An ultracold neutron facility at PSI

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Abstract. Fundamental particle physics experiments with ultracold neutrons (UCN) as well as potential applications require as many ultracold neutrons as one can possibly get. The two UCN flagship experiments, the search for an electric dipole moment (EDM) of the neutron and the precise measurement of the neutron decay life time, by far outperformed the non-UCN versions of these experiments. However, they suffer from too low UCN intensities, both for increasing their statistical accuracy as well as for further investigating their systematic limitations. Recent developments opened up the possibility to build new sources for UCN with orders of magnitude gains in UCN density over currently operated reactor sources. We report on the status of the UCN project at PSI which aims at setting up a facility providing UCN densities in excess of $2000\,\mathrm{cm}^{-3}$ in a large storage volume of about $2\,\mathrm{m}^3$. As a first experiment at the new facility we intend to search for the neutron EDM with a sensitivity of $5 \times 10^{-28}\,e\,\mathrm{cm}$.

INTRODUCTION

Ultra-Cold Neutrons (UCN) are defined as neutrons which are totally reflected from certain materials at all angles of incidence. They were first considered theoretically in 1959 by Zel'dovich [1], or maybe even earlier by Fermi, and first experimentally observed in 1968/69 [2, 3]. Typical UCN kinetic energies are a few hundred neV, corresponding to velocities below about 8 m/s. UCN can be stored in material traps ("UCN bottles"), using the total reflection from material surfaces. Due to the neutron magnetic moment, magnetic fields of the order of several Tesla provide potential energies of the same order as UCN kinetic energies. Also the change in the gravitational potential for height differences of a few meters is of the order of the kinetic energy. As a consequence UCN can be confined in material traps, magnetic traps, and combined gravitational traps.

Storage of UCN is a very important feature for a variety of fundamental experiments. It allows the measurement of the neutron lifetime from a well defined sample and leads to ingenious experiments searching for an electric dipole moment (EDM) of the neutron (see e.g. [4]). Although UCN offer greatly improved sensitivity and systematics compared to cold neutron based experiments, one main limitation of these experiments is the low UCN intensity. Typically, UCN densities of $\approx 10\,\mathrm{cm}^{-3}$ are obtained. Sources with increased UCN density of the order of $1000\ \mathrm{cm}^{-3}$ may lead to much improved measurements of the neutron lifetime and the neutron EDM.

Traditionally, UCN are produced at reactors. The principal difficulty of UCN production is that their energy region is far out in the tail of a thermal Maxwell distribution. Additional losses in the extraction from the reactor cold source result in large suppression factors (e.g. for a source at 300 K and a flux $\Phi_0[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$ one typically obtains $\rho_{\mathrm{UCN}} = 10^{-13}\,\Phi_0\,\mathrm{cm}^{-3}$). Methods to increase the UCN yield from a cold neutron source include vertical extraction [3], using gravity to decelerate neutrons of higher velocities into the UCN regime; and mechanical deceleration [5], using collisions of faster neutrons with a moving scatterer. The fast neutrons can more easily penetrate windows and can be transported over longer distances with few reflections. The distances for UCN transport to the experiments can thus be short and UCN losses small.

Alternative UCN production schemes have been proposed and demonstrated, such as conversion of cold neutrons

