American Journal of Modern Physics
2013; 2(4): 208-216
Published online June 30, 2013 (http://www.sciencepublishinggroup.com/j/ajmp)
doi: 10.11648/j.ajmp.20130204.15

Dark matter particle detection system SQUID - magnetic calorimeter

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To cite this article:
Alexander I. Golovashkin, George N. Izmaïlov, Vladimir A. Ryabov, Andrey M. Tshovrebov, Larisa N. Zherikhina. Dark Matter Particle Detection System SQUID - Magnetic Calorimeter. *American Journal of Morden Physic.* Vol. 2, No. 4, 2013, pp. 208-216.
doi: 10.11648/j.ajmp.20130204.15

Abstract: Physical principles underlying the concept of the Dark Matter (DM) are considered. Problems of Dark Matter particle detection are briefly reviewed. An original two-channel scheme for direct detection of cosmic DM particles is proposed. It is based on a super-low-temperature calorimeter and includes a nuclear spin system whose magnetic response is measured by a quantum interferometer (SQUID). Low threshold and the capability for efficiently suppressing the recoil-electron background are the most important advantages of the proposed scheme. They make it possible to detect DM particles with extremely low recoil energies and carry out direct DM search with high sensitivity.

Keywords: SQUID, Paramagnetism, Low Temperature, Dark Matter

1. Introduction

The enigma of Dark (i. e., non-luminous and non-light-absorbing) Matter is one of the major open problems of modern science. Swiss astronomer F. Zwicky was the first to suggest in 1933 the existence of “Dark Matter” on the basis of observations of the velocity dispersion of eight galaxies in the Coma cluster [1]. In succeeding years a great deal of convincing evidence of the DM existence was obtained at various scales (see, for example, reviews [2, 3]). A striking picture of the Universe arises as the result of the investigations pursued in the last decade. It consists of 2/3 of some repulsive cosmological component (Dark Energy) and 1/3 of matter, 85 of which are DM, whereas only 5% of the Universe content is accounted for by ordinary (baryon) matter [4—6]. The role of repulsive (“antigravity”) component is intimately related to the universal cosmological constant problem initially appeared in the general relativity theory (the Λ-term in the Einstein equation) and currently discussed in the superstring theory framework [7].

Detection of dark matter, i.e., matter emitting no light and unobservable with telescopes, is crucial for cosmology, astrophysics, and elementary particle physics. Numerous experiments in search of DM particles are presently underway in many countries. In none of them, however, have these particles thus far been detected. The search for DM particles and detailed studies of their properties require joint efforts of experts working in different fields of accelerator and nonaccelerator physics of elementary particles and astrophysics, as well as use of range of mutually complementary methods.

Direct detection of DM particles coming in from the galactic halo would give evidence that these particles constitute the hidden mass of the Universe. Creation of new particles in accelerator experiments would open up possibilities for their comprehensive investigation. Indirect detection of astrophysical signals from the annihilation of DM particles would provide important information, e.g., about the DM distribution. At the same time, it is clear that indirectly measured signals are often difficult to distinguish from signals produced by astrophysical sources. Generally, detailed studies of DM particles require the development and manufacture of sophisticated detectors, the creation of materials free from radioactive admixtures, and building underground laboratories protected from cosmic background radiation.

In the last decade, practically all underground laboratories in the world have been experimenting with the direct detection of WIMPs. These low-background facilities are operating and developing a variety of detectors involving different methods of recording small energy releases from WIMP scattering by target nuclei. The sensitivity attained in some of these experiments is sufficient to verify the predictions of the most realistic supersimmetric models in elementary particle physics. Recent progress in the development of cryogenic technologies, low-noise electronics, and hybrid methods for the suppression of phonon events has established the guidelines for future detector designers. New detectors must have various targets weighing from 100 to 1000 kg and use a combination of methods for discovery of recoil nuclei by recording light, heat and ionization signals. Once a meaningful signal is detected, it will be possible not only to measure the WIMP mass but also to elucidate the nature of certain weakly interacting particles and to choose a plausible scenario of its origin from numerous options offered by theoretical models.

In the bulk of the article, new method for the detection of DM particles, are describe.

2. Candidates for DM Particles: Weakly Interacting Massive Particles

In recent years, the WMAP [8], 2dFGRS [9], and SDSS [10] experiments have provided highly accurate measures of major cosmological parameters. All matter in the Universe can be detected using three parameters: the Hubble constant $h = 0.70^{+0.04}_{-0.03}$, the matter density $\Omega_M h^2 = 0{,}138 \pm 0{,}012$, and the baryonic density $\Omega_B h^2 = 0{,}0230^{+0{,}0013}_{-0{,}0012}$, with the Universe containing only $\sim 4\%$ baryons and $\sim 26\%$ DM.

These findings account for a rather paradoxical situation in modern cosmology, that is, the amount of DM is fairly well known, but its nature remains fully unknown. The existence of DM in the Universe is deducted exclusively from its gravitational effect on the behavior of astrophysical systems on different cosmological scales, from galaxies to the cosmological horizon. The presence of still unobservable massive DM particles in the Universe is thus far the most natural explanation of this paradox despite alternative models of modified gravity proposed to account for the anomalous gravitational behavior of astrophysical objects [11]. We consider the most popular candidates for DM particles.

