深圳先进光源研究院
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Postselection shifts the transition frequency of helium in an atomic beam

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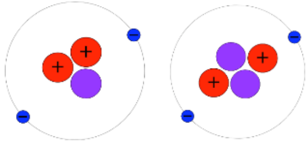
Outline

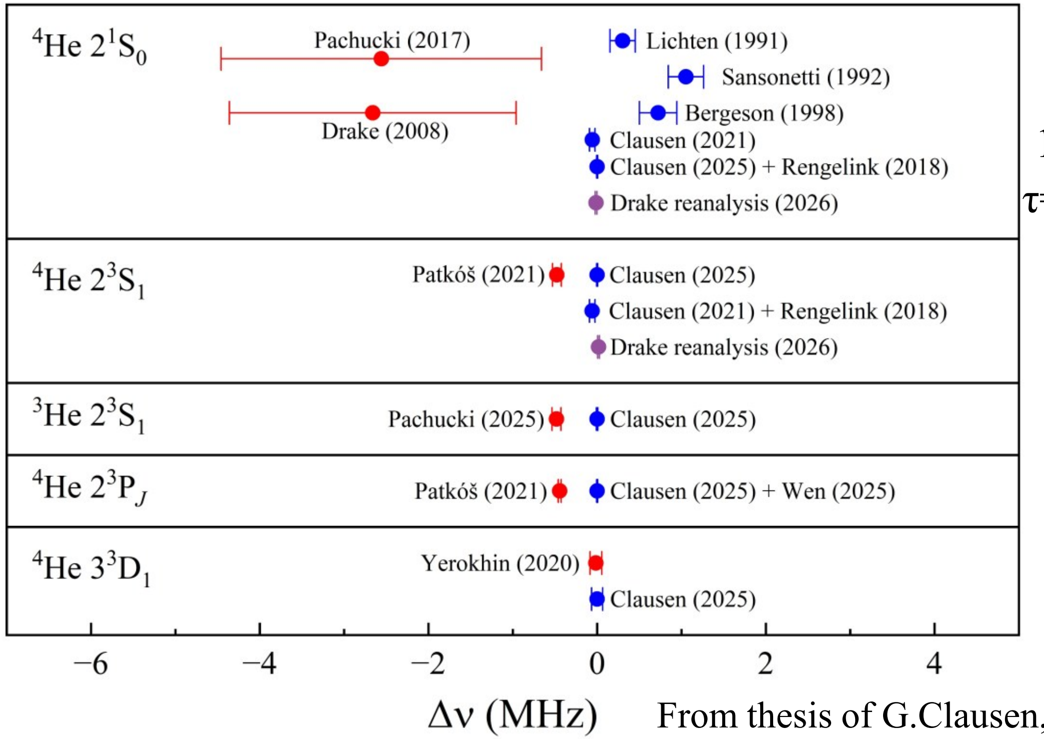
- Background & Former Experiment
- Postseletion effect & 2^3S-2^3P transition frequency of ^4He
- Magneto-Optical Deflection method for ^3He measurement

Background

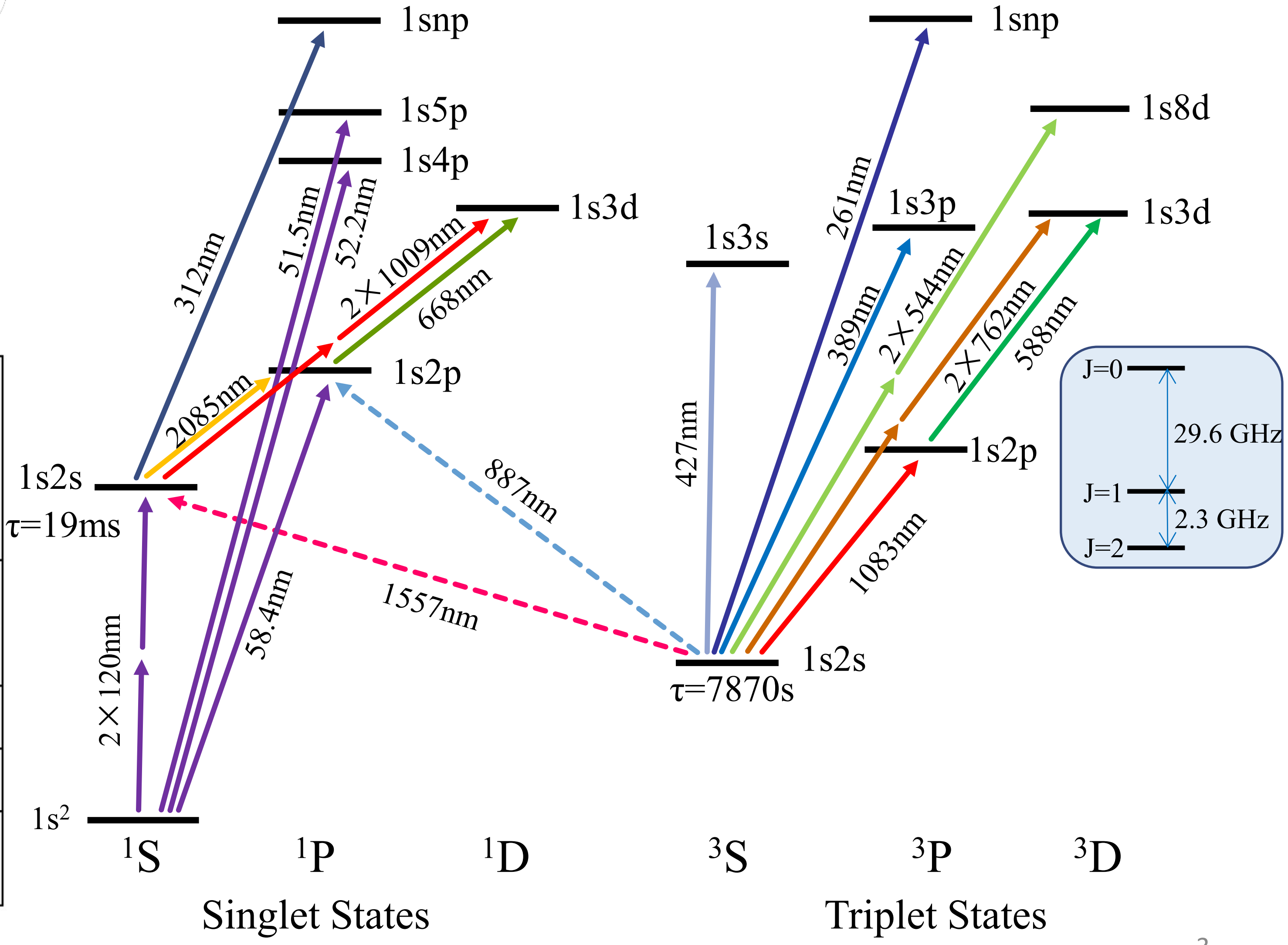
Helium



- Transition frequency → $\delta r^2 = r_h^2 - r_\alpha^2$
- FS of 2^3P → Fine-structure constant α
- High-n Rydberg → Ionization energy
- Tune-out wavelength



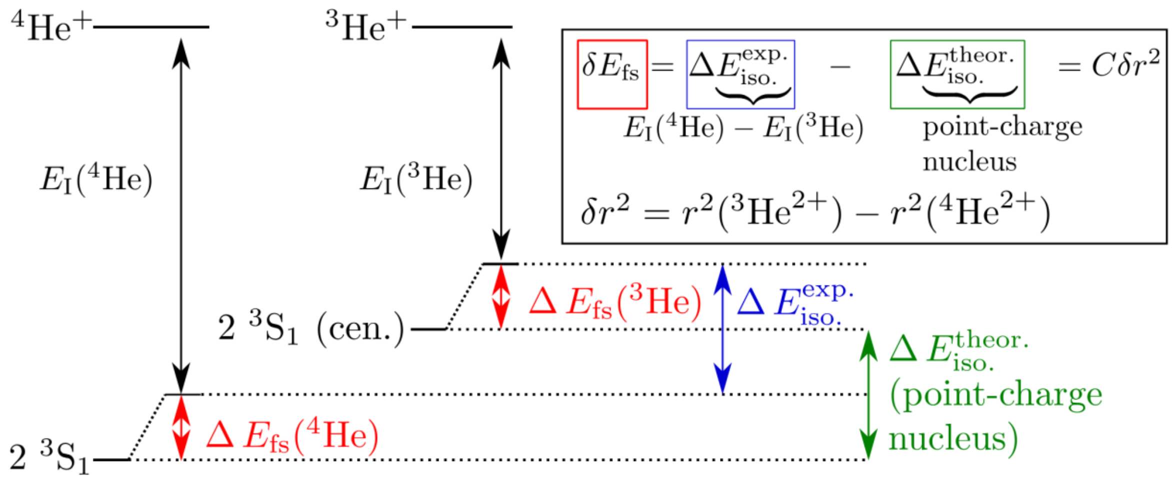
From thesis of G.Clausen, ETH(2025)



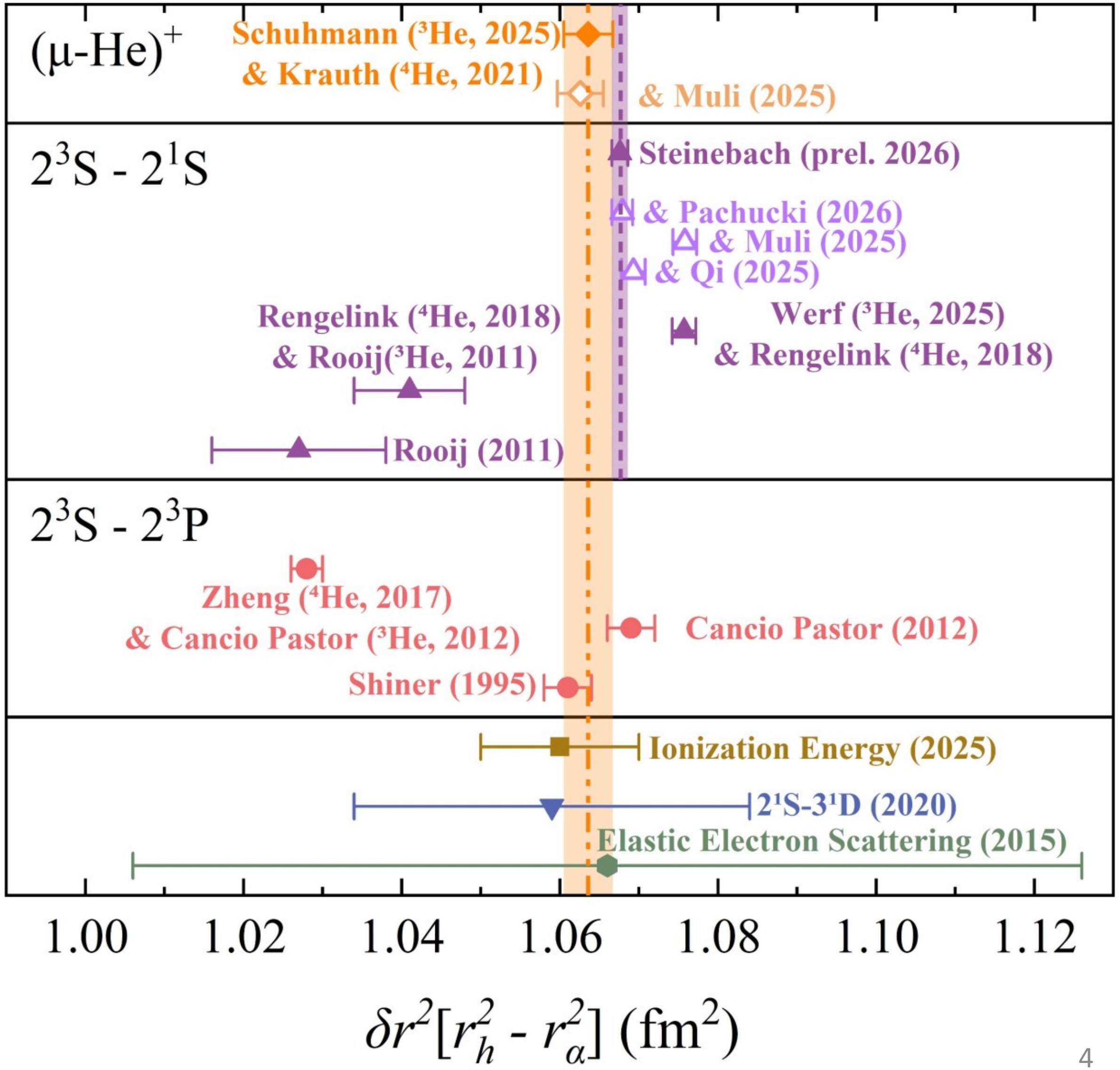
Background

Helium Isotope Shift

- More precise than one nuclide



Phys. Rev. Lett. **134**, 223001(2025)

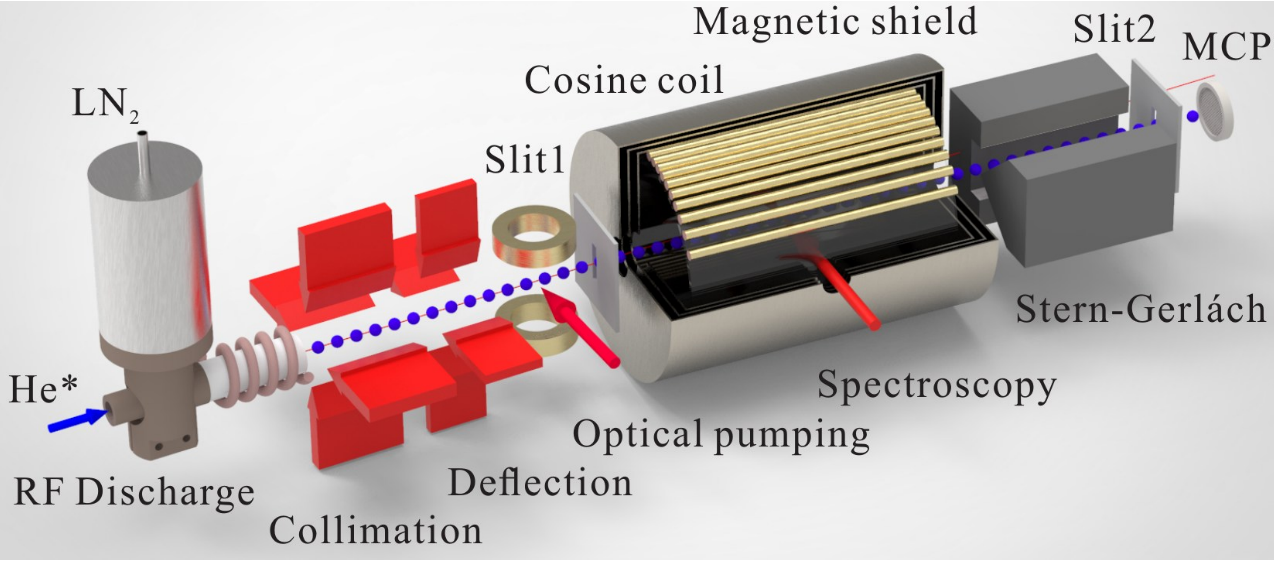


- μ-He$^+$ and 2^3S-2^1S almost in agreement
- Need more transition to confirm

Former Experiment

Spectroscopy experiment in a helium beam

- Transverse Cooling and active deflection
- Single state detection by OP and SGM
- 1.6 kHz precision for 2^3S-2^3P in 2017, but deviated nearly 50 kHz from saturation fluorescence result.
- Mainly originated from first-order Doppler



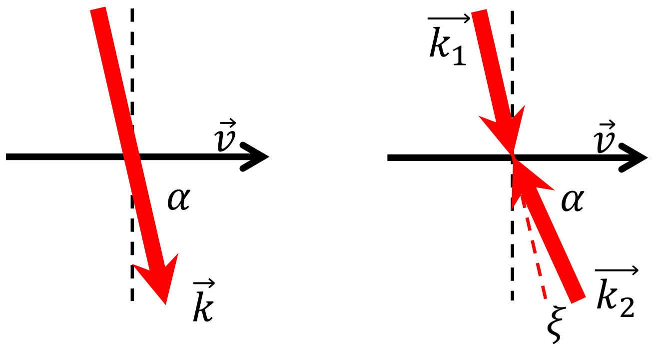
Source	Corrections	$\Delta f\,(1\sigma)$
Statistics		0.45
First-order Doppler		1.1
Second-order Doppler	+0.70	0.15
Frequency calibration		0.55
Quantum interference	+0.60	0.10
Laser power		0.10
Zeeman effect		0.01
Recoil shift	−42.48	
Line profile		0.30
Light-force-induced shift	+0.50	0.80
Total	276 734 477 704.0	1.6
Cancio Pastor *et al.*	276 734 477 752.5	2.1

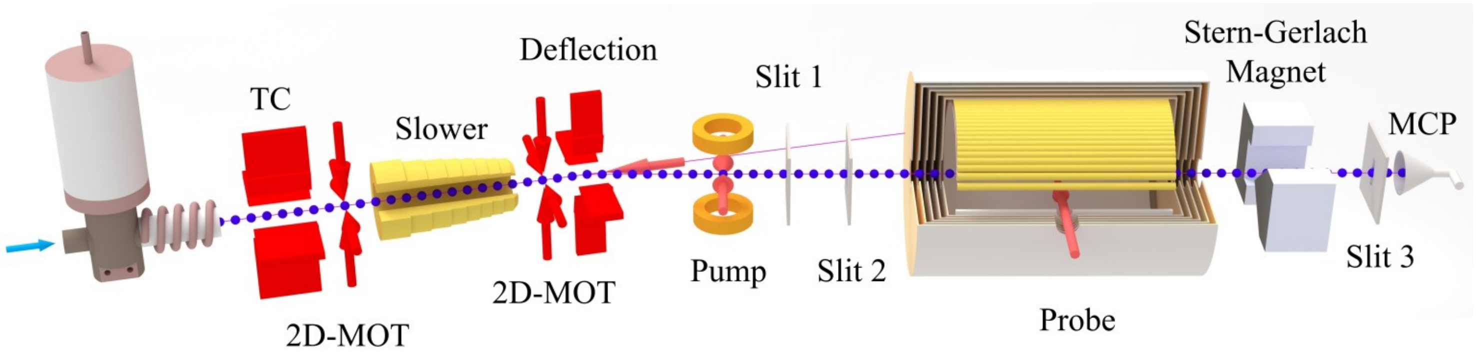
Phys. Rev. Lett. **119,** 263002 (2017)
Phys. Rev. A **99,** 032506 (2019)

