LOW-TEMPERATURE CALORIMETRY FOR RARE DECAYS

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ABSTRACT

The recent developments in underground low-counting experiments give limits to rare decays, which are hard to improve since scaling the size and the resolution of the combined source-detector is difficult with the existing techniques. We explore here the possibility of low-temperature calorimetry to improve the limits on processes such as neutrinoless double-beta decay and electron decay.

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1. INTRODUCTION

Detection of very low activities has become of considerable interest in nuclear and subnuclear physics. Recent examples are searches carried out with "passive" detectors, such as those on double-beta decay and electron stability.

Double-beta decay involves [1-4] a triplet of isotopes (A,Z), (A,Z+1) and (A,Z+2), where single-beta decay to (A,Z+1) is either energetically forbidden or at least strongly inhibited by a large change of the parity-spin states. In principle, two decays could occur:

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e \, ,$$

$$(A,Z) \rightarrow (A,Z+2) + 2e^- \, ,$$

where in the latter, the lepton non-conserving case, the two electrons would share the total transition energy. This channel would be favoured, if allowed, with respect to the lepton conserving one by a large factor due to the much larger available phase space. Double-beta decay represents, therefore, a very powerful tool to search for lepton number non-conservation.

Theory and recent experimental results [5] indicate for neutrinoless double-beta decay very large half lifetimes (of 10^{22} years or more). As a consequence, these experiments have to be carried out in a low radioactivity environment with detectors of good energy resolution. A much better efficiency can be reached if the detector itself can be used also as a source of double-beta decay [6]. This has restricted the choice so far to GeLi detectors (two experiments have been carried out recently [7,8] and others are planned [5]), and to xenon time projection chambers (TPCs) [9-12], since ^{76}Ge and ^{136}Xe are good double-beta decay candidates. It would be of obvious interest to extend the "passive" detector techniques to other double-beta active materials, and also to increase the mass and possibly the resolution of the above-mentioned detectors.

Similar considerations apply to the problem of electron stability, which has also been investigated with passive detectors [13-16]. A method consists in the search for the disappearance of a K-shell electron of the detector

atom. The corresponding vacancy would be filled by external electrons, and a peak would appear at the binding energy of the K shell. A less general method consists in the search for electron decays in the specific channel

$e^- \rightarrow \nu_e + \gamma$.

The possibility of using low-temperature detectors in subnuclear physics has already been suggested [17-19] and is by no means restricted to the above-mentioned problems. We will only discuss them because of their intrinsic physical interest and because it seems difficult to improve considerably their present experimental status with existing techniques.

2. THE PRINCIPLE OF LOW-TEMPERATURE CALORIMETRY FOR PARTICLE DETECTION

In order to detect the energy lost by a particle, in the final form of heat, one has to use detector materials of low specific heat. Most of the energy deposited by ionizing radiation appears in the form of heat within a delay only due to atomic transitions. A minor part (a few per cent at most) is stored as lattice faults: dislocations, F-centres, interstitials, and various types of stacking faults, or as chemical energy in compound crystals.

An event which is totally contained in a low-temperature calorimeter should therefore deposit in less than 10^{-8}s an amount of heat corresponding to the energy of transition less a few per cent due to chemically stored energy. The variation in the deposited heat would be equal to the variation in this stored energy, which we (optimistically) believe to depend on the statistical variation in the number of each kind of fault produced. Channelling effects, in principle, could cause systematic variation superimposed on the statistical one.

The following main contributions to the specific heat must be considered in the choice of the detector material:

i) The lattice specific heat

$$c_L = \beta \ (T/\Theta_D)^3 \ , \tag{1}$$

where β = 1944 J/(mole K) and Θ_D is the Debye temperature characteristic of the crystalline substance, arises from the lattice vibrations called phonons. The low-temperature phonons propagate at the speed of sound v_s and scatter from crystal faults (impurities, defects, boundaries), against each other and against other types of excitations, such as conduction electrons, magnons, and so on. This scattering causes the phonon system to come to an internal thermal equilibrium. In a pure faultless single crystal of a dielectric diamagnetic substance the boundary scattering dominates at low temperatures; the phonon thermalization time constant then depends on the characteristic dimension L of the crystal and on the speed of sound:

