Symposium on Spin Physics and Nanomagnetism

dedicated to the 60th birthday of the Distinguished

Professor Eugene Chudnovsky

Selected for a Viewpoint in *Physics*

PRL **101,** 057001 (2008) PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2008

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

H. Bary-Soroker,[1,*] O. Entin-Wohlman,[2,3] and Y. Imry[1]

[1]*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel*

[2]*Department of Physics, Ben Gurion University, Beer Sheva 84105, Israel*

[3]*Albert Einstein Minerva Center for Theoretical Physics, Weizmann Institute of Science, Rehovot 76100, Israel*

(Received 2 April 2008; published 28 July 2008)

We consider the mesoscopic normal persistent current (PC) in a very low-temperature superconductor with a bare transition temperature T_c^0 much smaller than the Thouless energy E_c. We show that in a rather broad range of pair-breaking strength, $T_c^0 \lesssim \hbar/\tau_s \lesssim E_c$, 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_c^0's.

DOI: 10.1103/PhysRevLett.101.057001 PACS numbers: 74.78.Na, 73.23.Ra, 74.25.Ha, 74.40.+k

PRL 95, 166603 (2005) PHYSICAL REVIEW LETTERS week ending 14 OCTOBER 2005

Field Dependence of the Electron Spin Relaxation in Quantum Dots

Carlos Calero,[1] E. M. Chudnovsky,[1] and D. A. Garanin[1,2]

[1]*Department of Physics and Astronomy, Lehman College, City University of New York, 250 Bedford Park Boulevard West, Bronx, New York 10468-1589, USA*

[2]*Institut für Physik, Johannes-Gutenberg-Universität, D-55099 Mainz, Germany*

(Received 18 April 2005; published 12 October 2005)

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

VOLUME 92, NUMBER 12 PHYSICAL REVIEW LETTERS week ending 26 MARCH 2004

Universal Decoherence in Solids

Eugene M. Chudnovsky

Department of Physics and Astronomy, Lehman College, City University of New York, Bedford Park Boulevard West, Bronx, New York 10468-1589, USA

(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

About the Author

Hélène Bouchiat

Hélène studied at Ecole normale supérieure (1977–1981) and completed her Ph.D. (1981–1986) at the Laboratoire de Physique des Solides, Université Paris Sud, in Orsay. From 1987 to 1988 she was a consultant for Bell Laboratories. In 1988 she returned to the Laboratoire de Physique des Solides, where she is now Directeur de Recherche. Her present research interests include the study of quantum transport in

Physics 1, 7 (2008) doi:10.1103/Physics.1.7

New clues in the mystery of persistent currents

By Hélène Bouchiat Laboratoire de Physique des Solides Université Paris-Sud, Bldg. 510, Orsay Cedex, France 91405Published July 28, 2008

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:

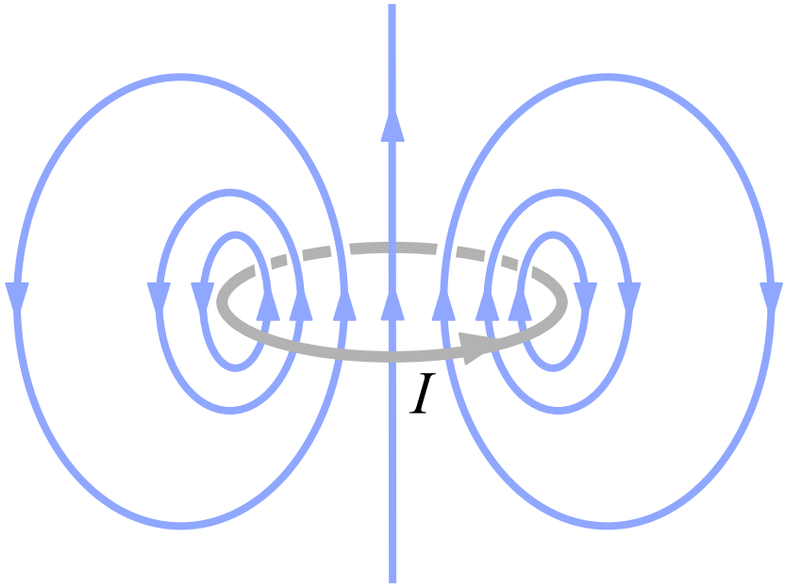
Effect of Pair Breaking on Mesoscopic Persistent Currents Well above the Superconducting Transition Temperature

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

Phys. Rev. Lett. 101, 057001 (2008) – Published July 28, 2008

Zero Resistance

Magnetic field

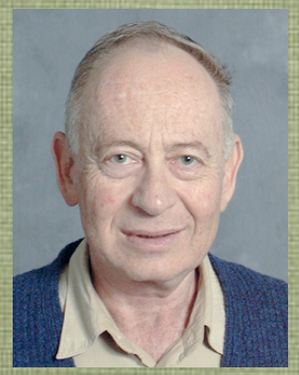


- Current persists forever
- Resistance at least one billion billion times less than copper
- **Basis of superconducting magnets**

Normal persistent currents

Physics Letters A
Volume 96, ,365, (1983)

I. O. Kulik, Sov. Phys. JETP 30, 944 (1970)

Josephson behavior in small normal one-dimensional rings

M. Büttiker, Y. Imry[1] and R. Landauer

IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA

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 2*e* is replaced by *e*.

The Aharonov-Bohm Effect

THE

PHYSICAL REVIEW

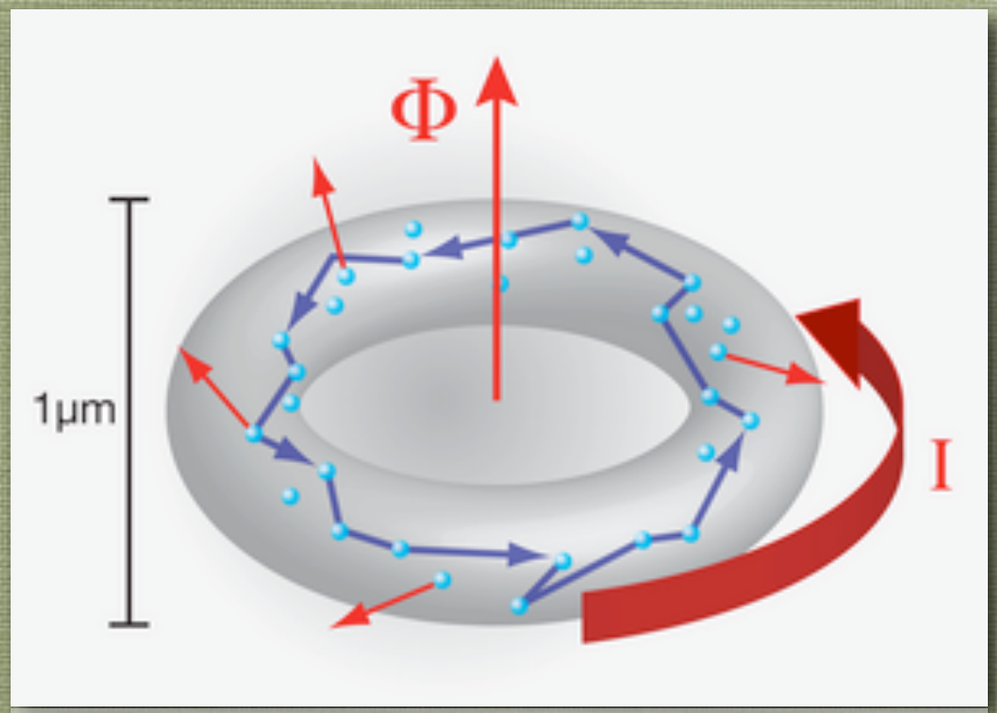
A journal of experimental and theoretical physics established by E. L. Nichols in 1893

