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■ RESEARCH ARTICLE

Discussions About Some Assumptions on Quantum Gravity-induced Entanglement of Masses

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ABSTRACT: Finding quantum characteristics in gravity has interested physicists for many decades. While there has been significant progress on the theoretical side, the experimental side still needs to yield sufficient evidence to prove the quantum nature of gravity. Therefore, the Bose *et al.*-Marletto-Vedral (BMV) experiment is proposed to resolve this problem. This paper analyzes two variations from the experiment that introduce the following changes: 1) linear increase in distance between masses and 2) significant time length for splitting and recombining. These variables affect the wave function by influencing the phases picked up during evolution and thus produce effects on the quantum witness. Nonetheless, despite these impacts, the entanglement between masses is reduced but not destroyed. At the end of this paper, the meaning of witnessing entanglement in the BMV experiment is discussed. Although proving the non-classicality of gravity does not guarantee the quantum nature of gravity, the experiment is sufficient to rule out classical gravity in the research of the nature of gravity.

KEYWORDS: Physics and Astronomy; Quantum Physics; Quantum Gravity; Gravity-induced Entanglement; Bose *et al.*-Marletto-Vedral Experiment.

Introduction

As the development of quantum theory has worked successfully with most interactions in nature, gravity has not been quantized, and no evidence of quantum gravity exists.[1] The classicality of gravity, nevertheless, is not certain.[2] On the other hand, there are strong reasons, including unification, the need for a quantum theory to understand the universe and black holes, and conflicts in the interpretations of time from quantum theory and general relativity, emphasizing the need for quantum gravity.[1] This then leads to the importance of quantizing gravity, whose studies could date back to around 1930. Towards the end of the last century, many theories have been constructed, such as loop and string theories.[3-5] Yet they can only be proved to be correct through compelling experimental evidence. The lack of such evidence keeps the study theoretical, awaiting a definite answer from the experimental side of the work of quantizing gravity.[6]

To respond to this need for experimental work, numerous directions of experiments were pointed out over the past few decades, and many experimental proposals were put forward. Gravitational vacuum fluctuations are an example of these proposals on which some studies are carried out,[7] while some other scientists are investigating the detection of gravitons.[8] However, to this day, these proposals cannot be implemented to give the answer we have been seeking, with technical challenges being one of the leading causes. Among the proposals, one is expected to be carried out in the foreseeable future: a test proposal introduced by Bose *et al.*[9] and Marletto and Vedral,[10] the Bose *et al.*-Marletto-Vedral effect (BMV effect). It has drawn many people's interest, and novel observations are expected to be obtained from realizing the BMV effect. It is considered that this proposal has renewed the aged quantum gravity unification research.[11] The importance of analysis is then shown. Imperfections during the realization of the proposal may impact the experiment's results. The exact meaning of the expected outcome from the BMV effect also requires thorough discussions. Therefore, in this paper, two possible variations of the BMV effect that may result from a few imperfections in the experiment will be studied, as well as the potential impacts of the variations on the outcomes. Also, a review of some supportive and opposing arguments from the discussion on the BMV effect will be presented to analyze the experiment further.

The BMV Effect:

The BMV effect is based on the argument that if a system A interacts with two quantum systems separately, and if the two systems are entangled by the mediator A, A then must be non-classical, as local operations and classical communication cannot create entanglement.[12] So, the main idea of the BMV effect is to observe gravitationally induced entanglement, which could show gravity's non-classicality. This can be achieved by placing two mesoscopic masses with embedded spins, each in a spatial superposition of two quantum states $|L\rangle$ and $|R\rangle$, in adjacent Stern-Gerlach interferometers. If entanglement is achieved between the two masses, then as the only interaction existing is gravitational, and this interaction is assumed to be local, the non-classicality of gravity is proved.[9,10] The process of the interferometry is explained in Figure 1.

