1 of 1

June 1993

TAUP N231-93

DOE-ER40200-326

LOCALIZABILITY AND THE PLANCK MASS

Yuval Ne'eman

Beverly and Raymond Sackler Faculty of Exact Sciences*
Tel-Aviv University, Tel-Aviv, Israel 69978

and

Center for Particle Physics†
University of Texas, Austin, Texas 78712

Abstract

We combine the assumption of environmental decoherence, as the mechanism generating the classical (i.e. no quantum interferences) nature of spacetime, with the limit on its other classical feature, point-like continuity, namely Planck length. As a result, quantum extended objects with masses larger than Planck mass have to derive their quantum behaviour from long-range correlations; objects with masses smaller than Planck mass cannot display classical behaviour.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

* Wolfson Chair Extraordinary in Theoretical Physics

† Supported in part by US DOE Grant DE-FG05-85-ER40200.

MASTER

ds
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

As an effective procedure, the Copenhagen prescriptions for the application of Quantum Mechanics have been overwhelmingly successful. Weighing this record, when considering the experimental verification of the Bell inequalities [1] by Aspect et al. [2], it seems hard to escape the conclusion that as non-intuitive as this be, and EPR [3] notwithstanding, the only "reality" in this world is the "Quantum Reality", the "reality" of complex quantum amplitudes. This is a reality represented by Hilbert space, rather than by spacetime. Moreover, the probabilistic nature of quantum mechanics is proven not to be of the "subjective" type. Rather than having fuzziness in a quantum variable just representing a lack of knowledge about its value, that fuzziness turns out to be "objective", i.e. the variable "really" does not possess a definite value, in that quantum reality, until this is settled in a measurement. This includes, first and foremost, the system's location, namely its spacetime coordinates.

In the last twenty years, the fact that we nevertheless appear to exist in seemingly "classical" surroundings is generally understood (though this is still far from unanimity) to arise dynamically, through the decohering action of the environment [4-9]. Starting from this paradigm, Joos has also shown [10] that the effects of decoherence include the emergence of a classical spacetime. The derivation uses a cube of volume L^3 situated in a homogeneous gravitational field $g_{\mu\nu}$. Assuming the (quantum) state to be in a superposition of two values of the field (or of the corresponding acceleration γ)

$$|\phi\rangle = a|\gamma^1\rangle + b|\gamma^2\rangle \quad (1)$$

Objects travelling through this cube (including dust particles) effectively become an "apparatus", "measuring" the field; their state $|x\rangle$ evolves according to the Schroedinger dynamics for the product

$$|\phi(0)\rangle|x(0)\rangle \rightarrow \{a|\gamma^1\rangle|x^{\gamma^1}(\tau)\rangle + b|\gamma^2\rangle|x^{\gamma^2}(\tau)\rangle\} \quad (2)$$

As a result, the density matrix

$$\rho(\gamma^1, \gamma^2, \tau) = \rho(\gamma^1, \gamma^2, 0) \langle x^{\gamma^1}(\tau) | x^{\gamma^2}(\tau) \rangle \quad (3)$$

involves (the last factor in eq. (3)) the overlap of the two evolved combined states (of that natural "apparatus" and the interacting field), which is approximately proportional to $\delta(\gamma^1 - \gamma^2)$. This gradually destroys the contribution of the interference between the two values of γ . We refer the reader to [10] for details and orders of magnitude in this example.

In this study, we assume with Joos that this is indeed the type of mechanism which would thereby attenuate the contribution of quantum phases and interferences and leave us with the impression of a classical spacetime in that sense. However, Joos' derivation assumes another classical attribute of spacetime: the interaction between the gravitational field and matter obeys Einstein's equation

$$R_{\mu\nu}(x) - 1/2 g_{\mu\nu}(x) R(x) = -\kappa T_{\mu\nu}(x) \quad (4)$$

and is thereby a local interaction in the sense of continuity (we have explicit the x arguments to make this obvious). The quantum wavefunctions are delocalized, but the x variable is continuous. Localizability in both senses is an evident requirement for our overall physical description of canonical spacetime. We would therefore now like to derive some additional information with respect to the notion of localizability.