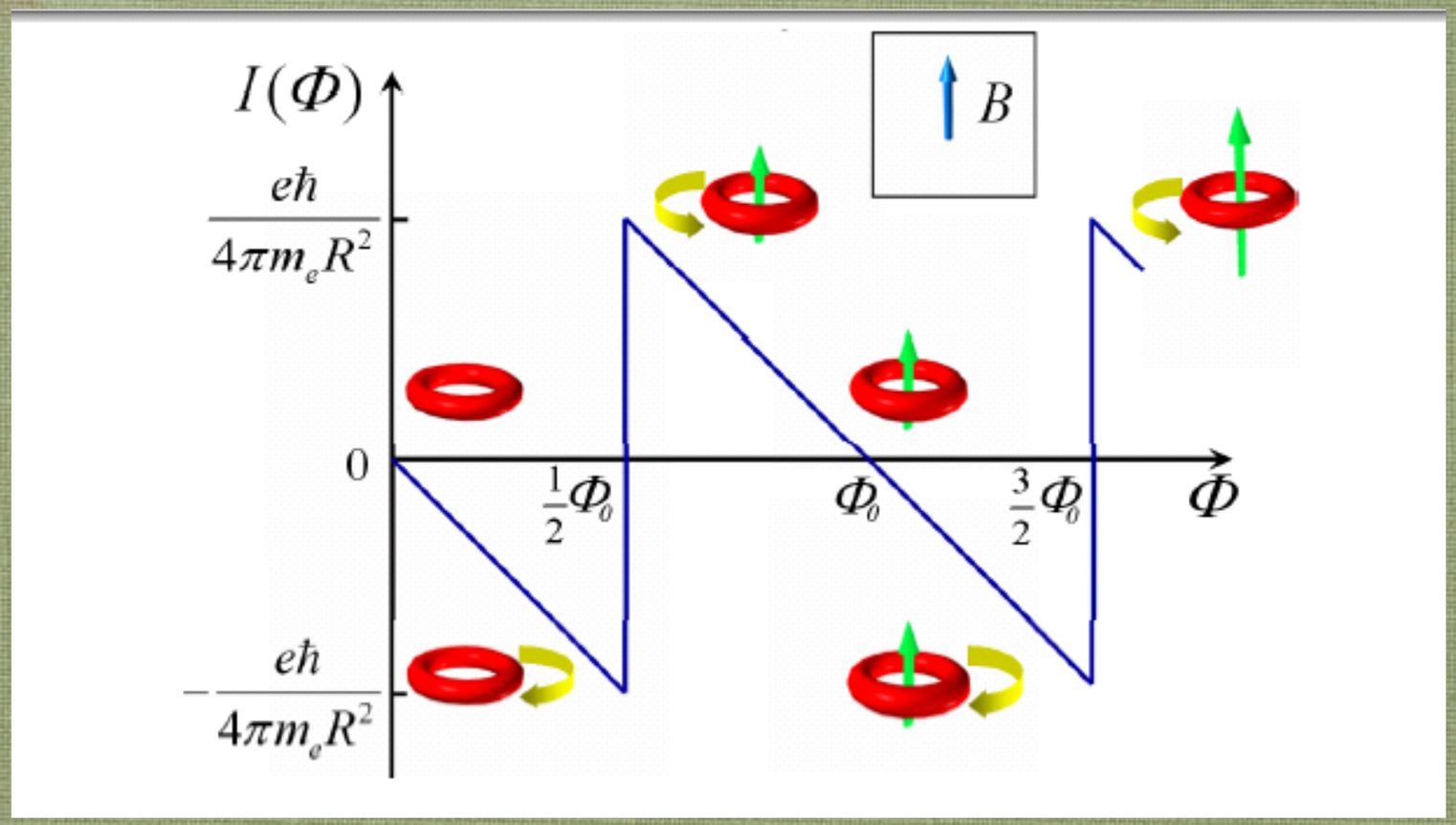
SECOND SERIES, VOL. 115, NO. 3 AUGUST 1, 1959

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.

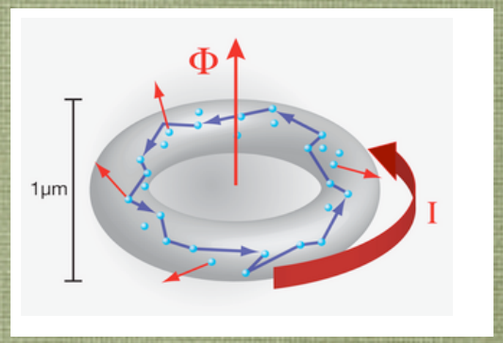

Φ
1μm
I


$I(\Phi)$
B
$\frac{e\hbar}{4\pi m_e R^2}$
$-\frac{e\hbar}{4\pi m_e R^2}$
0
$\frac{1}{2}\Phi_0$
Φ_0
$\frac{3}{2}\Phi_0$
Φ

$$\mathcal{H}\Psi(\mathbf{r}) = E\Psi(\mathbf{r})$$

$$\mathcal{H} = \frac{1}{2m}\left(-i\hbar\nabla - \frac{e}{c}\mathbf{A}\right)^2 + V(\mathbf{r})$$

$$\mathbf{A} = \frac{\Phi}{L}\hat{\phi}$$

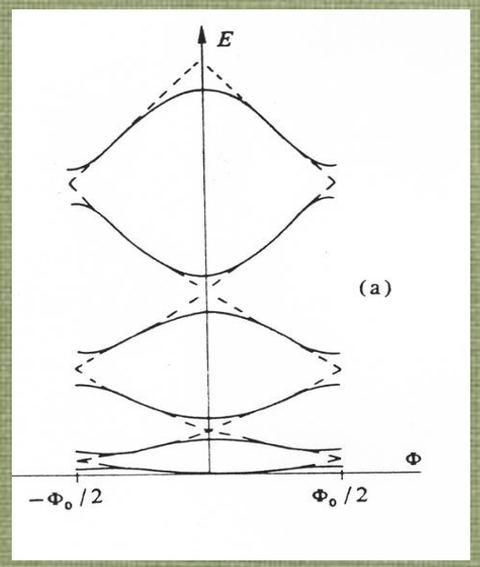


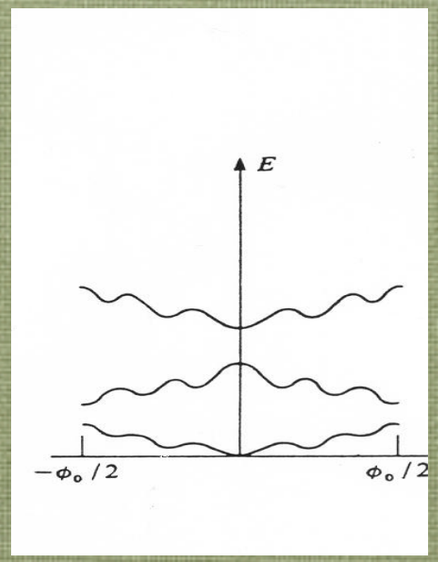
gauge transformation : $\Psi(\mathbf{r}) = e^{i\frac{2\pi}{\Phi_0}\int^{\mathbf{r}} \mathbf{A}\cdot d\mathbf{r}'}\tilde{\Psi}(\mathbf{r})$

$$\Phi_0 = hc/e$$

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r})\right)\tilde{\Psi}(\mathbf{r}) = E\tilde{\Psi}(\mathbf{r})$$

phase of the wave function changes by : $\Theta = 2\pi\Phi/\Phi_0$





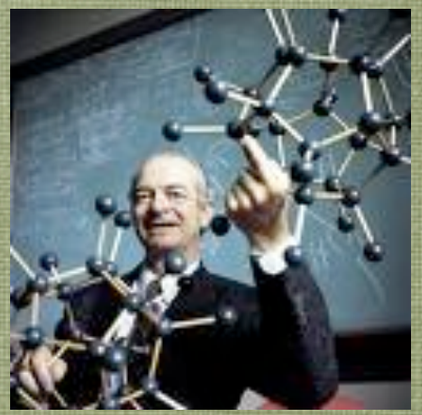
zero temperature; $I = -c\frac{\partial E}{\partial \Phi}$

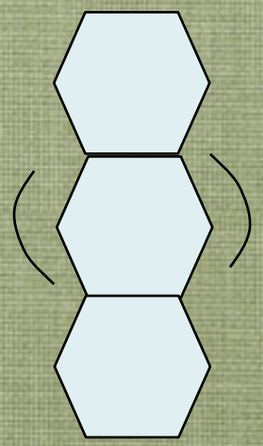
finite temperature : $I = -c\frac{\partial \Omega}{\partial \Phi}$

Byers and Yang, Phys. Rev. Lett. **7**, 46 (1961)
Bloch, Phys. Rev. B **2**, 109 (1970)

microscopic persistent currents

L. Pauling: "The **diamagnetic Anisotropy** of Aromatic molecules", J. Chem. Phys. **4**, 673 (**1936**);





F. London: "Theorie Quantique des **Courants Interatomiques** dans les Combinaisons aromatiques", J. Phys. Radium **8**, 397 (**1937**);

