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Hall effect in the pinned and sliding charge density wave state of $NbSe_3$

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Abstract
Results of Hall effect measurements are reported both below and above the threshold electric field, E_t, for depinning the low temperature charge density wave (CDW) in $NbSe_3$ in a wide temperature range. At low electric fields, below E_t, we have observed a change in the sign of the Hall voltage at all temperatures lower than T_{p2}. Comparison between the Hall effect and the magnetoresistance behavior indicates that the n-type conductivity in the low magnetic field range differs qualitatively from the p-type conductivity in the high field range. We demonstrate that at low temperature the CDW motion significantly alters the Hall voltage. These results indicate that, in $NbSe_3$, the CDW in the sliding state interacts essentially with holes. Possible mechanisms of this effect are discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

$NbSe_3$ is the most thoroughly studied charge density wave (CDW) material; its collective CDW sliding has been discovered and investigated over a period of more than three decades. Nevertheless, the development of new experimental methods in recent years has brought many new results, allowing the investigation of unresolved or contradictory issues. The recent successes [1] come from special x-ray and tunneling experiments, from high quality ARPES [2, 3] and scanning tunneling microscopy (STM) [4], and from studies in high magnetic field. The present work is devoted to the kinetics of $NbSe_3$ in magnetic fields which happens to revise a seemingly established picture of normal carriers and their participation in the collective CDW motion.

$NbSe_3$, a layered quasi-one-dimensional (Q1D) conductor, exhibits two incommensurate charge density wave (CDW) transitions at $T_{p1} = 145$ K and $T_{p2} = 59$ K [5–7]. In contrast to most CDW systems, the Peierls transitions in this material are not complete and ungapped carriers remain in small pockets at the Fermi level; this is confirmed by the observation of Shubnikov–de Haas (SdH) oscillations below T_{p2} with the magnetic field, H, applied perpendicular to the conducting chains [8–14]. As a result, $NbSe_3$ keeps metallic or semimetallic properties down to the lowest temperatures.

Results of Hall effect measurements in $NbSe_3$ in the low electric field region, $E < E_t$, have been reported in [8, 13, 15–18]. In the first Hall effect experiment [16], it was observed that the Hall constant in the zero field limit changes sign from n-type to p-type at 15 K, a result explained in the frame of a two-band model [18] in which the difference in population $n_p - n_n$ is equal to 3×10^{18} cm^{-3} below T_{p2}. In later Hall effect experiments [8], in fact, a field-induced change of the Hall voltage sign was observed in a wide temperature range beginning from the lowest temperature (1.1 K). With the increase of temperature this zero crossing point moves continuously to higher magnetic field. From these results it follows that the zero crossing of the Hall voltage is both magnetic field and temperature dependent. Recent measurements of Hall effect as well as of transverse magnetoresistance [15] confirm the experimental results of Coleman *et al* [8]. In [8] a qualitative explanation of the zero crossing of the Hall constant was proposed based on the Balseiro–Falicov model [19, 20]; this model predicts a magnetic field-induced condensation of normal carriers into the CDW ground state. However, the validity of this model was not confirmed experimentally for $NbSe_3$. Many experiments did not reveal any magnetic field-induced condensation of the non-condensed remaining carriers into the CDW [21–23] while a similar effect is easily observed as field-induced spin density waves in organic conductors [24].

The effect of the CDW sliding on the Hall constant was investigated in TaS_3 [25], $K_{0.3}MoO_3$ [26], and $NbSe_3$ [27]. For TaS_3 and $K_{0.3}MoO_3$ it was found that the Hall voltage decreases when the CDW threshold field, E_t, was exceeded. For both compounds the results were interpreted in the frame of the microscopic theory proposed in [28]. Assuming that the CDW itself gives no detectable contribution to the Hall voltage, it was shown that, because of the scattering of the normal carriers by impurities, the motion of the CDW effectively induces a normal electron current in the reverse direction, a so-called 'back-flow' of normal carriers; this 'back-flow current' is proportional to the CDW current, I_{CDW}, thus, always leading to an effective reduction of V_H. This theory [28] predicts that the same effect should be observed also in $NbSe_3$, especially at temperatures close to T_p. However, the available experimental results [27] showed that, although the Hall coefficient in $NbSe_3$, R_H, defined as V_H/I_T, where I_T is the total current, decreases strongly above E_t, the CDW gave no visible contribution to the Hall effect in this field region. Indeed, at $E > E_t$ the Hall voltage remained proportional to the current carried by the normal carriers. All the changes in R_H were explained by the contribution to R_H coming from the longitudinal conductivity. This was demonstrated by observing that the ratio V_H/V_L, where V_L is the longitudinal voltage, remained constant in all the investigated electric field region. Note that in [27] the measurements were performed at temperatures $T > 34$ K and at relatively low magnetic fields, $B < 1.5$ T.

