QUANTUM NON-LOCALITY, BLACK HOLES AND QUANTUM GRAVITY

Asghar Qadir

Centre for Advanced Mathematics & Physics (CAMP)
National University for Sciences & Technology (NUST)
Campus of College of Electrical & Mechanical Engineering
Peshawar Road, Rawalpindi
Pakistan

- Einstein-Podolsky-Rosen (EPR) "paradox"
- The Bohm formulation
- Bell's inequalities — I
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- Quantum non-locality
- General Relativity
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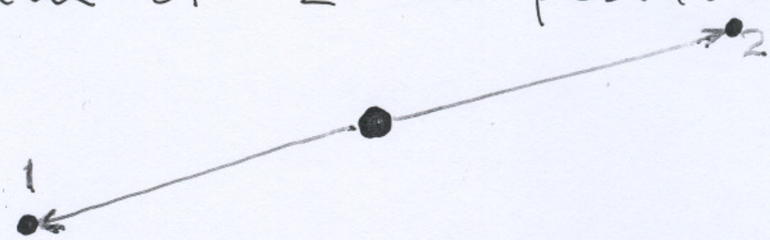
EPR "Paradox" PR 47(1935)777–780

- Defined "physical reality" as corresponding to physical theory; and without disturbing system predict measurable outcome with unit probability.
- QT contains quantities precise knowledge of one of which precludes knowledge of other.
- In rest frame break system into 2 parts. Measure position of 1 or momentum of 1 to obtain momentum of 2 or position of 2.

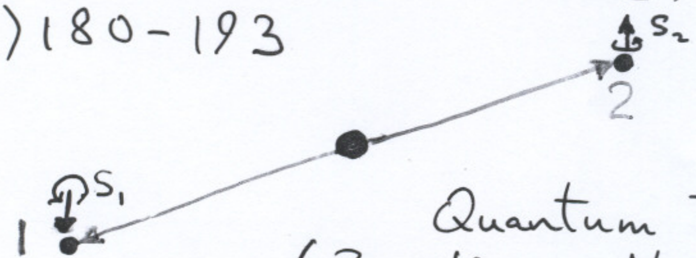


- Argued that since it is possible to have knowledge of 2 without disturbing it, it has physical reality but QT does not fully describe it, so it is an <u>incomplete</u> physical theory.
- Expressed <u>beleif</u> that complete physical theory does exist.

Bohm's Formulation

→ Furry W. H. PR 49 (1936) 393 – 399 cut across philosophical cross-talk about EPR by a concrete objection that the uncertainty in measurement of continuous variables destroys unit probability.

→ Bohm D. avoids by breaking up system into spin states, each carrying information of spin as a local hidden variable. PR 85 (1952) 166 – 179, 85 (1952) 180 – 193



Quantum Theory (Prentice Hall 1951)

→ Full formulation of suggestion: measure spin of object broken (say to be 1) then measure spin of part 1 of object and part 2 will have preisely known spin, as it is discretely quantized D. Bohm & Y. Aharanov PR 108 (1957) 1070 – 1076
NC 17 (1960) 964 – 976

Bell's Inequalities   J. S. Bell

✓ Physics 1 (1964) 195–200, RMP 38 (1966) 447–45[illegible]

Hidden variable λ, probability density ρ, spin $\underline{\sigma}$, spatial directions given by unit vectors $\underline{a}$, $\underline{b}$, $\underline{c}$.

Note $\underline{\sigma}$ is a Pauli spin matrix.

Expectation value measuring spins of parts in QT without hidden variables

$$P_{QT}(\underline{a},\underline{b}) = \langle \underline{\sigma}_1 \cdot \underline{a}\ \underline{\sigma}_2 \cdot \underline{b} \rangle = -\underline{a} \cdot \underline{b}$$

for initially unspinning particle.

$$P_{hv}(\underline{a},\underline{b}) = \int \rho(\lambda_1,\lambda_2)\, A(\underline{a},\lambda_1)\, B(\underline{b},\lambda_2)\, d\lambda_1\, d\lambda_2$$

A specifies value of $\underline{\sigma}_1$ along $\underline{a}$,

B 〃 〃 〃 $\underline{\sigma}_2$ 〃 $\underline{b}$.

