Proc. Int. Symposium on Neutron Optics and Related Research Facilities, Kumatori, 1996
J. Phys. Soc. Jpn. **65** (1996) Suppl. A pp. 255-258

Production and Storage of Ultra Cold Neutrons at Pulse Neutron Sources with Low Repetition Rates

Yuri N. POKOTILOVSKI and Alexey Yu. MUZYCHKA

Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia

(Received 1 February 1996; accepted 7 May 1996)

High densities of ultracold neutrons can be stored in experimental volumes if one uses pulse thermal neutron source with a low repetition rate, a very low temperature converter, a high quality curved neutronguide, and a shutter at the entrance window of the storage volume. Some results of a Monte Carlo simulation are presented of the nonstationary transport of very cold (VCN) and ultracold neutrons (UCN) in straight and curved horizontal, and vertical neutron guides with a rectangular cross section, in the presence of neutron losses due to neutron capture and diffuse scattering on imperfectly smooth reflecting surface of the guides wall. The gravitational neutron decceleration and bending of neutron trajectories are taken into account rigorously. The nonstationary storage of UCN in experimental chambers is modelled for a low periodic or aperiodic pulse neutron source.

KEYWORDS: ultra cold neutrons, pulse neutron sources, mirror neutron guides, Monte Carlo neutron transport simulations

§.1. Introduction

Ultracold neutrons (UCN) have proven to be useful instruments in several important experiments in low energy elementary particle physics[1]: search for the neutron electric dipole moment, precise measurement of the neutron lifetime, the planned measurement of correlations in neutron decay, and possible experiments with unprecedentedly high sensitivity to energy and momentum changes in UCN scattering and deviation under the influence of external forces. From the many different and partly used methods producing UCN,[2] only two reached sufficient UCN densities: extraction of UCN at stationary reactor from small sized liquid hydrogen moderator through vertical neutron guide[3] and Steyerl's turbine at ILL.[4] Achieved densities of UCN in experimental volumes are around $10 cm^{-3}$. To increase the precision and sensitivity of experiments, the UCN density is of crucial importance.

There were proposals for using pulsed sources for production of UCN (some of them are mentioned in the review.[2]). During a pulse, the density of UCN in the moderator-converter is orders-of-magnitude higher than the mean one, but the problem is: how to deliver this high pulse density to the experimental volume. Pulse reactors with low repetition rates and very high pulse neutron fluxes are especially suitable for experiments with UCN that have a **cyclic** nature: after filling the experimental camera with UCN, the shutter at the entrance window of the camera is closed and UCN are kept in the camera for long periods of time -- several or tens of minutes in some cases. During these intervals the UCN flux from stationary neutron source is not used. There was a proposal to trap a cloud of UCN left after generation in the fast moving converter, and to transport them to the experimental volume in a slow moving vessel.[5] Herein simpler way of extracting and storing UCN at an aperiodic pulse neutron source is discussed.[6]

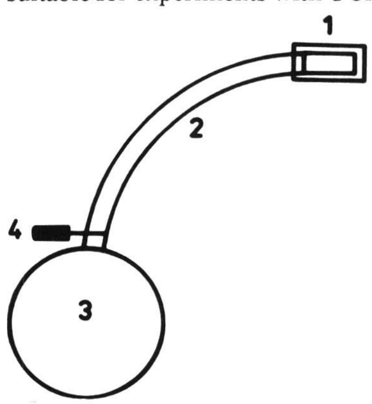

Fig. 1. The principal scheme of UCN storage at an aperiodic pulse neutron source.

