Universal liquid-hydrogen source of polarized cold and ultracold neutrons at the VVR-M reactor of the Leningrad Institute of Nuclear Physics

I. S. Altarev, N. V. Borovikova, A. P. Bulkin, V. A. Vesna, E. A. Garusov, L. A. Grigor'eva, A. I. Egorov, B. G. Erozolimskiĭ, A. N. Erykalov, A. A. Zakharov, S. N. Ivanov, V. Ya. Kezerashvili, S. G. Kirsanov, É. A. Kolomenskiĭ, K. A. Konoplev, I. A. Kuznetsov, V. M. Lobashev, N. F. Maslov, V. A. Mityukhlyaev, I. S. Okunev, B. G. Peskov, Yu. V. Petrov, P. G. Pikulik, N. A. Pirozhkov, G. D. Porsev, A. P. Serebrov, Yu. V. Sobolev R. R. Tal'daev, V. A. Shustov, and A. F. Shchevetov
B. P. Konstaninov Institute of Nuclear Physics, Academy of Sciences of the USSR

(Submitted 21 August 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **44**, No. 6, 269–272 (25 September 1986)

Record-high intensities and flux densities of polarized cold neutrons [3×10^{10} n/s and 6×10^{8} $n/(\text{s}\cdot\text{cm}^2)$] and a record-high intensity of ultracold neutrons (5×10^{5} n/s) with a flux density of 6×10^{3} $n/(\text{s}\cdot\text{cm}^2)$ have been attained for the velocity range $V_x, V_y, V_z < 7.8$ m/s at an intermediate-power reactor. The degree of polarization of the neutron beam is $90\pm5\%$. The yields of ultracold and cold neutrons have been studied with deuterium and hydrogen-deuterium mixtures.

A universal source of polarized cold and ultracold neutrons was started up at the VVR-M reactor in late 1985. The liquid-hydrogen moderator, with a volume of 1 liter, is placed at the center of the reactor core and is surrounded by a lead shield to reduce the heat load from the radiation (Fig. 1). The flux density of thermal neutrons at the position of the source is $(1.5\text{–}2)\times10^{14}$ $n/(\text{s}\cdot\text{cm}^2)$. The 2-kW total heat evolution in

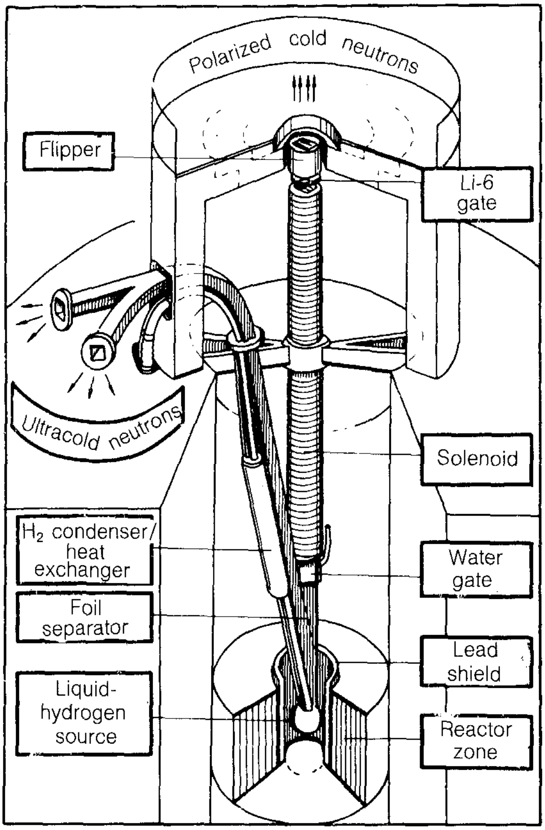

FIG. 1. Schematic diagram of the universal liquid-hydrogen source with a liquid-hydrogen moderator.

the source consists of the heat evolved in the cladding of the source (800 W) and that evolved in the hydrogen (1200 W). Heat is removed from the source by circulating the liquid hydrogen in a loop containing a heat exchanger connected to a helium refrigerator. The total volume of liquid hydrogen in the loop is 6 liters. The circulation of the liquid hydrogen arises because of the temperature-induced difference in the densities and the asymmetric position of the heat exchanger in the loop. The velocity at which the liquid hydrogen circulates reaches 1 m/s at full reactor power. A receiver with a volume of 20 m^3, connected by a drainage line to the liquid-hydrogen loop, is used to load and unload the hydrogen.

