Orbital Magnetization and the Anomalous Hall Effect in (Ga,Mn)As

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As shown over recent years, orbital magnetization and the anomalous Hall conductivity in a crystalline magnetic material comprise quantities directly related to the geometric properties of the material band structure, namely to the Berry curvature of the bundle of electronic Bloch functions. The "modern approach" based on this connection provides a way to compute the two quantities efficiently, either *ab initio* [1] or employing experimentally determined *k.p* parameters [2,3], circumventing the need for explicit diagonalization of the magnetic-field-dependent Schrödinger operator.

The purpose of this contribution is to communicate our recent work [2], which extends the fundamental results presented earlier. This includes:
1. We highlight the formula for orbital magnetization M_{orb}, which gives M_{orb} in terms of the velocity matrix elements (rather than in terms of derivatives of Bloch or Wannier functions), with no singularities in the integrand – thanks to a proper antisymmetrization.
2. We restate that the correctness of the modern approach can be verified by computing M_{orb} from the partition function Z of carriers in the Landau levels for bands in question (the Landau method).
3. This verification, applied to holes in ferromagnetic (Ga,Mn)As, reveals that the standard six band Kohn-Luttinger method, suitable to obtain accurate values of eigenvalues, does not provide – within the modern approach – proper values of M_{orb}, as its determination requires accurate information not only on the eigenvalues but also on the eigenfunction.
4. We propose a numerically efficient method that combines advantages of the modern and the Landau approaches.
5. Exploiting this new method we explain the sign and small magnitudes of M_{orb} observed experimentally by XMCD for (Ga,Mn)As and (Ga,In,Mn)As [4]. We describe also changes of the chemical potential with the magnetic field, determined from studies of the Coulomb blockade in a single electron transistor containing a (Ga,Mn)As gate [5].

Furthermore, we have found that rather the localized part than the itinerant part of the orbital magnetization is sensitive to the form of the wave functions. This suggests that the numerical magnitudes of the Berry curvature, to which the itinerant part of the orbital magnetization as well as the intrinsic anomalous Hall conductivity are proportional, can be obtained within a finite basis Kohn-Luttinger method.

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