Physics – Uspekhi **48** (5) 519 – 531 (2005)

CONFERENCES AND SYMPOSIA PACS number: 01.10.Fv

Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation (1 December 2004)

A joint session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) and the Joint Physical Society of the Russian Federation was held on December 1, 2005 in the conference hall of the Lebedev Physics Institute of RAS. The following reports were presented at the session.

(1) **Kuzmin L S** (Chalmers University of Technology, Gothenburg, Sweden) "Supersensitive cold-electron bolometers in studies of dark matter and dark energy";

(2) **Tkalya E V** (Lomonosov Moscow State University Research Institute of Nuclear Physics, Moscow, Russia) "Induced decay of the nuclear isomer ^{178m2}Hf and the 'isomeric bomb'".

Abridged versions of these reports are given below.

PACS numbers: **07.57.–c**, 07.57.Kp, 95.55.Rg
DOI: 10.1070/PU2005v048n05ABEH002128

Supersensitive cold-electron bolometers in studies of dark matter and dark energy

L S Kuzmin

1. Introduction

According to *Science*, the breakthrough of the year 2003 was the proof of the existence of *dark matter and dark energy* [1]. The portraits of the early Universe (Fig. 1) taken by the BOOMERANG balloon telescope in the submillimeter wavelength range and by the Wilkinson Microwave Anisotropy Probe (WMAP) in the millimeter range corroborated the assertion that 96% of the Universe consists of mysterious dark energy (73%) and dark matter (23%). The most shocking conclusion is that dark energy is the cause of acceleration of inflation of the Universe.

The most important problem that fundamental science of the 21st century must solve is to establish the nature of these mysterious forces that cause the Universe to expand with an increasing rate and to predict the fate of the Universe. Understanding the nature of these phenomena requires a more detailed picture of the cosmic background in the submillimeter range. An entirely new generation of telescopes and detectors is needed in order to solve these problems [2 – 4].

Uspekhi Fizicheskikh Nauk **175** (5) 549 – 561 (2005)
Translated by E Yankovsky; edited by A M Semikhatov

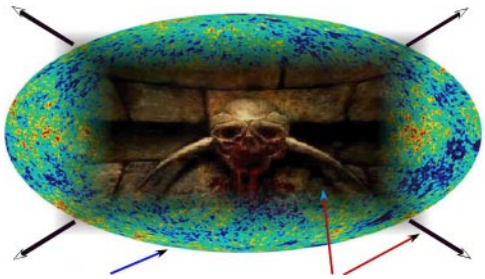

Figure 1. Proof of the existence of dark matter and dark energy, and increase in the rate of inflation of the Universe is the breakthrough of the year 2003 according to the classification of *Science*. The picture shows the temporary interpretation of dark energy, which will be replaced by a real explanation of the nature of the unknown forces after there is a little progress in this field of research.

Recently, Russian scientists, in collaboration with scientists from Chalmers University of Technology (Sweden), proposed and successfully developed a *cold-electron bolometer* (CEB), which appears to be the most probable candidate for the new generation of supersensitive detectors [5 – 9]. Here are the two main reasons why the development of such a bolometer became the turning point in the development of supersensitive detectors.

1. Because of the *effect of electron cooling* of the absorber, the bolometer operates at temperatures below the background temperature. This leads to the exceptionally high sensitivity of CEBs. The entirely new approach in the development of supersensitive detectors amounts to *replacing the artificial overheating of bolometers* (an unavoidable feature of bolometers of the transition-edge sensor (TES) type) by the *effective electron cooling* with a proportional increase in CEB sensitivity.

2. Because of direct application of *electron cooling of the absorber*, the input signal power is moved entirely from the absorber to the read-out system. This makes it possible to realize the idea of an ultimate bolometer, i.e., a bolometer whose sensitivity is limited only by background noise, and, which is especially important, to retain the high sensitivity of CEBs at high background loads. CEBs allow avoiding the saturation typical of TESs.

The problem of dark matter and dark energy has been acknowledged as the most important one by the European Space Agency (ESA) and NASA, because these two entities comprise 96% of the entire Universe. In the past, ESA organized a number of workshops in Cardiff, Delft, Madrid [4], and Paris [3], at which new concepts of future

space telescopes for studying the dark Universe were developed. The result of these workshops was the development of the new European Space Programme Cosmic Vision 2015 – 2025 [3].

To the question of whether European projects should be implemented with the US or independently, these workshops and meetings worked out the answer that the projects can be realized only in close cooperation with the US, because even the European Union does not have enough technological and financial resources for such projects. It was also emphasized that such cooperation must be carried out on the condition that each participant contribute in technological matters.

The same question can be formulated about cooperation between the European Union and Russia. And the answer is quite similar: cooperation is to be carried out with a sizable technological contribution in the areas of research where Russia still holds strong positions.

The program I discuss here proposes a realistic path for developing full-fledged international cooperation. The basic element of the program is the concept of a cold-electron bolometer. Such a concept will help unite the efforts of the cryogenics and radio astronomy schools (which are still very strong in Russia) and will make it possible to provide a leading contribution to the development of new systems of supersensitive detectors. This will be a good contribution to international projects.

2. A new generation of cold-electron bolometers

To understand the nature of dark matter and dark energy, cosmology of the future will need a more detailed picture of the cosmic background in the submillimeter range. A new generation of telescopes and sensors will be needed to solve this problem. The space missions proposed by NASA — SPIRIT, SPECS, and SAFIR — will in the near future determine the highest criteria for bolometers.

