Aharonov-Bohm Effect on Charge Density Wave (CDW) Moving through Columnar Defects in $NbSe_3$

Yu. I. Latyshev
Institute of Radio-Engineering and Electronics, Russian Academy of Sciences, 11 Mokhovaya Str., Moscow 103907, Russia

O. Laborde and P. Monceau
Centre de Recherches sur les Très Basses Températures, Associé à l'Université Joseph Fourier, CNRS, BP 166, 38042 Grenoble-Cedex 9, France

S. Klaumünzer
Hahn-Meitner Institut, D-14019 Berlin, Germany
(Received 26 April 1996)

The presence of columnar defects (CDs) in $NbSe_3$ is shown to induce oscillations in the nonlinear charge density wave (CDW) conductivity as a function of magnetic field, when the field is oriented parallel to the axes of the defects. The period of oscillation corresponds to a change in the magnetic field flux in each CD by an amount $\phi_0 = hc/2e$, the superconducting flux quantum. This result is considered as the collective response of the moving CDW to Aharonov-Bohm flux trapped inside the CDs. [S0031-9007(96)02262-4]

PACS numbers: 71.45.Lr, 03.65.Bz

Twenty years of studies of quasi-one-dimensional metals in which charge density waves (CDWs) occur have not yet clearly revealed their quantum properties [1]. A theory of depinning of the CDWs by quantum tunneling was derived by Bardeen [2], but important predictions of this theory, in particular photon-assisted tunneling, have not been observed. Most of the observed CDW properties could be explained by appropriate classical models. However, some indications of CDW quantum tunneling at very low temperature have been recently discussed [3,4]. Thus, up to now, there has been no observation of quantum effects associated with CDW motion, which directly include Planck's constant in the measured parameters (e.g., as with Josephson effects or Little-Parks effect in superconductors).

One possible demonstration of the quantum nature of the CDW has been considered in a theoretical paper [5] in connection with the possibility of observing the Aharonov-Bohm effect [6] in a ring formed by a CDW conductor. It has been shown that magnetic flux quantization is possible in this case due to large scale quantum fluctuations of the CDW order parameter phase, the instantons. As a result, oscillations of the CDW electric conductivity can occur with flux period $\phi_0 = hc/2e$. To observe this effect the diameter of the ring should have a size comparable to the order parameter coherence length. We have undertaken a search for a similar effect. The geometry suggested in [5] is beyond our present capabilities. Instead we use the geometry of a planar film (thin single crystal) containing an array of small holes of equal diameter. Such a type of geometry has been successfully used to demonstrate the Little-Parks effect in high T_c superconductors [7]. In the case of CDW materials the holes will cross the metallic chains. However, we can expect the CDW in motion to pass over a hole without conversion if the diameter of the hole is smaller than the transverse coherence length $\xi_\perp$ of the CDW order parameter amplitude. For $NbSe_3$ the value of $\xi_\perp$ can be estimated as $\xi_\perp \sim a_\perp(E_F/\Delta) \sim$ about a few hundred Å. $a_\perp$ is the unit cell parameter, E_F is the Fermi energy, and Δ is the Peierls gap. To produce "holes" of diameter, $D \approx 100$ Å, we used heavy ion irradiation on thin $NbSe_3$ samples. In a magnetic field each defect hole serves as a "solenoid" which contributes to the flux dependent scattering of the depinned CDW. If we have several million columnar defects and the CDW still moves coherently through most of the crystal, the contributions resulting from the majority of the holes may be synchronized, considerably increasing the value of the CDW conduction affected by Aharonov-Bohm flux.

