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Neutrino mass and low-temperature calorimetry

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Abstract

We describe how the problem of measuring the neutrino mass led us to the development of low-temperature calorimetry. The search for a "17-keV neutrino" concluded with a negative result, but a wide range of applications are now carried on by us and by other groups in the fields of x-ray astronomy, recoil measurements of dark matter particles, high precision particle spectrometry, specific heat determinations, neutron detection, rare decay studies. The masses of the bolometers (calorimeters) extend from 1 mg to 1 Kg, nearly as large as for quantum detectors. By lowering the temperature into the 10-20 mK range, calorimetry is on the way to surpass substantially the high precision of particle metrology obtainable with the quantum detectors. Calorimeter developments and perspectives are discussed.

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1 Introduction-Brief history of neutrino mass and road to low-temperature calorimetry

In his fundamental paper on the theory of beta decay, Fermi[1] accounts for the observed continuous electron spectrum. He based the analysis on the proposal by Wolfgang Pauli that in this radioactive decay process ”one could assume, for example, that not only is an electron emitted, but also a new particle, the so-called ’neutrino’ (mass of the order or smaller than the electron mass; no electrical charge).” (A lucid current overview of beta decay research can be found in the book of Heyde.[2] Zero mass for the neutrino was also not excluded. By considering the phase space available for the emission of the electron and the (anti)neutrino, Fermi pointed out that near the maximum energy E_0 of the beta electrons, the spectrum $n(E)$ is sensitive to a possible neutrino mass, μ,

$$n(E) \sim (E_0 - E + \mu\, c^2)[(E_0 - E)^2 + 2\mu\, c^2(E_0 - E)]^{1/2}. \qquad (1)$$

E is the electron energy and c the speed of light. From Eq. (1) one finds that for $\mu = 0$, n(E) varies as $(E_0 - E)^2$, approaching E_0 with a *horizontal* slope. For $\mu \neq 0$ the slope becomes *vertical*, and with $E_0 - E \ll \mu\, c^2$, n(E) varies as $(E_0 - E)^{1/2}$. Figure 1 shows Fermi’s plot of the spectra near E_0, the ”end point”. The energy available in the radioactive decay, given by the Q-value, from the parent atom ${}_ZA_N$ to the daughter ${}_{Z+1}A_{N-1}$ is

$$Q \approx [M(parent) - M(daughter)]c^2, \qquad (2)$$

if one neglects the difference in electron binding in the parent and daughter atoms. Z, N, A are, respectively, proton, neutron, and mass numbers. M are atomic masses. This energy is shared between the emitted electron and antineutrino, so that $E(max) = E_0 = Q$. Until recently the searches for neutrino mass have been based on the measurement of the spectrum $n(E)$ near E_0. The discrimination between zero and non-zero mass is clear as seen in Fig. 1. The difficulty is also clear: $n(E) = 0$ at E_0!

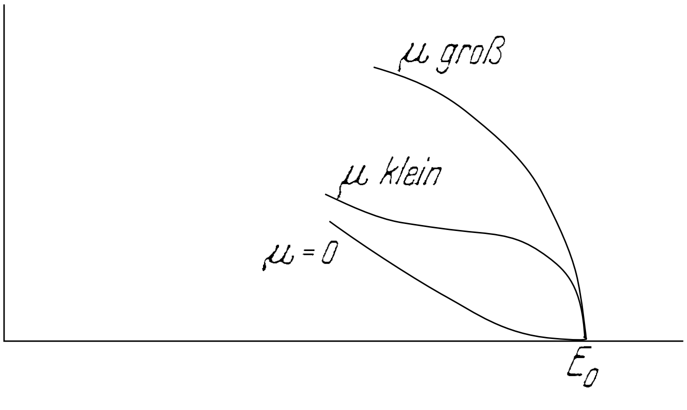

Figure 1: Beta decay electron spectrum near its maximum energy E_0 as shown in 1934 paper by Fermi (Ref. 1). The abscissa is the kinetic energy of the emitted beta electrons, the ordinate is their relative number. *Klein* and *gross* refer to *small* and *large* neutrino mass, respectively. (Reprinted with permission of Zeitschrift für Physik.)

1.1 Early spectrometer measurements

High resolution measurements, in an attempt to reveal whether the neutrino had a zero mass or not, were made early on the ^{3}H beta decay with the use of magnetic and electrostatic spectrometers.[3, 4] Tritium presented the advantage of not only a simple nuclear system, but a low Q-value (≈ 18.6 keV), so that the relative number of interesting counts near E_0 is enhanced. The experiment of Hamilton, Alford, and Gross gave values of μ that depended on the relative parities of the electron and neutrino emitted. With knowledge of parity nonconservation in beta decay, the upper limit $\mu < 250$ eV was obtained.[5]

A few years later high-energy physics experiments showed that in addition to the neutrino accompanying the electron in beta decay there is a different kind of neutrino, associated with the muon in the decay of the pion. This was a further motivation for a more precise neutrino mass measurement. By combining electrostatic and magnetic spectroscopic methods, Bergkvist[6] reduced the upper limit of Hamilton, Alford and Gross by a factor of 5 to $\mu < 55 - 60$ eV. Subsequently, a "high precision toroidal spectrometer" was used by Lubimov, Novikov, Nozik, Tretyakov and Kosik[7] to measure anew the β spectrum of tritium. This was contained as part of a valine $(C_5H_{11}NO_2)$ molecule, and, as in prior experiments, effects of source thickness and molecular structure had to be carefully studied. Their result was the first to give a range $14 \leq \mu \leq 46$ eV, rather than an upper limit on the neutrino mass. At this level of precision given for the μ values, refinements in the analysis of the beta spectrum, *e.g.* such as done later for atomic corrections[8], and possible measurement alternatives become important considerations.

