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Bi-Directional EPR Correlation in Cosmology and Planckeon Origin of Dark Energy

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I. Introduction

Since the advent of quantum mechanics in the mid-1920s there have benn continued interpretational controversies surrounding its counter-intuitive nature such as the wave-particle duality and the instantaneous collapse of the particle wave function at the detection point. But the paradox of nonlocal EPR[1] correlation between distant events without nonlocal interactions has been more problematic in recent times by Bell's experimental nonlocality test[2,3] proposed in 1964, though the paradox was first noticed by Schrödinger[4] and discussed in the dialogue between Einstein and Bohr[5] at 1935 Solvay Council. In emphasis of the signal transmission in EPR correlation Cavaicanti and Wiseman[6] asked: "What Bohr could have told Einstein at Solvay had he known about Bell experiments ?" In his recollection in 1990 Bell[7] wrote: "Suppose quantum mechanics were found to *resist* precise formulation. Suppose that when formulation beyond FAPP (For All Practical Purposes)[8] is attempted, we find an unmovable finger obstinately pointing outside the subject....to the Mind of the Observer..., or only Gravitation ?" We here show that the solution of quantum paradoxes can be found outside the EPR's reality criterion of local cauality[9] but within the framework of time-symmetric quantum electrodynamics for finite spacetme.[10] A cosmlogical implication of the bi-directional signal transmission P↔Q without common source S in the inflationary cosmology and a possible orgin of dark energy are also discussed.

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II. EPR Correlation in EPR Loophole

At the Solvay council EPR asked: "Are there spooky actions at a distance in quantum dmechanics ?" Recently, Yin et al.[11] led by Q. Zhang measured a superluminal speed of spooky acions between counter-propagating pair of photons emitted from an opticaly pumped atom in spin 0 state. During the measurement the locality and the freedom-of-choice loopholes of previous expriments were maximally closed by observing a 12-hour continuous violation of Bell's numerical expression (inequality) to EPR's reality criterion of local causality and separability of distant events. Let the spacetime positions of the photon source and the detection points be $S(x_S, t_S)$, $P(x_P, t_P)$ and $Q(x_Q, t_Q)$. Then the lower bound of the speed c_S of the spooky actions

$$c_S = |x_Q - x_P|/|t_Q - t_P| \qquad (1)$$

can be superluminal as $|t_Q - t_P| \to 0$. Here we can see a local and causal link P←S→Q ($t_S < t_P \approx t_Q$) and the nonlocal and acausal (spooky) link P→Q ($t_P < t_Q$). Let ε_P and ε_Q be the unit polarization vectors of photons measured at P and Q. The experiments verified the quantum expectations of the correlation function $C_{QM}(\boldsymbol{\varepsilon}_P,\boldsymbol{\varepsilon}_Q) = \boldsymbol{\varepsilon}_P\boldsymbol{\varepsilon}_Q = \cos\theta$, where θ is the Hilbert space angle between $\boldsymbol{\varepsilon}_P$ and $\boldsymbol{\varepsilon}_Q$, and showed a clear rejection of classical theories obeying Bell's inequlities. The experiments also confirmed the insenstivty of C_{QM} to observer's delayed decision as to which direction to measure each photon's polarization at P and Q after the photon left the source at S—too late for a message to reach the opposite photon,[8] making the causal link P←S→Q improbable and the bi-directional link P↔S↔Q probable in the loophole of EPR's reality criterion of local causlity between P and Q,

III. EPR Correlation on Double-Light Cone

Dirac[12] defined the two-point corrlation function or propagator $\Delta(x, t)$ between S(0,0) and P(x, t), and visualized the signal transmission S↔P on the light cone with the origin S as vertex:

$$(\partial^2/c^2\partial^2t^2 - \partial^2/^2\partial^2x^2)\Delta(x,t) = 0, \qquad (2)$$

$$\Delta(x,t) = \alpha(t)\delta(c^2t^2 - x^2)$$

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$$= [\delta(ct - x) - \delta(ct - x)]$$

$$= \Delta_{future} - \Delta_{past} = \Delta_{ret} - \Delta_{advt} , \quad (3)$$

where $\alpha(t) = t/|t| = 1$ $(t > 0)$; $= -1$ $(t < 0)$. There an electron at S(0, 0) moves under the retarded (causal) action Δ_{ret} . of a charged partcle at P on the past light cone $\delta(ct + x)$ of S as well as the advanced (retrocausal) action Δ_{adv} of a charged particle at Q on the future light cone $\delta(ct - x)$ of S, giving a divergence-free radiation damping of the electron at S. The bi-directional EPR link, $P(x_P, t_P) \leftrightarrow S(x_S, t_S) \leftrightarrow Q(x_Q, t_Q)$, can be visualized on the future light cone of the optically pumped metastble atom at S(0, 0) by replacing the step function $\alpha(t)$ by the square (step-up and down) function $\beta(t) = 0$ $(t < t_S)$; $= 1$ $(t_S < t < t_{P/Q})$; $= 1$ $(t > t_{P/Q})$

