Searching for exotic spin-dependent interactions with single electron spin quantum sensors

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Contents

CAS Key Lab of Microscale Magnetic Resonance

Leader of our Lab Prof. Jiangfeng Du (Academician of the CAS)

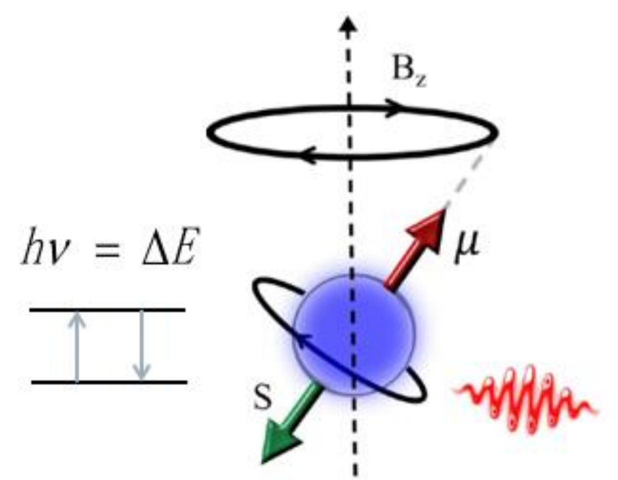
Our laboratory focuses on the research of spin quantum control and its applications in novel quantum technologies, with various experimental routes including nuclear magnetic resonance (NMR), electron spin resonance (ESR), optically-detected magnetic resonance (ODMR), magnetic resonance force microscopy (MRFM), and electrically-detected magnetic resonance (EDMR).

http://en.lmmr.ustc.edu.cn/
http://spin.ustc.edu.cn/

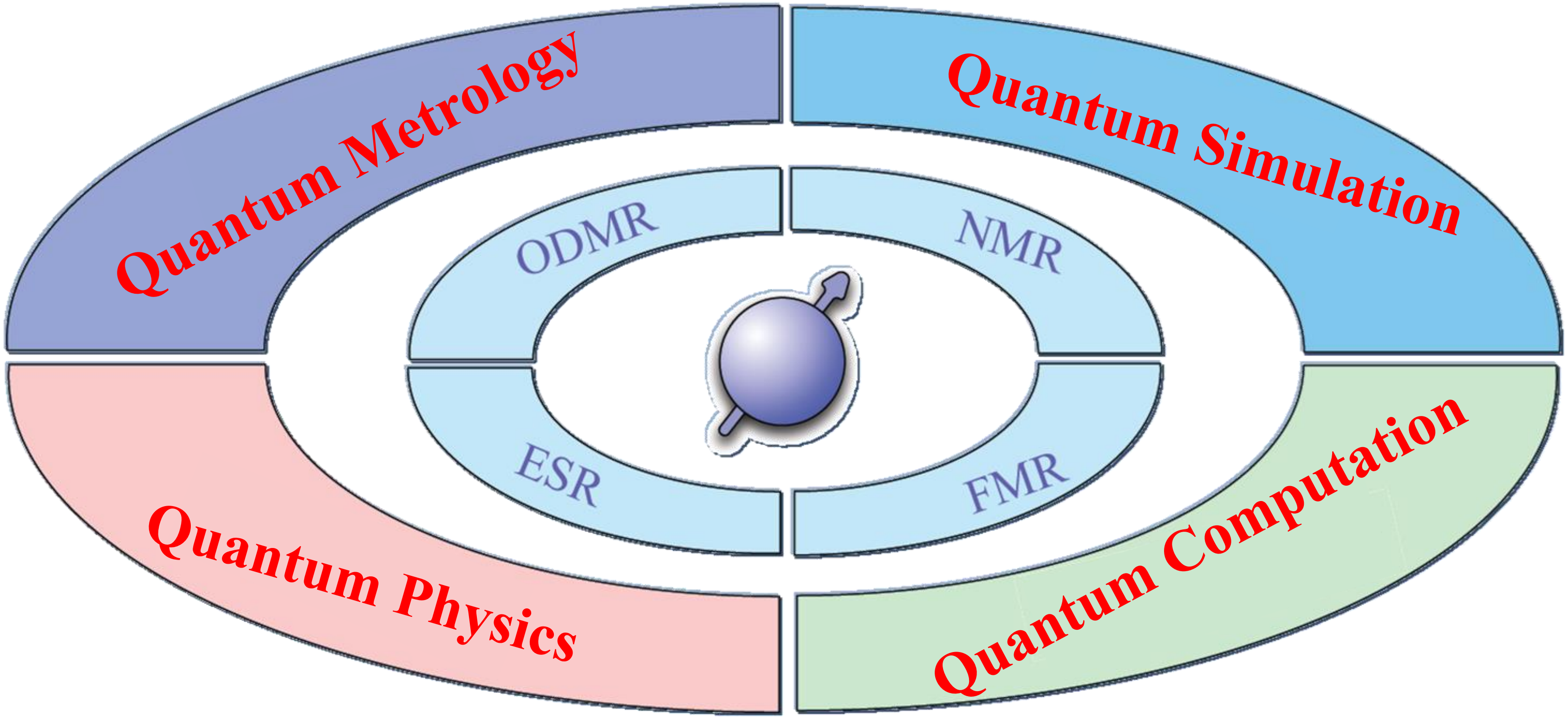
Spin Magnetic Resonance

Principle: The spins which locate in a magnetic field can absorb and re-emit electromagnetic radiation with a specific resonance frequency.

The MR technology is capable of obtaining information of subjects composition and structure in an accurate, rapid and non-destructive way.



Focuses on "Spin"



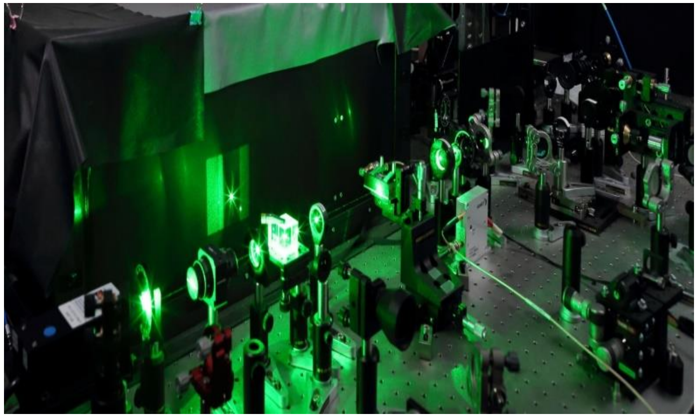
Science ⟺ Technology

- Published more than 190 scientific papers, including **Nature × 2, Science × 3, Nature Physics × 2, Nature Methods × 1, Nature Communications × 8, and Physical Review Letters × 37**.

Experimental instruments in our lab

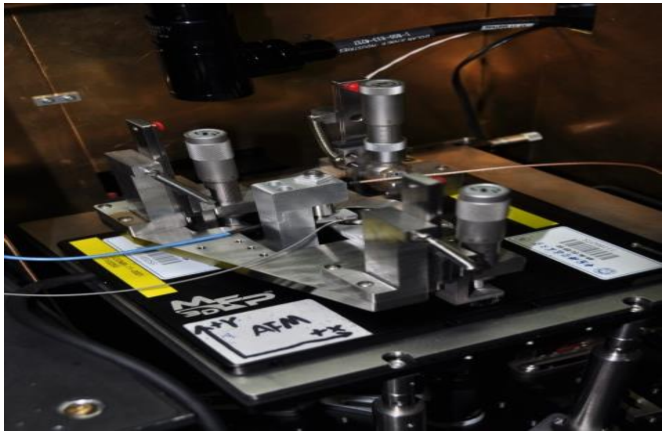
NMR

ESR

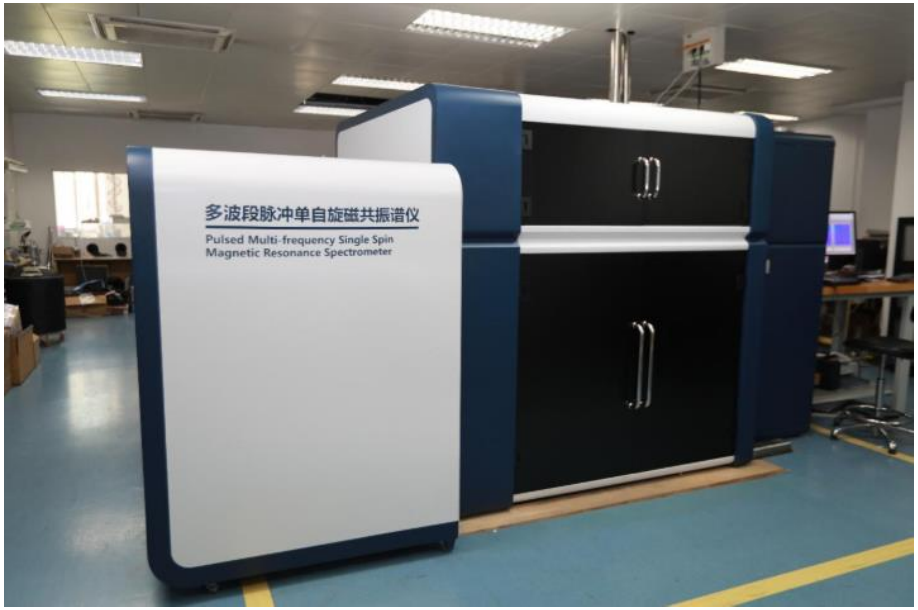


ODMR

FMR



Experimental instruments in our lab



Single molecule MR Spectrometer

Conventional MR spectrometer

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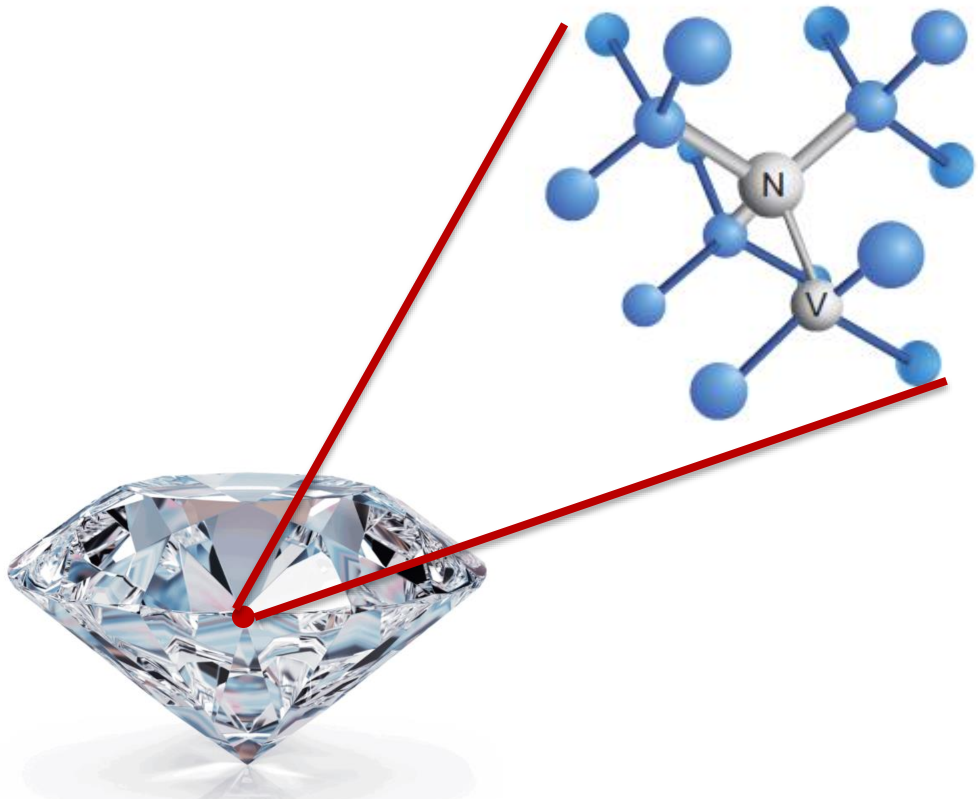
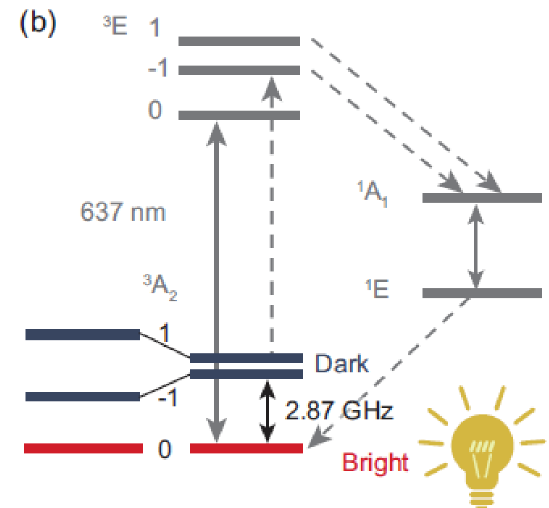
Single electron spin quantum sensors
NV- centers in diamond





