Cramer's Transactional Interpretation and the "Quantum Liar" Experiment

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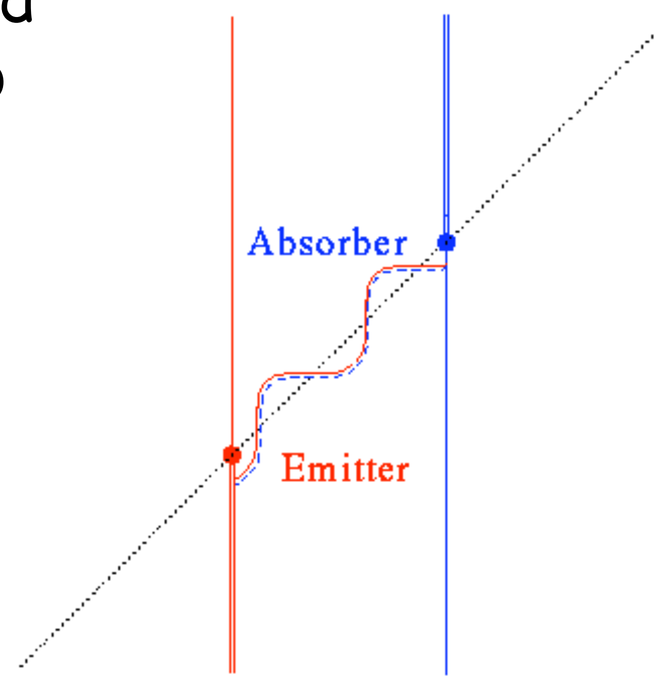
overview of talk

- quick review of TI
- review of IFM ("interaction free measurements")
- The QLE (quantum liar experiment) as a kind of IFM
- How TI resolves paradoxical aspects of the QLE
- 'paradigm-busting' aspects of this account

A Wheeler-Feynman Electromagnetic "Transaction"

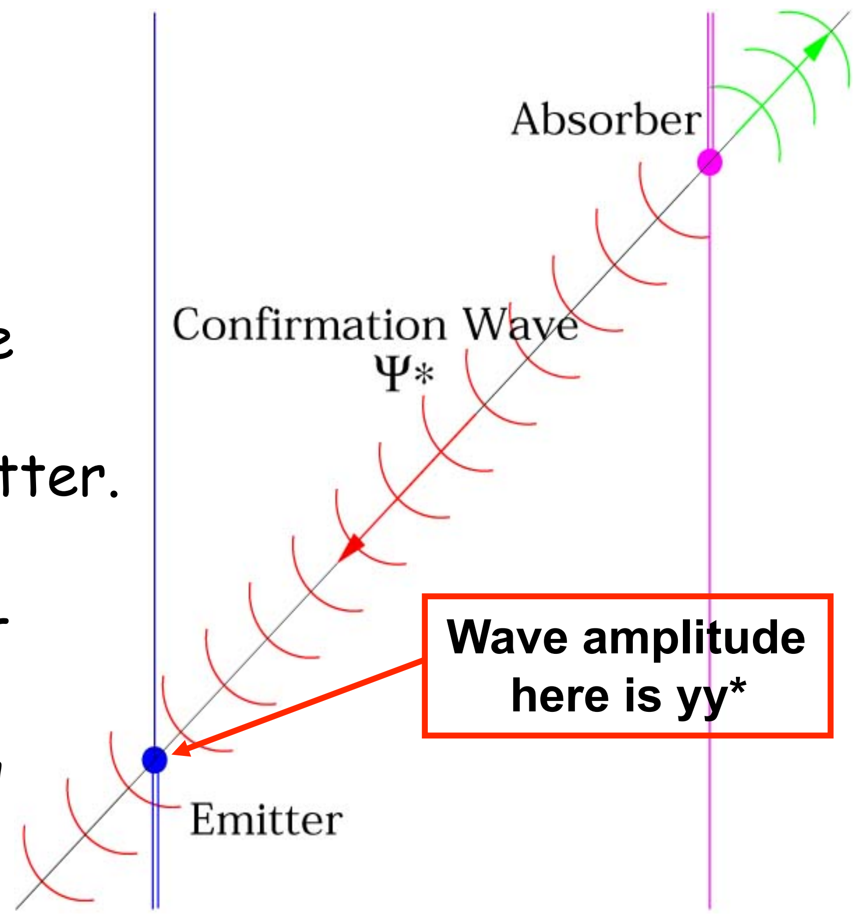
- The emitter sends retarded and advanced waves. It "offers" to transfer energy.
- The absorber responds with an advanced wave that "confirms" the transaction.
- The loose ends cancel and disappear, and energy is transferred.



(These two slides courtesy of John G. Cramer)

The TI and the Born Probability Law

- Starting from E&M and the Wheeler-Feynman approach, the E-field "echo" that the emitter receives from the absorber is the product of the retarded-wave E-field at the absorber and the advanced-wave E-field at the emitter.
- Translating this to quantum mechanical terms, the "echo" that the emitter receives from each potential absorber is $y_i\, y_i^*$, leading to the Born Probability Law.

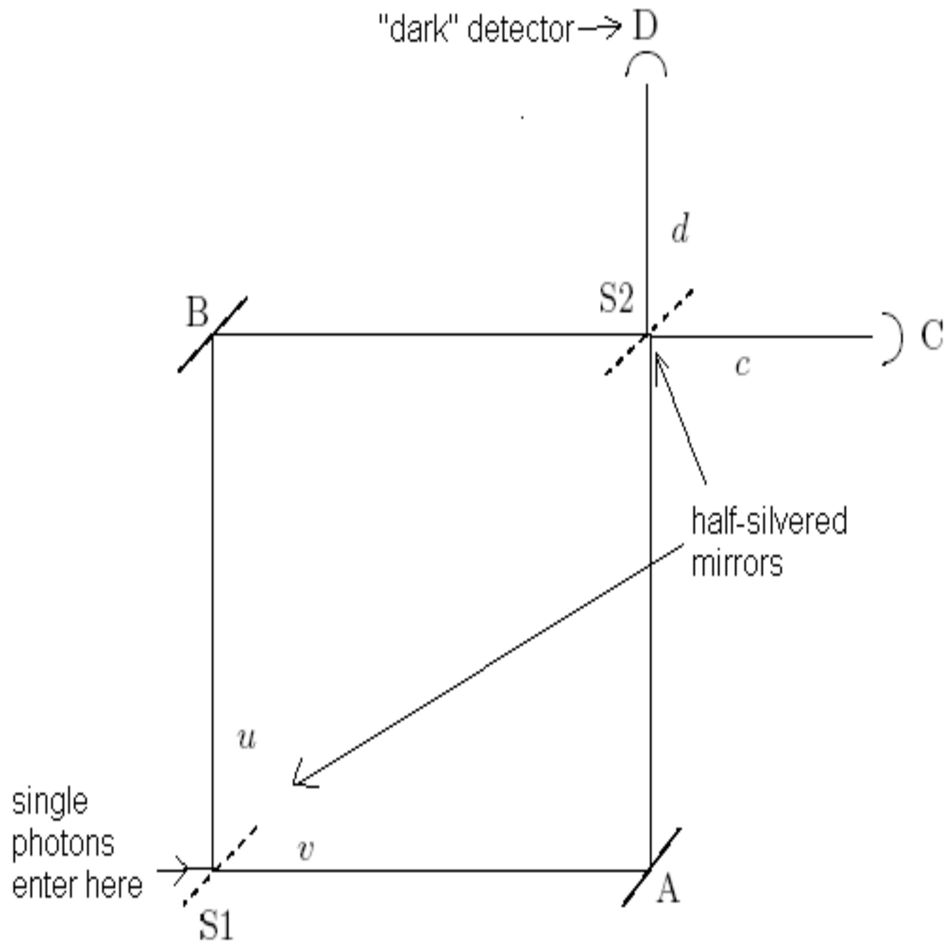


Review: Interaction-Free Measurements (IFM)

