Fractional effects in the mutual conversion of charge density waves

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The interaction of two charge density waves has been studied as the waves moved at different velocities in adjacent regions of a sample of the orthorhombic phase of TaS_3. A plot of the differential conductivity of region 1 (current I_1) as a function of the current I_2, in region 2, has dips. They occur at $I_1/I_2 = p/q$, where p is an integer, and q is odd. An analogy is drawn with the fractional quantum Hall effect in a 2D system of hypothetical excitations near a contact of two charge density waves.

The motion of a charge density wave (CDW) in a quasi-1D conductor is accompanied by the excitation of voltage oscillations (a narrow-band noise) with a frequency ω_1 proportional to the current of the CDW.[1] The interaction of a moving CDW with an alternating external current (at the frequency ω_2) gives rise to so-called Shapiro steps on the I–V characteristics. In other words, it gives rise to dips in the differential conductivity σ_d at $\omega_1/\omega_2 = p/q$, where p and q are arbitrary integers.

The purpose of the present study was to learn about the interaction of two CDWs moving through adjacent regions of a sample (regions 1 and 2 in Fig. 1). It was expected that region 1 would serve as a "receiver" with an internal frequency $\omega_1 \propto I_1^{cdw}$, while region 2 would be a "generator" with a given frequency $\omega_2 \propto I_2^{cdw}$. The differential conductivity $\sigma_d(I_1, I_2)$ of region 1 would have dips at rational numbers I_1^{cdw}/I_2^{cdw}. A similar geometry has been used in previous studies[2,3] to learn about the narrow-band noise in $NbSe_3$; a frequency locking was observed at $I_1^{cdw} \approx I_2^{cdw}$.

The measurements were carried out in a three-probe layout on samples of the orthorhombic phase of TaS_3. The samples had a length ~ 1 mm, a width ~ 10 μm, and a thickness ~ 2 μm. The size of the central contact was < 10 μm. The contact resistance amounted to $< 5\%$ of the resistance of the sample. A standard modulation method, with a modulation frequency of 700 Hz, was used to measure the differential

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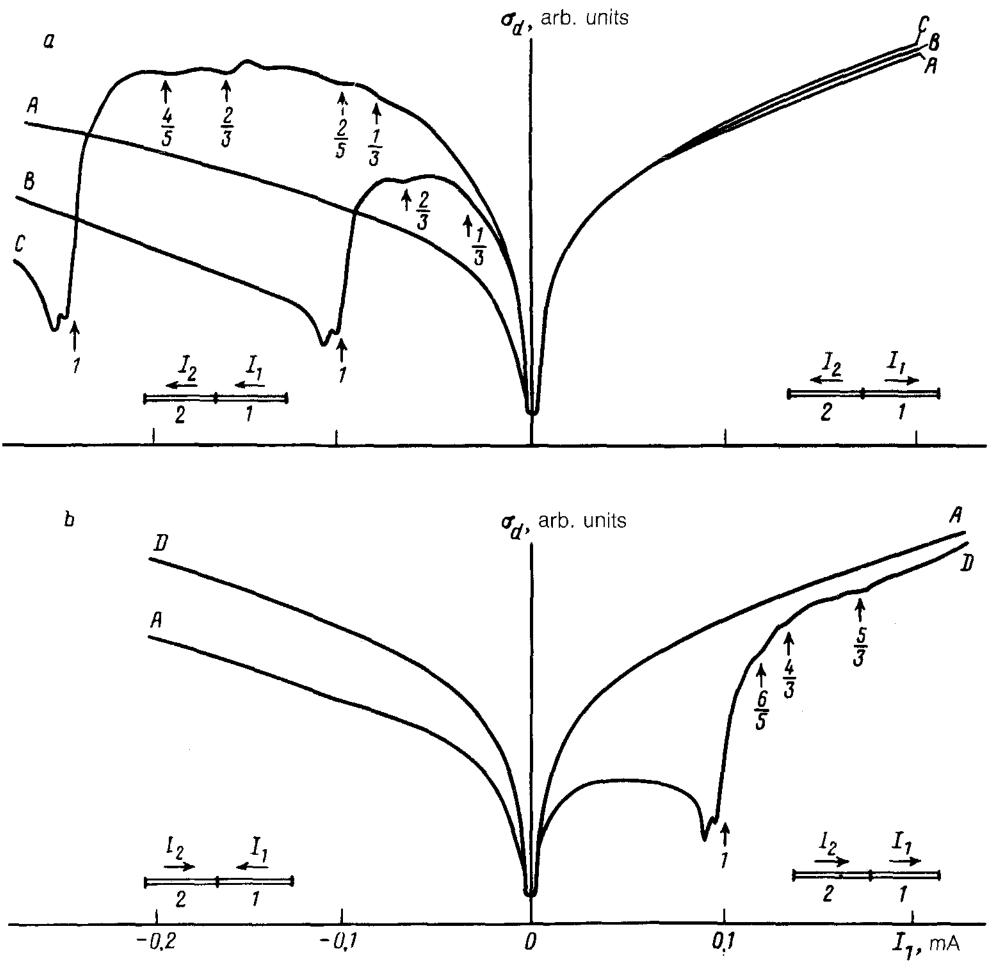