First, what is then the limit of localizability? Treatments of Quantum Gravity appear to have formulated an answer years ago: the "Planck length" is assumed to represent the ultimate "definition" of spacetime (the term being used in the optical sense). This is an accepted notion. Although Planck's introduction of this length was based on dimensional arguments, we nowadays define "Planck dimensions" by equating the Compton wavelength $\lambda_c = h/mc$ to the Schwarzschild radius, $r_s = 2Gm/c^2$, yielding

$$l_p = \sqrt{(2Gh/c^3)}, \quad m_p = \sqrt{(hc/2G)} \quad (5)$$

Using the decoherence paradigm, we can now formulate an additional interpretation of the logic behind this notion: a particle with mass m_p would generate its own strong gravitational field, rather than coupling mildly to our background spacetime field as in (4). It would develop a horizon, of radius l_p , a black-hole, thus also further inhibiting its interaction with the embedding gravitational field and the resulting decoherence process.

Like other "measurement" processes in QM, the decoherence-generating measurement of the field should involve a "macroscopic" apparatus (the dust particles) acting irreversibly (the "pointer"). We can combine Joos' results with the strong-field horizon limitation and formulate

Conclusion 1

Spacetime is fully classical, i.e. point-like, continuous and devoid of quantum interferences down to dimensions l_p .

In addition, we have a criterion for "macroscopicity": objects whose Compton wavelengths have no physically definable spatial spread, i.e. $M > m_p$, but which nevertheless interact with the gravitational field over more than one distinguishable point:

Conclusion 2

Macroscopic objects, in the sense of the apparatus in the Copenhagen interpretation, have $M > m_p$ and $l > l_p$.

We now have, however, another corollary relating to Planck dimensions. With our new definition of macroscopicity, since the Compton wavelength $\lambda_M < l_p$, the "extension" in this context can only have a "classical" implication. What then of macroscopic quantum systems?

Conclusion 3

Quantum behaviour in macroscopic objects involves long-distance correlations solely.

Examples include Cooper pair coherence lengths, white-dwarf electron degeneracy coherence lengths, etc. Another corollary relates to "microscopic" masses $M < m_p$,

Conclusion 4

Microscopic objects ($M < m_p$) are not fully localizable (i.e. down to l_p) and display quantum behaviour.

Examples: buckyballs ($M \sim 10^3 \text{ GeV}$), DNA ($M \sim 10^8 \text{ GeV}$), etc.

Developing criteria to distinguish between quantum and classical objects has been an aim of many studies in the Foundations of Quantum Mechanics. The above considerations appear to us to point to the notion of Planck dimensions as a related notion, thus providing at least one important criterion relating to localizability, perhaps the only quantifiable one - and a direct result of the decoherence mechanism philosophy.

References

1. J.S. Bell, Rev.Mod.Phys. 38 (1966) 447; Physics 1 (1964) 195.
2. A. Aspect, P. Grangier and G. Roger, Phys.Rev.Lett. 49 (1982) 91;
A. Aspect, J. Dalibard and G. Roger, Phys.Rev.Lett. 49 (1982) 1804.
3. A. Einstein, B. Podolsky and N. Rosen, Phys.Rev. 47 (1935) 777.
4. H.D. Zeh, Found.of Phys. 1 (1970) 69.
5. M. Simonius, Phys.Rev.Lett. 40 (1978) 980.
6. W.H. Zurek, Phys.Rev. D24 (1981) 1516 and D26 (1982) 1862.
7. E. Joos, Phys.Rev. D29 (1984) 1626.
8. E. Joos and H.D. Zeh, Zeit.für Physik B59 (1985) 223.
9. J.B. Hartle, in Quantum Cosmology and Baby Universes, S. Coleman, J.B. Hartle, T. Piran and S. Weinberg editors (Proc. Jerusalem Winter School for Theoretical Physics, Xmas 1989), World Scientific Pub., Singapore (1991), pp. 67-158.
10. E. Joos, Phys.Lett. A116 (1986) 6.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100

DATE

FILMED

4/29/94

END