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A COMPOSITE BOLOMETER AS A CHARGED-PARTICLE SPECTROMETER.

N.Coron[1),G.Dambier[1),G.J.Focker[2),P.G.Hansen[3),
G.Jegoudez[1),B.Jonson[5),J.Leblanc[1),J.P.Moalic[1),
H.L.Ravn[2),H.H.Stroke[6),O.Testard[4)

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Abstract:

The thermal pulse response of a composite diamond-germanium bolometer to individual alpha particles has been investigated. With 5-6 MeV alphas impinging on the diamond wafer of the bolometer a full width at half maximum (FWHM) of 36 keV was obtained at a temperature of 1.3 K. Estimates show that it should be possible to improve this performance by a large factor so that this new detection technique is likely to lead to much better energy resolution than today's semi-conductor detectors.

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1) LPSP, B.P. 10, F-91371 Verrières-le-Buisson, France
2) EP-Division,CH-CERN, 1211 Geneva 23, Switzerland
3) Institute of Physics, University of Aarhus,DK-8000 Aarhus, Denmark
4) Service d'Astrophysique,C.E.N,Saclay,F-91111 Gif-sur-Yvette,France
5) Chalmers University of Technology,S-41296 Goteborg,Sweden
6) Dept. of Physics, New York Univ., N.Y.10003,USA and CERN

The measurement of radioactivity by direct conversion of nuclear radiation into a temperature rise of a calorimeter is as old as as nuclear physics itself. As part of a general programme aiming at a determination of the mass of the electron neutrino, we have designed an improved version of a He - cooled composite diamond bolometer with a monolithic thermistor, developed at the Laboratoire de Physique Stellaire et Planètaire [1]. Our approach,based on an idea by De Rújula [2] is to study the shape, near the upper end-point, of the internal bremsstrahlung spectrum in electron-capture beta decay (IBEC). The best nucleus for a precise measurement seems to be ^{163}Ho for which we have determined [3] the Q_{EC}-value to be 2.83±0.05 keV. An especially interesting possibility is to use total-absorption spectrometry [4] (calorimetry), in which the radioactive holmium forms part of the sensitive volume of the detector. With 5 - 6 MeV alphas impinging on the diamond wafer of the bolometer a full widthe at half maximum of 36 keV was obtained at a temperature of 1.3 K. The theoretical resolution at 100 mK is of the order of a few eV, so this new detection technique should lead to greatly enhanced energy resolution over today's charge carrier collection based solid-state detectors.

In 1903 Curie and Laborde [5] used a calorimeter to verify that the heat produced by a radioactive substance is due to the absorption of its energetic radiation. In the following years microcalorimetry became of great theoretical importance through the determination of the 0.337 MeV average beta energy of ^{210}Bi (RaE) by Ellis and Wooster [6] in 1927. In fact, the contrast between this value and the maximum beta decay energy of 1.17 MeV for ^{210}Bi was one of the key arguments which led Pauli to the hypothesis of the neutrino. Microcalorimetry finally reached a sensitivity of about 3×10^{-5} W [7] at 300 K. The possibility of nuclear micro-calorimetry at low temperatures where heat capacities are very low, was first pointed to by Simon [8], and recently Dalmazzone [9] investigated a calorimeter at 1.8 K and reached a sensitivity of

10^{-9} W. The idea to use bolometers or thermometers at low temperature as detectors for radioactivity has recently reappeared [10-12] and it has been shown that a silicon thermistor may be used as an X-ray spectrometer [11].

The traditional use of low-temperature bolometers has been for the detection of continuous flux of infrared radiations [13-18]. The instruments based on semiconductors have been found to have better performance and to be simpler to use than those based on superconductivity. The semiconductors (doped Ge or Si) have a resistance varying as T^{-4} to T^{-9} in the temperature region of 0.3 to 5 K. In the beginning of the seventies a new type of bolometer,a so called composite one,has been developed at LPSP [1,14]. This device consists of an absorber with a large surface area (0.5-20 mm diameter) coupled thermally to a monolithic semiconductor thermistor with very small volume (typically 0.008 mm^3).The best performance of such a composite bolometer has been obtained with a diamond wafer as the absorber and a germanium crystal as thermometer. The reason why diamond is especially advantageous is its very high thermal diffusivity [1]. A schematic diagram of a composite bolometer is shown as an inset in Fig.1. An asset of this construction is that there is no need for soldering, which results in a mimimum of low frequency noise and low heat capacity.

