Rydberg atom interferometry for testing the Weak Equivalence Principle with antimatter

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Outline

- Motivation – WEP tests with positronium
- Concept of measurement
- Rydberg atom interferometry
- Test experiments with helium
- Outlook

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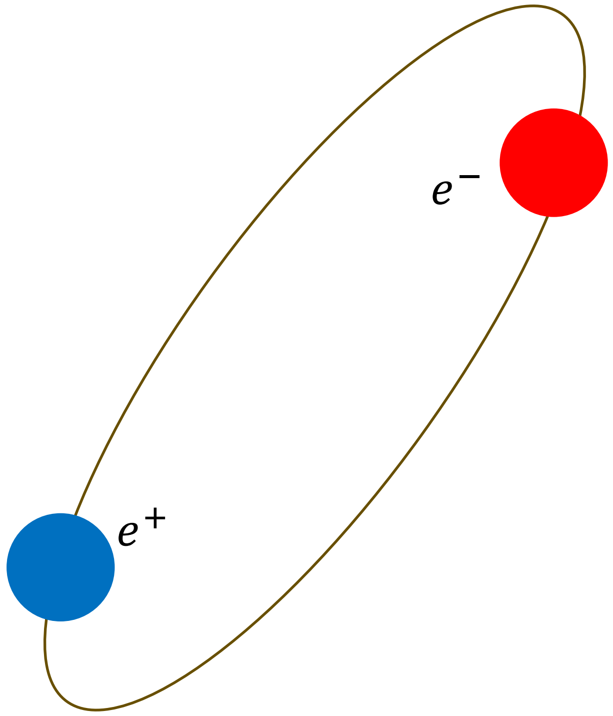
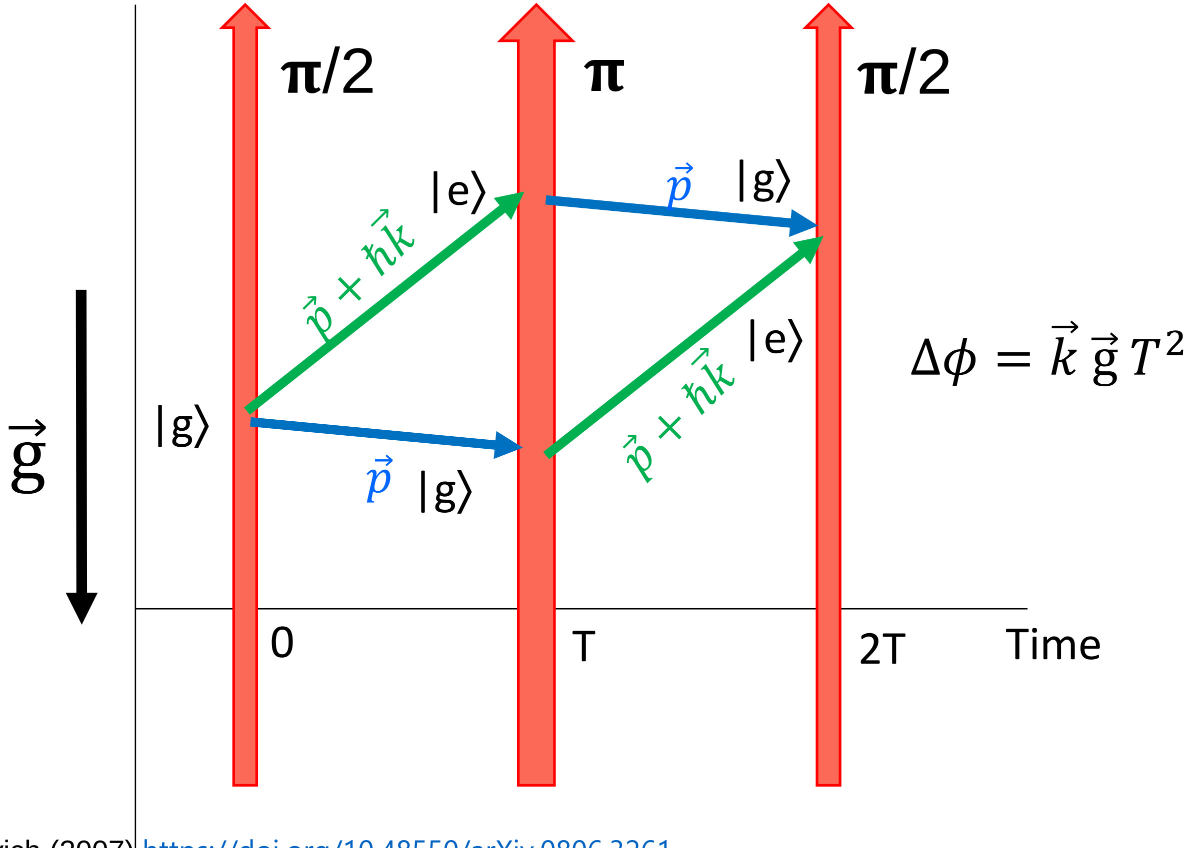
Motivation

- The Standard Model is incomplete for what we observe
- Experiments with positronium complement those with antihydrogen and muonium
- Positronium is a purely leptonic system
- Easier to produce than antihydrogen and muonium



Interferometry for gravity measurements

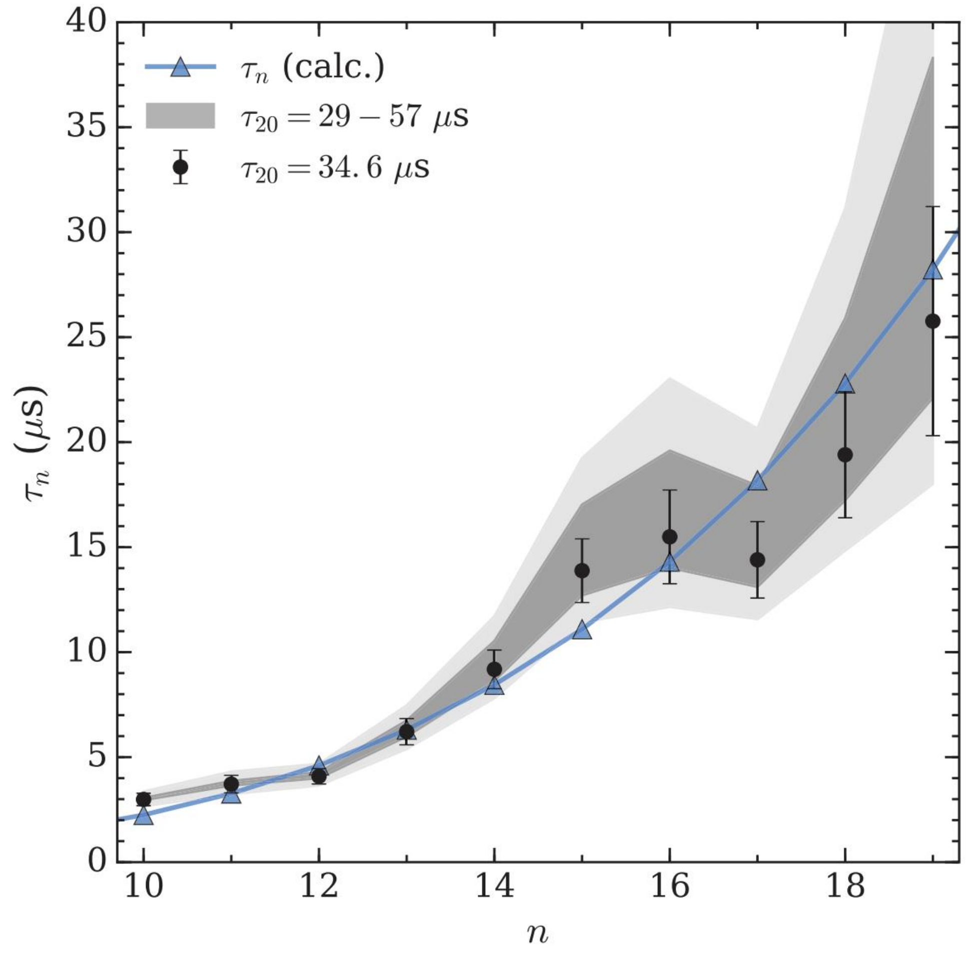
- Light-pulse interferometry with cold atoms is an established method for precision measurement of g [1]
- Positronium has a triplet ground state lifetime of 142ns [2]



[1] J.M. Hogan, D.M.S. Johnson, M.A. Kasevich (2007) https://doi.org/10.48550/arXiv.0806.3261
[2] R. S. Vallery, P. W. Zitzewitz, and D. W. Gidley, Phys. Rev. Lett. 90, 203402 (2003)

Interferometry for gravity measurements

- Light-pulse interferometry with cold atoms is an established method for precision measurement
- Positronium has a triplet ground state lifetime of 142ns
- Rydberg states give longer lifetimes
- Light-pulse very challenging



