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An ultracold neutron source at the NC State University PULSTAR reactor

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Abstract

Research and development is being completed for an ultracold neutron (UCN) source to be installed at the PULSTAR reactor on the campus of North Carolina State University. The objective is to establish a university-based UCN facility with sufficient UCN intensity to allow world-class fundamental and applied research with UCN. To maximize the UCN yield, a solid ortho-D_2 converter will be implemented coupled to two moderators, D_2O at room temperature, to thermalize reactor neutrons, and solid CH_4, to moderate the thermal neutrons to cold-neutron energies. The source assembly will be located in a tank of D_2O in the space previously occupied by the thermal column of the PULSTAR reactor. Neutrons leaving a bare face of the reactor core enter the D_2O tank through a 45 x 45 cm cross-sectional area void between the reactor core and the D_2O tank. Liquid He will cool the disk-shaped UCN converter to below 5 K. Independently, He gas will cool the cup-shaped CH_4 cold-neutron moderator to an optimum temperature between 20 K and 40 K. The UCN will be transported from the converter to experiments by a guide with an inside diameter of 16 cm. Research areas being considered for the PULSTAR UCN source include time-reversal violation in neutron beta decay, neutron lifetime determination, support measurements for a neutron electric-dipole-moment search, and nano-science applications. © 2001 Elsevier Science. All rights reserved

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1. Introduction

Since the discovery of the neutron by Chadwick in 1932, free neutrons have been studied in experimental apparatus where they have remained in the free state for times on the order of milliseconds or less. Conversely, with the advent of sources of ultracold neutrons (UCN) [1,2], free neutrons have been stored in material bottles for 100s of seconds. Such storage is due to UCN total reflection (analogous to total internal reflection of light) from surfaces of many materials at all angles of incidence.

The UCN interaction with the surface of solids depends on their kinetic energy. If the kinetic energy is above the material optical potential, neutrons enter the bulk and will be absorbed or upscattered, with probabilities proportional to $1/v$ where v is the speed of the UCN. If the kinetic energy is below the optical potential, then the neutron will be totally reflected with a probability approaching 1. Neutron optical potentials for various materials range up to 350 neV. Thus UCN are defined as neutrons with kinetic energies less than 350 neV, corresponding to a neutron speed of 8 m/s and wavelength of 500 Å. Due to the low energies of UCN, the Earth's gravitational field (102 neV/m) causes strongly curved parabolic flight paths for UCN. Also, magnetic traps can confine UCN due to the magnetic interaction with the neutron magnetic moment (60 neV/Tesla).

Material-bottle storage and magnetic trapping of UCN have been used for measurements of fundamental properties of the neutron as tests of theories beyond the

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Standard Model of particle physics. In condensed matter applications, it is the UCN selective probabilities of interaction that lead to unique techniques to study surface and bulk properties of materials However, more UCN sources than presently available are required for future fundamental experiments and to exploit UCN for studies of condensed matter.

For years the only UCN source available to users was the PF2 facility at the 50-MW research reactor of the Institute Laue-Langevin (ILL), Grenoble, France. A turbine of receding totally reflecting blades produces UCN from gravitationally slowed neutrons emitted by a liquid-deuterium cold-neutron source [3].

Another concept of UCN production is to use a converter coupled to a cold neutron moderator. In the converter a cold neutron becomes an UCN by a single down scattering event [1,2]. To be efficient the converter has to be cooled below the temperature of the incident cold neutrons. Two materials are proven to be the best as UCN converters: superfluid ^{4}He with its almost unlimited UCN life time at temperatures below 0.5 K [4,5] and, more recently, solid ortho-deuterium (SD_2) with its combination of a large production rate and reasonably long UCN life-time in the bulk of a crystal cooled below 5 K [6-7]. The requirement of a lower operational temperature restricts the use of liquid He mostly to cryogenic experiments [8-10], where the UCN are produced and studied in the same cryostat, while SD_2 is used for external user facilities. The conditions necessary for a SD_2 converter to achieve the highest UCN density are: a deuterium temperature of < 5K to limit UCN up-scattering by phonon absorption, minimizing ordinary-hydrogen content in the deuterium to limit UCN absorption, and maximizing the ratio of ortho to para deuterium to limit spin-flip up-scattering of UCN. A SD_2 based UCN source was recently successfully demonstrated at LANL [11].