$$P_{hv}(\underline{a},\underline{b}) - P_{hv}(\underline{a},\underline{c}) = \int [A(\underline{b},\lambda)\, A(\underline{c},\lambda) - 1]\, \rho(\lambda)\, A(\underline{a},\lambda)\, A(\underline{b},\lambda)\, d\lambda$$

$\lambda \doteq \lambda_1 \otimes \lambda_2$, using $B(\underline{b},\lambda) = -A(\underline{b},\lambda)$ as $P(\underline{b},\underline{b}) = -1$

$$\Longrightarrow |P_{hv}(\underline{a},\underline{b}) - P_{hv}(\underline{a},\underline{c})| \leq \int [1 - A(\underline{b},\lambda) A(\underline{c},\lambda)]\, \rho(\lambda)\, d\lambda$$

$$= 1 + P_{hv}(\underline{b},\underline{c})$$

Bell's inequality.

✓ Choose $\underline{a} = (\underline{b} - \underline{c})/|\underline{b} - \underline{c}|$. Get

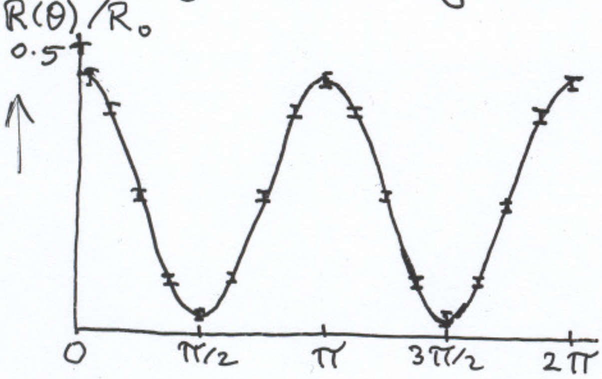
$|\underline{a} \cdot (\underline{b} - c)| \leq 1 - \underline{b} \cdot \underline{c}$, $P_{QT} = |\underline{b} - \underline{c}|$

Take $\underline{b} \perp \underline{c}$, $P_{QT} = \sqrt{2} \neq P_{hv} = 1$

The Aspect Experiment

A. Aspect, Phys. Lett. **54A** (1975) 117– , ...

" + P. Grangier + G. Roger, PRL **49** (1982) 91–, ...



R(θ) = coincidence rate

R_0 = normalization factor

→ θ Polarizer angle

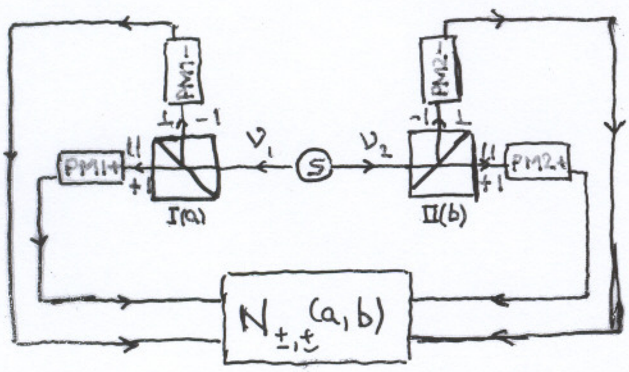
∿ QT predictions

I 1 standard deviation error bar either side

Coincidences for spin polarizations $N_{\pm,\pm}(\underline{a},\underline{b})$ used