A. Deller, B. S. Cooper, S. D. Hogan and D. B. Cassidy, Phys. Rev. A **93**, 062513 (2016)

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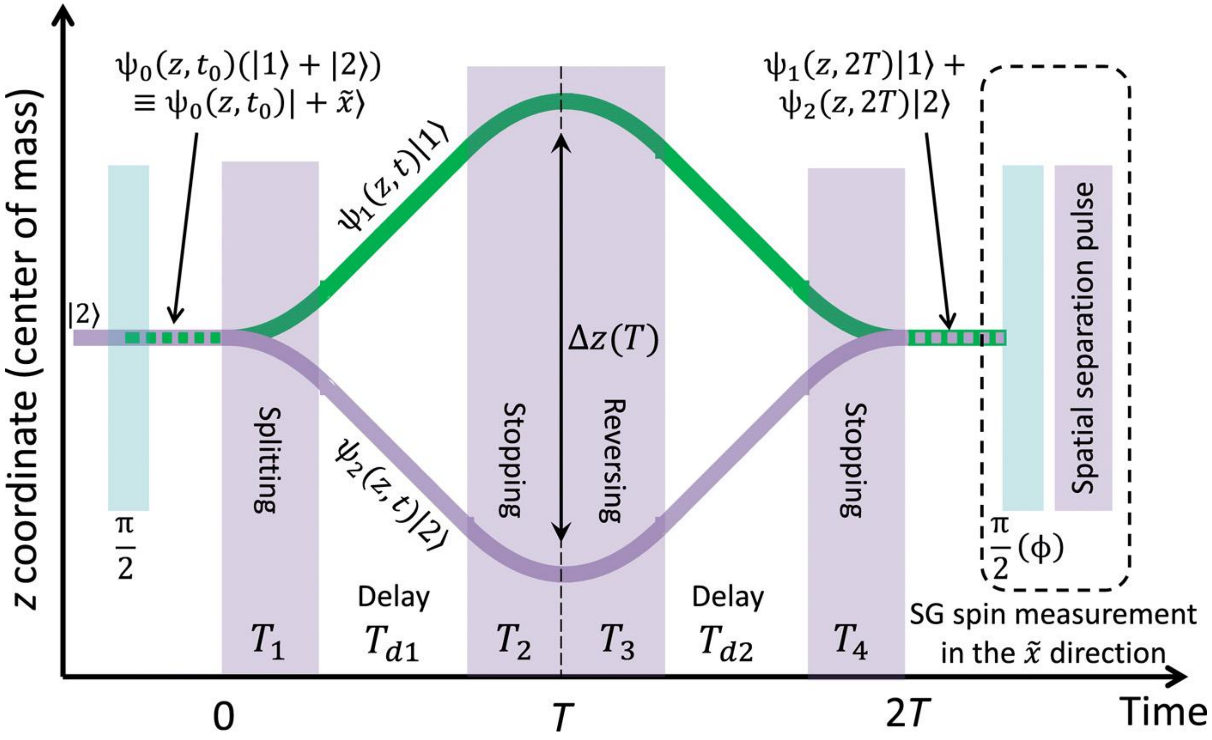
Interferometry with positronium

- Need something more like Stern-Gerlach interferometry
  - Atoms in superpositions of spin states
  - Forces exerted by inhomogeneous magnetic fields
  - Cold ground state atoms
- Rydberg atoms have large static electric dipole moments
- Implement electric analogue of this

J. E. Palmer and S. D. Hogan, Phys. Rev. Lett **122**, 250404 (2019)



Y. Margalit, O. Dobkowski, Z. Zhou, O. Amit, Y. Japha, S. Moukouri, D. Rohrlich, A. Mazumdar, S. Bose, C. Henkel, R. Folman, Sci. Adv **7**, 22 (2021)

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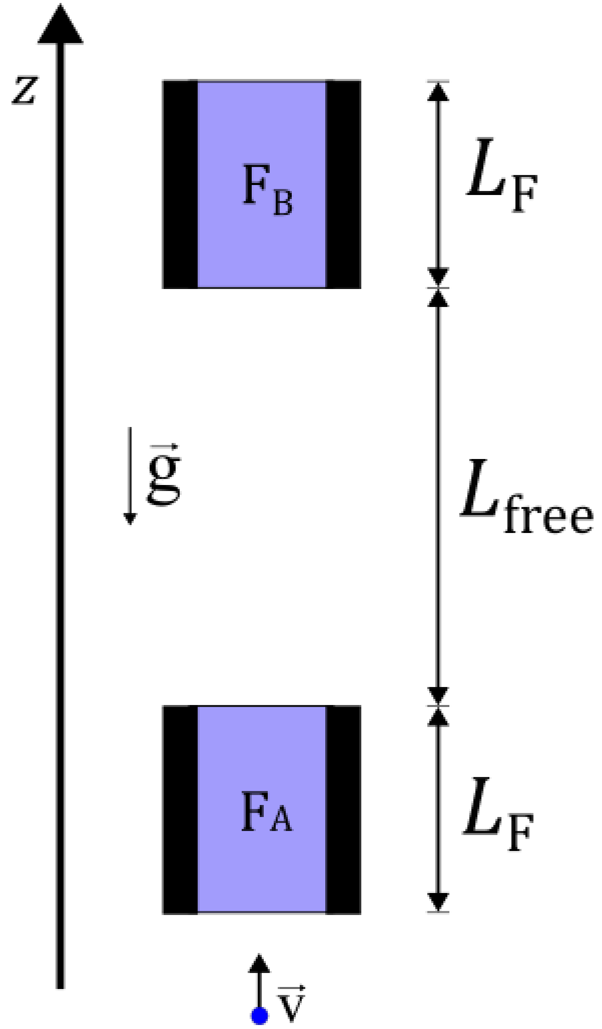
Basic concept

- Atoms travel vertically through two identical electric field regions
- Measure difference in flight times through each region
- Can use atom as a clock
- Measure Stark phase accumulated by atom in superposition of states with different electric dipole moments

$$\Delta\phi_{\text{Stark}} = -\frac{1}{\hbar}\int_0^t \Delta\vec{\mu}\cdot\vec{F}\,dt \qquad \Delta\phi_{\text{Stark},A} \neq \Delta\phi_{\text{Stark},B}$$



