve on the right of Fig. 2 are 274 000, including a small correction of about 1% for the detector dead time of 2 μs. For the given source volume, this observation demonstrates that a UCN density of 55 per cm^3 is made available for experiments connected to the source. Our apparatus has thus become the first "next generation" UCN source delivering a higher UCN density for users than presently available at ILL's turbine source. Compared to previous results obtained with the prototype [36], the UCN output both in terms of peak flux and total counts is improved by more than a factor of 15.

In the experiment described before, we did not observe any significant heating of the source due to the neutron beam. However, while the UCN valve was open for UCN extraction, the temperature of the helium bath rose by 0.1 K due to thermal radiation entering the converter along the UCN extraction guide. It takes the system about 20 minutes to recover back to below 0.7 K, so that the source can be operated with a "duty cycle" of 10% (fraction of time with UCN valve open per accumulation-extraction cycle). Since most neutrons leave the converter in a first short fraction of the period of 134 s during which the UCN valve was kept open (see Fig. 2), and in order to demonstrate a cyclic operation of the source, we also performed repeated tests using a much shorter opening time. Figure 3 shows the result of two experiments with repeated opening of the UCN valve for 10 s and with the neutron beam continuously irradiating the converter volume. Each UCN extraction was followed by a recovery time of 190 s (upper figure) or 90 s (lower figure). In the first case (i.e., with a duty cycle of 5%), the system behaved perfectly stably, reproducing converter temperatures of 0.69 K just before opening the UCN valve and 0.71 K just after closing it. The total number of counts collected in each extraction was about 140 000. In the experiment with a duty cycle of 10%, the temperature rose within 1 h of operation from 0.7 K to 0.9 K, with an associated drop in UCN count rate due to

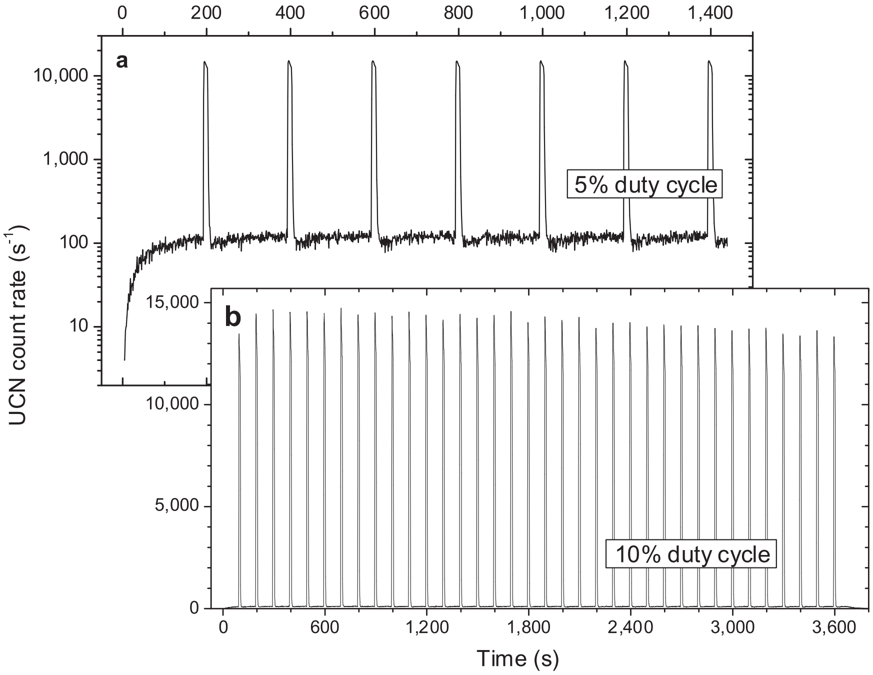

FIG. 3. Repeated extraction of UCNs with the neutron beam switched on at all times (a) for a duty cycle (defined as fraction of time with UCN valve open per accumulation-extraction cycle) of 5%—on the logarithmic scale, the replenishment of the converter after each UCN extraction is well visible—and (b) for a duty cycle of 10%—on the linear scale, one can well see the decrease of peak UCN flux due to the rise of temperature with time [which is absent in (a)].

increasing phonon up-scattering of the trapped UCN, i.e., the inverse process of UCN production in the converter.

Our new source is currently being prepared to feed a new instrument for further precise investigations of the quantum levels of the neutron in the Earth's gravitational field mentioned in the beginning. To this end, a special UCN extraction system with a buffer volume for UCN is being prepared. Work is in progress to increase the UCN storage time constant τ and the incident neutron flux, which is delivered by diffraction off a special crystal monochromator and is lower than projected numbers [37]. The fact that even in a situation where there is still large room for improvement a superior UCN density has been achieved shows the potential of the elegant UCN production method invented by Golub and Pendlebury to serve a broader user community. It might not only improve the research outlined in the beginning of this Letter but also opens up new fields of science which have been hampered by too low available UCN densities, such as neutron microscopy or spin echo with UCNs [38], which might become a tool for investigation of large scale structures in soft condensed matter.

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