A recoil measurement scheme in intermediate-scale atom interferometers for determining fundamental constants

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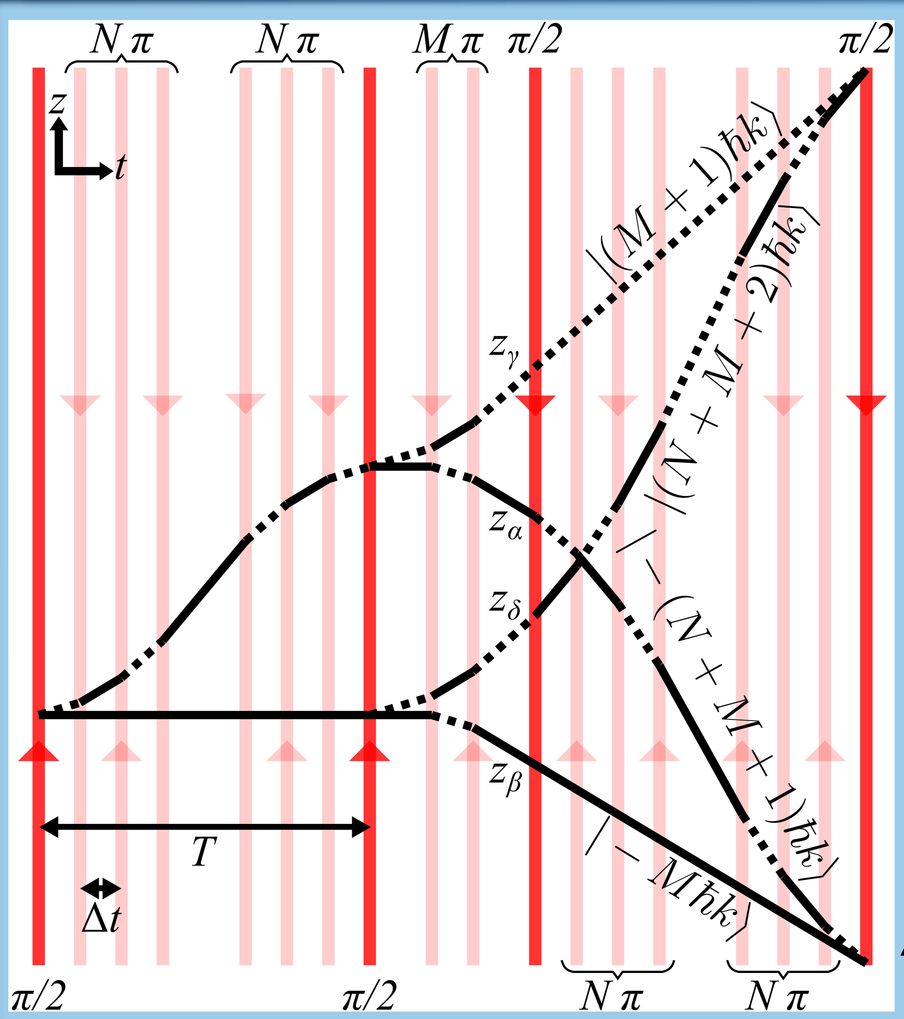
AION

Abstract

Atom-interferometric recoil measurements limit the precision of many fundamental constants, including α, m_u, μ_0, ε_0, and μ_B [1]. We have devised a scheme for photon-recoil measurement in intermediate-scale atom interferometers [2], whereby the recoil phase can be optimised through LMT and the gravity-gradient phase can be mitigated by crossing the trajectories of two interferometers. We find that our scheme implemented in a 10-metre instrument operating on the clock transition in Sr or Yb is more than sufficient to increase the precision of α by an order of magnitude. These measurements will aid the highest precision tests of the Standard Model of particle physics [3].

LMT-enhanced Ramsey-Bordé interferometry

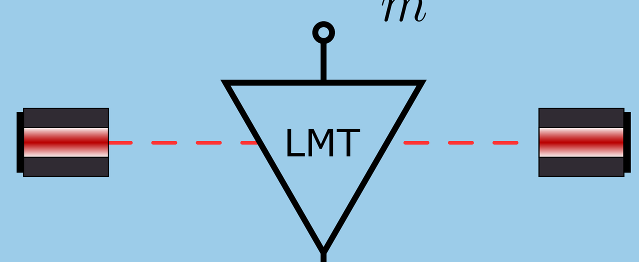


Recoil phase:
$$\Delta\Phi \propto \Delta E_{\text{rec}} = \Delta\left(\frac{(p-p_0)^2}{2m}\right)$$

Large momentum transfer (LMT):
$$|p_0\rangle \rightarrow |p_0 + N\hbar k\rangle$$