Hereafter we describe results of detailed investigations of the Hall effect in $NbSe_3$ in a wide range of temperatures and at magnetic fields up to $B = 9$ T. We demonstrate that the magnetoresistance $R_{xx}(B)$ changes qualitatively when R_{xy} changes its sign, indicating a different contribution to the magnetic field for holes and electrons. We show that at low temperatures and in high magnetic fields the CDW motion significantly alters the Hall voltage.

2. Experimental details

For the experiment we selected high quality thin (with a thickness 0.8–1.1 μm) $NbSe_3$ single-crystals with a residual resistance ratio $R_{300\ K}/R_{4.2\ K} = 30$–50. The threshold electric field for the CDW motion for different samples varied from 100 to 500 mV cm^{-1} at $T = 25$ K.

In the standard configuration the Hall voltage in CDW compounds is measured with a single pair of contacts on the opposite faces of the investigated crystal. The orientation of the magnetic field is perpendicular to the chain direction. As usual, normal metal evaporation or silver (gold) paint is used for contact preparation. In our case, such a configuration is suitable for successfully measuring the Hall effect at low longitudinal electric field ($E < E_t$) [8, 16]. However, using this configuration in the case of the sliding CDW state raises some problems. It was shown [29] that normal metal contacts strongly perturb the CDW conduction leading to an effective increase of E_t in the contact region. We then used the following configuration: two gold contacts with a width less than 20 μm were evaporated on a small part (<5 μm) of one face of

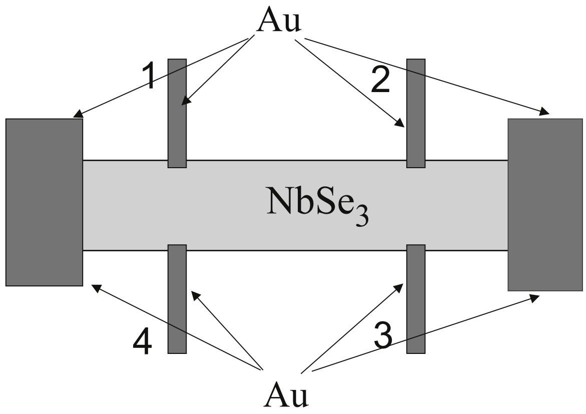

Figure 1. Sketch of the sample geometry for Hall measurements.

the (b, c) plane of the crystal and similar contacts on the opposite face as shown schematically in figure 1. Current is applied along the b-axis and magnetic field is oriented perpendicular to the $(b$–$c)$ plane of the crystal. To minimize the perturbation by the normal metal contacts on the CDW, a longitudinal distance (along the chains) typically of the order of a few hundreds μm separates the two pairs of contacts. To measure V_H and V_L simultaneously the measurements were performed for both magnetic field polarities. The change in voltage on the Hall pairs of contacts $[V_{1,3}(+B) - V_{1,3}(-B)]/2$ or $[V_{2,4}(+B) - V_{2,4}(-B)]/2$ was taken to be equal to the Hall voltage, V_H, and the sum $[V_{1,3}(+B) + V_{1,3}(-B)]/2$ or $[V_{2,4}(+B)+V_{2,4}(-B)]/2$ was taken as the longitudinal drop of voltage. Using this method we first minimize the influence of contacts on the Hall effect and second exclude the Hall voltage contribution to the longitudinal one.

All experiments were carried out using dc techniques in a helium-gas medium. At each temperature the Hall voltage was measured at 15 values of B in the magnetic field range 0–9 T, by sweeping the current from $-I_0$ to $+I_0$. Below threshold we determined the Hall resistance as $R_{xy} = V_H/I$. In this case I_0 was at least one order of magnitude less than the threshold current for CDW sliding. The Hall voltage is a linear function of current in this case [27]. At $E > E_t$ the determination of the Hall resistance using the relation V_H/I, where I is the total current, is not correct because, first, the CDW motion itself should not give any contribution to the Hall voltage and, second, the Hall voltage as expected may be a nonlinear function of the current [27]. The Hall voltage is then plotted as a function of the longitudinal voltage [26, 25].

