Dissipation less Anomalous Hall Current in the Ferromagnetic Spinel $CuCr_2Se_{4-x}Br_x$.

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Recommended and a commentary by J.R Cooper, Physics Department, University of Cambridge.

This paper reports a thorough and careful experimental study of the anomalous Hall effect (AHE) in single crystals of the ferromagneticspinel $CuCr_2Se_{4-x}Br_x$ for x values between 0 and 1. It is accompanied by an interesting and provocative analysis. The work is timely in view of modern approaches linking the AHE to the Berry phase and gauge fields (e.g. J. Ye et al. ref. 14), concepts that are also important in other areas of physics such as elementary particles.

Recall that the spinel structure is formed from a close-packed fcc lattice of anions (often oxygen, but in this case Se), in which one of the eight tetrahedral interstitial sites in the fcc unit cell is occupied by the A cation and two of the four octahedral interstitial sites by B cations. Insulating spinels are usually composed of A^{2+} ions and B^{3+} ions and even for this conducting spinel, J.B. Goodenough (ref. 23) suggests that there is an itinerant Cu 3d band with approximately 1 d-hole per Cu (i.e. ~ Cu^{2+} as in the cuprate superconductors) together with highly localised Cr^{3+} orbitals. Perhaps inevitably, band structure calculations (F. Ogata et al. ref. 25) disagree with this model and give an extremely complex multi-band structure.

The AHE has been studied extensively in classical metallic ferromagnets such as Fe, Ni and their alloys over many decades. Much of the older work is nicely summarised in an article by Campbell and Fert (1982). In short, the anomalous Hall voltage is proportional to the saturation magnetisation (M) of the ferromagnet, but it is typically 100-1000 times larger than would be expected from the product of internal magnetic flux density (at most μ_0M). and the normal Hall coefficient measured well above the Curie temperature. In the present case μ_0M corresponds to approx. 6 Bohr magnetons in $1nm^3$, i.e. 0.07T, so for the data in Fig. 2 the above factor is at least 140 for x = 0.25 and T= 5 K.

Broadly speaking the AHE in classical ferromagnetic alloys is thought to arise from the spin-orbit interaction, but as mentioned by the authors, despite many decades of research, the details have been very controversial. There are thought to be two distinct contributions. One is associated with the well-established, left-right asymmetry of a spin-polarised electron beam that is induced by scattering from an electrostatic potential (skew scattering or SK) and the other from an "anomalous" transverse velocity (AV) induced by the spin-orbit interaction, that was first proposed by Karplus and Luttinger (ref.3). The AV term corresponds to an extra "dissipationless" current density perpendicular both to the applied E field and to the magnetisation of the electron system, it depends only on the properties of the pure ferromagnet and is not affected by electron scattering from impurities. Because the Hall measurements are made on a long bar for which the net transverse current is zero, this anomalous current necessarily gives a Hall voltage that is proportional to ρ^2 where ρ is the measured electricalresistivity. (See Eqn. (4) in the authors' supporting on-line material.) On the other hand the Hall voltage from the skew scattering term is proportional to the residual resistivity $\rho.$ and its magnitude is determined by the properties of the different impurities. Significantly, for one particular impurity, Cu in Ni, the SK term is small, giving a concentration independent Hall angle as low as 0.002 radians, Fert and Jaoul (1972). Such a small SK term would hardly be detectable in the present experiments, even at x = 0.1.

The striking experimental result of the present paper is that, after making a correction for the changes in carrier concentration with x, the magnitude of anomalous Hall resistivity at 5 K varies as ρ^n, with n = 1.95 +/- 0.08, over at least two decades variation in ρ. This is despite the fact that there is a sign-change in the anomalous Hall voltage, and therefore a zero somewhere between x=0.25 and x=0.5, that the authors attribute to a change in the sign of the spin-orbit coupling constant as the Fermi energy changes with x. The authors emphasise that this is the first time that such a result has been obtained for any ferromagnet in the "residual resistivity" region at low temperatures and therefore they regard it as the most convincing evidence to date for the AV term in the anomalous Hall voltage. It must be said that many earlier investigators realised that there was a significant ρ^2 term in the AHE both at higher temperatures and for higher impurity concentrations at low temperatures and often ascribed it to the AV effect. In the present case, perhaps because of the nature of the Br dopant, the anomalous velocity term is much larger than any skew scattering term at low temperatures. Therefore it could be useful to explore the differences between $CuCr_2Se_{4-x}Br_x$ and classical ferromagnets further by carrying out similar analyses for all the higher temperature data that the authors have obtained.

It should be noted that if one accepts that the Cr d orbitals are conducting and that there are several bands conducting in parallel, then it is probable that the high temperature or normal Hall constant does not give a very reliable guide to the carrier concentration (n_h). If the n_h factor were not included in Fig. 4 then the exponent n would be somewhat lower, 1.7 rather than 2 and perhaps the data could be better fitted by an $a\rho + b\rho^2$ law of the type used for classical ferromagnets. If on the other hand, the model of Goodenough applies then the normal Hall constant is determined by the mobile carriers in the single, weakly spin-polarised Cu 3d band, and the correction involving n_h would be more justified. Moreover the strong effects of doping with Br (removing holes from the Cu 3d band) would be easier to understand. In this case one would be dealing with weakly magnetic carriers moving in a background of ordered Cr spins, and some slight modifications of the AHE theory would be required, perhaps using the modern approach by J. Ye et al. (ref.14).

Despite the above caveats the paper clearly shows that for this compound an intrinsic transverse current dominates the AHE over a wide range of ρ. The authors conclude with the intriguing suggestion that the AHE can be used to drive spin currents that could be useful in spintronic or “spin-valve” memory devices.

References:

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