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Macroscopic quantum coherence in charge density wave whisker NbSe$_3$ under strain

P Zheng, Z J Chen, Q Jiang and D Jin

Physics Institute, Laboratory of Ultra-Low Temperature Physics, Chinese Academy of Sciences, PO Box 2711, Beijing 100080, People's Republic of China

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Abstract. The magnetoresistance oscillation of the charge density wave (CDW) material NbSe$_3$ whisker has been studied under strain at different temperatures (4.2 K, 30 K, 40 K). With a constant measuring current, the magnetoresistance (MR) curves oscillate at 30 K while they are smooth at 4.2 K and become a series of zigzag curves at 40 K. These oscillation periods are ΔH, rather than $\Delta(1/H)$. It is found that either increasing the temperature to 40 K, or straining the sample to a displacement as large as $\varepsilon = 3.1\%$, makes the regular oscillations disappear. By analysing the data, we found our results can be interpreted as the quantum coherence effect of a moving CDW.

The properties of whisker NbSe$_3$ are of quasi-one-dimensional type. Usually a whisker can be easily cleaved into several slimmer whiskers along the (*ac*)-plane and /or the (*bc*)-plane [4]. It will undergo charge density wave (CDW) transitions (Peierls transitions) at $T_1 = 114$ K, $T_2 = 59$ K due to the nesting structure of the Fermi surface. In a real sample, there are a number of CDW chains. The chains will interact with each other especially in a magnetic field [9]. Each CDW chain is pinned by a pining centre in the material. When supplying an electric field larger than a threshold field E_c, the CDW chain will move. When the CDWs pass over a nanometre hole in a field, they will become coherent and cause a magnetoresistance (MR) oscillation. That is the Aharonov–Bohn quantum coherence effect (A–B effect) of a moving CDW chain [2]. As we know, straining whisker NbSe$_3$ will make it longer in the *b*-axis and shrunk in the (*ac*) plane, lower its Peierls transition temperatures and change its threshold electric field E_c of the CDW by a few mV cm^{-1} because strain changes the nesting structure of the Fermi surface [7, 8]. Therefore, it is possible that strain will affect the inter-chain interaction and even the Aharonov–Bohn quantum coherence effect of a moving CDW [1]. However, no result about strain dependence of moving CDW chain coherence has been reported so far. In this paper, we report the observation of a series of regular magnetoresistance oscillations in the CDW state. The period are ΔH. After changing the temperature and strain, more phenomena were found. The mechanism is discussed.

The sample (RRR $= R_{237\ K}/R_{4.2\ K} = 153$) in our experiment is provided by Dr D M Marone. Its size is 2 mm × 18μm × 5μm. The preparation method has been described elsewhere [8]. We placed our sample on the holder with four copper contacts in our top-loading stressing apparatus. Silver paint was used to make all four contacts nicely. To ensure the contacts were strong enough mechanically, an additional epoxy was used. The temperature could be controlled from 4.2 to 300 K with a precision of ±0.03 K. The strain direction is along the *b*-axis, which makes an angle of about 15° with magnetic field H.

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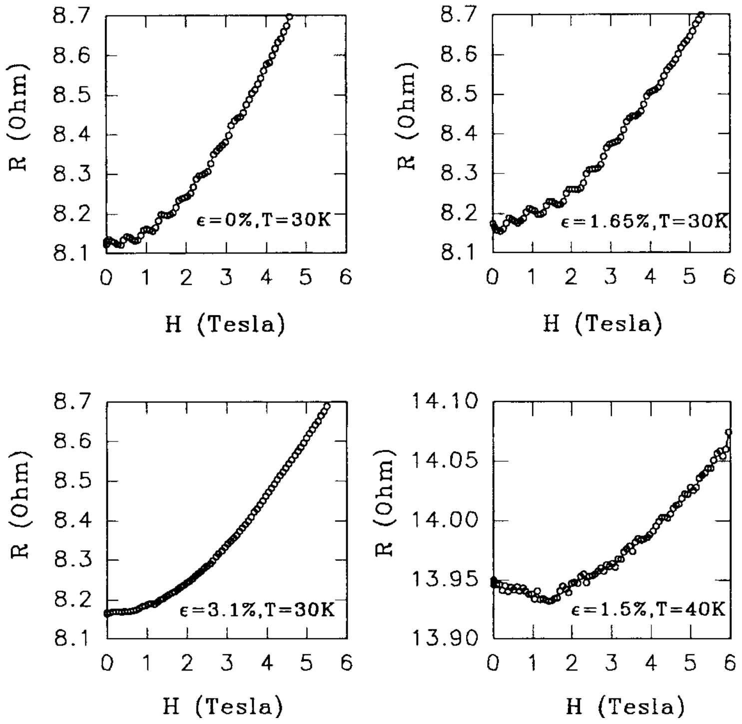

