Interferometric evidence for brane world cosmologies

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The hypothesis of brane-embedded matter appears to gain increasing credibility in astrophysics. However, it can only be truly successful if its implications on particle interaction are consistent with existing knowledge. This letter focuses on the issue of optical interference, and shows that at least one brane-world model can offer plausible interpretations for both Young's double-slit experiment, and the experiments that fit less neatly with it. The basic assumption is that particles can interact at a distance through the vibrations induced by their motion on the brane. The qualitative analysis of this mechanism suggests that fringe visibility in single photon interference depends on the energy levels and the interval between interacting particles. A double-slit experiment, performed with coherent single red photons should reveal the disappearance of interference when the time delay between individual particles is increased over 2.18 seconds. In the case of infrared photons with the frequency of $9 \cdot 10^{13} Hz$, interference must vanish already at the interval of one second.

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Analyses of recent galaxy clustering data and CMB measurements demand special explanations for the apparent flatness of the Universe, as well as for its accelerated expansion. Initial attempts to provide a simple answer in terms of vacuum energy ran into well-known theoretical difficulties. Quantum field theories yielded unrealistic values for the cosmological constant [1, 2], while various solutions to the problem required additional explanatory variables. In contrast, many of the most recent brane world cosmologies are offering explanations that appear to be both theoretically promising and empirically testable. Most of these involve scenarios with matter localized on flat domain walls (3-branes), embedded in higher dimensional bulk space-times. Following the successful general formulation of Randall and Sundrum [3, 4], brane-world cosmologies were applied to many problems, including the cosmological constant [5], cosmological phase-transitions [6], inflation [7, 8], baryogenesis [9]. Consistency with cosmological observations has also been suggested [10, 11]. It should be also noted, however, that the idea of matter localized on a brane cannot be entirely satisfactory theoretically, unless it is also shown to have plausible implications for small scale phenomena. (How can it be essential for large scale dynamics, and absent on smaller scales?). In other words, it must also have quantum-level implications that would be consistent with existing interpretations in terms of non-classic principles, such as non-locality, uncertainty, complementarity. However, if it were indeed possible to show that a brane model could offer a full explanation of particle interactions, then those mentioned principles would become redundant. The purpose of this letter is to show that at least one such model is possible, and that its implications can be verified with optical interferometric equipment.

Few other tests in physics are as conceptually important as the double-slit experiment. Because it reveals so clearly the non-classical properties of matter, it is one of the cornerstones of quantum mechanics. The essence of the mystery of double-slit interferometry is that individual photons are emitted and detected as particles, yet they seem to pass through the two slits as waves (non-locality). Any attempt to detect the trajectory of photons destroys the interference fringes on the detecting screen. This is the basis for the conclusion that which-path information and fringe visibility are complementary, just like the information about momentum and position of particles [12, 13]. The evidence in favor of this interpretation is almost overwhelming, and does not need to be listed here. Nevertheless, there are two special cases that do not exactly fit into the mainstream picture. For reasons that will become obvious later on, these exceptions need to be presented here in brief.

One of these odd cases is the interference of particles emitted by independent sources [14]. Just like in the double-slit experiment, photons produced by independent sources produce interference fringes, even when only one of them is present in the system at the same time. This phenomenon was initially demonstrated by Pfleegor and Mandel in the 1960's [15], and conclusively confirmed by Hariharan *et al.* in 1993 [16]. The problem with this phenomenon is that it provides partial which-path information without destroying interference. Initially, an interlocking mechanism between the two sources was assumed, in the attempt to suggest that which-path information would still be unavailable. Subsequent experiments with optically isolated photon sources ruled out this interpretation [17]. However, even if quantum processes washed which-path information away, the fact remains that each photon was only emitted by one source. This clearly shows that individual photons do not need to go through more than one slit at the same time in order to produce interference. Moreover, the fringes were only present when at least two sources were active. This opens up the possibility that photons might not interfere with themselves, as commonly assumed. They could also affect the trajectory of subsequent particles through some hidden mechanism.

