High Energy Resolution Bolometers for Nuclear Physics and X-Ray Spectroscopy

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Two bolometers composed of tin absorbers and neutron transmutation doped (NTD) Ge thermistors have been fabricated in preparation for experiments in nuclear and subnuclear physics. Both detectors fully resolve the two $K_{\alpha 1}$ and $K_{\alpha 2}$ lines of ^{55}Mn. The deconvolved FWHM resolution in this energy region ranges from 4.5 to 5.7 eV, for different published values of intrinsic widths and asymmetries of these lines, the best ever obtained at this energy with any energy dispersive detector. The $K_{\beta'}$ satellite peak is analyzed for the first time in a measurement with an energy dispersive spectrometer. [S0031-9007(98)08172-1]

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Measurements of low energy events (a few keV) in nuclear and subnuclear physics are attracting great interest. Typical examples are the studies of low energy beta decays in view of the determination of the electron antineutrino mass [1,2]. In astrophysics, high resolution x-ray spectroscopy in the region between 0.1 and 10 keV [3] is of considerable interest, for instance, in astronomical observations of x rays emitted thermally by interstellar or intergalactic gas. From a more general point of view, high resolution x-ray spectroscopy has numerous applications in atomic physics and material science [4].

Low energy x-ray spectroscopy is mainly performed with wavelength dispersive spectrometers (WDS) instrumented with Bragg crystals. This method yields an excellent energy resolution, but poor efficiency, since only a narrow band of energy can be analyzed at a time. The complementary energy dispersive spectroscopy is mainly performed with Si(Li) semiconductor detectors, whose best resolution in the energy region of a few keV is of ~120 eV [5]. Thermal detectors operated at low temperature can obtain resolutions better by at least an order of magnitude. This technique was suggested in 1984 [6,7] and is now being widely applied [8–10]. At low temperatures the heat capacity of a diamagnetic and dielectric crystal or of a superconductor well below the transition temperature is expected to be proportional to the cube of the ratio between the operating and the Debye temperature. As a consequence, even the tiny energy delivered by a single particle can be measured from the resulting temperature increase by a suitable thermal sensor. The best resolution obtained so far with this type of energy dispersive spectrometer in the typical regions of K_α and K_β lines of ^{55}Mn (5.9 and 6.5 keV, respectively) ranges from 7 to 8 eV FWHM [3,11,12]. The two microbolometers described here offer a considerably improved resolution and represent the most resolving detectors constructed so far for this energy region.

A series of measurements [13] has been performed in a dilution refrigerator to optimize the performance of microcalorimeters made by a thin tin absorber and Si:P and neutron transmutation doped (NTD) Ge thermistors [14]. In order to be able to operate several bolometers at the same time, we have implemented a multiple preamplifying system. It consists of ten silicon junction field effect transistors (JFET's) operating at a temperature of ~120 K near the detector in order to reduce parasitic capacitances. The required high temperature for FET operation is achieved by means of a proper thermal decoupling between the FET supporting structure and the cold point. The heat dissipated to reach the desired FET temperature, of the order of a few mW, flows to the 1.2 K stage of the dilution refrigerator.

The resolution obtained with the Si:P thermistors on the ^{55}Mn lines is reasonable (13.5 eV FWHM), but the implantation-compensation procedure is not yet optimized.

Better results have been achieved with two microbolometers made by NTD Ge thermistors of $300 \times 100 \times 20$ μm^3 glued to tin absorbers of $\sim 250 \times 250$ μm^2 surface and 25 μm thickness. Two 17-μm-diameter, 2-mm-long aluminum wires are ultrasonically bonded to two gold pads on the NTD Ge thermistors. The pads are placed on the same 300×100 μm^2 side of the thermistor and are separated by 200 μm. The wires provide both the electrical contact and the mechanical suspension of the devices.

The two detectors are operated at about 70 mK. At this temperature the thermistor resistance was 60 MΩ and its sensitivity was about 4 MΩ/mK. The bias current was 70 pA. They were exposed to weak sources obtained by drying a 0.1 molar water solution of NO_3H with ^{55}FeCl dissolved in it. The detectors give pulses with an amplitude of about 200 μV/keV and rise and decay times of ~0.5 and ~2 ms, respectively.

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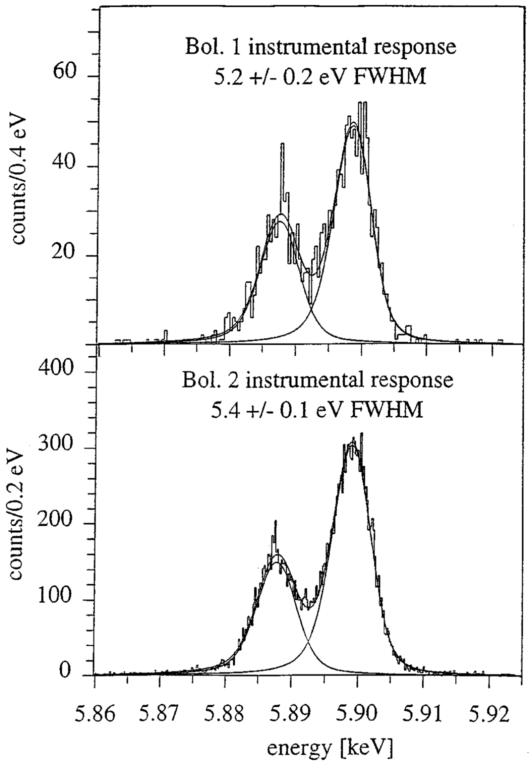

FIG. 1. Spectrum obtained with the two bolometers in the K_α region. Bolometer 1 and 2 have been operated for 26 and 71 hours of effective running times, respectively.

