Searching for exotic spin dependent interactions by solid-state-spin quantum sensors

Xing Rong & Jiangfeng Du

Univ of Sci & Tech of China (USTC)

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中国科学技术大学
University of Science and Technology of China

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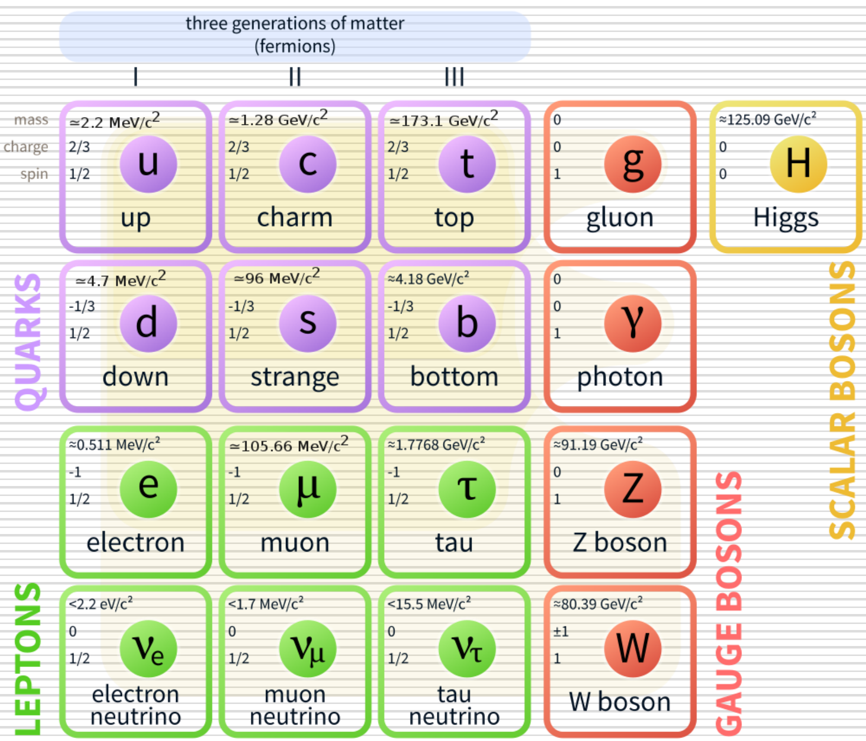
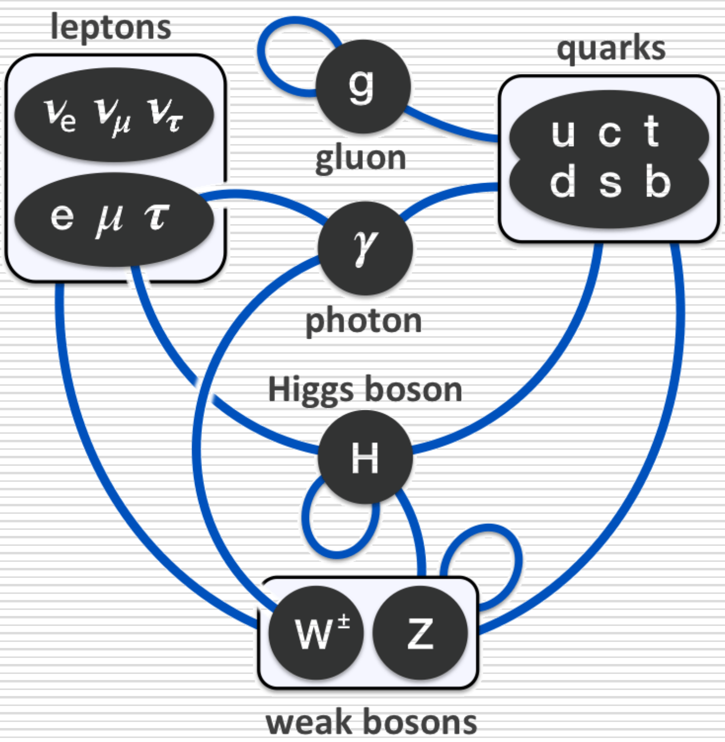
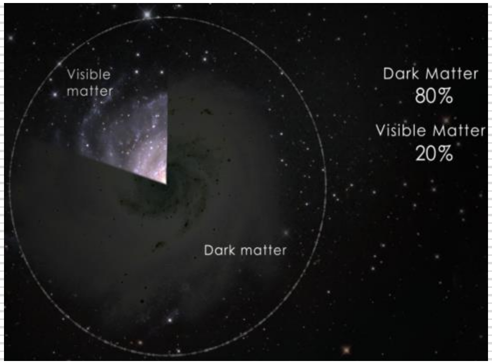
Standard model

Standard Model of Elementary Particles

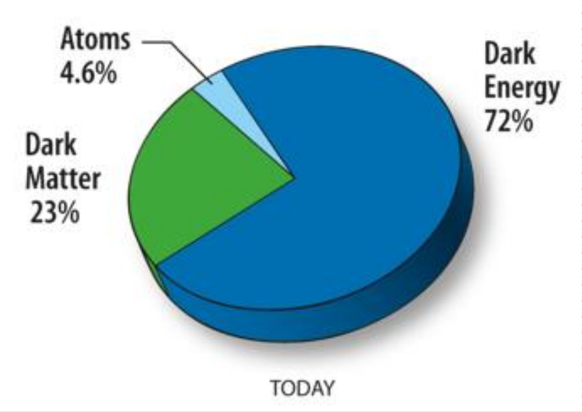


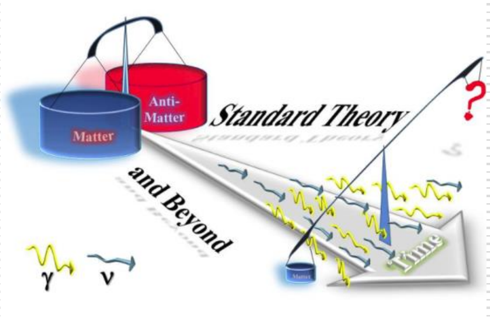


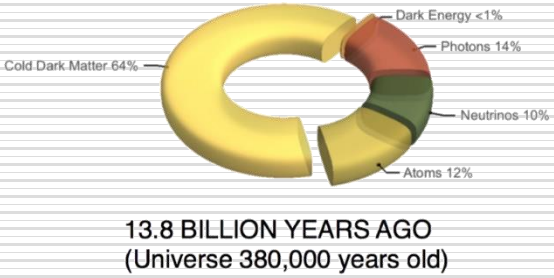
Phenomena can not be explained by SM



Dark matter







Matter–antimatter asymmetry

Dark energy

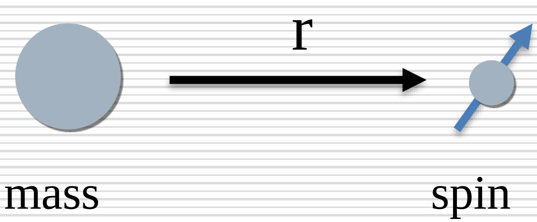
Frank Wilczek

New macroscopic forces?

J. E. Moody* and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 17 January 1984)

Spin can be used to explore interactions mediated by axions.

Axion and axion like particles, which are important candidates of dark matter, can mediate exotic spin dependent interactions

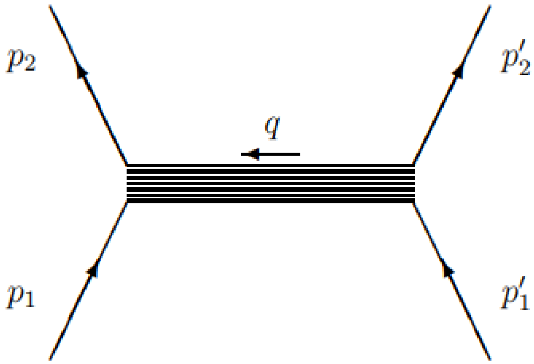


$$\mathbf{B}_{\rm sp}(\mathbf{r}) = \frac{\hbar g_s^{\rm N} g_p^{\rm e}}{4\pi m\gamma}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}\mathbf{e}_r,$$

Effective magnetic field   Mass-spin interactions

Phys. Rev. D 30, 130 (1984)

Spin-dependent macroscopic forces from new particle exchange



Bogdan A. Dobrescu

Theoretical Physics Department, Fermilab
Batavia, IL 60510, U.S.A.
E-mail: bdob@fnal.gov

Irina Mocioiu

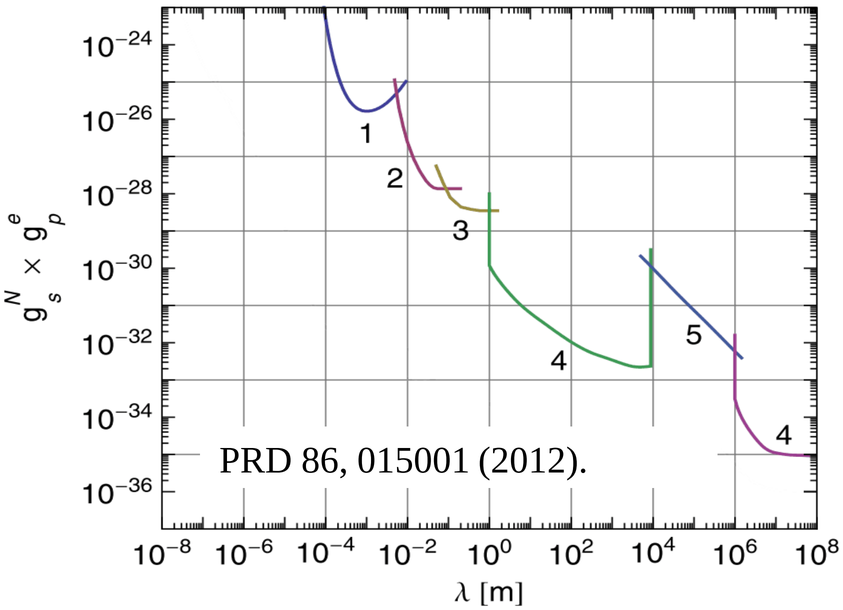
Pennsylvania State University, University Pa
PA 16802, U.S.A.
E-mail: irina@phys.psu.edu

$$
\begin{aligned}
\mathcal{V}_1 &= \frac{1}{r}\, y(r) \ , \\
\mathcal{V}_2 &= \frac{1}{r}\, \vec{\sigma}\cdot\vec{\sigma}^{\,\prime}\, y(r) \ , \\
\mathcal{V}_3 &= \frac{1}{m^2 r^3}\left[\vec{\sigma}\cdot\vec{\sigma}^{\,\prime}\left(1 - r\frac{d}{dr}\right) - 3\left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left(\vec{\sigma}^{\,\prime}\cdot\hat{\vec{r}}\right)\left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right)\right] y(r) \ , \\
\mathcal{V}_{4,5} &= -\frac{1}{2m\, r^2}\left(\vec{\sigma}\pm\vec{\sigma}^{\,\prime}\right)\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\left(1 - r\frac{d}{dr}\right) y(r) \ , \\
\mathcal{V}_{6,7} &= -\frac{1}{2m\, r^2}\left[\left(\vec{\sigma}\cdot\vec{v}\right)\left(\vec{\sigma}^{\,\prime}\cdot\hat{\vec{r}}\right) \pm \left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left(\vec{\sigma}^{\,\prime}\cdot\vec{v}\right)\right]\left(1 - r\frac{d}{dr}\right) y(r) \ , \\
\mathcal{V}_8 &= \frac{1}{r}\left(\vec{\sigma}\cdot\vec{v}\right)\left(\vec{\sigma}^{\,\prime}\cdot\vec{v}\right) y(r) \ , \qquad (3.6) \\
\mathcal{V}_{9,10} &= -\frac{1}{2m\, r^2}\left(\vec{\sigma}\pm\vec{\sigma}^{\,\prime}\right)\cdot\hat{\vec{r}}\left(1 - r\frac{d}{dr}\right) y(r) \ , \\
\mathcal{V}_{11} &= -\frac{1}{m\, r^2}\left(\vec{\sigma}\times\vec{\sigma}^{\,\prime}\right)\cdot\hat{\vec{r}}\left(1 - r\frac{d}{dr}\right) y(r) \ , \\
\mathcal{V}_{12,13} &= \frac{1}{2r}\left(\vec{\sigma}\pm\vec{\sigma}^{\,\prime}\right)\cdot\vec{v}\, y(r) \ , \\
\mathcal{V}_{14} &= \frac{1}{r}\left(\vec{\sigma}\times\vec{\sigma}^{\,\prime}\right)\cdot\vec{v}\, y(r) \ , \\
\mathcal{V}_{15} &= -\frac{3}{2m^2 r^3}\left\{\left[\vec{\sigma}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\left(\vec{\sigma}^{\,\prime}\cdot\hat{\vec{r}}\right) + \left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left[\vec{\sigma}^{\,\prime}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\right\} \\
&\quad \times\left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right) y(r) \ , \\
\mathcal{V}_{16} &= -\frac{1}{2m\, r^2}\left\{\left[\vec{\sigma}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\left(\vec{\sigma}^{\,\prime}\cdot\vec{v}\right) + \left(\vec{\sigma}\cdot\vec{v}\right)\left[\vec{\sigma}^{\,\prime}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\right\}\left(1 - r\frac{d}{dr}\right) y(r) \ .
\end{aligned}
$$

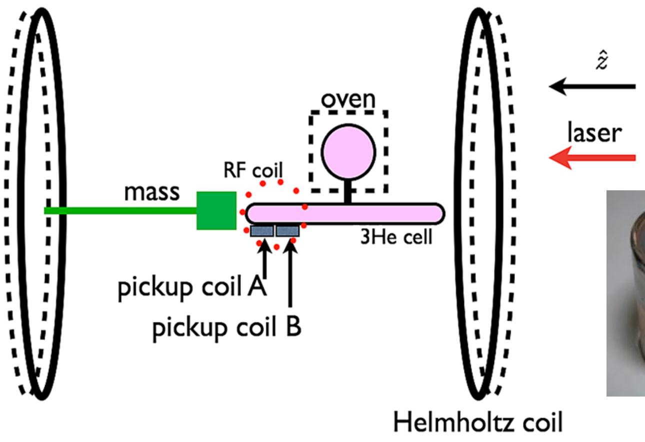
(3.8)

B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11, 005(2006).

