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ECOSS 22 2003,
PRAHA

Noise spectroscopy of a single spin with STM

Alexander V Balatsky

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Yishai Manassen(Ben Gurion)

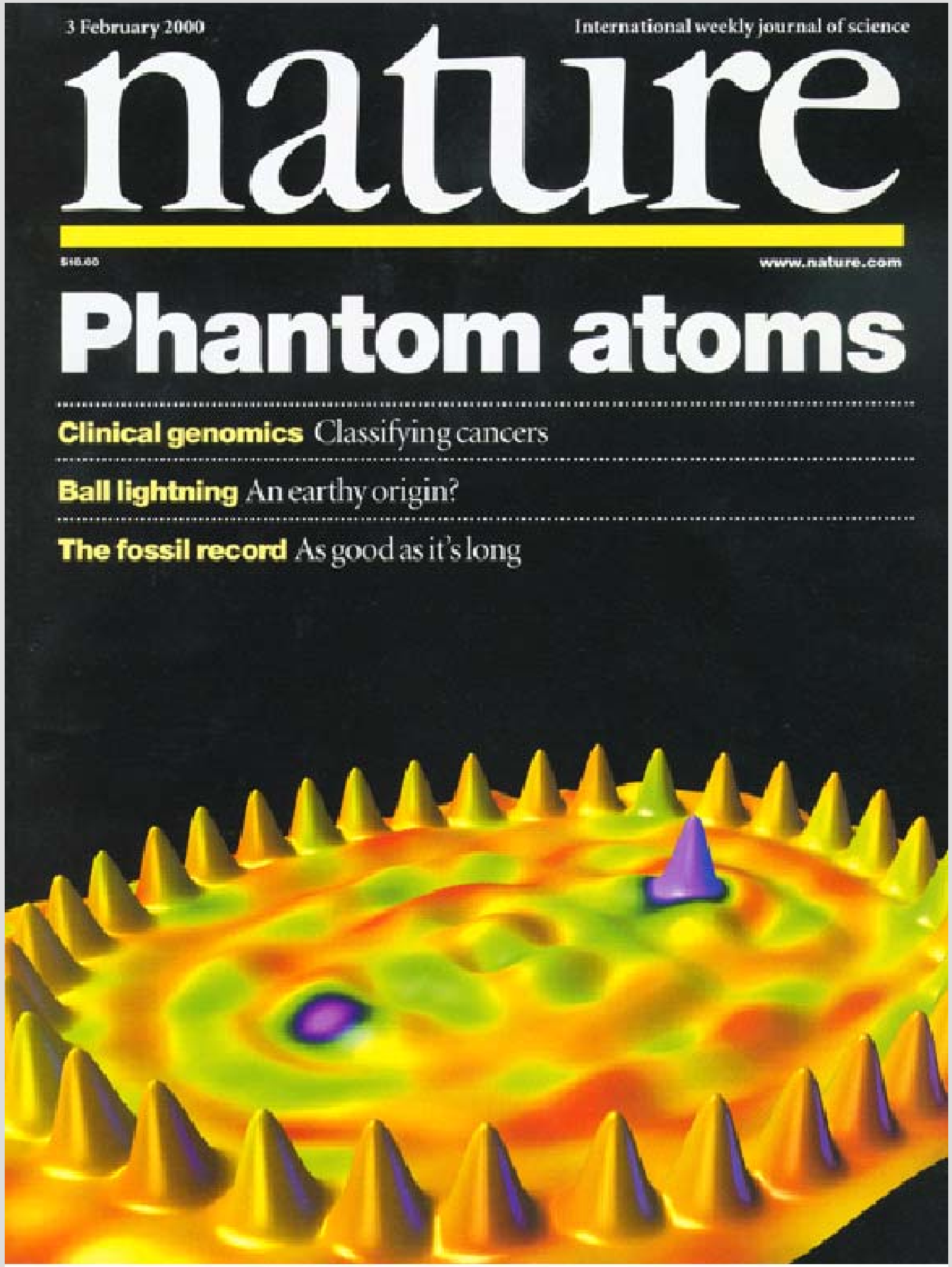
Introduction

- Manassen experiments (1989, 2000)

Also Cambridge Group, Durkan et al, 2001

- Spin precession STM
- Noise spectrosopy of spin. Colored noise as a useful information.
- Spin polarized STM current and single spin dynamics.
- 1/f spin current noise and noise spectroscopy
- Conclusion and predictions/extensions.

Not a direct
Spin
measurement



Experimental setup

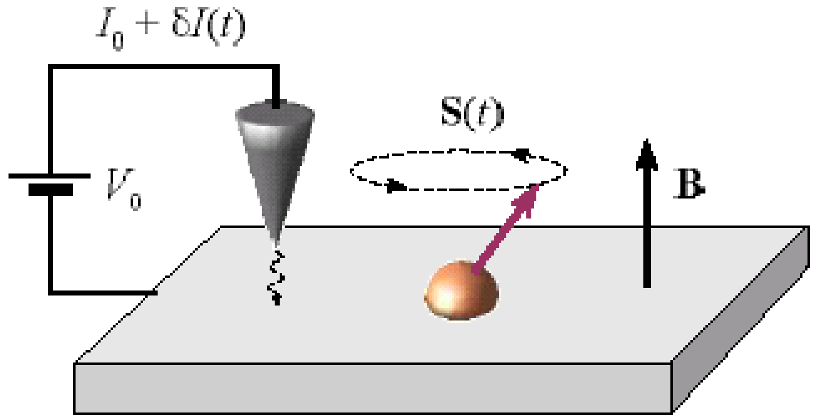


FIG. 1. Experimental setup for the electron spin precession STM. In the applied magnetic field B, spin of the magnetic atom (e.g. Gd, shown in gold) is precessing around the field direction. When precisely positioned next to the spin site (within a few Å), the STM tip can pick up an ac modulation of the tunnel current.

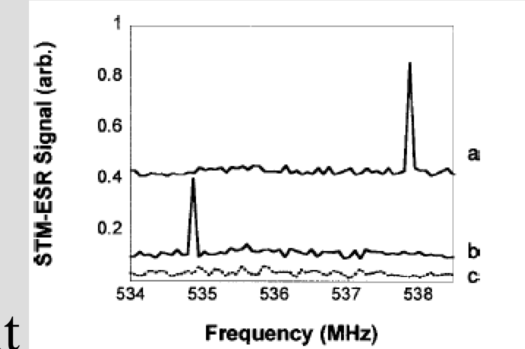
Energy scales of the Problem:

B= 100-300 Gauss

Idc~ 1 nA= 10^-9A

Iac~ 1 pA= 10^(-12)A

$\hbar\omega_L = 500MHz \sim 10^{-6} eV$



STM-ESR spectra of (a), (b) two different areas (a few nm apart)

$\delta I(t) \rightarrow \langle \delta I(t)\delta I(t') \rangle \rightarrow I_\omega^2$ noise in the current

This setup works as an AC generator

Dukan et al, APL 02

VOLUME 62, NUMBER 21 PHYSICAL REVIEW LETTERS 22 MAY 1989

Direct Observation of the Precession of Individual Paramagnetic Spins on Oxidized Silicon Surfaces

Y. Manassen, R. J. Hamers, J. E. Demuth, and A. J. Castellano, Jr.
IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598
(Received 12 December 1988)

The precession of individual spins on partially oxidized Si(111) surfaces has been detected using a scanning tunneling microscope. The spin precession in a constant magnetic field induces a modulation in the tunneling current at the Larmor frequency. This radio-frequency signal is shown to be localized over distances less than 10 Å and follows the expected magnetic field dependence.

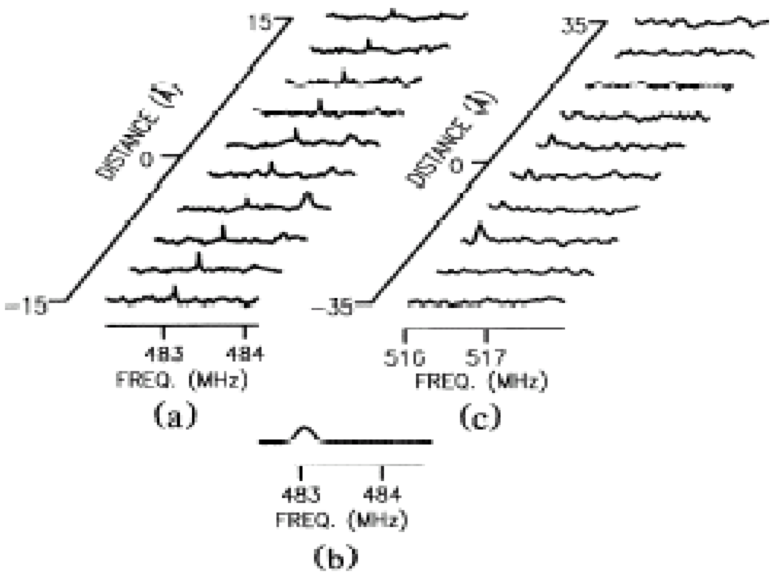


FIG. 1. (a) Consecutive rf power spectra of the tunneling current, measured at different lateral separations of the tip from a spin center in a field of 172 G. Each spectrum was taken at a point separated by 3 Å from the previous one. (b) A power spectrum near another spin center in a 172-G field, showing the nearly Gaussian line shape. (c) Same as (a), except for a field of 185 G; separation between scans = 7 Å.

