Stern-Gerlach Experiments

Now we repeat everything using electrons and Stern-Gerlach devices (real world devices)

—> we reinforce knowledge learned and expand our understanding.

Discussion involves the results of a classic experiment first done in 1922.

Stern-Gerlach (S-G) experiment studies how electrons behave in magnetic fields.

Illustrates how electrons behave in another context(beyond color/hardness)

and it thereby further develops the idea of quantum states

and the assumptions of quantum theory

and allows for later discussion of modern quantum experiments

and of ideas which seem so paradoxical to classical physicists.

Remember

Seemingly paradoxical nature of light/electrons has been called **wave-particle duality**

i.e., they could appear as wave in one situation

and a stream of particles in another.

To understand this,

we will need to discard the classical descriptions of waves or particles

(maybe there are no such things quantum mechanically)

and develop new set of rules and concepts to cover the strange microworld.

There will be no wave-particle duality in QM in the classical sense of the words!

We will find that:

Electrons can exhibit wave-like properties during measurements

if that is how we set up experiment in a certain way

or if **we are asking** questions that require “wave-type” answers.

Electrons can exhibit particle-like properties during measurements

if that is how we set up experiment in a certain way

or if **we are asking** questions that require “particle-type” answers..

The **context** of experiment will **determine** the experimental results(answers).

The quantum theory of microworld is **contextual** in nature as we shall see.

Quantum mechanics will correctly answer whatever question you ask and the answer will be in context of the question!

The Classic Stern-Gerlach Experiment

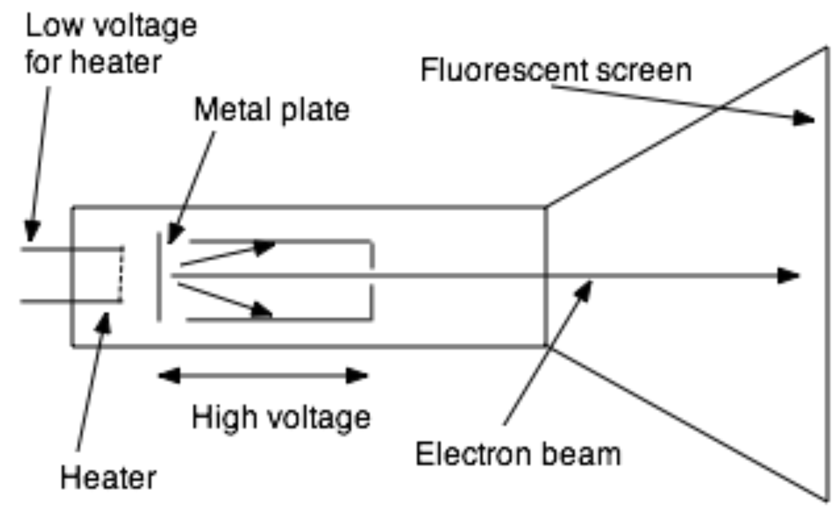
QM -> electrons are fundamental particles, have - charge and ~1/2000 proton mass.

Found isolated or inside atoms where held to +charged nucleus by electric forces.

If atoms subjected to large electric field, then one can ionize(remove) electron from atoms.

Old style CRT tubes are large glass containers with a vacuum inside

Electron gun -> uniform beam of electrons



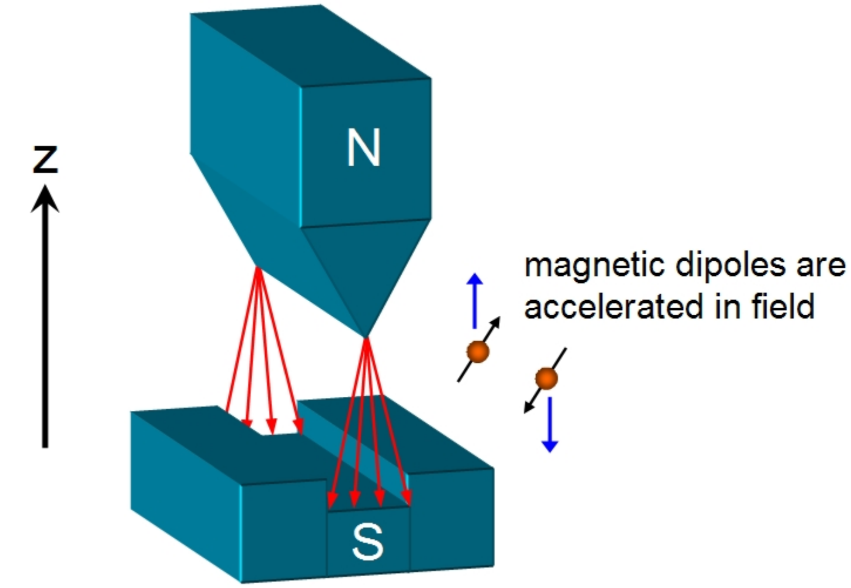
Electrons behave like tiny bar magnets(they have a magnetic moment) when sent into a magnetic field,