Single electron spin quantum sensors

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

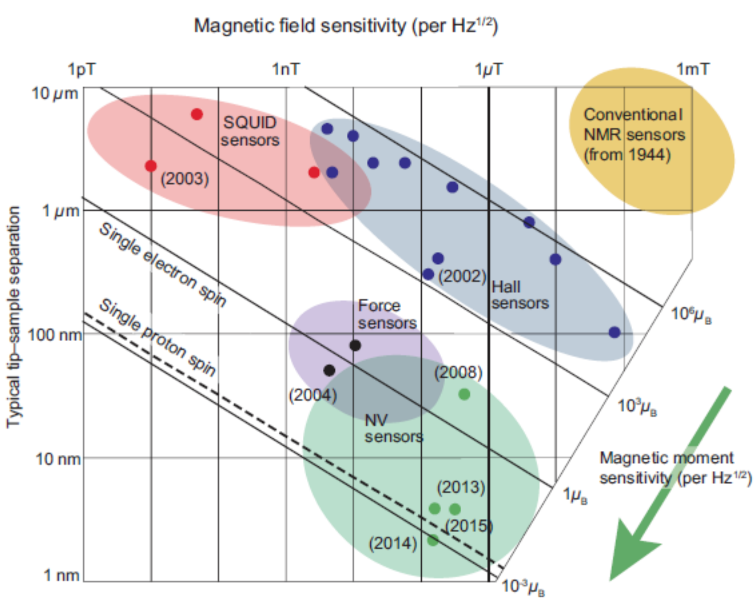
Temperature

Electric-field stress detection

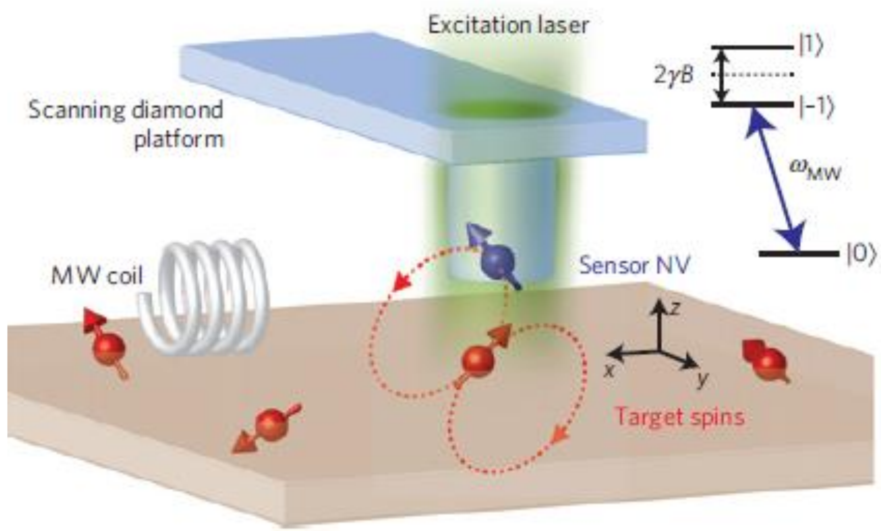
Magnetic field

Spin-coupling Spin-sensing

Diamond nanoscale magnetometry

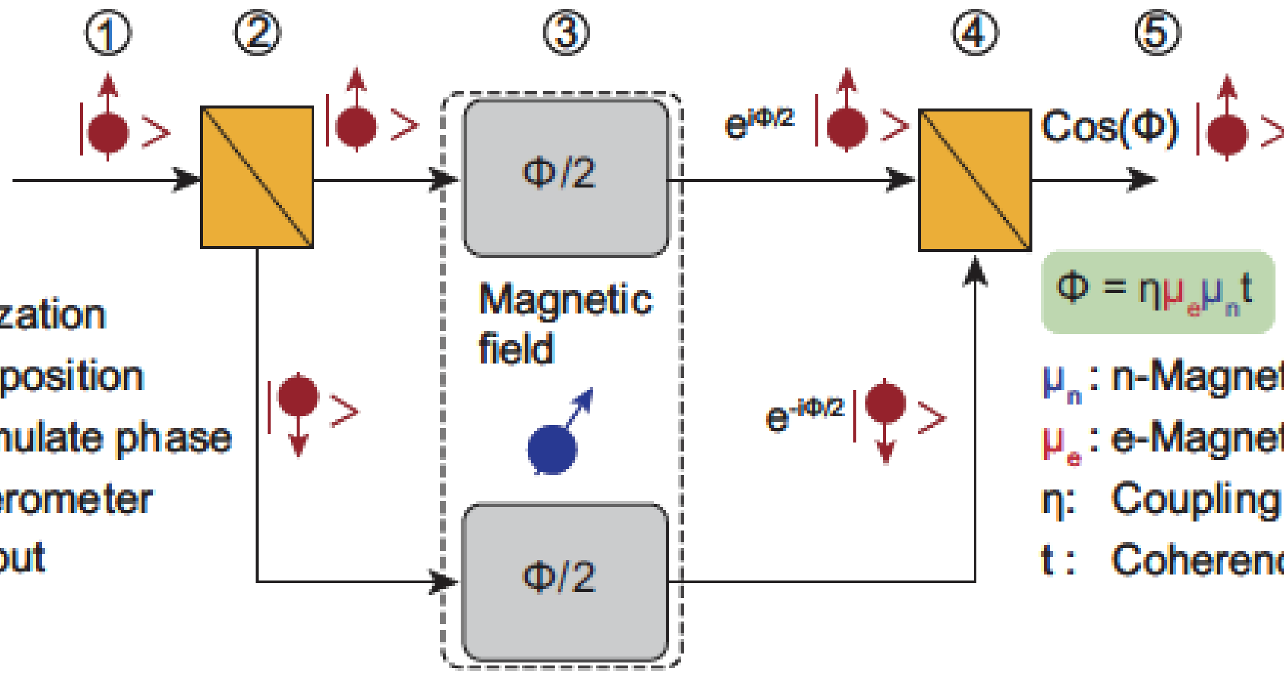


Nat. Nanotechnol. **3**, 643(2008)



Nat. Phys. 9, 215 (2013)

Single electron spin quantum sensors
The basic idea



1. Initialization
2. Superposition
3. Accumulate phase
4. Interferometer
5. Readout

$\Phi = \eta\mu_e\mu_n t$

μ_n : n-Magnetic moment

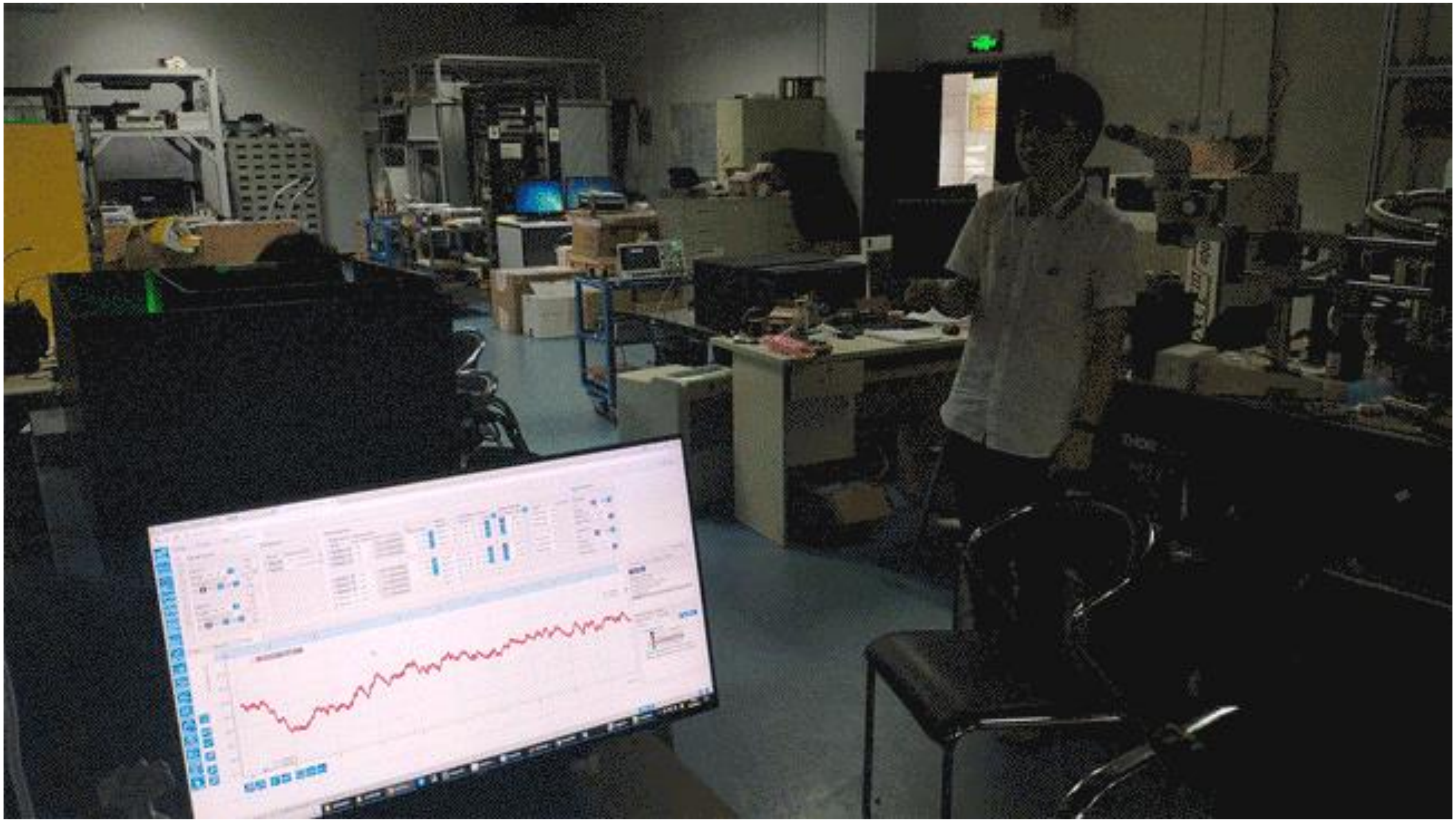
μ_e : e-Magnetic moment

η: Coupling strength

t : Coherence time

Convert weakly magnetic signal (such as nuclear dipolar μ_n) to phase Φ which can be detected by quantum interferometer.

Single electron spin quantum sensors
A video



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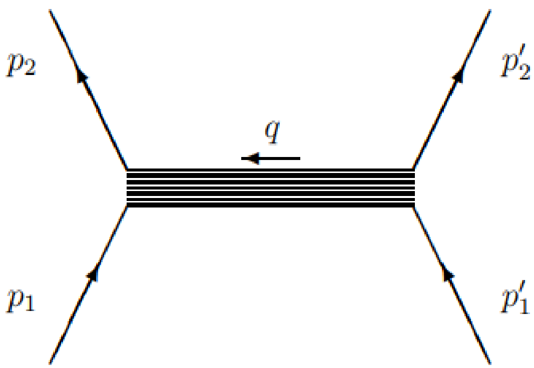
Spin-dependent macroscopic forces from new particle exchange



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$$
\begin{aligned}
\mathcal{V}_1 &= \frac{1}{r}\, y(r) \ , \\
\mathcal{V}_2 &= \frac{1}{r}\, \vec{\sigma}\cdot\vec{\sigma}\,'\, y(r) \ , \\
\mathcal{V}_3 &= \frac{1}{m^2\, r^3}\left[\vec{\sigma}\cdot\vec{\sigma}\,'\left(1 - r\frac{d}{dr}\right) - 3\left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left(\vec{\sigma}\,'\cdot\hat{\vec{r}}\right)\left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right)\right] y(r) \ , \\
\mathcal{V}_{4,5} &= -\frac{1}{2m\, r^2}\left(\vec{\sigma}\pm\vec{\sigma}\,'\right)\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\left(1 - r\frac{d}{dr}\right) y(r) \ , \\
\mathcal{V}_{6,7} &= -\frac{1}{2m\, r^2}\left[\left(\vec{\sigma}\cdot\vec{v}\right)\left(\vec{\sigma}\,'\cdot\hat{\vec{r}}\right) \pm \left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left(\vec{\sigma}\,'\cdot\vec{v}\right)\right]\left(1 - r\frac{d}{dr}\right) y(r) \ , \\
\mathcal{V}_8 &= \frac{1}{r}\left(\vec{\sigma}\cdot\vec{v}\right)\left(\vec{\sigma}\,'\cdot\vec{v}\right)\, y(r) \ ,
\end{aligned}
\tag{3.6}
$$

$$
\begin{aligned}
\mathcal{V}_{9,10} &= -\frac{1}{2m\, r^2}\left(\vec{\sigma}\pm\vec{\sigma}\,'\right)\cdot\hat{\vec{r}}\left(1 - r\frac{d}{dr}\right) y(r) \ , \\
\mathcal{V}_{11} &= -\frac{1}{m\, r^2}\left(\vec{\sigma}\times\vec{\sigma}\,'\right)\cdot\hat{\vec{r}}\left(1 - r\frac{d}{dr}\right) y(r) \ , \\
\mathcal{V}_{12,13} &= \frac{1}{2r}\left(\vec{\sigma}\pm\vec{\sigma}\,'\right)\cdot\vec{v}\; y(r) \ , \\
\mathcal{V}_{14} &= \frac{1}{r}\left(\vec{\sigma}\times\vec{\sigma}\,'\right)\cdot\vec{v}\; y(r) \ , \\
\mathcal{V}_{15} &= -\frac{3}{2m^2\, r^3}\left\{\left[\vec{\sigma}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\left(\vec{\sigma}\,'\cdot\hat{\vec{r}}\right) + \left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left[\vec{\sigma}\,'\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\right\} \\
&\quad \times\left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right) y(r) \ , \\
\mathcal{V}_{16} &= -\frac{1}{2m\, r^2}\left\{\left[\vec{\sigma}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\left(\vec{\sigma}\,'\cdot\vec{v}\right) + \left(\vec{\sigma}\cdot\vec{v}\right)\left[\vec{\sigma}\,'\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\right\}\left(1 - r\frac{d}{dr}\right) y(r) \ .
\end{aligned}
\tag{3.8}
$$