1.2 Internal bremsstrahlung accompanying electron capture (IBEC)

Electron capture (EC) provides another means of obtaining the neutrino mass. In general, in the radioactive decay of a nucleus ${}_ZA_N$ to ${}_{Z-1}A_{N+1}$ there is competition between the emission of positrons and the capture of an electron from the K, L,... atomic shell. When $Q < 2mc^2$, where m is the electron mass, only EC can take place. While filling of the hole left by the captured electron and accompanying x-rays are the main de-excitation process, there is a small probability that radiation is associated with the capture. De Rújula[9] has shown that near the end point of the spectrum this internal bremsstrahlung provides similar means for a neutrino mass determination as does the beta spectrum. Furthermore, he called attention to studies of Glauber and Martin[10] in which they show that IB spectra for capture from atomic P orbitals have huge peaks at energies that equal x-ray energies. De Rújula shows that in fact the great enhancement occurs for all the IBEC spectrum *below* the x-ray energies. He also points out that in the case of β decay "Electron energy uncertainties and 'atomic and molecular excitation problems' limit these experiments to (anti)neutrino masses above a figure of the order of 10 eV. The theoretical limitation implied by the atomic and molecular excitation is *not* relevant in the IBEC approach." He singled out two leading candidates for such a study, ^{193}Pt and ^{163}Ho. The latter isotope discovered by Naumann and coworkers[11], and subsequent nuclear studies by others, left a pretty wide range $10 \geq Q \geq 2$ keV for ^{163}Ho. It is uncertainty in Q-values which led one of us (H.H.S.) to suggest the possibility of using calorimetric techniques in such studies.[12] These are discussed in Sec. 1.3. The first IBEC spectroscopy experiments, done on ^{163}Ho and ^{193}Pt [13] gave successively limits of 1.3 keV and 500 eV, respectively, (the latter with a 90 percent confidence limit), for the electron neutrino mass. Additional isotopes for possible IBEC studies have been considered more recently.[14]

1.3 Low-temperature calorimetry for particle spectroscopy

De Rújula[9] writes "Imagine a detector device that would measure *all* the energy released in an electron capture process, but for the energy carried away by the neutrinos", and in a footnote adds "I am indebted ...and to E. Fiorini for discussions on how difficult to imagine such a detector could be." But then he proceeds to show that the neutrino mass could indeed be obtained by calorimetry *without the difficulty of various corrections* either with IBEC or in the previous

β decay measurements. As mentioned in Sec. 1.2, one of us (HHS) - in 1983 a total stranger at CERN to the neutrino mass searches - was apprised of the indispensability of the knowledge of the Q-value in the IBEC method. An elementary estimate for ^{163}Ho, given a half-life of $\approx$ 4500 y, a Q-value of 2 keV, and for $\sim 10^{14}$ atoms gathered at the ISOLDE mass separator facility at CERN, shows that $\sim 2 \times 10^{-13}$ W would be emitted from such a sample. (The number of atoms can be determined at the limit by weighing the sample and with use of Avogadro's number!) Though this may strike nuclear physicists as an unimaginably small power to measure, to an atomic physicist two papers came to mind immediately which argued well for a new type of particle spectroscopy: the first was in 1946 by Robert Dicke[15] where he reports on his radiometer with which he could detect 10^{-16} W; the second was in 1947 by Golay[16] in which the ”Golay cell”, a sophisticated pneumatic detector, is described. For room temperature, this paper gives an equivalent input noise of $\approx 10^{-9}$ W, but a sensitivity of 3×10^{-11} W with selected units was reported later.[17] The conclusion was that particularly with use of detectors at low temperature, one had the possibility of measuring not only Q-values by emitted power, but of making calorimeters sensitive to the energy deposited by single particles or quanta. This we demonstrated in our first experiment with α particles.[12] Independently, there was an intense effort at NASA, in a collaboration with the University of Wisconsin, to make x-ray spectrometers based on calorimetry[18] to be flown eventually on space vehicles for x-ray astronomy. We describe the principles of the calorimeter and its use in a number of applications by us and by others, and illustrate one study with our recent search for the ”17-keV neutrino”, which adds to a number of others, by different techniques, a negative result, by now an accepted conclusion for its non-existence.[19]

2 Principles of low temperature bolometers

Among traditional radiation/particle detectors, semiconductor detectors offer the best combination of energy resolution and detection efficiency. The consequence of particle absorption of energy E in the semiconductor detector is the creation of $N = E/w$ electron-hole pairs, where w is the energy required to generate an electron-hole pair inside the semiconductor material, usually of the order of electron volts. For example, at 77 K, $w = 3.81$ eV for silicon and 2.96 eV for germanium. The ultimate resolution of a semiconductor detector is limited by the statistical fluctuation in N, which, according to the Poisson distribution, is $\sqrt{N}$. This corresponds, in a somewhat modified form, to an ultimate energy resolution full width at half maximum (FWHM) of

$$\Delta E(FWHM) = 2.35\sqrt{FwE}. \tag{3}$$

The Fano factor[20], F ($F \sim 0.1$ for most semiconductor detectors), takes into account the correlation between the fraction of energy converted into heat and that into electron-hole pair formation.[21] For example, for 6 keV x-rays, the ultimate energy resolution achievable in a silicon detector is 110 eV.

