Haunted Quantum Entanglement: A New Scenario

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ABSTRACT

A haunted quantum entanglement scenario is proposed that is very close to the haunted measurement scenario in that: 1) the entity that is developing as a which-way marker is effectively restored to its state prior to its developing as a which-way marker, and 2) the entity for which the developing which-way marker provides information enters the state it would have had if the development of the which-way marker had never begun. In the hqe scenario, the loss of developing which-way information through 1 relies on the loss of a developing entanglement. The photon initially emitted in one of two micromaser cavities and developing into a which-way marker is effectively lost through the injection of classical microwave radiation into both of the microwave cavities: 1) after the atom initially emits the photon into one of the micromaser cavities and exits the cavity system, and 2) before this atom reaches the 2 slit screen. The atom enters the state it would have had if the atom had never emitted the photon into one of the micromaser cavities due to the injection of classical microwave radiation into both of the microwave cavities and the presence of an rf coil situated at the exit of the micromaser cavity system.

Haunted Quantum Entanglement

Text

GREENBERGER AND YASIN'S HAUNTED MEASUREMENT

In the haunted measurement of Greenberger and YaSin an isolated which-way measurement on a neutron passing through one arm of an interferometer is undone by reversing the result of the measurement before the which-way measurement result is released to the environment.[1,2] The orthogonalilty of the which-way markers is lost when the interference is regained. The interference regained is the same interference that characterizes the neutron before the isolated which-way measurement on the neutron began. This regaining of interference that appeared to be lost due to a which-way measurement was possible because the physical processes maintained coherence.

The basic scenario involving an interferometer used by Greenberger and YaSin in their thought experiment is depicted in Fig. 1. A four-mirror device that is effectively shielded from the environment is inserted into one of the two paths of the interferometer.[1] The mirrors in the device are rigidly connected to each other. The entire device can move along an axis perpendicular to the axis of the mirrors, as shown in Fig. 1. A particle entering the interferometer and passing through the four-mirror device in one arm of the interferometer would first interact with M_1 of the four-mirror device, changing both the position and momentum of M_1 and the rest of the four-mirror device. The particle's subsequent apparent physical

[1] Greenberger and YaSin did not explicitly note the separation of the four-mirror device from the environment, but that this separation was part of their thought experiment was communicated to me personally by Professor Greenberger. In Figure 1, this separation is accomplished by placing the four-mirror device in a box.

interactions with the other mirrors would return the device to its original position and momentum, thus leaving no sign that the particle passed through the device. Interacting with M_2 would restore the original momentum of the entire device, which was 0, and interacting with M_3 and M_4 would restore both the original position and momentum. If the four-mirror device were not effectively isolated from the environment, the first interaction of the particle and the device at M_1 would irreversibly eliminate the coherence of the component wave functions and thus the interference.

More specifically, the isolated mirror apparatus allowed for an atom to displace it upon interacting with the first of two sets of mirrors in this apparatus (a “measurement in process”) and then to effect another displacement of this mirror apparatus through further interaction with a second set of two mirrors in the apparatus (another “measurement in process”). The final result of the “measurements in process” was that the mirror apparatus assumed its original position at rest before the atom exited the shield around the mirror apparatus. Because step 2 (the exit of the atom from the shield around the mirror apparatus) occurred *after* the presumed second displacement that reversed the presumed initial one, it was possible to reverse the “measurement in process” consisting of these presumed displacements before the measurement result concerning the atom’s interaction with the mirror apparatus was made available to the environment. The first and second displacement measurements were both “in process” until information from these measurements was released to the environment after the elapse of time over which the atom could traverse the shielded mirror structure.

From A to M_1 and also from A to the point on the other interferometer arm corresponding to M_1 where there is the effective presence of a mirror identical to M_1, the wave function for the neutron is:

$$\psi = 1/\sqrt{2}[\psi_1 + \psi_2].$$ [2]

The probability for the neutron detection event is the absolute square of this probability amplitude.

$$P = |\psi|^2 = 1/2|\psi_1 + \psi_2|^2$$

From M_1 to M_4 and also from the point on the other interferometer arm corresponding to M_1 where there is the effective presence of a mirror identical to M_1 until the point on this other arm corresponding to M_4, the wave function for this situation can be represented as:

$$\psi = 1/\sqrt{2}\,[(A\_u)|P\_u\rangle + (A\_l)|P\_l\rangle]$$

where $|P\_u\rangle$ and $|P\_l\rangle$ are orthonormal wave functions representing the flexible mirror apparatus along one arm of the interferometer and the effective presence of an identical flexible mirror apparatus along the other arm of the interferometer. (A_u) and (A_l) are wave functions representing the neutron's traveling along one or the other of the arms of the interferometer. $|P\_u\rangle$ and $|P\_l\rangle$ do not overlap.

$|P\_u\rangle$ and $|P\_l\rangle$ then serve as which-way markers in that one obtains:

$$|\psi|^2 = 1/2\,[|(A\_u)|^2 \langle P\_u|P\_u\rangle + |(A\_l)|^2 \langle P\_l|P\_l\rangle + (A\_u^* A\_l)\langle P\_u|P\_l\rangle + (A\_l^* A\_u)\langle P\_l|P\_u\rangle]$$

[2] The use of the effective presence of a flexible mirror system along one arm of the interferometer follows Epstein[3].

or

$$|\psi|^2 = 1/2|(A\_u)|^2 + 1/2|(A\_l)|^2$$

Then from M_4 to F and also from the point on the other arm of the interferometer corresponding to M_4 to F, the system of the neutron and the flexible mirror apparatus (and the effective presence of the flexible mirror apparatus) can be represented as.

$$\psi = [1/\sqrt{2}\ [(A\_u) + (A\_l)]]\ [1/\sqrt{2}\ [|P\_u\rangle + |P\_l\rangle]]$$

The neutron and the flexible mirror apparatus (and the effective presence of the flexible mirror apparatus) are independent of one another. The neutron itself then can be represented accurately as:

$$\psi = 1/\sqrt{2}[\psi_1 + \psi_2]$$

since the neutron events and mirror apparatus events are independent of one another. The flexible mirror apparatus and its effective presence no longer serve as which-way markers for the path the neutron takes through the interferometer.

The probability for the neutron detection event at the exit of the interferometer (i.e., the arms of the interferometer) is the absolute square of this probability amplitude.

$$P = |\psi|^2 = 1/2|\psi_1 + \psi_2|^2$$

Which-way information supplied by |P_u> and |P_l> regarding the path of the neutron through the interferometer is lost.

Isolated events are not subject to Feynman's[4] position that which alternative taken does not actually have to be known to take the sum of absolute squares of the probability amplitudes for the event happening in alternative ways. Isolation characterizes both the neutron and the flexible mirror apparatus until the neutron exits the flexible mirror apparatus or its effective equivalent along the other arm of the interferometer. This situation where the orthogonality of the which-way markers is lost does not occur in what appears to be a similar experimental setup in the quantum eraser. The difference between a haunted measurement and a quantum eraser requires discussion.