$$\tau \simeq L \, v_s^{-1} \, . \qquad (2)$$

ii) The conduction electron specific heat

$$c_e \sim T \qquad (3)$$

dominates the lattice specific heat below ~10 K in metals. In a super-conducting state the pair correlations of the electrons make this contribution vanish exponentially:

$$c_{e,sc} \sim e^{-2\Delta/kT} \, , \qquad (4)$$

where $\Delta \simeq kT_c$ is the binding energy of the pairs. This energy is of the order of 10^{-3} eV in common superconductors; the energetic phonons created by ionizing radiation can thus break pairs in the superconducting state and cause some additional delay in the establishment of the thermal equilibrium in the phonon system.

Another problem in superconducting materials is that a perfect Meissner state (perfect diamagnetism) is hard to achieve owing to field vortex nucleation (flux-line trapping). These tiny flux-line filaments feature large specific heat characteristic of normal metal.

iii) The electron magnetism gives rise to very large specific heat at low temperatures. In dilute paramagnets the Curie law leads to the specific heat

$$c \sim T^{-2} \, . \qquad (5)$$

The related magnetization could be used for measuring the equilibrium phonon temperature, if the spin-lattice relaxation could be made fast enough. Such a detector for double-beta decay has been proposed by Mitsel'makher, Neganov and Trofimov [19].

The detailed analysis of the Curie-law paramagnetic thermometer, read by a superconducting flux-transformer and amplified by the best available DC-SQUID [20], leads to a calorimetric sensitivity several orders of magnitude below what can be achieved with resistance thermometry. The main problem lies in the coupling of the magnetic energy to the SQUID input while maintaining a reasonable bandwidth and impedance match.

In compounds of paramagnetic ions the high electron spin concentration leads to a very large specific heat due to spin-spin interactions, and ultimately results in a magnetic phase transition. These materials are not suitable for ultralow-temperature calorimetry.

iv) Nuclear magnetism and hyperfine interactions lead to large specific heats, giving rise to Curie-law magnetization and specific heat, or featuring a Schottky anomaly in the specific heat at low temperatures. Fortunately, the nuclear spin-lattice relaxation times are always so long that the fast variation of the phonon system temperature is practically not at all attenuated by nuclear magnetism. However, in the case of hyperfine anomalies, the slow nuclear spin-lattice relaxation may cause a nearly permanent heat leak, preventing the attainment of a low lattice temperature in a reasonable time.

v) Nuclear quadrupole interactions in a non-cubic crystal result in a large specific heat, but the quadrupole energy relaxes slowly allowing the phonon system to respond fast to heat pulses, as in the above case of nuclear magnetism.

vi) The specific heat due to the rotational and vibrational degrees of freedom in glasses and solids with large molecules excludes their use in our application.

vii) Low-lying excitations of impurity levels, and molecular spin conversions may make it impossible to reach a low specific heat in some solids.

In a pure and faultless single crystal of a diamagnetic, dielectric material the specific heat becomes unmeasurably low already at a few tenths of a degree Kelvin, using conventional measurement techniques.

The equilibrium time constants of the various heat reservoirs and the thermometer system, between one another, and towards the heat sink, determine the characteristics of the pulse response of the calorimeter to an event. In the following we shall discuss a projected calorimeter consisting of a semiconductor single crystal, a small area of which is doped with a suitable impurity to make a resistance thermometer integrated with the calorimeter. The heat sink would simply consist of a helium bath in which the crystal is submerged. This type of detector was first suggested for the detection of the non-ionizing energy loss of neutrinos by elastic (neutral current) scattering [17].

In a pure semiconductor single crystal the thermalization of the phonon system will occur mainly by scattering from boundaries. The thermalization time constant τ is then given by eq. (2), ignoring all geometric and impurity effects. The rise time of the thermometer temperature will be of the same order of magnitude, because there is no large thermal resistance between a doped area of the semiconductor and the pure bulk material.