One of the leading candidates for DM particles are weakly interacting massive particles (WIMPs), supposed to have been born in the very first instants after the Big Bang. The term WIMP applies to a class of particles distinguished first and foremost by a mass and annihilation cross section that enabled them to fall out of equilibrium in the early Universe with a density characteristic of DM. The appearance of WIMPs in theoretical physics was motivated by the problem of the electroweak symmetry breaking. In accordance with standart cosmological assumption, the thermal relic abundance of WIMPs naturally coincides with that necessary of DM. The requirement of a sufficiently effective annihilation of WIMPs implies that their interaction with matter must be strong enough to make them detectable in direct experiments.

The present WIMP density is estimated as [12] $\Omega_{WIMP} h^2 \approx 3\times10^{-27} cm^3 s^{-1} / <\sigma_{ann} v>$. For a particle of given mass, the mean annihilation cross section times the velocity, $<\sigma_{ann} v>$, has a maximum determined by the partial-wave unitarity of the *S*-matrix, $<\sigma_{ann} v>_{\max} \approx 1/m_{WIMP}^2$ [13, 14]. The requirement $\Omega_{WIMP} h^2 \le 1$ is compatible with the unitarity limit and provides a constraint on the mass of DM particles, $m_{WIMP} \le 340\ TeV$ [13]. Results of WMAP experiments suggest more rigorous constraint, $m_{WIMP} \le 120\ TeV$ [15].

2.1. Supersymmetric Particles

First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size. A few variants of extending the SM lead to a WIMP. The most popular of them is supersymmetry (SUSY), which extends the SM by including new particles and interaction. Supersymmetric theories postulate superpartners of ordinary particles, i.e., new particles whose spin differ by ½. A peculiar feature of supersymmetric theories is the unification of gauge coupling constants on the scale $M_U \sim 2\times10^{16} GeV$.

The minimal supersymmetric standard model (MSSM) is minimal supersymmetric extension of the SM. In this model, all gauge fields have fermionic superpartners. Gluons, gauge bosons B, W_3 (or γ and Z^0), and $W^{\pm}$ have fermionic superpartners called gluino ($\tilde{g}$), bino ($\tilde{B}$), and wino ($\tilde{W}^i$). All fermions have scalar superpartners, such as squarks and sleptons for quarks and leptons. An additional Higgs field, besides two Higgs doublets, is introduced, and each neutral Higgs boson (H_1^0 and H_2^0) has a corresponding Higgsino ($\tilde{H}_1^0$ and $\tilde{H}_2^0$) with spin ½.

In the MSSM lightest supersymmetric particle (LSP) is stable and disappear only in the case of pair annihilation. It makes the LSP an appealing candidate for DM [16]. The MSSM imposes many restrictions on the nature of the LSP. This particle may have neither the electric nor the color charge, otherwise, it would be able to create heavy isotopes with baryonic matter, at variance with experimental date. The fittest candidates for LSP are neutralinos, or linear combination of the superpartners of the photon, Z^0, Higgs H_1^0- and H_2^0-bosons [17].

Pair annihilation reaction and elastic scattering from nucleon are crucial for the detection of neutralinos. Presently, neutralinos must be essentially nonrelativistic, with the main annihilation channels into fermion-antifermion pairs (largely heavy ones), pairs of gauge bosons (W^+W^-, Z^0Z^0) and final states containing Higgs bosons.

2.2. Kaluza-Klein States

The early Grand Unification theories were based on the idea that unification of all interactions occurs near Plank scale $M_{Pl} \equiv G_4^{-1/2} \approx 10^{28} eV$ were $G_4 = 6,707 \times 10^{-33} TeV^{-2}$ is the gravitational constant in the four-dimensional space-time world. A new TeV scale of the interaction unification proposed in certain recent publication includes gravitation [18-21]. Such a 'premature' unification may result from the manifestation of extra dimensions on the scale, first suggested Kaluza and Klein. Recent string models have given evidence that some of these dimensions may be greater than that (~ 1 mm) without contradicting observational date, e.g., the proton lifetime [22-25]. In this approach to gravity, space-time has the so-called brane-bulk structure. The brane space has the (3+1) dimensions of the ordinary space-time in which all the usual SM particles and fields live. The brane space is embedded into a bulk space having n extra dimensions, besides the (3+1) dimensions of Minkowski space; moreover, it contains gravity and probably unobservable SM gauge particles and singlets. The fundamental gravity scale in such brane-world space is the new interaction unification scale $M_{n+4} \approx TeV$ rather then the macroscopic Plank scale M_{Pl}.

Theories with extra dimensions contain massive Kaluza-Klein (KK) gravitons that may emerge in the form of real and virtual particles. In our for-dimensional world, KK gravitons manifest themselves as towers of massive excided states (KK states).

At present, theories with unified extra dimensions (UED theories) are being developed in which all SM particles and fields can propagate in extra dimensions [26]. KK excitation in UED theories are observable states and the lightest of them corresponding to the first SM excitation are appealing candidates for DM. The mass of the lightest KK states is $m_{KK} \approx 400-1200$ GeV [27].

