THE VNIIFTRI MAGNETIC TEMPERATURE SCALE IN THE 0.3–3 K RANGE

D. N. Astrov, N. B. Ermakov,
and V. I. Sviridenko

A thermodynamic temperature scale in the range 0.3–3 K is established by a magnetic method. The results of investigations enable the range of the State Standard of temperature to be extended from 0.8 K to 0.3 K with a simultaneous increase in its accuracy by a factor of 2–3.

Key words: *magnetic thermometer, resistance thermometer, ITS-90 temperature scale.*

The purpose of this research was to produce a new improved instrumental and practical basis for developing and increasing the accuracy of the standard level of practical thermometry which approximates as closely as possible to the thermodynamic temperature scale in the 0.3–3 K range. The formulation of the problem provides for a subsequent transition to the reproduction of a temperature scale by a natural carrier – the melting pressure of pure ^{3}He. Exact thermometry at temperatures below 3 K is the basis of numerous fundamental investigations in the area of solid-state physics, quantum crystals and liquids, superconductivity and nuclear physics.

An improvement in the thermometric instruments and methods at the standard level of accuracy in this range undoubtedly involves a number of pressing problems. Today a single temperature scale below 1 K based on the melting pressure of ^{3}He has been produced in a number of leading foreign laboratories within the framework of an All-European project. It was proposed, in particular, to replace the scales based on the pressure of the saturated vapors of isotopes of helium, which are limited in range and of unsatisfactory accuracy, and was recommended for use by the International Consultative Committee on Thermometry in 2001 under the name ITS-2000. The results of research in both these areas and the apparatus constructed should in the near future be introduced into the composition of the State Standard of Temperature, which will enable the reliability and accuracy of its readings to be increased by a factor of 2–3 with an extension of the range below 0.8 K.

An analysis of the measurement possibilities of different methods for the accurate and reliable reproduction of the thermodynamic temperature scale in the 0.3–3 K range has shown that the magnetic method, based on Curie's law for a system of non-interacting dipoles should provide the maximum accuracy. The working material of the magnetic thermometer which is best and which has been investigated in greatest detail is an oriented single crystal of cerium-magnesium nitrate [1]. There are no exchange and superfine interactions in this material, and the dipole-dipole interaction is extremely small, so that there is a very small correction to Curie's law, constituting, according to the literature data, 0.27 mK in all [2]. Correspondingly, two temperature points are sufficient to calibrate the magnetic thermometer, one close to 3 K using a standard thermometer and the other at the fixed point of the ^{4}He transition to the superfluid state at a temperature of 2.1768 K, according to the ITS-90 [3]. Note that other well-known paramagnetic materials, that are suitable in principle for this purpose (chromopotassium or chromomethylamine alum), are capable of providing very high sensitivity, but for these materials it is necessary to introduce additional corrections to Curie's law. In this case, the number of calibration points required increases, and the accuracy of the result is reduced.

The structural features and form of the magnetic thermometer produced were largely dictated by the limited finance available for the work, but the main principle for obtaining the highest accuracy – not less than that of traditional methods of magnetic thermometry, remained unchanged. A feature of the instrument was the use as a reading instrument of a high-frequency squid (superconducting quantum interference device) which, in turn, enables small crystals of cerium-magnesium nitrate to be used. However, this leads to extremely high requirements in suppressing parasitic noise and pickup from external measuring instruments.

The values of the thermodynamic temperature obtained in magnetic thermometry are transferred to self-checked resistance thermometers made of an alloy of rhodium and iron, which we developed, with a heat exchange of the sensitive element through liquid ^{4}He in the superfluid state [4, 5]. The measurement of the thermodynamic temperature was based on Curie's law for an ideal paramagnetic material, which connects the magnetic susceptibility χ with the thermodynamic temperature T:

$$\chi = C/T.$$

where C is Curie's constant.

The effect of the demagnetizing factor is neutralized by using a spherical sample. Then, for cerium-magnesium nitrate only a single correction $\Delta = 0.27$ mk remains in Curie's law:

$$\chi = C/(T + \Delta).$$

The susceptibility of cerium-magnesium nitrate is extremely small, and it can be measured with an error of less than 0.01% by a mutual inductance bridge with a very high sensitivity. For the reasons given above, the dimensions of the magnetic thermometer produced are extremely limited, and high sensitivity can only be obtained using a squid. The current I in the primary coil (the solenoid) of the mutual inductance bridge produces a proportional uniform magnetic field. The magnetization of the material is recorded by an astatic pair of similar secondary coils, in one of which the sample is placed. If the mutual inductance of each of the secondary coils is identical with the primary coil, the signal that occurs is proportional to the magnetization of the sample. However, the inevitable difference between these two mutual inductances leads to the occurrence of a part of the signal that is independent of the presence of the cerium-magnesium nitrate. If the secondary coils are made from a superconductor and are connected in series with the superconducting signal coil, which is in the aperture of the squid, the possibility arises of measuring the susceptibility at constant current, while the use of a solenoid of superconductor eliminates the heating by the current I. The magnetic flux due to the current I induces in the superconducting transformer a current