The operating principle of bolometers as single particle detectors is quite simple. A bolometer typically uses a dielectric crystal as the energy absorber. The absorption of radiation (photon, neutron, charged particle and single atom) of energy E in the absorber produces a small temperature rise $\Delta T = E/C$, where C is the heat capacity of the bolometer. This temperature change is measured by a temperature sensor (for example, a thermistor) that is thermally attached to the absorber. It is clear that to make ΔT large enough for the temperature sensor, one strives to make C as small as possible. One way to make the heat capacity low is to cool down the bolometer to a temperature T far below the Debye temperature. In this region, C falls rapidly as T drops. For a pure dielectric, $C \propto T^3$, that is, $\Delta T \propto T^{-3}$. A continuous and stable low temperature environment can be provided by a commercially available ^{3}He-^{4}He dilution refrigerator. The best which can be achieved with its use is about 5 mK.

A valuable property of bolometers is the very low energy of fundamental excitations (quantization energy of lattice vibrations or phonons), which is typically $10^{-3} - 10^{-4}$ eV. If in a time shorter than the thermal time constant of the bolometer (defined in Eq. 6) all the energy is converted into heat, then, from a pure statistical standpoint, one would expect an improvement in the energy resolution by one to two orders of magnitude compared with that obtainable with use of a semiconductor detector. A great advantage of bolometric detectors is the large choice of possible target (absorber) material: complete conversion of the incident energy into heat (phonons) is possible with the use of very low band-gap materials, such as HgTe, or with superconductors (Nb), or semimetals (Bi).[22] The expected energy resolution of a low temperature bolometer is limited in principle only by the thermodynamic fluctuations (phonon noise) and by the Johnson noise of the thermistor. For an ideal bolometer, the resolution is given by[23]

$$\Delta E(FWHM) = 2.35\xi\sqrt{kT^2C}, \tag{4}$$

where k is the Boltzmann constant and ξ is a dimensionless constant whose value is typically between 1 and 2 depending on the thermistor. At low temperatures, the energy resolution is therefore proportional to $T^{5/2}$ and ΔE becomes very small.

The thermal model of a bolometer is shown in Fig. 2. An impulse of energy input $W(t)$ to the system raises the temperature of the bolometer by an amount ΔT above the base temperature T_o of the heat reservoir. A thermal link with thermal conductance G between the bolometer and the heat reservoir is provided to restore the bolometer temperature to T_o. From energy conservation,

$$C\frac{d\Delta T}{dt} + G\Delta T = W. \tag{5}$$

When a single particle of energy E strikes the bolometer, the particle energy is absorbed and the crystal is thermalized sufficiently rapidly so that we can take $W(t) = E\delta(t)$, where $\delta(t)$ is the Dirac delta function. The solution of the first order differential Eq. (5) for the temperature excursion of the bolometer as a function of time t is

$$\Delta T(t) = \frac{E}{C}e^{-t/\tau}, \tag{6}$$

where $\tau = C/G$ is the time constant of the bolometer. The bolometer is restored to the base temperature in a time which corresponds to a few time constants τ, and then it is ready for the next energy input event. Depending on the operating temperature and the thermal link material, τ is usually hundreds of microseconds. At a given temperature, by adjusting the thermal link, τ can be made to vary, by construction, from 100 ms to the minimum value permitted by the power handling properties of the sensor.[24] The minimum value for neutron transmutation doped (NTD) germanium sensors is well approximated by $\tau = 1.8 \times 10^{-8}T^{-4}$s.

To measure the temperature change ΔT, anything whose property changes strongly with temperature may be employed.[25] A simple and traditional thermometer at low temperature is obtained with use of a highly doped semiconductor (near the metallic to semiconducting transition, or Mott transition). Then by the hopping mechanism (electrons hopping primarily from impurity site to impurity site, instead of being thermally lifted into the conduction band) we have a resistance which varies with temperature typically as fast as T^{-6}. Such an implementation has been very successfully developed by a NASA-University of Wisconsin collaboration [22] for x-ray astronomy. In these x-ray detectors the thermistors are formed by ion implantation in 0.25

mm^2 ($< 10\mu g$) Bi or HgTe absorber pixels making up the array of the imager, achieving resolutions of $\approx$ 8 eV on 6 keV x-rays. The sharp $R(T)$ behavior of a superconductor at its transition from the normal to superconducting state has also been employed as a sensitive temperature sensor. The spontaneous magnetization $M(T)$ of a sample near its ferromagnetic transition at low temperatures has also drawn much attention. The last two techniques utilize state of the art SQUID (Superconducting QUantum Interference Device) electronics to read out the signals (electric current in the former and magnetic flux in the latter case) in the effort to reduce the front-end electronics noise to a negligible level.

In designing a bolometric detector for a specific application, the required energy resolution constrains the choices of the operating temperature, the temperature sensor and the detector mass. The time constant dictates the choice of the material and dimension of the thermal link (and also the bonding, or connections, methods). The dynamic range of the detector is also a function of the temperature. All these factors come into play and most of the time compromises have to be made.[26] As examples, we show two realizations of bolometers with which we have made studies in diverse areas, though we recall our initial motivation - neutrino mass measurements.

