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# PRODUCTION AND STORAGE OF ULTRACOLD NEUTRONS AT PULSE NEUTRON SOURCES WITH LOW REPETITION RATES

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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 of producing UCN [2] only two are used now: extracting of UCN at stationary reactor from small sized liquid hydrogen moderator through vertical neutron guide (Serebrov's group at Gatchina) [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 several proposals for using pulsed neutron sources for production of UCN (some of them are mentioned in the review [2]). During the pulse, the density of UCN in the moderator-converter is orders of magnitude higher than the mean one and 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.

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 and filling of the volume with UCN, the stored UCN are locked in the volume.

For a rough estimation let us 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 and upscattering, and the leakage of UCN through the entrance window

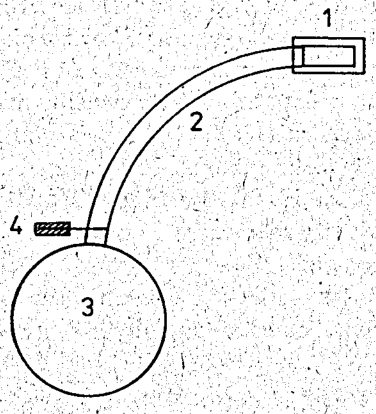

Fig.1. The principal scheme of the method:

1. The cooled moderator-converter of UCN.
2. The curved mirror neutron guide.
3. The camera for storage of UCN.
4. The shutter for UCN.

back to the neutron guide. In our simple model we do not take into account the possible return of UCN to the volume from the neutron guide after leaving it. The corresponding equation is:

$$dn/dt = \phi(t) - n/\tau_{loss} - n/\tau_{ret}, \qquad (1)$$

where $\tau_{loss} = 4V/(S\mu < v >)$ is the loss time of UCN in the volume, $S$ is the inner surface area of the volume, $\mu$ is the mean loss coefficient of UCN at the reflection inside the volume, $< v >$ is the mean velocity of stored UCN, $\tau_{ret} = 4V/(s < v >)$ 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:

$$n(v_z)dv_z = dv_z/v, \quad (0 < v_z < v). \qquad (2)$$

For neutrons with a normalized Maxwellian tail velocity distribution $\rho(v) = 3v^2/v_b^3$, the longitudinal component velocity distribution is:

$$\varphi(v_b, v_z)dv_z = \frac{3}{v_b^3}\int_0^{v_b} v\theta(v - v_z)dvdv_z = \frac{3}{2v_b}(1 - v_z^2/v_b^2)dv_z, \quad for \quad v_z < v_b;$$

$$\varphi = 0, \quad for \quad v_z > v_b. \qquad (3)$$

Substituting $t = L/v_z$, where $L$ is the length of the neutron guide between the converter and the entrance window of the storage volume we obtain the arrival time distribution:

$$\phi(t_0, t)dt = 3t_0(1 - t_0^2/t^2)/(2t^2) \cdot dt, \quad for \quad t > t_0; \quad \phi = 0, \quad for \quad t < t_0, \qquad (4)$$

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 (1) with $\phi(t)$ from (4) is:

$$n(x) = 3/2e^{-x/\eta}\int_1^x e^{\xi/\eta}(1-1/\xi^2)/\xi^2 \cdot d\xi, \quad for \quad x > 1; \quad n = 0, \quad for \quad 0 < x < 1, \qquad (5)$$

where $x = t/t_0, \eta = \tau/t_0$.

Fig.2 shows $n(x)$ for different $\eta$. For example at $v_b = 6m/s$, $L = 6m$, $t_0 = 1s$, $V = 25l$, $s = 50cm^2$, $\tau = 5s$, $\eta = 5$ almost half of the UCN generated during the reactor pulse can be stored in the experimental volume.

