Does the superfluid part of a supersolid, superfluid, or superconducting body have, of itself, "inertia?"

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ABSTRACT.

The contention discussed here, is that one might be able to get around the puzzle contained in the results of Kim and Chan:— That a quantity of inertial mass is *effectively* lost, (a so called non-classical-rotational-inertia NCRI,) but that being a "supersolid" there is no path for the normal fraction to slip past the 1 – 2 % supersolid fraction, which (it is supposed) remains stationary within the annulus.

As a solution we argue that the *effective* loss of inertial mass might be a *real* loss of inertial mass– that it might be *intrinsic* to a supersolid or superfluid "pool," (a portion which has gone supersolid or superfluid.) In this way the puzzle would be resolved because the normal part and the supersolid part do not need to slip past each other in order to produce the experimental results.

This Essai explores some consequences of a previous writing [1]. In that writing it was argued one could not define, (either in principle or in practice,) the inertial frame of the superfluid part of a superfluid or superconductor.

An inertial frame <u>has</u> to be based on something in the real world— i.e., matter or an experiment. Nothing exists "in-itself," —only in relation to something else [2]. The question we will ask here is; does, in the context described, an inertial frame exist? The answer will be "yes" for the normal and quasi-normal part, "no" for the superfluid part. This will be our hypothesis [1].

To help fix our ideas, let us think of a piece of matter moving uniformly, relative to the fixed stars, say, to the right. If I were moving with that matter it would appear stationary to me. If I were inside a room, (also moving with the matter,) I would assume the matter, myself and the room were all stationary. That would be an "inertial frame;" the matter would have inertia if I pushed it.

In the aforementioned writing this was taken a step further;— it was argued that inside a quantum object (a superconductor) it was impossible to define an "inertial frame" simply because you did not know where the matter was, or how it was moving.— Recall an Einstein Podolsky Rosen (EPR) experiment, with entangled photons where they, or their *properties*, are at both places at once or transiting between preparation and measurement [3]. In other words definitions based on real world things might break down for the superconducting part, the macroscopic QM aspect, of a superconductor.

This was argued to be consistent with the macroscopic electrodynamics of a superconductor (the Londons equations) [1]. Of course, if you cannot define an inertial frame, then you also cannot define a "clock period," according to Relativity Theory. This interesting point is not discussed further here.

Of crucial importance, in understanding what follows, is the notion of the "two fluid model" [4]. On cooling below the transition temperature, two fluids are thought to emerge. A normal fluid or quasi-normal fluid, —(normal part) and a pure superfluid,— (superfluid part.) Collectively they are *loosely* called a "superfluid." The superfluid part is not really a "fluid."

Incidentally, it has been argued elsewhere [5], that both superconductivity and the Josephson effect are manifestations not of physical transport, but of <quantum nonseparability> i.e., The Lorentz and CPT invariant <telegraphing of amplitudes>. [6]. In this way the Josephson effect is likened to an EPR pair tied in the barrier. As noted by Costa de Beauregard and Lochak an "evanescent wave" [7] (of order coherence length) can be thought upon as that which ties together a Josephson junction in a "time-like separated EPR pair."

1 The experiments of Kim & Chan and Hess & Fairbank.

Recent experiments by Kim and Chan [8], along similar lines to older investigations by Hess and Fairbank [9], have evidenced an "effective" loss of inertial mass, (a so called non-classical-rotational-inertia, NCRI,) on cooling liquid (or solid) helium below the transition temperature [10].

A schematic of the Kim and Chan or Hess and Fairbank experiment is shown in Fig. 1. A hollow annulus containing liquid (or solid) helium is suspended from a torsion wire, and made to rotate to and fro. The speed of this to-ing and fro-ing is dependent on the inertial mass of the liquid (or solid) helium contained within. A loss corresponding to a hastening, a gain to a slowing.

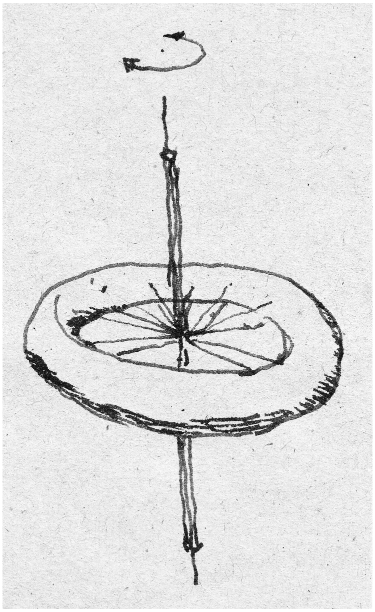

Fig. 1.

