LETTER

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Coherent coupling of a superconducting flux qubit to an electron spin ensemble in diamond

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GROUP MEETING

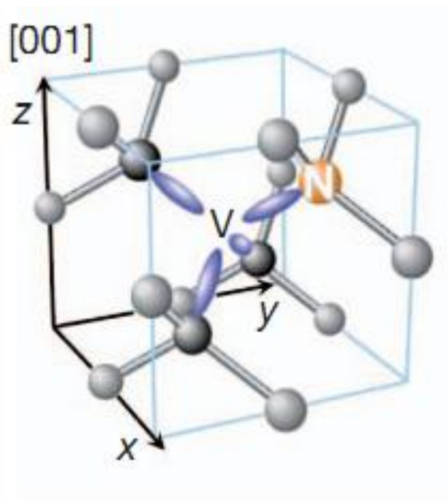
Xingxing Xing, Oct. 19, 2011

Outline

- A quick review of two types of quantum systems:
  - NV centre in diamonds
  - superconducting flux qubit
- A hybrid device – the advantages
- Strong coupling between a flux qubit and NV centres (collective enhancement)
- Experimental evidence: vacuum Rabi oscillations
- Summary and outlook

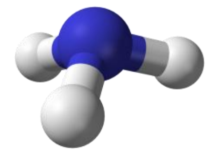
NV colour centre in diamonds

- Production:
  - Irradiation with high energy particles: create vacancies
  - Annealing: allow vacancies to move
  - Substitutional Nitrogen: form lattice strain to trap vacancy
  - High concentration is achieved by using $^{12}C^{2+}$ ion implantation
- Types:
  - NV^0: neutral
  - NV^-: extra e^-, commonly used
- Structure:
  - N: two non-bonded e^- form a lone pair
  - V in NV^0: 3 e^-, 1 quasi covalent bond + 1 unpaired
  - V in NV^-: extra e^- bond with the unpaired e^- (the interesting pair)



Energy levels

- Symmetry group: C_{3V}



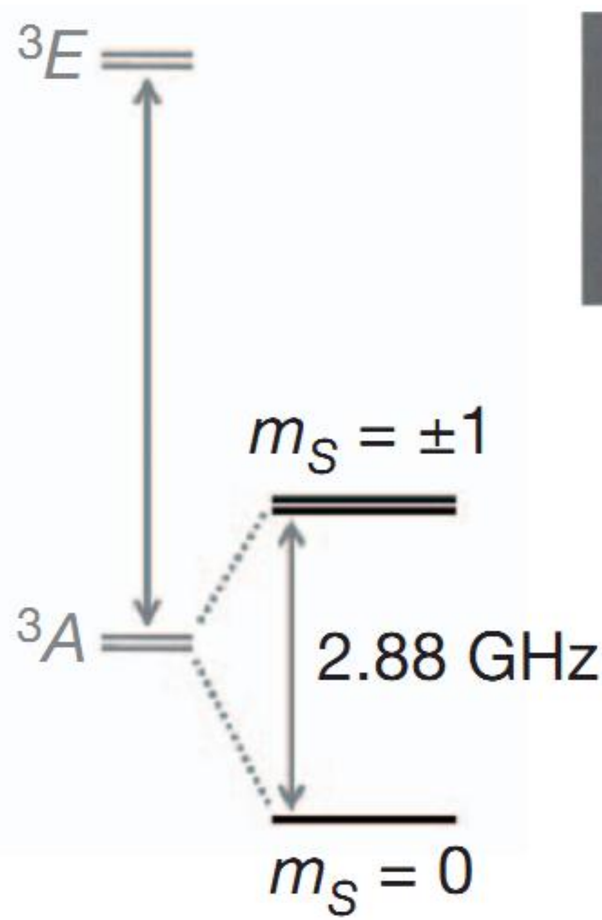
- At B=0:
  - the e^- pair can be anti-aligned: $m_S=0$
  - or aligned: $m_S= \pm 1$ (degenerate)
- Ground state Hamiltonian:

$$H_{NV} = hDS_z^2 + hE\left(S_x^2 - S_y^2\right) + hg_e\mu_B \mathbf{B}\bullet\mathbf{S}$$