THE QUANTUM ERASER

Following is a summary of the quantum eraser paper written by Scully, Englert, and Walther[5] that appeared in Nature in 1991 (Fig. 2). In their experiment an atom passes through a micromaser cavity system composed of two such cavities separated by shutters. Between the shutters there is a photodetector. The atom emits a photon into one of the cavities and then exits the cavity system. It then passes through a two slit arrangement and travels on to an atom detection screen. Whether the shutters are left closed or are instead opened after the atom leaves the cavity system, the authors maintain that the overall distribution pattern of atoms at the detection screen is the one wide hump characteristic of which-way information. If the shutters are opened, then depending on whether the photon interacts with the photodetector one gets interference fringes or anti-fringes when one pairs the photon detection/undetection with the emitting atom's striking the detection screen. In this situation:

1. The atom does not present any measurement information to the environment until it reaches the two-slit arrangement.

Passage through the micromaser cavity system does not affect the atom's motion in any relevant way.[3]

2. The photon does not itself present any measurement information to the environment while in the micromaser cavity system. A micromaser cavity can be compared to the box in which Schrodinger's cat is located. Its interior is effectively isolated from the environment.

Thus, the atom-photon system is isolated from the environment as far as measurement information is concerned regarding its state *before* the atom reaches the two-slit arrangement.

Notice that a difference between the haunted measurement and the quantum eraser concerns the information that is made available to the environment. In the haunted measurement none is made available to the environment until the which-way measurement is completely undone. In the quantum eraser, information that which-way information exists, but not information regarding the specific path taken, is made available before the which-way information is lost.

After the process of entanglement begins in both Greenberger and YaSin's experiment (with the initial interaction of the neutron and the mirror apparatus) and Scully, Englert, and Walther's experiment (with the emission of the photon by the atom) the system would initially be characterized by an equation of the form:

$$\psi = 1/\sqrt{2}\ [(A_u)|P_u> + (A_l)|P_l>]$$

[3] Scully and his colleagues wrote," No net momentum is transferred to the atom during the interaction with the cavity fields [i.e., in the course of which the atom emits a photon]" (p. 113). They also wrote: "We emphasize once more that the micromaser welcher weg detectors are recoil-free; there is no significant change in the spatial wave function of the atoms" (p. 114).

where A in the case of the quantum eraser represents the atom, P represents the photon emitted by the atom, and u and l represent the two micromaser cavities in the cavity system. In the case of Greenberger and YaSin the A refers to the neutron, u and l refer to the two arms of the interferometer, and P refers to the flexible mirror mechanism along one arm of the interferometer, as well as the implied presence of such a mechanism along the other arm of the interferometer (since whether or not the mirror apparatus located along one arm of the interferometer actually processes a neutron necessarily negatively correlates with whether that neutron passed along the other arm of the interferometer where there is no actual mirror apparatus).

So why then does one obtain fringes and anti-fringes that sum to an overall distribution of which-way information in the quantum eraser experiment instead of the type of interference that would occur if the cavities, lasers and other associated instrumentation were absent to begin with? Why are the results different in the quantum eraser as opposed to the haunted measurement? The results are different because in the quantum eraser scenario *part* of the information in the experiment is released to the environment by the passage of the atom through the two slit screen before quantum erasure is performed. The information that is released is *general* information that a which-way measurement has occurred. Information concerning into which *specific* cavity the atom emitted the photon is erased before the information is released to the environment. In the experiment by Greenberger and YaSin, *no* which-way information is released to the environment before this information is lost.

It appears that the atom's passage through the double slit screen makes public information that which-way information exists (and this constitutes a completed measurement) and the subsequent opening of the shutters eliminates the which-way information with the result that interference fringes and anti-fringes occur. Since the measurement of general which-way information has already occurred (since the information has been released to the environment with the passage of the atom through the two slit screen), the overall distribution of the atoms does not change. Essentially the purely formal mathematical orthogonality of the component wave functions for the photon is fixed with the passage of the atom through the two slit arrangement. If the shutters remain closed, then one obtains the two smaller round humps characteristic of specific which-way information (if one makes the necessary correlations) instead of the interference fringes and anti-fringes (if one makes the necessary correlations). In the haunted measurement, there is no purely formal mathematical orthogonality of the component wave functions for the flexible mirror apparatus and its effective equivalent along the other arm of the interferometer with the passage of the atom through either the flexible mirror apparatus or its effective equivalent.

HAUNTED QUANTUM ENTANGLEMENT

If one changed the Scully experiment for example so that *no* measurement information in the experiment is made available to the environment (i.e., general or specific which-way information as defined above) before all the which-way information is lost, one would expect the results to be like that of Greenberger and YaSin, that is the presence of interference as if the which-way information had never existed (not fringes and anti-fringes that sum to one broad hump) (Figs. 3 and 4)[6].

Haunted Quantum Entanglement

It has been proposed previously[6,7,8] to change Scully's quantum eraser setup according to the following specifications:

1. a single shutter is substituted for the two shutters that can open and close as well as for the photoelectric detector, and

2. the single shutter is opened after the atom emitted the photon and exited the micromaser cavity system and before the atom reached the two slit arrangement (Figs. 3 and 4).

After entanglement begins to develop in an isolated environment, the equation for both the Greenberger and YaSin haunted measurement experiment and haunted quantum entanglement would be:

$$\psi = 1/\sqrt{2}\ [(A_u)|P_u\rangle + (A_l)|P_l\rangle]$$

With elimination of all which-way information before this information is released to the environment:

$$\psi = [1/\sqrt{2}\ [(A_u) + (A_l)]]\ [1/\sqrt{2}\ [|P_u\rangle + |P_l\rangle]]\ .$$

Since A and P are independent of one another, the situation regarding the atom can be represented as:

$$\psi = [1/\sqrt{2}\ [(A_u) + (A_l)]]$$

which is the wave function that would characterize the atom in the haunted quantum entanglement scenario or the neutron in the haunted measurement scenario if the which-way markers had never been introduced.

As is the case in haunted measurement, in haunted quantum entanglement instead of fringes and anti-fringes in the atomic distribution *one obtains interference as if the which-way information* *had never begun to develop (i.e., no fringes and anti-fringes that sum to an overall which-way distribution pattern)*. In summary, the reason why Greenberger and YaSin obtained interference as if the which-way markers had never existed in a haunted measurement, as opposed to Scully, Englert, and Walther who obtained fringes and anti-fringes that sum to the one broad hump indicative of which-way information, is that in a haunted measurement *no* which-way information of any kind is released to the environment and in a quantum eraser *general* which-way information *is* released but information concerning the *specific* path taken *is not* released into the environment. The distribution results obtained in a haunted measurement are expected in haunted quantum entanglement since *no* which-way information of any kind is released in haunted quantum entanglement before which-way information is lost.