Setting aside any interpretations as to what may or may not be happening inside the annulus, the fact remains, that a quantity of inertial mass (previously present) has vanished.

The maximum speed of the to-ing and fro-ing ω should be kept below the critical speed ω_c above which vortices are thought to enter the superfluid. This is in analogy with the lower critical field H_{c1} of superconductors. Above this critical magnetic field H_{c1}, vortices (flux lines) enter the SC matter [9].

We shall now illustrate two different ways of looking at the experimental results. That is, two different interpretations. One we shall call "quasi classical thinking," the other we shall call "new thinking." These are shown schematically (superfluid & normal parts are depicted *logically* separated) in Fig. 2 and 3 respectively.

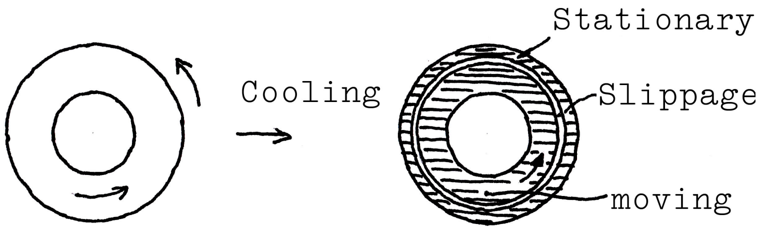

Fig. 2. "Quasi-classical thinking."

In the quasi classical thinking, it is as if some of the superfluid /supersolid inside the annulus has decoupled from the moving walls [11]. There is a natural tendency to think of the superfluid /supersolid part as a substance of the same kind as the normal part,— still a "fluid /solid," but with a vanishingly small viscosity;— the normal part slips past the superfluid part which can remain stationary within the annulus.

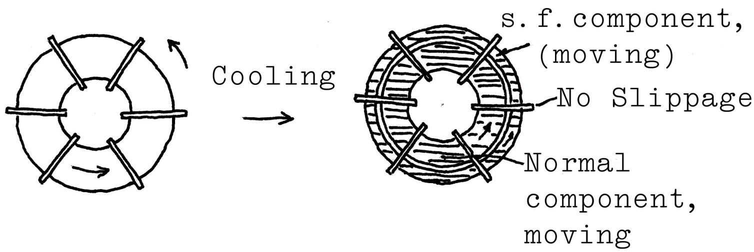

Fig. 3. "New thinking."

As shown in Fig. 3, the superfluid /supersolid is confined in such a way that the superfluid /supersolid part cannot slip past the normal part, as is the case in the quasi-classical view (fig. 2). We shall call this arrangement the "superfluid pools experiment."

In the new thinking, the loss of inertial mass is *intrinsic* to a superfluid pool, and not due to the particular way in which it is measured

[12,13].

A form of the "superfluid pools" experiment seems to have been performed in the paper of Kim and Chan in their so called "control experiment" with a blocked annulus. Here, the inertial mass appears to have vanished even with the blocked annulus. However, as Kim and Chan note, there are a number of possibilities for this, including, for example, a small gap may have been left in the blockage wall.

2 Superfluid pools experiment

A crucial experimental test of the "new thinking" is simply to confine the superfluid or supersolid to pools around the annulus, as shown in Fig. 3, and repeat the NCRI experiment of Kim and Chan or Hess and Fairbank.

If again the inertial mass vanishes [14], this will indicate an *intrinsic* loss of inertial mass, illustrated schematically in Fig. 4.

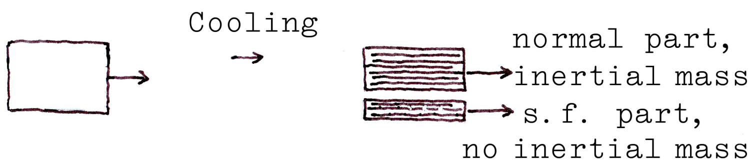

Fig. 4. "Intrinsic" loss of inertial mass for sf. part.

