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

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# Outline:

# 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:

$$\lambdabar_{\mathrm{Compton}} = \frac{\hbar}{mc}$$

- Schwarzschild radius:

$$R_{\mathrm{Schwarzschild}} = \frac{2G_{\mathrm{Newton}}\,m}{c^2}$$

# 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 “$2\pi$”.)

Related quantities:

$$E_{\mathrm{Planck}} = \sqrt{\frac{\hbar c^5}{G_{\mathrm{Newton}}}}$$

$$L_{\mathrm{Planck}} = \sqrt{\frac{\hbar G_{\mathrm{Newton}}}{c^3}}$$

$$T_{\mathrm{Planck}} = \sqrt{\frac{\hbar G_{\mathrm{Newton}}}{c^5}}$$

- **When gravity induces order $\hbar$ action differences in assemblages of elementary particles.**

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

- 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.**

# Radical viewpoint:

Ingredients:

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

# Page's experiment

# 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:

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

- Or do we see this:

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

- 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:

$$\rho \to \mathrm{diag}\{\rho_{ii}\}$$

- Quantum amplitudes $\to$ classical probabilities.
- Quantum expectation value $\to$ classical average:

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

# Page's experiment:

- But we do not see:

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

- 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:

$$\left|\frac{m_{\rm passive}}{m_{\rm inertial}} - 1\right| \lesssim \mathcal{O}(10^{-14})$$

- 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:

- 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

$$(\Delta R)_{\rm inertial} \leq \frac{\hbar c}{1\ TeV} \approx 2 \times 10^{-4}\ \text{fm}.$$

- Note:

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

# Active gravity for an individual elementary particle

# Active gravity:

- 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 $m = 510.998928$ keV$/c^2$. ($9.10938291 \times 10^{-31}$ kg.)
  - Charge: $q = 1.60217657 \times 10^{-19}$ C.
  - Angular momentum: $J = \frac{1}{2}\hbar$.
- The good news:
  - $g_{\mathrm{Dirac}} = 2$.
  - $g_{\mathrm{Kerr-Newman}} = 2$.
  - Naive substructure models (spinning spheres and the like):

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

  - QFT:

$$g_{\mathrm{QED}} = 2 + \frac{\alpha}{2\pi} + \mathcal{O}(\alpha^2).$$

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

# Kerr–Newman electron:

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:

$$a = \frac{J}{mc} = \frac{\frac{1}{2}\hbar}{mc} = \frac{1}{2}\,\lambdabar_{\mathrm{Compton}}$$

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

# Kerr–Newman electron:

- 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

# Kerr neutrino:

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

$$\lambdabar_{\rm Compton} = \frac{\hbar}{mc} > 10^8 \text{ fm} = 100 \text{ nm}$$

$$a = \frac{1}{2}\lambdabar_{\rm Compton} > 50 \text{ nm} = 500 \text{ A}$$

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

# Nucleons

# Nucleons:

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

$$\lambdabar_{\text{Compton}} = \frac{\hbar}{mc} \approx 0.2 \text{ fm}$$

$$a = \frac{1}{2}\lambdabar_{\text{Compton}} \approx 0.1 \text{ fm}$$

$$(\text{charge radius}) \approx 0.9 \text{ fm}$$

- 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:

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

For the Earth:

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

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

This is not a problem.

Estimate (generic):

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

But, if gravitationally bound:

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

Then:

$$\frac{v_{\rm equatorial}}{c} \ll \frac{a}{m_{\rm geom}} \ll \frac{c}{v_{\rm escape}}.$$

Leaves a lot of accessible territory...

# Macroscopic bodies:

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

# Smearing out the active mass

# 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 $\lambda\!\!\!^{-}_{\rm Compton}$.
- 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:

- 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

$$m_\gamma \leq 10^{-18} \text{ eV}/c^2.$$

$$\lambdabar_{\rm Compton} \geq 2 \times 10^{11} \text{ m} \sim 1 \text{ AU}.$$

- Utterly insane...

# Conclusions

# Conclusions:

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

- Planck-scale angular momentum:

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

- That is:

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

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

# Conclusions:

- 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.

Thank you.