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Analysis of a method for extracting angularly collimated UCNs from a volume without losing the density inside

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Abstract

In order to extract ultracold neutrons (UCNs) with a restricted range of vertical velocity components from a super-thermal UCN source without significantly reducing UCN density inside, we propose to use a horizontal escape slit with a mirror on the bottom and a rough ceiling. The behaviour of UCNs in such a slit is modelled, using a Monte Carlo simulation both to check its feasibility for this method and to determine the characteristic parameters required. The slit is found to perform well and a good choice of the parameters is presented.

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1. Introduction

Developing a high density source of ultracold neutrons (UCNs) is a highly desirable goal in the field of neutron physics. Such neutrons have a wide variety of applications. They undergo total reflection from surfaces so can be easily trapped and stored, making them perfect candidates for various sensitive measurements. These include (but are far from limited to) accurate measurement of the neutron lifetime [1], the search for a non-zero neutron electric dipole moment [2] or electric charge [3] and, more recently, the study of the gravitationally bound quantum states of neutrons in the Earth's gravitational field [4–6]. Further progress in many of these experiments is limited by available UCN densities; in other cases high UCN density would be very useful for studying false systematic effects.

Currently, the world's most intense UCN source resides at the Institut Laue Langevin (ILL) in Grenoble, France, but serious efforts are being undertaken all over the world to increase the available UCN density. Here, we investigate the method of extraction of UCNs from a helium UCN source [7,8], which could be installed on an external beam of 8.9 Å cold neutrons at the ILL. The present study consists of a description of this method, a feasibility study and an estimation of characteristic parameters of the problem. The trap is being developed [9] to be used for a future study of the gravitationally bound quantum states of neutrons, GRANIT [10], but if successful could easily find use in other experiments requiring high UCN densities.

The basic idea of the extraction method is as follows. A high density of UCNs could be accumulated in ^{4}He UCN sources on the condition that the UCNs are trapped inside the source for 10^2-10^3 s. However, a permanent extraction of UCNs (in a so-called *flow-through* mode required for many experiments such as, for instance, the GRANIT at its first stage) would unavoidably decrease the storage time and reduce the density. Simple estimations show that even an extraction slit as small as 10 μm high would already dramatically decrease the UCN density. Nevertheless, we could exploit the specific requirements of the GRANIT spectrometer. We would only be using UCNs within a very restricted range of vertical velocity components. Therefore we are going to extract only these "useful" neutrons and

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reflect other neutrons back inside a source volume. This is possible if the extraction slit is a long horizontal channel with a mirror on the bottom and a rough ceiling on top. Neutrons with a low vertical velocity component would escape the source just as neutrons penetrate a slit at specular trajectories in Refs. [3–6], while neutrons with larger vertical velocity components (sufficient to reach the ceiling) would be scattered diffusively and return back to the source with a high probability (if the slit is long enough and losses in the slit are low enough).

We will be dealing with the properties of the escape slit of the trap and what effect they have on the overall phase space density of UCNs extracted. At present we have constructed a classical Monte Carlo simulation of the escape slit although work is in progress on developing a full analytical model. The basic parameters of the slit open to adjustment include the obvious geometrical ones of height and length. In addition, we can adjust the absorption probability of the inner surfaces of the slit and the probability that a neutron is scattered (reflected non-specularly) from a given surface on collision. The latter property is tweaked by changing the roughness properties of the surface. We will show that through a suitable choice of these four parameters, a trap could feasibly be built to provide an improved phase space density of UCNs. Furthermore, the values of the parameters for which this is true can comfortably be attained from a practical point of view.

2. Trap description

A schematic of the proposed method can be seen in Fig. 1. It consists of a storage volume with a reflective inner surface (modelled here as an infinitely long cylinder) filled with liquid helium. Cold neutrons with wavelengths of 8.9 A enter this trap from the beamline and could excite rotons in the helium [7]. Such neutrons will be cooled down to the UCN energy range.