i.e., send some tiny bar magnets into non-uniform

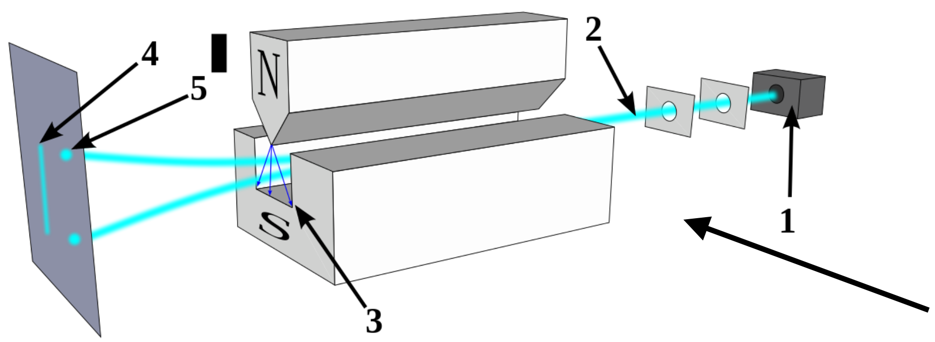
magnetic field (stronger at top than bottom of field region)

then field both deflects path of magnets and aligns(N-S axis) magnets with fields.

Assume that S-G magnet exerts similar magnetic force
on electrons (which have magnetic moment due to spin)
when they are passing between the poles
and that force will deflect the electron's path



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



Hypothetical experiment to see how much deflection takes place when we pass an electron beam between the poles of a magnet.

Detect deflected electrons **outside** field region;

Can detect **single** electrons.

expecting to see spread —> #4

but see only 2 spots—> #5

i.e., only TWO experimental values

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 result was very surprising to classical physicists:

i.e., amount of deflection(up or down) is same for each electron.

If electron were truly acting like a tiny magnet (classical picture),

then expect magnets to be pointing in random directions when they enter S-G field.

Consequently, amount of deflection,

which depends on initial orientation of electron's magnet

would be slightly different for each.

End result = range(in space) of detected deflection angles **not** just two fixed deflections.

Classical picture —> spread, but experiment sees only 2 spots !

Can interpret the results as follows:

Assume electrons have an internal property (UP/DOWN)

which determines which way they are oriented.

As they emerge from electron gun,

up and down types produced at random(but with equal numbers)

—> get two equal-sized sets of sorted electrons.

Define electrons deflected up as UP state electrons = $|U\rangle$

and those deflected down as DOWN state electrons = $|D\rangle$.

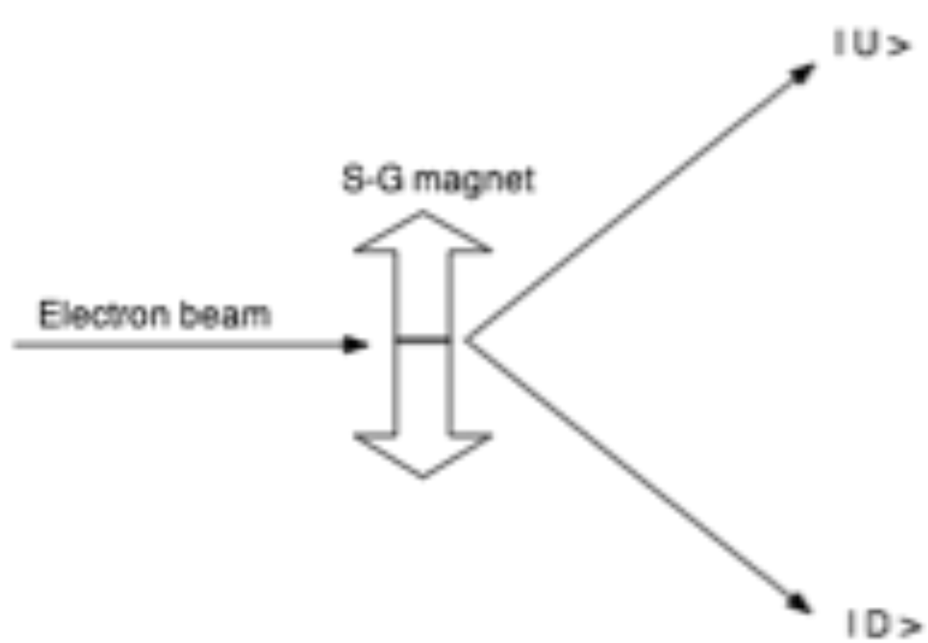
NOTE: Any assumption that state of electron is determined by an internal property will lead to problems later.

