Lab Expts to Probe Parity Violation in Gravitation and Their Theoretical Implications.

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Challenges for Witnessing Quantum Aspects of Gravity in a Lab
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A Disclaimer

- This work addresses certain novel gravitational interactions of Quantum Matter
- It says nothing about Quantum Nature of the Gravitational Fields.
- The importance of this distinction was stressed by Rovelli in his talk.
- There is voluminous literature on parity violations possibly manifested by the gravitational fields themselves also addressing their detection through Gravitational Waves(GRW).
- I suggest looking up Obukhov:Parity Violation in Poincare Gauge Gravity, arXiv:2010.16276v2 for an extensive literature on this type.
- They are mostly irrelevant for this talk(as also witnessed by the fact that he makes no mention of my works!)
- They mostly deal with the so called Chern-Simons Gravities and their extensions.

Motivations

- General Relativity(GR) demands that orbital angular momentum and Spin(intrinsic) angular momentum must respond the same way to a gravitational field.
- Else, the principle of equivalence and the consequent geometrical interpretaton would break down.
- **But do they?** This is something that has to be settled experimentally
- In the non-gravitational sectors of our understanding of elementary particles, what we notice is that as the interactions get weaker, more symmetries are violated.
- Thus it would be reasonable to expect gravitations to violate various discrete symmetries like C,P,T etc
- GR does not violate any of these.

Important References

- Tests for C,P,T nonconservation in gravitation, PhysRevLett 36 p.393(1976) – where I proposed simple experiments to probe these issues.
- Experimental tests for some quantum effects in gravitation, Ann.Phys(NY) 107 p.337(1977) – for a very detailed account of limits existing, theoretical interpretations and proposals for future expts.
- A new spin test for general relativity, Jour.Gen.Rel.Grav 8 p.89(1977)
- Cold atoms for testing quantum mechanics and parity violations in gravitation,arXiv:9908085v1, 28 August 1999 – where I analysed limits put by some very exciting experiments performed since my first publications.

The proposal

- My idea was to look for possible tests in the simplest physical systems. I chose non-relativistic particles with intrinsic spin interacting with very weak-field gravitation.
- The leading order spin-dependent potential, based only on translational and rotational invariance, is

$$V(\vec{r}) = \alpha_1 \frac{GM}{c\, r^3} \vec{S} \cdot \vec{r} + \alpha_2 \frac{GM}{c^2\, r^2} \vec{S} \cdot \vec{v} + \alpha_3 \frac{GM}{c^2\, r^2} \vec{S} \cdot (\vec{r} \times \vec{v})$$

- GR predicts $\alpha_1 = \alpha_2 = 0$ and $\alpha_3 = \frac{3}{2}$.
- Leitner and Okubo had, in PR 136 B1542 (1964), parametrised the potential as

$$V(\vec{r}) = V_N(\vec{r})\, \{1 + A_1 \vec{S} \cdot \hat{r}) + \frac{A_2}{c} \vec{S} \cdot \vec{v} + \frac{A_3}{c} \vec{S} \cdot \vec{L}$$

- Though at the level of parametrisations, the two are equivalent, it is not possible to cary out the kind of theoretical analysis I did, with the Leitner-Okubo parametrisation(the A_i's are actually r-dependent).

Some observable consequences and their limits

- In what follows I shall only focus on the α_1 effects as they are much larger for nonrelativistic systems.
- For relativistic particles like photons and gravitons the other terms are also important.
- **Differential Acceleration**

$$\eta = \frac{a_+ - a_-}{a} = 2\alpha_1 \frac{\hbar}{mcR}$$

- For $\alpha_1 \simeq 1$ this is $10^{-22}, 10^{-19}, 10^{-23} - 10^{-24}$ for neutrons, electrons, atoms.
- Eötvos type expts put no limits as they are not performed with polarised masses.
- Most recently, torsion balances with chiral masses have given the limits $\eta < 10^{-13}$, not yet useful.
  See Lin Zhu et al, PRL 121 261101 (2018);R. Cowsik et al, arXiv: 2101.02096[gr-qc]

Some observable consequences and their limits

- **Hyperfine structure in hydrogen**: attributing the entire experimental uncertainty of about 1mHz to our effects yields $\alpha_1 < 200$. This is based on very old numbers, needs urgent revision. Best is to rework, ab initio, the hyperfine splitting including our effects.
- **Differential bending of light**: Though one should be cautious about an immediate application to relativistic systems, a crude estimate can nevertheless be obtained by checking for polarisation dependence of bending of light.
- M. Harwit et al(Nature 249 p.230 (1974)) obtained $\alpha_1 < 10^{10}$ while an improved limit of $\alpha_1 < 10^4$ was obtained by B.K. Dennison(Cornell Thesis 1976).