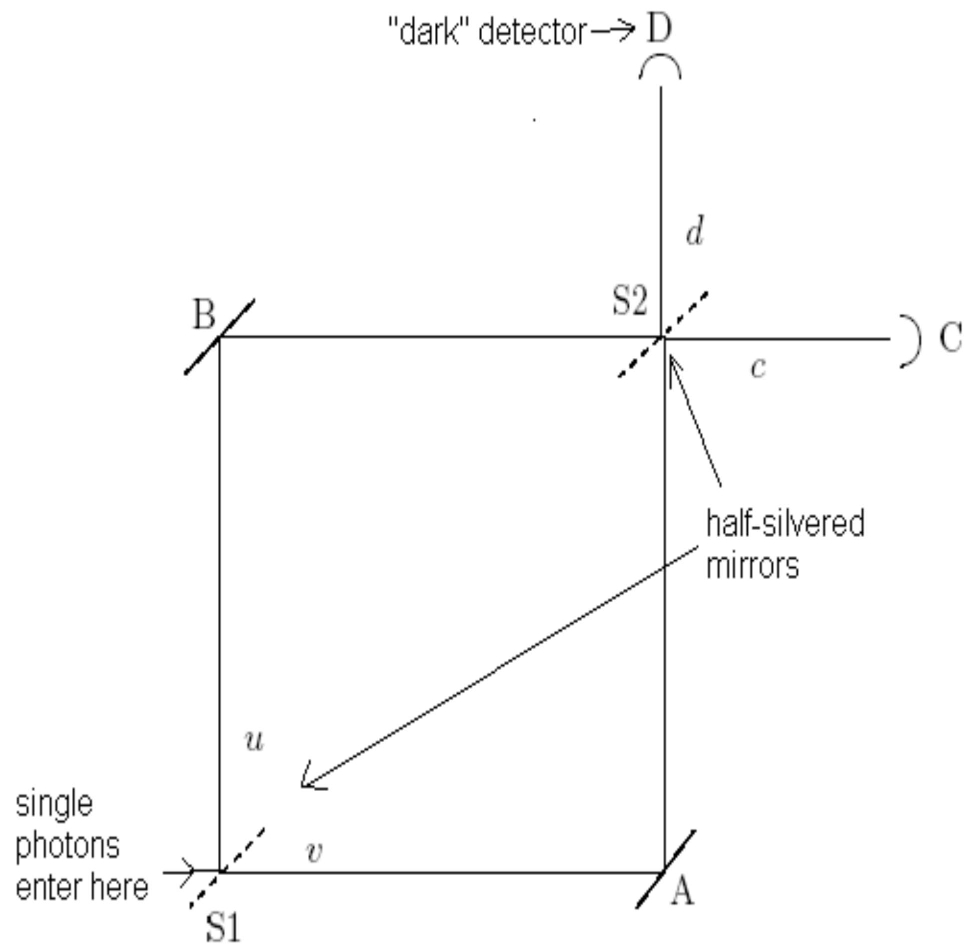
1. Elitzur-Vaidman (1993); Avshalom Elitzur gets his idea from Cramer's 1986 Rev.Mod.Phys. paper referencing Renninger "negative-outcome" experiment (1953). The E-V IFM is presented as a way to test whether a bomb is "live" and functional without setting it off.
2. Hardy (1992) replaces the bomb with a superposed atom
3. Elitzur, Dolev and Zeilinger (2002) add a second superposed atom to create the "quantum liar" experiment.

IFM Basics: The Mach-Zehnder Interferometer

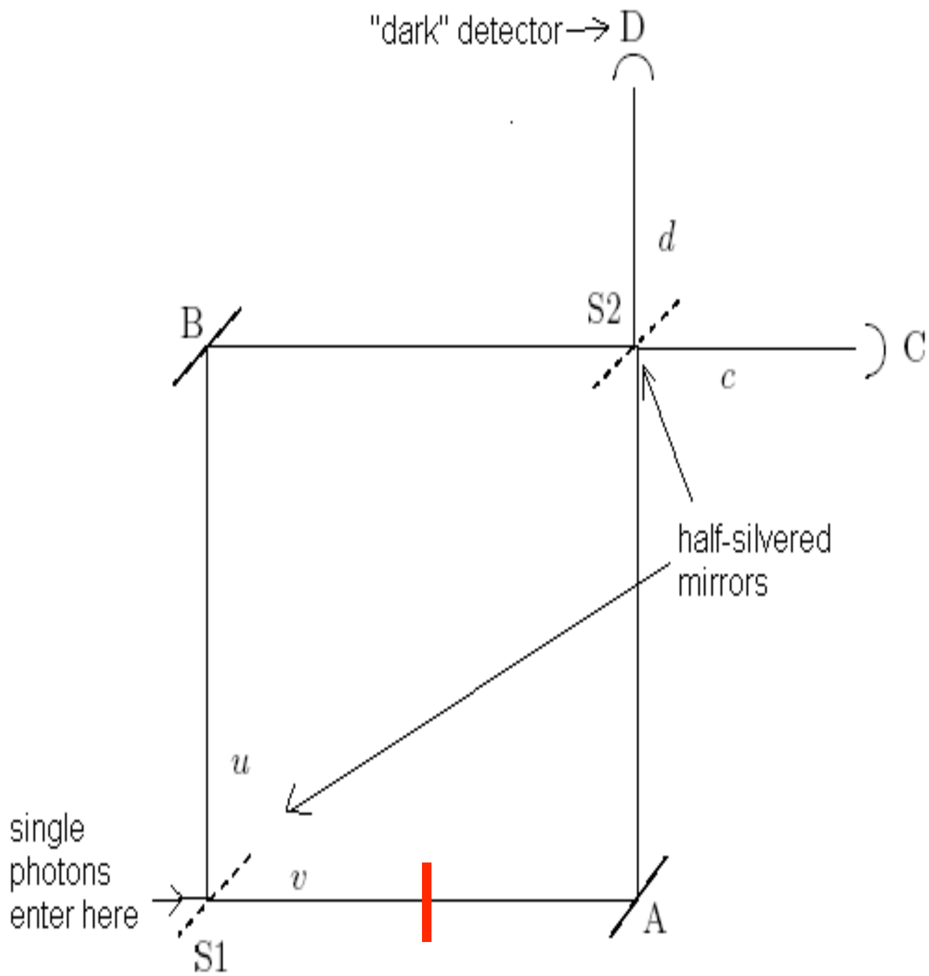
- photons reflected at beam splitters S_1 and S_2 acquire a quarter wavelength phase lag
- combined phase differences produce destructive interference on path d to detector D



So: all photons will be detected at C, and no photons will be detected at D; D is the “dark” detector.

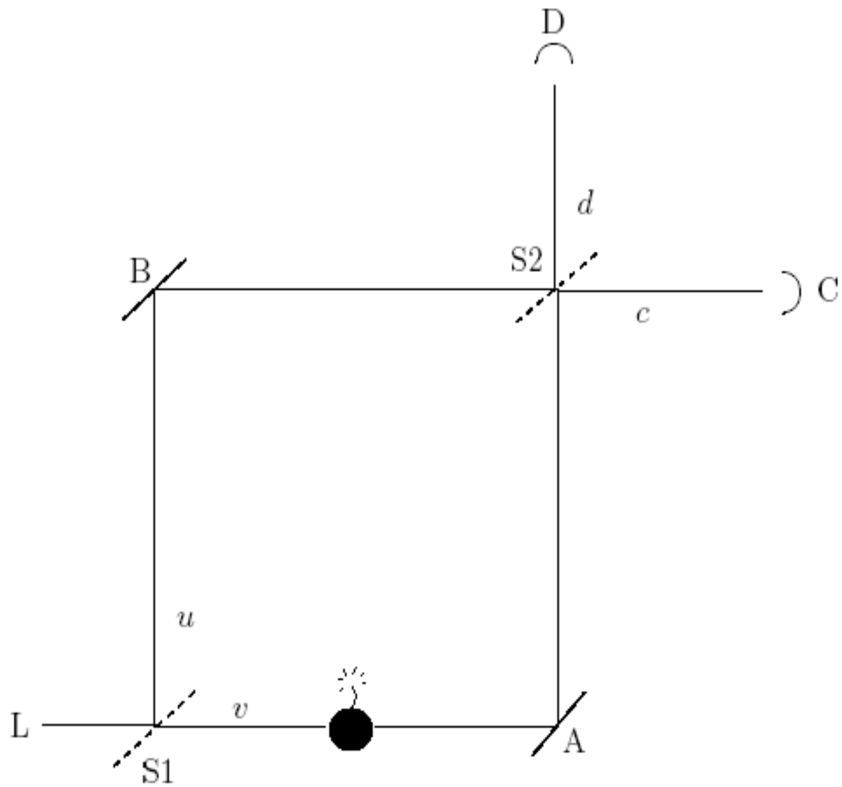


Suppose we place an opaque object in one of the arms (the lower one, v). Now, a photon can only get to the detector area by going along arm u (the upper arm in the diagram).
This disrupts the destructive inteference, allowing some photons to be detected at D. (Some will be absorbed by the object.)



