THE OPERATION OF AN ULTRA-COLD NEUTRON SOURCE AT THE ARGONNE ZING-P' PULSED NEUTRON FACILITY

by

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This report describes the operation of a converter, based on a Doppler shifting principle, for producing ultra-cold neutrons (UCN). Interest in long wavelength neutrons ($\lambda \sim 1000$ Å, $v < 7$ m/s) has grown in recent years with their possible application in interferometry, spectrometry, and studies of the fundamental properties of the neutron itself.[1] As a probe in material and biological sciences, UCN may provide new information in low momentum transfer interactions; but perhaps the most noteable advantage for UCN is the ability to confine them in material containers for long periods of time.[2] At Argonne we are designing a nuclear magnetic resonance spectrometer to search for the neutron electric dipole moment (EDM) in which we store UCN in a bottle in the central part of the apparatus.[3] With the increased sensitivity which this technique offers, we hope to improve the present experimental limits on the existence of the EDM by one to two orders of magnitude.

I will begin with a brief description of the Doppler shifter converter (for a more detailed description of the principles of operation, see Ref. 4). Neutrons generated in the ZING-P' uranium target are progressively cooled by a

room temperature and finally a liquid H_2 moderator to 20° K. A vertical beam tube looks at the moderator through a cooled Be filter, approximately 2/3 of the 5-m long tube is a Ni guide. Neutrons with a velocity near 400 m/s ($\lambda \sim 10$ Å) are transported up the tube toward the converter as shown on Fig. 1. A crystal of synthetic mica (Thermica, d = 9.963 Å) is mounted on the end of a 1.2-m long rotor spinning at 30 Hz (231 m/s on the periphery). The crystal angle on the rotor is set to Bragg reflect neutrons near 61.2° in the crystal frame and due to the large crystal mosaic spread ($\sim 3^{\circ}$, which is induced artificially), neutrons within a sphere in velocity space with $|v| < 7$ m/s are reflected. Because of the orientation, the reflected neutrons are Doppler shifted off the moving crystal into the UCN range in the laboratory and proceed as a slow moving cloud down a Ni guide tube leading to a bottle.

In principle the Bragg scattering process does not change the phase space density in the reflected cloud of UCN from that in the source. The spatial density in the cloud of 1000 Å neutrons is expected to be the same as the peak density in the source of 10 Å neutrons. In practice there are inefficiencies in the scattering which yield an overall efficiency near 10% for producing UCN from the available neutrons. The sources of the inefficiency are crystal reflectivity (47%), pulse broadening in the 5-m beam tube which reduces density at the crystal (32%), absorption losses, etc. (66%).

Due to the pulsed nature of the source, we take special measures to insure a maximum density of UCN in the bottle. In the present design the opening to the guide tube is fitted with a polished Ni shutter in the form of a rotating disk with a slot cut into it. The disk rotates synchronously with the rotor and opens the guide when each neutron pulse arrives and closes between pulses to keep the UCN from escaping. In this way the bottle is filled asymptotically over many pulses.

The design parameters for the Doppler shifter are given in Table I. The phase space density near 400 m/s in ZING-P' was determined to be 0.0075 n/cm^3 - (m/s)^3 using gold foils and direct time-of-flight (TOF) measurements in the incident beam (the source strength was measured to be $\phi_p = 1.2 \times 10^{13}$ n/cm^2 - s equivalent peak thermal flux). For a sphere of 7 m/s neutrons in velocity space, we expected 1.0 UCN/cm^3 in the reflected cloud for a 10% efficiency. From TOF spectral measurements[5] performed with a He^3 counter at the end of the UCN guide tube (see insert on Fig. 2), we deduced a cloud density of 0.15 UCN/cm^3. A representative example of such a measurement is shown as circles on Fig. 2. A Monte Carlo calculation was performed, and the results are in good agreement with the data. The measurement is sensitive to one component of the velocity, thus 70% of the neutrons below 7 m/s are true UCN. The detector also had a thin Al window which reflected neutrons below 3 m/s, so we were insensitive to the lowest part of the spectrum.

The observed lower density of UCN from what was expected is due to a distortion of the sphere in velocity space in the Bragg scattering process. As confirmed by a detailed examination with our Monte Carlo calculation, only a pancake-shaped region near the center of the reflected sphere was populated adequately. This suggested that the flux of UCN varied with direction. We redesigned the opening to the UCN guide to exclude the lower flux regions by adding a grooved plate as shown on Fig. 3. The computer simulation of the new guide suggested a possible gain of 3 to 7 in UCN density.