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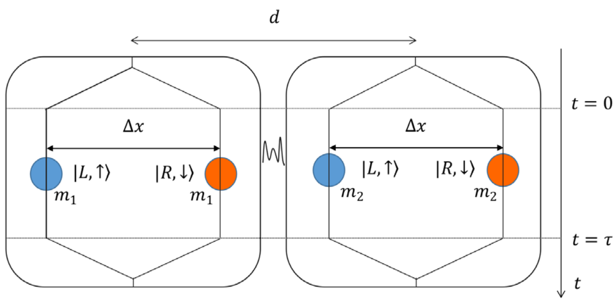

Figure 1: The original BMV setup is shown. There are two mesoscopic masses m_1 and m_2 in adjacent matter-wave interferometers. Their initial states are split according to their spin properties: a spin-up particle is diverted to the left, whereas a spin-down particle is diverted to the right. They are hence held in superposition of states $|L,\uparrow\rangle$ and $|R,\downarrow\rangle$,. L and R represent the location of masses, and ↑ and ↓ represent the spin embedded in the masses. Then each of the masses has state $\frac{1}{\sqrt{2}}(|L,\uparrow\rangle + |R,\downarrow\rangle)$.

As the spatial and spin properties have a constant corresponding relationship, for simplicity purposes, the symbols indicating spin variables ↑ and ↓ are omitted intentionally in the following text. For both masses, the distance between the two states $|L\rangle$ and $|R\rangle$ is Δx. The distance between the centers of superpositions is d.

Therefore, we have the initial wave function as

$$|\Psi(t=0)\rangle = \frac{1}{2}(|L\rangle + |R\rangle)(|L\rangle + |R\rangle) \quad (1)$$

After the superposition is held for a time τ, the states are recombined together to give the final state.

Note that when the states evolve with energy, they pick up a phase. The phases are found through two steps: 1) finding the gravitational energy with formula $E = \frac{Gm_1m_2}{r}$, where G is the gravitational constant, m_1 and m_2 are the masses of the two mesoscopic masses, and r is the distance between the two masses; 2) integration according to formula $\phi = \frac{\int_0^\tau E(t)\,dt}{\hbar}$ to give the value of each phase.

$$\rightarrow|\Psi(t=\tau)\rangle = \frac{e^{i\phi}}{2}\{|L\rangle(|L\rangle + e^{i\Delta\phi_{LR}}|R\rangle) + |R\rangle(e^{i\Delta\phi_{RL}}|L\rangle + |R\rangle)\} \quad (2)$$

where $\Delta\phi_{LR} = \phi_{LR} - \phi$, $\Delta\phi_{RL} = \phi_{RL} - \phi$, and

$$\phi = \frac{Gm_1m_2\tau}{\hbar d}$$

$$\phi_{LR} = \frac{Gm_1m_2\tau}{\hbar(d+\Delta x)} \quad (3)$$

$$\phi_{RL} = \frac{Gm_1m_2\tau}{\hbar(d-\Delta x)}$$

Entanglement can be witnessed when $|\Psi(t=\tau)\rangle$ cannot be written as a product state, which happens when $\Delta\phi_{LR}+\Delta\phi_{LR}\neq 2k\pi$ for some integer k.[10] While in Eq.(1), $|\Psi(t=0)\rangle$is the product of two $(|L\rangle+|R\rangle)$ states, showing that it is not entangled initially.

The fact that no entanglement takes place when $\Delta\phi_{LR}+\Delta\phi_{LR}=2k\pi$ can be proved by showing then $|\Psi(t=\tau)\rangle$ is a product state. Notice that if the phases $\Delta\phi_{RL}$ and $\Delta\phi_{LR}$ sum to a multiple of 2π, $e^{i\Delta\phi LR}$ and $e^{i\Delta\phi LR}$ are conjugates, as $\cos(\Delta\phi_{LR})=\cos(\Delta\phi_{RL})$, and $\sin(\Delta\phi_{LR})=-\sin(\Delta\phi_{RL})$. In other words,

$$e^{i\Delta\phi_{RL}} = cos(\Delta\phi_{LR}) + isin(\Delta\phi_{LR}) = \frac{1}{cos(\Delta\phi_{RL}) - isin(\Delta\phi_{RL})} = \frac{1}{e^{i\Delta\phi_{LR}}} \quad (4)$$

