Precision measurement of the hyperfine constant for $^{9}Be^{+}$ in a linear Paul trap

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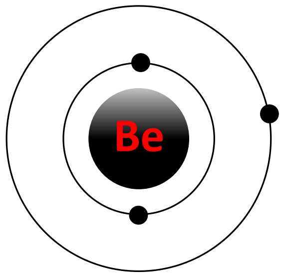
2026.05.18-22 PSAS ▪ Vienna

Outline

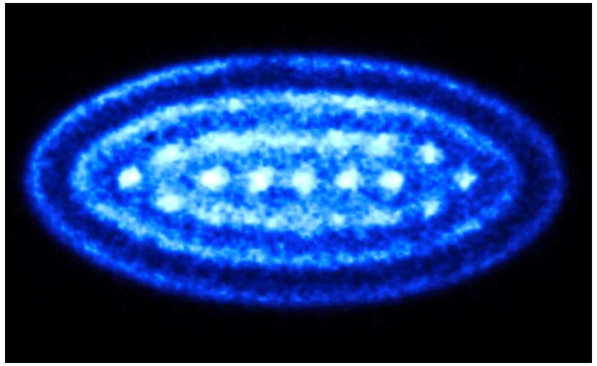
1. **Background and Motivation**
2. **Precision determination of hyperfine constant *A* for $^9Be^+$**
3. **Conclussion and outlook**

Background and Motivation



^{9}Be$^+$

^{9}Be$^+$ Coulomb crystal



- A few-body three-electron system， allowing for high precision QED calculation
- Forming Coulomb crystals after laser cooling
- Big charge mass ratio, good sympathetic coolants
- With 3/2 nuclear spin

Background and Motivation

☐ Hyperfine constant *A* and nuclear magnetic moment

- ***A*** stands for magnetic dipole hyperfine constant

$$A = \frac{2\mu_0}{3\pi}\mu_B \mu_I |\psi(0)|^2$$

nuclear magnetic moment

- Combining experiment measured *A* with theoretical calculations, the nuclear magnetic moment can be derived
- $|\psi(0)|^2$, Probability density of valence electrons at the nucleus. Substituting the nuclear magnetic moment can be used to test theoretical calculations

Background and Motivation

☐ Hyperfine constant *A* and Zemach Radius

- Zemach Radius，characterizing the spatial correlation between nuclear charge and magnetic moment distributions

$$r_Z = \int d^3r\, d^3r' \rho_e(r)\rho_m(r')|r - r'|$$

nuclear charge density　　magnetic moment density

- Comparing the experiment measured *A* with the QED calculated value based on point-nucleus model enables determining Zemach Radius

$$r_Z = \frac{a_0}{-2Z}\frac{A_{exp} - A_{theo}}{A_{exp}}$$

Qi X-Q, Zhang P-P, Yan Z-C, et al. Precision calculation of hyperfine structure and the Zemach radii of ^{6,7}Li^{+} ions. Phys Rev Lett, 2020, 125(18): 183002.

Background and Motivation

☐ Current state of ground state hyperfine constant *A* of ^{9}Be$^+$

*after diamagnetic correction

	Group	**Year**	**M fields**	***A* values / MHz**
Strong magnetic field (Penning Trap)	J. J. Bollinger	1983	0.82 T	-625.008 837 048(10)
	M. Wada	2002	0.47 T	-625.008 835 23(75)
	J. J. Bollinger	2011	4.4609 T	-625.008 837 371(11) -625.008 837 044(12)*
Weak magnetic field	J.Vetter（Hot steam）	1976	5×10^{-8} T	-625.009(25)
	M. Wada（Paul Trap）	1998	0.7 mT	-625.008 82(26)
	W. Nörtershäuser（Beam）	2009	Earth field	-624.97(4)

- Even considering the diamagnetic effect, there is still an error of 2.4σ
- Diamagnetic effect can be neglected under weak magnetic fields

