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Title: RECENT UCN SOURCE DEVELOPMENTS AT LOS ALAMOS

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RECENT UCN SOURCE DEVELOPMENTS AT LOS ALAMOS

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1 Introduction

The most intense sources of ultra cold neutrons (UCN) have been built at reactors where the high average thermal neutron flux can overcome the low UCN production rate to achieve usable densities of UCN. At spallation neutron sources the average flux available is much lower than at a reactor, though the peak flux can be comparable or higher. We have built a UCN source that attempts to take advantage of the high peak flux available at the short pulse spallation neutron source at the Los Alamos Neutron Science Center (LANSCE) to generate a useful number of UCN. In our source UCN are produced by Doppler-shifted Bragg scattering of neutrons to convert 400-m/s neutrons down into the UCN regime. This source was initially tested in 1996 and various improvements were made based on the results of the 1996 running. These improvements were implemented and tested in 1997. In sections 2 and 3 we will discuss the improvements that have been made and the resulting source performance.

Recently an even more interesting concept was put forward by Serebrov *et al.*[1] This involves combining a solid Deuterium UCN source, previously studied[2-4] by Serebrov *et al.*, with a pulsed spallation source to achieve world record UCN densities. We have initiated a program of calculations and measurements aimed at verifying the solid Deuterium UCN source concept. Our approach has been to develop an analytical capability, combine with Monte Carlo calculations of neutron production, and perform benchmark experiments to verify the validity of our calculations. Based on our calculations and measurements we plan to test a modified version of the Serebrov "UCN factory". We estimate that we could produce over 1,000 UCN/cc in a 15 liter volume, using 1 μamp of 800 MeV protons for two seconds every 500 seconds. We will discuss our recent UCN production measurements in section 4.

2 Rotor Source Improvements

Crystal Package

In our implementation of the rotor technique, a 6 x 6 cm^2 crystal moving at a velocity half the incident neutron velocity (396 m/s) is installed on the end of the 90-cm rotor arm. The crystal moves away from the incoming neutron pulse and Bragg scatters and Doppler shifts the neutrons down into the UCN regime. The velocity of neutrons that can be shifted down into the UCN regime depends directly on the lattice spacing of the crystal used.

In the past, synthetic thermica crystals having a 002 lattice spacing $d_{mica} = 9.96$ Å have been used. This spacing allows one to Doppler shift neutrons with velocities about 400 m/s. The range of velocities that can be Doppler-shifted is given by mosaic spread of the crystal in the scattering direction. Ideally, one would like a 3° spread in the scattering direction and a small spread in the transverse direction to completely fill the UCN velocity space of 0 to 8 m/sec. To accomplish this a crystal package can be designed using wedges of material between the mica converting layers to artificially broaden the mosaic in that direction.

The first version of the crystal converter, tested in 1996, used natural muscovite mica. The package was composed of 13 pieces of thickness about 0.0125 cm fanned at 0.2° with wedges of single crystal silicon separating the mica pieces. Rocking curves for this package were measured using 1.9-Å neutrons at the University of Rhode Island Research Reactor. The width of the rocking curve was measured several times, giving results between 1.6° and 3° (FWHM), about what was expected for this assembly. The reflectivity was rather low, about 1.8%, at least partially due to extinction effects in the very perfect muscovite crystals. Based on this we searched for improved reflector crystals; phlogopite was a potential candidate because artificial fluorinated phlogopite has been used in the Argonne rotor source.

The structure factors, which determine the strength of the coherent scattering and hence the reflectivity, for trioctahedral micas (such as phlogopite) are significantly larger than those for the dioctahedral micas (such as muscovite). The basic composition of phlogopite is $K_2Mg_6(Si_3Al)_2O_{20}(OH)_4$ - some of the Mg is often replaced by Fe, with the effect of further increasing the structure factor because of the relatively high scattering power of the Fe. Phlogopite crystals were obtained and rocking curves were measured on these samples. The crystals had macroscopic (mm to cm) ripples in the surface and rocking curves of width about 2° were measured on thick samples; thinner pieces mounted to flatten each other showed widths about 0.3°. The reflectivity of these crystals was about a factor of six higher than for muscovite of comparable thickness, mostly due to the increased structure factor and partially due to the imperfection of the phlogopite crystals.

