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Development of a High-Resolution, Single-Photon X-Ray Detector

Summary of Research

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Research on the development of a low-temperature, magnetic bolometer for x-ray detection was initiated under NASA grant NAGW-4792 and is now continuing under grant NAG5-5133. The principal accomplishments during the first phase of this research are as follows. 1) We have constructed SQUID magnetometers and detected both 122 keV and 6 keV x-rays in relatively larger metallic samples with high quantum efficiency. 2) The magnetic properties of a metal sample with localized paramagnetic spins have been measured and found to agree with theoretical expectations. 3) The size of the magnetic response of the sample to x-rays is in agreement with predictions based on the properties of the sample and sensitivity of the magnetometer, supporting the prediction that a resolution of 1 eV at 10 keV should be achievable.

The first year of this program has been largely devoted to assembling equipment and building the necessary cryogenic instrumentation to allow us to perform measurements of the response of a variety of different materials upon the absorption of x-rays. We have constructed two separate SQUID magnetometers that are now being used to characterize the behavior of a systems of dilute localized paramagnetic ions in metals. These magnetometers are satisfactory for determining the magnetic properties of materials, but other more sensitive systems will be required for the development of a very high resolution detector.

To date we have focused our attention on the erbium-gold system. It was believed that this material has relatively weak indirect exchange coupling among the erbium ions. We have measured the static magnetization of 1000 ppm and of 100 ppm concentrations of Er in the host Au. The temperature range of measurements extended from 0.2 mK to 1 K. The measurements below 10 mK were performed for us by a group in Berlin, who are interested in these materials for low temperature thermometry. The spin glass transition for the 100 ppm sample occurs at 0.25 mK and the 1000 ppm sample at 4 mK. Of more relevance to this research project are measurements of the response of the materials to both 122 keV and 6 keV x-rays. The dependence of the magnetic signal was determined as a function of temperature and magnetic field, and the results were compared with theory based on a mean field calculation of the exchange interaction among randomly positioned Er ions in the Au lattice. We find excellent agreement between theory and experiment over the entire region of field and temperature space for the 100 ppm sample with one adjustable parameter, the magnitude of the coefficient of the Ruderman-Kittel exchange interaction. To obtain this agreement the exchange interaction is found to be about 7 times larger than the dipole-dipole interaction, both interactions decreasing with ion separation as $1/r^3$.

With a 100 ppm Er/Au sample, approximately 0.7 mm diameter and 0.7 mm thick we obtained a resolution at 10 mK of 400 eV at 6 keV. The resolution at 122 keV was 2.4 keV. Several observations of the measurements deserve comment. 1) The response time of the detector was 10 μs limited by the frequency response of the SQUID electronics. The intrinsic time constant of the Er/Au system is predicted to be less than 10^{-7} s at the temperature of the measurement. The thermal time constant for return of the temperature of the detector to equilibrium was $\sim$1 ms and determined by the coupling to the thermal reservoir. This can be reduced considerably using different bonding techniques. 2) The quantum efficiency for x-ray detection of a 0.7 mm thick Au detector is $\sim$1 for 122 keV photons. 3) The resolution at 122 keV was limited by the temperature stability of the apparatus. The resolution at 6 keV was limited by the noise of the SQUID electronics.

These measurements point the way to developing much more sensitive detectors. Firstly, materials with smaller exchange interactions among spins can achieve an improvement of at least 10. Secondly, smaller magnetic sensors coupled to large-area, low heat capacity, x-ray absorbers, such as bismuth can increase sensitivity by another factor of 10. Thirdly, improved coupling of the magnetization of the detector to the SQUID as well as lower noise electronics can result in a further increase of 5. Research on all these topics is continuing.

Publications:

"Study of Paramagnetic Metals for Use in Calorimetric Particle Detection", S. R. Bandler, C. Enss, J. Schönefeld and G. M. Seidel, Czech. J. Phys. 46 Suppl. S5, 2889 (1996).

No inventions have been made under this grant.