§.2. Proposed method

Fig.1 shows the elements of a possible installation. UCN produced in the moderator-converter (1) during the pulse spread over the curved mirror neutron guide (2) and are stored in the experimental volume (3). The fast shutter (4) located **near the entrance window** of this volume closes at the proper moment after the pulse fills the volume with UCN: the stored UCN are locked in the volume. For a rough estimation we use the simplest model: all UCN are produced at $t = 0$ at point $z = 0$; the neutron guide is straight and ideally perfect (no losses due to capture, upscattering and diffuse reflection of UCN during transport along the neutron guide). The modern highly polished neutron guides have more than 0.99 probability of specular reflection; therefore the idealization used does not seem too crude for short neutron guides. The quantity n of UCN stored in the volume V is determined by the rate $\phi(t)$ of UCN entering from the neutron guide through the window and by the rate of UCN losses in the volume due to capture, upscattering, and the leakage of UCN through the entrance window back to the neutron guide. The corresponding equation is:

$$dn/dt = \phi(t) - n/\tau_{loss} - n/\tau_{ret} , \qquad (2.1)$$

where $\tau_{loss}=4V/(S\mu\langle v\rangle)$ is the loss time of UCN in the volume, S is the inner surface area of the volume, μ is the mean loss coefficient of UCN at the reflection inside the volume, $\langle v\rangle$ is the mean velocity of stored UCN, and

$\tau_{ret} = 4V/(s<v>)$ is the mean time of return of UCN back to the neutron guide through the entrance window of area s. In practical situations the second term is small in comparison with the third one and is omitted in this estimation.

To calculate $\phi(t)$, suppose that UCN are produced in the velocity interval $[0,v_b]$, where v_b is the boundary velocity of stored UCN and have isotropic angular distribution. Differential distribution of neutrons on the velocity component v_z along the neutron guide for monochromatic neutrons with velocity v is: $n(v_z)d\,v_z = d\,v_z/v$, $(0< v_z <v)$. For neutrons with a normalized Maxwellian tail velocity distribution $\rho(v)=3v^2/v_b^3$, the longitudinal component velocity distribution is:

$$\varphi(v_b,v_z)dv_z = \frac{3}{v_b^3}\int_0^{v_b} v\theta(v-v_z)dvdv_z$$
$$= \frac{3}{2v_b}(1-v_z^2/v_b^2)dv_z \text{ , for } v_z < v_b;$$
$$\varphi = 0, \qquad \text{for } v_z > v_b \text{ .} \qquad (2.2)$$

Here $\theta(x)=1$ if $x \geq 1$, and $\theta=0$ if $x<1$. Substituting $t = L/v_z$, where L is the length of the neutron guide between the source and the entrance window of the storage volume, we obtain the arrival time distribution:

$$\phi(t_0,t)dt = 3t_0(1-t_0^2/t^2)/(2t^2)dt \text{, for } t > t_0;$$
$$\phi = 0, \text{for } t < t_0 \text{ ,} \qquad (2.3)$$

where $t_0 = L/v_b$ is the delay time, which is equal to the moment of arrival of the fastest neutrons in the *stored* spectrum. Solution of equation (2.1) with $\phi(t)$ from (2.3) is:

$$n(x) = 3/2e^{-x/\eta}\int_1^x e^{\xi/\eta}(1-1/\xi^2)/\xi^2 d\xi \text{ , for } x > 1;$$
$$n(x) = 0 \text{ , for } 0 < x < 1, \qquad (2.4)$$

where $x = t / t_0$, $\eta = \tau / t_0$. Similar expression may be obtained for the case when UCN entering the neutron guide have nonzero lower boundary energy. Fig.2 shows the time dependence of filling the experimental volume with UCN when they are generated in the converter having boundary velocity for UCN v_{conv}=4.4 m·s^{-1} (solid deuterium), and boundary velocity of storage volume v_b=6 m·s^{-1}. The normalized Maxwellian tail velocity distribution in this case has the form $\rho(v)=3v^2/(v_b^3 - v_{conv}^3)$, and the reflection of UCN at the surface converter-vacuum is taken into account. It is seen from Fig.2 that half of UCN reaching the exit window of the neutron guide may be trapped in a small storage volume. (v_b = 6m/s, L = 6m, t_0=1s, V=5ℓ, s=40cm^2, τ= 5s, $\eta \approx 1$).