Nodal structure of the signal?

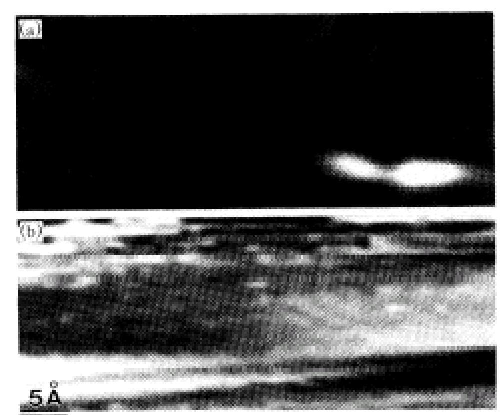


FIG. 2. (a) Gray-scale image showing the rf signal at a fixed frequency (483.8 MHz) as a function of the tip location. (b) The corresponding topographic image recorded simultaneously with (a).

APPLIED PHYSICS LETTERS VOLUME 80, NUMBER 3 21 JANUARY 2002

Electronic spin detection in molecules using scanning-tunneling-microscopy-assisted electron-spin resonance

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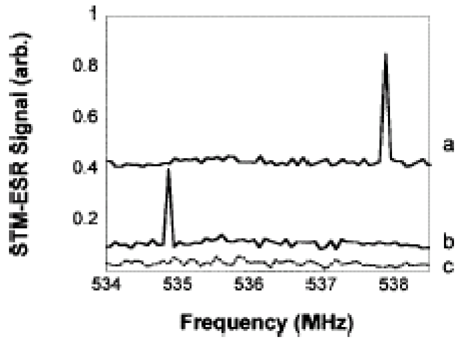


FIG. 3. STM-ESR spectra of (a), (b) two different areas (a few nm apart) of the molecule-covered sample and (c) bare HOPG. The graphs are shifted vertically for clarity.

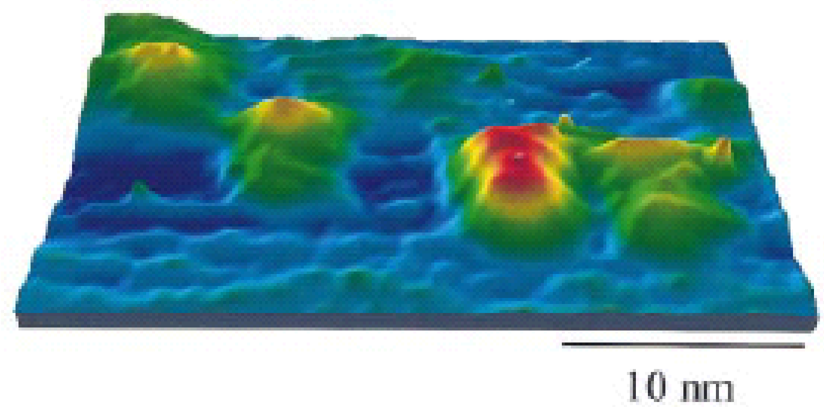
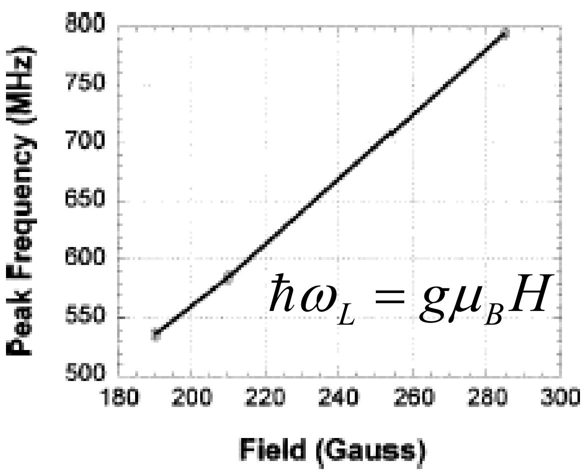


FIG. 2. (Color) STM image of a 250 Å×150 Å area of HOPG with four adsorbed BDPA molecules.



$$\hbar\omega_L = g\mu_B H$$

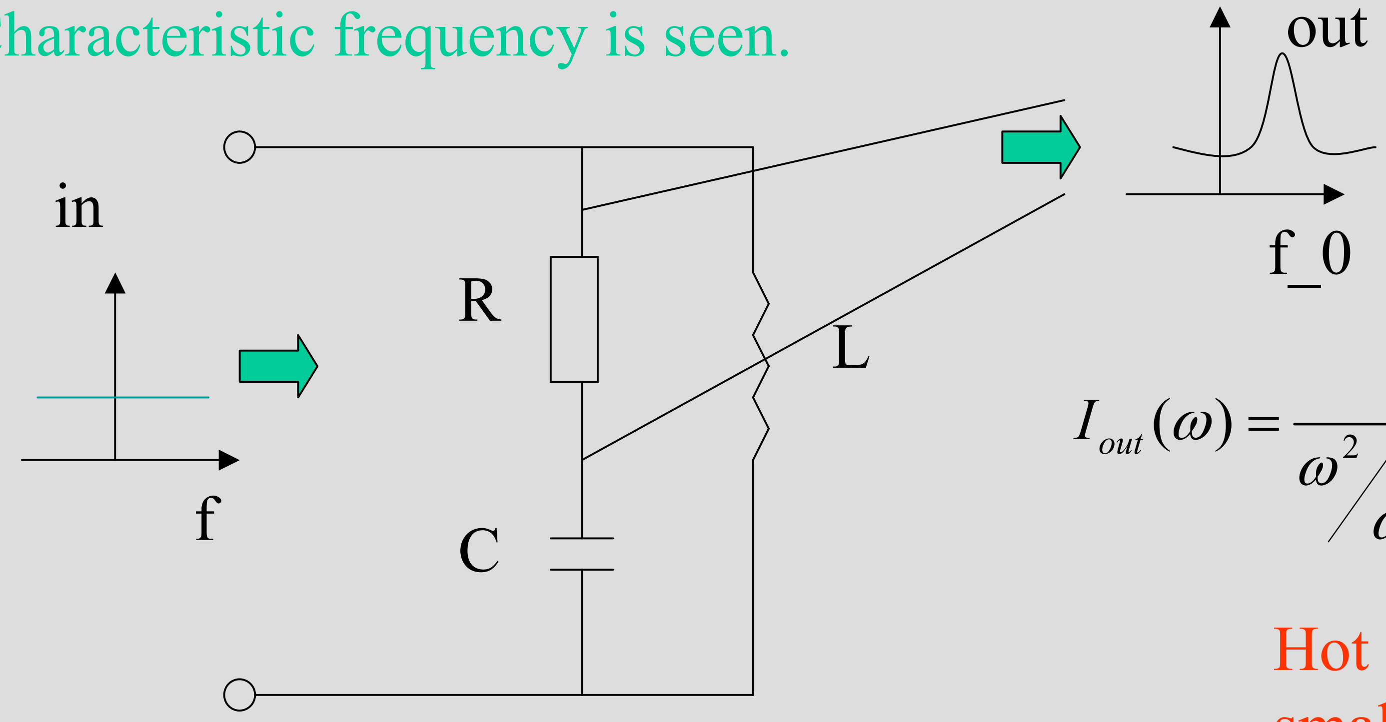
FIG. 5. Plot of the center frequency of STM-ESR peaks on clusters as a function of the applied magnetic field. From this, we obtain a value of $g=2\pm0.1$.

[14] N. S. Dalal, D. E. Kennedy, and C. A. McDowell, J. Chem. Phys. 61, 1689 (1974).

esr linewidth for BDPA is few gauss
At room temperature!