3. Experimental results

It was shown in [8, 15] that R_{xy} is strongly magnetic field dependent and demonstrates the reversal of the Hall constant sign (see figure 1 in [15]). The inset of figure 2 shows, as an example, the $R_{xy}(B)$ dependence measured at 25 K. The temperature dependence of the magnetic field B_{zc} corresponding to $R_{xy} = 0$ is shown in figure 2 by solid circles. As can be seen, B_{zc} increases monotonically with the increase of temperature. The experimental data are well fitted by the

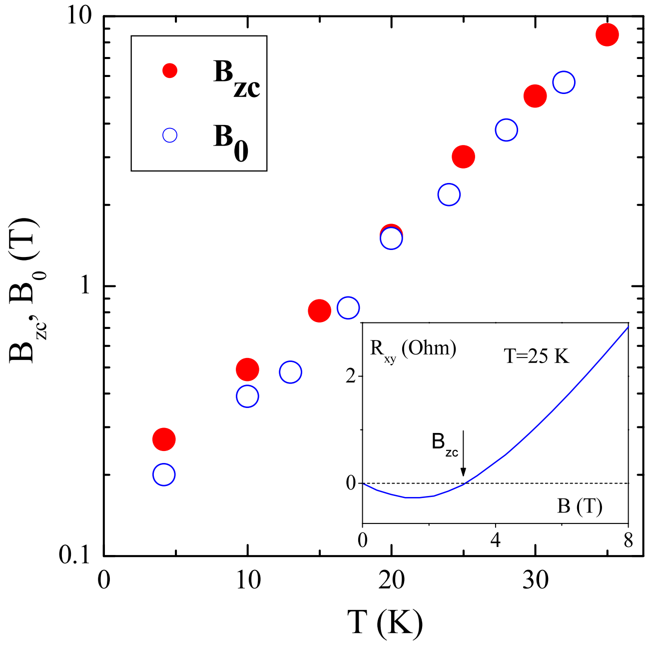

Figure 2. Temperature dependence of the magnetic fields B_{zc} corresponding to zero Hall resistance (solid circles), $R_{xy} = 0$ for $NbSe_3$ and the magnetic field B_0 corresponding to the maximum of dR_{xx}/dB measured in another $NbSe_3$ single crystal (open circles). The inset shows $R_{xy}(B)$ at $T = 25$ K.

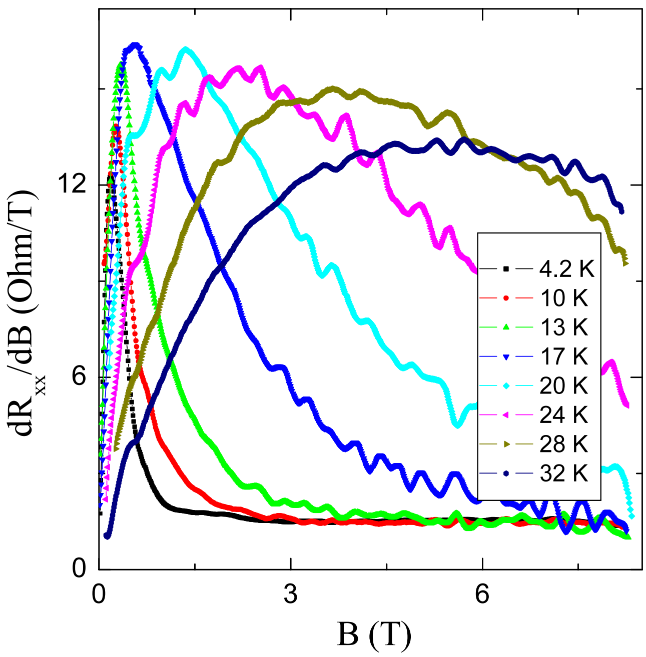

Figure 3. Magnetic field dependence of $dR_{xx}/dB(B)$ for a $NbSe_3$ single crystal at temperatures: 4.2, 10, 13, 17, 20, 24, 28, and 32 K.

function $B_{zc}(T) = B(0)\exp(T/T_0)$, where $B(0) = 0.17$ T and $T_0 = 8.9$ K. Note that the temperature dependence at low temperature of E_t follows qualitatively the same dependence such as $E_t(T) \propto \exp(T/T_0')$ with $T_0' = 8$ K for bulk $NbSe_3$ [30, 31].