3. Detection Methods and Experiments Designed to Search for WIMPs

WIMPs could be detected by "indirect" way in the experiments with cosmic rays by means of searching for particles produced in annihilation of the WIMPs in galactic halo. These particles can be antiprotons, positrons, or photons. Searching for neutrinos arising as final products of the WIMP annihilation in the Sun or Earth is possible in low-background underground observatories or underwater neutrino detectors. Such neutrinos are also searched for by detection of muons produced by neutrino interactions and coming "upward" from the center of the Sun or Earth.

WIMPs can be also detected through their direct interaction with ordinary baryon matter by detecting recoil nuclear produced at collisions of the WIMPs on target nuclei. The idea of the direct detection of WIMPs comes from the assumption that the Galaxy abounds in WIMPs and that many of them pass through the Earth. The main characteristics of the signal from directly detected WIMPs are their density distribution in the Galaxy, the distribution by velocities in the solar system, and the cross section of their scattering on nucleons. Based on these parameters, it is possible to estimate the event count rate R_{WIMP} using the expression $R_{WIMP} \approx \sum_i N_i n_{WIMP} < \sigma_{WIMP-nucleon}\ v_{WIMP} >$, were $N_i = M_{Detector} / A_i$ is the number of nuclei in a target of the i type in a detector of mass $M_{Detector}$, A_i is the atomic weight of a nucleus of the $\boldsymbol{i}$ type, $\boldsymbol{n_{WIMP}}$ is the WIMP flux density, and $< \sigma_{WIMP-nucleon}\ v_{WIMP} >$ is the WIMP-nucleon scattering cross section averaged over WIMP velocities v_{WIMP} relative to the detector. The cross section of the WIMP-nucleon scattering is very small, and therefore a large sensitive detector mass is needed.

WIMPs travel with the typical speed $< v_{WIMP} >= 270$ km/c and interact with nuclei in the processes of elastic and inelastic scattering. In the case of elastic scattering, the recoil spectrum has the typical energy $< E >\approx 50$ keV [28]. In inelastic scattering, WIMPs interact with the target orbital electrons by exciting them or by ionizing the target. Also, a WIMP can excite a nucleus in the inelastic process such that the resulting nuclear recoil is followed by the emission of a photon (in about 1 *ns*). Such a signature should be separated from the signatures of background events. The mean nucleus recoil energy in the collision of a WIMP and a nucleus with mass m_A can be approximated as $< E >\approx 1.6 A M_{WIMP}^2 / \left(M_{WIMP} + m_A\right)^2 [keV]$, where A is the number of nucleons in the nucleus interacting with the WIMPs.

In experiments for direct WIMP detection, it is necessary to somehow measure the energy released from WIMP scattering on the nuclear target. Ionization, scintillation, heat detectors and/or their combination may be used to record recoil nuclei and measure their energy (Fig.1.). We recall that almost 100% of the energy of a recoil nucleus ΔE is converted into a thermal signal in heat detectors. In ionization detectors, the quenching factor for the transformation of the recoil energy into the energy spent to the creation of electron-hole pairs is below 30%. Less then 10% of the energy is converted into light in scintillation detectors. In this case, a detector of recoil nuclei must have the threshold of a few *keV.*

Importantly, ionization and scintillation outputs significantly increase if the primary interaction occurs with an electron, i.e., if its product is a recoil electron instead of a recoil nucleus. Such a situation occurs for all background events induced by photon scattering from electrons. Normally, they constitute the main component of the background. It follows from experimental practice that suppressing these background electrons is a most challenging and important task because they persist despite the use of highly sophisticated background suppression system (underground laboratories from cosmic rays, passive and active protection, super high pure materials). In fact, sensitivity limits of experimental designed to directly detect WIMPs depends on solving these problems. One approach to suppressing this background component is to detect two signals simultaneously (e.g. phonon + ionization or ionization + scintillation) in 'hybrid' detection (see Fig.1). A neutron background can be suppressed by using the multiple scattering signature absent in the case of WIMPs. Generally speaking, the difficulty of direct experiments in the search for WIMPs is determined by the following factors: (a) a very small WIMP-nucleon scattering cross section ($<10^{-6}\ pb$) necessitating a large sensitive detector mass; (b) the low efficiency of measurement of small energies of recoil nuclei ($\sim 10-100\ keV$) necessitating the use of detectors with the threshold of several keV; (c) a very high CR and natural radioactivity background necessitating location of the detectors in underground laboratories and the use of protective shields or materials free from radioactive admixtures.