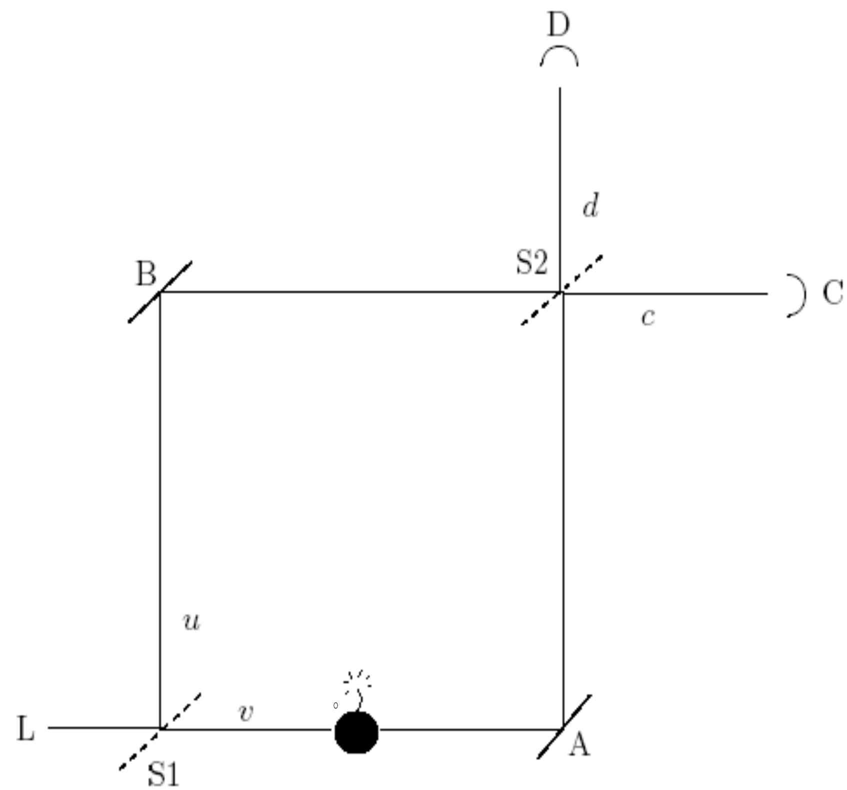
IFM 1: Bomb Tester

Now place a bomb, whose trigger is a photon detector, in one of the arms. If the trigger is working, its presence as a detector will disrupt the destructive interference on the path to D (as in the previous case). As we run the experiment many times,some of the bombs will detect a photon and explode, but in some cases, a photon will be detected at D. We know that these bombs are functional, even though they did not detonate!



A functional bomb can detect photons.

On the other hand, if the bomb's trigger is defective (i.e., is not capable of detecting a photon), it will never explode, but neither will it disrupt the destructive interference, and D will remain dark (no photons will be detected at D).



A defective bomb does not obstruct the photon's path.

IFM 1: Bomb Tester (quantitative)

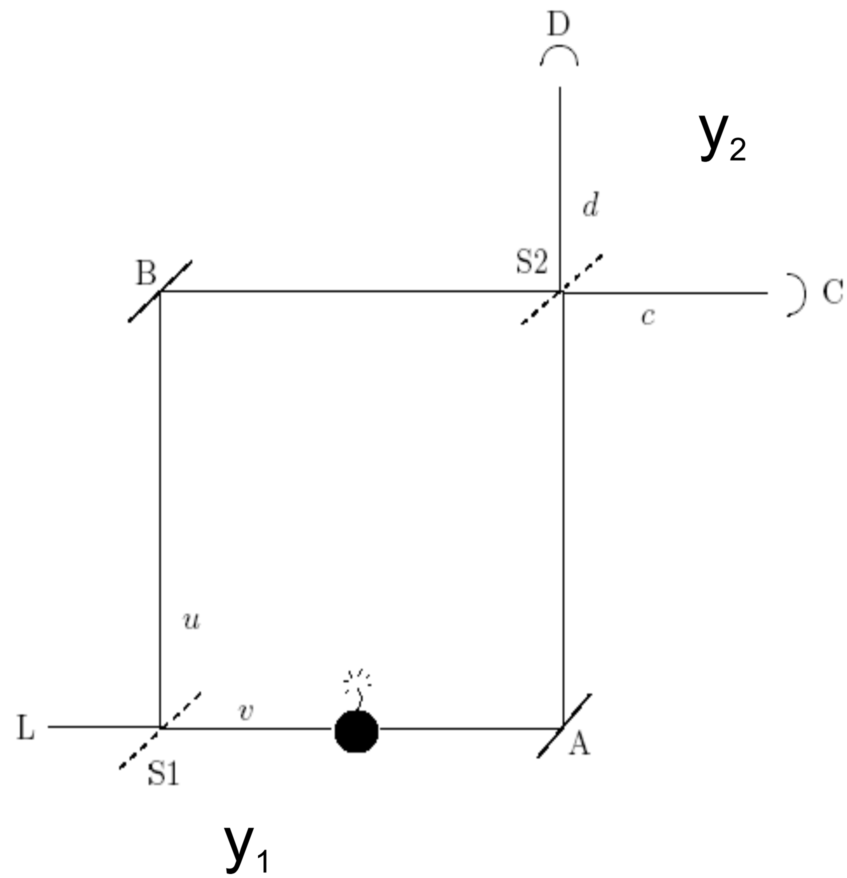
$y_1 = 1/\sqrt{2}[\, i|u\rangle + |v\rangle]$

$y_2 = i/\sqrt{2}\,[(1/\sqrt{2})\,(i\,|d\rangle+|c\rangle)]$

$+ \quad 1/\sqrt{2}\,|v\rangle$

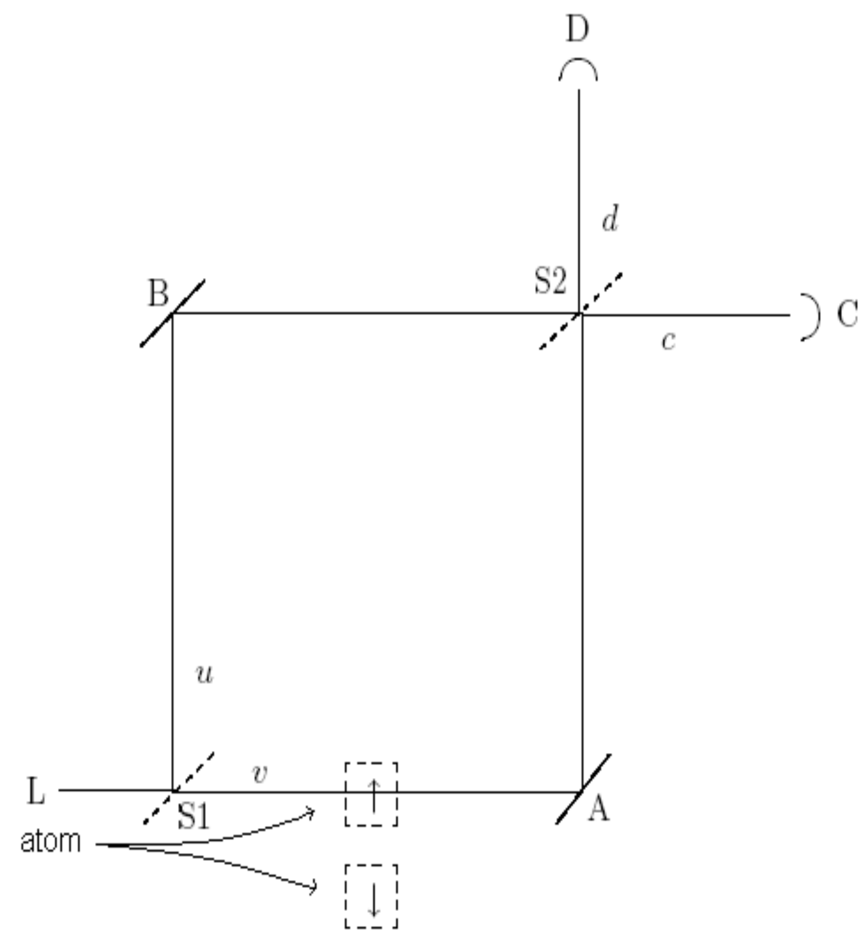
$=1/2[-|d\rangle + i\,|c\rangle] + 1/\sqrt{2}|v\rangle$

- P(D)= ¼ if bomb present and functional



IFM 2: a QM"bomb"

