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Magnetic calorimeter for registration of small energy release

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Abstract. A scheme of magnetic calorimeter for registration of rare events characterized by small energy release (cosmic rays, WIMPs, solitary X-ray quanta) is proposed. The calorimeter is brought to operation by adiabatic demagnetization, and its magnetic response is measured by a quantum interferometer (SQUID [1]). Special consideration is given to the specific features of calorimeter operation in the ferromagnetic transition region. The trigger registration of ultrasmall energy release by a ferromagnetic system in the metastable state is described.

PACS. 75.30.Sg Magnetocaloric effect, magnetic cooling – 85.25.Dq Superconducting quantum interference devices (SQUIDs)

1 Introduction

The SQUID sensitivity comparable with the quantum limit was obtained more than twenty years ago [2,3]. It was realized for the magnetic flux resolution at a level of $\delta\Phi = 5\times 10^{-7}\Phi_0/\sqrt{\mathrm{Hz}}$ [4–7], where $\Phi_0 = 2\pi\hbar/2e = 2.07\times 10^{-15}$ Wb is the flux quantum. Such high technical parameters were achieved using the rf-SQUIDs with microwave pumping [8] and also the two-stage dc-SQUIDs in which the second dc-SQUID played the role of an integrated low-noise amplifier of the electric signals coming from the first dc-SQUID [9,10]. However, the potentialities of such unique instruments are now used little in practice. The sensitivities of the operating installations are one or two orders of magnitude lower. Advances in this field refer to the high-T_c SQUIDs with comparable sensitivities [11,12].

Important practical problems demanding exceedingly high SQUID sensitivity include the registration of extremely-low-intensity radiation, solitary X-ray quanta, cosmic rays, weakly interacting massive particles (WIMPs), and so on [13].

In magnetic detectors [14–16], close in the operation principles to the magnetic calorimeter, proposed in this paper, the interaction between a particle and a paramagnetic substance (the working medium) causes heating of the latter and, as a consequence, a decrease in the magnetic susceptibility of the paramagnet, measured by the SQUID in a constant external magnetic field B. The same as the operation principle of the magnetic thermometer [17] well-known in cryogenics, this method is based on the Curie-Weiss law $\chi(T) = \alpha/(T - T_K)$, where α is a coefficient, T is temperature ($T > T_K$), and T_K is Curie temperature.

According to the Curie-Weiss law, the temperature derivatives of the magnetic moment of such a detector (magnetic detector — paramagnetic working medium) are $\frac{\partial M}{\partial T} = \frac{\partial(\chi B)}{\partial T} = \frac{\partial}{\partial T}\left(\frac{\alpha B}{T-T_K}\right) = \frac{-\alpha B}{(T-T_K)^2}$. Since the mixed derivatives of the free energy in the external magnetic field $F = U - BM - TS$ are equal $\frac{\partial^2 F}{\partial B\partial T} = \frac{\partial^2 F}{\partial T\partial B} \Rightarrow \frac{\partial S}{\partial B} = \frac{\partial M}{\partial T}$, one readily obtains the paramagnetic part of the entropy S_{pm}: $S_{pm} = \int \frac{\partial M}{\partial T} dB = -\frac{\alpha(B^2+B_r^2)}{2(T-T_K)^2}$, where B_r is the residual field of the paramagnet. Then the magnetic heat capacity is $C_{pm} = T\frac{\partial S_{pm}}{\partial T} = \frac{\alpha T(B^2+B_r^2)}{(T-T_K)^3}$ and at temperatures near T_K we have $C = C_{pm} + C_{ph} + ... \approx C_{pm}$, where C and C_{ph} are respectively the total and phonon heat capacities of the working medium. The response of the detector to the energy release ΔE in the working medium, i.e. the magnetic flux change $\Delta\Phi$ registed by the SQUID is

$$\Delta\phi = \frac{\mu_0 \Delta M}{h} = \frac{\mu_0}{h}\frac{\partial M}{\partial T}\Delta T = \frac{\mu_0}{h}\frac{\partial M}{\partial T}\frac{\Delta E}{C}$$
$$\approx \frac{\mu_0}{h}\frac{\partial M}{\partial T}\frac{\Delta E}{C_{pm}} \approx \frac{-\mu_0\ B}{h(B^2+B_r^2)}\frac{T-T_K}{T}\Delta E,$$

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where μ_0 is the vacuum permeability and the working medium is a paramagnetic cylinder of hight h. The formula remains valid after the correction of the Curie-Weiss law to the magnetization saturation which removes the divergence of C_{pm} as $T \to T_K$.