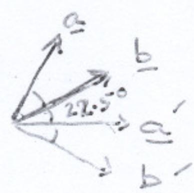
∥ ∼ +1

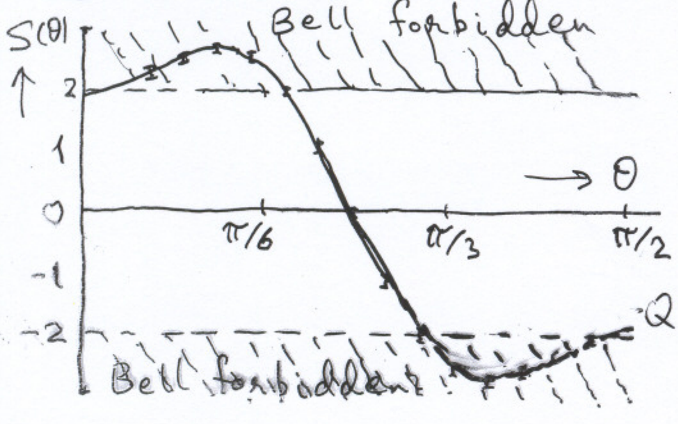
⊥ ∼ −1



$$E(\underline{a},\underline{b}) = \frac{N_{++}(\underline{a},\underline{b}) + N_{--}(\underline{a},\underline{b}) - N_{+-}(\underline{a},\underline{b}) - N_{-+}(\underline{a},\underline{b})}{N_{++}(\underline{a},\underline{b}) + N_{--}(\underline{a},\underline{b}) + N_{+-}(\underline{a},\underline{b}) + N_{-+}(\underline{a},\underline{b})}$$

$$S = E(\underline{a},\underline{b}) - E(\underline{a},\underline{b}') + E(\underline{a}',\underline{b}) + E(\underline{a}',\underline{b}')$$





$S^{QT}_{max} = 2.70$

$S^{exp}_{max} = 2.70 \pm 0.015$

QT prediction

Quantum Non-Locality

- Aspect experiment demonstrates the violation of Bell's inequalities showing that local hidden variables are incompatible with observation.
- If we continue to think of spin as well-defined we must accept that the system is non-locally defined.
- The violation of the spacetime picture as composed of spatial points at instants of time is over the scale of metres.
- Non-local self-interference has been seen in time over minutes, by building interference fringes from single photon (or electron) diffraction
- Aspect experiment has been extended over kilometre scales
- Quantum non-locality is <u>not</u> at microscopic scales only!

- Infact neutron stars and white dwarfs are Fermi-degenerate gases of nucleons and electrons respectivety.
- These are quantum objects of ~ 10 km and $\sim 10^4$ km. size!
- The latter, of mass $\sim 1.5\, M_\odot \approx 3 \times 10^{30}$ kg. has "classical" nucleii" (not degenerate). The degenerate matter $\sim 1.5 \times 10^{27}$ kg still enormous.
- Former has mass $\sim 2\, M_\odot \approx 4 \times 10^{30}$ kg all degenerate.
- Non-local effects do not seem to be eliminated by gravity but are in fact stabilised by it — at least here.
- The quantum domain is <u>not</u> limited to small size or mass or small times — cannot be "swept under the rug".

General Relativity

- Geometric theory of motion formulated to remove the restriction to uniform linear motion of Special Relativity, 1916.
- Einstein used gravity as the "cause" for acceleration.
- Failed to extend to other "causes", despite years of search for a "unified field theory".
- For gravity a tensor field theory — ($g_{\mu\nu} = g_{\nu\mu}$, $\mu, \nu = 0, 1, 2, 3$) (0 → time; 1, 2, 3 → space)
- Lagrange density

$$\mathcal{L}[g_{\mu\nu}, g_{\mu\nu,\rho}] = \sqrt{-g}\,(R+\Lambda)$$

($g_{\mu\nu,\rho} \to \frac{\partial}{\partial x^\rho} g_{\mu\nu}$; $g \to \det(g_{\mu\nu})$; $\Lambda \to$ cosmological constant)

$$R := g^{\mu\nu} R_{\mu\nu} \doteq g^{\mu\nu} R^{\alpha}{}_{\mu\alpha\nu}$$

($(g^{\mu\nu}) = (g_{\mu\nu})^{-1}$)

$$R^{\alpha}{}_{\mu\beta\nu} := \left\{{}^{\alpha}_{\mu\,\nu}\right\}_{,\beta} - \left\{{}^{\alpha}_{\beta\,\mu}\right\}_{,\nu} + \left\{{}^{\alpha}_{\sigma\,\beta}\right\}\left\{{}^{\sigma}_{\mu\,\nu}\right\} - \left\{{}^{\alpha}_{\sigma\,\nu}\right\}\left\{{}^{\sigma}_{\beta\,\mu}\right\}$$

$$\left\{{}^{\alpha}_{\mu\,\nu}\right\} = \frac{1}{2} g^{\alpha\rho}\left(g_{\mu\rho,\nu} + g_{\nu\rho,\mu} - g_{\mu\nu,\rho}\right)$$

