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# SWITCHING AND HYSTERESIS IN NbSe3

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### Résumé:

Nous avons étudié la commutation sujette à hystérésis associée avec l'apparition de l'état onde de densité de charge (CDW) porteur de courant dans NbSe<sub>3</sub> et trouvé des indices d'un état intermédiaire "fibrillant". La commutation ellé-même peut-être associée à un temps fini nécessaire pour coupler les diverses régions CDW, formant ainsi un état cohérent porteur de courant.

#### Abstract:

We have studied the hysteretic "switch" associated with the development of the current-carrying charge density wave (CDW) state in NbSe3, and find evidence for an intermediate "fibrillating" state. The switch itself may be associated with a finite time required to couple various CDW regions, thus forming a coherent current-carrying state.

The nonlinear conductivity observed in the charge-density-wave (CDW) state in NbSe3 at very low electric field strengths is suggestive of a new collective transport phenomenon. Early observations indicated a field dependence of the dc conductivity<sup>1</sup>, and subsequent experiments demonstrated that there is a sharp threshold field  $E_T$  for the onset of nonlinear conduction.<sup>2</sup> This, together with current fluctuation in the nonlinear region,<sup>2</sup>,<sup>3</sup> is highly suggestive that the current is carried by the sliding CDW through mechanisms suggested originally by Frohlich.<sup>4</sup> In this publication we shall investigate the onset of the non-linear dc conductivity in NbSe<sub>3</sub>.

#### A. Experimental

Fig. 1 shows several I-V curves for NbSe3 in the lower (T <59 K) CDW state. These curves were obtained using a four-probe sample mounting configuration, and by driving the sample with a current source through the outer contacts. At T = 42 K, a non-linear I-V curve with no other outstanding features is observed, and identical curves are obtained for forward and reverse current sweeps. At slightly lower temperatures a "knee" is observed in the I-V curves near E<sub>T</sub>, the threshold field for the onset of non-linear conduction. The knee becomes sharper with lowering temperature, and near approximately 36K a jump or "switch" is observed from the Ohmic to the non-linear conductivity region.<sup>5</sup> As the temperature is further lowered, the switch becomes more welldefined, and near 28K it shows clear hysteresis behavior for increasing and decreasing currents through the threshold valve. Fig. 1, along with data obtained at still lower temperatures, indicates that the switch (voltage) amplitude and hysteresis (current) loop





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magnitude increase with decreasing temperature.

As can be seen from the last trace in Fig. 1, at low temperatures the switch is well-defined, with a clear hysteresis loop. At intermediate temperatures, however, the switch is not as sharp, and the system briefly oscillates or "fibrillates" between the conducting and non-conducting states. This is shown more clearly in Fig. 2, where portions of the I-V curves near threshold are shown for T = 34 K and T = 26.5 K.

At low temperatures where the switch is sharp and well-defined, a current pulse method has been used to study the timedependent voltage response near the threshold current. By applying a rectangular current pulse to the sample and observing the voltage across the sample on an oscilloscope, the switching can be directly observed. Below a threshold current  $I_T$  we have observed a regular pulse response with no unusual features. Increasing the current I to  $I_T$ , the observed voltage shows a well defined jump from a voltage  $V_1$  to a smaller voltage  $V_2$ , as shown in Fig. 3a.  $V_1$  corresponds to the Ohmic conductivity observed



Fig. 3 a) Digitally smoothed response waveform to a current pulse with I just above  $I_{\rm T}.$  The switching phenomena is clearly seen at a time 120  $\mu sec$  from the start of the pulse. Relevant paramters are defined in the text;

b) I-V curves obtained from pulse measurements similar to the one shown in Fig. 3a, where the voltages  $V_1$  and  $V_2$  are defined. The full line is the Ohmic conductivity, while the dotted line is a guide to the eye for the nonlinear conductivity. Typical values of the time switch T, for a given sample current I, are shown.