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

Searches for exotic spin-dependent interactions with NV centers

- spin-mass interaction

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

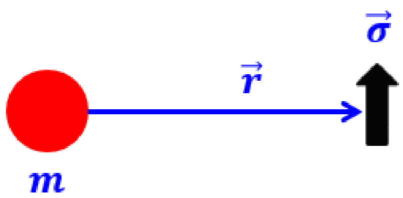
Xing Rong et al., Nature Communications, 9:739 (2018)

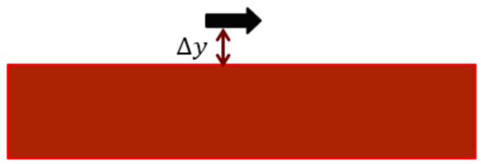
- exotic dipole-dipole interaction

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

Xing Rong et al., Phys. Rev. Lett. 121, 080402 (2018)
Man Jiao et al., to be submitted (2018)

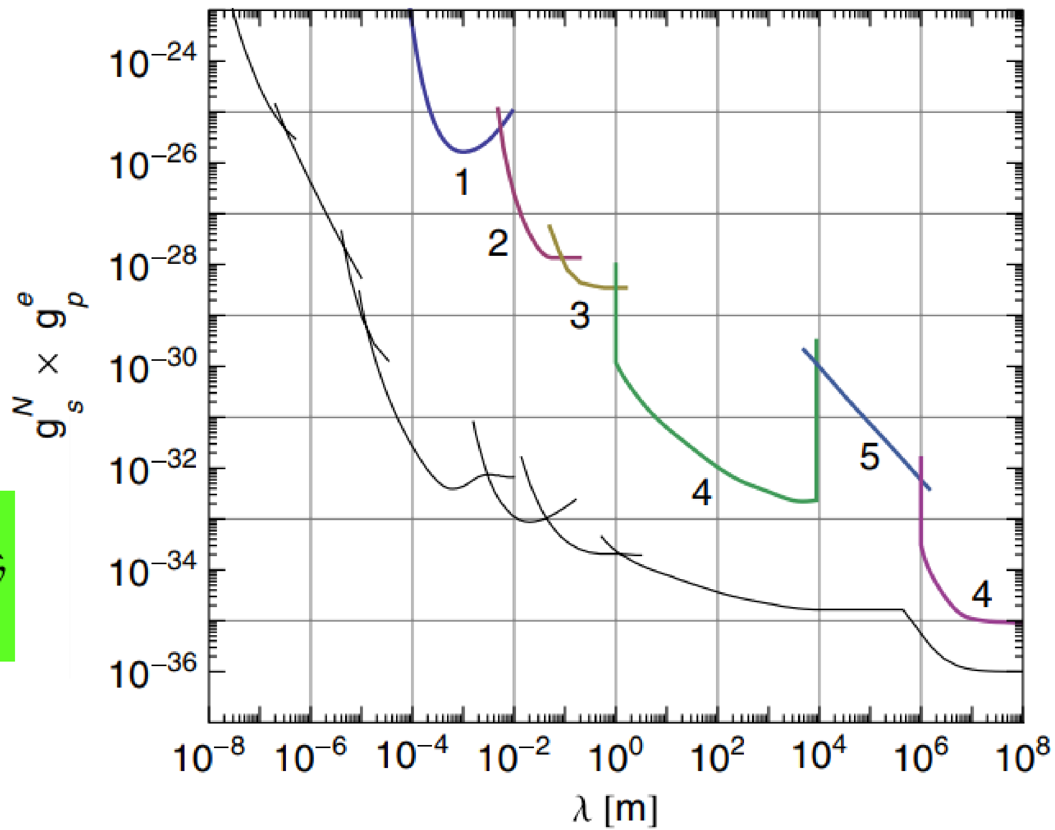
Constraints on spin-mass interaction





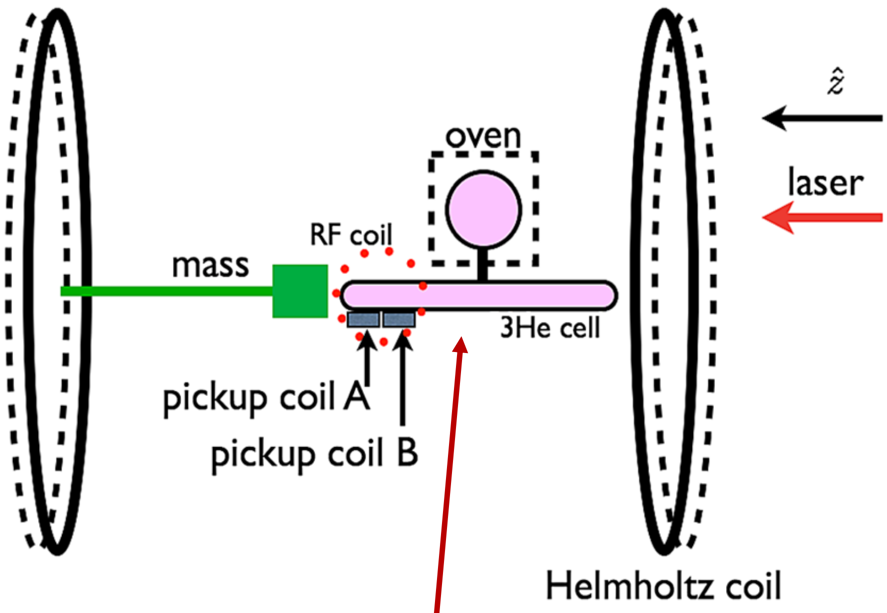
$$\vec{B}_{eff} = \frac{1}{\gamma}\frac{\hbar g_s g_p}{2m}\rho\lambda e^{-\frac{\Delta y}{\lambda}}(1 - e^{-\frac{d}{\lambda}})\hat{y}$$

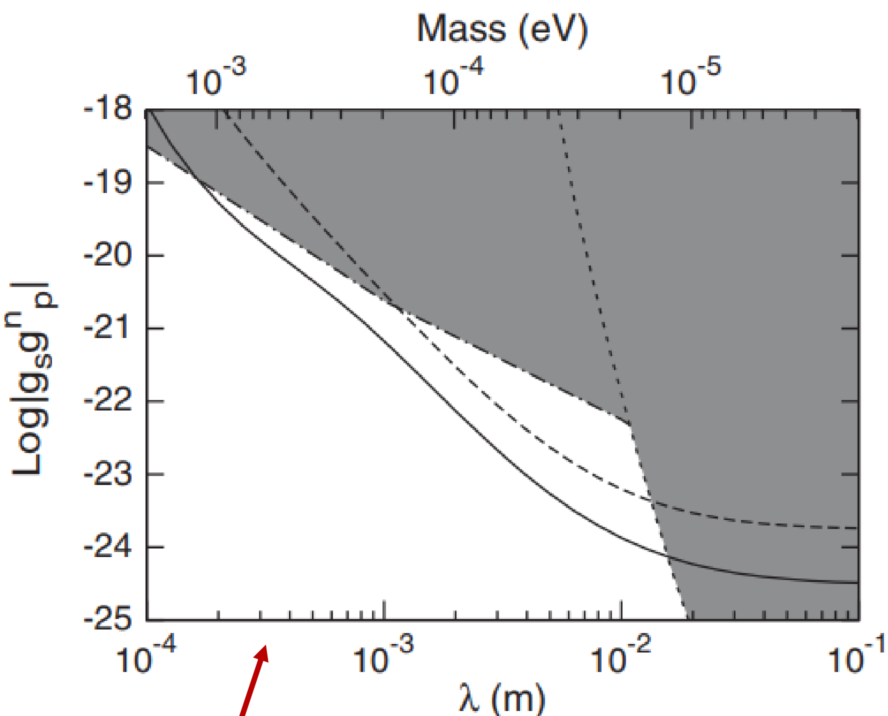
PRD 86, 015001 (2012)



Limitation：The size of the sensor!

Limitation of the sensor (an example)



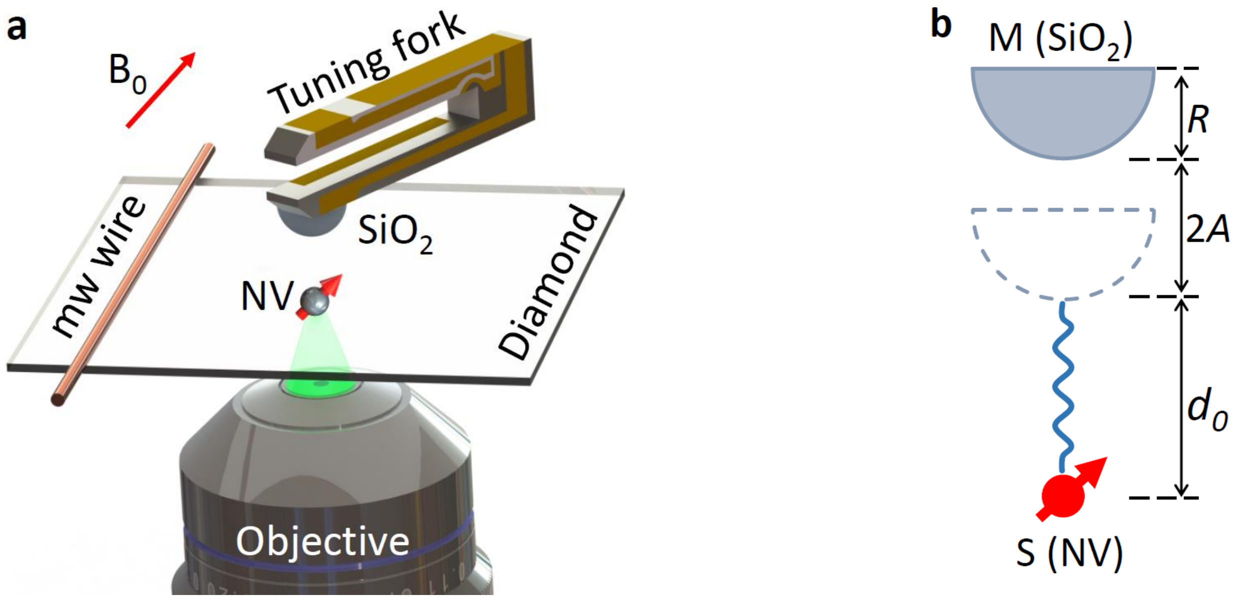


The thickness of the cell (the sensor) is 250 μm. It is very challenging to make it much thinner.

