A solid-deuterium source of ultra-cold neutrons at the FRM-II

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Ultra-cold neutrons (UCN) will be produced at the new high-flux reactor FRM-II at Garching near Munich in a solid-deuterium storage source (Mini-D_2). The UCN density in this source is expected to be nearly three orders of magnitude larger than that reached in the up-to-now strongest UCN source (at Institut Laue-Langevin in Grenoble).

The scheme of Mini-D_2 is simple: a small cylindrical volume (diameter about 6 cm, length 9 cm) with solid deuterium, the *converter*, is coupled to a large cylindrical evacuated *storage tube* with Be-coated walls (diameter also 6 cm, length about 7 m). The source will be installed with the converter very close to the cold source of FRM-II and the core-far end of the storage tube already outside the moderator tank.

Solid deuterium at temperatures around 5 K is a good converter. The UCN production rate from cold neutrons is large, the absorption cross section small (in the mbarn/atom region for 40-K neutrons), and the up-scattering cross-section at 5 K even smaller. Most of the UCN produced in the converter leave it into the storage tube before being up-scattered or absorbed. The losses in the tube, mainly by up-scattering or absorption at the Be-coated walls, are small, as its temperature is kept at about 25 K. The energy band of the neutrons in the tube reaches from 100 neV, the energy a neutron gains when it leaves the deuterium, to about 250 neV, the maximum energy for total reflection at the Be-coated walls. With a cold-neutron flux of $3 \cdot 10^{13}$ cm^{-2}s^{-1} at the place of Mini-D_2 we expect UCN densities of about $5 \cdot 10^{4}$ cm^{-3} and a corresponding UCN flux of about $3 \cdot 10^{6}$ cm^{-2}s^{-1}, when the end of the storage tube is opened to an experimental set-up.

The solid-deuterium in the converter will be produced by deposition of deuterium gas on the 5-K converter walls. As the storage tube is kept at 25 K, the amount of solid deuterium deposited on its walls is small. The necessary cooling power for the source, about 160 W at the 5-K level and 400 W at 25 K, is provided by two separate cooling systems.

Another UCN source is investigated at the moment at Garching. An existing set-up for super-fluid helium at 0.7 K, MARK 3000, has been transferred from Japan and successfully cooled. It shall be tested in autumn at FRM-I.

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Introduction

For a long while ultra-cold neutrons (UCN) have been successfully employed to study different aspects of fundamental physics, especially, two key properties of the neutron, its electric dipole moment and its lifetime. This is due to the fact that UCN have very special characteristics: owing to their very low energy (typically below 300 neV, which corresponds to a velocity of 7.5 m/s) they can be stored in bottles using three different fundamental interactions. Due to their long wavelength UCN impinging on a material surface see an effective potential which may be repulsive (for Be, e.g., as high as 252 neV). If absorption is small (suitable materials like Be have absorption probabilities of around 10^{-5}-10^{-4} per wall collision), neutrons will be reflected many times from the material just as light gets reflected from mirror-like surfaces. In addition, the interaction of the magnetic moment of UCN (μ_n = -60 neV/T) with a magnetic field gradient is of the same order, allowing to store neutrons in magnetic bottles or rings. Last but not least, the gravitational interaction is such, that neutrons loose about 100 neV/m moving upwards in a gravitational field. Thus, the study of particle properties of the neutron can ideally be performed with bottled neutrons, as trapping allows long observation times for the neutrons.

The precision of current experiments is mostly limited by the comparatively low number of UCN available for storage or in-flight experiments: At the measuring times available at high-flux reactors they not only impede to accumulate a sufficient number of events but also hinder a very thorough test for systematic uncertainties. An increase of UCN densities by orders of magnitude would open a completely new range of accuracy. It is just this aim that guided us to develop powerful sources for ultra-cold neutrons for the research reactor FRM-II at Garching.

Different concepts for improved UCN sources have been discussed. They partly require a dedicated design incorporated into the presently foreseen structure of the new research reactor.

Starting point for the design of the concept of a modern, powerful UCN source is a good matching of the source to the experiments. The importance of this statement becomes apparent, when the UCN density at the exit of the neutron turbine at ILL of 50 cm^{-3} is compared with the numbers for the initial densities finally obtained in the succeeding storage experiments some 5 m apart from the turbine exit: generally much less than 1 cm^{-3}. Almost two orders of magnitude are lost by transportation and mismatching. To avoid this large loss factor the experiment has to be joined carefully to the exit of the source. A special low-loss shutter system has to be developed. Complicated branched neutron-guide systems have to be omitted. Instead, the various experimental set-ups should be movable to be easily attached just in time to the terminal of the source.

