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REVIEW

Time and the Quantum: Erasing the Past and Impacting the Future

Yakir Aharonov[1,2] and M. Suhail Zubairy[3*]

The quantum eraser effect of Scully and Drühl dramatically underscores the difference between our classical conceptions of time and how quantum processes can unfold in time. Such eyebrow-raising features of time in quantum mechanics have been labeled "the fallacy of delayed choice and quantum eraser" on the one hand and described "as one of the most intriguing effects in quantum mechanics" on the other. In the present paper, we discuss how the availability or erasure of information generated in the past can affect how we interpret data in the present. The quantum eraser concept has been studied and extended in many different experiments and scenarios, for example, the entanglement quantum eraser, the kaon quantum eraser, and the use of quantum eraser entanglement to improve microscopic resolution.

The "classical" notion of time was summed up by Newton: "…absolute and mathematical time, of itself, and from its own nature, flows equally without relation to anything external." In the present article, we go beyond our classical experience by presenting counterintuitive features of time as it evolves in certain experiments in quantum mechanics. To illustrate this point, an excellent example is the delayed-choice quantum eraser, proposed by Marlan O. Scully and Kai Drühl (*1*), which was described as an idea that "shook the physics community" when it was first published in 1982 (*2*). They analyzed a photon correlation experiment designed to probe the extent to which information accessible to an observer and its erasure affects measured results. The Scully-Drühl quantum eraser idea as it was described in *Newsweek* tells the story well (*3*), and Fig. 1 is an adaptation of their account of this fascinating effect.

In his book *The Fabric of the Cosmos* (*4*), Brian Greene sums up beautifully the counterintuitive outcome of the experimental realizations of the Scully-Drühl quantum eraser (p. 149):

> *These experiments are a magnificent affront to our conventional notions of space and time. Something that takes place long after and far away from something else nevertheless is vital to our description of that something else. By any classical-common sense-reckoning, that's, well, crazy. Of course, that's the point: classical reckoning is the wrong kind of reckoning to use in a quantum universe …. For a few days after I learned of these experiments, I remember feeling elated. I felt I'd been given a glimpse into a veiled side of reality. Common experience—mundane, ordinary, day-to-day activities—suddenly seemed part of a classical charade, hiding the true nature of our quantum world. The world of the everyday suddenly seemed nothing but an inverted magic act, lulling its audience into believing in the usual, familiar conceptions of space and time, while the astonishing truth of quantum reality lay carefully guarded by nature's sleights of hand.*

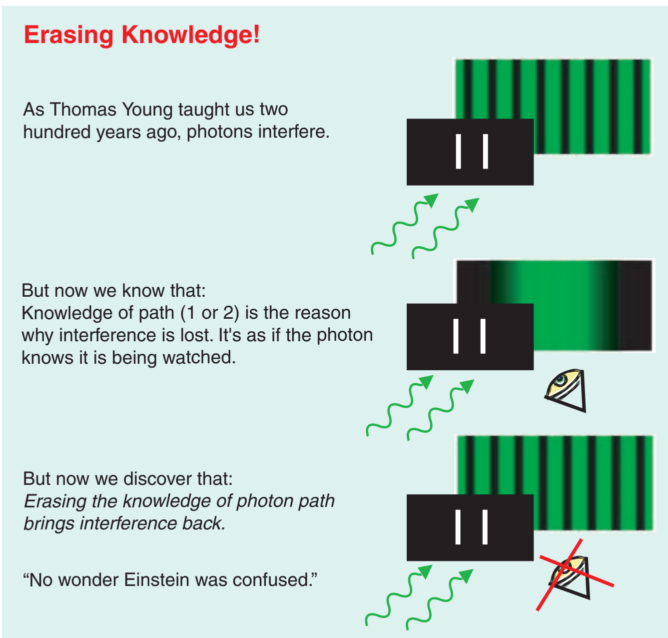

Fig. 1. Schematics for the Young's double-slit experiment. The which-path information wipes out the interference pattern. The interference pattern can be restored by erasing the which-path information.

