Symposium on Spin Physics and Nanomagnetism
dedicated to the 60th birthday of the Distinguished Professor Eugene Chudnovsky
Effect of Pair Breaking on Mesoscopic Persistent Currents Well above the Superconducting Transition Temperature

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We consider the mesoscopic normal persistent current (PC) in a very low-temperature superconductor with a bare transition temperature $T_0^c$ much smaller than the Thouless energy $E_c$. We show that in a rather broad range of pair-breaking strength, $T_0^c \lesssim \hbar/\tau_s \lesssim E_c$, the transition temperature is renormalized to zero, but the PC is hardly affected. This may provide an explanation for the magnitude of the average PC’s in the noble metals, as well as a way to determine their $T_0^c$’s.

DOI: 10.1103/PhysRevLett.101.057001

PACS numbers: 74.78.Na, 73.23.Ra, 74.25.Ha, 74.40.+k
Field Dependence of the Electron Spin Relaxation in Quantum Dots

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The interaction of the electron spin with local elastic twists due to transverse phonons is studied. The universal dependence of the spin-relaxation rate on the strength and direction of the magnetic field is obtained in terms of the electron gyromagnetic tensor and macroscopic elastic constants of the solid. The theory contains no unknown parameters and it can be easily tested in experiment. At high magnetic field it provides a parameter-free lower bound on the electron spin relaxation in quantum dots.

DOI: 10.1103/PhysRevLett.95.166603 PACS numbers: 72.25.Rb, 73.21.La

Universal Decoherence in Solids

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(Received 3 December 2003; published 26 March 2004)

Symmetry implications for the decoherence of quantum oscillations of a two-state system in a solid are studied. When the oscillation frequency is small compared to the Debye frequency, the universal lower bound on the decoherence due to the atomic environment is derived in terms of the macroscopic parameters of the solid, with no unknown interaction constants.

DOI: 10.1103/PhysRevLett.92.120405 PACS numbers: 03.65.Yz, 66.35.+a, 73.21.Fg
New clues in the mystery of persistent currents

By Hélène Bouchiat

A decade ago, experimentalists showed that persistent currents can flow in nonsuperconducting mesoscopic metal rings, but there was no theory that correctly explained the magnitude or direction of the unexpectedly large currents. Theorists are now proposing a simple idea that may at last explain these results.

A Viewpoint on:

Effect of Pair Breaking on Mesoscopic Persistent Currents Well above the Superconducting Transition Temperature

H. Bary-Soroker, O. Entin-Wohlman, and Y. Imry

Zero Resistance

Magnetic field

- Current persists forever
- Resistance at least one billion billion times less than copper
- Basis of superconducting magnets
Normal persistent currents

Josephson behavior in small normal one-dimensional rings

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Received 7 March 1983. Available online 10 August 2002.

Abstract

Small and strictly one-dimensional rings of normal metal, driven by an external magnetic flux, act like superconducting rings with a Josephson junction, except that $2e$ is replaced by $e$. 

Significance of Electromagnetic Potentials in the Quantum Theory

Y. Aharonov and D. Bohm
H. H. Wills Physics Laboratory, University of Bristol, Bristol, England
(Received May 28, 1959; revised manuscript received June 16, 1959)

In this paper, we discuss some interesting properties of the electromagnetic potentials in the quantum domain. We shall show that, contrary to the conclusions of classical mechanics, there exist effects of potentials on charged particles, even in the region where all the fields (and therefore the forces on the particles) vanish. We shall then discuss possible experiments to test these conclusions; and, finally, we shall suggest further possible developments in the interpretation of the potentials.
\[ \mathcal{H}\Psi(r) = E\Psi(r) \]
\[ \mathcal{H} = \frac{1}{2m} \left( -i\hbar \nabla - \frac{e}{c} A \right)^2 + V(r) \]
\[ A = \frac{\Phi}{L} \hat{\phi} \]

gauge transformation: \[ \Psi(r) = e^{i \frac{2\pi}{\Phi_0} \int^r A \cdot dr'} \tilde{\Psi}(r) \]

\[ \Phi_0 = \frac{hc}{e} \]
\[ \left( -\frac{\hbar^2}{2m} \nabla^2 + V(r) \right) \tilde{\Psi}(r) = E\tilde{\Psi}(r) \]

phase of the wave function changes by: \[ \Theta = \frac{2\pi \Phi}{\Phi_0} \]

zero temperature: \[ I = -c \frac{\partial E}{\partial \Phi} \]
finite temperature: \[ I = -c \frac{\partial \Omega}{\partial \Phi} \]


molecular scale only, no scattering
the magnitude of normal persistent currents

\[ I \sim \frac{e}{\tau_D} \]