Good matching in time is equally important. Conventional permanent beam-on experiments need high continuous neutron fluxes. Here a continuously operating nuclear reactor is well adapted as a driver for the source. However making use of the special feature of UCN – the possibility for storage experiments – requires a pulsed operating mode of the source. The source should provide high-density UCN pulses of at most some seconds duration with a frequency of typically one pulse every 5 minutes. If the source is driven by a continuously operating nuclear reactor as the FRM-II, then the UCN produced in the intervals between succeeding pulses should be accumulated (storage source). Accumulation may lead to a large gain factor.

The general path to achieve a source with high UCN intensity is to shift the maximum of the Maxwellian distribution to lowest possible energies by keeping the moderator temperature low. UCN are produced by inelastic down-scattering of higher-energy neutrons, i.e. neutrons which lose energy by creating excitations in the moderator material. The UCN produced travel through the moderator making elastic collisions, until they (a) leave the moderator, (b) are captured or (c) are up-scattered to leave the UCN-energy region. Disregarding the first two loss mechanisms, up- and down-scattering are balanced at thermal equilibrium. Up-scattering depends strongly on the moderator temperature. Below a certain temperature, where the up-scattering is negligible compared to absorption, the equilibrium becomes independent of temperature. It does not make sense to cool the moderator still more. The resulting source is called super-thermal.

The converter material should have a high inelastic scattering cross section and low absorption cross-section. The only stable converter material without any absorption is ^{4}He. At a temperature of about 0.5 K the equilibrium is dominated by losses due to the neutron decay and during wall collisions, and maybe also by absorption in ^{3}He-contaminations. The optimum energy for the incoming neutrons is about 1 meV, corresponding to a temperature of 12 K or a velocity of 440 m/s. Therefore the converter has to be exposed preferably to the neutron flux from a cold source.

A converter material with very low absorption cross section and rather high production rate is solid D_2 at a temperature of about 5 K. Below ~5.5 K up-scattering in solid deuterium is less important than absorption. The incoming neutron flux should have a temperature of about 30 K, which fits well to the cold-neutron flux from a liquid-D_2 cold source operated at about 25 K [Yu86]. The dimensions of the converter need not be larger than the effective diffusion length of UCN in deuterium (~14 cm). The probability to escape from the converter is small for UCN from deeper layers. Therefore the volume of the deuterium may be smaller than about 10^3 cm^3. A small volume is advantageous with respect to the heat load by neutron and γ radiation. The maximum temperature may be smaller, and with it the up-scattering.

In the beam tubes close to the core of FRM-II the thermal neutron flux will be about $8 \cdot 10^{14}$ cm^{-2}s^{-1}, which can be used to produce high UCN fluxes and densities. Three types of UCN sources are studied for the new facility, the storage source Mini-D_2 [Tri98], the storage source Mark3000 [Yos84] and a large solid- deuterium source as a second-generation cold source.

Mini-D_2 source

The Mini-D_2 UCN source proposed for the FRM-II [Tri99] will have a rather small converter (~150 cm^3) of solid deuterium at 5 K, positioned inside the SR4 beam tube near the cold source. A schematic view of the source is shown in Fig. 1. The converter is placed in a long evacuated storage tube. One end of this tube (containing the converter block) is directed towards the cold source of the reactor, the other towards the experiments outside the reactor shielding. UCN produced in the converter can escape into the storage tube. Here a UCN density builds up, which is given by the equilibrium of the production rate in the converter with the total loss rate, consisting of (a) absorption and up-scattering in the converter, (b) losses during wall collisions (absorption or up-scattering), (c) decay, and possibly (d) escape through holes. The walls are covered with a thin layer of beryllium (with a repulsive potential U_{Be} = 252 neV). They have to be cooled to temperatures below about 30 K to obtain wall losses as low as $5 \cdot 10^{-5}$ per collision. Furthermore the roughness of the surface should be less than the wavelength of the UCN (~0.1 µm).