FIG. 1. Curves of $\sigma_d(I_1)$. a: A—$I_2=0$; B—$I_2=-0.1$ mA; C—$I_2=-0.25$ mA. b: A—$I_2=9$; D—$I_2=+0.1$ mA. The numbers near the vertical arrows show the values of I_1/I_2. $T=110$ K.

conductivity of region 1, i.e., $\sigma_d = dI_1/dV_1$, as a function of V_1 or I_1 for various values of I_2 [I_2 was set by the dc current source, and V_1 was set by a sawtooth (in time) voltage source in such a way that the value of I_1 ranged from $-4I_2$ to $+4I_2$]. At certain rational ratios of I_1 and I_2, and at sufficiently low temperatures $T<140$ K, structural features (dips) were found on the $\sigma_d(I_1)$ curve (Fig. 1) when the following two conditions were satisfied simultaneously: (a) $I_{1,2} > I^T_{1,2}$ (where $I^T_{1,2}$ are the threshold currents for the disruption of the CDWs in regions 1 and 2) and (b) the currents I_1 and I_2 flow in the same direction.[1)]

The primary (largest) structural feature is observed at $I_1/I_2 \approx 1$. Its shape changes qualitatively upon simultaneous changes in the directions of I_1 and I_2, and it depends on whether I_2 is directed away from region 1, toward region 2 (Fig. 1a), or in the opposite direction (away from region 2 toward region 1; Fig. 1b). In the former case, $\sigma_d(I_1)$ initially falls sharply with increasing I_1 and then rises smoothly. In the latter case, σ_d initially falls slightly and then rises sharply. Figure 2 shows a part of Fig. 1a which has been reflected in the $I_1 = 0$ axis and superimposed on Fig. 1b. The shape of the primary structural feature can be related to a transition of the CDW near the central contact from a compressed state to an extended state. If one assumes[4] an n-

