An Interference Experiment with Photons

Suppose we direct a laser beam at a half-silvered mirror. For **intense** light beams, such mirrors reflect half of light striking them and allow half to pass straight through. When the intensity of the laser beam is high, two beams are seen emerging from mirror, each having 1/2 intensity of incoming beam. Arrangement is called **beam-splitter**.

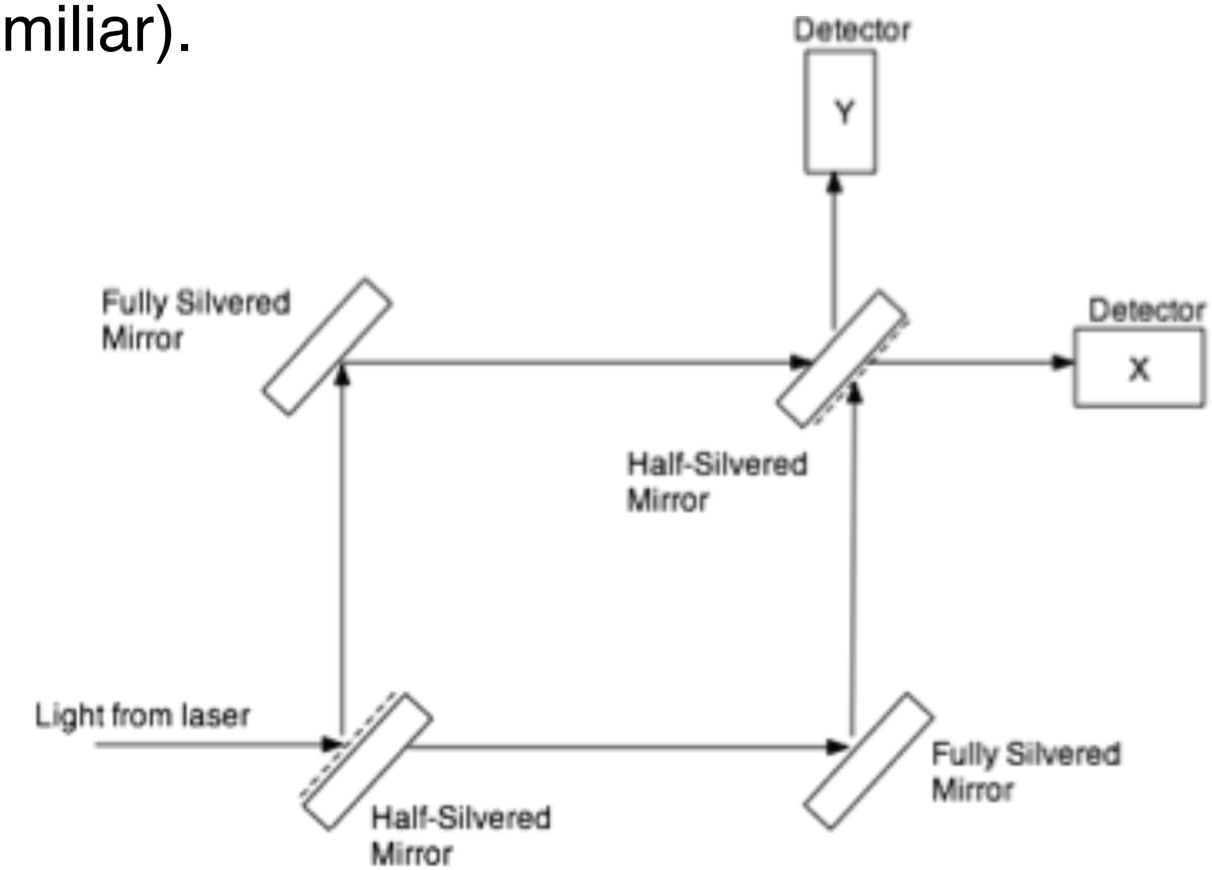
If we turn intensity of laser down(photons emerge with time gaps between them) -> only one photon around at any given time, and use a pair of C(harged)C(oupled)D(device) detectors to detect reflected and transmitted beams, something very interesting happens.

For each photon that leaves laser, one is detected either at transmission CCD (on transmitted path) or at reflection CCD (on reflected path). Photons not split in some odd manner so that half a photon goes one way at mirror and half other way. Instead, seems to be 50:50 chance(probability) that individual photon transmitted or reflected by half-silvered mirror.

No measurable difference between photons as they approach mirror, i.e., no property seems to determine which way they will go (sounds familiar).

Fundamental point that will come up repeatedly in context of quantum theory.

Next step is to remove detectors and replace them with two mirrors (fully silvered) that divert two beams(change their directions by 90°) to second half-silvered mirror as shown in figure.



At this point, same thing happens, with 1/2 of light arriving at half-silvered mirror passing straight through and other half being reflected. Two new beams emerge and eventually travel to pair of detectors placed at X and Y.

Beam heading to detector X is combination of light that was reflected by first half-silvered mirror (travelled top path), then transmitted by second half-silvered mirror with light that was transmitted by first half-silvered mirror(along bottom path) and reflected by second one. Detector Y collects light that is similar mixed combination.

Arrangement of mirrors and detectors called **Mach-Zehnder interferomete**r. Once interferometer set up, easy to confirm that intensity of light reaching each detector depends very critically on **distances travelled** by light along top and bottom paths.

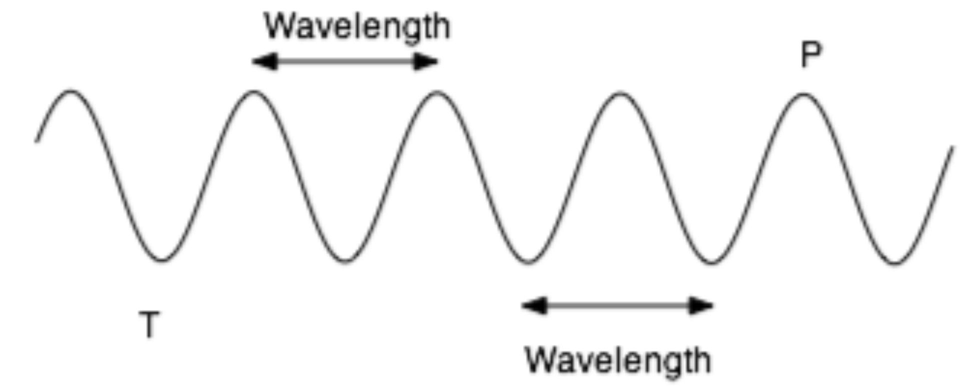
If equipment finely adjusted so that paths exactly same length, detector Y records no light while detector X records all of intensity (all photons) entering experiment.

Without critical adjustment, X and Y collect light in varying amounts: more light at X -> less reaches Y (and vice versa).

Using classical physics methods these effects can be completely explained by saying that light is a **wave**.

Interference as Wave Effect (reminder)

Consider ripples crossing surface of lake. Ripples consist of places where water level is higher than normal (peaks) and places where dropped below normal (troughs). Wavelength of ripple is distance between successive peaks(P), same as distance between successive troughs(T). Frequency of wave is rate at which complete cycles (peak to trough to peak again) pass fixed point, and period is time taken for one cycle.

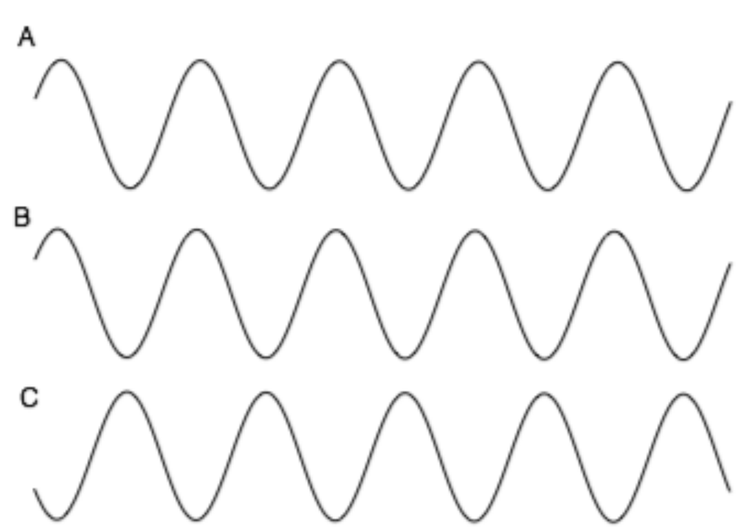


Light(E/M fields) more complicated than water wave. Peaks and troughs of light wave not physical distances (height of water wave) but are variations in strength of fields(E and B). Mathematically, however, **same** phenomena.

Thus, light waves are very sensitive measures of distance. In interference experiment with interferometer, divide distance travelled by light wave on route to detector into sections, each having length equal to wavelength of wave. Distance probably not whole number of wavelengths. Furthermore, two different possible routes through experiment have to be precisely same length to be precisely same number of wavelengths long.

If distances not precisely same, light traveling along each route consequently have gone through different number of complete waves when gets to the detector.

As light in two beams has common source at first half-silvered mirror, two beams will set off on different routes in phase (i.e., in step - simplest definition of phase - both at same point on wave) with each other.

