сообщения
объединенного
института
ядерных
исследований
дубна

E8-91-67

V.N.Trofimov

SQUIDS IN THERMAL DETECTORS OF WEAKLY INTERACTING PARTICLES

1991

1. INTRODUCTION. Problems associated with the cryogenic detection of rare events and weakly interacting particles are widely discussed now[1]. Thermometry is probably the main aspect of the question. In spite of rigid limitations on their characteristics several types of low temperature (LT) thermometers can be used. In Table 1 the desired characteristics are listed in accordance with their importance. Indeed, the temperature resolution and the thermal response time only are of absolute importance independent of a detector application. All the known submicrokelvin thermometers available for thermal detection can be divided into four types. They include resistance thermometry R(T), magnetic susceptibility measurments of an electronic paramagnet M(T), thermoelectric thermometer E(T) and at last, not least, a proximity effect-based thermometer PrM(T). Two remarks are essential for further discussion. Firstly, the last three types can be used only with SQUIDs, while the first one can be used either with SQUID or with a conventional semiconducting electronics. Secondly, the first three thermometers are already realized in various prototypes of the thermal detectors while the PrM(T)-thermometer is suggested for this aim first.

2. SQUIDS AND (MOS)FETS AS RECORDING UNITS. The use of SQUIDs to record the output signals of the LT thermometers is very attractive due to their outstanding energy sensitivity

δE [2]. The value $\delta E=3h$ has been obtained which is very close to the quantum limit (Plank constant) $h=6.6\ 10^{-34}J\ Hz^{-1}$. The ultimate δE of (MOS)FET can be estimated as $\delta E=C\overline{U_n^2}$ where C is an input capacitance of the transistor in parallel with a capacitance of detector and connecting line, and $(\overline{U_n^2})^{1/2}$ is a spectral density of noise voltage. With $C=(10 - 100)pF$ and $(\overline{U_n^2})^{1/2}=1nV\ Hz^{-1/2}$, the best value for commercial (MOS)FETs, $\delta E=(10^{-28}-10^{-29})J\ Hz^{-1}$ i.e. much poorer than that of SQUID. Moreover, the real sensitivity is few orders degraded by the other noise sources and a rapid increase of FET and MOSFET noise above the mentioned value below, say, 10KHz and 100KHz respectively. On the contrary, for a number of SQUIDs white noise is observed beginning from (0.1 - 1)Hz and can be made predominant over other sources. Thus the ultimate SQUID sensitivity can be realized in a suitable for thermal detection bandwidth under an important condition of low impedance of the signal source. Fortunately, all the above mentioned thermometers are consistent with this requirement.As for the need of LHe for SQUID operation, which frequently prevents its suitability in different measurements, it is of no importance in our case because the cryogenic detection by itself is based on LT application. Taking into account the other advantages of SQUID-based thermometry, e.g. a negligible power dissipation, a wide dynamic range, it is not surprising that SQUIDs were suggested to use in the early years of the field[3,4].

3. SQUID-ASSISTED LT THERMOMETERS. Since SQUID measures a magnetic flux the output signal of a sensor to be recorded should be converted into the magnetic flux change. The conversion is provided via a superconducting coil inductively coupled to SQUID with the current induced in it by the measured signal. This allows to separate SQUID and a sensor in space and to choose their operating conditions independently. An input circuit coupled to the signal coil, in turn, transform the measured signal into the current. Depending on the nature of the sensor SQUID acts as a voltmeter, a galvanometer, a magnetometer etc. The output signals of the LT sensors discussed below are a magnetic moment, current or voltage changes caused by a temperature impulsive change.