$$(t_S < t < t_{P/Q}); = 1 \ (t > t_{P/Q})$$

$$\Delta(|x_{P/Q} - x_S|, |t_{P/Q} - t_S|)$$

$$= [\delta(c|t_{P/Q} - t_S| - |x_{P/Q} - x_{S|}|)$$

$$- \delta[(c|t_{P/Q} - t_S| - |x_{P/Q} - x_{S|}|]/|x_{P/Q} - x_S| . \quad (4)$$

The double-light cone[13] $[\delta_{ret} - \delta_{adv}]$ in Eq.(5) tells that the detection point P/Q on the left/right arms of the future light cone of S is reached by retarded wave $\exp i(\omega t - kt)$ from S while advanced wave $\exp i(\omega t + kx)$ from P/Q reaches S on the right/left arms of the past light cone of P/Q, forming a bi-directional sinusoidal wave, $\exp i\omega t \sin kx$, standing in phase between S and P/Q with nodes fixed in space at $x = n\pi/k$ (n = integer).

IV. Bi-Directional Microscope

"Is the star (moon) there when nobody looks" asked Tetrode (Mermin).[14] At the 1947 Solvay Council Heisenberg proposed a thought experiment measuring the electron position on microscope's object plane. There the photon wave collapsing at S in the retinaof the oberver entails the retrocollapse (appearance) of an elecon at P scattering the photon to be observed at S. That is, the electron is not at P when nobody looks. at S. This point was emphasized by Weizäcker[15] in his delayed-choice thought experiment measuring the transverse photon momentum on the focal plane of Heisenberg's microscope. If the microscope is very long, the observer at S can make choice as to which property of the electron, position or momentum, to measure after the scattering process has taken place at P. To see the bi-directional signal transmission S↔P where $M = \rho_\Lambda V = 4\pi\rho_\Lambda R^3/3$ is the Newtonian mass. in microscope we write Eq.(5) in momentum space[14]

$$\Delta_{\omega,k}(|x_P - x_S|, |t_P - t_S|)$$

$$= [\exp ikc|t_P - t_S| \ |\sin k|x_P - x_S|]/|k|, \quad (5)$$

getting an uncertainty relation between photon momentum $p = \hbar k$ and the microscope length

$$p|x_P - x_S| = nh/2, \quad (6)$$

where n is the number of nodes of the sinusoidal wave standing between S and P.

V. Cosmological EPR Correlation

In his aether hypothesis Dirac[17,18] considered a nonlocal EPR connection without common source S between distant events P and Q on the 4-dimensional hyperboloid $(ct)^2 - r^2 = l_{pl}^2$, or the Lorenz sphere of radius l_{pl} , crossing the light cone at $ct = l_{pl}$ at $r = 0$ with spacelike velocity:

$$dr/dt = ct/r = c(1 + l_{pl}^2/r^2)^{1/2}. \quad (7)$$

Hawking[19] considered a cyclic cosmology where an expanding and contracting Lorenz-de Sitter universe starts and ends on the Lorenz sphere embedded into 4-dimensional Euclidean space $\tau^2 + r^2 \sim l_{pl}^2$ with imaginary time $\tau = it$. There the observable Hubble consant $H = v/d$ relating the relative velocity $v \sim c$ of extragalactic objects at a distance d receding from the Earth, is related to the cycle $C = 2\pi H^{-1}$, temperature $T = H/2\pi$ and entropy $S = \pi H^{-2}$. In high dimensional string theory,[20] the parallel orbifold branes collide periodically in cycle, expanding and contracting with dark energy.

We here consider the embedding of the Planck length l_{pl} in the radial line element ds of the Lorenz-de Sitter-Reissner-Nordstroem universe:

$$ds^2 = c^2 g_{tt} dt^2 - g_{rr} dr^2,$$

$$g_{tt} = g_{rr}^{-1} = c(1 - \Lambda r^2/c^2 + l_{pl}^2/r^2)^{1/2}. \quad (8)$$

Here Λ is the cosmolgical constant interpreted as the timelike vacuum energy density. Note that the light velocity $dr/dt = c(g_{tt}/g_{rr})^{1/2} = c(1 - \Lambda r^2/c^2 + l_{pl}^2/r^2)$ is spacelike at $r \sim l_{pl}$ but decreases with the increase of r towards $dr/dt = c$ at $r = (cl_{pl})\Lambda^{-1/2} \sim 10^{-23}\Lambda^{-1/2}$cm. In the inflationary cosmology starting from quantum fluctuations of preexisting spacetime metric, the radius of the causally related small region extends from $l_p \sim 10^{-33}$cm to $r \sim 10^{-25}$cm during electroweak and grand unification period followed by a brief interlude of reheating, returning to the pre-inflationary temperature of the universe. After the inflationary period, further evolution of the universe is described by the standard Friedman model universe starting the radiation dominated phase of Hubble's expansion history.