Assume $|U\rangle/|D\rangle$ state describes an electron in this context(using UP/DOWN language now):

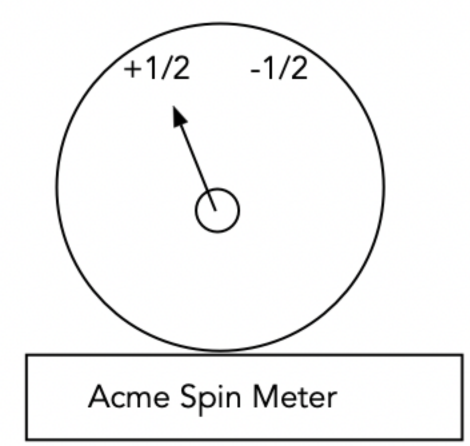
As they are moving along top/bottom path through S-G magnet,

some internal state property (U/D) of electron determines which path they follow,

and observing the path of electron is **only** way we can measure that state property.



Can check beam properties with meter



Presumably electron gun producing electron beam for the experiment

is designed to have electrons randomly emerge in either $|U\rangle$ or $|D\rangle$ state.

These electrons then pass through the poles of an S-G magnet

and are sorted by being deflected **according** to the state(ket) labels.

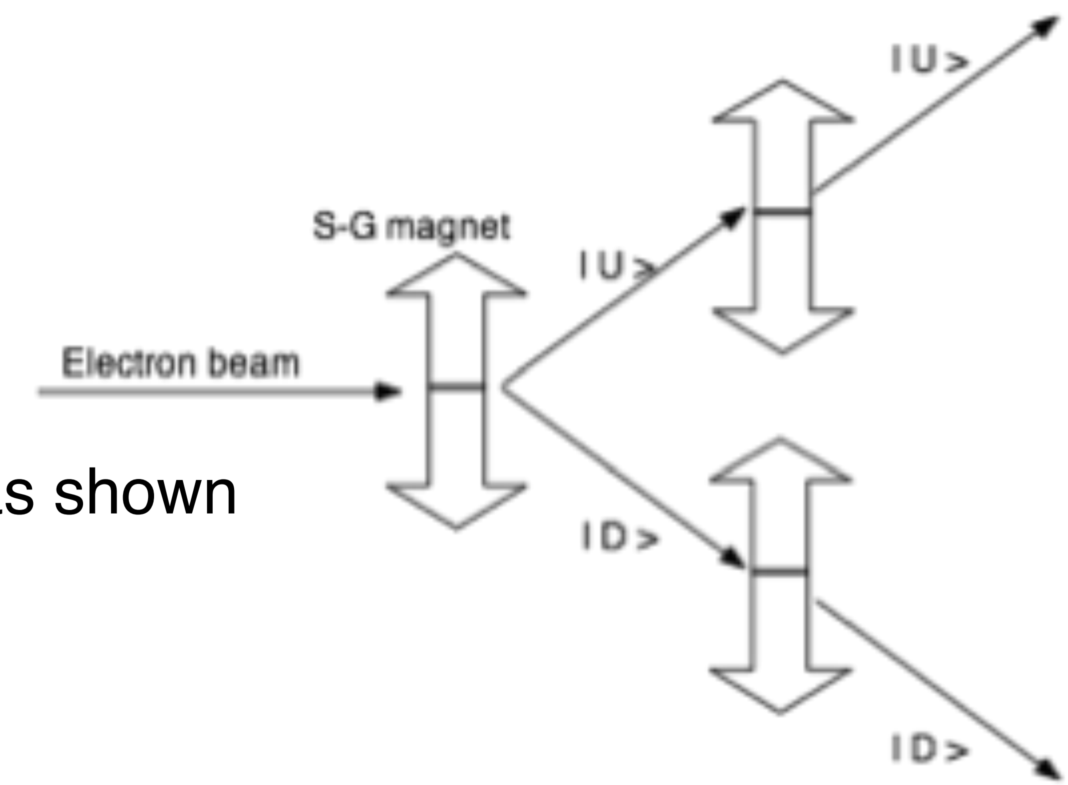
Now we ask if the experimental results

are genuinely measuring

some state property(U/D) of electrons,

or if magnet is simply randomly deflecting

them one way or other.



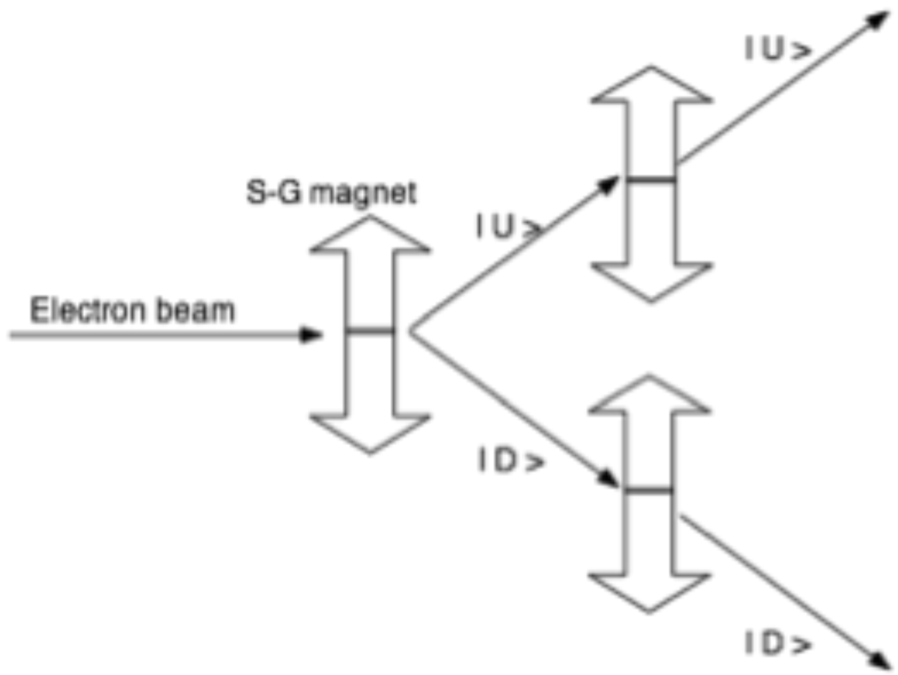
Answer this question by modification of experiment as shown