3.1. RESISTIVE THERMOMETRY R(T). Up to now this is the most widely used method in various LT measurements including the cryogenic detection. Fig.1a demonstrates the idea. In most cases a temperature sensor R(T) is biased by a current I_0 and

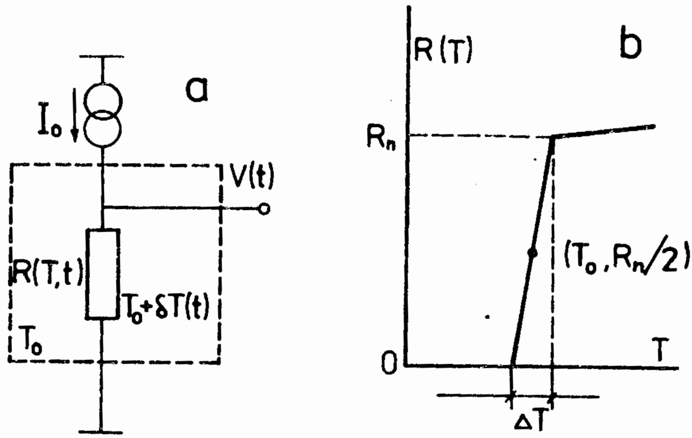

Fig.1: (a) a scheme of a resistive thermometry; (b) a resistive transition of SN bolometer. The operating temperature T_0 usually corresponds to $R_0 \cong 0.5R_n$ and $(dR/dT)_{max}$.

the output signal $\delta V = I_0 \delta R = I_0 (dR/dT)\delta T$ is read out. If the noise performance of the thermometer is provided only by the Johnson noise then an ultimate temperature resolution is:

$$\delta T/\sqrt{B} = (4kT_0/P)^{1/2}\alpha^{-1} \qquad (1)$$

where $\alpha = R^{-1}(dR/dT)$ is a figure of merit suitable for comparison of different temperature sensors, k is the Boltzmann constant, B is a frequency bandwidth, P is a power dissipated in the sensor. The power is limited by a permissible temperature rise of the detector and is connected with the operating temperature T_0 by relation $P \propto T_0^n$ with n=(2-4). For $T_0 \leq 0.1$K the upper limit for P can be taken to be 10^{-9}W. In order to evaluate the ultimate resolution let $P=10^{-9}$W and one obtaines:

$$\delta T/\sqrt{B} \cong 2.4\ 10^{-7}\alpha^{-1}\sqrt{T_0}. \qquad (2)$$

Of all the types of the resistive sensors only superconducting SN bolometers and semiconducting thermistors can be used for thermal detection. For both of them the best result should be expected when the sensors are formed by a film deposition onto the detector. In Fig.1b a resistive SN transition in superconductor is shown. It is obvious from this picture that $\alpha \cong 2/\Delta T$, where ΔT is the width of the transition and the operating temperature corresponds to $R=R_n/2$, R_n to be the bolometer resistance in the normal state. Because ΔT can be equal to few millikelvins and R can be choosen only slightly above zero, then α as high as $10^4 K^{-1}$ can be obtained. As for the thermistors the best recent result[5] is $\alpha=700K^{-1}$. Upon preparation the R_n of SN bolometer can be obtained within a wide range including very small values $R_n \le 1$Ohm. As was mentioned above that makes it possible to read out the output signal by SQUID. For thermistors the resistance various from few KOhms up to few MOhms and the use of SQUID is unefficient in this case. In Ref.[6] the first application of SN bolometer with SQUID monitoring for thermal detection has been reported. The iridium strip biased at the middle of the transition i.e. at 0.135K was used to measure the temperature pulses caused by the 5.8MeV alphas in a 280g saphire crystal, the largest thermal detector ever designed. DC-SQUID was operating as a null-detector in a flux-locked mode. From the published data the resolution $\delta T/\sqrt{B} \cong 5\ 10^{-10} K\ Hz^{-1/2}$ can be estimated which is consistent with (2) and some orders better than that of ever obtained with the thermistors and the conventional electronics.