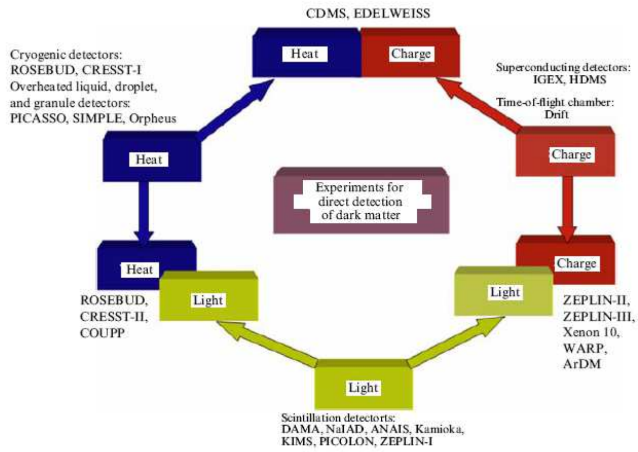

Figure 1. *Principal detection methods and experiments designed to direct detection for WIMPs. Charge detectors – semiconducting detectors IGES [29], HDMS [30], time-projection chambers Drift [31] and MIMAC [32]; scintillation detectors – DAMA/LIBRA [33,34], NaIAD [35], ANAIS [36], Kamioka-CaF$_2$ [37], KIMS [38], PICOLON [39], ZEPLIN [40]; cryogenic heat detectors – ROSEBUD [41], CRESST-I [42]; overheated droplet detectors and superconducting granule detectors – COUPP [43], PICASSO [44], SIMPLE [45], Orpheus [46]; combined light and heat detectors – CRESST-II [47]; combined heat and ionization detectors – CDMS [48], EDELWEISS [49]; combined light and ionization detectors – ZEPLIN-II [50], ZEPLIN-III [51], Xenon 10 [52], WARP [53], ArDM [54].*

4. The Original Two-Channel Detection Method Based on a Low-Temperature Magnetic Calorimeter to Search for Dark Matter Particles

In this paper a new scheme for the DM particle detection based on the use of a cryogenic magnetic calorimeter is proposed, which is free from the above-mentioned drawback and makes it possible to detect recoil nuclei in the low-energy region with the simultaneous discrimination of background events caused by the recoil electrons. Thus, the region of low recoil-nucleus energies, which is especially important for the WIMP searching, becomes accessible for the measurements.

Recent advancements in the low-temperature technique have made possible physical experiments at temperatures lower than 1 mK [55]. Decrease of the heat capacity for $T \to 0$ corresponding to the requirements of the third principle of thermodynamics allows for attaining, in technically accessible temperature regions in a macroscopic working substance, the temperature responses $\delta T = \delta E/C$ to the energy release, which comprises several eV. Thus, a heavily cooled working substance (adsorber) combined with a sensitive thermometric scheme forms a perfect proportional elementary-particle detector (here, $\delta T \sim \delta E$, δE is the particle energy spent for the working substance heating, δT is the resulting temperature response) [56]. The only drawback of the heat detectors, caused by the fact that their speed of response limited by characteristic times of thermal processes τ, is of no significance if the background-event frequency is less than $1/\tau$.

After the Josephson-effect discovery and considerable progress in the development of quantum interferometers (SQUIDs [57]), !which are based on this effect and allow the magnetic measurements to be done at the level of a fraction of the flux quantum $\Phi_0 = 2\pi\hbar / 2e = 2.07{\cdot}10^{-15}$ Wb, the SQUIDs came into wide use in the super-low-temperature thermometry [55]. The principle of the magnetic thermometer operation is based on the registration of a change of the magnetic moment of a paramagnetic, whose susceptibility follows the Curie—Weiss law $\chi(T) = \alpha(T - T_K)^{-1}$, where $T > T_K$, and T_K is the Curie temperature. The measurements are carried out at a constant magnetic field B and currently, generally with the use of SQUIDs.

The response to the energy release ΔE in magnetic calorimeters can be detected (1) at a fixed external field $B \neq 0$, or (2) at $B = 0$ after the adiabatic demagnetization cycle have been dine for a working substance [55]. First we estimate the magnetic response to the energy release ΔE for a cylindrical adsorber of height H for the first case ($B \neq 0$). We shall take into account that a SQUID [58] measures, as an input signal, an increment of the magnetic flux $\Delta\Phi$, which depends upon the adsorber magnetic moment increment ΔM according to the equation $\Delta\Phi = \mu_0 \Delta M / H$, where μ_0 is the vacuum magnetic permeability. Then:

$$\Delta\Phi = \frac{\mu_0\,\Delta M}{H} = \frac{\mu_0}{H}\frac{\partial M}{\partial T}\Delta T = \frac{\mu_0}{H}\frac{\partial M}{\partial T}\frac{\Delta E}{C} \qquad (1)$$

In the operating temperature interval all contributions into the absorber heat capacity may be considered as small in comparison with the spin system contribution which can be calculated as a partial derivative of the spin entropy

$$C \approx C_s = T\frac{\partial S_s}{\partial T} = \frac{\alpha T(B^2 + B_r^2)}{(T - T_K)^3}.$$

So from the equality of mixed derivatives of the free energy $\frac{\partial^2 F}{\partial B \partial T} = \frac{\partial^2 F}{\partial T \partial B}$, it follows that $\frac{\partial S_s}{\partial B} = \frac{\partial M}{\partial T}$, and then the spin system entropy is $S_s = \int \frac{\partial S_s}{\partial B} dB = \int \frac{\partial M}{\partial T} dB$. According to the Couri—Weiss law, the magnetic moment derivative is $\frac{\partial M}{\partial T} = \frac{\partial(\chi B)}{\partial T} = \frac{\partial}{\partial T}\left(\frac{\alpha B}{T - T_K}\right) = \frac{-\alpha B}{(T - T_K)^2}$, and then $S_s = -\frac{\alpha B^2}{2(T - T_K)^2}$.