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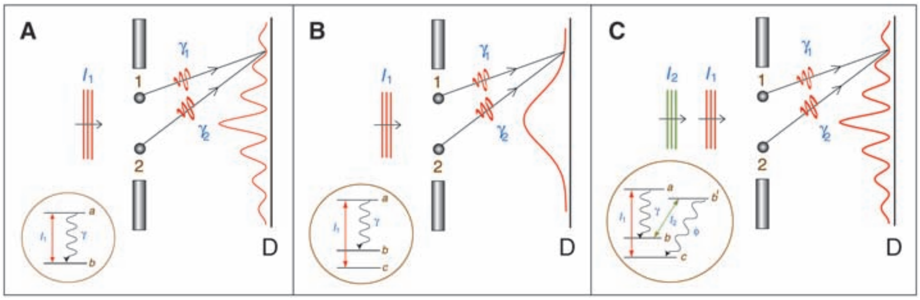

Fig. 2. Here, we consider three possible configurations of atoms that are placed at sites 1 and 2. In (**A**) we consider a two-level atom initially in the state b. The incident pulse l_1 excites one of the two atoms to state a from where it decays to state b, emitting a γ photon. In (**B**) the atom initially in the ground state c is excited by the pulse l_1 to state a from where it decays to state b. In (**C**) a fourth level is added. A pulse l_2 excites the atom to state b' after the atom has decayed to state b. The atom in the state b' emits a ϕ photon and ends up in state c.

Quantum Eraser Basics

We now present a simple description of the quantum eraser that brings out the counter-intuitive aspects related to time in the quantum mechanical domain. We consider the scattering of light from two atoms located at sites 1 and 2 on the screen D (Fig. 2) and analyze three different cases:

1) Resonant light impinges from the left on two-level atoms (Fig. 2A) located at sites 1 and 2. An atom excited to level a emits a γ photon. There are two possibilities for the atom, either it remains in the ground state b or it can get excited to the state a by the incident light and emit a γ photon. We look at the interference of these photons at the screen. Because both atoms are finally in the state b after the emission of photons, it is not possible to determine which atom contributed the γ photon. A large number of such experiments are carried out; i.e., any one photon will yield one count on the screen, and it takes many such photon events to build up a pattern. The resulting distribution of the detected photons exhibits an interference pattern (Fig. 2A). This is an analog of the usual Young's double-slit experiment. Instead of the usual light beams through two pin holes, we have considered scattered light from two atoms. The key to the appearance of the interference is the lack of which-path information for the photons.

2) In the case where the atoms have three levels (Fig. 2B), the drive field excites the atoms from the ground state c to the excited state a. The atom in state a can then emit a γ photon and end up in state b. Here, the photon detected on the screen leaves behind which-path information; that is, the atom responsible for contributing the γ photon is in level b, whereas the other atom remains in level c. Thus, a measurement of the internal states of the atoms provides us the which-path information and no interference is observed. That is, the state of the atom acts as an observer state. The precise mathematical description of photons γ_1 and γ_2 is the same in cases a and b. It is only the presence of the passive observer state that kills the interference.

There is an interesting connection to be made here with a statement of Richard Feynman. In his wonderful lectures on quantum mechanics for Caltech undergraduates (*5*), he discusses the problem of such observations rubbing out interference. He says (p. 9)

> *If an apparatus is capable of determining which hole the [photon] goes through it cannot be so delicate that it does not disturb the pattern in an essential way. No one has ever found or even thought of a way around the uncertainty principle. So we must assume that it describes a basic characteristic of nature.*

However, the loss of coherence in the present scheme does not invoke the uncertainty principle. In later work, Englert, Schwinger, Scully, and Walther came up with other such examples and in this sense have "thought of a way around the uncertainty principle" in this regard. We discuss this below.

The question, however, is whether we can erase the which-path information stored in the atom(s) and thus regain interference. If the loss of interference was caused by some kind of noise or uncertainty due to quantum fluctuations, the answer would be no. We now show that this is not the case, and the interference can be recovered. The question then is whether it is possible to wipe out the which-path information and recover the interference.

3) As shown in Fig. 2C, this can possibly be done by driving the atom by another field that takes the atom from level b to b' and, after an emission of a ϕ photon at the $b' - c$ transition, ends up in level c. Now the final state of both the atoms is c, and a measurement of internal states cannot provide us the which-path information. It would therefore seem that the interference fringes will be restored, but a careful analysis indicates that the which-path information is still available through the ϕ photon. A measurement on the ϕ photon can tell us which atom contributed the γ photon. Can we erase the which-path information contained in the ϕ photon and recover the interference fringes? Scully and Drühl considered an ingenious device based on an electrooptic shutter that can absorb the ϕ photon in such a way that the which-path information is erased (*1*). For the purpose of illustration, we consider a different and somewhat simplified version of such an eraser. A slightly modified version of such an eraser using a parametric process involving nonlinear crystal (instead of single atoms) was experimentally realized by Shih and co-workers in 2000 (*6*), which served as the motivation for Greene's presentation in (*4*).