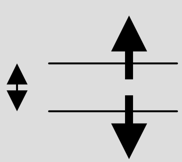
Noise spectroscopy of spin

White noise sent through the system with peaked susceptibility is filtered and results in colored noise. Characteristic frequency is seen.



$$I_{out}(\omega) = \frac{I_{in}(\omega)\omega^2 L}{\omega^2 / \omega^2_0 - 1 + iRC\omega}$$

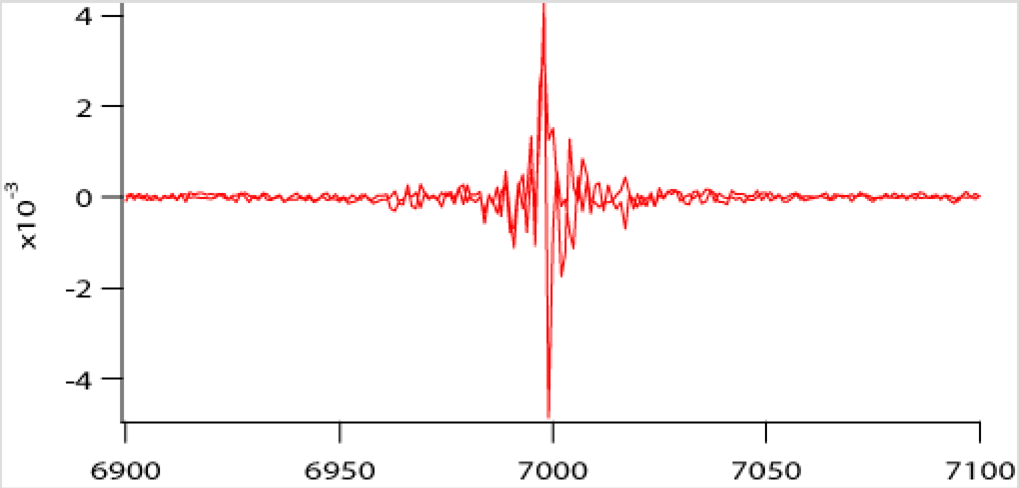
$$k_B T >> \Delta = g\mu_B B$$



Hot environment
small splitting
random dynamics
of spin S

Cantielever noise in MRFM set up.

Thermally induced noise can be used to measure Temperature, Q and eigenfrequency of resonator without ever driving it, just monitoring the noise.



J. Markert, UT Austin, unpublished.

Magnetic resonance in the Faraday-rotation noise spectrum

E. B. Aleksandrov and V. S. Zapasskiĭ

(Submitted 23 January 1981)
Zh. Eksp. Teor. Fiz. 81, 132–138 (July 1981)

A maximum at the magnetic resonance frequency of sodium atoms in the ground state is observed near the 5896 Å absorption line in the fluctuation spectrum of the azimuth of the polarization plane of light crossing a magnetic field in sodium vapor. The experiment is a demonstration of a new EPR method which does not require in principle magnetic polarization of the investigated medium, nor the use of high-frequency or microwave fields to induce the resonance.

PACS numbers: 32.30.Jc, 32.80. – t, 07.58. + g, 35.80. + s

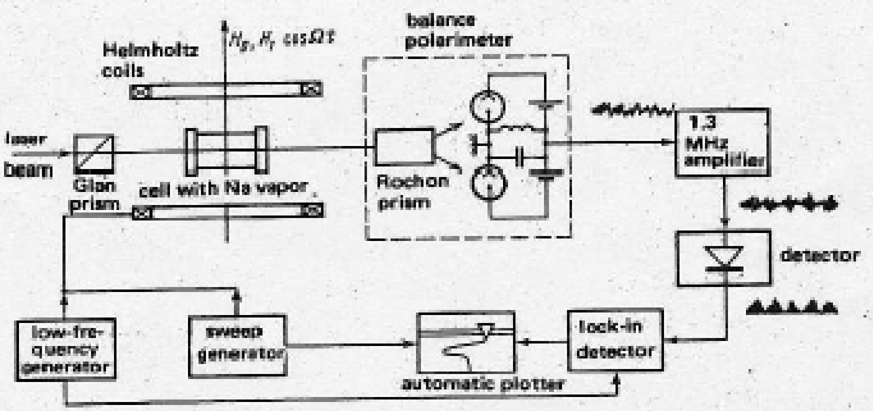


FIG. 1. Diagram of experimental setup. 1) Helmholtz coils, 2) balance polarimeter, 3) laser beam, 4) Glan prism, 5) cell with Na vapor, 6) Rochon prism, 7) 1.3 MHz amplifier, 8) detector, 9) low-frequency generator Ω, 10) sweep generator, 11) automatic plotter, 12) lock-in detector.

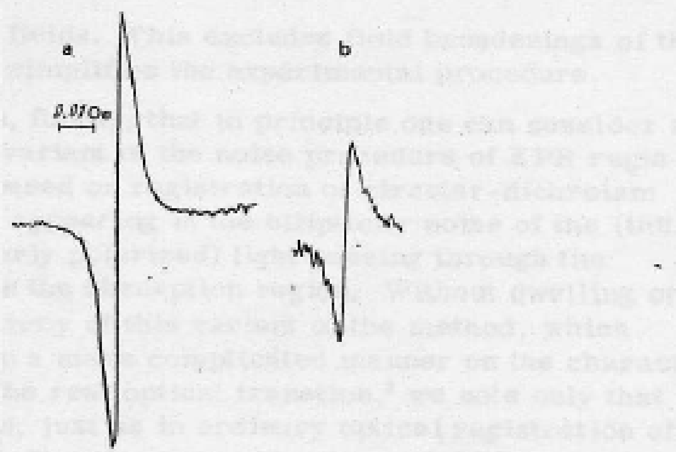


FIG. 2. Plots of EPR signal in Faraday-rotation noise: a—at the edges of the 5896 Å absorption line, b—between the 5896 and 5890 Å lines.

$$\text{For polarized in the field } \delta\Theta \propto N_\uparrow - N_\downarrow$$

$$\text{For noise:}$$

$$\langle \delta\Theta \rangle = 0, \text{ however } \langle \delta\Theta^2 \rangle = \langle (N_\uparrow - N_\downarrow)^2 \rangle = \overline{N}$$

VOLUME 55, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1985

Nuclear-Spin Noise

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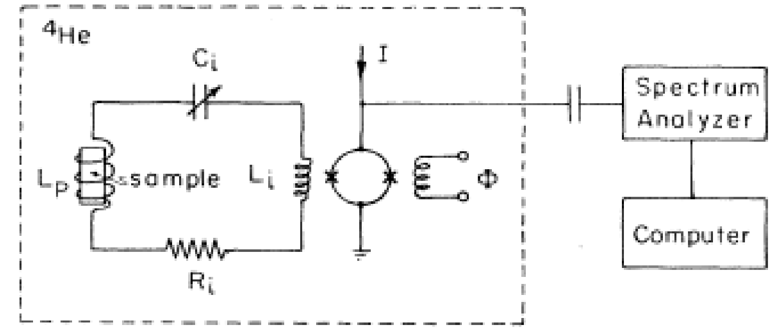
and

Claude Hilbert and John Clarke

In his pioneering paper[1] on nuclear induction, Bloch noted that in the absence of any external radiofrequency (rf) driving field a sample of N spins of magnetic moment μ contained in a pickup coil would induce very small voltage fluctuations proportional to $N^{1/2}\mu$. In this Letter, we report the observation of these temperature-independent fluctuations at liquid-^{4}He temperatures arising from the ^{35}Cl nuclei in $NaClO_3$ at the nuclear quadrupole resonance (NQR) frequency of about 30 MHz.



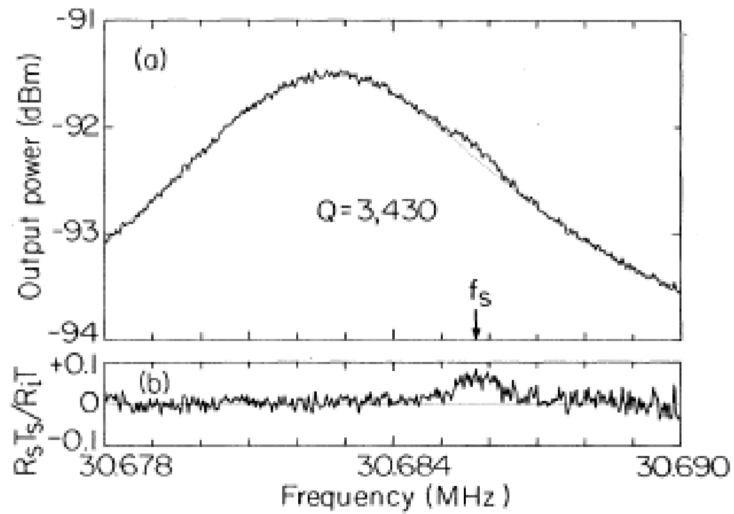


FIG. 3. Spectral density of (a) noise current for a $NaClO_3$ sample with saturated spins ($T_s=\infty$), and (b) nuclear-spin noise of $NaClO_3$ sample obtained from (a).