Experimental searches for exotic spin-dependent interactions



Constraints set by atomic magnetometer, SQUID, and torsion balance.

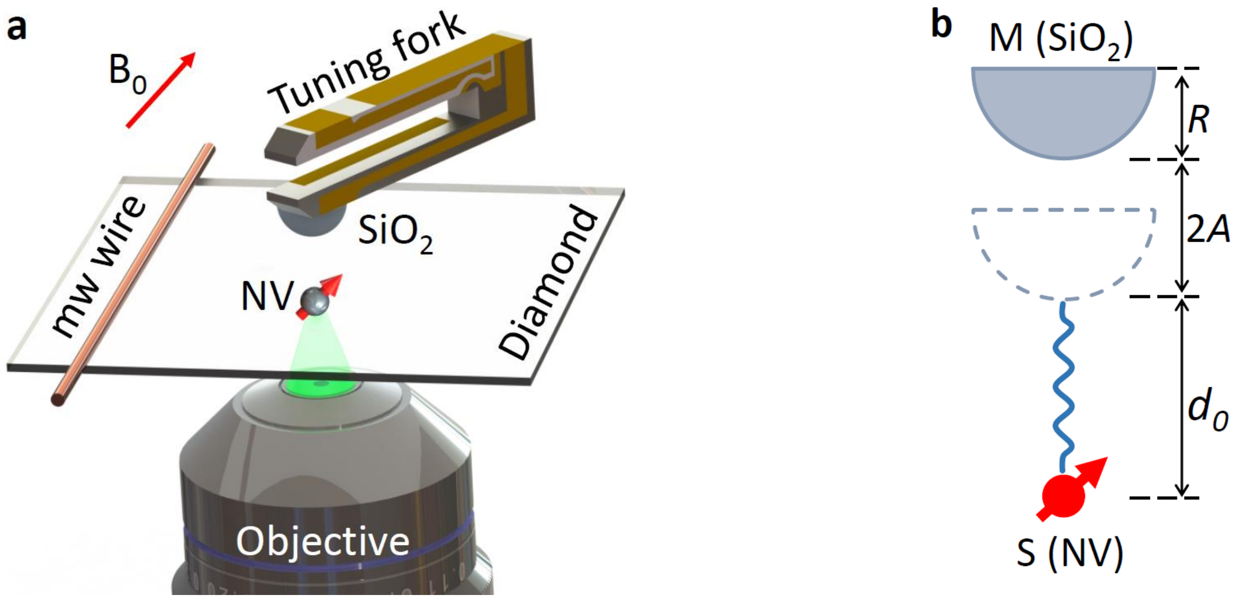


Thickness of vapor cell > 0.2 mm

Force range is limited by the size of the sensor of magnetometer.

How to search for exotic interactions with shorter force range?

Using single electron spin quantum sensors to searching for exotic spin interactions



advantages

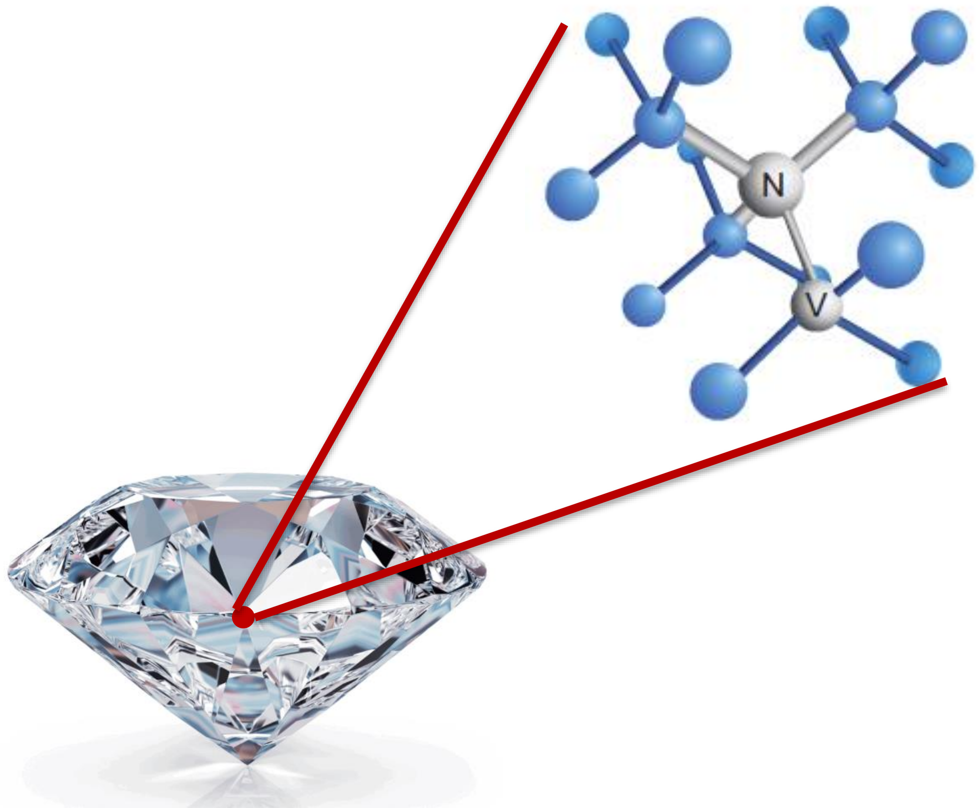
- ✓ Atomic scale
- ✓ Near surface

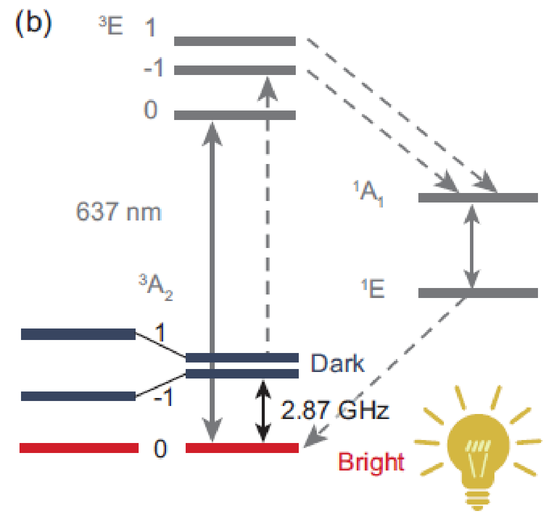
→ Shorter force range

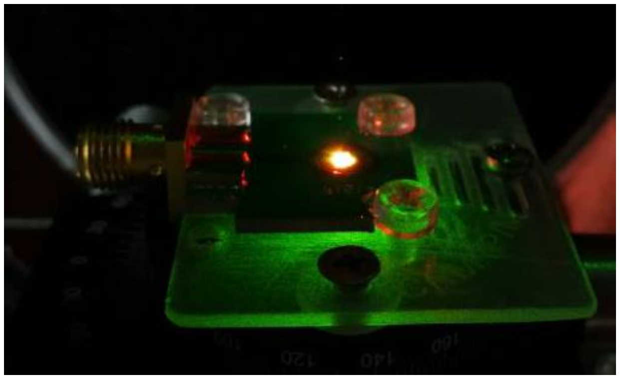
- ✓ Precise quantum control → Good sensitivity
- ✓ NV + AFM → Cancel unwanted signals

Xing Rong et al., Nature Communications 9, 739 (2018)

Single electron spin quantum sensors
NV- centers in diamond

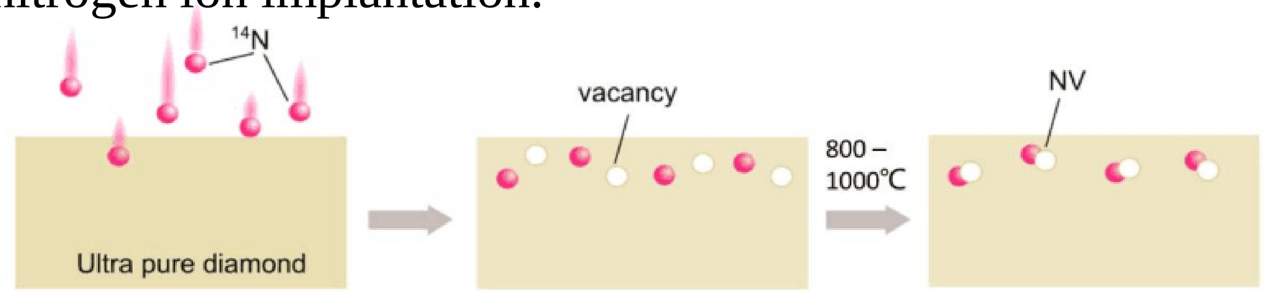




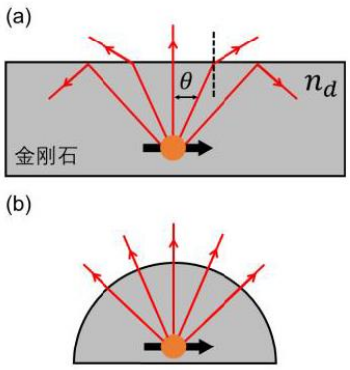


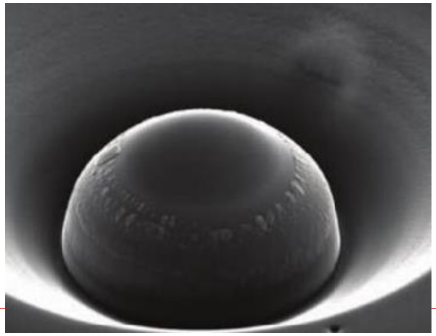
Preparing NV center quantum sensors

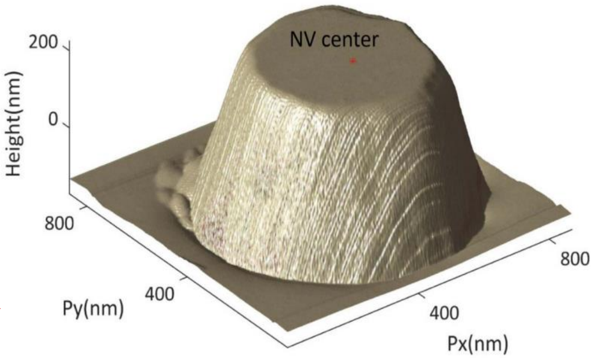
Near surface NV center (about 5-10 nm) were prepared by low energy (5 keV) nitrogen ion implantation.



Using ion beam etching to form micro-lens and other structures, so as to realize high-efficiency fluorescence collection ability





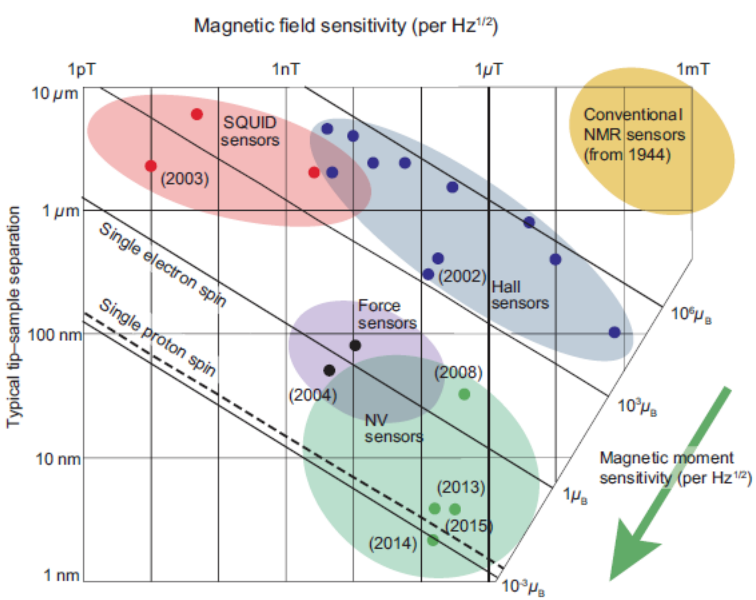


Single electron spin quantum sensors

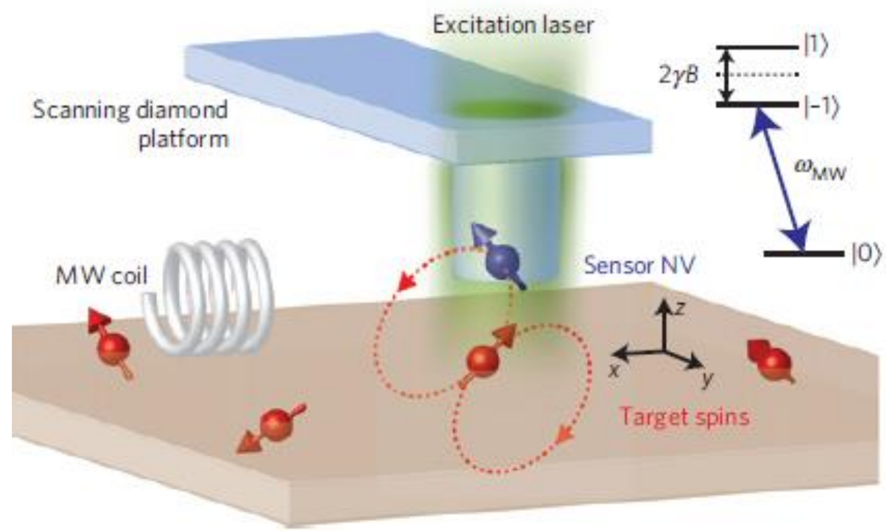
$$H = D \cdot S_Z^2 + E \cdot (S_x^2 - S_y^2) - \gamma_e B \cdot S + S \cdot \sum_i A_i \cdot I_i$$