However, before we proceed with discussions of Shih's experiment we should note that the erasure idea stirred up considerable controversy. Perhaps the best example is the well-written article by Mohrhoff (*7*). In the abstract, which we

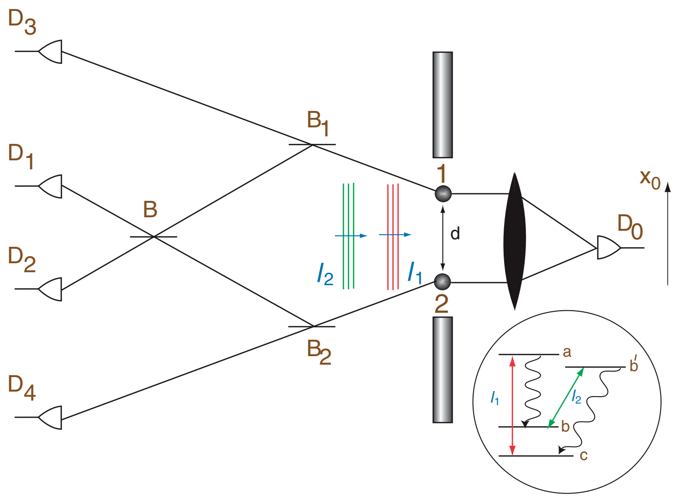

Fig. 3. Two atoms of the type shown in Fig. 2C are placed at sites 1 and 2. These atoms are excited by pulses l_1 and l_2 as in Fig. 2C such that one of the atoms emits γ and ϕ photons. We consider those events where the γ photon proceeds to the right and the ϕ photon to the left. The γ photon is collected by the detector D_0, whereas the ϕ photon is detected by D_1, D_2, D_3, or D_4 after passing through the optical setup consisting of the 50/50 beam splitters B_1, B_2, and B.

have adapted to fit the present example, he says (p. 1468)

> *a two-slit experiment…appears to permit experimenters to choose even after each photon has made its mark on the screen, whether the photon has passed through a particular slit or has, in some sense, passed through both of them. Through a misleading wording the authors even appear to endorse this interpretation.*

In a later paper, however, the author retracts this statement (*8*).

In fact, many people had a similar mind set, and it is only by carefully considering and analyzing several experiments (real and *gedanken*) that the issue is made clear.

We now turn to the particularly clear treatment of Shih and coworkers as depicted in Fig. 3. We again consider two atoms of the type shown in Fig. 2C located at sites 1 and 2. A pair of photons γ and ϕ are emitted either by the atom located at 1 or by the atom located at 2. The γ photon, as before, proceeds to the screen on the right and is detected by a detector on screen D at a location x_0. A repeat of this experiment yields an essentially random distribution of photons on the screen.

What about the appearance and disappearance of interference fringes discussed above? For this purpose, we look at the ϕ photon that proceeds to the left. We consider only those instances where the ϕ photon scattered from the atom located at 1 proceeds to the beam splitter B_1 and the ϕ photon scattered from the atom located at 2 proceeds to B_2. At either of these 50/50 beam splitters, the ϕ photon has a 50% probability of proceeding to detectors D_3 (for photon scattered from 1) and to D_4 (for photon scattered from 2). On the other hand, there is also a 50% probability that the photon will be reflected from the respective beam splitter and proceed to another 50/50 beam splitter, B. For these photons, there is an equal probability of being detected at detectors D_1 and D_2.

If the ϕ photon is detected at the detector D_3, it has necessarily come from the atom located at 1 and could not have come from the atom located at 2. Similarly, detection at D_4 means that the ϕ photon came from the atom located at 2. For such events, we can also conclude that the corresponding γ photon was also scattered from the same atom. That is, we have "which-way" information if detectors D_3 or D_4 register a count.