The imperfections of such a detector [1,18] are first of all the necessity of refined balance of the astatic pair of coils, which is the essential part of the SQUID system [6], and the stabilization of the external magnetic field B. Secondly, this scheme needs a thermal key with contradictory and hardly realizable demands imposed on it, namely, an extremely high heat conduction in an open state (needed because of the large magnetic heat capacity during cooling in an external magnetic field) and an almost zero thermal conductivity during the operation. Thirdly, the maximum sensitivity $\Delta\Phi/\Delta E$ (when $B \approx B_r$) is limited to B_r, as is clear from the upper formulas, but in real paramagnets $B_r \approx 100$ Oe. Weaker residual magnetic fields can be found in nuclei systems, for example, in copper $B_r \approx 3$ Oe. However, the nuclear magnetisation becomes dominating at rather low temperatures, i.e. below 100 mK. Moreover, the detector cooling down to T_K, where the Curie-Weiss law is no longer valid, is inadmissible since the detector sensitivity falls dramatically in this region: $\Delta\Phi/\Delta E \sim (T - T_K)/T$. These imperfections are naturally eliminated if the method of adiabatic demagnetization (widely applied earlier to produce cryogenic temperatures [17]) underlies the recording scheme of ultrasmall energy releases.

We propose here a new scheme for detection of extremely small energy releases based on an adiabatically demagnetized paramagnet with the magnetic moment permanently registered by the SQUID at an extremely low ($T \approx 100$ mK) working temperature. Such magnetic calorimeters can be used to detect elementary particles, WIMPs, and to solve a number of physical problems as discussed below.

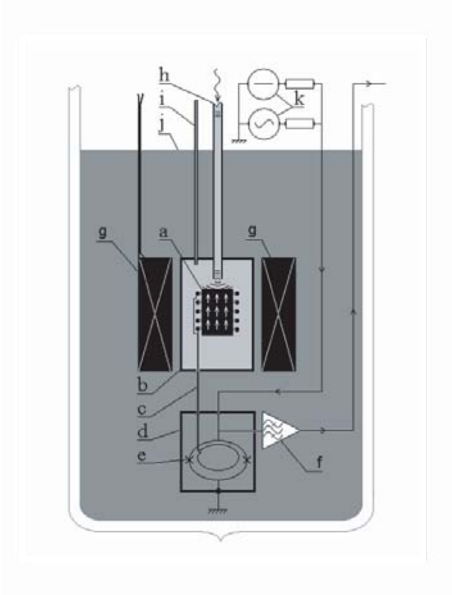

Fig. 1. Block-diagram of the adiabatic magnetic calorimeter. (a) Paramagnetic working medium of the calorimeter inside the coil of a superconducting flux transformer; (b) hermetic shell of the adiabatic calorimeter; (c) a low-inductive pair line of superconducting flux transformer; (d) a superconducting shield; (e) a dc-SQUID bound to the coil of the superconducting flux transformer; (f) a selective pre-amplifier of the dc-SQUID; (g) a superconducting magnet; (h) the radiation input into the calorimeter (hermetic fiber/waveguide); (i) the line of heat-exchange helium input/output; (j) the helium level in the cryostat (He^4 or He^3 pumped out, $T < 4.2$ K); (k) the generator of current running in the dc-SQUID. Four temperature levels are to be organized: $T = 77$ K — nitrogen cryostatting level and thermal shields; $T = 4.2$ K — helium level, cooling of the magnet (g) and of the pre-amplifier (f); $T = 1.3$ K — He^4 vapor pumping out, dc-SQUID cooling (d), He^3 condensation; $T = 0.3$ K — He^3 vapor pumping out, paramagnet cooling before demagnetization, thermal shields.