One might argue that in the scenario proposed for haunted quantum entanglement that the purely formal orthogonality of the component wave function states for the photon (i.e., s + a and s – a where s refers to a symmetric wave function and a refers to an anti-symmetric wave function) are fixed with the interaction of the atom and photon in the cavity system and that this purely formal orthogonality cannot be lost even though orthogonality based on the physical separation of |P_l> and |P_r> when the single shutter separating the cavities is in place (i.e., no overlap) is lost when the single shutter is opened, in particular before the atom reaches the two slit screen.

A new scenario is now proposed that does not allow for the possibility that the orthogonality of the photon (whether purely formal or instead based on no overlap of component wave functions of the emitted photon) could exist in any meaningful way that could affect the atom by providing the basis for which-way information. The photon is essentially lost in the new scenario, a feature which closely resembles the Greenberger and YaSin haunted measurement where the which-way markers are indeed lost (even though the flexible mirror system and its effective equivalent continue to exist) by the time the neutron exits the flexible mirror system or its effective equivalent. The orthogonality that characterized the flexible mirror system and its equivalent when they served as which-way markers is lost by the time the neutron exits the flexible mirror system or its effective equivalent.

A New Scenario

The new scenario proposed may be even closer to Greenberger and YaSin's haunted measurement scenario than the original scenario noted for haunted quantum entanglement. In the Greenberger and YaSin haunted measurement scenario, before any which-way information is made available to the environment: 1) the which-way markers (i.e., the flexible mirror system and its equivalent) are effectively restored to their state prior to the interaction through which the developing entanglement between the entity serving as the which-way marker and the entity for which the which-way marker provides which-way information starts developing, and 2) the entity for which the which-way marker provides which-way information (i.e., the neutron) is restored to its state before it interacted with the entity which subsequent to the interaction became a which-way marker.[4] These two characteristics of the haunted measurement essentially characterize the new scenario for haunted quantum entanglement. As

[4] This is the state the neutron would have had if there were no flexible mirror apparatus located along one arm of the interferometer (the which-way marker had never started developing).

regards characteristic 1, before any which-way information is made available to the environment, the created photon which serves as a which-way marker is essentially lost in the new scenario and any which-way information that the photon carried is also lost. As regards characteristic 2, before any which-way information is made available to the environment, the atom that emitted the photon in the micromaser cavity system enters the state it would have had if the atom had never emitted the photon into one of the micromaser cavities. Characteristic 1 in achieved in full and characteristic 2 is achieved in part by the injection of classical microwave radiation into both of the microwave cavities. The achievement of characteristic 2 also relies on the presence of an rf coil situated at the exit of the micromaser cavity system. The new scenario for haunted quantum entanglement relies on changing certain features of Scully and his colleagues' quantum eraser scenario that have been discussed here.

In the new scenario, the photon emitted by the atom initially into one of the two micromaser cavities is subsequently essentially lost after the atom exits the micromaser cavity system and before the atom reaches the two slit screen. In that the photon is effectively lost without providing any trail leading back to the which-way information it once indicated, the atom can be placed in essentially the state that the atom would have been in if the photon was ever emitted initially into one or the other of the micromaser cavities. The other step that restores the system (in our case the atom alone since the photon was originally not in existence and later was essentially lost) to essentially the same state it was in before the photon was emitted will be discussed shortly.

In the original scenario presented above for haunted quantum entanglement, the photon is not effectively lost since it continues to be known that the photon exists and its state is also known. In the original scenario for haunted quantum entanglement presented above, it becomes *unknown into which cavity the photon had been emitted before the atom reaches the two slit screen*.

In the new scenario, the photon is *effectively lost* through the injection of classical microwave radiation into both of the microwave cavities: 1) after the atom initially emits the photon into one or the other of the micromaser cavities (which are tuned to the same frequency) and exits the cavity system, and 2) before the atom reaches the two slit screen (Figs. 5 and 6) (step 1).

Scully and his colleagues described a situation at the end of their paper on the quantum eraser where the micromaser cavities were filled with classical microwave radiation before the atom entered the cavity system.[5] They did this so as to negate any possibility of the emitted photon providing which-way information regarding the path of the atom through the cavity system. Their method is adopted in the new scenario for haunted quantum entanglement described above. The goals in the new scenario as regards the photon are to: 1) negate

[5] Scully and his colleagues wrote: "The micromasers will serve as welcher weg detectors only if the one extra photon left by the atom changes the photon field in a detectable manner. Thus whether which-pay information is available or not depends on the photon states initially prepared in the cavities. One extreme situation has just been discussed: no photons initially, one photon in one of the detectors finally. Clearly, here one can tell through which cavity, and therefore through which slit, the atom came to the screen. The situation is quite different when the cavities contain classical microwave radiation with large (average) numbers of photons, N1 and N2, which have spreads given by their square roots. For instance, the change in photon number in cavity 1 is now from $N_1 \pm (N_1)^{1/2}$ to $N_1 + 1 \pm (N_1)^{1/2}$. This change cannot be detected, because $(N_1)^{1/2} >> 1$, so that there is no which path information available" (p. 114).

any which-way information that the emitted photon possessed before any measurement information regarding the emitted photon and the atom that emitted the photon is released to the environment (per Greenberger and YaSin's criterion for when a measurement is completed), and 2) effectively lose the photon before any measurement information regarding the emitted photon and the atom that emitted the photon is released to the environment. The result of attaining these goals is that the state of the atom after the photon is effectively lost is the state the atom would have had if it had never emitted the photon.

The atom (i.e., the entity about which the photon could possibly provide which-way information initially [but does not in fact because of the isolation of the atom photon system]) is placed in the state it would have been in if the atom had never emitted the photon into one of the micromaser cavities in part by an rf coil situated at the exit of the micromaser cavity system (step 2). The use of the rf coil in this way was noted by Scully and his colleagues[5] at the end of their paper where they briefly discuss a situation that is not a quantum eraser. As noted, in their discussion at the end of their paper of this other situation, Scully and his colleagues also provide the basis for the effective loss of the photon so that it cannot provide which-way information. Scully and his colleagues proposed that the micromaser cavities be filled with classical microwave radiation prior to the time the atom enters the cavity system and emits a photon into one or the other of the two cavities. Because of the presence of the classical microwave radiation in each cavity, the emitted photon does not provide which-way information as regards through which cavity the atom traveled.

Haunted Quantum Entanglement

In the new scenario for haunted quantum entanglement, the micromaser cavities are initially devoid of any microwave radiation so that when the atom passes through the cavity system and emits a photon initially into one or the other of the cavities, this photon could provide which-way information regarding the atom (if information that a which-way measurement has been made is released to the environment).[6] Subsequent to the atom exiting the cavity system and before the atom reaches the two slit screen, each of the cavities are filled with classical microwave radiation so that the photon emitted by the atom is effectively lost and of course does not provide which-way information. (Parenthetically, the wave functions for the emitted photon are no longer orthogonal once the cavities are filled with classical microwave radiation since the photon is lost and as far as the situation concerning the atom goes effectively no longer exists.)