3.2. PARAMAGNETIC THERMOMETRY. The idea is illustrated in Fig.2.

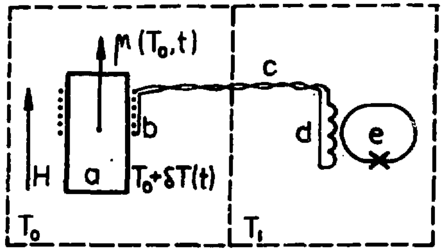

Fig. 2: a scheme of a paramagnetic thermometry; (a)-sensor, (b)-pickup coil, (c)-superconducting flux transformer, (d)-secondary coil, (e)-SQUID

In the simpliest case the magnetization M of the sensor is temperature dependent as $M = cH/T$ (Curie law), where c is the Curie constant, H is a magnetic field. The change of the magnetic moment $\mu = MV$, where V is the volume of a paramagnet, caused by a temperature change is read out by a pair of astatic pick-up coils and converted into a current change in a secondary coil of a superconducting flux transformer. The corresponding flux change is measured by SQUID coupled to the secondary coil. The temperature resolution is:

$$\delta T/\sqrt{B} = -(T^2/cHV)(\delta\mu/\sqrt{B}) \tag{3}$$

and may be as high as $8.8\ 10^{-11}$K $Hz^{-1/2}$, the best resolution obtained at LT up to now [7]. As follows from (3), the sensitivity of the paramagnetic thermometer increases upon cooling on the contrary to that of resistive and thermoelectric thermometers. Unfortunately, two serious disadvantages strongly narrow the applicability of this thermometry to thermal detection. First of all the coupling between electron spins and phonons failed rapidly with the temperature decreasing i.e. the thermometer becomes slow. This limits the operating temperature with, say, $T_0 \geq 0.3$K and prevents from the large volume detectors use because a background discrimination problem arises. Secondly, the M(T)-thermometer is very sensitive to all external mechanical disturbances owing to quite large value of H needed to reach high resolution. As a consequence the operation of SQUID in the flux-locked mode becomes unstable. The applicability of the paramagnetic SQUID-based thermometer for cryogenic particle detection was first discussed in Ref.[4]. In 1986 the author had been testing the prototype of the detector in which the M(T)-thermometer was combined with the detector within one single crystal of silicon doped with gadolinium (unpublished). With T_0=1K, H≅0.5KG, V≅20mm^3 and Gd concentration $10^{15}cm^{-3}$ the resolution $5*10^{-4}K*Hz^{-1/2}$ was reached. No background or ^{60}Co caused impulses were observed though the voltage up to 3KV have been applied to the crystal to realize a "thermal amplification" (see below) and thus to decrease the energy threshold. The possible reasons are a lack of the thermal amplification in this crystal, a long thermal response of Gd spin system and low concentration of Gd. The first succesful use of the discussed thermometer was reported soon in Ref.[8]. The composite detector including a 7.5g saphire crystal as an adsorber and a 0.15g Y(Er)Al-garnet as a thermometer was operating at 0.45K in a field of 300G. The garnet magnetization was measured with either a RF-SQUID or a DC-SQUID via a superconducting flux transformer. The resolution approximately 10^{-8}K $Hz^{-1/2}$ had been obtained enough to observe the 5.5Mev α-particles with a nearly 1% energy resolution.

3.3. THERMOELECTRIC THERMOMETER. This type is perhaps the simpliest one for helium and subhelium temperatures. Its application became possible after the SQUID-based measuring technique has been developed because a thermoelectric power (TEP) S is very small at these temperatures, say, S=10μV K^{-1} at 1K even for the special alloys with a "giant" TEP. So for a 10^{-8}K resolution a voltage 10^{-13}V should be measured. Taking into account that a thermocouple is a low impedance source SQUID ideally suit such requirement. In Fig.3 a scheme of the detector with a SQUID-based thermoelectric thermometer is shown. The thermocouple measures the nonequilibrium