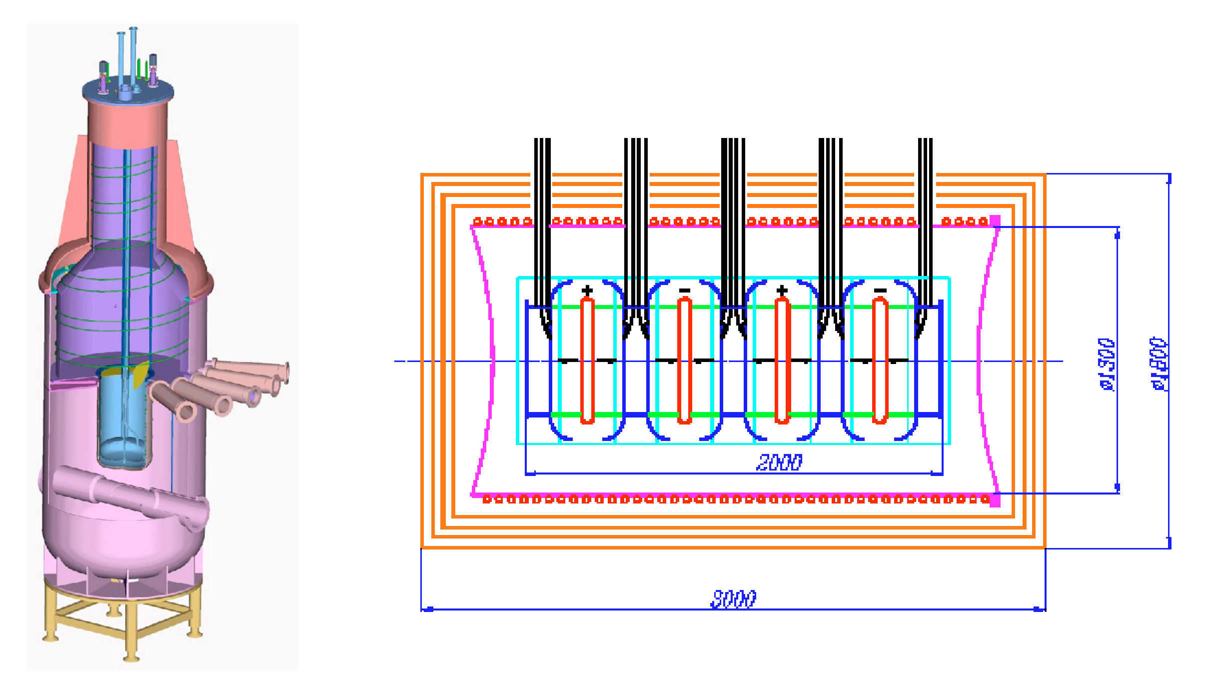

FIGURE 1. Left: Pre-engineering drawing of the PSI UCN source. The proton beam is delivered through the tube from the left-back. The spallation target is centered in the D_2O below the cryogenic insert which holds the SD_2 moderator. UCN are guided (^{58}Ni coated guide) from their place of production upwards into a Be coated storage vessel. Flapper valves separate the production guide and the storage trap and are closed after the production pulse. UCN can be extracted from the storage into experiments by the guide tubes at the bottom of the storage vessel. **Right:** A schematical top view of the planned EDM spectrometer. 5 guide tubes from the storage volume feed UCN through polarizers into the EDM apparatus, filling the 4 double high voltage chambers and the 5 control chambers without electric field. The magnetic field needed for the EDM experiment is provided by a solenoid which sits in an elaborate magnetic shielding. Only the 4 layers of the passive shielding are shown.

into UCN in superfluid helium [6, 7] or other suitable cold converters as, e.g., solid deuterium [8, 9, 10, 11, 12]. Especially the solid deuterium based pulsed sources have the potential to produce high UCN intensities with densities of about 10^3-$10^4\,\mathrm{cm}^{-3}$ [13, 14, 15].

THE PSI UCN SOURCE

The basic concept of the PSI UCN source is that of a pulsed production of UCN from solid deuterium. Figure 1 (left) shows a pre-engineering drawing of the PSI UCN source. Neutrons of 2 MeV average energy are produced on a lead spallation target in a macro-pulse (up to 4 s length) of the full PSI proton beam (590 MeV, 2 mA). There can be more beam pulses, but the total average proton beam current is limited to 10μA due to the shielding of the area. The spallation neutrons are slowed down and reflected in a large heavy water moderator tank. A block of solid deuterium (SD_2) is placed in the center of the D_2O and serves as a cold moderator for the production of a high cold neutron flux. UCN are produced in the SD_2 by down scattering of cold neutrons and are extracted from the top layer (several cm) of the SD_2 into a large storage volume ($2\,\mathrm{m}^3$). The UCN producing SD_2 layer will be operated below 8 K temperature, if possible around 6 K. The lower the temperature the more the reverse process of UCN upscattering can be suppressed. Care has to be taken to insure a good quality of the SD_2 moderator with respect to low ^{1}H contamination and low para-D_2 fraction. The importance of these quality aspects has been investigated recently [13, 16, 17]. The UCN from a proton pulse are extracted upwards by means of a ^{58}Ni coated guide into a Be coated storage volume. The production region will after the extraction be separated from the storage region by closing Be coated flapper valves. UCN can be extracted into experiments through a number of guide tubes, 5 of which are forseen to feed the first planned physics experiment, the search for an EDM of the neutron.