Figure 1. The magnetoresistance (MR) curves of the sample at $T = 30$ K in different strains $\varepsilon = 0\%$, 1.65%, 3.1% and $T = 40$ K, $\varepsilon = 1.5\%$.

The amount of strain is measured by detecting the displacement of a magnetic detector which connects with a sample holder. A high amplification microscope measured the displacement with an accuracy of $\pm 0.25\mu$m.

The dc resistance was measured with the standard four probe method at several stable strains in magnetic field H up to 7 T at each temperature. A constant measuring current 100 μA was supplied by a Keithley 224 programmable current source. A Keithley 181 nanovoltmeter was used to measure the voltage.

The zero field $R(T)$ curve implies that the second transition temperature of these samples is 59 K and the R peak value temperature is 43 K. We measured the R–H curves on sample A at different temperatures. Each curve corresponded to a fixed temperature and strain rate. We found distinct MR oscillations at $T = 30$ K while the MR curves at 4.2 K are smooth and appear as a series of zigzag profiles at 40 K (figure 1).

For the oscillating MR curves in figure 1, we suppose that $R(H)$ includes two parts: an oscillating part ΔR_{osc} and the monotonically increasing contribution R_s. Figures 2(a) and 2(b) are two typical profiles of the results of $\Delta R_{osc}(H) = R(H) - R_s(H)$ at $\varepsilon = 1.2\%$. Obviously the curve of $R_{osc}(H)$ is close to that of $\sin(ax + b)$. For the curve of $\varepsilon = 3.1\%$ the oscillations disappear.

Now a question arises: what is the mechanism of the oscillation? According to the experimental result, we do not think it is the Shubnikov–de Haas effect for the following reasons: (1) this novel oscillation appeared at 30 K, which is much higher than the temperature where Shubnikov oscillation can be found [5, 6]; (2) in contrast to the period $\Delta(1/H)$ of Shubnikov oscillation, the period of this oscillation is ΔH.

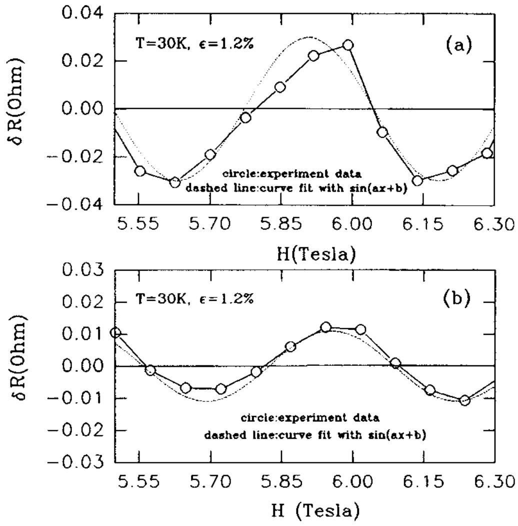

Figure 2. Two magnetoresistance curves of the sample at different times: (a) straining the sample to $\varepsilon = 1.2\%$ at the beginning of the experiment; (b) loosing the sample from the intense state to $\varepsilon = 1.2\%$ at the end of the experiment.

We suppose that the oscillation in $\mathrm{NbSe_3}$ is the Aharonov–Bohn oscillation (A–B effect) predicted in 1990 [1] and observed recently by Latyshev *et al* in 1997 [2]. They reported that the Aharonov–Bohn effect could be observed in a CDW material with nanometre size holes due to large-scale quantum fluctuation of the CDW order parameter when the CDW chain is driven to move in a magnetic field. The magnetoresistance oscillation period is:

$$\Delta H = (hc/2e)/(\pi D^2/4) \tag{1}$$

where $hc/2e = \Phi_0$ is the flux period. The value D is the mean diameter of holes. To compare the hole dimensions between our sample and that of [2], we found some crevices around 0.1 μm of size in the measured sample through a high-resolution microscope. One of the crevices is shown in figure 3. While the hole in the sample of [2] is only 15 nm in diameter, according to the formula (1), it is reasonable that in our case the period ΔH is much smaller than that of [2], in which ΔH is about 10 T.