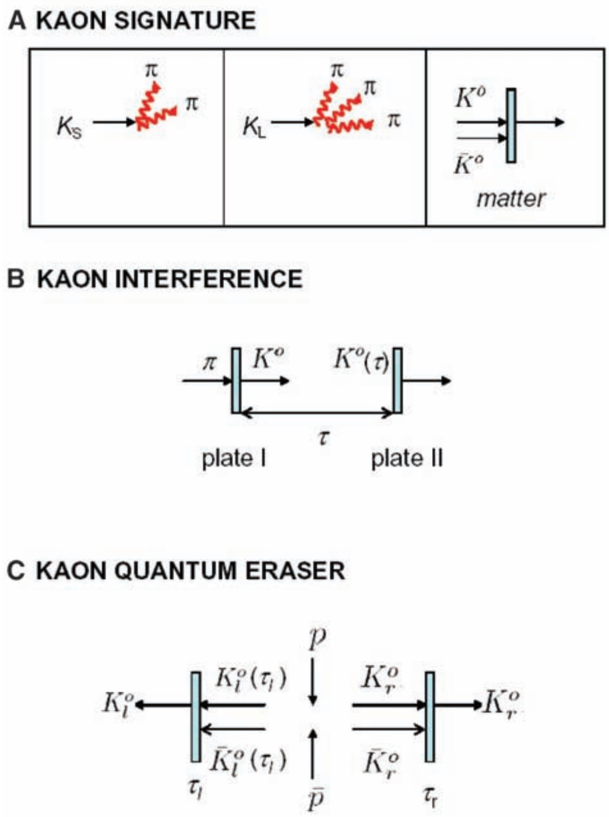

Fig. 4. (**A**) The four kaons K_S, K_L, K^0, and $\bar{K}^0$ have characteristic signatures; (the short-lived) kaon K_S decays into two π particles, whereas (the long-lived) kaon K_L decays into three π particles; the K^0 kaon (strangeness +1) mostly passes through matter, but the $\bar{K}^0$ (strangeness −1) interacts much more strongly with matter (nuclei) and is stopped. (**B**) The K^0 and $\bar{K}^0$ states are superpositions of K_S and K_L, i.e., $|K^0\rangle = (|K_S\rangle + |K_L\rangle)/\sqrt{2}$ and $|\bar{K}^0\rangle = (|K_S\rangle - |K_L\rangle)/\sqrt{2}$. Now K_S and K_L have masses m_S and m_L so that $|K^0(\tau)\rangle = (e^{-im_S\tau}|K_S\rangle + e^{-im_L\tau}|K_L\rangle)/\sqrt{2}$. Thus, if we produce K^0 particles in plate I and they propagate for a time τ to plate II then the probability for passage through plate II is $|\langle K^0|K^0(\tau)\rangle|^2$ which shows oscillations in time. (**C**) A kaon quantum eraser may be realized by noting that $p\,\bar{p}$ collisions generate the entangled states moving to the right (r) and left (l) which can be written in terms of which-way (K_S, K_L) or which-wave (K^0, $\bar{K}^0$). Quantum erasing is achieved by the left-moving kaon as the measured kaon (which will or will not show oscillations), and the right tag or ancilla kaon will serve to select the which-wave ensemble (K^0, $\bar{K}^0$) if we put in plate II and measure K_r^0. However, if we do not put in the second plate then we must describe the physics by the which-way subensemble. Thus, the entangled kaon state can be used to demonstrate quantum erasure by subensemble selection just as in the original photon case. However, if K_S or K_L propagates from I to II, the state of the kaon just before it enters II is $|K_S(\tau)\rangle = e^{-im_S\tau}|K_S\rangle$ and $|\langle K^0|K_S(\tau)\rangle|^2 = 1/2$ with a similar result for K_L. In this sense, K_S and K_L are "which-way" (short or long lived) states like photons going through slit 1 or 2, i.e., do not show oscillations. K^0 and $\bar{K}^0$, however, do show oscillation behavior and in this sense may be called "which-wave."

Returning to the quantum erasure protocol, if the ϕ photon is detected at D_1, there is an equal probability that it may have come from the atom located at 1, following the path $1B_1BD_1$, or it may have come from the atom located at 2, following the path $2B_2BD_1$. Thus, we have erased the information about which atom scattered the ϕ photon, and there is no which-path information available for the corresponding γ photon. The same can be said about the ϕ photon detected at D_2. The difference between counts in D_1 and D_2 is a phase shift such that a click at D_1 gives the fringes corresponding to $\gamma_1 + \gamma_2$, whereas a click at D_2 correlates with $\gamma_1 - \gamma_2$.