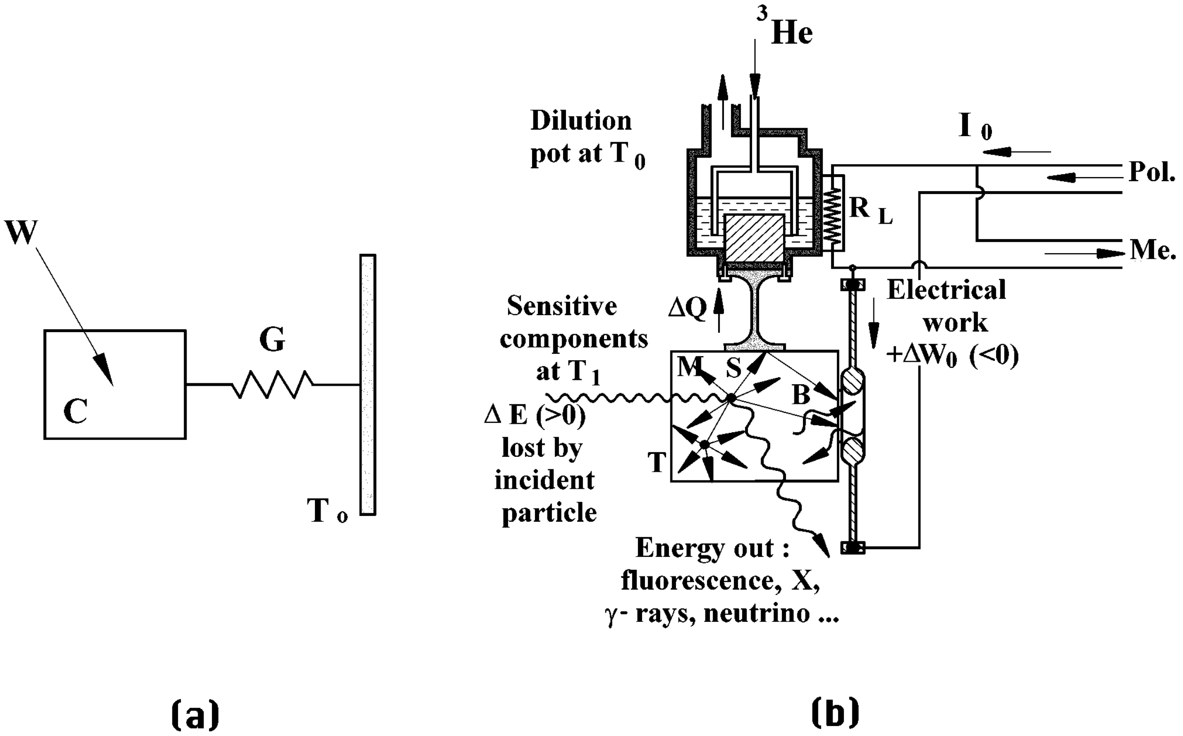

Figure 2: (a) Simplified thermal model of a bolometer: W is the input power, C the heat capacity of the bolometer, G the thermal conductance of the thermal link, T_o the temperature of the thermal reservoir. (b) Detailed heat transfers in the bolometer detector when absorbing a particle; the sensor (shown attached to the right side of the absorber), bias resistor (R_L), and dilution pot of the refrigerator are included in this picture. They constitute a Carnot engine operating between $T_1 = T_0 + \Delta T$ and T_0, work being done on the electrical polarization energy source (*Pol.*) via the polarizing circuit. *Me.* represents the measure of this transfer of electrical work $(-\Delta W_0)$ to the cooled polarizing resistor R_L. *M, S, B,* and *T* in the absorber denote, respectively, *metastable states, scattered phonons, ballistic phonons* reaching the sensor directly, and *trapping.*

3 Direct measurement of nuclear recoils

First, a few words of background. From astronomical observations and cosmological theory, it is believed that the majority of our universe (perhaps 90 percent) is made up of dark matter[27] which demonstrates its existence through the gravitational interaction. Since it is not seen through telescopes, it is believed that it does not participate in electromagnetic interactions. One of the postulated dark matter particles is called WIMP (Weakly Interacting Massive Particle), with a mass in the 1-100 GeV range. A possible way of detecting such WIMPs from our galactic halo in a terrestrial laboratory is through their elastic scattering from the constituent nuclei of the detector material.[28] Because of the better energy resolution and hence lower energy threshold, which is required for WIMP detection, massive low temperature bolometers are being constructed as dark matter detectors. To test the feasibility of using bolometers for this purpose, their detection efficiency for nuclear recoils induced by WIMP scattering must be demonstrated. We describe here our work toward that aim with use of radioactive decay.

When an alpha-radioactive nucleus decays, it disintegrates into an alpha particle and a daughter nucleus, conserving linear momentum. Typically, the alpha particles have energies $4-6$ MeV, with corresponding daughter nucleus recoil energies ~ 100 keV. While we were able in early work [29] to observe the *sum* of the recoil and alpha particle energies, we were unable to observe the recoil energy component alone. But it is the detection of the recoiling daughter nucleus that would, in some sense, mimic the nuclear recoils due to WIMPs.

Toward this goal, a ^{210}Po alpha source, which has a nearly 100 % decay channel to the ground state of ^{206}Pb with emission of 5.3 MeV α's, was prepared for such a measurement. The half-life of ^{210}Po (138 days) is sufficiently short to allow making a thin source and thereby reduce energy loss through self attenuation inside the source. [The polonium was electrodeposited on a 0.2-mm thick platinum disc, and the resulting ratio of recoils to detected alpha particles was 0.98(6).] The detector (Fig. 3) employed in this measurement is a composite-composite bolometer whose absorber consists of two 1 mm^3 diamond cubes separated by a 0.25 mm^3 diamond cube. The segmenting of the absorber facilitates full thermalization of phonons. (We discuss this further at the end of Sec. 5.) The temperature sensor is a Ga chemically doped Ge thermistor ($1650 \times 425 \times 99$ μm^3). The ^{210}Po source was placed about 7 mm in front of the bolometer, producing an alpha counting rate of $\sim$ 0.2 Hz. Both the bolometer and the source were placed inside the NYU ^{3}He-^{4}He dilution refrigerator [made by SHE (now BTI, San Diego, California)] at a temperature of 300 mK. Since the expected energy peak of the recoiling ^{206}Pb is 103 keV, as calculated from momentum conservation, the bolometer was calibrated with the use of a ^{109}Cd source which emits monoenergetic internal conversion electrons with two major discrete peak at 62.5 keV and 84.5 keV, and a third minor one ($\sim 9.8\%$) at 87.3 keV. The recorded pulse height spectrum is shown in Fig. 4. The energy of the recoiling ^{206}Pb was found to be 101 ± 3 keV[30], in agreement with that calculated from momentum conservation. The success of the measurement illustrates the detectability of nuclear recoils in bolometers and also suggests using them as a simple alternative low energy calibration source, instead of neutron beams obtained from specific nuclear reactions.[31] As a step in the actual dark matter search, we developed in 1991 a 25-g sapphire bolometer with a 1-keV resolution which we used for first underground observations in a tunnel in the Alps[32] for preliminary indispensable background measurements. Now we have reached a resolution of 130 eV with the same mass bolometer, which permits a new search for particles having a mass in the 1 to 10 GeV range.