Nevertheless, for this whisker, the oscillation amplitude decrease with a constant period ΔH when increasing the magnetic field up to 7 T (figure 1), which is in contrast to the predictions of the A–B effect.

The third possibility is the CDW chains are weakly localized near the hole. As in ordinary conductor-like metals in the shape of a hollow cylinder or multiconnected conductors [10], when an electron wave is initially scattered by a defect, its two conjugated partial waves spread clockwise and anticlockwise separately. After elastic scattering N times, they return to the starting point with the same phase and same amplitude. They will be coherent. This is the Altshuler–Aronov–Spivak (ASS) effect [10]. The flux period is $\Phi_0/2$ and the amplitude of oscillation decreases with increasing field. For a CDW chain, the flux period of the AAS effect is $\Phi_0/2 = hc/4e$. So the corresponding relationship between period ΔH and mean hole diameter D is

$$\Delta H = \Phi/(D^2/4\pi) = (hc/4e)/(\pi D^2/4). \tag{2}$$

Because in this experiment, the direction of supplied magnetic field deviates from the whisker's (ab)-plane by about 15°, we calculated the effective field period of this phenomenon

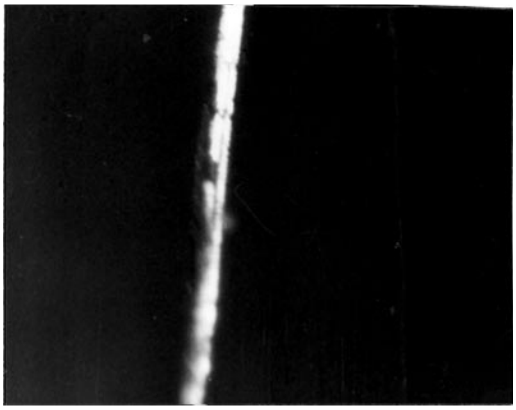

Figure 3. The profile of the sample used in this experiment: one side of the gap in sample has been broken after strain.

$\Delta H \approx 0.129$ T. By formula (2) we obtain the corresponding mean diameter $D \approx 99.1$ nm. The data coincide more with our measured sample than that from formula (1).

We find that strain does not change the oscillation conspicuously when $\varepsilon < 3.1\%$. When straining the sample to $\varepsilon = 3.1\%$, the oscillation is smoothed (figure 1). Increasing temperature to 40 K, the MR curves became a series of zigzag profiles. According to the relationship between threshold field and strain and temperature [3, 8] at low temperature $T < 40$ K, both increasing strain and increasing temperature will lower the threshold field. So, either straining to $\varepsilon = 3.1\%$ or increasing temperature to $T = 40$ K may cause more CDW chain movement. To study the effect of the increasing number of moving CDW chains, we perform the Fourier transformation of the data at $\varepsilon = 1.65\%$ at 30 K, $\varepsilon = 3.1\%$ at 30 K and $\varepsilon = 1.5\%$ at 40 K. The three corresponding Fourier spectra are shown in figure 4.