The other odd case, related to single-photon interference, refers to the possibility that interference might disappear entirely at extremely low emission rates of photons. It was reported in the 1960's by Dontsov and Baz [18], who obtained reliable evidence in favor of this effect, but had no means to detect its parameters with high precision. This experiment is in clear contradiction with existing theories and seems to stand alone in its field. However, the hypothesis of delayed interaction between photons, suggested in the previous paragraph, also requires the disappearance of interference beyond a certain interval between individual particles. So, either the hypothesis is wrong, or there is something special about the suggested hidden variable that might explain with greater success these findings. Thus, we need a model that could explain not only the classical double-slit experiment, but also its "anomalies". In light of the above, the most straightforward way to conceive of such a model is by assuming that the brane itself is the hidden variable.

Recall that the turning point in the development of brane-world cosmologies was the realization that a 3-dimensional domain wall could be embedded in a bulk with extra non-compactified dimensions [3,4]. But the same reasoning can be applied to a lower level: one dimensional infinite strings with perfect elasticity could be embedded in the domain wall. Accordingly, longitudinal waves propagating on the strings would be expected to leak into the domain wall at a rate that is inversely related to the distance of propagation, while transverse waves would leak according to the inverse square law. The entire brane (actually, a superstructure of such strings) would have to be precisely tuned, so that both s-waves and p-waves would propagate at the speed of light. Correspondingly, particles of matter would be moving through the brane by exciting an infinite number of strings. The collective effect of such excitations would amount to the production of fields that are capable to affect other particles on the same brane. (This provides an alternative to virtual particles).

In conformity with such a model, the elastic collisions of particles and their remote interactions are assumed to be mediated by the oscillating brane. The photons (assumed here to be particles) represent a special case, because they usually appear to produce no forces. This can be explained through the following considerations. First, photons travel in space at the speed of light, which is also the speed of wave propagation in the brane. Hence, their effect on the brane cannot precede them. Second, they must produce equal amounts of symmetric waves in the plane that is perpendicular to their direction of motion. Thus, photons can be neutral, while still having a real effect on the brane. Third, their effect in reverse must correspond to that of a very narrow electrostatic beam, but it should be extremely weak, because of the Doppler effect. Moreover, this force has to decay as it propagates, according to the inverse square law. Consequently, the spatial effect of photons must be temporary, and it can only be effective in deflecting the trajectory of other photons that cross their trails. When the trajectory of a photon is significantly bent under the influence of an external force, its lateral neutrality must be disrupted. Consequently, photons can produce other forces in special environments, as detected e.g. in the case of the photoelectric effect.

Despite the qualitative nature of this description, it can be used to make estimates of the maximum duration of the stipulated delayed photonic effects. Essentially, we need to calculate the distance (r) travelled by a transverse wave on a string, until enough of its energy leaks into the brane to disable its effect on other photons. Dividing this distance by the speed of propagation, we could get an idea about the amount of time that it takes for these photonic trails to fade away (r/c=t). Under the assumption that particles always interact through brane waves, the known energy of photons ($E_{max} = h\nu$) must be equal to their maximum effect on the spatial strings. Moreover, the impact of photons on strings must have a constant increment value during chosen units of time. This basic unit of action must be equal to h. Hence, the total energy of the photon comes from the cumulative number of such interactions. This also means that a string will always be able to deflect the trajectory of a photon if its own vibrations have an action potential comparable to h. Yet, when the waves on a string have already decayed to $E' = \nu' h$, with $\nu' = 10^{-3} Hz$, the deflection of the weakest photon cannot exceed 0.06 degrees (small enough to eliminate interference build-up in most experimental settings). Thus, the value of r corresponds to the distance travelled by a string wave until its energy E_{max} decays to E'. ($r_0^2 E_{max} = r^2 E'$, where r_0 is the unit of distance corresponding to the system of units used to measure E). The equation for the corresponding time simplifies to $t = r_0 \sqrt{\nu} / c\sqrt{\nu'}$.

This conclusion enables us to calculate the maximum time delay between individual coherent photons of known frequency, at which interference fringes might still be visible. For the red photons (the most widely used in interferometric experiments), $t = 2.18$ seconds. Other visible colors can produce interference at even larger intervals. At the same time, infrared photons with $\nu = 9 \cdot 10^{13} Hz$ must loose their fringe visibility at $t = 1$ second. Hence, it is only normal for the double slit experiment (and for settings with independently emitted coherent photons) to produce interference fringes, even when just one particle passes through the system at the same time, provided the gap (t) is below its critical values.