The paramagnetic residual field B_r is introduced in relation to the prohibition by the third principle of thermodynamics of reaching the absolute zero temperature upon completion of the adiabatic demagnetization, when $B = 0$.

Substituting the heat capacity C_s and derivative $\frac{\partial M}{\partial T}$ in Eq. (1) determines the magnetic flux response to the energy/heat release ΔE in the form

$$\Delta \Phi \approx \frac{-\mu_0 B}{H(B^2 + B_r^2)} \frac{T - T_K}{T} \Delta E \qquad (2)$$

For $T \gg T_K$, the following estimate for the calorimeter energy resolution corresponds to the maximum response $\Delta\Phi_{max} \approx \Delta\Phi(B = B_r)$:

$$|\delta E| \cong \left|\frac{2HB_r\delta\Phi}{\mu_0}\right| \qquad (3)$$

For the second case (B = 0) the calculation of the resolution by the partition function method [58] gives the result different from that for B ≠ 0 by the coefficient 1/2:

$$|\delta E| \cong |T\delta S| \cong \left|\frac{HB_r\delta\Phi}{\mu_0}\right| \qquad (4)$$

Thus, in both cases ($B = 0$, $B \neq 0$), upon establishing the thermal equilibrium in the adsorber, approximately the same energy resolution (3) and (4) is obtained, which does not depend on the base area of the paramagnetic sample. The value $\delta\Phi = 10^{-5}\Phi_0/\sqrt{Hz}$ can be taken as technically attainable for the SQUID effective resolution with allowance made for the flux transformer loss. Then, for H = 1 cm and $B \approx B_r \approx 100$ *Oe* (electron paramagnetic) the calorimeter resolution will be $\delta E_e = 3\times10^{-18} J/\sqrt{Hz} \approx 20 eV/\sqrt{Hz}$; for $H = 1$ cm, $B \approx B_r \approx 3 Oe$ (nuclear spin system) we have $\delta E_N = 10^{-19}$ *Дж* $/\sqrt{Hz} \approx 0{,}6 eV/\sqrt{Hz}$.

In what follows we consider the most promising variant of the use of nuclear paramagnetic for picking out the signal from the WIMP scattering by absorber nuclei. In the above discussion it was assumed that the whole energy release was uniformly distributed over the adsorber volume. Now we estimate the sensitivity in the case when the heat equilibrium is not achieved yet in the whole adsorber volume. It is well known that the local equilibration time τ_1 [55] in the nuclear spin system in the course of nuclear demagnetization caused by recoil nucleus energy release is much smaller than the spin-phonon relaxation time τ_2. It is precisely the time τ_2 in which the energy is transferred to the lattice, i. e., the nuclear demagnetization in the whole adsorber volume takes place, in the case when the energy is transformed through conductivity electrons. In just the same time, the complete thermal equilibrium is reached in the case of the energy release from a recoil nucleus produced by the WIMP impact.

The flux change $\Delta\Phi$ caused by the momentum decrease owing to the nonequilibrium local heating in a time τ_1 (for the recoil-nucleus case) is detected by the flux-transformer input turn with the radius *R*. The total flux in the turn plane is zero in view of the eddy nature of the magnetic field. Therefore, the flux change inside the input turn is equal to that outside the turn taken with the opposite sign:

$$\Delta\Phi = \Delta\Phi_{in} = -\Delta\Phi_{ex} = -\int_R^\infty \Delta B dS = -\int_R^\infty \frac{\mu_0 \Delta M}{r^3} 2\pi r dr$$
$$= -2\pi\mu_0 \Delta M \int_R^\infty \frac{dr}{r^2} = \frac{2\pi\mu_0 \Delta M}{R}$$

The energy release ΔE causes the local momentum decrease $\Delta M = -\frac{T\Delta S_s}{B_r} = -\frac{\Delta E}{B_r}$, therefore, $\Delta\Phi = -\frac{2\pi\mu_0\Delta E}{RB_r}$, and the calorimeter resolution under nonequilibrium conditions is:

$$|\delta E| \cong \left|\frac{RB_r\delta\Phi}{2\pi\,\mu_0}\right| \qquad (5)$$

Thus, the event sought (the recoil nucleus from the WIMP scattering) which produces the energy release ΔE in a cylindrical adsorber with radius *R* and height *H* is detected in the initial instant of time under nonstationary conditions with the resolution $\delta E(t < \tau_2) \cong \frac{RB_r\delta\Phi}{2\pi\,\mu_0}$, and then, upon reaching the thermal equilibrium, can be registrated with another (higher for $R > 2\pi H$, or lower for $R < 2\pi H$) resolution $\delta E(t > \tau_1) \cong \frac{HB_r\delta\Phi}{\mu_0}$. Under these conditions, the responses are $\Delta\Phi(t < \tau_2) = -\frac{2\pi\mu_0\Delta E}{RB_r}$ and $\Delta\Phi(t > \tau_1) = -\frac{\mu_0\Delta E}{HB_r}$, respectively, and the ratio of the mean demagnetization rates is