In Scully and his colleagues' discussion, the two cavities are tuned to two different frequencies so that the photon emitted by the atom has either one or the other of the frequencies of the micromaser cavities (Fig. 7). The atom thus exits the system in one of two differing states so the atom carries its own which-way information. (These changes in the atom's state are not related to the atom's motion.) Scully and his colleagues positioned an rf coil in one of the paths for one of the cavities in the cavity system so that if the atom exited along that path the atom would be placed in the same state as if the atom exited along the other path. In the atom's passing through the rf coil field, should it do so, which-way information carried by the atom is lost. (It is interesting that even though the atom thus is in the same state

[6] The release of such information follows Greenberger and YaSin own analysis for what would preclude a haunted measurement.

after having exited the cavity system by either path, the state of the atom after exiting the cavity system is nonetheless different from the state of the atom before it entered the cavity system and emitted the photon initially into one or the other of the micromaser cavities. Nonetheless, the interference exhibited for the atom distribution is no different according to Scully and his colleagues than would be the case if the atom had never passed through the cavity system or rf coil field on its path to the detection screen.)

In the new scenario presented for haunted quantum entanglement, the rf coil field extends over both paths for both of the micromaser cavities. Since the cavities are each tuned to the same frequency, the concern here is to place the atom in the original state it had before it entered the micromaser cavity system and emitted the photon initially into one of the two micromaser cavities (and not to match two differing states of the atom depending upon which cavity the atom passed through). In the new scenario, the atom exits either of the cavities in the same state since the cavities are tuned to the same frequency. The state of the atom after the atom exits the cavity system corresponds to the state of the neutron in the interferometer of Greenberger and YaSin in which the neutron is returned to the state it had before it entered the flexible mirror apparatus or its effective equivalent when it exits the flexible mirror apparatus or its effective equivalent.

As noted, the new scenario proposed here relies on methodology proposed by Scully and his colleagues at the end of their paper (i.e., the cavities filled with classical microwave radiation and the field generated by the rf coil) to accomplish a similar goal for the atom and photon that Scully and his colleagues wanted to accomplish with their methodology, that is restoring the atom to a state where it exhibits interference as if the atom had never passed through the micromaser cavity system. The only difference between the new scenario proposed here for haunted quantum entanglement and the scenario of Scully and his colleagues is that Scully and his colleagues relied on eliminating which-way information *carried by the atom itself* before it reached the two slit screen to obtain an interference pattern for the distribution of atoms that would exist if the cavity system and rf coil had never been used. In the new scenario here, the which-way information that is eliminated is *carried by the photon emitted by the atom* initially into one or the other of the two cavities before the atom reaches the two slit screen to obtain an interference pattern for the distribution of atoms that would exist if the cavity system and rf coil had never been used. For Scully and his colleagues, the atom serves as its own which-way marker. In the new scenario discussed here the photon is the which-way marker for the atom. For Scully and his colleagues, the which-way marker *travels* with the atom. For the new scenario here, the which-way marker *does not travel* with the atom.

As noted above, in the new scenario the atom (i.e., the entity about which the photon could possibly provide which-way information initially [but does not in fact because of the isolation of the atom photon system]) is placed in the state it would have been in if the atom had never emitted a photon into one of the two micromaser cavities by an rf coil situated at the exit of the micromaser cavity system. The basis for the use of the rf coil used to place the atom in the state it would have been in if the atom had never emitted a photon into one of the two micromaser cavities and how the rf coil is used are described above.

Conclusion

More evidence has been discussed that haunted quantum entanglement can be demonstrated empirically through the provision of a new scenario that essentially places the system concerning which which-way information begins to develop into the state it would have had if the which-way information had never developed. In so doing, the developing quantum entanglement in which the which-way information began to be developed is lost before any of the developing which-way information is released to the environment. Techniques are used in the new scenario that have been discussed by Scully, Walther, and Englert to discuss another phenomenon besides haunted quantum entanglement. There is no reason why these techniques are not applicable in the new scenario proposed here that demonstrate haunted quantum entanglement.

References

[1] D. Greenberger and A. YaSin, The haunted measurement in quantum theory. In D. M. Greenberger, New Techniques and Ideas in Quantum Measurement Theory (pp. 449-457) as part of Annals of the New York Academy of Sciences (Vol 480). New York: New York Academy of Sciences, 1986.

[2] D. Greenberger and A. YaSin, A. "'Haunted' measurements in quantum theory." Found. of Phys., **19**, 679-704, 1989.

[3] P. S. Epstein, "The reality problem in quantum mechanics." American Journal of Physics, **13**, 127-136, 1945.

[4] P. R. Feynman, R. B. Leighton, and M. Sands, (1965). The Feynman Lectures on Physics: Quantum Mechanics (vol. 3). Reading: Massachusetts: Addison-Wesley.

[5] M. O. Scully, B. G. Englert, and H. Walther, "Quantum optical tests of complementarity." Nature (London), **351**, 111-116, 1991.

[6] D. M. Snyder, "Is it possible to use a quantum eraser to send binary data to a remote location?" 2004, CERN preprint: http://doc.cern.ch//archive/electronic/other/ext/ext-2004-101.pdf .

[7] D. M. Snyder, "Haunted Quantum Entanglement", 2009 Joint Spring Meeting of the Ohio Sections of the APS and AAPT. http://meetings.aps.org/link/BAPS.2009.OSS.P1.27 .

[8] D. M. Snyder, "Is It Possible to Use a Quantum Eraser to Send Binary Data to a Remote Location?" – May 2009. http://cdsweb.cern.ch/record/1053182?ln=en .

