Linear and nonlinear Hall effect in the spin-density wave phase of $(\text{TMTSF})_2\text{AsF}_6$

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Measurements of the Hall effect at low electric fields in the metallic and spin-density wave (SDW) phases in $(\text{TMTSF})_2\text{AsF}_6$ shows that the scattering of single particles is strongly reduced in the SDW phase. This is attributed to a strong electron-electron scattering present in the metallic phase and absent in the SDW phase.

Above the depinning threshold field for the nonlinear SDW conductivity the Hall voltage is a reliable measure of the quasiparticle current. This current is reduced above the depinning threshold because of the backflow of quasiparticles due to the interaction with the moving SDW. At 4.2 K the backflow coefficient is comparable to what is observed in CDW systems.

The spin-density wave (SDW) state can, very much like the charge-density wave state, give rise to a collective mode conduction. The Bechgaard salts $(\text{TMTSF})_2\text{X}$, where TMTSF is tetramethyl-tetraselenafulvalene and X is a monovalent anion, i.e., PF_6 , AsF_6 , SbF_6 , ClO_4 , NO_3 , provide a set of model systems for the study of the collective mode of the SDW [1]. Above the depinning threshold field the damping of the SDW motion is described by a mechanism where dynamic deformations of the density wave (DW) create local charge fluctuations that are screened by the thermally excited "normal" electrons. The Hall effect can provide more information on the interaction between the moving SDW and the normal electrons.

At low electric fields the Hall effect gives an estimate of the number of conduction electrons. Above the depinning threshold field the total current is given by the sum of the current from the sliding SDW and the current from the normal electrons. It is normally assumed that the normal current is linear in the electric field, and this is used to determine the magnitude of two currents. However, assuming a constant Hall coefficient, one can determine the normal current by measuring the Hall voltage. Since the sliding motion of the SDW is assumed to be strictly one-dimensional, it does not directly contribute to the Hall voltage which is then entirely due to the normal electrons [2, 3]. It was however predicted [4] and later found in Hall effect measurements on CDW systems that there is a certain backflow of normal electrons, proportional to the CDW current [5, 6, 7]. Such a backflow is again a striking manifestation of the interaction of the density wave with the normal electrons [4].

In this article we present measurements of the Hall effect in the metallic and SDW phases of $(\text{TMTSF})_2\text{AsF}_6$. The low electric field Hall constant shows a large increase of mobility from the metallic to the SDW phase. We ascribe this to a significant electron-electron scattering in the metallic phase, suppressed in the SDW phase. In the SDW phase, above the depinning threshold, the Hall effect shows that there is a strong backflow of normal electrons similar to what has been seen in CDW systems.

Samples were prepared by the standard electrocrystallisation method by C. Lenoir and P. Batail. A single crystal of dimensions $2.5 \times 0.45 \times 0.125 \text{ mm}^3$ was chosen. Gold pads were evaporated on the ends for the current contacts, and a pair of gold pads were evaporated on each side of the sample for measurements

Fig. 1

Fig. 2

Figure 1: a) Longitudinal resistivity ρ and b) Hall resistivity $\rho_H = E_t/j_l$, both normalised to the zero field resistivity ρ_0 as a function of magnetic field at different temperatures.

Figure 2: Arrhenius plot of the Hall coefficient $R'_H = \rho_H(7 \text{ T})/7 \text{ T}$ and the resistivity.

of longitudinal and transverse voltages. The sample was mounted with clamped contacts for the current leads, and silver paint contacts for the voltage contacts on the sides of the sample. During cooling only minor anomalies were seen in the resistance due to micro-cracks due to the silver paint contacts. The configuration of the measurement was thus the following: the current was along the highly conducting a -axis; the transverse voltage was measured in the a - b plane, transverse to the conducting chains; finally the magnetic field was in the c^* direction, perpendicular to the a - b plane. Because of the possible misalignment of the Hall contacts, measurements were taken with the field pointing up and down, and then symmetrised to remove any contribution from the magnetoresistance to the transverse voltage, giving a transverse electric field E_t . For the measurements of transverse and longitudinal field, E_t and E_l , as a function of electric current, j_l , a lock-in technique was used at low fields, while a pulsed technique was used at high fields to avoid heating.

On Fig. 1 we show the longitudinal normal resistivity $\rho = E_l/j_l$ and the Hall resistivity $\rho_H = E_t/j_l$ as a function of magnetic field at low electric fields. A marked plateau in the magnetoresistance [8] and a peak in the Hall resistance around 3 T weakens below 4.2 K. Although it does not explain the peak in the Hall resistance, the two features could be related in the way that a huge peak in the Hall resistivity influences on the measurements of the longitudinal voltage because of finite sample dimensions [9]. The shape of the Hall resistivity makes the Hall coefficient, ρ_H/H , field dependent. For a systematic evaluation as a function of temperature we chose the value $R'_H = \rho_H(7 \text{ T})/7 \text{ T}$. At 4.2 K this gives a Hall coefficient $R'_H = 5 \times 10^{-5} \text{ m}^3/\text{C}$, corresponding to a carrier concentration of $n \sim 10^{23} \text{ m}^{-3}$, in good agreement with what one would expect for a quasi one-dimensional semiconductor with a gap of $\Delta = 21 \text{ K}$. In a previous study [10] of the Hall effect in $(\text{TMTSF})_2\text{PF}_6$ with the magnetic field along the b axis the carrier concentration was found to be one order of magnitude lower. No anomaly around 3 T was detected in the Hall resistance (however a weak feature can be seen in the magnetoresistance with the magnetic field along the c^* axis). The angle of the magnetic field is however an important parameter as the magnetoresistance is highly angle dependent [8], and this might explain the difference between the two Hall effect measurements.