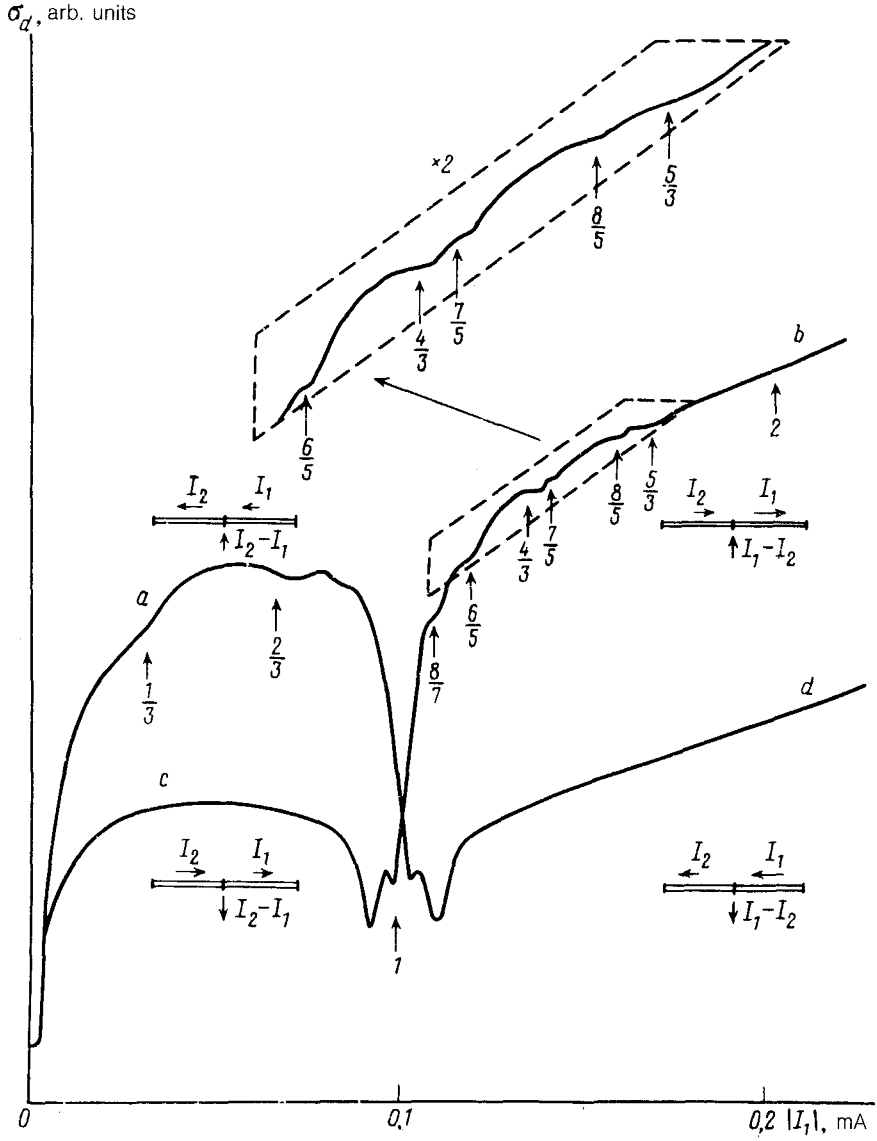

FIG. 2. Curves of $\sigma_d(|I_1|)$ for $I_2 = -0.1$ mA (the curve has been reflected in the ordinate axis) and for $I_2 = +0.1$ mA. Regions a and b correspond to a compression of the CDW, and regions c and d to an extension of it. The numbers near the vertical arrows are the values of I_1/I_2. The inset shows part of curve b in doubled scale along both axes. $T = 110$ K.

type conductivity for the CDW, then σ_d for a compressed CDW is larger than that for an extended one. The point at which the curves in Fig. 2 intersect in "clean" samples ($E_T < 0.5$ V/cm) is close to the point $I_1 = I_2$, at which there is a single, undeformed CDW throughout the sample. At $I_1 \neq I_2$ the CDW is deformed and may break. The process is reminiscent of the disruption of a fixed CDW in a process involving a threshold. In "dirty" samples ($E_T \sim 1$–2 V/cm) the primary structural feature is deeper.

In "clean" samples one also sees some much slighter structural features in $\sigma_d(I_1)$ at fractional values I_1/I_2. They are most obvious in the state of a compressed CDW. The dips in $\sigma_d(I_1)$ at $I_1/I_2 = 1/3$ and $2/3$ are the clearest ones for I_2 in the direction $1 \rightarrow 2$, while those at $4/3$ and $5/3$ are the clearest for I_2 in the direction $2 \rightarrow 1$. Some weaker features are seen at $I_1/I_2 = 2/5$, $3/5$, and $4/5$ in the first case and at $6/5$, $7/5$, $8/5$, $8/7$, and 2 in the second. With increasing I_2, the number of structural features increases; the features overlap and become difficult to identify. We wish to stress that we did not observe fractional features $I_1/I_2 = p/q$ with even q. In particular, near $p/q = 1/2$ there is a "dead" zone (without structural features). These results contradict the results expected on the basis of the "generator-receiver" model. We know of only one effect in which formally the same fractions are observed: the fractional quantum Hall effect.

For an interpretation, we invoke the concept of phase slippage centers for CDWs[5-8] in the model of Ref. 7. The ground state of a moving CDW is an undeformed state with $I_1/I_2 = 1$. Upon a deviation from this equality, the CDW near the central contact becomes deformed. The deformation increases with time, the order parameter becomes suppressed and drops to zero, its phase slips, and the process repeats itself. This is the way in which CDW 2 converts into CDW 1 and into a normal current $|I_1 - I_2|$, which goes off to the central contact. At a small value of $|I_1 - I_2|$ and with a narrow central contact, the slippage in thin samples occurs near the contact in the plane perpendicular to the velocity of the CDW, with the help of the formation of solitary phase dislocations.[5,6] Dislocations move in this plane, disrupting the phase at the surface of the sample. With increasing $|I_1 - I_2|$, the number of dislocations increases, and they undergo a progressively stronger interaction with each other and with normal electrons. As a result, a system of excitations forms in this plane. The structure of these excitations is not clear at this point; We will call them "vortices." Here is a possible scenario for the organization of a collective state in a system of vortices. If we assume that the vortices have a fairly short-range repulsion for each other, a low kinetic energy for motion in this plane (perhaps as a result of the quasi-1D nature of TaS_3), and Fermi statistics, then the problem of determining the properties of a system of "heavy" fermions of this type reduces to the corresponding problem for "light" 2D fermions in a strong magnetic field. Since the current I_2 is given,[2)] the quantity $\nu = |(I_1 - I_2)/I_2| = |1 - p/q|$ can serve as a measure of the relative density of vortices—an analog of the filling factor in the fractional quantum Hall effect. From the theory of the latter effect[9] we know that for integer p and odd q an incompressible Laughlin fluid forms with a gap for excitations. In the case with pinning centers (impurity centers, etc), this gap in the spectrum of a vortex fluid leads to the existence of a threshold value of $\Delta\nu$. An increase in ν near $|1 - p/q|$ introduces immobile vortices (localized at impurity centers in the gap), the rate of phase disruption does not increase, and the differential conductivity of the CDW should have a minimum. This scenario gives a qualitative explanation of the results which have been found.

Preliminary measurements on $NbSe_3$ show that the effects which have been observed are largely universal in nature.

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[1)] Under the same conditions, it has been observed[4] that I_2 also has an effect on the threshold field (E_T) for the disruption of the CDW in region 1—an effect qualitatively the same as one which had been observed[3] previously in $NbSe_3$.

[2)] The current I_1 is determined by the voltage source. In contrast with I_2, which is set by the current source, it is an average over time. This is why there is no $I_1 \leftrightarrow I_2$ symmetry.

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