



# Depolarization of UCN stored in material traps

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## Abstract

Depolarization of ultra-cold neutrons (UCN) stored in material traps was first observed. The probability of UCN spin flip per reflection depends on the trap material and varies from  $7 \times 10^{-6}$  (beryllium) to  $10^{-4}$  (glass). © 2000 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

Studies of depolarization of UCN stored in traps are very important for two reasons. The first one is to test a hypothesis which would support the idea of using UCN for a neutron  $\beta$ -asymmetry experiment. Such an experiment had been proposed in Ref. [1] and the main ideas there were to obtain 100% polarization of UCN by passing them through a strong magnetic field (superconducting solenoid) and to measure the  $\beta$ -asymmetry by means of magnetic collimation of electrons. The knowledge that the UCN polarization stays at 100% throughout the experiment would remove one of the main systematic difficulties in present  $\beta$ -asymmetry studies using cold neutrons, which is the uncertainty in the neutron polarization measurement. However, the hy-

pothesis that this is indeed true and that 100% polarization can be maintained during storage of UCN was never tested experimentally up to now. Preparations for realization of neutron  $\beta$ -decay experiments with polarized UCN gas were started in Gatchina [2] and Los Alamos [3].

A second reason for UCN depolarization studies is connected with the problem of anomalous losses of UCN stored in material traps [4]. Incoherent scattering of UCN and their subsequent localization in material has been put forward as a possible explanation of this phenomenon [5,6]. An obvious sign of spin incoherent scattering is depolarization (spin flip at scattering). Measurement of UCN depolarization makes it possible to detect the presence of incoherent scattering in the process of UCN reflection from a surface and to investigate any possible connection between this process, the anomalous losses phenomenon and the hypothesis of UCN localization in material.

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## 2. Experimental installation and measurements

The experimental apparatus worked out at PNPI in Gatchina was installed at the ILL reactor. The experimental scheme is represented in Fig. 1.

The installation consists of a super-conducting solenoid (4.5 T), traps for UCN storage with a system of shutters, neutron guides and detectors. The traps were coated with beryllium. The storage lifetimes were 175 and 130 s for traps I and II, respectively. The UCN density used in the experiment was about  $6 \text{ n/cm}^3$ . The scheme of the installation is symmetrical and makes it possible to study the process of UCN depolarization in any state of spin.

In order to carry out studies of depolarization of the negative spin component ( $\mu H < 0$ ), trap I is filled with polarized UCN gas through trap II and the solenoid. After UCN have been stored for the given time, shutters 3, 6 and 5 are opened and the process of UCN outflow can be observed by means of detector II. If there is no UCN depolarization then trap I can be completely emptied. In case of spin flip during storage such neutrons will not be able to leave the trap because of the magnetic barrier. The neutrons which have experienced

a spin flip can be observed when shutter 2 is opened and detector I registers them.

This effect was found during the first experiment. As soon as trap I was filled through the solenoid, shutter 5 was opened and the process of UCN outflow could be observed by means of detector II. The time diagram of the count rate of detector II is represented in Fig. 2A. The process of neutrons flowing out of traps II and I simultaneously is described by two exponents. After 200 s this outflow process practically ceases. However, when shutter 2 was opened, detector I registered 781 neutrons which were spin flipped during storage. (see Fig. 2B).

Studies of the depolarization of the positive spin component of UCN ( $\mu H > 0$ ) can be performed by means of the following procedure. Trap I is filled through shutter 1 with unpolarized neutrons. After that shutters 3, 6 and 5 are opened and neutrons with negative polarization ( $\mu H < 0$ ) flow out of trap I. Neutrons with positive polarization ( $\mu H > 0$ ) stay in the trap, they will be able to get into detector II only in the case of a spin flip.

An experimental diagram of the process of outflow from trap I is represented in Fig. 2C. After the first 200 s the outflow of negatively polarized UCN practically comes to an end. It is described by an exponential with a characteristic time of 35 s. The second exponential with a characteristic time of 175 s (which is the storage time of the closed trap) tells us about the process of neutron spin flip during reflection through which the remaining neutrons with positive polarization can leave the trap. The test experiment with the magnetic field switched off shows that the process of outflow from trap I into detector II can be successfully described by a single exponent.