After this experiment is done a large number of times, we shall have roughly 25% of ϕ photons detected each at D_1, D_2, D_3, and D_4 because of the 50/50 nature of our beam splitters. The corresponding spatial distribution of γ photons will be, as mentioned above, completely random. Next we do a sorting process. We separate out all the events where the ϕ photons are detected at D_1, D_2, D_3, and D_4. For these four groups of events, we locate the positions of the detected γ photons on the screen D.

The key result is that, for the events corresponding to the detection of ϕ photons at detectors D_3 and D_4, the pattern obtained by the γ photons on the screen D is the same as we would expect if these photons had scattered from atoms at sites 1 and 2, respectively. That is, there are no interference fringes, as would be expected when we have which-path information available. On the contrary, we obtain conjugate (π phase shifted) interference fringes for those events where the ϕ photons are detected at D_1 and D_2. For this set of data, there is no which-path information available for the corresponding γ photons.

Suppose we place the ϕ photon detectors far away. Then the future measurements on these photons influence the way we think about the γ photons measured today (or yesterday!). For example, we can conclude that γ photons whose ϕ partners were successfully used to ascertain which-path information can be described as having (in the past) originated from site 1 or site 2. We can also conclude that γ photons whose ϕ partners had their which-path information erased cannot be described as having (in the past) originated from site 1 or site 2 but must be described, in the same sense, as having come from both sites. The future helps shape the story we tell of the past.

Here again the eloquent and insightful Brian Greene says it well (p. 197):

> *Notice, too, perhaps the most dazzling result of all: the three additional beam*

splitters and the four idler-photon detectors can only be on the other side of the laboratory or even on the other side of the universe, since nothing in our discussion depended at all on whether they receive a given idler photon before or after its signal photon partner has hit the screen. Imagine, then, that these devices are all far away, say ten light-years away, to be definite, and think about what this entails. You perform the experiment in fig 7.5b today, recording–one after another–the impact locations of a huge number of signal photons and you observe that they show no sign of interference. If someone asks you to explain the data, you might be tempted to say that because of the idler photons, which path information is available and hence each signal photon definitely went along either the left or the right path, eliminating any possibility of interference. But, as above, this would be a hasty conclusion about what happened; it would be a thoroughly premature description of the past.

For the mathematically inclined reader we include a brief discussion (*9*) which sheds light on the physics using the language of modern quantum mechanics.

The Micromaser Which-Path Detector and Quantum Eraser

The Scully-Drühl quantum eraser was perhaps the earliest example of quantum entanglement interferometry and stimulated many experiments. However, another form of the quantum eraser based on cavity quantum electrodynamics and the micromaser has also stimulated debate as well as new experiments and calculations. In particular, Englert, Schwinger (who shared the Nobel prize with Feynman and Tomonaga), Scully, and Walther showed that excited atoms passing through a microwave cavity can leave a photon in the cavity without suffering overall recoil (*10–12*).

Thus, by using the wave-like properties of the atom and placing a cavity in front of each slit, we could obtain which-way information (photon left in one cavity or the other). Furthermore, it is easy to envision ways to erase this information and regain fringes.

Again, spirited debate and decisive experiments followed. In this regard, the beautiful experiments of Dürr, Nonn, and Rempe are summarized in the following quotations taken from (*13*), where they note that the party line has it that (p. 33)

> *[If] a which-way detector is employed to determine the particle's path, the interference pattern is destroyed. This is usually explained in terms of Heisenberg's uncertainty principle.*

They further note (p. 33)

> *However, Scully et al. (10, 11) have recently proposed a new gedanken experiment, where the loss of the interference pattern in an atomic beam is not related to Heisenberg's position-momentum uncertainty relation.*

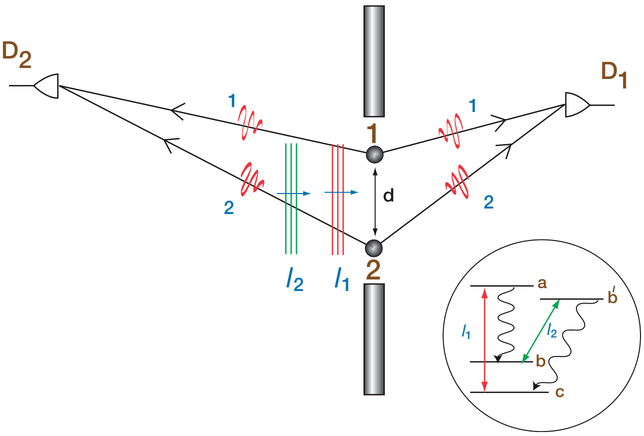

Fig. 5. Two atoms of the type shown located at sites 1 and 2 are separated by a distance d. Incident pulse sequence l_1 and l_2 leads to emission of γ and ϕ photons as in quantum eraser. The γ and ϕ photons are detected at D_1 and D_2, respectively. An intensity-intensity correlation yields resolution beyond the classical limit.