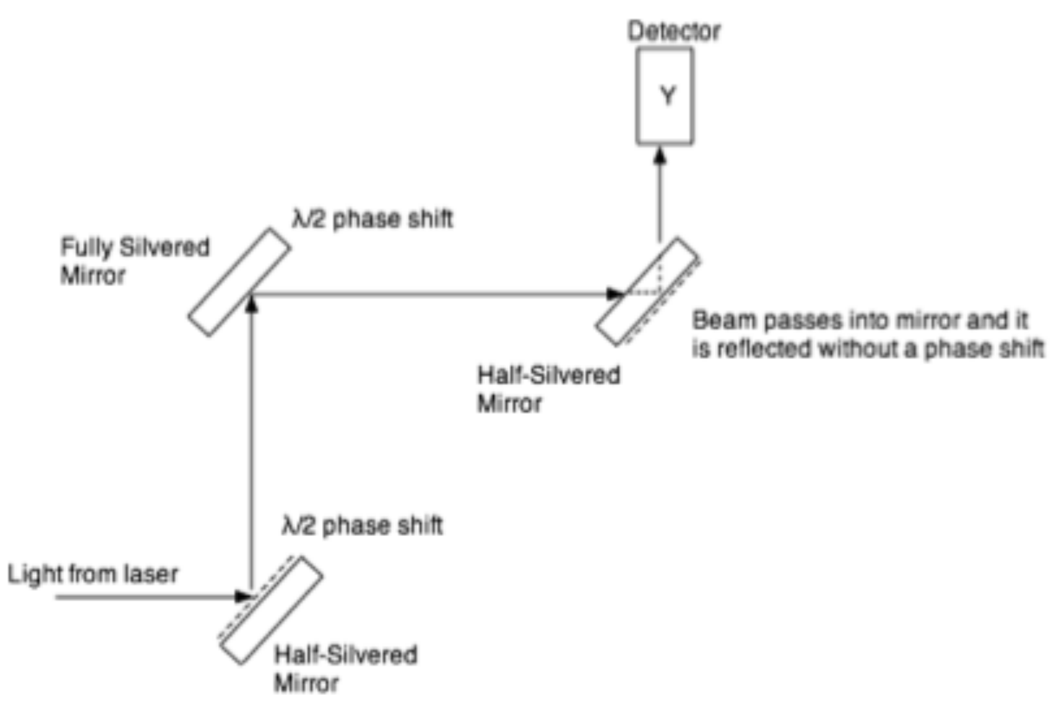


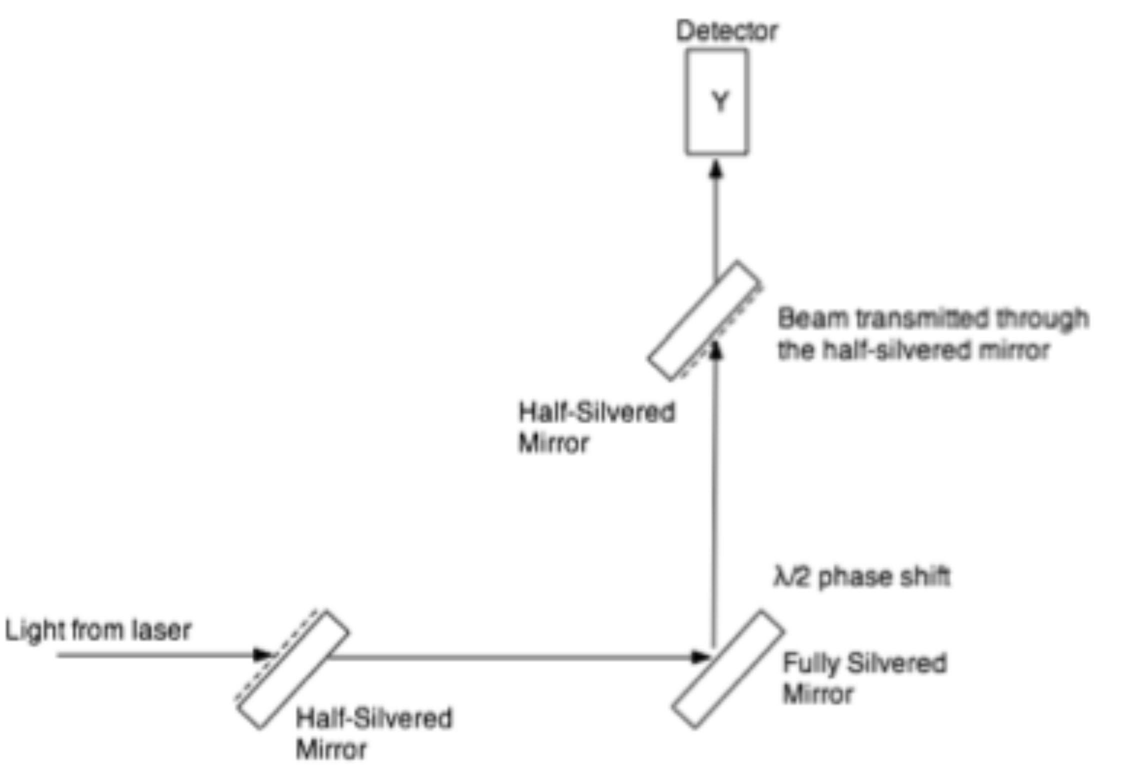
Waves labelled A and B in phase(peak to peak), waves B and C exactly out of phase (peak to trough). Set off peak for peak - were in phase.

By time get to detector two beams may no longer be in phase (different distances travelled). One could be arriving at peak, and other at trough (B and C). If this happens, then waves will cancel each out and no energy entering detector - called **destructive interference** (if still in phase would add up - called **constructive interference**). Exact cancellation only happens if waves met precisely peak to trough - not possible for any extended length of time due to small variations in distance (mirrors shaking slightly) and fluctuations in laser output.

Detailed analysis of interference experiment also takes into account what happens to light at various mirrors -> also influence phase of waves. When light reflects off mirror, reflected wave out of phase with incoming wave by half wavelength. Using λ = wavelength, wave has undergone λ/2 phase shift (shift by 1/2 wavelength) on refection. Slightly different with half-silvered mirror, surface that reflects from either side mounted on thin block of glass. Dashed line in figure indicates reflecting surface. If reflection takes place off surface before light enters glass block, then ordinary λ/2 phase shift takes place. However, any light that passes through block before reaching reflecting surface not phase shifted on reflection.

See two figures below.





Two light beams reaching detector Y will be (overall) $\lambda/2$ out of phase. Consequently, like waves B and C and will completely cancel (if travelled equal distances).

If carry out same analysis for detector X, i.e., chart progress of waves through interferometer to detector X, find arrive in phase provided travelled equal distances.

Most experimental setups, paths through interferometer not exactly equal so waves not exactly in/out of phase.

Consequently, some light reaches both X and Y. If equipment allowed movement of fully silvered mirrors, so relative path lengths were changed, then variation in brightness of light in X and Y could be studied as mirror moved - as relative paths changed.

Modern version of Mach-Zehnder interferometer with Photons

Able to turn down laser intensity so that light beam made up of single photons in apparatus at any time. Suppose reduce laser intensity so that only one photon in experiment at any time. Have control over average rate.

Expect photons arriving at half-silvered mirror have 50:50 chance of going through/reflecting off. Another possibility is two reduced energy photons emerge from mirror, in each direction. Can determine experimentally what happens: place photon detectors just after mirror in path of each possible beam.

Simple experiment produces interesting result. Half the time photon is reflected, and half the time is transmitted; never get two photons coming out at same time. However, no inherent difference between those photons that get through and those that reflect. No pattern to sequence, except that after long time half reflect and half get through. Sounds familiar!

Effect is common in quantum physics. Some aspects of nature's behavior lie beyond ability to predict (e.g., which way photon will go). Question - does this reflect fundamentally random aspect to nature, or is something more subtle going on that have not discovered yet?

Having established that photon reaching first half-silvered mirror in Mach-Zehnder interferometer will either reflect and travel top path through device, or transmit and follow bottom path, now turn attention to what happens at detector end of device.

First find between them, detectors pick all photon that enter experiment. However, number of photons arriving at either detector in given time depends on two path lengths, i.e., if exactly equal then no photons ever arrive at Y.

If paths not exactly equal, then find that detection rate at each detector reflects intensity of interference pattern that would be observed when intensity is turned up. What do we mean by that? Let's imagine that had arranged for path lengths such that 70% of total light intensity entering experiment arrives at X and 30% at Y. No double photon firings. Experiment done under well-controlled conditions and no doubt that photon arrival rate directly reflects an interference pattern.

Doesn't sound like a problem, but there is.

If photon is small particle of light, then how can different path lengths have any effect on one single photon?

Confirmed that photons randomly choose reflection or transmission at half-silvered mirror. After that, surely proceed along one path or other to detector. Hard to imagine single photon going along both paths at same time - remember rejected by experimental results (detectors only registered one photon at a time).

Now wave can do this. Can spread out throughout experiment (ripples on lake) so that parts of wave travel along each path at same time (i.e., wave energy divides between paths). When two parts of wave combine at far side of experiment, information about both paths is being compared, which leads to interference pattern.

A single photon must surely have information about only one path, so how can single photon experiments produce interference patterns?

Flaw in arguments. Extremely subtle and leads to primary issue physicists face when dealing with quantum world. Confirmed that photons divert at half-silvered mirror by placing detectors in two paths. However, doing this eliminated any chance of picking up interference pattern. If detectors have stopped photons, then **have not** travelled paths. In principle, does not tell anything about what happens when no detectors present.

