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Development of an Ultra Cold Neutron Source at MLNSC

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ABSTRACT

Ultra Cold Neutrons (UCN) can be produced at spallation sources using a variety of techniques. To date the technique used has been to Bragg scatter and Doppler shift cold neutrons into UCN from a moving crystal. This is particularly applicable to short-pulse spallation sources. We are presently constructing a UCN source at LANSCE using this method. In addition, large gains in UCN density should be possible using cryogenic UCN sources. Research is under way at Gatchina to demonstrate technical feasibility of a frozen deuterium source. If successful, a source of this type could be implemented at future spallation source, such as the long pulse source being planned at Los Alamos, with a UCN density that may be two orders of magnitude higher than that presently available at reactors.

1 Introduction

The coherent scattering of low energy neutrons can be described by an index of refraction. The index of refraction n is a function of the coherent scattering length b and density ρ of the material, and the neutron energy E:

$$n^2 = 1 - \frac{2\pi\hbar^2\rho b}{m_{neutron}E}. \tag{1}$$

At a given energy neutrons will be totally externally reflected for glancing angles of incidence satisfying Snells law for an angle of zero in the medium. Because the index of refraction is energy dependent, there exists for most materials an energy below which neutrons are totally externally reflected for all angles of incidence. This typically occurs for neutron velocities below 5-7 m/sec (500 Å), and these neutrons are called ultra cold. This leads to the possibility that UCN 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.

An area in which UCN have had and will continue to have a great impact is the study of neutron beta decay. Neutron beta decay is the simplest example of a nuclear beta decay, and one whose interpretation is not plagued by uncertainties in nuclear structure. The comparison of neutron lifetime, neutron beta-decay asymmetry, and decay rates for nuclear super-allowed beta decays can be used to test the Minimal Standard Model (MSM) prediction of V-A structure of the weak interaction. Neutron data of sufficient accuracy can be used to determine the weak vector and axial vector coupling constants G_V and G_A independent of the information from nuclear decays. The ability to make neutron lifetime measurements using both cold neutron beams and stored UCN was an important advantage in understanding the systematic effects in these measurements. We believe UCN will be similarly important in measurements of the various decay correlations in neutron beta decay.

UCN may also be of interest also in materials science, as UCN are highly sensitive probes of surface properties of materials. As the wavelengths are quite long (a few hundred Angstroms), UCN are well suited to studies of macromolecules, which are of great interest in areas such as biology. Current research in these areas employs reflectometry in which cold neutrons are scattered at glancing angles from materials. UCN may potentially provide a complementary approach to reflectometry. To date the low intensities of UCN available have precluded UCN as a normal method employed in materials research. Very intense sources of UCN are required before it will be possible to test the use of UCN as a materials science probe.

2 UCN Rotor Sources

The highest UCN density to date has been achieved at the ILL reactor using a *Steyerl turbine*. In this device cold neutrons ($40 - 50m/sec$) are gravitationally decelerated in an 18-m vertical guide tube and subsequently Doppler-shifted into UCN by multiple reflection from the rapidly moving blades of a turbine. This novel approach substantially reduces the losses in the transport of the cold neutrons as thick windows in the guide tube can be avoided and transport losses are less due to the smaller number of average reflections necessary for a neutron to reach the turbine. This device has produced measured UCN densities of $87UCN/cm^3$, a world record.[1]

The considerations for UCN production at a spallation source are quite different from a reactor. 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.[2] These fast neutrons are then thermalized and cooled in a variety of moderators. For UCN production, the spallation neutrons must be first moderated in a liquid hydrogen moderator. We will discuss UCN production at two different types of spallation sources: short pulse (SPSS) and long pulse (LPSS) spallation sources. The SPSS is characterized by facilities like LANSCE, ISIS, and IPNS where the proton pulse is typically a few microseconds or less and the pulse width of cold neutrons is determined by the moderator. At a LPSS, the pulse width may range from a millisecond to continuous wave (cw) and the pulse width of the cold neutrons is dominated by the pulse width of the proton beam. The SINQ (cw) neutron source is a LPSS, as is the proposed LANSCE 1-MW source.

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[3] 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 scattering crystal (for example, Mica) moves away from the neutron pulse emerging 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 reflects $199m/s$ 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 $398m/s$ neutrons are stopped. Thus, a puff of UCN 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 are installing such a rotor converter on the existing cold moderator at the Manuel Lujan Jr. Neutron Scattering Center (MLNSC). The moderator is a gadolinium-decoupled liquid para-hydrogen moderator, irradiated by neutrons from two tungsten targets arranged in a flux-trap geometry. The moderator is viewed by a ^{58}Ni-lined guide tube with a cross-section of $6cm \times 6cm$. A Mica crystal, moving away from the neutron pulse at a velocity of $199m/s$, will be installed on the end of a rotor that rotates in synchronism with the beam pulse rate (20 Hz) at a position about 8 m from the moderator.