The essential advantage of the composite bolometer is that it separates the absorbing and detecting functions. The absorber (diamond, sapphire,dielectric-metal sandwich) may be optimized independently of the thermometer.The latter,in turn,has to have maximal temperature derivative of the impedance,dZ/dT,and in addition an impedance, Z,matched to the preamplifiers [18]. The use of bolometers for flux detection of different kinds is steadily increasing : e.g. molecular beams [19,20], radiation in the millimeter wave-length range [14-18] and,most recently, X-rays [11]. It is also interesting to note that spurious pulses, caused by cosmic ray absorption in the infrared low- temperature detectors,were purposely eliminated with the use of a 'spike suppression circuit' by high altitude astronomers [21].

The diamond wafer,which acts as the absorber in our bolometer,has a volume of 0.25 mm^3 . At our working temperature (1.3 K) we have measured the thermalization time of the device to be less than 60 μs from any point of impact on its surface. The thermometer which has a surface area of 0.1×0.1 mm^2 is glued onto the diamond with a 10 μm layer of epoxy. This eliminates the possibility of charge collection since there is no bias across the absorber.

The only limitation of the detector resolution is due to the noise of the detector itself (Johnson noise and thermodynamic noise).A detailed analysis of these noise effects is given in refs. [10] and [18]. With optimal filtering, an order of magnitude estimate for the resolution is given by the expression :

$$\Delta U_{FWHM} = \alpha\sqrt{8\ln 2 k_B T^2 C}, \qquad (1)$$

where k_B is the Boltzmann constant, T the temperature of the helium bath (in K) and C the specific heat of the bolometer at the temperature T. The constant α depends on the details of the construction of the bolometer (dZ/dT and Z) and has generally a value between 1 and 2. In our case $\alpha = 1.5 \pm 0.2$. The limiting resolution calcaulated from this expression is shown in Fig. 1.

The bolometer used in this experiment is mounted in in the vacuum chamber of a commercial portable optical cryostat [22]. A mixed ^{239}Pu,^{241}Am,^{244}Cm α-source was positioned in front of the diamond so that no particles could reach the Ge thermometer.A lead shutter could be inserted between source and detector during background measurements. A typical α spectrum measured at a temperature of 1.3 K is shown in Fig.2. The low-noise preamplifier had a band pass filter of 2 Hz-120 kHz and a gain of 2000 [23]. A 5.5 MeV α particle gives a typical temperature increase of 1 mK. The resolution is 36 keV,which is not yet the best possible performance of the system. The main reason for this is that we have used standard nuclear electronics which could not be optimally matched to the time constant of the bolometer. We are presently working on improvements of both the electronics and the cryostat. We hope within a few months to have an operational α-detector with a resolution of around 3 keV at 1 K and we foresee that the technique of nuclear radiation detection via thermal pulses will have a large impact on many fields of physics.

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Figure captions

Figure 1.

Ultimate resolution with optimal filtering as a function of the temperature for the best available composite bolometer with a monolithic thermistor. The curves are calculated for three different detector volumes, V (mm^3), by means of eq.(1).The 0.02 mm thick detector represents the present technological size limit.The specific heat C is strongly material and geometry dependent and we have used the following expression

$$C = 7\times10^{-12}T^3 + 1.3\times10^{-12}T^{1.3} + 1.5\times10^{-12}T + 6.8\times10^{-11}VT^3 ,$$

which is a good approximation to available measurements.

The inset shows a schematic view of the experimental set-up where (1) is the α source, (2) the diamond substrate, (3) the Ga-doped Ge-thermistor which also serves as mechanical support and thermal conductor to the 1.3 K thermostate, (4) the bias supply and the cooled load resistor and (5) the preamplifier-amplifier chain (at room temperature).

Figure 2.

Alpha energy spectrum from a mixed source of ^{239}Pu,^{241}Am and ^{244}Cm obtained by recording the thermal pulses induced by the α-particles in a 0.25 mm^3 diamond bolometer. The resolution is 36 keV FWHM and the integral non-linearity is less than 10^{-3}.