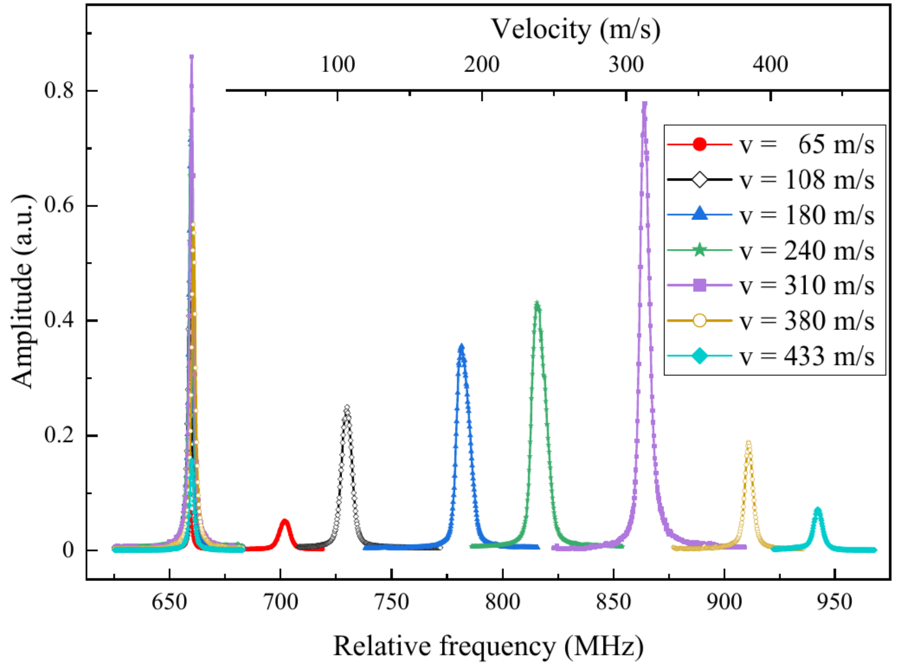
Former Experiment

Reduce influence of Doppler effect

- Doppler shift $\Delta\nu = \frac{\vec{k}\cdot\vec{v}}{2\pi}$
- Residual Doppler shift $\delta\nu_D \approx \nu_0 \frac{v}{c}\frac{\xi}{2}$
- Reduce longitudinal velocity using Zeeman slower from 700 m/s to 50 ~ 450 m/s
- Evaluate error by velocity extrapolation





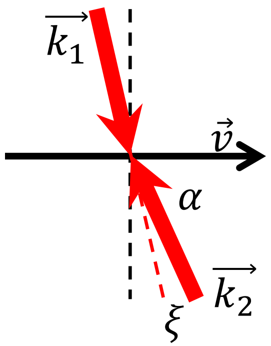


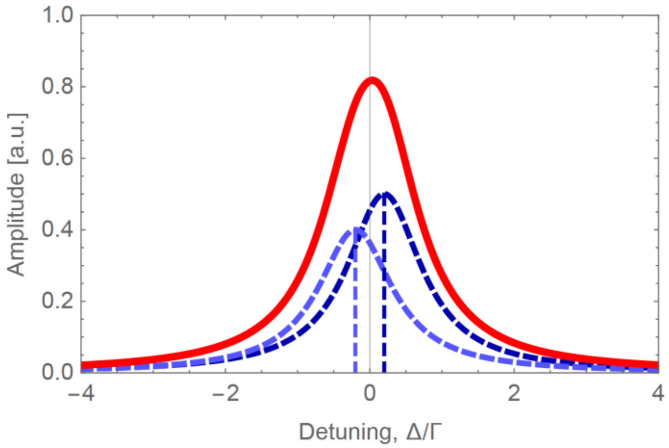
Phys. Rev. A **101**, 053824 (2020)

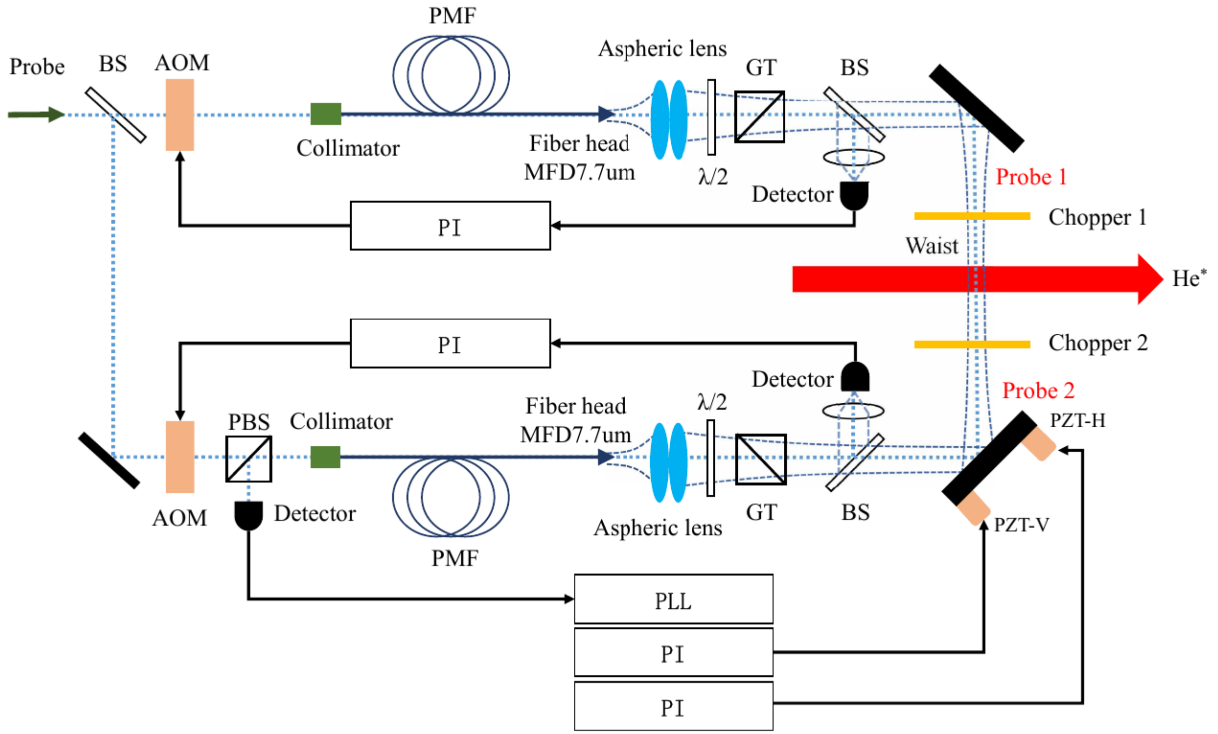
Former Experiment

Doppler-free spectroscopy in traveling-wave fields

- Standing-wave: envelope of both sides
  - ➢ perpendicular to atomic beam
  - ➢ balanced power on both sides



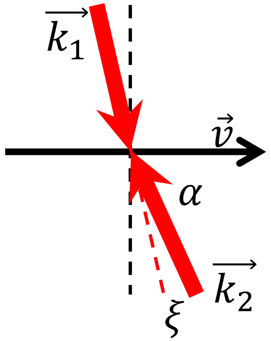




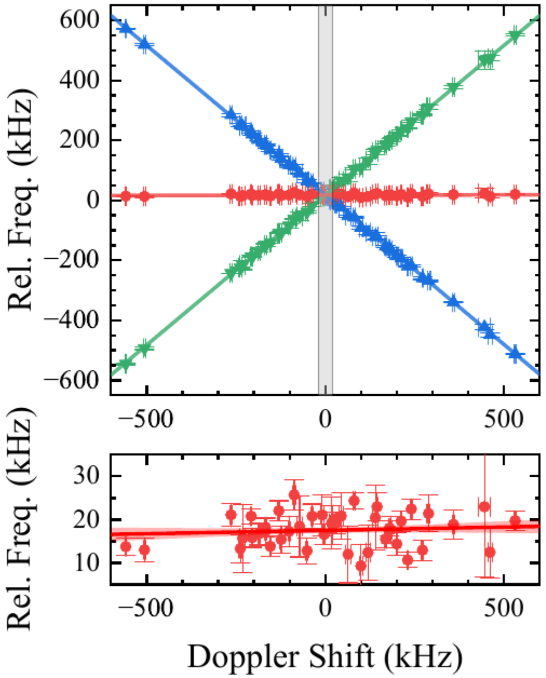
- Traveling-wave: fit on each side and average
  - ➢ switch choppers to detect on each side
  - ➢ keep overlapping with feedback loops

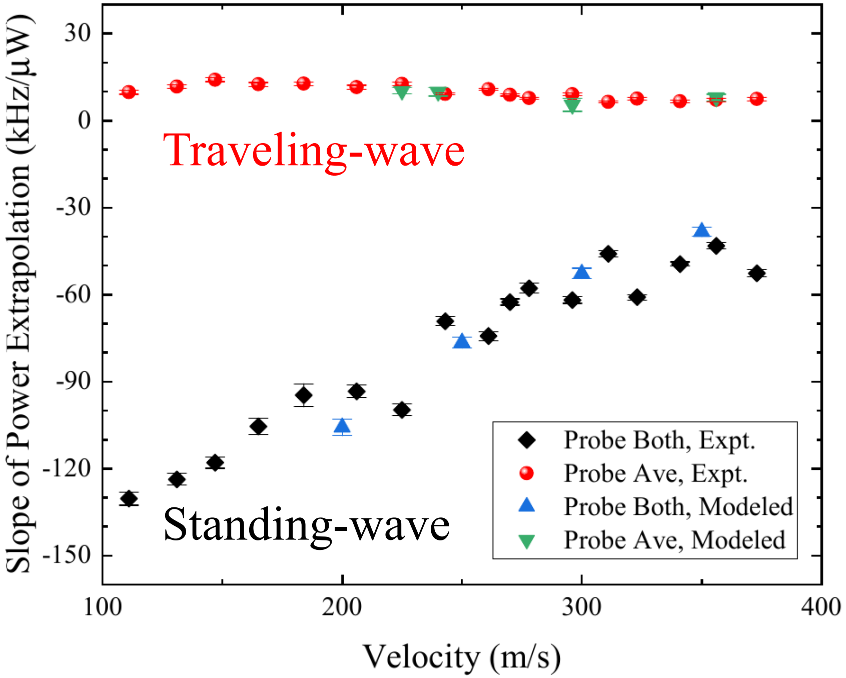
Former Experiment

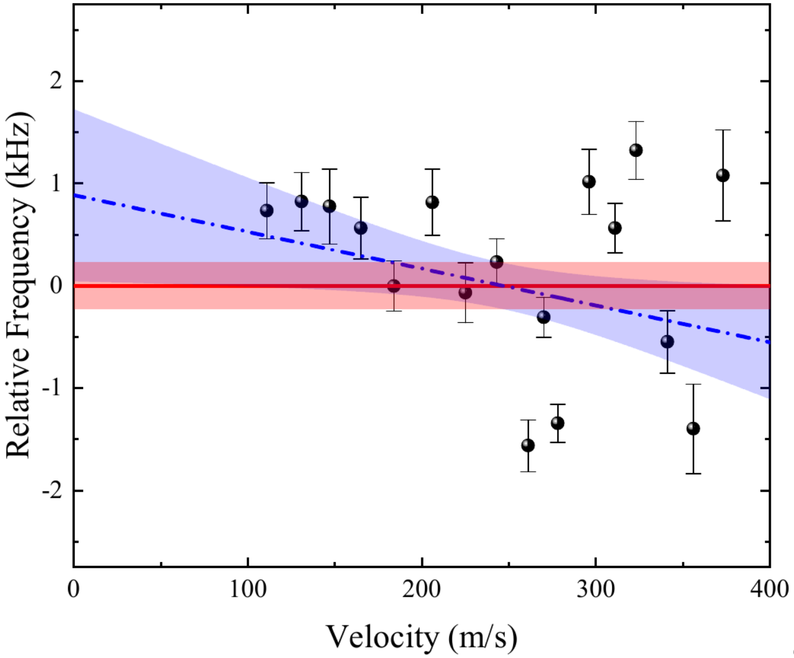
Doppler-free spectroscopy in traveling-wave fields



- Expand laser incident range
- Lower power dependence and insensitive to speed
- $\xi \approx 7.8 \pm 6.9$ μrad, comparable to standing-wave methods
- Influence of Doppler effect < 1 kHz





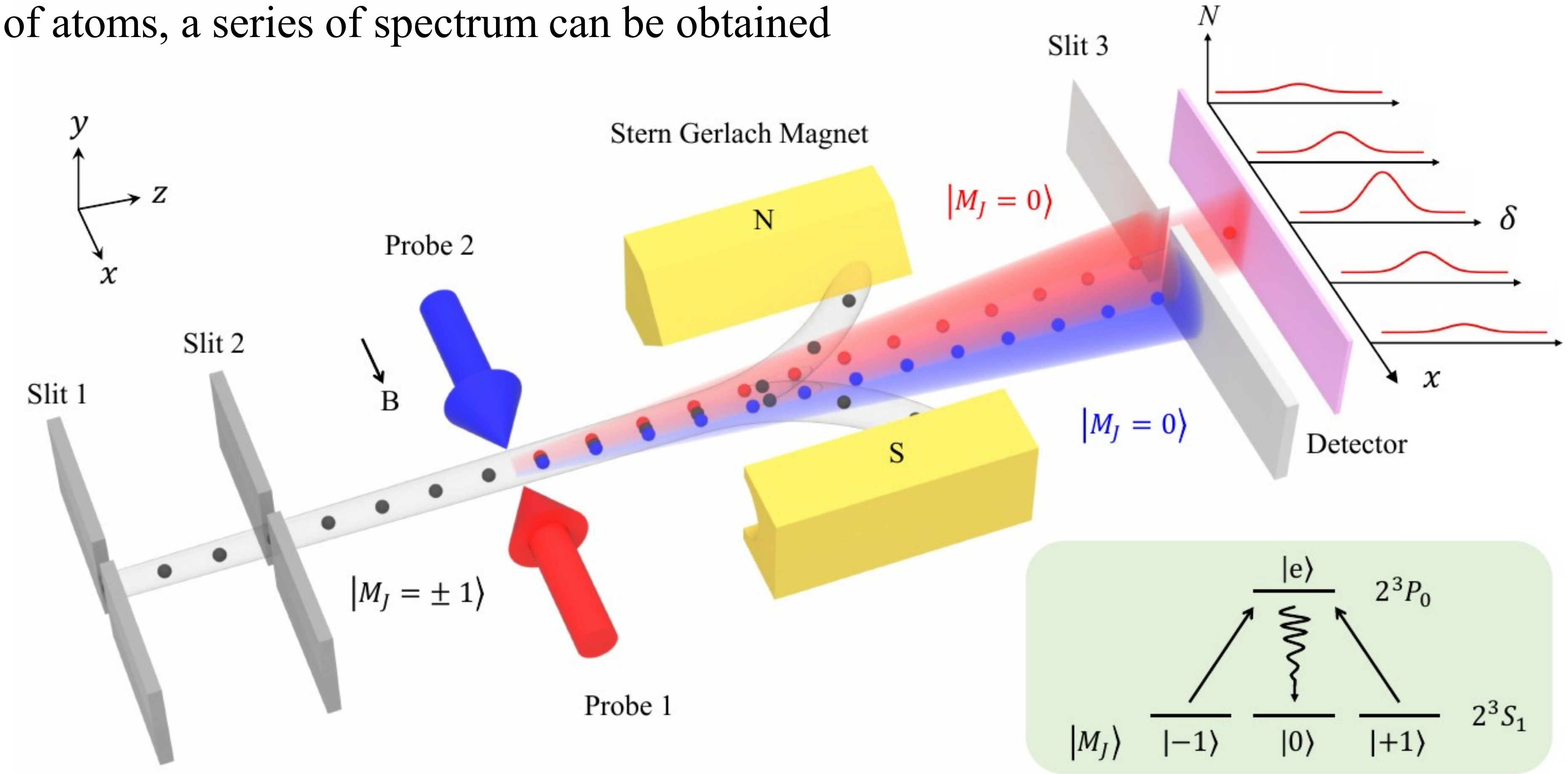


Phys. Rev. A **109**, 042811 (2023) (Editors' Suggestion)

Postselection effect & 2^3S-2^3P frequency of ^4He

Postselection effect

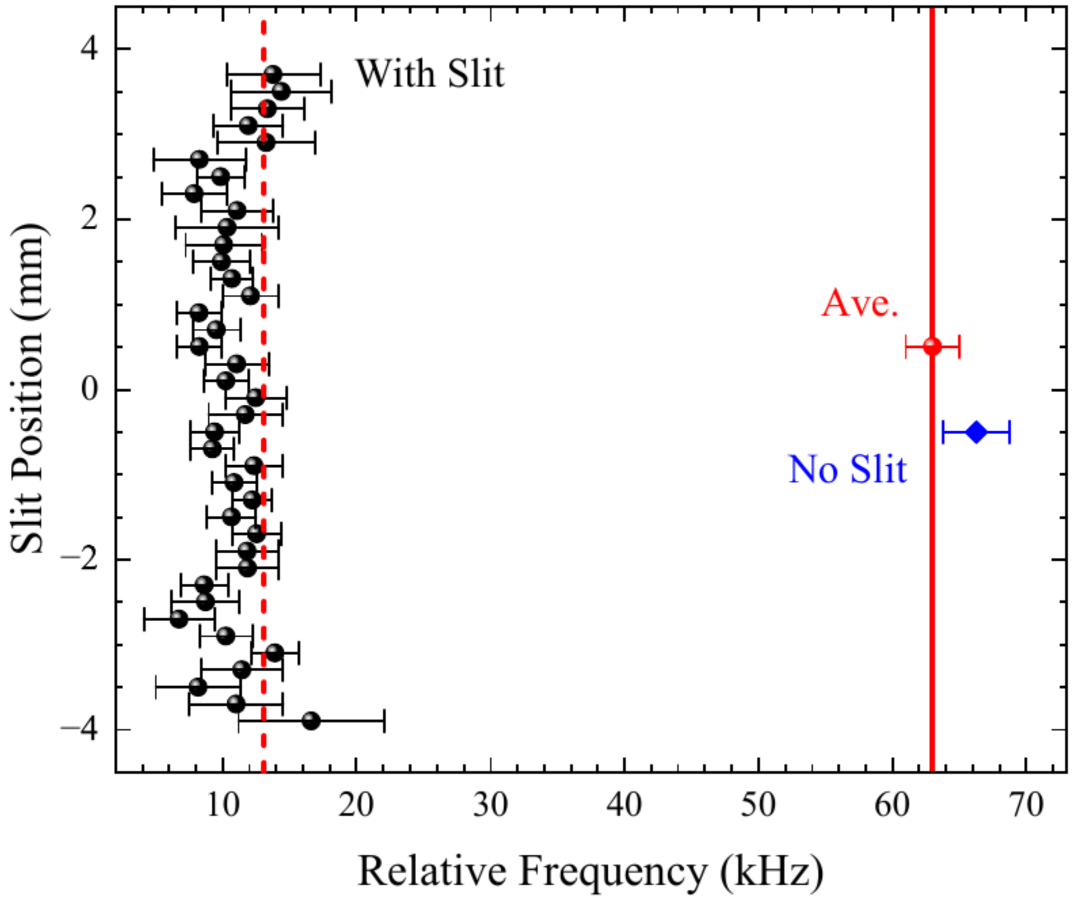
- By changing the position of the slit, the scanning frequency and recording the number of atoms, a series of spectrum can be obtained

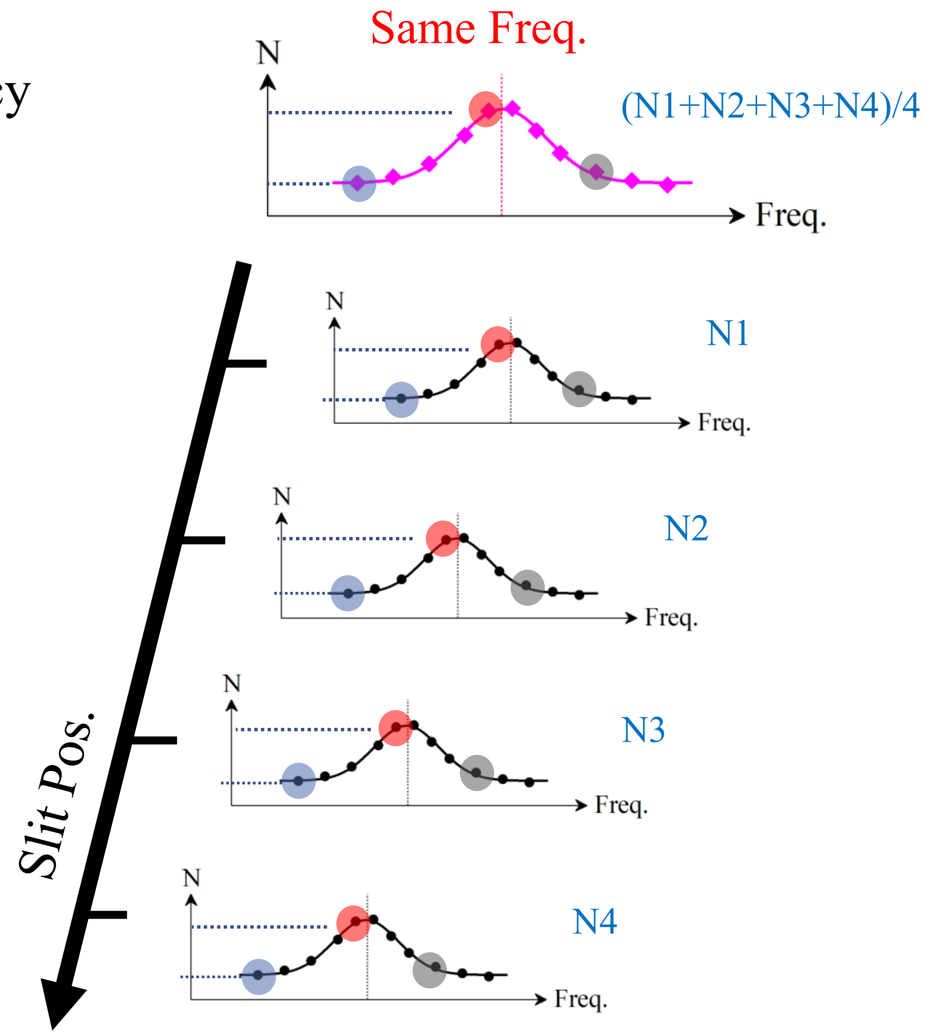


Postselection effect & 2^3S-2^3P frequency of ^4He

Postselection effect

- Measure at every pos. and average data with the same frequency
- A slit in front of the detector or not causes 50 kHz deviation.