For the experiment, we chose long (>2 mm), thin ($\sim$0.5 μm), and wide ($\sim$50 μm) $NbSe_3$ samples of rather good quality ($RRR = 50$). The single crystal was mounted on polished sapphire substrates, half of a sample having been masked by a 100 μm thick glass cover slide in order to provide an unirradiated part of the sample for reference measurements. The irradiation was carried out at the Hahn-Meitner Institut (Berlin), using Xe ions with an energy of 250 MeV, and the ion beam being directed along the a^* axis. The radiation dose corresponded to 4×10^9 defects/cm^2. The average distance between neighboring defects is estimated to be 0.16 μm. After irradiation six indium contacts were attached to the sample, giving the possibility of switching potential probes from the irradiated to the unirradiated part of the sample under the same experimental conditions of temperature, bias current, and sample orientation. The magnetoresistance (MR) was measured using a 40 Hz phase sensitive detector with an ac current amplitude of less than 10 μA. dc current was supplied by a high stability current source. High magnetic fields up to 20 T were supplied by a Bitter coil at the Laboratoire des Champs Magnétiques Intenses of Grenoble. The magnetic field experiments were carried out at a fixed temperature below T_{p2}, the lower Peierls transition temperature. The temperature was chosen to be high enough to avoid the influence of Shubnikov–de Haas MR oscillations on the experiments [8]. The dc current was changed in steps. For each current the magnetic field H was swept up and down with a sweep rate of 2 T/min. H was oriented parallel to the a^* axis. Detailed studies of the influence of columnar defects on the transport properties of $NbSe_3$ will be published elsewhere.

Figure 1(a) shows the variation of the differential resistance R_d of the irradiated and unirradiated parts of the sample as a function of the dc current I at $T = 52$ K. The irradiation increases substantially the depinning current I_t and the transition from the pinned CDW to the moving CDW state becomes more smeared. The influence of H on the $R_d(I)$ of the irradiated part is illustrated in Fig. 1(b). We can identify three current regions with different responses to the magnetic field. In regions I and III there is a positive MR, which we can consider as the pure response of the pinned and depinned CDW states to H. The MR in region I is about 10 times larger than in region III. In region II there is some negative

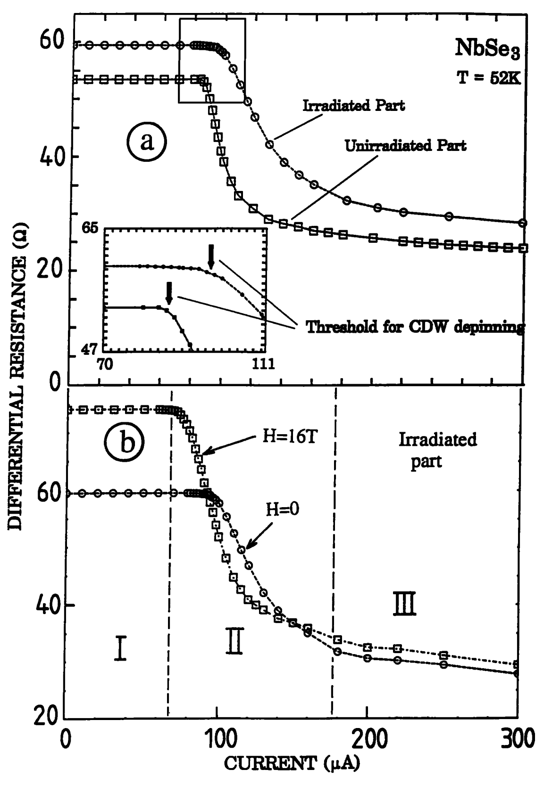

FIG. 1. The variation of the differential resistance of $NbSe_3$ as a function of the dc current along the b axis at 52 K (a) for the irradiated and unirradiated parts of the $NbSe_3$ sample in zero magnetic field (inset shows enlargement near the depinning current) and (b) for the irradiated part in zero field and in a field of 16 T applied parallel to the a^* axis.

MR contribution because the decrease of the threshold current due to the magnetic field. In this region all three contributions are mixed, making the analysis rather difficult. This was the reason for our more detailed studies of the MR in regions I and III. Similarly positive magnetoresistance in the pinned and depinned CDW states for $NbSe_3$ has been previously reported [9]. The decrease of the threshold field in high magnetic field has also been observed [10], but at lower temperatures.

