Quantum interference of electrons in Nb$_{5-x}$Te$_4$ single crystals

A. Stolovit$^*$ and A. Sherman

Tartu Ülikooli Füüsika Instituut, Riiia 142, EE-51014 Tartu, Estonia

R. K. Kremer, Hj. Mattausch, H. Okudera, X-M. Ren† and A. Simon

Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-70569 Stuttgart, Germany

J. R. O’Brien

Quantum Design, 6325 Lusk Boulevard, San Diego, CA 92121
(Dated: March 23, 2022)

The compound Nb$_{5-x}$Te$_4$ ($\delta = 0.23$) with quasi-one-dimensional crystal structure undergoes a transition to superconductivity at $T_c = 0.6$–0.9 K. Its electronic transport properties in the normal state are studied in the temperature range 1.3–270 K and in magnetic fields up to 11 T. The temperature variation of the resistivity is weak (< 2%) in the investigated temperature range. Nonmonotonic behavior of the resistivity is observed which is characterized by two local maxima at $T \sim 2$ K and $\sim 30$ K. The temperature dependence of the resistivity is interpreted as an interplay of weak localization, weak antilocalization, and electron-electron interaction effects in the diffusion and the Cooper channel. The temperature dependence of the dephasing time $\tau_\phi$ extracted from the magnetoresistance data is determined by the electron-phonon interaction. The saturation of $\tau_\phi$ in the low-temperature limit correlates with $T_c$ of the individual crystal and is ascribed to the scattering on magnetic impurities.

PACS numbers: 72.15.Rn,74.70.Ad,72.15.Lh,72.10.Di,74.62.Dh

I. INTRODUCTION

In disordered metals the coherence of the conduction electrons may extend over large distances and exceed the mean free path by several orders of magnitude. This large scale coherence manifests itself in interference effects such as weak localization, interference corrections to electron-electron interaction and various mesoscopic phenomena. In general, the temperature dependence of the dephasing time $\tau_\phi$ is governed by electron-electron and electron-phonon interaction. In disagreement with the standard theory of electron dephasing, a saturation of $\tau_\phi$ in the low-temperature limit has been observed in numerous experiments. It was suggested that this saturation is universal and reflects fundamental properties of disordered conductors. Various mechanisms for the saturation behavior have been discussed, including effects of magnetic impurities, tunneling two-level systems, electron heating, and separated superconducting grains (see Refs. [1–5]).

Recently the character of the disorder and its influence on $\tau_\phi$ have become an important issue of research. Weak localization studies of differently prepared PdAg films show that the microscopic structure of disorder determines the interaction of the electrons with the phonons. The nature of the scattering potential plays a crucial role in the Sergeev-Mitin electron-phonon interaction theory. While in dirty systems the scattering on vibrating impurities results in a $T^4$ dependence of the electron-phonon scattering rate $\tau_{ep}^{-1}$, scattering on a static potential leads to $\tau_{ep}^{-1} \sim T^2$. Disorder also influences the saturation value $\tau_0$ of the dephasing time. For example, Lin et al. found that annealing of moderately disordered three-dimensional polycrystalline metals raises $\tau_0$. This result can be explained in terms of two-level systems associated with the grain boundaries. However, annealing effects have not been observed in strongly disordered samples. To further investigate disorder effects, systems in which the crystallinity can be tuned in a broad range are desirable. Single crystalline systems with disorder, e.g., emerging from vacancies, which exhibit quantum interference effects are potential candidates for such studies.

In this paper we present electron transport studies on single crystals of Nb$_{5-x}$Te$_4$. Nb$_{5-x}$Te$_4$ belongs to the growing family of compounds crystallizing with the tetragonal Ti$_5$Te$_4$ structure-type (space group $I4/m$).
For a list of presently known compounds with this structure-type see Ref. 13. The basic elements of the structure are compressed Ti₅Te₈ clusters which condense to form infinite Ti₅Te₃ chains. These chains are linked through Ti-Te and Ti-Ti contacts (see Fig. I. Ti₅Te₁₅, Nb₅Te₄, Mo₃As₁₄, Nb₅Sb₁₄, and Nb₅Se₂S₂ are reported to be metals.14,15,16 Among them Nb₅Sb₁₄ and Nb₅Se₂S₂ are superconductors with critical temperatures $T_c = 8.6$ K and 3.4 K, respectively.15,17 Nb₅Te₄ and Ti₅Te₄ were reported to behave as normal metals down to 1.1 K.17