The best type of neutron source for realization of this method is pulse thermal pool TRIGA reactors. There were many reactors of this type constructed; some of them have the extreme capability of producing pulses of high power[7)] with fluences up to 1-5·10^{15}n/cm^2 per pulse with a width of several milliseconds. The best moderators-converters for UCN production are cooled hydrogen moderators (H_2,CH_4) and deuterium -- liquid and solid moderators.[3,4,8)] Recent

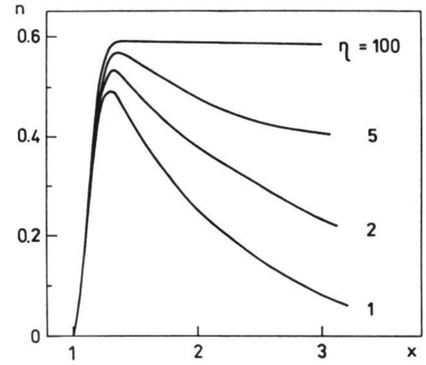

Fig. 2. The time dependence of filling of storage volume with UCN at different values of the parameter $\eta = \tau/t_0$, ($x = t/t_0$).

calculations[9)] in the Debye approximation of the gain factor of cooled deuterium showed that at a temperature 4K in a neutron field with a temperature 40K it was as high as 2.5·10^4. The results of early calculations[8)] have given a value for the gain factor several times lower and not as sharp an increase when decreasing the temperature of converter. The density ρ of UCN in the converter can be estimated from equation:

$$d\rho/dt = \Phi_{UCN}(t) - \rho/\tau_{UCN} \text{ ,} \qquad (2.5)$$

where $\Phi_{UCN}(t)$ is the rate of UCN generation in the converter, and τ_{UCN} is the lifetime of UCN in the converter. At a stationary regime[10)]

$$\rho = \Phi_{UCN}\tau_{UCN} \approx \phi_0(v_b/v_{th})^4 G(T_c,T_n)/v_b$$
$$= K\cdot\phi_0, \qquad (2.6)$$

where ϕ_0 is the Maxwellian thermal neutron flux with velocity v_{th}= 2.2·10^{5}cm/s, $G(T_c,T_n)$ is the gain factor, characterizing the efficiency of UCN production in converters in nonequilibrium conditions, when the temperature of the converter $T_c \neq T_n$, the temperature of the neutron spectrum. If the pulse width $t_p \leq \tau_{UCN}$, $\rho_{max} \sim K \cdot F/\tau_{UCN}$, where pulse fluence $F=\phi \cdot t_p$. In deuterium at very low temperature, $\tau_{UCN} \sim 0.1$s so that at a fluence
F = 10^{14}n/cm^2, v_b=6m/s, G = 10^4, and $\rho_{max} \sim 10^6$n/cm^3. Even if (because imperfection of the neutron guide) only one tenth of the UCN generated in the converter with volume 1ℓ reach the experimental volume, it would be possible at a pulse reactor with a moderate pulse fluence to store ~ 10^8 UCN, which is two to three orders of magnitude higher than that achieved now.

Virtually for successful storage of UCN in this method it is neseccary to have $t_p \leq t_{st}$, where t_{st} is the effective storage time, which is about 1s in our example.

There are several important advantages of the proposed method: 1) Low mean power of the reactor: if intervals between pulses are about 5min, the mean neutron flux is only ~ 3·10^{11}n/cm^2/s, corresponding to the low power stationary state reactor. It means low radiation heating of the cooled moderator and converter, that is important at very low temperature and low thermal conductivity. 2) Very low or zero neutron background during storage and measurements. 3) Possibility of using short neutron guides (several meters) due to the low mean power of the reactor. It will permit to avoid large losses of UCN during spreading along the neutronguide.