The fall time of the phonon temperature is given by the escape probability of the phonons through the crystal boundary to the surrounding helium bath. This probability is small due to the acoustic mismatch of the two media; the resulting thermal surface resistance, or Kapitza resistance, resembles photon heat transfer and can be described by

$$\dot{Q} = \alpha S \ (T^4_{body} - T^4_{helium}) \ , \tag{6}$$

where $\dot{Q}$ is the rate of heat flow, S the surface area, and α a constant.

For small temperature differences one obtains the expression:

$$\dot{Q} = 4\alpha \ ST^3 \Delta T \ , \tag{7}$$

which in the literature is often written in the form

$$\dot{Q} = \Delta T/R_K \quad . \tag{8}$$

Here the Kapitza resistance R_K can be related to the constant α by

$$R_K ST^3 = \text{constant} = 1/4\alpha \tag{9}$$

using eq. (7).

The phonon cooling time constant τ' is generally expressed by

$$\tau' = \Delta T \ [\ \frac{d}{dt} \ (\Delta T)]^{-1}. \tag{10}$$

If the helium temperature remains constant one gets, for small ΔT,

$$\dot{Q} \ dt = C \ dT = C \ d(\Delta T) \ , \tag{11}$$

and from eqs.(8), (9), and (10)

$$\tau' = \frac{\Delta T}{\dot{Q}/C} = CR_K = \frac{C}{4S\alpha T^3} \ , \tag{12}$$

which is independent of T if $C \simeq T^3$ (phonon heat capacity). For large ΔT the initial recovery is faster than eq. (12).

The resistance of a thermometer in a pulse measurement would be obtained by biasing it with constant current and measuring the voltage. This voltage U also causes Joule heating, and rise of the detector temperature by

$$\Delta T = \dot{Q}R_K = \frac{U^2}{R} \ R_K \quad . \tag{13}$$

The energy resolution δE of the calorimeter is given by

$$\delta E = C \ \frac{dT}{dR} \ \frac{\delta U}{U} \ R \ , \tag{14}$$

where dT/dR is the sensitivity of the resistance thermometer. If the voltage fluctuation δU is taken as equal to the noise voltage $e_n (\Delta f)^{1/2}$ of an FET amplifier of bandwidth Δf, one obtains:

$$\delta E = C \frac{dT}{dR} \left[\frac{R_K R}{\Delta T}\right]^{1/2} e_n (\Delta f)^{1/2} . \tag{15}$$

One can simply approximate the bandwidth equal to τ^{-1}, where τ is the time constant for reaching internal thermal equilibrium given approximately by eq. (2), i.e. $\Delta f \simeq v_s/L$. By substituting in eq. (15) this and the expression of the phonon heat capacity given in eq. (1) one has:

$$\delta E \simeq \overbrace{\frac{\beta}{V_m \Theta_D^3}\left[\frac{v_s}{4\alpha}\right]^{1/2}}^{1)} \times \overbrace{\frac{dT}{dR}\left[\frac{R}{\Delta T/T}\right]^{1/2} e_n}^{2)} \times \overbrace{\frac{V}{\sqrt{(SL)}}}^{3)} \times \overbrace{T}^{4)} , \tag{16}$$

where the four terms are grouped to reflect the effects: 1) of the material properties, 2) of the thermometer sensitivity and noise, 3) of the detector size and geometry and 4) of the temperature.

In order to evaluate the expected properties of various thermal detectors we have made the following assumptions:

a) a value $R_K S T^3 = 1400$ cm^2 K^4 W^{-1} as extrapolated for silicon [17];

b) an operating temperature of T = 5 mK;

c) a resistance of 1 MΩ and a thermal sensitivity dT/dR of 2×10^{-9} K/Ω;

d) a permissible heat-up of $\Delta T/T = 0.1$;

e) $e_n \simeq 10^{-9}$ V/$\sqrt{\text{Hz}}$.

We have taken the values of the Debye temperatures from other papers [21-27]. For the velocity of sound we have used, when a measured value was not available [27], a value extrapolated on the basis of its dependence on the Debye temperature and molar volume.