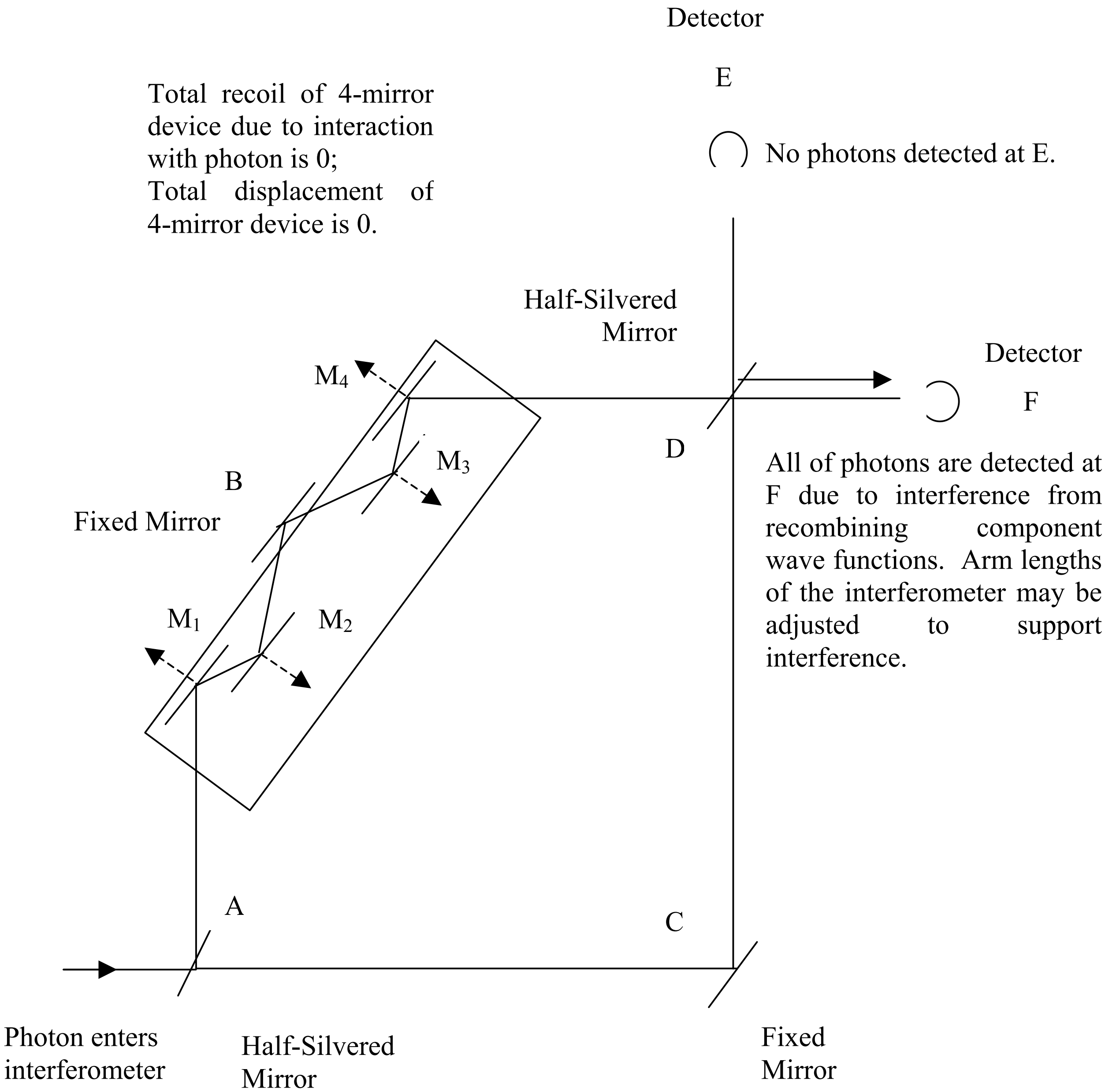
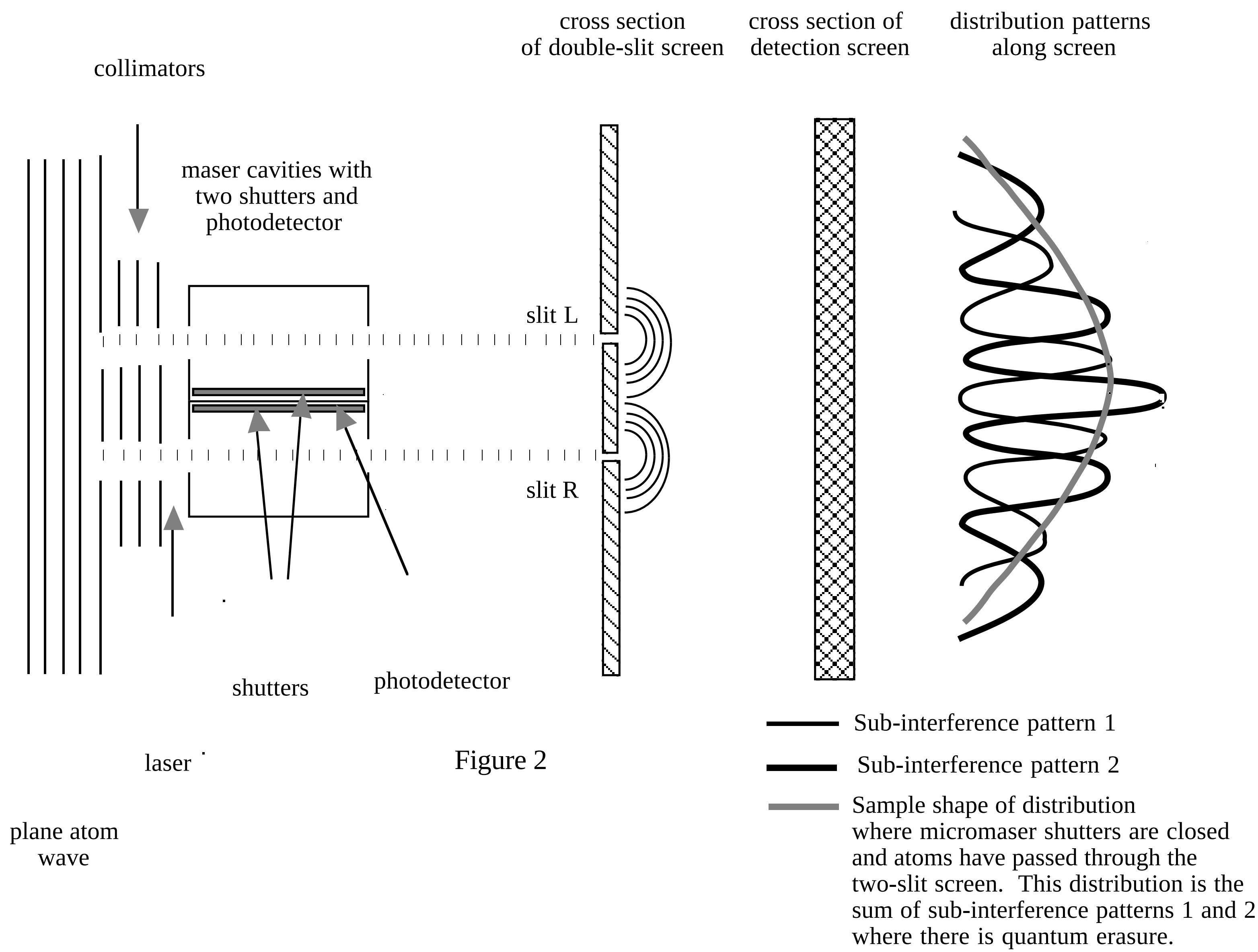


Figure 1: Interferometer with 4-Mirror Device Separated from the Environment: Component Wave Functions Are Recombined to Demonstrate Interference



cross section
of double-slit screen
cross section of
detection screen
distribution patterns
along screen
collimators
maser cavities with
two shutters and
photodetector
slit L
slit R
shutters
photodetector
laser
plane atom
wave
Sub-interference pattern 1
Sub-interference pattern 2
Sample shape of distribution
where micromaser shutters are closed
and atoms have passed through the
two-slit screen. This distribution is the
sum of sub-interference patterns 1 and 2
where there is quantum erasure.