$$i = (A + B/(T + \Delta))I, \tag{1}$$

measured by the squid, where the constant A enables one to take into account the temperature-independent difference of the mutual inductances of the secondary coils, and also the possible effect of diamagnetism. It follows from the equality that a measurement of the currents i and I at two known temperatures enables one to obtain the constants A and B and hence calibrate the magnetic thermometer.

An investigation of the characteristics of the first-version of the magnetic thermometer, operating using a high-frequency squid, revealed several important drawbacks, the appearance of which required additional investigations and improvements in a number of devices and components. Preliminary temperature measurements using the magnetic thermometer in the 0.3–3 K range revealed the presence of a considerable deviation from linearity on the graph of the magnetic susceptibility against the inverse emperature $\chi(T^{-1})$. The deviations obtained exceeded 0.2%, and reached 0.04% even in the narrower

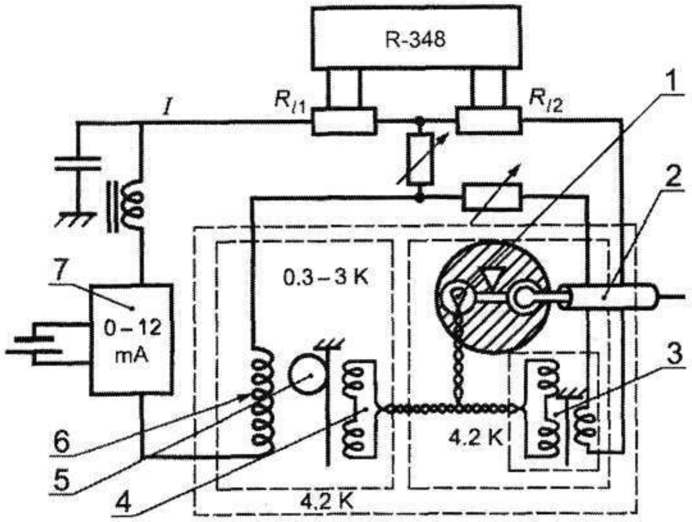

Fig. 1. Bridge-comparator with the high-frequency squid as the null instrument: *1*) signal opening of the squid; *2*) cable; *3*) compensator; *4*) superconducting coils; *5*) single crystal of cerium-magnesium nitrate; *6*) primary solenoid; *7*) regulated current source.

range of 0.7–2 K. In these experiments, the measured quantity was the feedback current of the squid apparatus, which, in principle, should be proportional to the magnetic flux with the salt sample placed in it and correspondingly to the current in the superconducting transformer. To obtain the necessary accuracy characteristics of the magnetic thermometer, this nonlinearity should not exceed 0.01%.

It was not possible to check the linearity of the characteristics of the squid apparatus experimentally. Hence, we designed a basically different circuit for making measurements with the magnetic thermometer, in which the squid is only used as a very sensitive null instrument in a necessarily linear instrument, called conventionally a bridge-comparator. The circuit of the comparator is shown in Fig. 1.

A constant magnetic field from the primary solenoid *6*, excited by a current I from a regulated source *7*, is applied to an oriented single crystal of cerium-magnesium nitrate *5*. The current is measured from the voltage drop across a standard resistance R_{I1} using a R-348 dc potentiometer. The magnetization of the crystal, which is in one of the superconducting coils of the astatic pair *4*, produces a current in the flux transformer and a change in the magnetic flux in the signal opening of the squid *1*. The squid apparatus introduces a compensating current along the high-frequency cable *2*, and a voltage is obtained at its output, the proportionality of which to the compensating current (and the primary current) it is not possible to verify. By having a linear compensator *3* in the comparator circuit we can introduce an opposite current I_c into the transformer, which is measured by the same potentiometer from the voltage drop across R_{I2}, so that the feedback signal of the squid is returned to the value which it had before the current in the primary solenoid *6* was applied. With this procedure, the squid amplifier operates as a null instrument, and the currents of the resistors are regulated without measurements by the potentiometer (the currents are measured later), which considerably increases the stability of the squid readings. If the temperature of the sample is constant, and the bridge is balanced, the readings of the squid are constant for any values of the primary current, while the magnetic susceptibility is proportional to the ratio of the current of the compensator I_c to the solenoid current I.

