Is it possible to produce next generation of UCN sources with a density 10^3–10^4 cm^{-3} ?

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(Submitted 4 May 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **59**, No. 11, 728–733 (10 June 1994)

The analysis of evolution of UCN sources is presented. It is shown that the gain factor of about 10^4 and the UCN density of about 10^3–10^4 cm^{-3} can be obtained by means of solid D_2 at 4 K.

Ultracold neutrons (UCN) were obtained for the first time 25 years ago in the experiments carried out by Shapiro *et al.*[1] in Dubna (Russia) and by Steyerl[2] in Munich (Germany). From that time the density of UCN has been increased by eight orders of magnitude and now it accounts for about 10–10^2 n/cm^3. Figure 1 shows UCN source evolution from 1968 until the present time. Here only those experiments are presented which demonstrate the best UCN densities every time. Total number of experiments related to this problem is considerably higher. The highest densities of UCN were obtained in Gatchina[3] (PNPI) and Grenoble (ILL).[4] They were achieved with high thermal neutron fluxes, with liquid hydrogen, and with deuterium sources. The dependence in Fig. 1 looks like a saturation function. It seems that future progress is problematic. Actually, the most intensive thermal-neutron fluxes have already been used.

Nevertheless, the following question must be raised: Is it possible to produce an alternative version of UCN sources at a very low temperature with moderate neutron fluxes? More detailed analysis shows that such an approach can be used, and that it makes it possible to obtain considerable UCN density up to 10^3–10^4 $n \cdot cm^{-3}$ and to create a new generation of UCN sources. Therefore, the slow development of UCN sources in recent years is a temporary phenomenon. In this article we consider the possibility of a new sudden change of the UCN density.

As is well known, the gain factor for the yield of very cold neutrons is proportional to $1/T_n^2$, where T_n is the temperature of the neutron flux. For example, the thermalization of neutron flux down to 30 K gives the gain factor of about 100. Since the thermalization of the neutron spectrum below 30 K is a very difficult experimental task, it seems that the temperature gain factor of about 100 is the upper limit for the method of low-temperature UCN sources. However, this conclusion is correct for the thermodynamic equilibrium between the neutron flux and the medium. It can be shown that for nonequilibrium systems the gain factor of the UCN yield can be large. For example, for D_2 the UCN source at a temperature of 4 K and a neutron temperature of 40 K the gain factor accounts for 2.5×10^4.

Let us consider the yield of UCN from a substance held at a temperature T with neutron flux of temperature T_n. The probability for the UCN production is

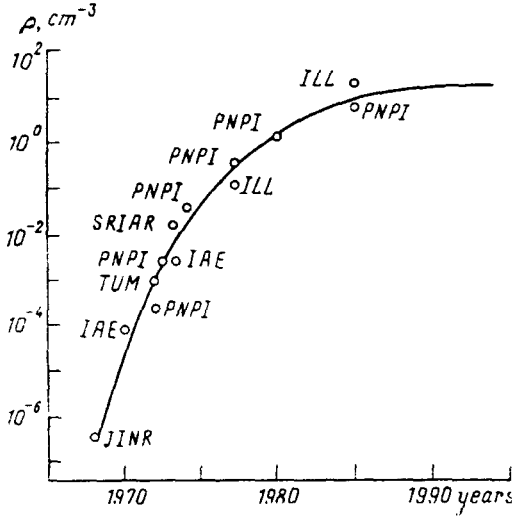

FIG. 1. Evolution of the UCN sources. JINR—Joint Institute for Nuclear Research (Dubna, Russia), IAE—Kurchatov Institute of Atomic Energy (Moscow, Russia), TUM—Technical University Munich (Garching, Germany), PNPI—St. Petersburg Nuclear Physics Institute (Gatchina, Russia), SRIAR—Scientific Research Institute of Atomic Reactors (Dimitrovgrad, Russia), ILL—Institute Max von Laue–Paul Langevin (Grenoble, France).