The spectra of polarized cold and ultracold neutrons are measured by a time-of-flight method. An ionization fission chamber is used to detect the cold neutrons, and a ^{3}He proportional detector is used to detect the ultracold neutrons. The flux density of polarized cold neutrons is calibrated by a gold-foil activation method. Figure 2 shows spectra of polarized cold neutrons obtained before and after the liquefaction of the hydrogen in the source. The ratio of these spectra determines the factor by which the yield of cold neutrons is improved by the use of the liquid-hydrogen moderator. This improvement factor has a characteristic spectrum, reaching a value of 40–50 at large wavelengths (10–20 Å). Lowering the hydrogen temperature from the boiling point,

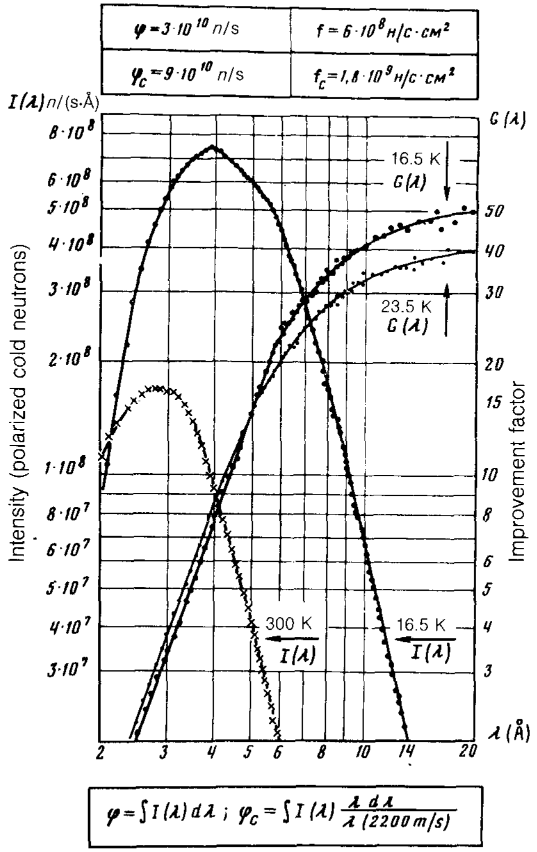

FIG. 2. Spectra of the neutron fluxes and of the improvement factors for the polarized beam of cold neutrons.

23.5 K, to 16.5 K results in a 25% increase in the yield of long-wavelength neutrons. The intensity of the neutron flux reaches a maximum at 4.0 Å. The spectrum is shaped by both the low-temperature moderator and the curved neutron duct, which cuts off the short-wavelength part of the spectrum. The total flux of polarized cold neutrons (φ) at the position of the experimental apparatus is 3×10^{10} n/s at a flux density (f) of 6×10^{8} $n/(\text{s}\cdot\text{cm}^2)$. The cross-sectional area of the neutron beam is 120×40 mm². A neutron flux is frequently characterized in units of the so-called capture flux, i.e., the flux of thermal neutrons which is equivalent in terms of capture. For the beam of cold neutrons produced, the capture of flux (φ_c) and the capture flux density (f_c) are 9×10^{10} n/s and 1.8×10^{9} $n/(\text{s}\cdot\text{cm}^2)$, respectively. Rough measurements of the degree of polarization of the neutron beam yielded the result $90\pm5\%$.

Figure 3 shows the temperature dependence of the yield of ultracold neutrons for gaseous and liquid hydrogen. At the hydrogen condensation point, $T=23.5$ K, the yield of ultracold neutrons increases sharply, because of the thermalization of the flux of thermal neutrons in the moderator. A further lowering of the temperature of the liquid hydrogen leads to a further increase in the yield of ultracold neutrons; the improvement factor reaches 55. As a unit we adopted the yield of ultracold neutrons

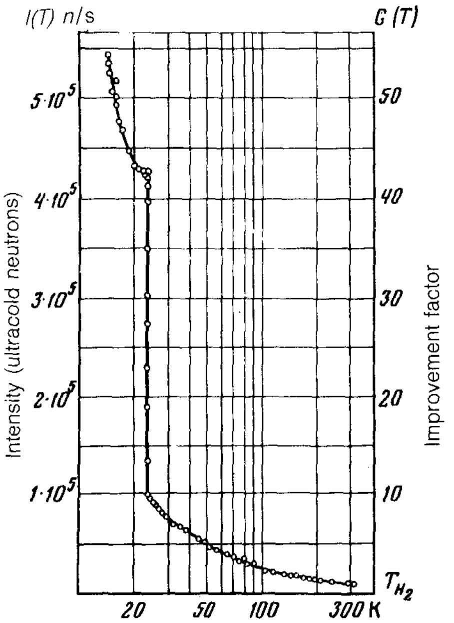

FIG. 3. Temperature dependence of the yield of ultracold neutrons.

from gaseous hydrogen at $T = 285$ K. The relative flux of ultracold neutrons generated by the zirconium cladding of the source was taken into account correctly by carrying out measurements with ^{3}He at a low pressure and with the source volume evacuated.

