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IS IT POSSIBLE TO PRODUCE NEXT GENERATION OF UCN SOURCES WITH DENSITY $10^3 - 10^4$ cm^{-3} ?

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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 4K.

For the first time ultracold neutrons (UCN) were obtained 25 years ago in the experiments, which were carried out by F.Shapiro with colleagues in Dubna (Russia) [1] and by A.Steyerl in Munich (Germany) [2]. From that time the density of UCN has been increased by eight orders of magnitude and now it accounts for around $10 - 10^2$ n/cm^3. Fig.1 shows UCN source evolution from 1968 up to now. Here only those experiments are presented which demonstrated the best UCN densities every time, total number of experiments related to this problem is considerably higher. Highest densities of UCN were obtained in Gatchina (PNPI) [3] and Grenoble (ILL) [4]. It was achieved with high thermal neutron fluxes, with liquid hydrogen and deuterium sources. The dependence in Fig.1 looks like saturation function. It seems that future progress is problematic. Actually, most intensive fluxes of thermal neutrons were used already.

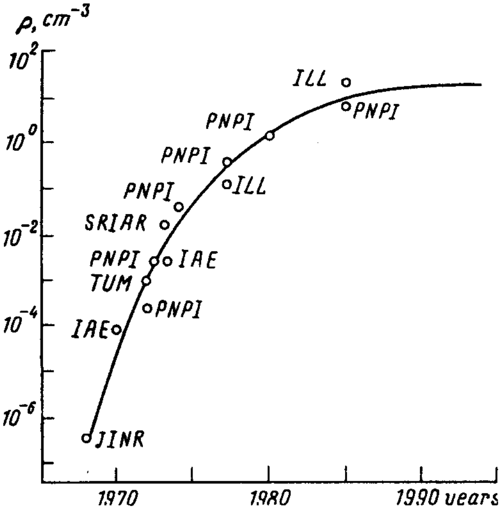

Fig.1 Evolution of UCN sources: JINR - Joint Institute of Nuclear Research (Dubna, Russia), IAE - Kurchatov Institute of Atomic Energy (Moscow, Russia), TUM - Technical University Munich (Garching, Germany), PNPI - St.Petersburg Nuclear Physics Institute (Gatchina, Russia), SRIAR - Scientific Research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

Nevertheless, the question is the following: is it possible to produce the alternative version of UCN sources at very low temperature, but with moderate neutron fluxes? More detailed consideration shows that such approach is possible to apply and it allows to obtain considerable UCN density up to 10^3–10^4 n $\cdot$ cm^{-3} and to create new generation of UCN sources. Therefore the slack development of

UCN sources last times is temporary phenomenon. New sudden change of UCN density is possible. The article is devoted to this question.

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

Let us consider the yield of UCN from a substance at temperature T with neutron flux at the temperature T_n. Probability of UCN production is:

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

where $\Phi(T_n, E_0) = \Phi_0 \cdot E_0/T_n^2 \cdot \exp(-E_0/T_n)$ is neutron flux, $\sigma(T, E_0 \to E_{UCN})$ is differential cross section for UCN production from energy E_0, n - number of nucleus per volume unit. Yield of UCN or the flux of UCN will be:

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

l - depth, where UCN was produced, Θ - angle of escape, E_{UCN} and v_{UCN} - UCN energy and velocity; $\sigma(E_{UCN}) = \sigma_a(E_{UCN}) + \int \sigma(T, E_{UCN} \to E_0)dE_0$ is total UCN cross section, which is the sum of capture cross section and upscatering cross section. After integration we have:

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

Let us define temperature gain factor as:

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

then

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

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

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

is the sum of 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

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

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

$$\frac{\ni}{\Theta} = \frac{1}{2}\left(\frac{\Theta}{T}\right)^2\left(\int\limits_0^{\Theta/2T} x\coth x dx\right)^{-1}.$$

Results of $G(T, T_n)$ calculations for D_2 UCN source are presented in Fig.2*a* and Fig.2*b*. Here the experimental results of measurements for the source with volume 150 cm^3 for the temperature range 10-19 K [6] and for the UCN source with the volume 1 liter for the temperature range 19-25 K [7] are presented also. Dotted line in Fig.2a is the extrapolation down to the temperature range 10-19 K for the 1 liter - source on the basis of experimental data for the 150 cm^3 source. Rather well agreement between experimental and theoretical parameter $\partial G/\partial T$ is seen. This allows us to hope that these calculations will be valid for the temperature range down to 4K. Fig.2*b* shows the UCN yield dependence on effective temperature of neutron spectrum. The calculations have been carried out taking into account multiphonon processes. The optimal temperature of neutron spectrum 40K corresponds to maximum of UCN rate production, which depends rather weak on the source temperature. Decreasing of source temperature provides increasing of the depth of UCN yield. This process provides mainly the temperature dependence of gain factor, as it is shown in Fig.2*a*.