Recently, a monoclinic form of Nb₅.₄Te₄ has been synthesized using a chemical transport reaction.18

In this work we found that Nb₅.₄Te₄ is a bulk superconductor with $T_c = 0.6–0.9$ K. In the normal state quantum interference effects determine the electronic transport properties in a broad temperature range. The observed nonmonotonic behavior of the temperature dependence of the resistance and the low-temperature positive magnetoresistance are interpreted in terms of weak localization and electron-electron interaction effects in disordered conductors. The temperature dependence of the dephasing time $\tau_\varphi$ is determined by electron-phonon interaction. Saturation of the dephasing time at low temperatures is ascribed to scattering on magnetic impurities.

II. EXPERIMENTAL

Nb₅.₄Te₄ single crystals were prepared by chemical vapor transport from powders of the elements Nb (Johnson Matthey Inc. 99.99% metals basis, excluding Ta, Ta < 500 ppm) and Te (Johnson Matthey Inc. 99.99%) in evacuated silica tubes with $I_2$ used as a transport agent. The samples were annealed for 1 day at 750°C, the following 30 days at 980°C, and then were slowly cooled to room temperature. X-ray powder-diffraction patterns were collected with a Stoe diffractometer using Cu $K\alpha_1$ radiation. They show a body-centered tetragonal unit cell with lattice parameters $a = 10.234(1)$ Å and $c = 3.7021(6)$ Å which are in agreement with those observed by Selte and Kjekshus.12 Energy dispersive x-ray analysis carried out on the three crystals used for the resistance measurements reveals a Nb deficiency of $\delta = 0.23(4)$. A single crystal x-ray diffraction measurement with a Stoe image plate detector system was carried out on a small crystal. It shows that the Nb deficiency is associated with the outer site of the Nb octahedral chains (Wyckoff position 8h). Single crystal x-ray measurements performed on the three crystals used for the resistance measurements gave lattice parameters in good agreement with the powder diffraction data.

The heat capacity of a 6.3 mg crystal was measured in a Quantum Design PPMS relaxation calorimeter in the temperature range 0.3–5 K and external fields of 0 T and 9 T. The sample was attached with a minute amount of Apiezon vacuum grease to the calorimeter platform the heat capacity of which was determined in a separate run and subtracted afterwards.

For resistance measurements needle-like crystals with the needle axis collinear with the crystallographic c-axis were selected. Crystals were 3–5 mm long with cross section of 0.005–0.05 mm². Four electrical contacts were placed along the needle at distances of ~2 mm with the two outer contacts as the current contacts such that the electrical current was directed along the c-axis.

Crystals stored in air get covered by a high-resistive oxide layer. Low-resistance ohmic contacts can be achieved after this layer has been etched off with an Ar plasma in a vacuum chamber followed by the immediate deposition of the gold contact pads through a shadow mask. Similar good contacts can also be made by gluing gold wires with silver epoxy resin on a crystal surface freshly cleaved in an argon atmosphere. The results do not depend on the way contacts have been applied.

The resistance was measured by a dc four-probe technique using a high resolution nanovoltmeter (7 1/2 digits) and a Keithley 2400 current source. Measurements were performed using a variable temperature Oxford 4He cryostat with a superconducting magnet. The rotatable sample holder with the rotation axis perpendicular to the magnetic field allows us to align the crystal either perpendicular or nearly parallel to the magnetic field. Magnetoresistance was measured at constant temperature in fields up to 11 T. The superconducting transition and its dependence on the magnetic field was measured in a home-built single shot 3He refrigerator. The bias currents were chosen such that the power dissipated in the sample remained below 30 pW and 2 $\mu$W for the measurements in the 3He and the 4He measurements systems, respectively.