It is interesting to compare the results for the Hall effect with the magnetoresistance measurements. It is well known that $R_{xx}(B)$ is proportional to B^2 at low field and to B in the high field region [8, 10, 12]. The dependences $dR_{xx}(B)/dB$ for $B \parallel a^*$ and $I \parallel b$ at different temperatures for a $NbSe_3$ single crystal are shown in figure 3. As can be seen, dR_{xx}/dB has a maximum at a certain field B_0. The normalized variation of $R_{xx}(B)/R_{xx}(0)$ as a function of the normalized field B/B_0 for the same sample as in figure 3 and at the same temperatures is shown in figure 4. For all temperatures these normalized dependences collapse in a unique curve, demonstrating the universal magnetoresistance behavior. Thus, below B_0 the magnetoresistance is proportional to B^2 while $R_{xx} \sim B$ at $B > B_0$. The temperature dependence of B_0 is shown in figure 2 by open circles. It can be seen that the temperature dependences of $B_{zc}(T)$ and $B_0(T)$ practically coincide and one can conclude that $B_{zc}(T) \approx B_0(T)$. Formally it means that the magnetoresistance for n-type conductivity (low field range) differs qualitatively from the magnetoresistance for p-type conductivity (high field range).

The correct investigation of the Hall effect in the sliding CDW state needs to take into account the possible threshold electric field dependence on magnetic field. As it was reported [32], at low temperature, E_t exhibits a strong magnetic field dependence. In our case, for all the samples for which we measured differential current–voltage characteristics (IVc),

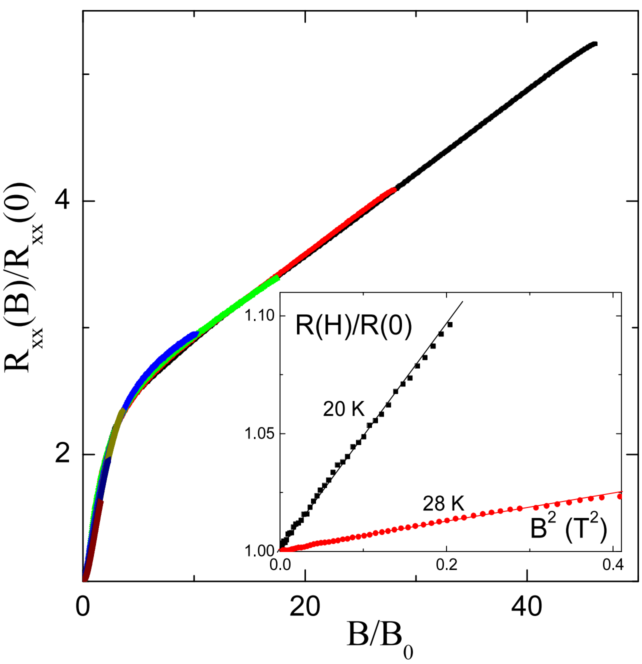

Figure 4. Variation of the normalized magnetoresistance $R_{xx}(B)/R_{xx}(0)$ as a function of the normalized magnetic field for the same $NbSe_3$ sample as in figure 3 and at the same temperatures. the inset shows the $R_{xx}(B^2)/R(0)$ at low magnetic field for $T = 20$ and 28 K, demonstrating square dependence of magnetoresistance in this field region.

we have found that, at least at temperatures above 25 K, E_t is independent of H. The behavior of E_t under magnetic field at temperatures below 25 K will be the subject of a separate publication. In the present paper we will consider only the temperature range above $T = 25$ K where no effect of H on E_t is detectable.

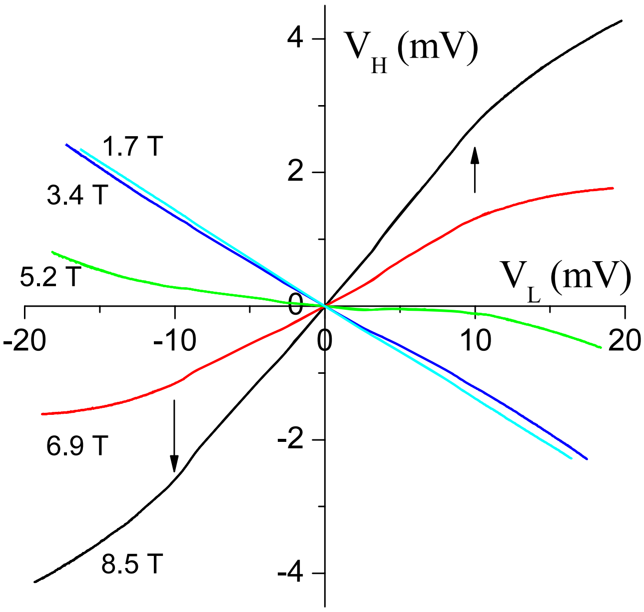

Figure 5. Hall voltage, V_H, as a function of the longitudinal drop of voltage, V_L, at $T = 30$ K for $NbSe_3$ at different magnetic fields. Arrows indicate the position of the threshold voltage.