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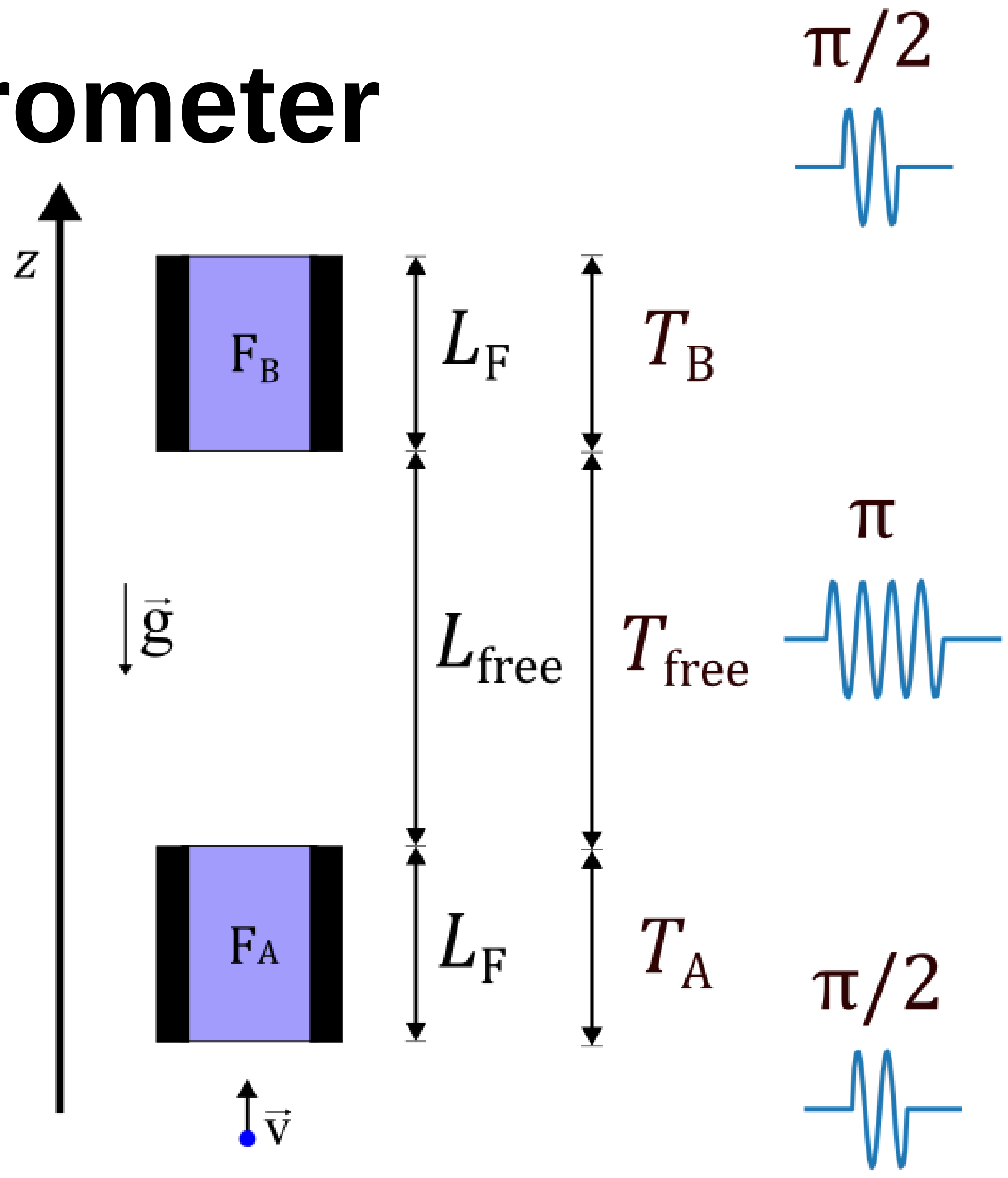
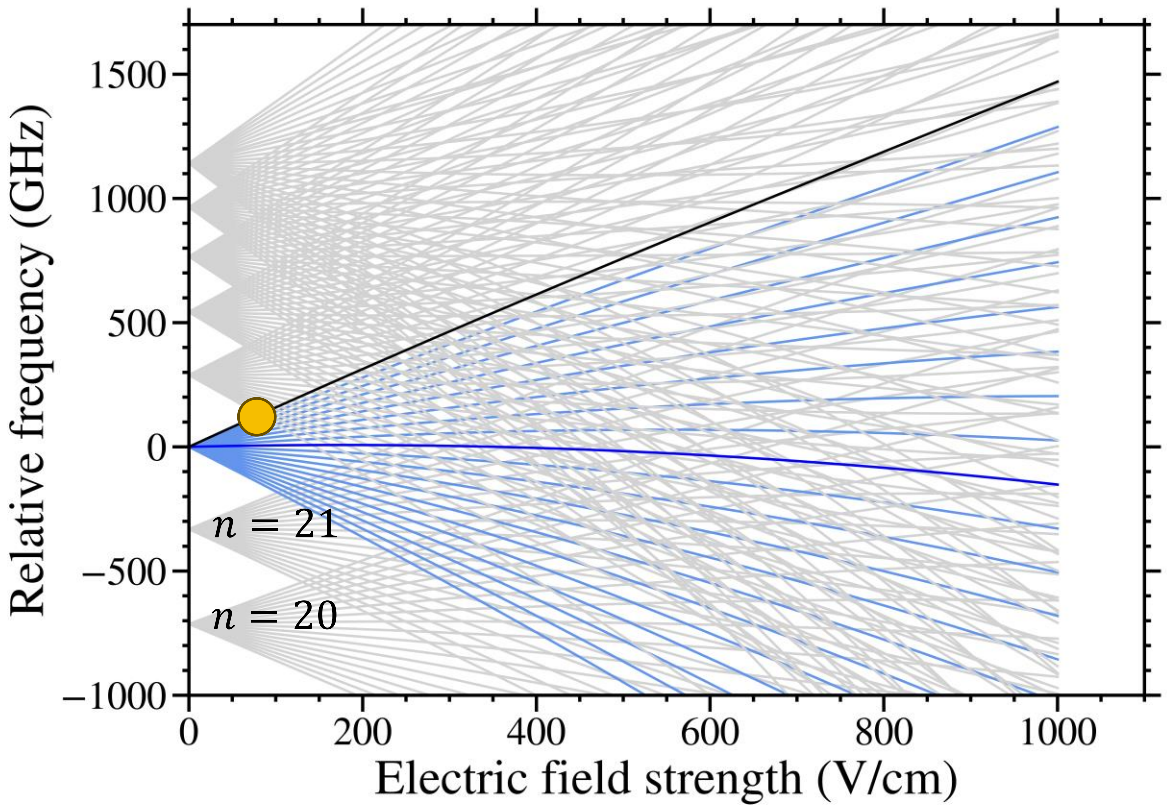
Rydberg-atom interferometer

- Superposition of Rydberg states prepared before entering field region A
- We must account for forces in field gradients
- These forces result in the generation of separated momentum states as in an atom interferometer

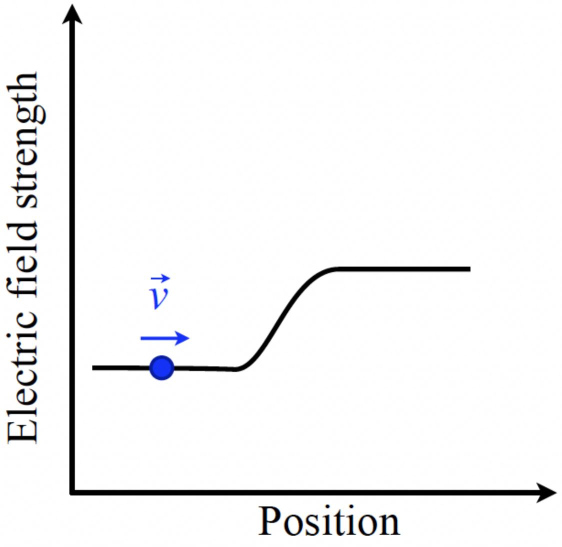


Stark effect



$$E_{\text{Stark}} = -\vec{\mu}_{\text{elec}} \cdot \vec{F}$$

$$\vec{f} = -\nabla E_{\text{Stark}}$$



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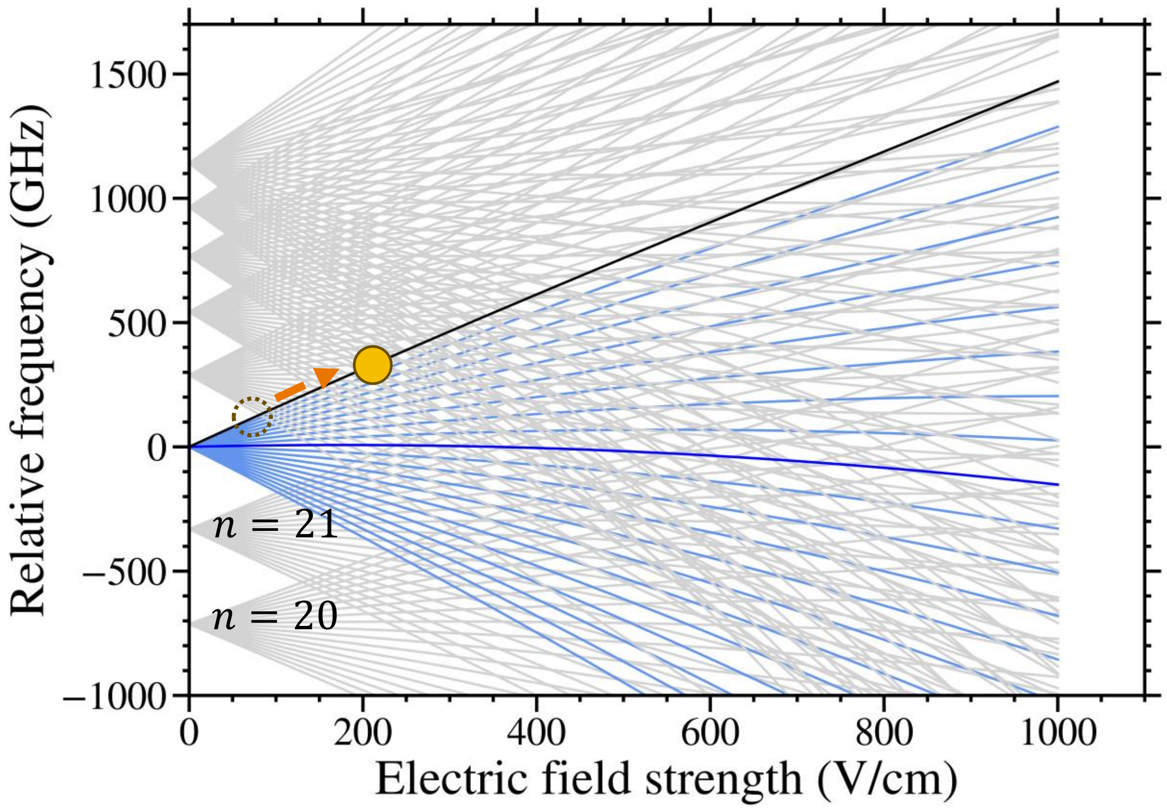
Stark effect