molecular scale only, no scattering

the magnitude of normal persistent currents

$$I \simeq \frac{e}{\tau_D}$$

$\tau_D -$ time to encircle the ring

$$I \simeq \frac{e v_{\mathrm{F}}}{L}$$

clean (ballistic) non-interacting ring

$L -$ circumference $\sim \mu m$

$E_{\mathrm{F}} -$ Fermi energy $\sim \mathrm{eV}$

$$I \sim 10^{-8} \mathrm{amp}$$

$$I \sim \frac{e v_{\mathrm{F}} \ell}{L^2} \simeq \frac{e E_c}{\hbar}$$

diffusive non-interacting ring

$E_c = \frac{\hbar D}{L^2} -$ Thouless energy

$D -$ 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

Chandrasekhar, Webb, Brady, Ketchen, Gallagher, Kleinsasser,

Phys. Rev. Lett. **67**, 3578 (1991) -- single gold ring

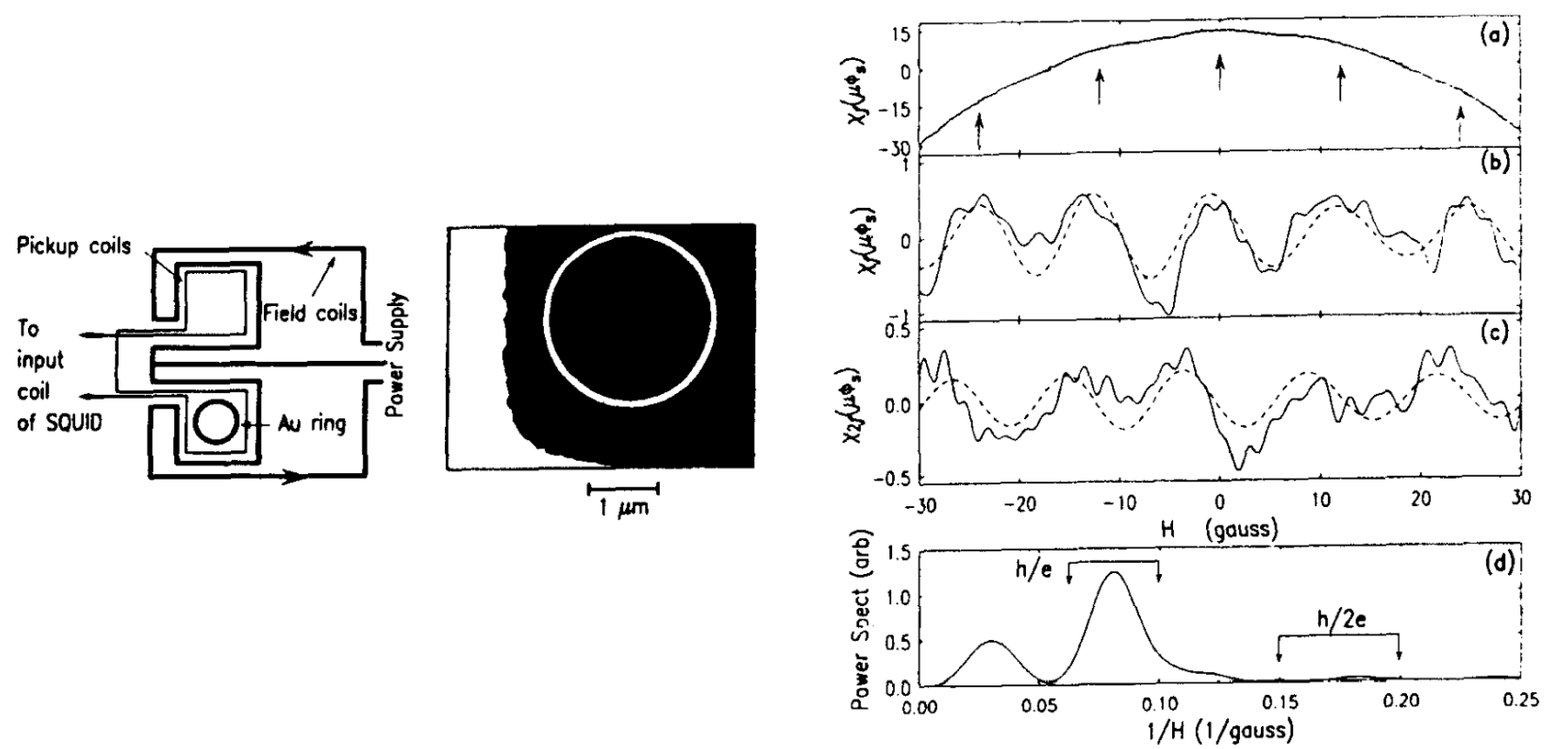
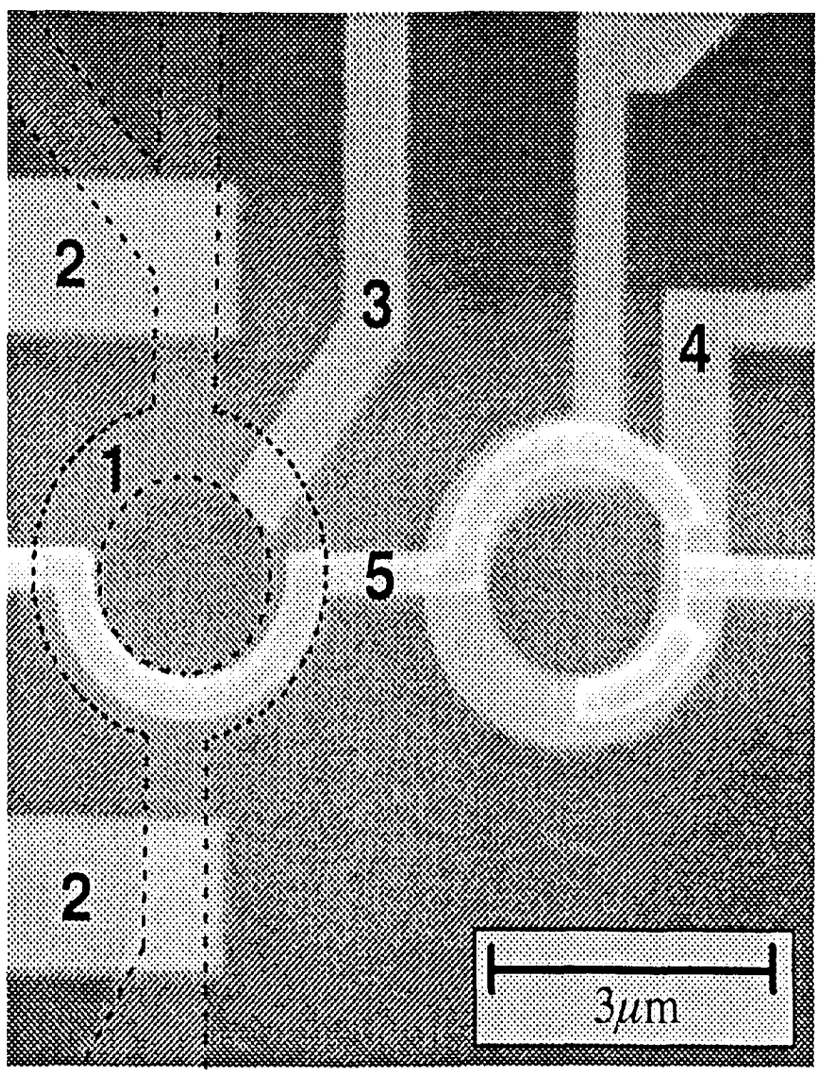


Figure 4.4 From Chandrasekhar et al. (1991). The experimental arrangement for obtaining the response of the single ring (shown) minus that of an empty substrate is depicted on the left. The results are shown on the right: the magnetic-field dependence of the amplitude of the f and $2f$ signals at 7.6 mK for the 1.4 μm × 2.6 μm 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,