\( \tau_D \) — time to encircle the ring

\[ I \sim \frac{ev_F}{L} \]

clean (ballistic) non-interacting ring

\[ L \text{— circumference} \sim \mu m \]

\[ E_F \text{— Fermi energy} \sim eV \]

\[ I \sim 10^{-8} \text{amp} \]

\[ I \sim \frac{ev_F l}{L^2} \sim \frac{eE_c}{\hbar} \]

diffusive non-interacting ring

\[ E_c = \frac{\hbar D}{L^2} \text{— Thouless energy} \]

\[ D \text{— Diffusion coefficient} \]

Cheung, Gefen, Riedel, Phys. Rev. Lett. 52, 587 (1989);
Entin-Wohlman, Gefen, EuroPhys 8, 477 (1989);
Altshuler, Gefen, Imry, Phys. Rev. Lett. 66, 88 (1991);
Experimental detection of normal persistent currents measuring the induced magnetic moment

low enough temperatures, to reduce inelastic scattering-----T<1 K

short enough circumference to retain phase-coherence-----L is a few micrometers

magnetic moment of a single ring----- ~100 Bohr magnetons
single-ring experiments


Figure 4.4 From Chandrasekhar et al. (1991). The experimental arrangement for obtaining the response of the single ring (shown) minus that of an empty substrate is depicted on the left. The results are shown on the right: the magnetic-field dependence of the amplitude of the $f$ and $2f$ signals at 7.6 mK for the 1.4 $\mu$m $\times$ 2.6 $\mu$m gold loop. (a) $f$ response with no signal processing. The arrows point to the maxima of the $h/e$ periodic signal. (b) Data of (a), with the quadratic background subtracted. (c) $2f$ response, after subtraction of a linear background signal. The amplitude of the 4 Hz a.c. drive field was 4.12 G. (d) Power spectrum for the data displayed in (b). The $h/e$ arrows show the region, centered about the expected frequency for $h/e$ oscillations, over which the data in (b) and (c) were bandpassed to produce the dashed curves. The region where an $h/2e$ signal is expected to appear based upon the inside and outside area of the sample is also shown. The data in (b) and (c) has been digitally filtered to eliminate high-frequency contributions above 0.50 G$^{-1}$. 
single-ring experiments (cont.)

Mailly, Chapelier, Benoit, 

FIG. 3. Square root of spectrum power of magnetization of the ring. The values are converted into the equivalent current in the ring using the calibration coil. Open circles correspond to experimental noise, i.e., differences between measurements with ring open. Solid circles correspond to experimental signal, i.e., differences between measurements with ring closed and ring open. The two arrows indicate the position of period $h/e$ and $h/2e$. 
single-ring experiments (cont.)

Bleszynski-Jayich, Shanks, Ilic, Harris
The authors report measurements of the magnetic response of 33 individual mesoscopic gold rings, one ring at a time, at low temperatures. The response of some sufficiently small rings has a component that is periodic in the flux through the ring and can be attributed to a persistent current circulating the ring. Its period is close to $h/e$, and its sign and amplitude vary from ring to ring. Including rings without a detectable periodic response, the amplitude distribution is in good agreement with predictions for the typical $h/e$ persistent current in diffusive metal rings. The temperature dependence of the periodic component, measured for four rings, is also consistent with theory. These results disagree with a previous experiment [1] that measured three individual metal rings and found a much larger response than expected. The measurements were taken using a scanning SQUID microscope, which enabled in situ measurements of the sensor background. All measured rings also show a paramagnetic linear susceptibility and a poorly understood anomaly around zero field, both of which are attributed to unpaired defect spins.
Diamagnetic Persistent Current in Diffusive Normal-Metal Rings

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(Received 9 December 1999)

We have measured a diamagnetic persistent current with flux periodicities of both $h/e$ and $h/2e$ in an array of thirty diffusive mesoscopic gold rings. At the lowest temperatures, the magnitudes of the currents per ring corresponding to the $h/e$- and $h/2e$-periodic responses are both comparable to the Thouless energy $E_c = h/\tau_D$, where $\tau_D$ is the diffusion time. Taken in conjunction with earlier experiments, our results strongly challenge the conventional theories of persistent current. We consider a new approach associated with the saturation of the phase coherence time $\tau_\phi$.