The compensator *3* consists of a small primary solenoid, and the regulated current through it is measured in the same way as the current in solenoid *6* of the cell of the magnetic thermometer. The magnetic flux is transferred into the superconducting winding, connected in series with the flux transformer. It can be seen that the electrical circuit is practically the same as for a classical mutual inductance bridge. However, in our case the magnetic flux produced by the primary current I leads to the occurrence of a secondary current i – such that the overall magnetic flux through the pair of astatic coils does not change. Whereas in the usual mutual inductance bridge, when it is compensated a voltage equal to the voltage on the astatic pair is produced, but of opposite sign, in the scheme described here the compensator *3* produces an opposite current equal to the current induced by the current *I* in the solenoid.

The optimum parameters of the compensator were chosen experimentally. The realization of the undoubted advantages of the comparator described required additional superconducting screening of the part of the circuit which is at low temperature (distinguished by the dashes in Fig. 1), and the introduction of mesh filters into the squid supply, which enabled the external high-frequency interference to be reduced to a level unrecordable by the apparatus. It was much more difficult to achieve a small level of interference when the supply of both primary solenoids of the comparator was connected. For this reason, the source *7*, which is miniature, screened and supplied from a battery, was placed right up to the cryostat. This enabled the effect of the network and high-frequency interference, reaching the magnetic thermometer connecting lines, to be practically eliminated.

It should be noted that the operating procedure with the magnetic thermometer described, in which a squid is used, differs from the most widely used arrangement [6]. (In the latter the external measuring field is produced by a superconductor, in the aperture of which the previously induced magnetic flux is frozen.) However, with this approach there must be complete assurance that, during the measurements, external noise does not lead to the "passage" of a reading via the squid by one or several flux quanta. It is impossible to verify the presence of such a "passage." Under these conditions, the level of external noise is comparatively high. Hence, it is necessary, at each temperature point, to introduce a measuring field of zero value and then again return it to zero. If the readings at the zero field are identical, this guarantees that there is no uncontrolled "passage" of flux into the squid, and only in this case can one assume a point to be correctly measured. The measuring field strength did not exceed 50 A/m [7].

The working material of the magnetic thermometer – an oriented bead of cerium-magnesium nitrate – was made from high-purity material. Analysis showed the presence in it of only lanthanum in a concentration of less than 0.01%. The material was additionally purified by double recrystallization in double distilled water. The crystals were ground in PTFE vessels, at the bottom of which there was a seed crystal with dimensions of about 3 × 3 × 0.2 mm. The vessels were placed in an ordinary refrigerator, which gradually removed the water from the previously boiled and concentration-selected solution. After two-three weeks, a colorless transparent crystal in the form of a plate with dimensions of about 20 × 20 × 5 mm appeared on the bottom of the vessel. For subsequent manufacture of a spherical sample, parts of the crystal without visible defects were selected. The spherical sample was made from two hemispheres, the plane of which coincided with the plane of the grown single-crystal plate. The trigonal axis of the cerium-magnesium nitrate grown in this way is always perpendicular to the plane, which is also the plane of easy magnetization, so that there is no difficulty in orienting the sphere.

The hemispheres were made by mechanical processing. They were then connected to one another, and a gold wire was glued between them to provide thermal contact and to preserve the orientation of the plane of easy magnetization of the sample along the axis of the first solenoid when it is mounted in the cell of the magnetic thermometer. Note that small deviations in the orientation can only lead to a slight reduction in sensitivity [8]. The deviation from sphericity of a sample of diameter 6.3 mm amounted to only 0.3 mm. Analysis showed that the gold used contained no magnetic impurities in a concentration greater than 0.005%. Earlier attempts to use a copper wire, coated with lacquer, for this purpose led to the situation where, after a few months, the initially colorless sample of cerium-magnesium nitrate became slightly pink-yellow colored, which, clearly indicated that the material had become contaminated due to the diffusion of copper into the cerium-magnesium nitrate.

The cell of the magnetic thermometer, containing the cerium-magnesium nitrate, the primary and secondary coils of the bridge and the system of screens, must satisfy a number of specific requirements. First, the chamber of the cell for positioning the working material – the oriented spherical single crystal of cerium-magnesium nitrate – must be hermetically sealed, so as to eliminate the loss by the material of water of crystallization during preliminary pumping out of the cryostat at room temperature. Second, the small bead of cerium-magnesium nitrate must be maintained in good thermal contact with the cell, which is at the temperature to be measured. Third, the primary magnetic field must be uniform, and the effect of external magnetic fields, including the field from the measuring apparatus, must be eliminated. Fourth, the response of the cerium-magnesium nitrate to the primary field must be recorded by the superconducting receiving coils in such a way that

