The Los Alamos Spallation Driven Solid Deuterium Ultracold Neutron Source: Working Notes of Mar. 30, 1998 with Embellishment

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(March 30, 2022)

The working notes which led to the physics demonstration ultracold neutron source that has been operated at Los Alamos are transcribed here. In addition to the transcribed notes, included are a Prologue that describes the path that led to the basic idea, and an Epilogue that describes some of the discoveries in the implementation of the idea.

I. PROLOGUE

The idea that solid deuterium could be a useful source of ultracold neutron (UCN) dates to the early 1980’s when R. Golub et al. [1] proposed the “thin film” UCN source. The basic idea is that a material, such as solid deuterium (SD$_2$) has a finite neutron absorption cross section, but a high rate of UCN production compared to superfluid helium. A small amount of SD$_2$ contained in a UCN storage cell and irradiated by cold neutrons will produce UCN until the rate of production equals the rate of absorption. Because both processes are proportional to the amount of SD$_2$, the steady-state UCN density is independent of the amount of material. Although the production rate is higher for SD$_2$ than for superfluid helium, the ultimate density of UCN in a superfluid helium filled long lifetime storage cell is around 10-100 times greater.

However, there are applications where SD$_2$ will be useful for a UCN converter. It has been suggested that the thin film source would be easier to use near the core of a high-flux reactor, primarily because less material is required to achieve a particular UCN current.

A specific application of SD$_2$ to UCN production at a spallation neutron source was brought to our attention in Jan. 1998 by A. Serebrov [2] at a workshop held near St. Petersburg, Russia. The basic idea is that the UCN storage bottle need only be connected to the SD$_2$ during a short time after the spallation pulse; one can then enjoy a high production rate together with an effectively increased storage lifetime. Upon returning to Los Alamos we (D. Bowman, S. Lamoreaux, C. Morris) discussed the “UCN Factory” described in [2] and came to the conclusion that it had a number of problems that include wasting phase space of the cold neutron flux, the necessity of a UCN window between the SD$_2$ and storage vessel, the use of an unwieldy amount of SD$_2$ (approaching 1 m$^3$), an overly complicated shutter mechanism, and it seemed that the SD$_2$ thickness was such that UCN might not be able to propagate out of the material irrespective of the window. Such a system might eventually be made to work, but without understanding the basic physical mechanisms involved, it seemed unwise to invest the large amount of resources required to build even a scaled version of the Factory.

In addressing these problems, in particular the cold neutron phase space, we were challenged as to why they were indeed problems. In answering the challenge, the following model source was proposed. Upon further reflection, the geometry is close to ideal for our specific application.

Our model source closely follows a proposal by Pokotilovski [3] who really came up with the idea of separating the production and storage regions, with a shutter that opens only around the time of the spallation pulse. R. Golub had provided S. Lamoreaux with a copy of this paper in 1995, but we had no conscious memory of this paper at the time of the St. Petersburg workshop; the paper emerged when we were digging through our notes. Our model source has only minor embellishments over the original Pokotilovski proposal which the interested reader can find by comparing these notes to [3].

II. NOTES OF MAR. 20, 1998

A. Basic scheme of source

A rough schematic of the physics demonstration UCN source is shown in Fig. 1.

B. Cold neutron production:

15 neutrons/800 MeV proton from spallation,

\[ P_c = 15 \frac{I}{e} \approx 10^{14} \text{/sec at 1} \mu \text{A} \quad (1) \]

\( P_c \) is the cold neutron production rate.

If the poly or LD$_2$ moderator is 30 K or lower, the produced neutrons will moderate to \( \sim 30 \) K (moderation processes turn off for neutron temperatures below \( \sim 25-30 \) K).

For poly, the albedo is about 90% for 30 K neutrons. We can estimate the mean free path of a cold neutron in the flux trap region as \( \sim 40 \) cm before loss (up the UCN guide) or absorption. This gives a cold neutron dwell time in the flux trap region
The cold neutron flux is

\[ \Phi_0 = 10^8 \text{neV}. \]

The cold neutron density in the flux trap region is then

\[ \frac{P \tau_c}{V_c} = \rho_c. \]  

Take \( V_c \) as 1.5 times solid \( D_2 \) volume \( V_D \)

\[ V_c = 1.5 \ell. \]  

So, at 1 \( \mu \)A,

\[ \frac{10^{14}}{\text{sec}} \times 0.66 \times 10^{-3} \text{sec} \times \frac{1}{1500 \text{cc}} = 4.4 \times 10^7/\text{cc} \]  

Then, the cold neutron flux is

\[ \frac{1}{4} \rho_c v_c; \text{ with } v_c = 700 \text{ m/s}. \]  

\[ \Phi_0 = 8 \times 10^{11}\text{n/cm}^2\text{s}. \]

C. UCN Production rate

See Fig 3.17 of Ultracold Neutrons (Golub, Richardson, Lamoreaux) [4]. For the thin film source, \( \rho = 150 \times 10^{-11} \Phi_0/\text{cm}^3. \)

The production rate (of UCN) is \( P_u = \rho/\tau \) and \( \tau = 0.12 \)sec at \( T < 4 \) K. So, \( P_u = 1.25 \times 10^{-8} \Phi_0 \) for \( \text{SD}_2 \) in a Be bottle. We must correct for the potential; \( U_{\text{SD}_2} = 108 \text{ neV}, \) this is compensated by the vertical rise. For the thin film source, \( P \propto (u_{1/2}/P_{\text{Be}} - u_{3/2}/P_{\text{SD}_2}) \) for our source, \( P' \propto U^{3/2}_{\text{Fomblin}} \)

\[ \frac{P}{P'} = \frac{252^{3/2} - 108^{3/2}}{160^{3/2}} = 1.42 \]

so for our system \( P_u = 9 \times 10^{-9} \Phi_0 \).