- Temperature
- Electric-field stress detection
- Magnetic field
- Spin-coupling Spin-sensing

Diamond nanoscale magnetometry



Nat. Nanotechnol. **3**, 643(2008)

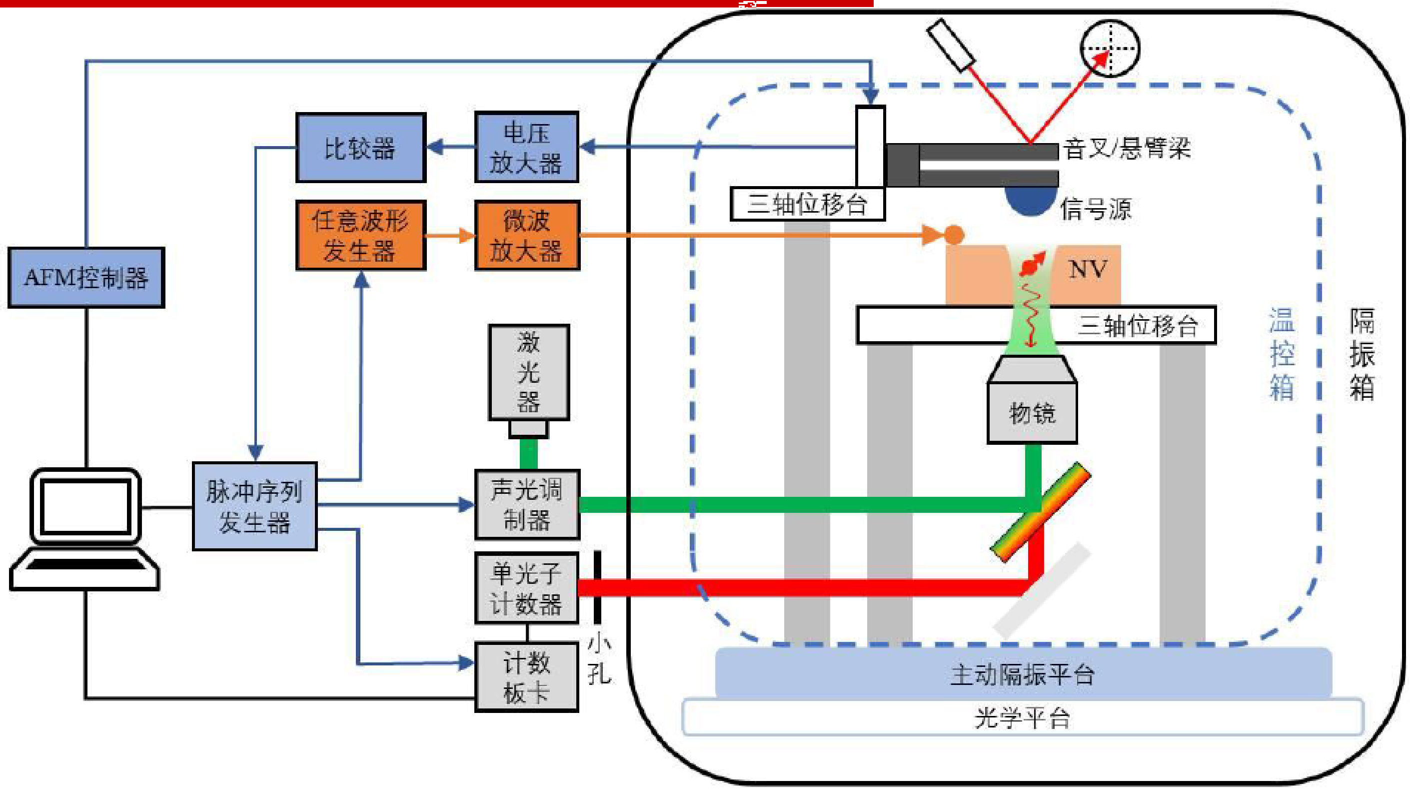


Nat. Phys. 9, 215 (2013)

Searching for exotic spin dependent interaction with single electron spin quantum sensors

Spin-mass Interactions	**Static spin-spin interactions**	**Velocity-dependent spin-spin interactions**
$V_{9+10} = f_{9+10}\frac{\hbar^2}{8\pi m_1}(\hat{\sigma}_1 \cdot \hat{r})\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$ $V_{4+5} = -f_{4+5}\frac{\hbar^2}{8\pi m_1 c}[\hat{\sigma}_1 \cdot (\vec{v}\times\hat{r})] \times \left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$ $V_{12+13} = f_{12+13}\frac{\hbar}{8\pi}(\hat{\sigma}_i \cdot \vec{v})\left(\frac{1}{r}\right)e^{-r/\lambda}$ Unpolarized nucleon source	$V_2 = f_2\frac{\hbar c}{4\pi}(\hat{\sigma}_1 \cdot \hat{\sigma}_2)\left(\frac{1}{r}\right)e^{-r/\lambda}$ $V_3 = f_3\frac{\hbar^3}{4\pi m_1 m_2 c}\left[(\hat{\sigma}_1 \cdot \hat{\sigma}_2)\left(\frac{1}{\lambda r^2}+\frac{1}{r^3}\right) - (\hat{\sigma}_1 \cdot \hat{r})(\hat{\sigma}_2 \cdot \hat{r})\left(\frac{1}{\lambda^2 r}+\frac{3}{\lambda r^2}+\frac{3}{r^3}\right)\right]e^{-r/\lambda}$ $V_{11} = -f_{11}\frac{\hbar^2}{4\pi m_\mu}[(\hat{\sigma}_1 \times \hat{\sigma}_2)\cdot\hat{r}]\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$ Polarized spin source	$V_{6+7} = -f_{6+7}\frac{\hbar^2}{4\pi m_\mu c} \times [(\hat{\sigma}_1 \cdot \vec{v})(\hat{\sigma}_2 \cdot \hat{r})]\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$ $V_8 = f_8\frac{\hbar}{4\pi c}(\hat{\sigma}_1 \cdot \vec{v})(\hat{\sigma}_2 \cdot \vec{v})\left(\frac{1}{r}\right)e^{-r/\lambda}$ $V_{14} = f_{14}\frac{\hbar}{4\pi}[(\hat{\sigma}_1 \times \hat{\sigma}_2)\cdot\vec{v}]\left(\frac{1}{r}\right)e^{-r/\lambda}$ $V_{15} = -f_{15}\frac{\hbar^3}{8\pi m_1 m_2 c^2} \times \{[\hat{\sigma}_1 \cdot (\vec{v}\times\hat{r})](\hat{\sigma}_2 \cdot \hat{r}) + (\hat{\sigma}_1 \cdot \hat{r})[\hat{\sigma}_2 \cdot (\vec{v}\times\hat{r})]\} \times \left(\frac{1}{\lambda^2 r}+\frac{3}{\lambda r^2}+\frac{3}{r^3}\right)e^{-r/\lambda}$ $V_{16} = -f_{16}\frac{\hbar^2}{8\pi m_\mu c^2} \times \{[\hat{\sigma}_1 \cdot (\vec{v}\times\hat{r})](\hat{\sigma}_2 \cdot \vec{v}) + (\hat{\sigma}_1 \cdot \vec{v})[\hat{\sigma}_2 \cdot (\vec{v}\times\hat{r})]\} \times \left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$ Polarized spin source and distance modulation

NV-AFM platform

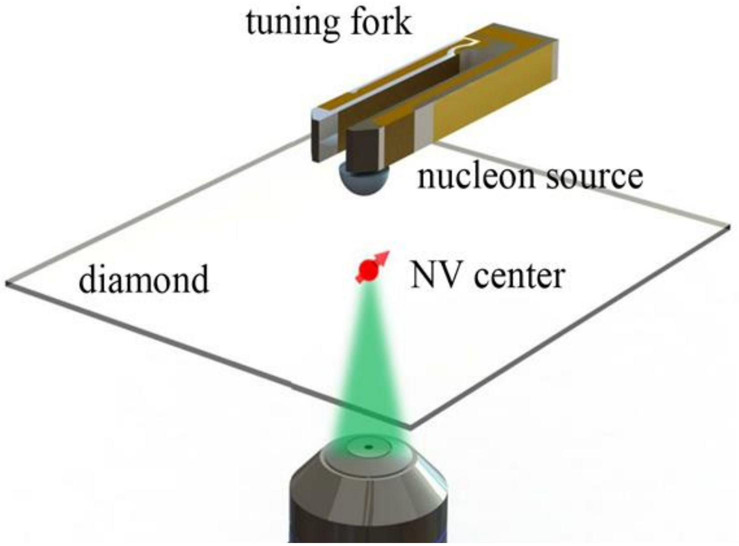


A series of signal sources such as silica, pentacene molecule, dysprosium iron garnet (DYIG) can be loaded on the cantilever beam of AFM.

Experimental results

solid-state-spin quantum sensors to search for physics beyond the standard model

- Single electron spin quantum sensors
  1. Nat. Commun. 9, 739 (2018)
  2. PRL 121, 080402 (2018)
  3. PRL 127, 010501 (2021)
- Ensemble quantum sensor
  1. arXiv: 2201.04408 (2022)



1. Spin-mass interaction

$$\mathcal{V}_{9,10} = -\frac{1}{2m\,r^2}\,(\vec{\sigma} \pm \vec{\sigma}\,') \cdot \hat{\vec{r}} \left(1 - r\frac{d}{dr}\right) y(r) \ ,$$

Xing Rong et al., Nature Communications, 9:739 (2018)

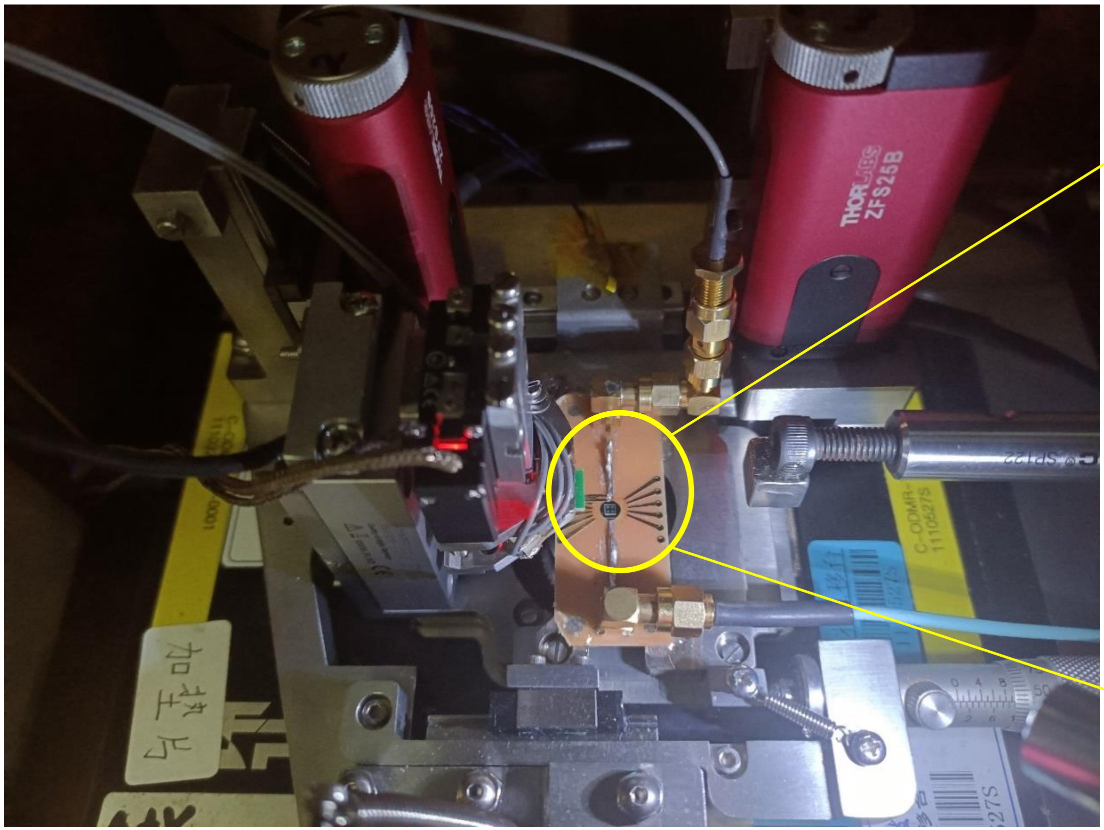
ARTICLE

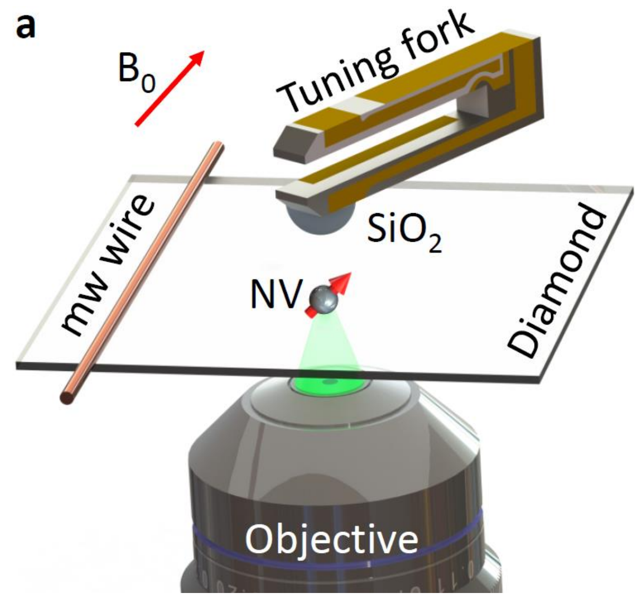
DOI: 10.1038/s41467-018-03152-9 OPEN

Searching for an exotic spin-dependent interaction with a single electron-spin quantum sensor