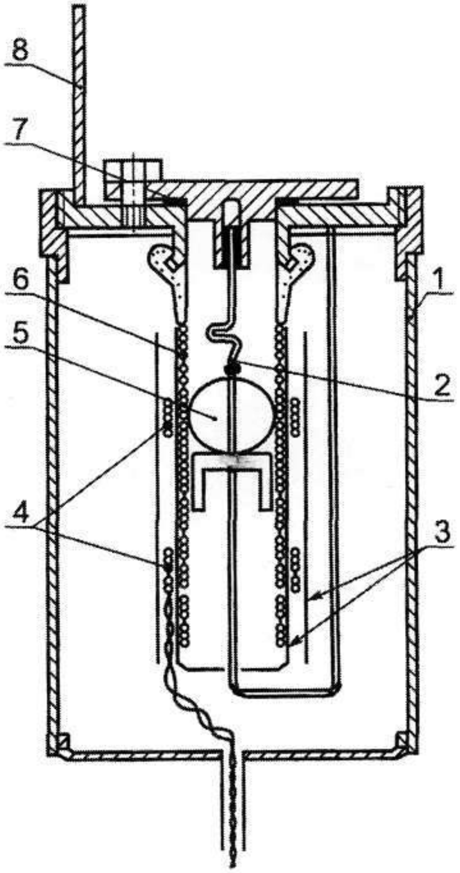

Fig. 2. Construction of the magnetic thermometer cell: *1*) housing of the superconductor; *2*) copper wire; *3*) screens; *4*) secondary (signal) coils; *5*) sample – a single crystal of cerium-magnesium nitrate; *6*) primary solenoid; *7*) packing washer of indium; *8*) strip.

the signal occurring in them is transmitted to the squid through the flux transformer. Fifth, screening is required between the primary solenoid and the secondary coils to prevent the penetration of noise from the primary circuit. During adjustment, this screening must not have short-circuited turns, in order to balance the astatic secondary coils when there is no cerium-magnesium nitrate present by choosing their position with respect to the primary solenoid, and after adjustment the screens must be closed.

The cell of the magnetic thermometer developed and constructed taking the above requirements into account is shown in Fig. 2. The spherical single crystal of the sample of cerium-magnesium nitrate *5*, the plane of easy magnetization of which is oriented along the primary field, was placed in a hermetically sealed ampoule. It is formed by the primary two-layer solenoid *6*, made of niobium wire and impregnated with ED-20 adhesive. Thermal contact is achieved by the gold wire glued between the halves of the sphere; the gold wire is welded to a copper wire *2* and connected to the lid of the ampoule, which enables the orientation of the sample to be maintained when it is placed in the ampoule. The lid of the ampoule is packed with a washer *7* made of indium. The ampoule is closed at the bottom with a plug, also made of ED-20 glue. The device remains hermetically sealed even when it is filled with liquid helium in the superfluid state. The astatic pair of similar secondary coils *4* is made of thin superconducting wire. Analysis of its composition showed that it contained 18% of ferromagnetic nickel. As a result of this, the external magnetic field of the solenoid could produce additional nonlinear magnetization at the penetration depth, which is very difficult to take into account. Hence, the wire was stripped of insulation, coated with a thin (2–3 μm) layer of tin-lead solder and again coated with insulation. Since the depth of penetration of the magnetic field into the superconductor is of the order 0.1–0.2 μm, we can assume that the effect of the magnetic impurity in the wire has been eliminated. Electrostatic screening between the primary and secondary coils is provided by slit screens, made of copper foil and insulated over the whole surface so that no short-circuited coils are formed. Two such screens were glued with ED-20 adhesive above the primary solenoid. One other insulated screen was made to be movable and the same secondary coils were placed on it. A current at a frequency of 25 Hz was applied to the solenoid, and by shifting the screen with the coils a position was found for which the signal in the secondary coils was a minimum. The screen was then clamped. All the screens had two strip-leads on the edges for grounding, which occurred through the opening in the lid of the cell (not shown in Fig. 2) and was connected to it on the outside by soft solder. This kept the screens closed and weakened the penetration of the magnetic component of the interference from the primary solenoid to the flux transformer. The fixed configuration of the primary field and the protection of the ensemble of measuring coils from external fields was achieved by superconducting screening of the body *1* made of Nb_3Sn over the cell and on its ends. In order to reduce the distortion of the primary field, the cell had maximum dimensions, compatible with the dimensions of the cryostat described below. Thermal contact of the cell in the vacuum cryostat was achieved by means of the strip *8*.