Therefore, through substituting Eq.(4) into $|R\rangle(e^{i\Delta\phi_{RL}}|L\rangle+|R\rangle)$, Eq.(2) can be rewritten as

$$|\Psi(t=\tau)\rangle = \frac{e^{i\phi}}{2}\left\{|L\rangle(|L\rangle + e^{i\Delta\phi_{LR}}|R\rangle) + |R\rangle\left(\frac{|L\rangle + e^{i\Delta\phi_{LR}}|R\rangle}{e^{i\Delta\phi_{LR}}}\right)\right\}$$

$$= \frac{e^{i\phi}}{2}\left\{\left(|L\rangle + \frac{1}{e^{i\Delta\phi_{LR}}}|R\rangle\right)(|L\rangle + e^{i\Delta\phi_{LR}}|R\rangle)\right\}$$

$$= \frac{e^{i\phi}}{2}\{(|L\rangle + e^{i\Delta\phi_{RL}}|R\rangle)(|L\rangle + e^{i\Delta\phi_{LR}}|R\rangle)\} \quad (5)$$

which is a product state, meaning that there is no entanglement created.

For maximum entanglement to happen, the final state needs to have the same amount of entanglement as a Bell state, meaning that $\Delta\phi_{LR}+\Delta\phi_{LR}=\pi$ is needed. To witness this entanglement, the spin correlations in complementary bases are measured to produce W, an operator that gives information about the existence of entanglement, with maximum entanglement giving the value W=2. Developed from the entanglement witness operator given by Bose *et al.*[9], it is defined as

$$\mathcal{W}_{xyz} = |1\otimes 1 + \sigma_x^{(1)}\otimes\sigma_x^{(2)} + \sigma_y^{(1)}\otimes\sigma_y^{(2)} + \sigma_z^{(1)}\otimes\sigma_z^{(2)}| \quad (6)$$

In the representation system of s_z, $\sigma_x = \begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}$, $\sigma_y = \begin{pmatrix}0 & -i\\ i & 0\end{pmatrix}$,

and $\sigma_z = \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$, where 1 and 0 stand for the spins embedded.

For a qubit in state $|\Psi\rangle$, the expected value of the measurement corresponding to W which we refer to as $\langle W\rangle$ is:

$$\langle\mathcal{W}\rangle = \langle\Psi'|\mathcal{W}|\Psi\rangle \quad (7)$$

Variations of the BMV effect:

Looking at a few assumptions made in the setting and performance of the experiment, one can see that imperfections are possible, from which different variations of the experiment can emerge. One example is the fluctuations in the strength of the magnetic field gradient, which bring the fluctuations in the phase of entanglement.[13] Similarly, other imperfections could be found. For instance, the falling routes of the masses are assumed to be equidistant as they fall in straight lines in the same direction, and the evolution time during splitting and recombining is much smaller than the time of constant superposition between them. Therefore, considering these assumptions, two variations are constructed from the BMV effect in this paper: 1) the two masses do not fall in the same direction due to effects of the magnetic field, raising the distance between them linearly along the way; 2) the time taken for the stages of splitting and recombining, which is the time

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before t=0 and after t=τ, is non-negligible, so must be taken into consideration. The two variations are analyzed below, with their settings illustrated and new $|\Psi(t=\tau)\rangle$ states computed. A brief investigation of the changes brought on the phases by the introduced variables is carried out. Some combinations of parameters that could create maximum entanglement are found. Graphs are presented to demonstrate the trends of the parameters as well.