§.3. Monte Carlo Simulation of UCN Nonstationary Transport and Storage

In the preceeding section the UCN nonstationary storage was considered through ideal straight neutron guide. The transmittance of real neutron guides is determined by the reflecting properties of the guide surface: the probability of neutron loss (neutron capture and inelastic scattering) and of non-specular reflection per neutron encounter with the reflecting walls. Non-specular reflection, in the case of UCN transport in the neutron guides, causes (besides the mentioned losses) a time delay in the neutron arrival at the end cross section of the guide tube, which is essential for the proposed method of UCN storage.

In our publications[11-13] the results are presented of detailed rigorous Monte Carlo simulations on UCN nonstationary transport and storage through realistic straight and curved horizontal (Fig.3) and vertical (Fig.4) neutron guides. In this report we present only several examples of our calculations.

In our simulations we used results of ref.14 and 15 for differential probabilities of diffuse scattering from microrough surfaces, when $k_z\sigma \leq 1$, which is interesting for the reflection of UCN from high quality mirror surfaces, taking as an example the following values of a surface roughness parameters: $\sigma \cong 25\text{Å}$, $T \cong 500\text{Å}$, the mean square amplitude and the correlation length, respectively. The last value characterizes the mean square slope of roughness: $\alpha = 2\cdot\sigma/T$.

In all calculations neutron guides were assumed to have a rectangular cross section (6×8cm).

UCN losses due to capture and inelastic scattering were described by the equation:

$$\mu(v,\theta) = 2\eta\frac{v\cdot\cos\theta}{v_b} \Bigg/ \sqrt{1-\left(\frac{v\cdot\cos\theta}{v_b}\right)^2} \quad .(3.1)$$

Here θ is the incident angle to the surface normal, $\eta = \text{Im } b/\text{Re } b$, $\text{Im } b = (\sigma_c+\sigma_{in})/\,2\lambda$, and σ_c and σ_{in} are the capture and the inelastic cross sections, respectively. In calculations we took $\eta = 5\cdot10^{-4}$. This value is approximately twice as large as the theoretical η for nickel or stainless steel.

Some results of calculations are shown in Figs.5-8.

In this method, there is an interesting additional possibility to deliberately choose the spectrum of UCN stored in the chamber by varying the moment of closing the shutter. It can be performed due to the fact that UCN with greater velocity arrive at the chamber earlier, and also leave it earlier. This is illustrated in Fig.6 where the spectral results of the Monte Carlo simulation of UCN storage are shown for different moments of closing the shutter. Fig.7 shows the transmission through "realistic" curved vertical guides of different curvatures. For comparison (curve 1) the transmission through a horizontal guide with the configuration "b" in Fig.3 is shown. Higher UCN losses for configuration "e" guide (curve 4) are due to a longer

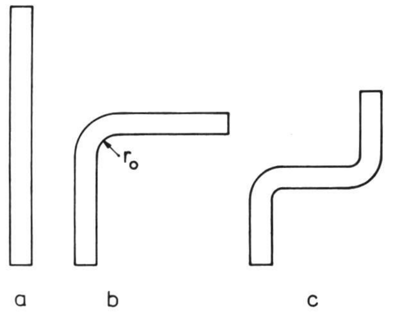

Fig. 3. Configurations of the horizontal neutron guides used in the Monte Carlo simulations; a: straight, b: $\pi/2$-bent, c: S-shaped.

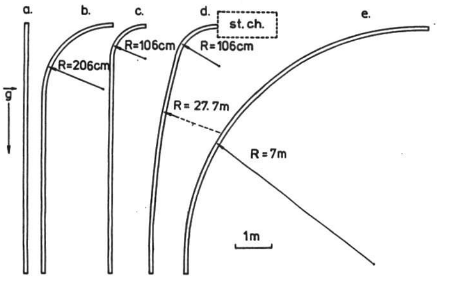

Fig. 4. Vertical neutron guides configurations used in Monte Carlo simulations. (st.ch. : storage chamber).