Figure 2

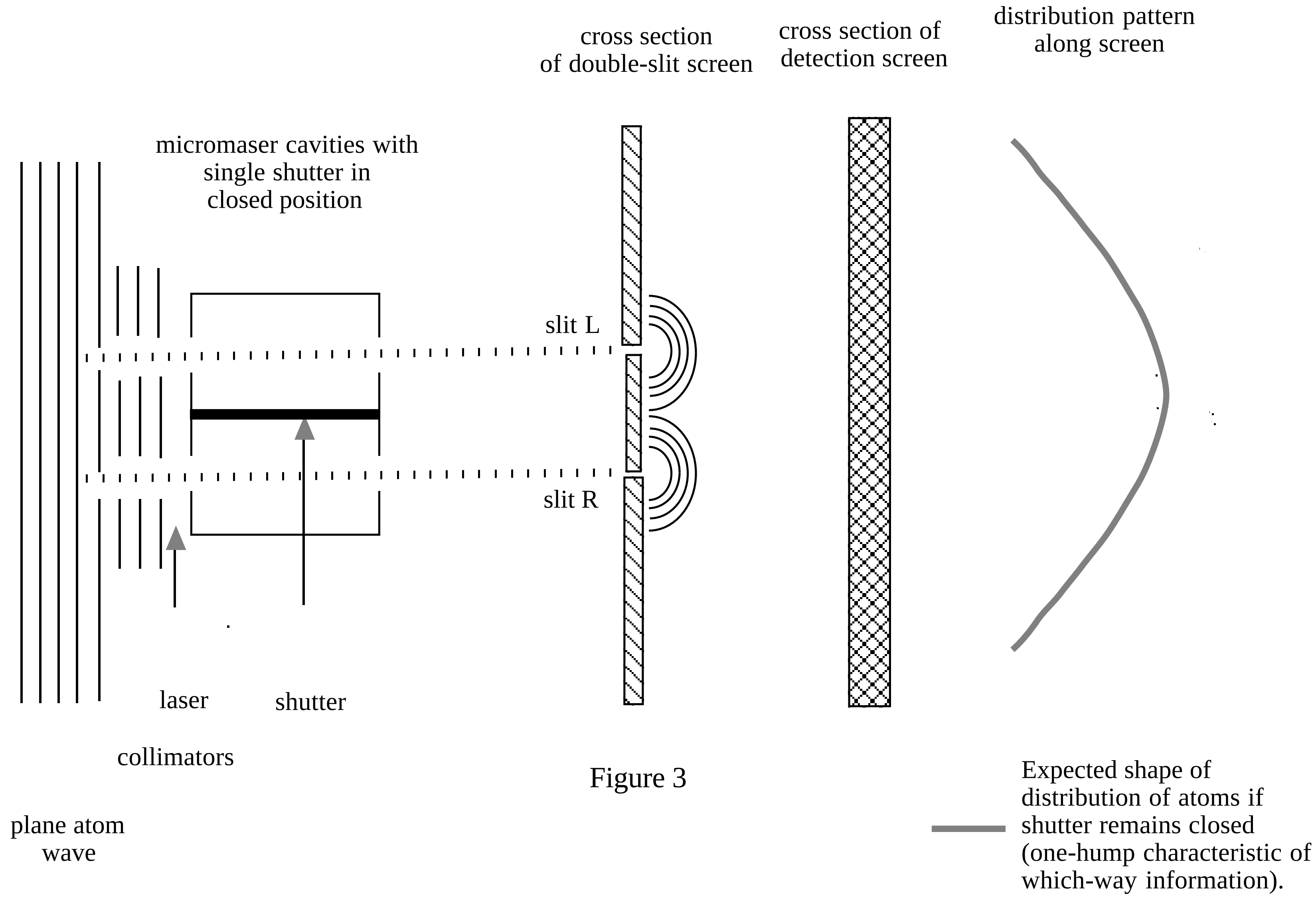

cross section
of double-slit screen
cross section of
detection screen
distribution pattern
along screen
micromaser cavities with
single shutter in
closed position
slit L
slit R
laser
shutter
collimators
plane atom
wave
Expected shape of
distribution of atoms if
shutter remains closed
(one-hump characteristic of
which-way information).