$$P(E_{\mathrm{UCN}})=n\int \Phi(T_n,E_0)\sigma(T,E_0\rightarrow E_{\mathrm{UCN}})dE_0, \tag{1}$$

where $\Phi(T_n, E_0)=\Phi_0\cdot E_0/T_n^2\cdot\exp(-E_0/T_n)$ is the neutron flux, $\sigma(T, E_0\rightarrow E_{\mathrm{UCN}})$ is the differential cross section for UCN production from energy E_0, and n is the number of nuclei per volume unit. The yield of UCN or the flux of UCN is

$$\Phi(E_{\mathrm{UCN}})=\frac{v_{\mathrm{UCN}}}{4\pi}P(E_{\mathrm{UCN}})\int \exp(-n\sigma_{\mathrm{UCN}}l/\cos\Theta)\sin\Theta d\Theta dl d\varphi. \tag{2}$$

Here l is the depth at which UCN were produced, Θ is the angle of escape, E_{UCN} and v_{UCN} are the energy and velocity of UCN, $\sigma(E_{\mathrm{UCN}})=\sigma_a(E_{\mathrm{UCN}})+\int\sigma(T, E_{\mathrm{UCN}}\rightarrow E_0)dE_0$ is the total UCN cross section, which is the sum of the capture cross section and the upscattering cross section. After integration we have

$$\Phi(E_{\mathrm{UCN}},T,T_n)=\frac{v_{\mathrm{UCN}}}{4}\frac{\int\Phi(T_n,E_0)\sigma(T,E_0\rightarrow E_{\mathrm{UCN}})dE_0}{\sigma_a(E_{\mathrm{UCN}})+\int\sigma(T,E_{\mathrm{UCN}}\rightarrow E_0)dE_0}. \tag{3}$$

We define the temperature gain factor as follows:

$$G(T,T_n)=\frac{\Phi_{\mathrm{UCN}}(T,T_n)}{\Phi_{\mathrm{UCN}}(T=300\ \mathrm{K},\ T_n=300\ \mathrm{K})}. \tag{4}$$

We can then write

$$G(T,T_n)=\frac{300^2}{T_n^2}\frac{\int E_0/E_{\mathrm{UCN}}\exp(-E_0/T_n)\sigma(T,E_0\rightarrow E_{\mathrm{UCN}})dE_0}{\sigma_a(E_{\mathrm{UCN}})+\int\sigma(T,E_{\mathrm{UCN}}\rightarrow E_0)dE_0}. \tag{5}$$

The cross section for inelastic scattering can be calculated on the basis of the Debye model by means of three parameters[5] Θ, σ_0, and μ, where Θ is the Debye temperature, σ_0 is the nuclear cross section, and μ is the reduced mass ($\Theta_{D_2}=110$ K).