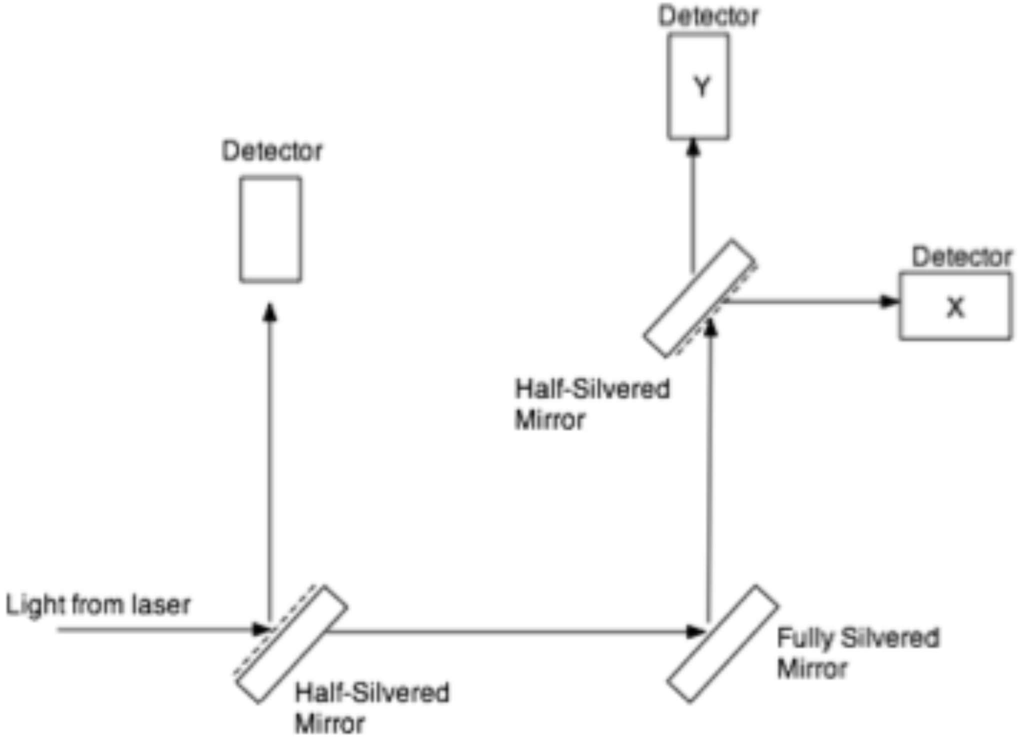
Common sense to assume that photons do same thing with or without detectors, but as already seen, interference pattern for photons is not a matter of common sense. In addition, color/hardness experiments say that it whether or not detectors are present!

Investigate this further.

Place one photon detector after half-silvered mirror - in path of reflected beam. If detect photon there, then would not get one at far side of experiment.

On other hand, if do not pick one up at detector then it has passed through mirror rather than reflecting and should see it at far end.

Experiment easily done and confirms that for every photon leaving laser pick one up either at far end or in reflected beam as below.



Find for transmitted photons half of arrive at Y and other half at X, no matter what length of path is. In other words, no interference takes place. Removing detector on reflected path (and replacing corresponding half-silvered mirror) opens up that route to far side of experiment again.

At same time it removes any direct knowledge that might have about behavior of photons at the half-silvered mirror. Observe that doing this restores interference pattern! Remember what happened in the color/hardness experiments.

Summarizing logic so can expose what is happening.

(1) Rate of photons arriving at far side of experiment related to intensity of bright beam.

(2) Moving mirror with bright beam maps out interference pattern in detectors.

(3) Reducing intensity of beam does not affect interference pattern - instead arrival rate of photons now depends on position of mirror

(4) If set up experiment so that can tell which path taken by photon (directly or indirectly), then interference pattern is destroyed.

(5) If unable to tell paths of photons, then there is interference pattern, implies photons arriving have information about both routes through experiment.

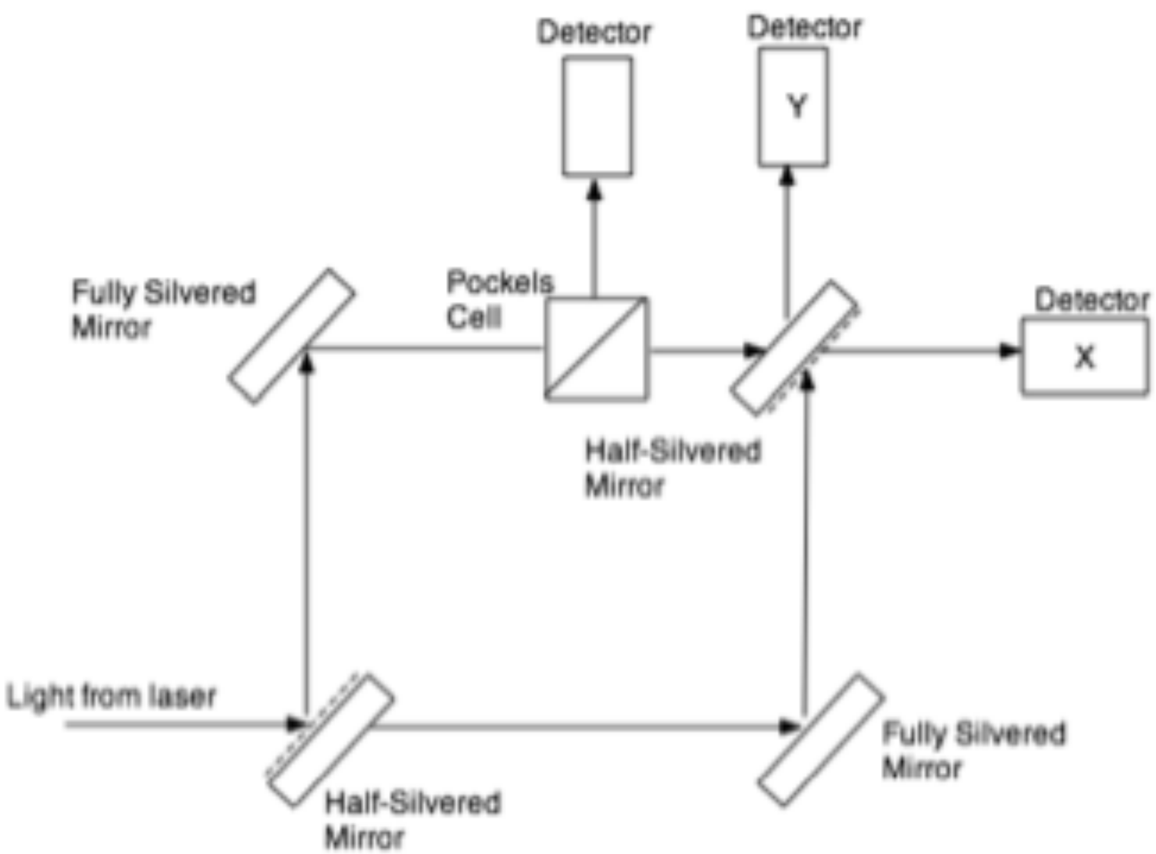
(6) Opening up top path (removing detector) can actually reduce number of photons arriving at Y. In fact, if paths' lengths are same, opening up top path means never get any photons at Y.

All experimental results equivalent to Young-type two-slit interference experiment and the two-path color-hardness experiment discussed earlier.

Delayed Choice - make result stronger!

Introduce Pockels cell(PC)(diverts photons extremely fast) on one route. Find out what photons doing while in interferometer.

Consider setup - PC set to divert photons(extra detector). Photon leaves laser and arrives at first half-silvered mirror.



If reflected, then PC will divert it so don’t see at X or Y. However, if photon transmitted by first half-silvered mirror, misses PC, and turns up at either X or Y. Either case - no interference pattern (have which-path information).

If set PC to pass photons, then changes what happens and get interference pattern. Extreme case of equal path lengths, no photons ever arrive at Y.

Assume two path lengths exactly same. So have:

(1) If PC set to transmit, then get no photons at Y and all at X.

(2) If PC set to divert, then half of photons detected have equal chance of either X or Y.

Result makes us stop and think. If photon takes lower route with PC set to divert, then can get to X or Y. If takes lower route with PC set to pass, then photon can never arrive at Y. But if takes lower route doesn't go anywhere near PC, so how can setting of that device affect things? Is this further hint that somehow or other photon travels both routes at same time? Again this should sound familiar!

Now get devious. Set PC to divert photons, but while photon in flight, switch cell over to transmit setting. Ability to do this very rapidly means can make change after photon has interacted with first half-silvered mirror. No magic in doing this. If know when photon left laser, can estimate how long takes to get to half-silvered mirror. Provided we switch PC after this time, but before photon had time to reach detectors X and Y, then can perform experiment as described.

If setting of PC has(someway) influenced photon, then original setting should have determined that photon take one path or other and certainly not both at once. Now have changed setting after decision made [**NOTE:** Of course, word decision not appropriate. Photons do not make decisions. Clearly, hard not to be anthropomorphic when describing experiments]. In fact, can trigger PC in random manner. Record setting of PC and match arrival of photons at one detector or another. Can then run experiment for many photons and record arrival at different detector positions.

After experiment run for while, can data. Have some photons arriving at Pockels detector and some at far end of experiment. Latter group sorted out into those that arrived when PC set to divert, and those that made it when PC set to transmit.

Remarkably, when data separated, photons that arrived at far side with PC set to transmit show interference pattern. Other photons that arrived with PC set to divert (obviously committed to other path and so missed it) show no interference pattern.