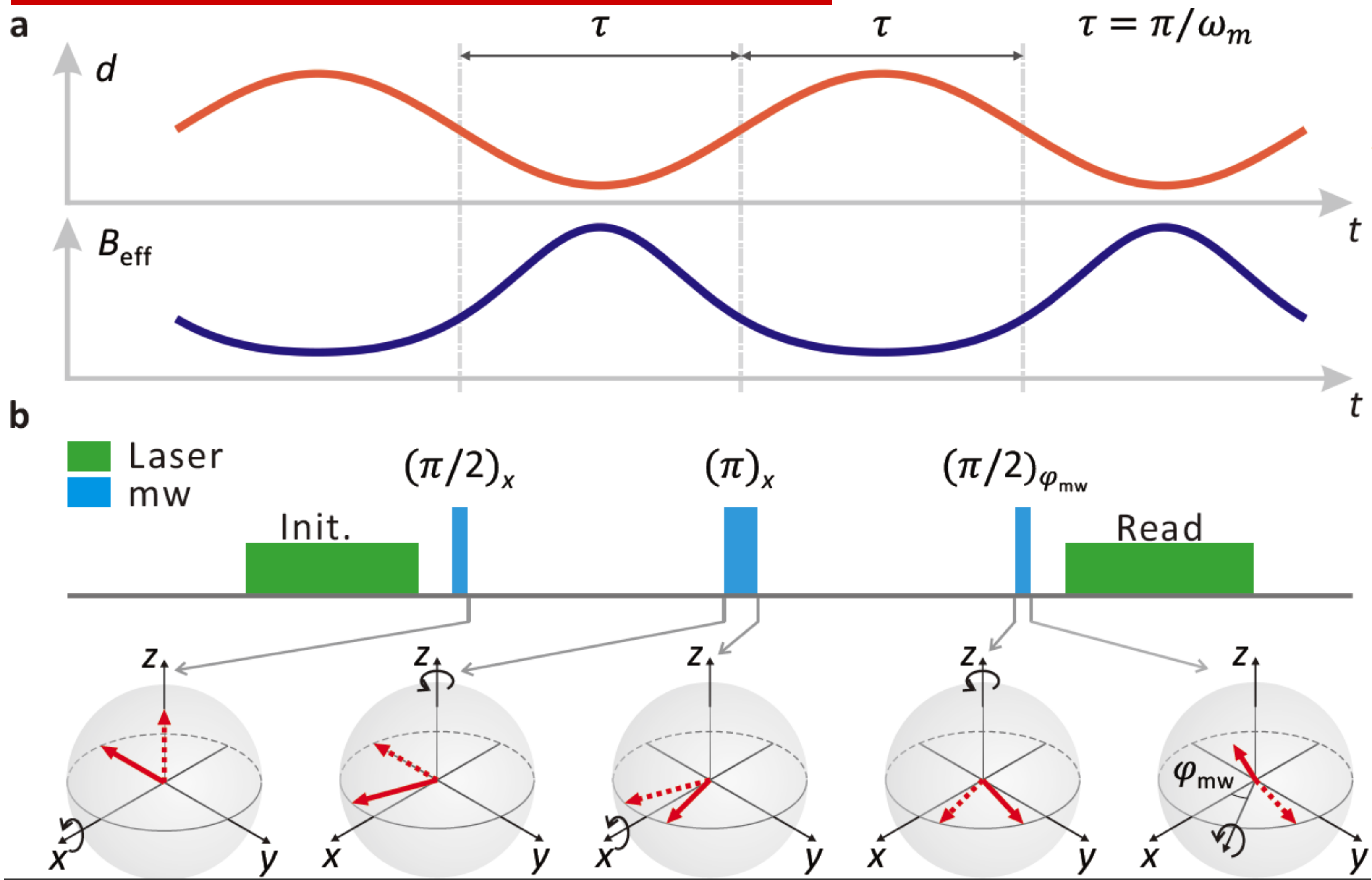
Xing Rong[1,2,3], Mengqi Wang[1,2,3], Jianpei Geng[1,2], Xi Qin[1,2,3], Maosen Guo[1,3], Man Jiao[1,3], Yijin Xie[1,3], Pengfei Wang[1,2,3], Pu Huang[1,2,3], Fazhan Shi[1,2,3], Yi-Fu Cai[4,5], Chongwen Zou[6] & Jiangfeng Du[1,2,3]

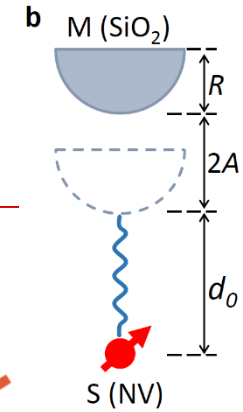
Experimental setup



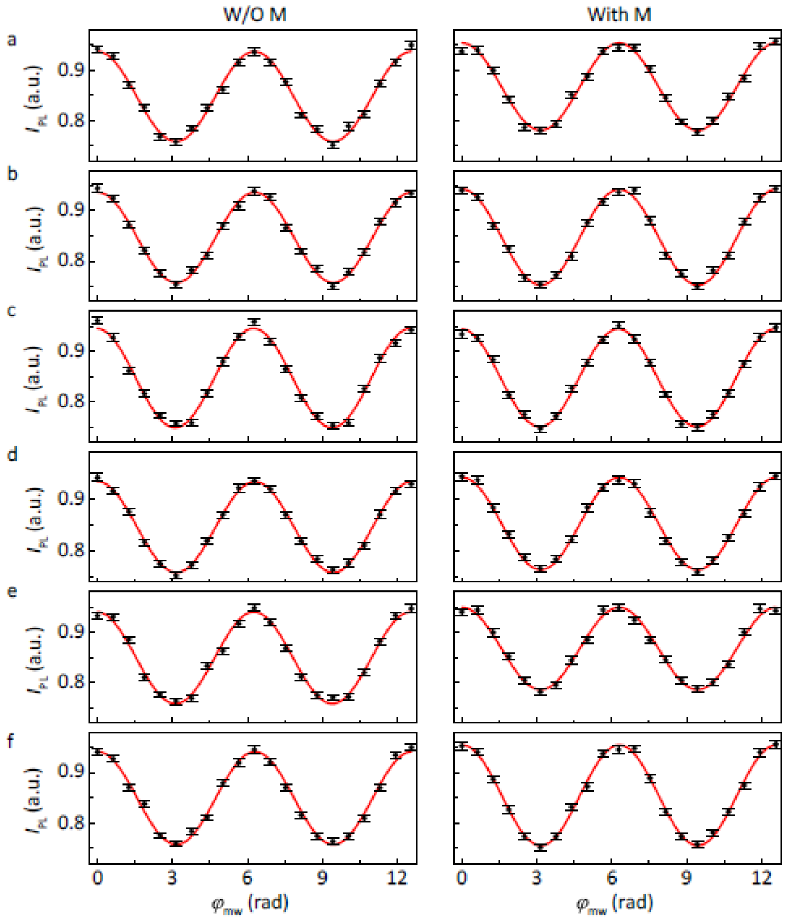


Experimental sequence

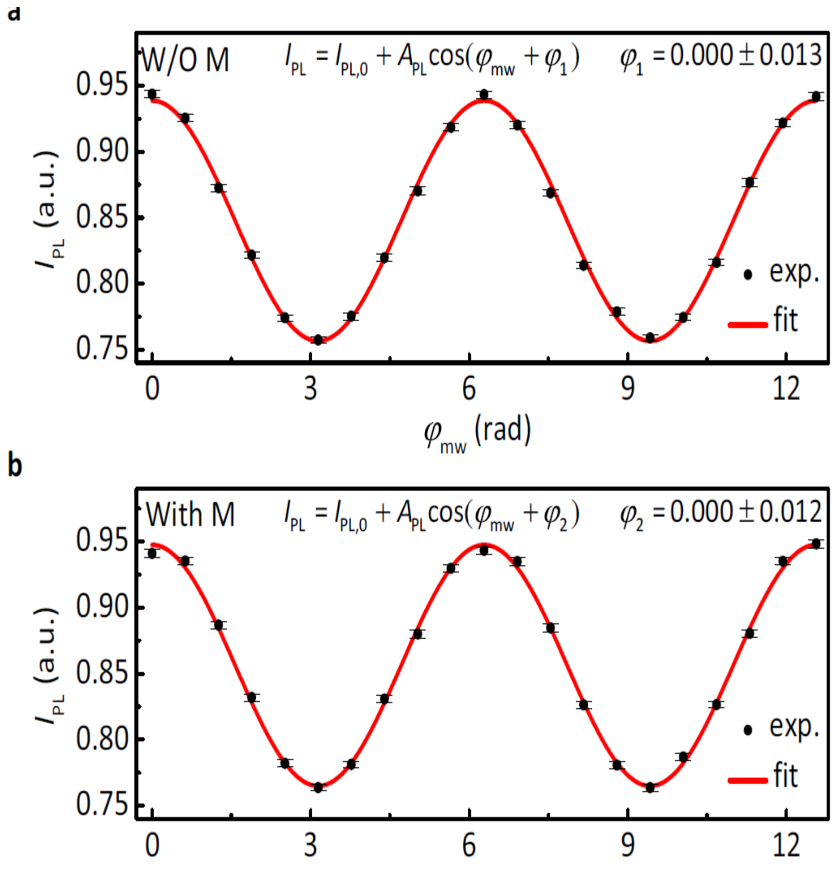




Experimental result



Six separated runs

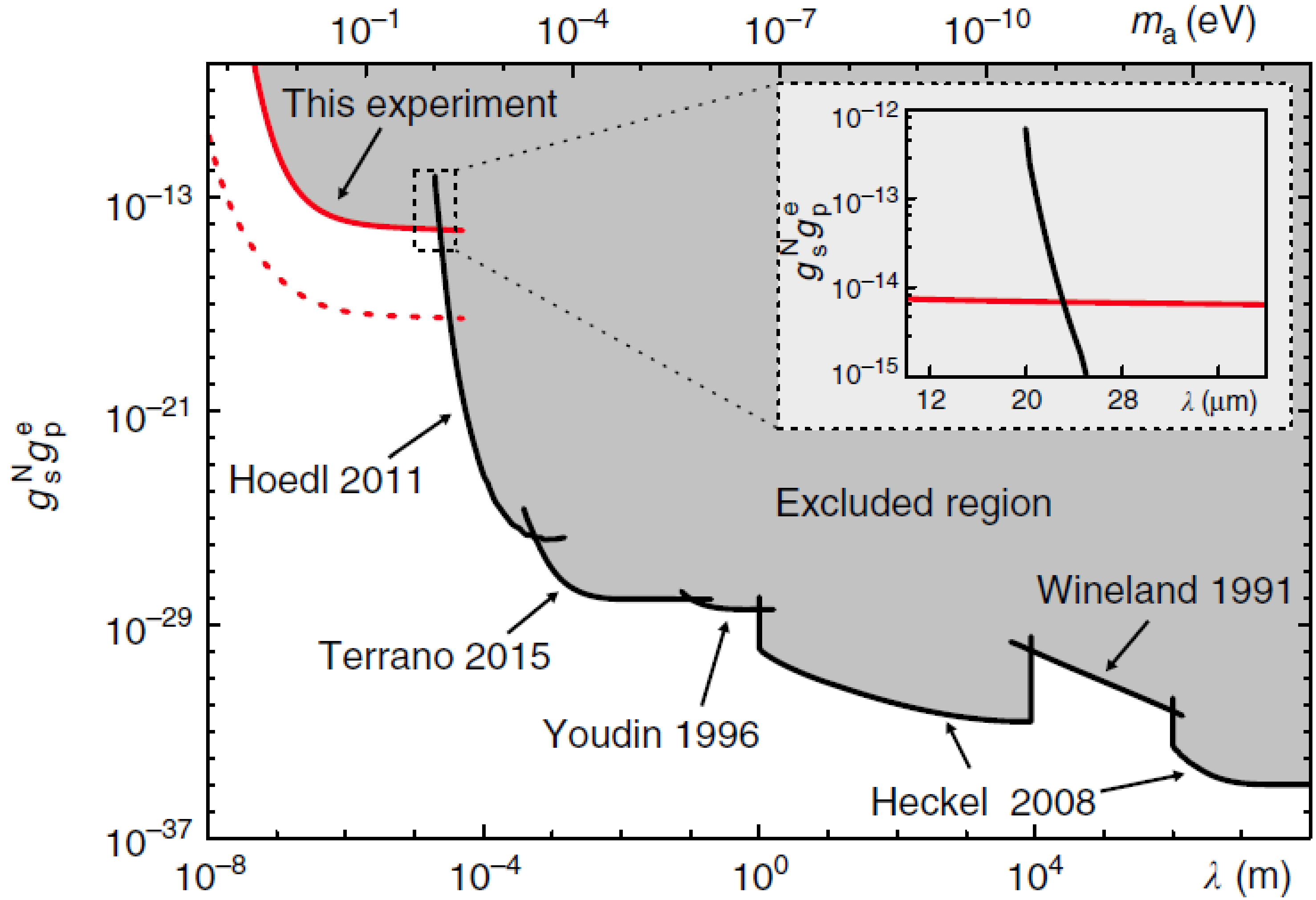


statistical errors： ～ 0.02 rad

Table 1: Systematic error summary.