The measured reflectivity must be extrapolated to 17.4 Å, the wavelength at which the rotor source operates. The wavelength dependence predicted by the ideally imperfect crystal model can be used to carry out the extrapolation. This model describes very well the absolute reflectivity measured at 1.9 Å and therefore it is probably reasonable. This model predicts that at 17.4 Å the average reflectivity will be 66%. Based on the measurements described above a crystal package was constructed using 10 layers of phlogopite material of thickness about 0.04 cm fanned out at 0.3°.

Beam Monitoring

Beam monitoring was performed with an ionization chamber mounted just before the beam stop, at a flight path distance of 10 m. The chamber consisted of an upstream electrode, a set of field defining grid planes, and a down stream electron collection region. The operating gas was a mixture of CF4 at a pressure of 1000 Torr and ^3He at 1000 Torr. The 4.34 atmosphere-cm of ^3He give an expected efficiency of near unity at velocities of up to 1000 m/sec . A low noise transimpedence amplifier amplified the current from the chamber; readout was performed using an LRS 9430 digitizing scope to store and average many beam pulses. The scope was readout over GPIB using the PCDAQ program.

The beam monitor was calibrated to determine the voltage output to neutron conversion by studying the channel-to-channel fluctuations in the voltage. If other sources of electronic noise can be eliminated, these fluctuations can be attributed to the counting statistics of the detected neutrons. The analysis is complicated by the fact that the current in the ion chamber has two components: a fast one due to the collection of the electrons and a slow on due to the collection of the positive ions. Therefore, the counting statistics at any time are a combination of those due to neutrons arriving at that time, and due to the sum of earlier neutrons. The slow and fast components of the ion chamber response were separated by moving the phase of the rotor across the neutron velocity spectrum and measuring the depth of the dips caused by the rotor moving through the beam. The result of the analysis described above gives a flux of cold neutrons (at 400 ± 7 m/s) of $1.1 \pm 0.3 \times 10^7$ neutrons/sec out of the 6 x 6 cm^2 guide tube.

UCN Guide Shutter

In order to take advantage of the high peak densities available at a spallation neutron source, it is necessary to use a shutter that allows the puff of UCN into the bottle in synchronism with the beam pulses and allows the shutter to be closed between beam pulses. The neutron shutter must be made out of a material that has a high critical velocity for UCN. The shutter must also make a seal with the UCN guide tube that is as hermetic as possible. The criterion that applies is that the area not sealed by the shutter should be small compared to the effective leakage area of the shutter, which is the cross-sectional area of the UCN beam guide multiplied by the fraction of time the shutter is open. In practice, a gap of a few mils provides minimal additional losses.

With a 6 cm x 6 cm^2 crystal package, the pulse width of the UCN is about 11 ms FWHM. In order to allow for reasonable opening and closing times of the shutter (a few ms), the shutter was designed to have a 33% duty factor, corresponding to an opening time of 17 ms. One concern is that the shutter be highly polished. As the shutter surface is moving at a velocity of more than 10 m/s, any surface roughness could cause the UCN to be upscattered beyond the critical velocity of the ^{58}Ni guides. In order to minimize this concern, the shutter was designed with two openings and run at 10 Hz, resulting in a velocity of the UCN shutter surface of about 6 m/s.

Two shutters were tested during the last run cycle. The first was made from polished stainless steel and the second from ^{58}Ni - coated polished stainless steel. The first shutter gave an indicated increase in the UCN flux of about 50%. Unfortunately, the second shutter was warped during laser cutting of the slots and thus did not make a good seal with the end of the UCN guide. We did not observe any measurable increase in the UCN flux with the second shutter.

3 UCN Measurements

A program of UCN measurements was made in 1997 with the purpose of characterizing the performance of the UCN source, identify possible areas in which improvements might be possible, and measuring the bottle lifetime of our proto-type UCN bottle. In all the measurements described here the UCN were detected in a proportional counter filled with 760 Torr of Ar-CO_2 and 20 Torr of ^{3}He. The pressures were chosen to make the detector very efficient for UCN while allowing them to penetrate far enough into the chamber to allow detector of both the proton and triton resulting from the capture on ^{3}He to be detected. Data were read in through FERA ADC's in CAMAC using the PCDAQ program. The results described here are based on our on-line data.