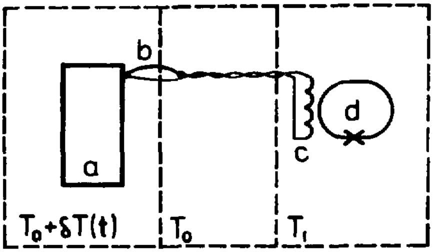

Fig. 3: a scheme of a detector with thermoelectric thermometer. (a)-detector, (b)-thermal, (c)-superconducting signal coil, (d)- SQUID.

temperature difference between the detector and the - thermostat. That means the thermometer is insensitive to slow thermostat temperature fluctuations and there is no need in its precise stabilization as for the case of SN bolometer. As the ends of the thermocouple are connected by a superconductive wire via a signal coil coupled to SQUID, the ultimate resolution limited only by the Johnson noise is:

$$\delta T/\sqrt{B} = (4kT_0R/S^2)^{1/2} \qquad (4)$$

where R is a thermocouple resistance. With T_0=1K, R=(10^{-2} - 10^{-4}) Ohm, S=10μV K^{-1} the resolution is 8(10^{-8}-10^{-9})K

$Hz^{-1/2}$. In spite of the thermal noise decreasing upon cooling the resolution gets worse due to the sensitivity S drop. Nevertheless the resolution 10^{-6}K $Hz^{-1/2}$ at 0.1K is available which is of the same order as the best results obtained with thermistors and conventional electronics. Both SQUID and thermocouple are consistent with the integral technology aeveloped in microelectronics and can be produced by a film deposition. As a result the multichannel segmented thermal detectors can be desined which will allow among all to reduce a background. Undoubtedly, E(T)-thermometer with SQUID read out is the most promising for the range (0.3-1)K.

As an example the prototype of the thermal detector designed in JINR is briefly described below. Fig.4 shows schematically the lower part of the cryogenic insert immersed

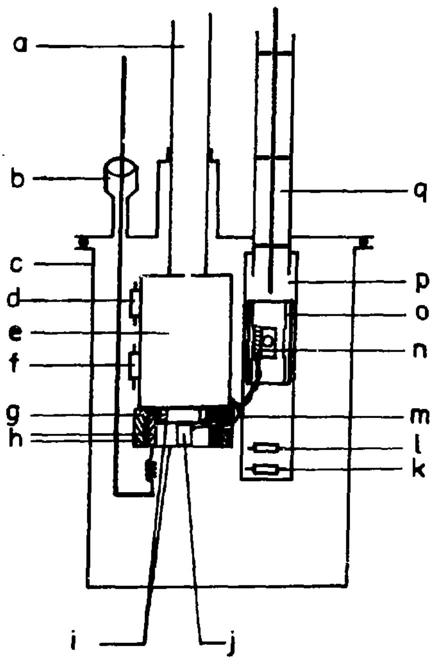

Fig.4: sketch of the experimental set-up. Symbols are defined in the text.

in LHe. The detector (j) is a p-Si crystal with ρ(300K)=10KOhm cm in the form of a cylinder with a volume