VOLUME 68, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1992

Macroscopic Quantum Tunneling in Magnetic Proteins

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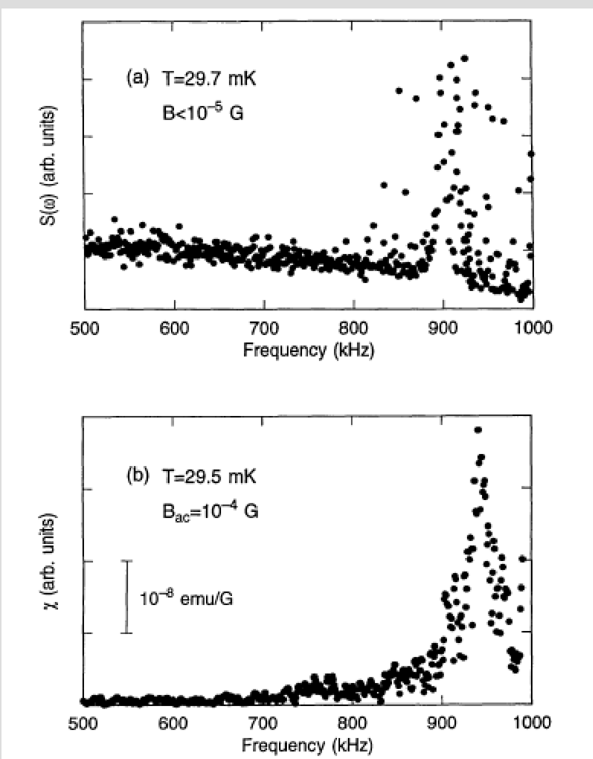
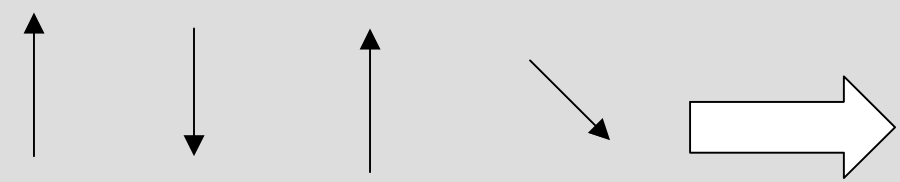
[2]*IBM Research Division, IBM T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598*
(Received 13 February 1992)

We report low-temperature measurements of the frequency-dependent magnetic noise and magnetic susceptibility of nanometer-scale antiferromagnetic horse-spleen ferritin particles, using an integrated dc SQUID microsusceptometer. A sharply defined resonance near 1 MHz develops below $T \sim 0.2$ K. The behavior of this resonance as a function of temperature, applied magnetic field, and particle concentration indicates that it results from macroscopic quantum tunneling of the Néel vector of the antiferromagnets.



Time dependent magnetic field
As picked up by SQUID—
Another example of noise spectroscopy



M(t)

Another example of noise spectroscopy

VOLUME 84, NUMBER 23 PHYSICAL REVIEW LETTERS 5 JUNE 2000

Spontaneous Noise Spectroscopy of an Atomic Magnetic Resonance

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(Received 14 September 1999)

We have experimentally demonstrated a new type of noise spectroscopy, which requires neither amplitude nor frequency noise of the light source. A highly stabilized diode laser provides low-noise light for the optical magnetic resonance of Rb atoms. The laser light transmitted through the Rb vapor contains significant intensity fluctuations whose power spectrum has a distinct peak at the Larmor frequency. The

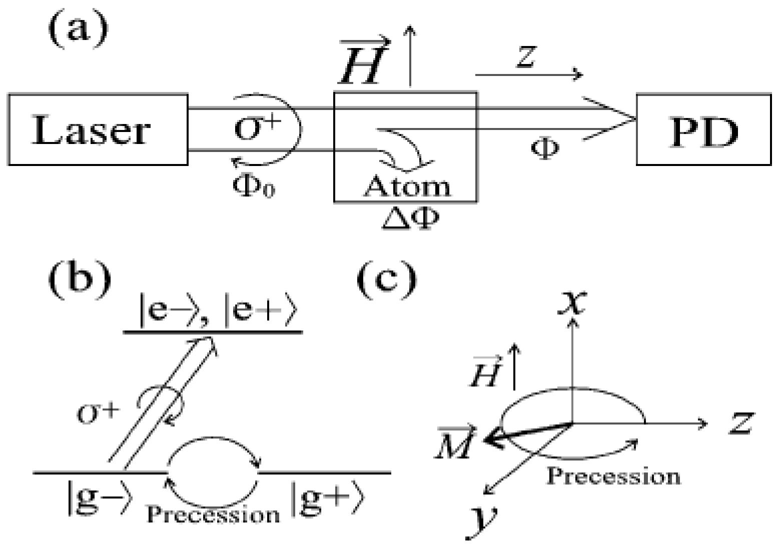


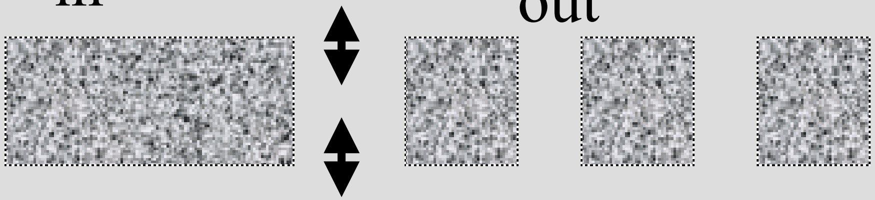
FIG. 1. (a) Optical system. (b) A four-level system, together with the laser excitation and the Larmor precession. The excited levels are represented by a single state, assuming the collisions mix them in the high pressure buffer gas. (c) The same four-level system is described in terms of a normalized magnetic moment $\vec{M}$, when the excited state populations are negligible. It precesses around the magnetic field at the Larmor frequency.

Photocurrent modulation due to precessing spin

$$I(t) \approx \eta q \left[\left(\Phi_0 - \sum_{j=1}^{N} \frac{1}{2} \phi(\vec{r}_j)\sigma \right) + \sum_{j=1}^{N} \frac{1}{2} \langle \phi \rangle \sigma M_{zj} \right], \quad (5)$$

in

out



Transparency is modulated at Larmor frequency

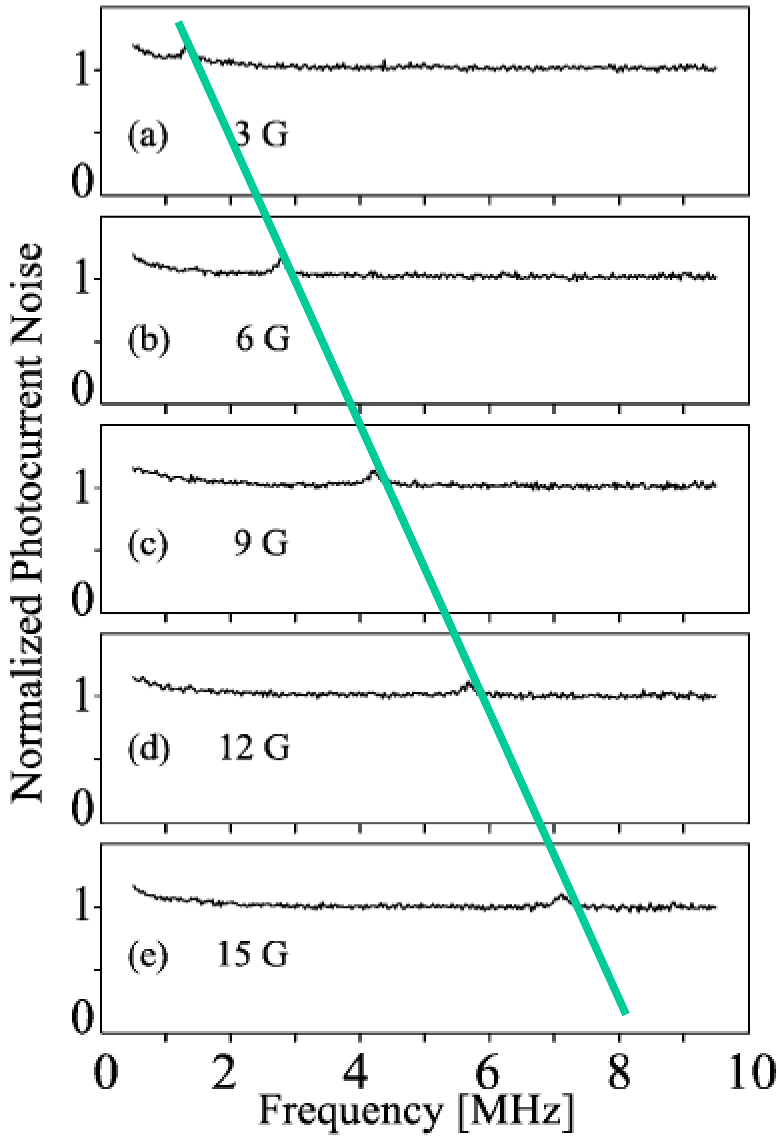


FIG. 3. The observed intensity noise spectra for various magnitudes of the magnetic field. The resolution bandwidth of the spectrum analyzer is 30 kHz.

$$P(t) \sim M_z(t)$$

$$\langle I(t)I(t')\rangle \sim \langle P(t)P(t')\rangle$$

$$\sim \langle M_z(t)M_z(t')\rangle \Rightarrow \text{peak at } \omega_\mathrm{L}$$

in Fourier transform

$$\langle M_{zj}(t)M_{zk}(t+\tau)\rangle = \frac{\delta_{jk}}{3}\exp(-\gamma|\tau|)\cos(2\pi\nu_0\tau)$$

$$\langle M_{zj}(t)\rangle = 0,$$

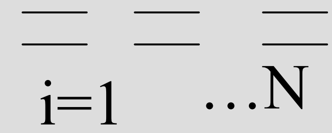
$$\omega_L = g\mu_B H$$

We believe that similar noise spectroscopy is what is measured in STM on single/few spins experiments

Noise Spectroscopy

Consider the signal S (magnetization, charge...) coming from an ensemble of two level systems:

$S(t) = \Sigma_i s_i(t)$, $i = 1 \ldots N$.