Results and discussion

Linear increase in distance between masses:

Motions of the masses in interferometry may not be as perfect as expected, as the magnetic field may influence the masses by changing the distance between them while they are falling. One that has been studied is the fluctuation in the distance over time.[14] Here, another type of possible change in distance is presented, specifically a constant linear increase in the distance between the two systems. This also may appear in modified versions of experiments. When the systems are not fixed, their relative paths can be considered linear motion with constant velocity. In this case, the interferometry will differ from what is shown in Figure 1. Instead, we have Figure 2.

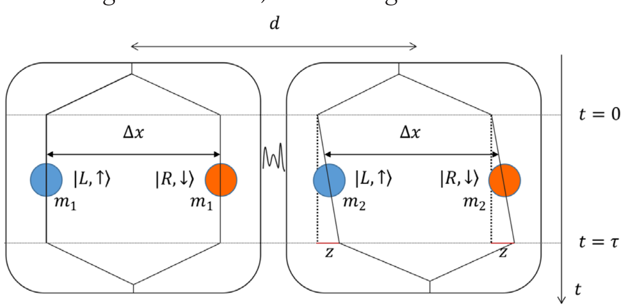

Figure 2: This is the variation one setup, where all apparatus is arranged similarly; only the falling routes of m_2 are modified to have an angle.

As shown in Figure 2, both routes of the superposition for m_2 are at a constant angle from those of the superposition for m_1, causing a horizontal displacement of length z at t=τ. This displacement is illustrated by the red line in Figure 2. A linear function $f(t)$ can be used to capture the change in distance with respect to time using z.

The linear function $f(t)$ is defined as $f(t)=z/\tau\cdot t$. If we let Δx^1 (the index is for identification purposes only) represent the distance between two masses, then we have

$$\Delta x^1_{LL}(t) = \Delta x^1_{RR}(t) = d + f(t) = d + \frac{z}{\tau}\cdot t$$

$$\Delta x^1_{LR}(t) = d + f(t) + \Delta x = d + \frac{z}{\tau}\cdot t + \Delta x \tag{8}$$

$$\Delta x^1_{RL}(t) = d + f(t) - \Delta x = d + \frac{z}{\tau}\cdot t - \Delta x$$

According to the formula of gravitational energy $E=(Gm_1 m_2)/r$, there are

$$E^1_{LL}(t) = E^1_{RR}(t) = \frac{Gm_1m_2}{d + \frac{z}{\tau}\cdot t}$$

$$E^1_{LR}(t) = \frac{Gm_1m_2}{d + \frac{z}{\tau}\cdot t + \Delta x} \tag{9}$$

$$E^1_{RL}(t) = \frac{Gm_1m_2}{d + \frac{z}{\tau}\cdot t - \Delta x}$$

Using $\phi = \frac{\int_0^\tau E(t)\,dt}{\hbar}$, we can find the phases:

$$\phi^1 = \frac{Gm_1m_2\tau[\ln(d+z) - \ln d]}{\hbar\cdot z}$$

$$\phi^1_{LR} = \frac{Gm_1m_2\tau[\ln(d+z+\Delta x) - \ln(d+\Delta x)]}{\hbar\cdot z} \tag{10}$$

$$\phi^1_{RL} = \frac{Gm_1m_2\tau[\ln(d+z-\Delta x) - \ln(d-\Delta x)]}{\hbar\cdot z}$$

Then the final state after a time τ is

$$|\Psi(t=\tau)\rangle = \frac{1}{2}\left(e^{i\phi^1}|LL\rangle + e^{i\phi^1_{LR}}|LR\rangle + e^{i\phi^1_{RL}}|RL\rangle + e^{i\phi^1}|RR\rangle\right)$$

$$= \frac{e^{i\phi^1}}{2}\{|L\rangle(|L\rangle + e^{i\Delta\phi^1_{LR}}|R\rangle) + |R\rangle(e^{i\Delta\phi^1_{RL}}|L\rangle + |R\rangle)\} \tag{11}$$

where $\Delta\phi^1_{LR} = \phi^1_{LR} - \phi^1$, $\Delta\phi^1_{RL} = \phi^1_{RL} - \phi^1$.

