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Physics

^{3}He-^{4}He Dilution Cryostat for Investigation of Interactions of Neutrons with Polarized Nuclei

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ABSTRACT. The ^{3}He-^{4}He dilution cryostat with superconducting solenoid has been put into operation on the pulse reactor IBR-2 at the Frank Laboratory of Neutron Physics, Dubna. The cryostat will be used to investigate interactions of polarized and non-polarized neutrons with polarized nuclei. *© 2008 Bull. Georg. Natl. Acad. Sci.*

Key words: *neutron, nucleon, spin, polarization, superconductivity, helium, magnetic field.*

I. Introduction

The dilution cryostat with superconducting solenoid is used for polarization of nuclei. The “brutal force” method is the most universal one used for orientation of nuclei – when the nuclear target is deeply cooled in a constant, strong magnetic field. In this case the nuclear polarization is achieved by orientation effect of the magnetic field on nuclear magnetic moments.

As thermal equilibrium between the system of nuclear spins and the substance of the nuclear target is attained, the polarization is given by the Brillouin function [1]

$$f_1 = \frac{2I+1}{2I} cth\left(\frac{2I+1}{2I}\frac{\mu H}{kT}\right) - \frac{1}{2I} cth \frac{1}{2I}\frac{\mu H}{kT} ,$$

where I is the nuclear spin, μ is its magnetic moment, T is the target temperature, k is the Boltzmann constant. For small $\frac{\mu H}{kT}$ a simplified expression holds true

$$f_1 \approx \frac{I+1}{3I}\frac{\mu H}{kT}$$

Because of smallness of nuclear magnetic moments μ, to achieve a noticeable rate of polarization requires very low temperatures and very strong magnetic fields. So, for a hypothetical nucleus with spin $I = 1$ and magnetic moment equal to one nuclear magneton, at achievable fields $H \approx 10$T and temperatures $T \approx 10^{-2}$ K, the calculations give $f_1 \approx 0.25$.

^{3}He-^{4}He refrigerator has been constructed. It comprises:

- ^{4}He cryostat
- ^{3}He circulation system and ^{3}He in ^{4}He dilution stages
- Superconducting solenoid
- Temperature control system
- Supply and control systems for the superconducting solenoid.

II. ^{4}He cryostat

The helium cryostat (Fig.1) consists of nitrogen bath 4 and two helium baths 6 and 8. All three baths are made of stainless steel and are mounted on central ^{3}He pumpout pipe 3. Leaktight three-sectional copper nitrogen screen 5 is connected to the nitrogen bath 4 (volume V=18.5 l). The screen divides the cryostat vacuum space into external and internal parts. The internal vacuum part of the cryostat includes helium bath 6 (volume V=13 l), which operates at 4.2 K with helium screen 7. Helium bath 8 (volume V=14 l) is located inside the screen 7, and is evacuated in turn by vacuum aggregates AVR- -150(1) or AVR-150(2) down to the temperature of 1.15 K. The housing of superconducting solenoid 11 is connected to bath 8. Easily demountable indium seals allow replacement of solenoids according to experiment requirements.

Helium baths 6 and 8 are interconnected through kryo-valve 10, which regulates the amount of liquid helium poured from bath 6 to bath 8. Copper vacuum screen 9 (vacuum shell VS), which serves as a vacuum jacket for the dilution stage, is connected through indium seal to bath 8. External cryostat housing 2 made of stainless steel is dismountable and consists of three sections.

In order to reduce neutron losses, the cryostat is equipped with leaktight windows manufactured from 0.2 mm thick stainless steel plates and two AD aluminium alloy flanges, decreased, in the neutron path, down to a thickness of 0.5 mm.

The cryostat is preliminarily cooled by filling all volumes with liquid nitrogen, which is removed after cooling down all heat screens, before the beginning of helium filling. Nitrogen cooling of the cryostat is controlled by TVO type carbon resistors [2]. It takes 80 litres of liquid nitrogen and 8 hours to cool the cryostat down to nitrogen temperature. Liquid nitrogen consumption in operating mode of the cryostat is 0.8 l/h. It takes 40 litres of liquid helium and 6 hours to cool the cryostat down to helium temperature. Liquid ^{4}He consumption in stationary operating mode of the cryostat is 0.8 l/h.

He exchange gas under the pressure of 20 Pa is used to cool the dilution stage down to helium temperature and the process takes 15 hours. The exchange gas is removed from VS before the beginning of ^{3}He-^{4}He mixture condensation.