Autocorrelation function

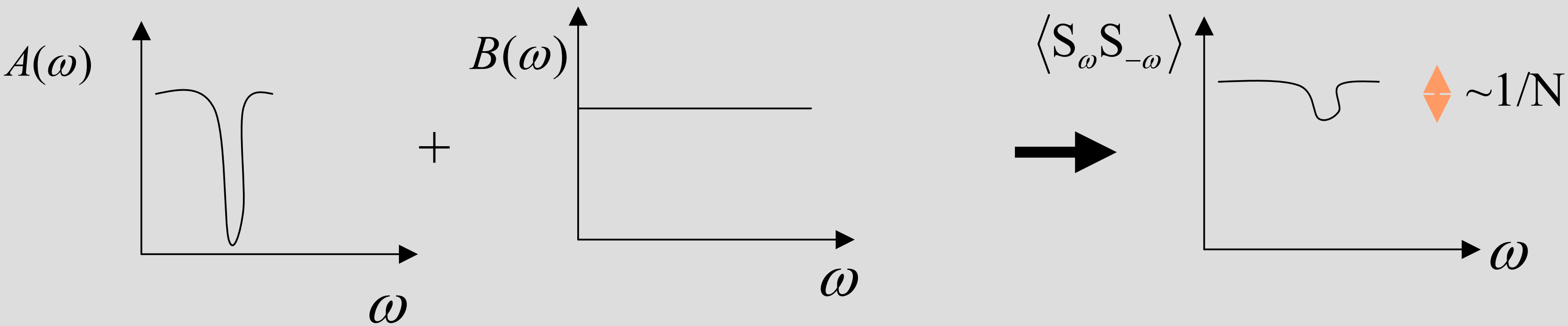
$$\langle S(t)S(t')\rangle = \sum_{i=j} s_i(t)s_i(t') + \sum_{i\neq j} s_i(t)s_j(t') =$$

$$\langle S(t)S(t')\rangle = NA(t-t') + N(N-1)B(t-t')$$

or in Fourier space:

$$\langle S_\omega S_{-\omega}\rangle = NA(\omega) + N(N-1)B(\omega)$$

When N=1 signal is large



Relevant time scales

Precession frequency 500 MHz,

$\tau_{precession} = 2ns$

linewidth $\gamma \sim 0.1\text{-}1\,\mathrm{MHz}$

$\mathrm{J} = 0.1\,\mathrm{eV},\ \mathrm{U} = 4\,\mathrm{eV}$

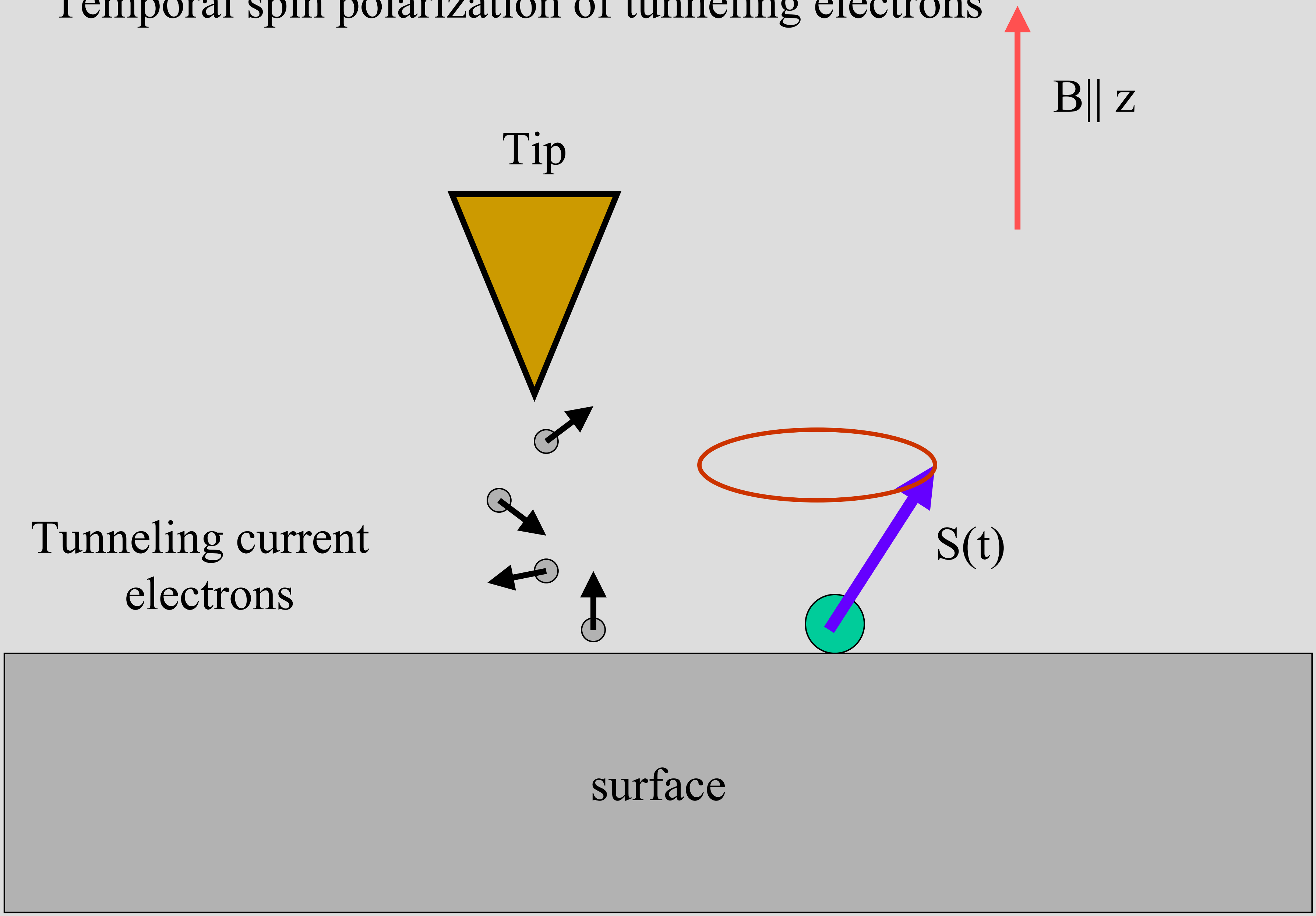
Electron tunneling rate, $\mathrm{I} = 1\,\mathrm{nA}$

$1/\tau_e = 10^{10}\,Hz \Rightarrow$ About $\overline{\mathrm{N}} = 20$ eletrons per cycle

$\sqrt{\overline{\mathrm{N}}} = 4$ is a net effective spin polarization

Imagine we have a situation of one electron per cycle. Even if there is no net spin polarization, there is a fluctuating temporal polarization on a time scale relevant for spectrum at Larmor frequency!
Truly a noise spectrocsopy!

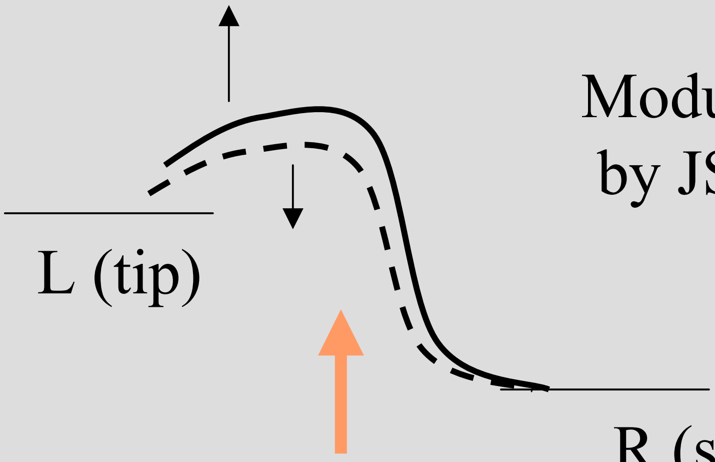
Temporal spin polarization of tunneling electrons



$$H = \sum c_{L\sigma}{}^{*} c_{L\sigma} + \sum c_{R\sigma}{}^{*} c_{R\sigma} + c_{L\sigma}{}^{*}[t_0 + t_1 JS\sigma_{\sigma\sigma'}]c_{R\sigma'}$$

$$t_0 = \exp(-U),$$
$$t_1 = J/U \exp(-U)$$

t_1/t_0 ~ J/U magnitude of modulation



Modulation of tunneling barrier
by JS/U due to exchange interaction

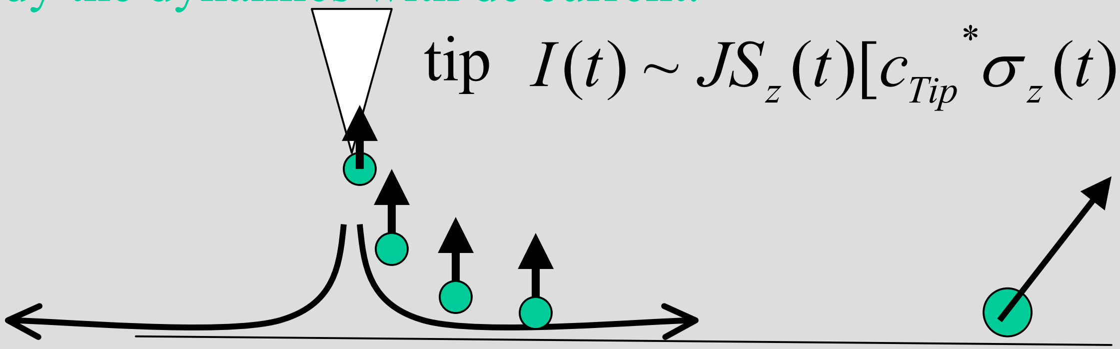
Localized spin S(t)