Phys. Rev. Lett. **70**, 2020 (1993) -- GaAs-AlGaAs ring



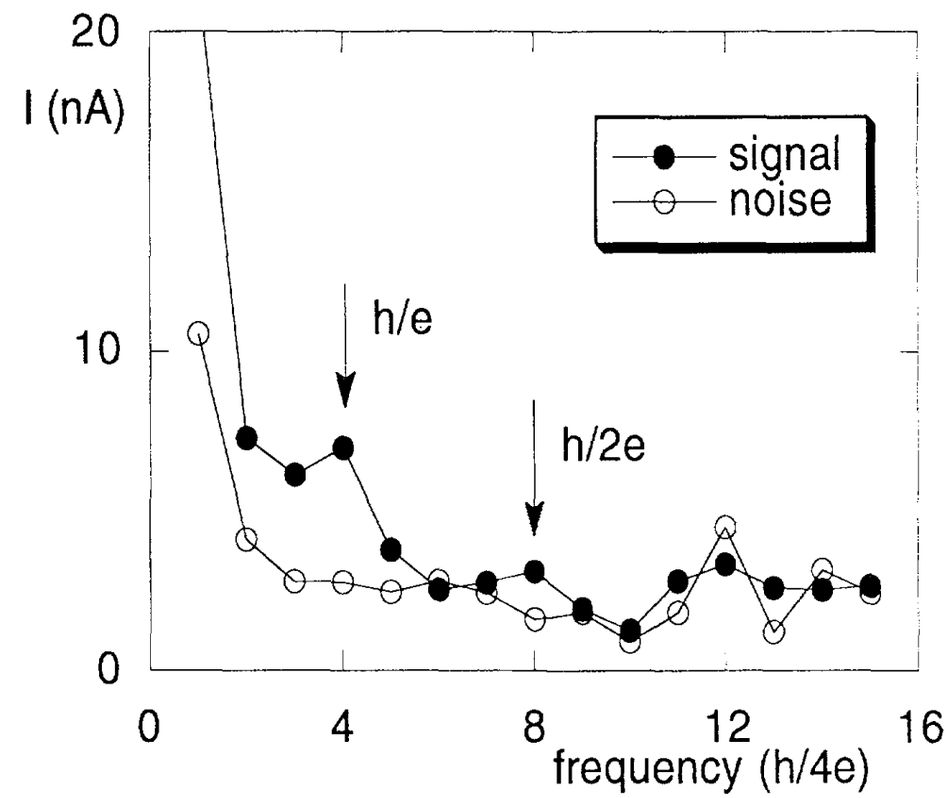
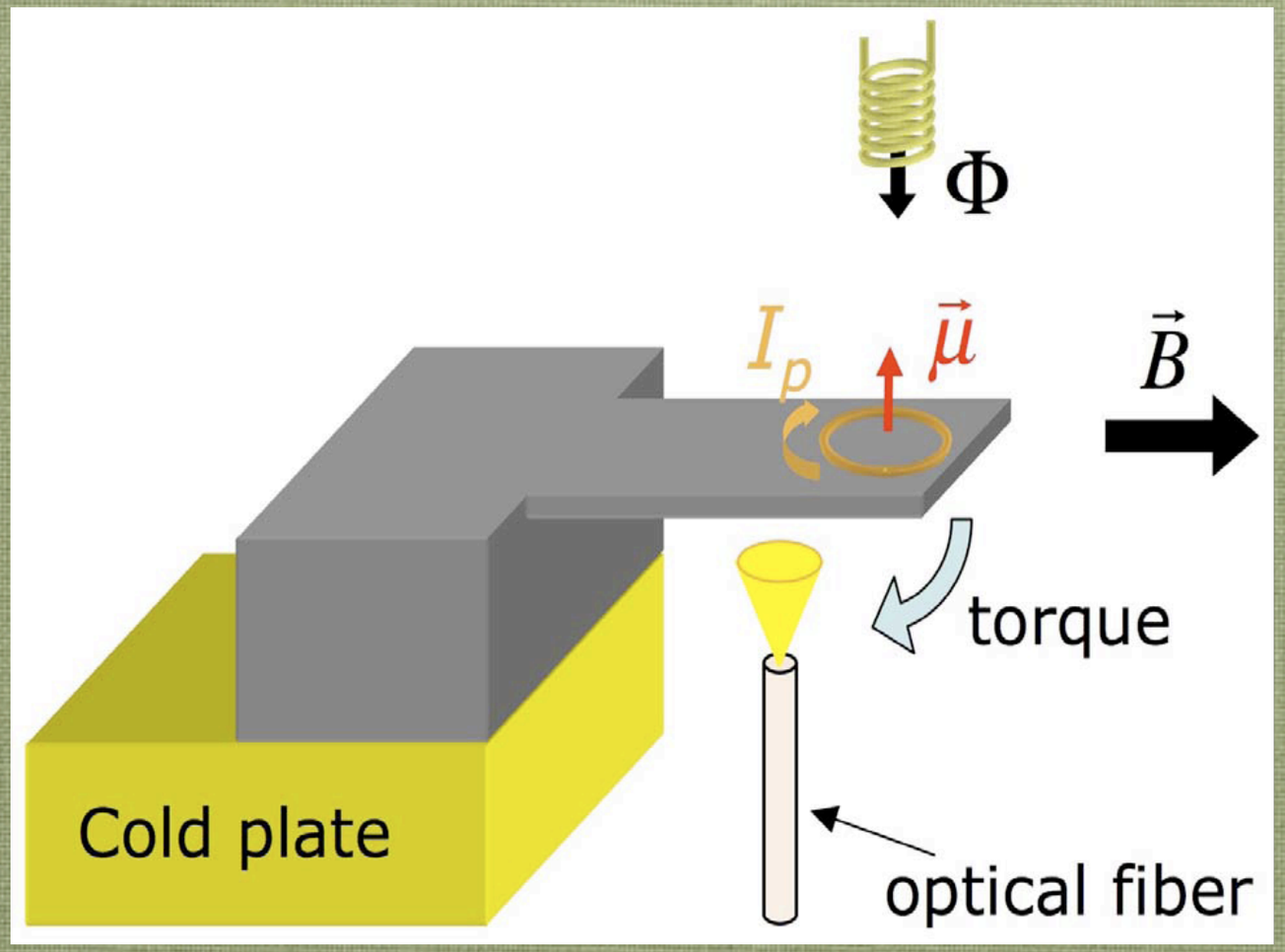
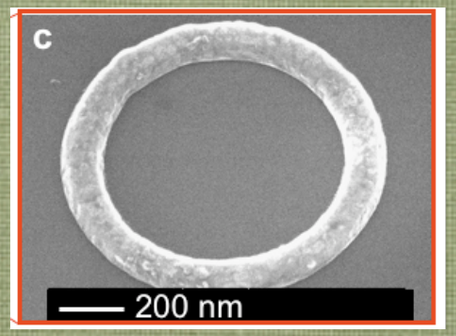


FIG. 3. Square root of spectrum power of magnetization of the ring. The values are converted into the equivalent current in the ring using the calibration coil. Open circles correspond to experimental noise, i.e., differences between measurements with ring open. Solid circles correspond to experimental 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
J. Vac. Sci.Tech B **26** (2008)





single-ring experiments (cont.)

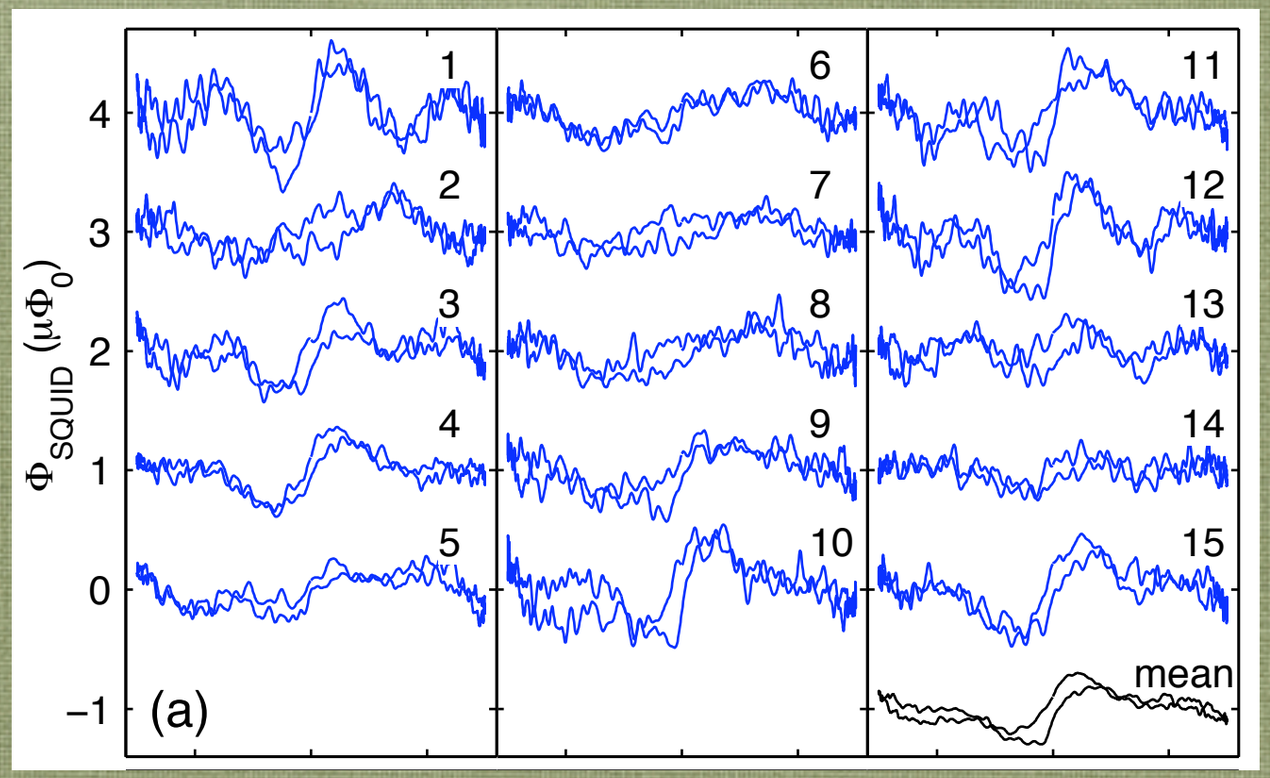
Persistent currents in normal metal rings

Hendrik Bluhm,[1,*] Nicholas C. Koshnick,[1] Julie A. Bert,[1] Martin E. Huber,[2] and Kathryn A. Moler[1,

[1] *Departments of Physics and Applied Physics, Stanford University, Stanford, CA 94305*
[2] *Departments of Physics and Electrical Engineering, University of Colorado Denver, Denver, CO 80217*

(Dated: 10/24/08)

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

E. M. Q. Jariwala,[1] P. Mohanty,[1,*] M. B. Ketchen,[2] and R. A. Webb[1]

[1]*Center for Superconductivity Research, Department of Physics, University of Maryland, College Park, Maryland 20742*

[2]*IBM T. J. Watson Research Center, Yorktown Heights, New York 10598*

(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 $E_c \equiv \hbar/\tau_D$, where τ_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 τ_φ.