Testing of the cell shown in Fig. 2, without the sample of cerium-magnesium nitrate, showed that the possible nonlinearity does not exceed the experimental spread of the data, while the level of inherent noise amounts to about 0.001 of a quantum. When the temperature of the cell increases to 7 K, the unbalance does not vary by more than 0.01%. Hence it follows that all the materials used in the sensitive part of the cell contain no appreciable extraneous magnetic impurities. It is also obvious that the coating of the superconducting wire of the secondary winding with an additional layer of nonmagnetic superconductor has eliminated the effect of the ferromagnetic nickel, contained in the initial material. This result has a very important advantage: there is no need for separate measurements of the correction curves of the readings of the comparator without the cerium-magnesium nitrate sample in the cell over the whole 0.3–3 K range. Such an investigation of the "zero drift" and subsequent measurements with the cerium-magnesium nitrate would require a considerable reassembly of the apparatus, and there is no certainty that the inevitable change in the geometry of the circuit of the superconducting flux transformer that would occur would remove the previously obtained "zero" corrections.

To reproduce the temperature scale established by the magnetic thermometer in the 0.3–3 K range using a convenient and accurate carrier, we developed and investigated highly stable resistance thermometers, suitable down to 0.2–0.3 K. Their main advantage is the considerable improvement in the heat exchange, the drop of which in thermometers of the usual construction limits their lower region of use to 0.5 K. No-one has previously constructed such thermometers.

It is well known that at temperatures below 14 K, wire resistance thermometers made of an alloy of rhodium and iron exceed all other thermometers in their reproducibility, which in the best samples is usually not greater than 0.2 mK. This is due to the high chemical stability of the material of the wire and its considerably greater mechanical stiffness in the annealed state, compared with platinum, as a result of which a thermometer with a freely laid helix is extremely stable. Such thermometers are used in the State Standard of temperature to store the temperature scale down to 0.8 K.

The sensitivity of these thermometers increases as the temperature falls, but the deterioration of the heat exchange due to the drop in pressure of the heat-exchange gas in them below 1 Pa makes it almost impossible to use them at temperatures of less than 0.5 K, when heat transfer can only occur along the wires of the sensitive element. However, if we depart from the usual approach, in which a thermometer of the same type is used both for practical measurements and to calibrate other instruments, we can produce a good working standard, which enables us to use a widely used technique for the accurate measurement of resistances. The price paid for these changes is a considerable increase in the size and heat capacity of the thermometer and the impossibility of using it in many experiments. The basis of the approach developed is a sharp improvement in the heat exchange with a helical sensitive element. This is achieved by filling the vessel of the thermometer with liquid helium in a state of superfluidity, the thermal conductivity of which is exceptionally high. Note that in this case there are no additional factors capable of considerably affecting the thermometric properties of the freely situated helix of the sensitive element that have been overlooked. For this reason, we rejected any attempts to increase the heat transfer of the glued helix, by depositing the alloy on a substrate etc., which in all known cases lead to a sharp deterioration in the stability due to the mechanical stresses which arise from the difference in the thermal expansion of the materials of the helix and the substrate. A compromise solution is described in [4, 5].

