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The PSI ultra-cold neutron source

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ABSTRACT

A new type of ultra-cold neutron (UCN) source based on the spallation process is under construction at PSI. The essential elements are a pulsed proton beam with highest intensity ($I_p \geq 2$ mA) and a low duty cycle (1%), a lead spallation target, a large D_2O moderator and a solid deuterium (sD_2) converter system. Spallation neutrons are thermalized in the D_2O, further cooled and partially downscattered into the ultra-cold neutron range in the sD_2. The expected UCN density is higher than 1000 UCN/cm^3 in typical experiments, an increase of almost two orders of magnitude over the best source currently available (at ILL). The new UCN source is expected to come into operation in 2009.

1. The PSI UCN source

The new UCN source under construction at PSI is based on the spallation process for neutron production followed by neutron thermalization in D_2O, and further cooling and downscattering in solid deuterium at 5 K. Protons from the 600 MeV PSI ring cyclotron with a continuous wave intensity of $I_p \geq 2$ mA, i.e. at a power of more than 1.2 MW, hit a spallation target made of lead-filled zircaloy tubes [1,2]. The proton beam is pulsed by deflecting the beam with a fast kicker magnet [3] into a beam line leading to the UCN source. The duty cycle is 1%, e.g. the pulse duration is 8 s every 800 s. The layout of the proton beam is shown in Fig. 1. As an alternative, mainly useful for the commissioning of the beam line, about 20 μA can be split off the full proton beam by means of an electrostatic splitter (EHT, see Fig. 1) situated very close to the kicker magnet in order to have almost identical beam envelopes of the kicked and split beams.

The average neutron yield from the spallation target is 10 neutrons per proton. The neutron energy distribution is broad with a mean around 2 MeV. These neutrons are thermalized in a 3.5 m^3 volume filled with D_2O (purity 99.75%), see Fig. 2. The lifetime of the neutrons in the D_2O moderator is about 5 ms, leading to a range of the neutrons in the moderator volume of typically 11 m.

The cold moderator (UCN converter) is installed near the center of the D_2O volume. It consists of an aluminium ($AlMg_{4.5}$) vessel with diameter 50 cm which can be filled with solid deuterium (purity 99.95%) up to 30 dm^3, corresponding to a thickness of up to ~15 cm, at a temperature of 5 K. The top of the vessel is formed by a toroidal lid of thickness 0.5 mm made from aluminium ($AlMg_3$), see Figs. 2 and 3. The deuterium can be solidified either from the gas or from the liquid phase. Neutrons entering the solid deuterium can be downscattered into the ultra-cold and very cold neutron range ($E_{kin} < 500$ neV) by phonon excitation. Upscattering is avoided by the low converter temperature and high ortho-deuterium concentration ($\geq 98\%$) [4,5]. Recently, the relevant slow neutron cross-sections of gaseous, liquid [6] and solid deuterium [7] have been measured as well as the integral UCN production from a cold neutron beam [8]. With a neutron lifetime in solid deuterium of about 30 ms

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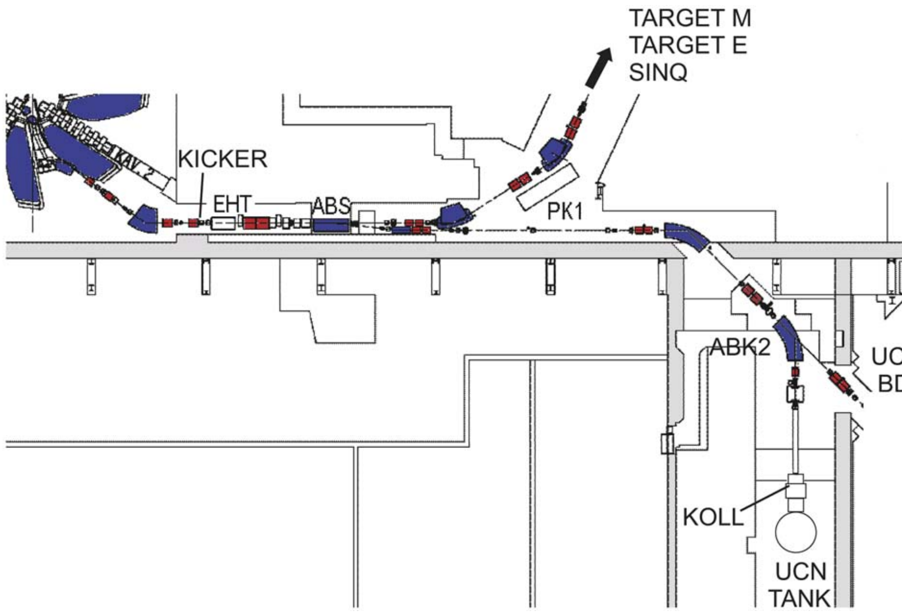