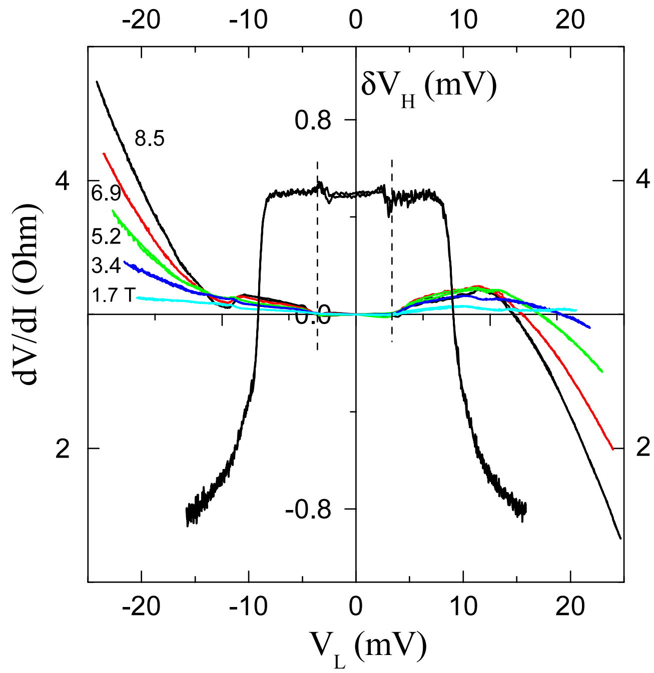

Figure 6. Differential resistance, $R_d = dV/dI$, and deviation of the Hall voltage, $\delta V_H = V_H - V_{lin}$, from a linear dependence as a function of the longitudinal drop of voltage for the same sample as shown in figure 5 and at the same magnetic fields. Dashed lines indicate the singularities of $dV/dI\,(V_L)$ corresponding to the deformation of the static CDW.

We measured the Hall effect in the temperature range from 25 to 50 K. However, in the study of the Hall effect in the sliding CDW state the most interesting temperature range is that close to $T \approx 25$–30 K for which $B_{zc} \approx 5$–6 T is near the middle of the investigated magnetic field range. In this case it is possible to find out the influence of the CDW sliding on both types of normal carriers in conductivity.

Figure 5 shows the Hall voltage, V_H, as a function of the longitudinal drop in voltage, V_L, at 30 K and at different magnetic fields. It can be seen that, at $B = 1.7$ T, the $V_H(V_L)$ dependence is practically linear in the whole current range, below and above the threshold. That is in agreement with the results of Tessema and Ong [27] performed at $B < 1.5$ T. However, at higher magnetic field a strong deviation from linearity is observed.

To emphasize this effect more, we have determined the difference $\delta V_H = V_H - V_{lin}$, where the last term is the linear Hall voltage observed at low electric field below E_t. Figure 6 shows the $\delta V_H(V_L)$ dependences for the same sample as in figure 5 at the same magnetic fields.

Qualitatively the same dependences were observed for all the samples we investigated. When the temperature is increased, the deviation from the linear dependence observed at E_t decreases monotonically. Figure 7 demonstrates, at the applied field $B = 8.5$ T, the deviation δV_H measured at $E = 2E_t$, at $E = 4E_t$, and at $E = 2E_t$ for another sample. The experimental data are well fitted by the function $\delta V_H = A \exp(-T/T_{o1})$ (dashed line), where $T_{o1} \approx 3.4$ K.

