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## An Ultra-Cold Neutron Source at the MLNSC

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### Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). We have carried out the research and development of an Ultra-Cold Neutron (UCN) source at the Manuel Lujan Neutron Scattering Center (MLNSC). A first-generation source was constructed to test the feasibility of a rotor source. The source performed well with an UCN production rate reasonably consistent with that expected. This source can now provide the basis for further development work directed at using UCN in fundamental physics research as well as possible applications in materials science.

### Background and Research Objectives

Ultra cold neutrons (UCNs) are neutrons whose wavelengths are sufficiently long (typically greater than 500 Angstroms) that they can undergo total internal reflection at all angles from the surfaces of a variety of materials. This leads to the possibility that UCNs can be totally confined within a bottle for periods in excess of 100 seconds, making a compact source of stored neutrons for use in measurements of fundamental physics.

The only existing sources have been at the ILL reactor in Grenoble and at the Gatchina reactor in St. Petersburg. UCN research at these facilities has resulted in the most sensitive measurements to date in the search for an electric dipole moment (EDM) of the neutron and in the highest precision measurements of the lifetime of the neutron. Both of these measurements are of great fundamental interest; the neutron EDM in trying to elucidate the origin of CP violation, and the neutron lifetime in determining the weak axial vector coupling constant and in a number of astrophysical applications, such as determining the number of light neutrino species in Big Bang nucleosynthesis.

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The benefit of using UCN in fundamental physics was recognized in the Long Range Plan formulated by the Nuclear Science Advisory Committee (NSAC) in 1989 in which it was stated: "A facility judged to be of major importance to this field (precision tests of fundamental interactions) is a source of cold and ultra cold neutrons." This need was again reflected in the 1995 NSAC Long Range Plan: "The lack of first-rate sources in the US is limiting basic experiments on parity violation, time-reversal violation, and the lifetime, electric dipole moment, and beta-decay angular correlation of the free neutron." The only two sources of available UCN are already oversubscribed. It is clear that additional sources with high UCN densities are required in order to advance the field of precise neutron measurements.

In addition to the fundamental measurements mentioned above, there is also interest in using UCNs to study gravity and other properties of the neutron (possibly electric charge, etc.). UCNs are also likely to be of interest in other areas of research, including material science, as they are highly sensitive probes of surface properties of materials, in contrast to thermal neutrons, which probe bulk properties. As neutrons can differentiate between light elements (such as hydrogen) and heavy elements (such as iron), and they are sensitive to the magnetic properties of the material, UCNs offer a unique new tool to study materials. In addition, as the wavelengths are quite long (a few hundred Angstroms), they are well suited to studies of macromolecules, which is of great interest in areas such as biology.

### **Importance to LANL's Science and Technology Base and National R&D Needs**

The research program using the LAMPF accelerator has moved towards a primarily neutron-based activity, with the Los Alamos Neutron Science Center (LANSCE) as the major facility. One of the goals of this program is to support a broad-based range of research, and as such, construction of a UCN source and establishment of a world-class research effort using UCNs will provide an entirely new (and unique in the US) research tool. Discussions with the Division of Nuclear Physics of the DOE have indicated their interest in a research program using UCNs and the nuclear physics planning effort carried at LANL in 1996 provides increasing funds over the next five years of DOE support for a strong program of UCN research using this source. The unique characteristics of UCNs have also been long realized in potential applications in materials science and biology. The dearth of available UCN sources has meant that this potential has never been explored. We expect that with a UCN source in the US there will be a significant prospect for applications of UCNs in research which may be of direct interest to both basic and applied research programs in materials science and biology. We plan to work closely with

personnel both within and outside of the Laboratory to ensure that all possible interests in these areas are explored.

The Laboratory has listed a UCN source at a Long-Pulse Spallation Source (LPSS) as its highest priority for a new facility in nuclear physics. A recommendation from NSAC in the 1995 Long Range Plan recommends support at the level of \$10M in funding to implement a UCN source at LANSCE if the LPSS is built.

With the move by the DOE Nuclear Physics program to no longer fund operations of the LAMPF accelerator, the future of all of the research programs at LANSCE is in question. The Laboratory has stated that a first-rate research program at LANSCE is one of its highest priorities. A broad-based research program at LANSCE is clearly vital to the future of basic research at the Laboratory. The Laboratory has developed a plan to assure a strong future for LANSCE-based research that will be primarily centered on neutron science with the Manuel Lujan Neutron Scattering Center (MLNSC) as the dominant facility. Efforts to realize this plan are well advanced and a strong program with continuing support has been put in place for neutron science at LANSCE in FY 1996. In the longer run, the Laboratory envisions construction of a LPSS, which would make LANL the premier neutron spallation facility in the world.