For these calculations the source temperature and the effective temperature of neutron spectrum were considered as independent parameters. However, they are connected closely and effective temperature of neutron flux inside source depends on the source volume and its temperature. The necessary source size is defined also by the depth of UCN yield, which grows up with the decreasing of the 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 the decreasing of source temperature below 4 K is not so effective. The exponential depth of UCN yield at this temperature amounts for 54 cm for UCN with velocity 7 m/s. The dependence of UCN yield as function of source size can be calculated with the formula:

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

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

For instance, when $L/L_0 = 1$ the UCN yield amounts for 78%, when $L/L_0 = 2$ the UCN yield will be 93%. For the source with ^{58}Ni coating the internal surface of its walls besides the window the source size can be reduced by the factor of two. Therefore in practical case the source size 30 cm should be sufficient. At the

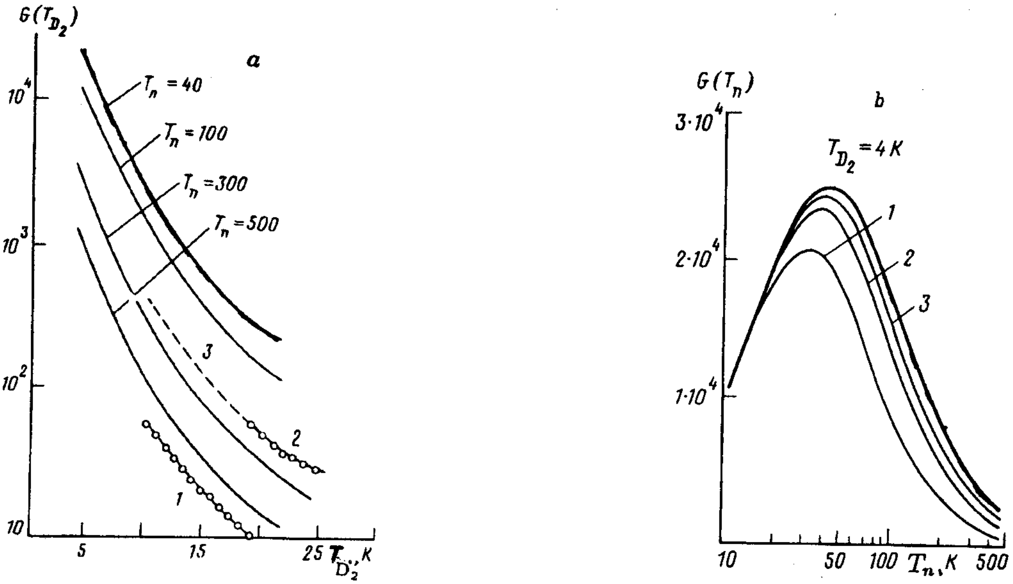

Fig.2. *a* – The calculated dependences of gain factor in UCN yield on the temperature of D_2. Different curves correspond to the different temperatures of the neutron flux: *1* - experimental dependence of gain factor in UCN yield on the temperature of the D_2 UCN source with volume $150\,\mathrm{cm}^3$, *2* - with volume 1 liter, *3* - extrapolation of experimental data (2) to the temperature range 10-19K by means of experimental data (1); *b* – the calculated dependence of UCN gain factor from the temperature of neutron flux: *1* - one-phonon approximation, *2* - two-phonon approximation, *3* - three-phonon approximation

same time the D_2 source with this size can thepmalize the flux of thermal neutron down to the temperature 60-100K. This is rather close to optimal conditions for this task and can give gain factor $(1 \div 2) \cdot 10^4$.

The density of UCN in source is:

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

where Φ_0 - total neutron flux, E_{lim}, v_{lim} - limit energy and limit velocity of UCN spectrum. Taking into account that $v_{lim}^{D_2} = 4.4$ m/s and $v_{lim}^{^{58}\mathrm{Ni}} = 8.2$ m/s we have: $\rho = 8.9 \cdot 10^{-14}\ \Phi_0 \cdot G(T, T_n)$. Thus for $\Phi_0 = 2 \cdot 10^{14}$ n/cm$^2\cdot$ s and $G = (1 \div 2) \cdot 10^4$, $\rho = (2 \div 4) \cdot 10^5\ \mathrm{cm}^{-3}$.