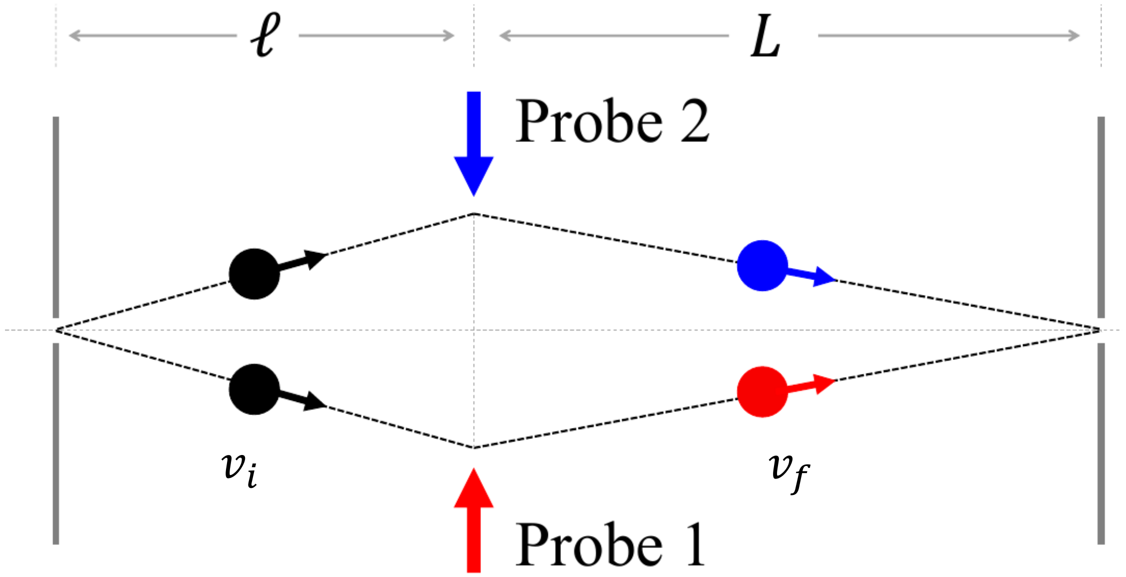




Postselection effect & 2^3S-2^3P frequency of ^4He

Postselection effect

- Simple model: Only atoms with an initial velocity $v_i = -v_R \frac{L}{\ell+L}$ can pass through the slit.
- Both sides are redshifted, and postselection shift cannot be eliminated



$$v_i \frac{\ell}{v} + v_f \frac{L}{v} = 0$$

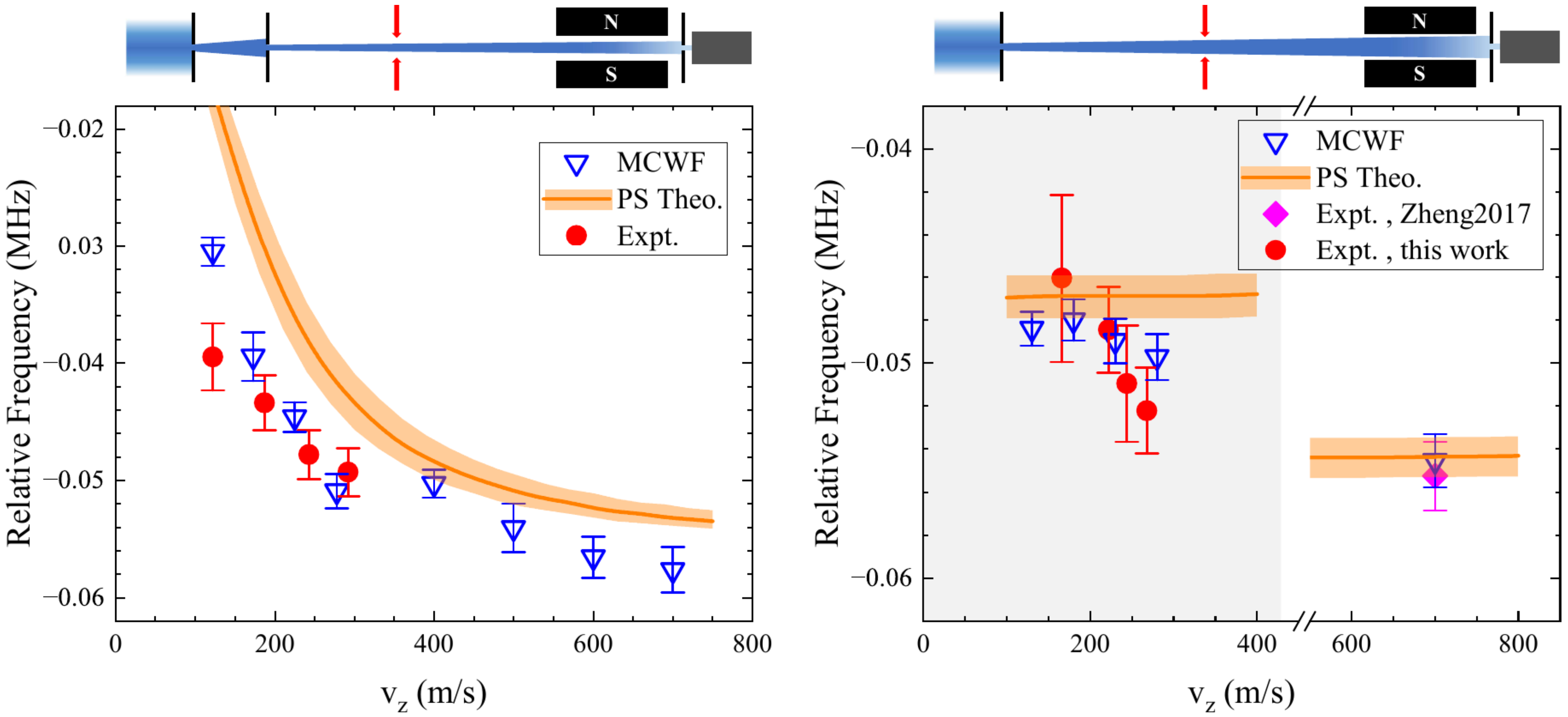
$$v_i + v_R = v_f$$

$$\Rightarrow \quad \Delta\nu = \frac{\vec{k}\cdot\vec{v}}{2\pi} = -\frac{h}{mc^2}\frac{L}{\ell+L}\nu_c^2$$

Postselection effect & 2^3S-2^3P frequency of ^4He

Postselection effect

- Theoretical explanation of postselection and simulations with Monte-Carlo wave function method
- Correction of previous results by +55(2) kHz

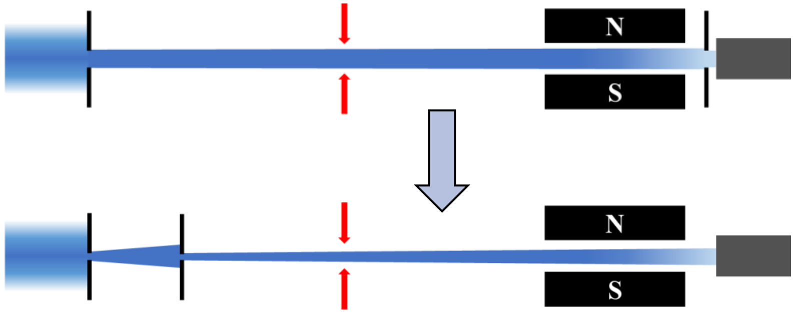


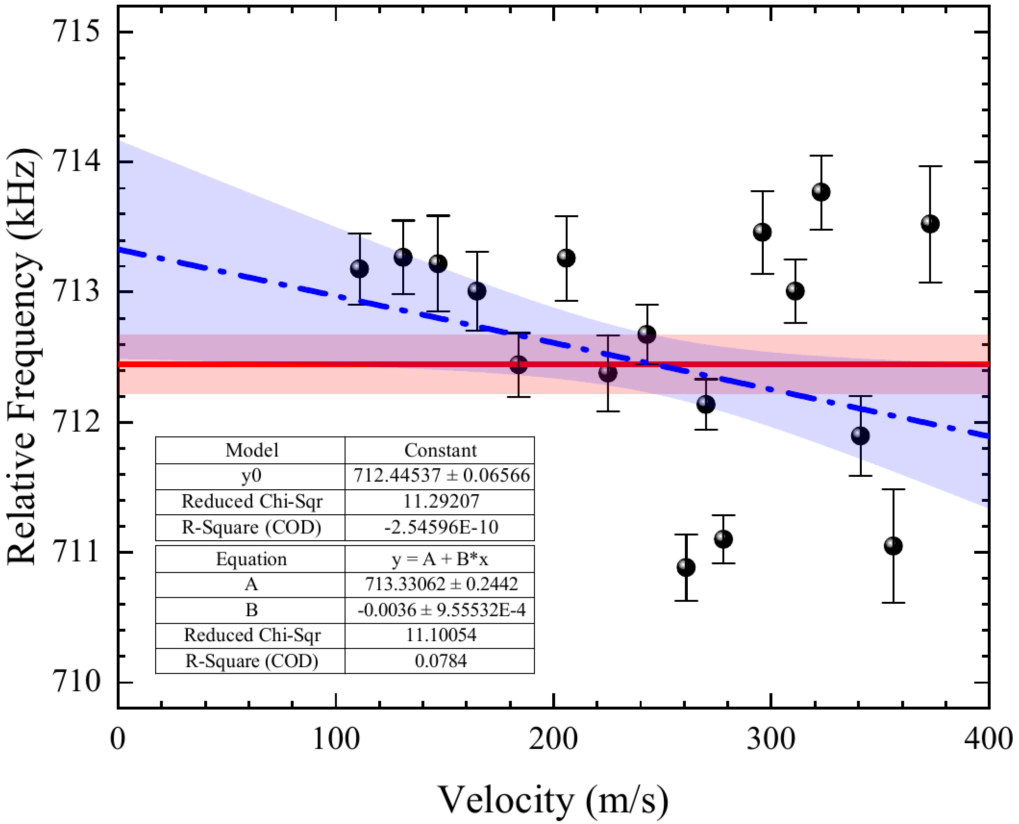
Phys. Rev. A **112**, 052814 (2025)

Postselection effect & 2^3S-2^3P frequency of ^4He

2^3S-2^3P transition frequency of ^4He

- To avoid postselection: slits are aligned before the probe laser
- Measure under different velocities, incident angles, and powers
- Reach sub-kHz precision for the first time



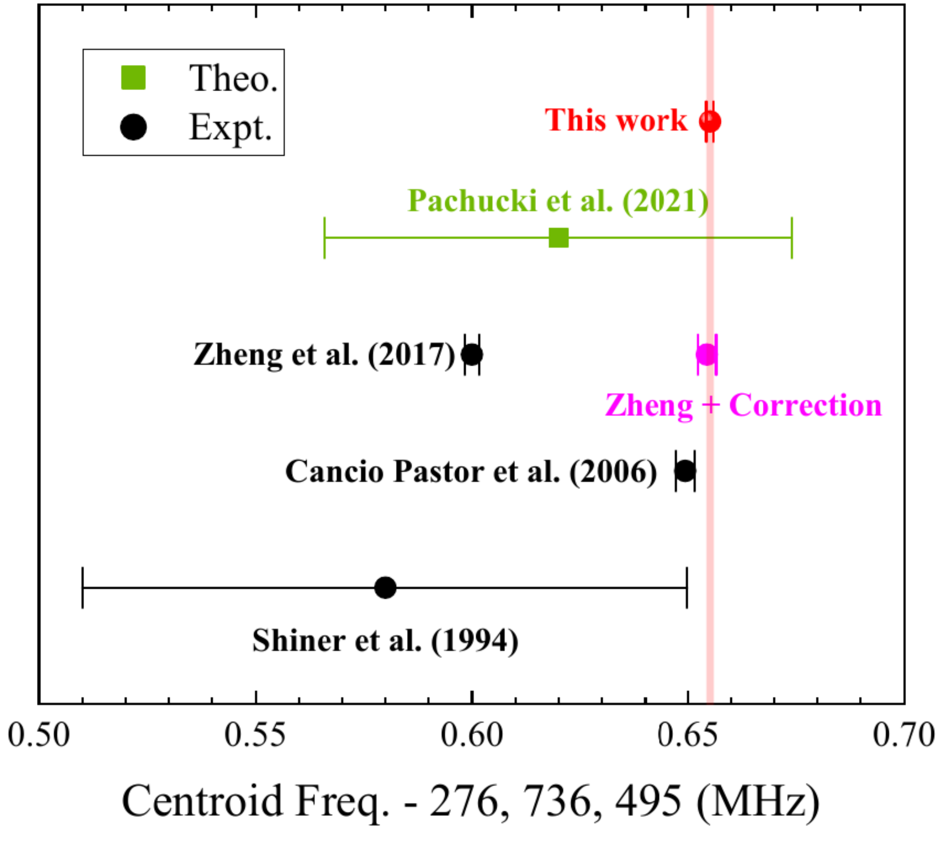


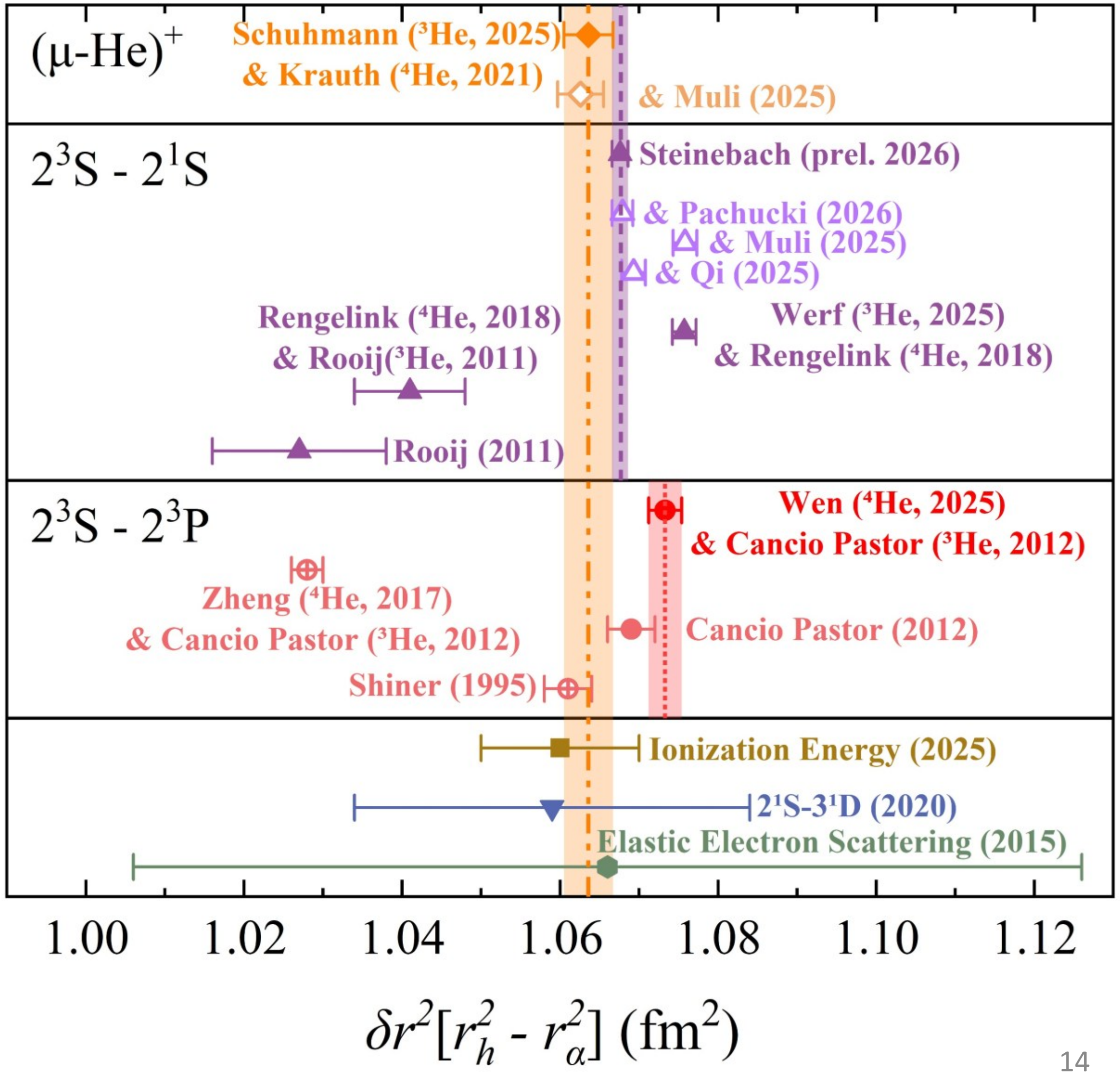
Source	Corrections	$\Delta f(1\sigma)$
Statistics		0.22
First-order Doppler		0.82
Second-order Doppler		0.01
Frequency calibration		0.06
Quantum interference	+0.06	0.02
Laser power		0.20
Zeeman effect		0.01
Recoil shift	−42.48	0.01
Total	276 764 094 712.45	0.86

Postselection effect & 2^3S-2^3P frequency of ^4He

2^3S-2^3P transition frequency of ^4He

- Consistent with saturation fluorescence and theory
- Isotope shift: 2.6σ with μ-He$^+$