The main goal of this Letter has been to clarify the influence of columnar defects on MR of pinned and moving CDW states. We have carried out detailed studies of the magnetoresistance $R(H)$ for the irradiated and the unirradiated parts of the $NbSe_3$ samples at the fixed temperature $T = 52$ K, and for different values of the dc current above and below I_t (Fig. 2). One can see that below I_t ($I = 50$ μA) there is practically no difference in $R(H)$ between the irradiated and unirradiated parts. They are both smooth and monotonic. The appropriate $\Delta R(H) = R(H) - R(0)$ curves coincide with each other over the whole range of H except for the region below 5 T, where the curve of the unirradiated part is more flat. This is not the case above I_t. While the $R(H)$ dependences of the unirradiated part show a similar smooth shape [Fig. 2(a)], the $R(H)$ dependences of the irradiated part change significantly [Fig. 2(b)]. In addition to a monotonically increasing part, a contribution appears which oscillates with H. These long period oscillations are most clearly observed in the dc current range around 2–3 times the threshold current (200–300 μA). At even higher currents they gradually weaken and become indistinguishable at $I \approx 900$ μA).

To estimate the amplitude of the oscillating part of the MR we suppose that the oscillating and the monotonically growing contributions are additive, the latter being some scaling function of $R(H)$, below the threshold current. This scaling is found to be valid for the unirradiated part, and we have considered it to be also valid for the irradiated section. Figure 3(a) shows that the four curves $\Delta R(H)$ for $I = 50$, 180, 300, 900 μA [shown in Fig. 2(a)] can be superimposed on a single universal curve by changing the vertical scale, i.e., they can be expressed in the form $\alpha \Delta R(H)$, where α is a scaling parameter which depends on I. Figures 3(b) and 3(c) show the $\Delta R(H)$ curves for both the irradiated and the unirradiated parts for the same current of 180 μA and the appropriate fitting curves $R_{\mathrm{fit}}(H)$ below the threshold at $I = 50$ μA. The oscillating part of the MR at each field has been extracted as an average value of the run up (↑) and run down (↓) as follows: $\Delta R_{\mathrm{osc}}(H_i) = [R(H_i)\uparrow + R(H_i)\downarrow]/2 - R_{\mathrm{fit}}$. The result of this procedure is shown in Fig. 4. One can see that for the irradiated part oscillations are quite symmetrical and regular. The average value of half-period, 4.9 T, is consistent within 10%. The amplitude of the oscillatory part of the MR is 0.7 Ω (peak to peak), at least 7 times larger than the background signal determined by the same procedure from the reference unirradiated part of the sample (shown also in Fig. 4).