3 Superfluid weight experiment.

If the loss of inertial mass (NCRI) is *real* or *intrinsic* to a supersolid /superfluid "pool" rather than effective or a consequence of the particular way of measuring it, then, from the principle of equivalence between inertial and gravitational mass ($m_i = m_g$), one would expect to see a weight loss on cooling a cup of liquid (or solid) helium below the superfluid transition

Decoherence may hamper this effect, (if it exists.) If it does exist, it should show up wherever the loss of inertial mass is evidenced— for example in the Hess and Fairbank or Kim and Chan experiments

This loss would be proportional to the superfluid (or supersolid) fraction n_s, of the two fluid model $n = n_s + n_n$. In the experiments of Kim and Chan it was estimated that around 1–2% became the supersolid fraction. For a cup of liquid (or solid) Helium weighing 13 grammes, with 1–2% becoming the superfluid fraction, we might expect a weight loss of order 0.1 grams.

The suggestions here are of very tentative nature. We do not think it inconceivable, however, that a weight loss, for say a thin film Josephson junction or a cup of superfluid or supersolid helium has hitherto been overlooked.

The considerations below are for a charged superfluid— that is a superconducting body. It will be argued below that some key properties of superconductor can be traced back to the hypothesis of the difficulty of defining the inertial frame for the superconducting part.

4 Superconductivity in a Minkowskian "Welt."

The laws of Euclidean geometry are "invariant" with respect to orientations, (in general linear orthogonal transformations,) of the system:

$$ds^2 = dx_1^2 + dx_2^2 + dx_3^2 \tag{1}$$

Similarly, the laws of Physical Philosophy are invariant with respect to the orientations of the system [15]:

$$ds^2 = dx_1^2 + dx_2^2 + dx_3^2 + dx_4^2 \quad \text{with} \quad x_4 = \sqrt{-1}\, ct \tag{2}$$

Why must this be so? Imagine one is looking over one's shoulder speeding away at velocity v from a fixed reference frame— say a laboratory performing an experiment. Then it is obvious that your view of that experiment must coincide with the account of the experiment given by the people located in the fixed laboratory frame. It can be argued, therefore, that Relativity theory is, at root, inter-subjective. It has intersubjectivity [16] at its core;— the moving and stationary observer must agree on the observed reality.

Recall:

$$ds^2 = dx_1^2 + dx_2^2 + dx_3^2 + dx_4^2$$

This is a Euclidean geometry of 4-dimensions, or more correctly a "statics" in four dimensional Euclidean continuum [15].

Each "static" orientation of these co-ordinates corresponds to a velocity (of an inertial frame.)

Such an orientation can be represented schematically as shown below in the Minkowski diagram [17].

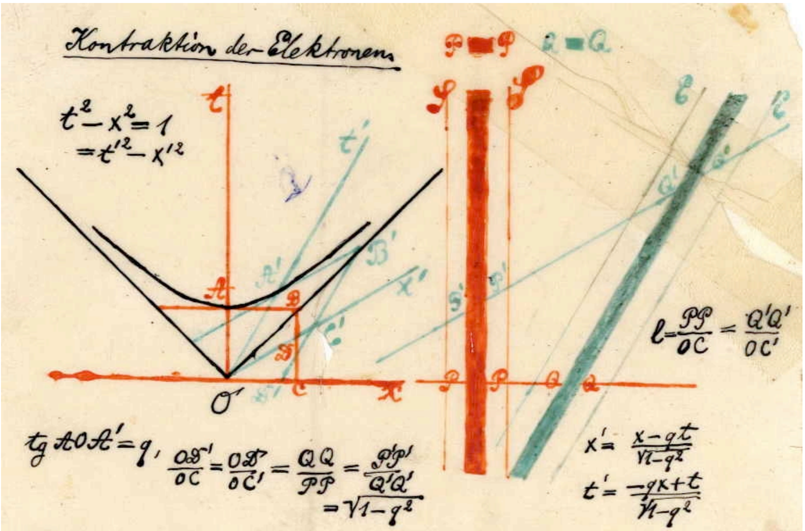

Fig. 5.

Here x', t' represent a static orientation in 4-dimensional space time. This is a dynamic representation in 3 dimensional space— a velocity v.

Rotations from one static orientation to another would then represent changes in velocity in ordinary 3 dimensional space and time— that is accelerations.