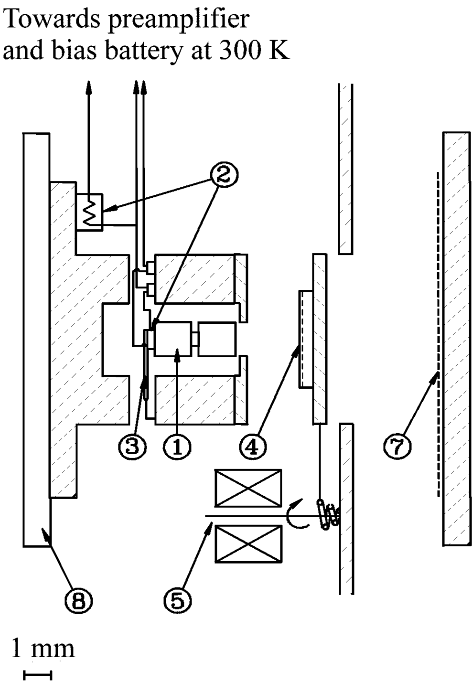

Figure 3: Schematic of the composite-composite bolometer and experimental setup. (1): the composite-composite bolometer absorber. (2): the chemically doped Ge sensor (not drawn to scale) and the bias resistor. (3): the thermal link (sapphire) to the 300 mK baseplate. (4): the ^{109}Cd source implanted on the surface of a sapphire substrate. (5): the actuator which can move the ^{109}Cd source out of the beam. (6): the copper shield at 2 K. (7): the ^{210}Po source deposited on a metallic substrate cooled at 2 K. (8): the ^{3}He cryostat baseplate at 300 mK.

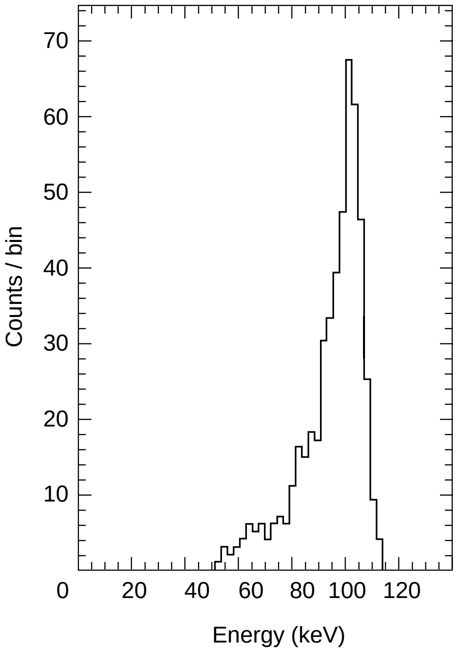

Figure 4: The recoil spectrum of the ^{210}Po source peaking at around 100 keV. The energy scale is obtained by the ^{109}Cd calibration.

4 Calorimetric measurement of beta decay with use of the bolometer - search for a 17 keV neutrino

A nonvanishing neutrino mass has been speculated on by particle physicists, and the search for it provides a probe for physics beyond the Standard Model. Solar neutrino measurements generally show a factor of 2 deficit in the count rate compared with that predicted from what we know about how the sun burns its fuel.[33] A popular explanation is that neutrinos have finite masses and they oscillate between different flavors (there are 3 known lepton flavors, electron, muon, tau). The search for neutrino mass is therefore crucial to physicists.

The spectral feature of beta decay (Fig. 1), derived solely from the kinematics of the particle final states [Eq. (1)], has been employed to determine the neutrino mass, and the mass upper limit has, as detector sensitivity improves, dropped from 10 keV in the first tritium β-decay measurement in 1947[34] to around 7.2 eV recently[35]. As pointed out in Sec. 1.3, the advantage of the calorimetric technique is the elimination of the complications associated with atomic or molecular final states in analyzing the spectrum. The slow response of bolometers is, however, the major drawback in such applications when one recalls that high overall statistics ($> 10^8$) are required to accumulate sufficient counts near the end point energy region for mass determination purposes. The counting rates allowed by bolometers are low so that a tritium end point beta-decay measurement would require a substantial expenditure for liquid helium and nitrogen. A more accessible experiment was the search by an independent method for ”17 keV neutrinos” in the β spectrum of ^{63}Ni, with end point energy of 66 keV. The motivation was contradictory results on the existence of these heavy neutrinos from magnetic spectrometer and semiconductor detector experiments. We describe this experiment briefly as it illustrates the implementation and concerns in such bolometer measurements.