Systematic error	Size of effect	Correction to $g_s^N g_p^e$ for $20\ \mu$m
diamagnetism of M	-11.28×10^{-6}	$(5 \pm 5) \times 10^{-20}$
diamagnetism of the tuning fork	-11.28×10^{-6}	$(3.8 \pm 0.3) \times 10^{-20}$
phase jitter of microwave	1.3 ps	$(0.0 \pm 1.7) \times 10^{-27}$
T_2^* dephasing	670 ± 41 ns	$(0.0 \pm 1.9) \times 10^{-27}$
shortest distance between M and S	$0.5 \pm 0.1\ \mu$m	$(0.1 \pm 3.0) \times 10^{-17}$
the amplitude of the modulation of M	41.1 ± 0.1 nm	$(0.0 \pm 1.3) \times 10^{-17}$
the radius of M	$250 \pm 2.5\ \mu$m	$(0.1 \pm 3.7) \times 10^{-18}$
the angle between $\mathbf{B}_{\text{eff}}$ and NV axis	$54.7 \pm 3°$	$(0.4 \pm 4.2) \times 10^{-16}$

Constraints by our experiment



2. Exotic dipole-dipole interaction

$$\mathcal{V}_2 = \frac{1}{r}\,\vec{\sigma}\cdot\vec{\sigma}\,'\,y(r)\ \ ,$$

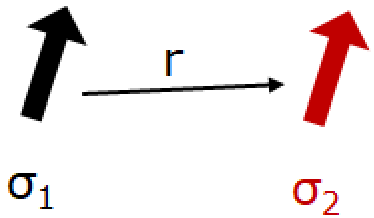
Xing Rong et al., Phys. Rev. Lett. 121, 080402 (2018)

PHYSICAL REVIEW LETTERS **121,** 080402 (2018)

Constraints on a Spin-Dependent Exotic Interaction between Electrons with Single Electron Spin Quantum Sensors

Xing Rong,[1,2,3] Man Jiao,[1,2,3] Jianpei Geng,[1,4] Bo Zhang,[1,2,3,*] Tianyu Xie,[1,2,3] Fazhan Shi,[1,2,3]
Chang-Kui Duan,[1,2,3] Yi-Fu Cai,[5,6] and Jiangfeng Du[1,2,3,†]
[1]*CAS Key Laboratory of Microscale Magnetic Resonance and Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China*

Constraint on exotic interaction between electrons



Magnetic dipole-dipole coupling

$$-\frac{\mu_0\gamma_e\gamma_e\hbar^2}{16\pi r^3}[3(\vec{\sigma_1}\cdot\hat{r})(\vec{\sigma_2}\cdot\hat{r})-(\vec{\sigma_1}\cdot\vec{\sigma_2})],$$

Exotic dipole-dipole coupling [1]

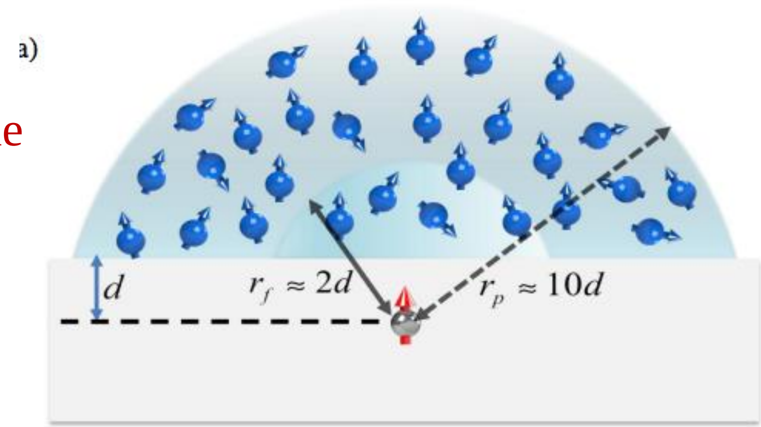
$$\frac{g_A^e g_A^e}{4\pi\hbar c}\frac{\hbar c}{r}(\vec{\sigma_1}\cdot\vec{\sigma_2})e^{-\frac{r}{\lambda}},$$

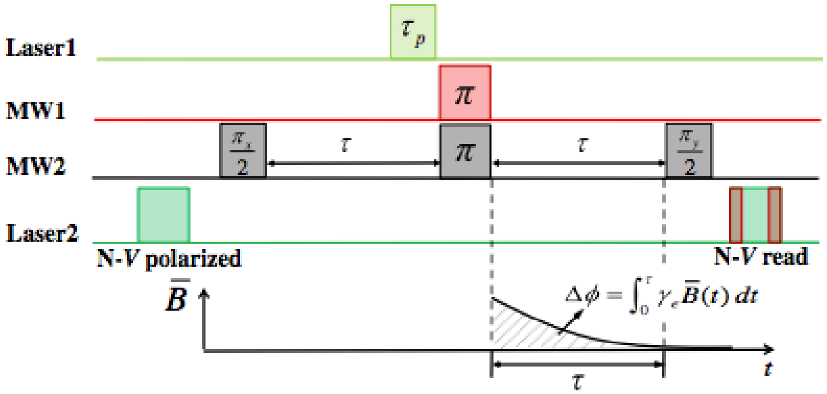
We now experimentally search for this type of exotic dipole-dipole coupling [2].

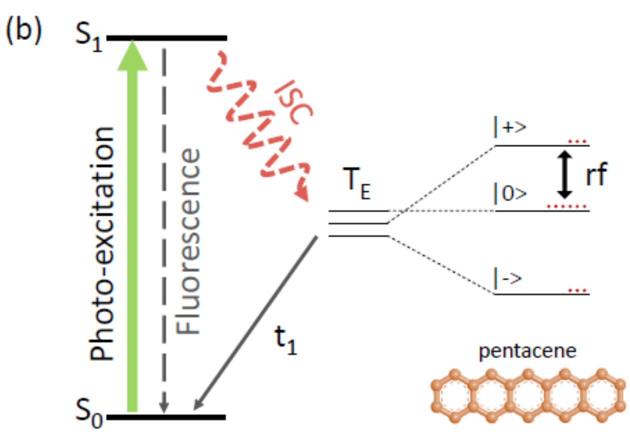
[1] B. A. Dobrescu and I.Mocioiu, J. High Energy Phys. 11, 005 (2006)
[2] Xing Rong et al., Phys. Rev. Lett. 121, 080402 (2018)

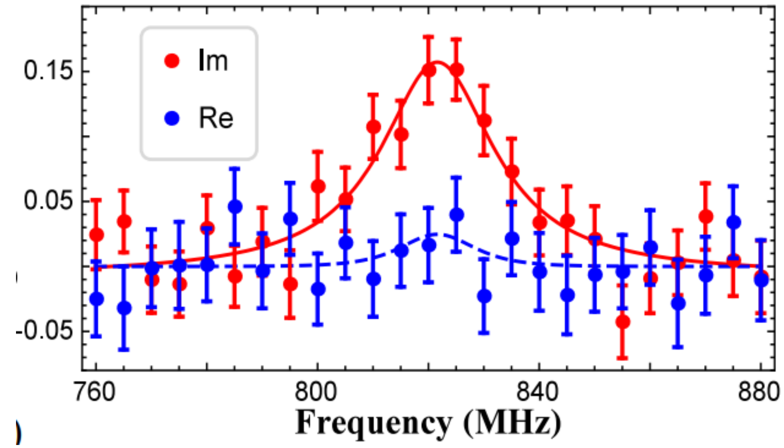
Experiment technique and setup

pentacene





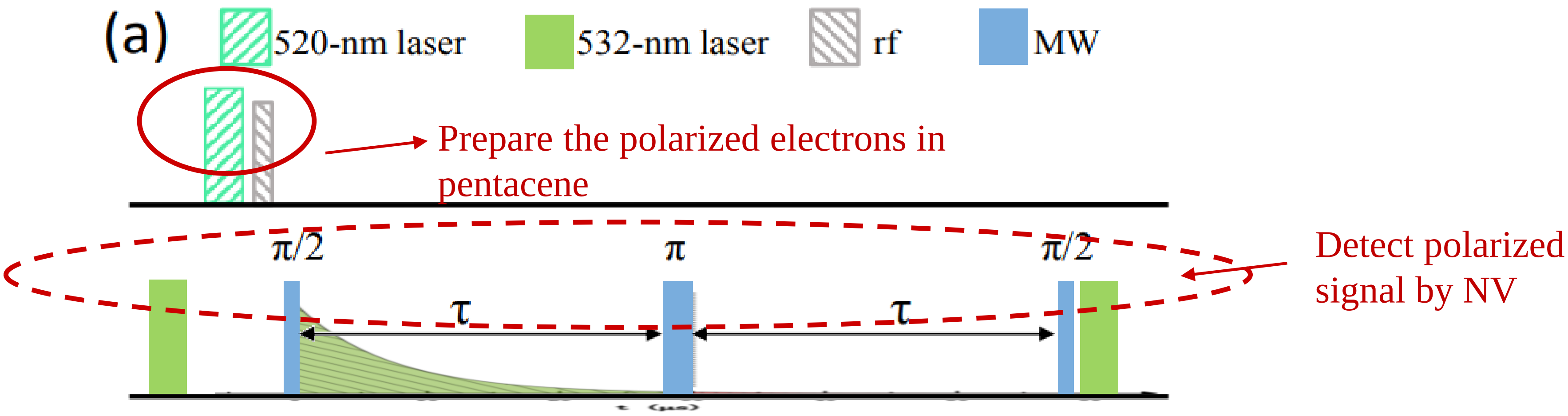


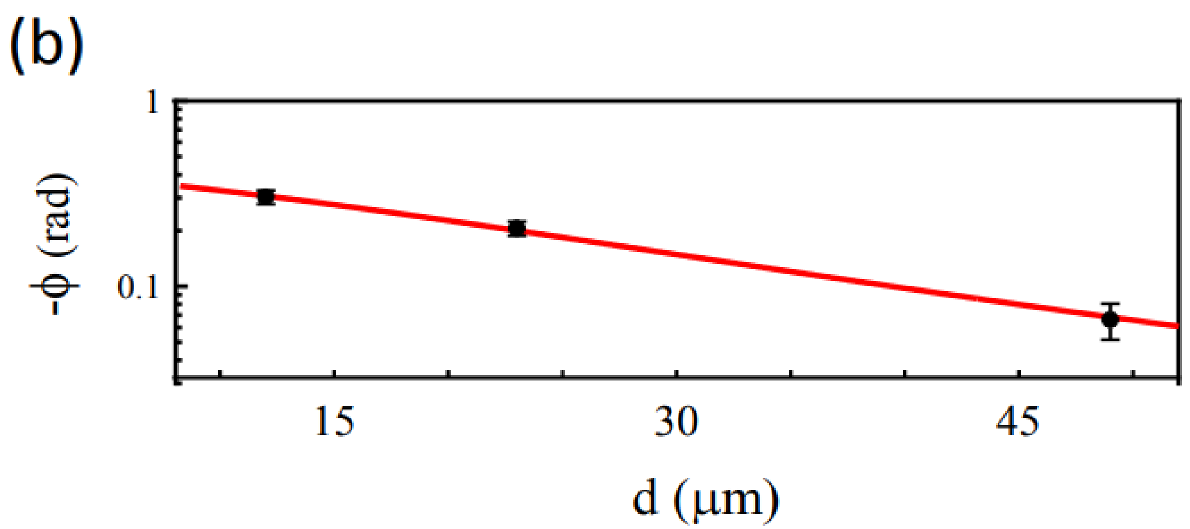


The measured polarized signal

T. Xie et al., Phys. Rev. Applied 9, 064003 (2018).

Experimental pulse sequence for searching exotic interactions





The fitting provides:

$$g_A^e g_A^e / 4\pi\hbar c = (0.04 \pm 2.16) \times 10^{-19}.$$

Xing Rong et al., Phys. Rev. Lett. 121, 080402 (2018)