Neither velocity nor acceleration can be defined for the superfluid part, since the inertial reference frame, (and so the orientation of the 4-co-ordinate system,) cannot, in principle or in practice, be determined.

A magnetic field exists where there is 1) (charged) matter and 2) a fixed inertial frame.

An electric field exists where there is 1) (charged) matter and 2) a fixed inertial frame.

Both the magnetic field and the electric field are properties of (charged) matter. They are also properties of a fixed inertial frame. If one removes the latter, in that we can no longer define a fixed inertial frame, (either in practice or in principle,) then one might expect this property—the magnetoelectric field— to disappear from the interior of a superconductor.

This is the Meissner-Ochsenfeld effect and the $E = 0$ effect.

This hypothesis, by extension, becomes a powerful predictive rule-of-thumb. The concept of a "force" is associated with acceleration. Once again, because of the impossibility of defining a fixed inertial frame for the superfluid part, we expect the force concept to be absent.

The concept of "force" is very closely related to that of "rigidity."

This ties in with an interesting remark made by Anderson in a discussion of the results of Kim and Chan: that "rigidity seems to be an emergent phenomenon of the classical limit" [18].

5 Discussion of— "the photon becomes massive."

It is not clear, experimentally at least, whether a *fieldless* electric or magnetic potential $(V, \mathbf{A})$ can exist in the interior of a SC body. However, the above arguments do suggest, like the fields, the potentials should be absent from the interior.

The vector potential $\mathbf{A}$ can remain at the perimeter as a screening current $m\mathbf{v} = -e\mathbf{A}$. In regions of this perimeter— (so called penetration depth λ,) the inertial frame can be defined, and hence $\mathbf{A}$ and V can here exist.

That "the photon becomes massive" is sometimes cited as the reason for the Meissner-Ochsenfeld effect i.e., The photon $\mathbf{A} \rightarrow m\mathbf{v} + e\mathbf{A}(= 0)$ at the perimeter. This is "true," however it can be framed in a converse way, namely that the "superconducting matter at the perimeter becomes massive," on coupling with the electromagnetic field i.e., $m = 0 \rightarrow m$, and so again we have $m\mathbf{v} + e\mathbf{A} = 0$. Higgs [19,20] deduced the following equations from a Lagrangian L along the lines of a similar Goldstone "massless" model, by treating real scalar fields $\Delta\varphi_1, \Delta\varphi_2$, and real vector field A_μ as small quantities.

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0 \tag{3}$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0 \tag{4}$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} \tag{5}$$

The important point here appears to be the appearance of 4- vectors, in particular the electromagnetic potential A_μ, now coupled with the scalar fields. That is— the terms inside the curly brackets in (3) & (5). For example, compare (as Higgs does) equation (5) with

$$\partial_l H^{kl} = j^k \tag{6}$$

where H^{kl} is the magnetoelectric field, the equation of conserved current. The term on the right had side is definitely a 4 vector. In the absence of a vector potential A_μ coupling, equations (3) and (5) describe a situation of zero mass scalar and vector bosons respectively [19].

So there seems to be a connection between the emergence of relativistic covariance, in this case the appearance of the 4- potential A^i into the description, and mass– that is inertia and weight.

* *

What one is asking people to believe is that a toy train pulling a series of carriages around a track, with one carriage full of *would be* supersolid, superfluid, or superconducting matter, speeds up on cooling below the transition temperature, —(just as the annulus does in the Kim and Chan experiment.)

This is because, as questions of simultaneity (time ordering) in Special Relativity, collapse for the superfluid part, (as they certainly do for EPR experiments,) then so does the property of inertia. In other words inertia, like simultaneity, can be thought of as a "perspective" effect, and disappears when the possible modes of perception (reference frames) become indistinguishable from one another.

Scholium

Retro-causality, and by necessity from the framework of Special Relativity (SR), advanced causality, are aspects of EPR correlations. Insensitivity to the distances, motions (velocities), and timings of the preparing and measuring apparatus, by SR, also follows. This is formalised concisely as the Lorentz and CPT invariance of EPR correlations. So much, has been established in fact [21].

Geometrical reversal $\Pi\Theta$ of all four space-time (or momentum-energy) axes, is the $\Pi\Theta = CPT = 1$ scheme, where C is "particle-antiparticle exchange," and PT "covariant motion reversal" [22].

Prop. I. Theor. I.