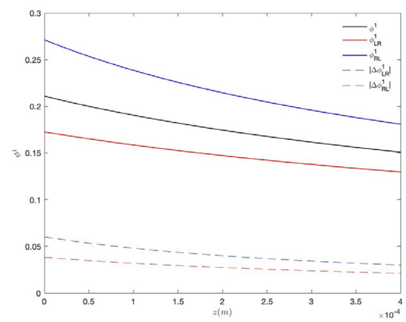

Figure 3: This graph analyses the impact of z, the extra horizontal distance created by the angle of m_2's trajectory, on the phases ϕ^1, ϕ^1_{LR}, ϕ^1_{RL}, $\Delta\phi^1_{LR}$, and $\Delta\phi^1_{RL}$.

The development of the phases with respect to z is shown in Figure 3. The range of z is extended to 4×10^{-4} m to present the general trend more clearly. The values of other parameters are taken according to the orders of magnitude from the original BMV effect setup,[10] and these values are:

$$m_1 = m_2 = 10^{-14}kg,\ \tau = 1.5s,\ d = 4.5\times10^{-4}m, \text{ and } \Delta x = 10^{-4}m \tag{12}$$

All three lines of the phases ϕ^1, ϕ^1_{LR}, and ϕ^1_{RL} have slowly decreasing magnitudes of their gradients, meaning that all three phases have non-linear relationships with z, and that their values fall as z increases. As z approaches 0, the phases reach the initial value in the original BMV effect, with parameters being set as in Eq.(12).

Compared with the original experiment, this final state takes a similar form of Eq.(2), thus it can be proved that for this case, there is always entanglement when $\Delta\phi^1_{LR} + \Delta\phi^1_{RL} \neq 2k\pi$ is not the same state, and maximum entanglement when $\Delta\phi^1_{LR} + \Delta\phi^1_{RL} = \pi$. One example of parameters which satisfy the latter condition is: m_1=3.50×10^{-14}kg m_2= 6.50×10^{-14}kg, d=4.50×10^{-4} m, τ=1.25s, Δx=2.39×10^{-4} m, and z=1.0×10^{-7} m. In this case, the relative size of z is negligible.

The impact of z on the occurrence of entanglement between the two masses can be found by examining the change of W.

As shown in Figure 4, when the value of z grows, W corresponds with a rising trend, indicating enhanced entanglement between the two masses. However, since z could vary in each run of the experiment, every time an entangled but different state can be produced, meaning that although each state produced in any given run of the experiment is entangled, the W obtained by averaging over measurement results from all runs may not show consistent entanglement throughout.

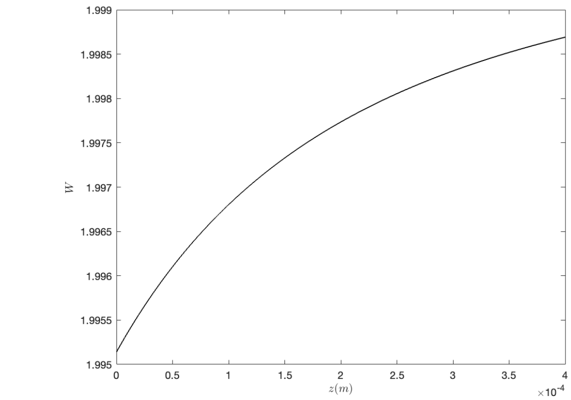

Figure 4: This graph shows the relationship between W and z, with other parameters taking the values of (8).

Significant time length for splitting and recombining:

Another assumption made in the original papers of the BMV effect is that the time taken for the processes of splitting and recombining is much smaller than the time the superposition is held constantly. In other words, $\tau' < \tau$. However, if the evolution time is not as expected, as shown in Figure 5, that τ' is significant enough to be accounted for, the final state is changed.

