The Search for Exotic Sub-Millimeter Range Forces

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Classification, parameterization (short-range gravity experiments)

Motivation and existing limits

Experimental challenges

Experiments above 1 μ m (torsion pendulums, high-frequency)

Experiments below 1 µm (Casimir suppression)

Spin-Dependent Experiments

Outlook

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IUPUI – IUB Indiana University Collaborative Research Grant Non-Newtonian gravity (sample)



$$\vec{F} = -G\frac{m_1m_2}{r^{2+\varepsilon}}\hat{r}$$

$$G_{\alpha\beta} \neq 8\pi T_{\alpha\beta}$$

Equivalence Principle Tests *Composition-dependence, < few % of F_G* Eötvös (1889-1909) Dicke (1960s) Eöt-Wash (~1990-present)

Tests of the Inverse Square Law Precision F_G , null tests, large effects >> F_G Long (1976) Newman (1980-85)

Eöt-Wash (~1990-present)

Tests of Lorentz Invariance

Precision F_G

Muller, Chu (2008-) [1]

Parameterization

Yukawa Interaction

Power Law



 r_0 = experimental scale



set limits on β_n for n = 2 - 5



$$\boldsymbol{V}(\boldsymbol{r}) = -\boldsymbol{G} \frac{\boldsymbol{m}_1 \boldsymbol{m}_2}{\boldsymbol{r}} \left[1 + \alpha \boldsymbol{e}^{-\boldsymbol{r} \boldsymbol{l} \lambda} \right]$$

 $\lambda = \hbar I m_B c = range$ $\alpha = strength relative$ to gravity

Limits from 1 mm to 1 light year [1,2]



[1] E. Fischbach and C. Talmadge, *The Search for Non-Newtonian Gravity* (Springer-Verlag, 1999)
[2] S. Reynaud and M.-T. Jaekel, Int. J. Mod. Phys. A 20 2294 (2005)

Short Range limits – mass coupled



Experimental limits:

Irvine, HUST, Eot-Wash, = torsion pendulum experiments

Stanford, IUPUI: MEMS-type experiment

Torsion Osc: JCL et al., Nature 421 922 (2003) Irvine: J. Hoskins et al., PRD 32 3084 (1985) HUST: W.-H. Tan et al., PRL 116 131101 (2016) Eot-Wash: D. Kapner et al., PRL 98 021101 (2007) Stanford: A. Geraci et al., PRD 78 022002 (2008) Casimir: Y.-J. Chen et al., PRL 116 221102 (2016) Short Range Limits and Predictions



Torsion Osc: JCL et al., Nature 421 922 (2003) Irvine: J. Hoskins et al., PRD 32 3084 (1985) HUST: W.-H. Tan et al., PRL 116 131101 (2016) Eot-Wash: D. Kapner et al., PRL 98 021101 (2007) Stanford: A. Geraci et al., PRD 78 022002 (2008) Casimir: Y.-J. Chen et al., PRL 116 221102 (2016)

Experimental limits:

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Limits still allow forces 1 million times stronger than gravity at 5 microns

Theoretical predictions:

"Large" extra dimensions

Vacuum energy: prediction from new field which also keeps cosmological constant small

Moduli, dilatons: new particles motivated by string models

Theory: S. Dimopoulos, A. Geraci, PRD 68 124021 (2003)

"Large" Extra Dimensions



Strong, Weak, EM force confined to 3 dimensions

• Gravity spreads out into *n* extra dimensions of size *R*, appears diluted

$$\boldsymbol{R} = \left[\frac{\boldsymbol{M}_{\boldsymbol{P}}}{\boldsymbol{M}^{*}}\right]^{2/n} \left[\frac{\hbar}{2\pi \boldsymbol{M}^{*}}\right]$$

• Gravity unifies with EW force (M* ~ 1 TeV) if n = 2, $R \sim 1$ mm n = 3, $R \sim 1$ nm

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B 429 263 (1998)