2 Adiabatic magnetic calorimeter

2.1 Paramagnetic case

We shall call our device for registration of extremely small energy release (Fig. 1) the "magnetic calorimeter" to distinguish between it and the magnetic detector described above. To bring the proposed magnetic calorimeter to operation, the paramagnet is first polarized by an intense magnetic field with a simultaneous heat eliminating by the heat exchanging gas. Then the paramagnet is heat-insulated (the exchange gas is pumped out) and the external field is reduced to zero. The paramagnet is cooled since the relation $\beta = B/T$ is an adiabatic invariant. It means that $\beta =$ const., which formally explains the temperature lowering during demagnetisation. The working medium remains polarized during demagnetisation, that follows from the simplest expression for the magnetic moment M borrowed from the Langevin theory of paramagnetism: $M(\beta) = N\mu_B \frac{e^{\mu_B\beta/k} - e^{-\mu_B\beta/k}}{e^{\mu_B\beta/k} + e^{-\mu_B\beta/k}}$ ($\beta =$ const. and, consequently, $M =$ const.). The magnetic moment remains unchanged after the end of demagnetisation in the absence of the outer thermal inflow. At the same time any energy release heats and disorders the spin system, which leads to a decrease of the magnetic moment and thus can be registered by the traditional low-temperature SQUID. The measurements are carried out without the external field, which is important for SQUID operation. The calorimeter does not contain a gradiometric system and does not require the use of a thermal key with extraordinary characteristics since the main heat abstraction takes place at a relatively high starting temperature when the paramagnetic contribution to the heat capacity is not large yet. (The "self-coolin" effect during the demagnetization cycle can be also useful for the development of an elementary-particle detector and a submillimeter-range radiometer intended for work in space because the dissolution refrigerator He3/He4, using the traditional circuitries, is non-serviceable in weightlessness.) The entropy S and the magnetic moment M can be expressed in terms of the partition function Z as $M = kT\,\frac{\partial}{\partial B}(\ln Z)$ and $S = k\frac{\partial}{\partial T}(T\,\ln Z) = k\ln Z + kT\frac{\partial}{\partial T}(\ln Z)$. The partition function is only dependent on the parameter $\beta = B/T$ which remains unchanged during the adiabatic demagnetization. Taking into account that

$$\frac{\partial}{\partial B} = \frac{1}{T}\frac{d}{d\beta}\bigg|_{T=\text{const.}} \quad \text{and} \quad \frac{\partial}{\partial T} = -\frac{\beta}{T}\frac{d}{d\beta}\bigg|_{B=\text{const.}}, \tag{1}$$

we have $M = k\,\frac{\partial}{\partial \beta}(\ln Z)$ and $S = k\ln Z - k\beta\frac{\partial}{\partial \beta}(\ln Z)$, respectively.

However, "for the sake of rescue" of the third law of thermodynamics we have to introduce a residual field B_r. Formally B_r obstructs reaching the absolute zero temperature when the external magnetic field B is completely removed. In its physical meaning B_r is the mean-square magnetic field of magnetic moments and it is included in the adiabatic invariant along with the external magnetic field: $\beta = \frac{B_t}{T} = \frac{1}{T}\sqrt{B^2 + {B_r}^2}$. Varying the entropy, we are led to $\Delta S = k\,\Delta(\ln Z) - \frac{B_t}{T}\Delta M$. We can disregard the first term in this expression supposing the temperature to be low enough. Then $\Delta S \cong -\left(\frac{1}{T}\sqrt{B^2 + B_r^2}\right)\Delta M \cong -\frac{B_r}{T}\Delta M$ when $B \to 0$. The particle interaction with the substance leads to the entropy enhancement: $\Delta S = \frac{\Delta E}{T} \cong -\frac{B_r}{T}\Delta M$ and hence to the decrease of the magnetic moment: $\Delta M = -\frac{\Delta E}{B_r}$. For the barrel shape of the working medium with vertical height h, the change ΔM corresponds to the change of the magnetic flux $\Delta\Phi = \mu_0\Delta M/h$ through its cross-section. The smallest registered increment δM of the magnetic moment and, consequently, δS of the spin entropy is limited by the SQUID flux sensitivity $\delta\Phi$: $|\delta\ S| \cong \left|\frac{B_r\delta M}{T}\right| = \left|\frac{hB_r\delta\Phi}{\mu_0 T}\right|$. This provides obtaining the calorimeter energy resolution $|\delta E| \cong |T\delta S| \cong \left|\frac{hB_r\delta\Phi}{\mu_0}\right|$. One can see that the energy resolution is independent of the paramagnet base area. This free parameter can be useful in choice of a flux transformer. Taking into account the transmission factor of the flux transformer, one can consider $\delta\Phi = 10^{-5}\Phi_o/\sqrt{\text{Hz}}$ to be admissible as SQUID effective sensitivity over the flux $\delta\Phi$. Then for $B \approx B_r \approx 100$ Oe and $h = 1$ cm the calorimeter sensitivity turns out to be about $\delta E = 3\times10^{-18}$ J$/\sqrt{\text{Hz}}$. A microcalorimeter in the form of a paramagnetic film of micron thickness, manufactured using the dc-SQUID planar technology, is of certain interest. The energy sensitivity can reach $\delta E = 3\times10^{-22}$ J$/\sqrt{\text{Hz}} = 0.002$ eV$/\sqrt{\text{Hz}}$ in this case, but the calorimeter operation in the adiabatic regime is substantially restricted by an uncontrolled heat leakage due to the very low heat capacity of the device.