![FIG. 2. Magnetic response of 30 Au rings from a run focusing on $h/2e$ oscillations. The dashed line in (a) represents raw data. The solid line represents the $h/2e$-periodic contribution, taken from the $h/2e$ window in the power spectrum in (b). The autocorrelation shown in (c) also demonstrates the $h/2e$-periodic signal.](image)

![FIG. 1. (a) Electron micrograph showing the Au rings, as well as the pickup and field coils of the SQUID. (b) Larger view illustrating the entire gradiometer design of the SQUID.](image)
many-rings experiments

\[ \sim 10^7 \text{ Cu rings} \]

\[ L = 2\mu m, \ l_{el} = 20\text{nm}, \ T = 10 - 200mK. \]
Diamagnetic Orbital Response of Mesoscopic Silver Rings

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We report measurements of the flux-dependent orbital magnetic susceptibility of an ensemble of 10⁵ disconnected silver rings at 217 MHz. Because of the strong spin-orbit scattering rate in silver this experiment is a test of existing theories on ensemble averaged persistent currents. Below 100 mK the rings exhibit a magnetic signal with a flux periodicity of ℏ/2e consistent with averaged persistent currents, whose amplitude is of the order of 0.3 nA. The sign of the oscillations indicates unambiguously diamagnetism in the vicinity of zero magnetic field. This sign is a priori not consistent with theoretical predictions for average persistent currents. We discuss several possible explanations of this result.

![Image](https://example.com/image.png)

**FIG. 1 (color online)**: (a) Photograph of a part of the resonator with the silver rings. (b) Image obtained by scanning electron microscopy of one silver ring. (c) Schematic picture of the resonator with the square rings on the inductive part. The resonator has an inductive part (meander line) and a capacitive part (comblike structure).

**FIG. 4**: Average persistent currents through the rings reconstituted from the field dependence of the resonance frequency in Fig. 2 according to expression (2) after high pass filtering at 0.025 G⁻¹ and integration of the signal.

many-rings experiments (cont.)
Dynamic Response of Isolated Aharonov-Bohm Rings Coupled to an Electromagnetic Resonator

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(Received 8 February 1995)

We have measured the flux dependence of both the real and the imaginary conductance of GaAs/GaAlAs isolated mesoscopic rings at 310 MHz. The rings are coupled to a highly sensitive electromagnetic superconducting microresonator and lead to a perturbation of the resonance frequency and quality factor. This experiment provides a new tool for the investigation of the conductance of mesoscopic systems without the need for invasive probes. The results obtained can be compared with recent theoretical predictions emphasizing the differences between isolated and connected geometries and the relation between ac conductance and persistent currents.
ac electric and magnetic responses of nonconnected Aharonov-Bohm rings

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The signature of phase coherence on the electric and magnetic response of \(10^3\) nonconnected Aharonov-Bohm rings is measured by a resonant method at 350 MHz between 20 mK and 500 mK. The rings are etched in a GaAs-Al\(_x\)Ga\(_{1-x}\)As heterojunction. Both quantities exhibit an oscillating behavior with a periodicity consistent with half a flux quantum \(\Phi_0/2 = h/2e\) in a ring. We find that electric screening is enhanced when time-reversal symmetry is broken by magnetic field, leading to a positive magnetopolarizability, in agreement with theoretical predictions for isolated rings at finite frequency. Temperature and electronic-density dependences are investigated. The dissipative part of the electric response, the electric absorption, is also measured and leads to a negative magnetoconductance. The magnetic orbital response of the very same rings is also investigated. It is consistent with diamagnetic persistent currents of 0.25 nA. This magnetic response is an order of magnitude smaller than the electric one, in qualitative agreement with theoretical expectations.