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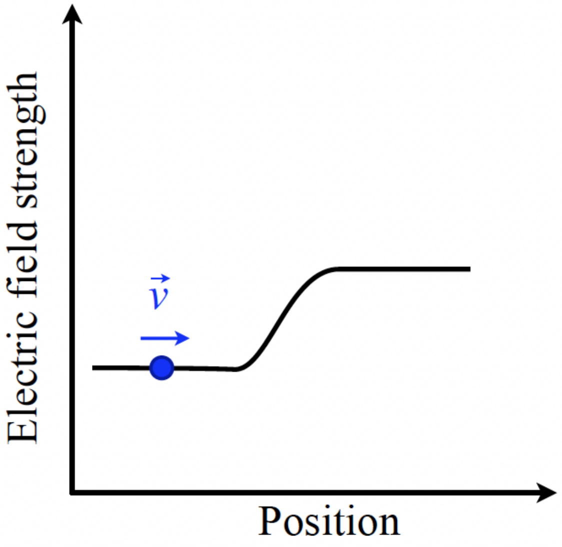

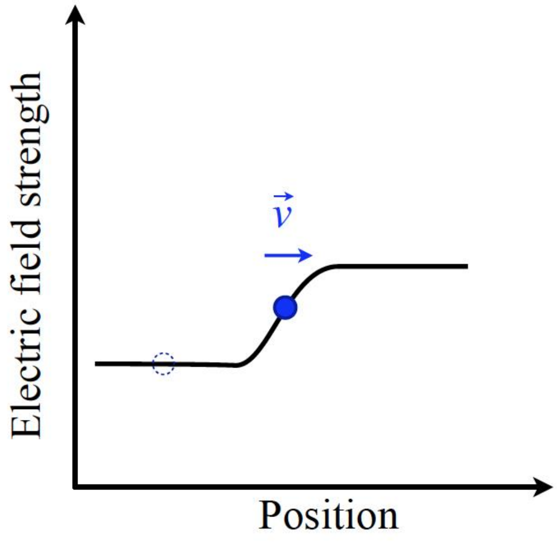

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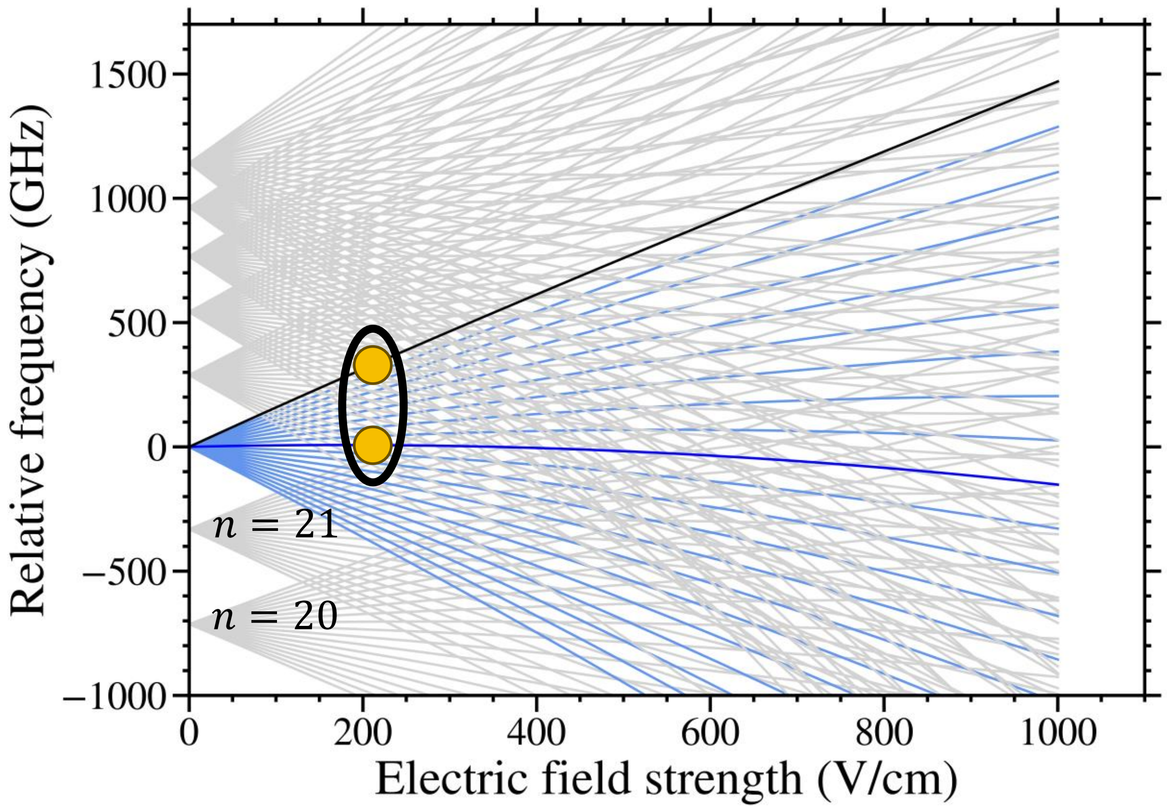

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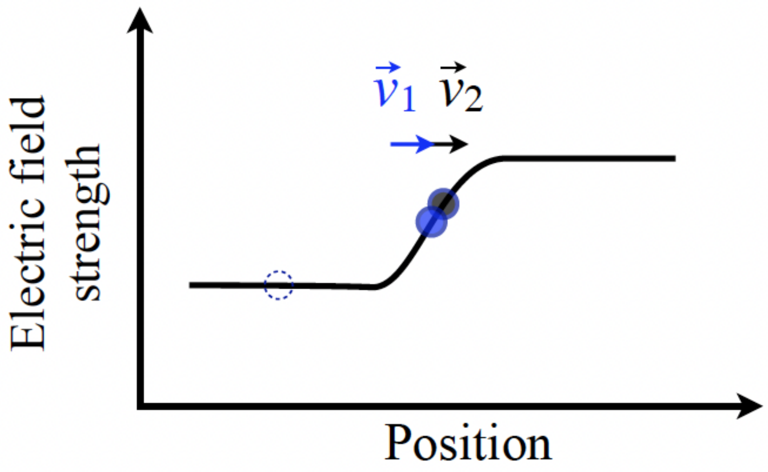

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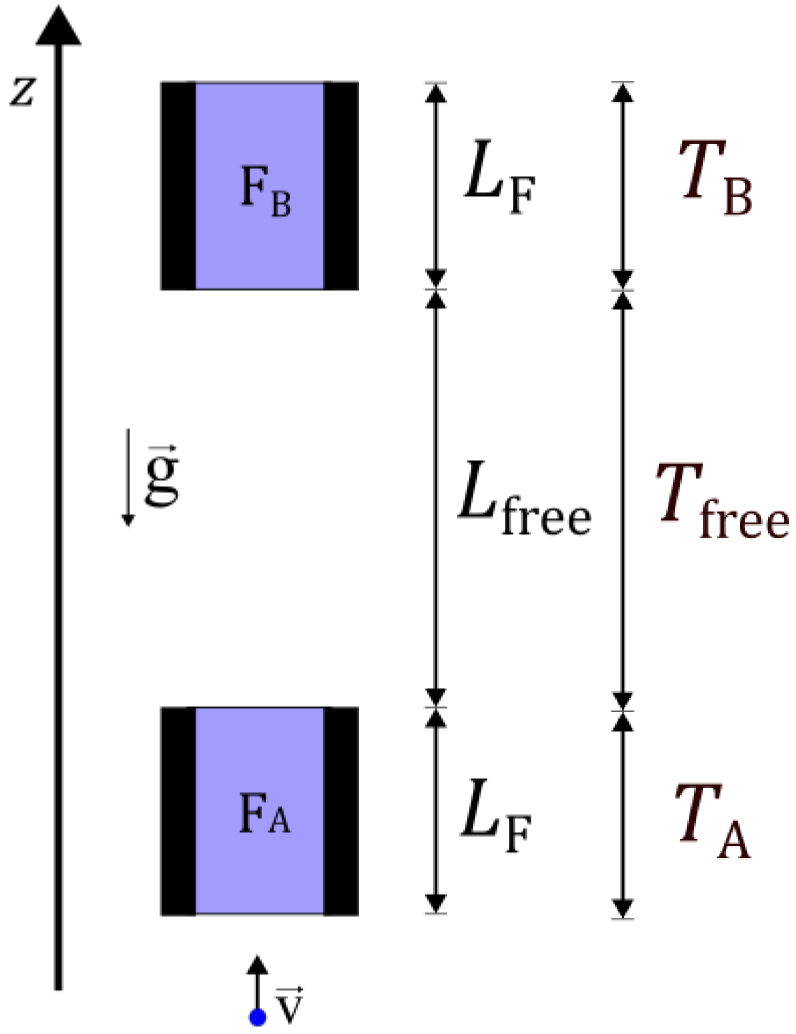
DQT