Figure 3

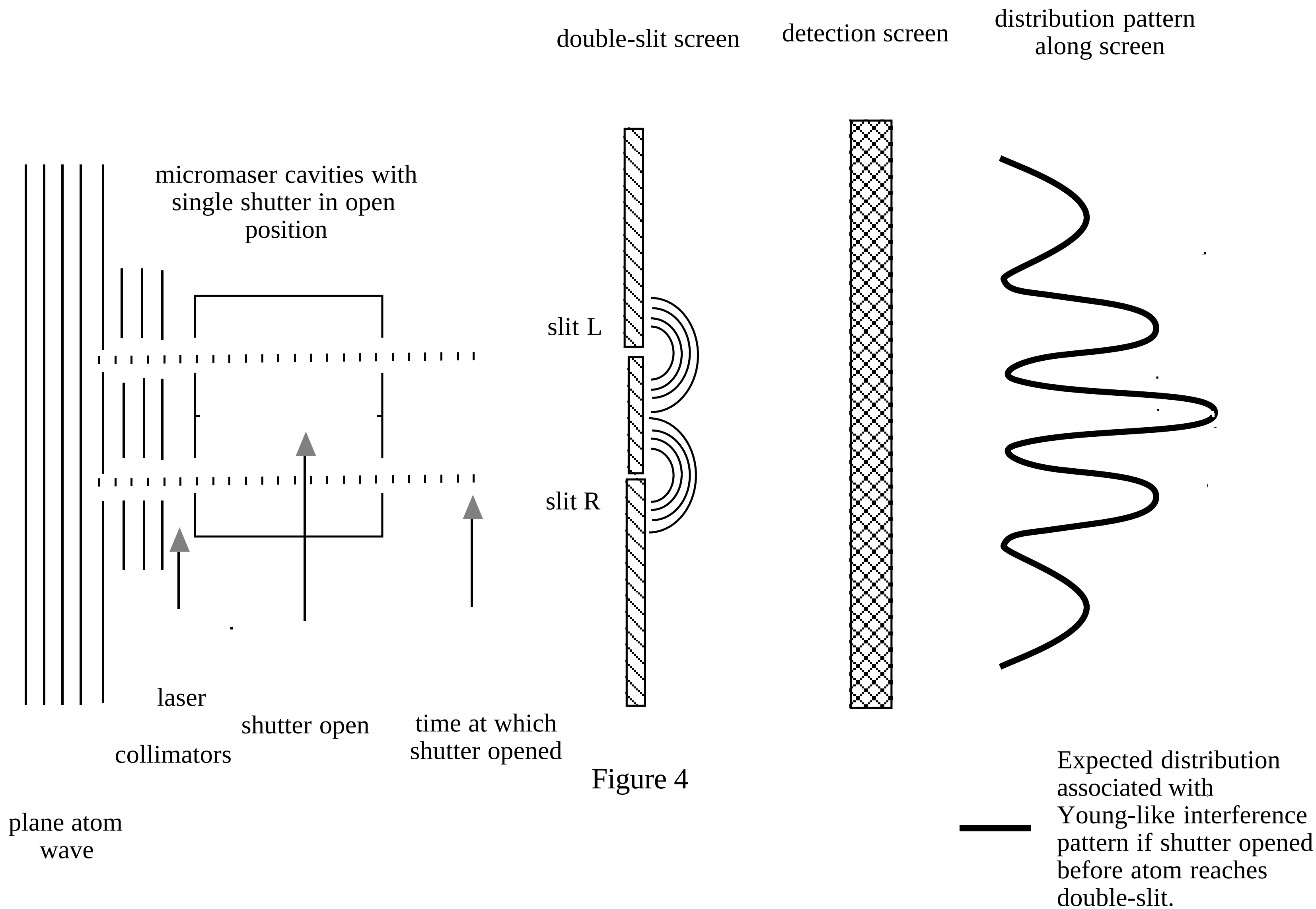
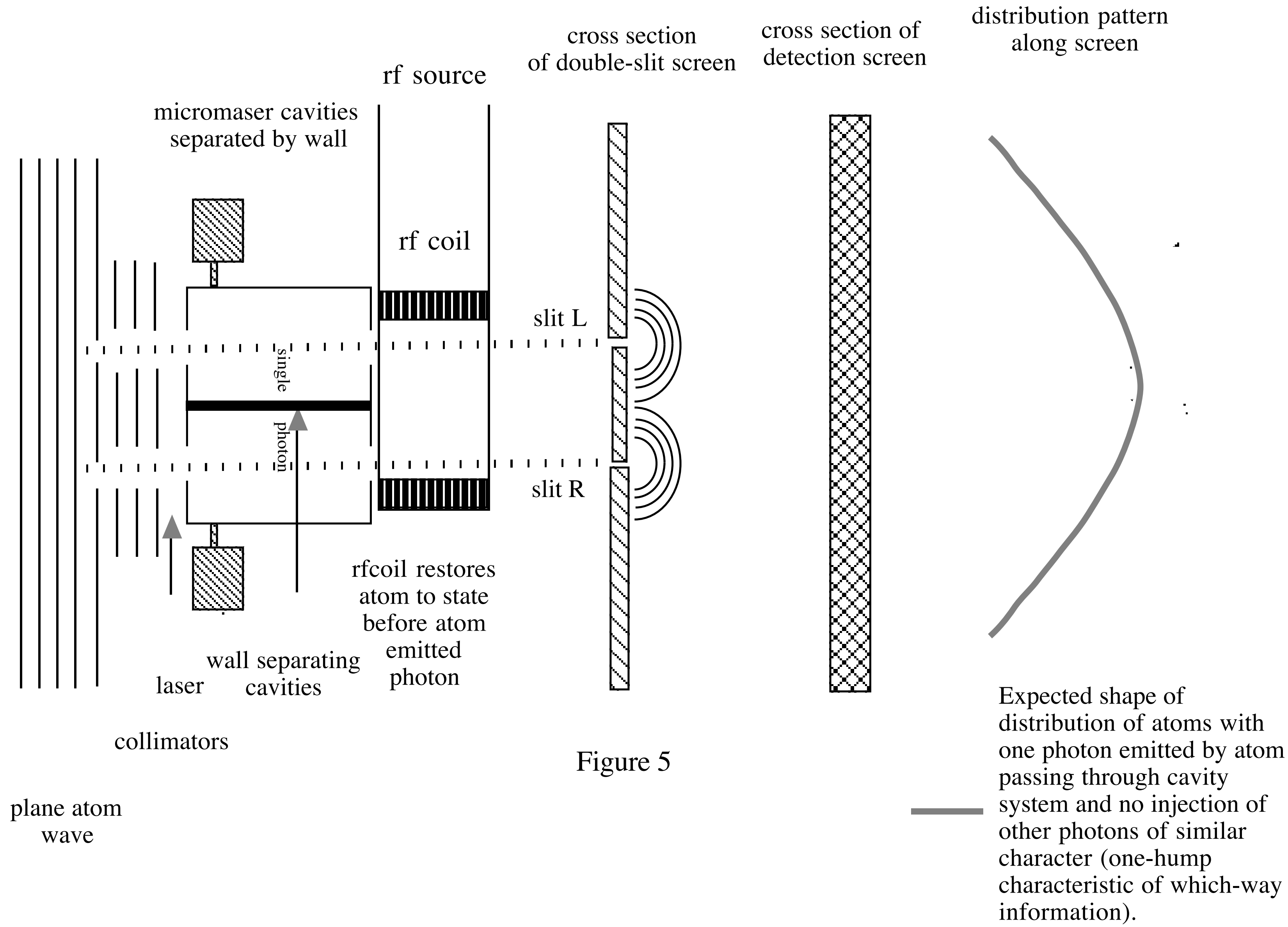

double-slit screen
detection screen
distribution pattern
along screen
micromaser cavities with
single shutter in open
position
slit L
slit R
laser
shutter open
time at which
shutter opened
collimators
plane atom
wave
Expected distribution
associated with
Young-like interference
pattern if shutter opened
before atom reaches
double-slit.

Figure 4



micromaser cavities
separated by wall
rf source
cross section
of double-slit screen
cross section of
detection screen
distribution pattern
along screen
rf coil
slit L
single
photon
slit R
rfcoil restores
atom to state
before atom
emitted
photon
wall separating
cavities
laser
collimators
plane atom
wave
Expected shape of
distribution of atoms with
one photon emitted by atom
passing through cavity
system and no injection of
other photons of similar
character (one-hump
characteristic of which-way
information).