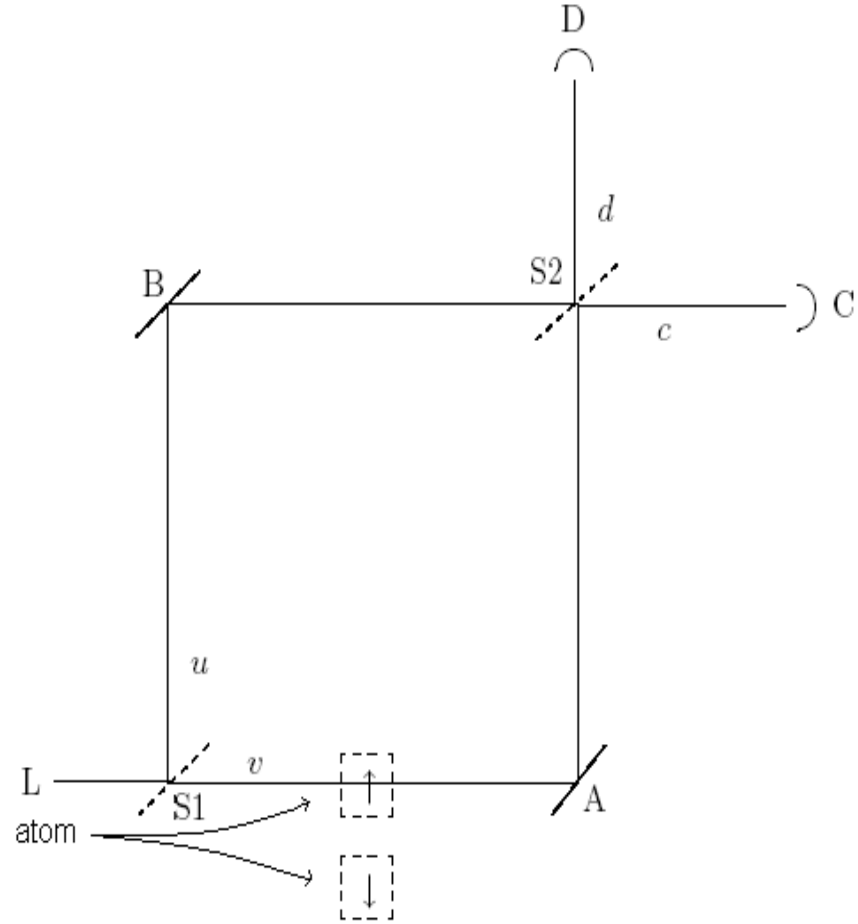
Hardy (1992) proposed
 replacing the bomb by
a quantum object, a
spin-1/2 atom. The atom is
spatially separated into its
component Z-spin states
('up' or 'down'), using a
suitably oriented Stern –
Gerlach (SG) device.



$|a\rangle = 1/\sqrt{2}(|\uparrow\rangle +|\downarrow\rangle)$

IFM 2: a QM"bomb"

The photon may be intercepted by the atom (probability = 1/4), or it may be detected at one of the detectors: C (P=5/8) or D (P=1/8).



|a>= 1/[illegible]2(|[illegible]> +| [illegible] >)

IFM 2: a QM "bomb"
(quantitative)

Y_1= ½ [i|u> + |v>] [|□> +|□ >]

= ½ { |v> |□> + i|u> |□>

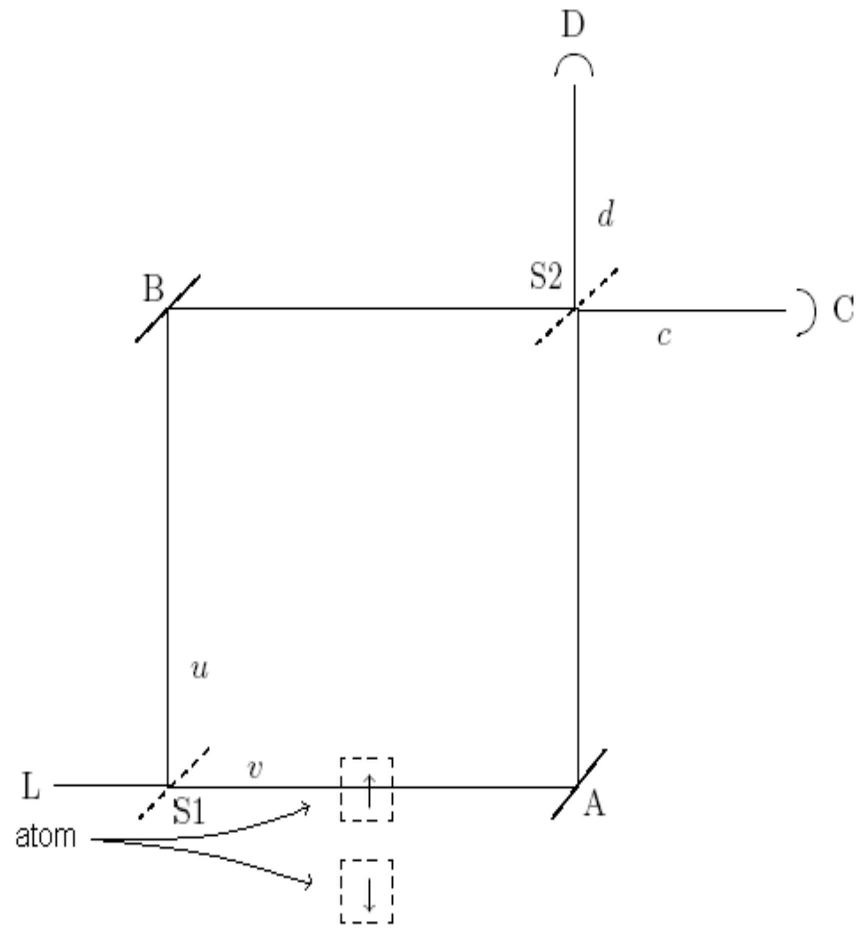
+ |v> |□ > + i|u> |□ > }

Omitting the term (in red) leading to interception by the atom:

Y_2 = ½ { i|u> |□> + |v> |□ > + i|u> |□ > }

= -1/(2□2) |d>|□> + i/(2□2) |c> |□>

+ i/□2 |c>|□ >

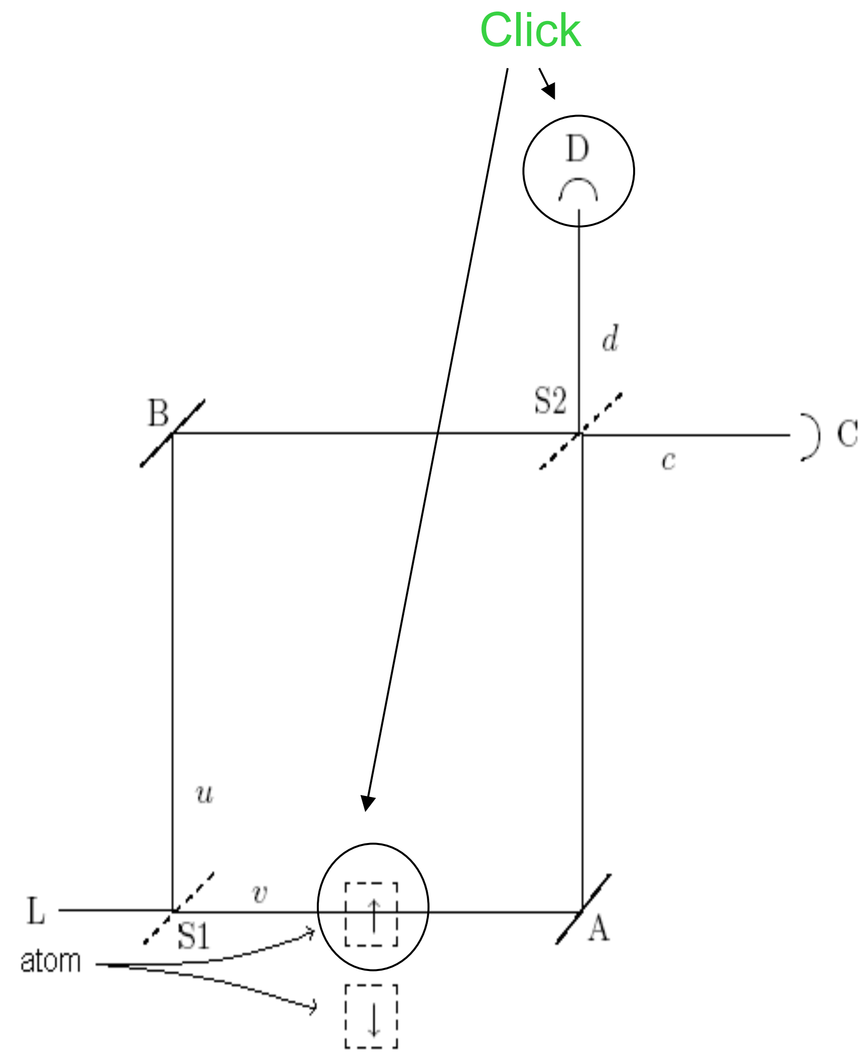


|atom>= 1/□2(|□> +|□ >)

IFM 2: a QM"bomb"

If the photon is detected at D, we find that the atom has been "collapsed" to the state 'up' (along path *v*), even though (according to the usual way of thinking)*, no photon has interacted with it.