TABLE 1. SD_2 parameters of the PSI UCN source.

SD_2 volume [liters]	SD_2 top surface area [cm^2]	SD_2 heat load [W μA^{-1}]	SD_2 energy deposit [J g^{-1} mAs^{-1}]
27	2000	0.5	0.1

TABLE 2. Neutronics of the PSI UCN source. The cold flux $\Phi_{\rm cold}$ is given at the location of the UCN producing SD_2 layers. The density and number of UCN is given for 8 mC (2 mA × 4 s) and conservatively assuming a SD_2 temperature of 8 K.

$\Phi_{\rm cold}$ [cm^{-2} mAs^{-1}]	stored UCN density [cm^{-3}]	storage volume [liters]	number of stored UCN
1.3×10^{13}	2400	2000	4.8×10^9

There are two major concerns for the realization of a SD_2 based UCN source: (i) will it produce sufficient UCN, (ii) will it be possible to keep the SD_2 cold.

Over the last year detailed calculations have been performed on the neutronics properties of the PSI UCN source. Various codes have been applied, the MORSE code package, which was benchmarked with reactor data from PNPI Gatchina, the MCNPX code, and the PSI version of the HETC package, which was benchmarked on the PSI spallation source SINQ. All calculations presently agree reasonably on the obtained cold fluxes and even better on thermal fluxes and heat loads. As an example, Fig. 2 gives results of calculations applying the HETC package. It can be seen from Figure 2 (right) that the heat load in the top SD_2 layer is enhanced due to the load of the Zr container which encloses the deuterium. Even though calculations suggest that the energy deposition in these SD2 layers will not lead to temperatures above 8 K for a 4 s long proton pulse, the final optimum pulse length will be found experimentally. The whole design is flexible enough to allow for different pulse modes. The proton beam is brought onto the UCN target by kicking a fast magnet (typical time: around 1 ms). The full proton beam can be handled by the target for several seconds as well as any scheme with shorter pulses. The flapper valves, which separate the UCN guide and storage, are opened and closed for each pulse in order to allow the UCN to enter and to remain in the storage volume. The timing of the flapper valves will finally limit the useful pulse frequency.

Tables 1 and 2 list some of the important parameters of the UCN source.

THE EDM EXPERIMENT [*]

Currently the interest in the search for electric dipole moments is increasing again. With a two order of magnitude improvement in sensitivity for the neutron EDM experiments, it will be possible to test a large part of the supersymmetric parameter space to be investigated with the next collider generation. While the standard model prediction for the neutron EDM is about $10^{-31}\,e\,$cm, there is a good possibility to find it above $10^{-27}\,e\,$cm in presently favoured models. The present best published limits on the neutron EDM are around $d_n < 10^{-25}\,e\,$cm[18, 19] for which the limitations dominantly come from too low statistics. Therefore, there are two avenues for improvements: The first one is to increase the UCN density, and the second one is to increase the volume of the EDM apparatus. Our proposed EDM experiment will take advantage of both approaches. As previously described, there will be an average UCN density of 2400 cm^{-3} available in the storage volume. This translates into a density of 1600 cm^{-3} in our EDM experiment (see Fig. 1) and can be compared to a number of about 6 cm^{-3} in the currently operated EDM experiment at ILL[19]. The experimental volume of our proposed experiment will be 220 l as compared to 20 l.

The statistical uncertainty of an EDM experiment is $\Delta d_n \propto (\sqrt{N}\,E\,P^2\,\tau)^{-1}$, with the EDM d_n, the sample statistic N, the electric field strength E, the neutron polarization P, and the observation time τ.

In order to assess the sensitivity of our proposed EDM experiment we consider improvements over the currently running experiment[19], which shows sensitivities on the order of $\Delta d_n \approx 5 \times 10^{-26}\,e\,$cm. We denote the factors of improvement for our experiment by (i) $F_{\sqrt{N}}$, (ii) F_E, (iii) F_{P^2}, and (iv) F_τ, respectively. (i) We have chambers without electrical field for systematic checks. Both chamber types yield about the same statistics and it is planned to subtract their results in the analysis. We therefore do not gain the full statistical factor coming from the density and volume

