Magnetic calorimeters for high resolution x-ray spectroscopy

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Abstract

Magnetic calorimeters for x-ray detection consist of an x-ray absorber, which is strongly coupled to a paramagnetic temperature sensor located in a small magnetic field. The energy deposition of an incident particle leads to a change of the absorber temperature and thus to a change of the magnetization of the sensor, which can be measured with high resolution using a sensitive DC-SQUID magnetometer. The performance of metallic magnetic calorimeters based on the paramagnetic alloy Au:Er has improved rapidly and has now reached a level where various applications are conceivable. We discuss the principle of operation of magnetic calorimeters and the design and performance of prototype detectors for x-ray detection.

Key words: low-temperature detectors; magnetic calorimeters, x-ray detection

High resolution x-ray spectroscopy is one of several important applications of low-temperature microcalorimeters. In the past decade, x-ray fluorescence spectroscopy for material analysis and x-ray astronomy have been the driving motivations for the development of such detectors. The leading techniques today are semiconductor thermistors, superconducting edge transition detectors, superconducting tunneling junctions and magnetic calorimeters. Energy resolutions better by more than a factor of ten in comparison to conventional ionization detectors have been demonstrated with each of these techniques (e.g. [1–4]).

Here we report the recent progress that has been made in the development of magnetic calorimeters. Such detectors consist of an x-ray absorber and a paramagnetic sensor which is located in a small magnetic field and serves as a thermometer. These two components are strongly coupled together thermally and weakly coupled to a thermal bath. The energy deposition of an incident x-ray quanta produces a change in the absorber temperature and thus a change of the magnetization of the sensor. The variation of the magnetization can be measured with high resolution using a sensitive dc-SQUID magnetometer.

The insert of Fig. 1 shows schematically the prototype of a two-pixel magnetic calorimeter, consisting of a commercial micro susceptometer [5] in which two small discs of Au:Er (diameter 50 µm, thickness 25 µm) are placed directly into the loops of a dc-SQUID gradiometer. The Au:Er discs are attached with a thin layer of vacuum grease to the substrate and serve as both, paramagnetic sensor and absorber, having a quantum efficiency of approximately 100% at 6 keV. Note that the low-temperature properties of gold doped with small amounts of erbium have been studied extensively in the past years with respect to its use in magnetic calorimeters and that a detailed understanding of its thermodynamic properties exists [4,6]. The resulting flux change of single 5.9 keV events into each of the two pixels are shown next to the sketch of the gradiometer in Fig. 1. The signal size and the thermalization time were equal for both pixels to within 10%. The detector was operated at 25 mK in a field of 2 mT. The thermalization time was roughly 10 ms due to the very weak thermal link via the vacuum grease. The pulse height spectrum obtained with this device using a ^{55}Fe source is shown in the lower part of Fig. 1. The K_α and K_β lines of ^{55}Mn

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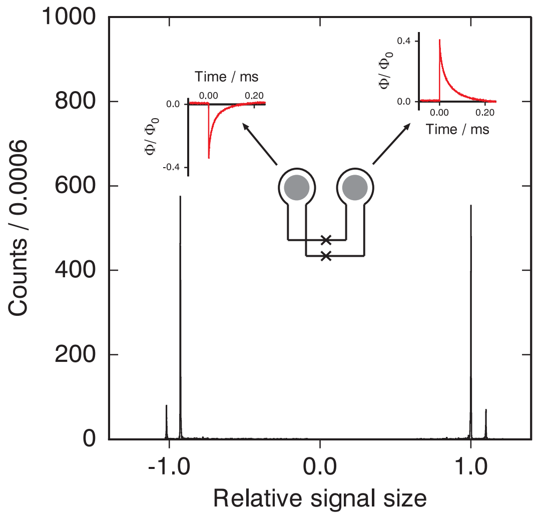

Fig. 1. Response of a two-pixel magnetic calorimeter. The insert schematically illustrates the set-up of the SQUID gradiometer with an Au:Er sensor in both loops. In addition, it shows a single pulse from each detector pixel. The lower part of the figure shows a pulse height distribution obtained with the two-pixel detector in an experiment with a ^{55}Fe source.

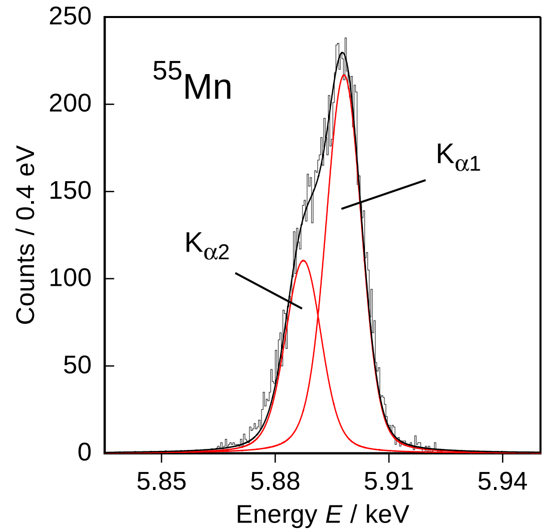

Fig. 2. K_α line of ^{55}Mn detected with the two-pixel magnetic calorimeter. The lines represent fits, which account for the instrumental resolution of 9 eV and the natural linewidth of $K_{\alpha 1}$ and $K_{\alpha 2}$ according to measurements with a wavelength dispersive spectrometer [7].

are clearly seen by both pixels. The pulse heights are plotted on a relative scale normalized to the K_α line measured with positive flux change. The rate into the two pixels were slightly different, because of a small difference in the collimator masks. The energy resolution at 6 keV is almost identical for both pixels, being about 9 eV. The slight difference in resolution observed in this experiment originated from the small difference in the signal size of the two pixels.

A blow up of the K_α line of the slightly better pixel is shown in Fig. 2 demonstrating that the fine structure of this line becomes evident with an instrumental resolution of 9 eV at FWHM. The shape of the experimental spectrum can be fitted very well with the sum of the expected $K_{\alpha 1}$ and $K_{\alpha 2}$ lines. The data were analyzed using an optimal filter. The baseline noise corresponded exactly to the measured instrumental resolution, indicating that the width of the lines are entirely determine by the noise of the measurement. The calculated thermodynamic fluctuations in connection with the white noise level of the SQUID perfectly account for the observed instrumental resolution. This means that no unidentified broadening mechanism exists at this level. The white flux noise of the SQUID was about $7\,\mu\Phi_0/\sqrt{\mathrm{Hz}}$ and limited the usable bandwidth in this measurement. In addition, we were forced to restrict the signal size to values below about $0.5\,\Phi_0$, because of the limited slew rate of our SQUID system.

If such a detector would be read out by a fast SQUID system with an effective flux noise level of $0.5\,\mu\Phi_0/\sqrt{\mathrm{Hz}}$ one should be able to improve the resolution to about 2 eV, which would be better than that of any other energy dispersive detector at the present time at 6 keV. To realize this we have developed a new read-out system for our detector SQUID using a second SQUID as an amplifier. In preliminary experiments, with no radioactive source installed, this new system has proven to possess the required low noise level.

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