Victoria University of Wellington

Te Whare Wānanga o te Ūpoko o te Ika a Maui



Low-energy oddities at the interface between quantum physics and gravity.

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Intrinsic decoherence in nature Galiano Island, British Columbia

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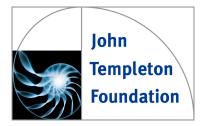
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What is the gravitational field generated by a single elementary particle?







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Outline:



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Where is the interface?



• When individual elementary particles reach Planck-scale energy-momentum.

Based on a trade-off between Compton wavelength (localization), and the Schwarzschild radius (compactness):

• (Reduced) Compton wavelength:

$$\lambda_{\text{Compton}} = \frac{\hbar}{mc}$$

• Schwarzschild radius:

$$R_{
m Schwarzschild} = rac{2G_{
m Newton}m}{c^2}$$

Traditional answer:

Schwarzschild radius equals Compton wavelength at the Planck mass:

$$m_{\mathrm{Planck}} = \sqrt{\frac{\hbar c}{G_{\mathrm{Newton}}}}$$

(Traditional to ignore the "2" and the "2 π ".)

Related quantities:

$$E_{
m Planck} = \sqrt{rac{\hbar c^5}{G_{
m Newton}}}$$

 $L_{
m Planck} = \sqrt{rac{\hbar G_{
m Newton}}{c^3}}$
 $T_{
m Planck} = \sqrt{rac{\hbar G_{
m Newton}}{c^5}}$

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When gravity induces order ħ action differences in assemblages of elementary particles.

$$\Delta\left(\frac{G_{\text{Newton}}m}{R}\right) \times \Delta T = \mathcal{O}(\hbar)$$

• Eg: Penrose (and related) wavefunction collapse proposals.



- I will argue that the situation is actually much more pressing.
- If you ask the right question, (the wrong question?), things are already quite weird at atomic scales.



Ingredients:

- Page's experiment.
- Eotvos experiment.
- Scattering experiments.
- Kerr–Newman geometry.



Page's experiment



- Page wanted to test semiclassical quantum gravity (in the macroscopic realm).
- Depending on the output of some random quantum process, move large object to one side or other of a Cavendish torsion balance.
- Does the torsion fibre deflect?
- Do we see this:

$$G^{ab} = 8\pi G_{
m Newton} \langle T^{ab} \rangle$$
?

Or do we see this:

With probability p_i one has: $G^{ab} = 8\pi G_{\text{Newton}} T_i^{ab}$?

- We see the latter...
- (With perhaps under-appreciated implications...)



Environmental decoherence is not enough to explain the result of Page's experiment.

• All that environmental decoherence does for you is to kill the off-diagonal elements of the density matrix:

 $\rho \rightarrow \operatorname{diag}\{\rho_{ii}\}$

- $\bullet~$ Quantum amplitudes $\rightarrow~$ classical probabilities.
- Quantum expectation value \rightarrow classical average:

$$\langle T^{ab} \rangle \rightarrow \overline{T^{ab}}$$



But we do not see:

$$G^{ab} = 8\pi G_{
m Newton} \overline{T^{ab}}$$

• What we actually see is this:

With probability p_i one has: $G^{ab} = 8\pi G_{\text{Newton}} T_i^{ab}$.

- Decoherence fails to "reify" the actual physical state of the universe...
- Coupling the spacetime metric to either quantum or classical average stress energy does not seem to be the way the universe works... (Ar least, not in the macroscopic realm.)
- Unfortunately this will soon lead us into a conundrum...



Eotvos experiment



• Inertial mass = (passive) gravitational mass.

In fact:

$$\left. rac{m_{
m passive}}{m_{
m inertial}} - 1
ight| \lesssim \mathcal{O}(10^{-14})$$

- Impressive precision.
- Indirect arguments suggest this equality must persist down to the level of individual elementary particles.
- Direct experiment, (drop an individual electron), verifies this down to about the 5% level. [Fairbanks.]