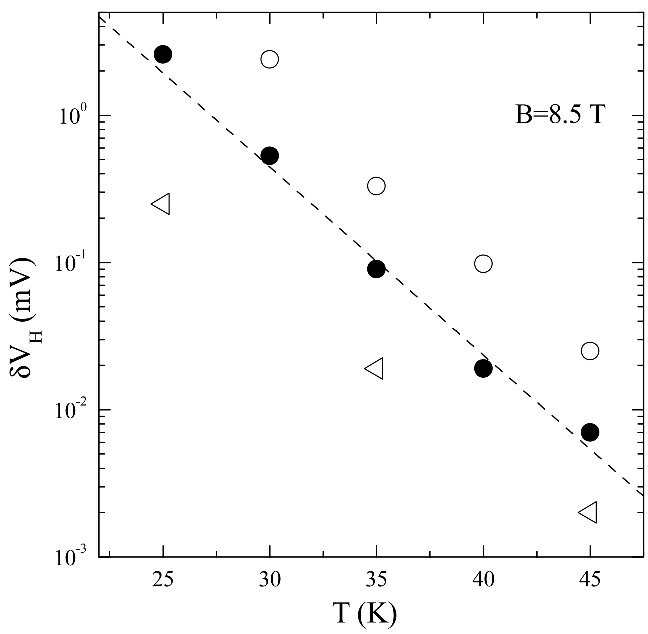

Figure 7. Temperature dependence of $\delta V_H = V_H - V_{lin}$ and deviation of the linear dependence of the Hall voltage above threshold measured at $B = 8.5$ T for $NbSe_3$ at $E = 2E_t$ (●) and $E = 4E_t$ (○) and for another sample at $E = 2E_t$ (◁).

4. Discussion

Note that at low electric fields ($E < E_t$) and at temperatures $T < T_{p2}$ the Hall voltage is a linear function of the magnetic field with the same slope after the change of sign of the Hall resistance ($B > B_0$) [15]. That gives an estimate of the net positive carrier density in the range $(3–5) \times 10^{18}$ cm^{-3}; which is in agreement with the calculations derived from the two-band model [18]. More recently, magnetoresistance data of $NbSe_3$ have been interpreted [33] in the frame of a modified two-band model [34] developed for explaining the magnetoresistance of quasi-two-dimensional purple bronzes, where new values for electron and hole carrier densities were used, the modification of concentrations of these two types of carriers by an applied magnetic field having been taken into account. It was found that the magnetoresistance data for $NbSe_3$ measured at $T > 20$ K can be well fitted with this model. However, as can be seen [33] measurements were performed with $B < B_{zc}$; thus, the experimental and fitted curves describe only the MR curve at low fields and at $T > 20$ K excluding the linear part of the $R_{xx}(B)$ dependence. Note that while the two-band model can account for $\mathrm{d}R_{xx}/\mathrm{d}B$ reaching a maximum at a fixed field B_0 close to B_{zc}, it predicts that at high fields R_{xx} will approach a saturation limit rather than the observed linear dependence on B. Besides, it is well known that saturation of magnetoresistance does not occur in the case of zero Hall voltage [35].

The appearance of pockets of uncondensed carriers in $NbSe_3$ comes from a tiny interplay of the electronic band structure [2, 3, 36–40], which is further complicated by the successive formation of two sets of energy gaps due to the two CDWs. The energy scale is at the limit of theoretical calculations, which agree only in robust features necessary to understand the two CDWs' formation. A natural and quite generic view attributes the appearance of two types of pockets to a poor nesting of the Fermi surfaces associated with the formation of the low temperature CDW, while it is commonly accepted that the CDW at high temperature removes all the Fermi surface of the bands concerned. If the system is commensurate, then the overlap between the branches would give an equal amount $N_e = N_h$ of electrons and holes, with identical masses and scattering rates (if defects are not charged). The possibility to change the CDW wavenumber along the chain axis already in the ground state (as confirmed by x-ray experiments [41]) modifies this balance to N_e–N_h which may well correspond to the commonly accepted two-pocket model. Another scenario is more specific to $NbSe_3$. It corresponds to the transfer of a small number of particles to the insulating type of chain with nominally empty band for which the bottom E_{bot} comes, according to all calculations, very close to the Fermi level E_F of two other nearly 1/4 filled bands on which both CDWs occur. The calculations diverge concerning the possibility that the bottom E_{bot} crosses the Fermi level; this ancient and forgotten possibility [36–40] was rediscovered, and confirmed by ARPES studies only a few years ago [2, 3]. Very recently, the polarity dependence of images obtained from high resolution STM measurements has been explained by the extreme vicinity of the bottom of one of the empty bands below the Fermi level in the range of a few tens of mV [4]. This tiny balance can be affected by the CDW formation; for the charge transfer to take place, the level E_{bot} should lie below the lower gap rim: $E_{bot} < E_F - \Delta_{p2}$ where Δ_{p2} is the smaller gap of the low temperature CDW. Now we obtain two essentially different entities: the pocket of heavy electrons is characterized by the low curvature of the overall band width, M_e; the pocket of holes is due to the CDW spectrum, and its effective mass can be very small $M_h \sim \Delta_{p2}/v_F^2$ at least in the chain direction. (Notice that such a division of pockets corresponds to the terminology of extrinsic and intrinsic carriers which was introduced to describe the inhomogeneous current conversion observed by the space-resolved x-ray studies of sliding CDWs just in $NbSe_3$ [41].)