*to be explicated...



|a>= 1/□2(|□> +| □ >)

IFM 3: the "Quantum Liar"

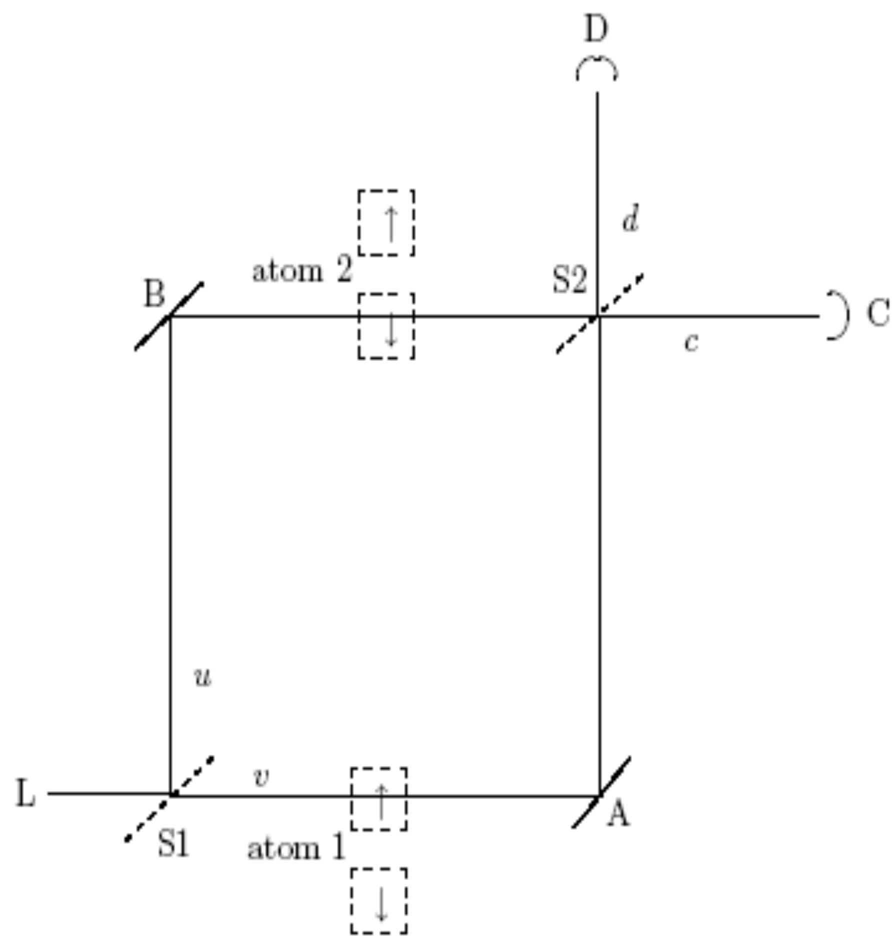
A second superposed atom is added along arm *u*.

Now photons can be absorbed on either arm, but can also reach D:

$$P(D) = 1/16$$

The total system state for photons reaching D is:

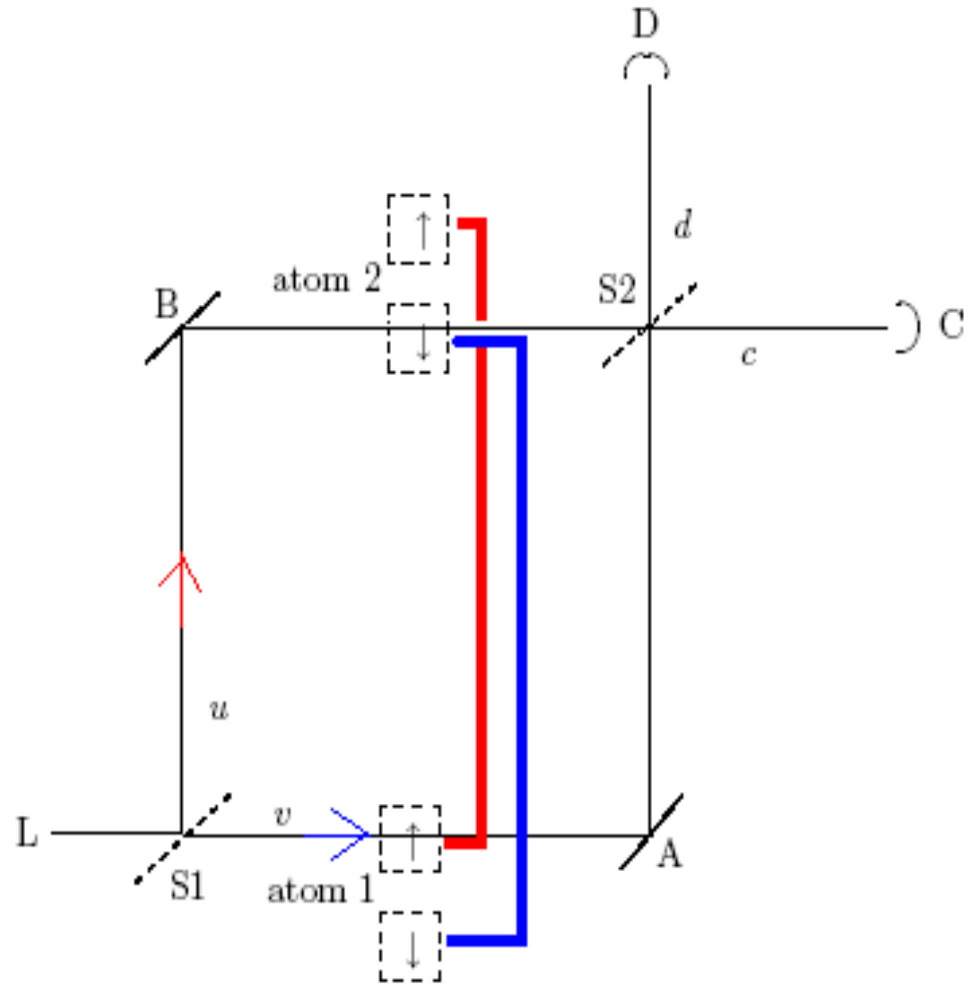
Y_D= ¼|d>(|[illegible] [illegible] > + |[illegible] [illegible] >)



$Y_D = \frac{1}{4}|d\rangle(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)$

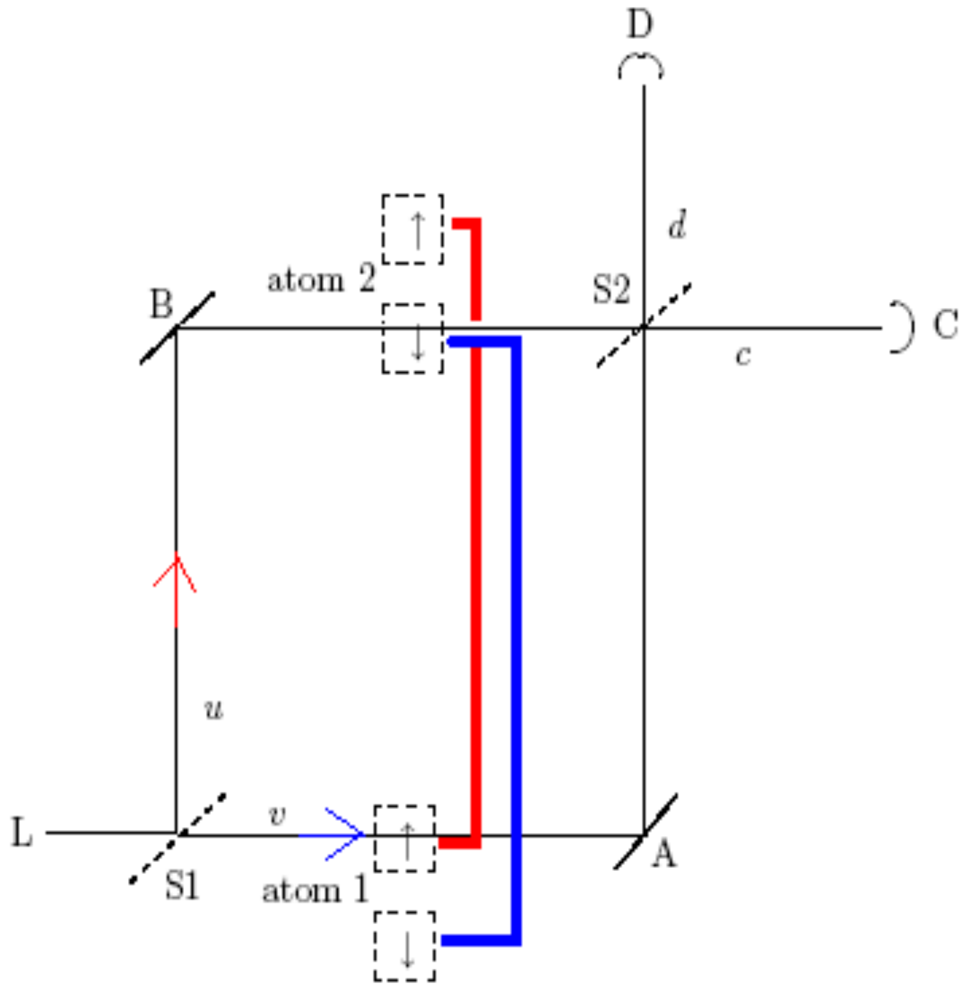
Note that this is an EPR state for the atoms! They are now entangled, despite having no mutual interaction, either in the past or the future.