Scattering experiments



- Scattering experiments, (and their analysis in terms of QFT, specifically the Dirac equation), indicate that elementary particles (leptons) are point-like down to at least TeV energy scales...
- More precisely inertial mass seems to be concentrated down to distances of order

$$(\Delta R)_{
m inertial} \leq rac{\hbar c}{1 \ TeV} pprox 2 imes 10^{-4} \ {
m fm}.$$

Note:

$$\hbar c = 0.197463578~\text{GeV}$$
 fm



Active gravity for an individual elementary particle



- Elementary particles are known, (from the point of view of inertia), to be point-like, some with electric charge, many with spin.
- Their inertial mass to a good approximation equals passive gravitational mass.
- Known "sane" theories of gravity equate passive and active gravitational mass.
- (This is to avoid self-acceleration problems which occur if the centre of passive gravitational mass is offset from the centre of active gravitational mass.)
- With specified mass, charge, and spin what are the options?
- Kerr-Newman geometry (electron)...
- Kerr geometry (neutrino)...



Kerr–Newman electron



- Represent an electron with, (as a zero'th approximation), the Kerr–Newman geometry.
 - Mass $m = 510.998928 \text{ keV}/c^2$. (9.10938291 $\times 10^{-31} \text{ kg.}$)
 - Charge: $q = 1.60217657 \times 10^{-19}$ C.
 - Angular momentum: $J = \frac{1}{2}\hbar$.
- The good news:
 - $g_{\text{Dirac}} = 2$.
 - $g_{\text{Kerr-Newman}} = 2.$
 - Naive substructure models (spinning spheres and the like):

$$g_{(most substructure models)} = 1.$$

• QFT:

$$g_{ ext{QED}} = 2 + rac{lpha}{2\pi} + \mathcal{O}(lpha^2).$$

• So something is going more or less right... (Brandon Carter 1968)



Now for the bad news (and it's really really bad):

- It's a naked singularity.
- It's a really big naked singularity.
- Radius of the ring singularity:

$$a = \frac{J}{mc} = \frac{\frac{1}{2}\hbar}{mc} = \frac{1}{2}\lambda_{\text{Compton}}$$

• Specifically:

- $a \approx 2 \times 10^{-13} \text{ m} = 200 \text{ fm}!$
- Bohr radius: $a_0 = \lambda_{\rm Compton} / \alpha \approx 5 \times 10^{-11} \text{ m} = \frac{1}{2} \text{ A}.$
- Classical radius: $R_{\rm classical} = \alpha \lambda_{\rm Compton} \approx 3 \times 10^{-15} \text{ m} = 3 \text{ fm}.$
- Nuclear radius ≈ 1 fm.



- The ring singularity is distressingly large by atomic standards, and freaking enormous by nuclear standards.
- Something is definitely very wrong here.
- (Warning: Some of the fringe members of the community do not know when to back off. There are still a few people out there castigating a defunct equine.)
- But if Kerr-Newman does not do the job, what should we replace it with?
- It would be distressing to claim that the electron does not have active gravitational mass, since it certainly has inertial mass, and passive gravitational mass...
- Quantum smearing of the active gravitational mass?
- (Oh oh... Wait just a minute...)



Kerr neutrino





- Things are even worse for a Kerr neutrino.
- Certainly for the lowest mass eigenstate $m < 2 \text{ eV}/c^2$.

Then

$$\lambda_{
m Compton} = rac{\hbar}{mc} > 10^8 \ {
m fm} = 100 \ {
m nm}$$
 $a = rac{1}{2} \lambda_{
m Compton} > 50 \ {
m nm} = 500 \ {
m A}$

- This is utterly enormous...
- Almost macroscopic, certainly mesoscopic...
- Not compatible with physical reality.