- Yields Einstein equations $R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$

(gravitational coupling $8\pi G/c^4$ → κ; $T_{\mu\nu}$ → stress-energy tensor)

Black Holes

- ✓ Regions of space from which not even light can escape.
- ✓ Simplest solution of Einstein equations for spherical symmetry, staticity and vacuum (i.e. $T_{\mu\nu} = 0 = \Lambda$)

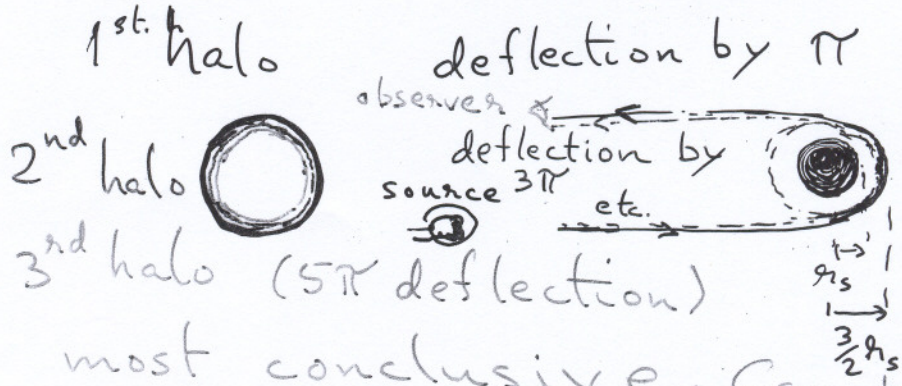
$$g_{00} = 1 - 2Gm/c^2 r = -1/g_{11}$$

$$g_{22} = -r^2 \,, \; g_{33} = -r^2 \sin^2\theta \,, \; g_{\mu\nu} = 0 \text{ otherwise.}$$

- ✓ For this, <u>Schwarzschild</u>, solution the region defined by $r \leq r_s \doteq 2Gm/c^2$.
- ✓ Expected to arise from gravitational collapse, if spherically symmetric, of stars of mass $m \geq 3.2\, M_\odot$ (after collapse) Christodoulou-Fang-Ruffini limit
- ✓ Axially symmetric, rotating star with same mass expected to give the <u>Kerr</u> solution incorporating the angular momentum per unit mass a of star, θ-dependence and $g_{03}(r,\theta) \propto a \neq 0$.

Observing Black Holes

- By definition, no direct observation possible for black holes.
- Indirect observation by gravitational effects in weak-field limit not reliable, as it is easily mimiced by other matter distributions.
- Strong gravitational field effect yields very high acceleration of ionized matter yielding a typical spectrum from accretion.
- Further, leads to electron-positron pair creation by vacuum polarization adding a 1 MeV γ-ray hump.
- D.E. Holz & J.A. Wheeler Ap. J 57 (2002) 330– propose using large-angle light bending to give a "retro-lensed" halo about the black hole



- If possible most conclusive. Can be using central black hole of Milky Way.

Observing Black Hole Spin

→ F. De Paolis et al A & A, 409 (2003) 809 – showed that rings may be detectable by next generation observational satellites for central black hole illuminated by Sgr A* ($\sim 10 M_\odot$) in orbit around it.

→ Central black holes expected to form with extreme angular momentum $L \lesssim GM^2/c$.

→ Can see effect of spin due to distortion of ring on  account of frame-dragging

FDP et. al. A & A, 415 (2004) 1–4.

→ Can see it even better due to frequency shifts blue for co-rotating and red for counter-rotating photons,

FDP, A. Nucita, AQ. Proc. 11th Regional Conf. Math. Phys. eds. S. Rahvar, N. Sadooghi, H. Shojai, World Scientific 2005.

→ Important for what follows.