Fig. 2 Detail of I-V characteristics of NbSe3 near threshold.

below IT, and we conclude that this corresponds to the pinned CDW state. After a time T a switching, usually of duration τ approximately a few microseconds, occurs to a state with lower voltage V2, i.e. to a state which has a higher conductivity. V1 and V2 measured simultaneously by pulse techniques for various applied currents is shown in Fig. 3b. The full line represents the Ohmic conductivity observed also below IT while the dotted line is a guide to the eye and represents the I-V behavior of the current-carrying state. We find that for a given current I near IT, the time before switching T is not a uniquely defined quantity, but varies slightly from one pulse to another. The probability distribution for T, as a function time (measured from the start of the pulse) is shown in Fig. 4 for two different values of I above IT.

#### B. Discussion

The switching and hysteresis phenomena observed in NbSe3 appear to be incompatible with any proposed theoretical description of CDW transport. The classical model of CDW transport by Gruner, Zawadowski, and Chaikin,<sup>6</sup> which treats the CDW as a classical particle in a periodic potential, is able to account for switching and hysteresis effects only if a CDW inertia term is included. Frequencydependent conductivity studies<sup>7,8</sup> have, however, indicated an overdamped (i.e. non-inertial) response of the CDW condensate. The quantum-mechanical CDW tunneling model by Bardeen<sup>9</sup> also leads to a smooth increase in the conductivity at threshold. However, if tunneling occurs between two macroscopically occupied states, leading to macroscopic quantum tunneling as suggested by Legett<sup>10</sup> then the tunneling may lead



Fig. 4 Distribution of time to switch T for two different driving currents I. The full line is a fit to a normalized Lorentzian distribution (Eq. 1) with  $\alpha$  = 6.32, while the dashed line is the same with  $\alpha$  = 3.07

to switching phenomena. However, the switching probability for such events is an exponential function, characteristic of stochastic events. Fig. 4 shows clearly that for NbSe<sub>2</sub> the switching is well described by the Lorentzian function

$$P(T) = \frac{\alpha}{\pi} - \frac{1}{1 + \alpha^2 (T - \overline{T})^2}$$
(1)

where the mean time before switching  $\overline{T}$  decreases with increasing applied current I.

It is important to note that both the classical model<sup>5</sup> and the tunneling model<sup>9</sup> are zero temperature formulations, and that both neglect any possible distributions<sup>11</sup> of CDW segments as might arise from inhomogeneties or grain boundaries<sup>12</sup>. The switching and hysteresis phenomena may be related to a distribution of CDW domains in that various CDW regions have first to be coupled together before a coherent current-carrying state can develop. The switching phenomenon observed is then associated with the finite time required for coupling after the application of a driving field. The situation is similar to that observed in coupled Josephson junctions, <sup>13</sup> and in granular superconductors. A single model which could account for our observations is the extension of the classical model<sup>5</sup>, <sup>11</sup> for weakly coupled particles moving in a periodic potential. A coupling term which depends on the relative position x of the particles (or on the relative phase of the CDW's) like A sin(x<sub>i</sub> - x<sub>j</sub>), describes the tendency of the CDW segments to be coupled. Due to the inherent nonlinearity of the problem, coupled or uncoupled regions may be obtained depending on the driving forces.

From Fig. 1 we see that the switching and hysteresis processes are clearly temperature dependent, becoming observable only below about 40 K. At intermediate temperatures (near 36 K) the switching is rather ill-defined, and fibrillation at the threshold  $I_T$  is observed. These fluctuations may reflect transitions between metastable states as described by Brill et al<sup>15</sup>, Gill, <sup>16</sup> and Fleming<sup>17</sup>. In addition, the low-temperature hysteresis most probably reflects long-term memory of the CDW condensate. Detailed measurements of the time dependent response in the fibrillating state, and also the dependence of the switching and hysteresis phenomena on sample quality and geometry, are currently underway.

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