A method of "External cold neutron source" for UCN production in superfluid ^{4}He

A.E. Verkhogliadov[1,2], E.V.Lychagin[1,2], A.Yu.Muzychka[1,2], G.V.Nekhaev[1,2],
V.V.Nesvizhevsky[2,3], G. Pignol[4], K.V.Protasov[4] and A.V.Strelkov[1,2]

[1] *Joint Institute for Nuclear Research, Dubna, Russia, 141980;*
[2] *Research Institute of Materials Technology, Presnenskii val 21/18, Moscow, Russia, 123557*
[3] *Institute Laue-Langevin, Grenoble, France.*
[4] *Laboratoire de Physique Subatomique et de Cosmologie, Grenoble, France*

Helium ultracold neutrons (UCN) sources [1], as well as solid-deuterium UCN sources, seem to be the most promising methods at the moment to produce UCN. There are several projects of helium UCN sources at the stage of their realization or feasibility study [2, 3, 4, 5, 6]. An advantage of helium sources is long time of UCN storage in super-fluid helium that provides accumulation of high UCN density in the source volume. A weakness of helium sources is low cross-section of UCN production (low probability of UCN production) and necessity to use very low temperatures as UCN lifetime in super-fluid He^4 depends sharply on He^4 temperature (the lifetime drops from ~1000 c to 30 c if the temperature decreases from 0.8 K to 1.2 K).

UCN density in a helium source is proportional to the average flux of cold neutrons with the wavelength of 8.9 Å also to the UCN lifetime in the source volume. The average cold neutron flux could be increased if a source is surrounded with an efficient reflector for cold neutrons; in case of monochromatic 8.9A wavelength, neutrons should be reflected elastically. A value of the maximum gain factor in the average cold neutron flux depends on the source geometry. For example, for the geometry of source [2], the maximum gain in cold neutron flux averaged over the source volume would reach a factor of ~20 for 100% efficient reflector, however, the gain factor drops sharply if the reflection efficiency decreases. An effective reflector for the existing UCN source should reflect cold neutrons elastically and the reflector thickness should be smaller than the characteristic source size to avoid diluting the cold neutron density over larger volume.

Fig. 1 shows the probability of neutron reflection from reflectors well known in neutron physics also from a reflector made of powder of diamond nanoparticles [7] as a function of neutron velocity; for initial neutron angular distribution is isotropic. As clear from this Figure, all there reflectors are not efficient for neutrons with the wavelength of 8.9 Å, except probably for a reflector made of powder of diamond nanoparticles. The results in Fig. 1 are calculated for realistic size distribution of diamond nanoparticles; the average diamond nanoparticle diameter is ~3.5 nm. However, the nano-powder reflection efficiency increases when nanoparticle size decreases. Fig. 2 shows calculations of the probability of reflection of neutrons with the wavelength of 8.9 Å from a layer of hypothetical powder of diamond nanoparticles as function of the layer thickness and temperature; the calculations are performed within a model of independent nanoparticles with the diameter of 2 nm in rest; the powder density is 0.4 g/cm^3; the hydrogen contamination equals to values characteristic for such powders [8]; hydrogen is assumed to be rigidly attached to nanoparticle surface. As clear from Fig. 2, thicknesses needed to efficiently reflect neutrons are too large (compared to the existing source size) thus such reflectors would not result to any gain in the existing source geometry. Presence of hydrogen decreases the optimum reflector thickness of equal efficiency; however it limits the best efficiency at the level of 80% (because of neutron capture in hydrogen) even if the reflector is cooled down to 4K. It is still interesting to study other hydrogen-containing reflectors from the point of view of maximum reflection efficiency providing that the reflector thickness should not exceed a few centimeters.