Electron detector removed/replaced

by further pair of S-G magnets

arranged so that electrons passing out of first magnet

pass through only one of two additional magnets



Results are conclusive.

(corresponds to earlier repeatability measurements)

Those electrons that emerged along

UP channel of first magnet

then pass through topmost second magnet

and **all** emerge from that magnet's UP channel.

None are deflected downward

(there would be some down if each magnet was randomly deflecting electrons).

Similarly,

For those DOWN electrons emerging from first magnet,

all subsequently deflected down by second magnet.

Second magnets(can even add more)

confirm sorting of first magnet.

Results give the **impression**

that S-G magnets are measuring some **state property** of the electrons.

Turning the Experiments Around

Up to now, we have been using S-G magnets oriented vertically

so they are deflecting electrons **upward or downward**.

The magnets can be turned through 90°

so that they now deflect the same electrons **right or left**.

In fact, S-G magnets can be oriented at any angle,

but **only need** (UP,DOWN) and (LEFT, RIGHT) for our present discussion.

Results of experiment with S-G magnet turned horizontally

are 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 arguments as earlier suggest

that there are two possible states in this context for the electron $|R\rangle$ and $|L\rangle$,

and the magnet sorts them (using RIGHT/LEFT language).

Thus, electrons **have** second state property (R/L)

that determines which way they are deflected by horizontal magnets.

Adding two further magnets, also arranged horizontally,

to check out the electrons in either deflected beam confirms this as before.

Results are not surprising. $|R\rangle$ electrons from first magnet

are deflected only to right by second magnet

and $|L\rangle$ electrons are deflected to left again by second magnet.

The similarities to Hardness and Color are striking! **By Design on my part!!**

For the physicist, the next step is

to see if ∣U⟩ and ∣D⟩ states are linked (**correlated**) to ∣R⟩ and ∣L⟩ states in any way.

—> “**determining**” whether state properties connected(correlated)?

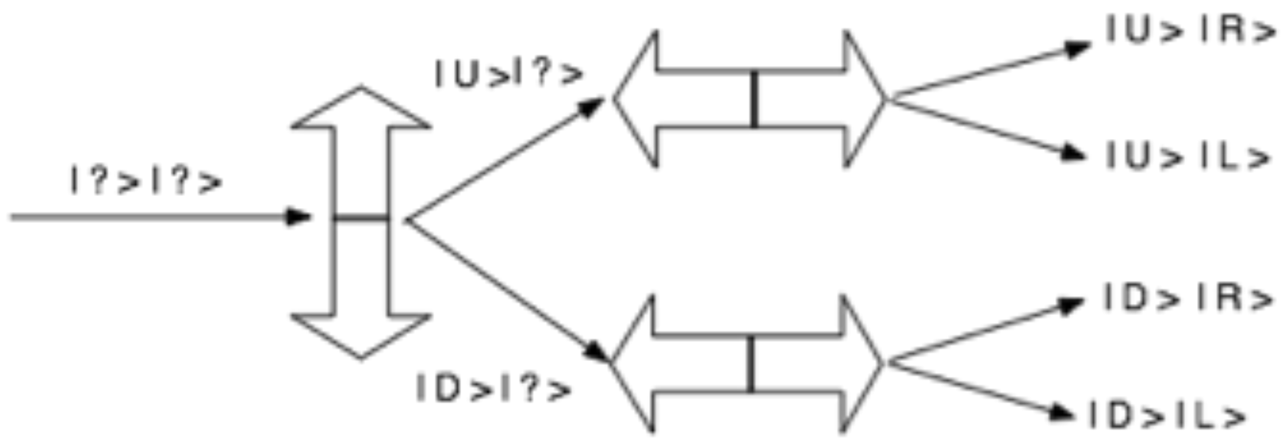
Easy to check by constructing experiment