This stirred up considerable controversy; to wit (p. 33):

> *Nevertheless, the gedanken experiment of Scully et al. (10, 11) was criticized by Storey et al. (14), who argued that the uncertainty relation always enforces recoil kicks sufficient to wash out the fringes. This started a controversial discussion about the following question: 'Is complementarity more fundamental than the uncertainty principle?'*

They summarize their results and conclusions as follows (p. 33):

> *Here we report a which-way experiment in an atom interferometer in which the 'back action' of path detection on the atom's momentum is too small to explain the disappearance of the interference pattern. We attribute it instead to correlations between which-way detector and atomic motion, rather than to the uncertainty principle.*

Entanglement Quantum Erasers

The preceding discussions showed how quantum eraser can be used to retrieve interference by means of tag ancilla photons $|\phi_\pm\rangle$ going with $|\gamma_\pm\rangle$ fringe and antifringe states. Garisto and Hardy (*15*) invented an interesting new class of quantum erasers, called the disentanglement eraser. These consist of at least three subsystems A, B, and T. The AB subsystem is prepared in entangled states of the type

$$|\psi_\pm\rangle = \frac{1}{\sqrt{2}} \times (|0_A, 1_B\rangle \pm |1_A, 0_B\rangle)$$

They then showed how tag states $|\phi_\pm\rangle$ can be used to remove or restore the entanglement. Thus, an outcome $|\phi_+\rangle$ for the tagged state restores the original state $|\psi_+\rangle$ for the AB subsystem, whereas the outcome $|\phi_-\rangle$ yields $|\psi_-\rangle$. Thus, a measurement of the tagging qubit restores the entangled state.

An implementation of such an eraser has been demonstrated in nuclear magnetic resonance systems (*16*). Furthermore, a cavity quantum electrodynamics–based implementation has been proposed in (*17*), which provides new insights into quantum teleportation and/or quantum dense coding.

Quantum Kaon Erasers

In a recent article (*18*), Bramon, Garbarino and Hiesmayr have extended these ideas to nuclear physics and showed that an entangled pair of neutral kaons can also display quantum erasure. In their set-up, strangeness oscillations between K^0 and $\overline{K}^0$ display oscillatory (wave-like) behavior and the alternative (which-path like) representation involving eigenstates of mass. The latter representations are called K_S and K_L because they live for about 10^{-10} and 10^{-8} s in free space. As indicated in Fig. 4, the oscillator involves a π incident on plate 1 produces a K^0 that has oscillations when expressed in terms of the K_S and K_L representation. Upon passing through the second plate, only K^0 emerges and this shows typical interference phenomena as indicated. Thus, the kaon oscillations are produced by changing the distance between the two plates. To summarize, then, with no plates we have which-way information associated with decay into two or three π particles. With the plates in place, nucleonic interactions occur, and we can observe oscillatory fringe information. Quantum eraser is achieved by using the entangled state produced by $p\,\overline{p}$ collisions.

Quantum Imaging via Quantum Eraser

Quantum interferometry using entangled photons, as in the paradigm of the quantum eraser, can be used to exceed the resolution limit of classical wave optics. The key resource needed is the ability to jointly measure and correlate the detection of two photons, as described by the intensity correlation function $G^{(2)}$. In the second order interferometry based on photon pairs, the resolution in the measurement of the distance d between the photon sources (Fig. 5) can be potentially improved by as much as an order of magnitude. In order to understand this enhanced resolution, we consider the Scully-Drühl quantum eraser configuration of Fig. 5. The atom of the type shown in Fig. 2C is first excited by a pulse l_1 of center frequency v_p and much later by a pulse l_2 at frequency v_d. A γ photon as well as a ϕ photon are emitted either by atom 1 or atom 2 that are detected by detectors D_1 and D_2. The photon-photon correlation function factorizes. The interference pattern observed by moving detector D_1 (and requiring a correlation with detector D_2) is now governed by $k_\gamma + k_\phi \approx 2k$, i.e., the effective radiation wavelength is now $\lambda/2$, leading to an immediate two-fold enhancement beyond the classical limit. In fact, Scully has shown that further improvement results from a more detailed analysis, leading to the possibility of an order of magnitude improvement of resolution (*19*).