The initial measurement made was a direct UCN rate, without the rotating shutter on the UCN source. We read in the pulse height from the UCN detector, the time relative to the T_0 pulse and diagnostics of the UCN rotor. The rotor diagnostics came from lasers mounted opposite to the position of the rotor arm when the crystal package is in the cold neutron beam. The laser light is reflected from the rotor arm at the time the crystal package is in the beam. The timing of this light pulse with respect to the beam T_0 pulse is a measure of how well the rotor is synchronized to the beam. A TAC that is read into a FERA ADC generates this laser time, called RTIME. There is not a one-to-one correspondence between RTIME and UCN events, however. The laser pulse come at 20 Hz (actually at 40 Hz, but the electronics are set up to choose the pulse which coincides with the beam) and the UCN are distributed uniformly in time. Further, the UCN Time of flight (TOF) to the detector, of order seconds, is long compared to the time between laser pulses (50 msec). In the on-line analysis simply use the most recent value of Rtime; on replay this will be replaced with some average of previous measurements. The peak UCN rate is obtained when the rotor phasing is within 100 μs or so of the optimum value. The UCN rate was increased by a factor of 5000 over that achieved in 1996. Some of the increase production is attributed to the improved crystal package, some due to improved rotor timing, and improved alignment.

With the rotor system optimized, we typically detected 600 UCN/s. Correcting for the UCN guide solid angle (16%), the guide transmission (83% for 3 meters of guide), the detector window transmissions efficiency (90%), and the detector efficiency (95%), we arrive at a UCN production rate at the source of about 5300 UCN/s. Translating this production rate measured in the UCN detector to an UCN density at the source results in a value of the UCN source density of about 0.75 UCN/cm3.

A proto-type UCN bottle was designed and constructed. The bottle consisted of a 7.82-cm diameter stainless steel tube of length about 1 m. The bottle was equipped with rotating valves at each end that allow computer controlled opening and closing of the bottle for filling with UCN and emptying UCN into a detector. The valves are designed to allow the bottle to be closed with one of four different materials. The materials can be chosen to have different critical velocities and the velocity spectrum of the UCN can be determined by measuring the total number of UCN stored as a function of valve material.

The first ever measurements of UCN storage at Los Alamos were made during the 1997 running period. Initial measurements were made controlling the UCN bottle manually, with data being acquired only when the downstream valve was opened to empty the bottle. All the measurements were made with the UCN guide shutter rotating at 10 Hz. The UCN bottle was initially in an open position. The downstream valve was then closed and UCN were allowed to enter the bottle for one minute. The upstream valve was then closed and the UCN were stored for a variable length of time after which the downstream valve was opened and UCN were counted. The background counting rate was measured by performing the same sequence, but without opening the downstream end of the bottle. The plot of detected UCN as a function of storage time is shown in Figure 1. The data were fitted with an exponential and the bottle lifetime was determined to be 25 s. The total number of UCN stored extrapolates to 400 in a bottle with a volume of 4.5 liters for a proton beam current of 71 μA.

Computer control was instituted for the second set of measurements. This allowed the filling, storage, and counting times to be programmed with a delay box; the DAQ and bottle valves were driven by these signals. A typical spectrum obtained for approximately 10 filling and emptying cycles is shown in Figure 2. This corresponded to a total cycle time of 25 sec., with 3 sec. for filling and storing, 25 sec. emptying time, and the remainder straight through UCN. It can be seen that the counting rate during the emptying time, after all the UCN have been counted, is higher than the background rate during the storage time. We believe that this is an indication that there is leakage around the up-stream valve. The bottle lifetime measured during this second set of tests was much smaller than during the first set. This could be due to either surface contamination of the bottle or leakage around the valves. We hope that further analysis of this data will allow us to better understand the bottle performance.

4 Cryogenic Source Development

The absolute cross section for UCN production in solid deuterium has not been measured. Serebrov et al. made measurements of the UCN gain factor with a solid source in the neutron flux of a reactor. Our goal in the experiment described here was to make a measurement under controlled conditions that could be used to benchmark the calculations of UCN production that we have carried out.

To do this we constructed a cryostat in which we were able to cool a 450 cc solid deuterium sample to 5 K. We illuminated this cell with the cold neutron flux from the Hahn-Meitner research reactor and measured the resulting UCN production from a temperature 5 K, through the triple point, to liquid and then to gas. The preliminary data is plotted in Figure 3. From this preliminary data we observed a production rate from the solid was 0.2 UCN/second, with no temperature dependence from 5 K to the triple point. The lack of temperature dependence indicates that the UCN that are produced leave the solid deuterium without scattering. If there had been considerable scattering, the UCN propagation from the solid would have been diffusive, thereby increasing the contact time with the solid during which upscattering would be likely, and an effective loss of production would have been observed. This loss of production would show steep temperature dependence. To a good approximation, our result shows that a UCN produced in the solid exits without scattering.