The goal of developing detectors is to attain a level noise equivalent power (NEP) of 10^{-20} W Hz$^{-1/2}$ in the 40 – 500 μm wavelength range for an array of 100×100 detectors equipped with low-dissipation read-out electronics [2 – 4]. There is not a single technology that can meet such criteria. To satisfy the necessary requirement, a technological breakthrough is needed. Analysis shows that the proposed concept of an ultimate cold-electron bolometer with strong electrothermal feedback (Fig. 2) has a real chance of becoming the leading concept in such development [5 – 9].

3. Comparison of CEBs and TESs

The introduction of TESs with strong electrothermal feedback was a big step in the development of superconducting detectors [10]. However, with TESs there is the problem of excessive noise, saturation, and artificial heating by the bias power for feedback. Artificial heating wipes out all attempts at deep cooling and provides no potential for implementing the limiting parameters of bolometers. Moreover, this heating places a limit on the saturation power and markedly narrows the dynamic range.

In contrast to artificial overheating, an entirely new concept of a cold-electron bolometer with direct electron cooling of the absorber was proposed in Refs [5, 6]. The CEB is the only active concept that allows removing background power from the absorber. There is no additional thermal overheating (the main problem of TESs) in CEBs

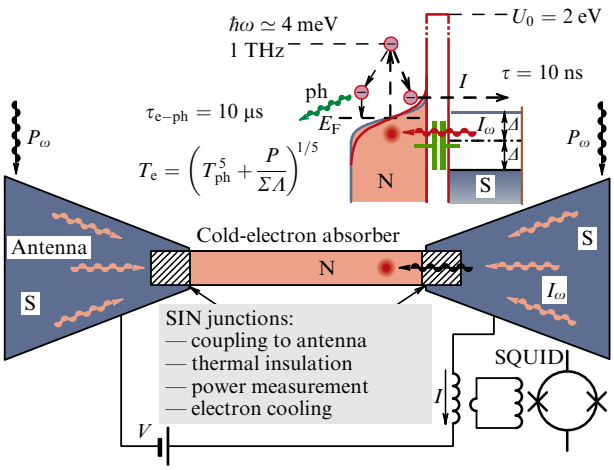

Figure 2. A CEB capacitively coupled to the antenna via superconductor – insulator – normal metal (SIN) tunnel junctions used for direct electron cooling and power measurements. The signal power is applied to the sensor via the capacitance of the tunneling junctions, dissipates in the absorber heating the cold electrons, and is released by the absorber by hot electrons through the same SIN tunnel junctions. Electron cooling serves as a strong negative electrothermal feedback, which improves all the CEB characteristics (time constant, response, and NEP).

and there is direct electron cooling of the absorber. This constitutes an essentially new approach to building modern supersensitive detectors. Direct electron cooling may prove to be especially important in implementing the system in the presence of a real thermal background load. Cooling helps avoid complete saturation of the detector, when the signal power is as high as the direct-current bias power, which constitutes a complex problem for TESs. The wide dynamical range of CEBs can be realized if a read-out system based on superconducting interferometers (SQUIDS) is used. In this case, the entire signal power lands in the read-out system, which has a wide dynamic range. The possible objection that electron tunneling enhances shot noise can be countered by the simple argument that if power is not removed by a tunnel junction, the same level of shot noise is generated by phonons due to the increase in the intensity of the electron – phonon interaction.

The operation of CEBs can be analyzed by using the heat balance equation [11, 12]

$$P_{\rm cool}(V, T_{\rm e}, T_{\rm ph}) + \Sigma\Lambda(T_{\rm e}^5 - T_{\rm ph}^5) + C_\Lambda \frac{{\rm d}T}{{\rm d}t} = P_0 + \delta P(t)\,. \tag{1}$$

Here, $\Sigma\Lambda(T_{\rm e}^5 - T_{\rm ph}^5)$ is the heat flux from electrons to phonons in a normal metal, Σ is a constant characteristic of the material, Λ is the absorber volume, $T_{\rm e}$ and $T_{\rm ph}$ are the electron and phonon temperatures of the absorber, $P_{\rm cool}(V, T_{\rm e}, T_{\rm ph})$ is the SIN-junction cooling power, $C_\Lambda = \gamma T_{\rm e}$ is the specific heat of the normal metal, and $P(t)$ is the input microwave signal power.

Equation (1) can be 'divided' into the temperature-independent part

$$\Sigma\Lambda(T_{\rm e0}^5 - T_{\rm ph}^5) + P_{\rm cool\,0}(V, T_{\rm e0}, T_{\rm ph}) = P_0$$

and the temperature-dependent part

$$\left(\frac{\partial P_{\rm cool}}{\partial T} + 5\Sigma\Lambda T_{\rm e}^4 + {\rm i}\omega C_\Lambda\right)\delta T = \delta P\,. \tag{2}$$