$\eta_{WIMP} = \frac{\Delta\Phi(t<\tau_1)}{\tau_1} / \frac{\Delta\Phi(t>\tau_2)}{\tau_2} = \frac{2\pi H \tau_2}{R\tau_1}$. In the electron-scattering case (which should be rejected as a background one) we have only one relaxation time τ_2, and consequently, the ratio of the mean demagnetization rates $\eta_{e^-} = \frac{\Delta\Phi(t<\tau_1)}{\tau_1} / \frac{\Delta\Phi(t>\tau_2)}{\tau_2} = \frac{2\pi H}{R}$ turns out to be τ_2/τ_1 times smaller. It means that the recoil electron response is suppressed in the fast channel, and this effect can be estimated quantitatively by means of introducing the rates of the magnetic channel changes in two registration channels (see insert in Fig.2). At the initial stage $t < \tau_1$, fast transfer of the energy ΔE to the nuclear spin system in the case of the recoil nucleus will provide higher rate of the change of the flux under measurement at the level of $\frac{\Delta\Phi(t<\tau_1)}{\tau_1} = -\frac{2\pi\mu_0\Delta E}{RB_r\tau_1}$. Here, the time τ_1 of the "fast" integration of the SQUID magnetic auto-compensation system in the first registration channel is taken equal to the spin-spin nuclear relaxation time τ_1. Upon reaching the thermal equilibrium over the whole adsorber volume, the flux variation rate will be at the level of $\frac{\Delta\Phi(t>\tau_2)}{\tau_2} = -\frac{\mu_0\Delta E}{HB_r\tau_2}$, where τ_2, the time of the "slow" integration of the SQUID magnetic auto-compensation system in the second registration channel, is taken equal to the spin-phonon relaxation time τ_2. Thus, one can set up the ratio of the rates of the detected flux changes before and after reaching the thermal equilibrium in the nuclear system $\eta = \frac{\Delta\Phi(t<\tau_1)}{\tau_1} / \frac{\Delta\Phi(t>\tau_2)}{\tau_2} = \frac{2\pi H \tau_2}{R\tau_1}$ to be sufficiently high by choosing appropriate dimensions and times. For example, for cupper, the relaxation time τ_1 may be of the order of 1 ms, and τ_2, of the order of 10 s or more [55], so that one obtains $\eta = 10^4$ for $\frac{2\pi H}{R} = 1$. On the other hand, an electron event, when the energy ΔE is transferred to conductivity electrons, will give the ratio of the corresponding rates in two channels at the level of $\eta \approx 1$. This fact can be used for selecting events with nuclear ($\eta >> 1$) and electron ($\eta \approx 1$) recoil, which is especially necessary in experiments on searching for DM particles interacting with matter through the scattering from nuclei.

By choosing τ_1 at the level of about 1 ms, which corresponds to the standard SQUID operating frequency band $\Delta f \approx 1/\tau_2 = 1$kHz, and taking for the estimates a "non-record" flux resolution $\delta\Phi = 10^{-5}\,\Phi_0/\sqrt{Hz}$, we shall obtain the following noise limit at the initial stage $\delta\Phi_1 = 3\cdot10^{-4}\Phi_0$. Under nonequilibrium conditions the corresponding energy resolution is $\delta E(t < \tau_1) \approx 10^{-19} J \approx 200\ eV$ (here, $R = 75\ cm$, $B_r(Cu) = 3 Oe$). Later, after the thermal equilibrium is reached (for $\tau_1 < t < \tau_2 \approx 10$ sec), the energy release may be not only recorded but also measured at the increased integration time $\tau_2 = 10$ sec and in narrower frequency band $\Delta f = 1$ kHz → 0.1 Hz (the modern SQUID electronics makes it possible to control the operation band, Fig. 2) with the accuracy of about $\delta E(t < \tau_2) \approx 10^{-21} J \approx 2\ eV$ (here, $H = 12\ cm$, $B_r(Cu) = 3\ Oe$, $\delta\Phi_2 = 3\cdot10^{-6}\Phi_0$). At the above specified parameters, the selection of the required events associated with nuclear recoil is performed according to the following criterion: the ratio η of the flux-change rates in the first and second channels must be $\eta \geq 10^4$. It is worth noting that the sensitive volume V = 0.25 m^3 (R = 75 cm, H = 12 cm) of the cupper adsorber with the working-substance mass of about 2 tons could provide the best to date statistic for the WIMP detection.

