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UCN sources at external beams of thermal neutrons. An example of PIK reactor

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ABSTRACT

We consider ultracold neutron (UCN) sources based on a new method of UCN production in superfluid helium (^{4}He). The PIK reactor is chosen as a perspective example of application of this idea, which consists of installing ^{4}He UCN source in the beam of thermal or cold neutrons and surrounding the source with moderator-reflector, which plays the role of cold neutron (CN) source feeding the UCN source. CN flux in the source can be several times larger than the incident flux, due to multiple neutron reflections from the moderator–reflector. We show that such a source at the PIK reactor would provide an order of magnitude larger density and production rate than an analogous source at the ILL reactor.

We estimate parameters of ^{4}He source with solid methane (CH_4) or/and liquid deuterium (D_2) moderator–reflector. We show that such a source with CH_4 moderator–reflector at the PIK reactor would provide the UCN density of $\sim 1 \cdot 10^5$ cm^{-3}, and the UCN production rate of $\sim 2 \cdot 10^7$ s^{-1}. These values are respectively 1000 and 20 times larger than those for the most intense UCN user source. The UCN density in a source with D_2 moderator-reflector would reach the value of $\sim 2 \cdot 10^5$ cm^{-3}, and the UCN production rate would be equal $\sim 8 \cdot 10^7$ s^{-1}. Installation of such a source in a beam of CNs would slightly increase the density and production rate.

1. Introduction

A new concept of super-thermal liquid-helium (^{4}He) UCN sources is presented in ref. [1]. Such sources can be installed in beams of thermal neutrons; thus at ILL (Grenoble) or PIK (Gatchina) such a source would provide parameters highly exceeding those of existing UCN sources. The present work develops ref. [1], considers source parameters in more detail, and applies the new concept to the PIK reactor. Note, however, that such a UCN source can be installed at any other thermal neutron source as well.

The idea of ^{4}He UCN sources was proposed in 1975 in ref. [2]; it is based on neutron scattering in liquid ^{4}He accompanied with exciting phonons with the energy of 1.02 meV. If the incident neutron energy is slightly higher than 1.02 meV then the cold neutron (CN) is converted into a UCN. As the UCN energy is lower than $\sim$300 neV, only CNs from a very narrow energy range contribute to the UCN production. Cross-sections of simultaneously exciting two or more phonons are lower by a few orders of magnitude. However, the energy of excited phonons is found in a broad range, thus UCNs are produced via multi-phonon processes from a broad spectrum of incident neutrons. Therefore total contributions of one-phonon and multi-phonon process are comparable to each other if the incident neutron spectrum is broad.

Work [2] showed also that produced UCNs can live for a long time in superfluid ^{4}He if its temperature is below 1 K. Long lifetimes of UCNs allow accumulating them up to high densities. Neutron storage time changes sharply as a function of helium temperature. It equals to the neutron lifetime $\sim$880 s at the temperature of 0.8 K, it is 10 times longer than that at the temperature of 0.6 K, and it is 10 times shorter than that at the temperature of 1 K. Thus it has no sense to decrease the ^{4}He temperature below 0.6 K; on the other hand, UCN densities in the source could not reach high values at temperatures above 1 K. UCN production rate depends on temperature only slightly.

There are several operational ^{4}He UCN sources in the world: in particular those at KEK (Japan) [3] and ILL [4,5]. The UCN source at KEK is fed by a neutron source installed at a proton accelerator.

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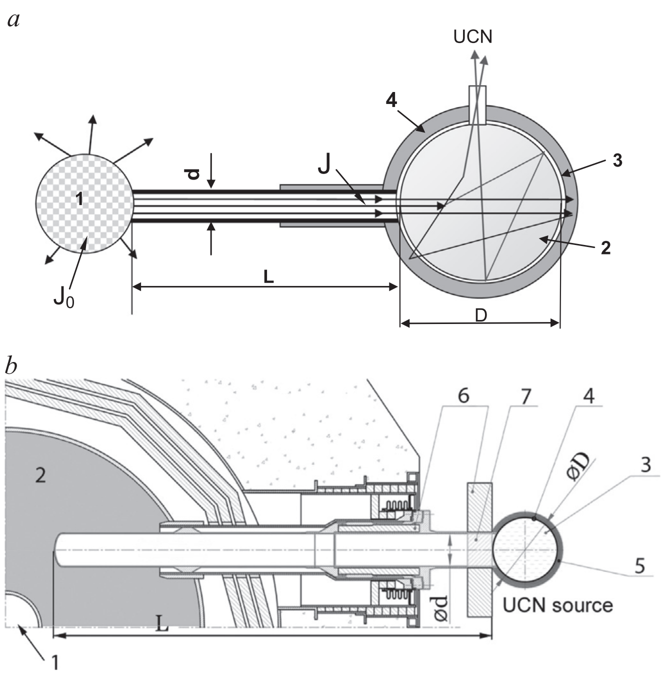

Fig. 1. a. A scheme of the UCN source surrounded with moderator–reflector. 1 – isotropic thermal or cold neutron source; 2 – superfluid ^{4}He at the temperature of 0.6 K; 3 – Be (BeO) spherical UCN trap with diameter D; 4 – moderator–reflector. b. A scheme of possible installation of the UCN source in the beam of thermal neutrons at the PIK reactor. 1 – reactor active core; 2 – D_2O moderator; 3 – superfluid ^{4}He at the temperature of 0.6 K; 4 – Be (BeO) spherical UCN trap; 5 – moderator–reflector; 6 – Pb shielding; 7 – Bi shielding.