that uses an (UP,DOWN) S-G magnet

with two (LEFT,RIGHT) magnets

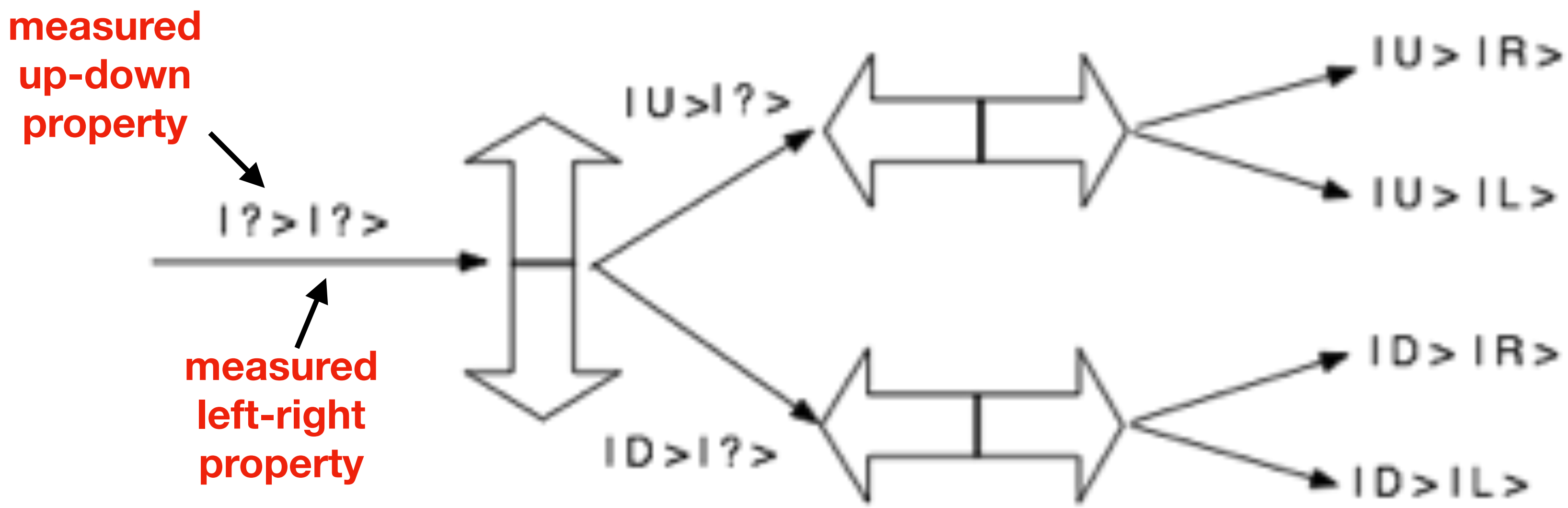
so that electrons in UP and DOWN channels

of first magnet are tested to see if either ∣L⟩ or ∣R⟩.



symbols mean |U/D property>|R/L property>

In figure used symbol ∣?⟩ -> not sure state electron in, i.e., property has not been measured yet!



Results of experiment are very interesting.

|D⟩ electron passing into (LEFT, RIGHT) magnet

comes out via either channel;

and also the same for |U⟩ electron (same as happened in color/hardness boxes).

Now if true,

it **appears** that we are dealing with 4 different combinations of electron states

that are determined by the 2 state properties.

An electron in state |U⟩ could also be in either state |L⟩ or state |R⟩, etc

So the possible combinations are

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

Suppose we say: Electron gun is producing equal numbers of each type of pair.

Then, combination of 2 differently oriented (perpendicular) magnets

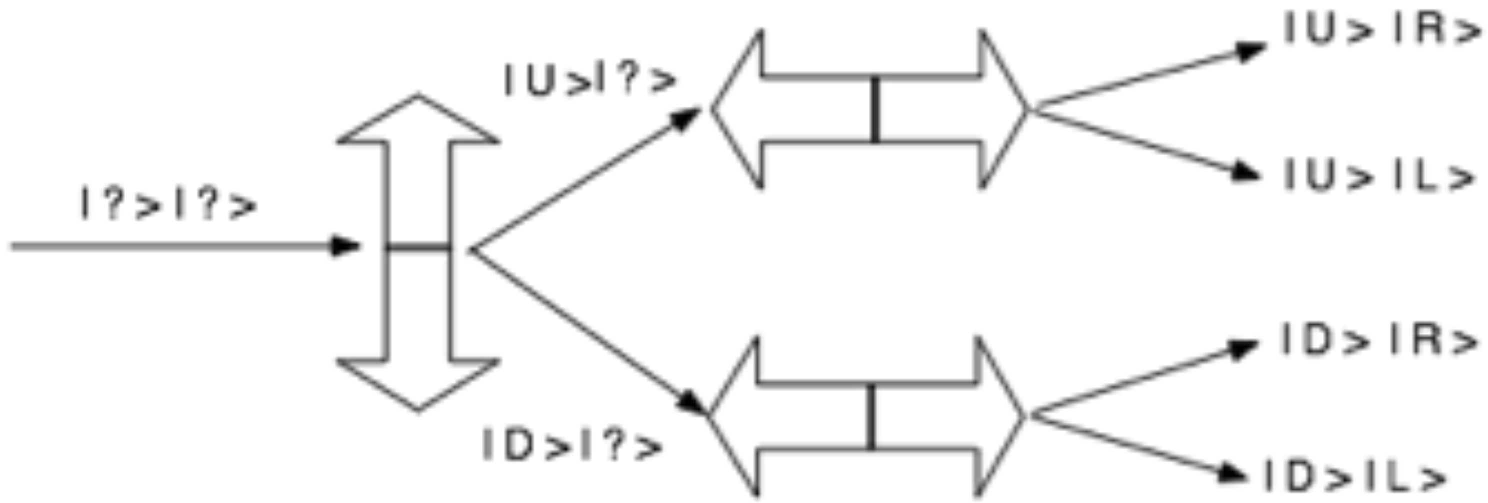
would sort out these electrons as shown above. **—> equal numbers in each group!**