Fig. 1. Layout of the UCN proton beam line. After extraction from the PSI ring cyclotron, the proton beam is deflected into the UCN beam line by the kicker magnet (KICKER). At the second bending magnet (ABK2) the protons can either be directed onto the spallation target (UCN TANK) or onto a beam dump (UCN BD) for beam tests. EHT: electrostatical splitter for continuous wave operation at 20 μA; ABS: window frame septum magnet; KOLL: collimator in front of the spallation target; Target M, Target E: pion production targets; SINQ: continuous wave neutron spallation source [14].

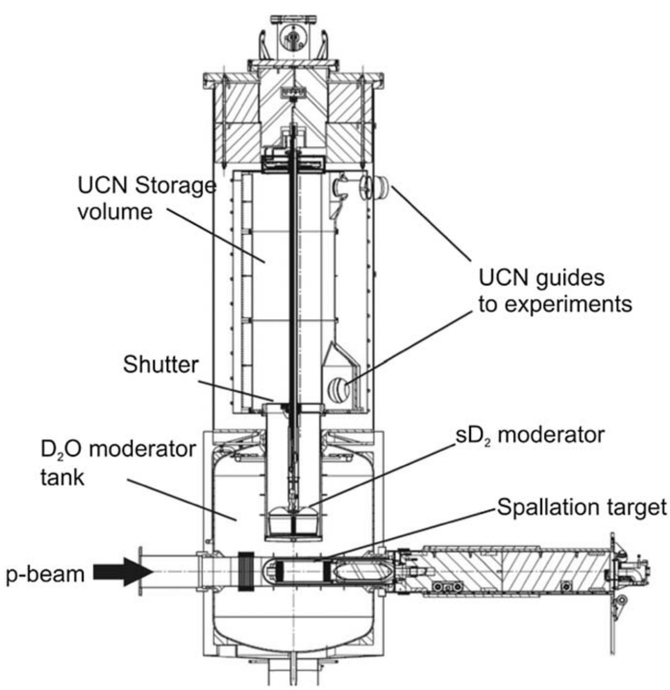

Fig. 2. Layout of the UCN source at PSI. The proton beam hits the spallation target from the left. Spallation neutrons will be thermalized in the ambient temperature D_2O moderator, further cooled and downscattered into the UCN regime in the cold sD_2 moderator. The UCN reaches the storage volume via a vertical neutron guide where they can be trapped and distributed to the experiments.

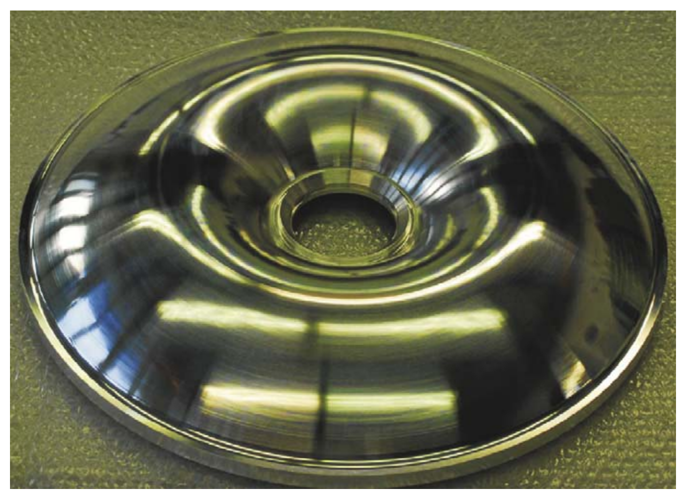

Fig. 3. The toroidal lid for the sD_2 converter made from $AlMg_3$.

[4,9,10] one expects a range of 15 cm for a UCN velocity of 5 m/s. Energy and velocity spectra of neutrons leaving the solid deuterium moderator have been measured recently [11,12]. Because of the material optical potential, $V_f(sD_2)\sim 105$ neV, the spectrum starts only at about 4.7 m/s. Downscattered neutrons leaving the moderator vertically are slowed down by gravity and a fraction of them (those with velocities $5\,m/s \leq v \leq 9\,m/s$ after leaving the deuterium) can be stored in the 2.4 m high UCN storage volume ($\sim 1.6\,m^3$), see Fig. 2.