$33mm^3$. It is glued between two sheets (i) of one-side aluminized mylar film supported by copper (g) and capton (h) rings at the bottom of copper 1K pot (e). Thus the detector is placed in a capacitor and can be exposed to an electric field by means of a voltage applied via a feedthrough (b). This enables to convert a primary ionization energy loss into heat with amplification on comparison with an initial thermal loss, as was first suggested and realised in Dubna[9], and hence to lower an energy threshold to the value corresponding, in principle, to one pair of free carriers arising. Thermal amplification had allowed to observe alphas from ^{241}Am and gammas from ^{60}Co and ^{57}Co with S/N ratio up to 100 in spite of the relatively high operating temperature for given volume of the detector. The temperature of the 1K pot is controlled by an Allen-Bradley resistor (f) and a heater (d). The temperature difference of the crystal and the pot is measured by an Au/Fe thermocouple (m) and a two-hole RF-SQUID (o) via a signal coil (n) wounded by a Nb wire. SQUID is excited with a coaxial line (q). SQUID holder (p) is equiped with a thermometer (l) and a heater (k). SQUID, the pot and the detector are inside a vacuum can (c) surrounded by a superconducting screen. The resolution is limited by SQUID electronics noise and is equal to $2\ 10^{-7}K\ Hz^{-1/2}$ at 1K which is approximately one order faltier than given by (4). Time response of the detector is perfomed by two time constants: $\tau=L/R$, where L is the inductance of the signal coil, R is the resistance of the thermocouple, and $\tau=C/\lambda$, where C is the detector heat capacity, λ is the thermal conductivity between the detector and the thermostat. They are equal to 0.5mS and 2.9mS respectively. Since the electric circuit including the detector is opened the polarization effect takes place. During operation under irradiation the thermal amplification decreases slowly. If to switch off the voltage the detector will yet demonstrate the amplification due to the inner electric field caused by the previous polarization of the crystal. In Fig.5 the impulses of the 5.5MeV alphas are shown for two values of thermal amplification. The left trace corresponds to 100V of applied voltage the right one to 500V. The full length of the traces is: left- 20ms, right-10ms.

3.4. PROXIMITY EFFECT BASED THERMOMETER PRM(T). This thermometer was suggested by Y.Oda, G.Fujii and H.Nagano[10] in 1979 but wasn't, to our knowledge, realized yet. As in the

Fig. 5: pulses from 5.5MeV ^{241}Am alphas. The pictures were taken with a digital storage oscilloscope. Left: 100V of applied voltage,20ms full length; right: 500V, 10ms. Vertical scales differ 5 times.

case of the paramagnetic thermometer, the idea is to measure the temperature dependent magnetization of the sensor, but, instead of an electronic paramagnet a bimetallic sandwich of superconducting and normal metals is used. Due to the proximity effect the normal metal near an interface becames superconducting and demonstrates the Meissner effect. The width of the proximity induced superconducting layer w strongly depends on temperature, $w \propto T^{-n}$ where $1/2 \le n \le 2$ [11]. As a result the temperature resolution of the PrM(T)-thermometer is expected to improve upon cooling. When the normal metals Cu or Ag are used the temperature range of operation may be $(10^{-3}-1)$K with the dw/dT exceeding 1mm K^{-1} at the lowest temperatures[10,11]. The polarizing magnetic field should be very weak, $H \le 0.1$G, but, nevertheless, the resolution is estimated to be as high as that of the paramagnetic thermometer due to much higher susceptibility of a superconductor in comparison with a paramagnet. From the other hand the weak field favoures the immunity of the thermometer to mechanical disturbances and thus allows to overcome one of the main disadvantages of the M(T)-thermometer. Furthermore, the principal limitation on thermal response of a paramagnet arising from the rapid increase of the spin-lattice relaxation time against cooling, vanishes for the PrM(T)-thermometer. The physics underlying it naturally leads to its promising application for $2\beta(0\nu)$-decay observation. The following elements, which exibit a superconducting transition and are attractive from $2\beta(0\nu)$-decay point of view, can be used as a decay source: Zn(0.9), Zr(0.55), Mo(0.9), Ru(0.47), Cd(0.56), Sn(3.73). In brakets a critical temperature is indicated. As was suggested by E.Fiorini and T.Niinikoski in Ref.[12] superconductors can be used for thermal detectors as well as dielectrics due to a negligible contribution of the conducting electrons to the total specific heat at $T<T_{cr}$. The thermometer can be performed by a normal metal film deposition onto the decay source and by applying the field parallel to the interface. Thus the source simultaniously acts as a detector with a corresponding high efficiency of registration. For a convinient cylindrical shape of the detector with the axis parallel to the field the pick-up coil of the flux transformer can be tightly wound around the detector just above the normal film as shown in Fig.6 where (a) is the superconducting decay source, (b) is the pick-up coil, (c) is the partly normal metal film, (d) is the secondary coil, (e)