The first term, $G_{\rm cool} = \partial P_{\rm cool}/\partial T$, on the left-hand side of Eqn (2) represents the heat conductance of cooling by SIN junctions, which yields negative electrothermal feedback (ETF); when ETF is large, the temperature response δT decreases, because the cooling power balances the variations in the signal power in the bolometer. The second term, $G_{\rm e-ph} = 5\Sigma\Lambda T_{\rm e}^4$, represents the electron–phonon conductance of the absorber. Equation (2) can be used to find the effective complex temperature response of a CEB to the input signal power:

$$G_{\rm eff} = G_{\rm cool} + G_{\rm e-ph} + {\rm i}\omega C_\Lambda\,. \tag{3}$$

By analogy with the operation of TESs [10], the effective CEB conductance increases due to the electron cooling effect (negative ETF). The current response can be written as

$$S_i = \frac{\partial I}{\partial P} = \frac{\partial I/\partial T}{G_{\rm cool} + G_{\rm e-ph} + {\rm i}\omega C_\Lambda} = \frac{\partial I/\partial T}{G_{\rm cool}}\,\frac{L}{(L+1)[1+{\rm i}\omega\tau]}\,, \tag{4}$$

where $L = G_{\rm cool}/G_{\rm e-ph} \gg 1$ is the ETF coefficient and

$$\tau = \frac{C_\Lambda}{G_{\rm e-ph} + G_{\rm cool}} = \frac{\tau_0}{L+1} \tag{5}$$

is the effective time constant, with $\tau_0 = C_\Lambda/G_{\rm e-ph}$ (about 10 μs at $T = 100$ mK).

The operation principles of CEBs and TESs in the voltage-biased mode are compared in Figs 3 and 4 (a detailed description can be found in Ref. [13]). TESs (see Fig. 3) are heated by the bias voltage up to the superconducting transition temperature $T_{\rm c}$ by the power $P_{\rm bias}$. This temperature is sustained in the entire dynamic range of the bolometer (up to saturation) by ETF. The CEB operational principles

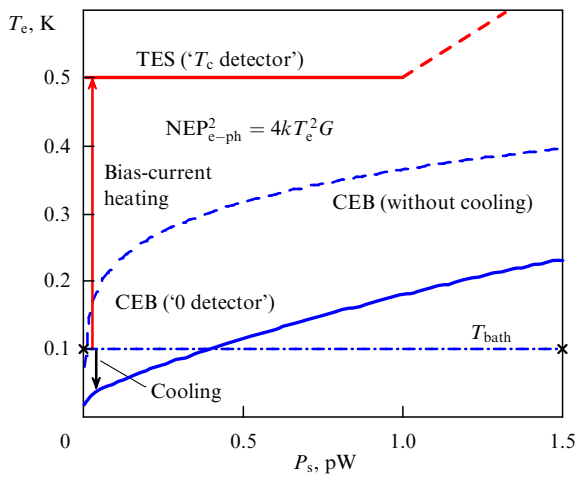

Figure 3. Electron temperature as a function of the signal power $P_{\rm s}$ at $T_{\rm bath} = 100$ mK for CEBs and TESs. For CEBs, $T_{\rm e}$ is always reduced to the minimum possible value. At $P_{\rm s} < 0.4$ pW, $T_{\rm e}$ for CEBs is lower than $T_{\rm bath}$ (actually, a CEB). For TESs, $T_{\rm e}$ is equal to $T_{\rm c}$ in the entire power range up to the saturation power. After saturation sets in, there is an uncontrollable rise in temperature and the bolometer ceases to operate.

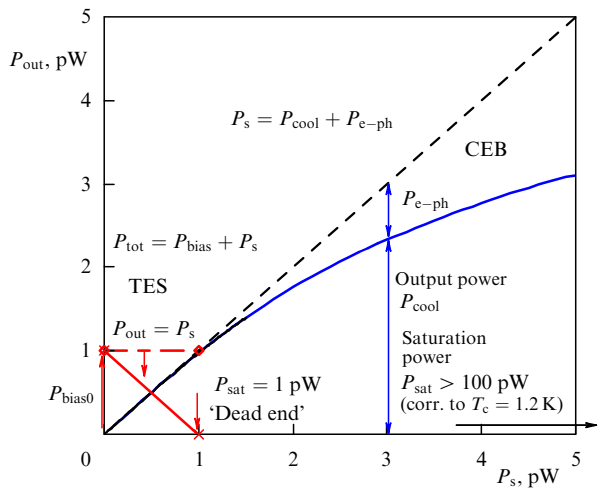

Figure 4. Output powers of CEBs ($P_{\rm cool}$) and TESs ($-\delta P_{\rm bias}$) as functions of the signal power. These powers are practically equal for a CEB at low signal power. At higher signal powers $P_{\rm s}$, the power is distributed between $P_{\rm cool}$ and $P_{\rm e-ph}$. Total saturation occurs only when the temperature rises to the critical temperature of the aluminum electrodes ($P_{\rm sat}$ is in the vicinity of 100 pW). The output TES power is equal to the reduction in bias power, which is proportional to the input signal power. The saturation power is equal to the initial bias power with total unresponsiveness to signals after this level is surpassed.

are similar, with one important difference: the operating point moves to zero temperature. Beginning with the base phonon temperature $T_{\rm ph} = 100$ mK, the cooling conductivity $G_{\rm cool}$ drives the electron temperature down to the minimum possible value. The dependence of the output power $P_{\rm out}$ on the signal power $P_{\rm s}$ is shown in Fig. 4. For both concepts, $P_{\rm out}$ is approximately equal to the input power in the heating-power range for TESs and at typical cooling powers for CEBs. The accuracy of power rejection in CEBs or compensation in TESs is determined by the strength of ETF, known as the feedback loop gain L. For TESs, L can be found from the nonlinear temperature dependence $R(T)$ and may be as high as 1000. For CEBs, L is determined by the ratio of thermal conductivities [see Eqn (4)]. The saturation problem is very important for TESs: the saturation power $P_{\rm sat}$ is exactly equal to the applied power of heating by dc bias voltage, $P_{\rm bias}$ (see Fig. 4).