In order to ensure a first-rate program at LANSCE, the Laboratory is seeking to support a very broad-based field of research in neutron science. As an UCN facility at LANSCE would provide a research tool which is unique in the United States, and will open up new areas of research, this fits perfectly into the Laboratory's vision. A significant fraction of the fundamental neutron physics community has expressed serious interest in participating in the research program that will be available at LANSCE with UCNs. We see the strong interactions with the outside scientific community that will be generated by the existence of an UCN facility at LANSCE as providing a real enhancement to the overall future program at LANSCE.

### **Scientific Approach and Accomplishments**

The considerations for UCN production at a spallation source are quite different from a reactor. At a reactor, the production has best been done by converting cold neutrons into UCNs by multiple reflection from the rapidly moving blades of a turbine. Such a device has produced measured UCN densities of 87 UCN/cm<sup>3</sup> at the ILL reactor, a world record. This technique involves Doppler shifting 40-50 m/s neutrons down into the UCN regime (< 8 m/s) and can make effective use of the high cold neutron flux from cold moderators at reactors to provide continuous beams of UCNs. In a spallation source, a proton beam strikes a high-Z target in which approximately 1 neutron per 30 MeV of beam

power (compared to about 180 MeV for a reactor) is produced. These fast neutrons are then thermalized and cooled in a variety of moderators. In a Short-Pulse Spallation Source (SPSS), the proton pulse on the spallation target is typically a few  $\mu\text{s}$  or less in duration. At the MLNSC SPSS, the proton pulse is 270 ns long. In this case the pulse width of cold neutrons is determined by the moderator, which provides a pulse width of about 100  $\mu\text{s}$ .

At a SPSS, the high-energy spallation neutrons are not fully moderated and at present, the time-averaged flux is at least an order of magnitude less than that at the ILL reactor. However, one can take advantage of the pulsed nature of the source to produce and store UCN at the peak intensities available, which are comparable to or can exceed that at a reactor. A technique for doing this was demonstrated many years ago at the ZING-P' source at Argonne National Laboratory and at a test setup at LAMPF. This technique involves Doppler-shifted Bragg scattering of neutrons to convert 400-m/s neutrons down into the UCN regime. A rotor carrying a mica scattering crystal moves away from the neutron pulse from the liquid hydrogen moderator at one half of the velocity of the neutrons that will be converted into the UCN regime. The rotor velocity required is determined by the Bragg scattering condition associated with the lattice spacing of the crystal. For mica, one converts 395-m/s neutrons. In the center of mass frame, the incident neutrons are reflected back from the crystal with the same velocity at which they impinge on the crystal. In the laboratory frame, the 395-m/s neutrons are stopped. Thus, a puff of UCNs is produced which then begins to expand. Some fraction of the UCN cloud will drift into a guide tube placed close to the position at which the rotor intersects the neutron beam. A shutter at the entrance to the guide tube opens while the puff is expanding and closes after a few ms. Thus, it is possible to bottle the UCN at the peak flux rather than the average flux. The penalty paid is that the filling time will be longer at a SPSS than at a reactor. However, for a rather wide range of experiments, this is not a serious concern.

At Los Alamos, we have installed such a rotor converter on the existing LANSCE cold moderator. The moderator is viewed by a  $^{58}\text{Ni}$ -lined guide tube with a cross-section of 6 cm x 6 cm. At a position about 8 m from the moderator a 6 cm x 6 cm mica crystal moving away from the neutron pulse at a velocity of 200 m/s has been installed on the end of a rotor that rotates in synchronism with the beam pulse rate. A schematic view of the UCN source at LANSCE is shown in Figure 1.

### Rotor Design

The requirements on the rotor are that it be frequency stable for long periods, free from vibrations, not affect other nearby instruments due to the drive motor, have a hydrogen-free vacuum system, and preferably that the plane of the conversion crystal be

normal to the direction of the neutron beam during conversion (i.e., that there be zero tracking error).

The rotor must rotate at the same (or a multiple of) frequency as the proton beam from the Proton Storage Ring (PSR), namely 20 Hz. The rotor must have high frequency stability, as phase variations of more than 0.5 degrees between the rotor and the beam arrival time will result in a loss of UCN density.