3. EFFECTS OF THE NATURAL BACKGROUND ACTIVITY IN THERMAL EXPERIMENTS

Low activity measurement always requires a strong reduction of the spurious counting rate, which is normally obtained by placing the detector deep underground in order to suppress the contribution coming from cosmic rays, and by shielding it against local radioactivity. Thermal calorimeters require a very low background for two additional reasons: i) the thermal pulse is likely to be much wider than for standard nuclear radiation detectors; ii) an excessive energy loss in the detector due to local activity could prevent it from reaching very low temperatures.

The background counting rate and energy loss in common detectors is roughly proportional to their mass. Their reduction in deep low-background laboratories can be evaluated from the results of the Milan group who were able to obtain recently one of the lowest counting rates in the literature. The counting rate of their detector in the laboratory at sea level, in a normal radioactive environment and without any shield, was found to be 0.54 counts $g^{-1}s^{-1}$ above 8 keV, corresponding to a total energy loss in the detector of 0.173 MeV $g^{-1}s^{-1}$. These figures were reduced to 7×10^{-5} counts $g^{-1}s^{-1}$ and 1.9×10^{-5} MeV $g^{-1}s^{-1}$, respectively, by installing the detector in the Mont Blanc laboratory under a massive shield against local radioactivity. Under these latter conditions the counting rate of the largest thermal detector considered in the present report (a 450 kg molybdenum cube, as discussed later) would be about 30 Hz, and the corresponding energy loss would be 1.3×10^{-12} W. The corresponding time constant to reach thermal equilibrium would be quite tolerable ($\tau' \simeq 16$ ms).

4. CALORIMETRIC DETECTION OF DOUBLE-BETA DECAY

We have chosen, for the present analysis, only those elements which are preferable as a source of double-beta decay for the isotopic abundance, the transition energy and, when available, the nuclear matrix element of the

corresponding active isotope [28]. The performances of various double-beta decay "passive" detectors operated at 5 mK and made of natural elements are reported in table 1. The energy resolution is calculated for a detector of a mass of 1 kg. We have also calculated the mass of a detector so as to achieve an energy resolution of 1 keV, definitely superior to that in the present solid- state detectors. The corresponding sensitivity, obtained in a year of effective running time, is compared with the most recent limit obtained with "classical" detectors.

We should like to add that the sensitivity could be improved at a large cost by using isotopically enriched materials, or by decreasing the temperature of operation. Conversely for some of these elements, especially for superconductors, the presence of impurities could prevent them from reaching a sufficiently low temperature and/or heat capacity.

The use of compounds, and particularly of oxides, of the elements listed in the table could substantially increase the Debye temperature and consequently decrease the heat capacity. For instance, in the case of GeO_2 and SnO_2 these temperatures are expected to be 760 K and 540 K, respectively [26]. It would also allow adding to the list double-beta active elements such as calcium, which we have not included since the thermal properties of the pure element are expected to be rather poor. A quantitative analysis of the thermal properties of all possible compounds of double-beta elements is, however, beyond the aims of the present report.

5. CALORIMETRIC DETECTION OF THE DECAY OF THE ELECTRON

Thermal detection of these processes should in our opinion be limited, at least at the beginning, to the decay of K-shell electrons. The search for the specific decay $e \rightarrow \nu_e + \gamma$ seems in fact to us much less appropriate, since Doppler broadening of the expected peak at 255 keV prevents us from taking advantage of the excellent energy resolution of the detector.

A considerable advantage in thermal detection of electron decay with respect to double-beta decay is that one is no longer limited to a few elements or compounds, but can choose materials practically only on the basis of their thermal properties. A list of possible thermal detectors of electron

decay is reported in table 2. A mass of 1 kg is taken for all these detectors, which are operated at 5 mK. The considerable uncertainty on the sensitivity of detectors with low K-energy is due to the fact that the background of spurious counting at low energies is poorly known and hardly reproducible.

6. CONCLUSIONS

The potential of thermal detectors is obviously only partially shown by the examples reported here. Their application could extend to all processes, possibly at low rate, where the deposited energy has to be measured precisely (measurements of energy transitions, of the energy of excited nuclear levels, of the neutrino mass, of very small radioactive isotope contamination, etc.). However, we have limited our analysis here to double-beta decay without neutrino emission and to electron decay because the present experimental sensitivity of these processes is less limited by the intrinsic background activity than by the difficulty of increasing the amount of active material and/or the resolution of the detector. Thermal detectors could allow these limitations to be overcome, with far-reaching consequences in nuclear and subnuclear physics.