Ouline

1. Background and Motivation

2. **Precision determination of hyperfine constant *A* for $^9Be^+$**

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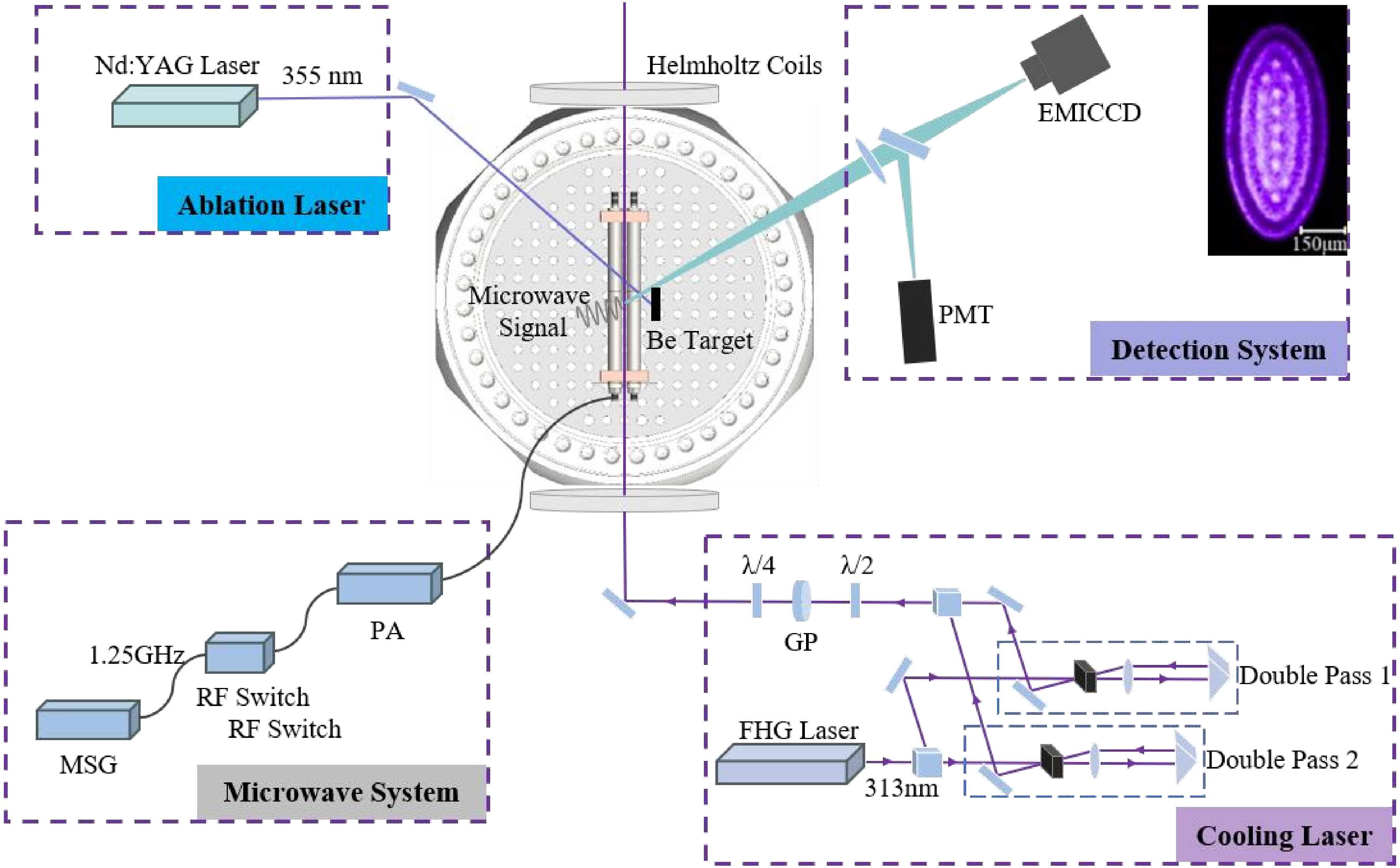
Precision determination of hyperfine constant *A* for ^{9}Be$^+$