With the proton beam on the spallation target, an equilibrium of produced and reabsorbed UCN is reached in the UCN storage volume after about 8 s (equivalent to the proton pulse duration, see above). At that time, a shutter at the bottom of the UCN storage volume (shutter in Fig. 2) is closed, the kicker magnet is switched off and the beam is taken away from the target. The UCN remaining in the tank have an expected storage time constant of about 500 s; this value is expected based on an experiment with a prototype storage volume coated with diamond-like carbon (DLC) [13].

2. Key components and their status

2.1. The proton beam line

The elements of the proton beam line (see Fig. 1) are installed and in operation. The new fast kicker magnet [3] which deflects the full proton beam into the UCN beam line, and the second dipole magnet (ABK2) which splits the proton beam again have been tested successfully. Protons can either be guided onto the spallation target or to a beam dump. The beam dump operation mode is to allow for tuning of the magnets of the first section of the beam line and to test major items including the profile and beam position monitors as well as their electronics under realistic conditions.

Proton beam tests with intensities up to 2 mA and duration of 10 ms using the fast kicker magnet have been successfully performed. It was demonstrated that the beam position monitors of the proton beam, necessary for the correct beam transport, are able to monitor the beam position along the beam line within 5 ms at a precision of better than 0.2 mm.

The diameter of the proton beam on the target is 20 cm; it is limited by a beam collimator in front of the target. Four beam-halo monitors (left, right, up, down) are mounted in this collimator to guarantee the correct beam size and maximal beam density ($40\,\mu A/cm^2$) on the target. The proton beam is ready for commissioning and operation of the UCN source.

2.2. The spallation target

The design of the neutron spallation target (see Fig. 2) is described in detail in Ref. [2]; it is similar to that of SINQ [14]. The target is made of 760 lead-filled reactor grade zircaloy tubes. During the proton beam pulse, about 70% of the beam power (approximately 840 kW at 2 mA proton beam intensity and, later, 1.3 MW at 3 mA) is deposited in the target assembly. The target array will be cooled with D_2O. During the proton pulse, the temperature of the coolant is increased by $\sim 10\,^{\circ}C$ leading to a D_2O temperature of $\sim 55\,^{\circ}C$. After the upgrade of the 600 MeV PSI ring cyclotron to 3 mA, this temperature will be $\sim 60\,^{\circ}C$. The target is ready for operation.

2.3. The D_2O moderator tank and the D_2O system

After their production in the spallation target, neutrons will be thermalized in a D_2O moderator at room temperature. The moderator tank is made of the aluminium alloy $AlMg_{4.5}$, has a diameter of 1600 mm and a D_2O volume of about $3.5\,m^3$. There are two inserts: (i) the horizontal proton beam pipe with the spallation target, see Fig. 2 and (ii) the vertical neutron guide.

During a proton pulse, the spallation target and the D_2O moderator will be heated by 6–10 MJ. In order to remove that heat, D_2O is pumped through the target with about $20\,dm^3/s$, through the target window with $3\,dm^3/s$ and through the ambient temperature D_2O moderator tank with $1\,dm^3/s$. The D_2O system of the UCN source is designed following the experience gained at SINQ [14]. The flux of the activated D_2O from the target and the moderator tank will be delayed in special pipe sections to reduce radiation levels in accessible areas. The D_2O system is equipped with an ion exchanger to remove corrosion and radioactive spallation products from the D_2O.

2.4. The solid deuterium converter

The solid D_2 converter is inserted through the vertical neutron guide. The design of the D_2 vessel is completed and the system is in production. Details about the cooling system are described in Ref. [15].

Previous R&D concerned, e.g. the investigation of materials with optimal transmission for very slow neutrons. Originally, reactor-grade zircaloy was favoured. The drawback of this material is connected with its unavailability in small quantities