2.2 Ferromagnetic case

The situation when the system of magnetic moments with paramagnetic interaction between them is under adiabatic conditions and the external magnetic field is zero should be discussed separately. According to the Nernst principle, the ferromagnetic phase transition in the system of magnetic moments should occur with necessity. Let us analyze the occurrence of such magnetization in adiabatic conditions. Comparing the expression for the magnetic susceptibility of a system of interacting paramagnetic moments at $T > T_K$ (T_K is the Curie temperature), obtained within the frameworks of the Ginzburg-Landau theory for second-order phase transitions [19], with the Langevin theory of paramagnetism [20] one is able to evaluate the first factor a of the free energy expansion in the order parameter (the magnetic moment) for paramagnetic ions:

$$F = F_0 + a(T - T_K)M^2 + bM^4,$$

$$\chi_{G-L}\,(T > T_K) = \frac{1}{2a\,(T - T_K)},$$

$$\chi_L = \frac{\alpha}{T - T_K} = \frac{\partial M}{\partial B}\bigg|_{B\to 0} \cong \frac{N\mu_B^2}{k\,(T - T_K)},$$

$$a = \frac{1}{2\alpha} = \frac{k}{2N\mu_B^2}.$$

According to the Ginzburg-Landau theory we have $S = -\frac{\partial F}{\partial T} = S_0 - aM^{*2} = S_0 + S_{fm}$, $M^* = \sqrt{\frac{a}{2b}\,(T_c - T)}$, where S_{fm} is the magnetic part of entropy of the body in the ferromagnetic state, S_0 is the remained part of entropy, undepended from the magnetic degrees of freedom, M^* is the value of spontaneous magnetic moment, corresponding to the free energy minimum. This dependence is confirmed by the calorimetric measurements for paramagnetic salts with residual magnetic moment at temperatures below T_K [21,22]. The direct relation between the entropy and the M^* value enables the detector to work in the vicinity of a ferromagnetic transition.

Let us choose the starting conditions of adiabatic demagnetization far from the residual field and Curie temperature: $B_i \gg B_r$, $T_i \gg T_K$. Then the entropy is constant owing to the adiabatic conditions: $S = \text{const.} = S_0 + S_{pm} \approx S_0 - \frac{\alpha B_i^2}{2T_i^2}$, where S_{pm} is the magnetic part of entropy of the body in the paramagnetic state and $S_{pm} = S_{fm}$ at the transition. Then for the spontaneous magnetic moment due to the adiabatic demagnetisation we have: $\frac{\alpha B_i^2}{2T_i^2} = aM^{*2} \Rightarrow M^* = \frac{B_i}{2aT_i}$. Let us vary the expression for "ferromagnetic" entropy of the system with spontaneous magnetic moment for a zero external magnetic field: $\Delta S_{fm} = -2aM^*\Delta M^* = -2a\frac{B_i}{2aT_i}\Delta M^* = -\frac{B_i}{T_i}\Delta M^*$. Re-counting the variation of the magnetic moment for the increment $\delta\Phi$ of the magnetic flux, measured by a SQUID, we get the calorimeter energy sensibility $|\delta E| \cong |T_K\delta S_{fm}| \cong \left|T_K\frac{B_i}{T_i}\delta M^*\right| \cong \left|\frac{T_K}{T_i}\frac{hB_i\delta\Phi}{\mu_0}\right|$. The initial conditions of adiabatic degaussing can be so chosen that $B(T_c) < B_r$. The latter formula implies that the energy sensitivity of the detector working in the phase change region can be much higher than that of the detector with conventional paramagnets.

2.3 Paramagnetic case 2

Concluding the study of the limiting sensitivity of a magnetic adiabatic calorimeter in the context of statistical mechanics, we shall return to the case of non-interacting spins. Let us determine the influence of the neglect of the contribution of the first term $\Delta S_1 = k\,\Delta(\ln Z)$ in the amount of entropy variations $\Delta S = k\,\Delta(\ln Z) + \frac{B_t}{T}\Delta M$ obtained before for the paramagnet.