The bolometer shown in Fig. 5, cooled to $\approx$ 50 mK with use of our dilution refrigerator [26], had a resolution of 500 eV, a dynamic range of 5 MeV, and a time constant shorter than 1 ms. Digital processing was used to reject possible pileup events. Electrons at 66 keV have a range of $\sim 2 \times 10^{-2}$ mm in silicon [36] and are completely stopped in the absorber. First, energy calibration of the spectrum was obtained with use of ^{109}Cd (see Sec. 3) implanted in sapphire at 80 keV to a depth of $\sim$ 70 nm.[37] The calibration source was then replaced by the ^{63}Ni, electroplated on a steel substrate to a thickness of tens of microns. A typical pulse is shown in Fig. 6, the calibration spectrum in Fig. 7, and the ^{63}Ni sprectrum, representing 5×10^5 counts accumulated in 3 days, in Fig. 8.

4.1 Some experimental considerations

The spectra obtained with bolometers are subject to a number of possible systematic errors. We point out some of them.

Electrons, traveling through matter, lose their energies mainly via inelastic collisions (Coulomb interactions) with atomic electrons, and thus ionize the atoms in the detector material. The loss through bremsstrahlung, i.e., emission of electromagnetic radiation from the decelerating electrons becomes important only at energies much higher than we are concerned with here. (In silicon, the two loss mechanisms become equal at about 50 MeV[38], and, for energies of $\sim$ 60keV, bremsstrahlung accounts for less than 1 percent of the energy loss.) If the ions and electrons do not recombine, and are thus not thermalized within the signal rise time of the pulse, or the small fraction bremsstrahlung escapes from the silicon absorber, the full energy of the incident electron is not collected. The losses contribute to the low energy shoulder in the spectrum of the monoenergetic electron peaks shown in Fig. 7. Electrons originating from an external beta source can be deflected by or scattered from walls and collimators before entering the bolometer and energy loss could therefore be appreciable. Energy-dependent loss from the backscattering of electrons [39] upon hitting the bolometer surface has been noted by Franklin [19] to have been an important cause that led to a positive result for the existence of a 17-keV neutrino. Self attenuation in the finite thickness source also contributes to the low energy tail and the flat low energy background of the peak.

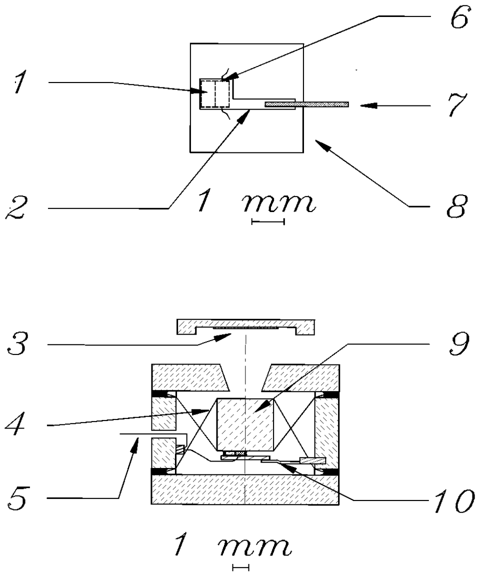

Figure 5: Schematic of the 0.1 g silicon bolometer with the antimicrophonic nylon suspension. The enlarged view shows the thermal link and sensor design, forcing heat to cross the sensor before going to the heat sink. 1: sapphire strut. 2: sapphire plate for heat link. 3: radioactive source. 4: 32 nylon thread supports (25 μm diameter). 5: electrical leads to sensor. 6: $0.26 \times 0.25 \times 0.6$ mm^3 NTD germanium temperature sensor. 7: copper wires. 8: enlarged bottom view of the heat link. 9: pure single crystal silicon $3.6 \times 3.74 \times 3.32$ mm^3. 10: high thermal conductivity pure copper wires.

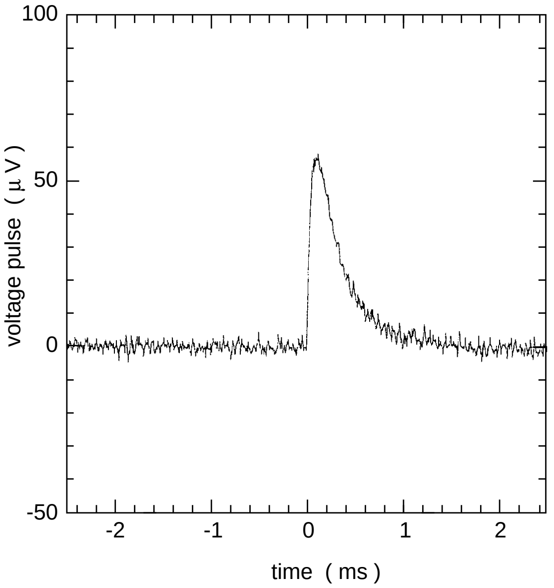

Figure 6: A typical voltage pulse resulting from energy deposition inside the silicon bolometer by a 62.5 keV beta particle. The time constant was about 280 μs, the electronic bandwidth 2 Hz - 100 kHz. Data were sampled at a rate of 200 kHz.