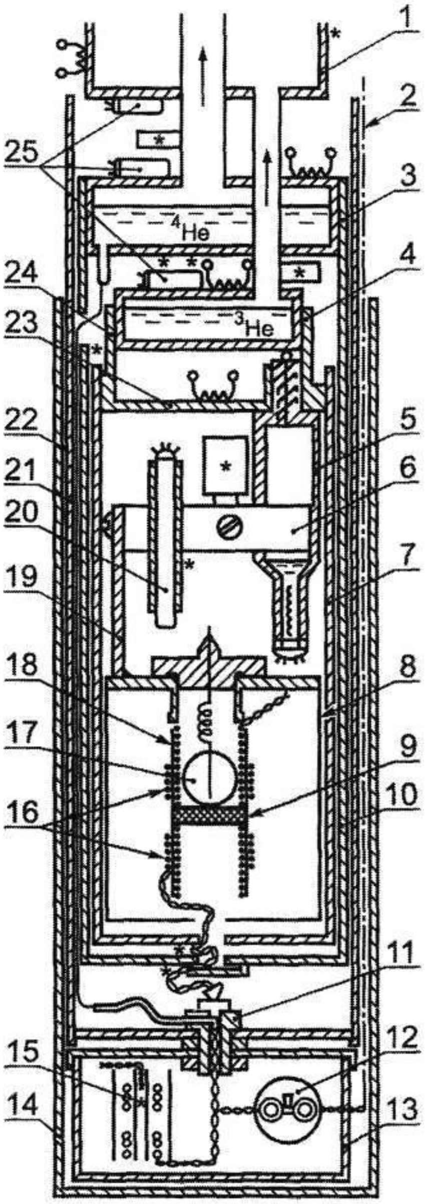

Fig. 3. Sketch of the precision cryostat for obtaining and measuring temperatures down to 0.3 K: *1*) sorption pump; *2*) coaxial cable; *3*, *4*) chambers with liquid helium; *5*) self-checked thermometer; *6*) clamp; *7*) internal screen; *8*) magnetic thermometer; *9*) screen; *10*) heat screen; *11*) ^{4}He intake unit; *12*) squid; *13*, *14*) superconducting screens; *15*) compensator; *16*) secondary coils; *17*) sample – a single crystal of cerium-magnesium nitrate; *18*) primary solenoid; *19*) strip; *20*) standard thermometer; *21*) throttle; *22*) vacuum jacket; *23*) copper plate; *24*) heat decoupler; *25*) carbon thermometers; * – thermal decouplings.

Note that such a thermometer, filled with ^{4}He, has one other very important advantage, which is the possibility of self-checking when a λ-transition of the helium filling it occurs from superfluidity to the normal state. The temperature of this transition is 2.1768 K on the ITS-90 scale. The technique for obtaining the temperature point of the transition is, in principle, well known [9]. To do this, at a temperature slightly below the λ-point a power of the order of 10^{-5} W is applied to the thermometer and a slow temperature drift is set. At the instant when the normal phase occurs, heat transfer from around the helix heated by the current falls sharply and a considerable change is observed in the rate of drift of the resistance.

We separately investigated the overheating of these thermometers by the current being measured over the working temperature range, the reproducibility of the values of the resistances when obtaining the λ-point, and also their long-term stability. The latter is of particular importance since these thermometers are intended for prolonged storage and for transferring the temperature scale. The need to investigate the long-term stability was also related to the possibility of slow diffusion of the ^{4}He, which is in the ampoule under pressure, into the helix of the sensitive element. Experiments showed that when the current is increased from the smallest values (30 μA), overheating of the helix can be described quite well by a linear function of the power Q. Then dT/Q corresponds to a $T^{-2.2}$ relation, whence it follows that the heat exchange is determined in practice by the Kapitsa surface resistance, as would have been expected.

The long-term stability of the thermometer (No. 222) was investigated when the λ-point in the liquid helium surrounding the sensitive element was reproduced [4, 5]. The investigations were carried out in the cryostat of the magnetic thermometer (see below). The thermometers investigated were compared several times with the working standard thermometer No. 75 of rhodium-iron alloy, the bearer of the ITS-90 scale in the 0.6–4.2 K temperature range. A certification was obtained by comparison with resistance thermometers, calibrated at the National Physical Laboratory (UK). As a result, it became possible to compare our data on the reproduction of the λ-point with the value of 2.1768 K, assumed in the ITS-90. The overall error in determining the phase-transition temperature with this thermometer was estimated to be 0.2 mK. According to the certification of the thermometer and the results obtained in 1998, the temperature was 2.1769 K and differed from that assumed in the ITS-90 [3] by 0.1 mK, which is half the estimate assumed above for the thermometer error. Subsequent self-checking showed that thermometer No. 222 is fairly stable and its reproducibility is within the limit of 0.2 mK. Consequently, it can be used successfully both to preserve and transfer the temperature scale, and to calibrate other high-accuracy thermometers at the λ point of the ^{4}He phase transition.

In Fig. 3, we show a sketch of a precision cryostat, which can be immersed in a transportable Dewar vessel of liquid helium. It contains the cell of the magnetic thermometer, which can be replaced by a low-temperature membrane manometer, which reproduces the temperature scale according to the melting pressure of ^{3}He. The magnetic thermometer *8*, a standard thermometer No. 75 (*20*), and a self-checked thermometer *5*, filled with liquid ^{4}He, are placed in thermal contact using a massive clamp *6*. Thermal contact between the ensemble and a copper plate *23*, which is connected, via a thermal decoupling device *24*, to the chamber *4* with liquid ^{3}He having a volume of 6 cm^3, is achieved at a single point, which enables the temperature drop between the thermometers to be reduced to a minimum. The internal screen *7* serves for this purpose. By regulating the evacuation of the chamber or by supplying power to the heater of the copper plate, one can obtain any temperatures in the 0.3–4.8 K range.