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Table 1: Possible thermal detectors for double-beta decay

Isotope	%	Z	A	$E_{trans.}$ (keV)	d (g/cm³)	Θ_D (K)	v_s (10³ m/s)	δE (1kg) (eV)	Mass (δE=1 keV) (kg)	Sensitivity (1 yr expos.) (yr)	Present limit (yr)
^{76}Ge	7.67	32	72.59	2041 ± 2.5	5.35	370	5.7	85	140	1.2×10^{24}	5×10^{22}
^{82}Se	9.19	34	78.96	3009 ± 12	4.5	90	1.5	2600	0.15	7×10^{22}	3×10^{21}
^{96}Zr	2.8	40	91.22	3356 ± 7	6.44	291	4.5	139	51	5×10^{23}	---
^{100}Mo	9.62	42	95.94	3033 ± 7	9.01	460	6.3	47	457	5×10^{24}	2×10^{21}
^{116}Cd	7.58	48	112.4	2808 ± 6	8.67	209	3.2	296	11.14	3.8×10^{23}	---
^{124}Sn	5.98	50	118.69	2277 ± 6	7.1	195	3.3	315	9.8	1.8×10^{23}	---
^{128}Te	31.79	52	127.6	870 ± 4	6.25	153	2.7	521	0.52	5.4×10^{22}	geolog.
^{130}Te	34.49	52	127.6	2534 ± 10	6.25	153	2.7	411	0.52	3.0×10^{23}	geolog.
^{136}Xe	8.86	54	131.3	2479 ± 11	3.52	64	1.4	3710	0.073	9.0×10^{21}	---
^{50}Nd	5.6	60	144.29	3366 ± 8	6.96	163	2.9	416	5.8	2.2×10^{23}	2×10^{21}

Table 2 : Possible thermal detectors for electron decay

Atom	Z	A	K-shell energy (keV)	d (g/cm³)	Θ_D (K)	v_s (10^3 ms^{-1})	δE(1 kg) (eV)	Sensitivity (1 yr exposure) (yr)
Be	4	9.0122	0.1117	1.83	1440	12.90	10	$(1-5) \times 10^{24}$
B	5	10.811	0.191	2.50	1315	13.8	14	$(1-5) \times 10^{24}$
C(Diamond)	6	12.011	0.2847	3.52	2220	21.15	4	$(2-6) \times 10^{24}$
Si	14	28.086	1.839	2.33	640	9.5	37	$(2-8) \times 10^{23}$
Cr	24	51.996	5.9908	7.14	630	7.9	33	$(2-5) \times 10^{23}$
Mo	42	95.94	20.000	9.01	460	6.3	47	$(1-2) \times 10^{23}$
Ru	44	101.07	22.117	12.3	499	6.5	41	$(1-2) \times 10^{23}$
Rh	45	102.906	23.22	12.41	480	6.3	45	$(1-2) \times 10^{23}$
W	74	183.85	69.523	19.3	405	5.5	49	1.4×10^{23}
Re	75	186.20	71.675	21.02	430	5.7	43	1.4×10^{23}
TiO₂	--	79.90	0.5431 / 4.9658	4.26	782	13.4	12	$(2-9) \times 10^{24}$ / $(2-5) \times 10^{24}$
GeO₂	--	104.59	0.5431 / 11.104	6.24	760	12.5	11	$(2-8) \times 10^{23}$ / $(2-4) \times 10^{23}$
BeO	--	25.01	0.1117 / 0.5431	3.01	1280	16.7	8	$(0.5-2) \times 10^{24}$ / $(0.5-2) \times 10^{24}$
SiC	--	40.10	0.2847 / 1.889	3.217	1172	19.5	5	$(0.5-2) \times 10^{24}$ / $(1-2) \times 10^{24}$
TiB₂	--	69.52	0.191 / 4.9658	4.5	1010	16.2	7	$(2-8) \times 10^{23}$ / $(4-8) \times 10^{23}$