At present there are several solid-deuterium sources in the design and construction stages worldwide: the SUNS facility at Paul Scherrer Institute (PSI) [12], the Mini-D_2 source at FRM-II, Munich, with its test-bed source at the TRIGA of the Mainz Technical University in Europe [13], the UCNA source at Los Alamos National Laboratory [14] and the PULSTAR source at North Carolina State University (NCSU) in the USA. Each of these UCN sources has a unique approach to producing and coupling cold neutron fluxes to a UCN converter. To produce primary neutrons, the UCNA and SUNS sources utilize pulsed spallation targets, and the Mainz TRIGA, a 200-kW reactor, utilizes 6-MJ pulses; whereas, the FRM-II and the PULSTAR are reactors operated in continuous power mode.

2. The PULSTAR reactor

The PULSTAR reactor at NCSU is a heterogeneous pool-type reactor. The core is located at the bottom of a light-water 15,600-gallon above-ground aluminum-lined reinforced-concrete pool. The pool water serves as the neutron moderator, core reflectors, and primary coolant. At high operating powers, up to the maximum of 1-MW, the core is cooled by forced convection, utilizing a secondary system with a cooling-tower.

The PULSTAR fuel is similar to that of nuclear power reactors, both in composition and geometry. It consists of pellets of sintered uranium dioxide stacked in long thin-walled zircaloy-2 tubes. The uranium is enriched to 4 % ^{235}U. A 5 x 5 closely packed array of these pins forms fuel assemblies. The reactor core (~ 40 x 38 x 60 cm) consists of a 5 x 5 array of the fuel assemblies. The UO_2 and lattice-water volume fractions are 0.38 and 0.39, respectively.

Compared to other 1-MW research reactor designs, the PULSTAR requires a core loading of significantly more ^{235}U, has a much higher ratio of fast to thermal flux in the core, and has a much higher rate of fast-neutrons leakage out of the core faces. These attributes give the following benefits: a) a significantly longer core lifetime both due to more ^{235}U and by replacing water reflectors, one face at a time, with graphite reflectors and then with beryllium reflectors, and b) the possibility of realizing a strong source of neutrons from one face of the core, rich in fast neutrons, by removing the reflector from that face.

3. The PULSTAR UCN source

The design of the PULSTAR UCN source is based on the concept of a SD_2 converter coupled to a solid methane (CH_4) cold neutron moderator. This structure is immersed in a tank of room temperature heavy water (D_2O) and located in the space previously occupied by the PULSTAR thermal-column facility. Consequently, core neutrons that enter the tank are thermalized in the D_2O, transformed to cold neutrons in the solid CH_4, and converted to UCN in the SD_2. A hollow graphite structure is inserted between the core and the D_2O tank. This structure (known as the nose port) was designed (by MCNP Monte Carlo simulations) to enhance neutron leakage from the core into the thermal-column enclosure. Specifically, a helium-filled 45 cm x 45 cm x 70 cm long void in the nose port channels neutrons from the bare face of the reactor core into the thermal-column enclosure. Figure 1 shows an MCNP diagram of the Monte Carlo model of the UCN source including the nose port between the core and the D_2O tank. To minimize radioactivity of the UCN source and auxiliary equipment in the thermal column enclosure, the void in the nose-port can be routinely filled with reactor pool water to act as a shutter to stop neutrons from entering the thermal-column enclosure. A shielding box that contains bismuth is placed between the core and the entrance of the nose-port to reduce heating of the UCN source by core gammas. This box can be removed independent of the nose-port to change the thickness of the bismuth. It also reduces the sensitivity of the reactor reactivity to the water filling of the nose port.

Figure 2 shows the nose port in location in the reactor pool during testing.

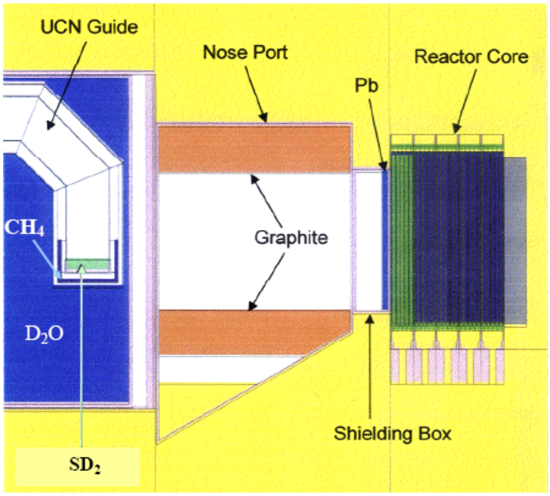

Fig. 1. MCNP geometry plot showing general layout of the nose port, UCN source, and UCN guide. The reactor-core and nose-port MCNP models have correct engineering details; the UCN source and UCN guide MCNP models are conceptual.

