EP Torsion Pendulum Experiments

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The most precisely tested prediction of the EP is that all bodies experience identical acceleration in a uniform gravitational field.
Equivalence Principle Violation
New forces?

\[ V = \alpha \left( \frac{\tilde{q}}{\mu} \right)_A \left( \frac{\tilde{q}}{\mu} \right)_B \frac{G m_A m_B}{r} e^{-r/\lambda} \]
Motivation

- General Relativity successfully describes all observed gravitational phenomena. Since the Equivalence Principle is a basic assumption of General Relativity, testing for violations constrains alternative theories of gravity and possible new forces weaker than gravity.


- Equivalence Principle tests provide a means of searching for non-gravitational interactions between ordinary matter and dark matter.
Different directions for “down”

are angles equal?

\[ \varepsilon = \omega^2 R \sin 2\theta / (2g) \quad (m^i / m^g) \]
If the EP is violated, *down* is not a unique direction

Balance twists only if force vectors are not parallel i.e., if EP is violated or if gravity field is not uniform
Rotating torsion balance modulates the signal toward lab-fixed attractors (Top View)

Turntable rotates with a period of ~20 minutes.

Fiber supports and forms weak torsion spring.

Torsion pendulum amplitude < 100 μrad.
Rotating turntable design
Torsion pendulum features

- 70 g pendulum suspended by a 20 μm thick, 1.08 m long tungsten fiber
- Screws to reduce residual coupling to gravitational gradients
- Design minimizes coupling to gravitational gradients. Four-fold azimuthal symmetry and top-bottom reflection symmetry
- Eight 4.84g test bodies (4 Be & 4 Ti) or (4 Be & 4 Al)

5 cm
Major systematic effects

- Gravity gradients
- Tilt
- Temperature gradients
- Magnetic
Gravity gradients

Gravitational potential energy between the pendulum and the source masses is given by

\[ U = -4\pi G \sum_{l=0}^{\infty} \frac{1}{2l + 1} \sum_{m=-l}^{l} Q_{lm} q_{lm} e^{-im\phi}. \]

\[ Q_{lm} = \int d^3 r' \rho_{\text{source}}(\vec{r}') r'^{-(l+1)} Y_{lm}(\hat{r}') \]

\[ q_{lm} = \int d^3 r \rho_{\text{pend}}(\vec{r}) r^l Y_{lm}^*(\hat{r}) \]

Torque for 1-\(\omega\) (m=1) signal:

\[ \tau_l = 8\pi G \frac{1}{2l + 1} |q_{l1}| |Q_{l1}| \]

Gravitational potential energy between the pendulum and the source masses is given by

not possible for a torsion pendulum

may mimic an EP violation
Gravity gradients compensation

Q21 compensators
Total mass: 880 kg
Q21 = 1.8 g/cm³

Q31 compensators
Total mass: 2.4 kg
Q31 = 6.7 \times 10^{-4} g/cm^4

360° rotatable

hillside & local masses
Gravity gradient measurement and compensation

- Produce a known signal by rotating the gravity gradient compensator to uncompensated positions
- Use a “gradiometer” pendulum with known larger moments

![Diagram showing gravity gradient measurement and compensation](image)
Correction for tilt of the turntable rotation axis

- Feedback removes tilt at upper tilt sensor
- However, local vertical varies with height
  - results in a deflection of the pendulum due to residual tilt

Lower tilt sensor measures:
measured tilt (~45 nrad) =
  local earth field (~60 nrad)
  — gravity gradient compensator (~15 nrad)

Tilt at pendulum is only due to local earth field:
~50 nrad of tilt $\rightarrow$ ~2.5 nrad correction to pendulum signal
Comparison of tilt with and without feedback
Lab-fixed result with 1-σ statistical and systematic uncertainty

- $\Delta a_N(\text{Be-Ti}) = (0.6 \pm 2.5 \pm 1.8) \times 10^{-15} \text{ m/s}^2$
- $\Delta a_W(\text{Be-Ti}) = (-2.5 \pm 2.4 \pm 2.5) \times 10^{-15} \text{ m/s}^2$
- $\Delta a_N(\text{Be-Al}) = (-1.2 \pm 1.9 \pm 1.1) \times 10^{-15} \text{ m/s}^2$
- $\Delta a_N(\text{Be-Al}) = (0.2 \pm 1.9 \pm 1.4) \times 10^{-15} \text{ m/s}^2$

- Classical EP Parameter $\eta = \Delta a / a$
- $\eta(\text{Be-Ti}) = (0.3 \pm 1.8) \times 10^{-13}$
- $\eta(\text{Be-Al}) = (-0.7 \pm 1.3) \times 10^{-13}$
95% CL Yukawa exclusion plot

\[ |\alpha| \]

\[ q = B - L \quad \tilde{\psi} = 90^\circ \]
Charge of test bodies and attractors

- Charge for new forces is unknown, but assume a coupling to protons, electrons, or neutrons

\[ \tilde{q}(\psi) = Z \cos \psi + N \sin \psi \]
Interaction strength versus charge
Is gravity the only long range force between dark and ordinary matter?

You are here
\[ a = R \omega^2 = 1.85 \times 10^{-10} \text{ m/s}^2 \]

Dark matter accounts for 25-30% of the mass of the galaxy inside the sun’s orbit
\[ a_{DM} \approx 5 \times 10^{-11} \text{ m/s}^2 \]

\[ \Delta a = \Delta a_{DM} = (2.3 \pm 2.6) \times 10^{-15} \text{ m/s}^2 \]
Limits on anomalous acceleration of neutral hydrogen toward galactic dark matter
Conclusions

- EP tests probe fundamental physics and as such set constraints on a broad range of possible interactions
- Torsion balances provide an exquisite tool for precision physics tests
The Future: Beryllium – Polyethylene

\[ \text{[CH}_2\text{]}_n \]

- Proton excess
- Density: 0.94 g cm\(^{-3}\)
- Solid
- Conductive

Will Terrano designed and built a prototype pendulum:

<table>
<thead>
<tr>
<th>Material Combination</th>
<th>Δ(Z/μ)</th>
<th>Δ(N/μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be – Ti</td>
<td>-0.016</td>
<td>0.013</td>
</tr>
<tr>
<td>Be – Al</td>
<td>-0.038</td>
<td>0.036</td>
</tr>
<tr>
<td>Be - PE</td>
<td>-0.126</td>
<td>0.125</td>
</tr>
</tbody>
</table>
The Future: Cryogenic Torsion Balance

$$S_{\tau}^{1/2}(f) = \sqrt{\frac{4k_B T}{Q}} \frac{2\pi f}{f}$$

Frank Fleischer