Rydberg-atom interferometer

- Superposition of Rydberg states prepared before entering field region A
- We must account for forces in field gradients
- These forces result in the generation of separated momentum states as in an atom interferometer
- $T_A \neq T_B$

$$T_{A,1} \neq T_{A,2}$$
$$T_{B,1} \neq T_{B,2}$$

1
2



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Phase contributions

- Using a semiclassical description, the atoms accumulate phase as they propagate through the interferometer due to:
  - Path of least action (gravity)
  - Electric fields
  - Spatial separation of wavepackets

Dynamic	$\Delta\phi_{\mathrm{dyn}} = \frac{m}{2\hbar}\int_0^t ({v_1}^2 - v_2^2)\,dt$
Stark	$\Delta\phi_{\mathrm{Stark}} = -\frac{1}{\hbar}\int_0^t ((\mu.F)_1 - (\mu.F)_2)\,dt$
Gravitational	$\Delta\phi_{\mathrm{grav}} = \frac{mg}{\hbar}\int_0^t (z_1 - z_2)\,dt$
Separation	$\phi_{\mathrm{sep}} = \frac{1}{\hbar}\left(\frac{p_1 + p_2}{2}\right)(z_2 - z_1)$

$$\Delta\phi(t_{\mathrm{f}}) = \Delta\phi_{\mathrm{dyn}}(t_{\mathrm{f}}) - \Delta\phi_{\mathrm{grav}}(t_{\mathrm{f}}) - \Delta\phi_{\mathrm{Stark}}(t_{\mathrm{f}}) + \phi_{\mathrm{sep}}(t_{\mathrm{f}})$$

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Phase contributions

- At output of closed loop interferometer
- $\Delta\phi_{\text{Stark}} \neq 0$
- $\Delta v = 0, \Delta z = 0, \ \phi_{\text{sep}} = 0$
- $\Delta\phi_{\text{grav}} \neq 0, \Delta\phi_{\text{dyn}} \neq 0$

Dynamic	$\Delta\phi_{\text{dyn}} = \frac{m}{2\hbar}\int_0^t ({v_1}^2 - v_2^2)\, dt$
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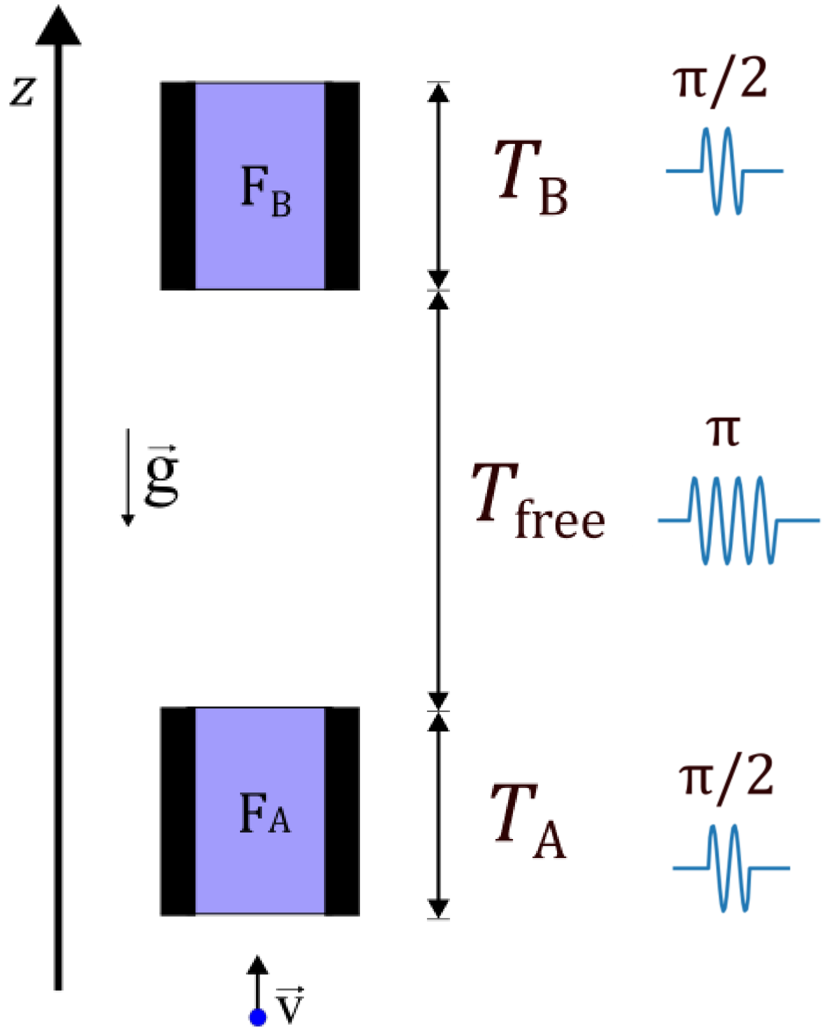
Phase contributions

- Total phase has multiple *g*-dependent components

$$\Delta\phi_{\mathrm{tot}}(t_f) = \frac{m}{\hbar}\left(\frac{1}{2}v_0^2\left(T_{A,1} - T_{A,2} + T_1 - T_2 + T_{B,1} - T_{B,2}\right)\right)$$

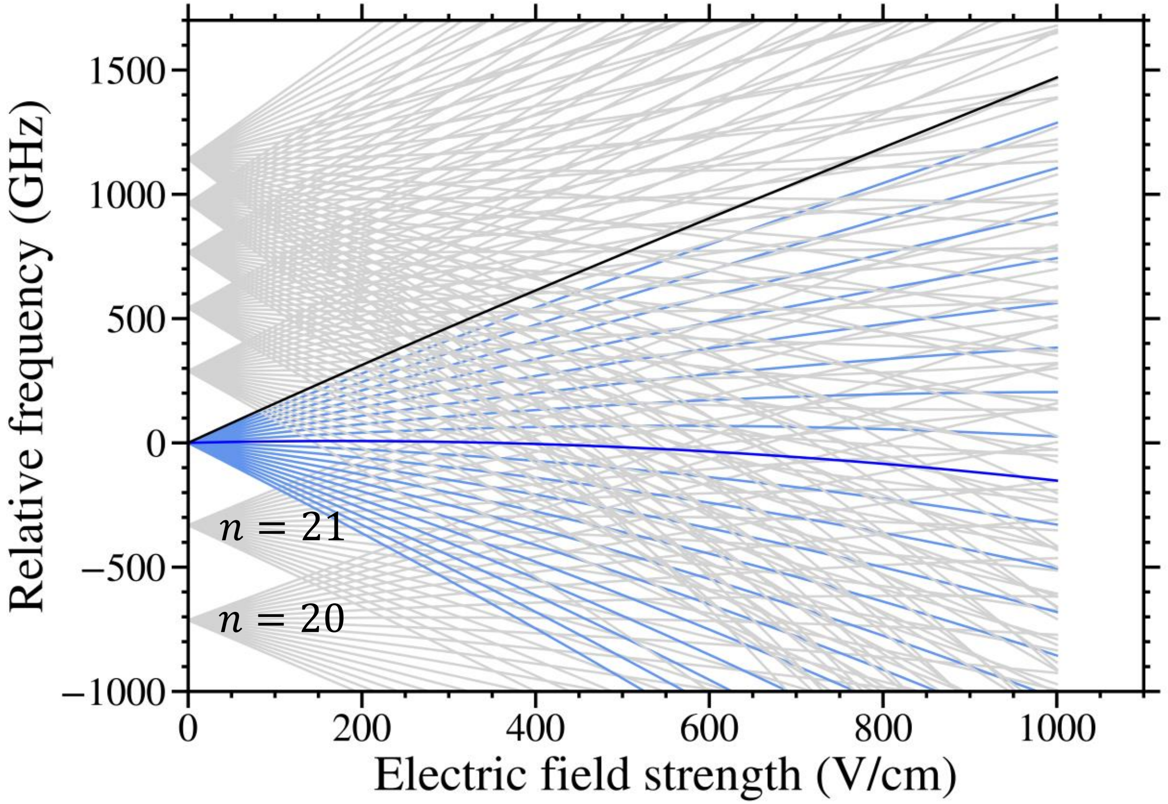
$$+\frac{2F}{\hbar}\left(\mu_1\left(T_{A,1} - T_{B,2}\right) - \mu_2\left(T_{A,2} - T_{B,1}\right)\right)$$

- Each *T* is *g*-dependent
- Also consider time spent in gradient



Planned experimental setup

- Select pair of positronium Rydberg states with large difference in electric dipole moment
- For example, central and outer Stark state, here shown for n = 22
- $\Delta\mu \cong 1500\, ea_0$ ($\cong 3800\, D$)



