Electromagnetic Field Energy as an Unaccounted Gravitational Source in Levitated Optomechanics Experiments

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Recent advances in levitated optomechanics have enabled experiments probing gravitational interactions at unprecedented scales, with the goal of detecting quantum signatures of gravity. These experiments use high-intensity optical traps to levitate nanoparticles and measure gravitational forces between them. We demonstrate that the electromagnetic field energy density in these optical traps constitutes a gravitational source through the stress-energy tensor $T^{\mu\nu}$, yet this contribution is not accounted for in current experimental analyses. Using the linearized Einstein field equations, we calculate the gravitational potential and field arising from concentrated laser fields at experimentally relevant power densities ($\sim 10^{15}$ W/m^2). We find that the EM field gravitational contribution can be comparable to or exceed the gravitational effects being measured between particle masses, potentially constituting a systematic error of order 10^{-2} to 10^0 in current experiments. We propose calibration protocols to detect and characterize this effect, including power-scaling tests and field geometry variations that can discriminate EM field gravity from particle-particle gravitational interactions.

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I. INTRODUCTION

A. The Experimental Landscape

A new generation of experiments aims to detect quantum signatures of gravity using levitated optomechanical systems [1–5]. The experimental strategy typically involves: (1) levitating nanoparticles (10^6–10^{10} atoms) using optical tweezers, (2) cooling them to quantum ground state via feedback cooling, (3) placing two such particles in proximity, (4) measuring gravitational interactions between them, and (5) looking for quantum entanglement mediated by gravity.

Notable efforts include the Aspelmeyer group's levitation of 143 nm silica nanospheres cooled to 12 μK [1], the Geraci group's optically trapped microspheres for gravity measurements [2], and various theoretical proposals for gravitational entanglement tests [6, 7].

B. The Unexamined Assumption

All current experimental analyses share a common assumption:

> *The optical trap is treated as a measurement tool that does not contribute gravitationally to the system.*

This assumption is physically incorrect. According to general relativity, the electromagnetic stress-energy tensor $T_{\mathrm{EM}}^{\mu\nu}$ is a source of spacetime curvature on equal foot-

ing with mass-energy:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}^{(\text{total})} \tag{1}$$

where $T_{\mu\nu}^{(\text{total})} = T_{\mu\nu}^{(\text{matter})} + T_{\mu\nu}^{(\text{EM})}$.

The EM field energy density in these experiments is substantial. Typical trap powers of 100 mW–1 W focused to wavelength-scale spots yield intensities of 10^{12}–10^{16} W/m^2, corresponding to energy densities:

$$\rho_{\mathrm{EM}} = \frac{I}{c} = 10^4\text{–}10^8 \ \mathrm{J/m}^3 \tag{2}$$

For comparison, the energy density of a 10^{-15} kg nanoparticle in a 1 μm^3 volume is:

$$\rho_{\mathrm{mass}} = \frac{mc^2}{V} = \frac{10^{-15} \times (3 \times 10^8)^2}{10^{-18}} \approx 9 \times 10^7 \ \mathrm{J/m}^3 \tag{3}$$

The EM field energy density can exceed the particle mass-energy density.

II. THEORETICAL FRAMEWORK

A. The Electromagnetic Stress-Energy Tensor

The electromagnetic contribution to the stress-energy tensor is:

$$T_{\mathrm{EM}}^{\mu\nu} = \frac{1}{\mu_0}\left[F^{\mu\alpha}F^{\nu}{}_{\alpha} - \frac{1}{4}g^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta} \right] \tag{4}$$

In component form for fields $\mathbf{E}$ and $\mathbf{B}$:

$$T^{00} = u = \frac{\varepsilon_0}{2}(E^2 + c^2 B^2) \quad \text{[energy density]} \tag{5}$$

$$T^{0i} = \frac{S_i}{c} = \frac{(\mathbf{E} \times \mathbf{B})_i}{\mu_0 c} \quad \text{[momentum flux]} \tag{6}$$

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B. Linearized Einstein Equations

For weak gravitational fields (appropriate for laboratory scales), the metric perturbation $h_{\mu\nu}$ satisfies:

$$\nabla^2 h_{00} = -\frac{16\pi G}{c^4} T_{00} = -\frac{16\pi G}{c^4} \rho_{\text{EM}} c^2 \qquad (7)$$

This gives a gravitational potential:

$$\Phi_{\text{EM}} = -\frac{G}{c^2} \int \frac{\rho_{\text{EM}}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d^3 r' \qquad (8)$$

The gravitational acceleration is:

$$\mathbf{g}_{\text{EM}} = -\nabla\Phi_{\text{EM}} = \frac{G}{c^2} \int \rho_{\text{EM}}(\mathbf{r}') \frac{\mathbf{r} - \mathbf{r}'}{|\mathbf{r} - \mathbf{r}'|^3} d^3 r' \qquad (9)$$

C. Key Scaling Relationship

For a localized EM field with total energy U_{EM} concentrated in volume V:

$$\Phi_{\text{EM}} \sim -\frac{G U_{\text{EM}}}{c^2 R} \qquad (10)$$

where R is the characteristic distance from the field region.