When saturation power is attained, the TES ceases to react to any input signal. Because it is impossible to predict the assumed level of maximum heat load beforehand, the choice of $P_{\rm sat}$ becomes a truly complicated problem.

The situation with CEBs is entirely different: the output cooling power simply deviates from the linear dependence $P_{\rm cool}(P_{\rm s})$. For a typical cooling power in the vicinity of 1 pW, the deviation from the linear dependence $P_{\rm out}(P_{\rm s})$ amounts to a few percent of this level (see Fig. 4). As the signal power grows, the deviation increases, but the CEB continues to operate, and the only problem is to calibrate this dependence. The final saturation of the CEB occurs at the input power about 100 pW, when the temperature reaches its critical value for aluminum electrodes.

4. Limiting noise characteristics of CEBs. The general limiting noise formula

The noise properties of bolometers are characterized by the noise equivalent power, or NEP, which is the sum of three

different contributions, as defined in Refs [11, 12]:

$$\mathrm{NEP}^2_{\mathrm{tot}} = \mathrm{NEP}^2_{\mathrm{e-ph}} + \mathrm{NEP}^2_{\mathrm{SIN}} + \frac{\delta I^2}{S_I^2}\,,$$
$$\mathrm{NEP}^2_{\mathrm{e-ph}} = 10 k_{\mathrm{B}} \Sigma \Lambda (T_{\mathrm{e}}^6 + T_{\mathrm{ph}}^6)\,. \tag{6}$$

Here, $\mathrm{NEP}^2_{\mathrm{SIN}}$ is the noise generated by the tunneling SIN junctions and the term $\delta I^2/S_I^2$ appears because of the output noise generated by the SQUID amplifier, δI. The noise generated by the SIN junctions has three components, namely, the shot noise $2eI/S_I^2$, fluctuations of the heat flux through the tunneling junction, and the correlation component linking these two processes [11, 12]:

$$\mathrm{NEP}^2_{\mathrm{SIN}} = \frac{\delta I_\omega^2}{S_I^2} - 2\,\frac{\langle \delta P_\omega\, \delta I_\omega \rangle}{S_I} + \delta P_\omega^2\,. \tag{7}$$

The correlation component can be used, in principle at least, to reduce shot noise by 30 – 70%. Correlation also reduces thermal noise in TESs.

The question of limiting noise characteristics emerges in view of the very strict requirements on NEP for future NASA and ESA projects [2 – 4] and is formulated as follows: How realistic is the requirement that $\mathrm{NEP} = 10^{-20}$ W $\mathrm{Hz}^{-1/2}$? Ultimate performance of CEBs was analyzed in Ref. [13]. Photon noise is not included in this analysis, because it can be considered an external noise of the signal, which is the same for all types of receivers. The NEP value is determined by the shot noise of the background load. Here, the shot noise is considered in a general form, including the electron – phonon shot noise generated by phonon emission. Other sources of noise are ignored in view of their weakness. For the power level $P_0 = 10$ fW, this limit is reached at low temperatures (~ 100 mK) and small absorber volumes ($\Lambda \leqslant 0.003$ $\mu\mathrm{m}^3$), when the electron – phonon noise component can be discarded.

We can derive a general limiting NEP formula with only shot noise taken into account [13],

$$\mathrm{NEP}_{\mathrm{shot}} = (2 P_0 E_{\mathrm{quant}})^{1/2}\,, \tag{8}$$

where E_{quant} is the power quantization energy and P_0 is the applied power; $E_{\mathrm{quant}} = k_{\mathrm{B}} T_{\mathrm{e}}$ for a normal-metal absorber and $E_{\mathrm{quant}} = \Delta$ for a superconducting absorber.

Estimates of the limiting NEP for the main types of superconducting bolometers (including a kinetic inductance detector, or KID) were made in the case of a relatively low background load $P_0 = 10$ fW; the results are listed in Table 1.

Table 1.

Bolometer type	Quantization energy, μeV	Characteristic absorber parameter, mK	$\mathrm{NEP}_{\mathrm{shot}}$, 10^{-19} W $\mathrm{Hz}^{-1/2}$
CEB	$k_{\mathrm{B}} T_{\mathrm{e}} = 9$	$T_{\mathrm{e}} = 50$	1
TES	$\Delta = 73$	$T_{\mathrm{c}} = 500$	4
KID [11, 12]	$\Delta = 200$	$T_{\mathrm{c}} = 1200$ (Al)	7

The smallest NEP is attained in a CEB with the lowest quantization level. But even these limiting parameters P_0 and E_{quant} show that the realization of $\mathrm{NEP} = 10^{-20}$ W $\mathrm{Hz}^{-1/2}$ required by NASA for future space flights [2 – 4] appears to be unrealistic.

Systems of two types can be distinguished.