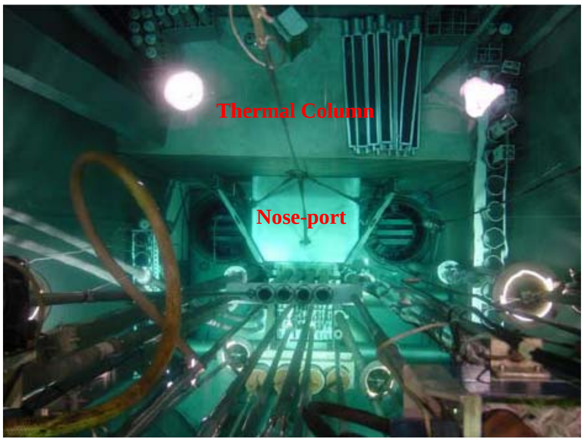

Fig.2 Photograph (top view) taken through 20 feet of tank water showing the Nose Port in place between the reactor core and the reactor tank liner.

The location of the UCN source in the thermal-column enclosure provides a relatively large well-shielded housing (120 x 120 x 200 cm) for the source and auxiliary equipment. Furthermore, this region is web-reinforced by 5-cm thick aluminum walls and constructed in such a way as to have safety isolation between the reactor core and the UCN source.

The entire UCN source structure is placed in a cryostat with vacuum housing that is surrounded by the D_2O. The UCN SD_2 converter is designed to be 4.5-cm thick and is placed at the bottom of a 17-cm inner diameter container that is shaped as a vertical elbow to guide the UCN out of the cryostat. The vertical rise of the guide is about 50 cm. The solid CH_4 cold moderator is designed to have a 1-cm thick cup-shape and surrounds the SD_2. Diamond-like-carbon (DLC) coated quartz tubing will be used as a UCN guide inside as well as outside the cryostat. This is expected to provide an excellent combination of high optical potential and high specularity of reflection for UCN transport. The UCN guide following the elbow to outside the biological shield of the PULSTAR reactor will be made of several segments combined at small angles to suppress the background of gamma-rays and neutrons down to the required radiologically and experimentally acceptable levels.

Based on the MCNP model shown above, the cold neutron flux (0 - 10 meV) averaged over the SD_2 converter is calculated to be 5 x 10^{11} n/cm^2·s for a reactor power of 1-MW. The calculations are based on the cross sections of liquid deuterium at 20 K and solid methane at 22 K. Using various models for the cold-to-UCN down-scattering cross sections (in SD_2) leads to a predicted UCN production rate for the neutronic conceptual design in the range of 0.8x10^4 – 1.5x10^4 n/sec·cm^3.

3. Cryogenic system for the PULSTAR UCN source

The proper operation of the PULSTAR UCN source requires solidifying 200 g of deuterium as a single crystal, and then maintaining this crystal below a temperature of 5 K during reactor operation. Approximately 600 g of CH_4 needs to be solidified and kept at a temperature between 20 and 40 K. The uncertainty in temperature is related to the uncertainty in the knowledge of the UCN production cross sections of the SD_2 [15].

The deuterium (D_2) and CH_4 gas handling systems will have ballast tanks connected permanently to the cryostat, through a filling line with a proportional valve, and a return line with a check valve. In the case of D_2, there will be an additional filling line bypassing the ballast tank and leading to a para-ortho converter. During conversion, the cryostat will act as a cryopump for collecting ortho-deuterium. After the conversion is done, deuterium will be warmed up and collected in the ballast tank for routine operation of the source.

The cryostat will incorporate a liquid He heat exchanger at the bottom of and around the sides of the D_2 container. A zircaloy ring will be inserted between the SD_2 chamber and the bottom of the vacuum jacket of the UCN guide to give a temperature gradient region. A thin aluminum window will seal the top end of the UCN-guide elbow (Fig. 1) to avoid D_2 access to the warm part of the UCN guide and to stop black-body radiation from warming the SD_2 converter. The CH_4 container will be surrounded by He-gas cooling channels followed by a black-body radiation shield. The latter will be thermally and mechanically attached to the He exhaust tubing of the CH_4 heat exchanger.