If you open one of the boxes, say #1, and find it 'up,' then you know for certain that the other atom is 'up' as well, and vice versa. This in turn seems to give information about which arm the photon took to get to D.



But this seems paradoxical:

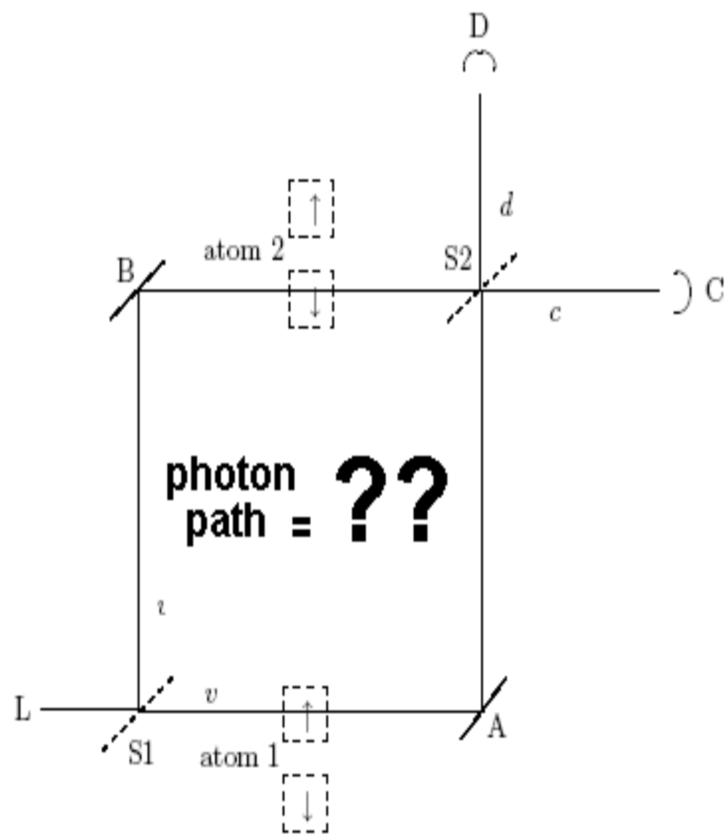
If the photon *really* went along the arm without the atom in the blocking box (which seems to be the only way it could get to D), how could it affect BOTH atoms to get them correlated in this way? As Elitzur and Dolev put it: *"The very fact that one atom is positioned in a place that seems to preclude its interaction with the other atom leads to its being affected by that other atom. This is logically equivalent to the statement: 'this sentence has never been written'"*. ED (2005)



And it get worse:

Even the idea of a determinate path for the photon is illusory, since we can instead bring the atoms back together and measure their spins along some other direction, say **y.**

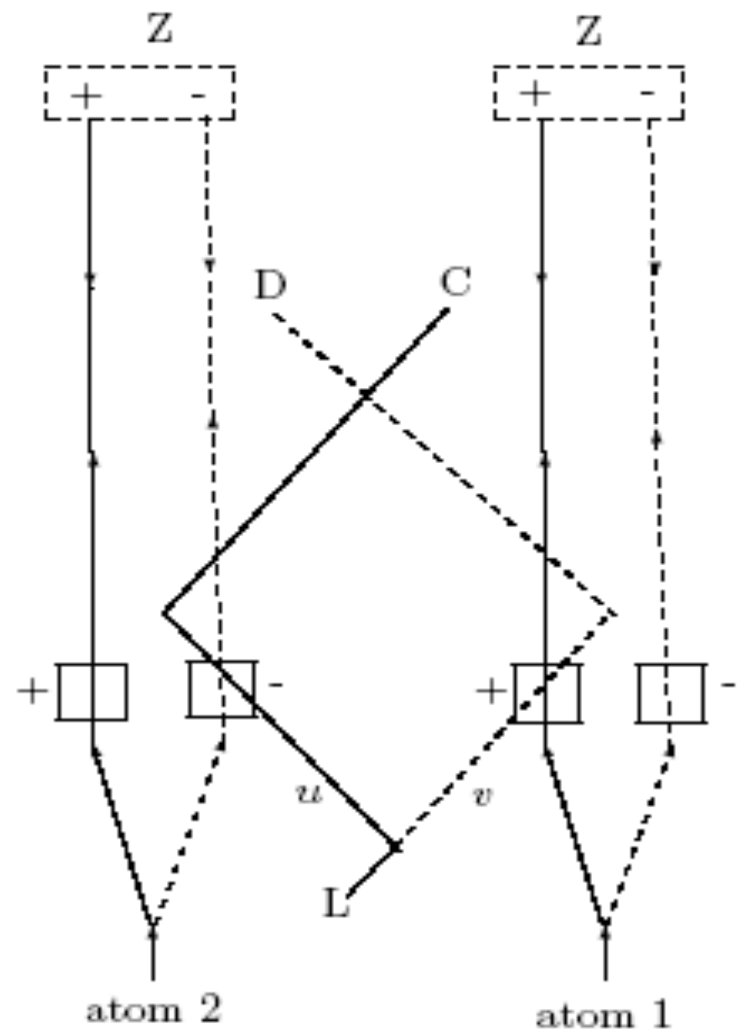
Until the atoms' spins are measured, there is no "fact of the matter" about what sort of path the photon took to get to D! For spin measurements along other directions than Z, the photon takes *both* paths.



TI: look at confirmation waves

Z-spin measurement: spacetime view

As noted earlier, we can open one or the other box to measure the atoms' spins along **z.** This is schematically indicated in the diagram as a "black box" labeled with the possible outcomes. (Time increases in the vertical direction)



Y-spin measurement: spacetime view

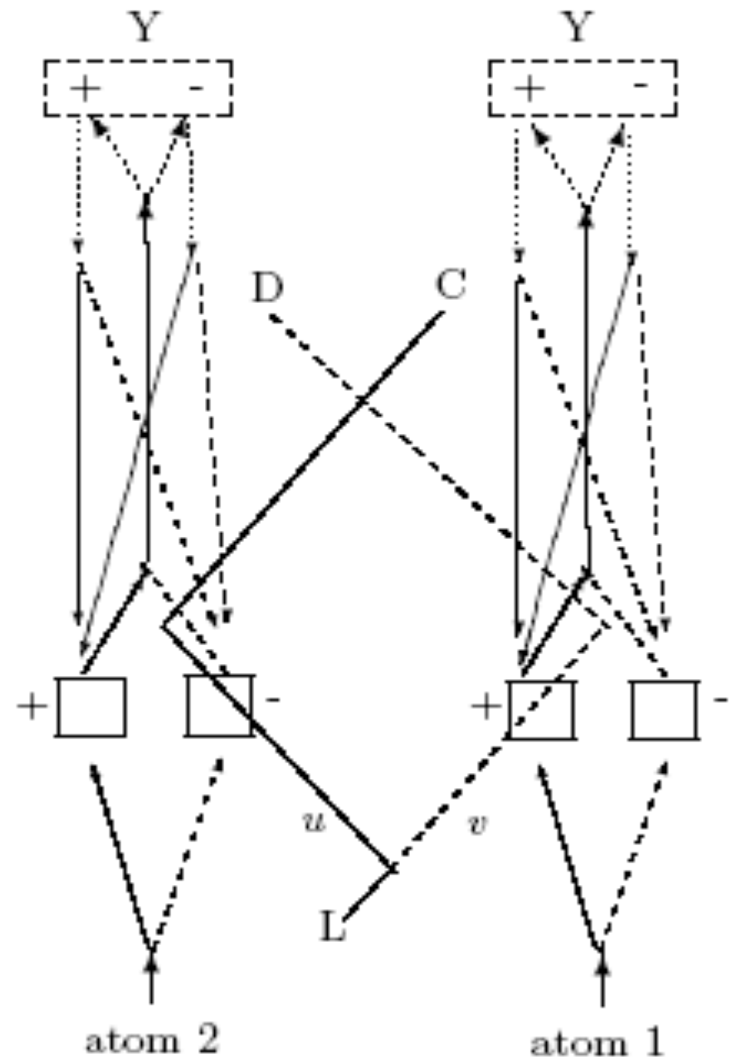
Or, we can bring the boxes back together and instead measure their spins along **y.**

In this case, each atom has to provide *both* z-up and z-down components to produce a y-spin eigenstate.