The superfluid part of a supersolid, superfluid, or superconducting body is a substance, which, like an EPR substance, is time symmetric.

Meaning, in particular, that it is Lorentz and CPT invariant. For such a substance, I say, that its inertia, or "force of inactivity" vanishes, by the arguments hitherto given.

Prop. II. Theor. II.

By the same token, it follows straight away from the principle of equivalence between inertial and gravitational mass, that the perspective effect of being accelerated in a gravitational field also vanishes. That is— weight is lost in proportion to the fraction of the substance which can be said to be of the pure superfluid part.

A more instructive demonstration can be given as follows:—

Consider:

$$\frac{d^2 x_\tau}{dt^2} = -\frac{1}{2}\frac{\partial g_{44}}{\partial x_\tau} \quad (\tau = 1, 2, 3) \tag{7}$$

the equation of motion of a material point, as a first approximation, according to Newton's theory [23], where the g_{44} are the forth or "temporal" components of the metrical tensor g_{uv} and differ from 1 only by small magnitudes (as compared to 1.) $g_{44}/2$ plays the part of the gravitational potential.

Mathematically speaking, our above considerations can be represented by the g_{44} "flicking" or "transiting" between g_{44} and $-g_{44}$. That is— between a full reflection of the space-time coordinates.

So, we would have, instead of (7):

$$\frac{d^2 x_\tau}{dt^2} = -\left\{\frac{1}{2}\frac{\partial g_{44}}{\partial x_\tau} + \frac{1}{2}\frac{\partial - g_{44}}{\partial x_\tau}\right\} = 0 \tag{8}$$

This is the equation of motion for the superfluid part. It illustrates that a time-symmetric substance— an EPR-like substance, being Lorentz and CPT invariant, does not, in the first approximation, suffer acceleration in a gravitational field.

6 Conclusion

We do not consider it experimentally proven, especially considering the puzzling results of Kim and Chan, (& Hess and Fairbank,) that the superfluid /supersolid part or the superconducting part, has, of itself, "inertia."

The hypothesis of the experimental inaccessibility, (both in principle and in practice,) of determining the inertial frame, seems to have produced some physical results. Among them appear to be the Meissner-Ochsenfeld effect and the $E = 0$ effect, possibly the loss of the inertia principle, and possibly also, (from the Einstein inertia-gravity equivalence,) the question of a loss of gravitational mass.

Lastly, at the risk of supererogation, we note a remarkable and singular passage in Poe's "An Essay on the Material and Spiritual Universe" [24]. Poe appears to have grasped *à priori* what we have adduced *à posteriori*:— "Now the very definition of Attraction implies particularity– the existence of parts, particles, or atoms; for we define it as the tendency of 'each atom &c. to every other atom' &c. according to a certain law. Of course where there are *no* parts– where there is absolute Unity– where the tendency to oneness is satisfied– there can be no Attraction:– this has been fully shown, and all Philosophy admits it."

The idea for this MS. presented itself during a conversation with H. Stoelum. The latter portion was prompted by a conversation with A. Betteridge.

In thanking H. Stoelum and A. Betteridge I extend my gratitude to G. Lochak without whose interest and kind encouragement this essai would never have been completed.

References

[1] G. Stephens, Found. Phys. Lett. **9**, 145 (1996)

[2] F. Nietzsche, The Will to Power, Vintage books, NY, (1968), p302, no. 577 (1885-1886):

The properties of a thing are effects on other "things":
if one removes other "things," then a thing has no properties,
i.e., there is no thing without other things,
i.e., there is no "thing-in-itself."

[3] O. Costa de Beauregard, Phys. Rev. Letters **50**, 867 (1983); Lettere al Nuovo Cimento **31**, 43 (1981). Costa de Beauregard hints at non-operation of a reference frame when considering EPR correlations:— "I prefer using a wording which is completely frame-of-reference free, and stresses the two quite obvious mathematical symmetries of retarded and advanced causality $D_R \rightarrow \ \leftarrow D_A$ and of positive and negative energies $D_+ \rightarrow \ \leftarrow D_-$." See also Lettere Al Nuovo Cimento **26**, 135 (1979) by the same author.