In every case PC set to divert photons and switched after photon left first mirror. With PC set to divert, photons follow one route or other. Then switched PC, destroying ability to know which path photons travelled, and producing interference pattern. Hard to believe that changing setting of PC can have influence that seems to **travel backward in time** to when photon reaches first mirror. **Last statement, made using ordinary words, may be total nonsense of course!**

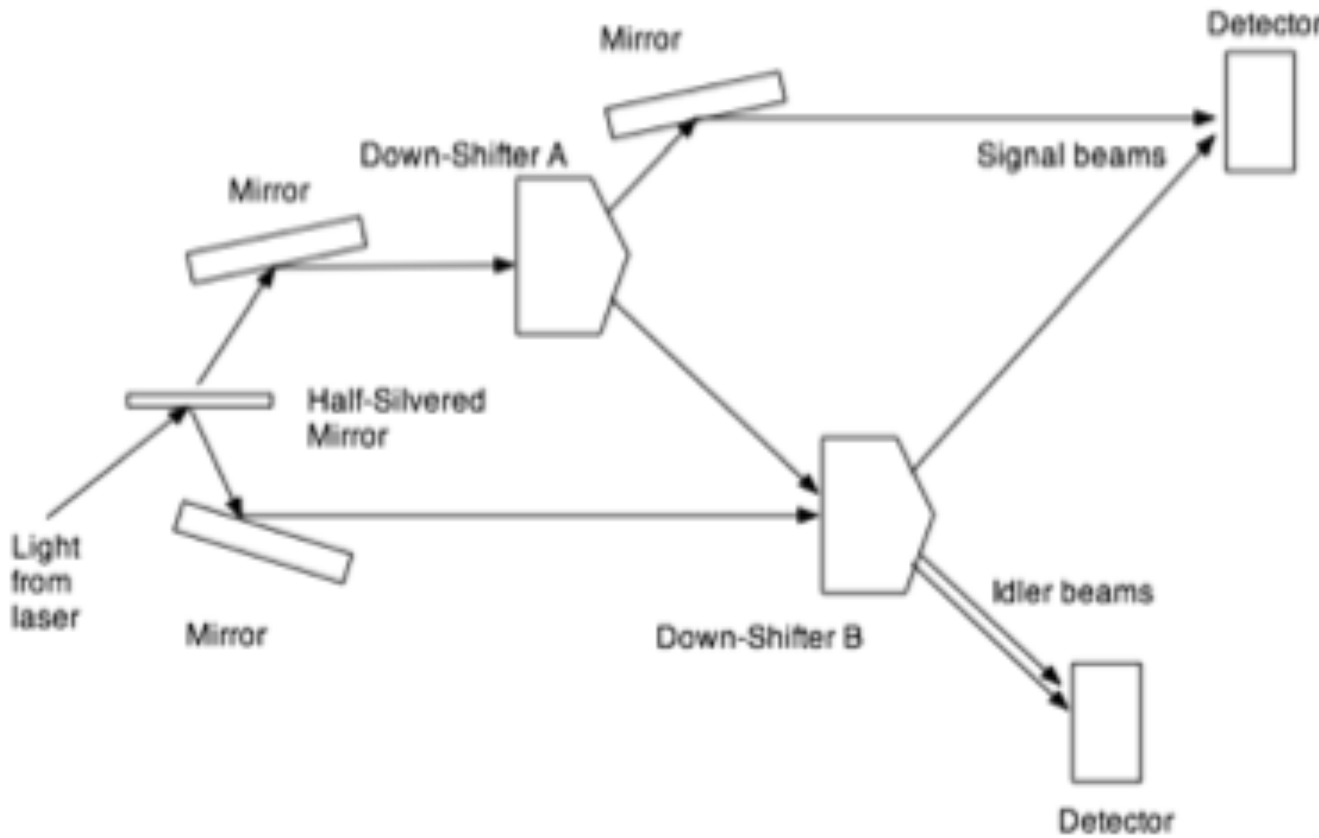
From both photon expts and color/hardness experiments have seen that quantum physics is contextual theory -> adequate description of behavior of quantum object (light/electrons) requires an understanding of whole (the context) experimental setup.

Quantum behavior depends on **context**! Experimental results (answers to questions) **depend** on what questions we are asking!

Another Interference Experiment

Clearly, get into difficulty with experiments when piece together understanding of whole by looking at component parts on own. When everything together, things behave differently. Results of one experiment not accurate guide to another. If this is case, then conclude that photons always take only one route, as indicated in experiments that look for route followed. However, know that as soon as do not have ability to tell path of photons they take both routes at once **or something that is equivalent to that**.

Another experiment pushed notion further by showing interference pattern can be destroyed without direct influence on photons creating it. Experiment uses crystal known as down-shifter. Device absorbs photons to produce 2 new photons, each with half the energy.



Laser light sent onto 1/2-silvered mirror and 2 beams separately directed into down-shifters. Each down-shifter produces signal beam and idler beam, difference between two beams nothing more than **subsequent** way used.

2 signal beams directed to detector - produce interference pattern (different path lengths) (same as Mach-Zehnder). Idler beam from down-shifter A mixed with that from down-shifter B and both beams arrive at second detector. Upshot is that every time photon leaves laser, photon of half energy arrives at each detector.

Fact that interference pattern emerges -> in some manner, each photon appears to have travelled along both signal beam paths.

Say photon arrives at half-silvered mirror and goes on top path (only that path). Photon arrives at down-shifter A and produces 2 further photons, one ends up at signal detector and other at idler. No interference pattern since no information carried to signal detector about other route. Same true if photon took lower route through experiment. Only way get interference pattern at signal detector is for information to arrive from both routes, have to be two signal beams, one from each down-shifter. If true, then down-shifters have to be activated by something arriving at each one - makes it appear that photon from laser went both ways at half-silvered mirror.

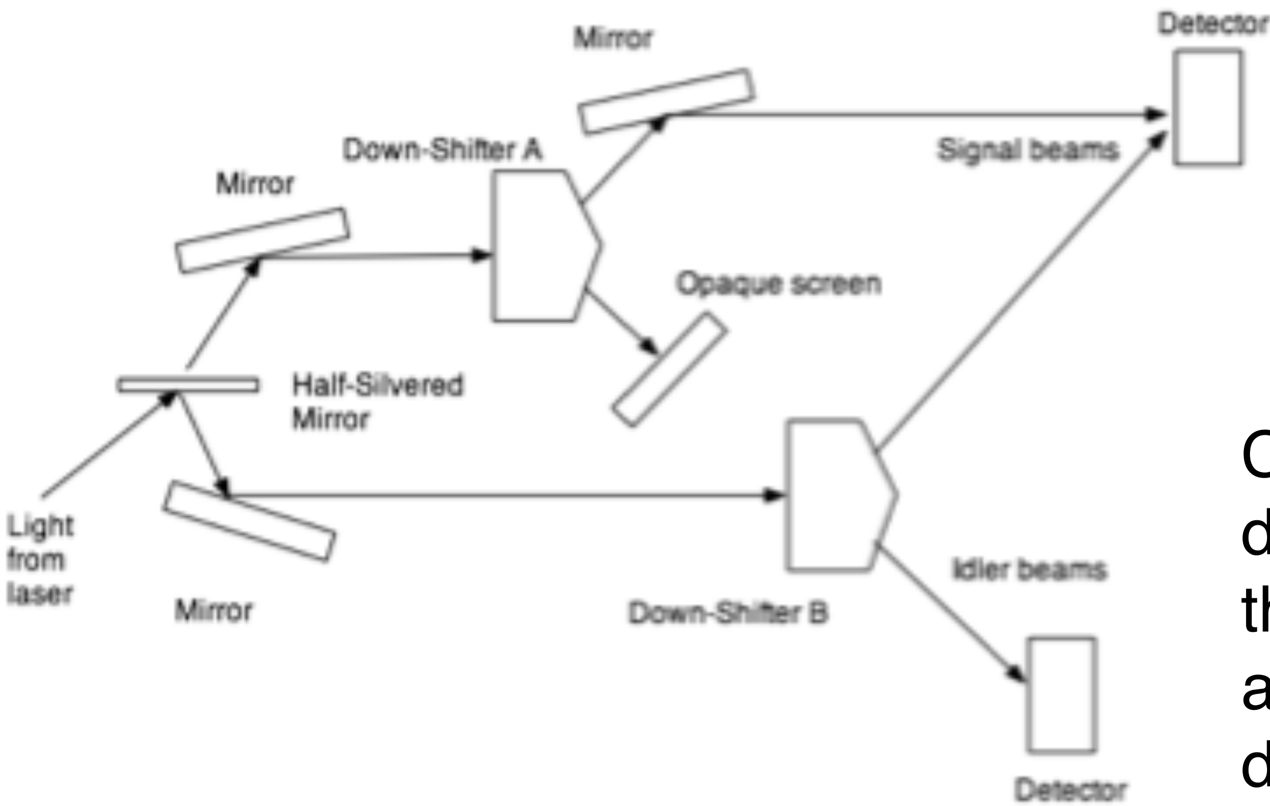
Presence of two signal beams doesn’t imply that two photons are arriving at signal detector - only one at a time arriving.

Most bizarre feature of experiment is way in which interference pattern can be destroyed if have ability to tell path of the photons, even if don’t choose to use this information.

Threat of doing this, or rather fact that experiment set up to allow possibility, is enough to destroy interference.

Dramatically confirmed by blocking one of idler signals, say from down-shifter A

Logic here remarkable.



Whenever photon picked up at idler detector know must have come from down-shifter B. Means that photon from half-silvered mirror must have hit down-shifter to be converted into photon that arrives at idler detector.

Can further deduce that other photon from down-shifter B travelled to signal detector and therefore is photon detected there. Tracing argument further back, photon that definitely hits down-shifter B must have come from from half-silvered mirror.

No ambiguity about route that this photon takes from mirror. Nothing goes along top route; nothing produced from down-shifter A, so interference pattern disappears.

As long as idler route from down-shifter A open, have no way of telling which shifter photon came from. Ambiguity sufficient to guarantee interference pattern at signal detector. If don't know that photon at idler detector came from B (or A), then don't know about signal photon either. Under those circumstances, can't say which route photon took at half-silvered mirror, so takes both routes or "something" like that.

Seems that behavior of photon determined by **context** of experiment as whole. Know no photons coming from down-shifter A, why does it matter that idler route from A is blocked? How is information conveyed back to half-silvered mirror so as to determine what happens there?

Stern-Gerlach Experiments

Repeat everything using electrons and Stern-Gerlach devices -> reinforce knowledge learned and expand understanding.