This contribution $S_1 = k\,(\ln Z)$ is close in form to the well-known statistical interpretation of the entropy $S = k\,(\ln W)$, following from the Boltzmann H-theorem, where W is the statistical weight. Hereinafter we shall use precisely this Boltzmann's definition of entropy.

Suppose all N spins were polarized by the external field at a rather low temperature (the case of paramagnet saturation). Then under adiabatic conditions the field was slowly brought to zero and the temperature reached a finite value T. If $B = 0$ and $B_r = 0$ ("perfect paramagnetism"), then the "spin up" and "spin down" states are equiprobable: $P_\uparrow = P_\downarrow = 1/2$. The probability $W_N(m)$ that m spins from the total amount N are turned up and the remaining $N - m$ are turned down is described by the familiar scheme of Bernoulli independent tests $W_N(m) = C_N^m P_\uparrow^m P_\downarrow^{N-m}$. Let us calculate the entropy change upon turning down a single spin:

$$\begin{aligned}\delta S &= S(m = N-1) - S(m = N)\\ &= k\ln\frac{W_N(m = N-1)}{W_N(m = N)} = k\ln\frac{C_N^{N-1}}{C_N^N} = k\ln N.\end{aligned}$$

Such δS will need the energy release $\delta E = T\delta S = kT\ln N$, and will be followed by a change of the magnetic moment by only two Bohr magnetons $\delta M = 2\mu_B$. Therefore the effective magnetic induction $B_{eff} \approx \delta E/\delta M = (kT/2\mu_B)\ln N$ at $T = 1$ K will show an enormous value $(\ln N)/2$ expressed in Tesla (dozens of T). So for the ideal polarization the B_{eff} value exceeds the normal B_r value by three orders of magnitude, which demonstrates weakness of the magnetic response ($\sim 1/B_{eff}$) corresponding to the first variational term $\Delta S_1 = k\,\Delta(\ln Z)$, and validates its neglect. The above arguments are close in sense to the well-known proof of ferromagnetic state instability in the one-dimensional Ising model [19].

But the situation changes radically if the system is demagnetized to show a limitingly low polarization in the end. Let us consider the case when the number of upward spins is larger than $K = N/2$ by one (i.e. $m = N/2+1$) and the number of downward spins is smaller than K by one (i.e. $N - m = N/2 - 1$), the external magnetic field being zero. Upon the flip-flop of the pair of spins the entropy change is

$$\begin{aligned}\delta S &= S(m{=}K) - S(m{=}K+1) = k\ln\frac{W_N(m{=}K)}{W_N(m{=}K+1)}\\ &= k\ln\frac{(K+1)!(K-1)!}{K!K!} = k\ln\frac{(K+1)}{K} \cong k\frac{1}{K}. \quad (2)\end{aligned}$$

Then the efficient magnetic induction $B_{eff} \approx \delta E/\delta M = (kT/\mu_B)N^{-1}$ will be $B_{eff} \approx 1\,\text{fT} = 10^{-15}$ T when $T = 1$ K and $2K = N = 10^{15}$ and the calorimeter sensitivity in this case is estimated as $\delta E = 10^{-31}$ J/$\sqrt{\text{Hz}}$ $\approx 10^{-12}$ eV/$\sqrt{\text{Hz}}$.

3 Characteristic features of establishment of thermal equilibrium and time selection of events

We shall now consider the specific features of establishment of thermal equilibrium between the spin system and the crystal lattice of the calorimeter working medium. The spin/lattice relaxation time τ_{sp} which largely determines the longitudinal magnetization relaxation grows significantly with decreasing temperature. The contribution to τ_{sp} of the inelastic Raman scattering of phonon with the electron spin flip is proportional to about $1/T^7$ [23]; the Orbach scattering with participation of an additional electron level provides a temperature dependence of the type $\exp(\Delta E/kT)$ [23], where ΔE is specified by the level position. However, below 1 K, where τ_{sp} appears to be of the order of seconds, the increase in the longitudinal relaxation time sharply slows down because of the direct exchange between the spin system and the lattice, and the relaxation time thus becomes $\tau_{sp} \sim 1/T$. It is the "moderate" τ_{sp} values that allow the use of the magnetic thermometer at cryogenic temperatures. The thermal equilibrium of a spin-lattice system sets in faster in metals than in dielectrics at these temperatures owing to the electron-phonon interaction. In this case the relaxation time is expressed in terms of the electron temperature T_e as $\tau_{sp} = K/T_e$, where K is the Korringa constant. This allows the use of paramagnetism of a metal in a calorimeter [16]. An absorber made of a heavy metal doped with a paramagnetic impurity provides a short time ($\sim 10^{-3}$ s) of establishment of thermal equilibrium and may appear to be promising for creation of a proportional heat counter of X-ray quanta with spectral resolution of 1–10 eV. This is the way of solution of applied problems of chemical analysis by X-ray fluorescence methods (the snap, the search for precious metals in samples of geological rocks, etc.).