The light holes can easily reach the ultra-quantum limit in high fields. Our data (magnetoresistance and Hall effect) show that in high magnetic fields ($B > B_0$) where $R_{xx} \sim B$, the magnetoresistance behavior can be assigned to be the property of holes. Recently, Abrikosov has proposed a theory of quantum linear magnetoresistance (QLMR) [42]. According to this theory, in the extreme quantum case when the distance between the Landau bands, proportional to the magnetic field, is so large that all carriers occupy only the lowest band, leaving the others empty, the resistance varies linearly with the magnetic field. The necessary conditions for QLMR are:

$$n_e \ll \left(\frac{eH}{\hbar c}\right)^{3/2}; \qquad T \ll \frac{eH\hbar}{m^* c k_B} \tag{1}$$

where n_e is the carrier density, m^* is the effective mass and k_B is the Boltzmann constant. The first condition implies that only the lowest Landau band is participating and the second one that the temperature is lower than the band splitting. For $NbSe_3$ to fulfil these conditions at $B \sim 1$ T and at $T = 4.2$ K where the linear magnetoresistance appears, one needs to have the hole concentration $n_h \sim 10^{17}$ cm^{-3} and the hole effective mass $m^* \sim 10^{-2} m_e$. With these magnitudes of n_h and m^* the conditions for the quantum linear magnetoresistance will also be fulfilled at high temperature because B_{zc} increases strongly with temperature. Thus, QLMR would be possible in $NbSe_3$ if hole pockets contain carriers with a low concentration and with a small effective mass (as estimated above) while electron pockets consist of relatively heavy carriers with $m_e^* = 0.3 m_e$ [8]. The observation at the lowest temperatures of Shubnikov–de Haas oscillations should be attributed to the electron pockets in this case. Thus, the present magnetotransport measurements indicate directly that the natures of the electron and hole pockets in $NbSe_3$ are different.

Let us now analyze the Hall effect in the sliding CDW state. Above the depinning threshold field the total current is given by the sum of the current from the sliding CDW and the current from the normal electrons. It is normally assumed that the normal current varies linearly with the electric field. Since the sliding motion of the CDW is assumed to be strictly one-dimensional, it does not directly contribute to the Hall voltage which is, thus, entirely due to the normal electrons [27]. In this case the dependence of the Hall voltage on the longitudinal voltage should be a linear function; that was observed in the experiment of Tessema and Ong [27] in $NbSe_3$ at temperatures $T > 34$ K and $B < 1.5$ T. Note that our results in a similar temperature and magnetic field range are in agreement with those results. Indeed, at $T > 30$ K and at $B < 2$ T we have not observed any detectable deviation of linearity above E_t in the $V_H(V_L)$ dependence.

However, as can be seen from figures 5 and 6, at higher magnetic fields, even at $T \geqslant 30$ K, a deviation of linearity in the $V_H(V_L)$ dependence above E_t becomes evident. Such a deviation strongly increases with the temperature decrease, as shown in figure 7. One may try to explain these results by attributing the nonlinearity of the $V_H(V_L)$ dependence observed at $E > E_t$ to the generation of free carriers from the CDW condensate [43]. The mechanism of this generation should be very specific because our results indicate that the CDW motion generates only a certain type of normal carrier, namely holes. So, we do not see any physical reasons for the realization of such a type of mechanism.

Another possibility for explaining our results is to assume that the increase or the decrease of the normal carrier concentration under the CDW motion does not result from CDW excitations but from the change in the concentration of carriers non-condensed into the CDW ground state. The results of transverse magnetoresistance measurements in $NbSe_3$ [10, 44] show that SdH oscillations are strongly modified after the application of a current larger than that for initiation of the CDW motion. Such changes in SdH oscillation frequencies may only be induced by perturbations of the metastable states of the static CDW, leading consequently to changes of the Fermi surface due to the transfer between normal carriers and the CDW condensate. Taking into account the nonlinearity of the $V_H(V_L)$ dependences for p- and n-type conductivity, we can conclude that, in the frame of this scenario, the CDW interacts effectively only with one type of carrier. If, because of the CDW motion, the pocket deformation yields an increase in the carrier concentration, the CDW interacts only with holes, in the opposite case—with electrons only. The mechanism of this discrimination is unclear.

