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# MAGNETOTRANSPORT STUDIES IN CHARGE DENSITY WAVE CONDUCTORS

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## ABSTRACT

We have performed transport studies on the lower charge density wave (CDW) state of $NbSe_3$ in the presence of applied magnetic (H) fields of up to 75 kG. Dc conductivity and narrow band noise measurements show that the spectacular magnetoresistance which occurs in the lower CDW state is associated with conversion of normal carriers into CDW carriers. Ac conductivity studies indicate that the CDW continues to behave overdamped in an H-field, but the crossover frequency increases. These results are compared to the predictions of Balseiro and Falicov for an anisotropic system with imperfect nesting.

Niobium triselenide ($NbSe_3$) is unique amongst quasi-one dimensional charge density wave (CDW) materials in that when it undergoes a Peierls distortion only a portion of the Fermi surface is destroyed [1]. As a result, $NbSe_3$ stays metallic below the transition; the normal carriers, those electrons whose states on the Fermi surface (FS) are unaffected by the transition, act as a conduction mechanism in parallel with the CDW.

Previous to the work presented here Coleman et al. [2] observed a large magnetoresistance in the lower CDW state in $NbSe_3$. At 25 K, and in the presence of a 230 kG magnetic (H) field, a relative increase in resistivity in the order of five was observed. A theory to account for this dramatic magnetoresistance was proposed by Balseiro and Falicov [3], who showed that the electron-hole pockets left over from the Peierls distortion due to imperfect Fermi nesting could be further destroyed by the application of a magnetic field. Their theory indicates that in a material such as $NbSe_3$ an applied magnetic field could directly convert remnant normal carriers into CDW carriers.

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We have performed careful narrow-band noise, resistivity, and ac conductivity measurements on $NbSe_3$ in H-fields up to 75 kG in an attempt to directly observe a possible H-induced increase in CDW carrier concentration $n_c$ [4,5]. We find H-induced changes in the narrow band noise spectrum which indicate clearly that $n_c$ increases with increasing H. The observed changes in $n_c$ correlate well with the percentage of FS destroyed by the magnetic field, as determined by the Ohmic and nonlinear dc conductivity. Ac conductivity measurements indicate that the CDW continues to behave overdamped in the presence of an H-field, but the crossover frequency increases with increasing H-field. This is in stark contrast to the observed decrease in the depinning threshold electric field with increasing H-field [2,4,5].

Single crystals of $NbSe_3$ were mounted in a two probe configuration with the chain (b) axis of the crystal perpendicular to the H-field. To carry out the noise and resistivity experiments, a dc current was applied through the sample, and the voltage across the sample was amplified and detected with either a dc voltmeter or high frequency spectrum analyzer. For applied electric fields exceeding the threshold, $E_T$, for the onset of CDW conduction, and with H=0, a clear narrow band noise spectrum was observed, with a dominant fundamental frequency peak and numerous higher harmonics. Application of H fields up to 75 kG were found to have no marked effect on the amplitude or quality of the narrow band noise spectrum, but, for fixed dc bias, the fundamental noise frequency f was highly H-field dependent.

In a simple model, the narrow band noise frequency is related to the excess CDW current $I_{CDW}$ through

$$I_{CDW} = n_c e v_d A = n_c e f \lambda A \tag{1}$$

where $I_{CDW} = I - V/R_o$ with I the total sample current, V the time averaged sample voltage, and $R_o$ the low field (ohmic) sample resistance. $v_d$ is the CDW drift velocity, A the sample cross sectional area, and $\lambda$ is a constant, usually taken to be the CDW wavelength. Hence for fixed $n_c$, $I_{CDW}$ is directly proportional to f, and the ratio $I_{CDW}/f$ directly reflects $n_c$.

Figure 1 shows $I_{CDW}$ vs. f for $NbSe_3$ at T=37.4 K, for H=0 and for an applied field H=75 kG. For H=0, the linear relationship is in accord with Eq. (1) and consistent with previous narrow band noise studies in $NbSe_3$ [6-8]. With H=75 kG, a linear dependence of f on $I_{CDW}$ is again observed, but with a different slope. Figure 1 clearly demonstrates that the ratio $I_{CDW}/f$ is increased in the presence of an applied magnetic field. With e, $\lambda$, and A independent of H in Eq. (1), Fig. 1 demonstrates that the effect of a magnetic field in $NbSe_3$ is to directly enhance the CDW carrier concentration. At 37 K and 75 kG the increase in CDW carrier concentration is approximately 30% over the zero field value.