III. RESULTS AND DISCUSSION

A. Superconductivity

A total of six crystals was checked for superconductivity by resistance measurements. All investigated samples show a transition to superconductivity with critical temperatures in the range 0.60–0.88 K and transition widths between 0.012–0.18 K. A typical resistive transition is shown in Fig. 2(c). Measurements in magnetic fields reveal a linear dependence of the upper critical field $H_{c2}(0)$ as a function of temperature down to 0.35 K, with a slope of $dH_{c2}/dT = -1.2$ T/K.

The heat capacity measured in zero field is characterized by an anomaly typical for a transition to superconductivity (Fig. 2(b)). The anomaly disappears in a field of 9 T. In the range 0.3–2 K the heat capacity can be well described by a polynomial $C_p = \gamma T + \beta T^3$, where the linear and cubic terms are electronic and lattice contributions, respectively (Fig. 2(a)). The fit yields the Sommerfeld term $\gamma = 17.29$ $\mu$J/gK², and the phonon term $\beta = 1.027$ $\mu$J/gK⁴ corresponding to the Debye temperature $\Theta_D = 259$ K. The superconducting anomaly
within experimental errors agrees well with the anomaly expected for a BCS-type superconductor. Resistivity and heat capacity results clearly prove that Nb$_{5-s}$Te$_4$ is a bulk superconductor.

The electronic density of states at the Fermi level $\nu$ was calculated from the Sommerfeld term using the formula:

$$\gamma = \frac{\pi^2 \nu k_B^2}{1 + \lambda}/3,$$

where $k_B$ is the Boltzmann constant. The electron-phonon coupling constant $\lambda = 0.44$ was estimated from the McMillan empirical formula:

$$\lambda = \frac{1.04 + \mu^* \ln (\Theta_D/1.45T_c)}{(1 - 0.62\mu^*) \ln (\Theta_D/1.45T_c) - 1.04}.$$  

with the Coulomb pseudopotential $\mu^* = 0.13$, which is typical for the transition metals. In Nb$_{5-s}$Te$_4$ we obtain $\nu \approx 1.59 \times 10^{27} \text{J}^{-1} \text{m}^{-3}$, which is comparable to the density of states in good metals such as silver, copper, and gold.

### B. Electrical Resistivity

The temperature dependence of the resistivity was measured on six crystals. All samples show resistivities between 200–300 $\mu\Omega \text{cm}$ (see Table I) and a weak variation with temperature (less than 2% in the range of 2–270 K, see Fig. 2). This finding points to strong scattering of conduction electrons. This is also reflected in the electron diffusion constant $D \approx 1 \text{ cm}^2/\text{s}$ and a low Hall mobility. The diffusion constant was determined from the temperature dependence of the critical magnetic field using $D = -4k_B/[\pi e (dH_c/dT)]$, where $e$ is the electron charge. An alternative estimation of $D$ from the resistivity $\rho_0$ using the Einstein relation $1/\rho_0 = e^2D\nu$ gives $D = 0.9–1.2 \text{ cm}^2/\text{s}$, which is consistent with the value determined from $H_c2(T)$ to within 20% (see Table I). The agreement is reasonable considering uncertainties in $\rho_0$ and $\nu$. As being more reliable, the value of $D$ estimated from the critical magnetic field measurements will be used in the analyses below. The Hall constant is negative indicating that electrons contribute to the charge transport. The Hall mobility is low, 0.25 $\text{cm}^2/(\text{V} \cdot \text{s})$, which in the free electron model gives an electron mean free path of $\ell \approx 2 \AA$ of the order of interatomic distances. The origin of strong electron scattering in Nb$_{5-s}$Te$_4$ is an open question. The Nb deficit is definitely essential, however deformations of the low-dimensional structure may also contribute to the scattering.

A closer inspection of the temperature dependence of the resistance reveals qualitatively different behavior above $\sim 50$ K with either positive or negative temperature coefficients (see Figure I(a)). The magnetoresistance behavior and the temperature dependence of the resistance of three representative samples Nb10, Nb19, and Nb09 have been studied in detail and the analysis is described in the following.