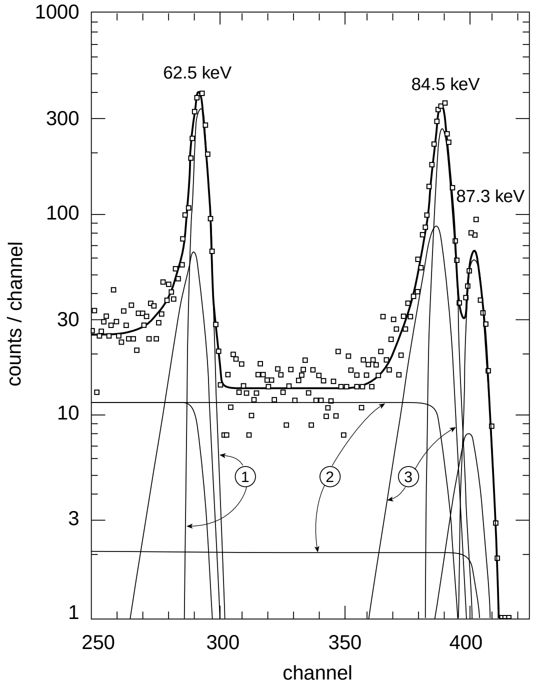

Figure 7: Pulse height spectrum of the ^{109}Cd calibration. Note the asymmetry of the Gaussian peaks on their low energy side, which are clearly seen with the logarithmic scale of the vertical axis. Open squares are data points. Thin solid curves show various components of the response function: curves 1 represent the main Gaussians; curves 2 and 3 are low energy components. The thick solid curve is their sum. The energy resolution (FWHM) is 1.25 keV at the 62.5 keV peak.

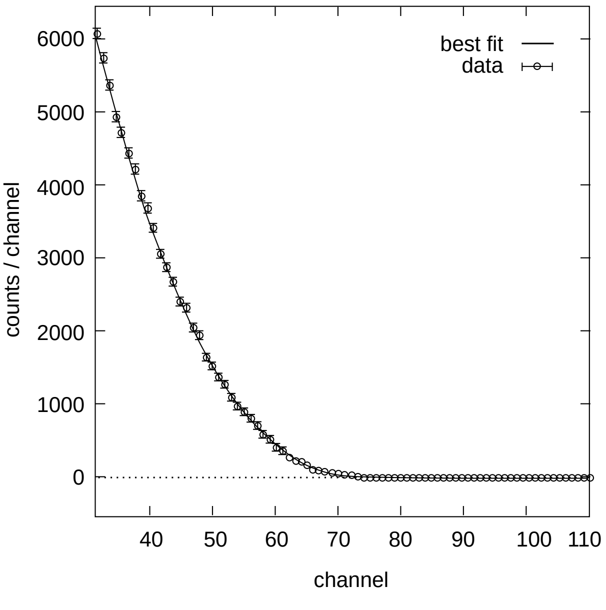

Figure 8: Best-fit theoretical curve assuming a 17 keV neutrino component in the ^{63}Ni beta spectrum, in addition to the dominant massless neutrinos. Measured data with associated Poisson errors are also plotted. Channels were rebinned (grouping of numbers of channels) before the spectrum was drawn, and the energy (E) channel-number (x) relation, E = 0.88 + 0.876x, was obtained from the ^{109}Cd calibration (Fig. 7).

4.2 Data analysis

The theoretical beta spectrum, *cf.* Eq. (2), assuming the usual dominant massless neutrinos plus a subdominant 17 keV heavy neutrino component can be written in the following form,

$$\frac{dN}{dE} = (1-X)\cdot\frac{dN(E,\mu c^2=0)}{dE} + X\cdot\frac{dN(E,\mu c^2=17)}{dE}, \tag{7}$$

where

$$\frac{dN(E,\mu c^2)}{dE} = C\cdot F(E,Z)\cdot p\cdot E\cdot(E_0-E)\cdot\sqrt{(E_0-E)^2-\mu^2c^4} \tag{8}$$

is the beta spectrum for finite neutrino mass. X is the probability for the emission of a 17 keV neutrino, C is an overall normalization constant, $F(E,Z)$ is the full relativistic Fermi function[40], p the momentum of the beta particle.

Because of the imperfection of apparatus, and the effects connected with the source discussed above, what is experimentally obtained is basically the convolution of the beta spectrum [Eq. (7)] and the detector response function (Fig. 7). The effect of convolution is, in the usual case, to smear the signal according to the recipe provided by the response of the instrument.

To fit the theoretical curve (after convolution with the detector response) to the experimental spectrum, a likelihood function is defined which is a product of Gaussians of the data counts about their means.[26][41] (The procedure is equivalent to a chi square fit.) To obtain the mixing amplitude X in Eq. (7), one adjusts X to maximize the likelihood function. X can be expressed as a function of $n = dN/dE$, which are statistical variables, and the fluctuations give rise to a *statistical error* which can be calculated according to the law of propagation of uncertainties in n, which is $\sqrt{n}$. We obtained, following this procedure, $X = -0.049 \pm 0.054_{stat}(1\sigma)$, where σ is the standard deviation. The negativeness of X is not too surprising and the interpretation is that *there is a 68.3 % chance (1σ) that the hoped true mixing fraction falls within -0.049 $\pm$ 0.054.*

Systematic errors, e.g. possibly caused by source thickness, energy loss mechanisms, geometry effects, separate calibration and beta spectrum runs, detector nonlinearities, and low energy shoulders in the spectrum, had to be considered, the last two found to be the most important.[26] Taking account of these gives an uncertainty ΔX_{syst} = 0.040(1σ). Combining this as independent of $\Delta X_{stat}, X$ = -0.049$\pm$0.067(1σ), and one obtains an upper limit on the mixing fraction $X <$ 1.8% at the 68.3% confidence level.

Since the inverse signal-to-noise ratio $[\frac{\delta N}{N}]^{-1} = [\frac{\sqrt{N}}{N}]^{-1} \approx 2.2\%$ (calculated from around the middle of the fitted data range), we conclude a negative result for the existence of 17 keV neutrinos. Recently, a similar experiment was made using a cryogenic detector with a ^{63}Ni source sandwiched inside the absorber.[42] In 28 days of running, 6 $\times 10^{7}$ counts were accumulated, and the experiment found similarly a negative result.