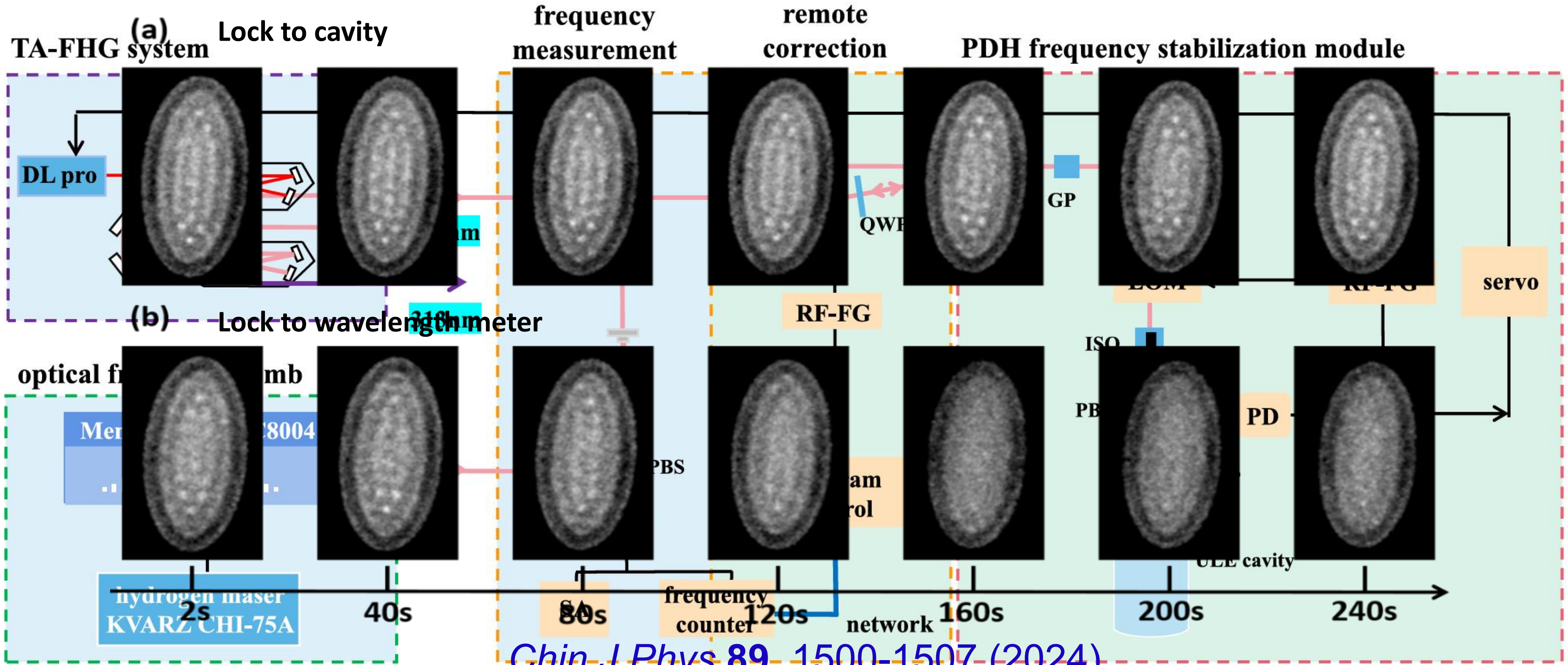
◻ Experimental setup



Precision determination of hyperfine constant *A* for ^{9}Be$^+$

◻ Preparation of stable ^{9}Be$^+$ Coulumb crystal

- 626 nm laser is locked to a ultra-stable cavity，resulting frequency instability of 1.8E-12@1s and 3.8E-15@1024
- ^{9}Be$^+$ Coulomb crystal maintains single-ion resolution in 240s



Chin.J.Phys **89**, 1500-1507 (2024)