Chamber *3*, filled with liquid ^{4}He from an external Dewar vessel and evacuated by a fore-vacuum pump, placed near the top of the cryostat, serves as the main cold source in the cryostat. When its temperature falls from 3 K to 1.7 K, ^{3}He liquefies on the walls of the tube for evacuation and runs off into the chamber *4*, filling it. A further reduction in the temperature of chamber *4* is achieved by evacuating it with a sorption pump *1*, which in turn is cooled by ^{4}He vapor, leaving chamber *3*. This chamber also cools the heat screen *10*, coated with Nb_3Sn superconductor, thereby reducing the effect of electromagnetic interference on the magnetic thermometer and reducing the heat transfer by radiation and by the residual gas in the vacuum jacket *22*. Chamber *3* is supplied with liquid helium from an external Dewar vessel through a thermally insulated valve *21* with a carefully chosen hydraulic resistance. The valve *11* for admitting ^{4}He from the external Dewar vessel is combined with a hermetic metal-ceramic superconducting outlet of the flux transformer of the magnetic thermometer and is fitted with a filter which prevents clogging of the throttle.

The compensator *15* and the high-frequency squid *12*, connected to the external apparatus by coaxial cable *2*, are placed outside the vacuum jacket directly in the liquid helium at a temperature of 4.2 K. The compensator and the squid are surrounded by an additional superconducting screen *13*. The temperature regime of the cryostat is set by TSU *25* carbon; thermometers and a set of heaters. The temperatures of the magnetic thermometer and the accurate resistance thermometers are monitored by a single TSU thermometer, connected to the plate *23* (not shown in the figure). The minimum temperatures obtained as a result of pumping out the ^{4}He are 0.3 K when liquid ^{3}He is present in chamber *4*, and 1.7 K without ^{3}He. Higher

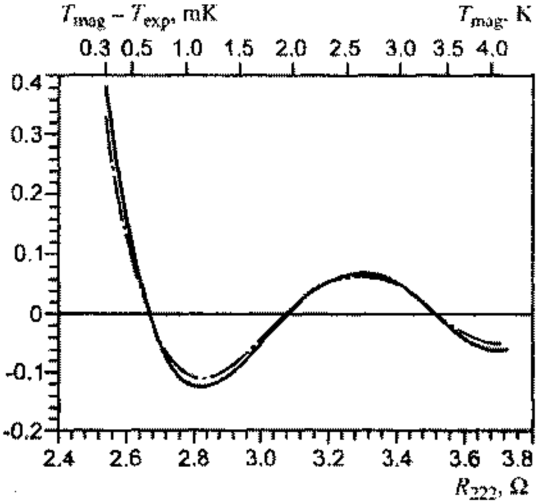

Fig. 4. Deviations of the magnetic scale from the VNIIFTRI scale, extrapolated to 0.3 K for two independent series of measurements.

temperatures are obtained by applying a constant current to the heater of plate *23*. The temperature instability of the thermometers after immersion did not exceed 0.1 mK over a period of half an hour.

The low-temperature part of the cryostat is protected by one more superconducting screen *14* of Nb_3Sn. The quality of the protection of the cryostat by the superconducting screens is such that the squid does not respond to movement of magnet in the vicinity of the Dewar vessel, which generates a field of the order of 0.01 T. The electrical assembly of the par of the cryostat which is at a temperature below 3 K, makes use of thin superconducting wires. The heat inflow along th wires can also be reduced by numerous thermal decouplers, represented in the diagram by an asterisk.

The classical method of calibrating the magnetic thermometer based on cerium-magnesium nitrate consists of determining its constants at two known temperatures. The reproducibility of the temperature of the λ point by the metho described above is approximately 0.15 mK. When choosing the second temperature point for the calibration, we took int account that even in the region of the λ point the reproducibility of the magnetic thermometer was about 0.3 mK, while a higher temperatures it turned out to be even worse. Consequently, the second temperature point for the calibration must b considerably lower. We decided to determine the constants of the magnetic thermometer not using two points, but using average readings of all points in the range of calibration of the magnetic thermometer. The main results were obtained in 200 in the fourth series of measurements in the calibration range of 0.5–1.1 K (29 experimental points) and in the sixth series i the calibration range of 0.8–2.2 K (72 experimental points). Note that in the calibration range of the magnetic thermomete we found no systematic deviations from the NPL scale [8].

Thermometer No. 75, calibrated initially in 1998 down to a temperature of 0.5 K, was compared with the thermometers obtained from the National Physical Laboratory, and also with thermometers Nos. 79 and 89, which participate in the key comparisons of standards in 2003–2004. As a result, we obtained that the readings of the State Standard in th 0.8–4 K range differed from the National Physical Laboratory scale by not more than 0.3 mK. Taking into account the reproducibility of the readings of thermometer No. 75, the uncertainty of the scale used to calibrate the magnetic thermometer wa estimated to be 0.25 mK.