We tested a plate fashioned out of triangular sections of stainless steel placed perpendicular to the motion of the crystal. The resulting grooves reduced the open area of the guide by a factor of 3. The measured spectrum is shown on Fig. 2 as crosses. For the spectrum below 5.6 m/s (the maximum velocity that can be reflected by stainless steel), the crosses agree with the circles indicating that the same number of neutrons per unit time entered the guide even though the opening was restricted. Therefore, we observed an increase in UCN flux by a factor of 3. (To obtain a corresponding increase in the bottle density, however, a three-fold increase in the filling time is necessary.)

We tested the effect of surrounding the UCN cloud with Cu reflectors. The number of neutrons in this spectrum is shown on Fig. 2 as squares. We observe a factor of 2 increase in counts in the UCN range. The use of reflectors does not yield a higher density in the bottle; however, it reduces the fill time. Reflectors also reduce our reliance on the shutter because the opening to the bottle can remain open twice as long before the UCN flux begins to drop. In our configuration, the resulting shutter interval would be 14 ms or about one-half the time between pulses. (Thus, for a 60 Hz source with reflectors we would have approximately a continuous beam of UCN.)

The final proof that we are producing UCN rests in our ability to confine them for periods of time. We placed a crude bottle consisting of a section of Ni-coated Cu pipe with two flapper valves at the end of the UCN guide. The results on the storage time are shown on Fig. 4 with the mean lifetime of about 4 seconds. This is far from hundreds of seconds observed in other experiments,[2,6] but may be understandable in view of the poor vacuum and loose fitting valves in our bottle. Nevertheless, the intercept of the lifetime curve gives us information on how well we are transporting neutrons into the bottle and whether we are coming close to the expected stored density. We observed an intercept of 6 counts/cycle. (A cycle consists of a 5-second fill time, a variable holding time and a 1.5-second count time).

For the conditions under which the data were taken, we expected 15 counts/cycle for a source density of 0.15 UCN/cm^3. (Because of the short lifetime of the bottle, we filled over 5 secs. even though the 6 ℓ volume would have required 35 secs. to fill. The expected count rate also includes counter efficiency, losses due to gaps in the guide tube and the lower velocity, $\sim$ 6 m/s, that can be contained by the Ni bottle.) The results indicate a loss of a factor of 2.5 probably occurring in transmission between the crystal and the bottle. We do not have an explanation for this loss as yet.

In conclusion, we have successfully produced UCN at the Argonne ZING-P' pulsed neutron facility with a source density of 0.45 to 1.0 UCN/cm^3. To date, we have been able to transport about 1/3 of these UCN into a bottle. These results are comparable to the stored densities observed at ILL, Grenoble[6] which are about 0.15 UCN/cm^3, even though the ZING-P' source strength is much below the HFR reactor. At the IPNS facility to be operational next year, we should have a better H_2 moderator and in general a tighter construction of the target cell which may yield an increase in flux by a factor of 10 over ZING-P'.

I would like to thank my colleagues on the neutron EDM experiment who helped design the equipment described in this paper: J. Carpenter, M. Freedman, V. Krohn, J. Lynn, R. Ringo, and S. Werner.

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Table I.

PARAMETERS FOR THE ARGONNE DOPPLER SHIFTER UCN SOURCE

A. ZING-P'

Pulse Rate	30 Hz
Peak Equivalent Thermal Flux	1.2 x 10^{13} n/cm^2 - s
Phase Space Density	0.0075 n/cm^3 - (m/s)^3
Pulse Width at Source	140 μs
Velocity Range Reflected	388 - 402 m/s
Distance Source to Crystal	4.78 m

B. ROTOR AND CRYSTAL

Radius	1.202 m
Bragg Angle	61.2°
d-Spacing	9.963 Å
Mosaic Widths (Broadened by Al Wedges)	3° x 1.2°
Crystal Dimensions	5.7 cm x 2.7 cm
Crystal Package Thickness	1.1 cm
Reflectivity	0.47
Absorption and Inelastic Scattering	0.36

C. COLLECTION SYSTEM

Guide Tube (Polished Ni)	9.5 cm diam.
Shutter Time Interval	7 ms
Volume In Guide Tube (Reservoir)	3.3 ℓ
Bottle Volume	3.0 ℓ
Velocities Contained (Ni)	$\leq$ 6.2 m/s