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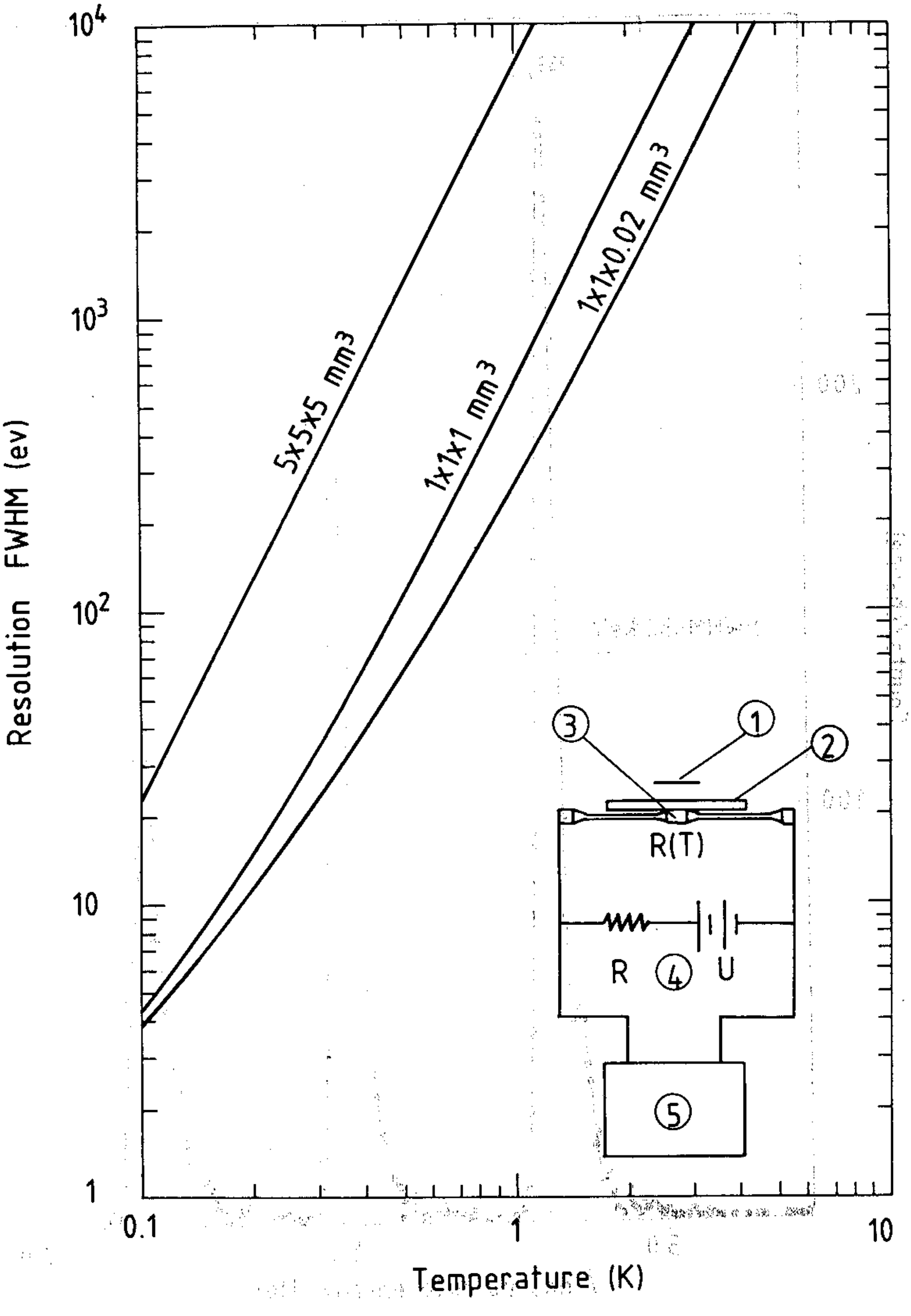
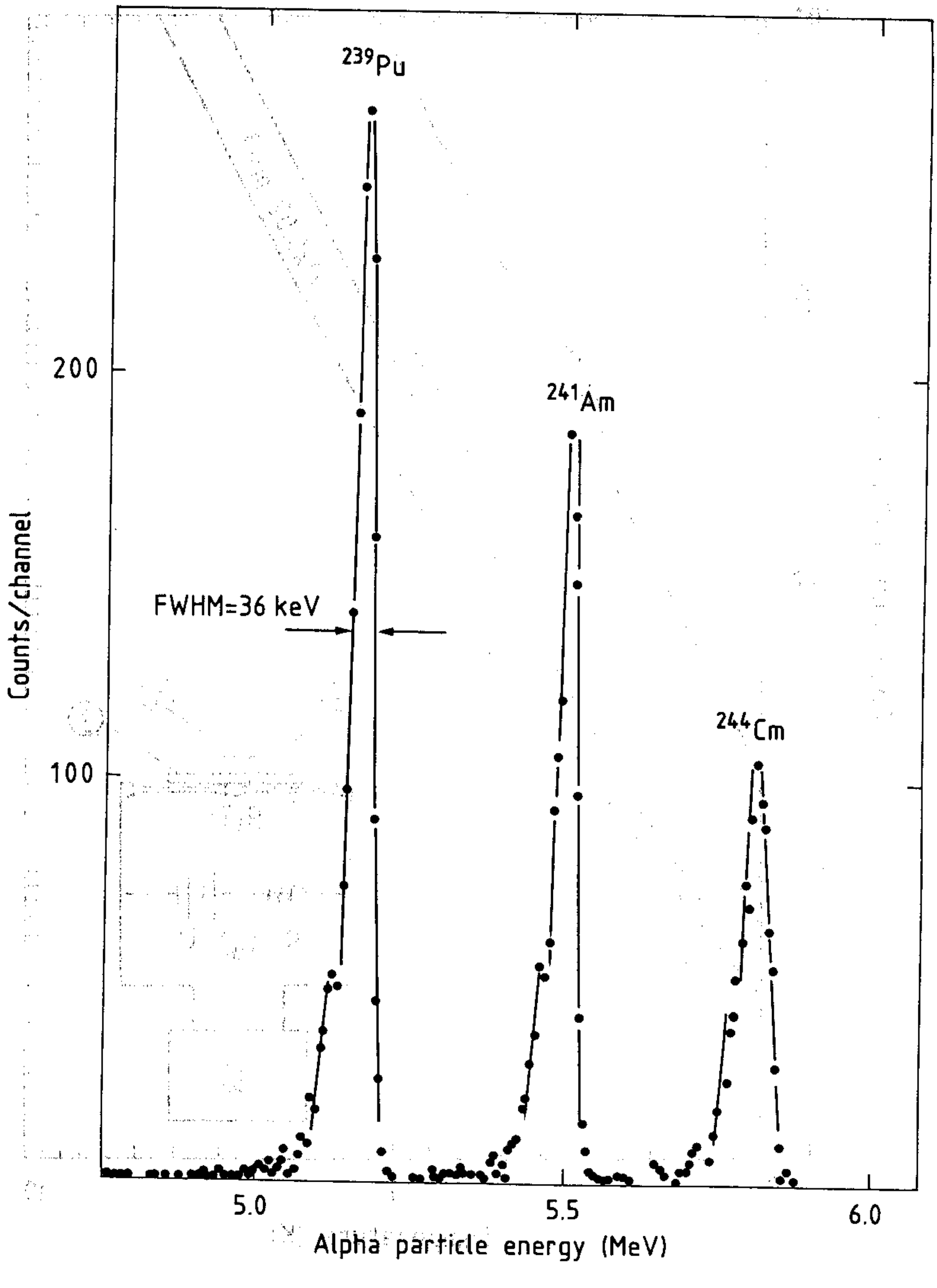


10^4
10^3
10^2
10
1
0.1
1
10
Resolution FWHM (ev)
Temperature (K)
5x5x5 mm3
1x1x1 mm3
1x1x0.02 mm3
1
2
3
R(T)
R
4
U
5

Fig.1



239Pu
241Am
244Cm
FWHM=36 keV
200
100
5.0
5.5
6.0
Counts/channel
Alpha particle energy (MeV)

Fig.2