Thermometer No. 222, filled with liquid, was compared a number of times with thermometer No. 75 in the 0.3–4.8 K range. The disagreement between the readings of both thermometers at temperatures higher than 0.5 K did not excee 0.1 mK, which corresponded to the capabilities of our apparatus for measuring resistances. It was established that the temperature dependence of the resistance of both thermometers is described by a function of the form $T = F(R)$ by third and fourt degree polynomials with deviations of not more than 0.15–0.1 mK. However, at temperatures below 0.5 K the reproducibil ity of thermometer No. 75 deteriorated and amounted to about 0.5 mK in the vicinity of 0.3 K. This is obviously due to overheating by parasitic power in the zone of poor heat exchange, which it was not possible to take into account with the required accuracy by introducing corrections. In turn, for thermometer No. 222 we obtained that even an increase in the power. delivered by the measuring current, from $2.5 \cdot 10^{-8}$ W to 10^{-7} W causes no appreciable (0.05 mK) overheating. These facts led us to choose thermometer No. 222 as the carrier of the temperature scale obtained from the magnetic thermometer. The dependence of the magnetic susceptibility on the temperature for both series of measurements was described by formula (1), in which, in particular, for the sixth series of measurements $A = 0.656175$, $B = 0.153060$, and $\Delta = 0.0003$.

The values of the temperatures on the magnetic scale obtained from (1) were drawn on thermometer No. 222 from 0.3 K to 0.5 K in the fourth series of measurements, and from 0.3 K to 0.8 K in the sixth series. Then, for each series these results were combined with the values of the calibration of the thermometer up to 4.8 K and smoothed by fourth-degree polynomials. As a result, we obtained two temperature dependences of the thermometer resistance in the range 0.3–4.8 K. In Fig. 4, we show the deviation of the values of the magnetic temperature for both series, if the temperature dependence of the resistance of thermometer No. 222 in the range 0.5–4.8 K is extrapolated below the range in which it is calibrated. The root mean square deviation was found to be 0.17 mK for a maximum deviation of 0.3 mK. Note that, when working with the magnetic thermometer in the range above 0.5 K, the root mean square deviation was estimated in [8] to be 0.3 mK. The small oscillations on the curves shown in Fig. 4 at a temperature of $T_{\text{mag}} > 0.8$ K reflect the behavior of the polynomial which approximates the calibration of thermometer No. 222. It can also be seen that the results of the measurements of both series are practically identical. Processing of the data enables us to conclude that the uncertainty in the established temperature scale does not exceed 0.35 mK at 0.3 K.

One other important fact should be noted. If third or fourth degree polynomials are used to describe the calibration of thermometers Nos. 222 and 75 above 0.5 K, and then to extrapolate both these temperature dependences into the region of lower temperatures, the disagreement between the readings at 0.3 K turns out to be less than 1 mK, which can be regarded as a very good characteristic for the overwhelming majority of practical applications.

The results obtained are quite sufficient to improve the State Standard of temperature and enables its range to be extended from 0.8 K to 0.3 K with a simultaneous increase in the accuracy by a factor of 2.5. The next step in improving the standard must be reproduction of the temperature scale by a natural carrier – the melting pressure of ^{3}He. The cryogenic capacitance manometers which are intended for operation in the cryostat shown in Fig. 3, and a bridge with an inductive divider for the exact measurement of the capacitance, and also the results of preliminary tests of these are described in [10].

REFERENCES

1. O. V. Lounasmaa, *Principles and Methods for Obtaining Temperatures Below 1 K* [Russian translation], Mir, Moscow (1977).
2. J. R. Peverley and P. H. Meijer, *Phys. Stat. Solids.*, **23**, 353 (1967).
3. H. Preston-Thomas, *Metrologia*, **27**, 107 (1990).
4. D. N. Astrov, S. V. Korostin, and S. P. Polunin, *Izmer. Tekh.*, No. 12, 29 (1995); *Measurement Techniques*, **38,** No. 12, 1356 (1995).
5. D. N. Astrov and S. V. Korostin, *Izmer. Tekh.*, No. 7, 50 (1999); *Measurement Techniques*, **42,** No. 7, 689 (1999).
6. R. P. Gifford, R. A. Webb, and J. C. Weatley, *Low Temp. Phys.*, **6**, 533 (1972).
7. G. Shuster, D. Hechtficher, and B. Fellmuth, *Reports Progress in Physics*, **57**, No. 2, 207 (1994).
8. R. L. Rusby and C. A. Swenson, *Metrologia*, **16**, 73 (1980).
9. R. V. Duncan and G. Ahlers, *TMCSI*, **5**, Pt. 1, 243 (1992).
10. D. N. Astrov, *Glavnyi Metrolog.*, No. 2, 17 (2004).