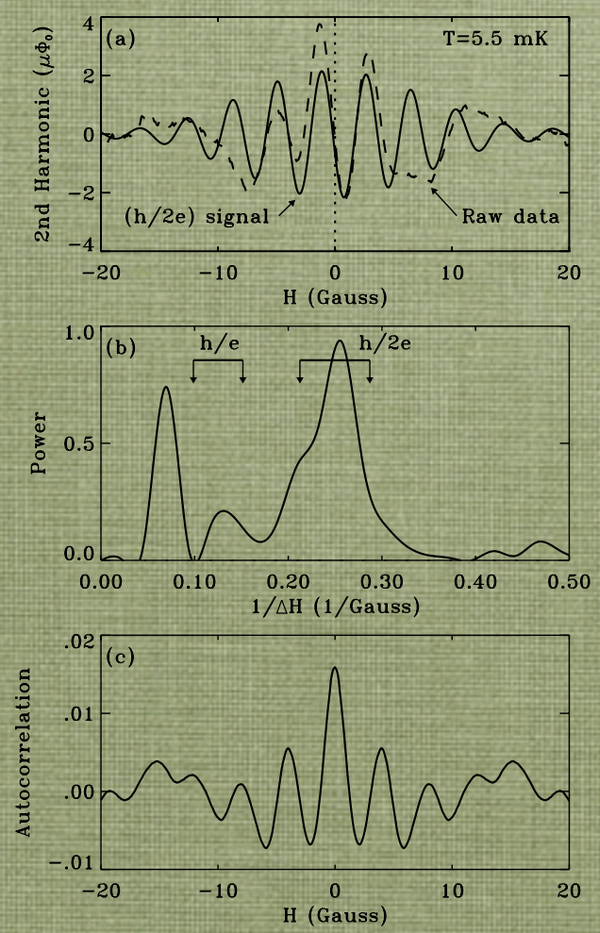


FIG. 2. Magnetic response of 30 Au rings from a run focusing on $h/2e$ oscillations. The dashed line in (a) represents raw data. The solid line represents the $h/2e$-periodic contribution, taken from the $h/2e$ window in the power spectrum in (b). The autocorrelation shown in (c) also demonstrates the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

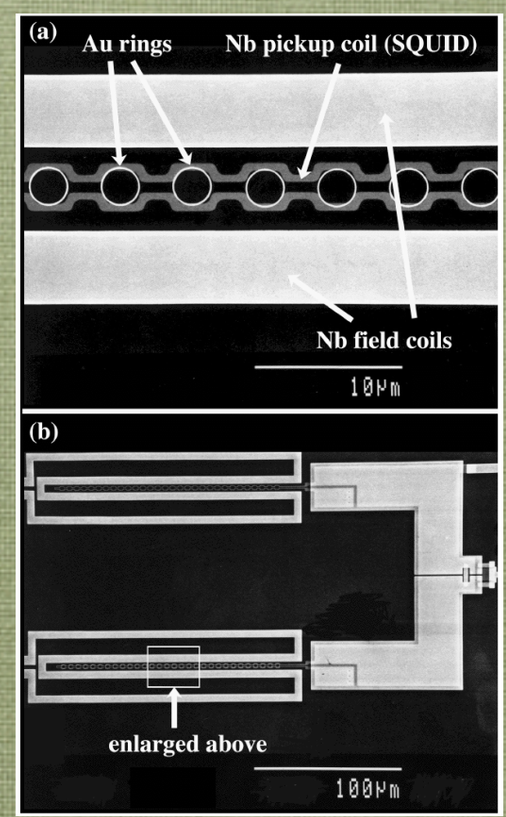
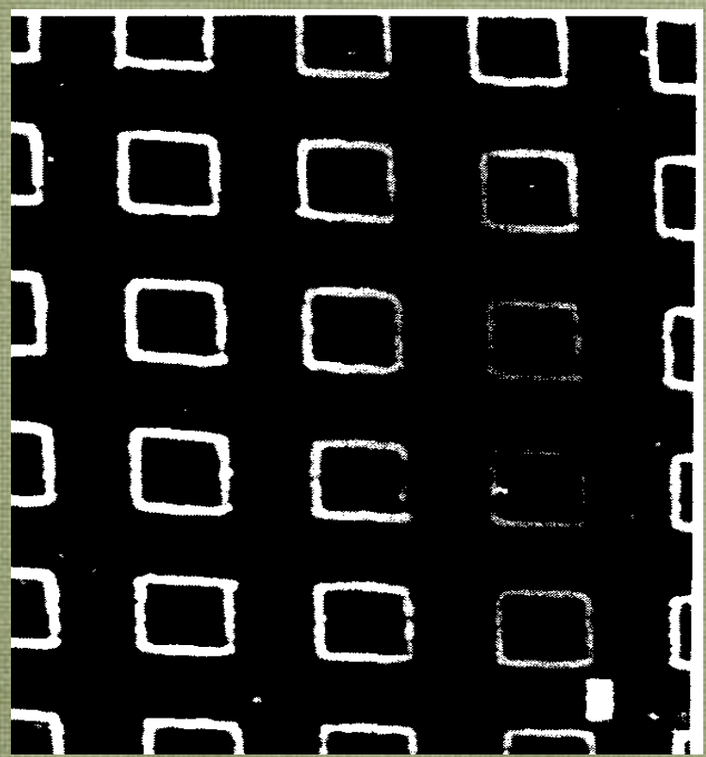


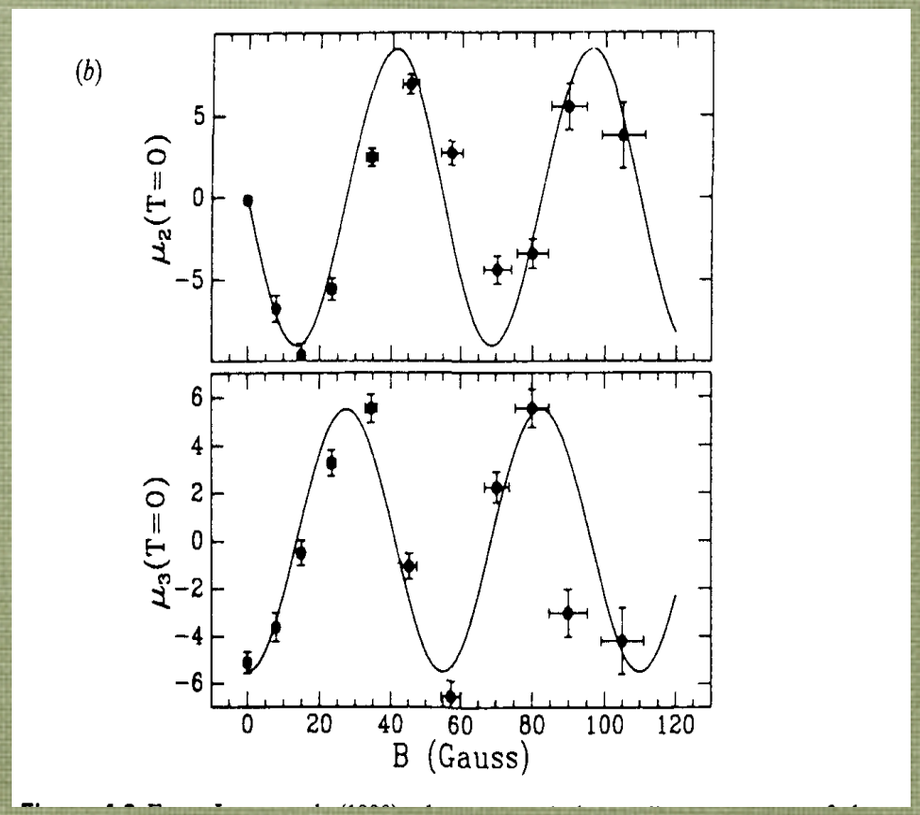
FIG. 1. (a) Electron micrograph showing the Au rings, as well as the pickup and field coils of the SQUID. (b) Larger view illustrating the entire gradiometer design of the SQUID.

many-rings experiments

Levy, Dolan, Dunsmuir, Bouchiat, Phys. Rev. Lett. **64**, 2074 (1990)

~10^7 Cu rings





$$L = 2\mu m,\ l_{el} = 20nm,\ T = 10 - 200mK.$$

Diamagnetic Orbital Response of Mesoscopic Silver Rings

R. Deblock,[1] R. Bel,[1] B. Reulet,[1] H. Bouchiat,[1] and D. Mailly[2]

[1]*Laboratoire de Physique des Solides, Associé au CNRS, Bâtiment 510, Université Paris-Sud, 91405 Orsay, France*

[2]*CNRS Laboratoire de Photonique et Nanostructures, route de Nogay, 91460 Marcoussi, France*

(Received 27 September 2001; published 28 October 2002)

We report measurements of the flux-dependent orbital magnetic susceptibility of an ensemble of 10^5 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 $h/2e$ 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.

many-rings experiments (cont.)

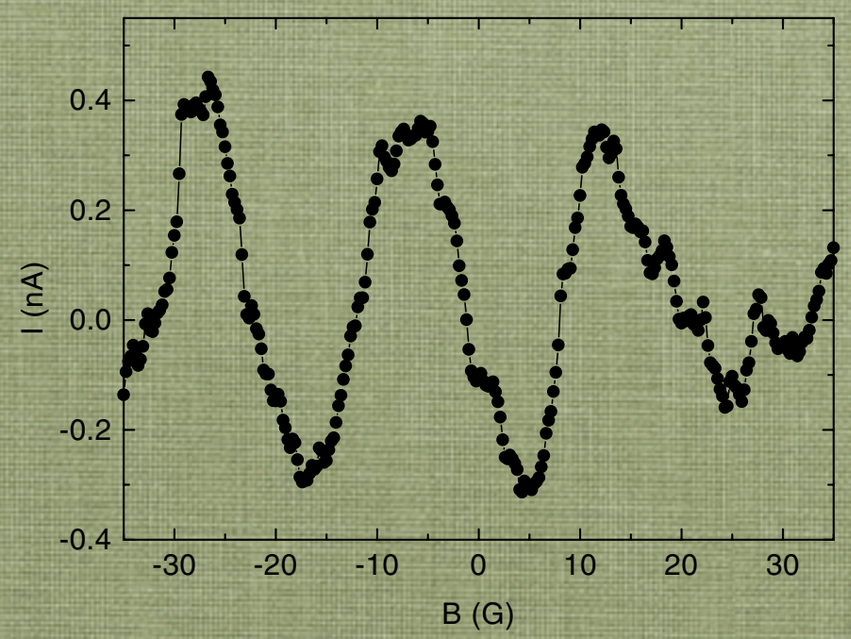


FIG. 4. Average persistent currents through the rings reconstituted from the field dependence of the resonance frequency in Fig. 2 according to expression (2) after high pass filtering at $0.025\ G^{-1}$ and integration of the signal.