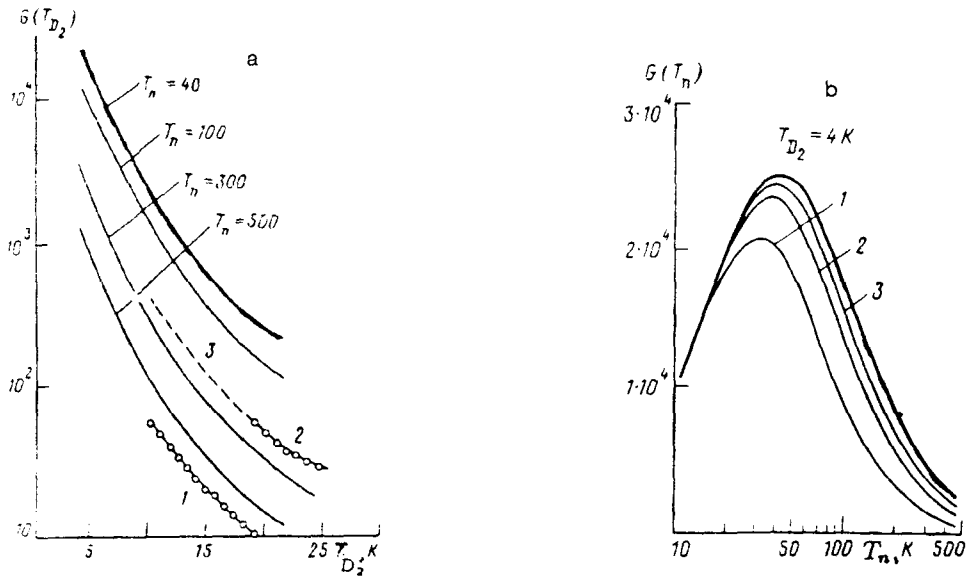

FIG. 2. a—The calculated dependences of the gain factor in the UCN yield on the temperature of D_2. Different curves correspond to different temperatures of the neutron flux. *1*—Experimental dependence of the gain factor in the UCN yield on the temperature of the D_2 UCN source with a volume of 150 cm^3; *2*—with a volume of 1 liter; *3*—Extrapolation of the experimental data (2) to the temperature range 10–19 K by means of experimental data (1); b—the calculated dependence of the UCN gain factor from the temperature of the neutron flux. *1*—One-phonon approximation; *2*—two-phonon approximation; *3*—three-phonon approximation.

$$\sigma(E_i \to E_f) = \sum_1^{\infty} \sigma_n(T, E_i \to E_f)$$

is the sum of the multiphonon processes

$$\sigma_n(E_i \to E_f) = \sigma_0 \left(1 + \frac{1}{\mu}\right)^2 \sqrt{\frac{E_f}{E_i}} \exp\left(-\frac{E_i + E_f}{\mu \ni}\right) \left(\frac{E_i + E_f}{\mu}\right)^n \frac{f_n(E_i - E_f)}{n!}, \qquad (6)$$

where

$$f_n(\varepsilon) = \int f_{n-1}(\varepsilon') f(\varepsilon - \varepsilon') d\varepsilon',$$

$$f(\varepsilon) = \frac{g(|\varepsilon|)}{\varepsilon \cdot (1 - e^{-\varepsilon/T})}, \quad g(\varepsilon) = \frac{3}{\Theta^3} \varepsilon^2, \quad |\varepsilon| < \Theta,$$

$$\frac{\ni}{\Theta} = \frac{1}{2} \left(\frac{\Theta}{T}\right)^2 \left(\int_0^{\Theta/2T} x \coth x dx\right)^{-1}.$$

The results of the $G(T, T_n)$ calculations for D_2 UCN source are shown in Figs. 2a and 2b. Here the experimental results of measurements for a source with a volume of 150

cm^3 in the temperature range[6] 10–19 K and for the UCN source with a volume of 1 liter in temperature range[7] 19–25 K are also shown. The dotted line in Fig. 2a is the extrapolation down to the temperature range 10–19 K for a 1-liter source on the basis of the experimental data for the 150-cm^3 source. The agreement between experimental and theoretical parameters $\partial G/\partial T$ is quite good. This allows us to hope that these calculations are valid for the temperature range down to 4 K. Figure 2b shows the dependence of the UCN yield on the effective temperature of the neutron spectrum. The calculations were carried out taking into account the multiphonon processes. The optimal temperature of the neutron spectrum (40 K) corresponds to the maximum of the UCN rate production, which depends only slightly on the source temperature. A decrease in the source temperature increases the depth of the UCN yield. This process provides mainly the temperature dependence of the gain factor, as is shown in Fig. 2a.