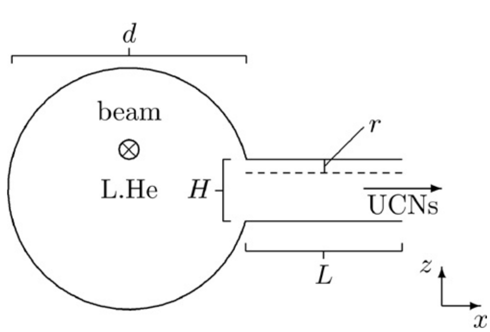

Fig. 1. A cross-section schematic of the proposed trap. The z-axis is aligned with the vertical axis in the lab and the trap extends along y-axis (into the page). The storage volume, filled with liquid helium, has diameter d. This should be chosen to be equal to the diameter of the cold beam cross-section. Neutrons enter the trap from an incoming beam (into the page). They are cooled down to UCN energies through interactions with the liquid helium then leave the trap through the escape slit on the right. The escape slit (not to scale) has height H and length L. The ceiling of the slit is rough, with roughness amplitude r.

These UCNs will be trapped inside the storage volume of the trap by its reflective inner surface and their density will begin to build up. Previous experiments have used traps like this as a source of UCNs [11], although the measurements on the UCNs were conducted while they remained in the trap. This will not be possible in the case of GRANIT because of the high sensitivity of its mirror trap to temperature gradients, contractions and expansions. To operate the trap in a flow-through mode we require an escape slit to be appended to the trap. Taking inspiration from the recent experiment on the gravitationally bound quantum states of neutrons [4], we propose a narrow horizontal slit with a smooth, reflective lower internal surface (the floor) and a rough, scattering upper internal surface (the ceiling).

The phase space density of UCNs inside the storage volume is proportional to their lifetime within the cylinder volume. In order to maximise the phase space density of UCNs we must therefore try to maximise their lifetime within the storage volume. The phase space density of UCNs released from the slit will then be the same as their phase space density inside the storage volume. It is clear that the lifetime of UCNs in the storage volume will be maximised for a very narrow slit. However, the narrower the slit, the lower the total flux of extracted neutrons will be. For the trap to be of any use it must provide a reasonable flux of UCNs; so we must find some kind of compromise for the height of the slit. It is also worth noting that the following model is only really applicable for a slit of height greater than 50 μm. Below this height, the individual gravitational quantum states of the neutrons become important [4]. These are not accounted for here.

3. Constructing the model

We now need to determine what the best choice of the four variable escape slit parameters are. These parameters are the escape slit length L, its height H, the probability p_a that a neutron incident on an inner surface of the slit is absorbed and the roughness amplitude of the slit ceiling r. The problem lends itself well to the Monte Carlo simulation technique.

The first step is to make some assumptions about the UCN velocity distribution at the entrance to the escape slit. Due to multiple random scatterings off the storage volume walls, it will certainly be isotropic. We are interested in the extreme low speed regime of this distribution ($4\,\mathrm{m\,s^{-1}} \leqslant u \leqslant 6\,\mathrm{m\,s^{-1}}$), which is much narrower than the speed range corresponding to roton production in the helium [7]. We can therefore approximate the UCN speed distribution as uniform over the given region of phase space. As the UCN velocity distribution is isotropic and the effects of gravity inside the storage volume can be ignored (the diameter of the storage volume, around 10 cm, is much smaller than the couple of metres a typical UCN is able to travel vertically under the influence of gravity), we may also assume that the UCNs are uniformly distributed in space at the escape slit entrance.

A UCN is generated at the escape slit entrance with a random z-coordinate. We note that motion along y-axis is not important, other than the effect it has on the resulting velocity distributions. This is built into the model by projecting the three-dimensional isotropic scattering distribution into two dimensions and summing over the y-coordinate. Due to the symmetry along y-axis of the trap the only extra effect it could have on the final reflection probability would be via a loss of UCNs through absorption by the walls of the escape slit. As we will see later, absorption by the slit walls does not play an important role in the process under certain conditions and can be neglected.