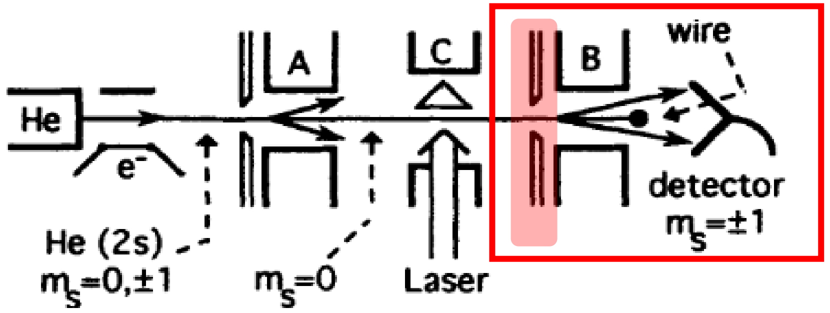
Sci. Adv. **11**, eadu9796 (2025)

Postselection effect & 2^3S-2^3P frequency of ^4He

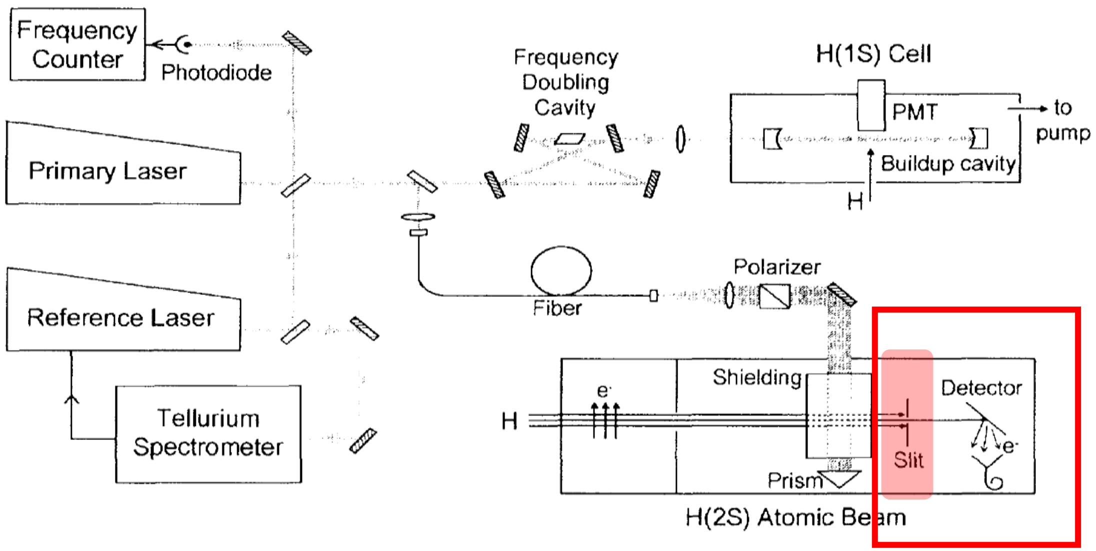
Postselection effect

- Spatial effects caused by slits or small holes also appeared in other experiments
- Considered in ionization energy measurement

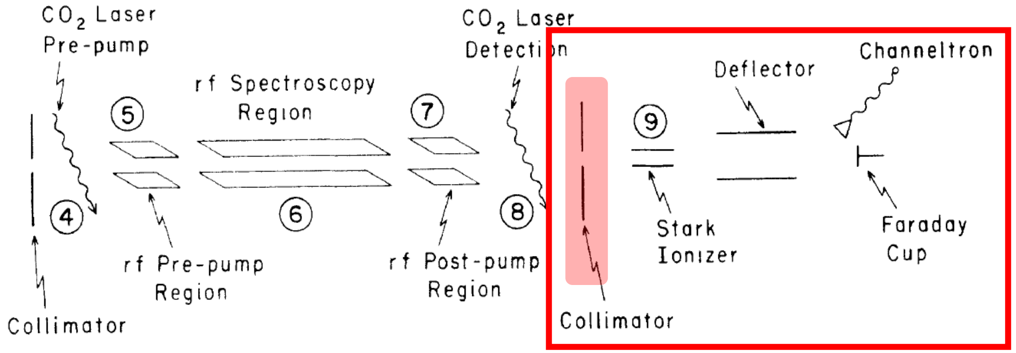
Phys. Rev. A **111,** 012817 (2025)



- D. Shiner, *et al.* Phys. Rev. Lett. **73,** 3553 (1995)



- D. J. Berkeland, *et al.* Phys. Rev. Lett. **75,** 2470 (1995)

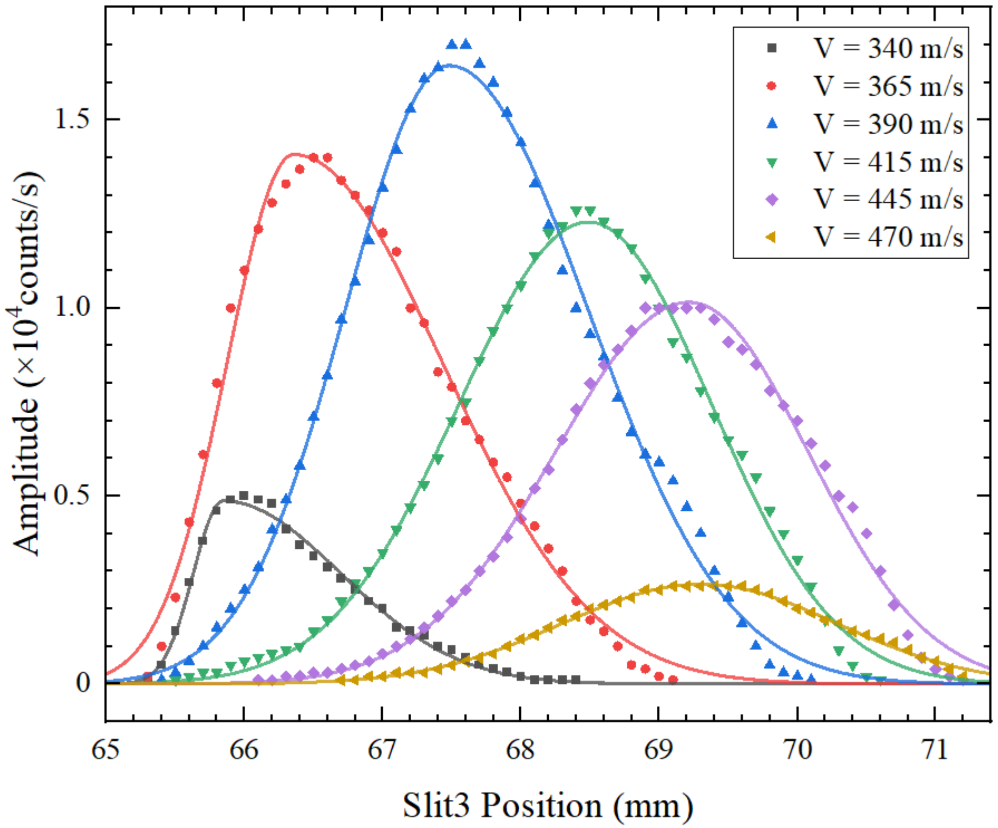


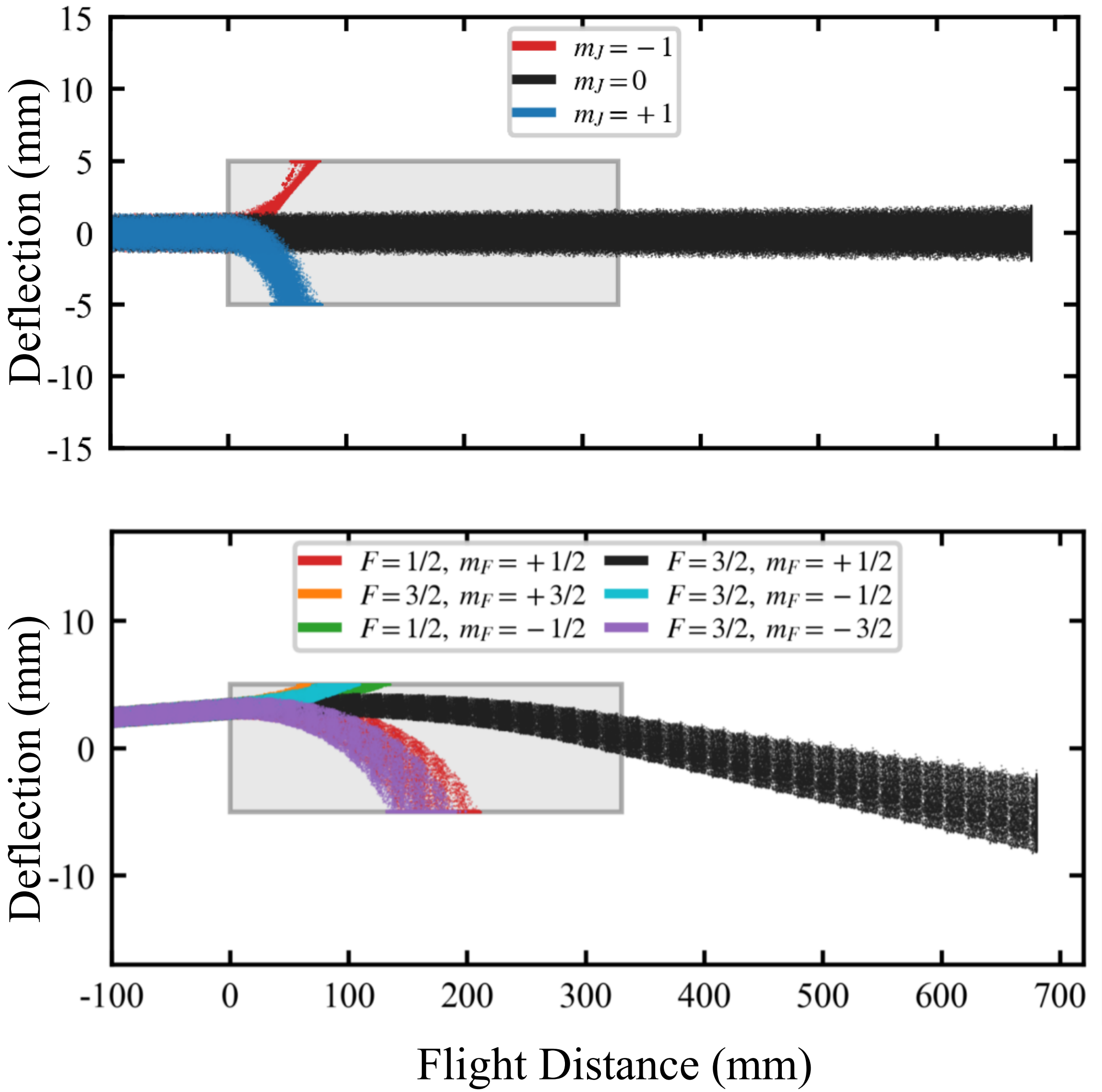
- E. A. Hessels, *et al.* Phys. Rev. A **46,** 2622 (1992)

Magneto-Optical Deflection method for ^3He

Measure ^3He with SGM

- Deflection in SGM due to $I = 1/2$
- More sensitive to postselection
- Distribution changs with beam velocity

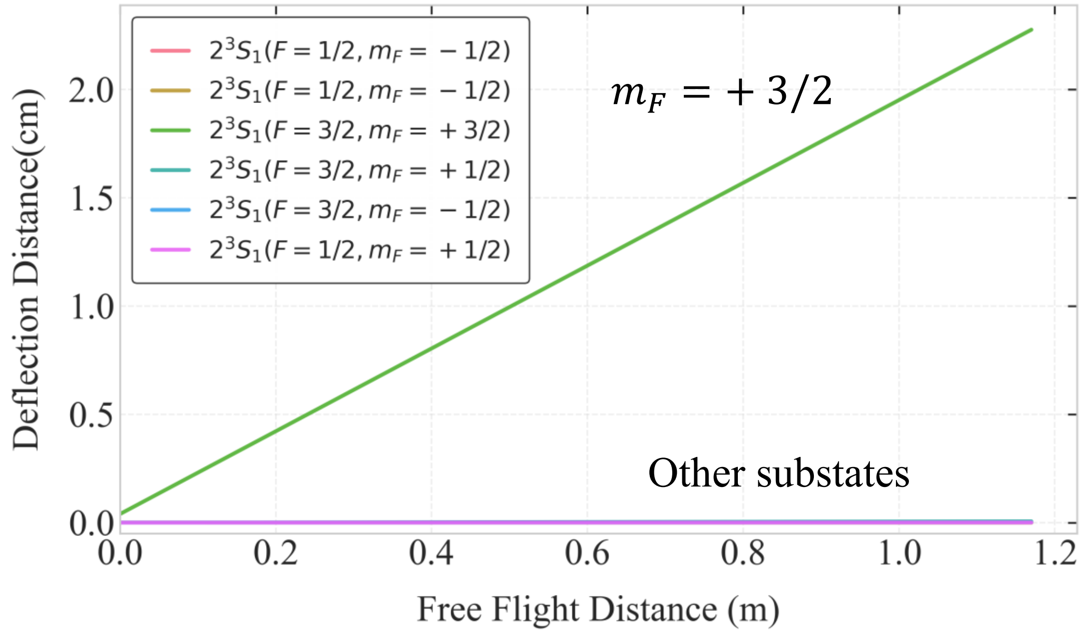


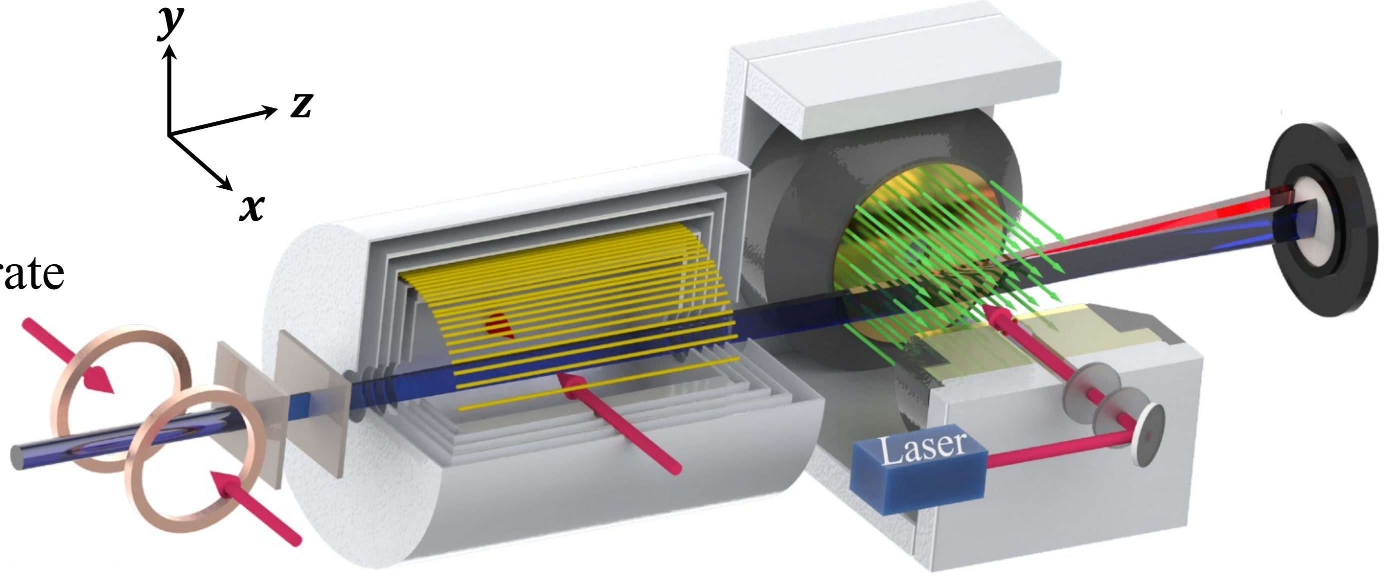


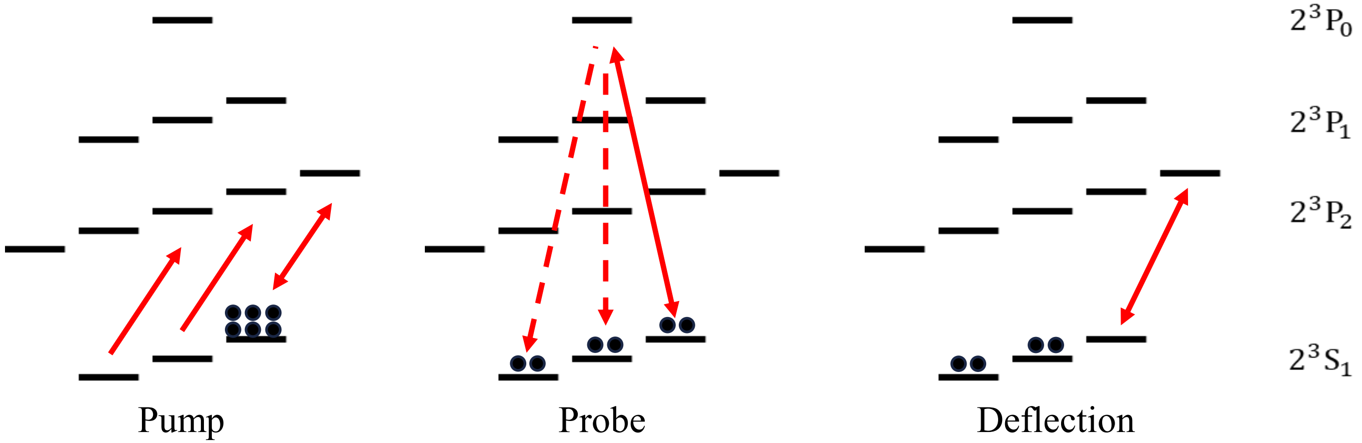
Magneto-Optical Deflection method for ^{3}He

MOD method for ^{3}He

- Radiation force of laser on atoms to deflect
- only one sub-state is deflected.
- High uniform magnetic field to spatially separate
- ~3400 Gauss permanent magnet