The question of mechanical stability, freedom from vibrations, and noninterference with other instruments were concerns that affected the design of the rotor and Flight Path 11B (FP11B). The crystal package experiences 5600 G of acceleration and thus must be carefully designed and constructed in order to survive for a long period of time. We designed the rotor arm to be very close to statically balanced and then had the arm dynamically balanced by ET Balancing in California. The rotor drive motor and vacuum vessel were equipped with sensitive piezoelectric accelerometers that were monitored during all operations in order to ensure that no large vibrations were being experienced by the rotor drive. All of this proved to work extremely well. The vibrations were minimal and the rotor system basically works like a light bulb - you turn it on and forget about it.

#### *Mica Crystal Package*

A 6-cm x 6-cm crystal moving at a velocity that is half of 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 have been used that have a 002 lattice spacing  $d_{mica} = 9.96 \text{ \AA}$ . 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  $3^\circ$  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 used natural muscovite mica. The package was composed of 13 pieces of thickness about 0.0125 cm fanned at  $0.2^\circ$  with wedges of single crystal silicon separating the mica pieces. Rocking curves for this package were measured using  $1.9\text{-\AA}$  neutrons at the University of Rhode Island Research Reactor. The width of the rocking curve was measured several times, giving results between  $1.6^\circ$  and  $3^\circ$  (full width at half maximum-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  $2^\circ$  were measured on thick samples; thinner pieces mounted to flatten each other showed widths about  $0.3^\circ$ . 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  $17.4 \text{ \AA}$ , 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  $1.9 \text{ \AA}$  and therefore it is probably reasonable. This model predicts that at  $17.4 \text{ \AA}$  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  $0.3^\circ$ .

### ***FP11B Design***

The present UCN source makes use of the existing cold moderator at LANSCE. The moderator is a gadolinium decoupled liquid para-hydrogen LH<sub>2</sub> moderator 12-cm x 12-cm x 5-cm deep which is irradiated by fast neutrons from both the upper and lower tungsten LANSCE targets in a flux-trap geometry. The decoupling serves to reduce the neutron pulse width at the expense of both total and peak intensity; we would benefit strongly by going to a fully-coupled moderator.

The existing UCN source uses Flight Path 11B. A vacuum finger insert fits into the FP11 penetration through the bulk shield. The distance from the moderator surface to the guide entrance is 116 cm. The FP11 penetration views the moderator surface at an angle of about 15 degrees. Inside the finger insert is an assembly consisting of a thin aluminum entrance window, shielding materials, and two 6-cm x 6-cm cold neutron guide tubes. The guide tubes are composed of 1.5-m long, 1-cm thick flat glass plates polished to an optical finish and coated with  $^{58}\text{Ni}$ . At the edge of the bulk shield the finger insert mates

to an external shutter box. This allows the last 2 m of the guide assembly to be rotated through 90 degrees in order to shut off the neutron beam to the two guides, FP11A and FP11B.

The critical velocity depends on the material used to coat the guide tubes. A list of the critical velocities,  $v_{lim}$ , of a variety of materials is given in Table 1. The critical velocity is determined from the measured coherent neutron scattering length of the material by the formula  $v_{lim} = h/m \sqrt{N a_{coh}} / \pi$ , where  $m$  is the neutron mass,  $N$  is the density of scattering centers,  $a_{coh}$  is the coherent scattering length, and  $h$  is Planck's constant.

Table 1. The coherent scattering lengths  $a_{coh}$ , density  $\rho$ , and critical velocities  $v_{lim}$  are given for a variety of materials.

Material	$a_{coh}$ ( $10^{-12}$ cm)	$\rho$ (gm/cm <sup>3</sup> )	$v_{lim}$ (m/s)
Al	0.35	2.70	3.24
Al <sub>2</sub> O <sub>3</sub>	2.42	3.7	5.13
Be	0.774	1.80	6.89
BeO	1.35	3.02	6.99
C	0.665	1.80	5.47
C (graphite)	0.665	2.25	6.11
C (diamond)	0.665	3.25	7.65
Ni	1.03	8.9	6.84
<sup>58</sup> Ni	1.44	8.9	8.14
SiO <sub>2</sub> (glass)	1.58	2.3	4.26
Stainless Steel	0.86	8.03	6.0