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PACS number(s): 73.20.Fz, 73.23.Ra

FIG. 3. Magnetoconductance of a ring and a mesh. The \(\Phi_0\) signal disappears with ensemble average, so that in the mesh only the \(\Phi_0/2\) component remains. Note the triangular shape of the magnetoconductance on the mesh. The curves are shifted for clarity.
single-ring persistent currents:

1. random direction; 2. $h/e$ periodicity;

ensemble-averaged persistent currents:

1. diamagnetic response; 2. $h/2e$ periodicity;
summary: experiment vs. theory

independent electrons: \[ \frac{I_{\text{exp}}}{I_{\text{theo}}} > 10^2 \]

interacting electrons: \[ \frac{I_{\text{exp}}}{I_{\text{theo}}} > 5 \]

repulsion-paramagnetic \quad \leftrightarrow \quad attraction-diamagnetic


~10^7 Cu rings

theory: \[ 0.05 \frac{e}{\tau_D} \text{ per ring} \]

experiment: \[ 0.3 \frac{e}{\tau_D} \text{ per ring} \]

Ambegaokar and Eckern, Europhys. Lett. 13, 733 (1990)
Renormalization of the effective interaction

\[ \lambda = \left[ \text{interaction matrix element} \right] \times \left[ \text{density of states at } E_F \right] \]

\[ \lambda_{\text{eff}} = \frac{\lambda}{1 + \lambda \ln(\frac{E_>}{E_<})} \rightarrow \begin{cases} \frac{\lambda}{\ln(\frac{E_>}{E_<})} & \text{for } \lambda \ln(\frac{E_>}{E_<}) \ll 1 \\ \frac{1}{\ln(\frac{E_>}{E_<})} & \text{for } \lambda \ln(\frac{E_>}{E_<}) \geq 1 \end{cases} \]

Example is the renormalization of the repulsive Coulomb interaction in the theory of superconductivity:

\[ \mu_{\text{eff}} = \frac{\mu}{1 + \mu \ln(\frac{E_F}{\omega_D})} \]

Morel and Anderson, Phys. Rev. 125, 163 (1962)
renormalization of **attractive** electronic interactions
(once the repulsive Coulomb interactions had been overcome)

\[
\lambda(E_<) = \frac{\lambda(E_>)}{1 - \lambda(E_>) \ln(E_>/E_<)}
\]

Example is the renormalization of the attractive interaction from the Debye frequency scale to the superconducting transition temperature:

\[
\frac{\lambda(\omega_D)}{1 - \lambda(\omega_D) \ln(\omega_D/T_{c0})} \to \infty
\]

Copper does not superconduct even at 10 micro-Kelvin. How can the attractive interaction be so weak that it does not cause superconductivity, yet permits a large persistent current in the normal state?

Our answer:

copper is superconducting at about 1 mili-Kelvin, provided that it is cleaned from magnetic imps.
pair-breaking in superconductivity

\[ \frac{T_c}{T_{c0}} \]

\[ \frac{\hbar}{(\pi k_B T_{c0} \tau_S)} \]

less than 1 ppm pernicious magnetic imps knocks down superconductivity from 1mK to 0

Abrikosov and Gor’kov, Sov. Phys. JETP 12, 1243 (1961)
pair-breaking in superconductivity

\[
\frac{T_c}{T_{c0}} \leq 1 \quad \frac{\hbar}{(\pi k_B T_{c0} \tau_S)} < 1 \text{ ppm}
\]

less than 1 ppm pernicious magnetic imps knocks down superconductivity from 1mK to 0

Abrikosov and Gor'kov, Sov. Phys. JETP 12, 1243 (1961)
pair breakers destroy the superconducting transition

\[ T_c \to 0 \quad \text{when} \quad T_{c0} \simeq \frac{1}{\tau_S} \]

the relevant energy scale for the persistent current is the Thouless energy

\[ E_c \]

superconductivity will be destroyed but the persistent current will be hardly affected for:

\[ T_{c0} \leq \frac{1}{\tau_S} \leq E_c \]
FIG. 1. The first flux harmonic \([m = 1; \text{see Eq. (2)}]\), in units of \(I(s = 0)\), of the PC at \(T = E_c\) (full line) and \(T_c/T_c^0\) (dashed line) as functions of the pair-breaking strength, \(s = 1/(\pi T_c^0 \tau_s)\), displayed on a logarithmic scale.
details of the calculation