The spectra in the K_α region obtained with the two microbolometers are presented in Fig. 1. The corresponding effective running times are 26 and 71 hours, respectively. In both spectra the $K_{\alpha 1}$ and $K_{\alpha 2}$ lines are fully resolved for the first time with an energy dispersive spectrometer. The base line widths of the two detectors are the same: about 3.4 eV.

The instrumental resolution of our microbolometers can be obtained by deconvolving the peaks with the Lorentzians corresponding to the intrinsic widths of the ^{55}Mn $K_{\alpha 1}$ and $K_{\alpha 2}$ lines determined in WDS measurements. In the pioneering work by the NASA-Wisconsin Collaboration [3] and in the more recent experiment by Silver *et al.* [11], the Lorentzians determined by Shnopper [15] were adopted. This procedure yields intrinsic resolutions at about 7.5 eV in both experiments. More precise WDS measurements of the K_α doublet are, however, available and yield smaller natural widths [16–20]. Wollmann *et al.* have performed a more detailed analysis on their K_α spectra obtained with a bolometer made by an Ag absorber and a transition edge strip as the thermal sensor [12]. By deconvolving their K_α with the natural widths determined by Shnopper, they obtain an instrumental Gaussian resolution of 6.4 ± 0.4 eV. This is better than the heat-pulse energy resolution itself. When using, however, the natural width from the WDS experiment by Lee and Salem [16] their instrumental resolution becomes 7.2 ± 0.4 eV. In Table I we report the results of our measurements and compare them with those obtained by the most resolving energy dispersive detectors. In addition to the deconvolution according to Shnopper, we consider for our experiment the results of Lee and Salem, and the more recent ones of Holzer *et al.* [20]. The instrumental resolution of our two bolometers is the same, thus indicating the reproducibility of our technique, while the long running times shows the stability of their gain.

Two peaks appear in the K_β region of ^{55}Mn, as shown in Fig. 2, where only the spectrum of the bolometer with a longer running time is reported. The upper one lies at 6.490 keV, in agreement with the average value for the $K_{\beta_{1,3}}$ doublet [20,21] whose separation is about 3 eV [17,20,22,23]. We are obviously unable to resolve this doublet. The presence of the satellite $K_{\beta'}$ peak at lower energy has already been reported in WDS [15,17,22,23], but never in energy dispersive spectroscopy (EDS) measurements. Fitting the doublet and the satellite peak, we obtain a $K_{\beta_{1,3}} - K_{\beta'}$ energy shift of 16 ± 1 eV, in reasonable agreement with the above-mentioned WDS experiments.

We would like to stress that, even if the resolutions of our detectors are the best so far obtained in energy dispersive x-ray spectrometry, there is still some space for further improvements. This could be achieved, for instance, by a reduction of the electronic noise, by optimization of thermistor sensitivity and geometry, and by a better choice of the absorber itself and/or a reduction of its thickness. It therefore seems possible to reach resolutions comparable to those of wavelength dispersive spectrometers with obvious advantages offered by high efficiency single quantum detectors.

TABLE I. Instrumental resolution (FWHM) of the most resolving energy dispersive spectrometers on the K_α lines of ^{55}Mn (eV).

Experiment	Deconvolution with WDS data of Ref. [14]	Deconvolution with WDS data of Ref. [15]	Deconvolution with WDS data of Ref. [20]
McCammon *et al.* [3]	7.3 ± 0.4	⋯	⋯
Silver *et al.* [11]	7.1 ± 0.7	⋯	⋯
Wollmann *et al.* [12]	6.4 ± 0.4	7.2 ± 0.4	⋯
This expt (Bolometer 1)	4.5 ± 0.2	5.5 ± 0.2	5.2 ± 0.2
This expt (Bolometer 2)	4.9 ± 0.1	5.7 ± 0.1	5.4 ± 0.1

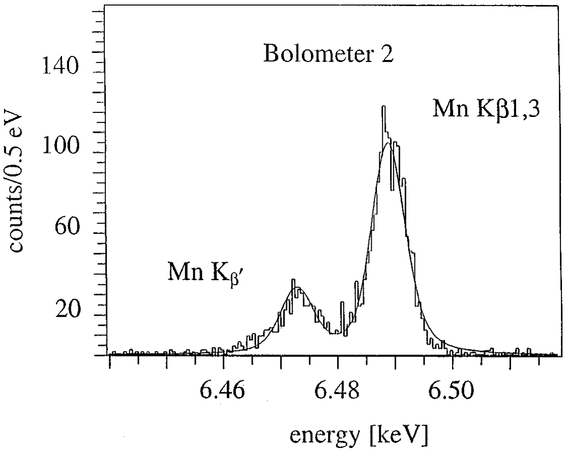

FIG. 2. Spectrum obtained with the second bolometer in the K_β region.

The results of the measurements reported here show that energy dispersive bolometric detectors can perform x-ray spectroscopy with a resolution approaching that of Bragg crystals. This may lead to a broad range of applications in x-ray astronomy, in fluorescence analysis of materials, and even in a totally different subject such as biomolecule spectroscopy [24–26]. In nuclear and subnuclear physics these microbolometers provide a powerful tool for the search for a nonzero neutrino and antineutrino mass or to detect solar neutrinos. Experiments on low energy e captures such as those of ^{7}Be, ^{183}Ho [27] and ^{71}Ge and ^{37}Ar [28], or on β decays such as that of ^{187}Re [13,27], are typical examples.

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