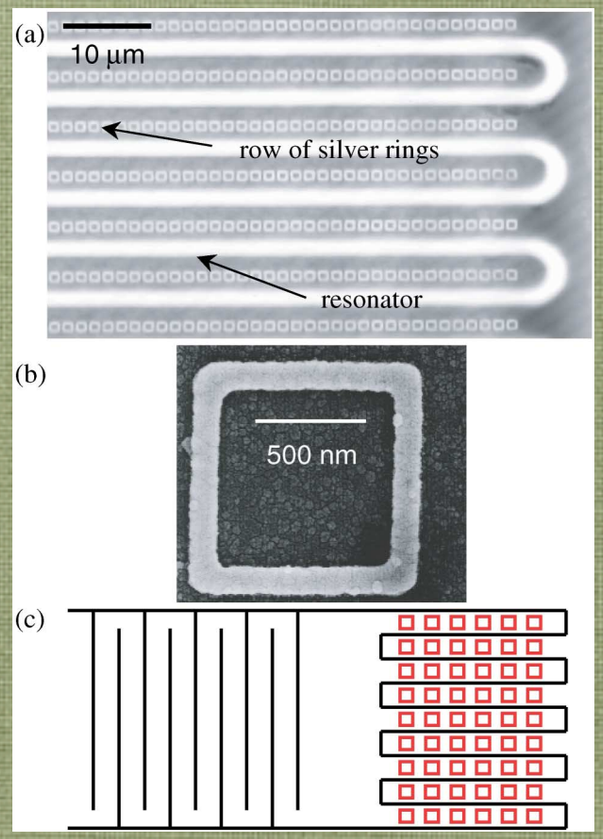


FIG. 1 (color online). (a) Photograph of a part of the resonator with the silver rings. (b) Image obtained by scanning electron microscopy of one silver ring. (c) Schematic picture of the resonator with the square rings on the inductive part. The resonator has an inductive part (meander line) and a capacitive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

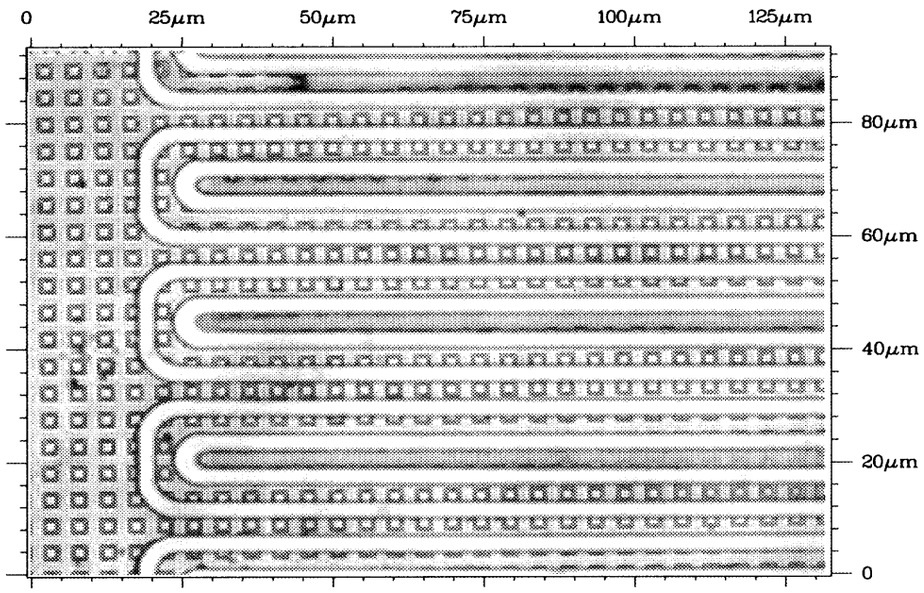
many-rings experiments (cont.)

VOLUME 75, NUMBER 1 PHYSICAL REVIEW LETTERS 3 JULY 1995

Dynamic Response of Isolated Aharonov-Bohm Rings Coupled to an Electromagnetic Resonator

Bertrand Reulet,[1] Michel Ramin,[1] Hélène Bouchiat,[1] and Dominique Mailly[2]
[1]*Laboratoire de Physique des Solides, Associé au CNRS, Bâtiment 510, Université Paris-Sud, 91405, Orsay, France*
[2]*CNRS Laboratoire de Microstructures et de Microélectronique, 196, Avenue Ravera, 92220, Bagneux, France*
(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.



many-rings experiments (cont.)

PHYSICAL REVIEW B, VOLUME 65, 075301

ac electric and magnetic responses of nonconnected Aharonov-Bohm rings

R. Deblock,[1] Y. Noat,[2] B. Reulet,[1] H. Bouchiat,[1] and D. Mailly[3]
[1]*Laboratoire de Physique des Solides, Associé au CNRS, Bâtiment 510, Université Paris-Sud, 91405, Orsay, France*
[2]*Kamerlingh Onnes Laboratory, Niels Bohrweg 5, Leiden, Netherlands*
[3]*CNRS Laboratoire de Microstructure et Microélectronique, 196 Avenue Ravera, 92220, Bagneux, France*
(Received 22 June 2001; revised manuscript received 12 September 2001; published 7 January 2002)

The signature of phase coherence on the electric and magnetic response of 10^5 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-$Al_xGa_{1-x}As$ 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.

DOI: 10.1103/PhysRevB.65.075301 PACS number(s): 73.20.Fz, 73.23.Ra

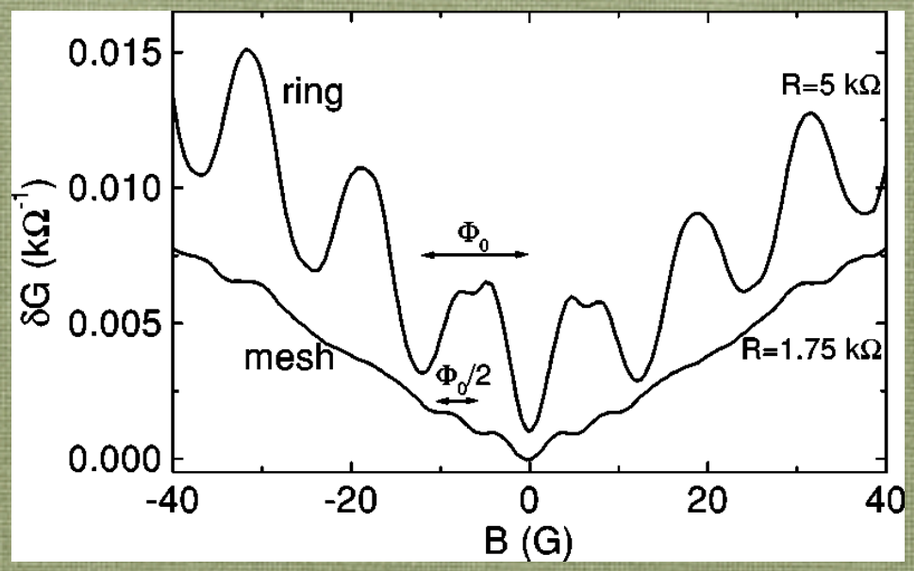


FIG. 3. Magnetoconductance of a ring and a mesh. The Φ_0 signal disappears with ensemble average, so that in the mesh only the $\Phi_0/2$ component remains. Note the triangular shape of the magnetoconductance on the mesh. The curves are shifted for clarity.