Quantum Relativistic Limits

- Classical limit from SR $c^{-1} \to 0$, from QT $\hbar \to 0$ and from GR to SR $G \to 0$. In these limits can neglect change from previous theory.
- Contrariwise, if the limit does not hold, cannot neglect the change.
- Planck defined units:

  $l_p = \sqrt{G\hbar/c^3} \approx 10^{-32}$ cms.

  $t_p = \sqrt{G\hbar/c^5} \approx 10^{-40}$ sec.

  $m_p = \sqrt{c\hbar/G} \approx 10^{-5}$ gm. $\approx 10^{19}$ GeV/c^2

  Corresponding energy

  $E_p = m_p c^2 \approx 10^{19}$ GeV , Planck energy
- At these scales must have a theory incorporating GR & QT!
- No such theory (including Superstrings, M-theory etc.) exists as yet.

The Problems of Quantum Gravity

✓ At surface level problem comes in setting up a QFT of gravity. It turns out to be non-renormalisable when viewed as quantization of a spin 2 field with the Einstein-Hilbert Lagrangian.

✓ "Covariant quantization", by requiring manifest covariance attempted by B.S. De Witt failed.

✓ Since SUSY can get cancellation of divergences between the Fermion and Boson sectors, SUGRA is the natural successor. Runs into serious problems and one must take extended SUGRA. Still runs into problems. For N-extended SUGRA finite to N-loops, divergent beyond.

- ✓ Dirac's original, canonical, quantization was carried forward by Arnowitt, Deser & Misner, but with no success. Later developments by Ashtekar allowed for some hope but have not yielded a meaningful theory of quantum gravity so far.
- ✓ An alternate approach was to change the Lagrangian and the dimension of spacetime. This leads to attempts such as Superstring theory, M-theory, etc.
- ✓ More fundamental changes try to modify the spacetime structure to discrete form (fuzzy geometry) or construct an effective spacetime from discrete entities (spin networks, twistors, etc.)
- ✓ Most attempts assume QFT remains unchanged, GR modified at Planck scale — and not before.
- ✓ All recognise problem of time, not given by a linear operator. (Covariance.)

✓ Canonical procedures can also be used to obtain the equivalent of the Schrödinger equation. This is the Wheeler-DeWitt equation. It requires two constraints to be satisfied: the Hamiltonian constraint $H = 0$ and the diffeomorphism constraints ($\sim p_a = 0$).

✓ Developed by Hawking for a toy model of the whole Universe by taking mini-superspace and using the Hartle-Hawking "no-boundary" boundary condition.

✓ This is the field of "Quantum Cosmology" and does not lead to any new predictions but does provide a consistent framework.

Other Attempts to Resolve Problems

- There have been various suggestions that gravity modifies quantum theory, starting with Einstein.
- Going further, it is pointed out that QT has one big weakness — the measurement, or wave function "reduction". All quantum processes are represented by unitary operators and are time-reversible, but measurement is neither of these.
- The Copenhagen view is that the wave function is "reduced" when the "quantum system" interacts with a "classical measuring device".
- If QT is <u>the</u> correct theory, the "classical measuring device" is composed of "quantum" parts and must remain unitary, as pointed out by Bell.
- It has been proposed that gravity may be responsible for the reduction.

✓ F. Károlyházy, Rep. Prog. Phys. 41 (1978) 1881
" + A. Frenkel + B. Lukács, Quantum Concepts in Space & Time eds. R. Penrose & C. J. Isham Clarendon Press, Oxford 1986
proposes a mis-match between the flat spacetime QFT at two places due to curvature. Gives estimates of effects due to this fuzziness of enhanced Brownian motion of a pendulum bob at the top of its swing. The sensitivity required is unrealistic. (Other attempts to see QFT effects on the basis of similar reasoning also do not seem to be more testable.) They also propose a space-based experiment to detect the additional Brownian motion. It may be difficult to distinguish it from other effects.

✓ J. Barbour has similar views on the **basis** of the problem but does not address these issues or agree here.

✓ **These** effects are at cm. scale.