We crudely determined the UCN spectrum by filling a 1 m long section of UCN guide with ^{3}He. We measured the observed UCN rate as a function of the ^{3}He pressure in the guide. The pressure dependence was combined with the $1/v$ dependence of the $n + {}^3He$ cross section to extract a mean velocity for the detected neutrons. The mean velocity from the solid was about 6.5 m/s, while somewhat higher from the gas, about 8.5 m/s.

Our results are significant in that we have confirmed our theoretical prediction of the UCN production rate based on the Debye model, and have shown the lack of temperature dependence of the UCN production rate from the solid. This result differs from that of Serebrov, in which an increase in UCN gain factor was observed as the temperature was lowered. The temperature dependence, however, is strongly dependent on the Deuterium volume as well as on the length of time the UCN stay in contact with the Deuterium (i.e. is it in a bottle). The PNPI Deuterium was a much larger volume (6 liter compared to .4 liter). In addition, our sample was in a much more controlled environment, and the conditions on the sample were precisely determined. Both experimental results confirm solid D_2 as a suitable material to be used in a spallation UCN source.

5 Summary and Future Plans

We are planning a number of improvements to the rotor source. A new mica crystal package is being prepared using artificially fluorinated phlogopite material. The incoherent scattering and absorption in this material is greatly reduced, allowing a package to be constructed with thicker scatterers. In addition, we found much variation in the reflectivity of individual mica pieces in the package used in 1997. We have therefore selected pieces for the new package by measuring the reflectivity of each individual piece. We estimate an increase in UCN production by a factor of more than 3 based on the reflectivity measurements we have performed.

A new target moderator system is being installed in the Lujan center. The cold neutron flux (per proton) from the new moderator should be increased by a factor of 2.3 over what was available in 1997. The proton beam current will be increased from 70 μamp to 100 μamp. We expect that the increase in UCN rate from the total of all improvements will be a factor of 10-15.

We are in the process of designing, and constructing a system to test the spallation UCN source concept. Neutrons will be generated by spallation on a Pb or W tungsten target using the 800 MeV proton beam at LANSCE. The production target will be surrounded by cold moderator material, which in turn will be surrounded by a Beryllium reflector. UCN will be produced in a cryogenic Deuterium sample, volume about 1 liter, within the cold neutron flux trap. The production volume will be connected to a 15-liter storage system that can be shuttered off when the proton beam is off, and opened when the proton beam is on. We expect the lifetime to be about 3 sec. when the shutter is opened, and 200-400 sec when the shutter is closed. We have estimated that we will be able to produce 400-1000 UCN/cc in the storage volume using 2 μamp-sec of proton beam. We hope to have this system ready to test during the upcoming LANSCE running period.

6 References

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4. A. P. Serebrov, V. A. Mityukhlyaev, A. A. Zakharov et. al. JETP Lett. (1997) (to be published)

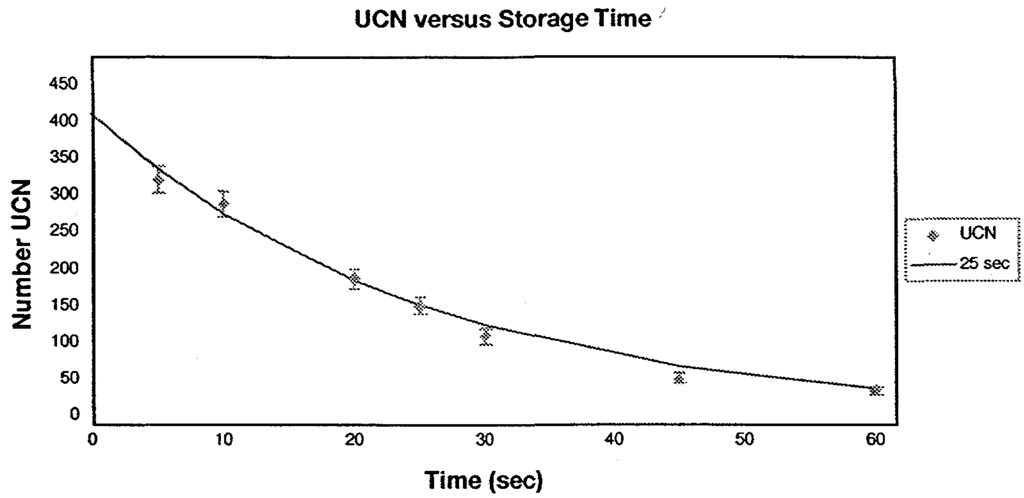

Figure 1: Number of UCN plotted as a function of the storage time (data points) and exponential decay curve using a decay constant of 25 seconds.