Noise spectroscopy of a single spin with spin polarized STM

Z. Nussinov[1], M. F. Crommie[2,3], and A. V. Balatsky[1]

Cond-mat/ 0301032.
PRB, 2003, to be pub

Main idea: dc spin polarization of tunneling electrons
is all that is required to measure the dynamics of a single spin.
Study the dynamics with dc current.



$$I(t) \sim JS_z(t)[c_{Tip}^{*}\sigma_z(t)c_{surface} - h.c] = JS_z(t)I_{Spin}(t)$$

polarized tunneling current I

$$\langle I(t)I(t')\rangle = J^2\langle S_z(t)S_z(t')\rangle\langle I_{z\,Spin}(t)I_{z\,Spin}(t')\rangle$$

$$\langle I^2(\omega)\rangle \sim \int d\Omega\langle S^2{}_z(\omega-\Omega)\rangle\langle I^2{}_{z\,Spin}(\Omega)\rangle$$

$$\langle I^2{}_{zSpin}(\Omega)\rangle \sim A\delta(\Omega),$$

$$\langle I_{z\,Spin}(t)I_{z\,Spin}(t')\rangle \to_{t-t'\to\infty} A$$

$$\langle I^2(\omega)\rangle \sim A\langle S^2{}_z(\omega)\rangle$$

Current dynamics reflects the spin
Dynamics: S/N ~ 1

1/f spin noise and noise spectroscopy

Basic idea is that we do not have a steady spin polarization of tunneling Spins. Polaization long enough on the scale of precessing S spin is sufficient. Assume spin current out of the tip has 1/f spectrum.
if one has a paramagnetic center (say easy axis)
on the tip then tunneling electrons will acquire a time dependent spin polarization.

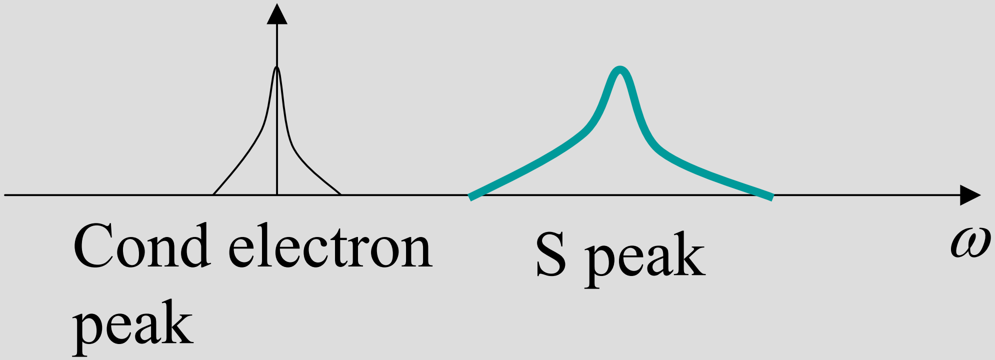
AVB and Manassen
In progress

$$I(t) \sim S_{\perp}(t)\sigma_{\perp}(t) \xrightarrow{Fourier} I_{\omega} \sim \int d\omega_1 S_{\perp,\omega-\omega_1}\sigma_{\omega_1}$$

and similar for dispersion

$$\left\langle I^2{}_{\omega} \right\rangle \sim \int d\omega_1 S^2{}_{\perp,\omega-\omega_1}\sigma^2{}_{\omega_1} \sim$$

$$\frac{\gamma_{\max}}{\gamma^2{}_{\max} + (\omega - \omega_L)^2}$$



1/f noise in unpolarized STM current

Spatial variation of 1/*f* current noise in scanning tunneling microscopes

K. Maeda, S. Sugita, H. Kurita, M. Uota, S. Uchida, M. Hinomaru, and Y. Mera
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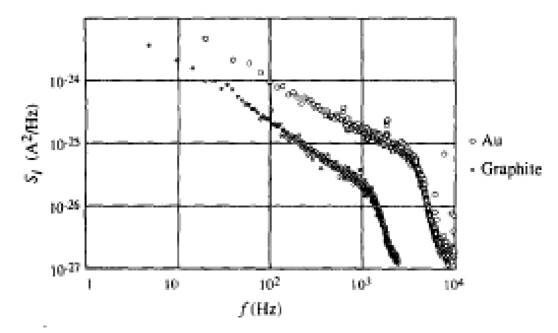
(Received 9 August 1993; accepted 24 December 1993)



Thermal noise in vacuum scanning tunneling microscopy at zero bias voltage

R. Möller, A. Esslinger, and B. Koslowski
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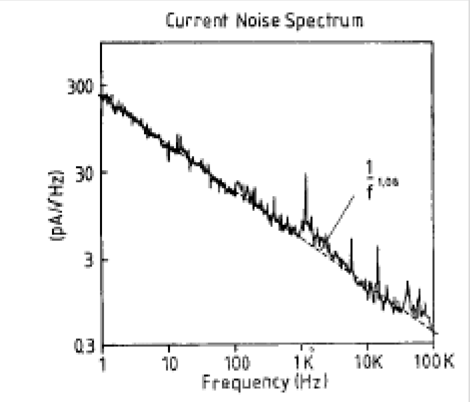
(Received 10 July 1989; accepted 1 August 1989)



Exchange Based Noise Spectroscopy of a Single Precessing Spin with STM

A. V. Balatsky[1], Yishay Manassen[2] and Ran Salem[2]
[1] Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545,
[2] Department of Physics and the Ilse Katz Center for Nanometer Scale Science and Technology, Ben Gurion University, Beer Sheva, 84105, Israel
(Dated: April 10, 2002)

ESR-STM is an emerging technique which is capable of detecting the precession of a single spin. we discuss a mechanism based on a direct exchange coupling between the tunneling electrons and the local precessing spin **S**. We claim that since the number of tunneling electrons in a single precessing period is small (~ 20) one may expect a net temporary polarization within this period which will couple via exchange interaction to the localized spin. This coupling will modulate the tunneling barrier with the Larmor frequency of the precessing spin ω_L. This modulation although randomly changing from cycle to cycle, will produce an elavated noise in the current at ω_L. We find that for relevant values of parameters signal to noise ratio in the spectral characteristic is 2-4 and is comparable to the reported signal to noise ratio [1, 2]. The magnitude of the current fluctuation is a relatively weak increaing function of the DC current and the magnetic field. The linewidth produced by the back action effect of tunneling electrons on the precessing spin is also discussed.