Remembering from last lecture, when electrons arrive at first magnet,

no way of knowing either

(UP,DOWN) or (LEFT,RIGHT) state,

hence $|?\rangle|?\rangle$.



First magnet sorts into ı U〉 or ı D〉,

but tells us nothing about IR〉 or ı L〉 state.

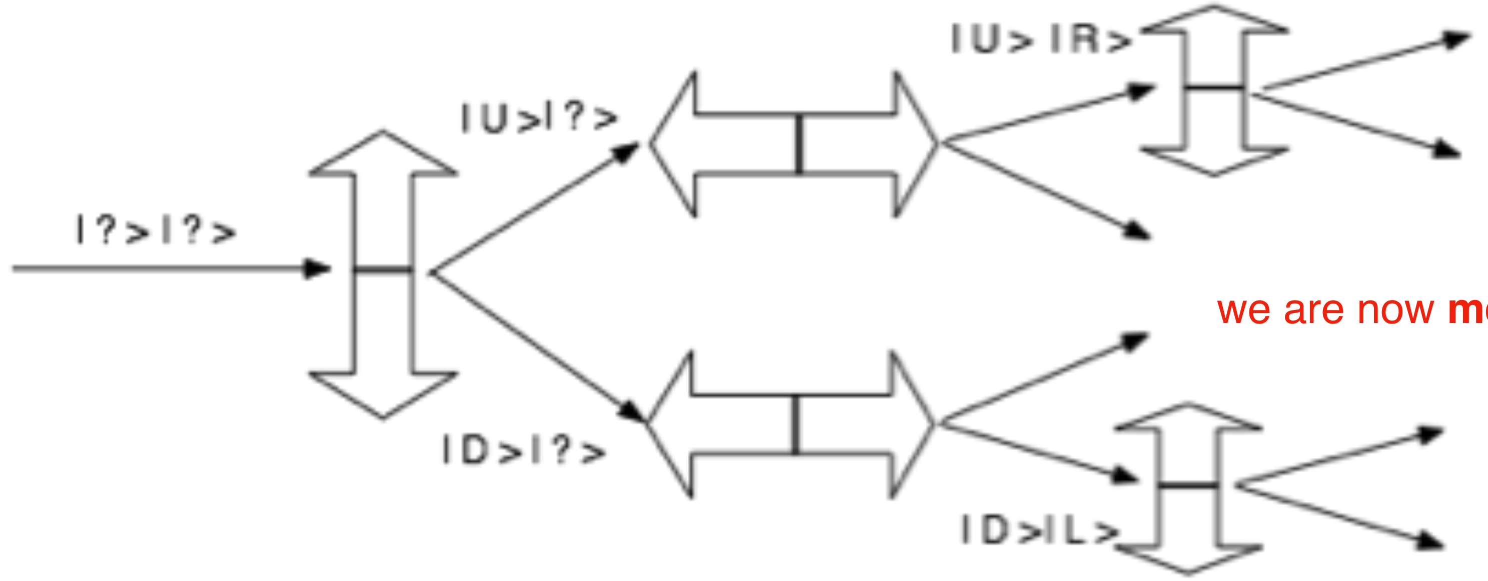
Final pair of magnets completes sorting

-> four piles of distinct state combinations, with roughly equal numbers of in each pile.

I note here we are only guessing at labels = labels may not have meaning!

Things Get More Puzzling

Let us make an extension to the experiment by adding two more magnets to check results



we are now **measuring** electrons before they go into final magnet

Results of experiment are truly remarkable(as they were in color-hardness experiments).

Electrons from beam labelled |U⟩|R⟩

(thought to contain electrons only in |U⟩ state)

we have just done two measurements

classical view

now pass through last magnet

and emerge from **either** the UP- or DOWN-channel!

Both channels have electrons!

Seems some |D⟩ state electrons got mixed with beam that we thought was pure |U⟩.

But that cannot be the explanation since we find no extra electrons in beam.

Results show each of emerging beams contains roughly half of electrons.

Better explanation

(LEFT,RIGHT) magnet changed

the 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.