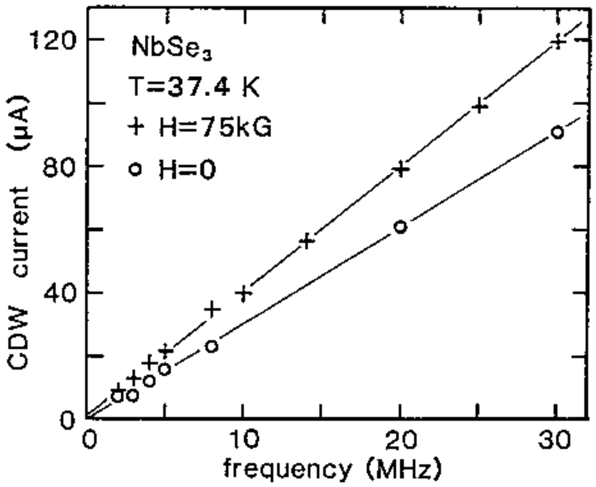

Fig. 1. $I_{CDW}$ vs. narrow band noise frequency in $NbSe_3$ with and without an applied magnetic field.

The H-field induced carrier conversion accounts entirely for the (low electric field) magnetoresistance in $NbSe_3$, and hence the present experiments rule out normal carrier mobility effects as being the source of magnetoresistance.

Data such as that shown in Fig. 1 was taken at various values of magnetic field strength and temperature in the lower CDW state. Figure 2 shows the slope $I_{CDW}/f$ vs. H for T fixed at 37.4 K. Up to 75 kG, a virtually linear dependence of $I_{CDW}/f$ (and hence $n_c$) on H is obtained, with $d[I_{CDW}/f]/dH=1.8\times10^{-2}$ μA/MHz/kG. With $\lambda = 14$ Å, this corresponds to an H-field induced carrier conversion rate $dn_c(H)/dH=3.6\times10^{18}$ carriers/kG $cm^3$.

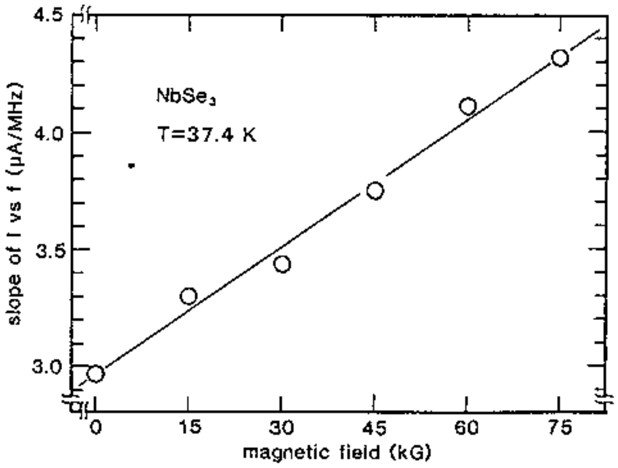

Fig. 2. $I_{CDW}/f$ $n_c$ vs. H in $NbSe_3$. An increasing magnetic field results in an increase in CDW carrier concentration up to 75 kG. The carrier conversion rate is linear in H.

The ac conductivity $\sigma(\omega)$ of $NbSe_3$ with and without a 75 kG H-field at 25 K is shown in Fig. 3. The data indicates that the CDW continues to act overdamped in the presence of the H-field, but the crossover frequency increases; this is evident in both the real (Re) and imaginary (Im) components of $\sigma(\omega)$. In the low frequency limit (4 MHz), Re$\sigma$ is greatly reduced by the applied H-field, while at high frequencies (>1 GHz) it is evident that Re$\sigma$ at H=0 and H=75 kG approach the same value. In addition, the peak in Im$\sigma$ is enhanced by the 75 kG field. These results are consistent with carriers being removed from free electron states near the Fermi energy and condensed in the CDW.

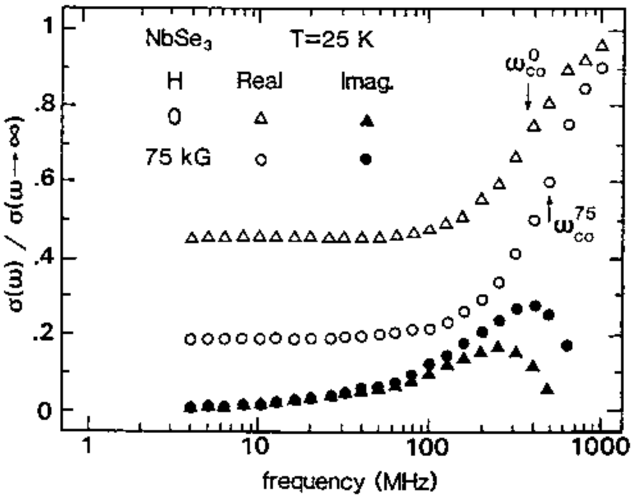

Fig. 3. Real and imaginary ac conductivity of $NbSe_3$ both with and without a 75 kG H-field. As noted, the crossover frequency is increased by the H-field.