The spectrum of neutrons at the exit from the neutron duct for the ultracold neutrons has a maximum at a velocity of 18.5 m/s. This velocity is determined by the boundary velocity of the coating (7.8 m/s) and the radius of the turns in the neutron duct (1 m). The differential flux density at the maximum is 5×10^3 $n/[\mathrm{s \cdot cm^2 \cdot (m/s)}]$. The flux density of ultracold neutrons with velocities $V_z < 7.8$ m/s along the axis of the neutron duct was determined by the method of a screen-induced difference. For these measurements, a thin (10-μm) aluminum foil with a deposited coating with a cutoff velocity of 7.8 m/s—the same as the cutoff velocity of the wall of the neutron duct—was placed in the beam path. Spectral measurements carried out with and without this screen show that 20% of the difference spectrum is made up of neutrons with velocities $V_z > 7.8$ m/s, which are absorbed or scattered by the foil. The corrected flux density or ultracold neutrons with velocities $V_x, V_y, V_z < 7.8$ m/s is 6×10^3 $n/(\mathrm{s \cdot cm^2})$, while the total intensity for the two neutron ducts is $2 \times 2.5 \times 10^5$ n/s. The neutron density in phase space is 8.1×10^{-3} $n/[\mathrm{cm^3 \cdot (m/s)^3}]$. The density of the ultracold neutron gas calculated from the phase-space density for our neutron duct ($|V| < 7.8$ m/s) is 16 cm^{-3}. For a trap of stainless steel ($|V| < 6.2$ m/s), for example, the corresponding figure would be 8 cm^{-3}.

There is definite interest in studying the yields of ultracold and cold neutrons for deuterium and hydrogen-deuterium mixtures. Measurements carried out with the same source provided the following results: At the deuterium condensation point (25

K), the yield of ultracold neutrons (in units of the improvement factor for normal hydrogen) is 31–32, but the yield increases very rapidly with decreasing temperature, reaching 66 at 17 K. At 19 K, the curves for hydrogen and deuterium intersect, and the yields are the same. The curves for the hydrogen-deuterium mixtures intersect in the same place. For cold neutrons, the improvement factor is lower by a factor of about three in the case of pure deuterium. For a mixture of 40% H_2 and 60% D_2, however, there is a 10% increase over the result for pure hydrogen.

A hydrogen-deuterium mixture consisting of 40% H_2 and 660% D_2 is presently being used in the source. Over the time the source has been in operation (more than half a year), no decrease in the intensity of either ultracold or polarized cold neutrons has been noted. The flux density of ultracold neutrons achieved in our source is about five times lower than that in the new channel of ultracold neutrons from a liquid-deuterium moderator at the high-flux reactor at Grenoble.[1] It is difficult to make a really accurate comparison because of differences in the measurement methods and correction procedures. The intensity and flux density of the beam of polarized cold neutrons are new records, exceeding by a factor of three to five the previous records for beams of polarized cold neutrons[2] at the Grenoble reactor. These improvements have been achieved by making maximum use of the capabilities of the reactor (by placing the source at the center of the reactor core; this placement became possible because of the highly effective liquid-hydrogen cooling system) and because of the multislit neutron-duct focusing system, which simultaneously polarizes the beam of cold neutrons.

We wish to thank our colleagues in the design department, the experimental instrumentation shop at Leningrad Institute of Nuclear Physics, and the neutron-research mechanical workshop laboratories for their active participation in the development of this universal neutron source. We also thank the staff at the VVR-M reactor and in the department of cryogenic and superconducting technology for much assistance in the design and operation of this source. We are indebted to A. V. Strelkov (Joint Institute for Nuclear Research) for furnishing monitor detectors which he had developed especially for an ultracold neutron duct and P. S. Yaĭdzhiev (Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences), A. V. Vasil'ev, V. V. Nesvizhevskiĭ, V. G. Syromyatnikov, N. K. Pleshanov, V. A. Priemyshev, M. S. Lasakov, Yu. V. Borisov, and A. B. Brandin for assistance in various stages of this work.

---

[1] P. Ageron and W. Mampe, in The Investigation of Fundamental Interactions with Cold Neutrons. Proceedings of the Workshop. NBS Special Publication, Gaithersburg, 1986, 711, p. 16.

[2] Neutron Research Facilities at the ILL High Flux Reactor, Institute Max von Laue-Paul Langevin, Grenoble, France, 1983.

Translated by Dave Parsons