The temperature in one-degree helium bath is determined using McLeod compression pressure gauge. The level of liquid ^{4}He in helium baths is determined with Allen Bradley carbon resistors assembled according to Lavrentyev-Churakov scheme [3].

III. ^{3}He circulation system and ^{3}He-^{4}He dilution stages

The ^{3}He circulation system is assembled on the basis of 2500 l/s vacuum booster pump NVBM-2.5, 50 l/s vacuum rotary unit AVR-50 and leakproof mechanical pump NVG-2 connected in series (Fig.1). This pump group provides for ^{3}He circulation rate $c = 1.07 \times 10^{-3}$ mole/s. To prevent the ingress of oil from pump NVBM-2.5 into the cold part of ^{3}He pump-out duct, nitrogen trap 12 is used, which is positioned directly over the inlet flange of the pump NVBM-2.5. Liquid nitrogen-cooled external carbon trap 13, as well as filters from sintered copper powder installed between baths 6 and 8 at ^{3}He supply lines serve to clean oil, which is returned to cryostat, from decomposition product vapours and from a small amount of air, which may enter the system due to possible seal failure. Such cleaning system prevents interlocking of ^{3}He return line.

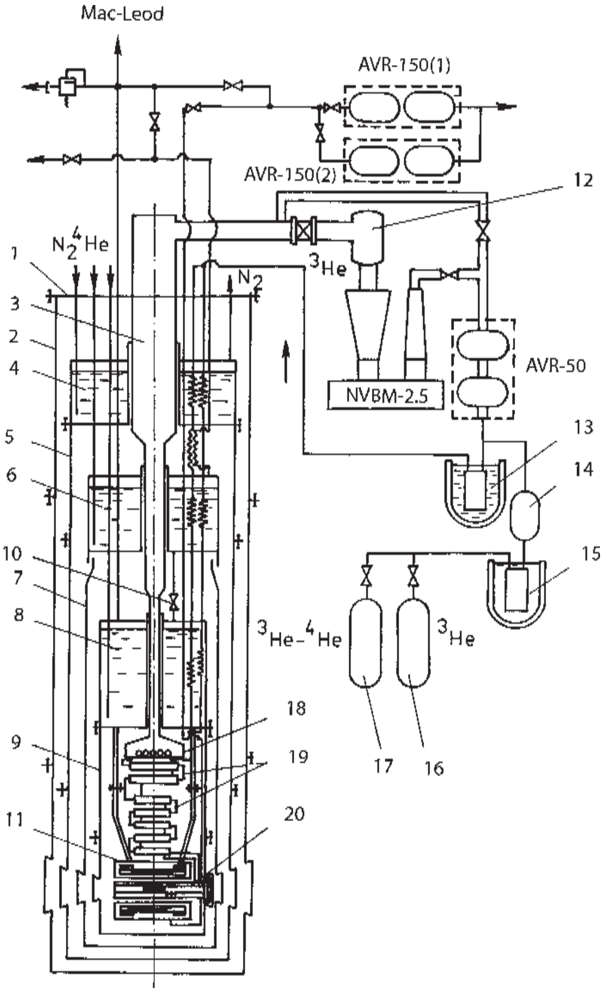

Fig. 1. ^{3}He-^{4}He dilution cryostat diagram with a superconducting solenoid.

1 – main flange; 2 – vacuum housing; 3 – central ^{3}He pump-out pipe; 4 – nitrogen bath; 5 – nitrogen screen; 6 – helium bath; 7 – helium screen; 8 – helium bath to be evacuated; 9 – dilution stage helium screen; 10 – cryo-valve; 11 – superconducting solenoid; 12 – nitrogen trap of booster pump NVBM-2.5; 13 – oil filter; 14 – pump NVG-2; 15 – carbon trap; 16 – ^{3}He storage cylinder; 17 – ^{3}He-^{4}He mixture storage cylinder; 18 – evaporation bath; 19 – heat exchangers; 20 – dilution bath.

After completion of a working cycle, the ^{3}He-^{4}He mixture is pumped by canned pump NVG-2 through carbon trap 15 into the cylinder 17 for storage purposes.