Precision determination of hyperfine constant *A* for ⁹Be⁺

☐ Hyperfine constant *A* and involved physical quantities

- Based on Breit-Rabi parameterized framework, hyperfine splitting under magnetic field **B** for ground state can be expressed as:

$$\Delta E(x) = \Delta \mathbf{E}_{\mathbf{HFS}}[-\mathbf{g}_{\mathbf{I}}^{'} m_F x \pm \frac{1}{2}\sqrt{1 + \frac{4m_F}{2I+1}(\mathbf{g}_{\mathbf{J}} + \mathbf{g}_{\mathbf{I}}^{'})x + (\mathbf{g}_{\mathbf{J}} + \mathbf{g}_{\mathbf{I}}^{'})^2 x^2}]$$

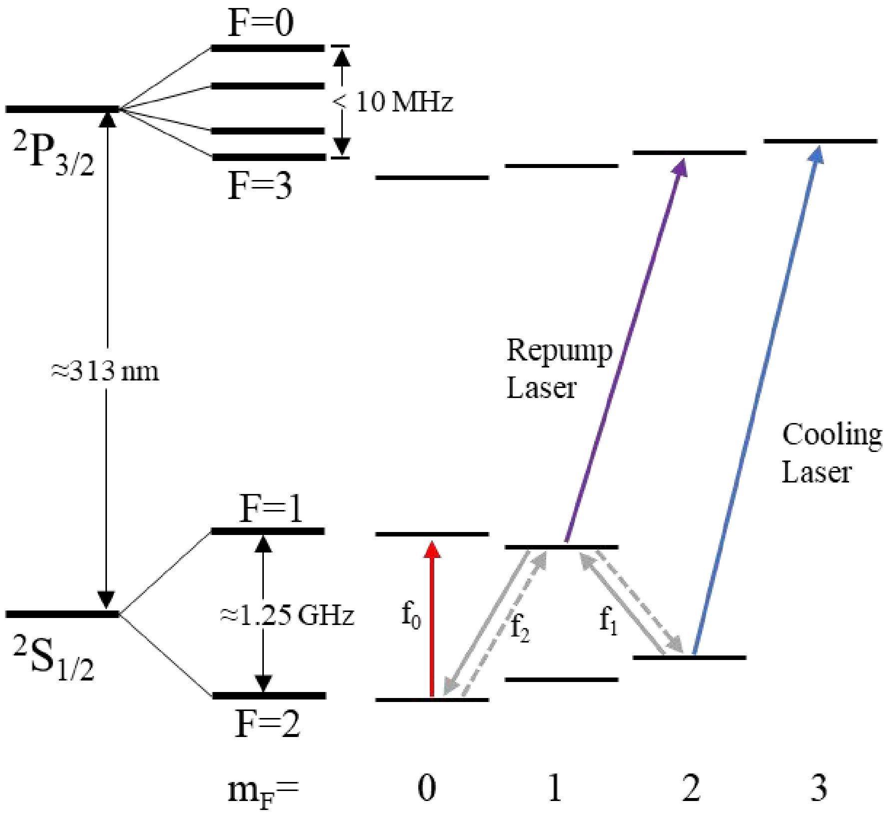
where $\Delta \mathbf{E}_{\mathbf{HFS}} = \mathrm{h}\boldsymbol{A}(I + \frac{1}{2})$, ***A*** stands for magnetic dipole hyperfine constant;

$x = \frac{\boldsymbol{\mu_B B}}{\Delta E_{HFS}}$, implied another physical constant $\boldsymbol{\mu_B}$