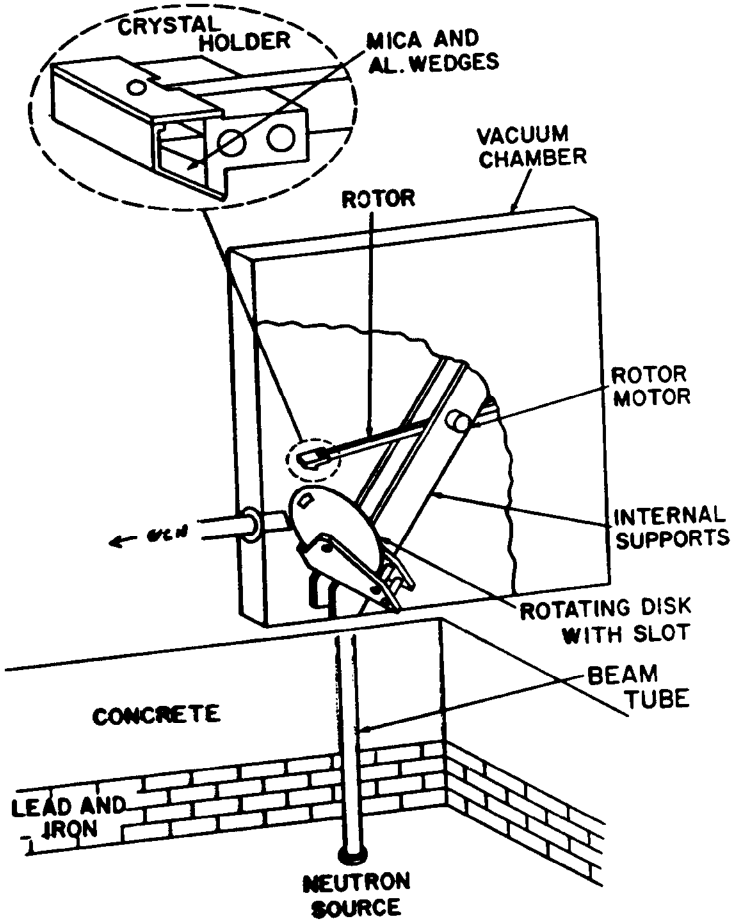

Fig. 1. The layout is shown schematically for the Doppler shifting converter.

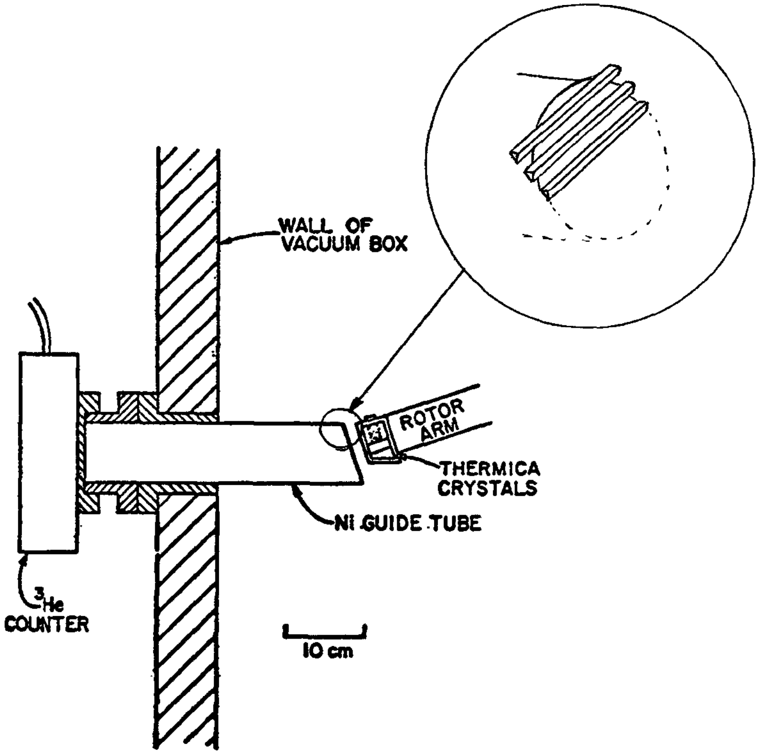

Fig. 3. The experimental arrangement for the grooved plate test is shown. The insert shows schematically how the stainless steel wedges were placed over the end of the Ni guide tube.