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: $\mathrm{I}_{\mathrm{exp}}/I_{\mathrm{theo}} > 10^2$

interacting electrons: $\mathrm{I}_{\mathrm{exp}}/I_{\mathrm{theo}} > 5$

repulsion-paramagnetic

attraction-diamagnetic

Ambegaokar and Eckern, Phys. Rev. Lett. **65**,381 (1990)
Ambegaokar and Eckern, Europhys. Lett. **13**, 733 (1990)

Levy, Dolan, Dunsmuir, Bouchiat, Phys. Rev. Lett. **64**, 2074 (1990)
~10^7 Cu rings

$$\text{theory}: \ 0.05\ e/\tau_{\mathrm{D}} \ \text{ per ring}$$

$$\text{experiment}: \ 0.3\ e/\tau_{\mathrm{D}} \ \text{ per ring}$$

renormalization of the effective interaction

$$\lambda = \Big[\text{interaction matrix element}\Big] \times \Big[\text{density of states at } E_{\rm F}\Big]$$

$$\lambda_{\rm eff} = \frac{\lambda}{1+\lambda\ln(E_>/E_<)} \to \begin{cases} \lambda & \text{for } \lambda\ln(E_>/E_<) \ll 1 \\ \dfrac{1}{\ln(E_>/E_<)} & \text{for } \lambda\ln(E_>/E_<) \geq 1 \end{cases}$$

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

$$\mu_{\rm eff} = \frac{\mu}{1+\mu\ln(E_{\rm F}/\omega_{\rm D})}$$

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:

$$\frac{\lambda(\omega_{\rm D})}{1 - \lambda(\omega_{\rm D})\ln(\omega_{\rm D}/T_{c0})} \to \infty$$

Ambegaokar and Eckern, Phys. Rev. Lett. **65**,381 (1990)
Ambegaokar and Eckern, Europhys. Lett. **13**, 733 (1990)

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

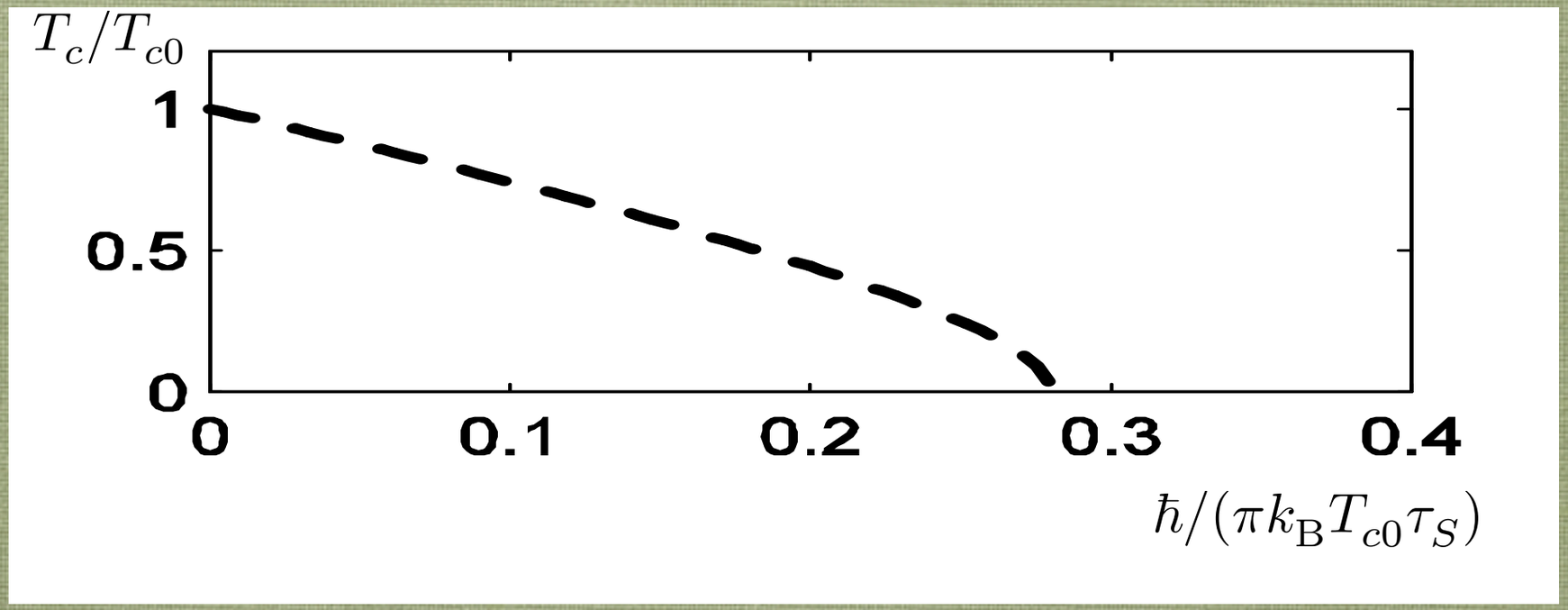
T_c/T_{c0}

$\hbar/(\pi k_{\mathrm{B}} T_{c0} \tau_S)$

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



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

$$T_c \to 0 \quad \text{when} \quad \mathrm{T_{c0}} \simeq \frac{1}{\tau_\mathrm{S}}$$

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:

$$T_{c0} \leq \frac{1}{\tau_S} \leq E_c$$

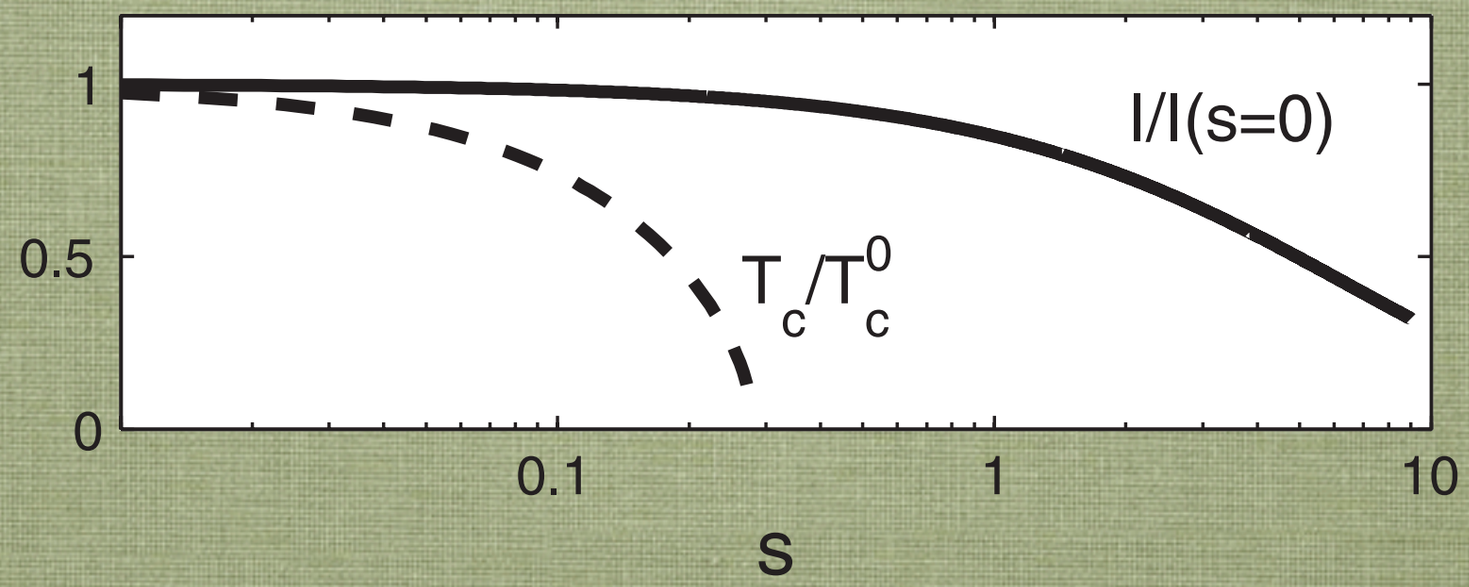


FIG. 1. The first flux harmonic [$m = 1$; see Eq. (2)], in units of $I(s = 0)$, of the PC at $T = E_c$ (full line) and T_c/T_c^0 (dashed line) as functions of the pair-breaking strength, $s = 1/(\pi T_c^0 \tau_s)$, displayed on a logarithmic scale.

details of the calculation

Hamiltonian:

$$\mathcal{H} = \int d\mathbf{r}\Big(\psi^\dagger_\alpha(\mathbf{r})\Big[(\mathcal{H}_0 + u_1(\mathbf{r})\delta_{\alpha\gamma} + u_2(\mathbf{r})\mathbf{S}\cdot\sigma^{\alpha\gamma}\Big]\psi_\gamma(\mathbf{r}) - \tfrac{g}{2}\psi^\dagger_\alpha(\mathbf{r})\psi^\dagger_\gamma(\mathbf{r})\psi_\gamma(\mathbf{r})\psi_\alpha(\mathbf{r})\Big)$$

partition function:

$$\mathcal{Z} = \int \mathcal{D}\Big(\Psi(\mathbf{r},\tau),\overline{\Psi}(\mathbf{r},\tau)\Big)\mathcal{D}\Big(\Delta(\mathbf{r},\tau),\Delta^*(\mathbf{r},\tau)\Big)e^{-\mathcal{S}}$$

action:

$$\mathcal{S} = \int d\mathbf{r}\int_0^\beta d\tau\Big(\frac{|\Delta(\mathbf{r},\tau)|^2}{g} - \frac{1}{2}\overline{\Psi}(\mathbf{r},\tau)G^{-1}_{\mathbf{r},\mathbf{r};\tau,\tau}\Psi(\mathbf{r},\tau)\Big)$$

inverse Green function:

$$G^{-1} = \begin{bmatrix} -\partial_\tau - h^\phi_\uparrow & -2u_2S_- & 0 & \Delta \\ -2u_2S_+ & -\partial_\tau - h^\phi_\downarrow & -\Delta & 0 \\ 0 & -\Delta^* & -\partial_\tau + h^{-\phi}_\uparrow & 2u_2S_+ \\ \Delta^* & 0 & 2u_2S_- & -\partial_\tau + h^{-\phi}_\downarrow \end{bmatrix}$$

details of the calculation (cont.)

partition function:

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

$$\Pi(\mathbf{q}, \nu) = \Psi\left(\frac{1}{2} + \frac{2\omega_{\mathrm{D}} + |\nu| + Dq^2}{4\pi k_{\mathrm{B}} T} \right) - \Psi\left(\frac{1}{2} + \frac{|\nu| + Dq^2 + 2/\tau_{\mathrm{S}}}{4\pi k_{\mathrm{B}} T} \right)$$

spin-flip time:

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

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

$$\frac{1}{\lambda} = \Psi\left(\frac{1}{2} + \frac{\omega_{\mathrm{D}}}{2\pi k_{\mathrm{B}} T_{c0}} \right) - \Psi\left(\frac{1}{2} \right)$$

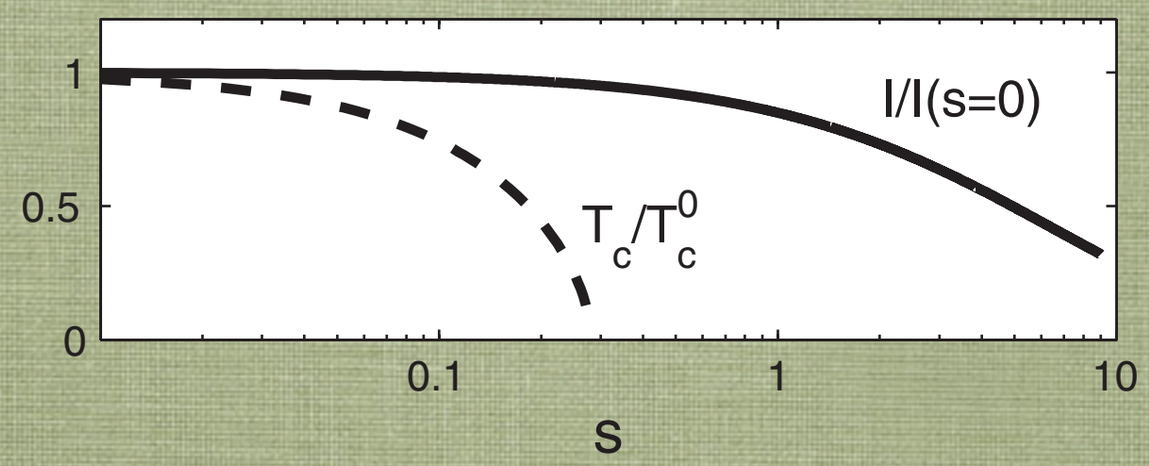


FIG. 1. The first flux harmonic [$m = 1$; see Eq. (2)], in units of $I(s = 0)$, of the PC at $T = E_c$ (full line) and T_c/T_c^0 (dashed line) as functions of the pair-breaking strength, $s = 1/(\pi T_c^0 \tau_s)$, displayed on a logarithmic scale.

$$I = -8\frac{eE_c}{h}\sum_{m=1}^{\infty}\frac{\sin(4\pi m\Phi/\Phi_0)}{m^2}$$

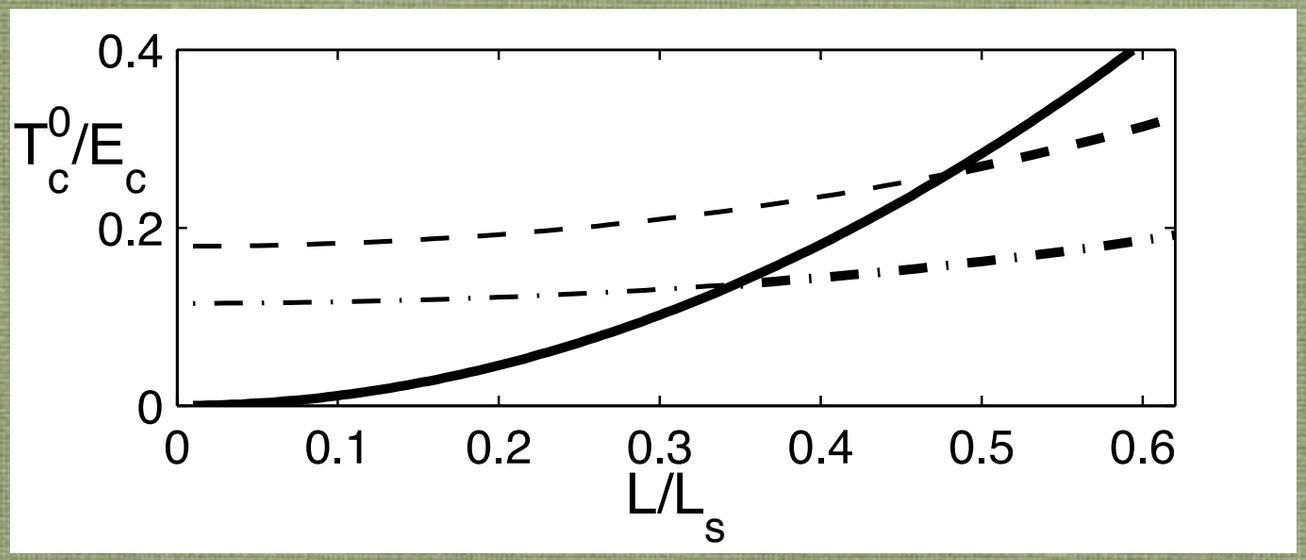
$$\times\sum_{\nu}\int_0^{\infty}dx\,\frac{x\sin(2\pi x)\Psi'(F(x,\nu))}{\ln(T/T_{c0})+\Psi(F(x,\nu))-\Psi(1/2)}$$

$$F(x,\nu) = \frac{1}{2} + \frac{|\nu|+2/\tau_{\mathrm{S}}}{4\pi k_{\mathrm{B}}T} + \frac{\pi E_c x^2}{m^2 k_{\mathrm{B}}T}$$

deducing the superconducting transition temperature

	E_c	T	I/eE_c	L	L_φ	min T_c^0
Copper[3]	15 mK	7 mK	1	2.2 μm	2 μm(1.5 K)	a few mK
Gold[7]	4.9 mK	5.5 mK	0.65	8.0 μm	16 μm(0.5 K)	a fraction of a mK

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_φ 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

F. Pierre,[1,2,3,*] A. B. Gougam,[1,†] A. Anthore,[2] H. Pothier,[2] D. Esteve,[2] and Norman O. Birge[1]
[1]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-2320, USA*
[2]*Service de Physique de l'Etat Condensé, Direction des Sciences de la Matière, CEA-Saclay, 91191 Gif-sur-Yvette, France*
[3]*Department of Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
(Received 11 February 2003; published 26 August 2003)

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

Sample	τ_ϕ^{max} (ns)	L_{so} (μm)	w_{WL} (w) (nm)
Ag(6N)a	9↗	0.65	57 (65)
Ag(6N)b	12↗	0.35	85 (100)
Ag(6N)c	22↗	1.0	90 (105)
Ag(6N)d	12↗	0.82	75 (90)
Ag(5N)a	2.9	0.65	108 (108)
Ag(5N)b	3.5	0.75	82 (90)
Au(6N)	11↗	0.085	85 (90)
Cu(6N)a	0.45	0.67	155 (155)
Cu(6N)b	0.95	0.4	70 (70)
Cu(6N)c	0.2	0.35	75 (75)
Cu(6N)d	0.35	0.33	80 (80)
Cu(5N)a	1.8	0.52	110 (110)
Cu(5N)b	0.9	0.67	100 (100)

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

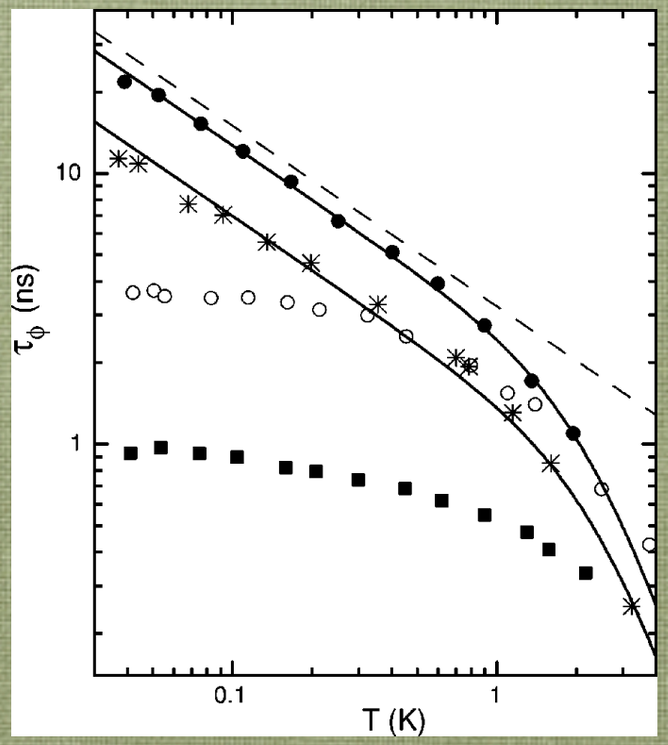


FIG. 3. Phase coherence time τ_ϕ versus temperature in wires made of copper Cu(6N)b (■), gold Au(6N) (*), and silver Ag(6N)c (●) and Ag(5N)b (○). The phase coherence time increases continuously with decreasing temperature in wires fabricated using our purest (6N) silver and gold sources as illustrated 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!!!