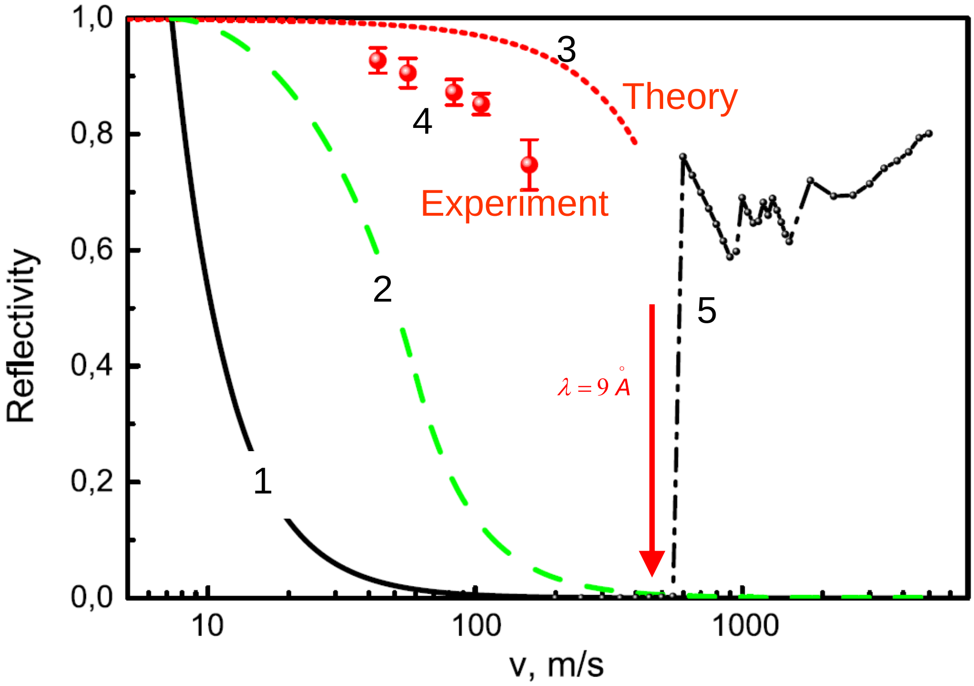

Fig. 1. The elastic reflection probability for isotropic neutron flux is shown as a function of the neutron velocity for various carbon-based reflectors: (1) Diamondlike coating (DLC) (solid line), (2) The best supermirror [9] (dashed line), (3) Hydrogen-free ultradiamond powder with the infinite thickness (dotted line). Calculation. (4) VCN reflection from 3 cm thick diamond nanopowder at ambient temperature (points), with significant hydrogen contamination [**Ошибка! Закладка не определена.**]. Experiment. (5) MCNP calculation for reactor graphite reflector [10] with the infinite thickness at ambient temperature.

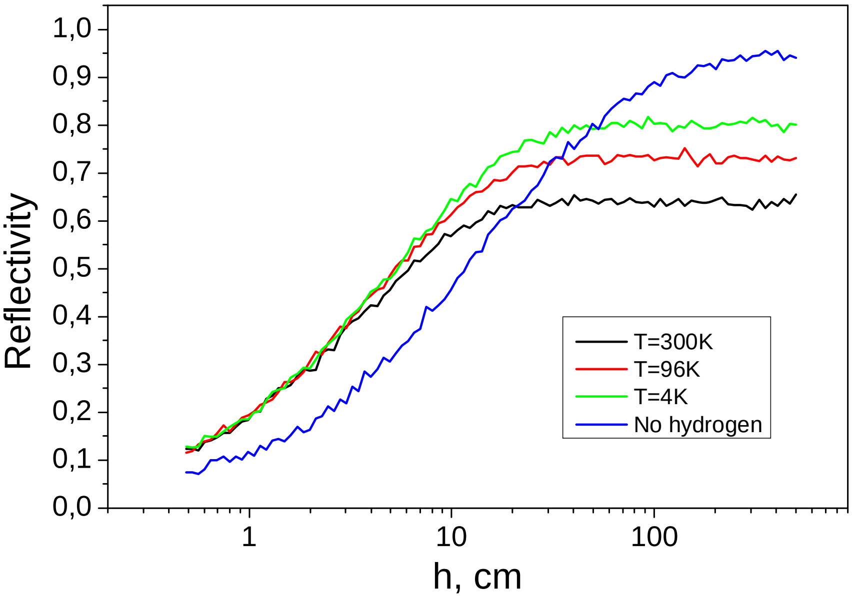

Fig. 2. The probability of reflection of neutrons with the wavelength of 8.9 Å from a hypothetical powder of diamond nanoparticles with the diameter of 2 nm; the powder density is 0.4 g/cm^3; the hydrogen contamination equals to values characteristic for such powders.