In principle, it is possible to work with the nuclear magnetism of metals. The value of Bohr magneton is not manifestly included in the expression for the energy sensitivity, but because of the smallness of the nuclear magneton the starting conditions for nuclear polarization should be more rigorous, namely, the magnetic fields up to 10 T and the temperature of about 10 mK will be needed. The relaxation time at cryogenic temperatures is not large either because of the conduction electrons. The use of the copper working medium with $B_r \sim 3$ Oe allows one to obtain the energy sensitivity $\delta E = 10^{-19}$ J/$\sqrt{\text{Hz}}$ = 0.6 eV/$\sqrt{\text{Hz}}$ (for $h = 1$ cm, $\delta\Phi = 10^{-5}\Phi_o/\sqrt{\text{Hz}}$). The "nuclear" calorimeter can be prospective in experiments on registration of weakly interacting massive particles (WIMP) that presumably constitute the major part of our universe (up to 90%, according to the modern point of view). The non-baryonic nature of WIMPs and the absence of electric and other charges permit the registration of these strange particles through only their nonzero mass in a "frontal" collision with the nuclei of a conventional substance. Thus, the observation of the change of the magnetic moment of a nuclear system will enable us to register "directly" such a collision.

As an alternative way it is possible to apply a paramagnet (the working medium in a calorimeter) with rather large spin-lattice relaxation times. The low interaction intensity of elementary particles with a substance is determined, in particular, by the lack of their electric charge (neutrinos of three generations, super-symmetric satellites of photon and neutron, WIMPs, etc.). The birth in the working medium of secondary charged particles or recoil nuclei as the result of interaction with these "exotic" particles allows registering the latter by the proposed detector. Similarly to the registration of weakly interacting particles, it is possible to consider the observational problem of rare events such as a double β-decay (the neutrino mass measurement) and the search of Goldstone bosons. According to the well-known Bethe-Bloch formula, the ionization loss of secondary charged particles cannot be less than 2 MeV cm^2/g. Consequently, a single secondary charged particle loses at least 10 MeV per 1 cm of path length when the paramagnetic density is about 5 g/cm^3. It means that the secondary particle loses more than 1 eV per lattice period along the path, which leads to an instantaneous local heating up to 10^4 K and, as a concequence, τ_{sp} will fall instantaneously by many orders of magnitude and will be at the level of microseconds, while a quick and strongly non-equilibrium heat exchange will take place between the lattice and the spin system. As the heat exchange stops, the greatest part of the energy will be transferred to the electrons "nearest" to the path. The magnetic system comes to thermal equilibrium in the time of the spin-spin relaxation, which usually is much less than τ_{sp}. The advantage of the detector with a large equilibrium value τ_{sp} lies in the possibility of a natural time selection of events by the sharp jumps of the magnetic moment against the background of the slow drift caused by the uncontrolled heat inflows corresponding to the long time of establishment of thermal equilibrium.

The adiabatic magnetic calorimeter with a short setting-in time of thermal equilibrium can be regarded as a perfect proportional particle detector. It is obvious that the heat response in it is proportional to the energy loss by a particle in the absorber, and if the total interaction cross section with the working medium of the calorimeter is large enough, the response amplitude corresponds to the initial particle energy. The above estimates of the energy sensitivity show the attainability of energy resolution at the level of fractions of eV for a flux of about 10^{-4} particle/s. Such high resolution would allow a significant increase in the efficiency of the X-ray fluorescence method for detection of the content of precious metals in a rock. The resolving capacity of the currently used Si-Li semiconductor proportional detectors reaches hundreds eV. The direct incident-particle energy conversion into the heat response with a high pulse-height resolution would allow solution of the well-known problem of creation of a proportional neutron detector. In order to measure the neutron energy, it is necessary first of all to transfer it to a charged particle. In organic scintillators, the energy is transferred to a proton, and then it is flashed and determined by the intensity of the resultant burst. The process of a proton energy conversion into radiation is quite determined. However, the part of the energy transferred from a neutron to a proton depends on an undetermined parameter, i.e. the turning angle of the neutron trajectory after collision in the center-of-mass system. This uncertainty can be demonstrated in a solution of the system of equations corresponding to the energy and momentum conservation laws for an elastic collision of two particles.