### **Beamline 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 downstream electron collection region. The operating gas was a mixture of CF<sub>4</sub> at a pressure of 1000 Torr and <sup>3</sup>He at 1000 Torr. The 4.34 atmosphere-cm of <sup>3</sup>He give an expected efficiency of near unity at velocities of up to 1000 m/sec. The current from the chamber was amplified by a low-noise trans-impedance amplifier and was read out using an LRS 9430 digitizing scope to store and average many beam pulses. The scope was read out 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 one 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  $400 \pm 7$  m/s) of  $1.1 \pm 0.3 \times 10^7$  neutrons/sec out of the  $6 \times 6$  cm<sup>2</sup> 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 UCNs into the bottle in synchronism with the beam pulses and to have the shutter closed between beam pulses. The neutron shutter must be made out of a material that has a high critical velocity for UCNs. The shutter must also make a seal with the UCN guide tube that is as hermetic as possible. The applicable criterion 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 crystal package, the pulse width of the UCNs 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 UCNs to be upscattered beyond the critical velocity of the <sup>58</sup>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 <sup>58</sup>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.

### Monte Carlo Calculations

Extensive Monte Carlo calculations were carried out at Los Alamos and at the University of Rhode Island in order to be able to predict the expected UCN density and

production rate of the UCN rotor source. The comparison between the Monte Carlo calculations and the production rates agree within a factor of three with the Monte Carlo results predicting higher than the observed UCN rates. Thus, in terms of an absolute prediction, the Monte Carlo simulations provide reasonable guidance. A primary factor in the difference between the Monte Carlo predictions and our measurements may be due to the fact that the input to the Monte Carlo simulations assumes a reflectivity at 17.4 Angstroms that is scaled from the measured reflectivity at 2 Angstroms using a scaling law of  $\lambda^3$ . Thus, we are extrapolating the reflectivity by an order of magnitude from that measured at 2 Angstroms. We have now carried out measurements of the reflectivity of the mica crystal package at 17 Angstroms both statically (with the rotor stopped) and dynamically (with the rotor running at full speed). We are currently analyzing the data and expect to have results soon that should shed some light on this difference.

The Monte Carlo simulations have proved particularly good in reproducing the observed relative performance of the rotor source. Thus, we have confidence in the ability of the Monte Carlo simulations to reliably predict the change in UCN production rate when a given parameter is changed. This allows us to model various different situations and to predict the change in performance. This is quite important in being able to design upgrades of the source.

### 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 prototype UCN bottle. In all the measurements described here, the UCN were detected in a proportional counter filled with 760 Torr of Ar-CO<sub>2</sub> and 20 Torr of <sup>3</sup>He. The pressures were chosen to make the detector very efficient for UCNs while allowing them to penetrate far enough into the chamber to allow both the proton and triton resulting from the capture on <sup>3</sup>He to be detected. Data were read in through FERA ADCs in CAMAC using the PCDAQ program.

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<sub>0</sub> 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<sub>0</sub> 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 pulses come at 20 Hz (actually at 40 Hz, but

the electronics are set up to choose the pulse that coincides with the beam) and the UCNs are distributed uniformly in time. Further, the UCN time of flight to the detector, of order seconds, is long compared to the time between laser pulses (50 msec). In the on-line analysis we simply use the most recent value of Rtime; on replay this is replaced with some average of previous Rtime values to get a better estimate of the rotor phasing at the time the UCNs were produced.

A typical plot of UCN rate versus Rtime is shown in Figure 2. This plot was generated by sweeping the rotor phase through the correct value by changing the electronic delay that determines the overall phasing of the rotor with respect to the beam. The peak UCN rate is obtained when the rotor phasing is within 100  $\mu$ s or so of the optimum value.

We have been able to obtain some preliminary information about the velocity distribution of the UCNs that are being detected. We were able to rotate the lower part of the UCN guide about an axis through the horizontal section; this allowed us to make measurements when the detector was 41 cm below the production point, 41 cm above it, and level. When the detector is level we expect to detect only neutrons with velocity greater than 3.22 m/s, the critical velocity of aluminum. In the lower position all neutrons will be detected and in the upper only neutrons with velocity above 7.2 m/s. The results are shown in Figure 3. About 25% of the neutrons being detected are above 7.2 m/s.