We have measured the H-field induced change in the crossover frequency, $\omega_{co}$, as a function of temperature between 20 and 50 K. The results are shown in Fig. 4. We find that the difference $\omega_{co}(H) - \omega_{co}(0)$ is zero just below the transition and then grows as the temperature is lowered. This result is similar to the temperature dependance found for the H-field induced increase in the CDW carrier concentration [4], indicating that the H-field is affecting the CDW concentration and the crossover frequency in a similar way.

The increase in $\omega_{co}$ with increasing H-field is in stark contrast to the corresponding decrease in $E_T$ with increasing H [2,5]. This behavior appears inconsistent with simple models of CDW transport, where the ac and dc responses go hand in hand, i.e. any decrease in $E_T$ (as might arise from decreased impurity concentration or change in temperature) should accompany a corresponding decrease in the crossover frequency. Indeed, both classical (deformable) [9] and quantum tunneling models [10] predict a direct scaling between dc and ac conductivities,

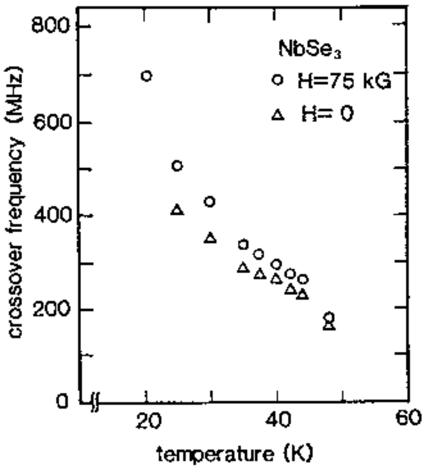

Fig. 4. The crossover frequency in the low temperature CDW state of $NbSe_3$ with and without a 75 kG H-field.

as is observed experimentally in the absence of an applied H-field [11]. However, as Fig. 4 clearly demonstrates, there is no $\sigma_{dc}(E)=\sigma_{ac}(\omega)$ scaling relationship between ac and dc conductivities in $NbSe_3$ in the presence of a magnetic field.

Another scaling relationship predicted for CDW conductors applies to the low frequency dielectric constant $\varepsilon_o$ and the threshold electric field $E_T$

$$\varepsilon_o E_T = \text{const.} \tag{2}$$

The particular form of the constant in Eq. (2) depends on the model; for example, in the rigid particle approach of Grüner, Zawadowski, and Chaikin [12],

$$\varepsilon_o = \pi n_c e^2/m\omega_o^2; \quad E_T = \frac{\lambda}{2}\, m\omega_o^2/2\pi e \tag{3}$$

leading to

$$\varepsilon_o E_T = n\lambda e n_c/2 \tag{4}$$

where m is the CDW effective mass and $\omega_{co} = \omega_o^2\tau$ where $\tau$ is the CDW relaxation time. Similar results follow from Bardeen's quantum tunneling model and the deformable medium model of Fukuyama and Lee [13].

Eqn. (4) predicts that $E_T$ should scale linearly with $\omega_{co}$; in the absence of a magnetic field this has been confirmed by irradiation studies [14]. Our conductivity measurements [5] indicate that $\varepsilon_o$ and $\tau$ in $NbSe_3$ are unaffected by the application of a magnetic field. Since $n_c$ is increased by the H-field (see Fig. 2), Eqn. (3) indicates that $\omega_o^2$ should also be increasing under the influence of the field, as observed. Eqn. (3) however, also indicates that $E_T$ scales as $\omega_o^2$, in contrast to the experimental observations. In a magnetic field the expected linear relationship between $E_T$ and $\omega_o^2$ no longer exists.

In conclusion, we find that dc magnetoresistance effects in $NbSe_3$ are well accounted for by a straightforward enhancement in the CDW carrier concentration induced by the applied magnetic field, consistent with the theoretical predictions of Balseiro and Falicov [3]. Additionally, we find that the relationship between $E_T$ and $\omega_o$ in the presence of a magnetic field appears inconsistent with current models of CDW conduction.

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