Astrophysical Constraints

- For details see NDH arXiv:9908085v1[quant-ph]
- **Differential propagation of neutrinos and Photons** Almeida et al PRD 39 p.672 1989: $\alpha_1 < 10^{30}$
- **Differential propagation times of polarised photons** Losecco et al Phy.Lett A 138 p.5 1989: $\alpha_1 < 10^{23}$
- **Helicity flip scattering of massive neutrinos and cooling of neutron stars** Choudhury et al CQG 6 L167 1989: under the assumption that τ-neutrino mass is 1KeV, they derived $\alpha_1 < 300$.
- **Cosmology**: Nodland and Ralston PRL 78 p.3043 1997: Cosmological rotation of photon polarisations
- A.Lue, L.Wang and M.Kamionkowski, arXiv:9812088[astro-ph]: Some P-violation models.

Atom Techniques: Mercury Cell Comagnetometre

- For details see NDH arXiv:9908085v1[quant-ph]
- B.J.Venema, P.K.Majumdar, S.K. Lamoreaux,B.R. Heckel,and E.R. Fortson, PRL 68 p.135 1992
- The α_1-term leads to additional Spin Precession:

$$\frac{d\vec{S}}{dt} = \alpha_1 \frac{GM}{cR^2} \hat{R} \times \vec{S}$$

- The effect is independent of the mass of the spinning particle and when earth is the gravitating body, leads to a precession frequency of $\simeq 4.5 \cdot \alpha_1 \, nHz$.
- Even a random magnetic field of $\alpha_1 \cdot 10^{-11}$ Gauss can mimic the effect!
- In the comagnetmeter, two isotopes with different gyromagnetic to spin ratios are trapped in the same cell.
- In this expt. the isotopes $^{192}Hg(I = \frac{1}{2})$ and $^{201}Hg(I = \frac{3}{2})$ were used.

Atom Techniques: Mercury Cell Comagnetometre

- Both isotopes are subjet to the same stray magnetic field.
- The effect of stray magnetic fields can be eliminated through appropriate combinations of observables.
- The ambient magnetic fields were reduced to level of $20\mu G$. A uniform field of 10mG was also applied.
- The experiment is so sensitive that earth's rotation frequency of $\Omega_E \simeq 11.6\mu Hz$ has to be taken into account.
- Their result for $\mathcal{A} = \alpha_1 \frac{GM}{cR^2}$ is $\mathcal{A} = -0.08 \pm 0.1 \pm 0.1(Syst)\mu Hz$
- This translates to the limit $\alpha_1 \simeq 50 - 60$
- This is by far the best limit on α_1.
- This expt stands the best chance of settling the existence or otherwise of my proposed interactions.
- In view of the very deep theoretical implications of these(elaborated at the end of this talk), it is highly imperative that this expt is performed reducing both systematic and random errors.

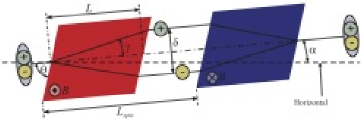
Atom/Ion Trap Expts

- In these expts ions are trapped in a Penning Trap
- D.J. Wineland et al PRL 67 p.1735 1991
- 5000 $^9Be^+$ in ground state with magnetic field of $B_0 \simeq 0.8194T$. As in the Mercury cell expt of Venema et al, the magnetic field was flipped.
- Hyperfine transition $(F = 1, m_F = 0) \rightarrow (F = 1, m_F = -1)$
- The additional interactions manifest as a change $\Delta\,\nu_0$
- The result was $\Delta\,\nu_0 = -6.4 \pm 2.9 \pm 6.4\,\mu\,Hz$
- The large systematic error of $6.4\,\mu\,Hz$ was due to so called Pressure Shift Variation that occurs when the magnetic field is flipped.
- Using quadrature, $\Delta\nu_0 < 13.4\mu Hz$ This translates to $\alpha_1 < 300$
- Pressure shift variation could be reduced by Cryogenic Pumping. The number of ions could be increased to 10^7.
- With all these improvements the limits on $\Delta\nu_0$ could be improved to $\simeq 3nHz$ resulting in $\alpha_1 \simeq 1$.