Hamiltonian:
\[ \mathcal{H} = \int d\mathbf{r} \left( \psi_\alpha^\dagger(\mathbf{r}) \left( \mathcal{H}_0 + u_1(\mathbf{r}) \delta_{\alpha\gamma} + u_2(\mathbf{r}) \mathbf{S} \cdot \sigma_{\alpha\gamma} \right) \psi_\gamma(\mathbf{r}) - \frac{g}{2} \psi_\alpha^\dagger(\mathbf{r}) \psi_\gamma^\dagger(\mathbf{r}) \psi_\gamma(\mathbf{r}) \psi_\alpha(\mathbf{r}) \right) \]

Partition function:
\[ Z = \int \mathcal{D} \left( \Psi(\mathbf{r}, \tau), \overline{\Psi}(\mathbf{r}, \tau) \right) \mathcal{D} \left( \Delta(\mathbf{r}, \tau), \Delta^*(\mathbf{r}, \tau) \right) e^{-S} \]

Action:
\[ S = \int d\mathbf{r} \int_0^\beta d\tau \left( \frac{|\Delta(\mathbf{r}, \tau)|^2}{g} - \frac{1}{2} \overline{\Psi}(\mathbf{r}, \tau) G^{-1}_{\mathbf{r}, \mathbf{r}; \tau, \tau} \Psi(\mathbf{r}, \tau) \right) \]

Inverse Green function:
\[ G^{-1} = \begin{bmatrix} -\partial_\tau - h_\phi^+ & -2u_2 S_- & 0 & \Delta \\ -2u_2 S_+ & -\partial_\tau - h_\phi^- & -\Delta & 0 \\ 0 & -\Delta^* & -\partial_\tau + h_\phi^- & 2u_2 S_+ \\ \Delta^* & 0 & 2u_2 S_- & -\partial_\tau + h_\phi^+ \end{bmatrix} \]
details of the calculation (cont.)

partition function:

$$Z = \prod q^\nu \left( \frac{1}{\lambda} - \Pi(q, \nu) \right)^{-1}$$

$$\Pi(q, \nu) = \Psi \left( \frac{1}{2} + \frac{2\omega_D + |\nu| + Dq^2}{4\pi k_B T} \right)$$

$$- \Psi \left( \frac{1}{2} + \frac{|\nu| + Dq^2 + 2/\tau_S}{4\pi k_B T} \right)$$

spin-flip time:

$$\frac{1}{\tau_S} = 2\pi N N_i S(S + 1)u_2^2$$

bare transition temperature is found from the pole of the partition function at zero wave vector and zero frequency:

$$\frac{1}{\lambda} = \Psi \left( \frac{1}{2} + \frac{\omega_D}{2\pi k_B T_c} \right) - \Psi \left( \frac{1}{2} \right)$$
FIG. 1. The first flux harmonic \([m = 1;\) see Eq. (2)], in units of \(I(s = 0)\), of the PC at \(T = E_c\) (full line) and \(T_c/T_c^0\) (dashed line) as functions of the pair-breaking strength, \(s = 1/(\Gamma T_c^0 \tau_s)\), displayed on a logarithmic scale.

\[
I = -8 \frac{eE_c}{\hbar} \sum_{m=1}^{\infty} \frac{\sin(4\pi m \Phi / \Phi_0)}{m^2} \times \sum_{\nu} \int_0^{\infty} dx \frac{x \sin(2\pi x) \Psi'(F(x,\nu))}{\ln(T/T_{c0}) + \Psi(F(x,\nu)) - \Psi(1/2)}
\]

\[
F(x, \nu) = \frac{1}{2} + \frac{|\nu| + 2/\tau_S}{4\pi k_B T} + \frac{\pi E_c x^2}{m^2 k_B T}
\]
deducing the superconducting transition temperature

<table>
<thead>
<tr>
<th></th>
<th>$E_c$</th>
<th>$T$</th>
<th>$I/eE_c$</th>
<th>$L$</th>
<th>$L_\phi$</th>
<th>min $T_c^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper$^3$</td>
<td>15 mK</td>
<td>7 mK</td>
<td>1</td>
<td>2.2 $\mu$m</td>
<td>2 $\mu$m (1.5 K)</td>
<td>a few mK</td>
</tr>
<tr>
<td>Gold$^7$</td>
<td>4.9 mK</td>
<td>5.5 mK</td>
<td>0.65</td>
<td>8.0 $\mu$m</td>
<td>16 $\mu$m (0.5 K)</td>
<td>a fraction of a mK</td>
</tr>
</tbody>
</table>