## Publications

1. "Ultra Cold Neutrons at Spallation Sources", to be published in Proc. of New Instrumentation for Neutron Physics, Les Houches, France, June, 1995.
2. "Ultra Cold Neutrons at a Spallation Source", Proc. Int. Symposium on Neutron Optics and Related Research Facilities, Kumatori, 1996, J. Phys. Soc. Jpn. **65** (1996) Suppl. A 264.
3. "Plans for an Ultra Cold Neutron Source at Los Alamos", Proceedings of Workshop on Nuclear Physics and Fundamental Physics with Neutron II, KEK, Tsukuba, Japan, March 1996, KEK Proceedings 96-5, JHP-29.
4. "Development of an Ultra Cold Neutron Source at MLNSC", *International Conference: Neutrons in Research and Industry*, George Vourvopoulos, Ed. Proc. SPIE 2867, 521 (1997).
5. "Initial Testing of an Ultra Cold Neutron Source at Los Alamos", to be published in the *Proceedings of the 5<sup>th</sup> International Seminar on Interaction of Neutrons with Nuclei*, May 1997, Dubna, Russia.

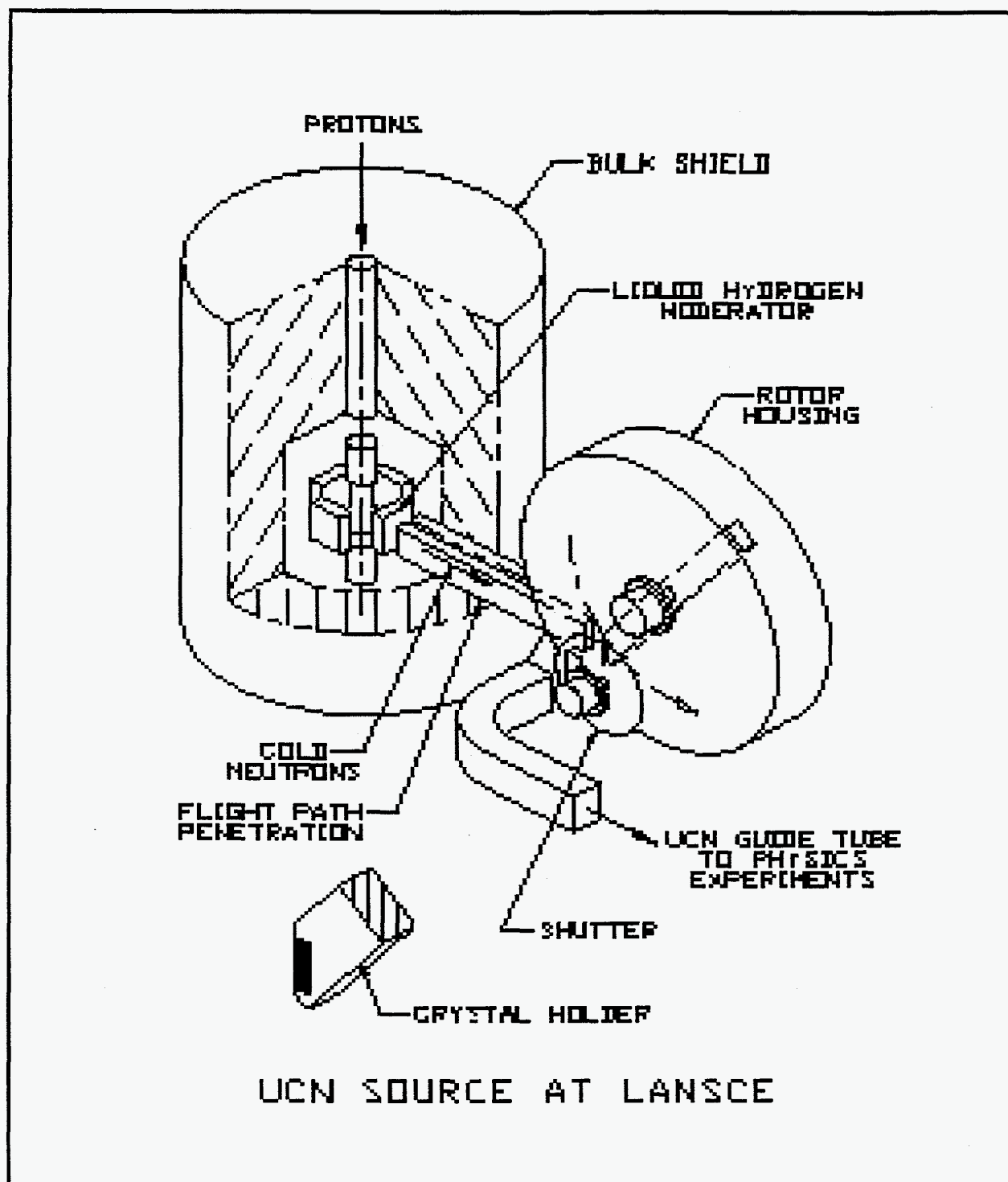


Figure 1. Schematic view of the UCN rotor source at the MLNSC

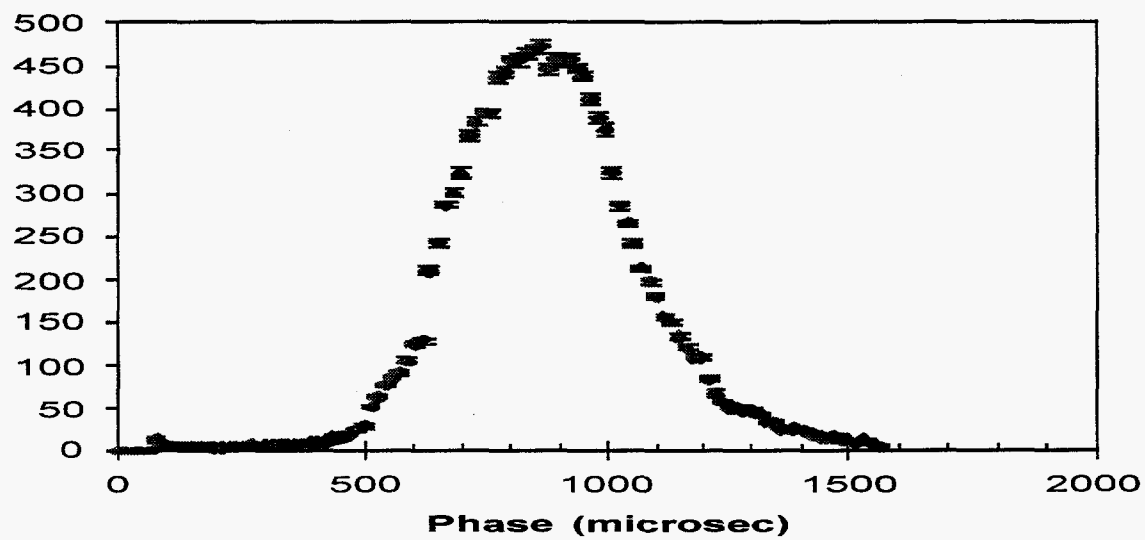


Figure 2. UCN production rate vs rotor phase with respect to the proton pulse on target.

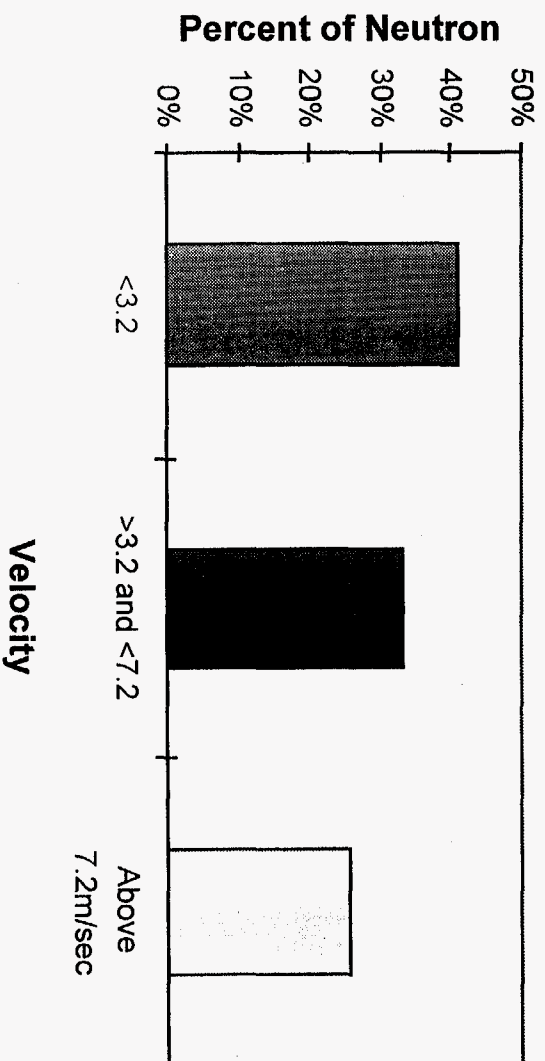


Figure 3. Measured UCN velocity distribution