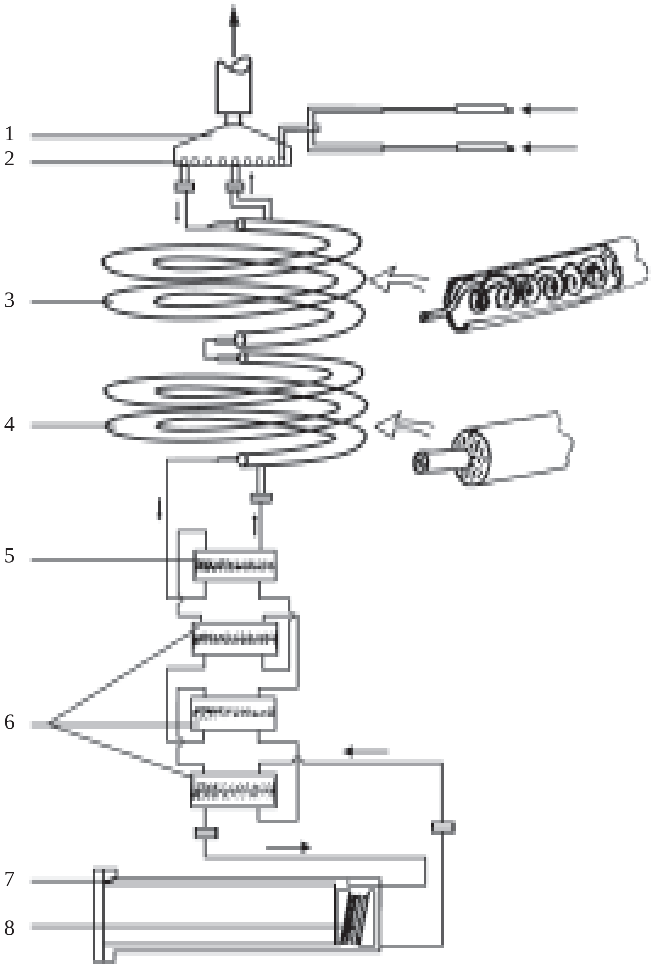

Fig. 2. Diagram of ^{3}He-^{4}He dilution stages.
1 – evaporation bath; 2 – evaporation bath heat exchanger; 3 – continuous tubular heat exchanger; 4 – continuous sintered heat exchanger; 5 – discrete copper heat exchanger; 6 – discrete heat exchangers from sintered silver powder; 7 – dilution bath; 8 – ferromagnetic neutron resonator with polarized nuclear target.

Gaseous ^{3}He is supplied to the cryostat through two independent return lines I and II. Along the return lines, ^{3}He passes through tubular heat exchangers, placed in the bottom parts of nitrogen bath 4 and helium baths 6 and 8. The diameters of copper pipes of heat exchangers are 6×0.5, 4×0.5 and 3×0.3 mm, respectively. The length of each pipe 5m. Upon condensation in tubular heat exchangers of bath 8, ^{3}He passes through throttles D_1 and D_2 and then enters the heat exchanger located in the bottom part of evaporation bath 1 (Fig.2). The impedance of the throttle D_1 is $z = 10^9$ cm^{-3} and that of the throttle D_2 is $z = 10^{11}$ cm^{-3}. In the course of mixture condensation, both ^{3}He supply lines are used, afterwards the line I is closed.

The evaporation bath 1 accommodates a heater, which is designed for ^{3}He circulation rate control and thermometers for measuring the bath temperature. To suppress the ^{4}He superfluid film, a polished diaphragm from stainless steel is soldered at the exit of the evaporation bath.

Upon leaving the evaporation bath heat exchanger, ^{3}He is supplied to the system of continuous and discrete heat exchangers. The refrigerator contains six heat exchangers, which are similar to those described in [4]: continuous spiral heat exchangers 3 and 4 (tubular and sintered), discrete heat exchanger 5 from sintered copper powder, three discrete heat exchangers 6 from sintered silver powder.

Discrete heat exchangers are compact, they have large heat exchanging area and small impedance z. They are all assembled from components of unified design: a disc and two covers of oxygen-free copper soldered together with tin solder. Both sides of the disc in the heat exchanger 5 are covered with 2 mm sintered copper powder layer (grain size 10-40 μm), corresponding to rated heat exchanging area of 0.75 m^2 on each side. The heat exchangers 6 use silver powder with grain size 0.15 ìm (purity 99.99%). Changing geometrical sizes and thickness of sintered powder layer, it is possible to obtain heat exchangers with various heat exchanging areas. In the produced heat exchangers 6, the design surface area of sintered powder on each disc side is 5, 7.5 and 10 m^2.

From the last heat exchanger ^{3}He arrives at the dilution bath 7, where ^{3}He atoms undergo transition from concentrated phase to ^{3}He-^{4}He solution, i.e. ^{3}He dissolves in ^{4}He accompanied by heat absorption. The osmotic pressure difference makes ^{3}He diffuse through heat exchangers from dilution chamber 7 to evaporation chamber 2, from where ^{3}He is evacuated.