1. Systems with thermal conductivity that is a linear function of temperature:

• spider-web TESs with thermal conduction along the wires;

• CEBs with SIN-junction cooling (a weak temperature dependence: $G \sim T^{1/2}$).

The limiting shot noise in this case is described by general formula (8) with the numerical factor equal to 2.

2. Systems with prevailing electron – phonon conduction (strong nonlinearity in temperature: $G_{\mathrm{e-ph}} \sim T^4$):

• all bolometers on a thick substrate with electron – phonon conductance;

• antenna-coupled TESs with Andreev mirrors: a receiver whose operation is based on electron heating in a normal metal with Andreev mirrors.

Due to the strong nonlinearity of the electron – phonon coupling, the limiting shot noise is described by a modified equation with the numerical factor increased to 10:

$$\mathrm{NEP}_{\mathrm{shot-e-ph}} = (10 P_0 E_{\mathrm{quant}})^{1/2}\,. \tag{9}$$

This means that if the system is left to relax via the electron – phonon coupling, the shot noise intensity increases due to the strong nonlinearity of the electron – phonon thermal conduction, in contrast to linear systems with a weak temperature dependence (or even with no temperature dependence). Formulas (8) and (9) can be effectively used to estimate the limiting parameters of CEBs and other bolometers for given parameters of the detection system.

5. Time constant

The dependence of the CEB time constant on the arriving power (5) is shown in Fig. 5. As for TESs, it is substantially reduced by the gain of the ETF loop L (5). The thermal conductivity of the cooling channel, G_{cool}, depends only weakly on the arriving power and only slightly grows at small powers (τ_{cool} decreases). In contrast, the electron – phonon conductivity $G_{\mathrm{e-ph}}$ strongly depends on power, because it is proportional to T_{e}^4, and rapidly decreases at small powers (the corresponding value of $\tau_{\mathrm{e-ph}}$ grows). As a

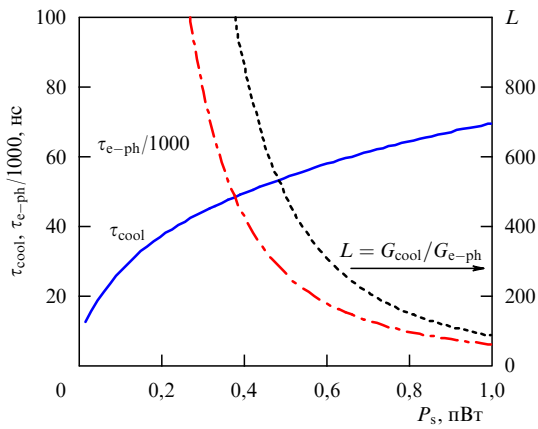

Figure 5. The CEB time constant τ_{cool} as a function of the signal power P_{s}. The electron – phonon time constant $\tau_{\mathrm{e-ph}}$ is shown for comparison (it is diminished by a factor of 1000). The time constant τ_{cool} is much smaller than $\tau_{\mathrm{e-ph}}$, and this difference grows as the signal power decreases and the intensity of electron cooling grows. The gain of the feedback loop L of negative ETF is shown by the dashed curve. This amplification increases at small values of P_{s} due to the decrease in $G_{\mathrm{e-ph}}$.

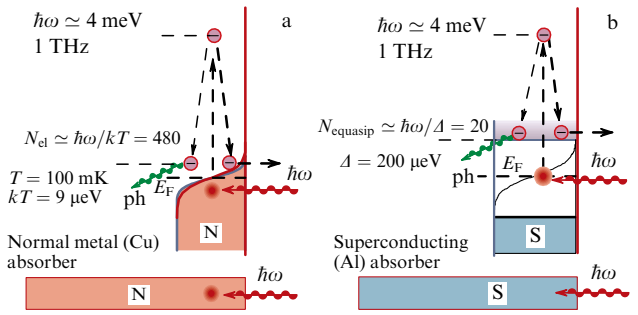

Figure 6. Quantum efficiency of metallic (a) and superconducting (b) absorbers. An electron is excited by photon absorption to the same energy (4 meV for the signal frequency 1 THz) in both absorbers. The electron then relaxes via the electron–electron interaction and the energy is distributed between the hot electrons at the quantization level $E_{\rm quant} = kT$ for the normal metal (a) and between quasiparticles at the quantization level $E_{\rm quant} = \Delta$ for the superconductor (b). Quantum efficiency amounts to 480 for the normal metal and 20 for the superconductor.

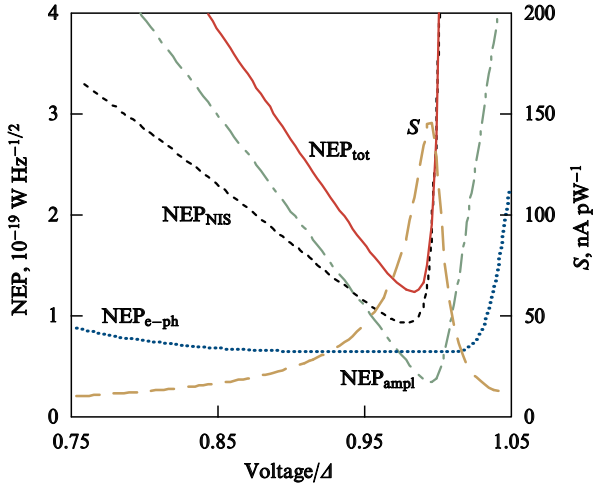

Figure 7. NEP of an optimal bolometer in the presence of 0.01 pW background power at $\Lambda = 0.01$ μm^3, $R = 1$ kΩ, $S_{\rm SQUID} = 5$ fA Hz$^{-1/2}$, and a physical temperature of 100 mK.

result, L noticeably grows at small powers and exceeds 1000.