Precision determination of hyperfine constant *A* for $^9Be^+$

◻ Preparation and detection of magnetic field insensitive transition

- **Experimental scheme**



- **Sensitivity to magnetic field**

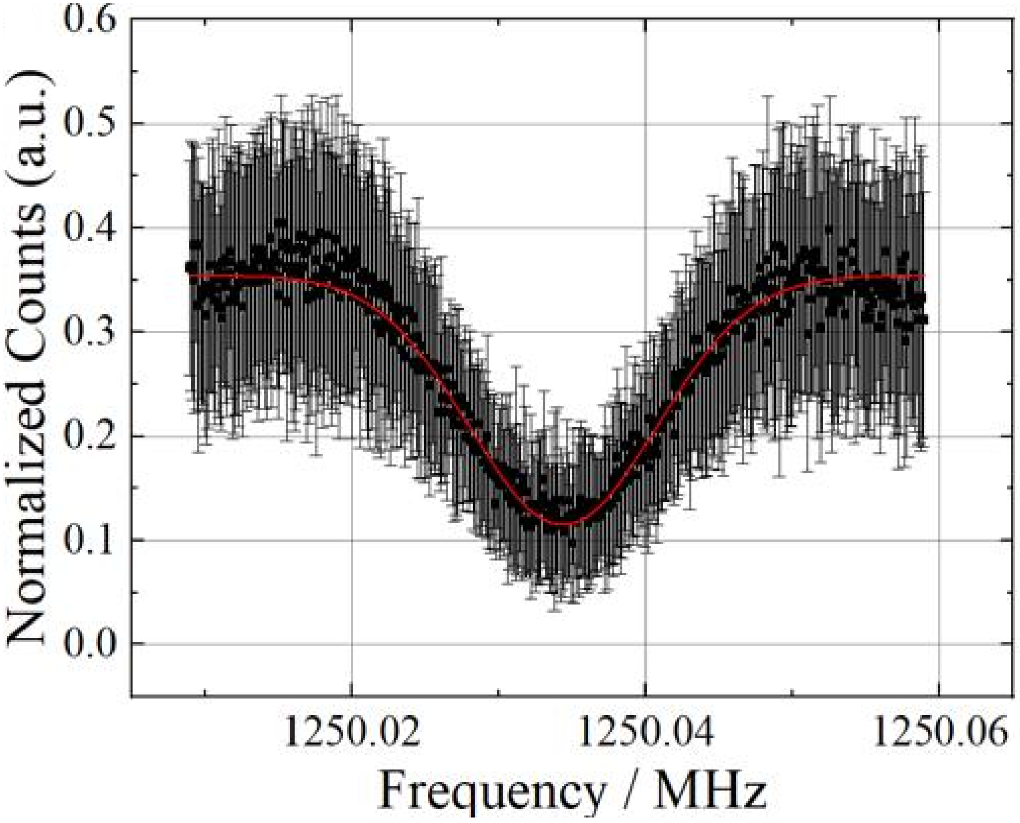
	1μT	10μT	100μT
$F=2, m_F=2$ to $F=1, m_F=1$	~21kHz/μT	~21kHz/μT	~21kHz/μT
$F=1, m_F=1$ to $F=1, m_F=0$	~7kHz/μT	~7kHz/μT	~7kHz/μT
$F=1, m_F=0$ to $F=1, m_F=0$	~0.6Hz/μT	~6Hz/μT	~60Hz/μT

- **Experimental sequence**
  - Optically pump to $F=2, m_F=2$
  - Two pulse transfer to $F=2, m_F=0$
  - Drive target transition
  - Transfer the remaining ions back to $F=2, m_F=2$
  - Detecting by measuring the flurescence reduction

Precision determination of hyperfine constant *A* for $^9Be^+$

□ Spectrum of magnetic field insensitive transition

- Measuring the relative change in the population by varying the frequency of the microwave