The next principal question is: could the source of this type be placed in the neutron flux $2 \cdot 10^{14}$ n/cm$^2\cdot$ s? Sure, the allocation of this source close to reactor core is impossible because of the heating by fast neutrons and γ-rays from fuel elements, but at the distance 1 m from reactor core inside D_2O reflector γ-field is decreased by a factor of 100, while the flux of thermal neutrons is decreased no more than six times. For instance, at the edge of D_2O reflector of HF ILL reactor the γ-heating is $4 \cdot 10^{-2}$ *W/g* at the flux of thermal neutrons $2 \cdot 10^{14}$ n/cm$^2\cdot$s. The heavy water is a good shielding from γ-rays of core and it almost completely restricts the flux of fast neutrons.

The minimal limit for the ratio of 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, respectivetly. Thus the γ-heating is: $q(W/g) = \Phi_\gamma \mu_{D_2} \rho_{D_2}^{-1} E_\gamma = 2.8 \cdot 10^{-17} \Phi_{th}$ ($\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$) or $5.5 \cdot 10^{-3} (W/g)$ for $\Phi_{th} = 2 \cdot 10^{14}$ $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$. This is the minimal limit. Unfortunately any shell, which provides the cavity in D_2O medium will give a considerably higher contribution for the source heating. One of the best materials for this purpose is zirconium. For the 3 mm vacuum shell and 1 mm cold shell the γ- heating will be: $q_\gamma(W/g) = 0.92 \cdot 10^{-16} \Phi_{th} (\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1})$ or $1.8 \cdot 10^{-2} (W/g)$ for $\Phi_{th} = 2 \cdot 10^{14}$. This estimation should be increased by 30% because of the partial thermalization of neutron flux. Thus for practical case the total γ-heating for D_2 of UCN source will be about $(6 \div 7) \cdot 10^{-2} (W/g)$ at the edge of D_2O reflector. This level of heating can be reduced by the factor of 2 or 3 by means of interchannel Bi shield if it will be necessary.

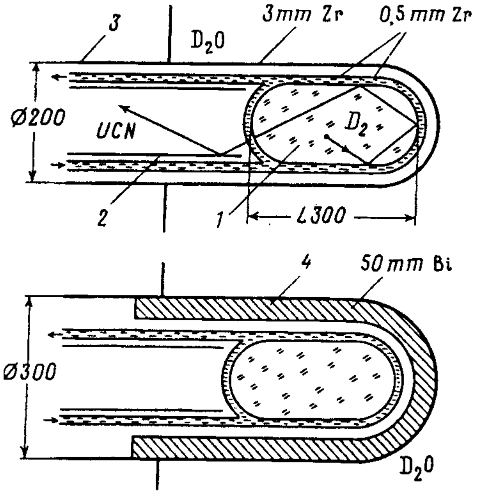

Fig.3. Simplest layouts of solid D_2 UCN source at the edge of D_2O reflector: *1* - UCN source, *2* - UCN guide, *3* - reactor channel, *4* - Bi shield

The next principal question is: what temperature will be inside the solid D_2 source at this level of radiation? The temperature difference between the wall and center of source: $\Delta T = q\rho/6\lambda R^2$ for the spherical form or $\Delta T = q\rho/4\lambda R^2$ for cylindrical form, where λ -the coefficient of thermal conductivity, R - radius. The thermal conductivity of solid deuterium considerably depends on its orto-para modification. For 98% orto-deuterium (equilibrium concentration at 4K) $\lambda = 0.12$ $W \cdot \mathrm{cm}^{-1} \cdot K^{-1}$. For UCN source the most close to practical realization (cylinder with 150-180 mm diameter and 300 mm length, see Fig.3) the temperature in the center of source will differ from the wall temperature by 1.2K. The possibility to keep 98% concentration of orto-deuterium under radiation must be check experimentally. In the worst case, if this will be impossible, the problem of thermal conductivity may be solved by means of sectionalization of source with cylindrical cells with 50 mm diameter.

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

The thermal power released in solid deuterium will be about 60-70 W, the same power will be released in zirconium source walls. To cool this source a refrigerator with the power 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 $10^3 - 10^4$ cm^{-3} for experimental researches is possible. The increase of UCN density by two orders of magnitude will allow to improve the accuracy of measurements considerably in the field of fundamental physics investigations (neutron electric dipole moment, neutron lifetime, asymmetry of the neutron decay and so on). Apparently, applied researches for the solid state and surface physics will be possible if this density of UCN will be obtained.

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

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