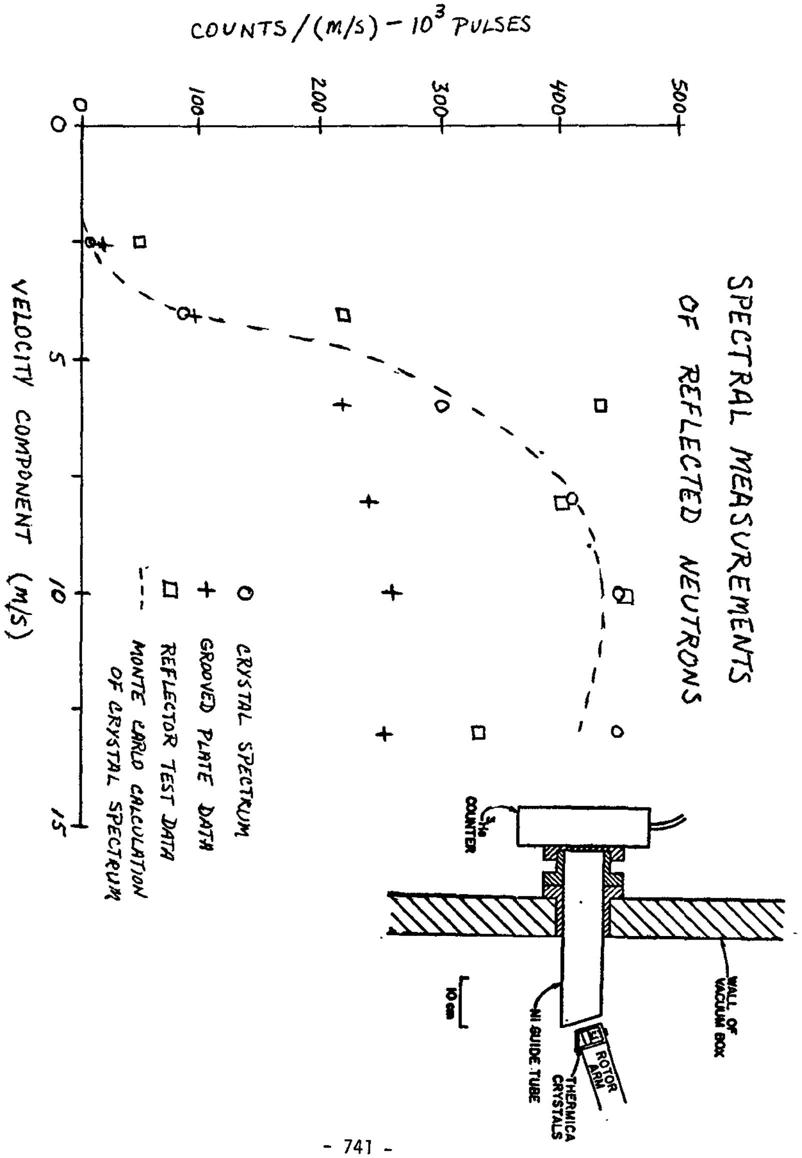

Fig. 2. The spectral measurements of the reflected neutrons is shown comparing the grooved plate, reflector test and open guide data. The insert shows the experimental arrangement for these measurements.

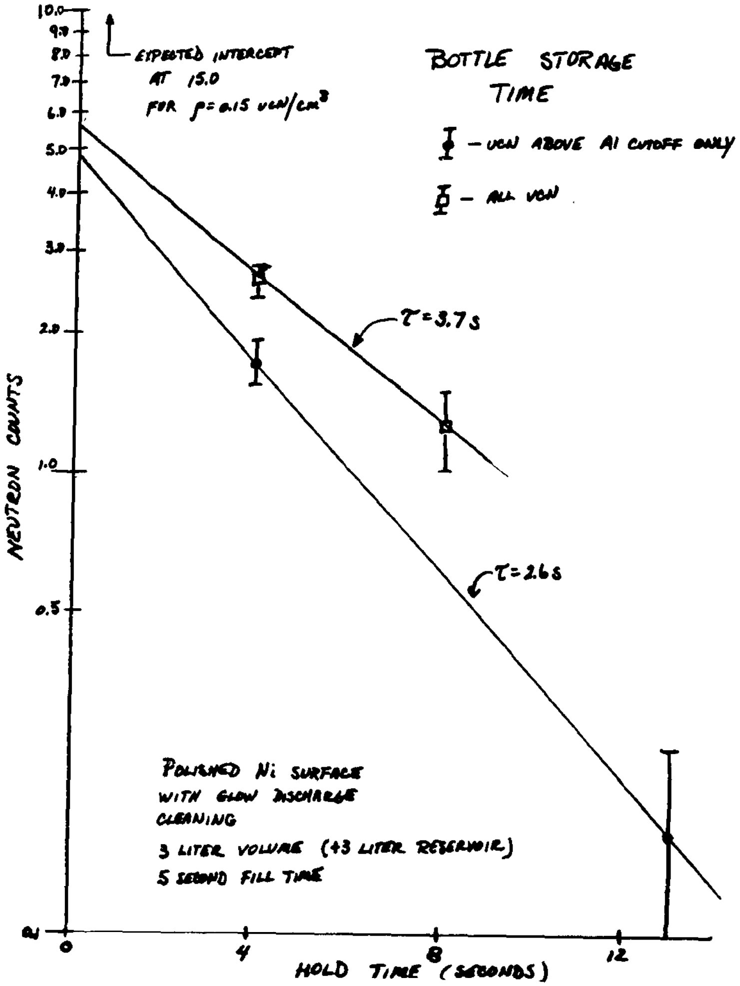

Fig. 4. The lifetime measurements are shown for UCN in a Ni coated bottle.