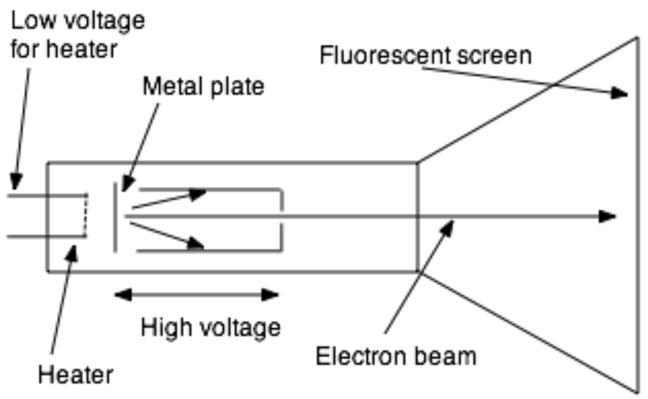
Discuss results of classic experiment(1922). Stern-Gerlach (S-G) expt studies how electrons behave in magnetic fields. Illustrate how electrons behave in another context and in thereby further develop idea of quantum states and assumptions of quantum theory - allows later discussion of modern quantum experiments and ideas which seem so paradoxical to classical physicists.

Seemingly paradoxical nature of light/electrons has been called wave-particle duality - could appear as wave in one situation and stream of particles in another. To understand, need to discard classical descriptions of waves or particles (maybe no such things quantum mechanically) and develop new set of rules and concepts to cover strange microworld.

There will be no wave-particle duality. Electrons exhibit wave-like properties during measurements if that how set up expt or that question are asking. Electrons can exhibit particle-like properties during measurements if that how set up expt or that question are asking. Context of expt will determine exptl results - quantum theory of microworld is contextual in nature.

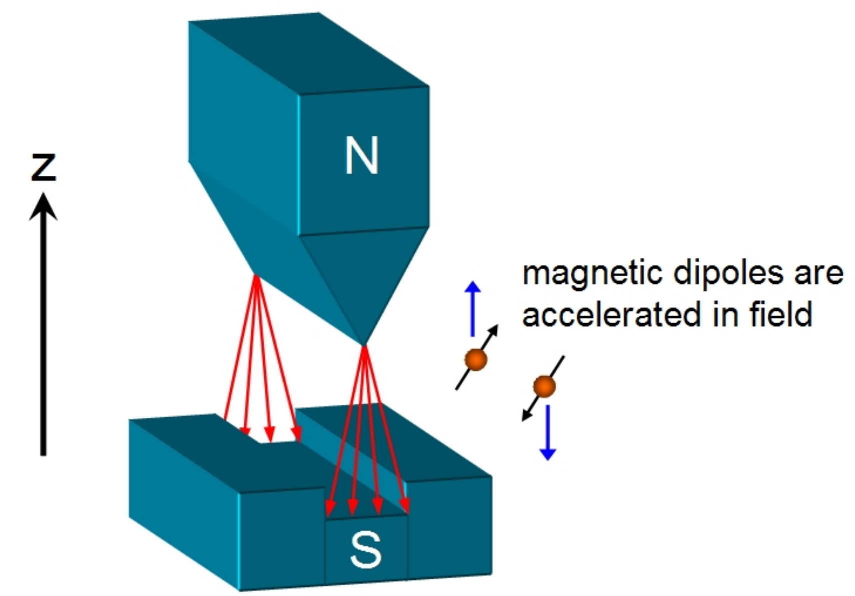
Classic Stern-Gerlach Experiment

QM -> electrons are fundamental particles, have - charge and ~1/2000 proton mass. Found isolated or inside atoms where held to + charged nucleus by electric forces. If atoms subjected to large electric field, then can ionize(remove) electron from atoms. Old style CRT tubes are large glass containers vacuum inside



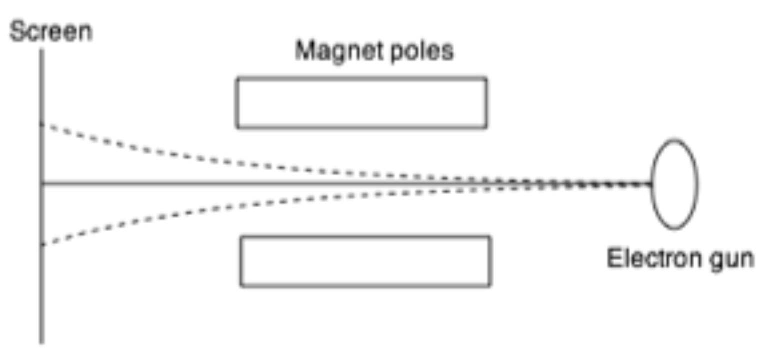
Electron gun -> uniform beam

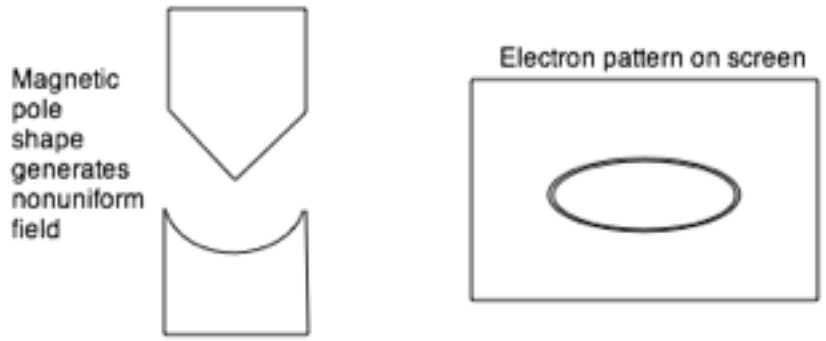
Electrons behave like tiny bar magnets when sent into magnetic field, i.e., send some bar magnets into non-uniform magnetic field (stronger at top than bottom of field region) then field both deflects path of magnets and aligns(N-S axis) magnets with fields.



non-uniform magnetic field (red arrows) generated between magnets

Assume that S-G magnet exerts similar magnetic force on electrons (have magnetic moment) passing between poles and that force will deflect electron's path





Hypothetical experiment to see how much deflection takes place when pass electron beam between poles magnet. Detect deflected electrons outside field region; Can detect single electrons.

Run experiment - observe two things:

(1) No pattern determining which way electrons are deflected; Either up or down - apparently at random.

(2) Each electron deflected upward or downward, by fixed amount (final deflection angle).

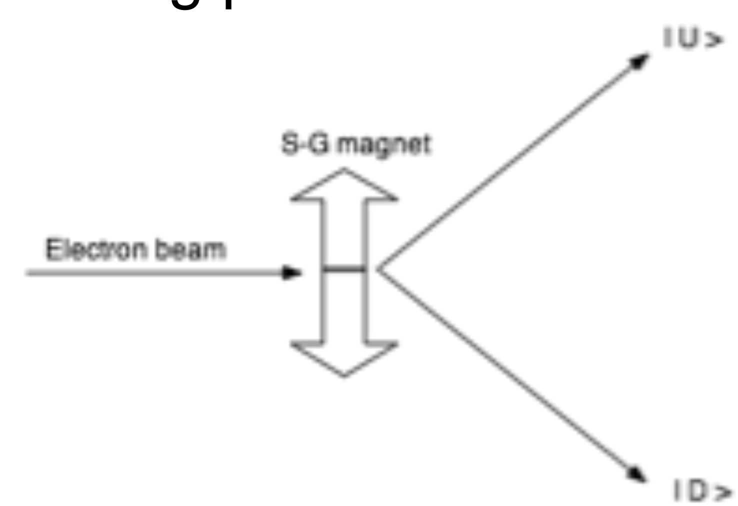
2nd point surprising to classical physicist: amount of deflection same for each electron. If electron acting like tiny magnet (classical picture), expect magnet pointing in random direction when enters S-G field. Consequently, amount of deflection, which depends on initial orientation of electron's magnet slightly different for each. End result = range(in space) of detected deflection angles not just two fixed deflections.

Can interpret results - assume electrons have internal property -> determines which way deflected. As emerge from electron gun, up and down types produced at random(equal numbers) -> two equal-sized sets of sorted electrons.

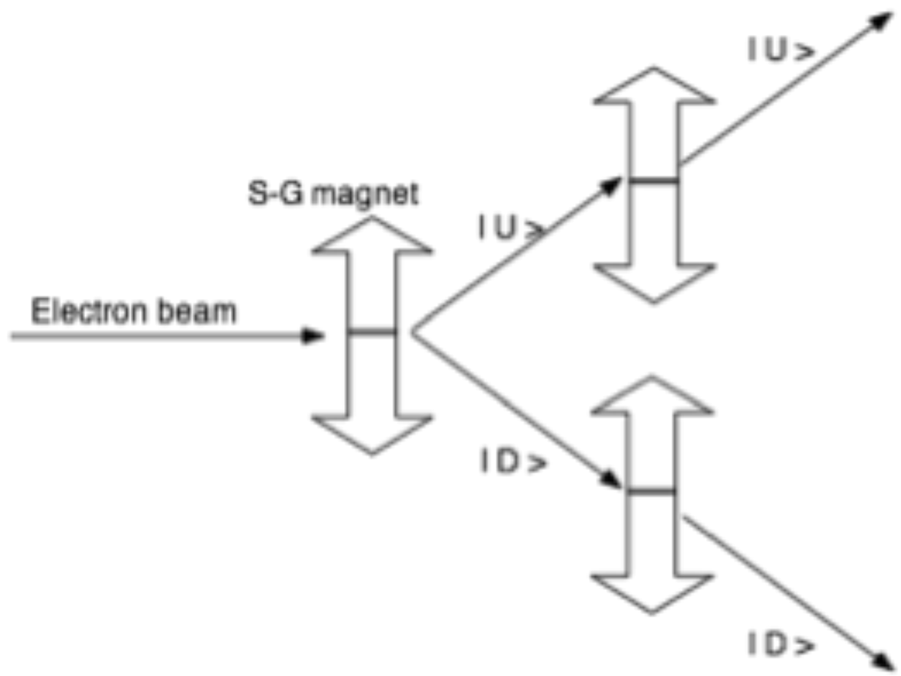
Electrons deflected up = UP state electrons = $|U\rangle$ and deflected down = DOWN state electrons = $|D\rangle$. Assume state of electron determined by internal property(-> problems later).