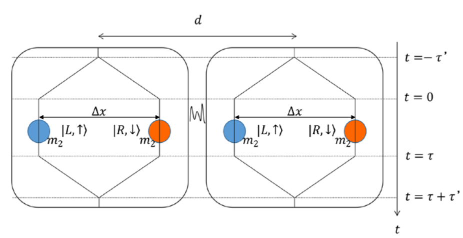

Figure 5: This is the variation 2 setup, where all apparatus is arranged in the same way as in Figure 1. The only difference is the consideration of τ'.

In this case, the evolution of states could be separated into three stages: 1) the stage of splitting, 2) the stage of coherent superposition, and 3) the stage of recombining. The second stage is the same as the original BMV effect. Therefore, the evolution of states in Stage 2 is the same as in the initial setup. Whereas the first and third stages are different and require new calculations for the phases picked up during the processes.

Applying the method used in Variation 1, we have the distance between two masses in Stage 1 being

$$\Delta x_{LL}^2(t) = \Delta x_{RR}^1(t) = d$$

$$\Delta x_{LR}^2(t) = d + \frac{\Delta x}{\tau'}(t+\tau') \tag{13}$$

$$\Delta x_{RL}^2(t) = d - \frac{\Delta x}{\tau'}(t+\tau')$$

As $\phi = \frac{\int_0^\tau E(t)\,dt}{\hbar} = \frac{\int_0^\tau \left(\frac{Gm_1m_2}{\Delta x^2(t)}\right)dt}{\hbar}$, The phases accumulated in Stage 1 are therefore

$$\phi_{LL}^2 = \phi_{RR}^2 = \frac{Gm_1m_2\tau'}{d\hbar}$$

$$\phi_{LR}^2 = \frac{Gm_1m_2\tau'[ln(d+\Delta x) - ln(d)]}{\Delta x \hbar} \tag{14}$$

$$\phi_{RL}^2 = \frac{Gm_1m_2\tau'[ln(d) - ln(d-\Delta x)]}{\Delta x \hbar}$$

Since the distance between the masses in Stage 3 is the same as the distance in Stage 1 but in a reversed order of development, the phases picked up in Stage 3 equal those in Stage 1. Thus, given that the phases accumulated in Stage 2 are identical to this final state takes a similar form of Eq.(3), the total phases can be found as below:

$$\phi^2 = \frac{Gm_1m_2(\tau + 2\tau')}{\hbar d}$$

$$\phi_{LR}^2 = \frac{Gm_1m_2\{\tau \cdot \Delta x + 2\tau'[ln(d+\Delta x) - lnd](d+\Delta x)\}}{\Delta x \cdot \hbar(d+\Delta x)} \tag{15}$$

$$\phi_{RL}^2 = \frac{Gm_1m_2\{\tau \cdot \Delta x + 2\tau'[lnd - ln(d-\Delta x)](d-\Delta x)\}}{\Delta x \cdot \hbar(d-\Delta x)}$$

Then the wave function at $t = \tau + \tau'$ is given as

$$|\Psi(t=\tau+\tau')\rangle = \frac{e^{i\phi^2}}{2}\left[|L\rangle(|L\rangle + e^{i\Delta\phi_{LR}^2}|R\rangle) + |R\rangle(e^{i\Delta\phi_{RL}^2}|L\rangle + |R\rangle)\right] \tag{16}$$

where $\Delta\phi_{LR}^2 = \phi_{LR}^2 - \phi^2$, $\Delta\phi_{RL}^2 = \phi_{RL}^2 - \phi^2$.

Since this state has a similar form to Eq.(2), it can be proved in a consistent way that the entanglement holds for $\Delta\phi_{LR}^2 + \Delta\phi_{RL}^2 \neq 2k\pi$ for an integer value of k.

As in the previous cases, for a maximum entanglement to be achieved, a relationship of $\Delta\phi_{LR}^2 + \Delta\phi_{RL}^2 = \pi$ is required.

One example of parameters which achieve maximum entanglement: $m_1 = 2.00\times10^{-14}kg$ $m_2 = 2.50\times10^{-14}kg$, $d = 4.50\times10^{-4}m$, $\tau = 1.30s$, $\Delta x = 3.55\times10^{-4}m$, and $\tau' = 0.129s$. For this combination, τ' is no longer negligible.