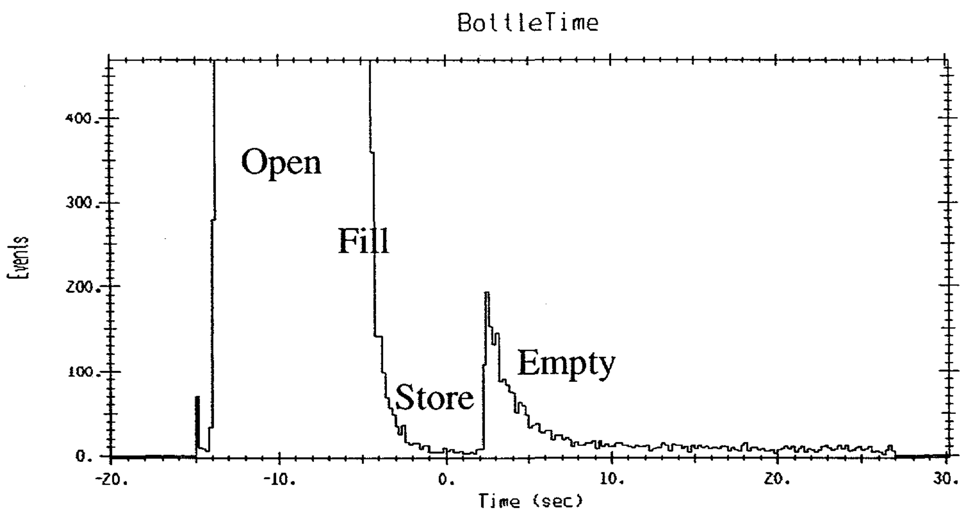

Figure 2: UCN counting rate as a function of time in the filling cycle.

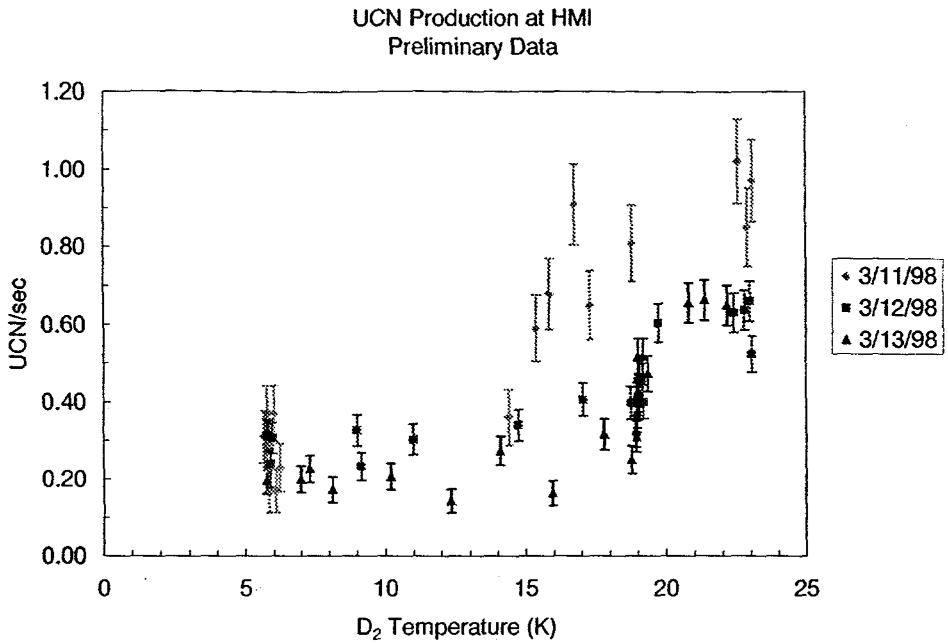

Figure 3: Preliminary data for UCN production from Cooled Deuterium.