Figure 5

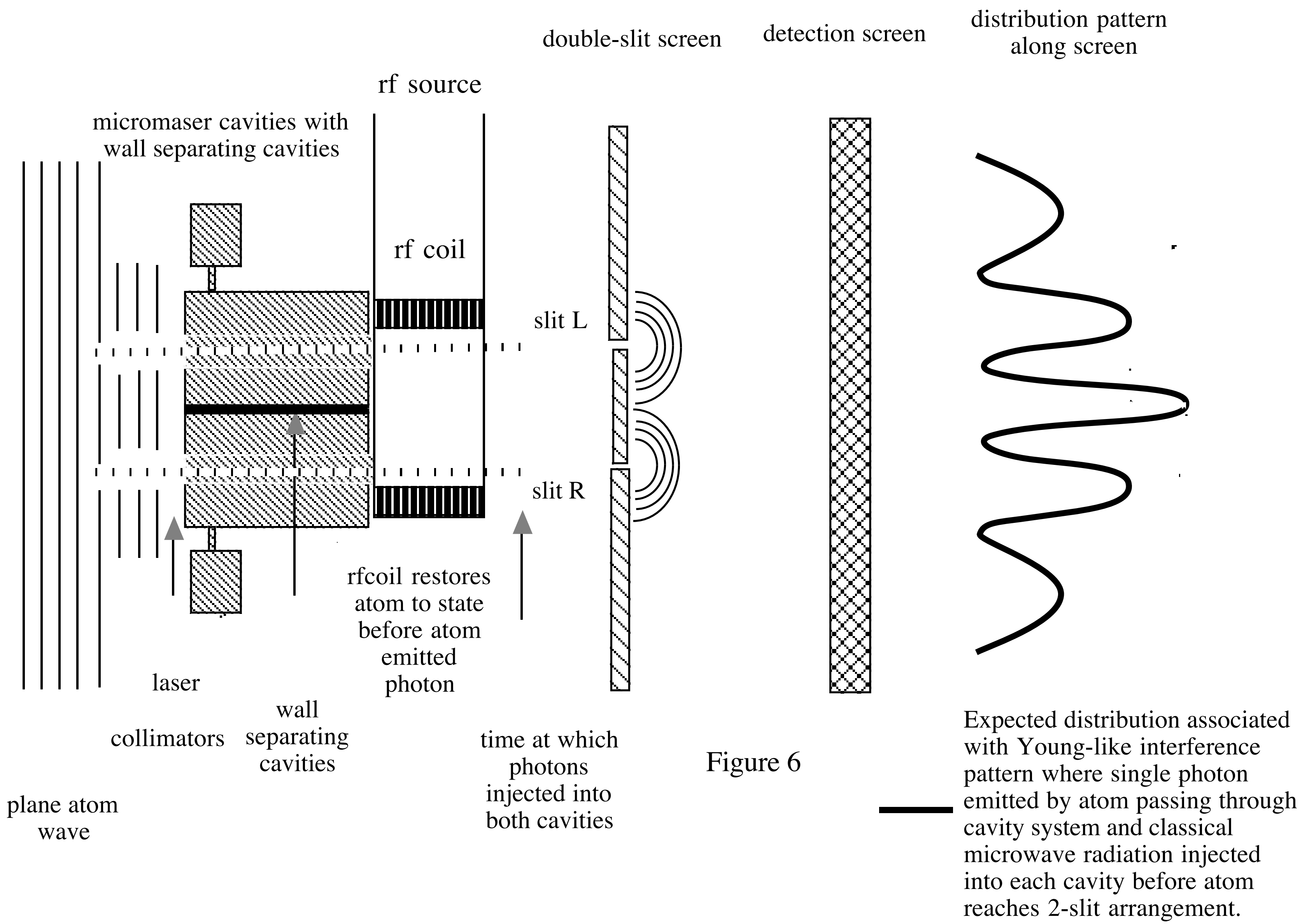

double-slit screen
detection screen
distribution pattern along screen
rf source
micromaser cavities with wall separating cavities
rf coil
slit L
slit R
rfcoil restores atom to state before atom emitted photon
laser
wall separating cavities
collimators
time at which photons injected into both cavities
plane atom wave
Expected distribution associated with Young-like interference pattern where single photon emitted by atom passing through cavity system and classical microwave radiation injected into each cavity before atom reaches 2-slit arrangement.

Figure 6

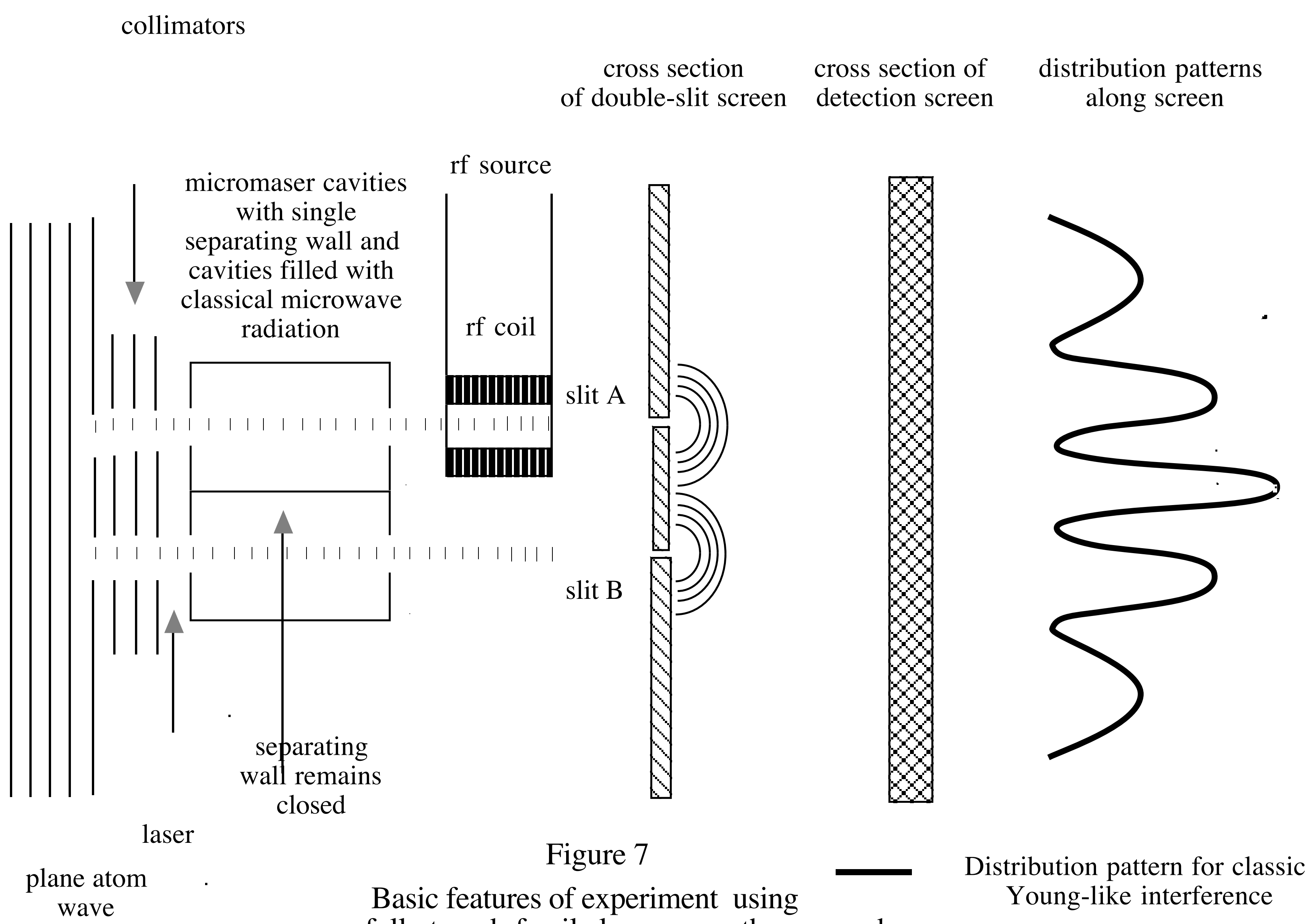


Figure 7

Basic features of experiment using
a carefully tuned rf coil along one path proposed
by Scully and colleagues where
passage by coil changes state of atom
on path to slit A to the same state the
atom would have were it on path to slit B.