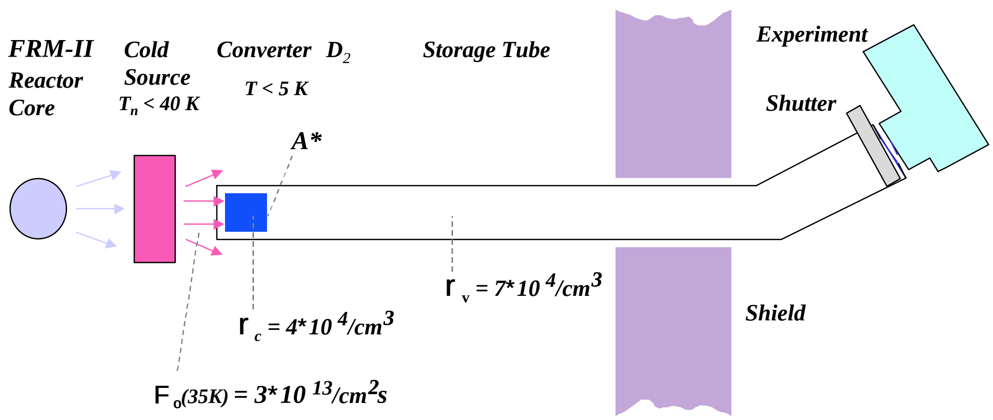

Figure 1. Scheme of the reactor-driven UCN source Mini-D_2

The UCN density in the tube will reach about the same magnitude as in the converter, if the total losses in the storage tube are small compared with those in the converter. The storage-tube first works as a buffer, where the UCN can survive much longer than they would do in the converter, and secondly it transfers the high UCN density from near the converter to the experimental area. Of course the probability of diffuse reflection at the walls should be small. After reaching saturation density (~200 - 300 s) the UCN can be extracted at the far end of the storage tube into the experiment.

The storage tube with a diameter of 6 cm, a length of 7 m and an outside bend of 45^o is made of aluminum alloy. It is double-walled to provide helium for cooling. There are two separate cooling circuits: the 5 K circuit is only for the very end of the converter. The total heat load at this level will be ~160 W. The second circuit keeps the rest of the tube at a temperature of ~25 K, slightly above the boiling temperature of D_2 under normal pressure. Thus the deuterium block can be solidified in place directly from the gas phase at the cold end, while the rest of the tube stays free of deuterium. The total heat input at the 25 K level is ~400 W. The storage tube is inside a vacuum vessel, which is inserted into the SR4 beam tube of the FRM-II reactor. A plan view is shown in Fig. 2.

Engineer's cutaway views of the inner part of the beam tube, the vacuum vessel and the storage tube are shown in Fig. 3. Additional shielding against γ radiation and neutrons is worked out at the moment.