The investigated force range is above ~100 μm

PHYSICAL REVIEW D 87, 011105(R) (2013)

Constrain spin-mass interaction with μm scale



advantages

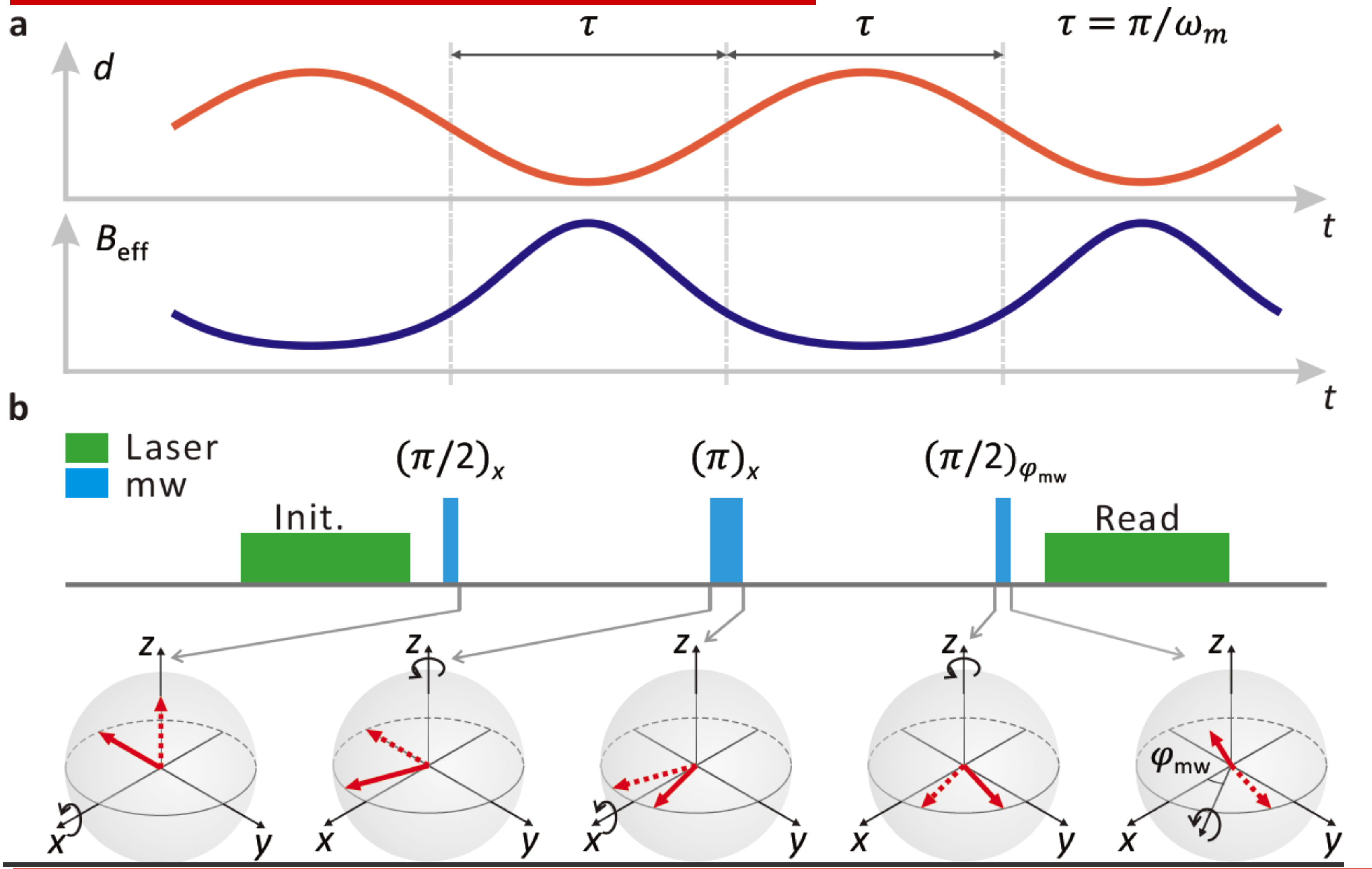
- ✓ Atomic scale
- ✓ Near surface

→ Shorter force range

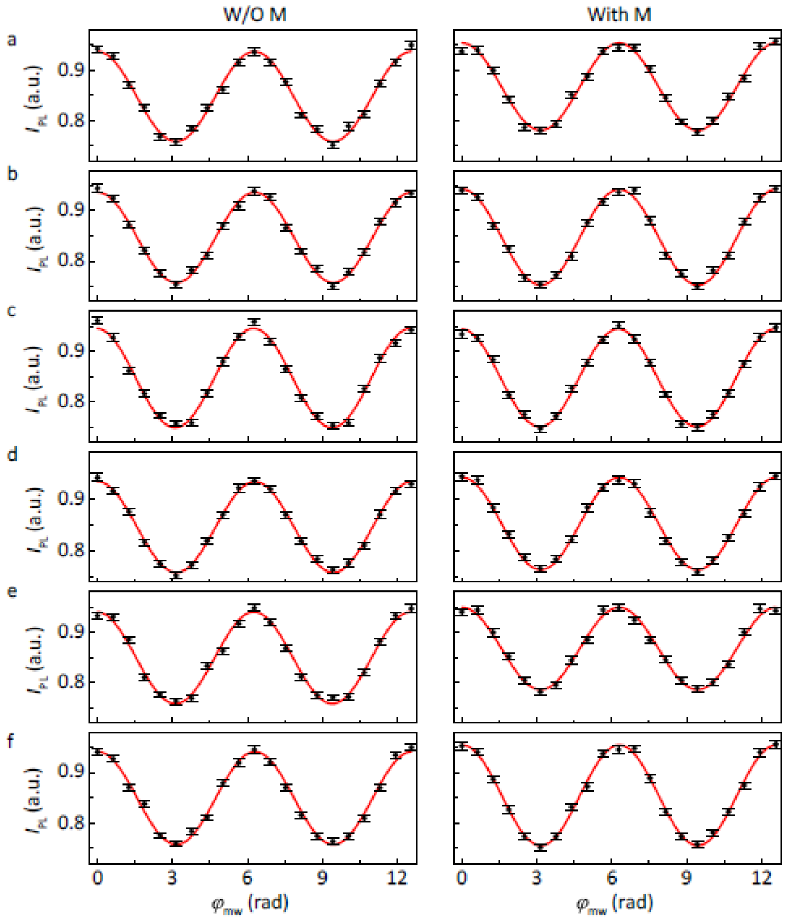
- ✓ Precise quantum control → Good sensitivity
- ✓ NV + AFM → Cancel unwanted signals