Assume $|U\rangle/|D\rangle$ state describes electron moving along top/bottom path through S-G magnet and some state property of electron determines path. Observing path of electron is only way can measure state property.

Presumably electron gun feeding experiment producing electrons that randomly emerge in either $|U\rangle$ or $|D\rangle$ state. These Electrons pass through poles of S-G magnet and sorted by being deflected according to labels.



Ask if experimental results -> genuinely measuring some state property(U/D) of electrons, or if magnet is simply randomly deflecting them one way or other. Answer question by modification of experiment - electron detector removed/replaced by further pair of S-G magnets arranged so that electrons passing out of first magnet pass through one of two further magnets



Results(corresponds to repeatability measurements) are conclusive. Electrons that emerge along UP channel of first magnet then pass through topmost second magnet and all emerge from that magnet's UP channel.

None deflected downward(some down if magnet randomly deflecting electrons). Similarly, DOWN electrons emerging from first magnet all subsequently deflected down by second magnet.

Second magnets(can add more) confirm sorting of first magnet. Results give impression that S-G magnets are measuring state property of electrons.

Turning Things Around

Been using S-G magnets vertically so deflecting electrons upward or downward. Magnets can be turned through 90° so deflect electrons right or left. S-G magnets can be oriented at any angle, but only need (UP,DOWN) and (LEFT, RIGHT).

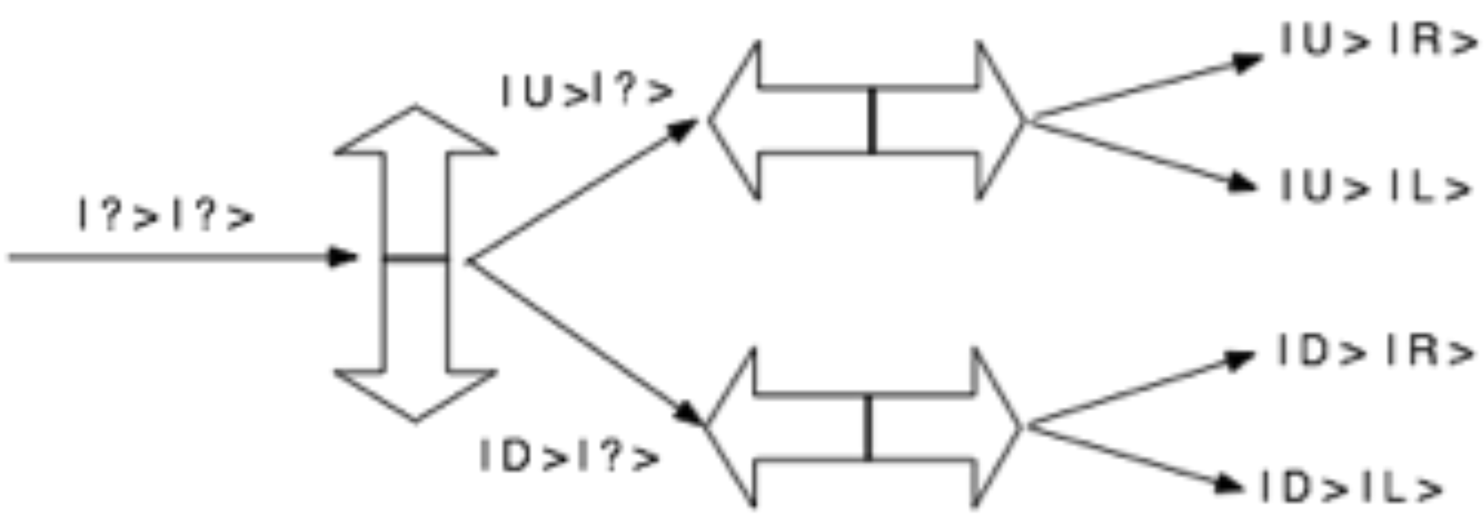
Results of experiment with S-G magnet turned horizontally exactly the same as previous experiments but now in reference to new orientation of magnets. Half of electrons deflected to right, and half to left. No obvious pattern that predicts which electron will go which way.

Same argument suggests there are two possible states for electron $|R\rangle$ and $|L\rangle$, and magnet sorts them.

Electrons have second state(R/L) property that determines which way deflected. Adding two further magnets, also arranged horizontally, to check out the electrons in either deflected beam confirms this. Results not surprising. ∣R〉 electrons from first magnet are deflected only to right by second magnet and ∣L〉 electrons are deflected to left again by second magnet.

Similarities to Hardness and Color is striking!

For physicist, next step - see if ∣U〉 and ∣D〉 states linked (correlated) to ∣R〉 and ∣L〉 states. Are "determining" state properties connected? Easy to check by constructing expt that uses an (UP,DOWN) S-G magnet with two (LEFT,RIGHT) magnets so that electrons in UP and DOWN channels of first magnet are tested to see if either ∣L〉 or ∣R〉.



Results of experiment interesting. ∣D〉 passing into (LEFT, RIGHT) magnet -> out either channel; also ∣U〉 electron. (same as color/hardness boxes)

Now if true, appears that dealing with 4 different combinations of electron states determined by 2 state properties.

An electron in state ∣U〉 could also be in either state ∣L〉 or state ∣R〉. possible combinations are

$$|U\rangle\,|R\rangle \quad |U\rangle\,|L\rangle \quad |D\rangle\,|R\rangle \quad |D\rangle\,|L\rangle$$

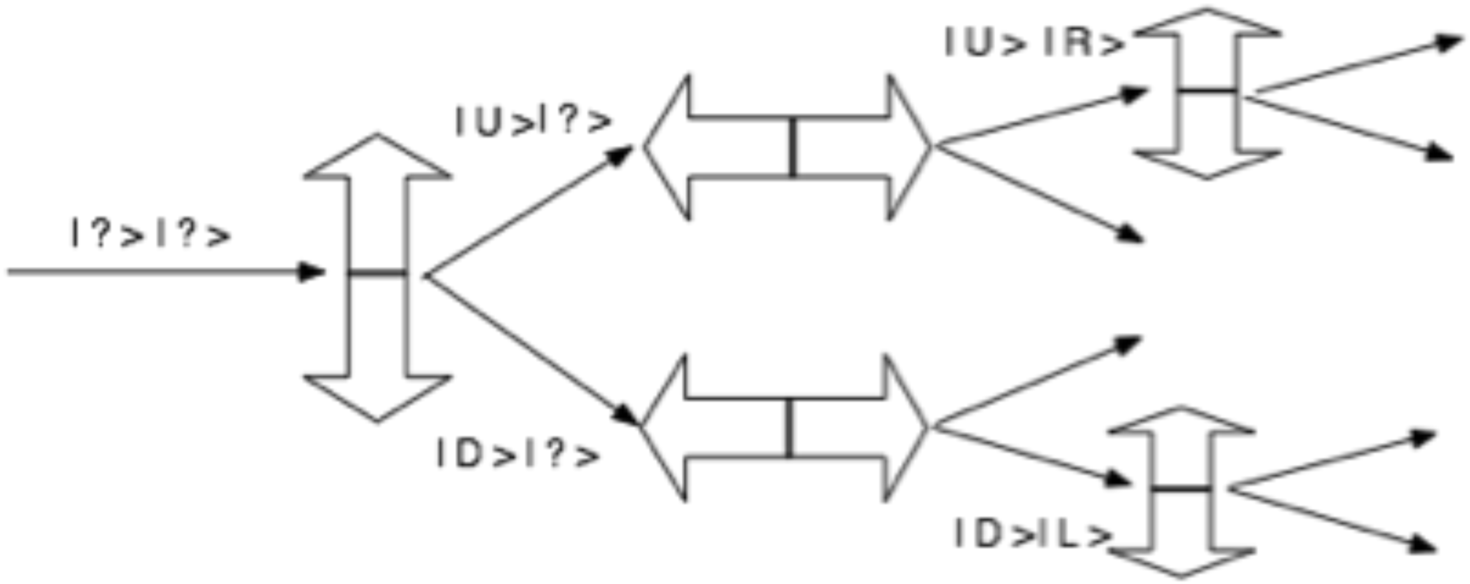
Electron gun is producing equal numbers. Combination of 2 differently oriented (perpendicular) magnets sorts out these electrons as shown.

In figure used symbol ∣?〉 -> not sure state electron in. When electrons arrive at first magnet, no way of knowing either (UP,DOWN) or (LEFT,RIGHT) state, hence ∣?〉∣?〉.

First magnet sorts into ∣U⟩ or ∣D⟩, but tells nothing about ∣R⟩ or ∣L⟩ state. Final pair of magnets completes sorting -> four piles of distinct state combinations, roughly equal numbers of in each.