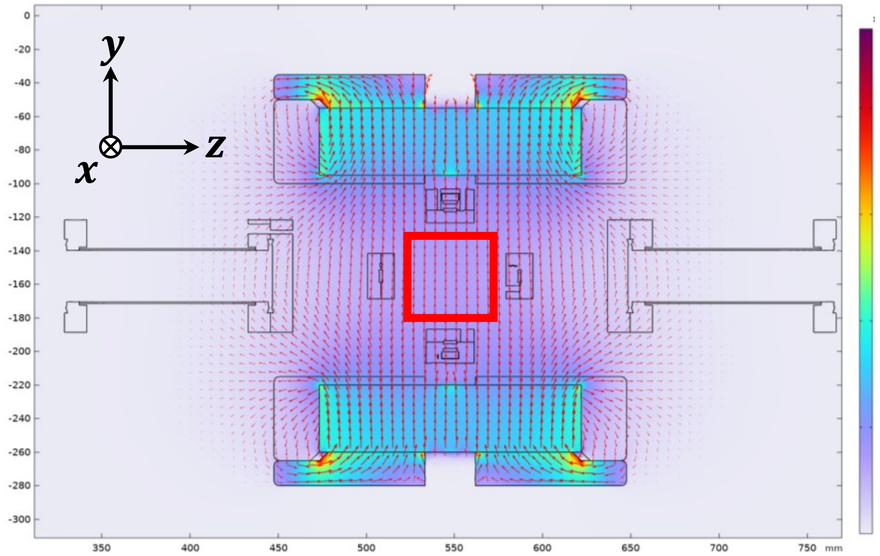


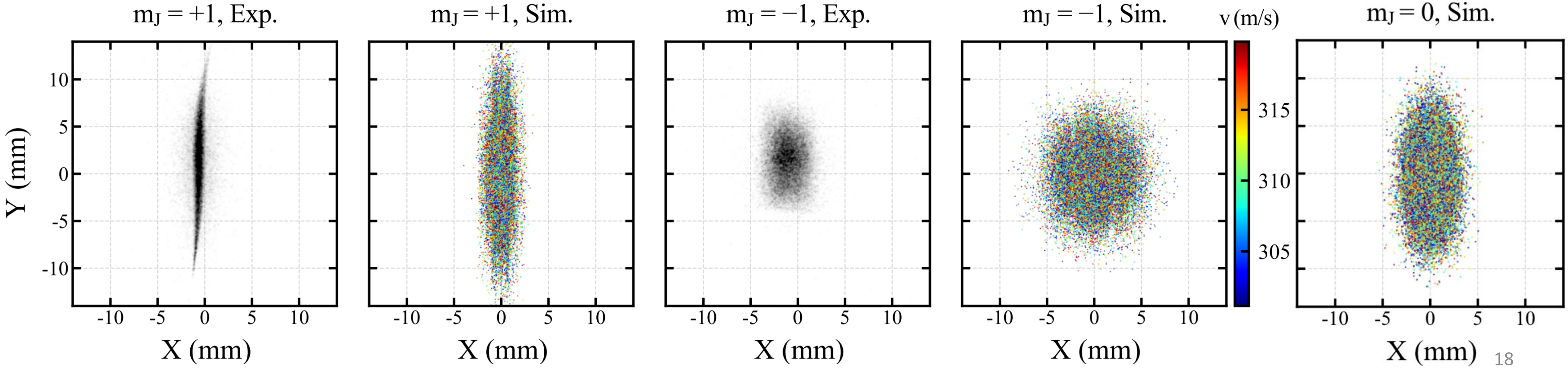


Magneto-Optical Deflection method for ^{3}He

MOD method for ^{3}He

- Within the central area (20×20×20 mm) uniformity ±0.6% (3397.1 to 3440.3 Gauss)
- Compress or stretch due to the gradience
- Can be fully detected (D~40mm) → No postselection

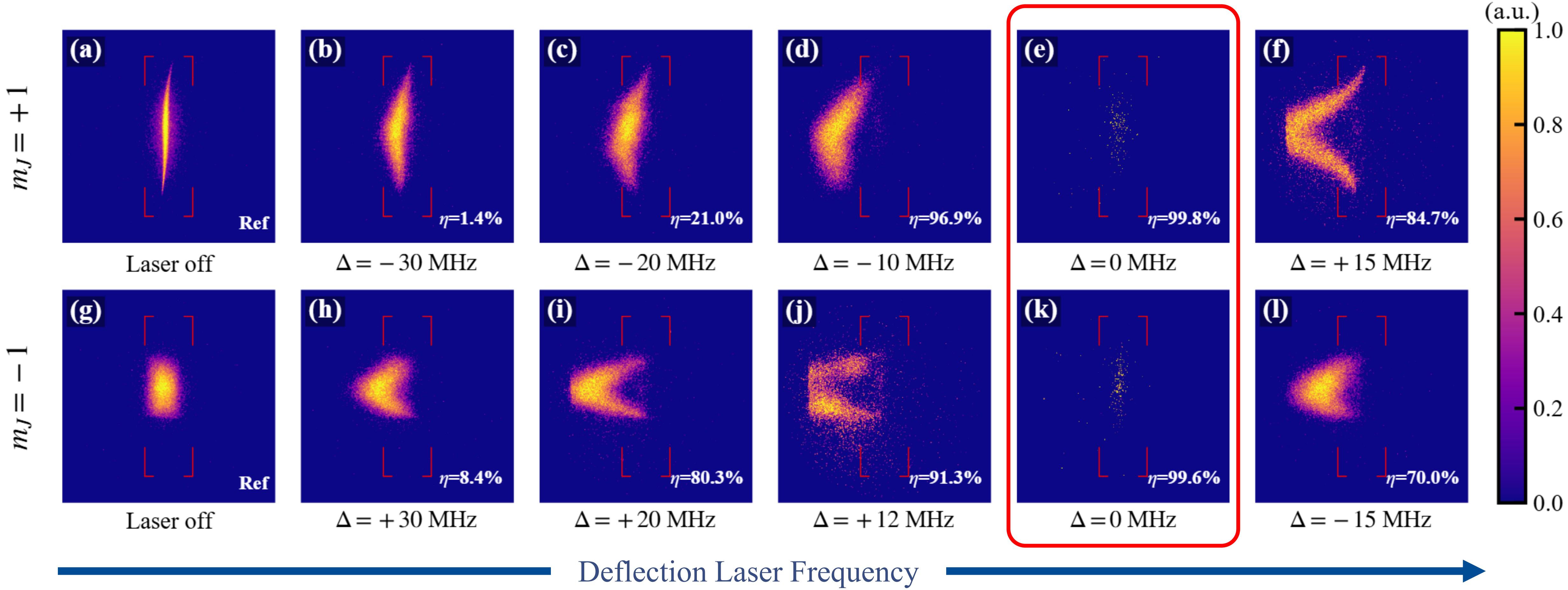




Magneto-Optical Deflection method for ^{3}He

MOD method for ^{3}He

- Almost fully deflected on resonance, residual due to imperfect optical pumping

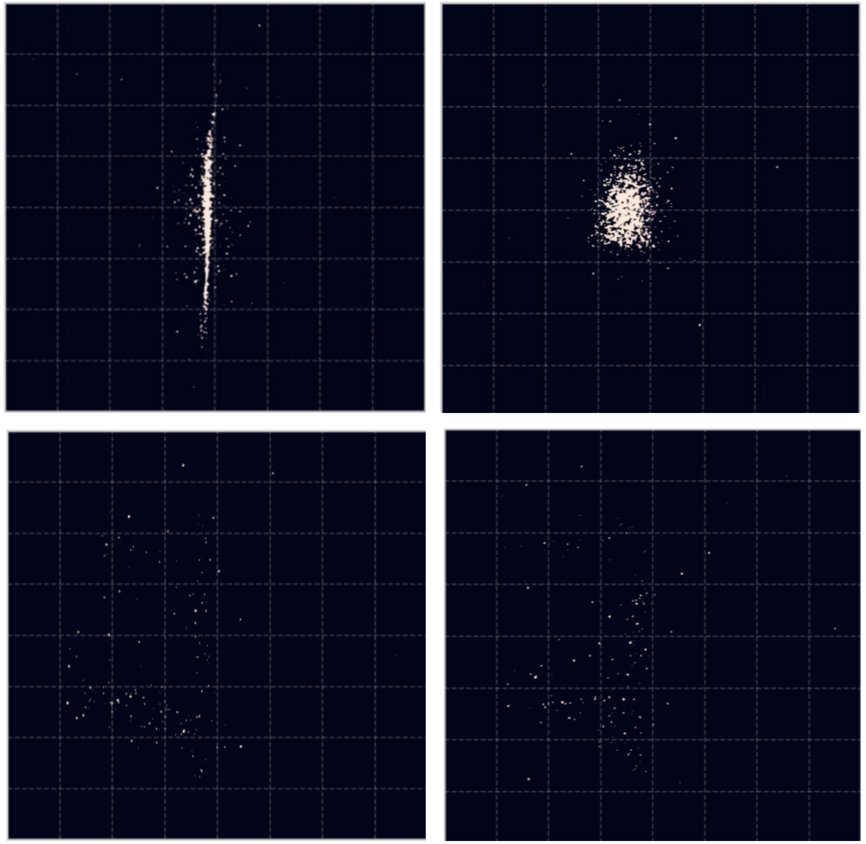


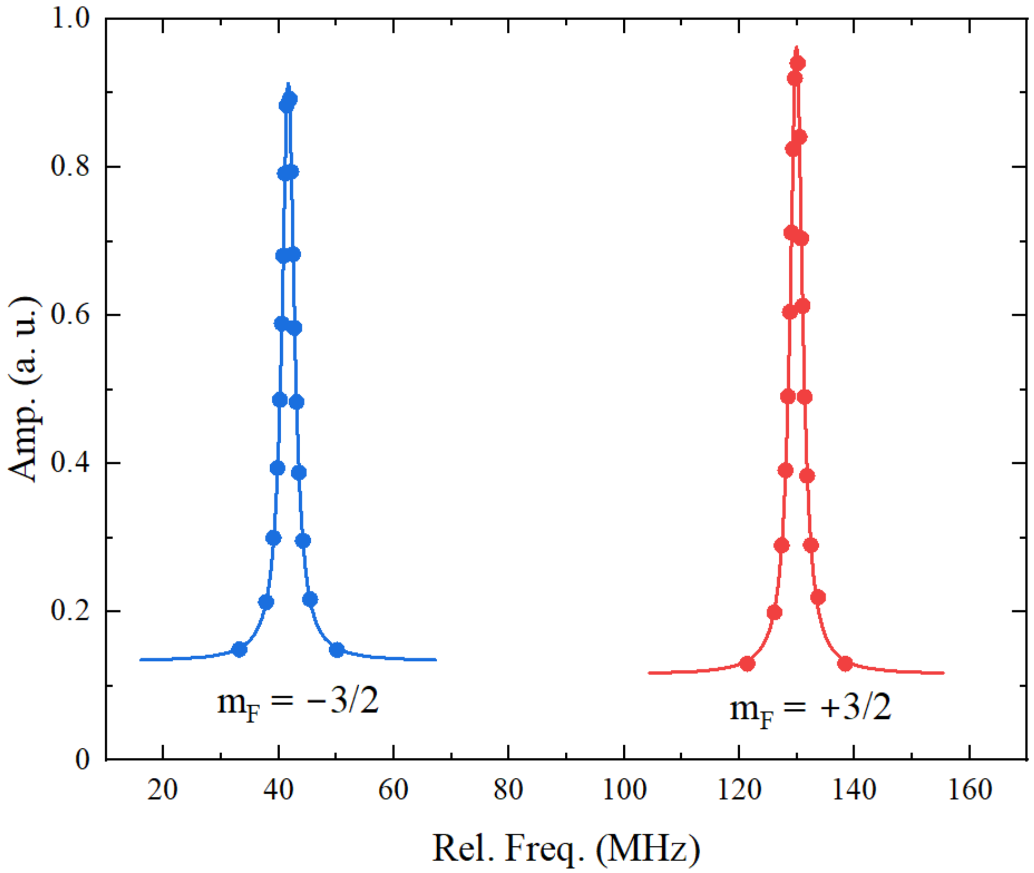
Magneto-Optical Deflection method for ^{3}He

MOD method for ^{3}He

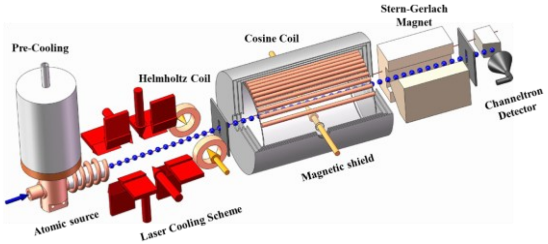
- Measurement for ^{3}He with MOD method and evaluation of systematic errors are ongoing

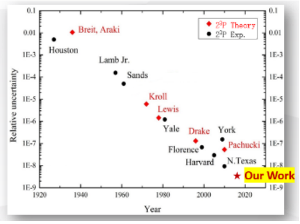
$m_F = +3/2$ $m_F = -3/2$

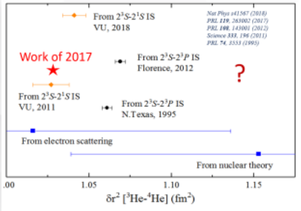


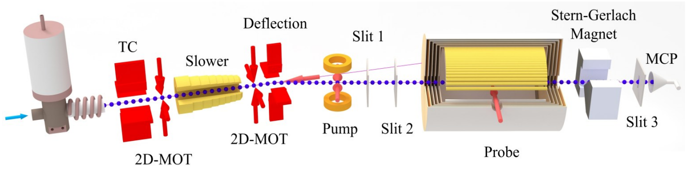


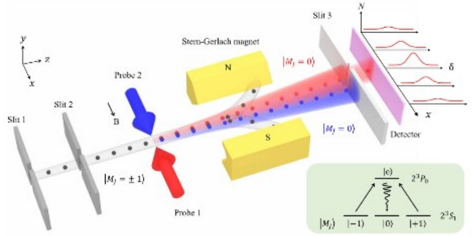
Moving to Shenzhen









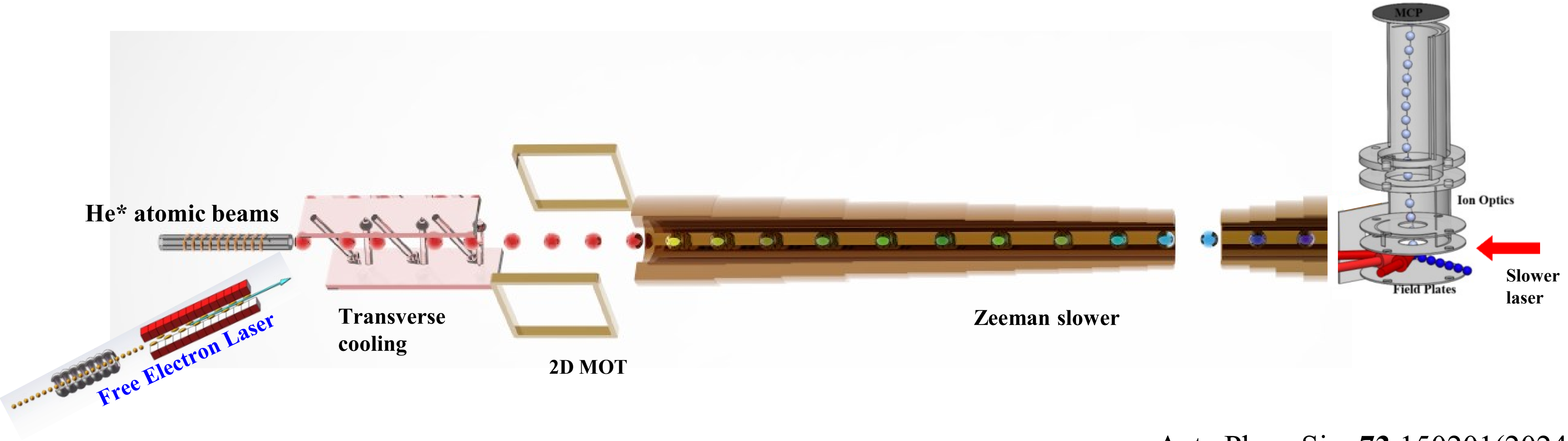


2009-2015
- Proposal
- Setup building

2015-2017
- ^{4}He 2^3P interval to 2ppb
- Measurement of 2^3S-2^3P

2017-2023
- New setup with Zeeman slower
- Reduce Doppler effect

2024-Now
- Check systematic errors
- Measurement of ^{4}He/ ^{3}He



Acta Phys. Sin. **73**,150201(2024)
Acta Phys. Sin. **74**,183103(2025)

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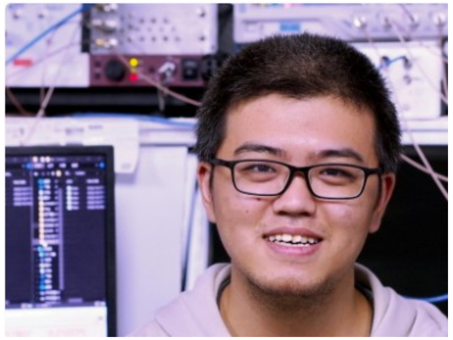

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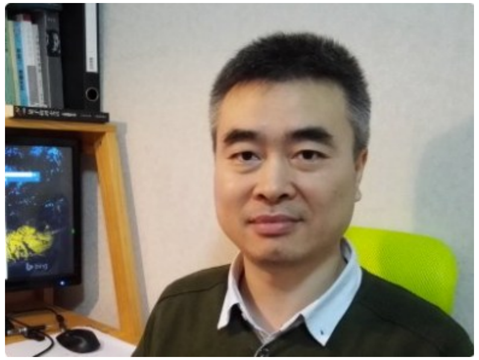

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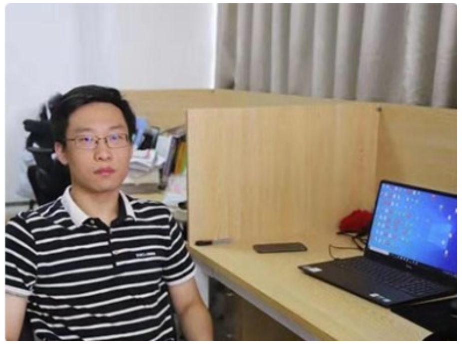
Professor



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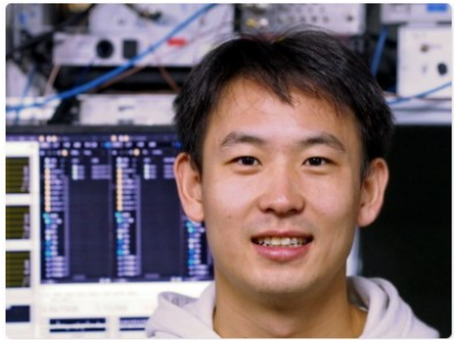

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Cun-Feng Cheng

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Fei Meng

NTS
Hai-Feng Jiang

UW(PL)
K. Pachuchi

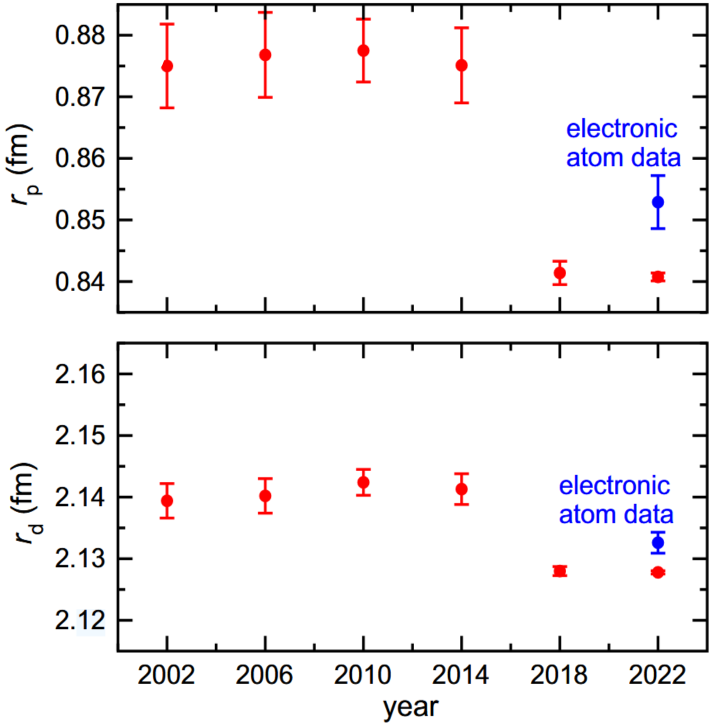
UNB (CA)
Zong-Chao Yan

Funding:

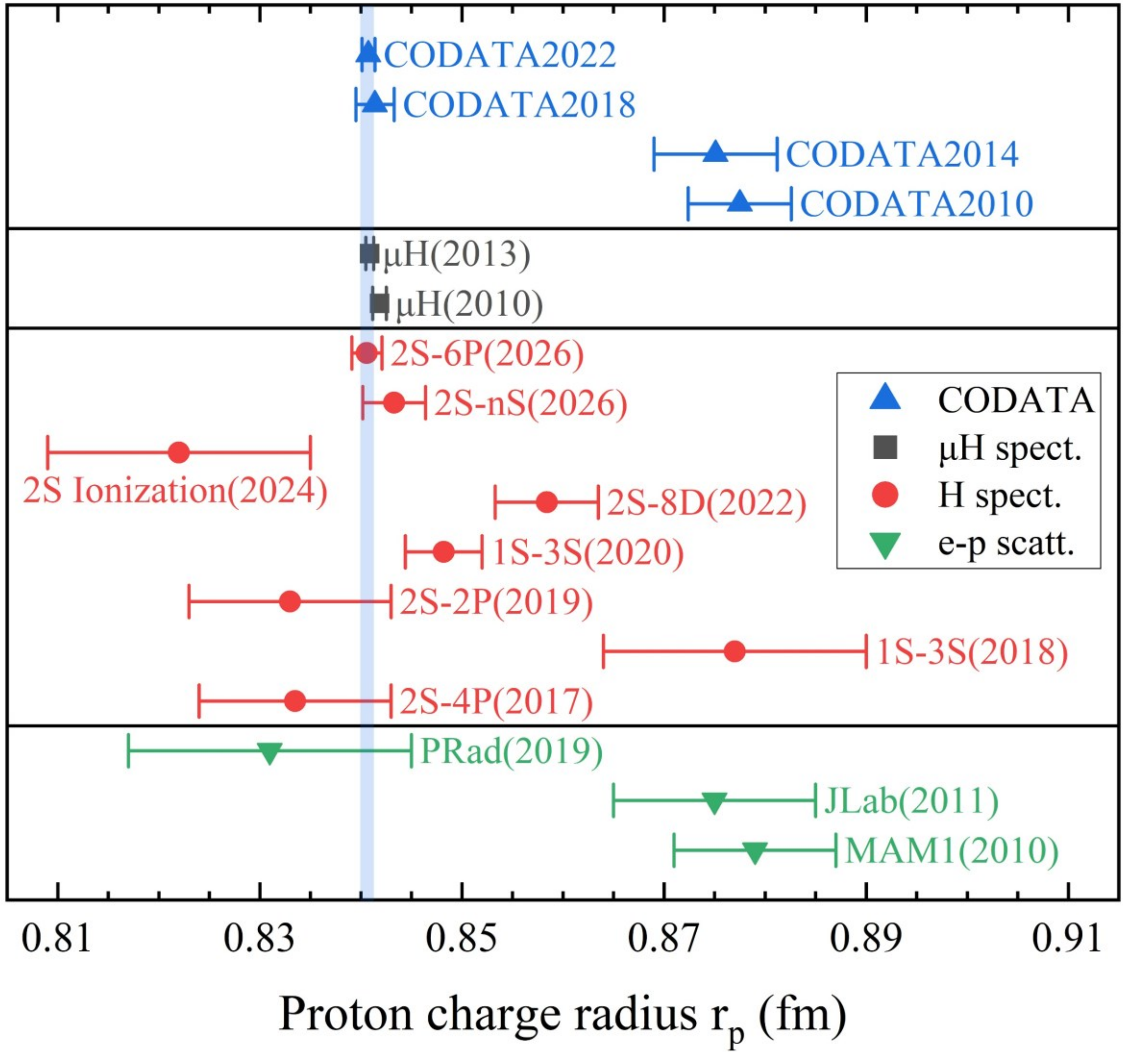
Appendix

Proton Size Puzzle

- r_p differed in μH/H/e-p scatt.
- H-D Isotope shift r_d^2-r_p^2 is consistent
- 2.8σ for H or D



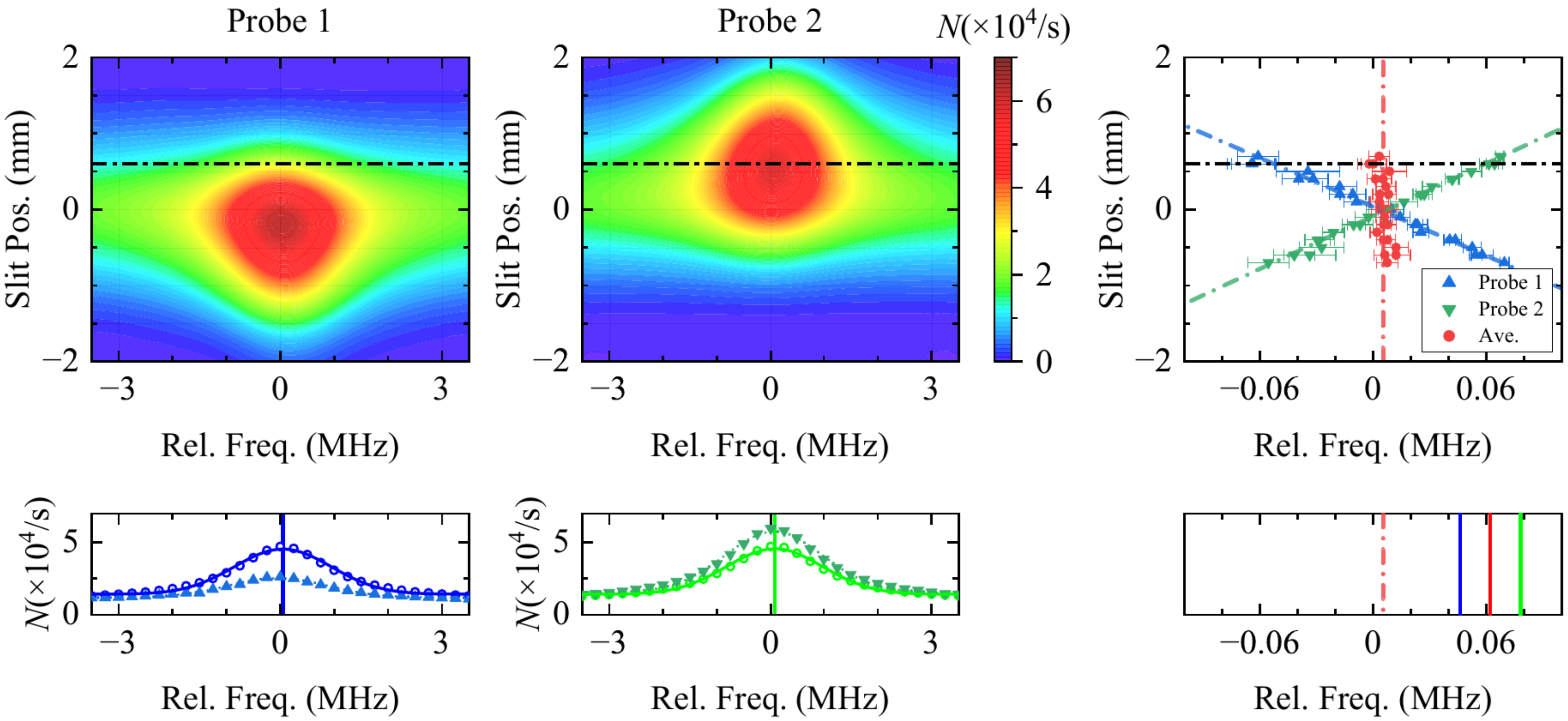
Rev. Mod. Phys. **97,** 025002 (2025)



Appendix

Postselection effect

- Fit at each position, and the final result is independent of the position.
- Average all the counts at the same frequency and then fit, corresponding to the case without slits.
- Same data, the deviation between the two methods is approximately 50 kHz.

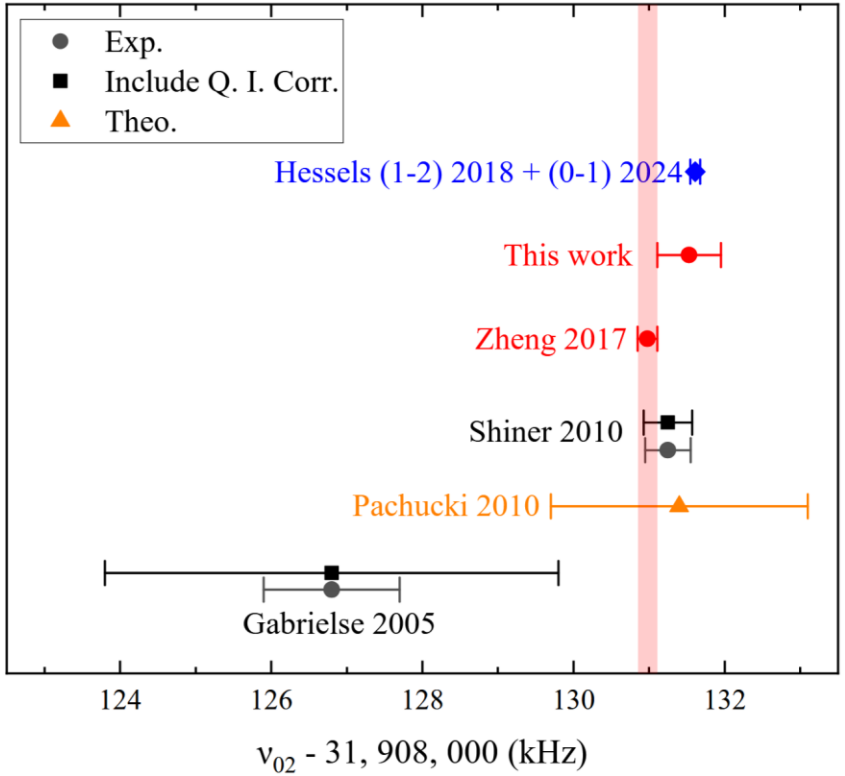


Appendix

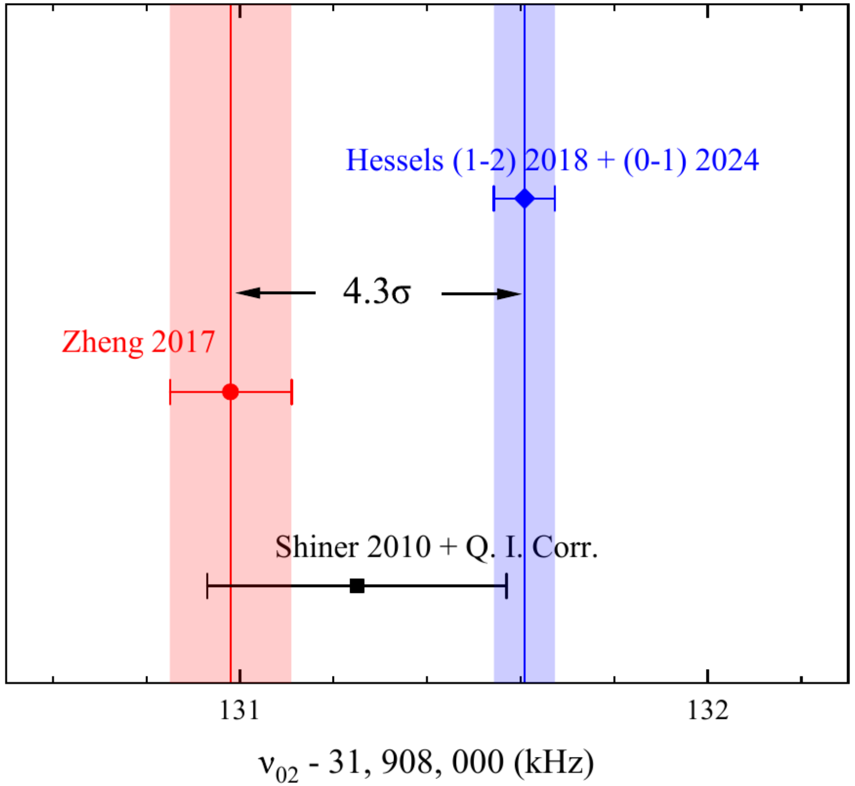
Postselection for 2^3P fine-structure

$$\Delta\nu = \frac{\vec{k}\cdot\vec{v}}{2\pi} = -\frac{h}{mc^2}\frac{L}{\ell + L}v_c^2$$

$$\delta\nu_{02} = -\frac{h}{mc^2}\frac{L}{\ell+L}(v_0^2 - v_2^2) \sim -13\ \text{Hz}$$



- ν_{02} is least affected by quantum interference (<100Hz)
- 630 Hz deviation (4.3σ) between Laser and Microwave measurements



Appendix

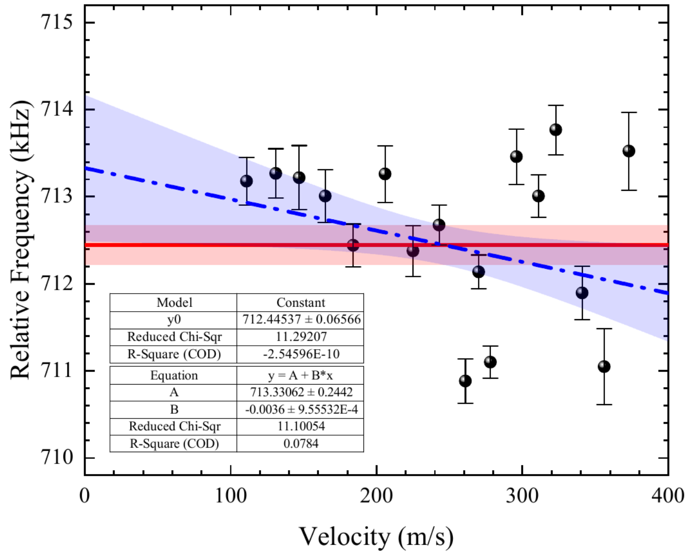
Systematics

- Statistics： Intercept of constant fit
- First-order Doppler: Intercept of Velocity extrapolation linear fit
- Second-order Doppler: $\Delta f = -\frac{v^2}{2c^2} f_0$
- Freq. Ref.： H maser and comb

$$\Delta f \approx 2 \times 10^{-13} \times 276 \text{ THz} \approx 55 \text{ Hz}$$

- Recoil: $m\Delta v = \hbar k$， $m\Delta v^2/2 = h\Delta f$

$$\Delta f = \frac{hc^2}{2mf_0^2} = 42.48 \text{ kHz}$$



Source	Corrections	$\Delta f(1\sigma)$
Statistics		0.22
First-order Doppler		0.82
Second-order Doppler		0.01
Frequency calibration		0.06
Quantum interference	+0.06	0.02
Laser power		0.20
Zeeman effect		0.01
Recoil shift	−42.48	0.01
Total	276 764 094 712.45	0.86

Appendix

Zeeman Effect

- Calculate Zeeman shift coefficient from Lander factor g
- Average to eliminate first-order Zeeman:

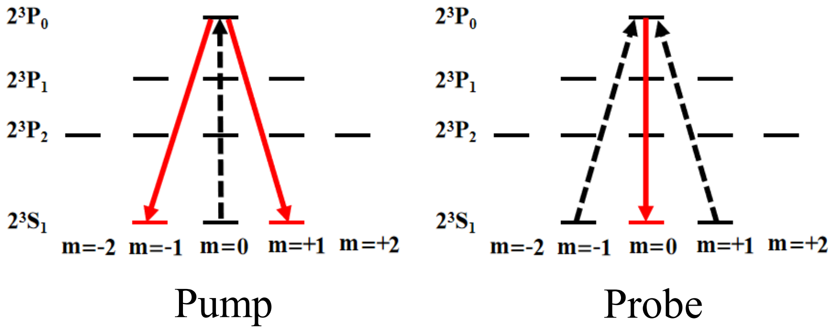
$$f_+ = f_c + \alpha B + \beta B^2$$

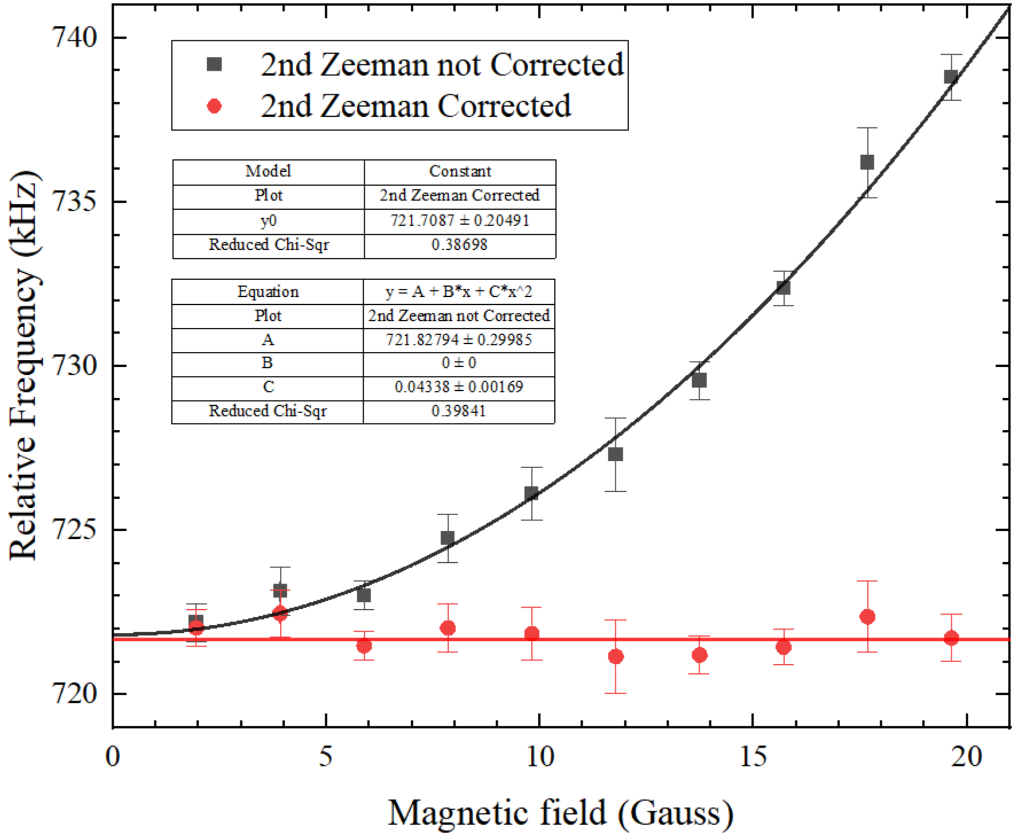
$$f_- = f_c - \alpha B + \beta B^2$$

- Need to correct the second-order Zeeman:

$$f_c = f_0 - \beta B^2$$

$$f_c = \frac{f_+ + f_-}{2} - \beta \left(\frac{f_+ - f_-}{2\alpha}\right)^2$$





Appendix

Zeeman effect

- Different g factor, and consider $(\mu_B B^2)^2$ or not: 1~2 Hz
- Error from current fluctuation：

$$\frac{\Delta f}{f} = 2\frac{\delta B}{B} = 2\frac{\delta I}{I} = \frac{2 \times 2 \times 10^{-3}}{8} = 5 \times 10^{-4}$$

Second-order Zeeman is about 10.9 kHz, so error from fluctuation of current is 5.5 Hz