Analysis of the systematic errors

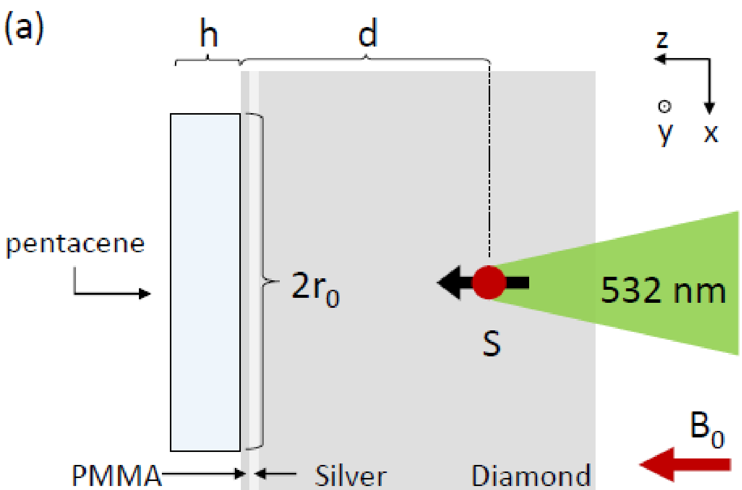
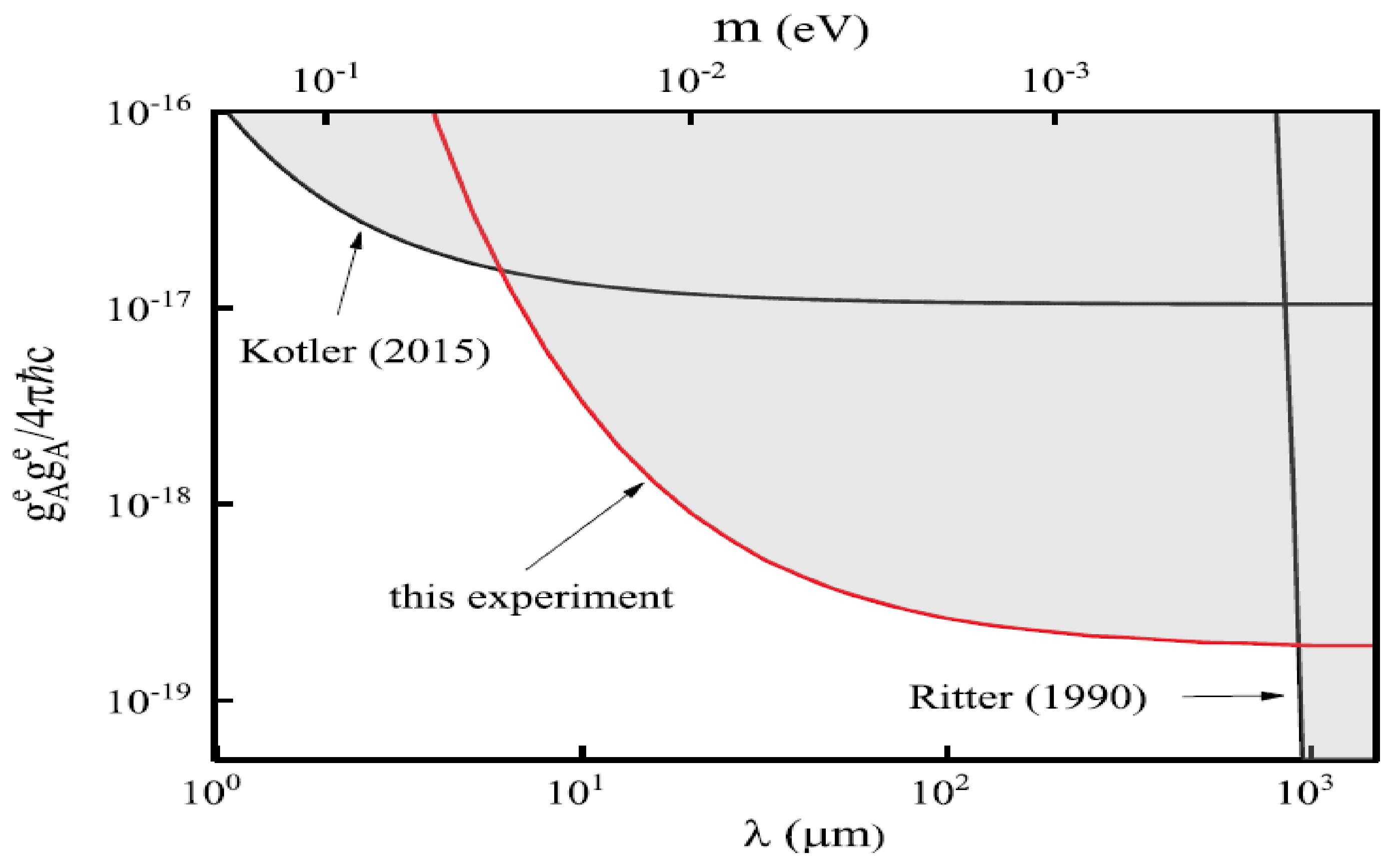


TABLE I. Summary of the systematic errors in our experiment. The corrections to $g_A^e g_A^e / 4\pi\hbar c$ at $\lambda = 500\ \mu$m are listed.

Systematic error	Size of effect	Corrections
Deviation in x-y plane	$0 \pm 10\ \mu$m	$(-0.6 \pm 1.3) \times 10^{-20}$
Distance	$12 \pm 1.3\ \mu$m	$(1 \pm 80) \times 10^{-22}$
Decoherence of S	$405 \pm 23\ \mu$s	$(-55 \pm 6) \times 10^{-22}$
Decay time	$7 \pm 1\ \mu$s	$(-5 \pm 36) \times 10^{-21}$
Radius	$35 \pm 5\ \mu$m	$(-3 \pm 7) \times 10^{-21}$
Thickness	$15 \pm 3\ \mu$m	$(-9 \pm 45) \times 10^{-21}$
Polarization	$4.7 \pm 0.1\%$	$(-1 \pm 52) \times 10^{-22}$
Total		$(-2.9 \pm 6.0) \times 10^{-20}$

Xing Rong et al., Phys. Rev. Lett. 121, 080402 (2018)

Constraint on exotic interaction between electrons



We established upper limits on this type of exotic spin-dependent interaction in the force range 10 to 900 μm.

Xing Rong et al., Phys. Rev. Lett. 121, 080402 (2018)

3. parity-odd spin- and velocity- dependent interaction

$$V = g_A^e g_V^N \frac{\hbar}{4\pi}(\boldsymbol{\sigma} \cdot \boldsymbol{v})(\frac{e^{-\frac{r}{\lambda}}}{r})$$

Dr. Jiao

PHYSICAL REVIEW LETTERS **127,** 010501 (2021)

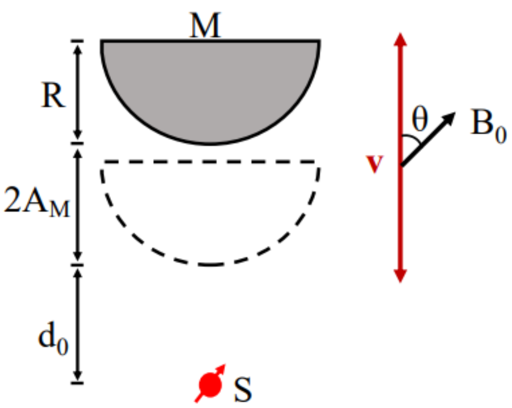
Experimental Constraint on an Exotic Parity-Odd Spin- and Velocity-Dependent Interaction with a Single Electron Spin Quantum Sensor

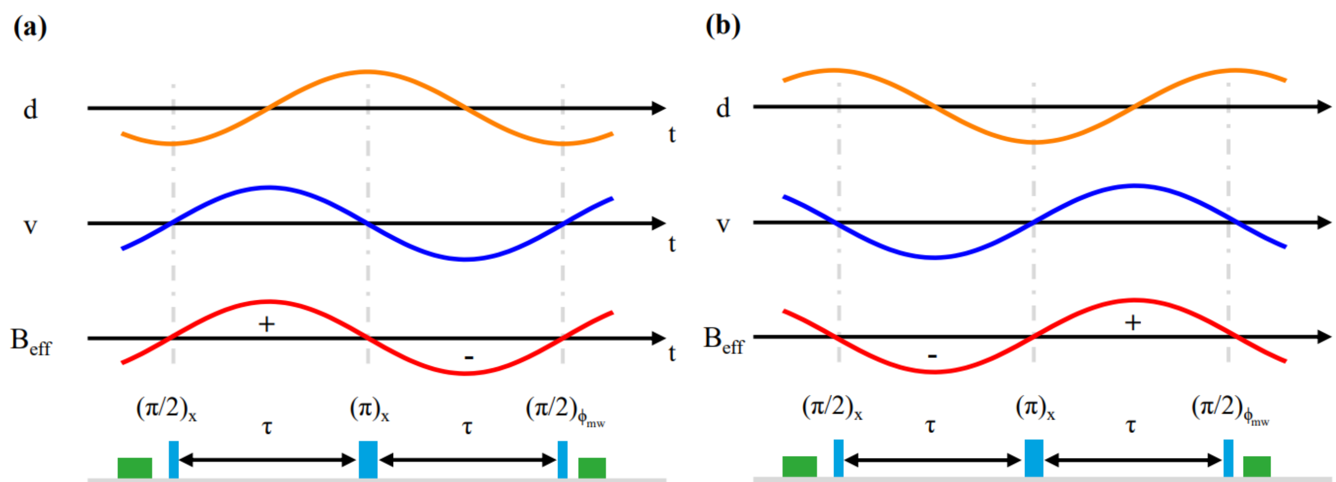
Man Jiao,[1,2,3] Maosen Guo,[1,2,3] Xing Rong,[1,2,3,*] Yi-Fu Cai,[4,5] and Jiangfeng Du[1,2,3,†]
[1]*Hefei National Laboratory for Physical Sciences at the Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China*

Man Jiao, et al., Physical Review Letters 127, 010501 (2021).

Experimental scheme

Pulse sequence is designed to accumulate the possible velocity dependent effect





$$\vec{B}_{\text{eff}} = \frac{g_A^e g_V^N}{2\pi\gamma_e} f(\lambda, R, d)\vec{v},$$

$$P_+ = [1 + \cos(\phi_{\text{mw}} + \phi)]/2 \quad P_- = [1 + \cos(\phi_{\text{mw}} - \phi)]/2$$

Phase factor due to exotic interaction

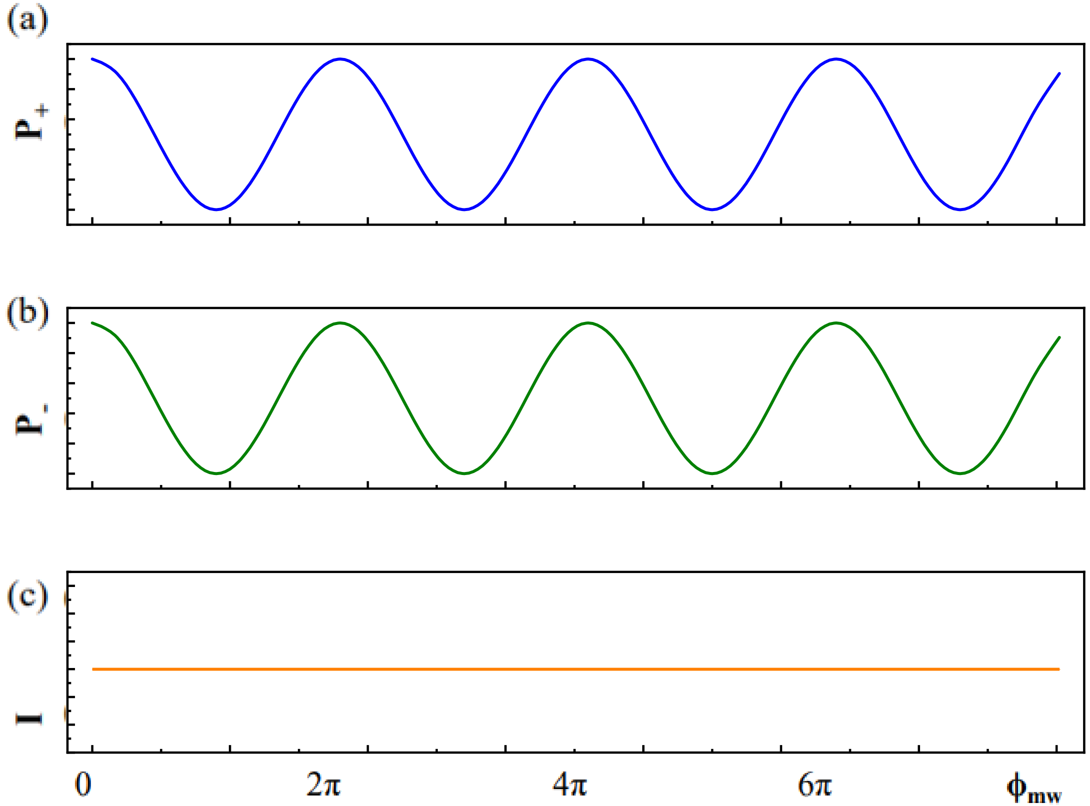
$$\phi = 2\gamma_e \int_0^\tau \mathrm{B}_{\text{eff}}(t) \cos(\theta) dt$$

Man Jiao, et al., Physical Review Letters 127, 010501 (2021).

Experimental scheme

Suppose effective magnetic field is zero

P_+ and P_- is modulated with the phase factor of microwave ϕ_{mw} 。



$$P_+ = [1 + \cos(\phi_{\text{mw}})]/2$$

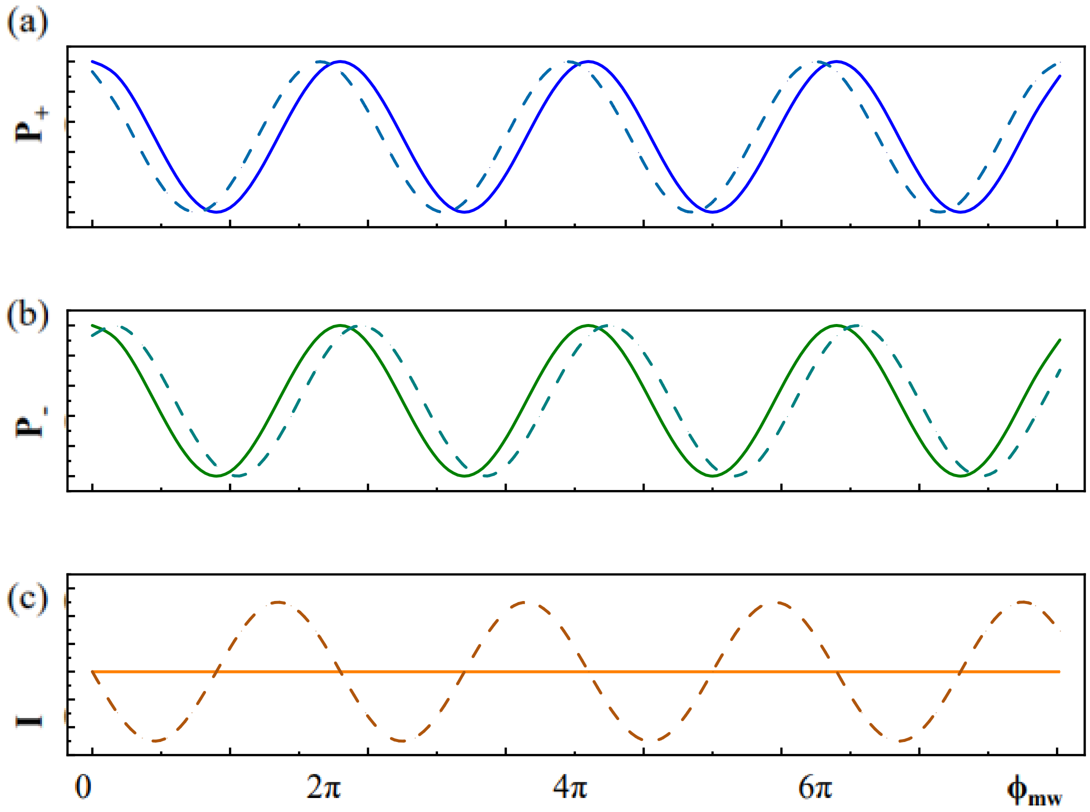
$$P_- = [1 + \cos(\phi_{\text{mw}})]/2$$

$$\text{I} = P_+ - P_- = 0$$

Man Jiao, et al., Physical Review Letters 127, 010501 (2021).