The UCN is allowed to propagate through the slit along a classical trajectory under the influence of gravity. Each time it collides with an inner surface (the floor or the ceiling of the slit) it may be absorbed with probability p_a, which can be calculated using standard results [12]. Using a standard simplified expression for the probability of specula/diffusive reflection of a wave by a rough surface we find that, each time it collides with the ceiling of the slit and is not absorbed, the neutron may be isotropically and elastically scattered with probability

$$p_s = \left(\frac{r}{\lambda_\perp}\right)^2 \equiv \alpha^2 v_z^2. \tag{1}$$

$\lambda_\perp$ is the component of the neutron's de Broglie wavelength perpendicular to the ceiling [12,13]. The formula can be more conveniently written as it is on the right, in terms of the z-component of the UCN velocity and the constant

$$\alpha \equiv \frac{rm}{h} \tag{2}$$

where m is the neutron mass and h is the Planck constant. Otherwise, the UCN is simply reflected from the ceiling and continues along through the slit. Note that this is a simplification of the referenced formula which takes into account only the leading term for the scattering probability and is valid with a typical accuracy of 10−20%. It can be used effectively to estimate the characteristic parameters of the system, but not for precise (and very complicated!) calculations. For any real system with known parameters, precise calculations can be carried out using the approach developed in Ref. [13], which also takes into account the corrections related to the gravitationally bound quantum states of neutrons. However, such analysis is far more complicated and depends on additional parameters, therefore is less transparent.

The UCN carries on in this way until it is either absorbed, reflected back out of the escape slit or transmitted through the escape slit. The number of UCNs performing each feat is recorded and, using this information, the absorption, reflection and transmission probabilities can easily be calculated.

4. Results

We can now begin to investigate certain combinations of H, L, p_a and r. We are looking for the characteristic values where the benefits of increasing or decreasing the parameters stop yielding a large increase in reflection probability relative to other points in the parameter space. This process is somewhat qualitative and will be finetuned through experimental testing. However, we can assess the general feasibility of the trap and will arrive at characteristic parameters which will make a good starting point for experiment. Evidently, we favour a solution with large slit height H, short slit length L and large absorption probability p_a. Such a combination would provide a compact device with large neutron flux and little sensitivity to impurities on the mirror surfaces. Therefore we search for solutions with minimum L value and maximum H and p_a values, which nevertheless provide high probability of neutron back reflection and low neutron losses.

Starting with the initial combination of parameters $H = 100\,\mu m$, $L = 3\,cm$, $p_a = 10^{-4}$ and $r = 1.5\,\mu m$, each parameter was independently varied and its effect on the reflection probability P_R noted. The value of P_R the model produces has been averaged over the speed range $4\,ms^{-1} \leqslant u \leqslant 6\,ms^{-1}$, which is the useable UCN range for the experiment motivating the design of the trap. This initial combination highlighted several important features of the system.

- P_R increases with L. By $L \approx 20\,cm$ the rate of increase of P_R begins to slow noticeably, reaching half its value relative to $L = 5\,cm$. Even if L is as small as 3 cm, the reflection probability is as high as $P_R > 90\%$. This means that only 10% of neutrons in the slit escape from a trap (which is sufficient for the proposed method). Moreover, a significant fraction of those neutrons are "useful" UCNs delivered to GRANIT. The reflection probability could be further increased by increasing the slit length L.
- Within the explored range of p_a ($<10^{-4}$) the effect on P_R of adjusting p_a is negligible (less than 0.005). This implies that absorption of neutrons inside the slit is unimportant in this parameter range. Almost all neutrons are either reflected or transmitted; so the extraction process will be very efficient.
- P_R increases with r. Above $r \approx 5\,\mu m$ the rate of increase of P_R begins to slow noticeably, reaching half its value relative to $r = 2\,\mu m$.

In addition, the data show P_R to decrease with H; yet again the behaviour we expect to see. This will be dealt with in more detail shortly.

We want to attain a high value of P_R, around 95%, in order to achieve a useful increase in UCN phase space density. Based on what we have learnt from this initial combination of parameters, the simulation was repeated centred around the new combination of parameters

$H = 100\,\mu m$, $L = 20\,cm$, $p_a = 10^{-4}$ and $r = 5\,\mu m$. The data from this run are shown in Fig. 2 and reinforces the features described above. If anything, the slit length at which the rate of increase of P_R begins to noticeably slow is now lower; closer to $L = 10\,cm$ than $L = 20\,cm$.