[4] F. London, Nature. **141**, 643 (1938); L. Tisza, Nature. **141**, 913 (1938)

[5] G. Stephens, Ann. Fond. Louis de Broglie. **25**, 27 (2000):–

The experiment sketched here involves the entanglement of two Josephson junctions, followed by their subsequent *physical separation*. Phase locking, of a quantum nonseparability nature, rather than electrodynamic, is looked for between two physically separated Josephson junctions. A Josephson junction (singular) can be thought of, with a few caveats, as a solid state version of the timelike EPR correlation experiment elaborated here: *Proposed Einstein Correlation experiment with Timelike separation of detections*. O. Costa de Beauregard, Lettere Al Nuovo Cimento. **25**, 91 (1979).

[6] O. Costa de Beauregard (private communication) (1997)

[7] O. Costa de Beauregard and G. Lochak, Ann. Fond. Louis de Broglie. **25**, 303 (2000)

[8] E. Kim and M. H. W. Chan, Science. **305**, 1941 (2004)

[9] G. B. Hess and W. M. Fairbank, Phys. Rev. Lett. **19**, 216 (1967)

[10] NCRI is a term coined by A. Leggett.

[11] Balibar describes it thus:— "as if some of the mass inside the box had decoupled from the moving walls." This careful description could apply either to the "quasi-classical thinking" or to the "new thinking," depending on how you interpret "decoupled."— S. Balibar, Physics. **1**, 16 (2008).

[12] The notion of a loss of inertia for matter in which a quantum mechanical description dominates is not new. It was anticipated by de Broglie as early as 1923.— "It is then *necessary* to give up the inertia principle, and we must suppose that any moving body follows always the ray of its 'phase wave' ; its path will then bend by passing through a sufficiently small aperture."— L. de Broglie, Nature. **112**, 540 (1923)

[13] This is analogous to the Meissner-Ochsenfeld effect, which was deemed a consequence of a new thermodynamic phase and happens irrespective of how the experimental situation was reached. i.e., Cooling then applying the magnetic field versus cooling within an already applied magnetic field. (If the latter case had not produced an expulsion of the magnetic flux, (Meissner-Ochsenfeld effect,) then it *might* have been caused by perfect conductivity, instead of a new property of the superconducting state.)

[14] a "superfluid pools" experiment is somewhat reminiscent in character of a Michelson-Morley experiment.

[15] A. Einstein, Nature. **106**, 782 (1921)

[16] "Intersubjectivity" as understood here— O. Costa de Beauregard, Maximum Entropy and Bayesian Methods, A Mohammad-Djafari and G. Demoments eds, Kluwer Academic Publishers (1993), p.9-14

[17] H. Minkowski. Niedersachsische Staats und Universitatsbibliothek, Math. Archiv. 60: 2.

[18] P.W. Anderson, cond-mat/0504731

[19] P.W. Higgs, Phys. Rev. Lett. **16**, 508 (1964)

[20] P.W. Higgs, Comptes Rendus Physique **8**, 970 (2007)

[21] O. Costa de Beauregard, C. R. Acad. Sci (Paris) 236, 1632 (1953). Nuovo Cimento B**42**, 41 (1977); **51**, 267 (1979). "Causality as identified with conditional probability and the quantal nonseparability," in Microphysical Reality and Quantum Formalism, F. Selleri, G. Tarozzi, and A van der Merwe, eds. (Reidel, Dordrecht, 1987); Found. Phys Letters **5**, 489 (1992). Distance independence has been tested by A. R. Wilson, J. Lowe, and D. K. Butt, J.Phys. G**2**, 613 (1976); M. Bruno, M. d'Agostino, and C. Maroni, Nuovo Cimento B**40**, 142 (1977); A. Aspect, P. Grangier, and G. Roger, Phys.Rev.Lett **47**, 460 (1981). Timing of twin measurements has been tested by A. Aspect, J. Dalibard, G. Roger. Phys Rev Lett 49, 1804 (1982); H. Zbinden, J Brendel, N Gisin, W. Tittel, Phys. Rev. A63, 022111 (2001). Independence of motion of the detectors has been tested by A. Stefanov, H. Zbinden, and N. Gisin, Phys. Rev. Lett. 88, 120404 (2002).

[22] Costa de Beauregard, Found. Phys. **17**, 775 (1987) p779

[23] A. Einstein, Annalen der Physik 4, 49, (1916)

[24] E. A. Poe, EUREKA: A PROSE POEM. Geo P Putnam, NY, (1848) p138

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