Experimental scheme

Suppose nonzero magnetic field exist,
P_+ P_- will have by additional phase factor



$$P_+ = [1 + \cos(\phi_{\rm mw} + \phi)]/2$$

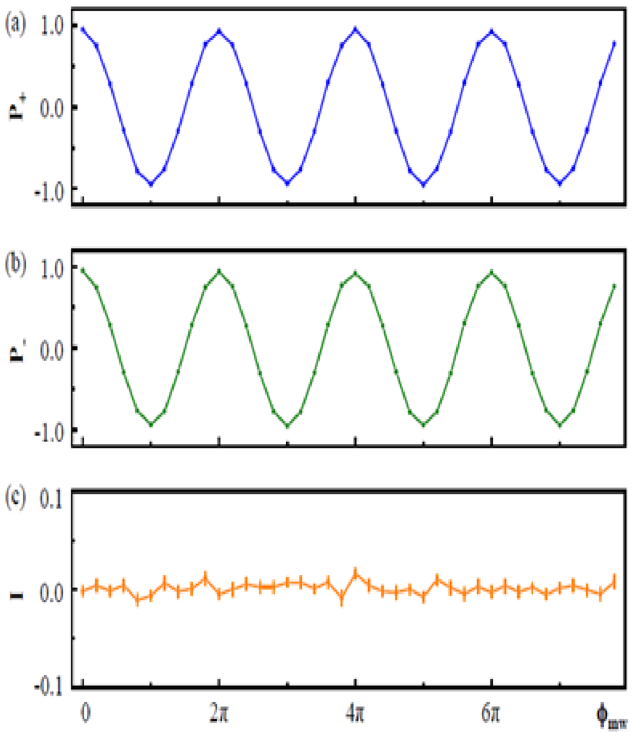
$$P_- = [1 + \cos(\phi_{\rm mw} - \phi)]/2.$$

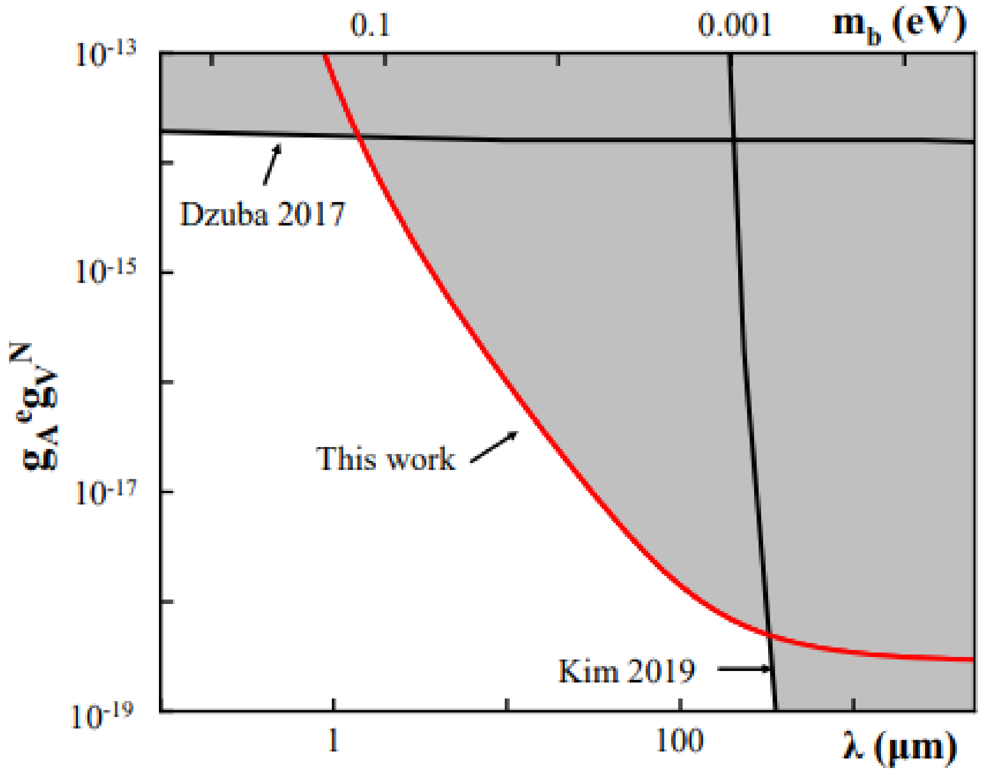
$$I = P_+ - P_- = \sin(\phi_{mw})\sin(\phi)$$

Man Jiao, et al., Physical Review Letters 127, 010501 (2021).

Experimental result and constraints

$$V = g_A^e g_V^N \frac{\hbar}{4\pi}(\boldsymbol{\sigma}\cdot\boldsymbol{v})(\frac{e^{-\frac{r}{\lambda}}}{r})$$



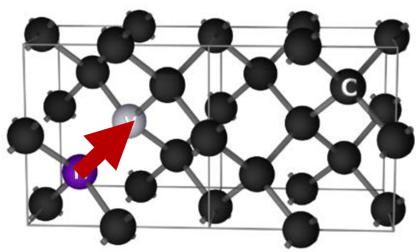


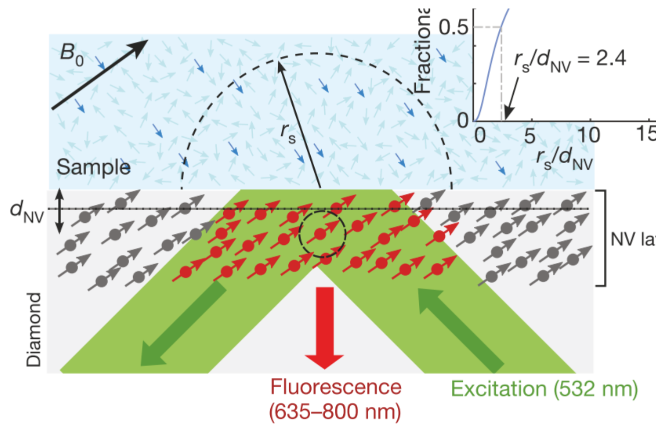
No signal has been observed

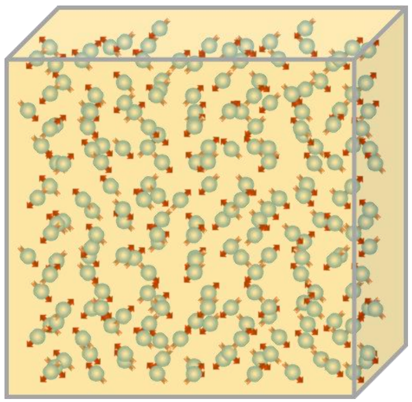
Experimental constraint has been set for the force range from 1.4 - 330 μm

Man Jiao, et al., Physical Review Letters 127, 010501 (2021).

From Single to Ensemble NV sensor







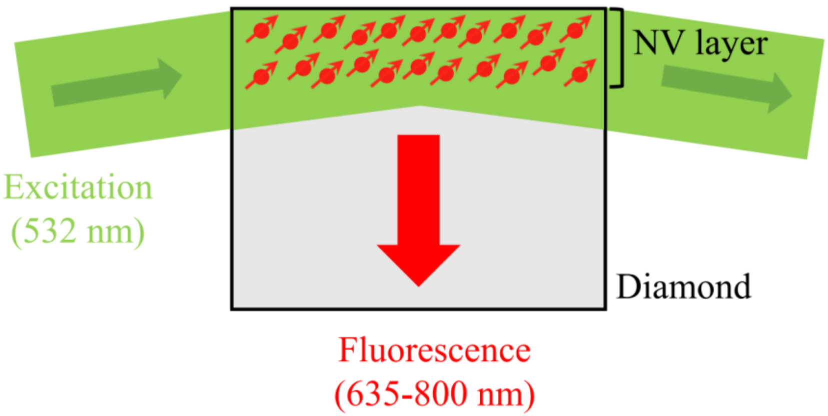
Single NV	Subensemble NV	Bulk NV
4.3 n/$\sqrt{Hz}$	~50 pT/$\sqrt{Hz}$	~0.9 pT/$\sqrt{Hz}$
Nat. Mater. 8, 383(2009)	Nature 555, 351(2018)	Phys. Rev. X 5, 041001(2015)

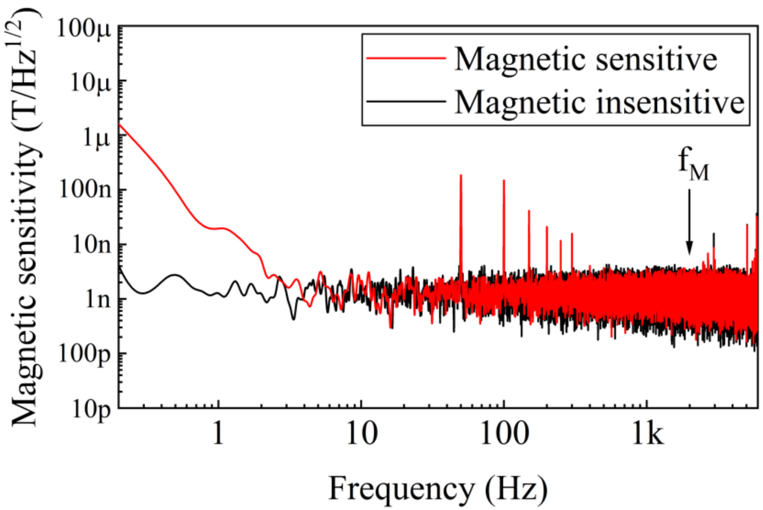
$$\eta \sim \frac{1}{\gamma}\frac{1}{\sqrt{NT_2^*}}$$

N: number of electron spin

Ensemble NV sensor in our experiment

Prof. Wang





a 23-μm-thick NV layer with NV concentration of 14 ppm is employed as quantum sensor

Reach a sensitivity of 1.4 nT/ $\sqrt{Hz}$ from 0.4 to 2 kHz

Search for exotic interactions with ensemble NV quantum sensor

$$V_{AV}(\mathbf{r}) = g_A^e g_V^N \frac{\hbar}{4\pi}\left(\frac{e^{-\frac{r}{\lambda}}}{r}\right)\boldsymbol{\sigma}\cdot\boldsymbol{v},$$

$$V_{SP}(\mathbf{r}) = g_S^N g_P^e \frac{\hbar^2}{8\pi m_e}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}\boldsymbol{\sigma}\cdot\boldsymbol{e_r},$$

Mr. Liang

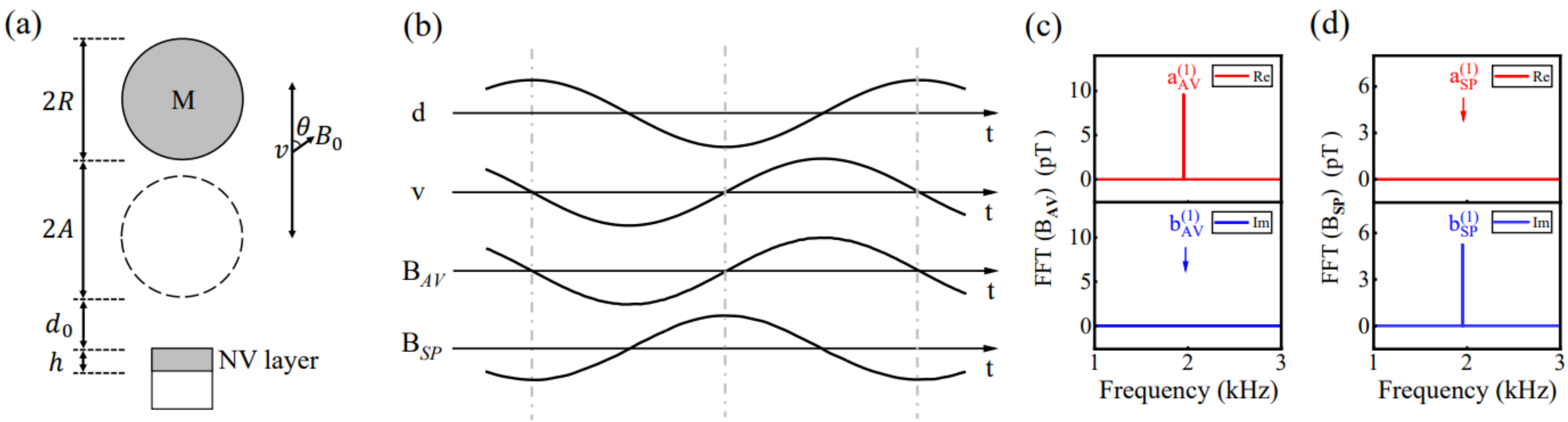
Experimental Constraints on Exotic Spin-Dependent Interactions by a Magnetometer with Ensembles of Nitrogen-Vacancy Centers in Diamond