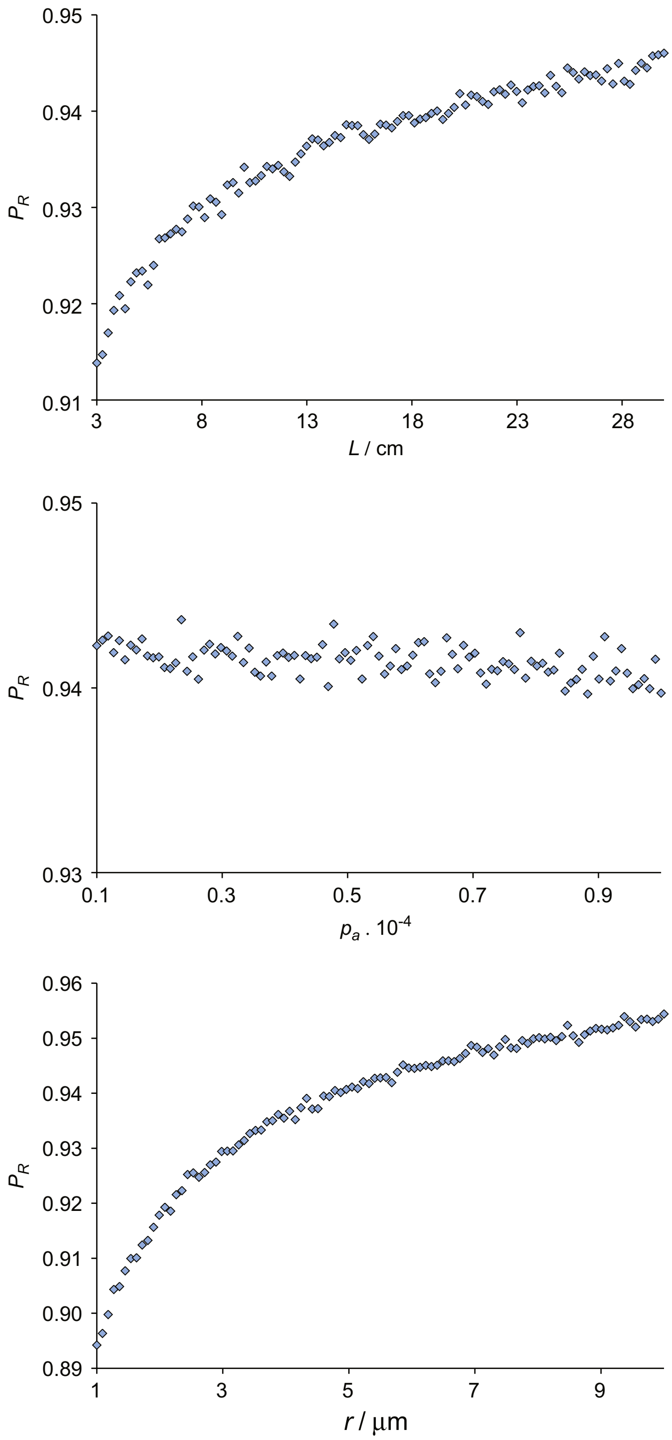

Fig. 2. The variation of the escape slit reflection probability P_R with respect to the slit length L, the inner surface absorption probability p_a and the slit ceiling roughness amplitude r. When not being varied the parameters take the values $H = 100\,\mu m$, $L = 20\,cm$, $p_a = 10^{-4}$ and $r = 5\,\mu m$.

We now determine how high the slit can be without damaging the phase space density of UCNs too much. As such, the average UCN lifetime in the trap over the range $4\,ms^{-1} \leqslant u \leqslant 6\,ms^{-1}$ was simulated for a variety of different escape slit heights and lengths. The results can be seen in Fig. 3. The values of p_a and r can be considered fixed at 10^{-4} and $5\,\mu m$, respectively.