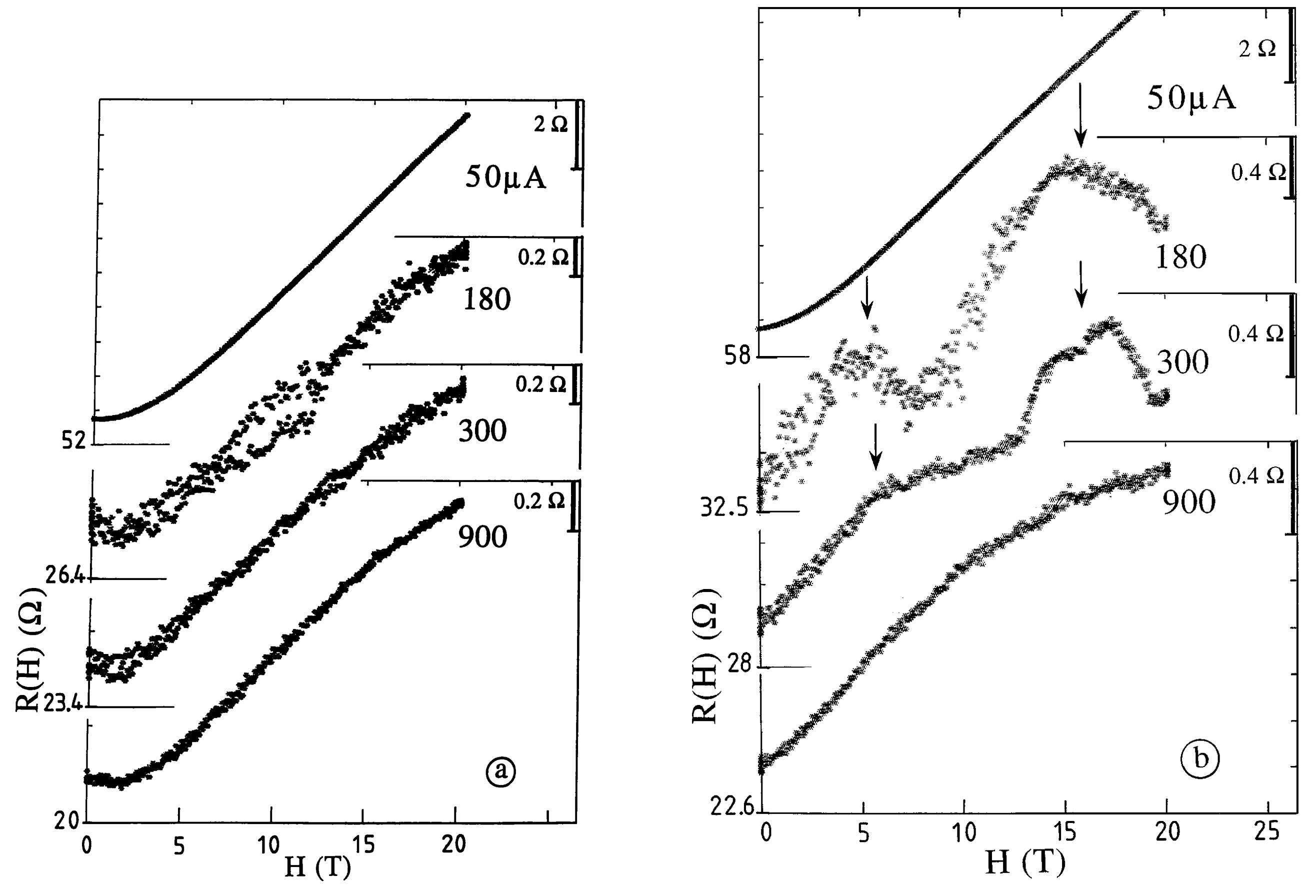

FIG. 2. Variation of the magnetoresistance of $NbSe_3$ at 52 K for different dc currents I applied along the chain axis (a) for the unirradiated part of the sample and (b) for the irradiated part of the sample. The magnetic field is applied along the a^* axis, parallel to the columnar defect axes.

The oscillations in the CDW conduction are about 0.25% of the total CDW conduction.

Since these long period oscillations have been observed only above I_t and only on the part of the sample containing columnar defects, it is reasonable to identify them as a manifestation of macroscopic quantum interference of CDW coherently moving over columnar defects (CDs). The principal point is that the CD size is smaller than both, the longitudinal and transverse coherence length of the CDW order parameter amplitude. It means that the CDW can pass over CD without conversion, i.e., without phase breaking. The interaction of CDW with Aharonov-Bohm flux trapped inside the CD causes the time dependent phase difference between local CDWs passing the CD from the right and from the left. It leads to the appearance of a persistent current around the CD due to the excitation of the instantons as it was considered in [5] for a small CDW ring. The instanton theory of the Aharonov-Bohm effect predicts that the amplitude of the persistent current and the CDW conduction of the ring should be an oscillating function of Aharonov-Bohm flux ϕ/ϕ_0, where ϕ is a flux trapped inside the ring and ϕ_0 is a superconducting flux quantum $\phi_0 = hc/2e$. If we consider the instanton model to be valid for our case, we can expect that the local CDW conduction associated with CDW passing over the CD will be a periodic function of the Aharonov-Bohm flux, i.e., Hs/ϕ_0 where H is the external magnetic field and s the effective area of the CD inside which the CDW cannot move. All the CDs have about the same cross sectional area. Hence we can expect that the local Aharonov-Bohm contributions of a large number of CDs are synchronized due to the coherent CDW motion over large distances. The phase coherence length of moving CDW in $NbSe_3$ is known to be several hundred of microns.