In order to demonstrate the fact that depolarization occurs in the trap the following test experiment was carried out. Shutter 3 was closed after 200 s and reopened after 320 s. The neutrons which had experienced a spin flip were accumulated in the trap and then let out. Fig. 2D shows the comparison of the two processes: (1) with accumulation (curve 2) and (2) without accumulation (curve 1). The difference between the curves within the ranges 200–320 and 320–550 s appeared to be the same after storage losses were taken into account. This

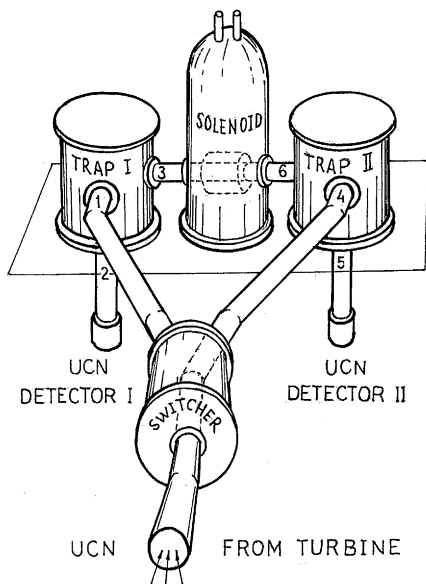


Fig. 1. Scheme of the apparatus. 1, 2, 3: shutters of trap I; 4, 5, 6: shutters of trap II.

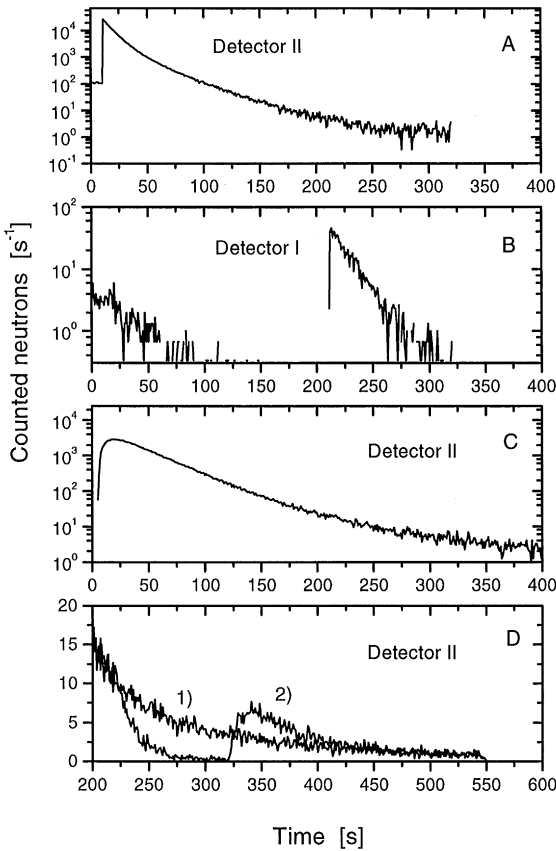


Fig. 2. (A) Time diagram of UCN outflow from trap I through solenoid to detector II (shutters 3, 6, 5 open); trap I was filled by polarized UCN through trap II and solenoid during 100 s, just then shutter 4 was closed and shutter 5 was opened. (B) Counting rate of detector I during the same process. With the shutter 2 closed, detector I registers UCN leakage through a small slit in shutter 2. After 210 s shutter 2 was opened to register neutrons which were spin flipped during storage. (C) Time diagram of UCN outflow from trap I through the solenoid to detector II (shutters 3, 6, 5 open). Trap I was filled by unpolarized UCN through shutter 1. (D) Curve 1 – leakage of UCN with positive polarization from trap I through the magnetic barrier due to depolarization in the trap; curve 2 – the same process with accumulation of spin flipped UCN (shutter 3 was closed after 200 s and opened after 320 s).

result shows that the observed process of depolarization occurs mainly in the trap.