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

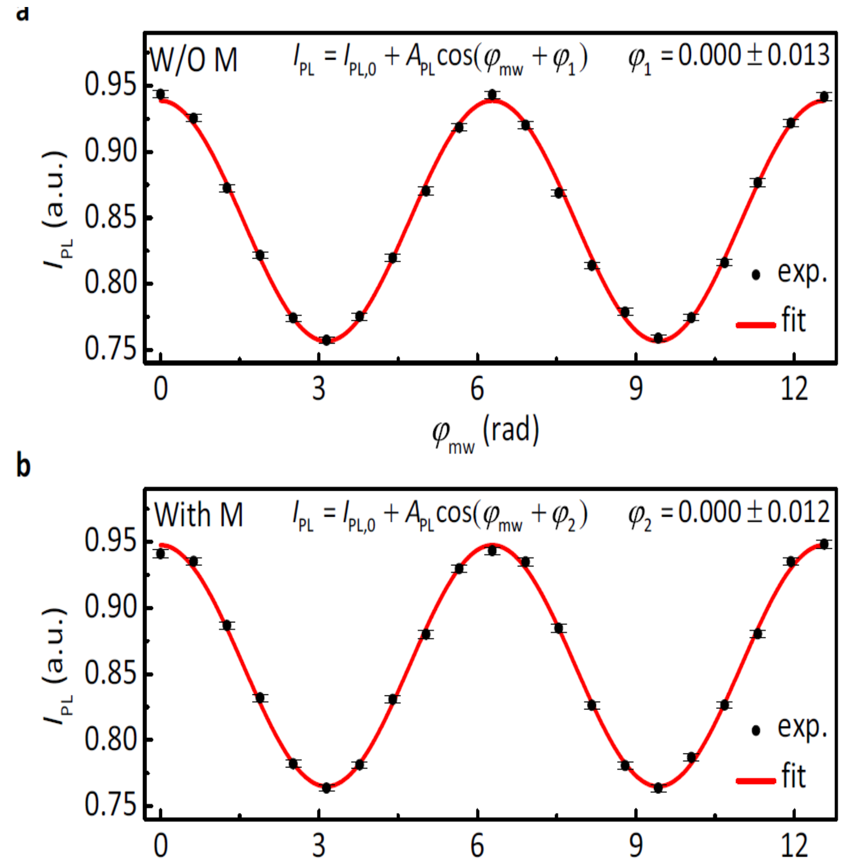
Experimental sequence



Experimental result



Six separated runs

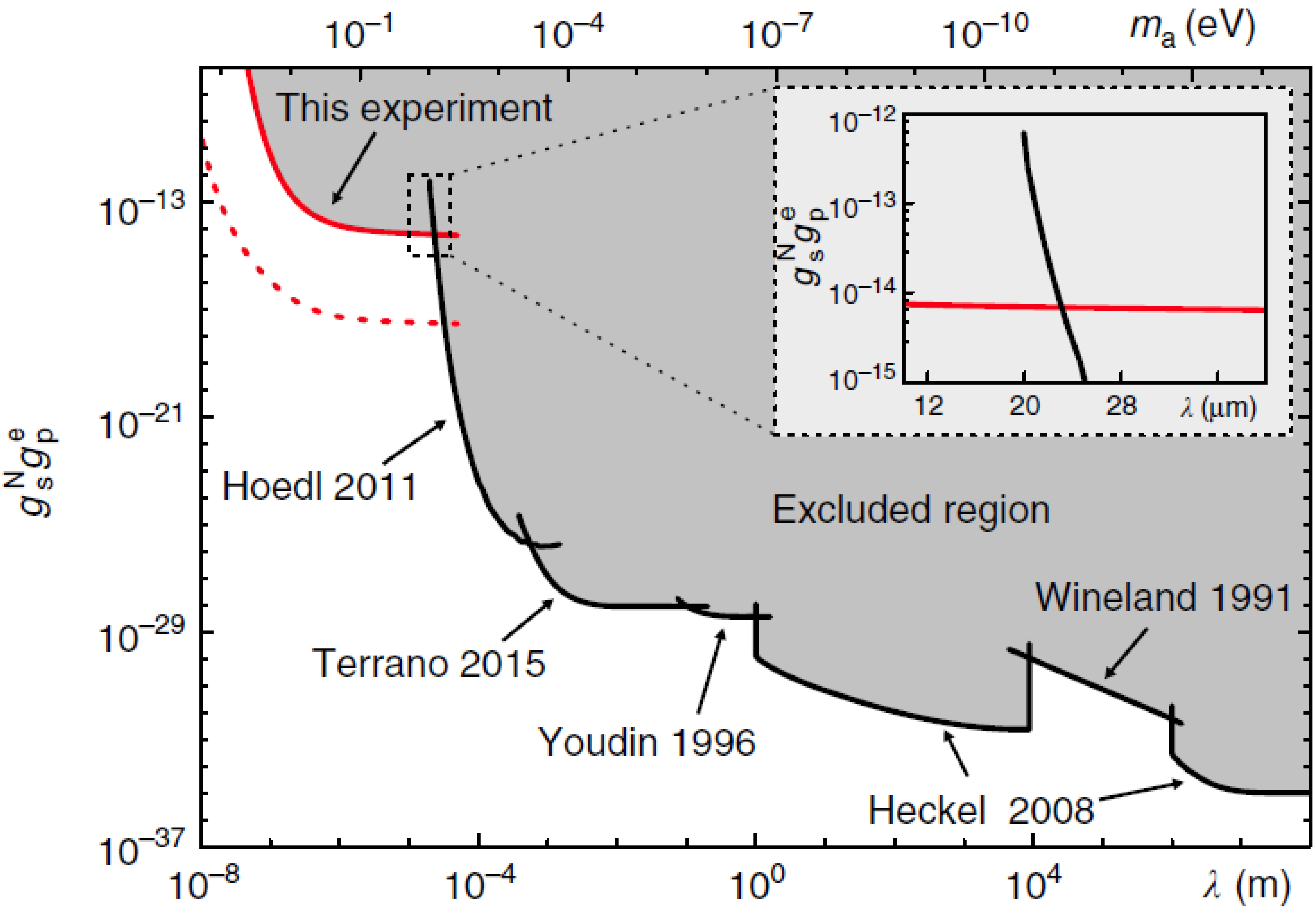


statistical errors: $\sim$ 0.02 rad

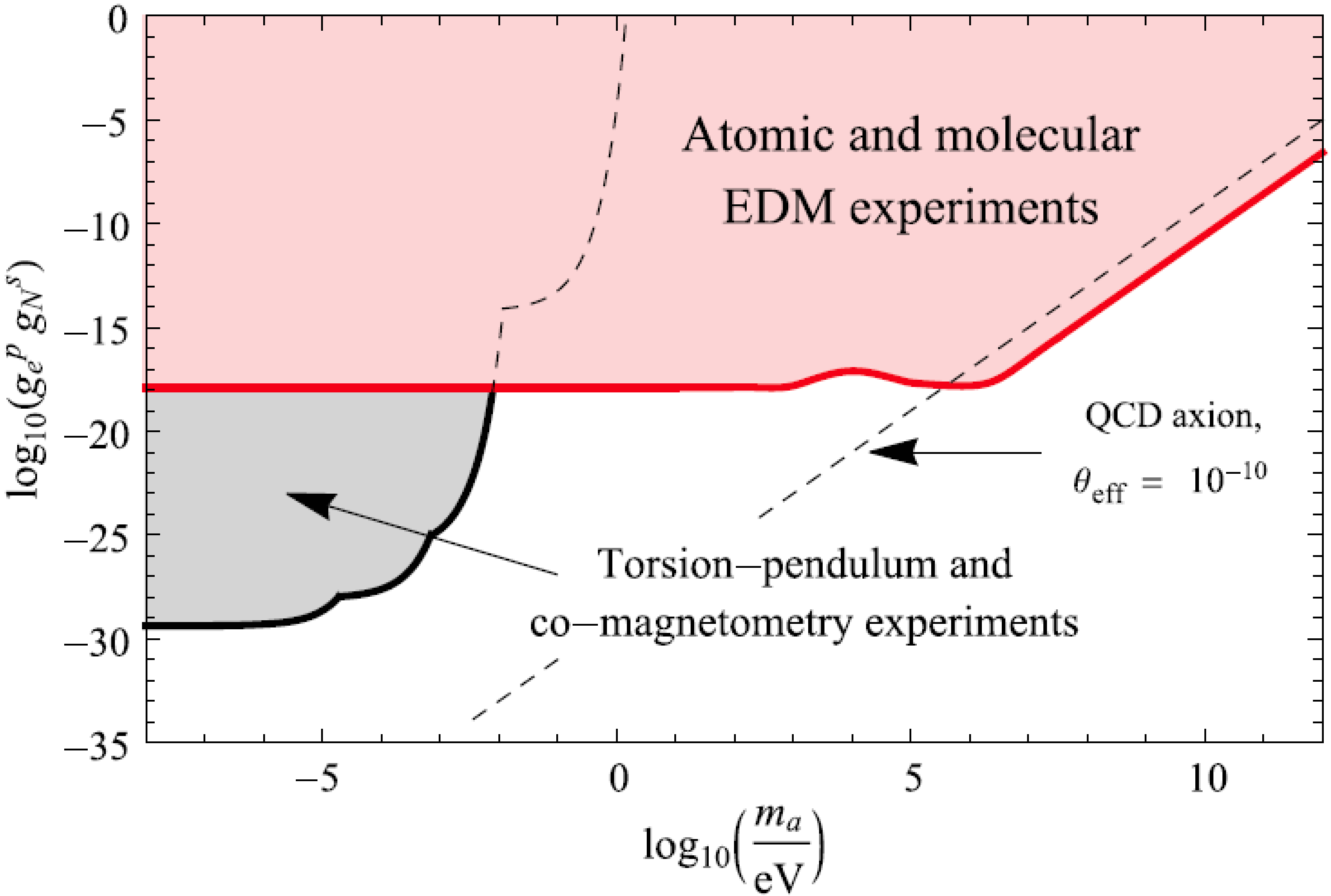
Table 1: Systematic error summary.

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 $\mathbf{B}_{\mathrm{eff}}$ and NV axis	$54.7 \pm 3°$	$(0.4 \pm 4.2) \times 10^{-16}$

Constraints by our experiment

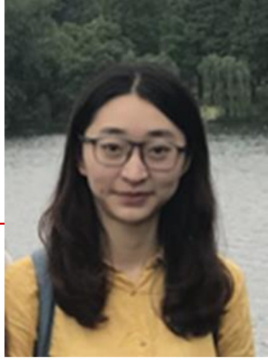


Improved constraints

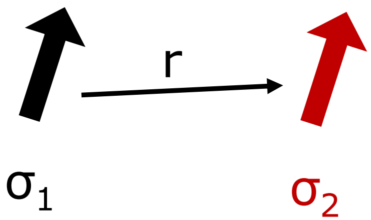


Y. V. Stadnik, V. A. Dzuba, and V. V. Flambaum, PRL120, 161801 (2018)

Constraint on exotic interaction between electrons



Man Jiao



Magnetic dipole-dipole coupling

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

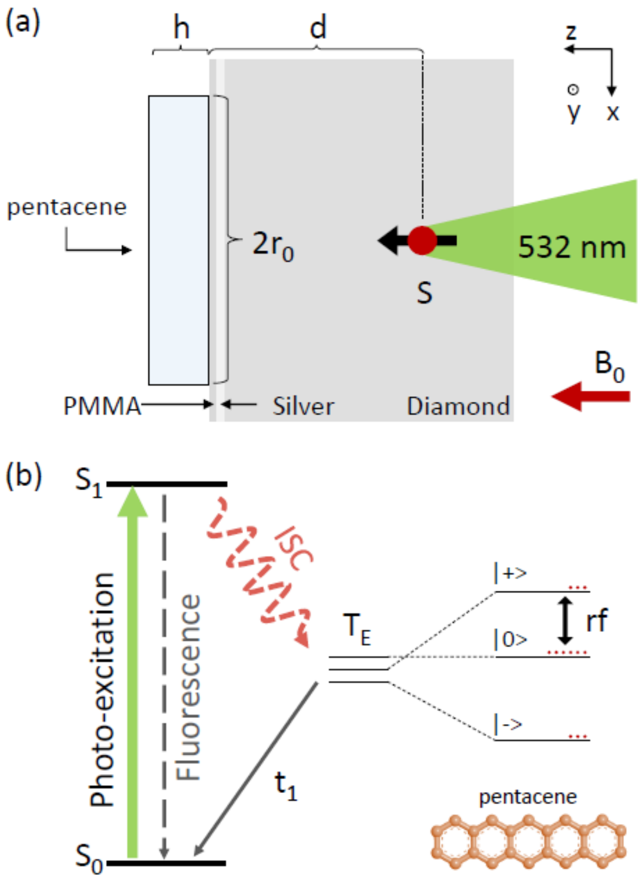
Exotic dipole-dipole coupling [1]

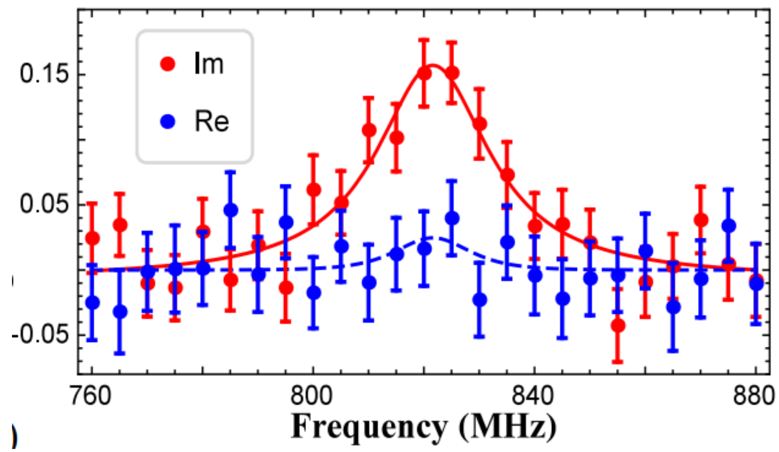
$$\frac{g_A^e g_A^e}{4\pi\hbar c}\frac{\hbar c}{r}(\vec{\sigma_1}\cdot\vec{\sigma_2})e^{-\frac{r}{\lambda}},$$

We now experimentally search for this type of exotic dipole-dipole coupling [2, 3].

[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)
[3] Man Jiao et al., to be submitted (2018)

Experiment technique and setup

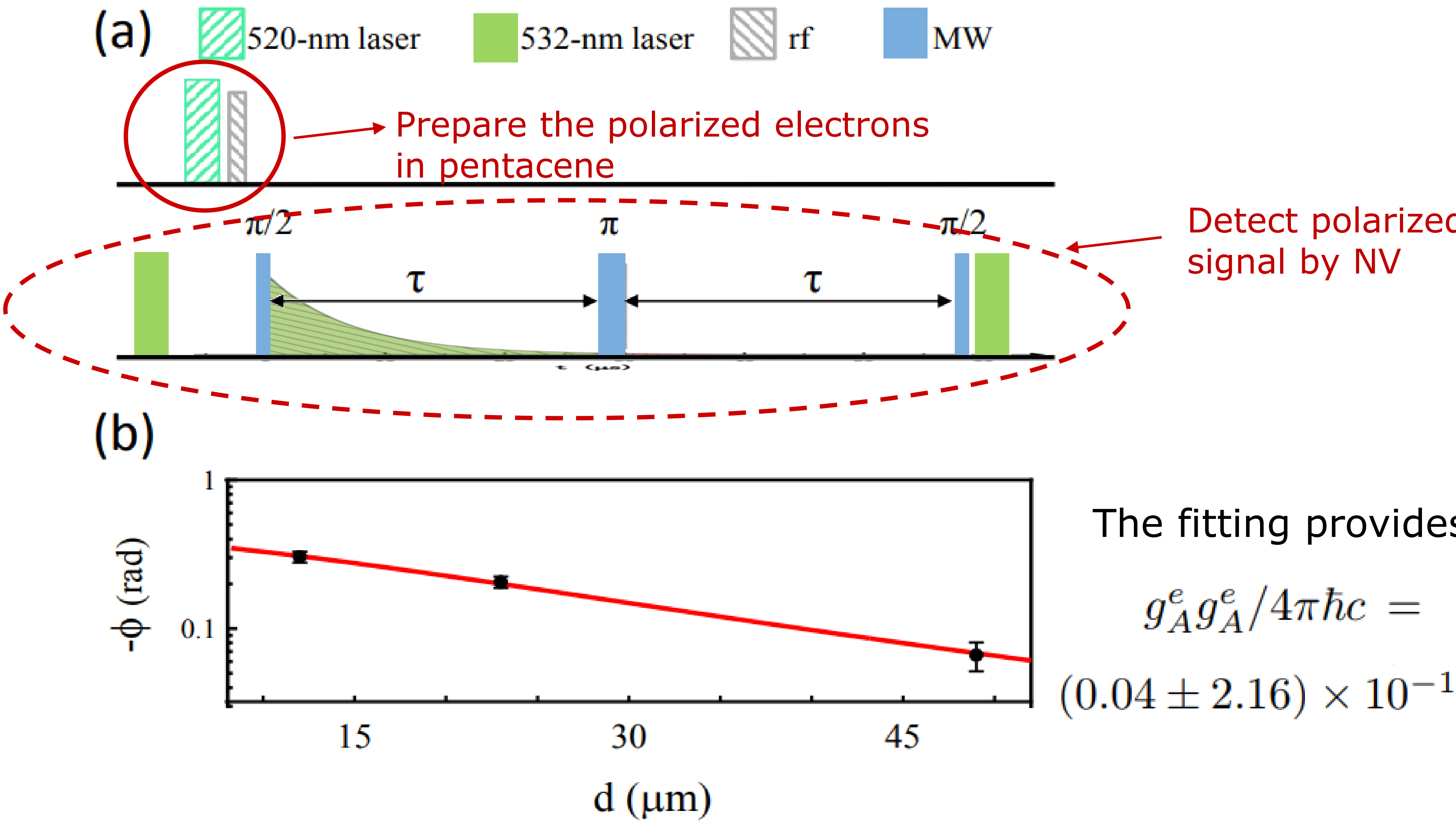




The measured polarized signal

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)