5 Conclusion

We have described low-temperature calorimetry as a new high-resolution experimental method for particle (α, β, γ) spectrometry introduced by the NASA-Wisconsin group [18] for x-ray astronomy and by us and our colaborators at CERN, the Institut d'Astrophysique Spatiale [12], Göteborg, and CEN-Saclay, for neutrino mass measurements devoid of uncertainties in atomic surroundings effects on the beta spectrum. Our search for a possible 17-keV neutrino illustrates some of the advantages and disadvantages of the technique: A salient disadvantage is the present limitation in counting rate ($\sim 10/s$). Among the advantages, as discussed in Secs. 4.1 and 4.2, is the fact that the systematic errors with external sources, caused by source thickness, deflection and scattering from walls and collimators, and back scattering from the detector surface, can be avoided by embedding the radioactive source *in* the calorimeter, as we had envisaged for the measurement of the (anti)neutrino mass.[12] As noted above, this has now been done[42] in the case of the 17-keV neutrino mass search. More generally, the bolometer provides the advantage of being a *windowless* detector, so that the energy of the incident particles or quanta is not degraded.

In conclusion, we want to point out several other applications of the low- temperature calorimeters. These range from a search for neutrinoless double beta decay [43], which would test the ”Standard Model” of electroweak interactions, to biological applications in which the cryogenic detector provides great gain of detection efficiency in mass spectrometry of DNA fragments.[44] One can turn the calorimeter problem around: knowing the energy deposited by a particle and the temperature rise, the heat capacity can be determined. This has been used to obtain the heat capacity of silicon at low temperatures.[45]

The greater spectral resolution and efficiency of low temperature calorimeters, when compared with the more conventional solid state detectors[46], are to be exploited at the Gesellschaft für Schwerionenforschung (GSI) facility in Darmstadt (Germany) for precision Lamb-shift measurements.[47] For hydrogen-like lead and uranium (atomic numbers Z=82 and 92), the principal quantum number n=2 and 1 levels are separated by $\approx$ 100 keV, the n=2 fine structure $\approx$ 4.6 keV, and the Lamb shifts are 458 eV and 75 eV for the 1s and 2s electrons. These features in the Lyman-α transitions are to be resolved with an energy resolution possibly as low as 30 eV. The precision results will be of importance for testing quantum electrodynamics (QED) in strong electromagnetic fields. This follows their earlier experiments [48] investigating more generally the application of calorimeters to spectrometry of energetic heavy ions. With use of a composite bolometer (separate absorber and thermistor) they obtained an energy resolution $\approx\ 2\times10^{-3}$ for 2.4-GeV ^{209}Bi ions (which limit may in fact represent the energy spread of the beam). This result is reported to be substantially better than obtainable with solid state and ionization chamber detectors.

Low-temperature calorimetry, in addition to dark matter detection experiments, is envisaged for neutron spectrometry.[49] For this, experiments have been done with a fairly heavy (2g) LiF bolometer; the use of a sample enriched in ^{6}Li is expected to enhance the efficiency. Discrimination between thermal pulses produced by different types of incident particles (α,γ) has been demonstrated [50]: this is achieved by a novel combination of the calorimeter and an optical link with use of a luminescent CaF_2(Eu) bolometer. Besides the use of pulse shapes and of fluorescence coupled with heat detection, particle recognition can be achieved with use of another combination - charge plus heat. Future applications include detection of recoil events (down to $\sim$ 4keV) and ion beam experiments with low counting rates. In both of these, the possibility of suppression of the γ-ray background is crucial. (Our detection of the ^{210}Po recoils was in fact possible because of the fortuitous paucity of γ rays in the energy region of interest.)

Finally, we cite the important developing application of low temperature calorimetry to metrology.[51, 52] Here the increased resolution is of particular value in quantitative assays of radioisotopes when the nuclear spectra are dense and have substantial overlap. We must point out that there are details of the calorimeter design and operation which have to be considered for high-resolution work: *e.g.* where is the point of impact of the particle in the detector? This can influence the pulse shape, as a small fraction of the incident energy gives rise to ”ballistic phonons”. [53] Their detection time is thus different from that of the thermalized phonons. To circumvent some of the potential problems associated with the phonon propagation time, a ”composite-composite” bolometer [52, 54], which incorporates a scattering crystal, was developed. The calibration of the point of impact (”center-edge”) effects is investigated by studying the pulse shape as a function of position and by utilizing particles, be they the heavy ^{210}Po ions, which penetrate $\sim$100Å into the calorimeter, or 82-keV electrons that go to depths of the order of tens of microns. A further advantage that the bolometer has over semiconductor detectors, such as diffused junction silicon diodes, is that there is no *dead layer*. This is a region of heavy doping which the incident particle must traverse before reaching the sensitive detection region (the *depletion zone*), and in which energy degradation occurs.[55]

We have attempted to give a flavor of some of the accomplishments of current low-temperature calorimetry and a small indication of physical characteristics to be studied in terms of processes. Andersen [56] has made initial analyses of the physics and resolution limits of the calorimeters. But it is a big open field in which exploration is intense [57] with expectation of reaching higher resolution, efficiency, dynamic range, large mass at very low temperature ($\simeq$10 mK) - though here accompanied by the deleterious longer time constants. We have gone a long way since our initial work thirteen years ago with a 1-mg sapphire calorimeter and 35 keV resolution to present-day 20 keV with a 1120-g sapphire![58]

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We should like to dedicate this article to the memory of Robert H. Dicke, who died very recently. He made many fundamental contributions to experimental and theoretical physics, from early cosmic background emission studies, gravitation, the electron gyromagnetic ratio and radiative processes, to the phase sensitive detector (”lock-in amplifier”), one of which was seminal in the origin of our work

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