The gravitational acceleration at distance R:

$$g_{\text{EM}} \sim \frac{G U_{\text{EM}}}{c^2 R^2} \qquad (11)$$

This has the same form as Newtonian gravity with effective mass:

$$m_{\text{eff}} = \frac{U_{\text{EM}}}{c^2} \qquad (12)$$

which is simply $E = mc^2$ applied to field energy.

III. APPLICATION TO OPTOMECHANICAL EXPERIMENTS

A. Experimental Parameters

We consider parameters representative of current and proposed experiments (Table I).

TABLE I. Representative experimental parameters

Parameter	Aspelmeyer-type	Cavity-enhanced
Particle mass	10^{-17} kg	10^{-17} kg
Separation	10 μm	10 μm
Laser power	100 mW	1 W input
Beam waist	1 μm	10 μm
Cavity finesse	1	10^5
Circulating power	100 mW	32 kW

B. Effective Gravitating Mass of EM Field

For a cavity-enhanced system with stored energy $U \approx 0.05$ J:

$$m_{\text{eff}} = \frac{U}{c^2} = \frac{5 \times 10^{-2}}{9 \times 10^{16}} \approx 5.6 \times 10^{-19} \text{ kg} \qquad (13)$$

C. Gravitational Forces Comparison

Particle-particle gravity:

$$F_{pp} = \frac{G m_p^2}{d^2} = \frac{6.67 \times 10^{-11} \times (10^{-17})^2}{(10^{-5})^2} \approx 6.67 \times 10^{-35} \text{ N} \qquad (14)$$

EM field gravity on particle (at beam waist $R = 1$ μm):

$$F_{\text{EM}} = \frac{G m_{\text{eff}} m_p}{R^2} \approx 3.7 \times 10^{-35} \text{ N} \qquad (15)$$

D. The Ratio

$$\frac{F_{\text{EM}}}{F_{pp}} = \frac{m_{\text{eff}}}{m_p} \times \left(\frac{d}{R}\right)^2 \approx 0.5\text{–}5 \qquad (16)$$

This represents a 50–500% systematic error in current high-power proposals.

Table II shows how the ratio scales with circulating power.

TABLE II. EM field gravity scaling with power

Circ. Power	Stored Energy	m_{eff}	F_{EM}/F_{pp}
100 kW	0.05 J	5.6×10^{-19} kg	0.55
1 MW	0.5 J	5.6×10^{-18} kg	5.5
10 MW	5 J	5.6×10^{-17} kg	55

IV. PROPOSED CALIBRATION PROTOCOLS

A. Power Scaling Test

Principle: EM field gravity scales with stored energy; particle mass does not.

Protocol: Measure apparent gravitational coupling at power levels P, $2P$, $4P$, $8P$.

Expected signature:

- If EM field gravity dominates: $F_{\text{measured}} \propto P$

- If particle gravity dominates: $F_{\text{measured}} = \text{constant}$

B. Geometry Variation Test

Principle: EM field gravity depends on field spatial distribution.

Protocol: Expand beam waist by factor of 3 at constant total power. Peak intensity decreases by $9\times$, changing EM field gravity at particle location while particle-particle gravity remains unchanged.

C. Single vs Dual Trap Test

Principle: Two traps double the EM field energy.

Protocol: Compare single particle/single trap to two particles/two traps. With EM field gravity, each particle feels gravity from both traps, creating cross-terms not present in pure particle-particle gravity.

D. Trap Position Modulation

Principle: Shift trap position while particle remains stationary.

Protocol: Small trap displacement δx produces force change:

$$\Delta F = -\frac{\partial \Phi_{\text{EM}}}{\partial x} \times m_{\text{particle}} \qquad (17)$$

This directly probes the EM gravitational potential gradient.

E. Pulsed vs CW Comparison

Principle: Same average power with different peak intensities.

Protocol: Compare CW laser at power P with pulsed laser at same average power but $100\times$ peak power. Nonlinear effects from instantaneous energy density may produce different effective EM field gravity.

V. IMPLICATIONS

A. For Current Experiments

Published systematic error budgets do not include EM field gravitational effects. Our analysis suggests this may constitute a significant uncharacterized error for cavity-enhanced systems.

B. For Quantum Gravity Tests

Experiments seeking quantum signatures of gravity (e.g., gravitational entanglement) must first characterize and subtract the classical EM field gravitational contribution. Effects from the trapping field could potentially mimic or mask quantum gravitational signatures.

C. Opportunity

EM field gravity provides a *controllable, tunable* gravitational source that can be used to:

- Calibrate gravitational measurement sensitivity

- Test apparatus response to known gravitational perturbations

- Validate measurement techniques before searching for quantum effects

VI. CONCLUSIONS

We have demonstrated that:

1. **EM field energy gravitates:** According to general relativity, the stress-energy tensor of electromagnetic fields sources spacetime curvature.

2. **Current experiments don't account for this:** Published systematic error budgets do not include EM field gravitational effects.

3. **The effect can be significant:** For cavity-enhanced systems with ~100 kW circulating power, EM field gravity can be 50–500% of particle-particle gravity.

4. **Calibration is possible:** Five experimental protocols can detect and characterize this effect.

5. **This affects quantum gravity tests:** The classical EM field contribution must be characterized before claiming detection of quantum gravitational effects.

The Einstein field equations treat all energy equally. Whether energy is "rest mass" or "electromagnetic field" is a distinction that matters for chemistry, but not for gravity.

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