A schematic view of the apparatus planned at MLNSC is shown in Fig. 1. We expect to produce UCN at a density of at least $10UCN/cm^3$ using the existing liquid hydrogen moderator at LANSCE. It is expected that in the near future MLNSC will begin operations on a nine-month production schedule every year. This will allow a fundamental physics program to begin. As the power of SPSS at MLNSC is expected to increase from the current 100-kW level to initially 1 MW and later to 510 MW, one can expect substantial advances in the UCN densities to be achieved.

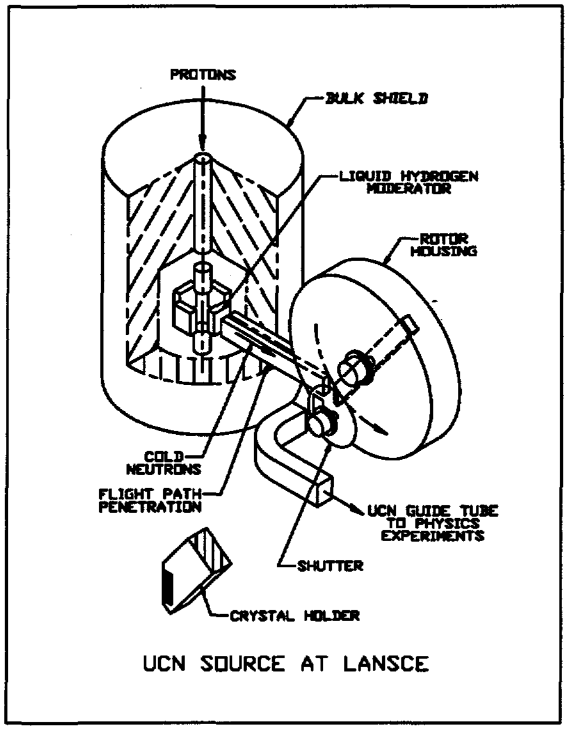

Figure 1: Schematic of planned UCN apparatus at LANSCE

3 Cryogenic UCN Sources

In order to obtain significant gains in UCN density over existing sources it is likely that one will need to go to some form of cryogenic UCN moderators. Investigations have been carried out to study production of UCN in superthermal (e.g. producing a UCN density higher than the thermal UCN density of the source) sources in which neutrons are down scattered by phonon emission in liquid ^{4}He.[4] The upscattering rate should be very low as the phonon density in such a moderator is very low. Proof-of-principle tests of this idea have been carried out at reactors and it appears that high densities of UCN can be obtained in the liquid He moderator.[5] However, it has proven difficult to implement this as a realistic source because there have been technical problems in trying to efficiently extract the UCN from the source. Efficient extraction from the liquid source requires a windowless extraction system that is compatible with the reactor requirements.

While the LHe superthermal source certainly merits further efforts, especially for experiments that can be performed in the LHe production volume, a potentially attractive scheme for producing UCN is a technique now under development by the research group of A. Serebrov at the Gatchina reactor.[6] This employs a frozen D_2 moderator at $46K$ placed close to the active zone of the reactor. The density of UCN in this source is significantly increased over that in a liquid D_2 cold source by the Boltzmann factor at the lower temperature. Very preliminary results from the Gatchina group have shown a gain in UCN densities achieved of a factor of 10 compared to a liquid deuterium source. Such a source implemented at a LPSS has the advantage that the heat loads on the moderator are much less than at a reactor, thus providing one more freedom to optimize the moderator design and minimize its distance from the spallation target, thus increasing the flux.

A 1-MW Linac-only spallation source based on the LANSCE accelerator has been proposed as a means to provide complementary capabilities to those available at the short-pulse MLNSC spallation source. The LANSCE linac is envisaged to operate at 60 Hz providing 1.25 mA (with some potential to go to 2.5 mA) current of 800-MeV protons with a duration of 1.0 ms per pulse. The accelerator would operate at 60 Hz to the LPSS with a 1-ms beam pulse width, thus yielding a 6The beam would impinge on a tungsten flux trap split target viewed by up to six moderators that could be either water or liquid hydrogen. These moderators would produce beams of thermal and cold neutrons for use in materials science and defense programs. We are planning for a UCN source that could be installed at the LPSS.

The time-averaged beam power of this source is as much as sixty times less than the thermal power of research reactors. However, the energy required to produce a neutron at a spallation source is roughly 30 MeV as compared to 180 MeV at a reactor. In addition, it is possible to make a brighter neutron source using a spallation target than at a reactor. These factors yield a gain of ten for thermal neutrons and a gain of fifteen for cold neutrons relative to a reactor. In addition, it is possible (for some classes of experiments) to make use of the time structure of the beam to advantage.

For UCN, estimates indicate that densities of $10^3 - 10^4 UCN/cm^3$ could be achieved. Such a source would provide the densities required to carry out a fundamental physics research program that could probe for physics beyond the standard model with substantially improved sensitivity. The existence of such an intense UCN source may also prove of interest to materials science as a complementary probe to reflectometry. Assuming funding is provided in the near term, a cryogenic UCN source could be implemented at a LANSCE LPSS within the next five years.

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