#### 1. Magnetoresistance

Figure 2 shows a typical dependence of the resistance on the magnetic field measured for temperatures between 1.3 K and 13 K. The small positive magnetoresistance (< 0.3%) with a minimum centered at zero magnetic field, which broadens as the temperature is increased, is a typical fingerprint of quantum interference effects of the conduction electrons. The positive magnetoresistance is expected in disordered superconductors containing heavy elements in which both the scattering on virtual Cooper pairs and weak antilocalization of conduction electrons induced by spin-orbit scattering are essential. We found that the magnetoresistance is independent of the orientation of the magnetic field. This result is rather unexpected in view of the anisotropic crystal structure. We tentatively ascribe this finding to averaging effects caused by strong electron scattering.

In the following we compare our magnetoresistance data with results of a theory treating three-dimensional quantum interference corrections to resistivity. In the limit of low fields the relative change of the resistance is
expressed by the equation

\[ R(R) - R(0)/R(0) = A e^{2} \frac{eH}{2\pi\hbar f_{3}} \left( \frac{4eD\tau_{\ell}H}{\hbar} \right) + \frac{BH^{2}}{2}, \]  

where \( h \) is the Planck constant and \( f_{3}(1/x) = 2(\sqrt{2 + x} - \sqrt{x}) - [0.5x]^{-1/2} + [1.5 + x]^{-1/2} + [2.03 + x]^{-3/2}/48 \). In Eq. (2), the first term with the prefactor \( A = \rho_{0}/2 \) describes weak antilocalization in the limit of strong spin-orbit scattering, \( \tau_{s}^{-1} \ll \tau_{s}^{-1} \), where \( \tau_{s}^{-1} \) is the spin-orbit scattering rate. In superconductors for \( T > T_{c} \), the scattering on virtual Cooper pairs, the Maki-Thompson-Larkin effect, is also described by the first term in Eq. (2) with a temperature-dependent prefactor \( A = \rho_{0}c_{\text{MT}}/2 \beta(T/T_{c}) \). Here \( \beta \) is the function tabulated in Ref. [24] and \( c_{\text{MT}} = 1 \) and 0.25 in the limits of weak and strong spin-orbit scattering, respectively. This expression is valid for magnetic fields \( H \ll k_{B}T/eD \). Expressions for larger fields have been derived for the two-dimensional case \( 25,26 \). For the three-dimensional case, results for an extended range of fields have only been analyzed numerically for an MgB\(_{2}\)/Zn\(_{33}\) alloy sample \( 27 \).

In the field limit set by the Maki-Thompson-Larkin effect, \( H \ll k_{B}T/eD \), contributions of the classical magnetoresistance and electron-electron interaction are described by the quadratic term in Eq. (2). The magnetoresistance due to the electron-electron interaction in the Cooper channel is negative and diverges as \( T \) approaches \( T_{c} \). Its contribution is described by the parameter \( \tilde{F} \)

\[ B = -8.49 \times 10^{-3} \left( \frac{D}{\hbar k_{B}T} \right)^{3/2} \frac{e^{4}}{\rho_{0}k_{C}} \frac{\rho_{0}k_{C}}{\ln(T/T_{c})}, \]  

where \( k_{C} = 1 \) and 0.25 in the limit of weak and strong spin-orbit scattering, respectively. In fields \( H \ll k_{B}T/g\mu_{B} \) the electron-electron interaction in the diffusion channel is described by the coefficient

\[ B = 9.5 \times 10^{-4} \rho_{0}\tilde{F} \sqrt{k_{B}T/\hbar D} \left( \frac{g\mu_{B}}{k_{B}T} \right)^{2}, \]  

where \( \mu_{B} \) is the Bohr magneton and \( g \) is the gyromagnetic ratio. The electron-screening parameter \( \tilde{F} \) approaches 1 in the limit of complete screening and 0 if screening is negligible. In superconductors due to the exchange with virtual phonons, negative values of \( \tilde{F} \) are expected \( 1,25 \).