Zero field splitting
D = 2.88GHz

Strain-induced splitting
E <10 MHz

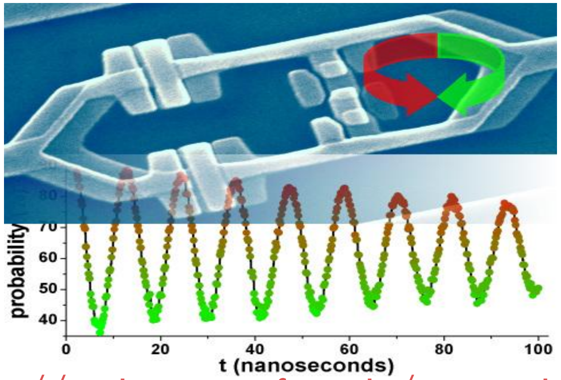
Bohr magnetron
< 1.4MHz



3-Josephson-Junction flux qubit

- Two Josephson Junction (JJ) forms a SQUID (Superconducting QUantum Interference Devices) on the left; the right one is the flux qubit.
- When B=0, the input current I will equally split into the two branches.
- When B≠0, the currents are $I/2+I_s/2$, and $I/2-I_s/2$. If any of these values exceeds I_c, it becomes resistive.
- The flux must be a integer multiple of the flux quanta $\Phi_0=h/2e$.
- When external magnetic flux $\Phi_{ext} \sim \Phi_0/2$, the lowest energy states are clockwise circulating current state |1> and counter-clockwise state|0>
- The Hamiltonian

$$H_{qb} = \frac{h}{2}(\Delta\sigma_x + \varepsilon\sigma_z)$$

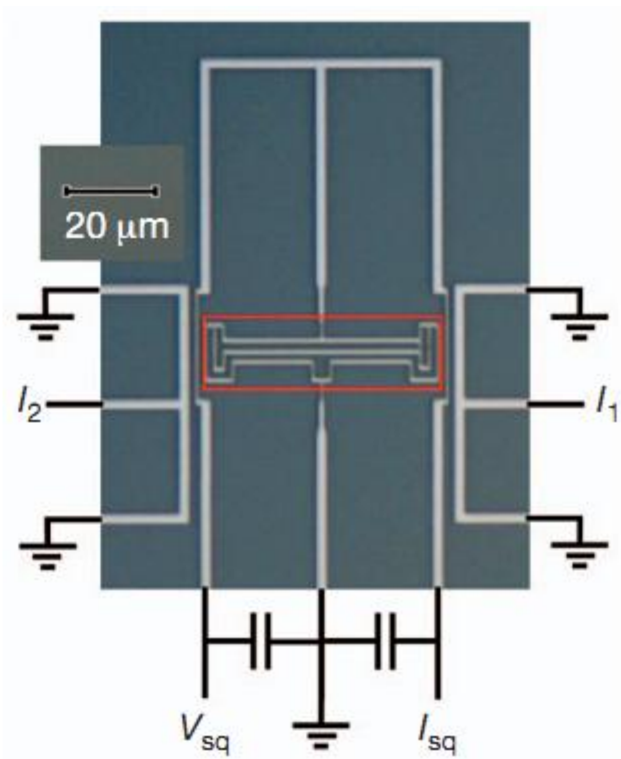


http://qsd.magnet.fsu.edu/research.html

I. Chiorescu, et.al., Science, 299, 1869 (2003)

Superconducting flux qubit

- The flux qubit in the experiment:
  - Based on the 3-Josephson-junction design
  - Modification: gap-tunable



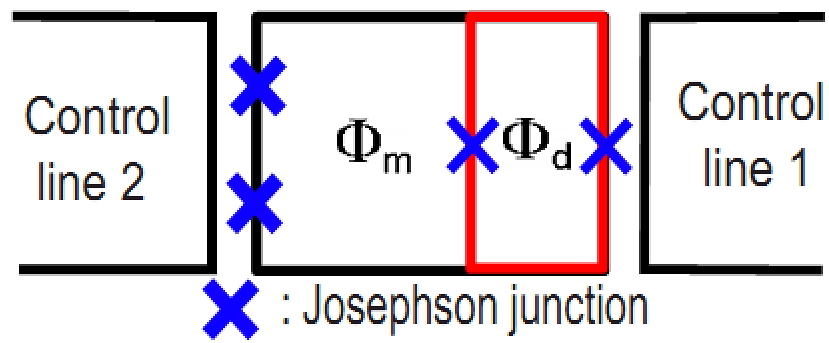
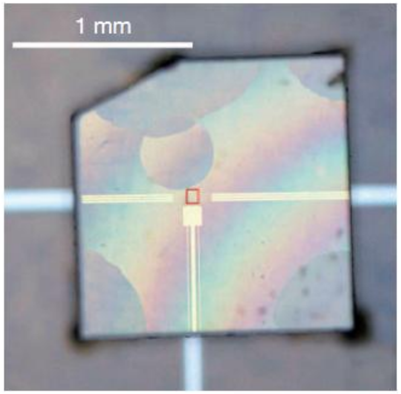