Hang Liang,[1,2] Man Jiao,[1,2] Yue Huang,[1,2] Pei Yu,[1,2] Xiangyu Ye,[1,2] Ya Wang,[1,2] Yijin Xie,[1,2] Yi-Fu Cai,[3,4] Xing Rong,[1,2,*] and Jiangfeng Du[1,2,†]

[1] *CAS Key Laboratory of Microscale Magnetic Resonance and School of Physical Sciences, University of Science and Technology of China, Hefei 230026, China*

Hang Liang et al., arXiv: 2201.04408 (2022)

Experimental scheme



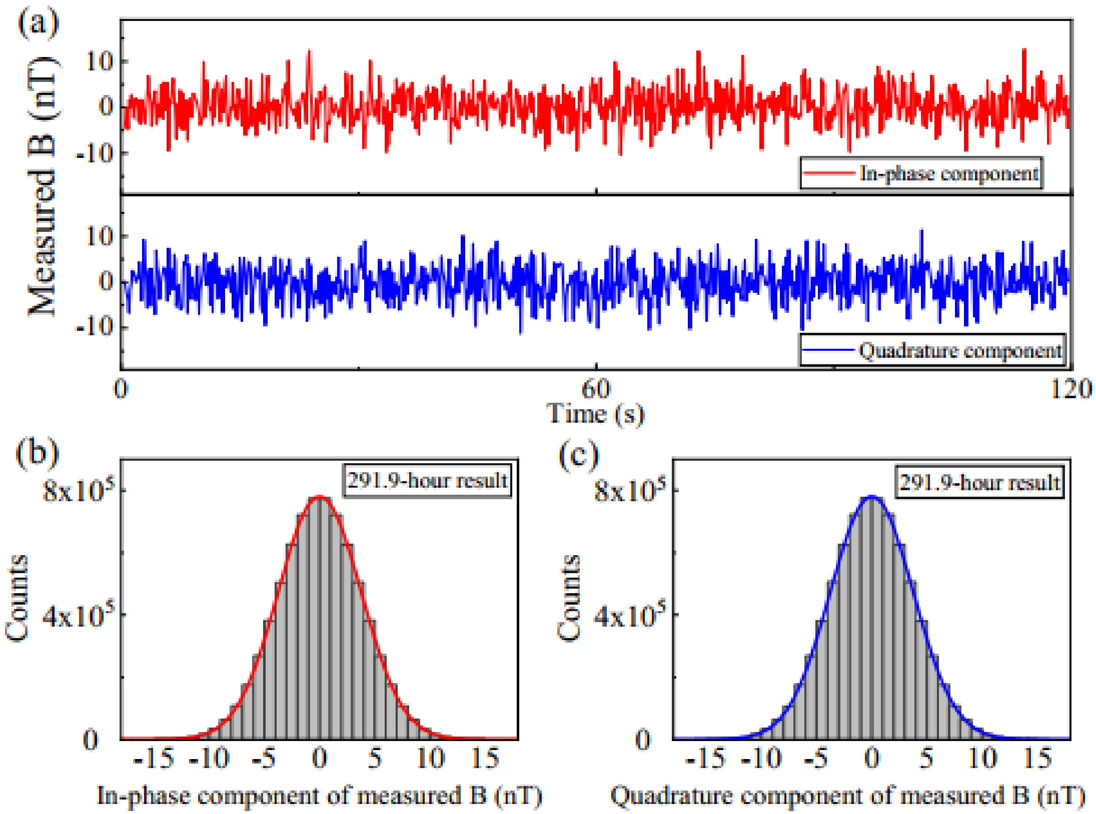
Lead sphere and a 23-μm-thick NV layer serve as mass and spin source

The time evolution of distance, velocity, and effective magnetic fields due to exotic interactions

Fourier transform spectrum

Experimental results

Measurement of the effective magnetic fields



Systematic errors

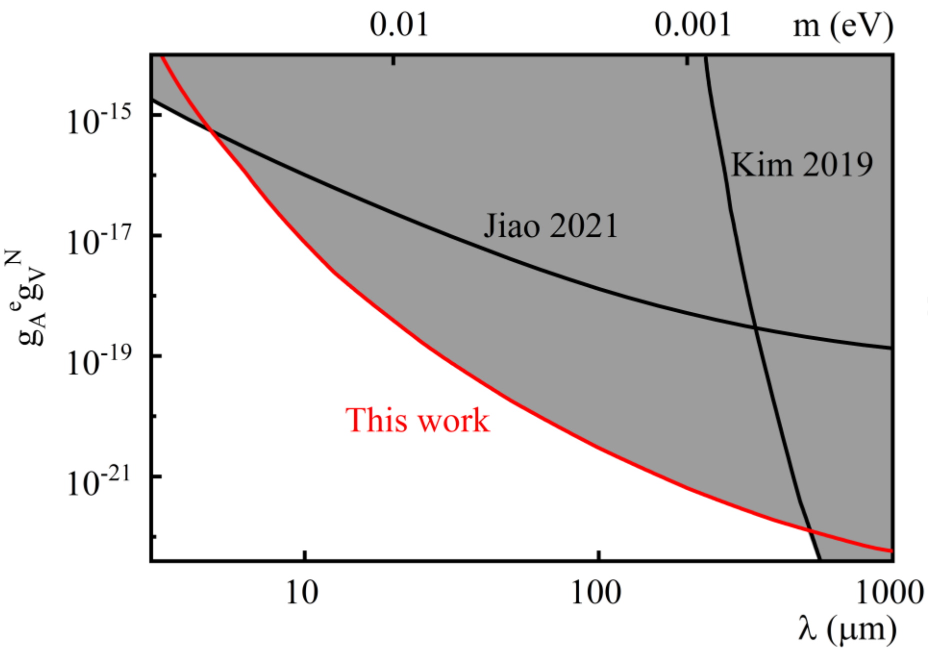
TABLE I. Summary of the systematic errors. The corrections to the constraint on $g_A^e g_V^N$ with $\lambda = 330$ μm and $g_S^N g_P^e$ with $\lambda = 30$ μm are listed.

Parameter	Value	$\Delta g_A^e g_V^N$ ($\times 10^{-25}$)	$\Delta g_S^N g_P^e$ ($\times 10^{-21}$)
Diamagnetism	-1.6×10^{-5}	± 0.3	± 2.9
θ	$54.7 \pm 1.3°$	$^{+2.9}_{-2.8}$	± 0.4
Distance	9.3 ± 0.5 μm	± 0.2	± 0.4
Radius	978 ± 3 μm	± 0.2	± 0.3
Thickness	23 ± 1 μm	± 0.2	$^{+0.3}_{-0.4}$
Amplitude	718 ± 7 nm	$^{+0.8}_{-1.0}$	$^{+0.3}_{-0.4}$
Deviation	0 ± 10 μm	± 0.2	$^{+0.3}_{-0.4}$
Phase delay ϕ	$-32 \pm 9°$	$^{+2.6}_{-0.6}$	± 0.3
Calib. Const.	$2.29 \pm 0.03 \times 10^5 V/T$	± 1.2	± 0.3
Final		± 4.3	± 3.1

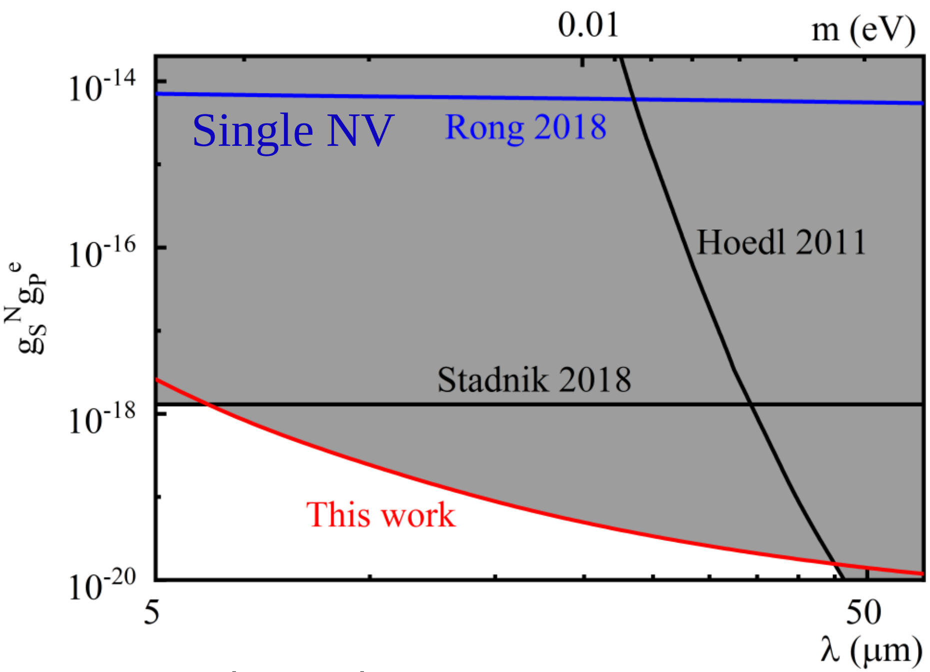
Experimental constraints

$$V_{AV}(\mathbf{r}) = g_A^e g_V^N \frac{\hbar}{4\pi}\left(\frac{e^{-\frac{r}{\lambda}}}{r}\right)\boldsymbol{\sigma}\cdot\boldsymbol{v},$$

$$V_{SP}(\mathbf{r}) = g_S^N g_P^e \frac{\hbar^2}{8\pi m_e}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}\boldsymbol{\sigma}\cdot\boldsymbol{e_r},$$



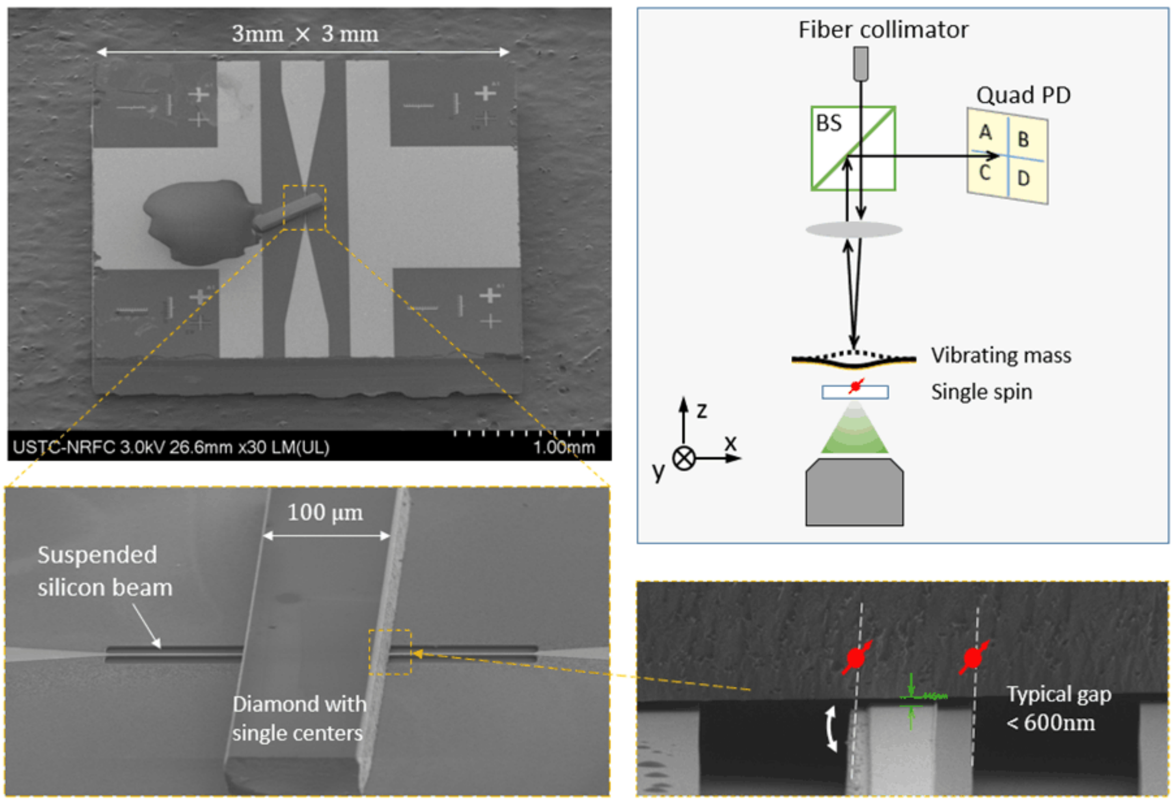
$|g_A^e g_V^N| \leq 2.5 \times 10^{-22}$ ($\lambda = 330\ \mu m$)



$|g_S^N g_P^e| \leq 2.5 \times 10^{-20}$ ($\lambda = 30\ \mu m$)

Summary and outlook

- NV centers can be a powerful platform for investigating new physics.
- Experimental search for more types of interactions are been carried out.
- In future, on-chip sensor will be utilized.



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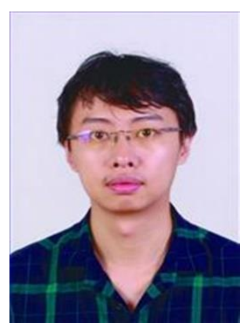

Pu Huang

中华人民共和国科学技术部

The Ministry of Science and Technology of the People's Republic of China

Thanks for your attention!

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