π-pulses in alternating directions [4]

$$\Delta\Phi \sim \frac{2\hbar k^2 T}{m}$$

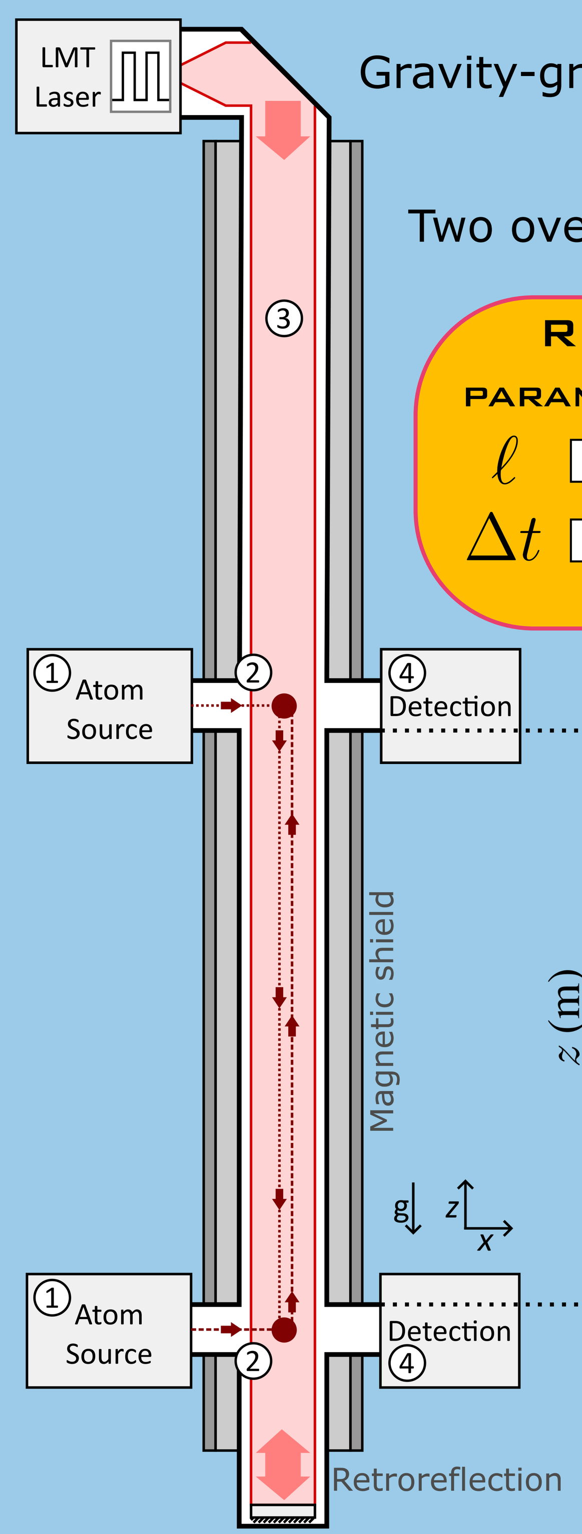


$$\Delta\Phi \sim \frac{(N+1)(N+2M+2)\hbar k^2 T}{m}$$

Optimal gravity-gradient-nullifying trajectories

Gravity-gradient phase: $\Phi_{\text{GG}} = -\frac{mG_{zz}}{\hbar}\int \bar{z}\Delta z dt$