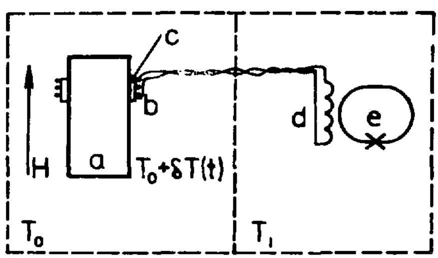

Fig.6: a schematic diagram of a superconducting detector with the PrM(T) -thermometer. (a)-detector, (b)-pickup coil, (c)-partly normal metal film, (d)-secondary coil (e)-SQUID.

is SQUID. The expected resolution in this case is:

$$\delta T/\sqrt{B} = [k\pi DH(dw/dT)]^{-1}\delta\Phi/\sqrt{B} \qquad (5)$$

where D is a diameter of the sample, H is a field, k is a transfer coefficient of the flux transformer, $\delta\Phi/\sqrt{B}$ is a flux resolution of SQUID. Taking D=10cm, k=0.1, H=0.1G, (dw/dT)= =0.1cm K^{-1}, $\delta\Phi/\sqrt{B}==10^{-5}\Phi_0 Hz^{-1/2}$ (Φ_0=2 10^{-15}Wb is a flux quantum), one obtaines $\delta T/\sqrt{B}\cong 10^{-10}K\ Hz^{-1/2}$.

3.5. A COMPARISON OF THE THERMOMETERS. In Table 1 an attempt is made to compare the discussed thermometers with "5" cor

TABLE 1. A comparison of different thermometers for cryogenic detection.

thermometer * * * * thermometer * feature	SQUID-based					conventional electronics-based	
				R (T)			
	M(T)	PrM(T)	E(T)	SN	thermistor	SN	thermistor
temperature resolution	5	5	3	5	2	3	3
response time	1	5	4	4	5	5	4
heat capacity	2	3	4	4	4	4	4
measuring power	3	5	4	4	2	3	2
linearity	4	4	5	4	4	4	4
reproducibi-lity	3	5	5	5	4	5	4
integral tech-nology compa-tibility	1	3	4	4	4	5	5
temperature range	4	5	4	4	4	4	4
APPRAISAL	25	35	33	34	29	33	30

responding to the best quality. Indeed, some characteristics can be mutually dependent but in most cases in a manner that a variation of one of them preserves the integral appraisal. A variety of the desired characteristics as well as a number of the thermometers available make it possible to choose a thermometer specially for the projected experiment. For example the thermoelectric thermometer is thought to be the most suitable for WIMPs search, the SN bolometer - for solar neutrinos while the PrM(T)-thermometer preferably can be used for $2\beta(0\nu)$-decay detection. The final choice depends also on the financial abilities of the project. For a better guide the operating features for all thermometers in $\log(\delta T/\sqrt{B})$ - $\log T$ scales are plotted in Fig.7 together with the temperature ranges covered by three methods of continious LT performance.