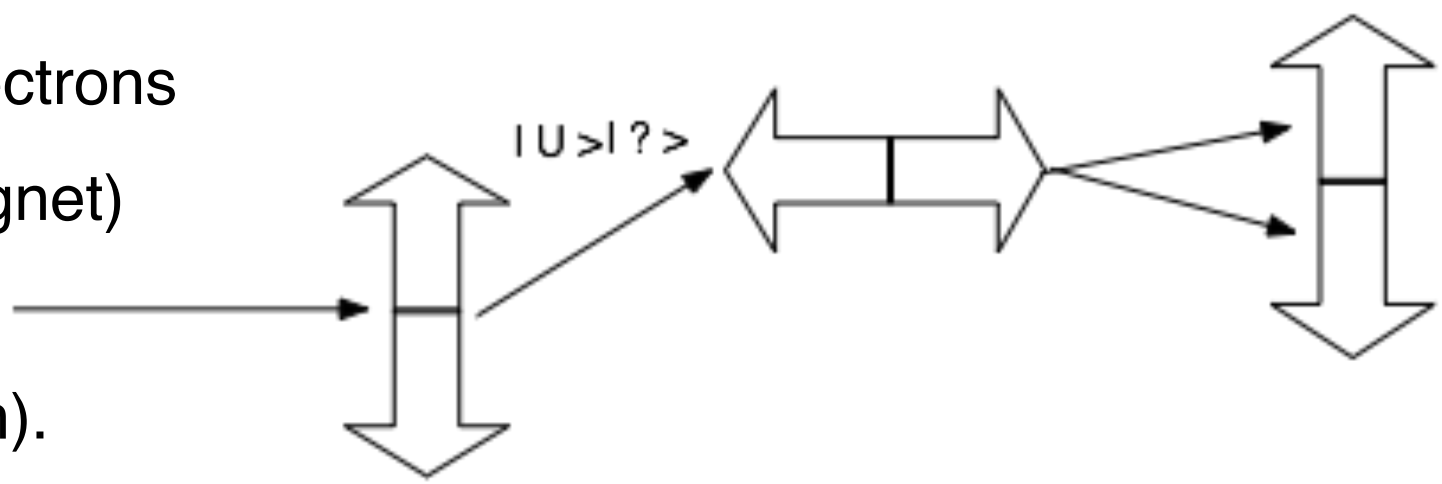
Get Answer from another new experiment(only experiment can give answers!):

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

-> both beams now pass through final magnet (we are **NOT** measuring electrons before they go into final magnet).

Not difficult - deflections small -> big distance is needed to separate the beams by measurable amounts.

Before we discuss what actually happens, let us summarize our thinking:

1. Going through (UP,DOWN) magnet splits 1 beam into 2 beams.

2. Implies electron in 2 possible states and magnet is sorting them.

3. Called these states $|U\rangle$ and $|D\rangle$.

4. Similarly, horizontal magnet sorts electrons into $|R\rangle$ and $|L\rangle$ states.

5. —> four combinations of electron states: $|U\rangle$ and $|R\rangle$, $|U\rangle$ and $|L\rangle$, and so on.

6. Passing beam of electrons that is only $|U\rangle|R\rangle$
(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 $|U\rangle$ beam through (LEFT,RIGHT) magnet
flips (UP,DOWN) state of some of electrons.

If so - which electrons get switched? Is there any determining property?

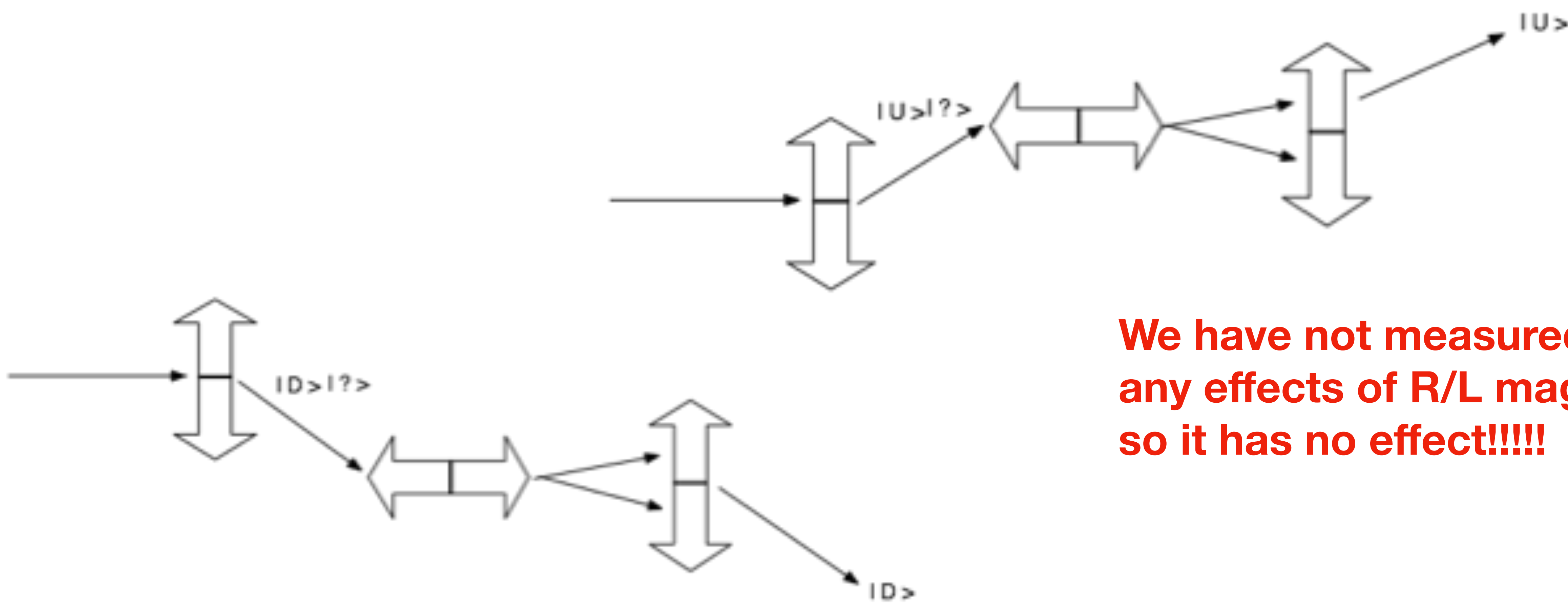
Remember hardness/color experiments. Sound familiar!