Challenge: scaling and backgrounds



Electrostatic: F

$$E_E \sim \frac{\varepsilon_0 V^2}{r^2}$$

Magnetic (contaminant): F_{M}

$$_{M} \sim \frac{\mu_{0}[\vec{\mu}_{1} \cdot \vec{\mu}_{2} - 3(\vec{\mu}_{1} \cdot \hat{r})(\vec{\mu}_{2} \cdot \hat{r})]}{r^{4}}$$

Casimir:
$$F_C \sim \frac{\hbar c}{r^4}$$

Eot-Wash Torsion Pendulum Experiment

D. Kapner, E. Adelberger et al., PRL 98 021101 (2007)



- 55 μ m minimum gap
- 10 μm BeCu membrane (not shown)

Limits: Scenarios with $\alpha \ge 1$ excluded at 95% CL for $\lambda \ge 56 \mu m$

Largest extra dimension: $R < 44 \mu m$

ADD Model (2 equal-sized extra dimensions compactified on a torus): $R < 56 \ \mu m \Rightarrow M^* \ge 3.2 \ TeV$

01

s [mm]

0 05

0 07

test mass flatness...

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Experimental Approach

- **Planar Geometry null for 1/r²**
- **Resonant detector with source mass driven on resonance**
- 1 kHz operational frequency simple, stiff vibration isolation
- Double-rectangular torsional detector: high Q, low thermal noise
- Stiff conducting shield for background suppression



Central Apparatus

Vibration isolation stacks: Brass disks connected by fine wires; soft springs which attenuate at $\sim 10^{10}$ at 1 kHz (reason for using 1 kHz)

Readout: capacitive transducer and lock-in amplifier referenced by source drive frequency



Vacuum system: 10⁻⁷ torr

Figure: Bryan Christie (www.bryanchristie.com) for Scientific American (August 2000)

Interaction Region



Thinner shield

60 μm thick sapphire plate replaced by 10 μm stretched copper membrane

Compliance ~5x better than needed to suppress estimated electrostatic force

Minimum gap reduced from 105 μ m (2003) to 40 μ m.

Central Apparatus



Sensitivity: increase Q and statistics, decrease T

Signal

Force on detector due to Yukawa interaction with source:

 $F_{Y}(t) \approx 2\pi\alpha G\rho_{s}\rho_{d}A_{d}\lambda^{2} \exp(-d(t)/\lambda)[1 - \exp(-t_{s}/\lambda)][1 - \exp(-t_{d}/\lambda)]$ ~ 3 x 10⁻¹⁵ N rms (for $\alpha = 1, \lambda = 50 \ \mu\text{m}$)

Thermal Noise

$$F_T = \sqrt{\frac{4kTD}{\tau}} \qquad D = \frac{\omega m}{Q}$$

~ $3 \times 10^{-15} \text{ N rms}$ (300 K, Q = 5×10^4 , 1 day average) ~ $7 \times 10^{-17} \text{ N rms}$ (4 K, Q = 5×10^5 , 1 day average)

Force Measurement Data – March 2012

19 hours on-resonance data collected over 3 days with interleaved diagnostic data

On-resonance: Detector thermal motion and amplifier noise

Off-resonance: amplifier noise



Current Limits (2 σ) and Projected Sensitivity



 $2012 \text{ gap} \sim 100 \text{ microns};$ need flatter, more level elements

Projected: 1 day integration time, 50 micron gap, 4.2 K, factor 50 Q improvement



n-scattering: Y. Kamiya, et al., PRL 114 161101 (2015); V. Nesvizhevsky, G. Pignol, K. Protasov, PRD 77 034020 (2008)

Casimir Background Shielding



- Effect calculated using finite thickness corrections in: A. Lambrecht and S. Reynaud *Eur. Phys. J.* **D** 8 (2000) 309
- Ideal for Yukawa forces with $\lambda \approx D > \lambda_P$

Indiana – Purdue "Casimir-less" Experiment Y.-J. Chen, R. S. Decca, et al., Phys. Rev. Lett. 116 221102 (2016)