- Residual magnet after shielding: $B_0 < 0.2$ mG

$$f_+ = f_c + \alpha(B + B_0) + \beta(B + B_0)^2$$

$$f_- = f_c - \alpha(B + B_0) + \beta(B + B_0)^2$$

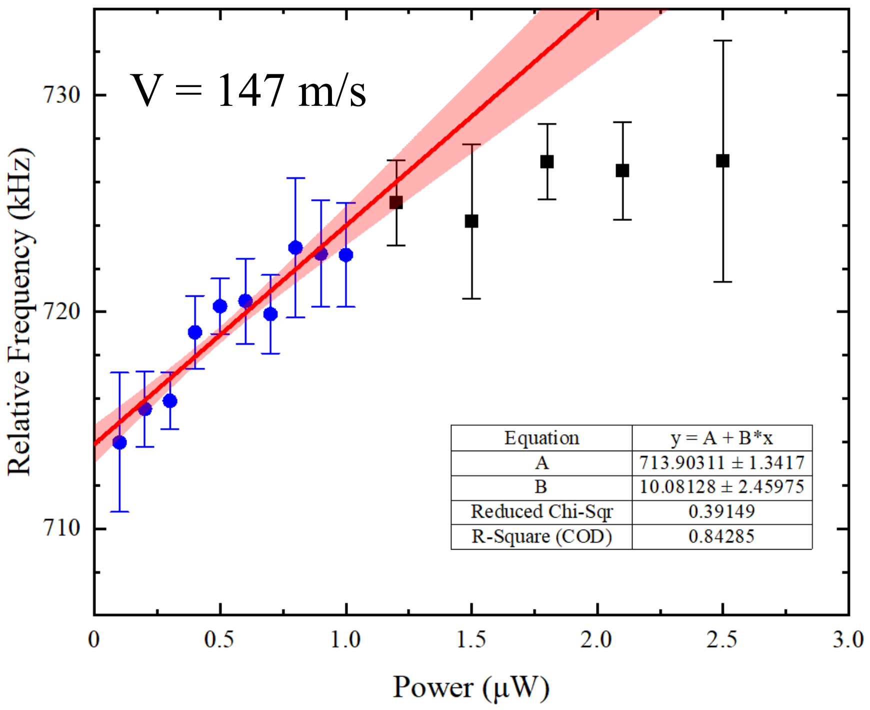
$\delta f_{B_0} \approx -2\beta B B_0 < 1$ Hz

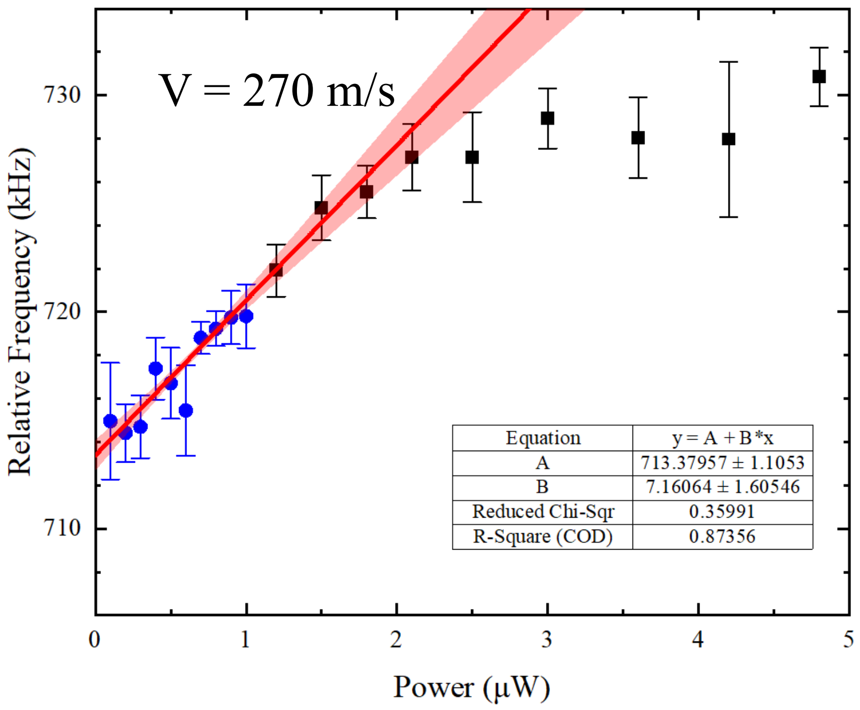
- Total error from Zeeman effect is less than 10 Hz

Appendix

Laser power

- Reasonable for linear extrapolation below 1μW
- Linearity of power meter 0.5% , < 5 nW
- Fluctuations and zero-point deviations during measurement < 5 nW
- Slope of power extrapolation < 20 kHz/μW, so total error < 200 Hz

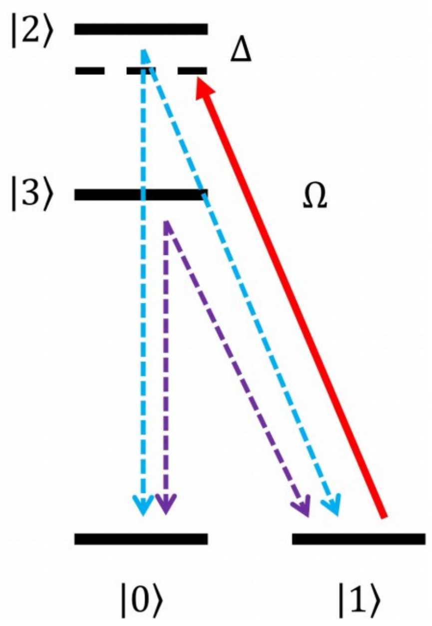


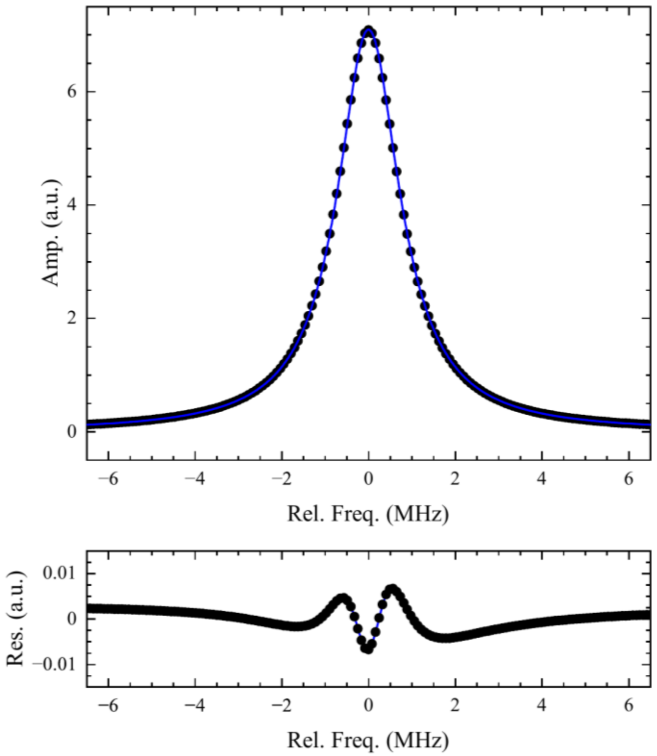


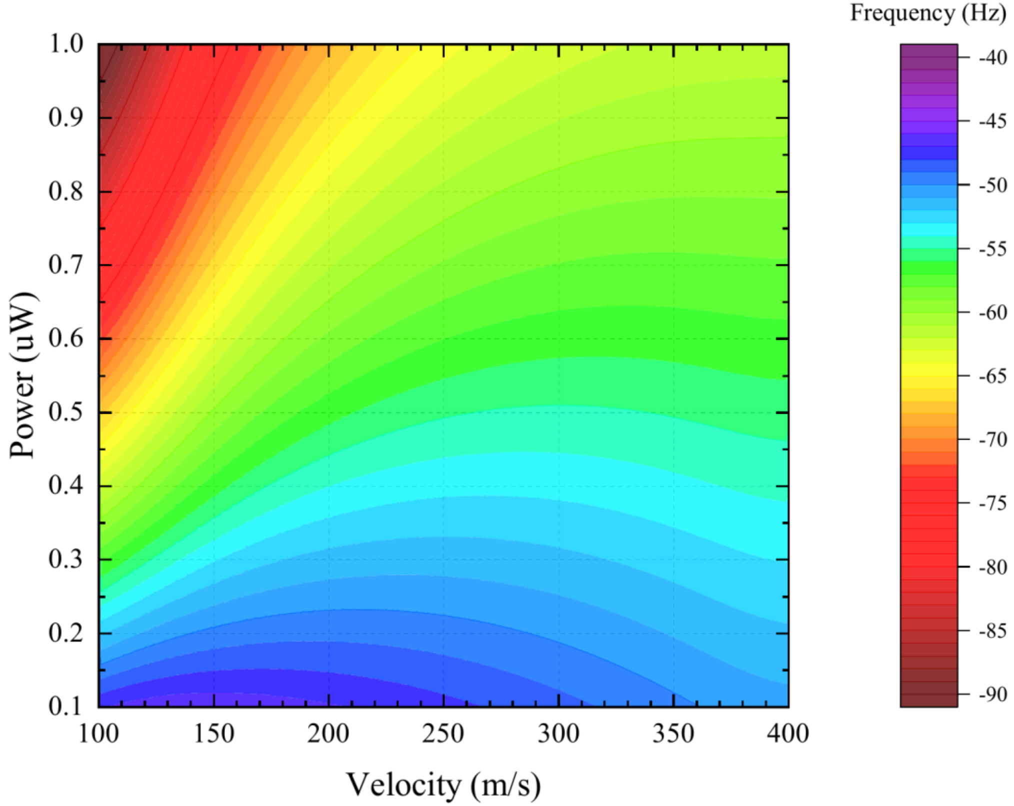
Appendix

Quantum Interference

- Same calculation methods with Hessels group
- Simulation Linewidth is consistent with the experiment at all velocities and powers
- +0.06(2) kHz for 2^3S_1-2^3P_0 transition



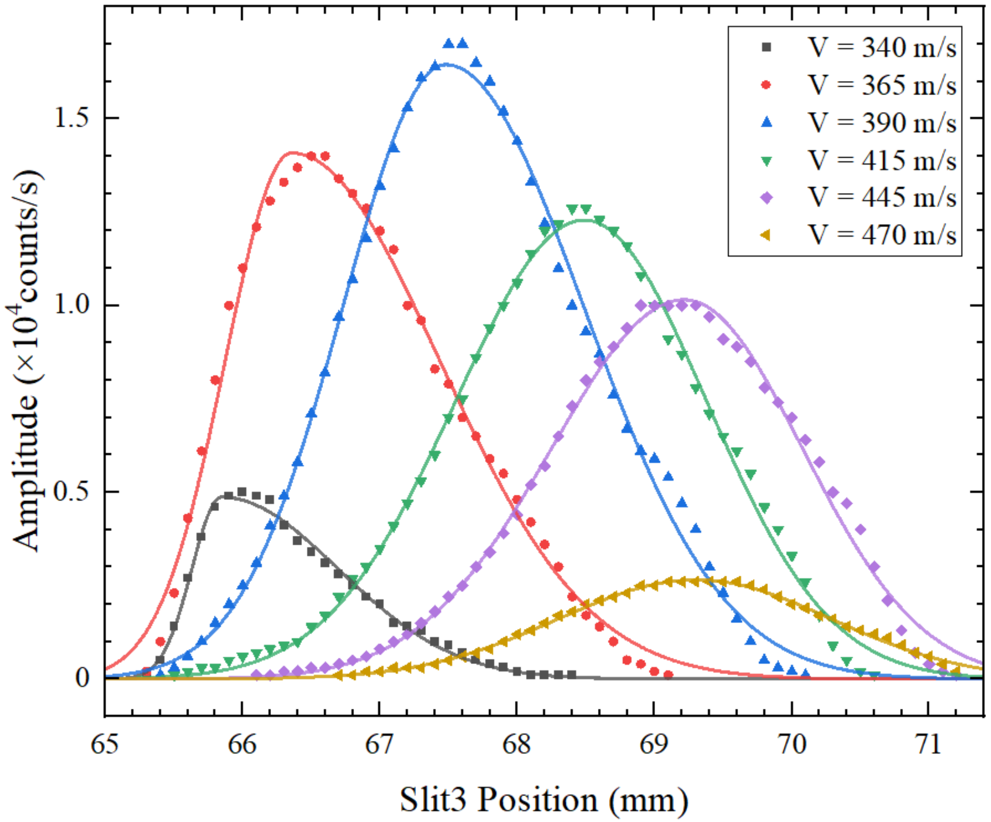


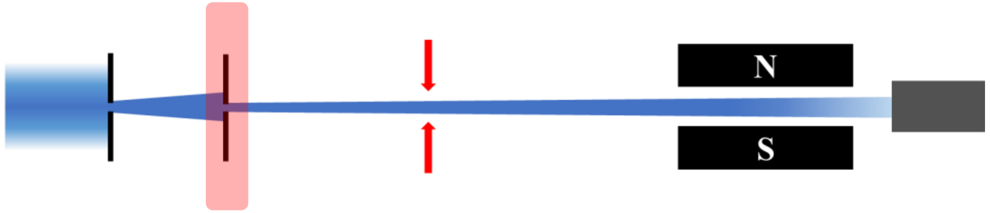


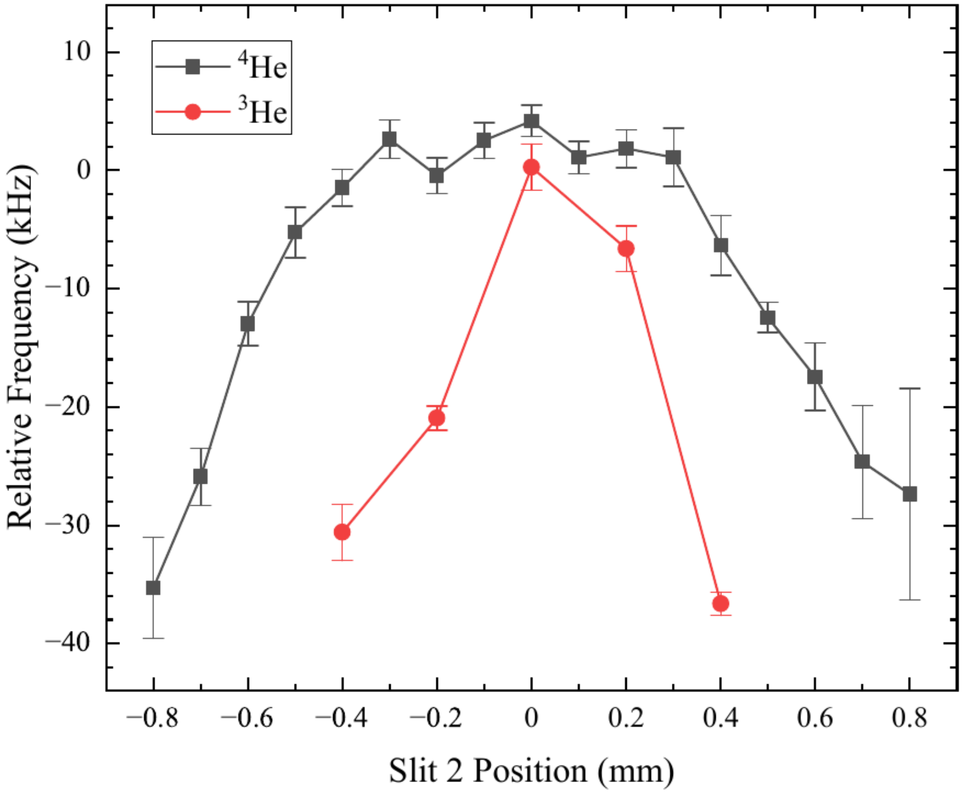
Appendix

Measure ^{3}He with SGM

- Distribution varied with velocity
- Hard to find atomic beam direction
- A bigger SGM to test systematic errors