The results from Eq.(10) show that the phases have a linear relationship with τ', and if τ is taken as $1.5s$, a range of values from 0 to 10% of τ can be assigned to τ' to present the trends of the phases in the form of a graph (Figure 6) with experimental parameters taking the values in Eq.(12).

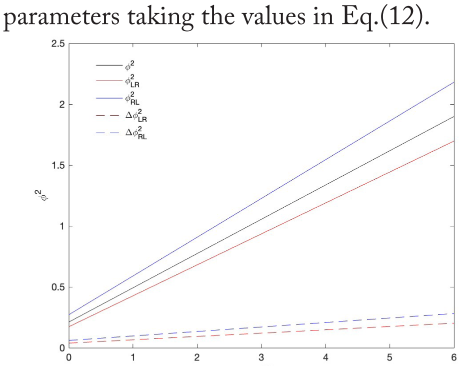

Figure 6: This graph demonstrates the effects of τ' on the phases ϕ^2, ϕ_{LR}^2, ϕ_{RL}^2, $\Delta\phi_{LR}^2$, and $\Delta\phi_{RL}^2$

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Compared to the values of phases from the original BMV experiment, which can be found along the y-axis ($\tau' \approx 0$ relative to τ), the three phases ϕ^2, ϕ^2_{LR}, and ϕ^2_{RL} grow with τ', as during the stages of splitting and recombining they accumulate linearly. These three lines have gradients (∇) similar to each other, with minor differences forming $\nabla_{\phi_{LR}} < \nabla_{\phi} < \nabla_{LR}$.

Looking at Figure 7, one can see that raising the value of τ' lowers the value of *W*, which demonstrates a reduced entanglement, and the degree of impact is higher than that of z, for here the change ~O(0.1), whereas in the case of z, it is ~O(0.001). However, the reduction in *W* does not result in collapses of entanglement within the presented range, as the rate at which *W* decreases is relatively small compared to the magnitude of *W*. In other words, entanglement still exists for possible variations of τ'.

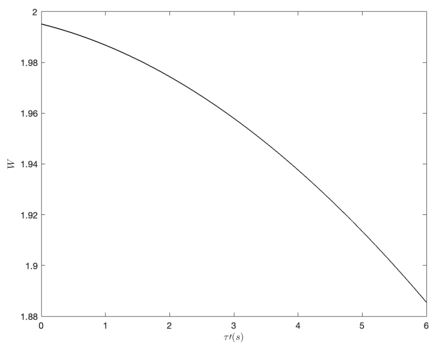

Figure 7: This graph shows the variation of *W* due to τ', in the setting that all other parameters are held as in (12).

Non-classicality and quantum:

Apart from the assumptions discussed above, there is a major assumption made in the original proposals that will be investigated in this paper, "non-classicality" is the same as "quantum". To review this assumption, note that the experiment is proposed based on two main issues: 1) the two masses have no direct interaction; 2) local operations and classical communication (LOCC) do not induce entanglement.[9,10] The first has brought many discussions about how to control such interactions, while the second leads to the determination of the role of the experiment. The principle of LOCC ensures that classical gravity cannot entangle masses as there is only a classical communication channel built between the masses. Then, the original papers claimed that the third system, the mediating gravitational field, is therefore quantum if entanglement is observed, assuming that non-classical gravity is equivalent to quantum gravity.[9,10] However, some later studies pointed out that the quantum nature of gravity is not necessarily guaranteed by this principle. In the best condition, an assumption of quantum gravity could explain the BMV effect, yet it is insufficient to prove this assumption directly.[14]