VI. Time-Symmetric and Inflationary Friedman .....Universe

Consider a Friedman universe filled with the uniform disrtribution of constant dark energy density ρ_Λ described by the Lorenz-Reissner-Nordstroem metric:

$$g_{tt} = g_{rr}^{-1} = (1 - r^2/r_g^2)^{1/2} + r_{pl}^2/r^2$$
$$= (1 - r/r_g)^{1/2}(1 + r/r_g)^{1/2} + r_{pl}^2/r^2, \quad (9)$$

where $r_g = 3c^2/8\pi G\rho_\Lambda$ is the gravitational radius of the universe determinig the cosmological event horizon. We find superlminal signal trasmission $dr/dt = c(g_{tt}/g_{rr})^{1/2} >> c$ and causally related small regions at radii $r = r_c$ and $r = r_g - r_c$ where $r_c = (r_{pl}/r_g) \sim 10^{-2}$cm for $r_g = R \sim 10^{28}$cm, that is, the inflationary epochs of expanding and contracting almost closed Friedmanan universe, joined onto asymetrically flat Euclidean spaces through double-valued Schwarzschild bottle-neck.

VII. Mass Defect of Semiclosed Friedman Universe

For $r >> r_{pl}$ the evolutinary history of Friedman universe is determined by the Hubble constant $H = 8\pi G/\rho_\Lambda$ where ρ_Λ is the dark energy density. The dimensionless density parameter Ω_Λ is defined by $\Omega_\Lambda = \rho_\Lambda/\rho_{c\Lambda}$ where $\rho_{c\Lambda}$ is the critical density to make the univese flat. For $r >> r_{pl}$ we have

$$ds^2 = c^2 g_{tt} dt^2 - g_{rr} dr^2,$$
$$g_{tt} = g_{rr}^{-1} = (1 - r^2/r_g^2)^{1/2}. \quad (10)$$

Using the integral $\int dx(1 - x^2)^{1/2} = \sin^{-1}x$ the proper mass M_p and volume V_p of the universe of radius R are calculated ss

$$M_p = \rho_\Lambda V_p = 2\pi\rho_\Lambda \int^R r^2 g_{rr} dr = (3/2)(R/r_g)^3[\sin^{-1}(R/r_g)$$
$$\dots - (R/r_g)(1 - (R^2/r_g^2)^{1/2})]M, \quad (11)$$

where $M = 4\pi R^3\rho_\Lambda/3$ is the Newtonian mass and $M - M_p$ the mass defect. Equation (11) tells that the proper radius $R_p = \int^R g_{rr} r dr$ increases with the increase of the world radius from $r \sim l_{pl}$, where $\sin^{-1}(l_{pl}/r_g) \sim 1$, until V_p fills the lower hemisphere of the closed Friedman universe, where $\sin^{-1}(l_{pl}/r_g) = \pi/4$. With further increase of r, R_p decreases towards $R_p \sim l_{pl}$, where $\sin^{-1}(l_{pl}/r_g) \sim \pi/2$, forming a gravitational semiclosure with $V_p \sim M_p \sim 0$ in the evolutionarily earlier upper hemisphere, creating Planck scale black holes[19] outside the event horizon of almost closed Friedman universe joined onto asymptoticlly flat space through Schwarzschil bottle-neck pulsating with Planck scale period.[21]

VIII. Source of Dark Energy

We note that the negative equation of state $\rho_\Lambda + p_\Lambda c^2 < 0$, where $p_\Lambda c^2 << \rho_\Lambda$ is the pressure, required by the dark energy, is satisfied in the upper hemisphere of the closed Friedman universe where the gravitationally bound pairs of quantized metric fluctuations or Planckeons of mass m_{pl}, or graviational Bohr atoms, creating negative attractive potential $Gm_{pl}^2/l_{pl} = \hbar c/l_{pl} = m_{pl}c^2$ dominate, forming Bose-Einstein condensate, while the single Planckeon excitations with positive rest mass energy $m_{pl}c^2$ prevail in the lower hemisphere where the positive equation of state $\rho_\Lambda + p\ c^2 > 0$ is satisfied by the dark matter. The evolutionarily earlier upper hemishere is chracterized by the density parameter $0.5 < \Omega_\Lambda = (R/r_g)^2 = 1$ and the less earlier lower hemisphere by $0 < \Omega_m < 0.5$, The recently updated density parameters[21] fall into these ranges: $\Omega_\Lambda \sim 0.685$, $\Omega_m \sim 0.266$, $\Omega_{atom} \sim 0.049$ where Ω_{atom} is the density parameter of the evolutionarily recent atomic matter. The fact that $\Omega_\Lambda + \Omega_m + \Omega_{atom} = 0.965 \sim 1$ can be taken an indication of the asymptotical flatness of the outer space detecting asymptotic solutions of Einstein equations.

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