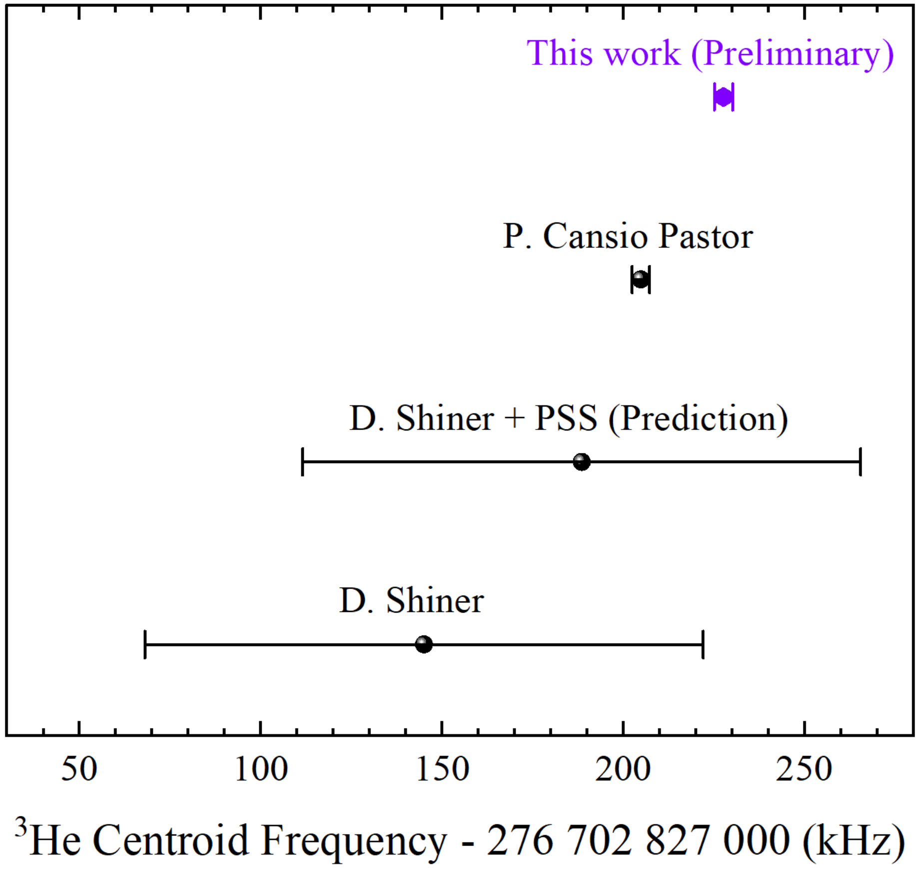


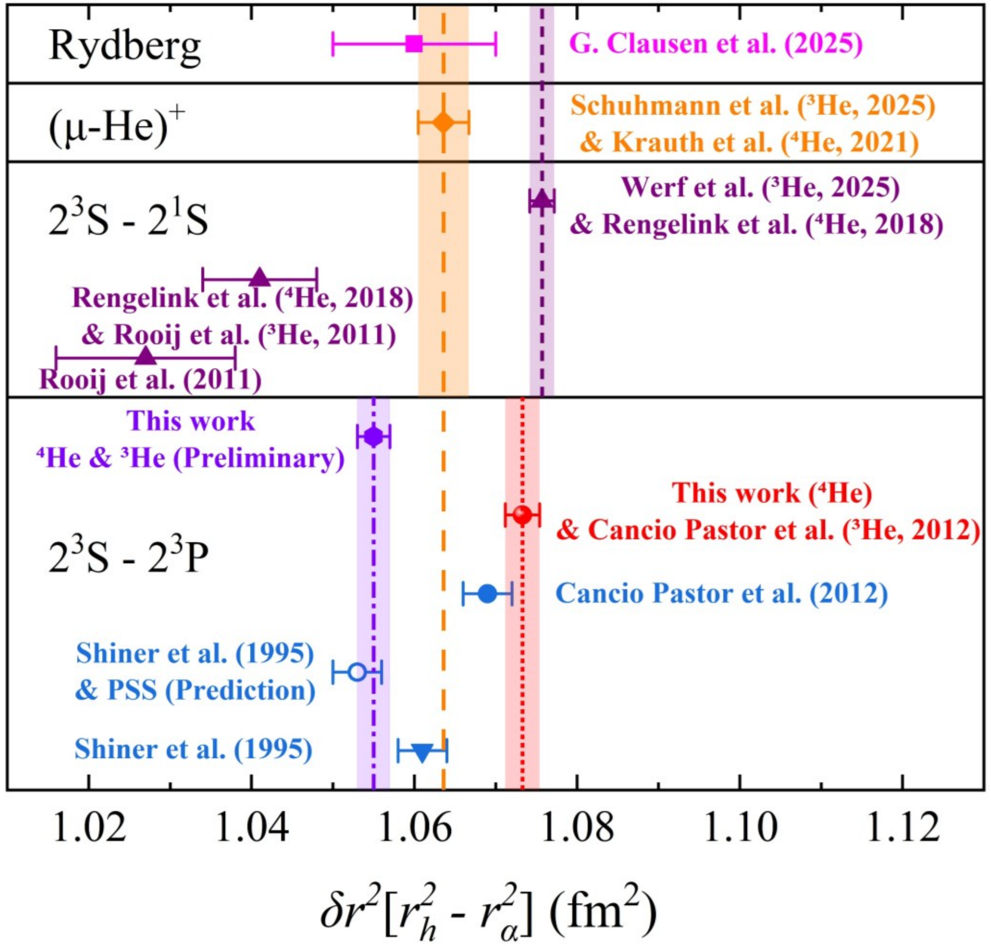




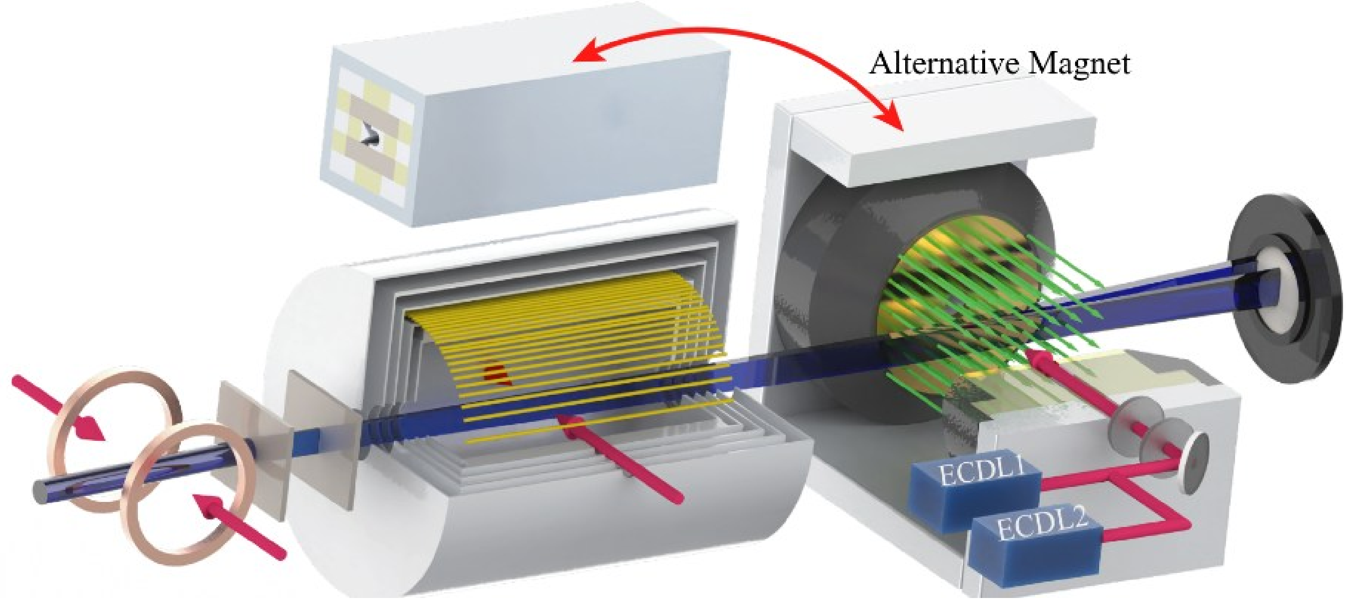
Preliminary result of ^{3}He with SGM in 2023 (WRONG!!!)

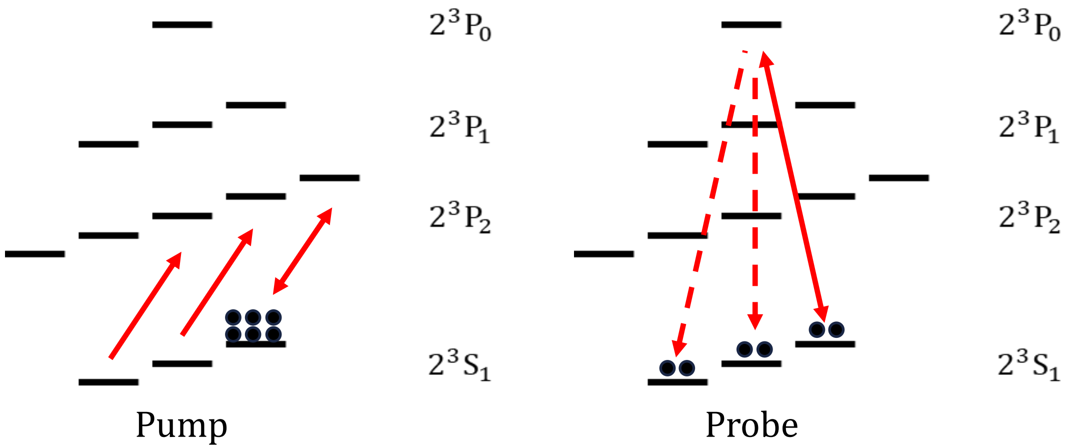
- Affected by Postselection, the Isotope shift result should be smaller

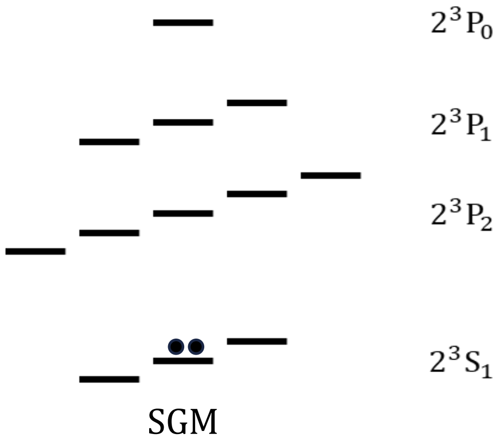


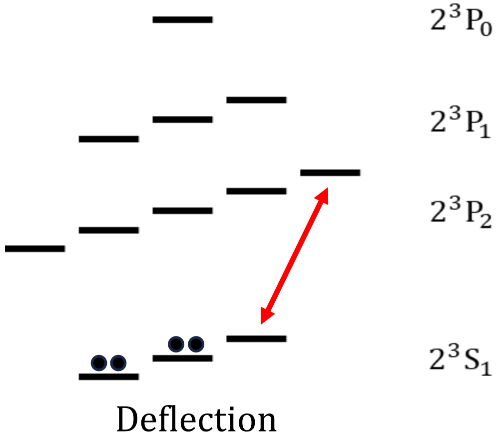


Appendix

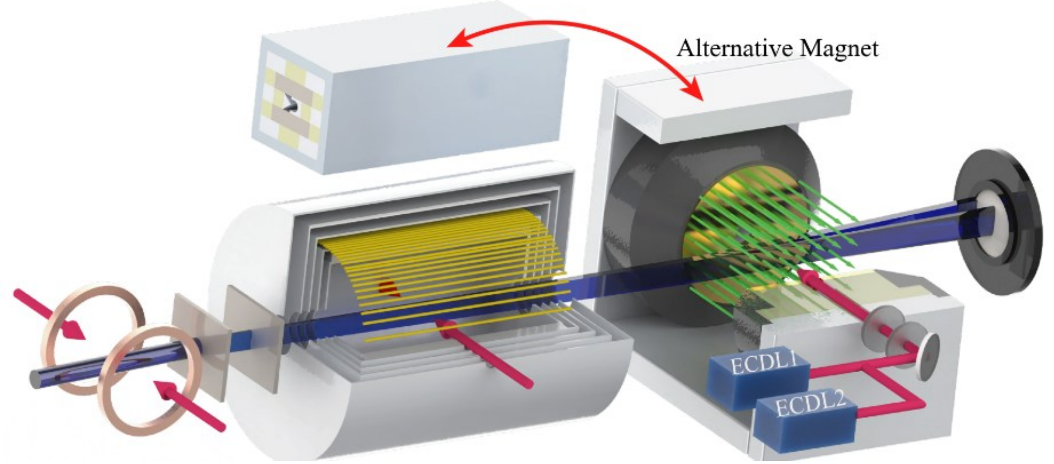

Alternative Magnet
ECDL1
ECDL2

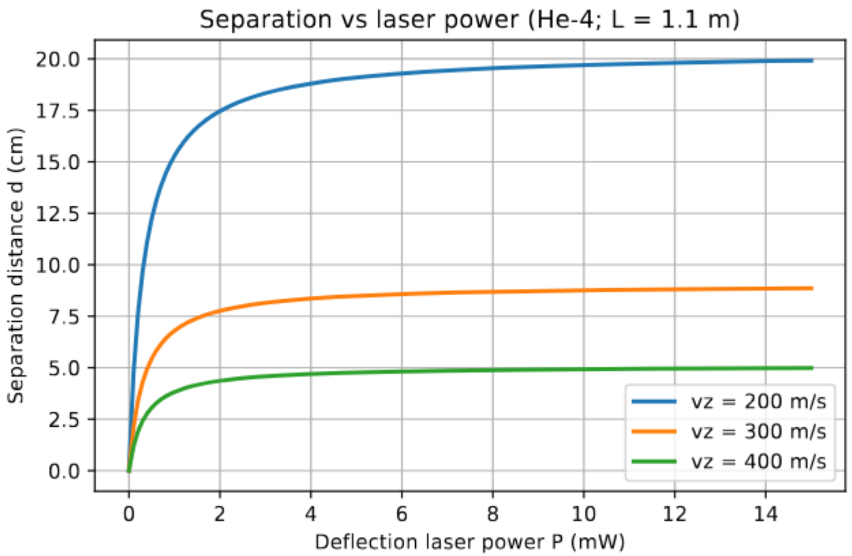

2^3P_0
2^3P_1
2^3P_2
2^3S_1
Pump
2^3P_0
2^3P_1
2^3P_2
2^3S_1
Probe

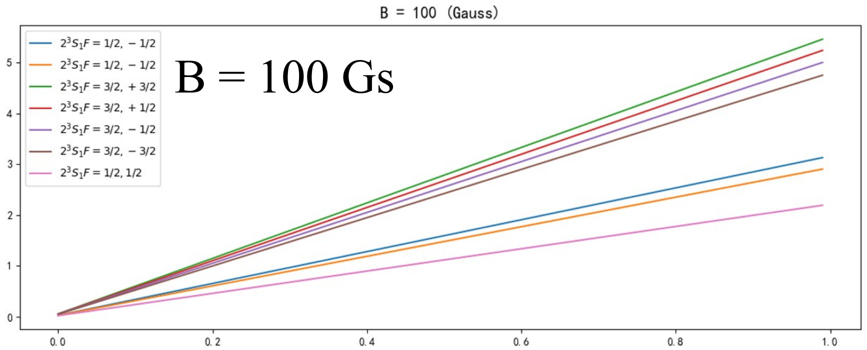

2^3P_0
2^3P_1
2^3P_2
2^3S_1
SGM

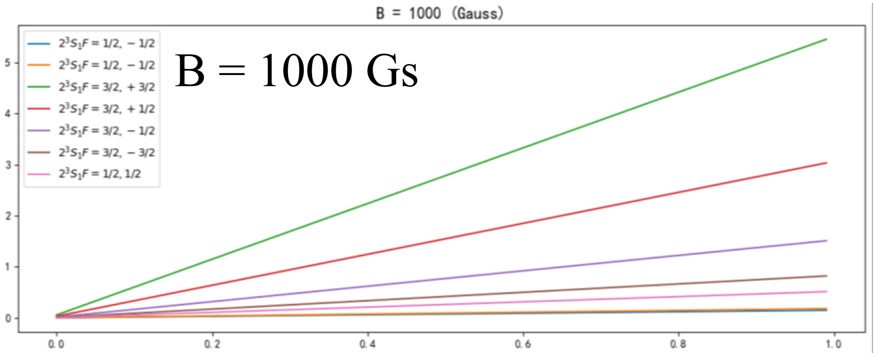

2^3P_0
2^3P_1
2^3P_2
2^3S_1
Deflection

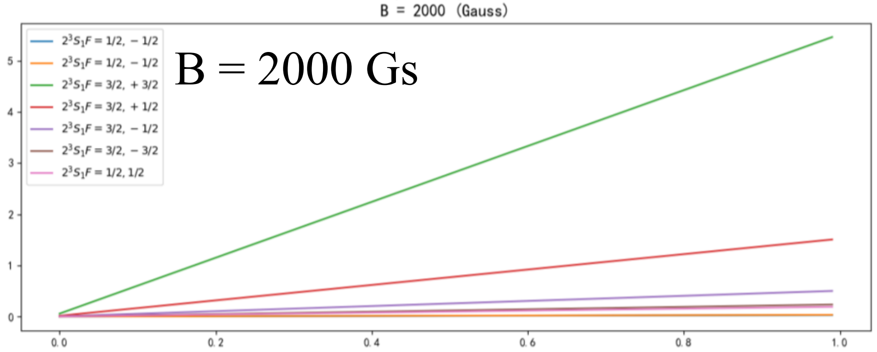
Appendix





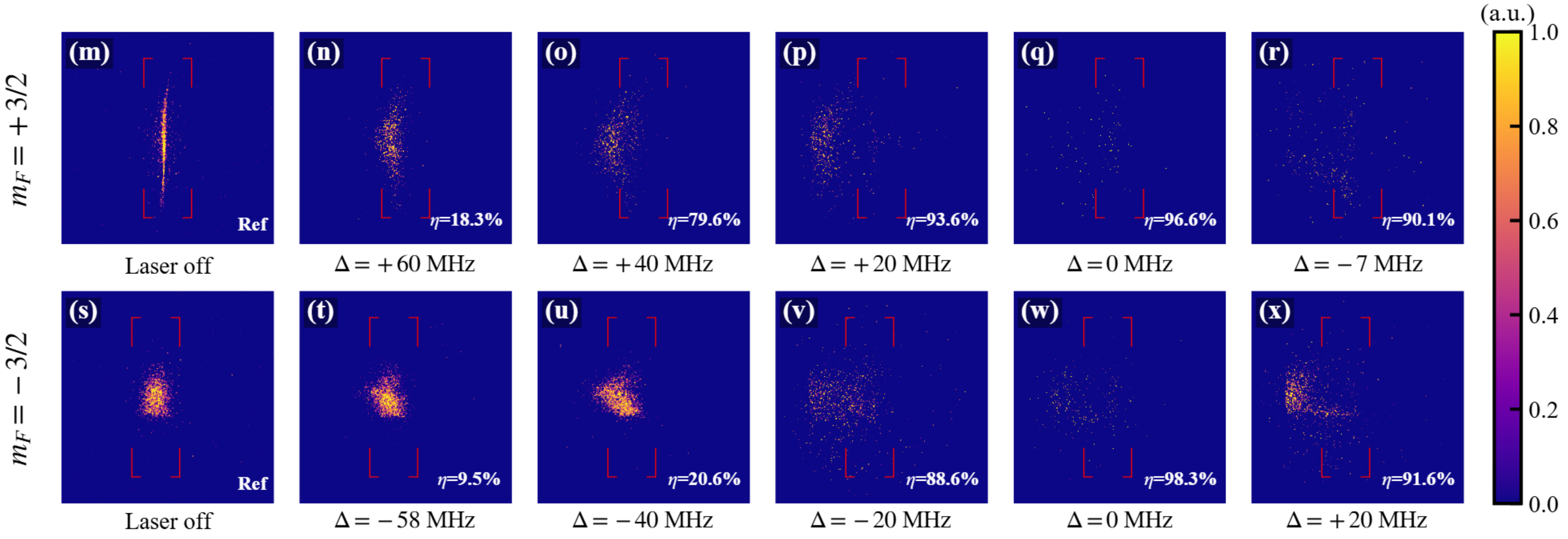






P = 100 mW
D = 2.0 cm

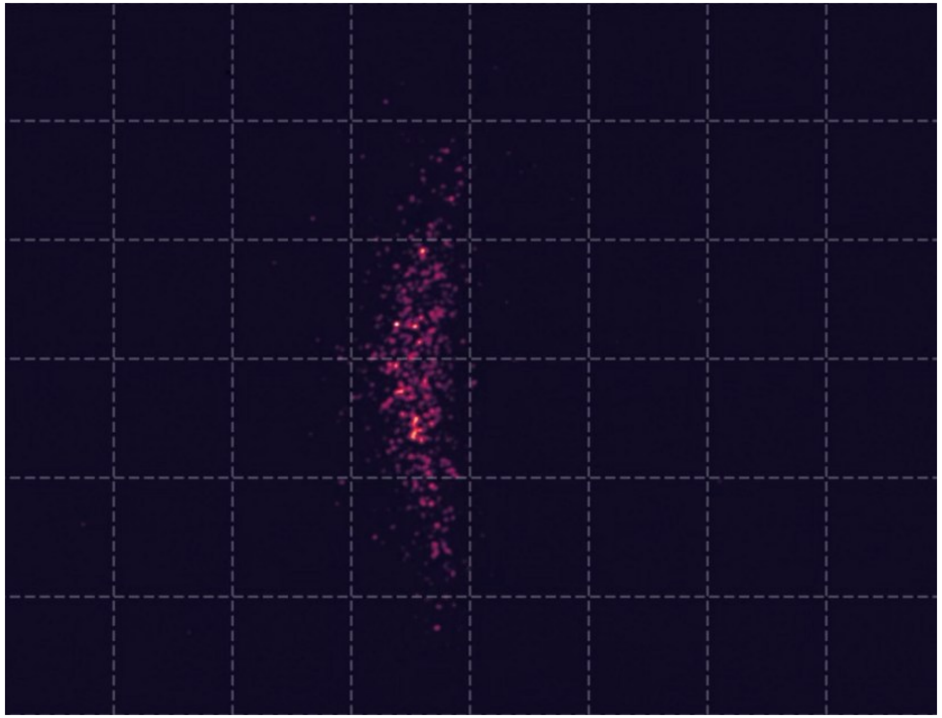
Appendix



(a.u.)
1.0
0.8
0.6
0.4
0.2
0.0
$m_F = +3/2$
(m) Ref
Laser off
(n) η=18.3%
$\Delta = +60$ MHz
(o) η=79.6%
$\Delta = +40$ MHz
(p) η=93.6%
$\Delta = +20$ MHz
(q) η=96.6%
$\Delta = 0$ MHz
(r) η=90.1%
$\Delta = -7$ MHz
$m_F = -3/2$
(s) Ref
Laser off
(t) η=9.5%
$\Delta = -58$ MHz
(u) η=20.6%
$\Delta = -40$ MHz
(v) η=88.6%
$\Delta = -20$ MHz
(w) η=98.3%
$\Delta = 0$ MHz
(x) η=91.6%
$\Delta = +20$ MHz

Appendix

$m_F = +3/2$



$m_F = -3/2$