Interestingly, the CEB time constant in the current setting mode grows in comparison to the internal electron–phonon time constant [11], and the reason is the decrease in the total thermal conductivity of the bolometer due to the negative response of the junction in voltage (positive ETF).

6. Quantum efficiency

Limiting shot-noise formulas (8) and (9) place limits on NEP that depend on two parameters, the background power P_0 and the quantization energy $E_{\rm quant}$. The dependence on P_0 is obvious: the higher the applied power, the stronger the noise in the sensitive element in any variant of the receiver. Usually, we are unable to significantly vary this parameter, and hence external parameters determine the implementation of this dependence. The second parameter $E_{\rm quant}$ proves to be more important in implementing minimal NEP. This energy level characterizes the quantum efficiency of the bolometer (Fig. 6). The excitation of an electron by a photon with a typical frequency of 1 THz to the energy level of 4 meV after the photon has been absorbed is the same for all concepts. After that, energy relaxation occurs caused by the electron–electron interaction, which lowers the energy to different levels.

For CEBs, the energy is distributed among electrons at the level $kT = 9$ μeV (Fig. 6a). This yields the quantum efficiency after absorption of one photon of $N = 480$ electrons per photon at the temperature 100 mK. For TESs and KIDs, energy relaxation stops at the energy gap (Fig. 6b), which yields the following quantum efficiencies: $N = 96$ for TESs (where $\Delta = 45$ μeV) and $N = 20$ for KIDs (where $\Delta = 200$ μeV). Hence, the introduction of a superconducting absorber substantially reduces quantum efficiency, which leads to a higher level of shot noise and requires a read-out circuit with a higher sensitivity.

7. Optimization of CEB operation

Our analysis of the effect of a thermal background load on the noise properties in different CEB configurations has shown that a bolometer with a voltage setting across the SIN junctions and a current read-out by SQUIDs is the optimal one [12]. To analyze the limiting characteristics, we adopt the following typical values: the absorber volume is 0.01 μm^3 (which is a realistic figure for modern technology), the SQUID current noise is 5 fA Hz$^{-1/2}$ [12], and the junction resistance is 1 kΩ. The results are shown in Fig. 7 for the background level $P_0 = 0.01$ pW. This value is sufficiently low and has been adopted for the analysis of the bolometer's limiting characteristics. The total NEP $= 1.2 \times 10^{-19}$ W Hz$^{-1/2}$ is determined mainly by the shot noise from the SIN junctions due to the arriving power. The electron–phonon component and the amplifier noise are below the noise produced by the SIN junctions, which corresponds to the limit set by the background. The response $S = {\rm d}I/{\rm d}P$ reaches its maximum value 150 nA pW^{-1} and is determined mainly by the absorber's electron temperature (the quantization energy) and, in the final analysis, by the CEB quantum efficiency. For comparison, similar values $S = 200$ nA pW^{-1} can be obtained for TESs in the case of a fairly small bias voltage $V_{\rm bias} = 5$ μV.

We also analyzed the concept of an optimal CEB for the temperature 300 mK in the presence of background power ($P_0 = 0.1$ pW) and the same SQUID parameters [12]. The optimal operational mode can be implemented when the thermal 'cooling conduction' through the tunneling junctions exceeds the fundamental electron–phonon conductance. In these conditions, NEP equal to 10^{-18} W Hz$^{-1/2}$ at 300 mK can be attained in the presence of $P_0 = 0.1$ pW for typical values of junction resistances near $R = 1$ kΩ, $S_{\rm SQUID} = 10$ fA Hz$^{-1/2}$, and the absorber volume $\Lambda = 0.005$ μm^3. Such an absorber volume is very close to the technological limit.

An experimental test for a CEB in the current-biased mode has been conducted by Agulo et al. [8]. The minimum NEP values are below 10^{-18} W Hz$^{-1/2}$ at read-out frequencies higher than 100 Hz (Fig. 8). The high-frequency response of the bolometer has been recorded up to 1.8 THz in a system with a high-temperature Josephson junction [14].

8. Planned international projects

1. NASA has been developing an ambitious project of a space IR interference telescope, SPIRIT, and a submillimeter probe for estimating the structure of the Universe,

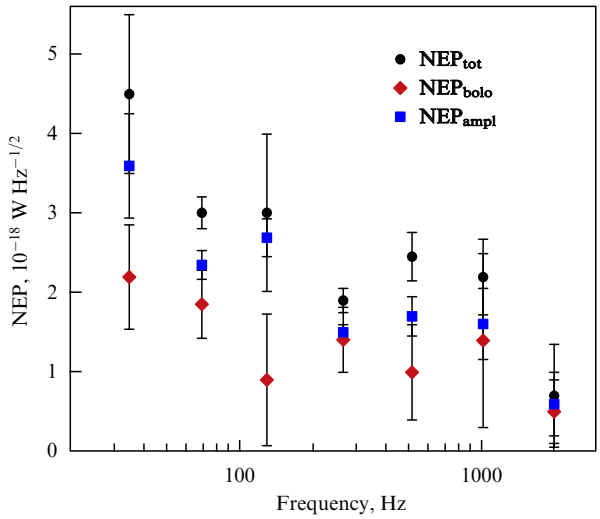

Figure 8. NEP of an optimal bolometer in the presence of 0.01 pW background power at $\Lambda = 0.03\ \mu m^3$, $R = 14\ k\Omega$, and a physical temperature of 100 mK [8].