The system that provides liquid He to cool the D_2 and CH_4, is based on a small permanently installed He liquefier/refrigerator with a maximum of either refrigeration power of 60 W or 17 l/h of liquefaction without liquid nitrogen pre-cooling. From MCNP and COSMOS SolidWork simulations, it is expected that at 1-MW reactor power, the total heat load to the SD_2 converter and CH_4 cold neutron moderator is about 5 W and 8 W, respectively. A mixed liquefaction/refrigeration mode will be used to provide 20 W of refrigerating power for the solid SD_2 and 12 l/h to cool the CH_4 and the neutron guide inside the cryostat. At this stage, this is found to be sufficient even when taking into account additional heat leaks in the transfer lines, bayonets, and valves. The cooling system will have a 1000-liter dewar with liquid He available to keep the cryostats cold in case of a power failure. This is desirable since growing a suitable SD_2 crystal is a long and uncertain process.

A detailed conceptual design of the cryostat has been completed. At present, optimization of the cryogenic He flow inside the cryostat is being performed using the ANSYS CFD code system. The main design objectives are to maximize the heat transfer coefficient, provide the optimum conditions for the SD_2 crystal growth from either vapor or liquid, and to reduce the instability of the flow due to abrupt change in geometry, for instance, at the entrance of the He evaporation chamber.

Figure 3 shows an example of the SD_2 temperature distribution for two cases: (a) deuterium crystal filling the container homogenously, and (b) partly separated from the wall. The latter situation can happen due to shrinking when the crystal is cooled from 18 K down to 5 K. The maximum temperature gradient over the crystal is 0.37 K for (a) and 0.29 K for (b). Isothermal surfaces are symmetric relative to the center. The simulation model used only a gaseous phase flow at 1 g/s mass flow rate. Usage of a He liquid-vapor mixture will decrease the absolute temperature at the same mass flow rate. Analysis of other geometries is in progress.

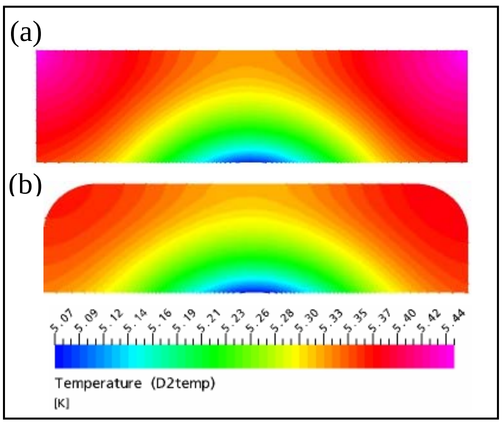

Fig. 3. CFD simulation results for the SD_2 temperature distribution for 2 cases: (a) deuterium crystal filling the container homogenously, and (b) crystal partly separated from the wall. In both cases the He mass flow rate is 1 g/sec; and the He temperature is 4.5 K at the inlet. The inlet is at the center of the bottom. Neutron and gamma volumetric heat loads are 1 W to deuterium and 1 W to aluminum. The conduction heat load is 2 W through the surfaces of the aluminum walls.

Conclusion

The design of the PULSTAR UCN source is based on the concept of a SD_2 converter coupled to a cold neutron moderator (solid CH_4) and to a thermal neutron moderator (room temperature D_2O). The cold neutron flux (0 - 10 meV) averaged over the SD_2 volume is calculated to be 5 x 10^{11} n/cm^2·s at a reactor power of 1 MW leading to an estimation of the UCN production rate in the range of (0.8 – 1.5) x 10^4 n/sec·cm^3. At 1-MW reactor power, the total heat load to the SD_2 converter and CH_4 cold-neutron moderator is expected to be approximately 5 W and 8 W, respectively. The cryogenic system of the source will use a He refrigerator in a mixed liquefaction/refrigeration mode to provide 20 W of refrigerating power for the SD_2 converter at 5 K and 12 l/h to cool the CH_4 to temperatures between 25 k – 40 K. Optimization of the He heat exchanger geometries for deuterium and methane are in progress using the computational fluid dynamics code ANSYS CFD.

Acknowledgments

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