Nucleons





- Nucleons are not probematic.
- $m \approx 1 \text{GeV}$.
- Then:

$$egin{aligned} \lambda_{\mathrm{Compton}} &= rac{\hbar}{mc} pprox 0.2 \ \mathrm{fm} \ a &= rac{1}{2} \lambda_{\mathrm{Compton}} pprox 0.1 \ \mathrm{fm} \ (\mathrm{charge\ radius}) pprox 0.9 \ \mathrm{fm} \end{aligned}$$

- So compatible with known size of internal structure.
- Certainly should not be using Kerr-Newman for proton, (or Kerr for neutron), below 1 fm.
- It's only the "point particles" that are problematic, most notably the electron and neutrino.



Macroscopic bodies





Macroscopic bodies are never problematic.

First:

$$a = rac{J}{mc} = rac{I\omega}{mc} \sim rac{mR^2\omega}{mc} = R\left(rac{R\omega}{c}
ight) \ll R.$$

For the Earth:

$$a \sim rac{(20,000/\pi \text{ km})^2 \times 2\pi}{3 \times 10^8 \text{ m/s} \times 24 \times 3,600 \text{ s}} \sim 10 \text{ m}$$

 $rac{a}{m_{
m geom}} = rac{a}{Gm/c^2} \sim rac{10 \text{ m}}{1 \text{ cm}} \sim 100$

This is not a problem.



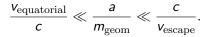
Estimate (generic):

$$rac{a}{m_{
m geom}} = rac{a}{Gm/c^2} \sim rac{R^2 \omega/c}{Gm/c^2} = rac{R\omega/c}{Gm/Rc^2} = rac{2v_{
m equatorial}\ c}{v_{
m escape}^2}.$$

But, if gravitationally bound:

$$R\omega^2 \ll \frac{Gm}{R^2};$$
 $(R\omega)^2 \ll \frac{Gm}{R};$

Then:



Leaves a lot of accessible territory...



- Many uncollapsed astronomical bodies have $a/m_{
 m geom}\gg 1$.
- Most black holes seem to have $a/m_{
 m geom}\simeq$ 0.85, (near extremal).
- All elementary particles with spin have $a/m_{
 m geom}\gg 1.$
- No uniqueness theorem if no horizon forms.
- No Birkhoff theorem for rotating bodies.



Smearing out the active mass



- To prevent formation of the ring singularity one would need to invoke quantum physics to somehow smear out the active gravitational mass on distance scales comparable to $\lambda_{Compton}$.
- While keeping the center of active mass and center of passive mass coincident; and total active and total passive masses equal.
- While also concentrating the inertial mass for these "point particles" on distance scales $\lesssim 10^{-6}~\lambda_{\rm Compton}!$
- While satisfying an Eotvos-inspired "sum rule" that the total inertial and total passive gravitational masses are equal.
- This is a tough order; especially since we are now trying to do in the microscopic realm what Page's experiment tells us does not happen in the macroscopic realm.



Photons



- Photons are a bit of a nightmare.
- If photons are exactly massless need a Kerr version of the Aichelburg–Sexl ultra-boost "shockwave" spacetime...
- This would be seriously messy.
- If photons are not exactly massless, (Proca Lagrangian), then we can at least say

$$m_\gamma \leq 10^{-18}~{
m eV}/c^2.$$
 $\lambda_{
m Compton} \geq 2 imes 10^{11}~{
m m} \sim 1~{
m AU}$

• Utterly insane...



Conclusions





Why is it that spin causes so much of a problem?

• Planck-scale angular momentum:

 $J_{\mathrm{Planck}} = m_{\mathrm{Planck}} \times L_{\mathrm{Planck}} \times (L_{\mathrm{Planck}}/T_{\mathrm{Planck}}) = \hbar.$

That is:

 $J_{\text{Planck}} = \hbar.$

• Spin sneaks "Planck-scale physics" in by the back door.



- No matter how you twist and turn, the active gravitational fields of the electron and neutrino require (subtle and non obvious) quantum physics modifications at distances of order the Compton wavelength.
- This is far removed from Planck-scale energies.
- The interface between gravity and quantum physics is much closer and much more subtle than you might think.
- Some experiments already done, some do-able.
- Some interesting matters of principle to consider.

End:





Thank you.