The dilution bath is located in the effective volume of the superconducting solenoid and it is insulated from the solenoid walls by means of textolite needles. The dilution bath structure (Fig.3) can be easily disassembled. The plug 2 seals the internal volume of the bath by means of indium seal. The bath contains the following assemblies: ferromagnetic neutron resonator with a sample 6, NMR-resonator 5, temperature sensors 4 and heater 7. The bellows 3 ensure that the plugs are pressed to a sample, thus yielding insignificant neutron intensity losses because of neutron absorption by ^{3}He nuclei. Since the sample is placed in a solution, it has solution temperature (no Kapitza temperature jump is observed, because there is no significant heat generation in the sample). Dilution bath temperature is T=23 mK at ^{3}He circulation rate $c = 1.07 \times 10^{-3}$ mole/s.

III. Superconducting solenoids

Two superconducting solenoids have been developed and tested for the facility, which can be, in turn, easily connected through indium seals to one-degree helium bath 8 of the cryostat (Fig.1). Depending on experiment requirements, an appropriate solenoid is installed. They

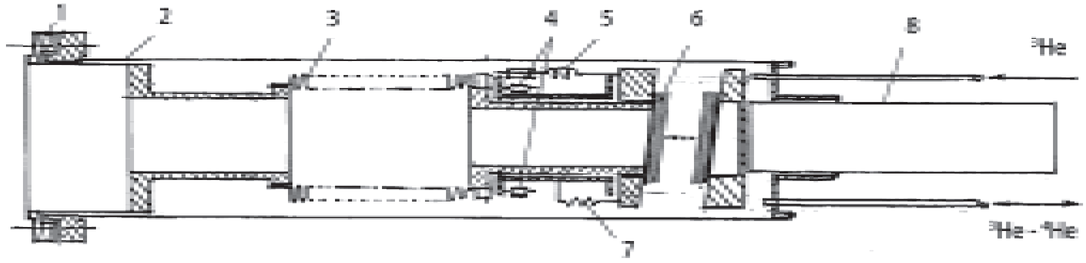

Fig. 3. Dilution bath.
1 – plug; 2 – housing; 3 – bellows; 4 – temperature sensors; 5 – NMR-resonator; 6 – ferromagnetic neutron resonator with a sample; 7 – heater; 8 – centering plug-tube.

differ by magnetic field strength H and by field homogeneity $\Delta H/H$. Let us denote them arbitrarily as I and II.

Solenoid I with correcting coils (Fig. 5) is wound with the SNTE-2 superconducting cable 0.51 mm in diameter. The superconducting coil is placed in stainless steel leakproof housing.

The solenoid parameters:

- Solenoid constant $K = 0.063$ T/A
- At a temperature of 1.18 K the critical current is $I_c = 96.5$ A and, correspondingly, the magnetic field strength is $H = 6$ T
- Magnetic field homogeneity in the center of the solenoid in the sphere 14 mm in diameter is $\Delta H = 2.4 \times 10^{-4}$ Solenoid II with correcting coils is wound with the NT-50 superconducting wire 0.7 mm in diameter. The magnetic field of the solenoid II is highly inhomogeneous. The solenoid constant is $K = 0.044$ T/A. At a temperature of 4.2 K the critical current is $I_c = 151.6$ A and, correspondingly, the magnetic field strength is $H = 6.6$ T. The solenoid inner diameter is 36 mm. The dependency of cryostat cooling productivity on the temperature, at ^{3}He circulation rate $c = 1.07 \times 10^3$ mole/s is shown in Fig. 4.

V.3. Temperature and supply control systems of the superconducting solenoid

The following temperature sensors are installed to control temperature in the dilution bath:

- Lace Shore graduated ruthenium oxide thermometer RX-202A-AA,
- Speer graduated carbon resistor R=100Ω and
- Mitsubhiti non-graduated thermometer.

The dilution bath is also equipped with a heater for quick removal of the solution and for determination of refrigerating capacity of the cryostat. The Speer graduated carbon resistor R=100Ω is installed at the exit of heat exchangers. The Allen Bradley non-graduated resistor and the 28Yu-42 graduated carbon resistor are arranged in the evaporation bath.

A multi-channel resistance meter for low-temperature thermistors has been developed to control temperature. The resistance meter is in the CAMAC standard and controlled by a personal computer.