Fig.3 shows the time dependence of filling of the experimental volume with UCN when they are generated in the converter having boundary velocity for UCN $v_{conv} = 4.4m \cdot s^{-1}$ (solid deuterium), boundary velocity of storage volume as previously $v_b = 6m \cdot s^{-1}$. The normalized Maxwellian tail velocity distribution in this case has the form $\rho(v) = 3v^2/(v_b - v_{conv})^3$ and the reflection of UCN at the surface converter-vacuum is taken into account.

The best type of neutron source for realization of this method are pulse thermal pool TRIGA reactors. There were constructed many reactors of this type, some of them have the extreme capability of producing pulses of high power [6] with fluences up to $(1 - 5) \cdot 10^{15} n/cm^2$ per pulse with a width of several $ms$. The best moderators-converters for UCN production are cooled hydrogen moderators $(H_2, CH_4)$ and especially deuterium – liquid and solid [7][3][4]. Recent calculations [8] 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 is as high as $2.5 \cdot 10^4$. The results of early calculations [7] have given a value for the gain factor several times lower and with not as sharp an increase when decreasing the temperature of converter. The density $\rho$ of UCN in the converter can be estimated from equation:

$$d\rho/dt = \Phi(t) - \rho/\tau_{UCN}, \qquad (6)$$

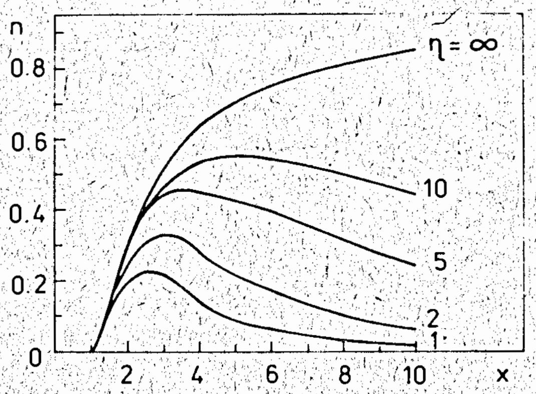

Fig.2. The time dependence of filling of storage volume with UCN at different values of the parameter $\eta = \tau/t_0$, $(x = t/t_0)$.

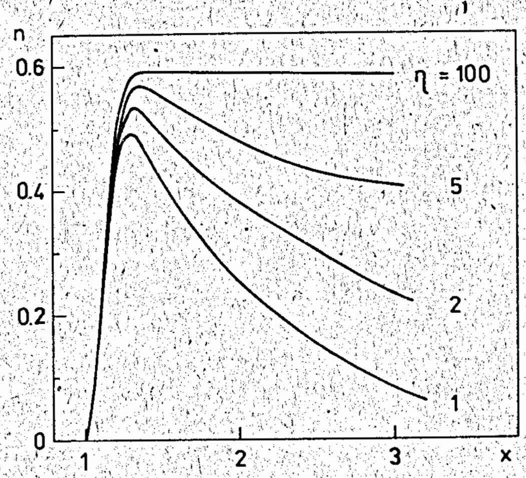

Fig.3. The same as in Fig.2 for the case when converter has boundary velocity $v_{conv} = 4.4 m \cdot s^{-1}$ (solid $D_2$).

where $\Phi(t)$ is rate of UCN generation in the converter, $\tau_{UCN}$ is the lifetime of UCN in the converter. At a stationary regime

$$\rho = \Phi_0 \tau_{UCN} \simeq \Phi_0 (v_b/v_{th})^4 G(T_c, T_n)/v_b = K \cdot \Phi_0, [9] \tag{7}$$

where $v_{th} = 2.2 \cdot 10^5 cm/s$, $G(T_c, T_n)$ 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, $\tau_{UCN} \sim 0.1s$ so that at a fluence $F = 10^{14} n/cm^2$, $v_b = 6m/s$, $G = 10^4$, $\rho_{max} \sim 10^6 n/cm^3$. Even if (because imperfectness 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 storage $\sim 10^8$ UCN, which is three-four orders of magnitude higher than 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 $\sim 3 \cdot 10^{11} n/cm^2/s$, 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[7] [8].

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 the the spreading along the neutronguide.

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