Experimental pulse sequence for searching exotic interactions

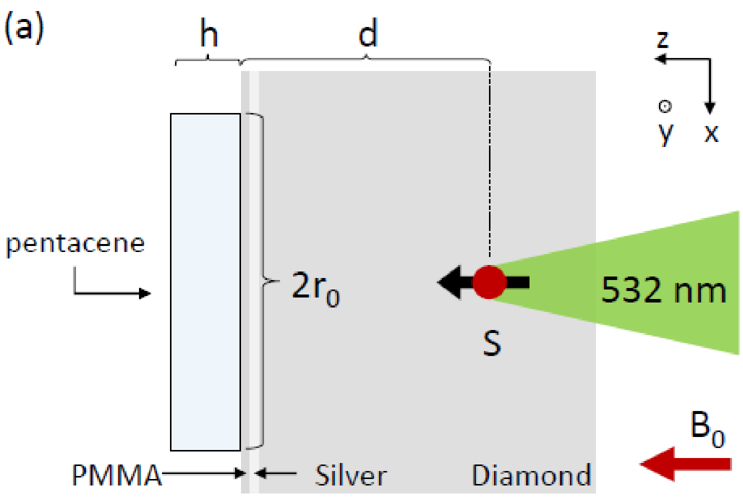
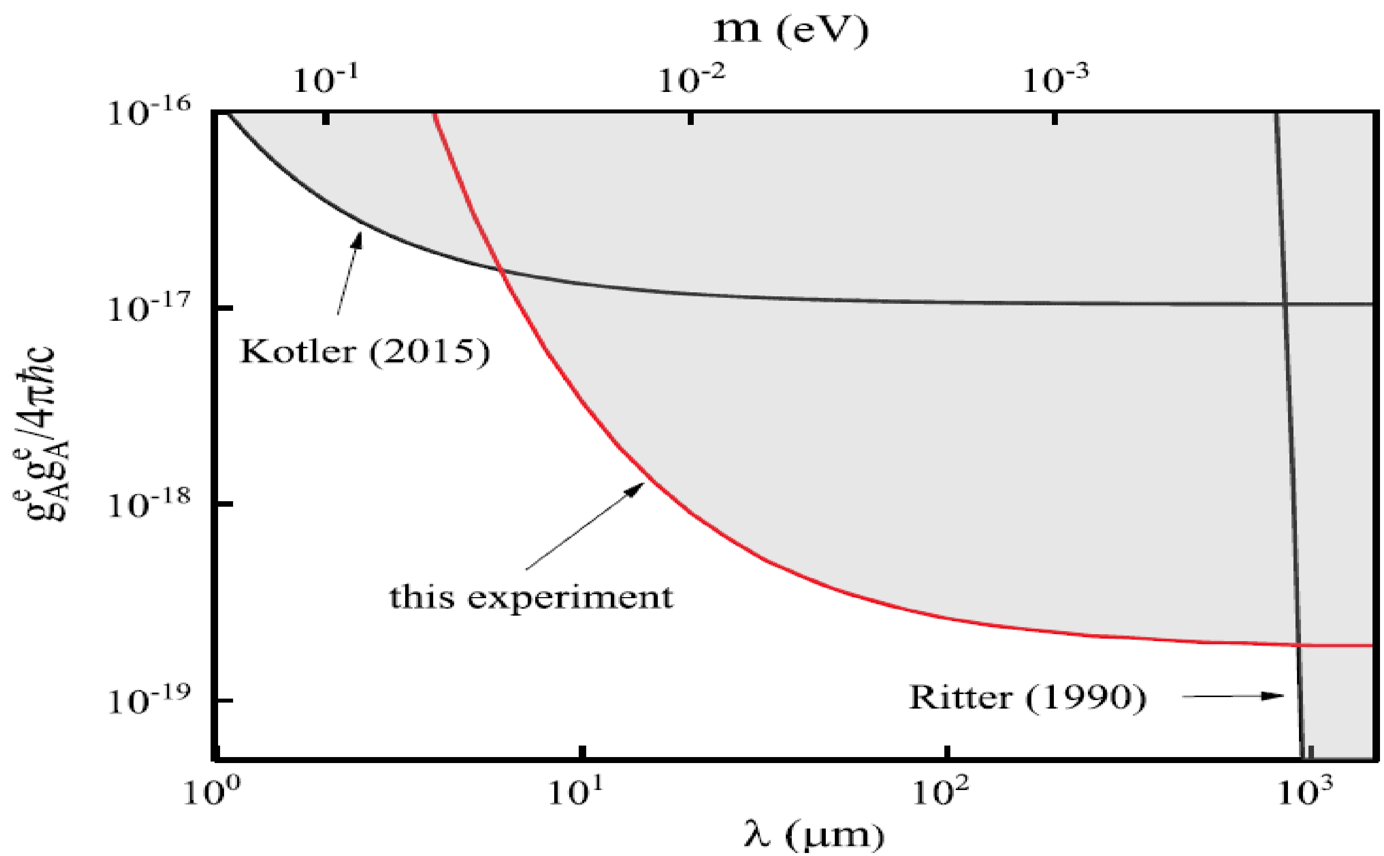


TABLE I. Summary of the systematic errors in our experiment. The corrections to $g_A^e g_A^e / 4\pi\hbar c$ at $\lambda = 500\ \mu m$ are listed.

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)

New 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)

Can we search the exotic spin interactions at nanometer scale?

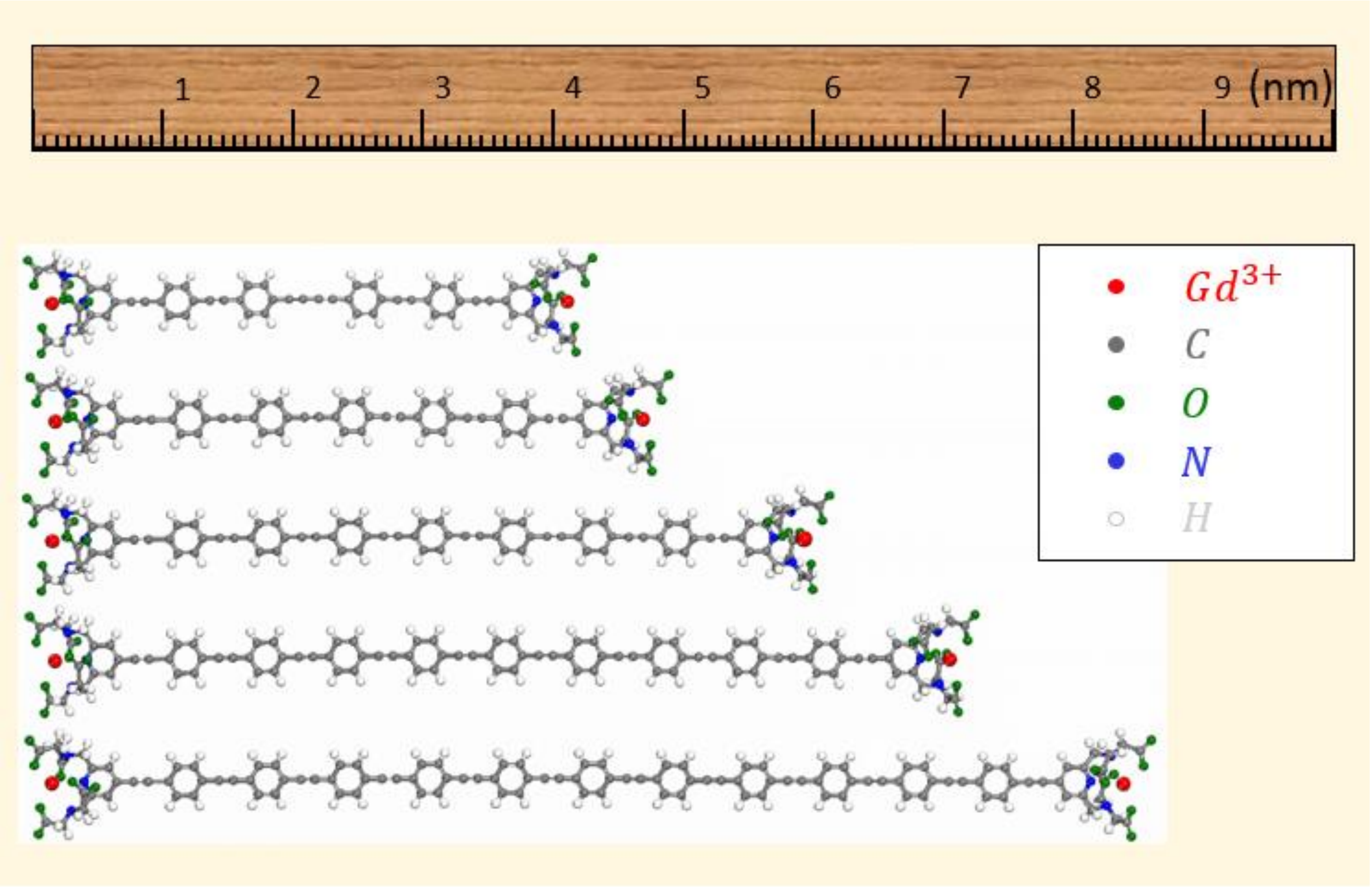
Yes.

- We can engineering the distance between two electron spins by designing and synthesis molecule.

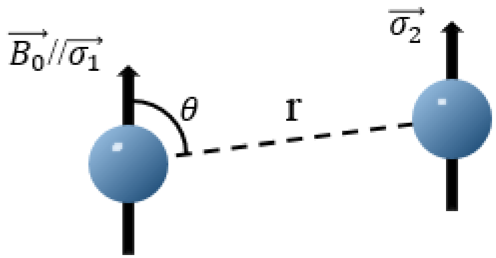
- Then we can explore new physics with the power of the chemistry.

Man Jiao et al., to be submitted (2018)

Molecules with tunable distance



Arina Dalaloyan et al., Phys. Chem. Chem. Phys. 17, 18464 (2015)



Magnetic dipole-dipole interaction

$$-\frac{\mu_0\gamma_1\gamma_2\hbar^2}{16\pi r^3}[3(\vec{\sigma_1}\cdot\hat{r})(\vec{\sigma_2}\cdot\hat{r})-(\vec{\sigma_1}\cdot\vec{\sigma_2})]$$

Exotic axial-vector interaction

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

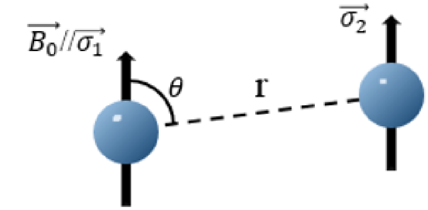
$$\omega_{\text{coupling}}[MHz]=\frac{\mu_0\gamma_1\gamma_1\hbar^2}{4\pi}\frac{3\cos^2\theta-1}{r^3}+4\frac{g_A g_A}{4\pi\hbar c}\frac{\hbar c}{r}e^{-\frac{r}{\lambda}}$$