SPECS. The requirements imposed on bolometric receivers are extremely high in these projects. The goal for developing detectors is to approach the power level equivalent to NEP $< 10^{-20}$ W Hz$^{-1/2}$ in the 40 – 500 μm wavelength range for an array of 100×100 detectors equipped with low-dissipation read-out electronics. At present, there is no technology that satisfies such requirements. A CEB presents a chance to achieve such high demands.

2. The European Space Agency has organized a consortium 'Development of Superconducting Ultra-sensitive Sensors' (the coordinator is Ravinder Bhatia, Ravinder.Bhatia@esa.int). A group of Russian scientists in collaboration with scientists from Chalmers University of Technology was invited to this consortium to develop the concept of an ultimate CEB. At first, in 2003, the TES, KID, and CEB concepts had equal status. In 2004, the TES concept was excluded from the ESA list of priorities, and today the CEB concept has been adopted as one of the two leading concepts for future balloon and outer space projects. We believe that this is an acknowledgment of the big success of international cooperation in which the strongest groups of scientists from Russia participate. If this concept also finds support in Russia, the CEB concept has all the chances of becoming a leading candidate for European programs. The financial support of RAS will help transfer the technology developed by Russian scientists to Russian scientific institutions.

3. At present, the developers of the CEB concept have been invited to participate in the OLIMPO balloon experiments carried out by the group of scientists of the BOOMERANG project (the coordinators are Cardiff University, Philip.Mauskopf@astro.cf.ac.uk, and the University of Rome, and the participants are Cambridge University, the Netherlands Space Research Organization, the VTT Co. (Finland), and a number of US and Italian universities). If this project is successful, new prospects for introducing the developed bolometers into other projects will open.

4. The CEB developers have also been invited to participate in the European PILOT balloon project (http://www.cesr.fr/%7Ebernard/ELISA/) and to build a multichannel system with a CEB array (the coordinator is CESR, Toulouse, France, Martin.Giard@cesr.fr). A read-out system with high electron mobility transistors and a multiplexor with frequency separation of channels will be built at IPHT (Jena, Germany) with the participation of Russian scientists. We believe that active participation of RAS institutes is very promising.

5. The CEB developers have been invited to participate in the European Space Project 'Far IR Proto-Galaxy Imager: Interferometer' under the auspices of the 'European Space Programme Cosmic Vision 2015 – 2025' [3]. It is in the interest of Russian science not to miss this opportunity. The active participation of RAS will substantially strengthen our position in this European project.

6. The international project SUBMILLIMETRON (http://www.asc.rssi.ru/submillimetron/submill.htm, http://fy.chalmers.se/~kuzmin/Projects/Platform.html), headed by the Astro Space Center (ASC) of the Lebedev Physics Institute of RAS (FIAN) and the 'Energy' Corporation, presupposes the building of a space scientific platform with a cryogenic telescope and an array of superconducting detectors.

7. Two joint projects of Chalmers Technical University and ASC FIAN have been submitted to the Swedish National Space Bureau, 'Submillimeter Space Telescope for Photometric Sky Survey (http://fy.chalmers.se/~f4argo/Submillimetron/SubmmSNSB.htm) and 'Imaging Arrays of Superconducting Detectors' (http://fy.chalmers.se/~kuzmin/Projects/SUPERIMAGE.html).

8. ASC FIAN has received an invitation to participate in a suborbital program of NASA and to propose a balloon experiment. Such a balloon will fly over the territory of Russia, and clearance may be obtained on the condition that Russian hardware be installed on board. A possible variant is a system similar to the OLIMPO radio telescope, which is being built by international collaboration.

9. The ground-based telescope SAO RT-70 can be equipped with a highly sensitive bolometric receiver. This could become a good demonstration of the performance of the receiver in conditions of a real telescope.

9. Concluding remarks

Summarizing, I would like to propose taking the following steps so as to participate in programs that study dark matter and dark energy.

1. Obtain the approval of this program from the Physical Sciences Division of RAS.

2. Actively participate in the development of a *new generation of cold-electron bolometers* with JFET/SQUID read-out systems for the *international balloon project OLIMPO*.

3. Actively participate in building a receiver system for the *international balloon project PILOT* (http://www.cesr.fr/%7Ebernard/ELISA/).

4. Participate in *the European-led consortium 'Development of Superconducting Ultra-sensitive Sensors'*, in the *'European Space Programme Cosmic Vision 2015 – 2025'* (http://sci.esa.int/science-e/www/object/index.cfm?fobjectid = 35858), and in *the European Space Project 'Far IR Proto-Galaxy Imager: Interferometer'*.

5. Participate in *the NASA-led balloon project* with the use of devices to be developed in items 3 and 4.

6. Build a submillimeter cryogenic receiver system with CEBs for the ground-based telescope RT-70.

7. Develop a cryogenic space telescope within the SUBMILLIMETRON project on the basis of broad interna-

tional cooperation and receivers designed for balloon projects (http://www.asc.rssi.ru/submillimetron/submill.htm).