In the magnetic field range \( |H| \leq 0.5k_{B}T/eD \) the magnetoresistance data were fitted to Eq. (2) using \( A, B, \) and \( \tau_{\ell} \) as fitting parameters. The fits shown as solid lines in Fig. 3 are in good agreement with the experimental data for all temperatures. The temperature dependence of \( A, B, \) and \( \tau_{\ell} \) is displayed in Fig. 4 and 5. \( A \) is positive and increases as the temperature decreases below 9 K. The temperature dependence of \( A \) is well described by the formula

\[ A = \rho_{0} \left[ c_{\text{MT}}\beta(T/T_{c}) + 1/2 \right], \]  

with the Maki-Thompson-Larkin correction and weak antilocalization due to strong spin-orbit scattering as first and second terms, respectively. The fit parameters \( \rho_{0} \) coincide within 10% with the measured values of the electrical resistivities (see Table I). Below, the fitted values for \( \rho_{0} \) will be used for the description of the temperature dependence and the electron-electron interaction in the Cooper channel. For strong spin-orbit scattering, \( c_{\text{MT}} \) is expected to be 0.25 (see above). The fits rather give
With comparable exponents has been observed for NbC, phonon interaction. A similar temperature dependence (see Fig. 4(b)) allows us to identify the origin of the second term in Eq. (2) with the electron-electron interaction in the Cooper channel. The single-parameter dependence (see Fig. 4(b)) allows us to identify the origin of the second term in Eq. (2) with the electron-electron interaction in the Cooper channel. The single-parameter fit with Eq. (6) is in good agreement with the experimental data. As in the case of the Maki-Thompson-Larkin correction, the value of the fitting parameter $k_C$ (see Table I) lies between the strong and weak spin-orbit scattering limits.

Figure 4 shows the temperature dependence of $\tau_\varphi$ for samples Nb09, Nb10, and Nb19. The solid lines correspond to fits with the formula

$$\tau_\varphi^{-1} = KT^n + \tau_0^{-1},$$

with the fitting parameters $\tau_0^{-1}$, $K$, and $n$ listed in Table I. In Eq. (6) the exponent $n \approx 2.5$ indicates that the temperature dependence of $\tau_\varphi^{-1}$ arises from electron-phonon interaction.

A similar temperature dependence with comparable exponents has been observed for NbC, Sb, and Pd$_{60}$Ag$_{40}$.$^{3,23-33}$ Dephasing due to electron-electron interaction with small energy transfer is also described by a power law but with a smaller exponent, $n = 3/2$, and the coefficient $^{34,35}$

$$K = \frac{k_B^{3/2}}{12\sqrt{2\pi^3\hbar^{5/2}\nu D^{3/2}}}. \quad (7)$$

Numerical estimates with this formula give a dephasing rate which is more than two orders of magnitude smaller than that observed in the experiment. Therefore, as is often the case in three-dimensional systems, this mechanism can be neglected for Nb$_{0.7}$Te$_{6}$.

Deviation of $\tau_\varphi^{-1}(T)$ from the power law are observed below 5 K and are described by the parameter $\tau_0^{-1}$. The fitted values for $\tau_0^{-1}$ correlate with the critical temperatures (see inset in Fig. 5). This points to scattering on magnetic impurities which decreases both $T_c$ and the dephasing time. The spin-flip scattering rate $\tau_s^{-1}$ is proportional to the concentration of magnetic impurities $x_{mag}$ according to $^{36}$

$$\frac{1}{\tau_s} = \frac{x_{mag}}{\pi\hbar\nu} \frac{\pi^2 S(S+1)}{\hbar^2 S(S+1)+\ln^2(T/T_K)}, \quad (8)$$

where $S$ is the impurity spin and $T_K$ is the Kondo temperature. For impurities with $S > 3/2$ and $T_K < 0.3$ K we obtain $x_{mag} = 9 \times 10^{-6}, 30 \times 10^{-6}$, and $42 \times 10^{-6}$ per host atom for Nb19, Nb10, and Nb09 respectively. These concentrations correlate with the purity of the starting materials used for the sample preparation. Additionally, we carried out temperature dependent magnetization measurements on Nb$_{0.7}$Te$_{6}$. These reveal a
Curie type susceptibility contribution with a Curie constant which is consistent with these impurity estimates if we assume Fe$^{3+}$ ions ($S = 5/2$) as major impurities.