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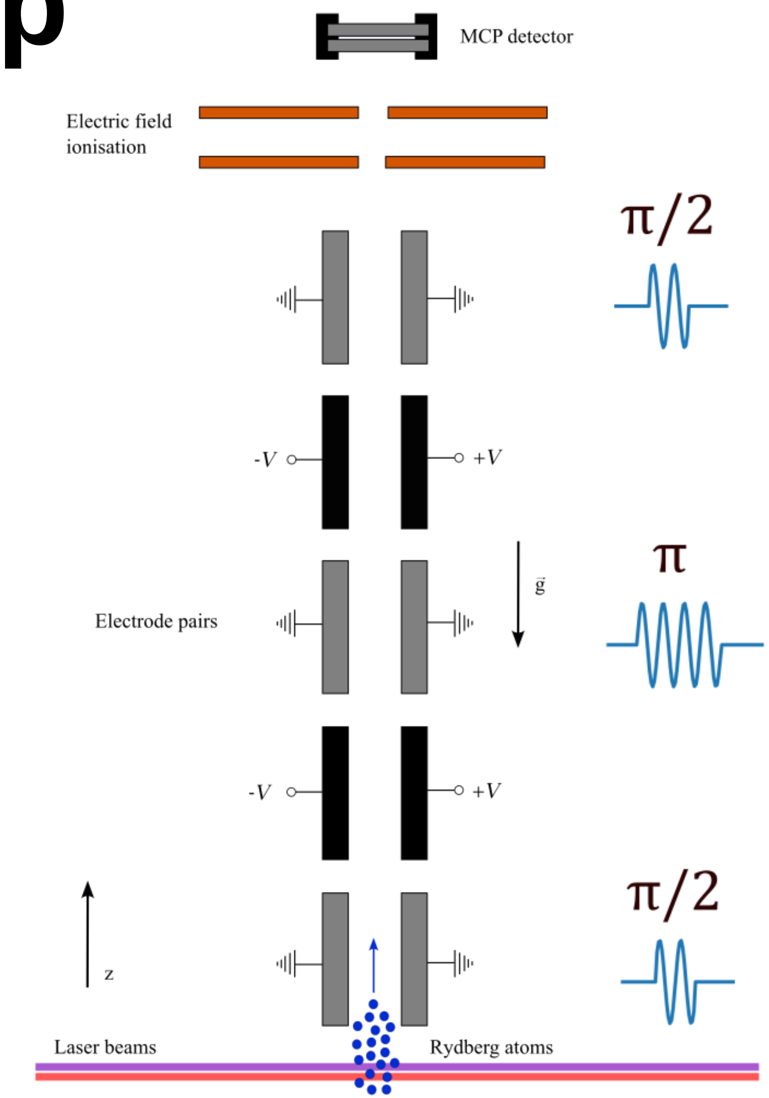
Planned experimental setup

- Prepare Rydberg atoms
- Series of pairs of parallel electrodes
- Internal states evolved by microwave/mm-wave pulses
- State selective electric field ionisation



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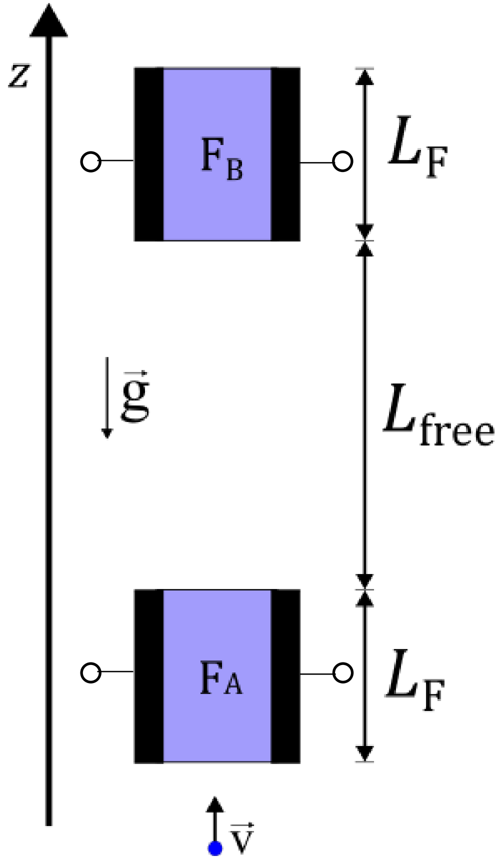
Expected magnitude of phase shifts

- $\Delta\mu \cong 1500\, ea_0$ ($\cong 3800\, D$)
- $L_\mathrm{F} = 20$ cm
- $L_\mathrm{free} = 1.4$ m
- $F = 900$ V/cm,
- $\Delta\phi = \frac{\pi}{2}$
- Possible with $\sim 90\mu s$ flight time and $v_0 \sim 20$ km/s



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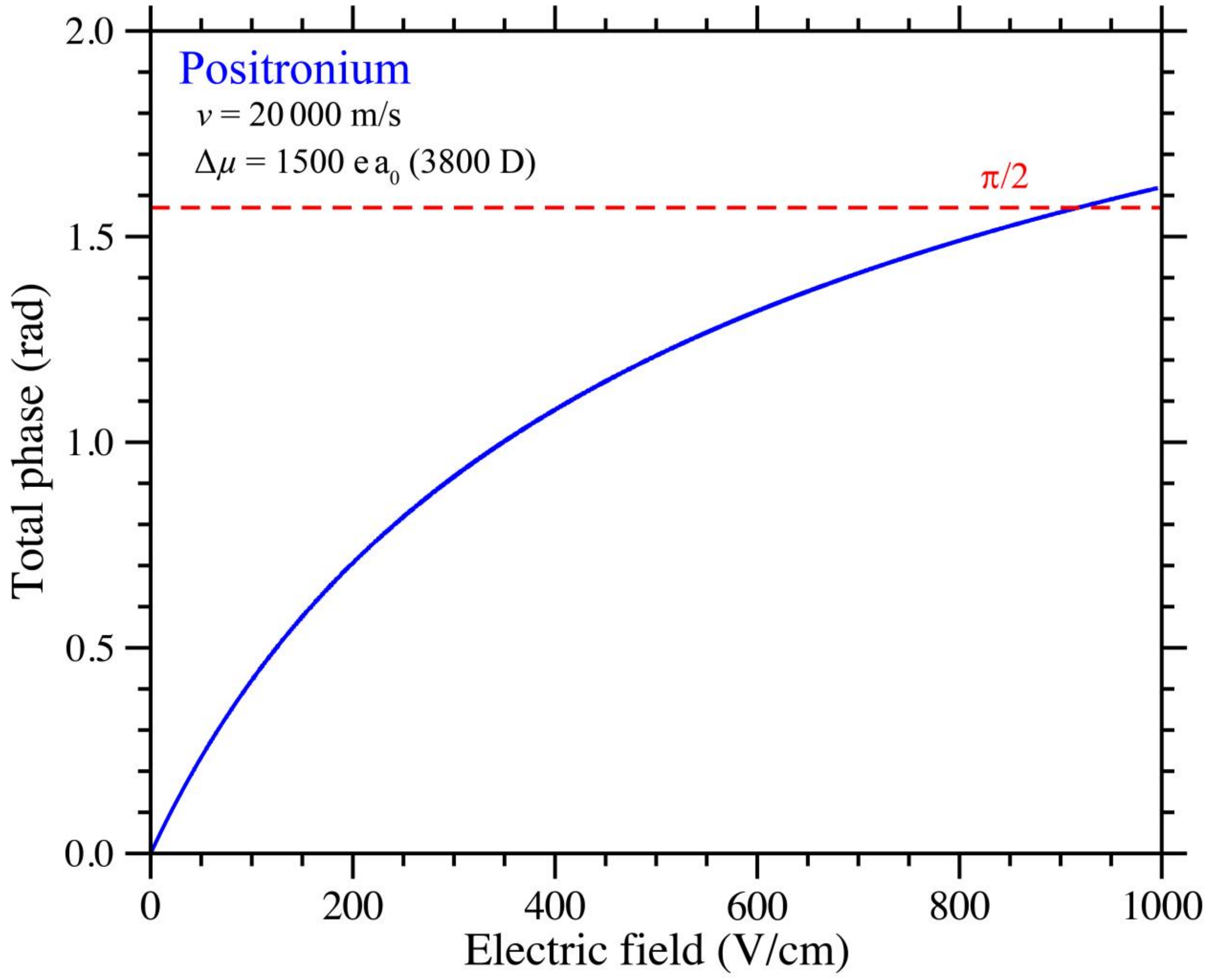