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9. Mathematically we can understand the essential results of the Scully-Drühl quantum eraser by first realizing that the photon state emitted by the atoms located at sites 1 and 2 is given by

$$|\psi_0\rangle = \frac{1}{\sqrt{2}}(|\gamma_1\rangle|\phi_1\rangle + |\gamma_2\rangle|\phi_2\rangle)$$

i.e., either the photon pair γ_1, ϕ_1 is emitted by the atom located at site 1 or the pair γ_2, ϕ_2 is emitted by the atom at site 2. Thus if the ϕ photon is detected by D_3, the quantum state reduces to $|\gamma_1\rangle$. A similar result is obtained for the ϕ photon detection by the detector D_4. This is the situation when the which-path information is available and the sorted data yields no interference fringes. The physics behind the retrieval of the fringes is made clear by rewriting the state $|\psi_0\rangle$ as

$$|\psi_0\rangle = \frac{1}{\sqrt{2}}(|\gamma_+\rangle|\phi_+\rangle + |\gamma_-\rangle|\phi_-\rangle)$$

where $\gamma_\pm$ and $\phi_\pm$ are the symmetric and antisymmetric combinations.

$$|\gamma_\pm\rangle = \frac{1}{\sqrt{2}}(|\gamma_1\rangle \pm |\gamma_2\rangle)$$

$$|\phi_\pm\rangle = \frac{1}{\sqrt{2}}(|\phi_1\rangle \pm |\phi_2\rangle)$$

The state of the ϕ photon after passage through the beam splitter B is either $|\phi_+\rangle$ or $|\phi_-\rangle$. Thus, a click at detectors D_1 or D_2, reduces the state of the γ photon to $|\gamma_+\rangle$ or $|\gamma_-\rangle$, respectively, leading to a retrieval of the interference fringes.
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REVIEW

Astrophysical Observations: Lensing and Eclipsing Einstein's Theories

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Albert Einstein postulated the equivalence of energy and mass, developed the theory of special relativity, explained the photoelectric effect, and described Brownian motion in five papers, all published in 1905, 100 years ago. With these papers, Einstein provided the framework for understanding modern astrophysical phenomena. Conversely, astrophysical observations provide one of the most effective means for testing Einstein's theories. Here, I review astrophysical advances precipitated by Einstein's insights, including gravitational redshifts, gravitational lensing, gravitational waves, the Lense-Thirring effect, and modern cosmology. A complete understanding of cosmology, from the earliest moments to the ultimate fate of the universe, will require developments in physics beyond Einstein, to a unified theory of gravity and quantum physics.

Einstein's 1905 theories form the basis for much of modern physics and astrophysics. In 1905, Einstein postulated the equivalence of mass and energy (*1*), which led Sir Arthur Eddington to propose (*2*) that stars shine by converting their mass to energy via $E = mc^2$, and later led to a detailed understanding of how stars convert mass to energy by nuclear burning (*3*, *4*). Einstein explained the photoelectric effect by showing that light quanta are packets of energy (*5*), and he received the 1921 Nobel Prize in physics for this work. With the photoelectric effect, astronomers determined that ultraviolet photons emitted by stars impinge on interstellar dust and overcome the work function of the grains to cause electrons to be ejected. The photoelectrons emitted by the dust grains excite the interstellar gas, including molecules with molecular sizes of ~1 nm, as estimated by Einstein in 1905 (*6*). Atoms and molecules emit spectral lines according to Einstein's quantum theory of radiation (*7*). The concepts of spontaneous and stimulated emission explain astrophysical masers and the 21-cm hydrogen line, which is observed in emission and absorption. The interstellar gas, which is heated by starlight, undergoes Brownian motion, as also derived by Einstein in 1905 (*8*).

Two of Einstein's five 1905 papers introduced relativity (*1*, *9*). By 1916, Einstein had generalized relativity from systems moving with a constant velocity (special relativity) to accelerating systems (general relativity).

Space beyond Earth provides a unique physics laboratory of extreme pressures and temperatures, high and low energies, weak and strong magnetic fields, and immense dimensions that cannot be reproduced in laboratories or under terrestrial conditions. The extreme astrophysical environments

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