The effect of the magnetic impurities on $T_c$ is characterized by the slope $dT_c/dx_{\text{mag}}$. In Nb$_{5-x}$Te$_4$ we have $dT_c/dx_{\text{mag}} = -5.3 \times 10^3$, which is of the same order of magnitude as observed for Zn-Ni, Zn-Co, and Al-Mn alloys.  

Other mechanisms of the dephasing saturation can be excluded based on experimental data. Electron scattering by the exchange of superconducting fluctuations modifies the temperature dependence of $\tau_\varphi$ near $T_c$. In various systems this effect manifests itself either through a negative temperature coefficient or a saturation of $\tau_\varphi(T)$. In the latter case an increase in $\tau_0^{-1}$ with increasing $T_c$ is expected which is not seen in the experiments. This result is also in line with the conclusion that contribution of the electron-electron interaction in $\tau_\varphi$ is negligible.

Nonequilibrium effects of the conduction electrons can lead to saturation of $\tau_\varphi$ in several cases. Measurements of $R$ and $\tau_\varphi$ at different bias currents show that heating effects are not important in our experiment. Besides, the internal thermometers associated with the Maki-Thompson-Larkin effect and the electron-electron interaction in the Cooper channel (Fig. 4) follow the variation of the external temperature, while $\tau_\varphi$ saturates. This also indicates that for the chosen measuring parameters the system is in thermal equilibrium.

We note that our $\tau_0$ values agree with the scaling relation for this parameter found by Lin and Kao for numerous three-dimensional polycrystalline alloys with small diffusion constant $(D = 0.1 - 10 \text{ cm}^2/\text{s})$. However, in view of the magnetic impurities found in our samples the agreement rather appears to be accidental. Investigations crystals with a reduced impurity level are necessary to compare the saturation behavior of $\tau_\varphi$ in single- and polycrystalline materials.

2. Temperature dependence of resistance

Figure 4 displays the temperature dependence of the resistance for $T > T_c$. Up to 270 K, the resistance varies by less than 2% which indicates that the contribution of the electron-phonon scattering to the resistivity is largely suppressed. A closer inspection reveals that the temperature dependence is nonmonotonic and characterized by one maximum around 2 K and a second maximum/hump between 20 K and 40 K. We ascribe this behavior to an interplay of weak localization and electron-electron interaction effects, some of which also contribute to the magnetoresistance. At $T > 50$ K the temperature dependence is sample dependent. Typical behaviors are illustrated by samples Nb09, Nb10, and Nb19 in Fig. 5(a). While in Nb09 a negative temperature coefficient extends up to room temperature, Nb10 shows a metallic behavior with a positive temperature coefficient at all temperatures. Nb19 with a resistance minimum at 130 K falls between these two limiting cases.

We begin the data analysis with the low-temperature region around the first maximum. We associate it with the interplay of the superconducting fluctuation effects and the electron-electron interaction in the diffusion channel. For these temperatures the weak antilocalization is suppressed because of the saturation of $\tau_\varphi$. In the range 1.2–4.2 K the experimental data are well fitted by the formula:

$$\frac{R(T)}{R(T_m)} = \left(1 - \frac{T}{T_m}\right)^{F/4} + 4/F\tau_\varphi(T_c, T_m)$$

The first term in Eq. 9 corresponds to the electron-electron interaction in the diffusion channel with $F_d = 0.915(2/3 - F/4)$. The electron-electron interaction in the Cooper channel, the Maki-Thompson-Larkin correction, and the weak antilocalization, also observed in the magnetoresistance, are described by the second, third and fourth terms, respectively. $I_{\text{MT}}$ is a triple integral (see Eq. (56) in Ref. 42), which determines the dependence of the Maki-Thompson-Larkin correction on $T/T_c$ and $\tau_\varphi$. The values of the fitting parameters $F$, $k_C$ are listed in Table I. The values of $k_C$ determined from $R(T)$ and $R(H)$ are consistent with each other. As expected for superconductors, $F$ is negative in Nb09 and Nb19. Their values -0.234 and -0.323 for Nb09 and Nb19, respectively, are close to those found, for example, in Ti$_{1-x}$Sn$_x$ and Ti$_{1-x}$Ge$_x$ alloys which show higher critical temperatures. In Nb10 $F$ is larger and positive, $F = 0.048$. We attribute this to the Boltzmann transport term which extends to lower temperatures in this sample and is not included in Eq. 9. Indeed, the sample Nb10 exhibits the best metallic properties and consequently a larger contribution of the Boltzmann term is expected.