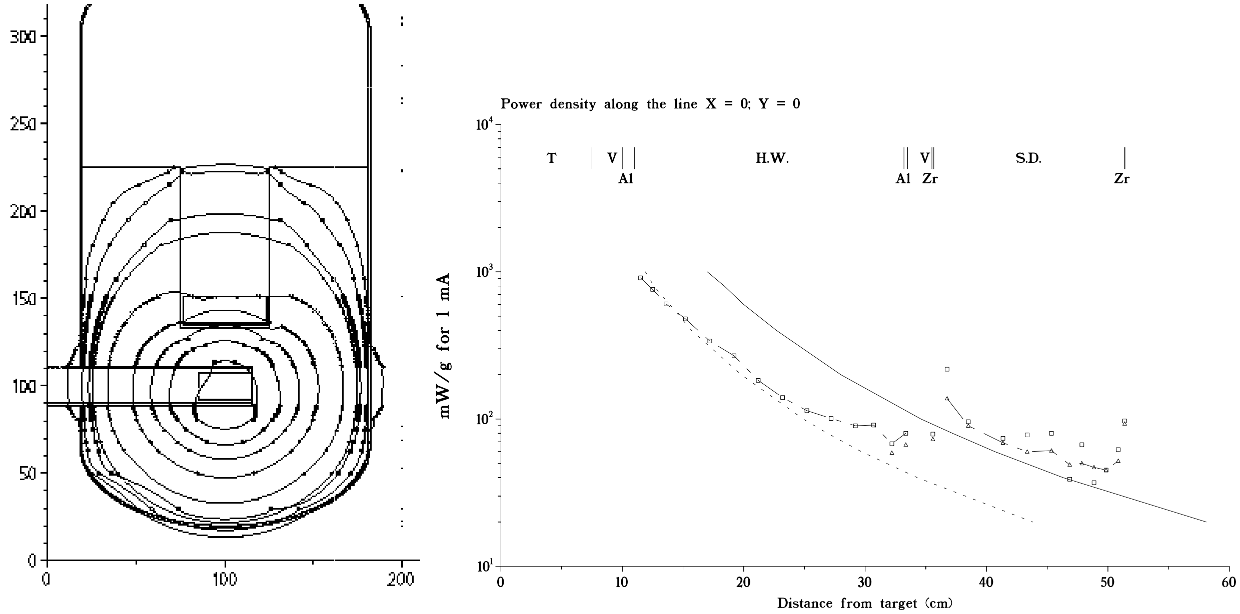

FIGURE 2. Calculational results obtained with the PSI version of HETC. **Left:** Total neutron flux contours superimposed onto an outline of the UCN source. Contours for 9 flux levels are shown, 10, 8, 6, 4, 2, 1, 0.8, 0.4 and 0.2 × 10^{13}/cm^2/sec for 1 mA proton current. **Right:** Power distribution along the vertical axis of the UCN source. At the top of the figure are shown the materials: T target lead; V void; Al Aluminium; H.W. heavy water; Zr Zircaloy; S.D. solid Deuterium. The squares and triangles correspond to different averaging (the power deposition is obtained from volume averaged track length estimates), the connecting lines are only guiding the eye. The two other lines are the results one obtains for a simple spherical model with a uniform moderator around the spallation target zone; the solid line is for SD$_2$ and the dashed line for D$_2$O.

increase, but $1/\sqrt{2}$ of it. $F_{\sqrt{N}} = 38$. (ii) The electric field in the ILL experiment[19] is limited to $8\,\mathrm{kV\,cm}^{-1}$ due to the Hg comagnetometer. The former PNPI experiment[18] was operated at $15\,\mathrm{kV\,cm}^{-1}$. Our experiment will run with $15\,\mathrm{kV\,cm}^{-1}$ and, therefore, $F_E = 1.9$. (iii) Our experiment will have less depolarization of the neutrons in wall collisions, because no compromise for the wall coating has to be made for an additional comagnetometer. We estimate $F_{P^2} = 1.3$. (iv) Due to less polarization loss, a slightly longer storage time will be possible, yielding a moderate improvement of $F_\tau = 1.1$. Overall, we obtain $F_{\sqrt{N}}\,F_E\,F_{P^2}\,F_\tau \approx 100$ which corresponds to a sensitivity of $\Delta d_n \approx 5 \times 10^{-28}\,e\,\mathrm{cm}$.