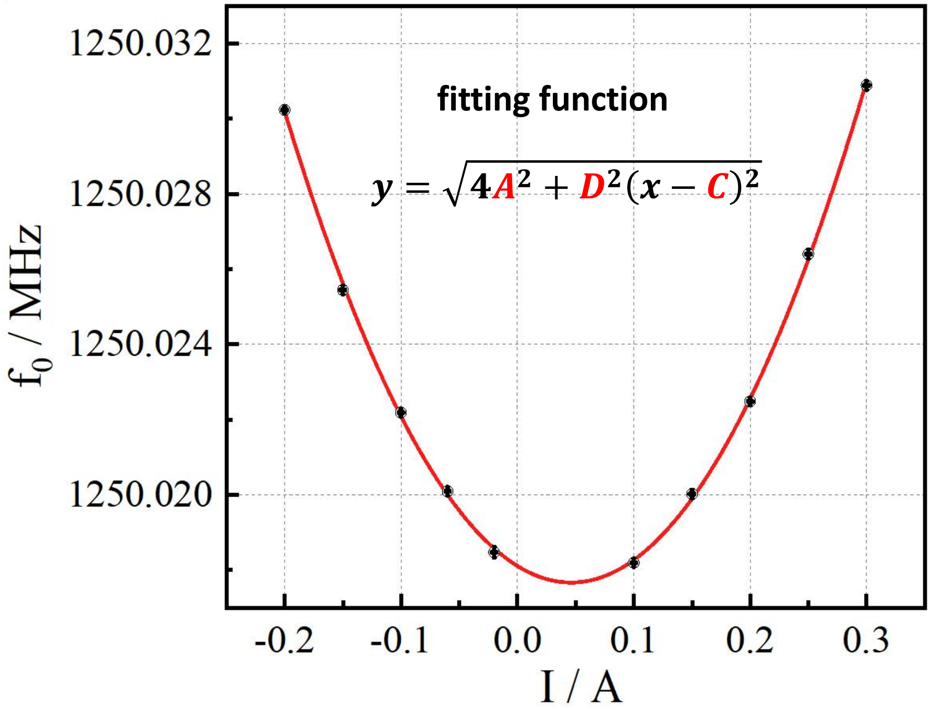


- $F=2, m_F=0 \rightarrow F=1, m_F=0$ @0.3A coil current (~190μT)

Precision determination of hyperfine constant *A* for ^{9}Be$^+$

☐ Determination of hyperfine constant *A*

$$f_{00}=\frac{\Delta E_{HFS}}{h}\sqrt{1+\left[\frac{\mu_B(g_J-g_I{}')}{\Delta E_{HFS}}\right]^2 B^2}=\sqrt{4A^2+\left[\frac{\mu_B(g_J-g_I{}')}{h}\right]^2 B^2}$$



- f_{00}: magnetic field insensitive transition frequencies
- *A* : hyperfine structure constant in near-zero filed
- $D=\frac{\mu_B(g_J-g_I{}')}{h}k$, k current to magnetic field coversion coefficeint
- C: current offset from zero magnetic field ($B=k(I-C)$)

$A=-625.008833(34)$ MHz

$D=22.8(1)$ MHzA^{-1}

$C=0.0462(6)$ A

Phys.Rev.A 113,042822 (2026)

Precision determination of hyperfine constant *A* for $^9Be^+$

☐ systematic error evaluation

- Determination of *A* : $\mathbf{-625.008833(35)\ MHz}$ (5.6×10^{-8})
- Statistical error represents the maximum error due to the magnetic field drifts
- Errors arising from magnetic field inhomogeneity, microwave frequency uncertainty, power broadening and the electric field are negligible

Source of uncertainty	Shift (Hz)	Uncertainty (Hz)
Statistical error	0	34
Magnetic field inhomogeneity	0	0.02
Second-order Doppler	0.058	0
Microwave signal generator (MSG)	0	0.003
Lifetime	17.4*	1.4
Total	0	35

Precision determination of hyperfine constant *A* for ^{9}Be$^+$

☐ Zemach radius

- Bohr radius（CODATA2022)
- Experimental determination *A* value： -625.008833(35)MHz
- Theoretical value from Pachucki: -625.3927(36)(16)MHz

$$r_z = \frac{a_0}{-2Z} \frac{A_{exp} - A_{theo}}{A_{exp}}$$

- Zemach radius of ^{9}Be$^+$ is determined to be **4.03(5) fm**

M. Puchalski and K. Pachucki, Ground-state hyperfine splitting in the Be+ ion. Phys Rev A, 2014, 89, 032510

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Conclusion

- Zero-field ground-state hyperfine constant: −625.008833(35) MHz (5.6×10^{-8})
- Combining experimental and theoretical value, ^{9}Be’s nuclear Zemach radius is calculated as 4.03(5) fm.