We considered H_2, D_2 and methane as possible reflectors as well. Two isomeric states of H_2 orto- and para- molecules differ by the spin 0 and 1 respectively [11]. If the temperature is lower than 20 К para-state is the equilibrium one. The cross-section of elastic scattering of neutrons on para-hydrogen is small (a factor of 10 lower than that for orto-hydrogen); it is compatible with the cross-section of absorption of neutrons with the wavelength of 8.9Å [12].

Thus the reflection probability is low because of neutron absorption and application of H_2 for neutron reflectors is not efficient. The cross-section of scattering of neutrons on orto-deuterium (equilibrium state of deuterium at low temperatures) is compatible to that on para-hydrogen [13], but it is nearly a factor of 600 larger than the absorption cross-section. So the probability of reflection of neutrons from D_2 could be high, but the reflector thickness has to be as large as about a meter.

Unlike H_2, elastic scattering cross section of solid methane below 20 K (in so-called phase II) increases considerably with decreasing neutron energy in the range of $10^{-4} \div 10^{-2}$ eV and with decreasing temperature of methane [14]. However, the inelastic part of the scattering cross section is large enough [15] to use the methane as an elastic reflector. Thus we have not yet found any elastic reflector for neutrons with the wavelength of 8.9A. However, the present analysis motivated us to propose a new concept of cold neutron source at an exit of a neutron guide for producing UCN in helium.

A principle scheme of such a source is shown in Fig. 3. A cavity in a cryogenic cold-neutron reflector installed at the exit of a thermal (cold) neutron guide. The total flux of neutrons with the wavelength of 8.9 Å in the cavity increases compared to that in the incoming neutron guide due to multiple neutron reflection from the cavity walls as well as due to cooling the neutrons to the temperature below ~12K corresponding to the neutron wavelength of 8.9Å. Relative γ-quanta and fast-neutron background (normalized to the total flux of useful cold neutrons) would be much lower than that present in vicinity of cold neutron sources.

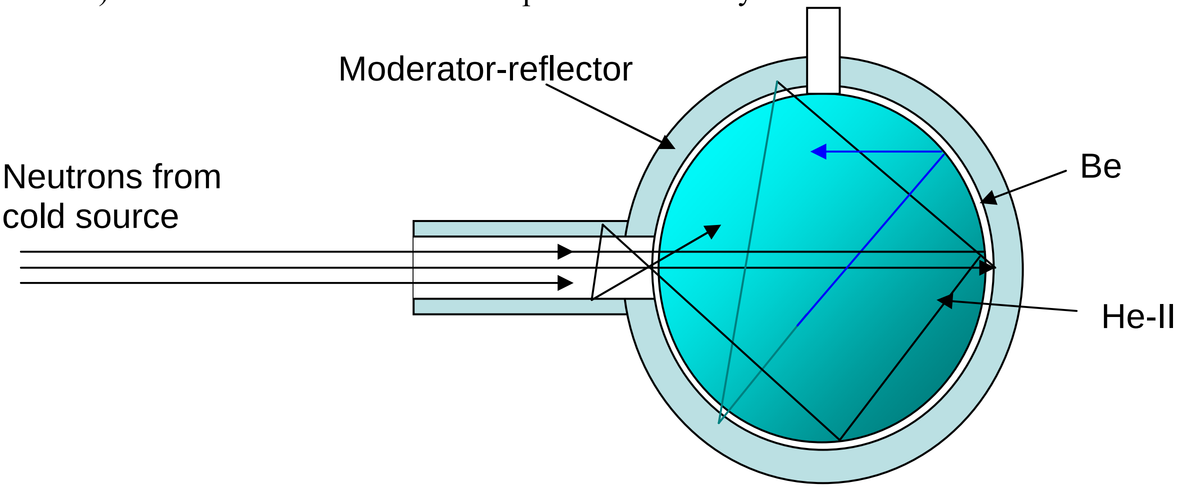

Fig. 3 Principal schema of "external" cold neutron source for UCN superthermal helium source