For these calculations the source temperature and the effective temperature of the neutron spectrum were assumed to be independent parameters. However, they are connected closely and the effective temperature of the neutron flux inside the source depends on the source volume and the temperature. The necessary source size is defined also by the depth of the UCN yield, which increases with decreasing source temperature, reaching its limit because of the capture cross section. The inelastic scattering cross section and the capture cross section for D_2 are comparable at 4 K; therefore, a decrease of the source temperature below 4 K is not so effective. The exponential depth of the UCN yield at this temperature amounts to 54 cm for UCN with a velocity of 7 m/s. The UCN yield as a function of the source size can be calculated with the formula

$$\Phi(E_{\mathrm{UCN}})=\frac{1}{4}PL_0\left[1-e^{-L/L_0}\left(1-\frac{L}{L_0}\right)+\left(\frac{L}{L_0}\right)^2\cdot Ei\left(-\frac{L}{L_0}\right)\right], \tag{7}$$

where $L_0=(n\sigma)^{-1}$, and Ei is the Airy function.

For example, when $L/L_0=1$, the UCN yield amounts to 78%; when $L/L_0=2$, the UCN yield is 93%. For the source with a ^{58}Ni coating on the inner surface of the walls near the window the source size can be reduced by a factor of 2. Therefore, in the practical case a 30-cm source should be sufficient. At the same time, a D_2 source of this size can thermalize the thermal neutron flux down to temperatures of 60–100 K. This is rather close to the optimal conditions for this task and can give a gain factor of $(1–2)\times10^4$.

The density of the UCN in the source is

$$\rho=\frac{2\Phi_0}{3}\left(\frac{E_{\mathrm{lim}}}{T_n=300\ \mathrm{K}}\right)^2\frac{G(T,T_n)}{v_{\mathrm{lim}}}, \tag{8}$$

where Φ_0 is the total neutron flux, and E_{lim} and v_{lim} are the limiting energy and the limiting velocity of the UCN spectrum. Since $v_{\mathrm{lim}}^{D_2}=4.4$ m/s and $v_{\mathrm{lim}}^{^{58}\mathrm{Ni}}=8.2$ m/s, we have $\rho=8.9\times10^{-14}\,\Phi_0\cdot G(T,T_n)$. Thus, for $\Phi_0=2\times10^{14}$ n/cm^2·s and $G=(1–2)\times10^4$ we have $\rho=(2–4)\times10^5$ cm^{-3}.

The next basic question is: Can a source of this type be placed in a neutron flux 2×10^{14} n/cm^2·s? This source cannot be located near the reactor core because of the heating by fast neutrons and γ rays from the fuel rods, but at a distance of 1 m from the

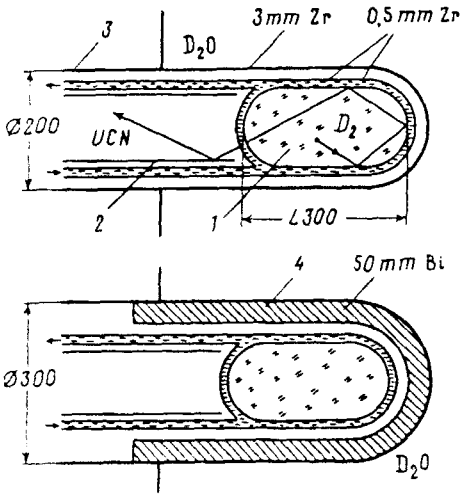

FIG. 3. Simple schematic diagram of the solid D_2 UCN source at the edge of a D_2O reflector. *1*—UCN source; *2*—UCN guide; *3*—reactor channel; *4*—Bi shield.

reactor core inside a D_2O reflector the γ field decreases by a factor of 100, while the thermal neutron flux decreases no more than six times. For example, at the edge of a D_2O reflector of the HF ILL reactor the γ heating is 4×10^{-2} W/g at a flux of thermal neutrons of 2×10^{14} n/cm^2·s. The heavy water provides good shielding from γ rays of the core and it almost completely restricts the flux of fast neutrons.