As the temperature is increased above 13 K the weak antilocalization contribution starts to dominate. This results in a positive slope of $R(T)$ (see the extrapolation curve from Eq. 9 in Fig. 4(b)). However, in comparison with the experiment the calculated transition is shifted to somewhat higher temperatures. This discrepancy indicates that in the considered range a mechanism with positive $R(T)$ slope, e.g. the Boltzmann term, is essential in all samples.

We associate the high-temperature maximum in $R(T)$ (a “bulge” in Nb10) with the emergence of the weak localization with increasing temperature so that $\tau_\varphi^{-1} \gg \tau_0^{-1}$. In this case the temperature dependence of the resistance is described by the formula
FIG. 6: The resistance vs. temperature in the linear (the left panel) and in the logarithmic (the right panel) temperature scales for samples Nb09, Nb10, and Nb19 (see TABLE I). The resistances are normalized to the value at the low-temperature maximum $T_m$. For better visibility curves and symbols of samples Nb09 and Nb10 are shifted vertically. The dashed lines are the best fits of the data in the range 1.2–4.2 K with Eq. (9). The solid lines are the best fits of the data with Eq. (10) in the range from 12 K to the value shown by arrows in left panel.

\[
\frac{R(T)}{R(T_m)} = \frac{e^2}{2\pi^2\hbar\rho_0} \left[ -F_d \sqrt{\frac{k_B T}{\hbar D}} - 3 \sqrt{\frac{1}{4\tau_v D}} + \frac{1}{4\tau_v(T)D} + \sqrt{\frac{1}{4\tau_v(T)D}} \right] + L^{p} + R_0, \tag{10}
\]

where the extrapolation of the low-temperature behavior of the electron-electron interaction in the diffusion channel (the first term) and the weak localization and antilocalization\(^{43}\) (the second and third terms) is used.

The Boltzmann transport term is described by the term $LT^p$ and the superconducting fluctuation effects are ignored. The solid lines in Fig. 6 represent the best fit with Eq. (10) with parameters $L$, $p$, $R_0$, and a universal $\tau_v^{-1} = 2.3 \times 10^{12}$ s$^{-1}$ for all samples. It can be seen that Eq. (10) gives a good approximation for the feature around 20–40 K and extrapolates to higher temperatures reproducing both "metallic" and "insulating" behavior. In all cases the temperature exponent of the Boltzmann term lies in the range $p = 1.2–1.4$ (see Table I). This finding points to non-Fermi-liquid behavior of conduction electrons in Nb$_{5-\delta}$Te$_4$. Usually the quantum interference of conduction electrons in disordered conductors is considered as a low-temperature effect. Its extension to higher temperatures is possible when the dephasing length is still larger than the electron mean free path, $\sqrt{D\tau_v} \gg \ell$. This occurs in systems with strong potential scattering such as Ti-Al alloys\(^{44}\), Mo/Si multilayers\(^{45}\), and ion-implanted polymers\(^{46}\), where the interference effects persist above 250 K. Therefore in Nb$_{5-\delta}$Te$_4$, which is also characterized by a short mean free path, high-temperature quantum interference of conduction electrons is also possible.

In summary, we studied the dependence of the resistance on the magnetic field and temperature in Nb$_{5-\delta}$Te$_4$ single crystals with $\delta = 0.23$. The compound is a superconductor with $T_c = 0.7–0.9$ K. Both the magnetoresistance and the temperature dependence of the resistivity are quantitatively well described in the framework of the theory of quantum interference effects in disordered conductors. The electron dephasing times extracted from the magnetoresistance are determined by the electron-phonon interaction and scattering on magnetic impurities.
Acknowledgments

The authors thank V. Doppel for the microprobe analysis, E. Brücher for magnetic susceptibility measurements, and D. Martien for assisting the heat capacity investigations. This work was supported by the Estonian Science Foundation Grant No. 5033. ASt kindly acknowledges support from the Max-Planck-Gesellschaft.