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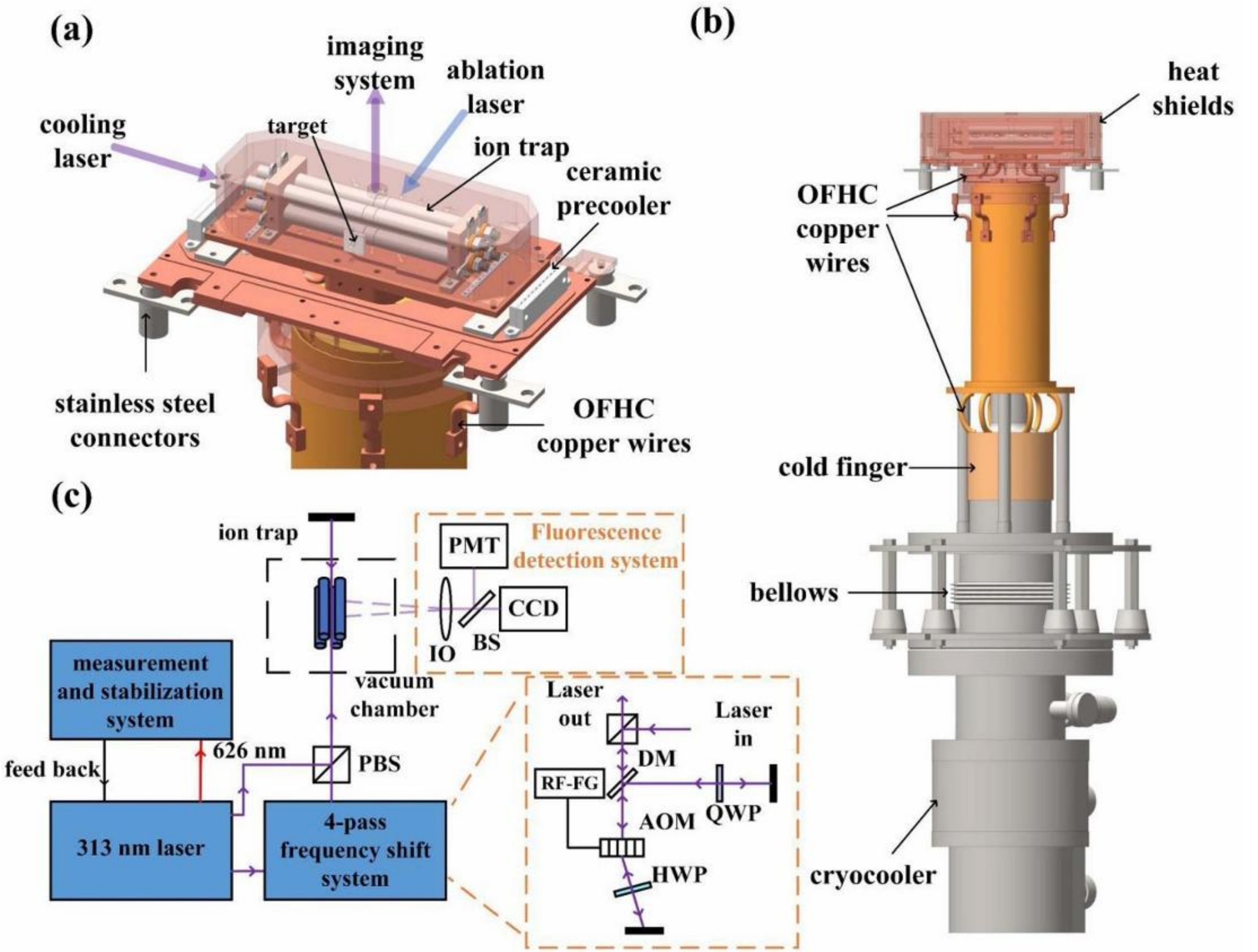
	W. Nörtershäuser (Beam)	2009	Earth field	-624.97(4)
	Our work (Paul Trap)	2025	<0.3 mT	−625.008 833(35)
Theory	V. A. Yerokhin	2008	\	-625.08(2)
				-625.11(3)
	K. Pachucki	2014	\	-625.3927(36)(16)

