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 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 erase 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, lulled 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.

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**References and Notes**

1. A “fluffy-bunny” is a cheap, manufactured toy given as a prize in British fairs.  
15. Another way to find evidence for a cat, not discussed here, is to disentangle the particles, but this also amounts to recombination and destroys the cat.  
24. This work was supported by the UK Engineering and Physical Sciences Research Council and the Royal Society and Wolfson Foundation.

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**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.
**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 $\gamma$ 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 $\gamma$ 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 $\gamma$ 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 $\gamma$ 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 $\gamma$ 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 $\gamma_1$ and $\gamma_2$ is the same in cases $a$ and $b$. It is only the presence of the passive observer state that kills 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 $\phi$ 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 $\phi$ photon. A measurement on the $\phi$ photon can tell us which atom contributed the $\gamma$ photon. Can we erase the which-path information contained in the $\phi$ photon and recover the interference fringes? Scully and Drühl considered an ingenious device based on an electrooptic shutter that can absorb the $\phi$ 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
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 x₀. 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 B₁ and the φ photon scattered from the atom located at 2 proceeds to B₂. At either of these 50/50 beam splitters, the φ photon has a 50% probability of proceeding to detectors D₁ (for photon scattered from 1) and to D₂ (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 D₁ and D₂.

If the φ photon is detected at the detector D₁, it has necessarily come from the atom located at 1 and could not have come from the atom located at 2. Similarly, detection at D₂ 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 D₁ or D₂ register a count.

Returning to the quantum erasure protocol, if the φ photon is detected at D₁, there is an equal probability that it may have come from the atom located at 1, following the path 1B₁BD₁, or it may have come from the atom located at 2, following the path 2B₂BD₁. 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 D₂. The difference between counts in D₁ and D₁ is a phase shift such that a click at D₁ gives the fringes corresponding to γ₁ + γ₂, whereas a click at D₂ correlates with γ₁ − γ₂.

After this experiment is done a large number of times, we shall have roughly 25% of φ photons detected at D₁, D₂, D₃, and D₄, 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 D₁, D₂, D₃, and D₄. 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 D₁ and D₂, 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 D₁ and D₄. 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. 7.3b 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 that excited atoms passing through a micro-

depth 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 that excited atoms passing through a micro-

![Diagram](image-url)

**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 \(\gamma\) and \(\phi\) photons as in quantum eraser. The \(\gamma\) and \(\phi\) 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 \(|\phi_1\rangle\) going with \(|\gamma_1\rangle\) fringe and antifringe states. Garisto and Hardy (15) invented an interesting new class of quantum erasers, called the dis-

erentanglement eraser. These consist of at least three subsystems \(A\), \(B\), and \(T\). The \(AB\) sub-

system is prepared in entangled states of the type

\[
|\psi_e\rangle = \frac{1}{\sqrt{2}} \left( |0_A, 1_B \rangle \pm |1_A, 0_B \rangle \right)
\]

They then showed how tag states \(|\phi\rangle\) can be used to remove or restore the entangle-

ment. Thus, an outcome \(|\phi_1\rangle\) for the tagged state restores the original state \(|\psi_e\rangle\) for the \(AB\) subsystem, whereas the outcome \(|\phi_0\rangle\) yields \(|\psi_e\rangle\). Thus, a measurement of the tagging qubit restores the entangled state.

An implementation of such an eraser has been demonstrated in nu-

clear magnetic resonance systems (16). Furthermore, a cavity quantum electrodynamics–based implementa-

tion 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 entan-

elled pair of neutral kaons can also display quantum erasure. In their set-up strangeness oscillations between \(K^0\) and \(\bar{K}^0\) display oscillatory (wave-like) behavior and the alternative (which-path like) repre-

sentation 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 \(\pi^0\) 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 osc-

illations are produced by changing the distance between the two plates. To sum-

marize, then, with no plates we have which-way information associated with decay into two or three \(\pi\) 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 \(p\ \bar{p}\) 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 $v_{fr}$. A $\gamma$ photon as well as a $\phi$ photon are emitted either by atom 1 or atom 2 that are detected by detectors $D_1$ and $D_2$. The photon-photon correlation factorizes. The interference pattern observed by moving detector $D_1$ (and requiring a correlation with detector $D_2$) is now governed by $k_g + k_f \approx 2k$, 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).

References and Notes

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 $\gamma_1$, $\phi_1$ is emitted by the atom located at site 1 or the pair $\gamma_2$, $\phi_2$ is emitted by the atom at site 2. Thus if the $\phi$ photon is detected by $D_2$, the quantum state reduces to $|\gamma_2\rangle$. A similar result is obtained for the $\phi$ photon detection by the detector $D_1$. 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

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

where $\gamma_1$ and $\phi_1$ are the symmetric and antisymmetric combinations.

The state of the $\phi$ photon after passage through the beam splitter $B$ is either $|\phi_1\rangle$ or $|\phi_2\rangle$. Thus, a click at detectors $D_1$ or $D_2$ reduces the state of the $\gamma$ photon to $|\gamma_1\rangle$ or $|\gamma_2\rangle$, respectively, leading to a retrieval of the interference fringes.

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Astrophysical Observations:
Lensing and Eclipsing Einstein’s Theories

Charles L. Bennett

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 $\sim 1$ 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...