In the metallic phase the Hall field is linear in the magnetic field, and the Hall coefficient $R_H = E_t/j_l H$ is well defined and equal to $R_H = 1.9 \times 10^{-9} \text{ m}^3/\text{C}$ at both 31 K and 41 K. The sign of the Hall coefficient gives electrons as the charge carriers. Assuming a single type of carrier this gives a carrier density of $n = 3.3 \times 10^{27} \text{ m}^{-3}$ in reasonably good agreement with the expected value of one conduction electron per unit cell: $n = 1/V_{\text{unitcell}} = 1.39 \times 10^{27} \text{ m}^{-3}$. The Hall coefficient as a function of temperature is shown in Fig. 2 together with the resistivity. In the semiconducting phase the Hall coefficient shows, as expected, an

Fig. 3

Figure 3: Differential resistance dV_l/dI and differential Hall resistance dV_t/dI as a function of the current.

Fig. 4

Figure 4: Total current density j_{tot} and normal current density $j_n = E_t/\rho_H$ and SDW current density as a function of electric field. The dashed line is the extrapolation of the low field linear current. The backflow current j_b (see text) is proportional to the SDW current j_{SDW} (inset), with a proportionality constant of 0.2.

activated behaviour with the same gap as the resistivity, and a constant Hall mobility $\mu_H = 3.1 \times 10^4 \text{ cm}^2/\text{Vs}$. In the metallic phase the Hall mobility is considerably lower, $\mu_H = 26 \text{ cm}^2/\text{Vs}$. Going from the metallic phase to the SDW phase there is thus an increase in the mobility of three orders of magnitude.

The Hall effect and longitudinal conductivity was measured at 4.2 K at several magnetic fields. In the Fig. 3 we show a measurements of differential resistance and differential Hall resistance as a function of longitudinal current at 12 T. A well defined threshold field is seen at a current corresponding to around 2 mV/cm. The two curves have the same shape, however the Hall effect shows a slightly bigger non linearity. The normal current density is given by $j_n = E_t/\rho_H$ and plotted in Fig. 4 together with the total current j_{tot} as a function of the longitudinal voltage. The actual current from the normal electrons is described by $j_n = j_{lin} - j_b$, where $j_{lin} = E_t/\rho_n$ is a current linear in the longitudinal voltage and j_b is an effective backflow current, proportional to the SDW current. From the Fig. 4 we find a backflow proportional to the SDW current, $j_b = \alpha j_{SDW}$, with the backflow coefficient $\alpha = 0.2$. The values for α at 1 T and 3 T are somewhat higher, around 0.4.

A backflow coefficient of 0.2 is close to what has been observed in CDW systems [5, 6, 7, 11]. Clearly the similarity of these numbers shows that the backflow effect is an intrinsic feature of the interaction between a density wave and normal electrons in a two fluid model. A fundamental element in the theory of the backflow [4] is the change in the interaction between quasi-particles and impurities due to the moving DW reference frame. At two times threshold the velocity of the SDW is however typically four orders of magnitude smaller than the drift velocity of the quasi-particles. We therefore believe [12] that the backflow is related to the quasi-particle screening of SDW deformations, that is that the damping of the SDW current and the backflow has the same origin.

An important effect of the backflow is that if one assumes a linear normal current, one will underestimate the amount of SDW current. This can partly explain a “missing” current in recent NMR and “narrow band noise” measurements of the SDW sliding [13].

A radically higher mobility in the SDW phase than in the metallic phase is the sign of a strong electron-electron scattering in the metallic phase. Contrary to other scattering mechanisms, electron-electron scattering is expected to be suppressed by the change in electronic structure due to the SDW transition. A similar effect is also seen at the superconducting transition in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ [14, 15]. A large electron-electron scattering in $(\text{TMTSF})_2\text{X}$ has been proposed on the basis of other physical properties, i.e., a resistivity that

goes as $\rho = \rho_0 + AT^2$ [16], and a magnetoresistance and a sensitivity to disorder that is much bigger in the SDW phase than in the metallic phase [17]. A strong electron-electron scattering will only influence the transport properties in presence of a big probability for Umklapp scattering, and this is favoured by the half filled band in the Bechgaard salts, together with the relatively small bandwidth [18].

In conclusion we have seen that the Hall coefficient in the metallic and SDW phases support a picture with a large electron-electron scattering in the metallic phase, but absent in the SDW phase. The nonlinear Hall effect gives a large backflow of normal carriers, proportional to the SDW current, with the backflow coefficient $\alpha = 0.2$. This is similar to what has been seen in CDW systems, and this underscores that the effect is intrinsic to the interaction between normal carriers and the moving CDW.

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