Depolarization of UCN in the trap occurs due to their interaction with the material surface, depolarization due to the gradient of magnetic field is

virtually impossible, as numerical evaluations show that even for a considerable gradient of magnetic field the relaxation of UCN polarization in magnetic fields of several hundred gauss would take many years. (The average value of the magnetic field in our traps was 300–400 G.) In order to demonstrate that depolarization occurs when UCN collide with the material surface, beryllium foils were installed in trap I. The surface of interaction was increased by 1.85 times. The effect of UCN depolarization was increased by 2.02 times, which is approximately proportional to the surface area increase.

In order to determine the probability of spin flip per collision with the surface of the trap, the number of neutrons with reverse polarization accumulated during storage in the trap was measured. This function can be described by the following formula:

$$N^+(t_s) = \alpha \nu t_s N_0^- e^{-t_s/\tau_s}, \tag{1}$$

where  $N^+(t_s)$  is the number of neutrons with reverse polarization accumulated in the trap after storage time  $t_s$ ,  $N_0^-$  is the number of neutrons with initial polarization at the starting time,  $\alpha$  is the probability of spin flip per one collision,  $\nu$  is the frequency of UCN collisions,  $t_s$  is the storage time of UCN in the trap and  $\tau_s$  is the characteristic lifetime of UCN in the trap. For the  $N^+(t_s)$  measurement the procedure represented in Fig. 2A and B was used, but for different storage times.

The ratio  $R(t_s)$  of the number of neutrons which experienced spin flips to the number of neutrons with initial polarization is a linear function of storage time with the coefficient  $\alpha \nu$ . This function also includes an additional constant value which is connected with the processes of spin flip during the trap filling and emptying times:

$$R(t_s) = \alpha \nu t_s + C. \tag{2}$$

In the course of an experiment the following values are measured:  $N^+(t_s)$ ,  $N_0^-$  and  $\tau_s$ . The average frequency of UCN collisions ( $\nu$ ) can be calculated from the gas kinetic formula:  $\nu = Sv/4V$ , where  $S$  is the square of the trap surface,  $V$  is the trap volume and  $v$  is the average velocity of UCN. Determination of the coefficient  $\alpha \nu$  from the experimental dependence (2) and calculation of the average frequency of collisions  $\nu$  makes it possible to obtain

the probability of spin flip per single collision of UCN on the trap surface.

A graph of  $R(t_s)$  for the beryllium trap is shown in Fig. 3. The probability of spin flip per second is  $1 \times 10^{-4} \text{ s}^{-1}$ , and the probability of spin flip per collision is  $7 \times 10^{-6}$ .

In order to study UCN depolarization on different materials the corresponding foils were installed inside the trap and the procedure described earlier was repeated for all instances. The probability of spin flip for the foil can be determined from the relation:  $(\alpha\nu)_{\text{exp}} = \alpha_{\text{foil}}\nu_{\text{foil}} + \alpha_{\text{Be}}\nu_{\text{Be}}$ , where  $(\alpha\nu)_{\text{exp}}$  is

the measured probability of spin flip per second for a trap with foil,  $\alpha_{\text{Be}}$  is the pre-measured probability of spin flip per collision for Be,  $\alpha_{\text{foil}}$  is the probability of spin flip per collision for the studied foil, and  $\nu_{\text{foil}}, \nu_{\text{Be}}$  are the calculated frequencies of UCN collisions on the foil and trap walls, respectively.

The measurement errors do not allow one to determine the depolarization effect if the depolarization effect for the foil is significantly less than that for the beryllium trap. The main source of systematic errors is the accuracy of the calculation of the UCN collision frequency ( $\nu_{\text{foil}}, \nu_{\text{Be}}$ ), which depends on the form of the UCN spectrum. The problem is that the presence of the foil changes the UCN spectrum in the trap. For calculations of collision frequency the Maxwell spectrum cut at the point of critical foil energy was used. For this reason the measurement accuracy cannot be better than  $10^{-6}$  even when the foil surface is made of the same material as the trap surface.

Table 1 represents the measured results for the probability of UCN spin flips and probability of UCN loss per collision for different materials: beryllium, quartz, beryllium oxide, glass, graphite, copper, brass and Teflon. For graphite, copper, brass and teflon UCN depolarization was not discovered outside the range of the measurement accuracy of  $10^{-6}$ . The most considerable UCN depolarization was observed with glass and beryllium oxide.