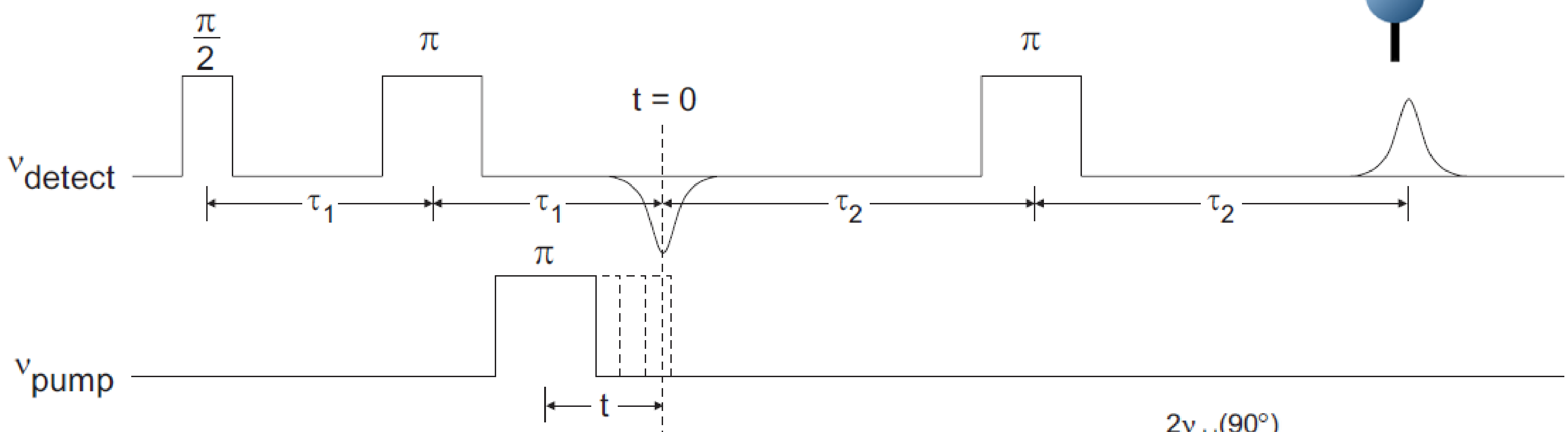
Magnetic dipole-dipole interaction

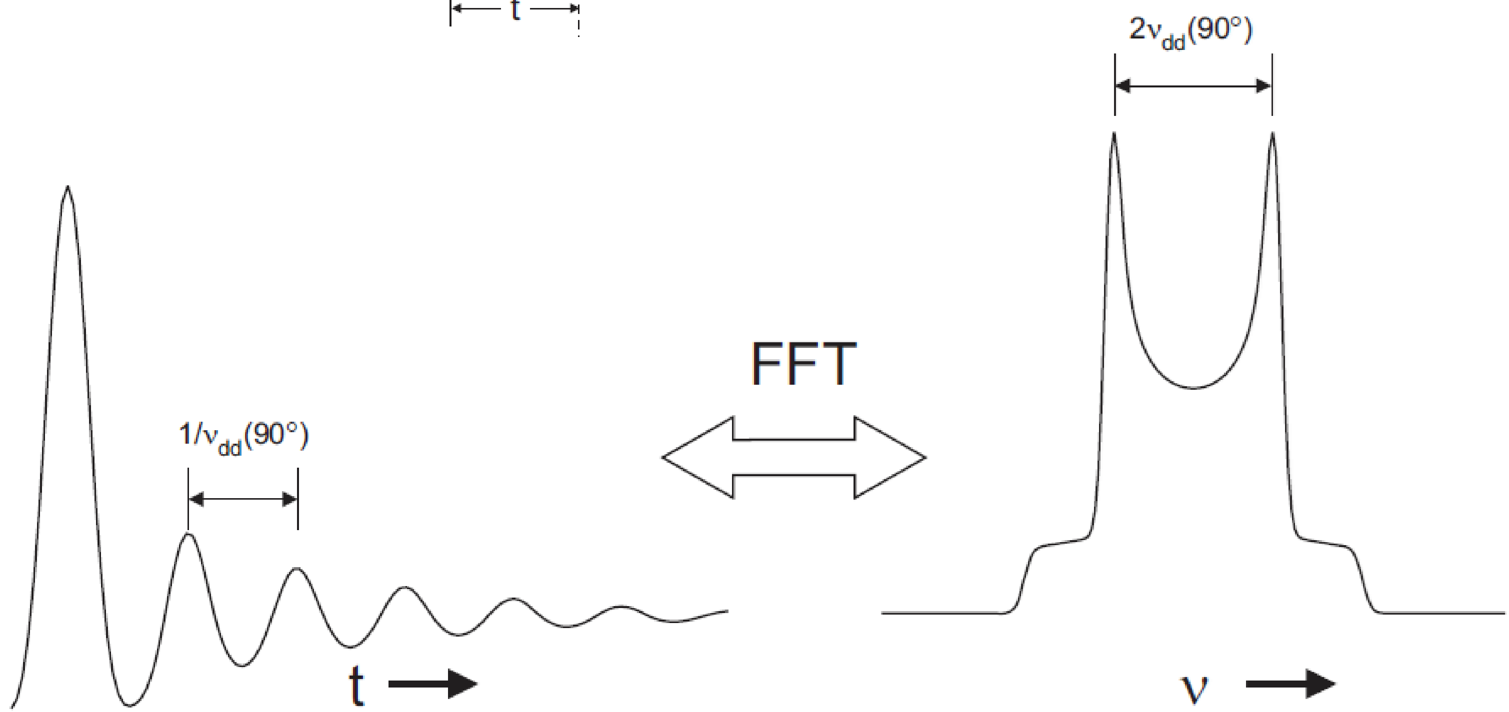
Exotic axial-vector interaction

Man Jiao et al., to be submitted (2018)

Measuring the coupling between two electron spins





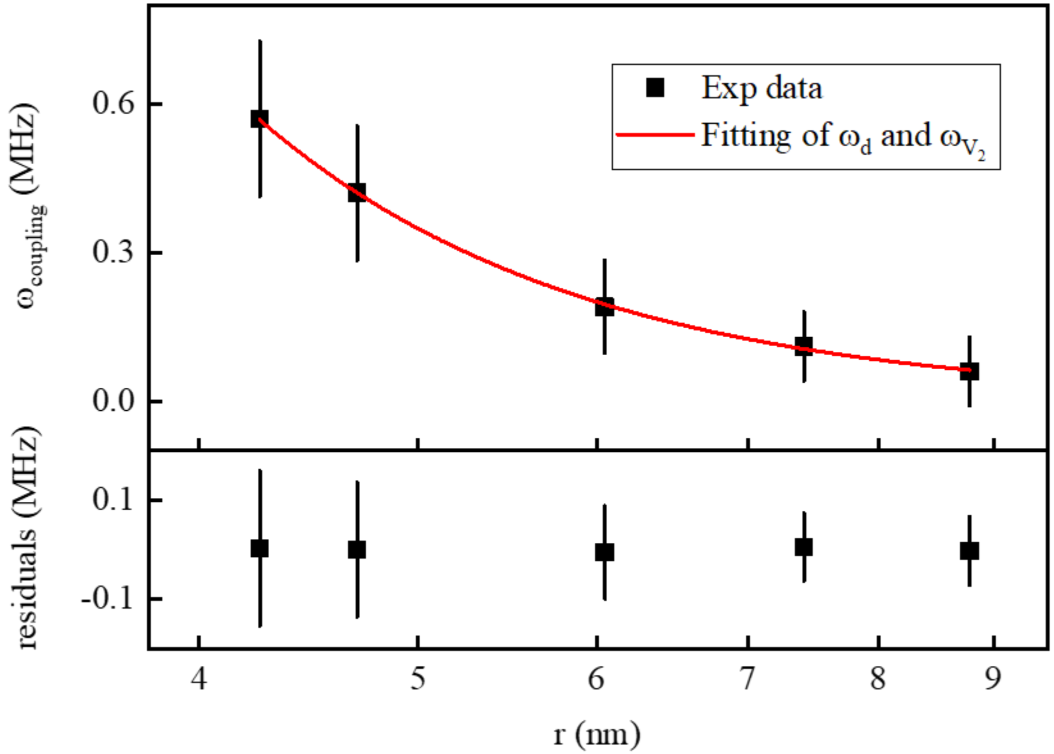


Pictures from Bruker’s manual

$$\omega_{\mathrm{coupling}}[MHz] = \frac{\mu_0 \gamma_1 \gamma_1 \hbar^2}{4\pi} \frac{3\cos^2\theta - 1}{r^3} + 4 \frac{g_A g_A}{4\pi\hbar c} \frac{\hbar c}{r} e^{-\frac{r}{\lambda}}$$

Magnetic dipole-dipole interaction

Exotic axial-vector interaction



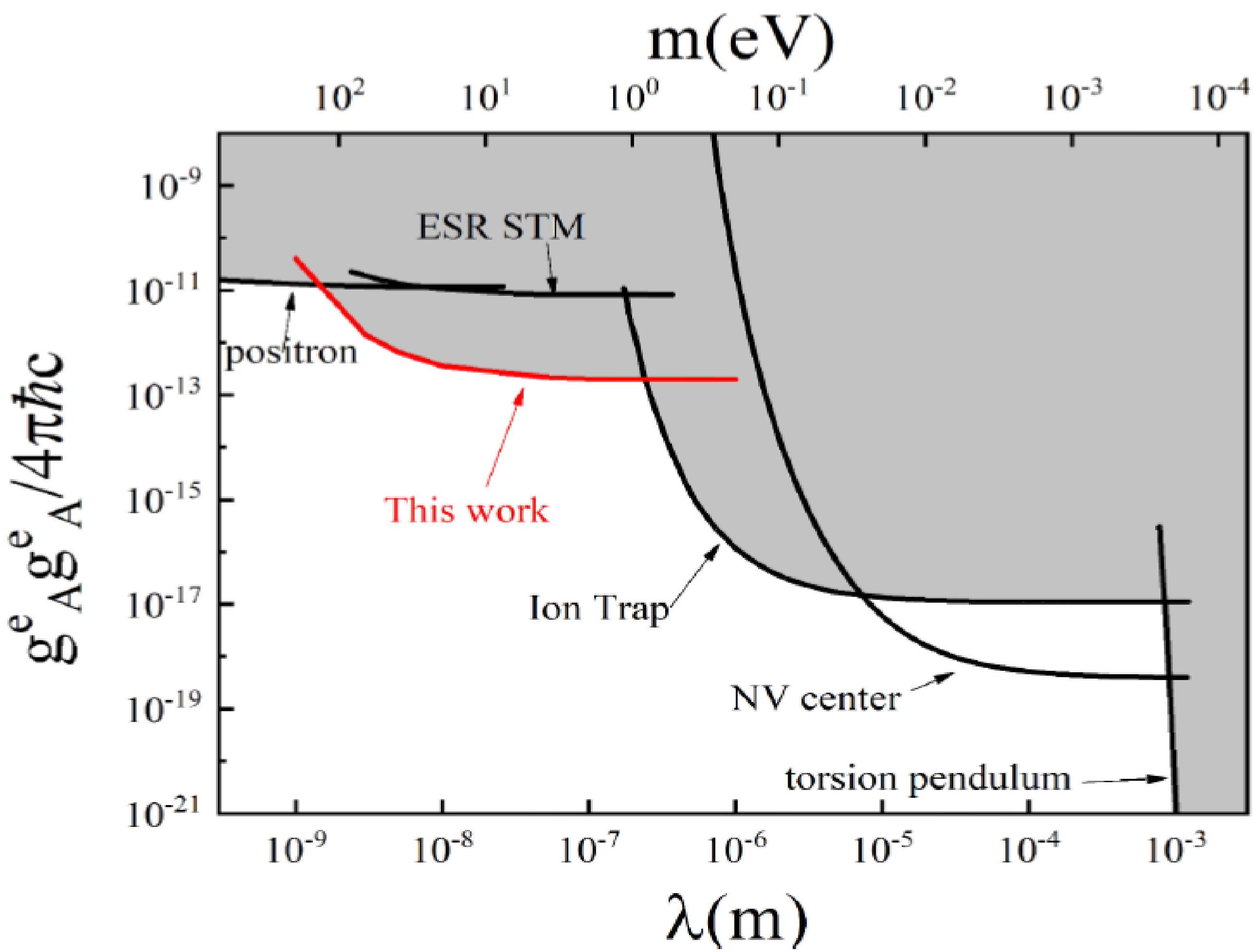
$\lambda = 500\ nm,$

$\frac{g_A g_A}{4\pi\hbar c} < 1.8 \times 10^{-13}$

(with 95% confidence level)

Man Jiao et al., to be submitted (2018)

Constraints on Exotic spin-spin interaction



Man Jiao et al., to be submitted (2018)

Summary

1. Spin is good platform to explore new physics beyond standard model
2. NV centers in diamond can be utilized as sensors for exotic spin dependent interactions
3. Chemistry also can contribute to this excited field

Acknowledge

spin.ustc.edu.cn

- Jiangfeng Du
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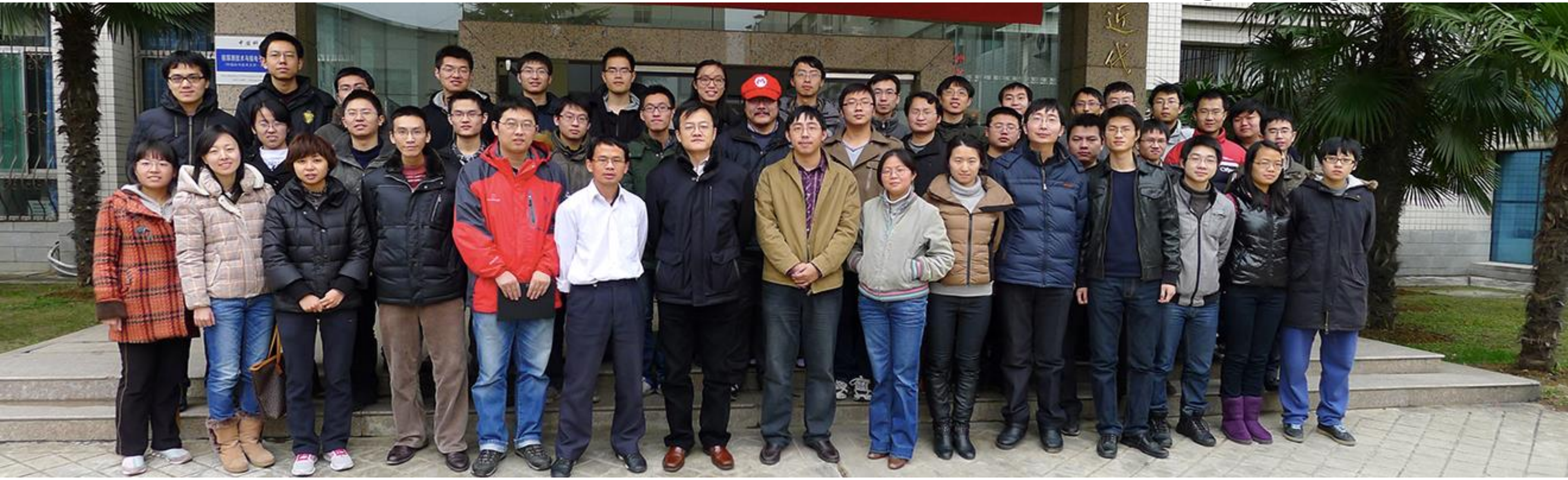
- Jihu Su
- Changkui Duan
- Chenyoug Ju
- Qi Zhang
- Xi Kong
- Xiaoting Wang



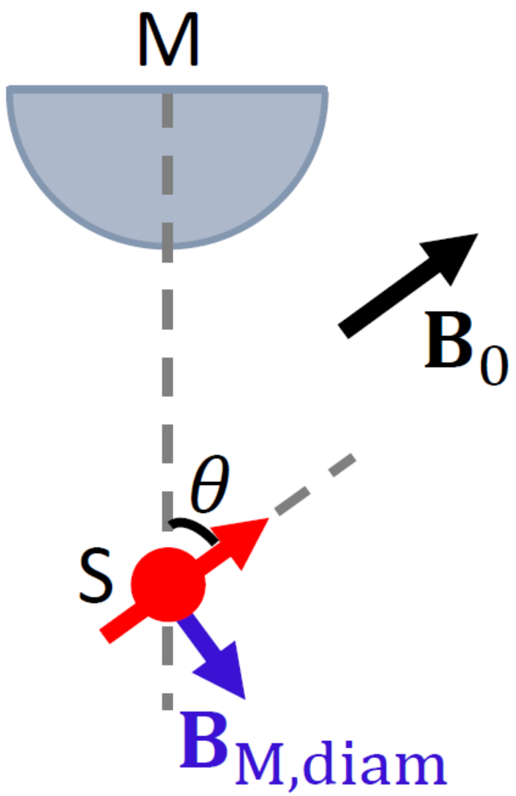
Hope for collaborations with you!