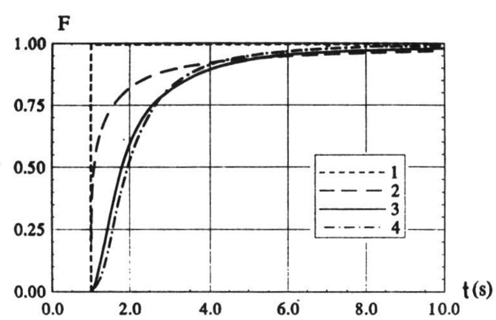

Fig. 5. Integral arrival time distributions for an ideal horizontal neutron guides (Fig.3) with a length of 6m without losses:

1) monochromatic neutrons with velocity 6m/s along the tube axis of a straight neutron guide;
2) the same for 90°-bent neutron guide, r_0=0;
3) Maxwellian tail spectrum, with cosine angular distribution at the entrance of a straight neutron guide;
4) the same for S-shaped neutron guide, r_0=0.

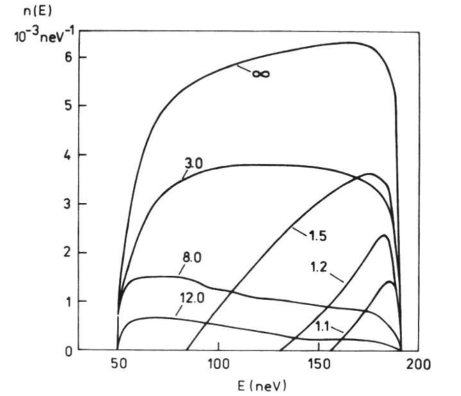

Fig. 6. The stored UCN spectra after closing the shutter at different moments (sec) after the neutron pulse: guide length is $6m$, storage volume 20ℓ, and diffuse reflection from guide surface with parameters: σ=25 Å, T=250 Å, and η=5·10^{-4}.

guide with a radius of curvature 7 m.

Calculations[12] showed that for vertical arrangment of very high quality curved neutron guides, UCN storage has better characteristics than for the horizontal one in view of lower spreading of the neutron bunch over neutron guide.

It is necessary in some experiments with UCN to have significant UCN density in small volume. In ref.13 we present the results of the Monte Carlo simulation for nonstationary UCN transport when the end part of the guide is equipped with a reflector and may be used for UCN storage. Fig.8 shows one example of these simulations. In this case 30-50% of UCN reaching the end section may be trapped in small volumes (1-2ℓ).

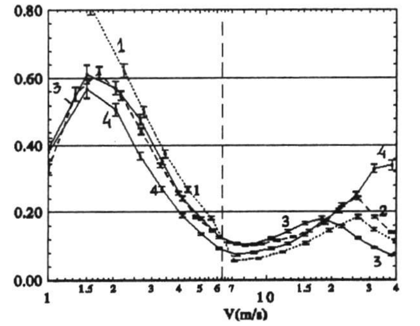

Fig. 7. The arrival velocity dependence of neutron transmission through "realistic" guides in Fig.4 (capture coefficient η =$5\cdot 10^{-4}$, surface roughness parameters σ=30Å, T=250Å): 1) **horizontal** guide with configuration "b", the transmission is normalized to the ideal straight horizontal guide; 2) vertical configuration "b"; 3) the same for configuration "c"; 4) the same for configuration "e". All curvas are normalized to transmission through ideal straight vertical guide of Fig.4a.

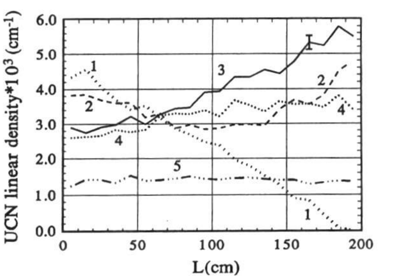

Fig. 8. UCN linear density distributions at the end of a 2m-long horizontal section of neutron guide for configuration Fig.4b, at different time moments t after the source pulse for an ideal neutron guide with a diffuse reflector at the end; 1 : t=1.2s; 2 : t=1.4s; 3 : t=1.6s; 4 : t=2.1s; 5 : t=2.9s.

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