FIG. 1. (Color online) Schematic diagram of our qubit design showing the main loop (left loop), the dc-SQUID loop (right red loop), and the control lines.

Appl. Phys. Lett. 97, 102503 (2010).

A hybrid device

- The diamond with NV^- centre is glued to the SC circuits, with the ^{12}C-implanted (001) surface facing the flux qubit, at a distance < 1um
- Advantages
  - Coupling strength ~1000x stronger than the coupling between SC – transmission line resonator
  - Strong coupling possible by collective enhancement
  - coherence time can be extended
- The Hamiltonian



$$H = \underbrace{\frac{h}{2}(\Delta\sigma_x + \epsilon\sigma_z)}_{H_F} + \underbrace{h\sum_i^N \left[DS_{z,i}^2 + E\left(S_{x,i}^2 - S_{y,i}^2\right) + g_e\mu_B B_{z,i}S_{z,i}\right]}_{H_{NV}} + \underbrace{\frac{h}{2}\sum_i^N g_i S_{x,i}\sigma_z}_{H_{int}},$$

Energy spectrum with coupling

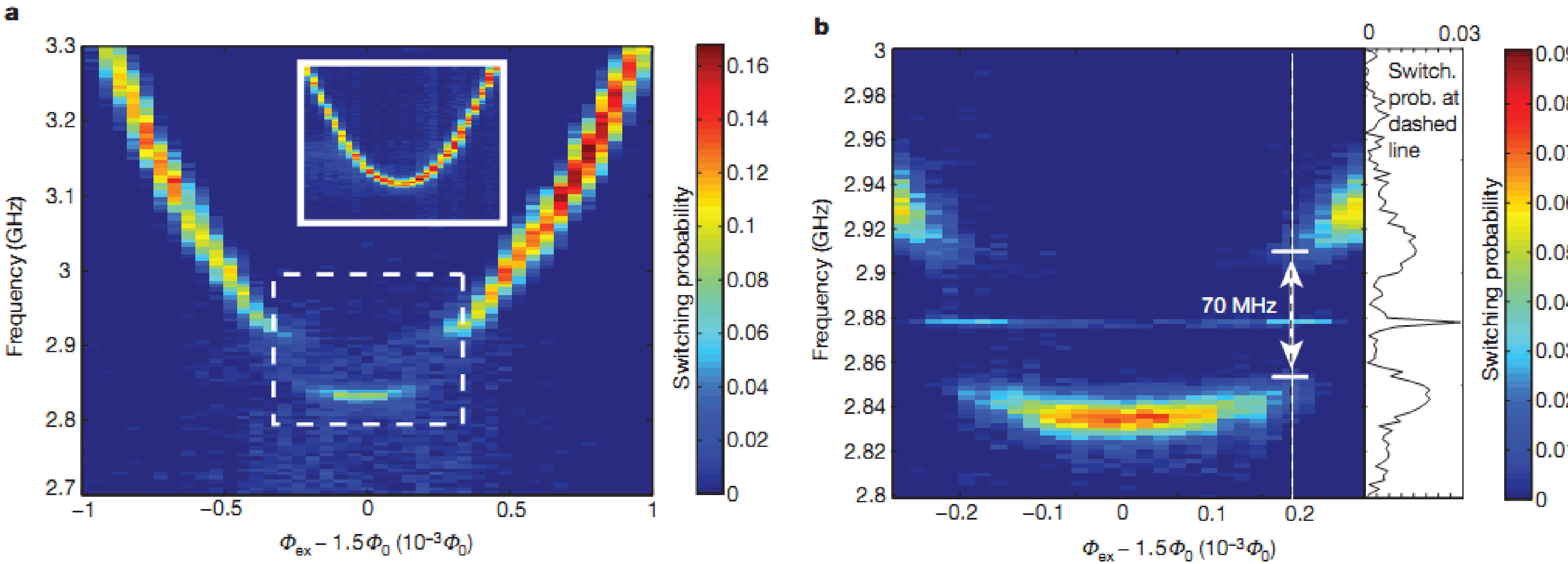
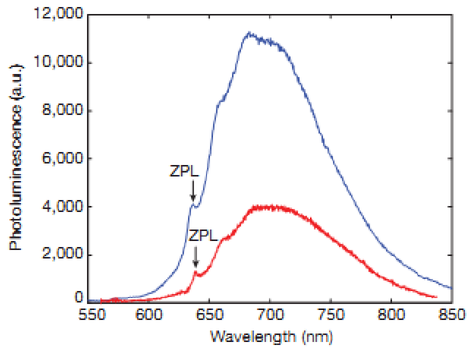