As the angular divergence of neutrons in the guide is small (typically ~2^o for neutron with the wavelength of 8.9Å), cold neutrons enter the cavity of the "virtual cold neutron source" with minor scattering in the reflector entrance channel walls. If the probability of neutron reflection from the cavity walls equals unity, cold neutrons accumulate in cavity until equilibrium is reached; if so, neutron flux back to the neutron guide equals to the incoming neutron flux. One should note that the long entrance channel reflects efficiently off-axis cold neutrons back to the cavity, in analogy to phenomena considered in refs. [16, 17]. If (for the ideal reflectivity of the cavity walls) cold neutrons in the cavity would get any angle within 4π, the total cold neutron flux would become equal to that inside the reactor cold neutron source. In this case the total flux of neutrons with the wavelength of c would increase by 4 orders of magnitude (approximately the ratio of 4π- solid angle to the solid angular divergence in the incoming neutron beam) compared to that in the incoming neutron guide. We place a spherical (cylindrical) ^{4}He source in such a cavity. Storage times of UCN in the UCN accumulation volume with such shape are significantly larger than those in "guide-shape" volumes, as the storage times are proportional to the UCN mean free path. UCN transport losses are largely suppressed as experimental devices are placed close to such UCN source. There is no UCN extraction loss related to long UCN storage volumes; there is no loss related to transport of cold neutrons.

The proposed configuration of a helium UCN source provides other advantages:

- low radiation load to the cryogenic system installed to the exit of a neutron guide allows reaching the temperature of ~0.7 K thus long storage times of UCN in the source and consequently high UCN density in the source;

- utilization of a reflector-moderator allows us to install a helium UCN source to a thermal neutron beam; so no need for a cold neutron source in the active reactor zone.

Solid methane at a temperature of less then 4 K is a good candidate to use as a reflector / moderator in the proposed source. Estimates show that reflection probability about 70% could be obtained for 8.9Å wavelength neutrons at 3 cm thickness of methane. Increasing of neutrons density in the methane cavity due to reflection and thermalization must be measured experimentally.

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1 Golub and Pendlebury, Phys. Lett. A **62**, 337 (1977)

2 P. Schmidt-Wellenburg et al. Nuclear Instruments and Methods in Physics Research A **611** 267–271(2009)

3 Y Masuda *et al. Phys. Rev. Lett.* **89** 284801 (2002)

4.Geoffrey Greene et al. [J. Res. Natl. Inst. Stand. Technol. 110, 149-152 (2005)

5 http://nuclear.uwinnipeg.ca/ucn/triumf/post-acot-5-26-8/ucn-post-acot-may08.pdf

6 A. P. Serebrov ye al. Physics of the Solid State, **52** (5) 1034–1039 (2010) [А.П. Серебров и др. Физика твердого тела, 2010, том 52, вып. 5]

7 E.V. Lychagin et al. Physics Letters B **679** 186–190 (2009)

8 V Yu Dolmatov Russian Chemical Reviews, **70** (7) 607-626 (2001)

9 R. Maruyama, et al., Thin Solid Films **515** 5704 (2007)

10 E. Fermi, A course in neutron physics, in: Collected Papers, The University of Chicago Press, Chicago, 1965.

11 L. Farkas Ergebn. d. exakt. Naturwiss., **12**, 163, (1933)

12 L.L. Daemen and T.O. Brun .LA-UR-98-1022

13 F. Atchison Nuclear Instruments and Methods in Physics Research A **611** 252–255 (2009)

14 Yunchang Shin at al. arXiv:0705.0824v2

15 S. Grieger et al Journal of chemical physics **109** (22) (1998)

16 Schmidt-Wellenburg, Ph. et al. NIM A **577** 623-635 (2007)

17 Barnard, J. et al. NIM A **591** 431-435 (2008).