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PACS numbers: 21.10.Re, 23.20.Lv, 23.20.Nx, 25.20.Dc, **27.70.+q**
DOI: 10.1070/PU2005v048n05ABEH002190

Induced decay of the nuclear isomer ^{178m2}Hf and the 'isomeric bomb'

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1. Introduction

Recently, there have been reports in the mass media about plans to build what became known as an 'isomeric bomb' based on ^{178}Hf [1]. What all the publications are speaking about is no less than the possibility of building a radically new weapon that does not fall under a single article of the existing nonproliferation treaties. The publications were based on the sensational results on induced decay of the long-lived isomer ^{178m2}Hf(16^+, 2446 keV, 31 yr) [2–10], obtained in 1999–2004 by a group of researchers headed by Carl B Collins, the Director of the Center for Quantum Electronics, University of Texas at Dallas. Despite the five-year history of the issue, so far there have been no scientific publications on this topic in Russia. The present report is an attempt to fill this gap.

A substance with stored energy and a physical process that ensures the rapid liberation of this energy are two components of any explosive device. In the case of a 'hafnium' bomb, the energy is stored in a metastable state and amounts to 2.446 MeV per nucleus, or 1.3 GJ per gram of substance. In the opinion of Pentagon experts [11], "such extraordinary energy density has the potential to revolutionize all aspects of warfare." The only question is how to ensure the controllable decay of ^{178m2}Hf.

A simple way of accelerating the decay of the isomer was developed in the experiments of the Texas Collaboration [2, 3]. A target containing ^{178m2}Hf was subjected to the radiation

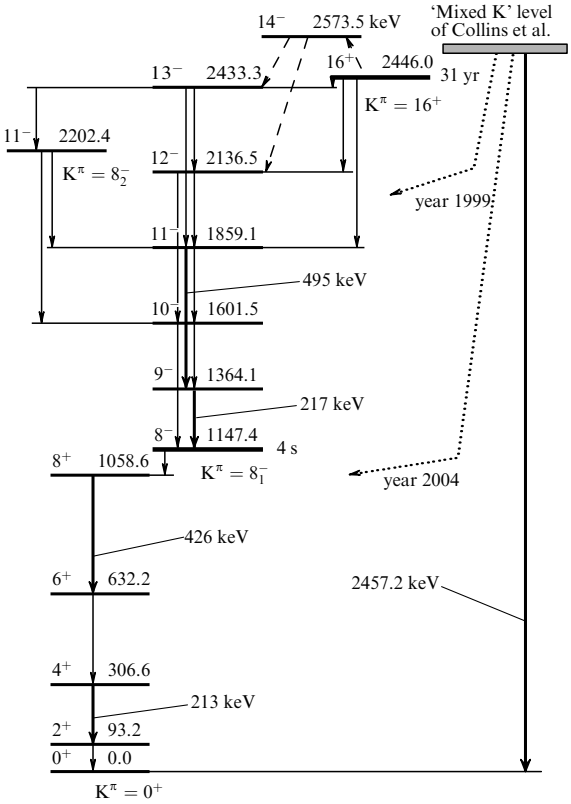

Figure 1. Decay of ^{178m2}Hf according to the data in Refs [12, 13]. Depicted are transitions in the spectrum of ^{178}Hf in which, according to Refs [2, 3, 7], an increase in the gamma-radiation intensity exceeding the measurement errors and the 2457.2 keV line discovered by Collins et al. [10] were detected. The dotted lines show the evolution of the Texas Collaboration ideas in Refs [2–10] concerning the decay of intermediate 'mixed K' states from Ref. [2] published in 1999 to Ref. [10] published in 2004. The dashed lines show the scheme of the possible experiment in the induced decay of the isomer through the 14^-(2573.5 keV) level (see Section 4 of the present paper).

emitted by a dental X-ray unit. The upper edge of the photon spectrum in the experiment described in Ref. [2] was 70 keV in one set of measurements and 90 keV in another. In the first case, no statistically significant increase in the intensity of gamma transitions was recorded, but in the second case, a 6% increase in the intensity of the 495 keV gamma line and a 2% increase in the intensity of the 426 keV gamma line were recorded in the decay spectrum of the isomer ^{178m2}Hf (Fig. 1). In the experiment described in Ref. [3], the electron bremsstrahlung spectrum was cut off at 63 keV, and a 1.6% increase in the intensity of the 213 keV gamma line was recorded.

The experiments described in Refs [7, 10] were conducted with the synchrotron radiation beam on the SPring-8 accelerator (Japan). In the first experiment (see Ref. [7]), the photon energies were varied from 9 to 13 keV. As the photoionization threshold for the L_{III}-shell of the hafnium atom was reached, a 1% increase in the total intensity of the 213 keV and 217 keV gamma lines was recorded. As the photoionization threshold for the L_I-shell of the hafnium atom was reached, the increase in the intensity of the 213 keV gamma line amounted to 3%. In the second experiment (see Ref. [10]), all photons with energies higher than 100 keV were recorded. When the energy of the synchrotron radiation reached 9567 eV, then, first, the overall count of such photons was found to increase by 3.6 to 5% and, second, a

[1] Accepted at the European Science Community Meeting, Paris, 15 October 2004.