As a result, the instrument function of such a detector appears to be too wide. The proportional neutron detector could be designed using SQUID-assisted measurements of the heat response of a large enough crystal of heavy water (for a complete slow-down of a neutron, several centimeters of length are needed) containing dissolved paramagnetic salt.

4 Metastable-states detectors

The theoretical estimates of the limiting sensitivity of the overheated superconducting grain detector working in a proportional regime [24] appear to reach nearly 1 meV. However, it is needless to say that the practical implementation of such limiting values of sensitivity of overheated grain detectors is out of the question, and their real resolution is estimated to equal hundreds eV. This apparently makes impossible their use in high-precision spectral investigations of β-decay or in the applied problems of X-ray fluorescence. A serious shortcoming of such detectors is a low efficiency of the use of the whole superconductor mass (about one percent of the total number of granules), which significantly decreases the detection probability for a particle captured by the detector. The expected frequency of events, such as WIMP registration, is estimated at a level of 10^{-4} events/day kg. In principle, the mass of the above-discussed magnetic adiabatic calorimeter remains a free parameter, which also makes promising its use in experiments on WIMP registration. Moreover, the magnetic heat detectors (including the proposed adiabatic calorimeters) have a substantial advantage over the other types of heat detectors of elementary particles, namely, they admit an increase in mass of the working medium without loss of sensitivity. As is known, the total interaction cross section and the particle detection probability increase with increasing detector mass. In "conventional" non-magnetic systems (for example, adsorber/semiconductor thermal resistance) the heat capacity of the working medium increases with increasing mass and accordingly the temperature response falls. In the magnetic detectors the temperature response also falls with increasing mass, but at the same time the registered change of the magnetic moment grows. In fact the sensitivity remains unchanged because the magnetic system functions as the working medium and the temperature sensor simultaneously. One can say that the proposed magnetic adiabatic calorimeter measures not the temperature response, but the total entropy change of the system.

The method of particle detection using overheated superconducting granules exploits the trigger effect, i.e. a jump-like transition from the metastable to the ground

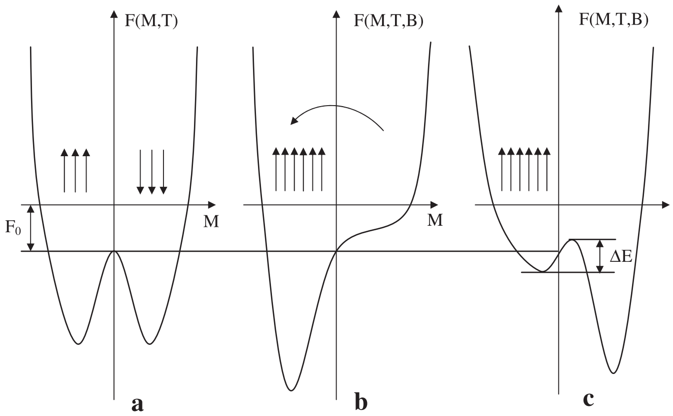

Fig. 2. Sequence of the external-field transformations in the system with second-order phase transition for bringing it into a metastable state. (a) Initially, in the absence of an external field, both states with oppositely aligned spins are degenerate in energy and are equally occupied; (b) after the field is excited, one of the system states, for example, the "left" one, appears to be energetically lower, and this dictates its preferable occupation; (c) when the field reverses its sign, the energy level of the "left" state heightens, and the state thus becomes metastable; the occupation is preserved owing to the potential barrier.