Outlook

◻ Doing better

- Adding magnetic shielding to reduce the effects of magnetic field fluctuations and magnetic field gradients
- Increase the vacuum level to reduce the effect of ion lifetime



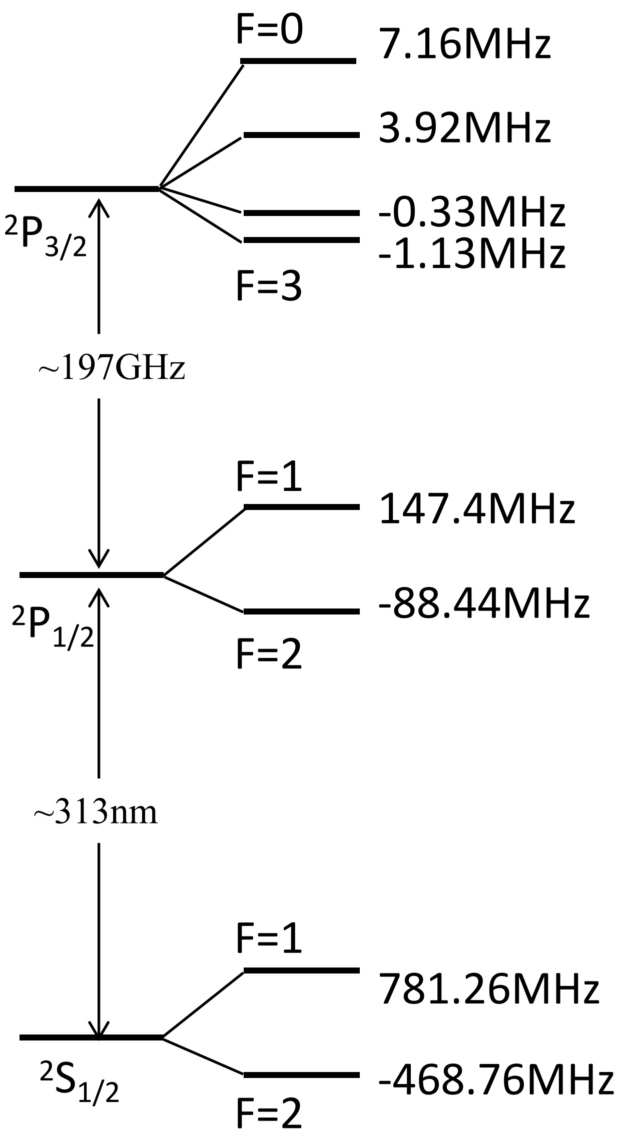
J.Phys.D:Appl.Phys.59,025205 (2026)

Outlook

☐ Going futher

- Determination the hyperfine constant $A_{P_{1/2}}$ for $^2P_{1/2}$ state
- Determination the hyperfine constant $A_{P_{3/2}}$ and $B_{P_{3/2}}$ for $^2P_{3/2}$ state

	Theory		**Experiment**
$A_{P_{1/2}}$	-117.919(4)	-117.932(3)	-117.92(4)
$A_{P_{3/2}}$	-1.015(3)	-1.026(3)	-1.01(2)
$B_{P_{3/2}}$		-2.29940(3)	-2.23(8)



Acknowledgement

Group leader: Tong Xin

Group member: Peng Wencui, He Shengguo, Hua Xia

Graduate student: Zhang Qianyu,Bai Wenli, Ao Zhiyuan, Qiao Xiaoxiao, Li Zi, Wang Chen, Gan Wenting, Ding Yanhao

中华人民共和国科学技术部
Ministry of Science and Technology of the People's Republic of China

NSFC
National Natural Science Foundation of China
国家自然科学基金

中国科学院
THE CHINESE ACADEMY OF SCIENCES

中国科学院精密测量科学与技术创新研究院
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