Consider the following experimental setting. A strong coherent red laser beam is divided into two jets with a beam splitter. The jets are focused with two mirrors in front of a screen, producing interference fringes visible to the naked eye. A disc, connected to a source of angular motion, is placed in front of the focal point such as to cut off both jets. The disc has just one small hole close to its edge, and is calibrated such as to open the access to the screen of only one jet at a time, when it is spinning. In other words, this is an alternator switch, whose frequency can be adjusted by controlling its angular velocity. When the disc has a very small velocity (less than one revolution per minute), there can be no interference. However, at very high velocities the interference fringes should reappear on the screen, just like in all the other experiments with independent sources. At this point, two video cameras are introduced into the lab. One is used to film the switch; the other is focused on the screen. The two recordings must later be compared frame by frame, in order to link every interference image to its beam, and every blank screen to intermediate states. As a result, the experimenter acquires complete which-path information without destroying interference. The next step is to test the correlation between energy levels and maximum gap admissible for interference. This can be achieved by gradually accelerating the alternator, until the moment of qualitative shift is identified. Note that this moment does not have to correspond to the presence of sharp fringes on the screen. Any sign of interference works for the proposed interpretation. The experiment can be repeated with monochromatic lasers of different colors, in order to verify the suggested variation of maximum gap values with changes of ν.

The same findings can also be verified for non-classical states of light, even though at higher expense. A classical Young setting is all that is necessary, but a deterministic source of single photons is preferable. (The development of such sources was first announced in 2000 [19–21], but many others have been reported since). The idea is to perform the double-slit experiment at very large intervals between individual coherent photons (beyond two seconds), in order to verify the equation for t. It is quite difficult to obtain good fringe visibility at such gaps, given the drift problem. However, as specified above, high image quality is not required in this case. Any sign of interference beyond the specified values of t would falsify the theory. However, if the first experiment proposed above turns out to be successful, such falsification becomes highly unlikely.

As a final note, these two experiments should not be perceived as contradictory to existing scientific data, because they are based on non-invasive methods of path detection. Traditionally, which-path information is obtained with filters or detectors, both of which affect the spatio-temporal properties of photons. In other words, these techniques have a real (negative) impact on coherence. It is a well-established fact that coherence is a necessary condition for interference. Therefore, previous experiments are not reliable as tests of locality and/or realism.

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[1] S. Weinberg, Rev. Mod. Phys. **61**, 1 (1989).
[2] V. Sahni and A. Starobinsky, Int. J. Mod. Phys. **D9**, 373 (2000).
[3] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999).
[4] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 4690 (1999).
[5] S.-H. H. Tye and I. Wasserman, Phys. Rev. Lett. **86**, 1682 (2001).
[6] S. C. Davis, W. B. Perkins, A. Davis, and I. R. Vernon, Phys. Rev. **D63**, 083518 (2001).
[7] G. Dvali and S.-H. H. Tye, Phys. Lett. **B450**, 72 (1999).
[8] J. Khoury, P. J. Steinhardt, and D. Waldram, Phys. Rev. **D63**, 103505 (2001).
[9] G. Dvali and G. Gabadadze, Phys. Lett. **B460**, 47 (1999).
[10] C. Deffayet et al., astro-ph/0201164.
[11] J. S. Alcaniz, astro-ph/0202492.
[12] P. D. D. Schwindt, P. G. Kwiat, and B.-G. Englert, quant-ph/9908072.
[13] A. Trifonov, G. Björk, J. Söderholm, and T. Tsegaye, quant-ph/0009097.
[14] H. Paul, Rev. Mod. Phys. **58**, 209 (1986).
[15] R. L. Pfleegor and L. Mandel, J. Opt. Soc. Am. **58**, 946 (1968).
[16] P. Hariharan, N. Brown, and B. C. Sanders, J. Mod. Optics **40**, 113 (1993).
[17] L. Basano and P. Ottonello, Am. J. Phys. **68**, 245 (2000).
[18] Y. P. Dontsov and A. I. Baz, Sov. Phys. – JETP **25**, 1 (1967).
[19] P. Michler et al., Science **290**, 2282 (2000).
[20] C. Santori et al., Phys. Rev. Lett. **86**, 1502 (2001).
[21] B. Lounis and W. E. Moerner, Nature **407**, 491 (2000).