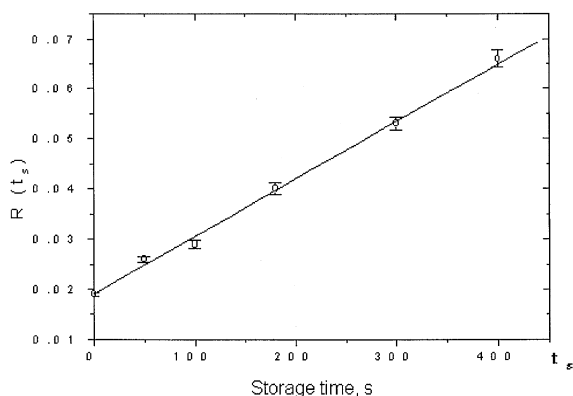


Fig. 3. Ratio of the number of neutrons which experienced spin flip to the number of neutrons with initial polarization as a function of UCN storage time in trap I.

Table 1

	Probability of spin flip/collision $\times 10^{-6}$	Probability of losses/collision $\times 10^{-5}$
1. Be (trap)	$7.2 \pm 0.7$	
2. Be (trap + foils)	$7.7 \pm 0.7$	$7.1 \pm 1.1$
3. SiO (quartz)	$14 \pm 1$	$59.8 \pm 6.0$
4. BeO (before outgassing)	$48 \pm 5$	$168 \pm 15$
5. BeO (after outgassing)	$44 \pm 4$	$74 \pm 7$
6. Glass	$95 \pm 9$	$315 \pm 30$
SiO <sub>2</sub> 81%		
B <sub>2</sub> O <sub>2</sub> 13%		
Na <sub>2</sub> O + K <sub>2</sub> O   4%		
Al <sub>2</sub> O <sub>3</sub> 2%		
7. C (graphite)	$1.9 \pm 1.0$	$18.6 \pm 2.0$
8. Brass (63% Cu, 37% Zu)	$1.1 \pm 1.0$	$19.3 \pm 2.0$
9. Cu	$-1.2 \pm 1.0$	$20.0 \pm 2.0$
10. Teflon (CF <sub>4</sub> )	$1.8 \pm 1.0$	$23.5 \pm 2.0$

### 3. Conclusion

The phenomenon of UCN depolarization during their interaction with a material surface was first observed in the described experiment. The existence of such an effect proves that the process of reflection of UCN from the material surface is not completely coherent. The most probable reason of UCN depolarization is the presence of impurities at the surface of the material, first of all, paramagnetic atoms and hydrogen atoms.

It is a well-known fact that incoherent scattering with neutron spin flip accounts only for  $\frac{2}{3}$  of incoherent scattering events,  $\frac{1}{3}$  of the events take place without spin flip. Interpreting the observed depolarization in terms of incoherent scattering, the full probability of incoherent scattering of UCN at the beryllium surface with subsequent return of the neutron to vacuum thus is  $\approx 1 \times 10^{-5}$  per collision.

Concerning the possible relation of the observed phenomenon to the proposed mechanism of UCN localization in material after incoherent scattering [5,6], the question arises, what is the probability for UCN to stay in the material after incoherent scattering in the surface layer? Approximate evaluations based on this model show that the proportions of UCN which return back into the vacuum and of those which stay in the material are in reasonable agreement with the experimental results (the probability of anomalous losses for beryllium accounts for  $3 \times 10^{-5}$  [4], and the probability of return into the vacuum after incoherent scattering is  $1 \times 10^{-5}$ , as was estimated above). Unfortunately, such coincidence of numerical

results cannot yet be considered as proof of UCN localization in the material. More detailed studies of UCN depolarization as well as studies of the connection between this phenomenon and that of anomalous losses are required. Joint studies of temperature dependence of UCN losses and UCN depolarization would be very interesting for instance, for beryllium oxide.

As far as plans for neutron  $\beta$ -decay experiments with polarized UCN gas are concerned, it should be mentioned that the proposed method has some difficulties regarding the choice of appropriate materials for UCN traps. The prospects of this method are not clear yet.

### Acknowledgements

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