UCN sources at ILL are fed by monochromatic neutrons with the wavelength of 8.9 Å, selected from an incident beam of CNs using special crystals-monochromators [16]; one source is used for tests, another one feeds the GRANIT spectrometer [6]. All these sources provide UCN density comparable to that at the UCN facility PF2 at ILL [7]. The production rate in ^{4}He sources is much lower than the production rate at PF2. Several projects of helium UCN sources are in the stage of realization or development [17–19,21].

The new concept [1] consists of installing ^{4}He UCN source in the beam of thermal or cold neutrons at the edge of the biological shielding and surrounding the source with cold moderator-reflector (see Fig. 1). The moderator-reflector plays the role of CN source feeding the UCN source; CN flux in the UCN source can exceed the incident neutron flux by several times due to neutron multiple reflections. The idea of surrounding helium UCN source with warm reflector of cold neutrons was proposed in [20] (see more details in [1]).

Such a ^{4}He source is a closed spherical trap made from a material with high neutron-optical potential (for instance Be) filled in with superfluid ^{4}He at the temperature of $\sim$0.6 K. Thermal and cold neutrons can easily penetrate through the trap walls, but produced UCNs are trapped; they can be extracted to external experimental setups via a small hole in its upper side.

UCN production rate is defined by the integral flux of incident neutrons-“parents” and by their total path in ^{4}He. Thus the shorter and larger guides, the larger UCN production rate and density. For an isotropic source of thermal or cold neutrons with flux density J_0, the flux density J of neutrons incident to the source is proportional to the reciprocal square of neutron guide length L and to the square of neutron guide diameter d. Thus integral flux F of incident neutrons is proportional to d^4.

The proposed geometry enables utilizing neutrons with broad angular distribution at the neutron guide exit; such neutrons cannot be efficiently transported further away from the reactor active zone through mirror neutron guides.

Table 1
Comparison of characteristics of PIK and ILL reactors.

Reactor characteristics	ILL reactor “optimistic”/“realistic”	PIK reactor “optimistic”/“realistic”
L_{min}, m	5/5	3/3
d, cm	20/15	30/20
J_0, s^{-1} cm^{-2}	$\sim 1\cdot 10^{15}/\sim 1\cdot 10^{15}$	$\sim 1\cdot 10^{15}/\sim 1\cdot 10^{15}$
J, s^{-1} cm^{-2}	$\sim 1\cdot 10^{11}/\sim 6\cdot 10^{10}$	$\sim 8\cdot 10^{11}/\sim 4\cdot 10^{11}$
F, s^{-1}	$\sim 4\cdot 10^{13}/\sim 1\cdot 10^{13}$	$\sim 6\cdot 10^{14}/\sim 1\cdot 10^{14}$

The path of “parents” in ^{4}He is proportional to the trap diameter D and the number of their reflections from moderator-reflector; also it depends on the probability of their back escape through the entrance neutron guide. Thus the larger trap diameter D, the larger UCN production rate.

Complementary to the production rate, another important parameter is the UCN density accumulated in the source; it is proportional to the production rate and the reciprocal source volume, i.e. to D^2.

Thus the source diameter should be optimized in order to balance the two parameters.

Table 1 compares relevant characteristics of PIK and ILL reactors. L_{min} is the minimum neutron guide length defined by the thickness of the reactor biological shielding and the size of the heavy water (D_2O) reflector around the active zone; d is the maximum neutron guide diameter defined by the reactor channel size; J_0 is the maximum thermal neutron flux density in the D_2O reflector in the vicinity of the reactor active zone; J is the thermal neutron flux density at the guide exit; F is the integral flux of thermal neutrons at the guide exit.

“Optimistic” characteristics are defined by the maximum neutron guide diameter that can be in principle installed. “Realistic” characteristics are defined by the diameter of existing available neutron guides.

As clear from Table 1, the incident integral neutron flux at the PIK reactor can be an order of magnitude higher than that at the ILL reactor. Respectively, the UCN density and production rate can be an order of magnitude higher at the PIK reactor as well.

Precise calculations for the channel HEC-4 at the PIK reactor (the diameter of 20 cm) using MCNP program resulted to the following estimation of the thermal neutron flux density at the guide exit, three meters away from the reactor active zone center:

$$J = 3.66\cdot 10^{11}\ cm^{-2}s^{-1}, \quad (1)$$

and thus

$$F = 1.15\cdot 10^{14}\ s^{-1}. \quad (2)$$

2. UCN source with methane moderator

We showed in ref. [1] that solid methane (CH_4) in phase II at the temperature of $\sim$4 K is among best materials for moderators-reflectors for such UCN sources.

Fig. 2 shows cross sections of neutron scattering on solid CH_4 as a function of neutron energy at different temperatures (the data from refs. [8,9]). As clear from the figure, solid CH_4 provides large cross sections of inelastic and elastic scattering; the cross section of elastic scattering increases with the decrease of the neutron energy. The later property is very important, as it allows accumulating large quantities of CNs inside solid CH_4 cavities.

We simulated neutron spectra accumulated in solid CH_4 cavities. The calculation was performed using the program MCNP 4c with a special kernel for solid CH_4 used in works [9,10] and kindly