Points: sphere over alternating Au/Si strips Squares: over annular region with Au only (Signal: Casimir force from disk wobble)

Limits and Projections $-1 \mu m - 1 m$

R. Newman, Space Sci. Rev. 148 (2009) 175



Spin-Dependent Forces



"*V*₃"

Axion m-d [1]:
$$g_{S}^{1}g_{P}^{2} = \frac{\theta_{QCD}(60 \text{ MeV})m_{2}}{F_{PQ}^{2}}\frac{2m_{u}m_{d}}{(m_{u}+m_{d})^{2}}$$

 $\lambda = 2 \operatorname{cm}\left[\frac{F_{PQ}}{1 \times 10^{12} \text{ GeV}}\right]$

 m_1

 m_2

[1] J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984)

[2] B. Dobrescu and I. Mocioiu, J. High Energy Phys. 0611, 005 (2006)

Spin-Dependent Forces [1]

$$\begin{split} V_{2} &= f_{2}^{ee} \frac{\hbar c}{4\pi} (\hat{\sigma}_{1} \cdot \hat{\sigma}_{2}) \left(\frac{1}{r}\right) e^{-r/\lambda} \\ V_{3} &= f_{3}^{ee} \frac{\hbar^{3}}{4\pi m_{e}^{2} c} \left[(\hat{\sigma}_{1} \cdot \hat{\sigma}_{2}) \left(\frac{1}{\lambda r^{2}} + \frac{1}{r^{3}}\right) - (\hat{\sigma}_{1} \cdot \hat{r}) (\hat{\sigma}_{2} \cdot \hat{r}) \left(\frac{1}{\lambda^{2} r} + \frac{3}{\lambda r^{2}} + \frac{3}{r^{3}}\right) \right] e^{-r/\lambda} \\ V_{11} &= -f_{11}^{ee} \frac{\hbar^{2}}{4\pi m_{e}} \left[(\hat{\sigma}_{1} \times \hat{\sigma}_{2}) \cdot \hat{r} \right] \left(\frac{1}{\lambda r} + \frac{1}{r^{2}}\right) e^{-r/\lambda} \end{split}$$

 $V_{12+13} = Z \left[f_v^{ee} + f_v^{ep} + \left(\frac{A-Z}{Z}\right) f_v^{en} \right] \frac{\hbar}{8\pi} (\hat{\sigma}_1 \cdot \vec{v}) \left(\frac{1}{r}\right) e^{-r/\lambda}$

$$\begin{split} V_{6+7} &= -f_{6+7}^{ee} \frac{\hbar^2}{4\pi m_e c} [(\hat{\sigma}_1 \cdot \vec{v})(\hat{\sigma}_2 \cdot \hat{r})] \left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda} \\ V_8 &= f_8^{ee} \frac{\hbar}{4\pi c} [(\hat{\sigma}_1 \cdot \vec{v})(\hat{\sigma}_2 \cdot \vec{v})] \left(\frac{1}{r}\right) e^{-r/\lambda} \\ V_{14} &= f_{14}^{ee} \frac{\hbar}{4\pi} [(\hat{\sigma}_1 \times \hat{\sigma}_2) \cdot \vec{v}] \left(\frac{1}{r}\right) e^{-r/\lambda} \\ V_{15} &= -f_{15}^{ee} \frac{\hbar^3}{8\pi m_e^2 c^2} \{ [\hat{\sigma}_1 \cdot (\vec{v} \times \hat{r})](\hat{\sigma}_2 \cdot \hat{r}) + (\hat{\sigma}_1 \cdot \hat{r})[\hat{\sigma}_2 \cdot (\vec{v} \times \hat{r})] \} \left(\frac{1}{\lambda^2 r} + \frac{3}{\lambda^2 r^2} + \frac{3}{r^2}\right) e^{-r/\lambda} \\ V_{16} &= -f_{16}^{ee} \frac{\hbar^2}{8\pi m_e c^2} \{ [\hat{\sigma}_1 \cdot (\vec{v} \times \hat{r})](\hat{\sigma}_2 \cdot \vec{v}) + (\hat{\sigma}_1 \cdot \vec{v})[\hat{\sigma}_2 \cdot (\vec{v} \times \hat{r})] \} \left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda} \\ V_{4+5} &= -Z \left[f_{\perp}^{ee} + f_{\perp}^{ep} + \left(\frac{A-Z}{Z}\right) f_{\perp}^{en} \right] \frac{\hbar^2}{8\pi m_e c} [\hat{\sigma}_1 \cdot (\vec{v} \times \hat{r})] \left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda} \\ V_{9+10} &= Z \left[f_r^{ee} + f_r^{ep} + \left(\frac{A-Z}{Z}\right) f_r^{en} \right] \frac{\hbar^2}{8\pi m_e} (\hat{\sigma}_1 \cdot \hat{r}) \left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda} \\ \end{array}$$