Let us compare the period of the oscillating part of the MR with that predicted by the instanton model. We can estimate the size of the CD in $NbSe_3$ on the basis of TEM on high T_c cuprates $Bi_2Sr_2CaCu_2O_8$ whiskers which had been irradiated by Xe ions under quite similar conditions [11]. It was shown that a CD is a real hole with a diameter of 10–12 nm surrounded by a damaged region which adds a further 2–4 nm to the effective diameter. The hole diameter is not expected to depend strongly on the material, and we take the CD size for the scattering of the sliding CDW in $NbSe_3$ to be $D = 15$ nm with an uncertainty of order 2 nm. The expected period of the MR oscillation ΔH is as follows:

$$\Delta H = (hc/2e)/(\pi D^2/4). \quad (1)$$

Equation (1) yields $\Delta H = 11.3$ T. That is consistent with the experimental value $\Delta H = 9.8$ T (Fig. 4) within experimental uncertainty.

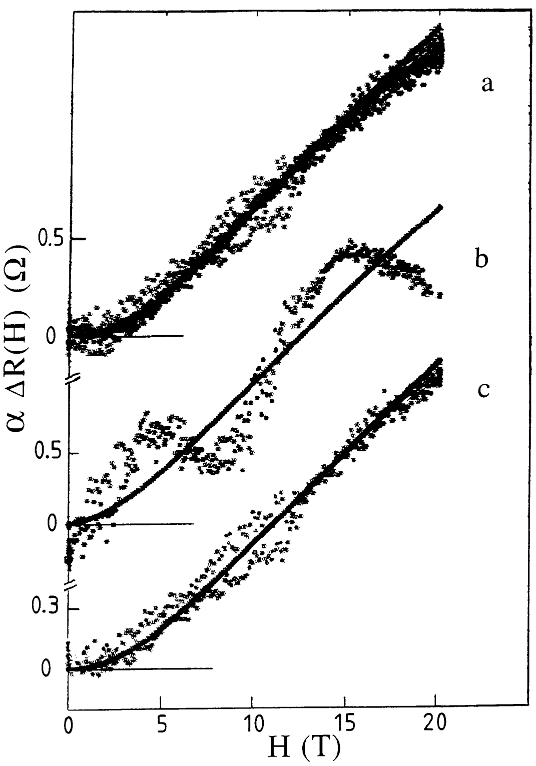

FIG. 3. (a) Scaling of the magnetoresistance [shown in Fig. 2(a)] $\alpha\Delta R(H) = \alpha(I) \times [R(H) - R(0)]$ of the unirradiated part of $NbSe_3$ at 52 K as a function of the magnetic field for the dc currents 50, 180, 300, 900 μA. (b) $\alpha\Delta R(H)$ of the irradiated part of the sample for the dc currents 50 and 180 μA ($\alpha = 0.125, 1$). (c) $\alpha\Delta R(H)$ for the unirradiated part ($\alpha = 0.09, 1.0$) for the same current 50 and 180 μA.

Another observation, that the oscillatory part of MR has a minimum at $H = 0$, is also consistent with the instanton Aharonov-Bohm picture. Zero field corresponds to the zero amplitude of circulating persistent currents and hence to the minimum of the oscillating MR.