Figure 3 | Energy spectrum of the flux qubit coupled to a NV^- ensemble. **a**, Resonant frequencies indicated by the SQUID detector switching probability (when a 500-ns microwave pulse excites the system before the read-out pulse) versus the external magnetic flux, $\Phi_{ex} = \Phi_m + \Phi_\alpha/2$, where Φ_m and Φ_α are the fluxes through the qubit main loop and the qubit α-loop, respectively. Inset, spectrum over the same region before mounting of the diamond crystal. **b**, Magnified view of the dashed region in **a**, including a cross-sectional view of the cut along the dashed line. A vacuum Rabi splitting of 70 MHz is observed. Because the qubit phase relaxation time is $T_2^{echo} \approx 0.25\ \mu s$, we are operating in the strong-coupling regime.

Coupling strength

- Estimation of number of NV centres
  - The coupling is measured to be $g_{\text{ens}} \sim \sqrt{2N} g_i \sim 70\,\text{MHz}$
  - A single NV centre gives a coupling $g_i = 2 g_e \mu_B B$
  - N can be estimated: $N = g_{\text{ens}}^2 / 2g^2 \approx 3.2 \times 10^7$
- In comparison, from photoluminescence spectra, $N \sim 3.1 \times 10^7$



- Strong coupling
  - $g_{\text{ens}} / \gamma_{\text{flux-qubit}},\ g_{\text{ens}} / \gamma_{\text{ensemble}} \gg 1$
  - Cooperativity parameter $C = g_{\text{ens}}^2 / (\gamma_{\text{flux-qubit}} \gamma_{\text{ensemble}}) > 500$