Our MOT Proposal

- This is a proposal worked out with Y. Takahashi at Kyoto University.
- The idea is to trap two different isotopes in a Magneto-Optic Trap(MOT).
- The following parameters seem realizable: Number of trapped atoms $\simeq 10^8$, total measurement time $\simeq 10^6 s$.
- By exploiting various angular dependencea, the systematic errors may also be better controlled.s
- It seems feasible to probe $\alpha_1 \simeq 1$

Spin-Echo techniques



- In my Ann.Phy(NY) 107 p.337 1977 paper itself I had identified Spin-Echo techniques as a promising direction.
- This was based on F.Mezei's Z.Physik A 255 p.146 1972 claim that EDM sensitivities can be improved to $10^{-26} - 10^{-28}$ ecms. This would have translated to a potential realisation of $\alpha_1 \simeq 1$ regime.
- Parnell et al PRD 101 122002 2020 have used a Spin-Echo Neutron Interferometer to measure spin-dependent gravitational interactions.
- This interferometer is essentially Humpty-Dumpty type SG-interferometer much discussed in this meeting.
- The results quoted by Parnell et al for α_1 is rather poor.
- This needs better understanding.

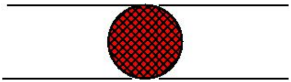
Deep Theoretical Implications.

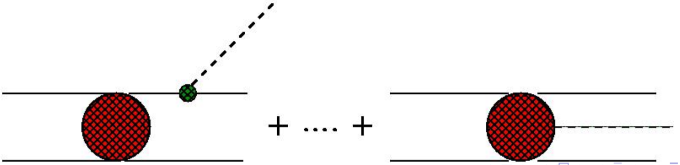
- Discussed at great length in my Ann.Phy(NY) 107 p.337 1977. See also for all the relevant references.
- If $\alpha_1 \neq 0$, parity is violated in gravitational interactions.
- It also means a breakdown of GR at quantum level.
- It means inrinsic spins and classical gyroscopes precess differently in a gravitational field.
- It means freely falling frames are not inertial. Breakdown of both the equivalence principle as well as local lorentz invariance.
- The implications are even deeper!
- To see that, let us introduce Hiida and Yamaguchi's t general alertone particle matrix elements of a conserved,symmetric stress-tensor of a spin-1/2 particle(for full expression, see my paper; will only consider what is relevant for the α_1 effect):

$$S_{\mu\nu}(k) = G_5(k^2)\gamma_5\{P_\mu\sigma_{\nu\alpha}k^\alpha + \mu \rightleftharpoons \nu\}$$

Deep Theoretical Implications.

- α_1 is a constant multiple of $G_5(0)$
- What Deser and Boulware showed was that even though the single particle matrix element above is perfectly consistent in itself, it leads to trouble in graviton bremstrahlung.
- More specifically, bremsstrahlung processes break gauge-invariance unless $G_5(0)$ or equivalently α_1 vanishes!





Deep Theoretical Implications.

- The reason for this was that Deser and Boulware had assumed the stress tensor and consequently the gravitational field to be symmetric.
- Turning this around, if experiments find $\alpha_1 \neq 0$, no theory with a symmetric gravitational field is valid!
- As shown in my Ann.Phys paper, this is consistent with Schwinger's demonstration that in the tetrad formalism it is the local lorentz invariance that yields a symmetric stress-tensor.
- This has the deep consequence that if $\alpha_1 \neq 0$, we have to not only give up GR, spin-2 theories, the standard Einstein-Cartan theories etc
- Even the so called Chern-Simons gravities, upon which the so called most general parity violating gravitational theories are based, will all have to be given-up.
- The sweeping claims that these are the most general parity violating gravitational theories are utterly false!

Deep Theoretical Implications.

- As possibly viable alternatives, I suggested using Einstein's non-symmetric theory, with which he was grappling towards the very end of his life.
- S.N. Bose collaborated with him on this and came up with a number of strong improvements, but he abruptly gave up his researches on this topic as soon as he heard of Einstein's death.
- The other was the work of Kenji Hayashi(1972-73) on Poincare Gauge Theories of Gravitation.
- He found that minimal coupling in such theories just produces the Einstein-Cartan theories with symmetric gravitational fields, although the connection could be asymmetric(Torsion).
- More remarkably, he found that the parity violations of the type discussed here amount to non-minimal couplings which necessarily break local Lorentz invariance, and lead to theories in which the gravitational field is asymmetric.,