state if the initiating energy release exceeds the potential barrier separating these states. The metastable state is realized in systems with first-order phase transition: slowly heating the superconductor above the critical temperature in a given field ($T > T_c(B)$) it is possible to preserve it in the metastable superconducting state. However, the trigger effect is also possible in systems with second-order phase transition. According to the Ginsburg-Landau theory two minima, i.e. two ground states, two excitations vacuums exist in the expression of free energy in terms of the order parameter: $F(M) = F_0 + a(T - T_K)M^2 + bM^4$ (Fig. 2a). If the free energy also depends on the external field $F(M, B) = F_0 + a(T - T_K)M^2 + bM^4 + |B|M$, then introducing it one can "skew" the characteristic dependence of energy on the order parameter, $F(M, B) = F_0 + a(T - T_K)M^2 + bM^4 + |B|M$, so much that only a single minimum remains in the system, i.e. the only ground state, where $|B| > B_0 = \frac{4}{3}\sqrt{\frac{a^3}{6b}}\,(T_K - T)^{3/2}$ (Fig. 2b). Hence, introducing an intense magnetic field $|B| > B_0$, it is possible to send all the electron spins in one direction and then to switch off the field so as to make the magnetization direction correspond to a definite (either of the two) energy minimum. If we now introduce the field in a reverse direction, the characteristic dependence of energy on the order parameter will be "skewed" to the other side and for $|B| < B_0$ the energy minimum, in which the electron spins are, will be metastable (Fig. 2c). The described operations bring the spin system into the state of inverse population. When in this state, the system can act as a quantum amplifier of external magnetic fluctuations or as a generator of induced emission at a ferromagnetic-resonance frequency corresponding to the magnetization-reversal field. However, for registration of weak energy release another fact is rather important: the potential barrier separating the metastable and ground states depends on the field approximately as $\Delta E(T, B) \cong \frac{(B_0 - |B|)^{3/2}}{(ab(T_K - T))^{1/4}}$, where B is the demagnetizing field. Consequently the barrier height can be decreased arbitrarily by choosing a demagnetizing field. Of course, the potential barrier should not be dropped below the characteristic energy of thermal excitations (below the physical temperature) or otherwise the inverse population will experience thermal relaxation. If the temperature is low enough, the spins are in the metastable state arbitrarily long until the initiating energy release brings the spin system into the ground state. Thus the incoming particle will cause an abrupt remagnetization of the working medium of the detector. At the same time the magnetic response can be registered by the coil with a pulsed amplifier, by a Hall sensor, or by a SQUID.

The trigger effect is in a sense analogous to induced radiation of masers. But the trigger type transition from one stable state to another, induced by an external signal, can take place in classical electronic generators with positive feedback working in the hard excitation regime. Two minima of the Lyapunov function which is used in the steadiness theory correspond to two steady states of the generator. In fact, the minima of the Lyapunov function are analogous to the two free-energy minima in the Ginzburg-Landau theory of second-order phase transitions. The steady states of the generator are characterized by zero and finite amplitudes of oscillations and the latter plays the role of the order parameter, while the characteristics of the electronic circuit, that determine the type (soft or hard) of regime, have the sense of temperature.

A positive feedback could cause trigger type transitions under the influence of a slight signal not only in oscillating systems. In a bolometer with positive thermal resistance $\frac{dR}{dT} > 0$ (for instance, the bolometer on the basis of a superconductor, working at a temperature below T_c, $T \approx T_c$) a positive feedback is provided by a proper value of the operating current, sufficient to cause the bolometer self-heating initiated by a small temperature jump due to the registration of external radiation.

A similar trigger jump from the metastable state under the action of a weak external pulse is also possible in ferroelectrics and ferroelastics. The free energy for them is expanded in even powers of internal mechanical deformation. Ferroelectrics with second-order displacement type phase transitions are of particular interest because both the electric polarization and the mechanical sublattice displacement can be chosen as the expansion parameter of free energy. It is possible to bring a ferroelectric into the metastable state by a sequence of operations with the electric field analogous to the magnetic field reversal in a ferromagnet. In this metastable state, the ferroelectric possesses a nonzero electric moment and shows a nonzero displacement of the sublattices. The metastable state lies higher than the absolute energy minimum and is separated from it by the potential barrier. The barrier height can be made arbitrarily small by setting the necessary polarization field. Any pulse "shakeup" mechanically affecting the sublattice will lead to trigger repolarization which can easyly be registered by the electrometric amplifier. This "shakeup" can be induced by acoustic or seismic waves. The sensitivity of such a system is only restricted by the sensor temperature because to avoid spontaneous depolarization the potential barrier should not be dropped below the physical temperature. Hence, such devices as a recording sensor can be used in Weber type gravitational antennas [25].

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