Michael J. W. Hall and Marcel Reginatto showed in their paper on two recent proposals for witnessing nonclassical gravity that the claim made on the quantum nature of the mediator of entanglement is not valid for all models of quantum-classical interaction. For instance, they discovered that this claim can be verified using Koopman and mean-field models, but this cannot be done for general configuration-ensemble models. This finding results in them concluding that whether the BMV effect can be a proof for quantum gravity depends on the model applied. Thus, a definite answer to the question of quantizing gravity cannot be expected from the experiment. They also argued that there may be ways to explain the BMV effect based on theories of classical gravity and that constraints need to be imposed to exclude such explanations. In other words, the non-classicality of gravity can only be proved if the BMV experiment is successfully carried out under certain constraints.[15] Furthermore, Thomas D. Galley, Flaminia Giacomini, and John H. Selby pointed out that non-classical gravity is not the same as quantum gravity and supported their claim with models identified that are neither classical nor quantum but still suitable for creating entanglement.[14]

Nonetheless, the study of Thomas D. Galley, Flaminia Giacomini, and John H. Selby proved a no-go theorem, showing that classical gravity does not generate entanglement between two systems. The theorem demonstrated the failure of coexistence of the following three conditions: gravity creating entanglement, gravity being the mediator between two systems, and gravity having a classical nature. In other words, their theorem states that the BMV effect is sufficient to prove the non-classical nature of gravity by observing the entanglement caused by the gravitational interactions.[14] In fact, C. Marletto and V. Vedral responded to this discussion over the expected aim of the BMV effect in their "Answers to a few questions regarding the BMV experiment." They agree that one cannot say gravity is completely quantum from this experiment, yet a classical theory would not be sufficient to solely explain the effect.[16] According to this, the more appropriate description for what can be learned from the experiment is the non-classical nature of gravity. That is to say, if entanglement is observed in the BMV experiment, all classical models constructed for gravity are excluded.[17]

However, further research on the feasibility and possible adjustments to the BMV effect are still needed to obtain the expected results. From the BMV proposal, several modified experimental designs are presented. On mitigating the Casimir-Polder potential, the long-range interaction between a neutral polarizable atom and a macroscopic object[18], Thomas W. van de Kamp *et al*. provided a protocol, further developed by Martine Schut et al., involving a conducting plate inserted between the two interferometers, improving the experiment's parameters.[13,19] Considering the loophole due to the possible simulation of entangled correlations by local hidden variable theories, an extension of the BMV effect, including a Bell experiment, is proposed for a stronger proof of the non-classical nature of gravity.[20] As the BMV effect can only be explained in either way: 1) gravity is quantum; 2) the world has a non-relativistic nature or is determined by something we do not know of yet,[21] the implementation of the BMV experiment in the near future, which might be different from the original proposal to some extent, is very worth looking forward to.[22]

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Conclusion

In this work, two variations of the BMV effect are proposed and analyzed. The first variation shows a linear increase in the distance between masses. In contrast, in the second, the time for the two masses to split and recombine is considered. Looking into the first variation, we can see a general trend that a greater magnitude of the linear distance means smaller phases picked up. In contrast, the quantum witness W decreases as the distance increases. Nevertheless, in the possible range of the linear distance, the corresponding values of W still show the presence of entanglement between the two masses. The second variation, on the other hand, has the magnitudes of phases increasing along with the time for splitting and recombining. Although W decreases for time values, it continues to indicate entanglement between masses as in Variation 1.

Then, considering the assumption made in the BMV effect that non-classical gravity is equivalent to quantum gravity, this paper reviews the debate over the claim that successfully witnessing entanglement in the BMV experiment gives firm proof for quantum gravity.[10,11] Recent research has confirmed that a successful witness will exclude classical gravity; however, quantum gravity is not the only choice left. There exist models of gravity that fall outside the realms of both classical and quantum physics, indicating that gravity could be distinct from both classical and quantum characteristics. Nonetheless, the realization of the BMV experiment still carries significant anticipation, and novel findings are highly expected to yield from the experiment. It is genuinely hoped that the BMV experiment will be performed in a few decades to effectively rule out the possibility of classical gravity, contributing significantly to quantum gravity research.

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