Things Get More Puzzling

As extension to experiment, add two magnets to check results



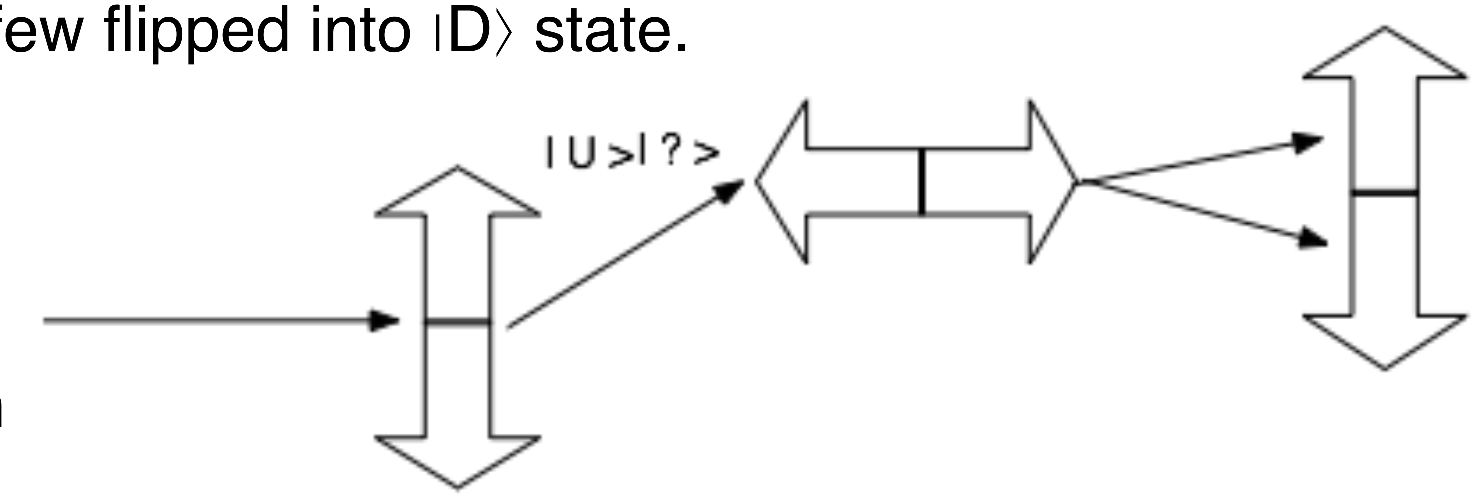
Results of experiment are truly remarkable.

Electrons from beam labelled as ∣U⟩ ∣R⟩ (thought to contain electrons only in ∣U⟩ state) now pass through last magnet and emerge from either UP- or DOWN-channel!

Seems some ∣D⟩ state electrons got mixed with beam thought pure ∣U⟩., but cannot be explanation since no extra electrons. Results show each of emerging beams contains roughly half of electrons. Better explanation - (LEFT,RIGHT) magnet changed state of some of electrons passing through. All electrons arriving at magnet are in ∣U⟩ state, but perhaps after passing through (LEFT,RIGHT) magnet, a few flipped into ∣D⟩ state.

Answer from new experiment:

Experiment starts with pure beam of ∣U⟩ electrons (select UP channel of (UP,DOWN) S-G magnet) passing through (LEFT,RIGHT) magnet, producing two beams(half of electrons each).



Now move another (UP,DOWN) magnet very close beams pass through magnet.

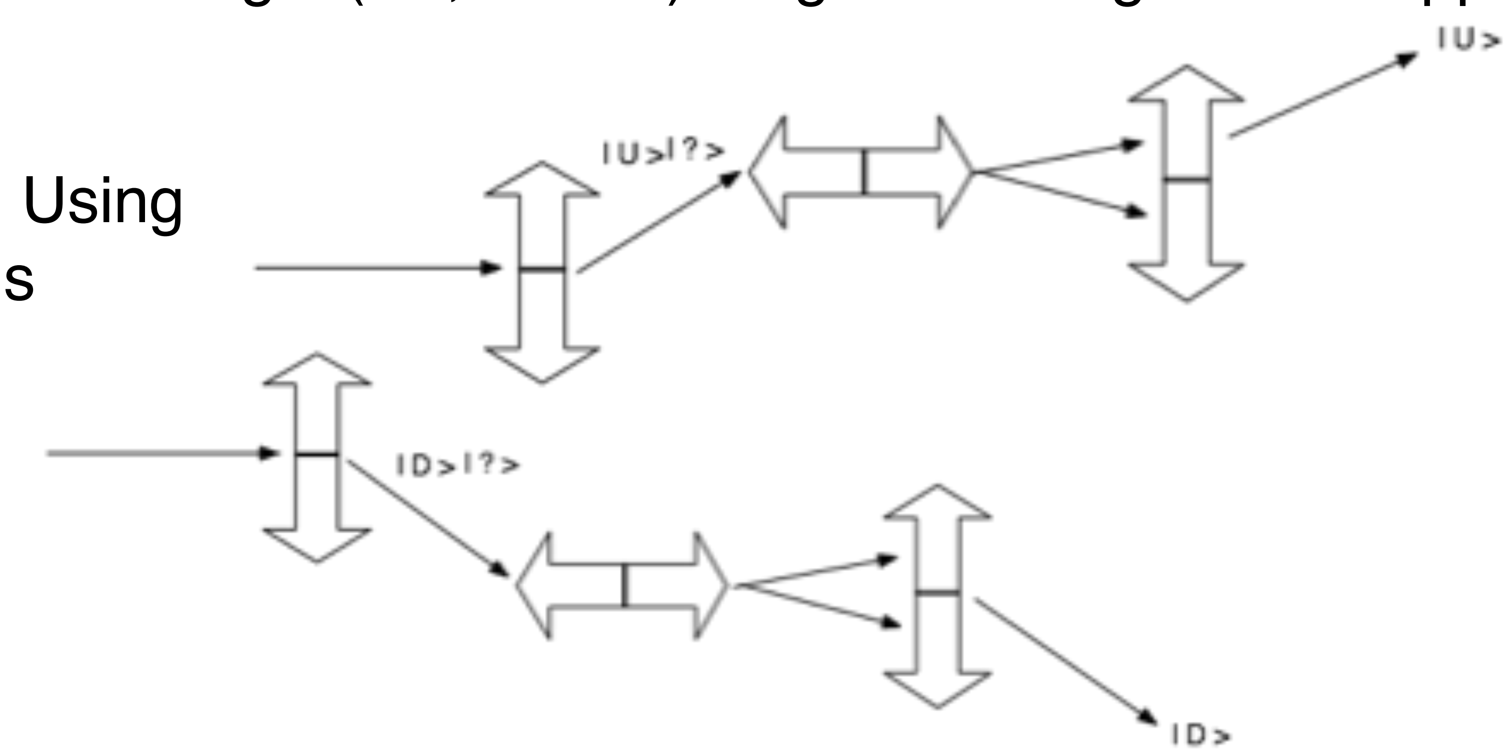
Not difficult - deflections small - big distance needed to separate beams measurable amounts.

Before we discuss what actually happens, summarize thinking.

1. Going through (UP,DOWN) magnet splits 1 into 2 beams.
2. Implies electron in 1 of 2 states and magnet is sorting them.
3. Called these states |U⟩ and |D⟩.
4. Horizontal magnet sorts electrons into |R⟩ and |L⟩ states.
5. -> four combinations of electron states: |U⟩ and |R⟩, |U⟩ and |L⟩, and so on.
6. Passing beam of electrons that is only |U⟩|R⟩ (came from UP channel and RIGHT channel in that order) into another (UP,DOWN) magnet divides beam into 2 again.
7. Conclusion from experiment is that passing |U⟩ beam through (LEFT,RIGHT) magnet flips (UP,DOWN) state of some of electrons. If so - which electrons get switched? Is there any determining property?

Based on (1-7), predict that allowing both beams from (LEFT,RIGHT) magnet to pass through single (UP,DOWN) magnet produces same result as having an (UP,DOWN) magnet on each beam. Should get two beams emerging from single (UP,DOWN) magnet as magnet has flipped state of some of electrons.

Of course we get an unexpected result! Using 1 magnet to catch both emerging beams produces just single beam of pure |U⟩ electrons (and for lower beam also).



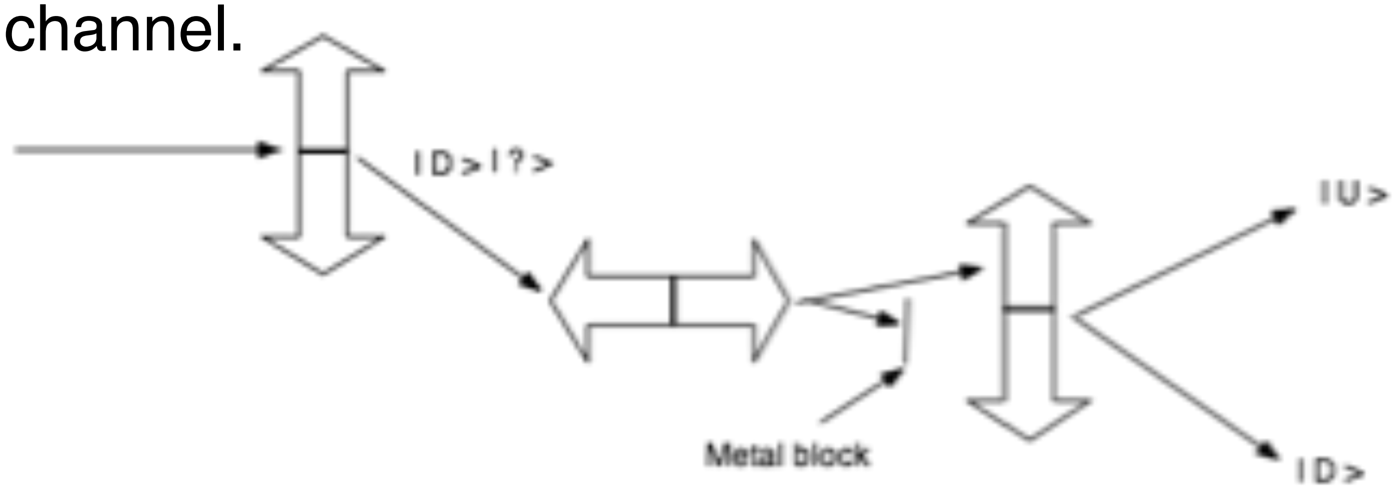
Conclusion is clear.