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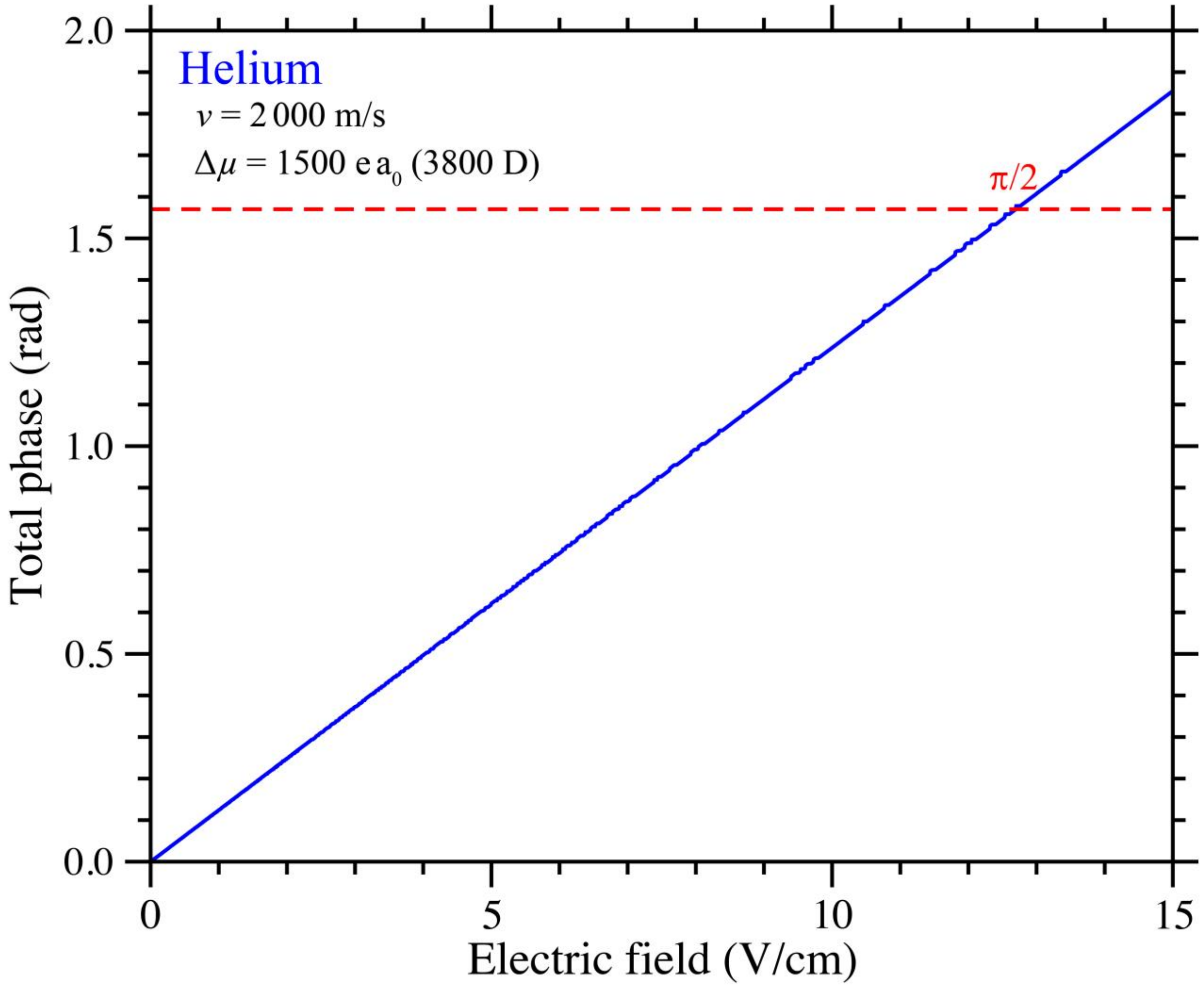
Phase shifts in test apparatus with helium

- $\Delta\mu = 1500\ ea_0\ (3800\ D)$
- F = 13 V/cm
- $L_F = 1\ \text{cm}$
- $L_{\text{free}} = 10\ \text{cm}$
- $\Delta\phi = \frac{\pi}{2}$
- $v_0 = 2000$ m/s



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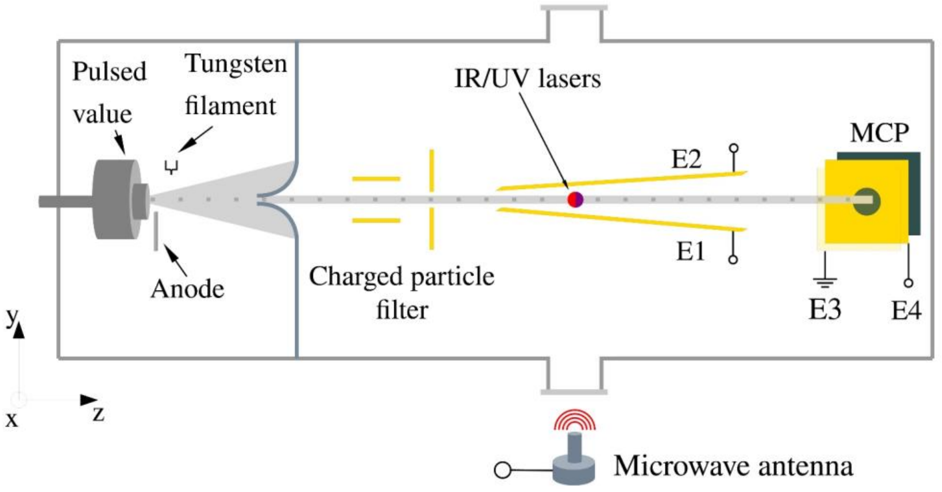
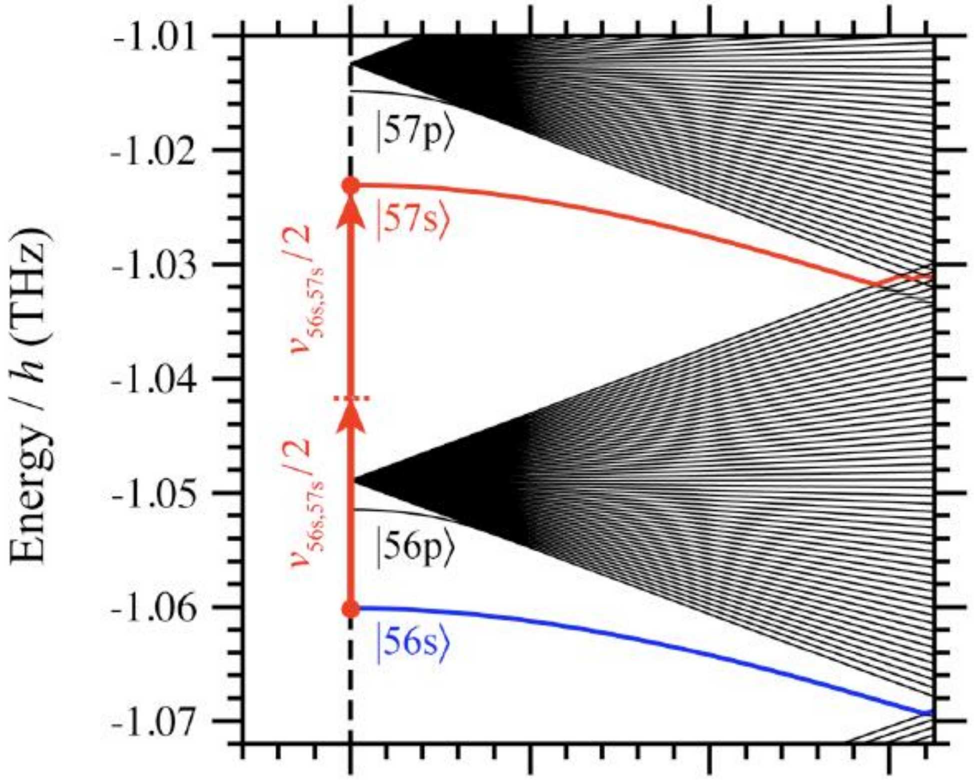
Previous experiments with helium

- Coherent moment splitting with helium atoms in superpositions of $|ns\rangle$ Rydberg states
- Horizontal half-loop interferometer
- Implemented with pulsed electric field gradients