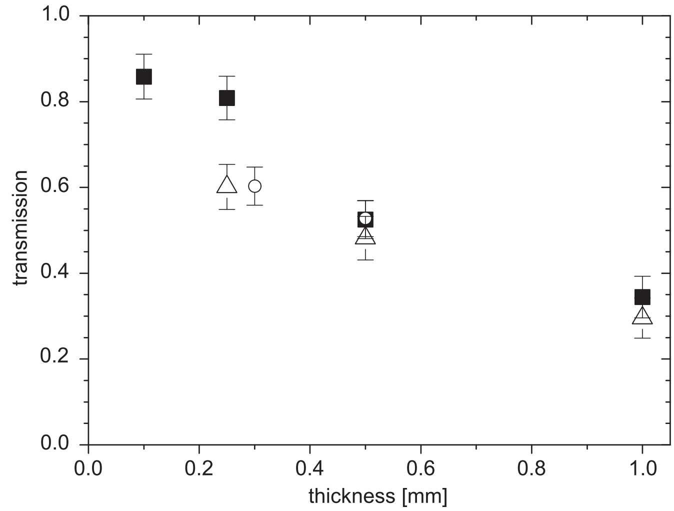

Fig. 4. Transmission of slow neutrons with velocities $5\,m/s \leq v \leq 9\,m/s$ through material foils. $AlMg_3$ (black squares), Zr_{110} (open triangles) and Zr_{125} (open circles).

and its purity (hafnium contamination less than 5×10^{-4}). At room temperature, the tensile strength of zirconium (and zircaloy) is about a factor 1.75 higher than that of $AlMg_3$, but the factor at low temperatures is only about 1.1. This means that the lid thickness of the solid deuterium vessel is very similar for the two materials.

The transmission of UCN was measured for a variety of materials. Aluminium alloys have a slightly better transmission compared to reactor grade zircaloy, see Fig. 4 and Ref. [30].

The geometry of the critical top part of the moderator vessel is optimized. The top of the moderator should be as thin as possible to minimize the loss of UCN, but the vessel has to withstand at least 3 bar over- and 1 bar under-pressure. Several lid geometries have been investigated (all using 0.5 mm $AlMg_3$): (i) a flat foil, (ii) a spherical dome and (iii) a toroidal shape. The third option (see Fig. 3) performed the best and will be used; samples broke at overpressures above 6 bar.

2.5. The UCN storage volume

Storage of UCN requires their total reflection under all angles at the walls of the bottle. So far, the best wall coatings for UCN storage containers, combining a high reflection potential and relatively low losses per bounce, are Be and BeO; the toxicity of Be and BeO give cause for concern. The neutronic properties of carbon are ideal if films of sufficient density are used. Pure diamond offers the best reflection potential, however, the cost for coating a several square meters area are prohibitive. Diamond-like carbon, where both tetrahedral (sp^3) and trigonal (sp^2) hybridized carbon atoms are incorporated into an amorphous structure, has been investigated for its use for UCN storage [16].

In a series of experiments [13,17–23], we have investigated the properties of DLC and other materials for the storage of UCN using different methods like storage in material bottles, foil transmission, cold neutron reflectometry, X-ray absorption near-edge spectroscopy (XANES), X-ray induced photoelectron spectroscopy (XPS), laser induced surface acoustic waves (LAwave), and Raman spectroscopy. We find in all cases that the optical potential for DLC in use is comparable (even slightly higher) to that of Be, and the losses per wall collision are slightly lower than those on Be. As a conclusion, the storage volume of the PSI UCN source will be made of aluminium coated with nickel and, on top of the nickel, a 300 nm DLC layer will be applied. The storage volume will be operated at a temperature of less than 100 K. In order to avoid cryo pumping of rest gas contaminations (hydrogen, nitrogen, etc.) on the surface of the storage volume, an overall vacuum of better than 10^{-7} mbar is required. This will be obtained by means of a cryo pump at 5 K above the storage volume. Clearly, the 5 K cryo pump will be switched on before cooling down the storage volume.

The UCN storage container has a volume of 1.6 m^3 and has an almost square cross-section with edge lengths of 0.8 m and height of 2.4 m, see Fig. 2. The engineering design is completed. For fitting into the coating facility, it is composed of rectangular aluminium plates which will be screwed together along their edges. Tests concerning the slit sizes have been performed with a downscaled prototype. From these tests, we expect an overall slit size of 120 mm^2, i.e. a surface fraction of 1.4×10^{-5}. This value does not include the slits around the UCN shutter at the bottom of the storage volume (Fig. 2) and those at the connections leading to the experiments, that is the UCN guides and their shutters, see Ref. [24].

3. Conclusions

Most of the difficult design and manufacturing challenges of the PSI UCN source have been successfully solved. The PSI UCN source is nearing completion. Commissioning of the project will start in 2009 with an expected UCN density delivered for experiments of about 1000 UCN/cm^3. This number is extracted from UCN production and downscattering data [25–28] and Monte Carlo calculations of UCN transport in guides through the biological shield [29].

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