Rabi oscillations

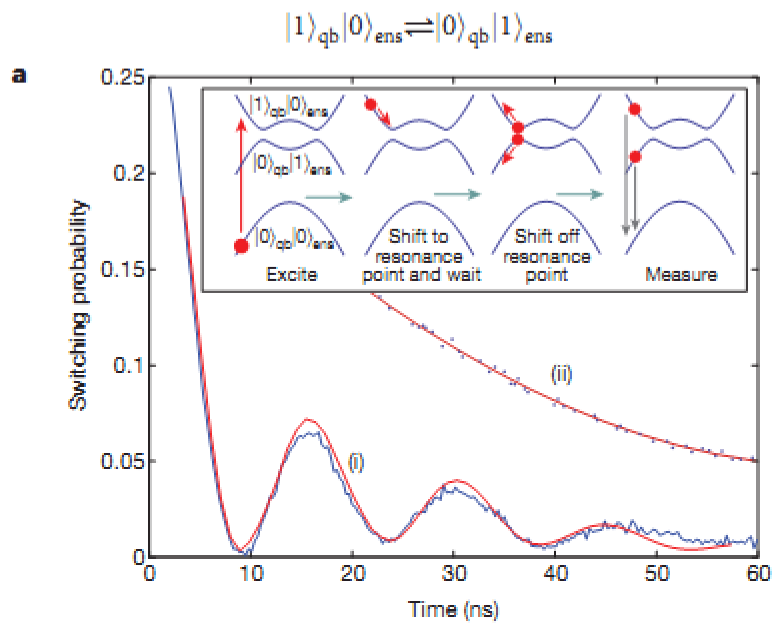
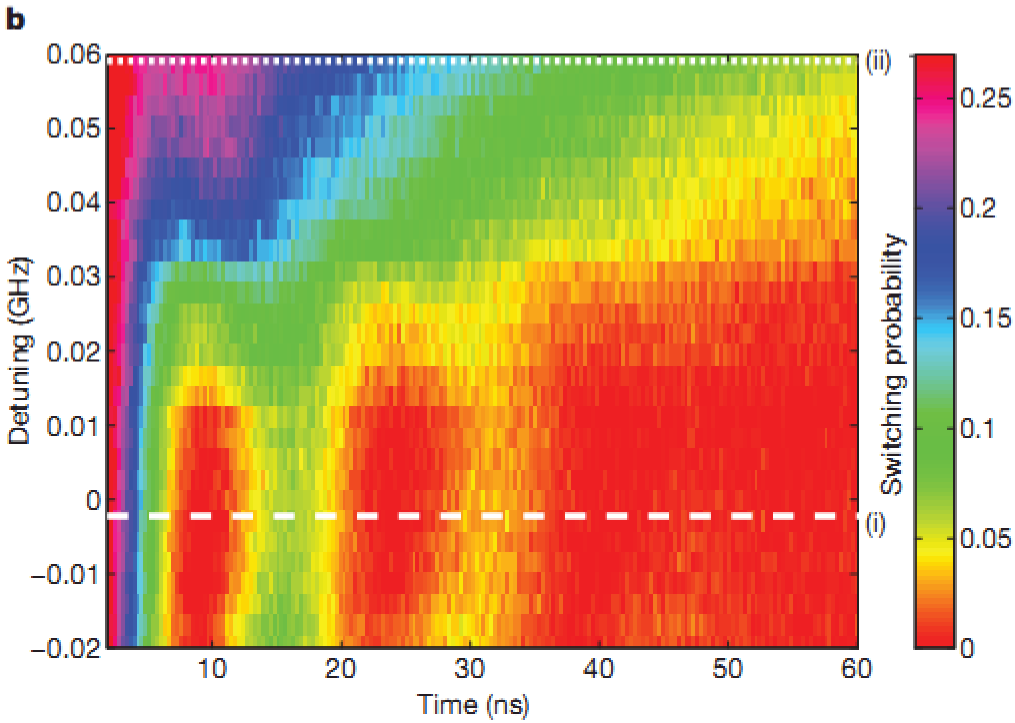


Figure 4 | Vacuum Rabi oscillations of the flux qubit/NV$^-$ ensemble coupled system. a, Line (i): damped oscillation (blue) of an initially excited flux qubit resonantly coupled to a NV$^-$ ensemble. The red line shows the results of a numerical model (Supplementary Information, section III). Line (ii): the same sequence as in line (i), but with 60-MHz detuning from resonance. Inset, measurement sequence. **b,** Two-dimensional plot of the SQUID detector



measurement sequence. **b**, Two-dimensional plot of the SQUID detector switching probability as a function of both time and the detuning by flux bias shift. The white dashed and dotted lines correspond to the switching probabilities shown in **a** (as indicated).

Source of decoherence

- Decay of the oscillation: ~20ns
  - Less than either the flux qubit $T_{1,\mathrm{qb}} \approx 150\,\mathrm{ns}$
  - or NV$^-$ centre $T_{1,\mathrm{NV}} \gg 10\,\mu\mathrm{s}$
- Possible dephasing mechanisms:
  - A large e$^-$ spin-half bath by P1 centres: coupling of P1 and NV$^-$ leads to dephasing
    - Solution 1: use magnetic field to lift the degeneracy of $m_S = \pm 1$
    - Solution 2: reduce P1 centres using differently synthesized diamond
  - Strong hyperfine interaction between NV$^-$ and C^{13}
    - Solution: polarize the nuclear spin

Summary and outlook

- A hybrid device incorporates both NV centres and superconducting flux qubit
- Strong coupling is demonstrated
- Unknown source of dephasing which may be improved by a few measures
- First step towards long-lived quantum memory in condensed-matter systems
- Provides a way to interface between optical and microwave domains