TABLE I: Experimental parameters in the left six columns. The magnitude of the $h/2e$ periodic current (column 4) is given for the lowest temperature (column 3) reached in the experiment. The coherence length $L_\phi$ is given together with the temperature at which it was measured. The last column is our fit for a lower limit on $T_c^0$ according to Eq. (34), see also Fig. 9.

\[
\frac{T_c^0}{E_c} \leq \frac{2\gamma_E}{\pi} \left( \frac{L}{L_s} \right)^2
\]
Apparent “saturation” of dephasing at low T due to ~10^{-6} amount of magnetic imp’s

PHYSICAL REVIEW B 68, 085413 (2003)

Dephasing of electrons in mesoscopic metal wires

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In the fit procedure, we use the measured sample resistance and length given in Table I. Our experimental setup being designed to measure resistance changes with an higher accuracy than absolute values, ΔR is known only up to a small additive constant that we adjusted to fit each magnetoresistance curve. The width was fixed at a value w_{WL} giving the best overall fits for the complete set of data at various temperatures. The difference between the width w measured

TABLE II. Fit parameters of the magnetoresistance data to weak localization theory: maximum phase coherence time \( \tau_{\phi}^{\text{max}} \), obtained at the lowest temperature of ~40 mK; spin–orbit length \( L_s \), and effective width \( w_{WL} \). We also recall the width w obtained from SEM pictures. The upwards arrow ↑ indicates that \( \tau_{\phi} \) keeps increasing down to 40 mK. In the other samples, \( \tau_{\phi} \) is nearly constant at low temperature.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \tau_{\phi}^{\text{max}} ) (ns)</th>
<th>( L_s ) (( \mu )m)</th>
<th>( w_{WL} ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag(6N)a</td>
<td>9.65</td>
<td>0.65</td>
<td>57 (65)</td>
</tr>
<tr>
<td>Ag(6N)b</td>
<td>12.35</td>
<td>0.35</td>
<td>85 (100)</td>
</tr>
<tr>
<td>Ag(6N)c</td>
<td>22.10</td>
<td>1.0</td>
<td>90 (105)</td>
</tr>
<tr>
<td>Ag(6N)d</td>
<td>12.82</td>
<td>0.82</td>
<td>75 (90)</td>
</tr>
<tr>
<td>Ag(5N)a</td>
<td>2.95</td>
<td>0.65</td>
<td>108 (108)</td>
</tr>
<tr>
<td>Ag(5N)b</td>
<td>3.50</td>
<td>0.75</td>
<td>82 (90)</td>
</tr>
<tr>
<td>Au(6N)</td>
<td>11.085</td>
<td>0.85</td>
<td>85 (90)</td>
</tr>
<tr>
<td>Cu(6N)a</td>
<td>0.45</td>
<td>0.67</td>
<td>155 (155)</td>
</tr>
<tr>
<td>Cu(6N)b</td>
<td>0.95</td>
<td>0.4</td>
<td>70 (70)</td>
</tr>
<tr>
<td>Cu(6N)c</td>
<td>0.2</td>
<td>0.35</td>
<td>75 (75)</td>
</tr>
<tr>
<td>Cu(6N)d</td>
<td>0.35</td>
<td>0.33</td>
<td>80 (80)</td>
</tr>
<tr>
<td>Cu(5N)a</td>
<td>1.8</td>
<td>0.52</td>
<td>110 (110)</td>
</tr>
<tr>
<td>Cu(5N)b</td>
<td>0.9</td>
<td>0.67</td>
<td>100 (100)</td>
</tr>
</tbody>
</table>

FIG. 3. Phase coherence time \( \tau_{\phi} \) versus temperature in wires made of copper Cu(6N) (■), gold Au(6N) (▲), and silver Ag(6N)c (●) and Ag(5N) (○). The phase coherence time increases continuously with decreasing temperature in wires fabricated using our purest (6N) silver and gold sources as illustrated respectively with samples Ag(6N)c and Au(6N). Continuous lines are fits of the measured phase coherence time including inelastic collisions with electrons and phonons [Eq. (4)]. The dashed line is the prediction of electron–electron interactions only [Eq. (3)] for sample Ag(6N)c. In contrast, the phase coherence time increases much more slowly in samples made of copper (independently of the source material purity) and in samples made of silver using our source of lower (5N) nominal purity.
Днем Рождения!!!