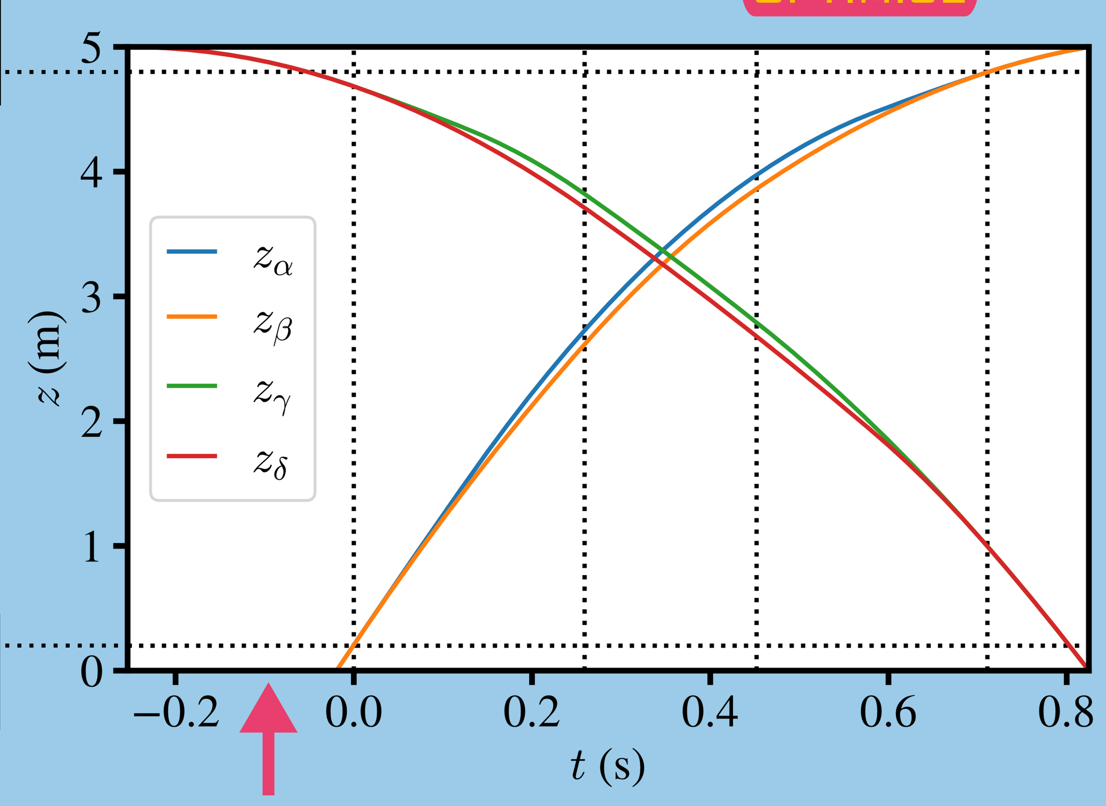
Two overlapped interferometers [5]: $\Delta\Phi_{\text{GG}} = 0$



RECOIL PHASE OPTIMISER 3000

PARAMETERS	CONSTRAINTS	VARIABLES
ℓ 5 m	☑ $\Delta\Phi_{\text{GG}} = 0$	☑ LMT
Δt 1 ms	☑ End at detector	☑ Launch
	☑ Magnetic shielding	☑ Drop

OPTIMISE



Optimal trajectories for Sr on 698nm clock transition

AION-10: $\ell = 5\,\text{m}$

$$N = 129,\ M = 192 \Rightarrow \Delta\Phi = 4.7\times 10^8$$

Fine-structure constant (α)

An empirical parameter in the Standard Model of particle physics that quantifies the strength of the electromagnetic interaction

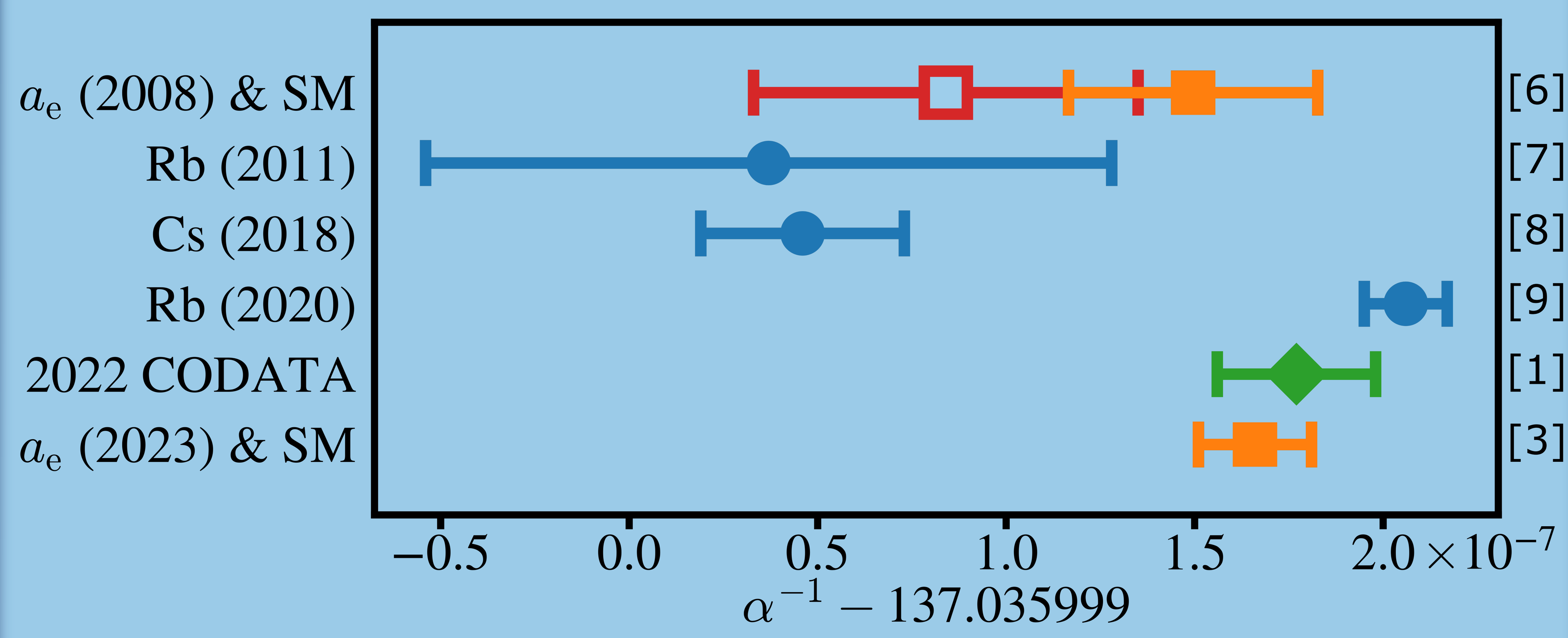
QED calculations sum Feynman diagrams in a power series of α:

$$a_e = \frac{g_e - 2}{2} \stackrel{?}{=} \sum_n C_{2n}\left(\frac{\alpha}{\pi}\right)^n + a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}}$$

Experiment — Calculation

Highest-precision test of Standard Model

SM test limited by discrepancy between Rb- and Cs-recoil values for α [3]



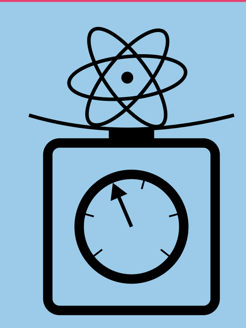
$$\frac{e^2}{2\varepsilon_0 hc} = \alpha = \sqrt{\frac{2hR_\infty}{m_e c}}$$

	u_r	
R_∞	1.1×10^{-12}	[1]
$A_r(\text{e})$	1.8×10^{-11}	[1]
$A_r(^{87}\text{Rb})$	7.0×10^{-11}	[10]
$m(^{87}\text{Rb})$	1.5×10^{-10}	[9]

Precision of α is limited by recoil measurement

$$m_e = A_r(\text{e})m_u$$

$$\frac{m(^{12}\text{C})}{12} = m_u = \frac{m(\text{X})}{A_r(\text{X})}$$



Conclusion

Intermediate-scale (~10m) atom interferometers using Sr or Yb are under development, e.g. AION-10, MAGIS prototype, VLBAI teststand

At AION-10 initial target phase resolution of 1mrad/shot:

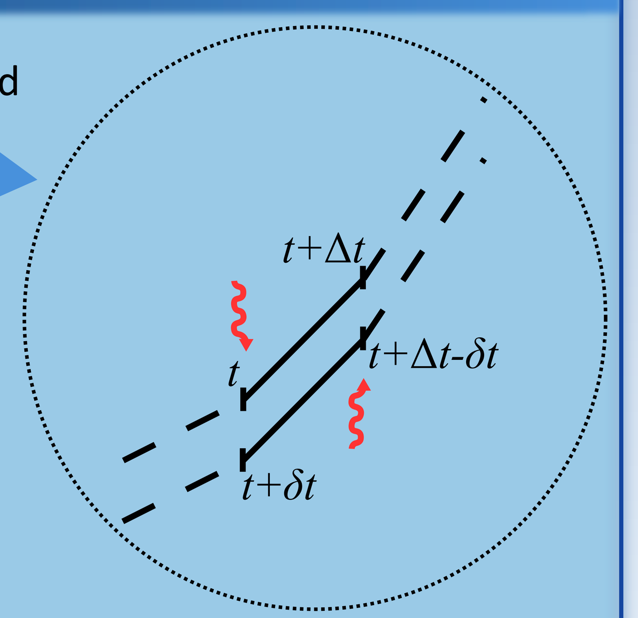
$$u_r(m(^{87}\text{Sr})) = 2.2\times10^{-12}$$

- ✓ Improve precision of α by factor of 2
- ✓ α limited by relative masses
- ✓ Improve α by > 10× with better A_r
- ✓ Additional datum for resolving α discrepancy

Recoil measurements
⇓
α
⇓
Test of SM

Outlook: Systematics

- ✓ Light propagation delay found to contribute above 1mrad
- Mass difference between ground and excited states:
$$\frac{m(\text{Sr } 5s5p\ ^3P_0)}{m(\text{Sr } 5s^2\ ^1S_0)} - 1 = 2.2\times10^{-11}$$
- Laser wavefront curvature and distortion
- ac-Stark shift
- Laser beam alignment
- Blackbody radiation
- ⋮



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