At this level of sensitivity there is a number of systematic effects which might influence the experiment. It is of course absolutely necessary to provide a stable magnetic environment and a resonance stabilization, which will be based on 16 Cs magnetometers sitting next to the measurement chambers. Most crucial are the systematic effects with a potential to mimic an EDM effect, thus giving a false positive result. The scheme proposed for our experiment has the capability to check on all these systematic effects. A scheme with double chambers, in which the electric field in one half is opposite to the other, greatly reduces the influence of spatially homogeneous magnetic field fluctuations. A set of 4 double chambers allows magnetic field fluctuations with gradients to be handled, the most nasty of which might be caused by leakage currents. Any leakage current in one chamber will be seen with decreasing signal amplitude in the neighbouring chambers. The chambers without electric field, sandwiching the measurement chambers, provide a close additional magnetometer system. An in-situ magnetometer is also given by the neutrons in the measurement chamber themselves, where one can add the signals from the differential chambers in order to cancel the high voltage induced effects. Detailed Monte Carlo studies of a variety of systematic effects and their possible treatment are under way. The magnetic field homogeneity and stability themselves are subjects of demonstration experiments which are presently set up.

CONCLUSION AND OUTLOOK

The UCN source project at PSI and the preparations for the EDM experiment are making good progress. The proton beam line to the UCN source has been put into place during the last shutdown in early 2001. Most of the shielding for the source and the experimental area is already in place. The modifications to the main proton beam line, which are needed in order to put in the fast kicker magnet, will take place during the next shutdown in early 2002. It will then be possible to insert the kicker magnet in a regular two day service break in summer 2002. Presently the investigations concentrate on the following important points: (i) magnetic field control and resonance stabilization for the EDM, (ii) proton beam kicking, (iii) spallation target development, (iv) SD_2 properties and preparation, (v) technology of large UCN storage volumes. We expect to have resolved all major physics and technology issues within a year's time. Assuming full funding at this point makes it feasible to have the UCN source running by 2004. The EDM experiment could be installed shortly thereafter.

REFERENCES

*. in addition to the listed institutions, St. Petersburg Polytechnical Institute, Russia and the State Optical Institute, St. Petersburg, Russia belong to the EDM collaboration. Both, the UCN and EDM collaborations are still open to new collaborating institutes. We also invite Letters of Intent for possible experiments to take place at the new UCN facility.

1. Zel'dovich, Ya. B., *Sov. Phys. JETP* **9**, 1389 (1959)
2. Luschikov, V. I., et al., *JETP Lett.* **9**, 23 (1969)
3. Steyerl, A., *Phys. Lett.* **B29**, 33 (1969)
4. Ignatovich, V. K., *Ultracold Neutrons*, Clarendon Press, Oxford, 1990; Golub, R., Richardson, D. J., Lamoreaux, S. K., *Ultra-cold Neutrons*, Adam Hilger, Bistol, 1991
5. Steyerl, A., *Nucl. Instr. Meth.* **125**, 461 (1975)
6. Golub, R., Pendlebury, J. M., *Phys. Lett.* **62A**, 337 (1977)
7. Huffman, P. R., et al., *Nature* **403**, 62 (2000)
8. Altarev, I. S., et al., *Phys. Lett.* **A80** (1980) 413
9. Golub, R., and Böning, K., *Z. Phys.* **B51**, 95 (1983)
10. Yu, Z.-Ch., Malik, S. S., Golub, R., *Z. Phys.* **B62**, 137 (1986)
11. Serebrov, A. P., et al., *JETP Lett.* **59**, 757 (1994)
12. Serebrov A. P., et al., *JETP Lett.* **62**, 785 (1995)
13. Serebrov, A. P., et al., *JETP Lett.* **66**, 802 (1997)
14. Pokotilovski, Yu. N., *Nucl. Instr. and Meth.* **A 356**, 412 (1995)
15. Serebrov, A. P., et al., *Nucl. Instr. and Meth.* **A 440**, 658 (2000)
16. Liu, C.-Y., et al., *Phys. Rev.* **B62**, R3581 (2000)
17. Kirch, K., et al., "Status of the New Los Alamos UCN Source," in *Application of Accelerators in Research and Industry 2000*, edited by J. L. Duggan and I. L. Morgan, AIP Conference Proceedings.
18. Altarev, I. S., et al., *Phys. At. Nucl.* **59**, 1152 (1996)
19. Harris, P. G., et al., *Phys. Rev. Lett.* **82**, 904 (1999)