If beams from (LEFT,RIGHT) magnet passed into separate (UP,DOWN) magnets, then ıU〉/ıD〉 state of electrons is modified. However, if both beams from (LEFT,RIGHT) magnet pass through same (UP,DOWN), then no state flip. Original state of electrons that entered (LEFT,RIGHT) magnet preserved. Remember hard/soft electrons in 2-path experiment(all stay magenta).

Very puzzling. Up to now, everything said about electron states and way electrons are deflected (sorted) by S-G magnets could be simple extension to classical ideas about electrons. Now, this experiment -> starting to see states have quantum nature -> behave in rather different (non-classical) way.

Retain some common sense - speculate that flipping of electron's state is process that needs certain distance over which to happen. Moving (UP,DOWN) S-G magnet closer have not given enough opportunity for flip to happen. Can kill idea and any similar lines of thought by making simple modification to experiment.

Small metal plate sufficient to block LEFT channel of (L,R) magnet - stop electrons in that channel.

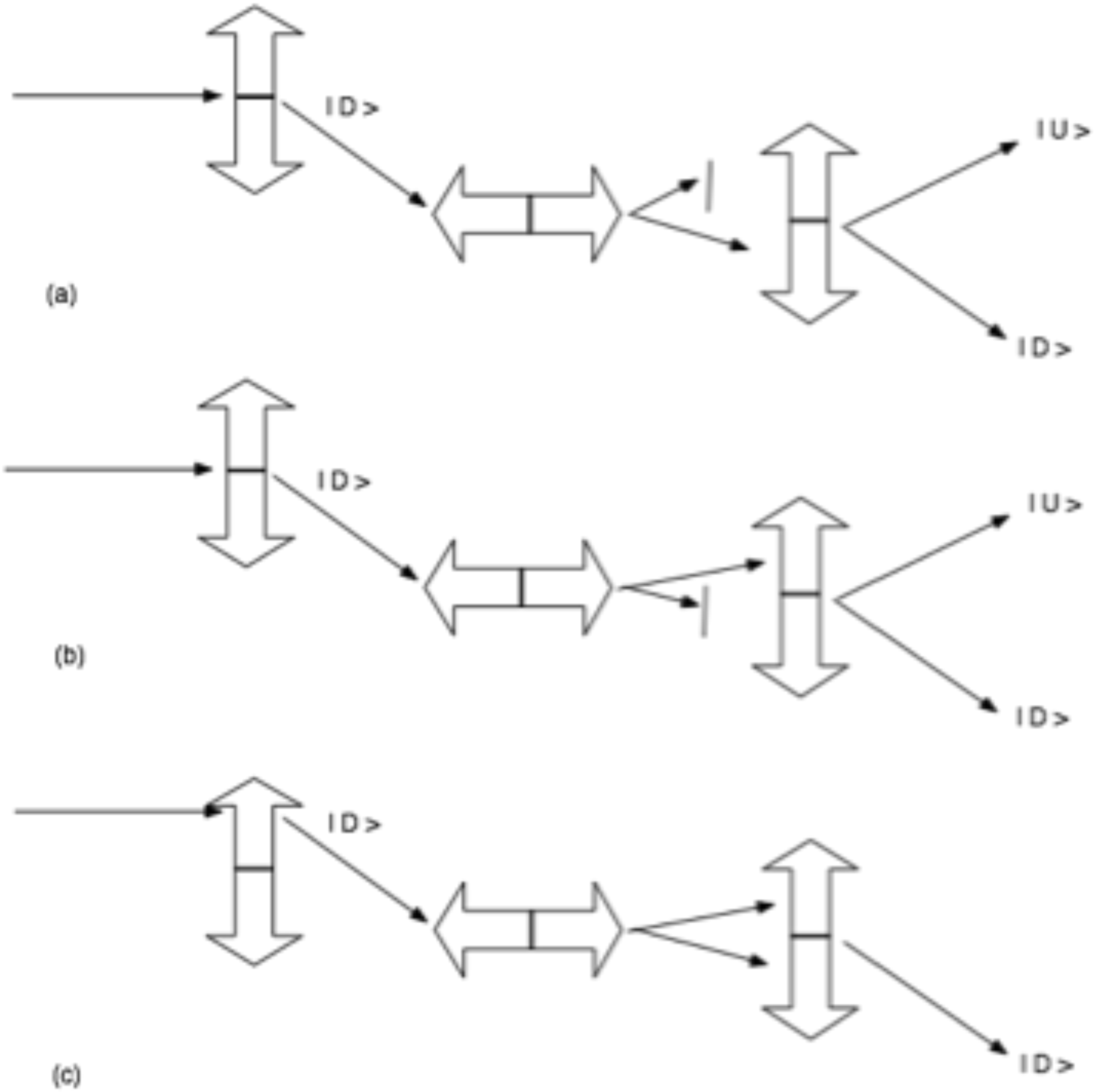


Have not moved magnet any further away, so all ıD〉ıL〉 electrons will presumably, if guess about distance being needed correct, stay in ıD〉 state and come out of second magnet along bottom channel.

Wrong again!

Modification adds another puzzle. Blocking LEFT channel restores flipping (UP,DOWN) state. As experiment doesn't alter distance travelled by electrons in RIGHT channel, have eliminated argument based on flipping needing certain distance to work. Can turn flipping on or off by blocking one of paths and doing nothing to distance. (Blocking RIGHT channel same)

Summarize results of experiments below.



(a) Blocking RIGHT channel produces mixture of $|U\rangle/|D\rangle$ states in electrons that pass through LEFT channel.

(b) Blocking LEFT channel produces mixture of $|U\rangle/|D\rangle$ states in electrons that pass through RIGHT channel.

(c) Having both LEFT and RIGHT channels open produces only $|D\rangle$ state electrons.

What Does It All Mean?

Started with idea that electrons possess certain state property that determines path through S-G magnet. Some electrons start in $|U\rangle$ state and some in $|D\rangle$ state, and when electrons are formed into beam, $|U\rangle$ and $|D\rangle$ electrons randomly distributed, so can't tell which type coming next.

Crucially, we are assuming that state of electron fully determined before enters any magnet in its path. This is assumption behind classical idea of a state (that measurement reveals what is already there).

Results of experiments completely undermine this idea.

1. Passing beam |D⟩ electrons through (LEFT,RIGHT) magnet separates them into |D⟩|L⟩ and |D⟩|R⟩ states(equal numbers)

2. Passing |D⟩ |L⟩ and |D⟩ |R⟩ electrons into separate (UP,DOWN) magnets produces both |U⟩ and |D⟩ electrons at each magnet. |D⟩ state does not always survive passing through (LEFT,RIGHT) magnet.

3. Passing |D⟩ |L⟩ and |D⟩ |R⟩ electrons into same (UP,DOWN) magnet produces pure |D⟩ beam. |D⟩ state is now preserved.

4. Undermines thought expressed in (1) that can specify (UP,DOWN) and (LEFT,RIGHT) states at same time. No |D⟩ |L⟩ and |D⟩ |R⟩ states, just |U ⟩/|D⟩ OR |R⟩/|L⟩ states.

5. **Suggestion:** distance travelled by electrons or passage through magnet causes effects contradicted by experimental results produced by blocking one of beams.

6. Blocking left- or right-hand beam through (LEFT,RIGHT) magnet separately before reach same single (UP,DOWN) magnet as in point (3) results in some electrons going up and some going down.

7. Nature of electron's state depends on **context of experiment**.

Another point makes things even stranger. If block LEFT channel, then electrons passing along RIGHT channel into (UP,DOWN) magnet emerge either |U⟩ or |D⟩. However, if passed along RIGHT channel, how can have known that LEFT channel closed? Another way, if suddenly open up LEFT channel, add more electrons passing into (UP,DOWN) magnet - those that would have gone through RIGHT channel anyway and those that were blocked in LEFT channel. Suddenly all electrons are now in |D⟩ state. Remember magenta electrons coming out all magenta!

No results depend on intensity of beam. If one electron present in apparatus at a time, all experiments => same results. Disposes of idea that electrons are interacting. No way that electron passing through one channel could be influenced by other channel being blocked, unless there is another electron in that channel at same time to mediate influence. Clearly, as experiment gives same result with low-intensity beam, that idea can't work either.

Results can made coherent whole. Consider what information we can obtain from each experiment. When one channel through (LEFT,RIGHT) magnet blocked, clear that any electron emerging from experiment must have passed through open channel.

With both channels open, cannot tell which path the electrons followed through (LEFT,RIGHT) magnet. Cannot just watch them go past. Any method used to determine which path electrons take = blocking the path.

Similarities to photon experiments. Again context of whole experiment proves crucial. Evidently, knowing electron either $|L\rangle$ or $|R\rangle$ state prevents us from saying it is in $|U\rangle$ or $|D\rangle$ state.

Look at figure: having 1 path blocked after 2nd magnet -> electron entering (UP,DOWN) magnet clearly either $|L\rangle$ or $|R\rangle$ state -> lose any idea of being $|U\rangle$ or $|D\rangle$. Both paths open -> no information from expt tells us $|L\rangle/|R\rangle$ state of electrons. Then, can retain some information about $|U\rangle/|D\rangle$ state.

Interpretation not required by results of experiments discussed so far. Look at other quantum experiments - see consistency of approach. Earlier color/hardness showed getting different results depended on not being able to tell which path electrons were using. Here can tell if it is $|U\rangle/|D\rangle$ as long as cannot tell if is $|L\rangle/|R\rangle$.

Results showing something important about nature of quantum state.