In the Fourier spectrum of $\varepsilon = 1.65\%$ at 30 K (figure 4(a)), we find four peaks with frequency $\Delta H^{-1} = 1$, 2, 3 and 4 T^{-1}. Increasing ε to 3.1% (figure 4(b)), all of the four frequencies of oscillation remained but their intensities changed: the 2 T^{-1} peak in figure 4(b) was much lowered and comparable with the others. The first peak 1 T^{-1} is the frequency of period $\Phi_0 = hc/2e$ oscillation (A–B effect) and the second one represents the period $\Phi = hc/4e = \Phi_0/2$ oscillation (AAS effect). Besides, a broad peak with mean frequency of 8 T^{-1} just appeared in figure 4(b). The existence of 3, 4 and 7 T^{-1} peaks for $\varepsilon = 3.1\%$ implies that there are inter-chain interactions in this sample [1]. Because the greater the strain, the lower threshold field of the CDW chain, when $\varepsilon = 3.1\%$, the threshold current I_c is much lower than measuring current 100 μA and the possibility of inter-chain interaction increases in the sample. So, a new peak in the Fourier spectrum emerges, see figure 4(b). Increasing temperature should lead to a similar consequence. Now, we check the Fourier spectrum at $T = 40$ K, $\varepsilon = 1.5\%$ (figure 4(c)). It is found that all the low frequency peaks that we did not find in figure 4(a) or (b) appeared, and meanwhile another three higher frequency peaks emerged in the spectrum. Further study is needed.

Here, we conclude: (1) we have observed a series of resistance oscillations in magnetic field H from 0 to 7 T at 30 K. The period is about 0.5 T. (2) These oscillations are attributable to the AAS effect of a moving CDW rather than Shubnikov–de Haas oscillation. (3) If too many CDW chains are in a moving state, their interactions could blur the oscillations.

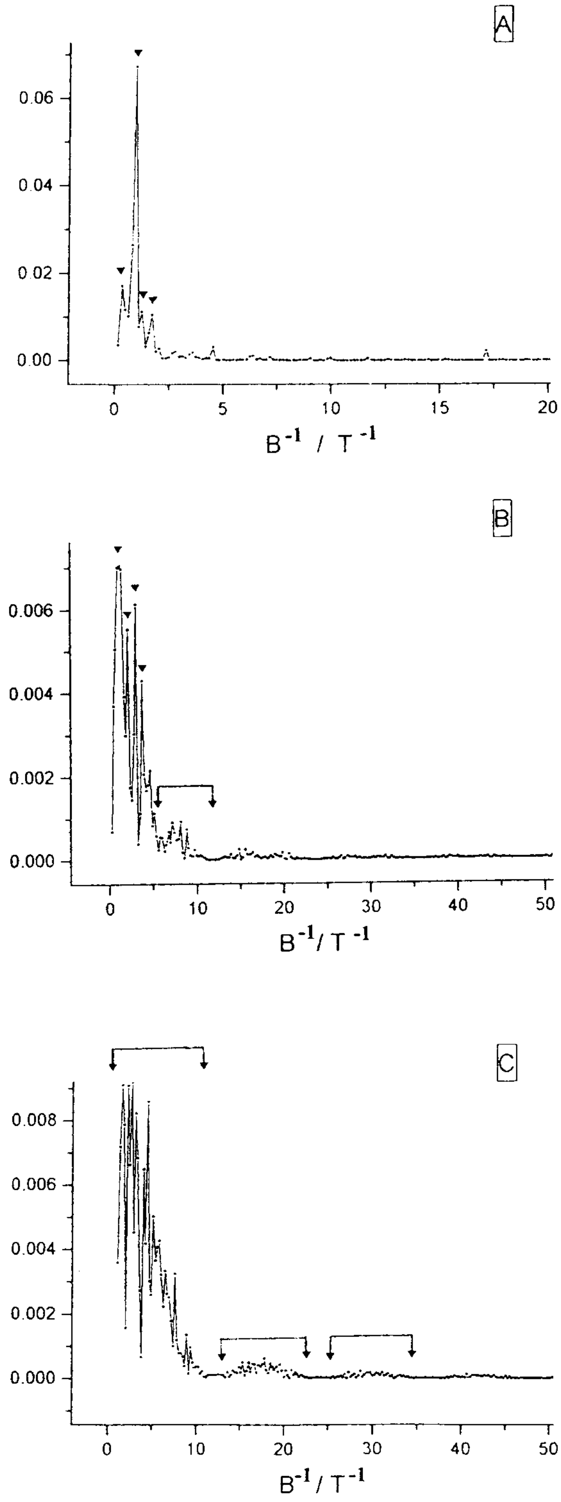

Figure 4. The corresponding Fourier spectra of the magnetoresistance at (a) $T = 30$ K, $\varepsilon = 1.65\%$, (b) T=30 K, $\varepsilon = 3.1\%$, (c) $T = 40$ K, $\varepsilon = 1.5\%$.

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