monopole-dipole

[1] B. Dobrescu and I. Mocioiu, J. High Energy Phys. 0611, 005 (2006)

Spin – Dependent experiments (electron)

$$V(r) = g_S^N g_P^e \frac{\hbar^2}{8\pi m_2} \hat{\sigma} \cdot \hat{r} \left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}$$

Eot-Wash ALP torsion pendulum



S. Hoedl et al., PRL 106 (2011) 041801



Astrophysical: g_S^N from torsion pendulums, g_P^e from white-dwarf cooling limits [2]

Axion constraint from neutron EDM [3]: $\theta_{\text{QCD}} = 2.78 \times 10^{15} d_n (\text{e-cm})$

[2] G. Raffelt PRD 86, 015001 (2012)

[3] R. J. Crewther, et al., Phys. Lett.91B, 487 (1980)

Spin – Dependent experiments (electron)

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Eot-Wash ALP torsion pendulum





S. Hoedl et al., PRL 106 (2011) 041801

Compensated Ferrimagnet



Dysprosium Iron Garnet

E. Weisman, R. Khatiwada

Dy₃Fe₅O₁₂



G. Dionne, Magnetic Oxides (N.Y., Springer, 2009)

Dy₃Fe₅O₁₂ recipe [1]

- 1. Add H₂O to Dy(NO₃)₃·H₂O powder for a 1M solution
- 2. Combine with 1M H₂O and FeCl₃·6H₂O solution
- 3. Add drops of base NaOH to precipitate rust colored solid
- 4. Dry and press into pellet
- 5. Fire at 900C color changes to olive green
- 6. Grind and fire again to increase purity [1] M. Gesselbracht, et al., J. Chem. Educ 71 (1994) 696



Projected sensitivity

T. M. Leslie [1]



[1] T. M. Leslie, E. Weisman, R. Khatiwada, JCL, PRD 89 (2014) 114022

Beams near a wall – velocity-dependent

$$V_{AA} \propto g_A^2 \ \vec{\sigma} \cdot (\vec{v} \times \hat{r}) \left(\frac{1}{\lambda} + \frac{1}{r}\right) \frac{e^{-r/\lambda}}{r}$$

PSI: F. Piegsa and G. Pignol, PRL 108 181801 (2012)



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Static NMR near a mass – axion search



[1] A. Arvanitaki, A. Geraci, PRL 113, 161801 (2014)

Conclusions

- Dark matter
- Dark energy
- Unification models with
 - extra dimensions
 - extended symmetries

Great interest in macroscopic forces with weak couplings to matter

Macroscopic mass experiments: ~ 10 square decades of parameter space below 1 cm in past 10 years, continuing progress expected

IU High-frequency experiment currently excludes spin-independent forces > 10⁵ times gravitational strength above 10 microns

Cryogenic experiment with gravitational sensitivity at 20 microns proposed

Spin-dependent experiments: greater exclusion of parameter space below 1 cm in past 5 years, many new channels identified

spin-dependent experiments with high frequency, NMR and other nuclear techniques \Rightarrow unique sensitivity (or 8 orders of magnitude more than current experiments) to 15 interactions 30