In order to calculate the lifetime, τ, of UCNs inside the storage volume we use the following formula:

$$\frac{1}{\tau} = \left(\frac{\pi d - H}{\pi d} p_a^{sto} + \frac{H}{\pi d}(1 - P_R)\right) v^{sto} \tag{3}$$

which is valid for escape slit heights satisfying $H \ll d$, when the curvature of the escape slit entrance can be ignored. Here d is the diameter of the storage volume (see Fig. 1), p_a^{sto} is the mean probability that a UCN will be absorbed by the walls of the storage volume upon collision, and v^{sto} is

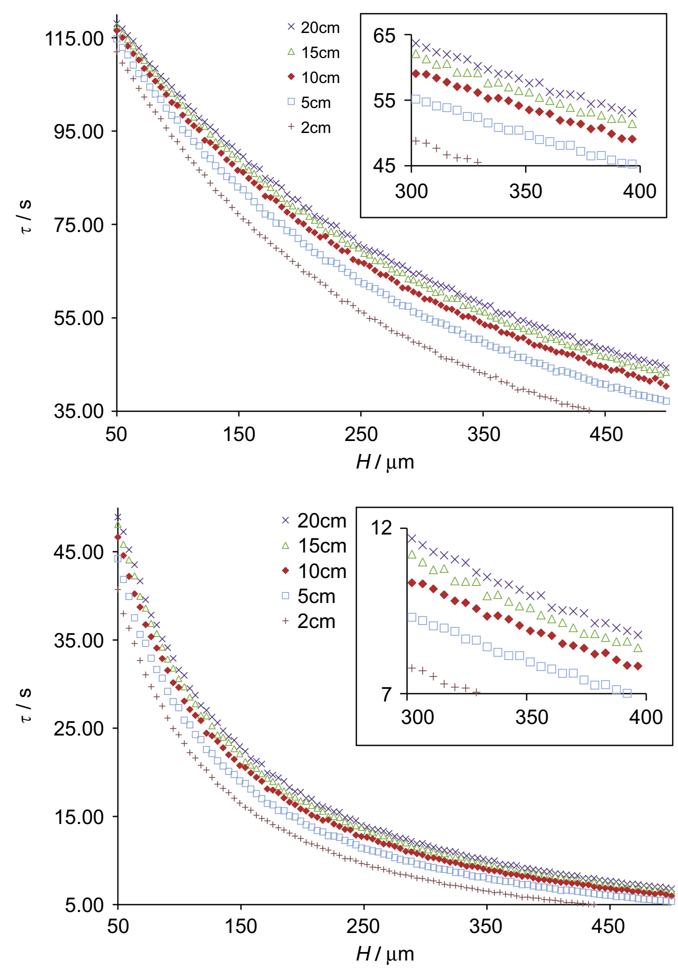

Fig. 3. The lifetime, τ, of UCNs inside the storage volume as a function of escape slit height. The top figure displays the data for a storage volume with diameter 9 cm, whereas the bottom figure shows the results for a storage volume with diameter 3 cm. Parameter values are $p_a = 10^{-4}$ and $r = 5\,\mu m$. The dependence is shown for slit lengths $L = 2, 5, 10, 15$ and 20 cm. The secondary graph is an enlarged version of the range $300\,\mu m \leqslant H \leqslant 400\,\mu m$, provided to highlight the differences between the data sets. The figure shows that τ decreases more slowly with increasing H for longer slits.

the mean frequency of such collisions, which can easily be calculated. The first term represents losses through the walls of the trap, whereas the second term represents losses through the escape slit.

5. Conclusions

We proposed and investigated theoretically a method for extracting an angularly collimated beam of UCNs from a trap (UCN source) without significantly decreasing UCN density inside. The extracting slit consists of two long plates: a well-polished mirror on the bottom and a plate with a rough surface on top. This approach is of particular interest for extracting UCNs from ^{4}He UCN sources. The characteristic optimal parameters of the extracting slit are the following. The slit length should be 10 cm. The absorption probability for the slit and storage volume walls must be less than 10^{-4} (so the absorption on the escape slit surface is not important in the region of parameter space explored). The roughness amplitude of the slit ceiling should be 5 μm. The slit height could be around one or two hundred micrometers. The absorption on the escape slit surfaces is not important in the region of parameter space explored. These optimal parameters can easily be achieved. Experimental testing of the trap has now begun. The results of the first test have been published [14]. They prove general feasibility of the proposed idea and will be followed by a more detailed investigation.

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