Total number of UCN produced is

\[ V_D \cdot P_u = 1000 \cdot 9 \times 10^{-9} \cdot 8 \times 10^{11} = 7.2 \times 10^6 \text{UCN/sec}. \]

D. UCN lifetime and UCN density

We have

\[ \frac{7.2 \times 10^6 \text{UCN/sec}}{15000 \text{ cc total}} = 480 \text{ UCN/sec cm}^3. \]

The lifetime is given approximately by the ratio of the total volume \( V_T \) to the solid \( D_2 \) volume, times the UCN lifetime in solid \( D_2 \).

\[ \frac{V_T}{V_D} \tau_D = \frac{15}{4} \cdot 0.12 \text{sec} = 1.8 \text{ sec}. \]

This gives

\[ \rho_{\text{ucn}} = \frac{480 \text{ UCN}}{\text{cm}^3\text{s}} \cdot 1.88 = 764 \text{ UCN/cm}^3. \]

E. Equilibration time etc.

The equilibrium time for the system is 1.8 sec, the shortest lifetime in the system. Thus, the 1 \( \mu \)A beam would have to be turned on for 3.6 sec (two lifetimes) after which the shutter to the storage volume is closed.

After 3.6 sec of filling, the storage volume will be filled with \( \approx 10^7 \) UCN. If these are released at a constant rate over 400 sec, loss will be minimized, and the UCN current will be \( 10^7/400 = 2.5 \times 10^4/\text{sec}. \)

The 800 MeV beam would have to be applied every 400 sec; this rate could be increased for a higher UCN flux. Also, the 800 MeV beam current could be increased; it’s a question of radiation damage and heat load. (Power for 1 \( \mu \)A, 800 MeV=800 Watts.)

III. EPILOGUE

The prototype source was constructed and tested in Aug. 1998. As anticipated, the window created a significant UCN loss; e.g., there is an effectively small shunt impedance in parallel with the source, as shown in Fig. 2.
A windowless system was designed and built; yet, a substantially lower UCN density compared to these notes was obtained. This was due to a number of causes. The state of affairs as of late 1998 are given in [5].

First, the flux trap is rather more complicated that the simple estimate above would indicate. The cold flux density extends further into the moderator and Be reflector, so the mean free path is modified. Monte Carlo calculations by R. Hill indicate that the flux trap lifetime is closer to $160\ \mu\text{sec}$, and the effective volume is larger. This results in a factor of 10 reduction in cold neutron flux.

In a test of the production rate of UCN by scattering cold neutrons in solid deuterium in March 1998, done at the Hahn-Meitner Institut in Berlin, the rate was within a factor of 3-5 of the expected rate given in Sec. II.C above, assuming all detected neutrons were UCN. However, the expected temperature dependence to the apparent production rate was not observed (possibly due to loss of UCN before they can propagate out of the solid). The observed UCN flux and lack of temperature dependence could be explained by assuming a UCN lifetime of a few milliseconds in the solid. The same lack of temperature dependence was initially observed in the demonstration source; we eventually found that the para molecular state, which persists from its room temperature concentration through freezing at 4 K, can upscatter UCN with a lifetime of about 4 milliseconds [6].

A para/ortho converter was installed on the demonstration source and the observed UCN production rate agrees well with Monte Carlo calculations, and a temperature dependence is observed.

The hydrogen contamination of available deuterium gas (0.1 at%), upscattering by phonons at 5 K (lowest practical temperature), and 2% para contamination (lowest practical conversion temperature is 17 K at which temperature there is still a reasonable vapor pressure), gives a net lifetime of 25 milliseconds.

A final weakness in the working notes is the assumption that one liter of solid $\text{D}_2$ could be used; in fact, the mean free path of a UCN is about 8 cm due to the incoherent cross section alone (and is possibly shorter for an amorphous material) and limits the volume; roughly 200 cc is a practical upper limit for the solid volume for the geometry shown in Fig. 1.

These factors taken together give a factor of 10-100 less UCN than the simple calculation. Nonetheless, the concept still has potential to be the basis of the world’s most intense UCN source, and with minor modifications we expect 300 UCN/cc densities in bottles of volumes 10’s of liters; the practical limit to a spallation pulse for a target assembly amenable to this project is 50 $\mu\text{C}$ in one second; this would be repeated every 10 sec so the average current would be about 5 $\mu\text{A}$. Questions relating to heating of the sample and generation of the ortho state due to radiation remain to be studied. Details of the Los Alamos effort will soon be published by the collaboration.

[1] R. Golub and K. Böning, Z. Phys. B 51, 187 (1983).
[2] Unpublished proceedings, “First UCN Factory Workshop”, Jan 18-22, 1998, Pushkin, Russia. See talk by A. Serebrov.
[3] Yu. N. Pokotilovski, NIM A 356, 412 (1995).
[4] Ultracold Neutrons, R. Golub, D. Richardson, S.K. Lamoreaux (Adam-Hilger, Bristol, 1991).
[5] R.E. Hill et al., NIM A 440, 674 (2000).
[6] C.-Y. Liu, A.R. Young, S.K. Lamoreaux, arXiv:nucl-ex/0004007 7 April 2000. Phys. Rev. B 62, R3581 (2000).