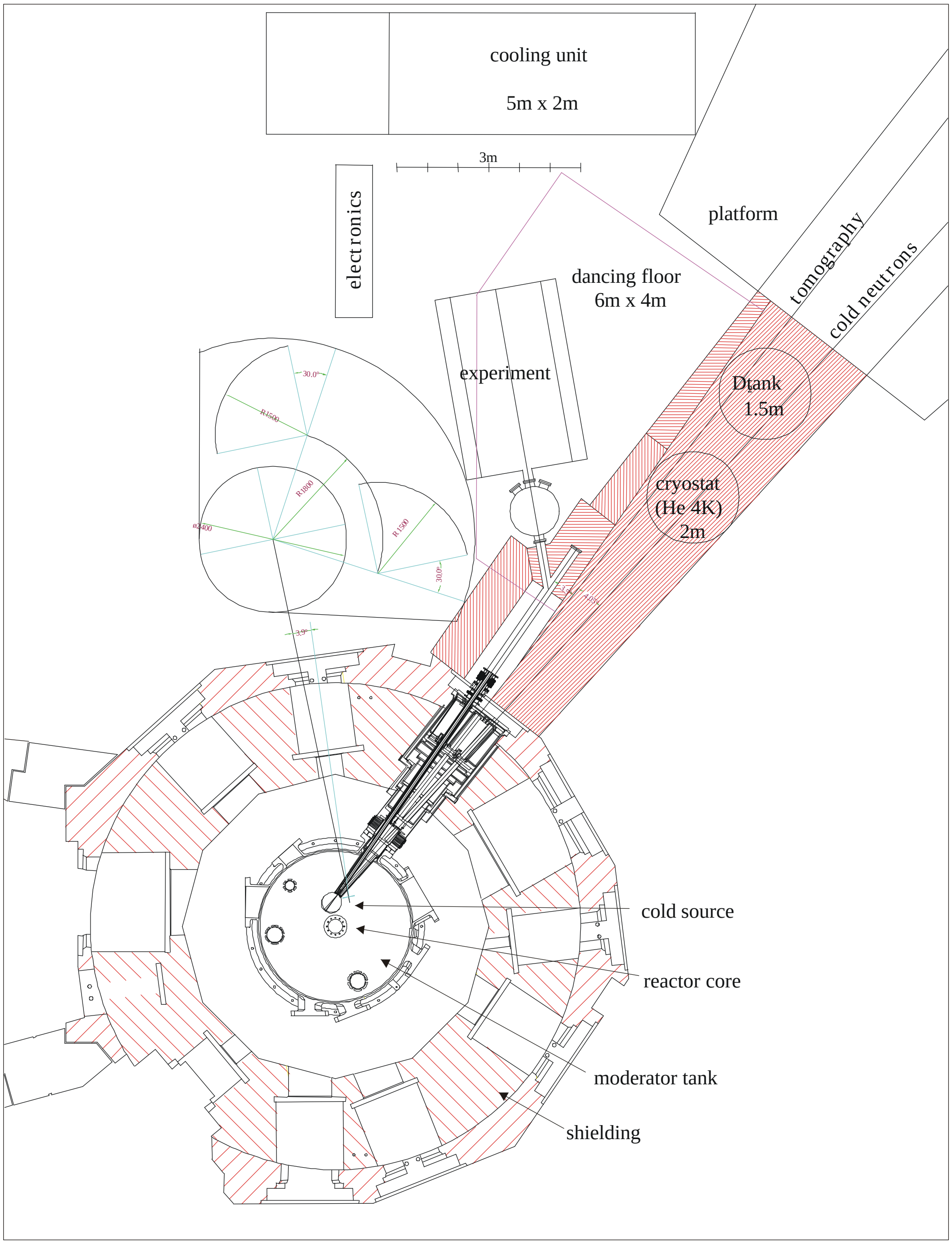

Figure 2. Plan view of the reactor core with the UCN source in beam tube SR4

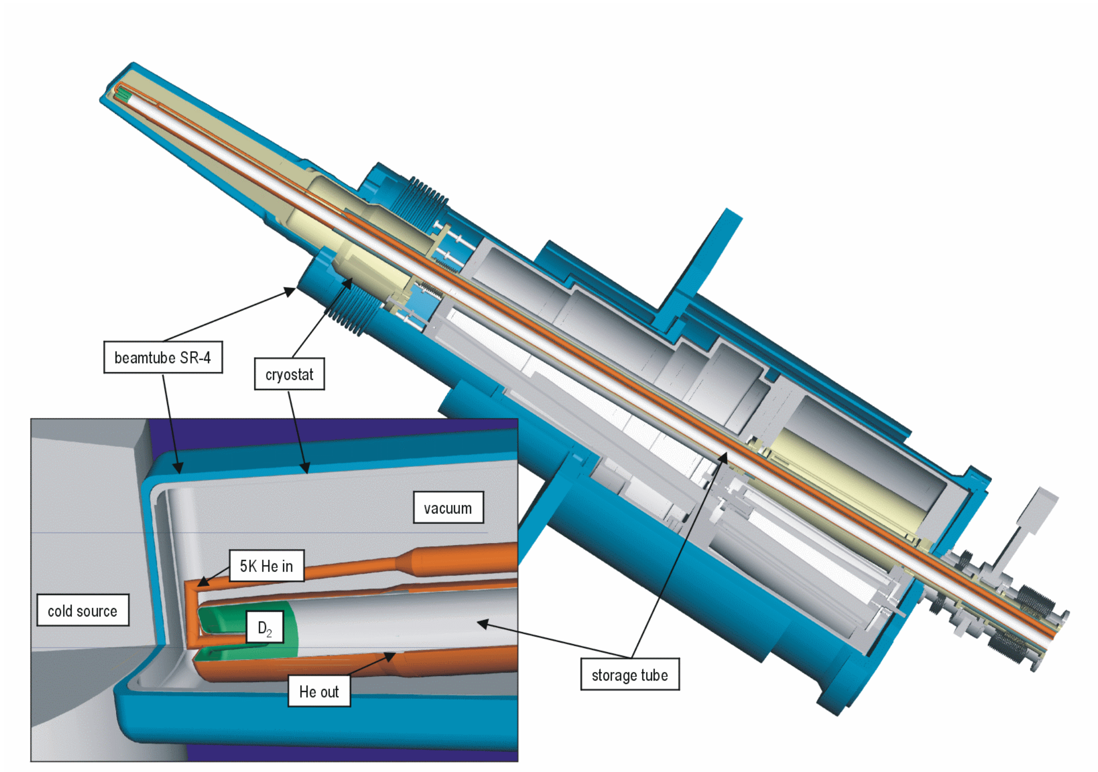

Figure 3. Cutaway view of the inner part of the beam tube SR4 with the Mini-D_2 UCN source.

The expected UCN densities were calculated in incoherent approximation using realistic phonon spectra [Yu86]. The production rate in the solid-deuterium converter with a temperature of 5 K is $5{\cdot}10^5 cm^{-2}s^{-1}$ for an incoming cold neutron flux (30 K) of $3{\cdot}10^{13}$ $cm^{-2}s^{-1}$. The maximum UCN density in the converter will be $4{\cdot}10^4$ cm^{-3}. Due to the effective potential of U_D = 102 neV of deuterium the UCN are accelerated when entering the vacuum of the storage tube. This causes, according to Liouville´s theorem, an increase in density by a factor of 1.6 in the vacuum part. This factor is somewhat reduced by the fact, that UCN have to flow permanently away from the converter interface to replace the losses at the walls and by decay. Therefore directly in front of the converter a UCN density of $\sim 6{\cdot}10^4$ cm^{-3} results. Depending on the probability of diffuse reflection during wall collisions (less than 20% for well polished surfaces) one gets between $2{\cdot}10^4$ cm^{-3} and $6{\cdot}10^4$ cm^{-3} at the end of the storage tube in front of the experiment. In the whole tube (volume $2{\cdot}10^4$ cm^3) more than 10^9 UCN will be confined, that may be extracted from the tube by opening a shutter at its end. If this shutter would stay open all the time, then the continuous UCN flux would be up to $3{\cdot}10^6$ $cm^{-2}s^{-1}$.

The density distributions along the axis of the converter and the storage tube are shown in Fig. 4. The calculations are based on the diffusion theory for UCN transport; the results shown here are obtained with a wall loss factor of $\mu=5{\cdot}10^{-5}$ and for different diffuse-reflection probabilities [Tri99a].