The minimal limit for the ratio of the γ field and the field of thermal neutrons is formed by $\Phi_\gamma=\Phi_{th}\Sigma_{D_2O}\mu_{D_2O}^{-1}$, where Σ_{D_2O} and μ_{D_2O} are the macroscopic neutron capture cross section and the absorption coefficient for the γ rays, respectively. Thus the γ heating is $q(\mathrm{W/g})=\Phi_\gamma\mu_{D_2}\rho_{D_2}^{-1}E_\gamma=2.8\times10^{-17}\ \Phi_{th}$ (cm^{-2}·s^{-1}) or 5.5×10^{-3} (W/g) for $\Phi_{th}=2\times10^{14}$ cm^{-2}·s^{-1}. This is the minimal limit. Unfortunately, any shell which is the cavity in a D_2O medium gives a considerably higher contribution to the source heating. One of the best materials for this purpose is zirconium. For a 3-mm vacuum shell and a 1-mm cold shell the γ heating will be $q_\gamma(\mathrm{W/g})=0.92\times10^{-16}\ \Phi_{th}$ (cm^{-2}·s^{-1}) or 1.8×10^{-2} (W/g) for $\Phi_{th}=2\times10^{14}$. This estimate should be increased by 30% because of the partial thermalization of the neutron flux. Thus, for a practical case the total γ heating for D_2 of the UCN source is about $(6-7)\times10^{-2}$ (W/g) at the edge of the D_2O reflector. This level of heating can be reduced by a factor of 2 or 3 by means of an interchannel Bi shield, if it is necessary.

The next basic question is what is the temperature inside the solid D_2 source at this radiation level? The temperature difference between the wall and center of the source is $\Delta T=q\rho/6\lambda R^2$ for the spherical form or $\Delta T=q\rho/4\lambda R^2$ for the cylindrical form, where λ is the coefficient of thermal conductivity, and R is the radius. The thermal conductivity of solid deuterium depends considerably on the orto-para modification. For 98% orto-deuterium (equilibrum concentration at 4 K) we have $\lambda=0.12$ W·cm^{-1}·K^{-1}. For a UCN source closest to practical realization (cylinder with 150 to 180 mm diameter and 300-mm length; Fig. 3) the temperature at the center of the source differs from the wall temperature by 1.2 K. The possibility of maintaining 98% concentration of orto-deuterium under radiation must be checked experimentally. In the worst case, if this is

impossible, the problem of thermal conductivity could be solved by means of sectionalization of the source with cylindrical cells 50 mm in diameter.

When a source is cooled with liquid helium and the thermal flux is about 6×10^{-2} $W\cdot cm^{-2}$, the difference in the wall and helium temperatures could amount to 0.1–0.2 K. Thus the average source temperature of about 5 K can be provided. When the effective neutron temperature is about 100 K, the gain factor will be about 10^4. Then $\rho_{UCN}=8.9\times10^{-10}\,\Phi_{th}$ or $\rho=1.8\times10^5$ cm^{-3} for $\Phi_{th}=2\times10^{14}$ $cm^{-2}\cdot s^{-1}$. Taking into account the UCN losses in the source walls and the transmission factor through UCN guide, we should expect a UCN density of about $(1-2)\times10^4$ cm^{-3} determined experimentally.

The thermal power released in solid deuterium is about 60–70 W; the same power is released in the zirconium source walls. To cool this source, a refrigerator with a power of 150–200 W will be required. This task may be solved using available cryogenic equipment.

Thus the next generation of UCN sources with UCN density of 10^3–10^4 cm^{-3} is possible for experimental research. The increase of the UCN density by two orders of magnitude will allow us to considerably improve the accuracy of measurements in the field of fundamental physics research (neutron electric dipole moment, neutron lifetime, asymmetry of the neutron decay, etc.). Apparently, applied research in the solid state and surface physics will be possible if this density of UCN can be obtained.

The UCN source of this type can be installed at the high flux beam reactor with a heavy water reflector like HFR at ILL (Grenoble, France): at the PIK reactor, which is being constructed at PNPI (Gatchina, Russia) and the ANS reactor, which is being constructed at ORNL (Oak Ridge, USA).

We wish to thank E. A. Garusov for useful discussions. We also thank G. Greene, C. West, T. Bowles, M. Pendlebury, and R. Golub for contacts which stimulated the development of this proposal.

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