This means that the photon

must go along *both* paths!

The bottom line: the photon's path is determined by our choice of what measurement to make on the atoms, long after the photon has already been detected at D.

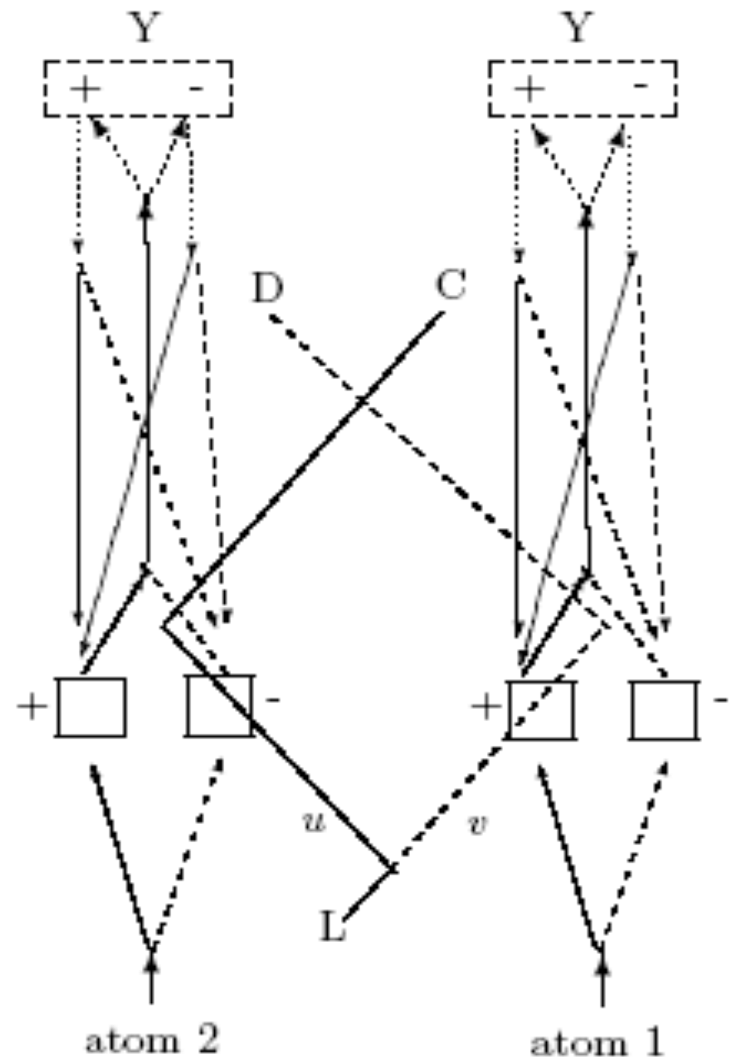


~T I to the rescue~

Under TI, confirmation waves (CW) from the future detection points help to determine what kinds of transactions are possible. PARTICLES ARE NOT IDENTICAL WITH EITHER OFFER WAVES (OW) OR CW.

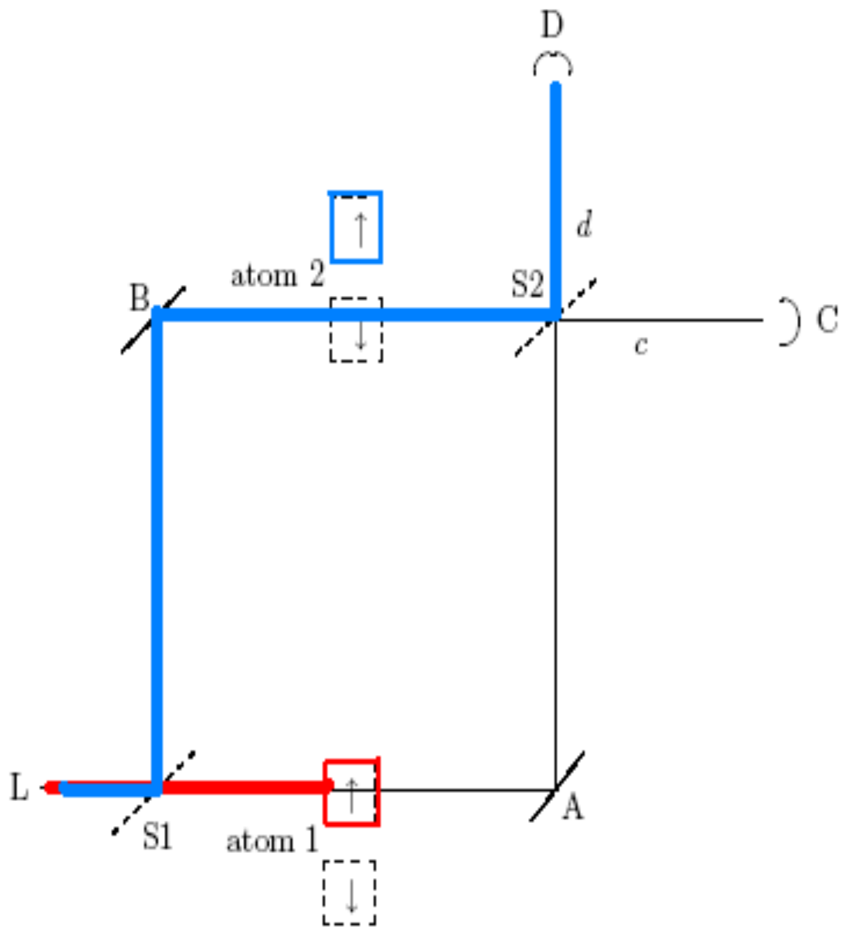
So we are liberated from the “usual way of thinking” about particles as following trajectories, and thereby sidestep the paradoxes presented by the QLE.

Correlations are brought about through the interactions of OW and CW rather than ‘particles.’



But, a new conceptual challenge for TI arises.

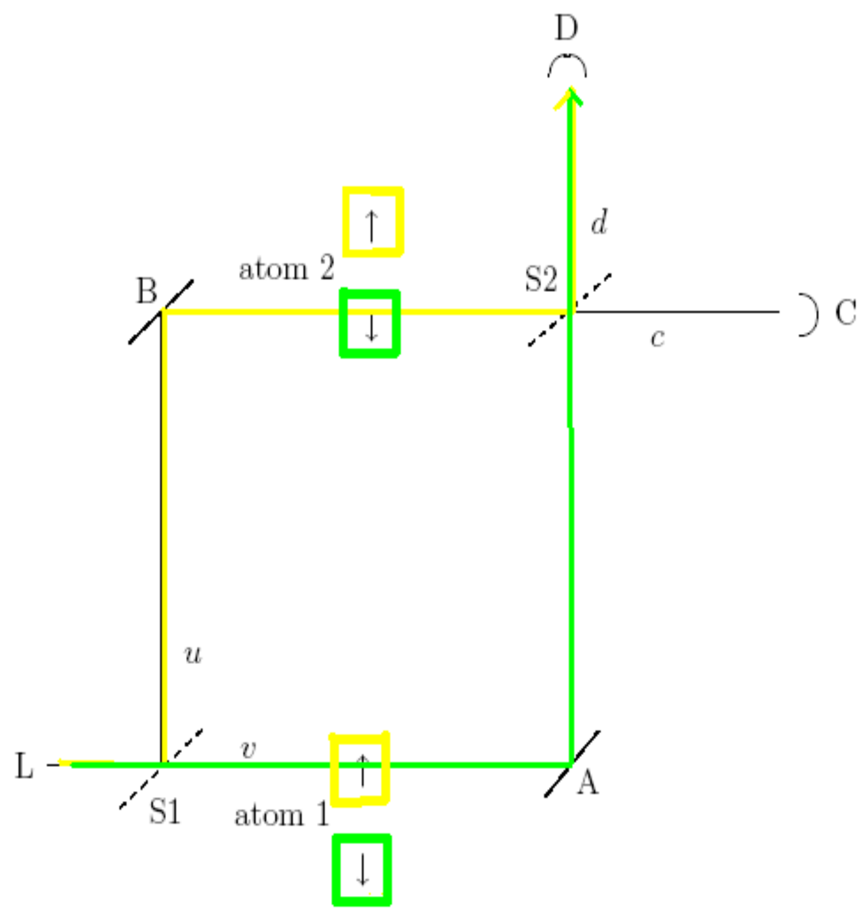
In the QLE, the photon has a choice of a one-path transaction leading to absorption by an atom, a one-path transaction leading to detection, OR a two-path transaction leading to detection (next slide).