The above numerical estimates of the basic characteristics of the two-channel scheme of the DM particle detection with the use of nuclear-magnetic

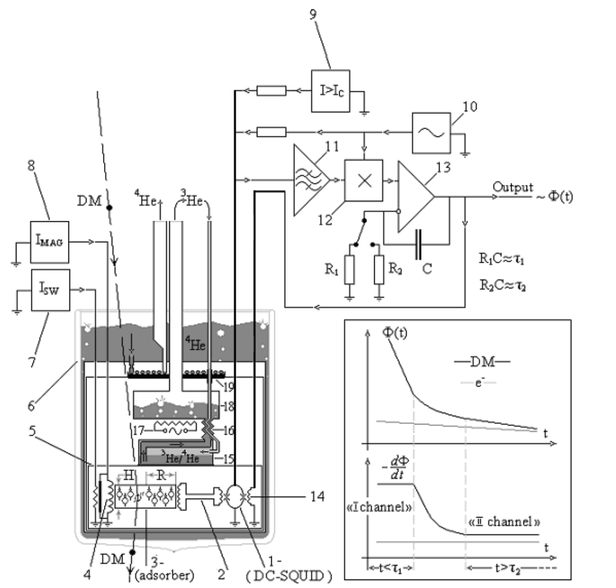

Figure 2. The basic elements of the apparatus: 1 – DC SQUID (Josephson junction are marked by crosses); 2 – superconducting flux transformer; 3 – adsorber with a nuclear spin system; 4 – superconducting solenoid with a valve for the magnetic field "freezing"; 5 – superconducting screen; 6 – cryostat with liquid ^{4}He; 7 – current source for controlling the superconducting valve; 8 – power supply for superconducting solenoid. Components of the SQUID electronics [57]: 9 – current source for the DC-SQUID operating-point shift above the overall critical current for the first and second Josephson junctions; 10 – alternative current generator (f = 100 kHz); 11 – selective amplifier; 12 – phase detector; 13 – integrator with a variable time constant; 14 – biasing coil of the SQUID autocompensation system; analysis of the bias rate is perceived to be done by a computer after the analog-digital conversion of the output signal; analog blocks 9, 10, 12, and 13 may be also replaced by digital systems DAC and ADC under general computer control. Refrigerator for helium-3 solution in helium-4 [55]: 15 – solution chamber; 16 – counter heat exchanger; 17 – heater of the evaporation chamber; 18 – evaporation chamber (lines of the helium-3.

calorimeter with a SQUID are based not on "record" but on quite technically accessible parameters of the instrumentation required for creating the scheme proposed thus suggesting its feasibility. We emphasize that with a large adsorber volume one can reach: (1) a high detection sensitivity and good accuracy of the WIMP energy-release measurements; (2) a sharp suppression of the electron events, thus allowing for releasing requirements to the passive shielding from the electron background, for example, associated with the purity of the adsorber material; and (3) a substantial simplification of the system as a whole since in this case there is no need in multi-modular system which is usually used when small-mass thermometric sensors are employed. A peculiarity of the scheme proposed is that the taking of readings for the both signals (under nonequilibrium and equilibrium conditions) is carried out from the same nuclear-magnetic module. Recording two independent signals from a single measuring channel provides a mean for the adoptive integration constant tuning in the quantum interferometer feedback system (Fig.2). The two-channel configuration of the registration scheme assists in excluding background events (first of all, electrons masking the sought DM effect), and, as can be shown by some extra calculations, in principle, makes possible to relax requirements to passive screening by an order of magnitude. The heat capacity reserve of the nuclear-magnetic system provides the tolerance to the exposure to cosmic ray particles with high (up to 10 TeV) energies and penetrability. For example, under conditions of an underground laboratory at the depth of 5 km of water equivalent with experimentally measured muon flux $J \approx 10^{-9}$ cm^{-2} sec^{-1} sr^{-1} [59] for detectors with 0.25 m^3 volume, for which we have made our foregoing estimates, the degradation rate (i. e., the fraction of the volume removed from operating conditions per unit time) is about $2\cdot10^{-10}$ sec^{-1}. This follows from the fact that for the case under discussion the nuclear spin system has about 10^{30} spins, whereas one muon with the energy of 20 TeV can produce about $2\cdot10^{20}$ spin flips.

In figures 3 and 4 other utilization variants of magnetic calorimeter with SQUID in register systems of DM particle are presented, which extend the capabilities of single-channel methodics. In contrast to detail described above(fig.2) two-channel circuit of ultra low temperature magnetic calorimeter, that uses the nuclear magnetism, in presented on fig. 3 and 4 calorimeters variants with SQUID paramagnetism of electronic system is operated. Moreover in contrast to the first scheme in variants 3, 4 it is assumed that SQUID doesn’t register directly the demagnetization of whole adsorber. Instead of this the quantum interferometer fixes the flux of magnetic field, emanating from small paramagnetic concentrator of heat, which is in thermal contact with metallic non-magnetic adsorber.

Action of heat concentrator is explained by the possibility to have the value of heat capacity of small paramagnetic concentrator (C_{pmc}) high compared to the heat capacity of non-magnetic adsorber (C_{ads}), $C_{pmc} >> C_{ads}$, since the low temperature specific heat of metallic adsorber tends to zero with temperature lowering, while the concentrator heat capacity is growing as $C_{pmc} \sim B_r^2/T^2$, where B_r - residual field of electronic paramagnetics. Then due to relation $C_{pmc} >> C_{ads}$ heat response ΔQ, corresponding to interaction of WIMP with the adsorber material, must completely «settle» in heat concentrator: $\Delta Q_{pmc} = \Delta Q\ C_{pmc} /(C_{ads}+C_{pmc}) \Rightarrow \Delta Q_{pmc} \approx \Delta Q$. Hence compact concentrator (black cylinder on fig. 3, 4) will be able to collect practically all energy release from big metallic adsorber (the gray cylinder on fig. 3, 4). In this case the large sizes of adsorber will aid to advance the required interaction cross section, and the small dimension of concentrator will provide the convenience of its interface with SQUID when minimal losses in transmission factor of superconducting transformer of flow is achieved.