Finally, as mentioned above, the previous studies of the influence of the CDW sliding on the Hall effect showed that $V_H(V_L)$ deviates also from a linear dependence above E_t in fully gapped CDW compounds as TaS_3 [25] and $K_{0.3}MoO_3$ [26]. In both cases the Hall voltage decreases at E_t. The results were explained by the theoretical model [28] where the CDW motion induces a 'back-flow' of normal carriers which causes the effective reduction in the Hall voltage. Note that in the frame of this model the $|V_H|$ always should decrease at E_t because a 'back-flow' of normal carriers effectively decreases the normal current. As can be seen from figure 6, we observe a decrease of $|V_H|$ for the p-type conductivity, that is in agreement with the 'back-flow' model [28]. However, for the n-type conductivity we observe the inverse picture: $|V_H|$ starts to increase at the threshold electric field. Formally, it means that the 'back-flow' effect takes place only for holes and is practically absent for electrons. In fact, this result agrees well with the picture of coexisting 'extrinsic' and 'intrinsic' carriers. For the first ones, the states are not affected by the CDW—at least at the first order because a coupling may take place only via Coulomb forces in inhomogeneous circumstances—and, hence, there is no reason for the appearance of back-flow currents. Thus, the nonlinearity of $V_H(V_l)$ does exist only for intrinsic carriers (holes, in the present case); this effect is essentially microscopic and cannot appear in a phenomenological two-band model.

The nonlinearity becomes more pronounced with the temperature decrease, as it can be seen from figure 7. This behavior may result from the increase of thermal excitations of the CDW as the temperature increases. Normal excitations can screen effectively the pockets–CDW interaction and consequently lead to the decrease in the Hall voltage nonlinearity. Moreover, in the back-flow picture, states of intrinsic carriers (holes here) are the superpositions of right and left moving particles at $\pm p_F$ and the mixing coefficients are given by the CDW amplitude Δ and Δ^*, hence the phase factors $\exp(\pm\phi/2)$ and the components 'rotate' with opposite phase velocities $d\phi/dt$ when the CDW slides. The kinetic imbalance comes from the energies $\pm(\hbar/2)d\phi/dt$ the effect of which is naturally leveled out by thermal equilibration at rising T.

Another interesting feature of the Hall effect is the visible deviations of the Hall voltage observed at low longitudinal voltages below E_t. As can be seen from figures 5 and 6, these deviations correlate with the singularities observed in the corresponding differential IV characteristics. We can explain these V_H deviations by local CDW deformations taking place below the threshold. The application of an electric field smaller than E_t may lead to a local extension or compression of the CDW near defects and correspondingly to a change in the CDW wavevector. The deformation of the CDW also occurs near current contacts, which can affect measurements of V_L in two-probe measurements. Any change in the CDW wavevector is associated with a change in the CDW charge and, hence, with a change in the balance between extrinsic and intrinsic carriers [45–47]. This effect is more pronounced, as seen in figure 6, when the singularities of $dV/dI(V_L)$ indicated by the dashed lines can be associated with the so-called first threshold field [48], at which noise first occurs without any decrease in the differential resistance. It can be seen that, just at this voltage, V_H starts to deviate from the linear dependence. Note that for positive and negative electric fields these deviations correspond to different types of one-particle excitations that may result from different types of deformation of the CDW in positive and negative fields, i.e. extension and compression. Thus, the investigation of the Hall effect in CDW materials gives one more possibility to study the effects of local CDW deformations.

5. Conclusion

We have reported the results of detailed investigations of the Hall effect in $NbSe_3$ under magnetic fields up to $B = 9$ T, both below and above the threshold electric field for depinning the low temperature charge density wave. We have shown that at low magnetic fields the B^2 dependence of the magnetoresistance is associated with a negative Hall voltage (n-type conductivity); at high magnetic fields the magnetoresistance varies linearly with H (without any sign of saturation) and the Hall voltage is positive, indicating a p-type conductivity. We have presented a scenario based on band structure calculations with coexisting 'extrinsic' and 'intrinsic' carriers: the extrinsic carriers arise from a transfer of a small amount of particles to the insulating type of chains, normally with empty band, but the bottom of which can be located in the extreme vicinity of the Fermi level of the other bands, the extrinsic carriers originate from the non-perfect nesting of bands associated with the lower temperature CDW. We have demonstrated that in high magnetic field the CDW motion significantly changes the Hall voltage at all temperatures below T_{p2}, implying only hole carriers and thus confirming our picture of two essentially different entities of carriers in the transport properties of $NbSe_3$.

Acknowledgments

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