The two-path route to D: yellow and green paths are superimposed.

If this two-path transaction occurs, that means the transactions corresponding to absorption at either atom did not occur.

Does that mean the OW had to “start out again” from the photon source to enable this two-path transaction??



Quantitative details:

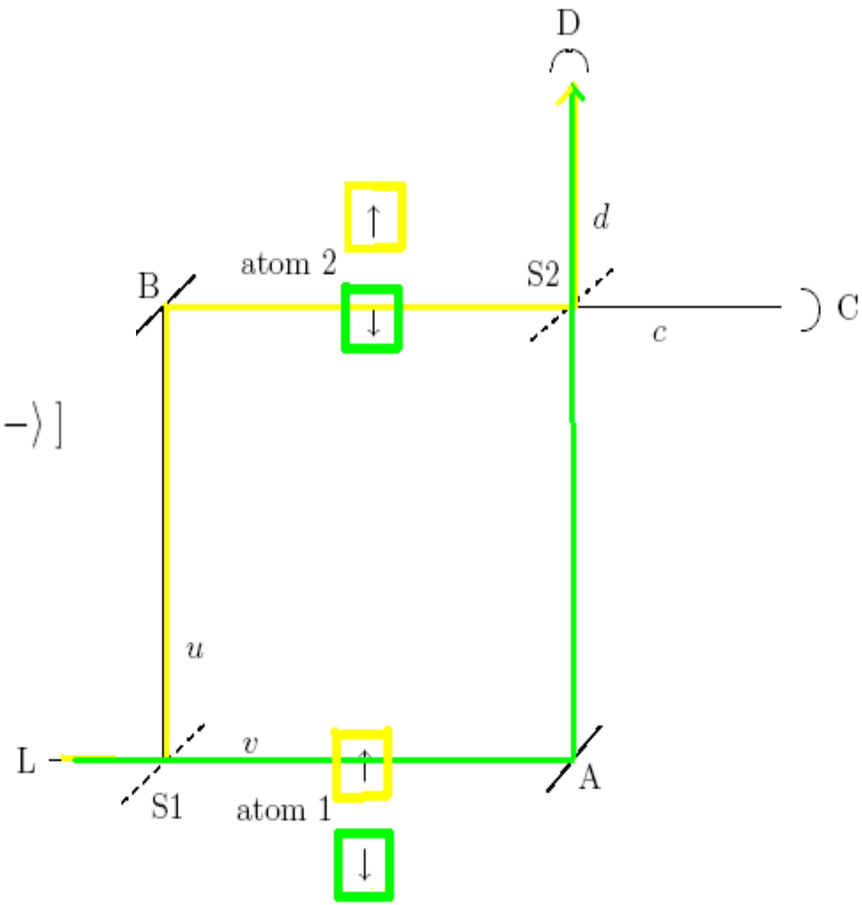
$$|\Psi\rangle = \frac{1}{2\sqrt{2}}[i|u\rangle + |v\rangle] \otimes [\, i|z\uparrow\rangle_1 + |z\downarrow\rangle_1 \,] \otimes [\, i|z\uparrow\rangle_2 + |z\downarrow\rangle_2 \,]$$

Let $|z\uparrow\rangle_1 |z\uparrow\rangle_2 = |++\rangle$, etc.

The photon will be absorbed by an atom in transactions corresponding to OW components with atomic states |+ - > and for components |u>| - - > and |v>|++>.

Omitting those terms,

$$|\Psi\rangle = \frac{1}{2\sqrt{2}}[-i|u\rangle\,|++\rangle \; - |u\rangle\,|-+\rangle \; + i|v\rangle\,|-+\rangle \; + |v\rangle\,|--\rangle\,]$$

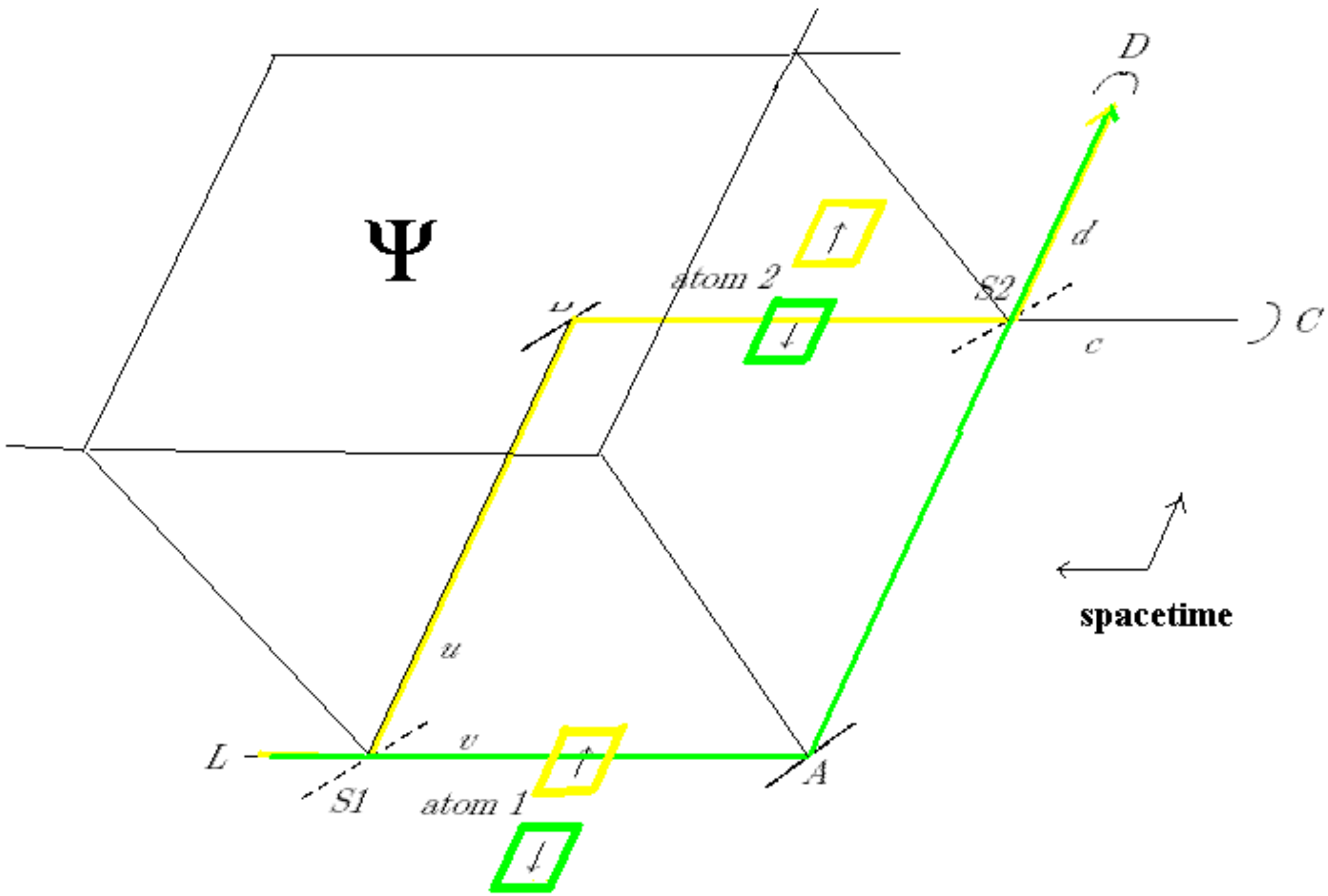


The photon can bypass a transaction corresponding to absorption at an atom, say via |v>|++>, but can then still use path ***v*** to get to D via |v>| - - > while atomic state |++> is still in play (via path ***u***). Does this mean the photon "goes back home and tries again"?

Solution: OW and CW propagate in a higher space corresponding to the configuration space of the combined system.

- photons do not move in trajectories, in a corpuscular sense, along one or the other arm of the MZI. They are transfer points of energy, etc. resulting from atemporal, a-spatial transactions.
- Transactions can project out a subsystem (e.g., absorption by one or the other atom)
- or, they can involve the entire system (detection at D and measurement of spin along *y)*

The forward and backward quantum states (OW and CW) of the combined system live in a higher space; transactions project out a specific outcome which is experienced in ordinary spacetime.



"Why will you refuse to listen to reason?
I had hoped to find in you--as being a man of sense and an accomplished mathematician—a fit apostle for the Gospel of the Three Dimensions, which I am allowed to preach only once in a thousand years;
but now I know not how to convince you."

-The Sphere, Edwin A. Abbott, *Flatland*

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