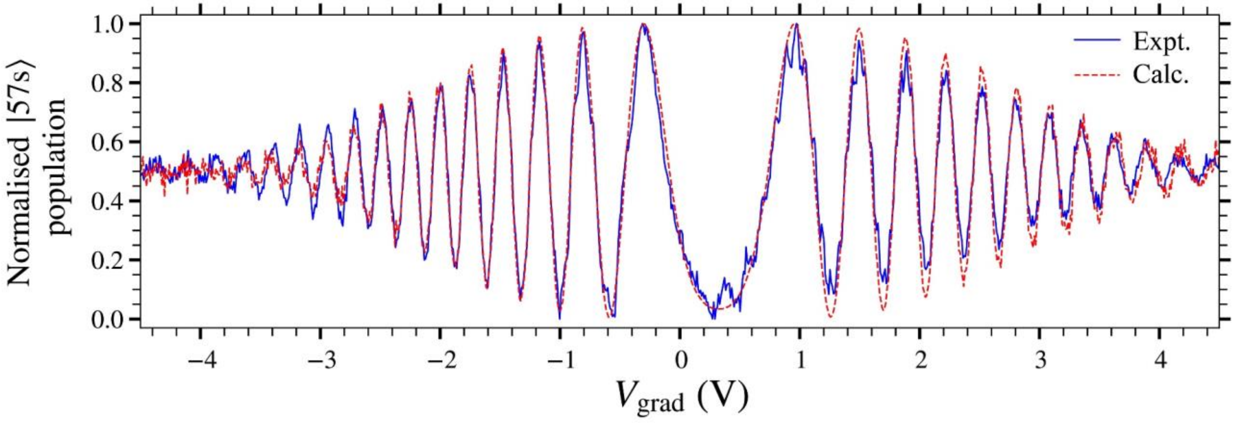


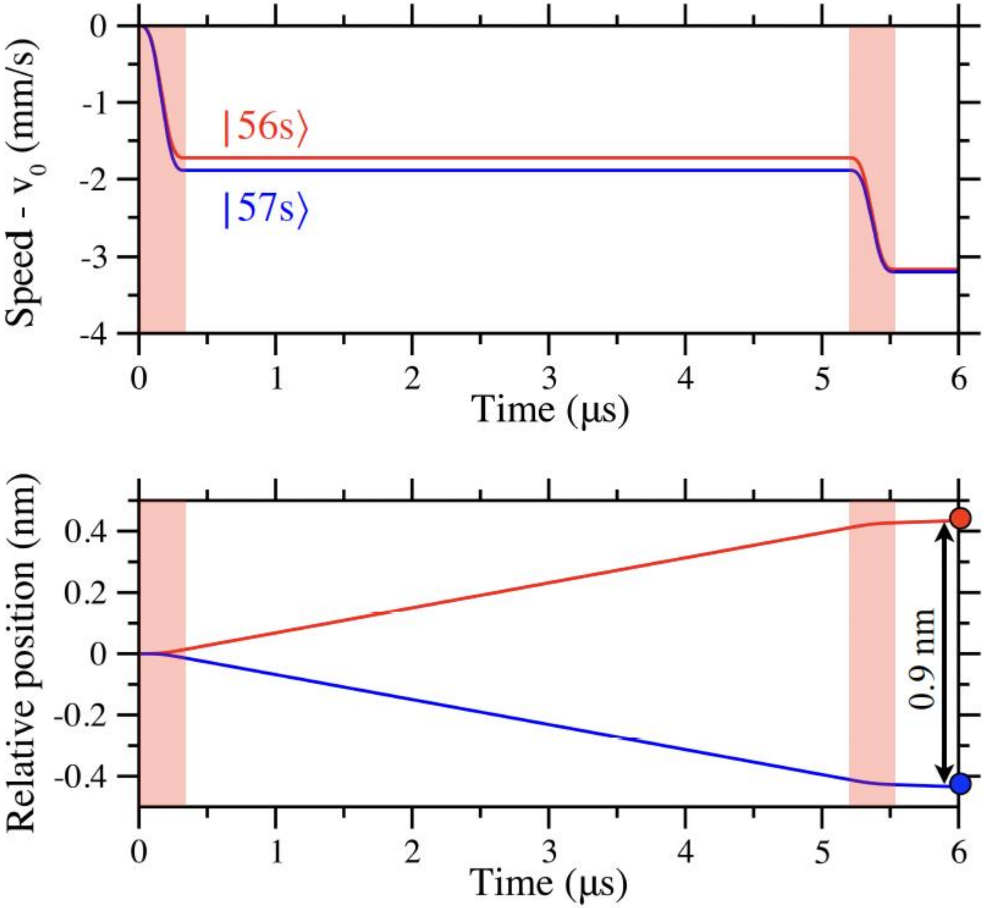


J. D. R. Tommey and S. D. Hogan, Phys. Rev. A **104**, 033305 (2021)

Current status with helium

- Phases determined by measuring populations of the Rydberg states
- Coherent evolution observed for momentum state separation up to 1 nm





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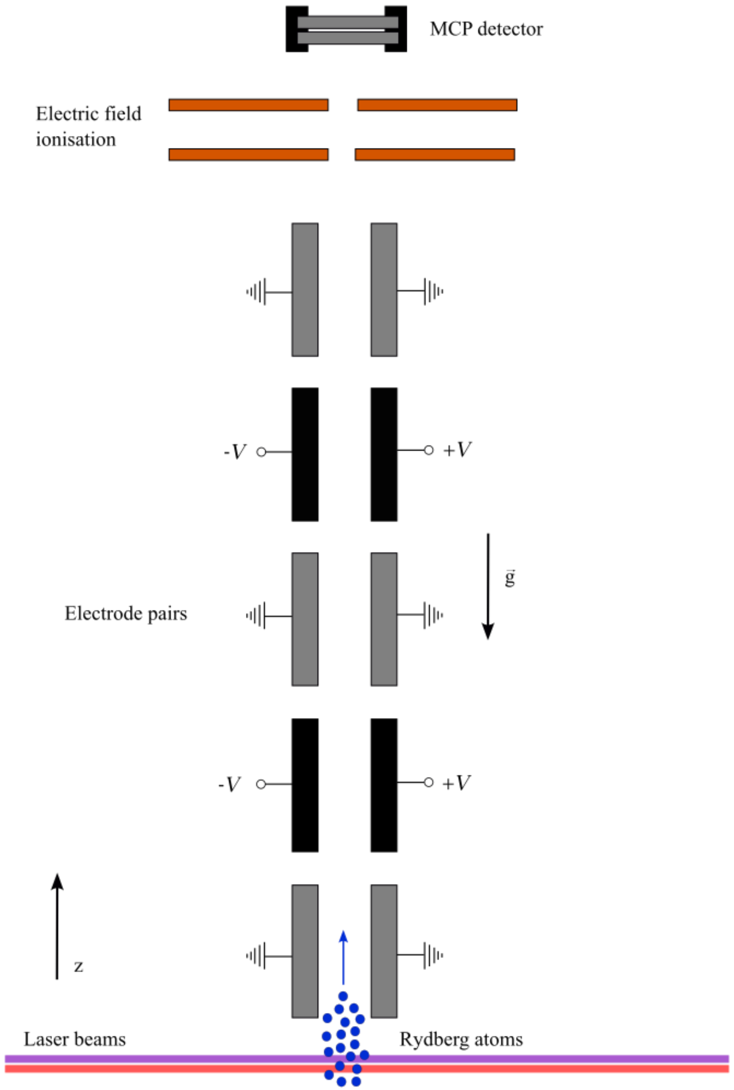
Next steps

- Demonstrate full loop interferometer with helium in horizontal configuration
- Characterise stray fields and systematic errors
- Rotate setup for *g*-sensitive measurement

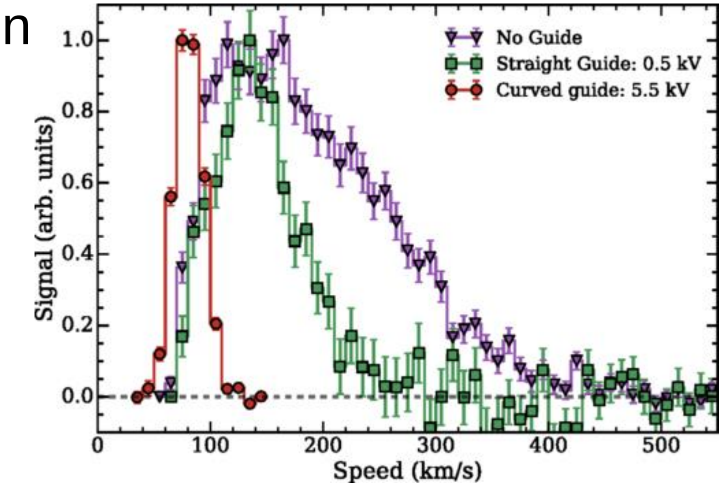
- Further in the future -> positronium!



Next steps

- Perform full loop interferometer with helium in horizontal configuration
- Characterise stray fields and systematic errors
- Rotate setup for *g*-sensitive measurement
- Further in the future -> positronium!

- Continued development of Ps techniques:
  - Rydberg positronium state production/coherent manipulation
  - Guiding of positronium
  - Velocity selection



A. M. Alonso, B. S. Cooper, A. Deller, L. Gurung, S. D. Hogan, and D. B. Cassidy Phys. Rev. A **95**, 053409

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Conclusions

- Described method suitable for measuring gravity with Rydberg positronium atoms
- Electric analogue of Stern-Gerlach interferometry
- Measure phase shift with sensitivity of ~0.1 π
- Sensitive to <10% g for helium
- Ultimate aim is to achieve similar precision with positronium