In scheme presented on fig 3 feasibility extensions of single-channel methodic of registration of DM particle is achieved by division of massive cylindrical body of adsorber on the large number of circular plate sections, each of which is served by the individual SQUID. The false events, corresponding to particles passing with big interaction cross section, are excluded by coincidence of responses, registered in neighboring sections. Such veto-system suppresses not only lepton component with high penetrating power, but the background neutrons, difficult distinguishable from DM particle, as well.

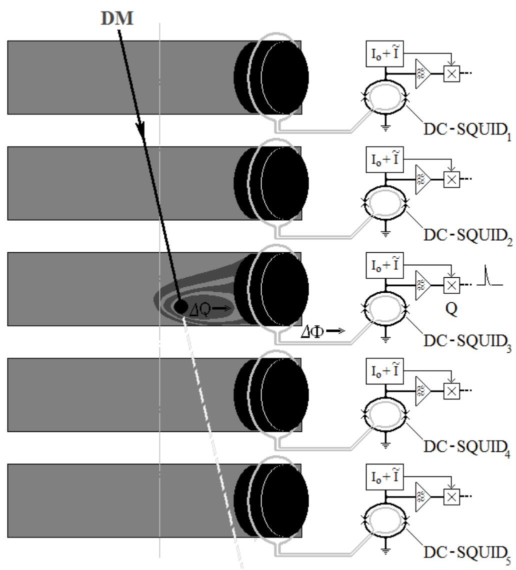

Figure 3. *The scheme of magnetic multichannel calorimeter with SQUID, destined to search DM particles, where the veto system operates at anticoincidence concept in adjacent channels: gray cylinders - separate blocks of metallic absorbers; the black cylinders - the paramagnetic concentrators of heat micro release, each concentrator is connected with separate SQUID by means of superconducting flux transformer; crosses - Josephson junctions, included in SQUID.*

Respectively, in the scheme, given on fig. 4, capability enhancement of single-channel methodic the registration is achieved at the expense of additional channel (playing the role of a veto-system), in which the emission of secondary electrons from the surface of metallic adsorber is recorded. It is supposed that under the action of primary charged lepton the plasma waves appear in metal (the lepton energy divides into quanta of plasma oscillations). In case the electron work function from adsorber material is smaller than the plasmon energy i.e. $A_{e-} < \hbar\omega_{pl}$, then the plasma wave, reached up to the surface, will cause the emission of secondary electrons. In scheme, given on fig 4, secondary electrons are registered by electron multipliers (upper and lower), and the event, replying the interaction of WIMP with adsorber material is identified by anticoincidence of signals of output of SQUID with both electron multipliers.

Recoil nuclei spectrum, replying the scattering of DM particles, dictates the actuality of the recording of nuclear response in the energy range ÷ 100keV. The low-energy part of this interval, including as far as this is possible and energies below 1keV is of a special interest. A nucleus in this spectral region is deeply nonrelativistic, and moving with velocity of about 10km/sec, is practically incapable to excite the electronic system of atom, since the electron Bohr speed appears to be an order higher.

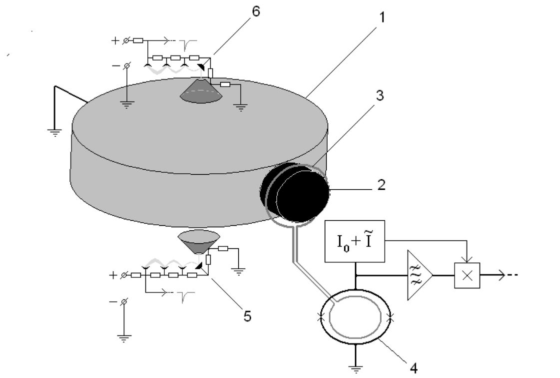

Figure 4. *The scheme of magnetic calorimeter with SQUID, destined to search DM particles, where the veto system records the emission of secondary electrons from the surface of metallic adsorber: 1 – the metallic adsorber; 2 - paramagnetic concentrator of heat micro release; 3 - superconducting transformer of the magnetic flux; 4 – DC SQUID; 5, 6 - electron multiplier and system for collecting of secondary electrons.*

This circumstance makes it difficult (in essence eliminates) application of ionization, scintillation and photographic methods for registration of keV recoil nucleus. In principle it becomes possible to register such events by methods, in which the keV nucleus induces in substance the collective excitations - phonons, thermal waves, etc. As has been shown above just thermal registration procedures based on measurement of magnetocaloric response by SQUID potentially possess the possibilities sufficient to operate with resolution at the level of less than 1keV.

In conclusion it should be pointed out that the proposed nuclear-magnetic calorimeter in view of its flexibility can be used in various modifications for solving many other topical fundamental and applied problems [60] where high sensitivity, detection and precise measurement of a small energy release are required (such as the search for neutrino magnetic moment, detection of low energy solar neutrinos, etc.).

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