Technical data of the resistance meter:

- Number of measured channels 12
- Working range of measured resistances, Ohm 10^2 - 10^6
- Measurement current range, A 10^{-7} -10^{-10}
- Resistance measurement error in the working range at input power of

10^{-10} W	2%
10^{-12} W	3%
10^{-14} W	5%

- Measurement time for one channel, μs 60

To supply the superconducting solenoids, a stabilized DC source AIST-110 has been developed, which is controlled via a PC serial port. A built-in control module makes it possible to vary output source current in the range 0-110 A with an accuracy of 5 mA.

Conclusion

In conclusion we can establish a fact that we have created the dilution cryostat ^{3}He-^{4}He with superconducting solenoid, which allows us to orient nuclei for most elements in the periodic system. The experimental setup also includes a possibility for dynamic polariza-

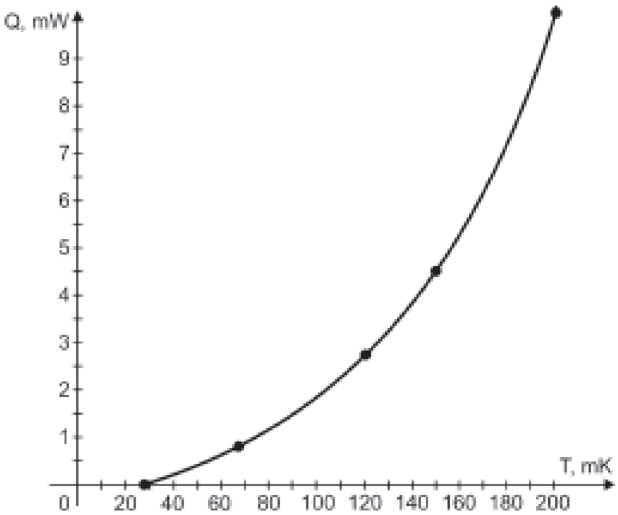

Fig. 4. The dependency of cryostat cooling productivity on the temperature, at ^{3}He circulation rate $c = 1.07 \times 10^3$ mole/s.

tion of nuclei.

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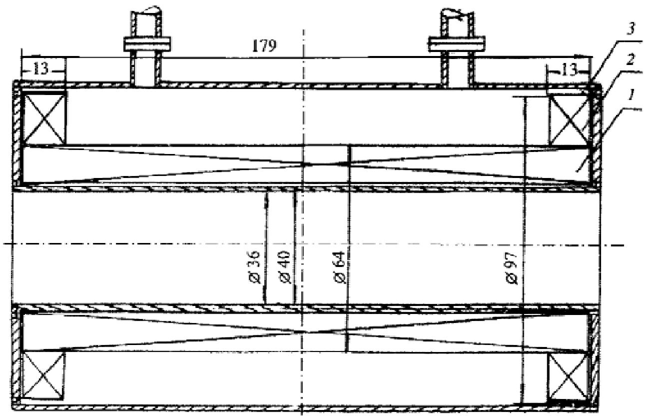

Fig. 5. Diagram of superconducting solenoid I.

ფიზიკა

პოლარიზებული ბირთვების სამიზნის (პბს) დანადგარი ნეიტრონებით კვლევებისათვის

მ. წულაია, ვ. წულაია, ვ. ალფიმენკოვი

ე. ანდრონიკაშვილის ფიზიკის ინსტიტუტი, თბილისი
ფრანკის ნეიტრონული ფიზიკის ლაბორატორია (ბირთვული კვლევების გაერთიანებული ინსტიტუტი, დუბნა, რუსეთი)

(წარმოდგენილია რუსეთის მეცნიერებათა აკადემიის აკადემიკოსის ა. სისაკიანის მიერ)

დუბნის ბირთვული კვლევების გაერთიანებული ინსტიტუტის ფრანკის ნეიტრონული ფიზიკის ლაბორატორიაში შექმნილია ნეიტრონული კვლევებისათვის გამიზნული "პოლარიზებული ბირთვების სამიზნე". სამიზნე შესდგება ^{3}He-^{4}He განზავების კრიოსტატისაგან, ზეგამტარი სოლენოიდებისაგან, მართვისა და კონტროლის სისტემებისაგან. სამიზნეზე შესაძლებელია ბირთვების ორიენტირება მასური რიცხვების დიდ დიაპაზონში. ბირთვების პოლარიზება ხდება როგორც დინამიკური, ასევე "უხეში ძალის" მეთოდით. ექსპერიმენტული კვლევები შეიძლება ჩატარდეს როგორც პოლარიზებული, ასევე არაპოლარიზებული ნეიტრონებით.

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