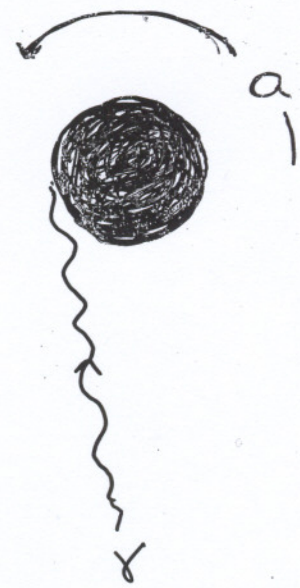
Penrose's Proposal

- Penrose had earlier related the black hole entropy (the Bekenstein-Hawking quantity) to quantum gravity considerations via black hole evaporation. He concluded that the entropy should be measured, not by the black hole area but by the Weyl curvature, Proc. Roy. Soc. (Lond) A381 (1982) 53-.
- He later argued that gravity should play a role in reduction of the state vector GRG 28 (1996) 581-600
- Precise role not spelled out, but should "explain" non-locality.
- Assumed that QT applies for small masses and large masses break quantum coherence — takes quantum domain large but small mass and energy.

Reducing the Planck Limit

- ✓ Planck scale inaccessible, except in very early Universe — not observable without strongly distorting theoretical glasses.
- ✓ Many have tried to bring QG to accessible scale.
- ✓ Most attempts, like the Superstring ones of "large extra dimensions" based <u>not</u> on observation of Nature but <u>desire</u> that QG be observed.
- ✓ Nature does not care about our desires.
- ✓ Some, like Károlházy, Barbour, Penrose, expect it to arise at "cm" or "km" scale in delicate experiments on other counts.
- ✓ Try following up at larger scales.

- ✓ Bring extreme quantum object, photon (γ), face to face with extreme gravitational object, black hole.



- ✓ Use near extreme Kerr black hole.
- ✓ Counter-rotating γ will spin-up the black hole —
- ✓ Provided the black hole "sees" it.
- ✓ If wavelength too large for hole, the photon will "miss".
- ✓ More precisely, ideally prepared photons will spin-up and spin-down equally.
- ✓ To spin-up, photon wavelength must be less than radius of black hole.

$$r_h = \frac{GM}{c^2} + \sqrt{\frac{G^2M^2}{c^4} - \frac{L^2}{M^2}}$$ → angular momentum

Near extreme Kerr

$$L = \frac{GM^2}{c}\sqrt{1-\varepsilon}$$ → small number

Distance of closest approach of photon is

$$b = \left(1 + 2\sqrt{\varepsilon/3}\right) GM/c^2$$

Wavelength shift for n^{th} ring is

$$\frac{\delta\lambda}{\lambda} \approx \frac{\sqrt{1-\varepsilon}}{\left(1+2\sqrt{\varepsilon/3}\right)^2} \times (2n-1)$$

↳ unity for $n=1$

Require $\lambda < b$ for spin-up to work

The QG effect will appear for a photon of energy

$$E > \frac{c^3 h}{GM + \sqrt{G^2M^2 - L^2c^2/M^2}}$$

[Note similarity to photo-electric effect]

Energy increase by

$$\delta E \approx GLE/b^2c^2$$

and angular momentum by

$$\delta L \approx GLE/bc^3$$

Conclusion & Summary

→ No theory of QG exists but it is needed for degenerate stars already.
→ Most people **assume** that QG is only relevant at Planck scale.
→ Some theories may even require i
→ Minority view that measurement **problem** and understanding Bell's inequality implications requires QG.
→ Most of this minority expect QG effects at "cm" to "m" scale.
→ Penrose expects unlimited scale of size and time but low energy.
→ Confronting the quantum (photon) with gravity (a black hole) seems to give a scale, for any mass, at which QG becomes relevant.
→ The behaviour is reverse of the expectation on Penrose's argument
→ Larger masses stabilize the quantum behaviour

→ What happened to the Planck scale here?

→ Consider the case of the photon energy equal to the rest energy of the black hole. In that case both will be

$$E = \sqrt{\pi}\, E_p .$$

<u>This</u> is when QG could not be ignored in the experiment.

→ Note that for the extreme black hole (not necessarily at Planck scale) the entire energy of the photon would get absorbed with the increase of angular momentum due to orbital angular momentum, leaving a "zero-energy" photon to come out.

→ More general limits for QG onset need to be explored.