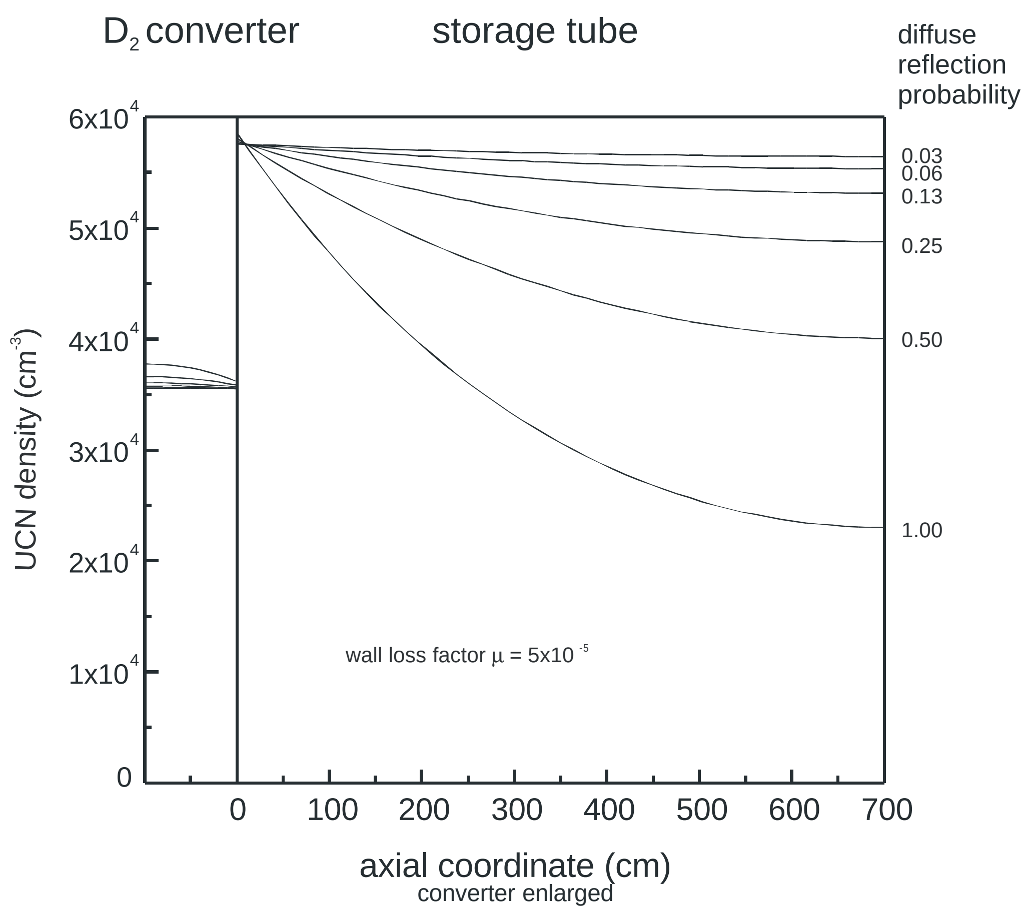

Figure 4. UCN density distributions along the axis of the converter and the storage tube.

Mark3000

A very high UCN density may be produced in super-fluid helium at low temperature(0.4 K) by single and multi-phonon processes after a rather long storage time (400s). Since the ^{4}He absorption cross section is zero, the storage time *t* is limited only by the neutron lifetime, the helium purity and the absorption cross-section of the wall material. While passing through a super-leak (compressed Al_2O_3 powder with 200   grain size) the super-fluid helium in the storage volume is cleaned. Neutron absorption can be reduced by sputtering Be on the storage volume walls, which at the same time enables UCN with up to 252 neV to be stored.

The super-fluid helium UCN source Mark3000 [Yos94] has been recently transferred from Japan to Germany. We intend to improve its performance by coating the walls of the storage volume with beryllium. In the upgraded 15-liter storage volume of Mark3000 mounted at the cold-neutron (CN) guide QR-II of FRM ($d\Phi/d\lambda\,(\lambda = 8.89$ Å$) = 4\cdot10^6$ cm^{-2}s^{-1}Å^{-1}) the UCN density should become $\rho = 100$ cm^{-3} after $t = 400$s. At the CN guide H17 of ILL ($6\cdot10^7$ cm^{-2}s^{-1}Å^{-1}) a density as high as

ρ = 580 cm^{-3} may be achieved. The comparatively large neutron density at QR-II is due to the small curvature of the QR-II CN guide. This leads to a shift in the CN spectrum to smaller wavelengths and a larger contribution from multi-phonon processes (61.6% for QR-II at FRM, only 3.2% for H17 at ILL). At a FRM-II CN guide with small curvature, $\rho = 10^5$ cm^{-3} may be achieved.

The UCN will be detected in super-fluid helium by means of a special PIN-diode detector [Kaw96]. 150 double layers of ^{62}Ni (30 Å) and ^{6}LiF (60Å), whose scattering lengths have opposite signs, are vaporized on a 880 Å thick ^{58}Ni reflector on the PIN-diode surface. The reflectivity of the layer arrangement will be about 20%. Therefore the UCN will penetrate into the multi-layer and can be detected via the ^{6}Li(n,α)t reaction, where either the α particle or the triton is measured by means of the PIN diode (4π detector).

Big SD_2 source

As an alternative a large solid-deuterium source has been proposed by [Ser98]. A 40-cm diameter sphere of solid deuterium will be cooled by super-critical helium to about 6K. Three neutron guides will transport cold, very cold and ultra-cold neutrons to the experimental hall. The expected UCN flux at the periphery of the source is $1.2\cdot10^7$ $cm^{-2}s^{-1}$. According to the calculations, the CN flux should reach $1.3\cdot10^{14}cm^{-2}s^{-1}$ and the VCN flux still $1.2\cdot10^{12}cm^{-2}s^{-1}$. The heat release is expected to be around 500 W, but may be decreased by shielding the source with bismuth. One could imagine other schemes, e.g. with the solid deuterium partially replaced by deuterium liquid. However, at this moment the net advantage of such an additional installation is not yet clear, in particular in view of the cost and safety aspects involved.

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