Tunneling barier height is modulated due to exchange J

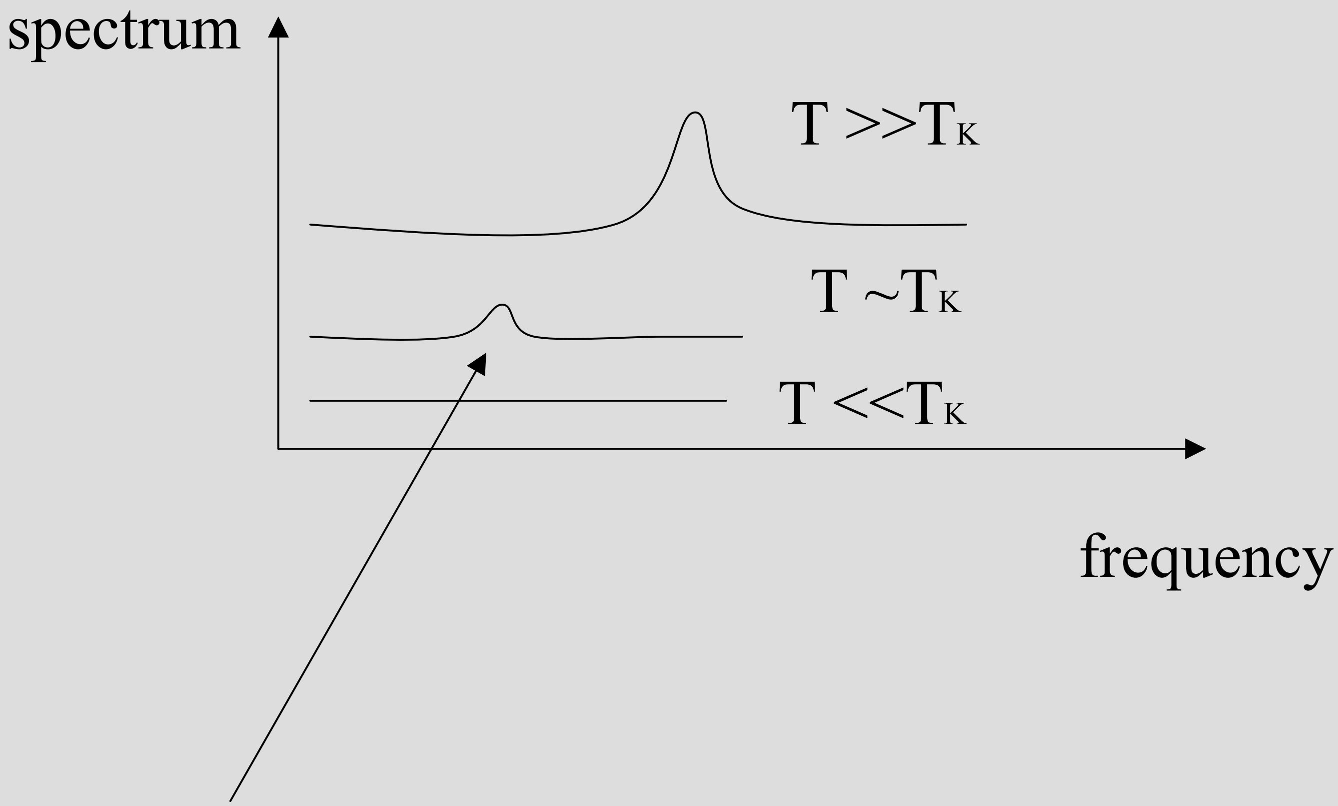
$$I(t) \sim \frac{J}{U} S^x(t)\sigma^x(t) + (x \to y), \text{linewidth } \gamma \sim \frac{1}{\tau_e}\left(\frac{JS}{U}\right)^2 \sim 1MHz$$

$$\frac{\langle I^2{}_\omega \rangle}{\langle I^2{}_{shot} \rangle} = \frac{1}{\tau_e \gamma}\left(\frac{JS}{U}\right)^2 \sim 2-10$$

Phil Mag **B82**, p. 1291, (2002); PRB, **66**, 195416 (2003) .

Potential applications of ESP-STM

- Emergent technique for detection of magnetic defects
- Fully capable of single spin detection. Quantum computing.
- General sample characterization. Surface science.
- Study the dynamics of the Kondo spin: temperature evolution of the ESP line (above and below T_K)
- Potential for a new imaging technique (similar to MRI)



Line shifts because of spin renormalization
Due to Kondo effect?? A possibility.
ESR STM allows to address the Kondo dynamics directly.

Quantum wire or dot with spins

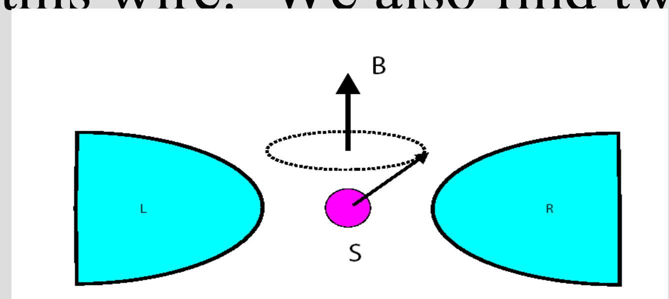
VOLUME 89, NUMBER 28 PHYSICAL REVIEW LETTERS 31 DECEMBER 2002

Quantum Electronic Transport through a Precessing Spin

Jian-Xin Zhu and A.V. Balatsky

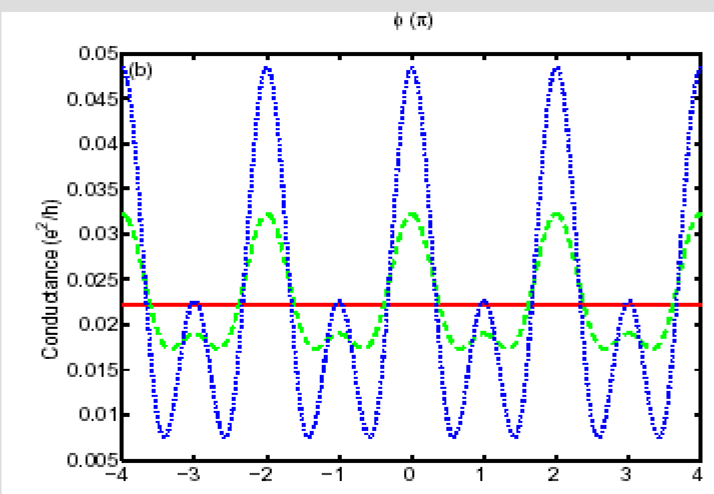
PRL, v 89 286802,(2002)

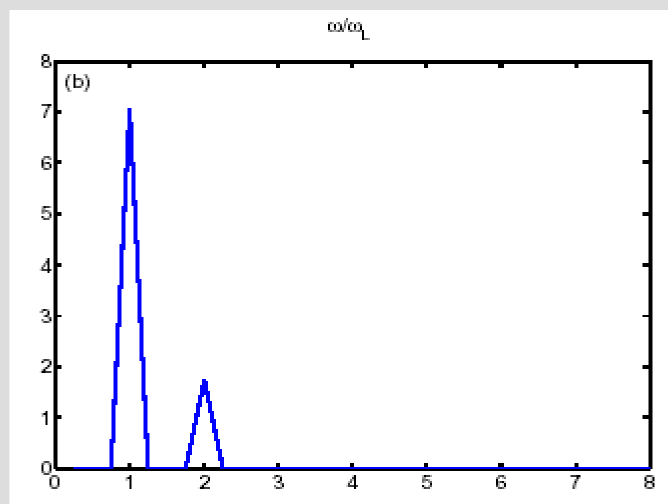
Imagine single wire or single dot with spins geometry. SO coupling will produce a modulation in the conductivity of this wire. We also find twice Larmor frequency signal



$$\mathcal{H} = \sum_{k\in(L,R),\sigma} \epsilon_{k\sigma} c^{\dagger}_{k\sigma} c_{k\sigma} + J \sum_{\sigma,\sigma'} d^{\dagger}_{\sigma} \Omega_{\sigma\sigma'} d_{\sigma'} + \sum_{k\in(L,R),\sigma,\sigma'} (V_{k\sigma,\sigma'} c^{\dagger}_{k\sigma} d_{\sigma'} + \text{H.c.}).$$

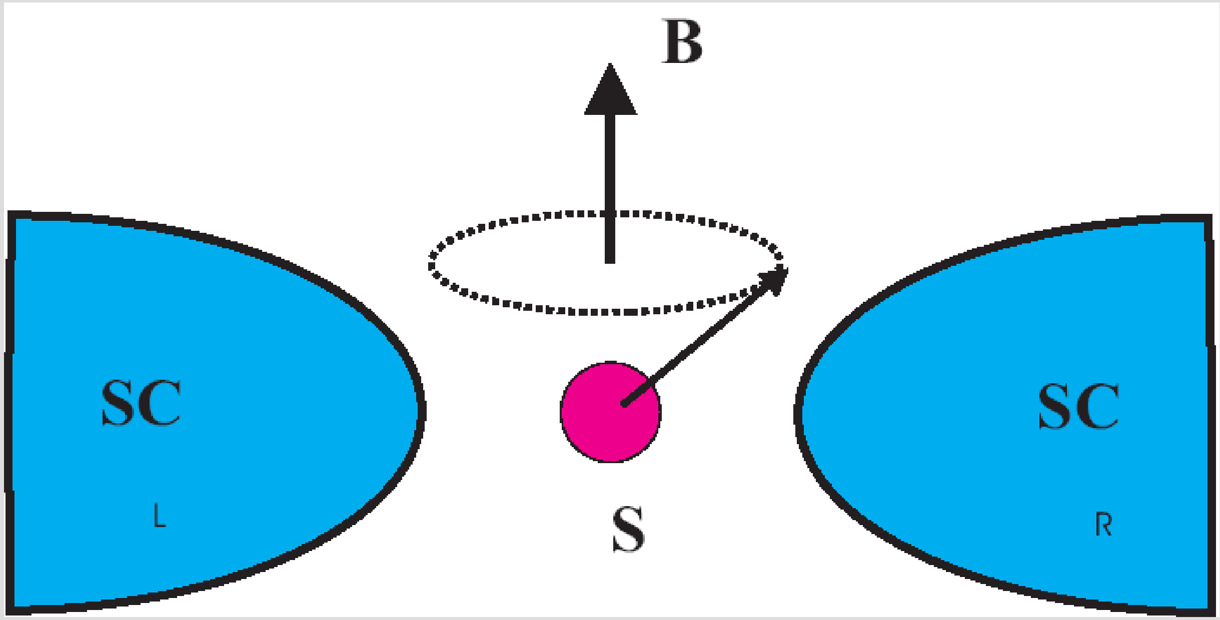
$$G(t) = G_0 + g_{so}[I \times S(t)]_n$$