We cannot properly analyze the expected amplitude of the oscillations, since there is not yet a microscopic theory, similar to that of [5] which is applicable to our experimental geometry. The experiments show that ΔR_{osc} decreases rather rapidly with the current increase above $\approx 2I_t$. It may be considered as the loss of the phase coherence between local CDWs passing over different CDs at higher velocities. This view is consistent with experiments on Shapiro step response of sliding CDW to an rf field with frequency 5–15 MHz carried out on irradiated samples. It was shown that complete mode locking response, corresponding to the coherent CDW motion over the whole sample volume, was observed only within the current range just above the threshold value.

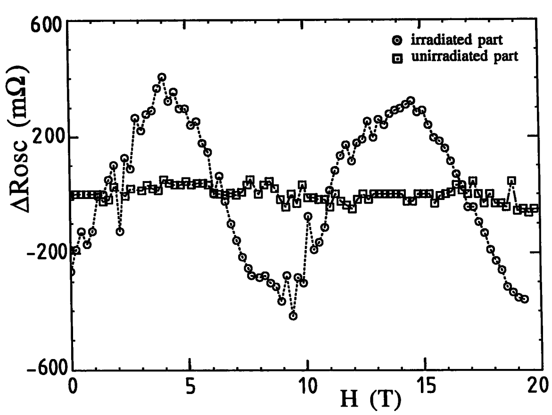

FIG. 4. Variation of the oscillatory part of the magnetoresistance of $NbSe_3$ $\Delta R_{osc}(H)$ as a function of the magnetic field extracted from the data of Figs. 3(b) and 3(c) according to the procedure described in the text.

In summary, we have observed oscillations of the CDW conduction as a function of magnetic field due to the CDW passing columnar defects containing trapped magnetic flux. This observation is consistent with the instanton Aharonov-Bohm effect predicted in CDW systems. Until recently superconductors were the only systems known to exhibit the flux-quantization effect produced by the collective response of a condensate.

We acknowledge fruitful and stimulating discussions with A. S. Rozhavsky and P. Main. We are thankful to Dr. P. J. King for support of this work and for organizing the collaboration with Hahn-Meitner Institute and to V. E. Minakova for selection of some samples for irradiation. The work was partly supported by the Russian Fund for Fundamental Research (Project No. 95-02-04456) and INTAS (Grant No. A92-056).

Note added in proof.—We have observed similar oscillations of the MR on two more thin $NbSe_3$ samples irradiated with Pb ions of 6 GeV at the GANIL accelerator [12] (Caen, France). Preliminary TEM observations have revealed [13] latent tracks produced by Pb ions of 6 GeV with amorphous cores in the crystalline matrix. The diameters of the amorphous cylinders were measured to be 16 ± 2 nm. The period of the MR oscillations was 8.6 T, consistent with Eq. (1) which yields $\Delta H = 10.3$ T and was independent on defect density n for samples with $n = 5 \times 10^9$ and 10^{10} def/cm^2. The oscillations were observed within the temperature range 50–36 K without noticeable change in the period value.

[1] For a review, see *Density Waves in Solids,* edited by G. Grüner (Addison-Wesley, Reading, MA, 1994).
[2] J. Bardeen, Phys. Scr. **127**, 136 (1989).
[3] S. V. Zaitsev-Zotov, Phys. Rev. Lett. **71**, 605 (1993).
[4] F. Ya. Nad', Soviet JETP Lett. **58**, 111 (1993).
[5] E. N. Bogachek *et al.*, Phys. Rev. B **42**, 7614 (1990).
[6] Y. Aharonov and D. Bohm, Phys. Rev. **115**, 485 (1959).
[7] P. L. Gammel *et al.*, Phys. Rev. B **41**, 2593 (1990).
[8] P. Monceau and A. Briggs, J. Phys. C **11**, 1465 (1978).
[9] R. V. Coleman *et al.*, Phys. Rev. B **41**, 460 (1990).
[10] P. Monceau and J. Richard, Phys. Rev. B **37**, 7982 (1988).
[11] V. N. Timofeev and I. G. Gorbova (private communication).
[12] Irradiation of $NbSe_3$ at GANIL was performed by M. Konzyckowski.
[13] Th. Fournier (private communication).