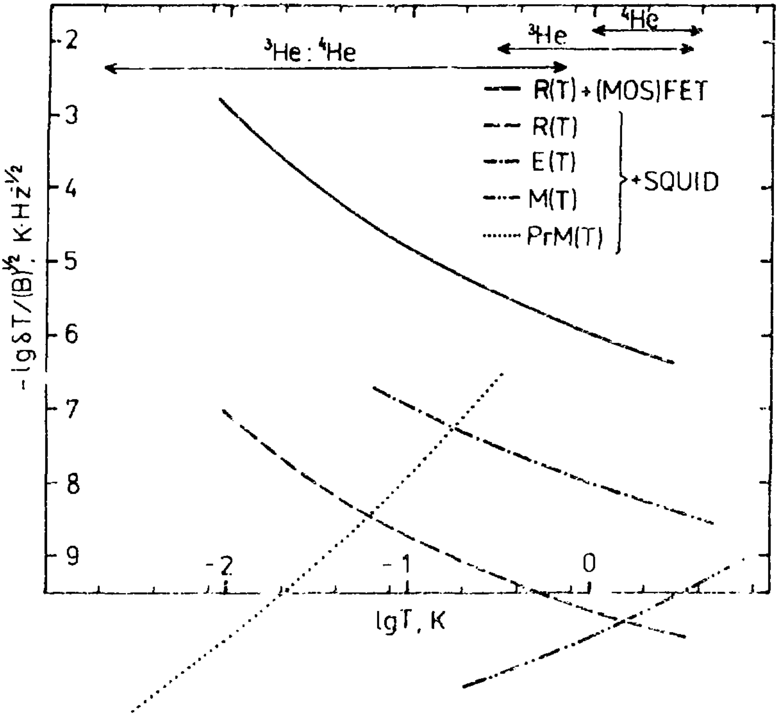

Fig. 7: a relation between an operating temperature and a temperature resolution for all types of thermometers.

4. CONCLUSION. The aim of this report is to demonstrate the new possibilities and advantages of SQUID-based thermometry application to cryogenic detection of particles. SQUIDs broaden a choice of the thermometric sensors and essentially improve the temperature resolution. As follows from (2), (3), (5) the resolution 10^{-10}K $Hz^{-1/2}$ and better can be obtained which enables to reach the energy threshold (1-10)eV Kg^{-1} even without thermal amplification. Of course, various experimental problems should be overcome to realized that and all of them demand a separate analysis. Further efforts are needed to discuss in details every SQUID thermometry modification.

REFERENCES:

1. Proc. of the 2nd European Workshop on Low Temperature Devices for the Detection of Low Energy Neutrinos and Dark Matter, L.Gonzales-Mestres, D.Perret-Gallix, eds.(Editions Frontieres, 1988).
   Proc. of the 19th Int. Conf. on Low Temp. Phys. LT-19, Brighton, 1990, Part1, PhysicaB, v.165/166, pp.1-8, (1990).
2. M.Odehnal, Sov. J. Low Temp. Phys., v.11, 1, (1985).
   T.Ryhanen et.al., J. Low. Temp. Phys., v.76, N5/6, 287, (1989).
3. B.Neganov, V.Trofimov, Pis'ma Zh. Eksp. Teor. Fiz., v.28, N6, 356, (1978).
4. G.Mitcelmaher, B.Neganov, V.Trofimov, JINR Communications, P8-82-549, Dubna, 1982.
5. B.Neganov et.al., JINR preprint P8-90-127, Dubna, 1990.
6. W.Seidel et.al., Phys. Lett., v.236B, N4, 483, (1990).
7. T.C.P.Chui, J.A.Lipa, in Proc. 17th Inter. Conf. on Low Temp. Phys. LT-17, Karlsruhe, 1984, Part2, p.931, (North-Holland, Amsterdam, 1984).
8. M.Buhler, E.Umlauf, Europhysics Lett., 5(4), 297, (1988).
9. B.Neganov, V.Trofimov, USSR patent N1037771 (1981); - Otkrytiya, izobreteniya, N14, 215, (1985).
   B.Neganov, V.Trofimov, M.Kolać, in Proc. of the 22nd Allunion Workshop on Low Temp. Phys., Kischinev, 1982, Part3, 246.
10. Y.Oda, G.Fujii, H.Nagano, Jap.J.of Appl.Phys. v.18, N7, 1411, (111.A.C.Mota, P.Visani, and A.Pollini, J. Low. Temp. Phys., v.76, N5/6, 465, (1989).
12. E.Fiorini, T.Niinikoski, Nucl. Instrum. Methods, v.224, 83, (1984).

Received by Publishing Department
on February 5, 1991.