Zhu et al, Cond mat 0306710

Josephson effect and single spin



$$H = H_L + H_R + H_T \ .$$

$$H_{L(R)} = \sum_{\mathrm{k(p)};\sigma} \epsilon_{\mathrm{k(p)}} c^\dagger_{\mathrm{k(p)},\sigma} c_{\mathrm{k(p)},\sigma} + \frac{1}{2} \sum_{\mathrm{k(p)};\sigma,\sigma'} [\Delta_{\sigma\sigma'}(\mathrm{k(p)}) c^\dagger_{\mathrm{k(p)},\sigma} c^\dagger_{-\mathrm{k(-p)},\sigma'} + \mathrm{H.c.}]$$

$$H_T = \sum_{\mathrm{k,p};\sigma,\sigma'} [T_{\sigma\sigma'}(\mathrm{k,p}) c^\dagger_{\mathrm{k}\sigma} c_{\mathrm{p}\sigma'} + \mathrm{H.c.}]$$

$$\hat{T} = T_0 \delta_{\sigma,\sigma'} + T_1 \mathbf{S}(t) \cdot \sigma_{\sigma\sigma'}$$

Integrable equations of motion

$$\frac{d\mathbf{n}}{dt} = \alpha \mathbf{n} \times \frac{d\mathbf{n}}{dt} \sin \omega_J t + g\mu_B \mathbf{n} \times \mathbf{B}$$

$$S(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

$$\alpha = S \sum_{\mathbf{k},\mathbf{p}} \frac{|\Delta|^2 |T_1|^2}{E_{\mathbf{k}} E_{\mathbf{p}}} \left[\frac{1}{(E_{\mathbf{k}} + E_{\mathbf{p}} - eV)^2} - \frac{1}{(E_{\mathbf{k}} + E_{\mathbf{p}} + eV)^2} \right]$$

$$\frac{d\phi}{dt} = -\frac{\omega_L}{1 + \alpha^2 \sin^2(\omega_J t)},$$

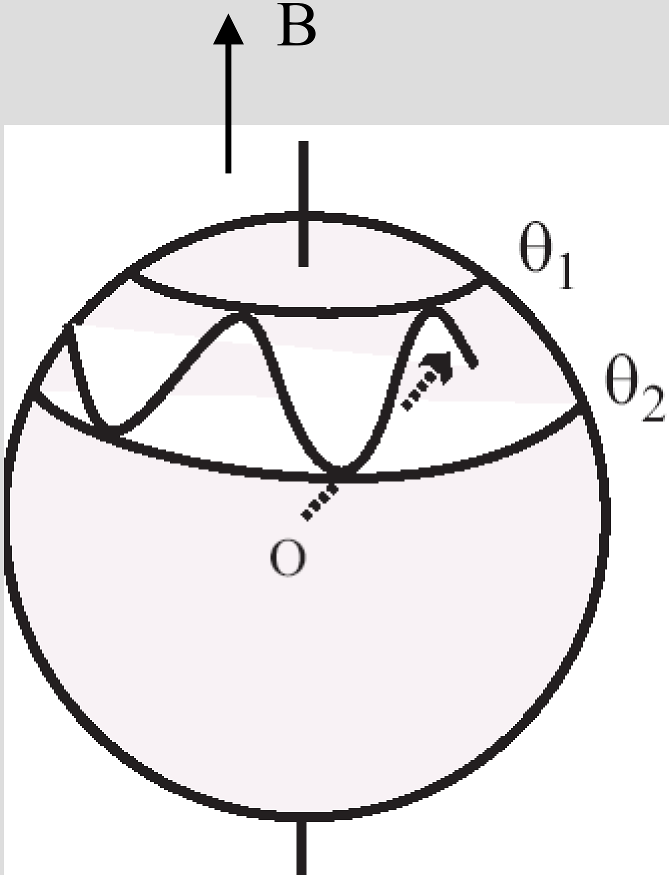
$$\frac{d\theta}{dt} = -\alpha \frac{d\phi}{dt} \sin\theta \sin\omega_J t .$$

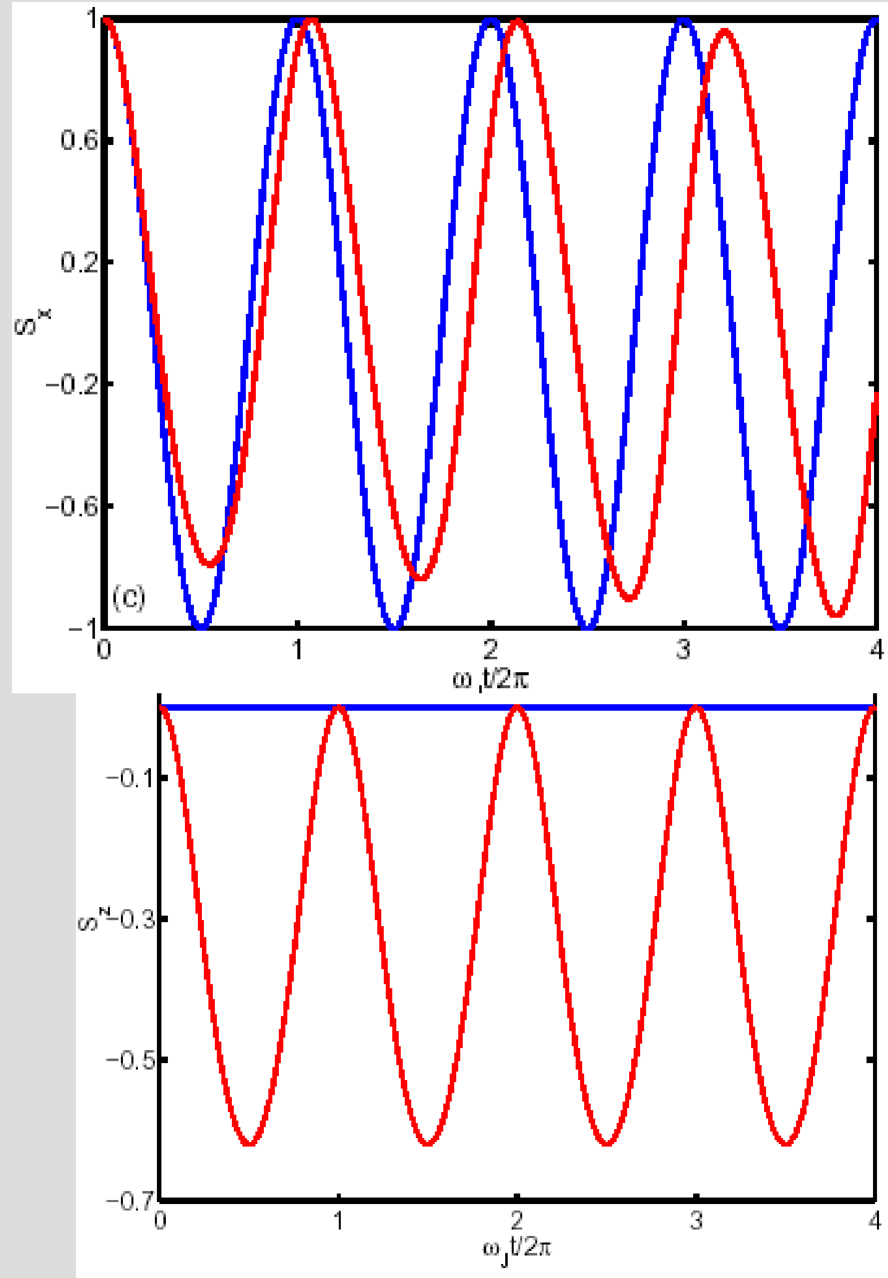
$$\phi(t) = -\frac{\omega_L}{\omega_J \sqrt{1+\alpha^2}} \tan^{-1}[\sqrt{1+\alpha^2}\tan(\omega_J t)]$$

$$\theta(t) = 2\tan^{-1}\left[\frac{(1 - c\cos(\omega_J t))(1+c)}{(1 + c\cos(\omega_J t))(1-c)} \right]^{\gamma},$$

$$\gamma = -\alpha\omega_L / 2\omega_J c.$$

Nutation of a spin due to Josephson current





Larmor precession in XY plane +
oscillations in polar direction
With Josephson frequency.

Conclusion

- STM can be used as a tool to detect a single spin signal.
- Noise spectroscopy is a mechanism for single spin detection.
- Spin polarized tunneling allows one to detect dynamics of a single spin with S/N ~ 1.
- 1/f spin noise in the tunneling current allows to couple to the spin dynamics with no dc spin polarization.
- Extentions for SC transport and for q dots and wires.