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

Error Analysis： Diamagnetism

Diamagnetism of the SiO2 half ball



If NV center locat

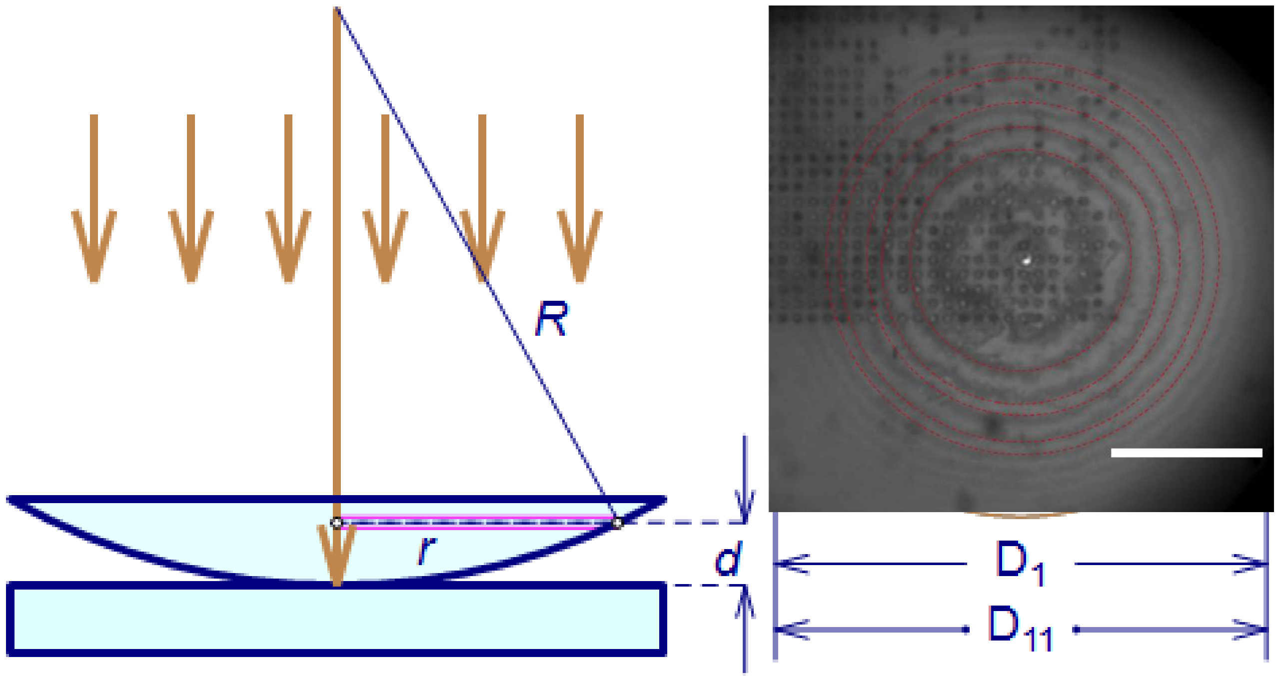
- 抗磁性导致的外磁场垂直于NV主轴

- NV 跃迁频率：~ 2 GHz

- $B_{M,diam}$导致的频率移动：~ mHz 对应相位为 10^{-10} rad

- 可以忽略抗磁性影响

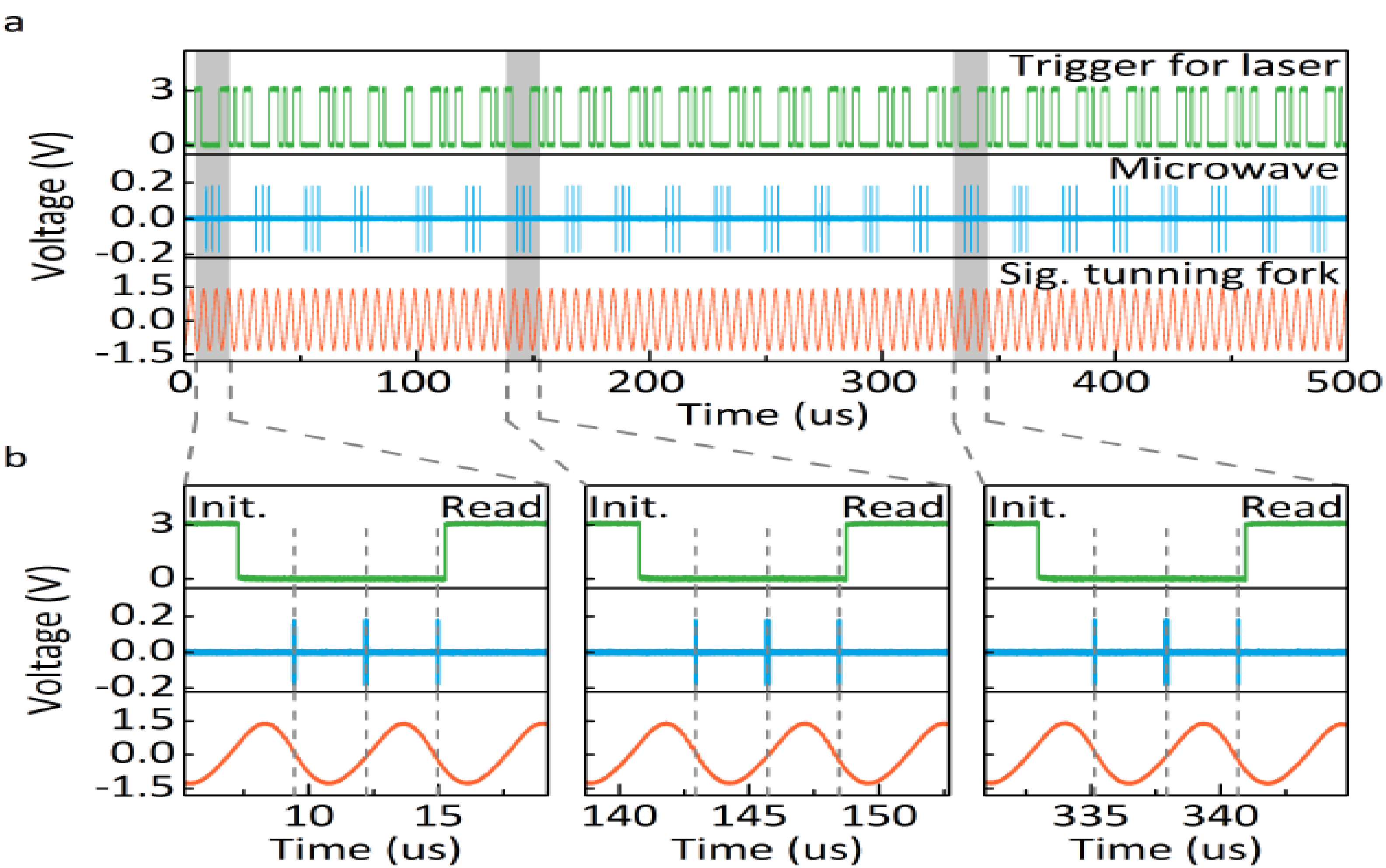
误差分析：定位误差



定位误差为 0.7(8) μm

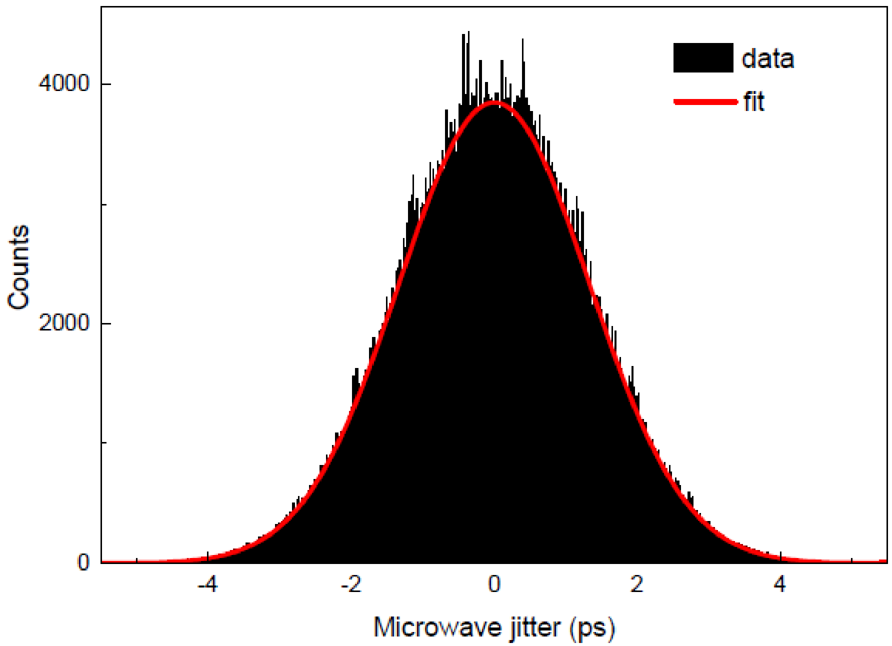
定位误差导致抗磁性对最终相位测量的误差为 3(3) $\times 10^{7}$ rad 远小于0.02 rad，可以忽略。

误差分析：时序



a
Trigger for laser
Microwave
Sig. tunning fork
Voltage (V)
3
0
0.2
0.0
-0.2
1.5
0.0
-1.5
0
100
200
300
400
500
Time (us)
b
Init.
Read
Voltage (V)
10
15
140
145
150
335
340
Time (us)

误差分析：相位抖动



微波源的相位抖动

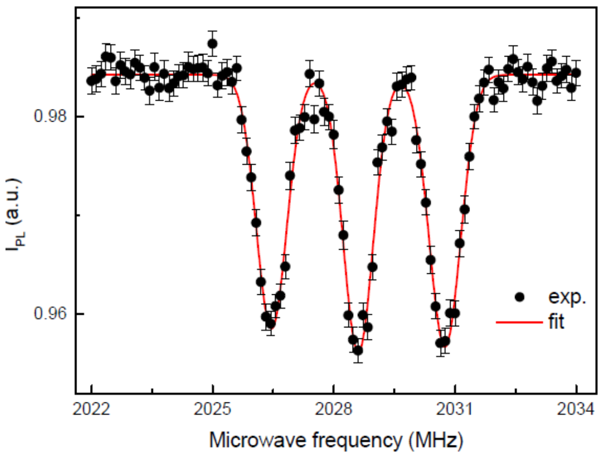
Observer operator: <Sx>

微波源相位抖动导致
观测算符不完美：
$\langle \cos(\delta)\, S_x + \sin(\delta)\, S_y \rangle$

相位抖动导致测量误差：
$3.5\times10^{-5} \pm 7.6\times10^{-15}$ rad

远小于 0.02 rad，可以忽略

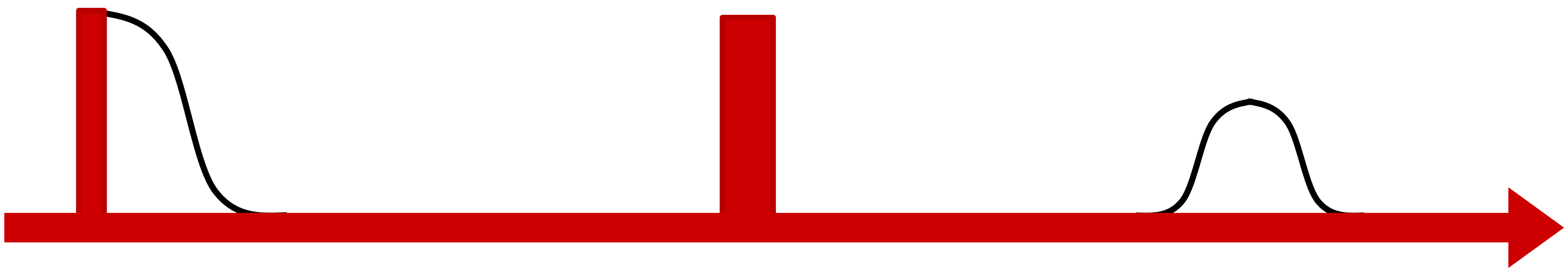
误差分析：退相干效应



核自旋热库诱导的展宽

$T_2^* = 0.67\ \mu s$

使用动力学解耦技术后可以极大提升相干时间至 8.3 μs



核自旋热库导致的误差 0± 1.3×10^{-14} rad