Based on (1-7),
we 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 (LEFT,RIGHT) 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).



We have not measured any effects of R/L magnet so it has no effect!!!!!

Conclusion is clear.

If beams from (LEFT,RIGHT) magnet passed into separate (UP,DOWN) magnets,

then $|U\rangle/|D\rangle$ 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 is preserved.

Remember hard/soft electrons in 2-path experiment (all stayed magenta).

Very puzzling until explained.

Up to now, everything we have said about electron states

and the way electrons are deflected (sorted) by S-G magnets

could be a simple extension to classical ideas about electrons.

Now, in this experiment

we are starting to see that the states have a quantum nature

—> behave in rather different (non-classical) way.

Let us try to retain some common sense

We speculate that the flipping of an electron's state

is a process that needs to travel a certain distance(time) in order to happen.

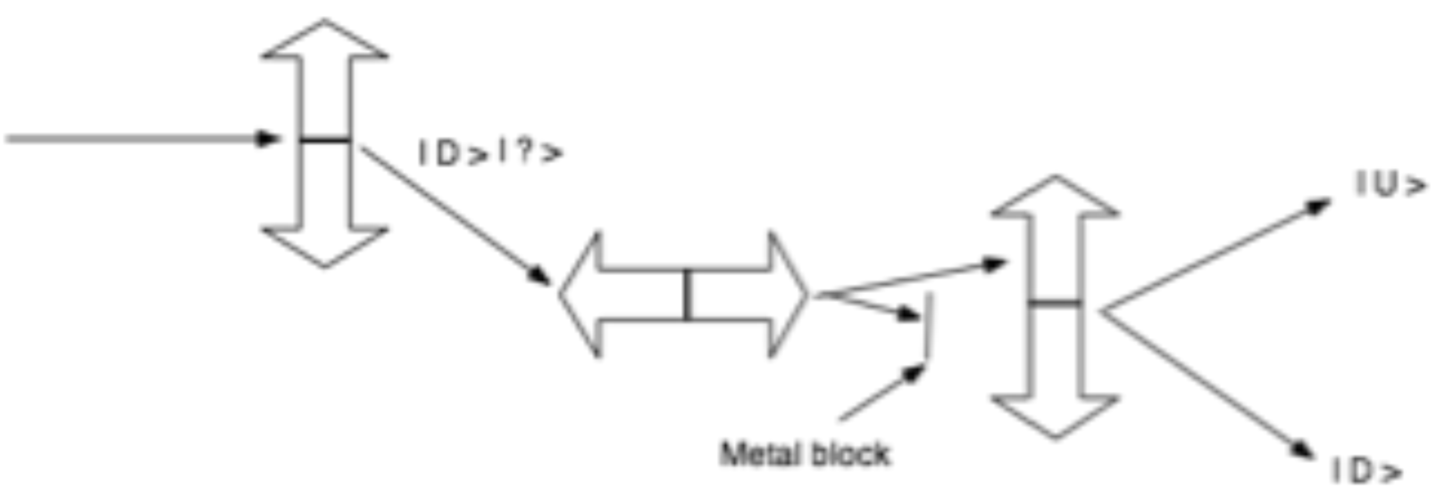
Moving (UP,DOWN) S-G magnet closer

—-> has not given enough opportunity for flip to happen.

Can kill idea and any similar lines of thought by making simple modification to experiment.

Insert 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 $|D\rangle|R\rangle$ electrons will presumably,

if guess about a distance

being needed is correct,

stay in $|D\rangle$ 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.

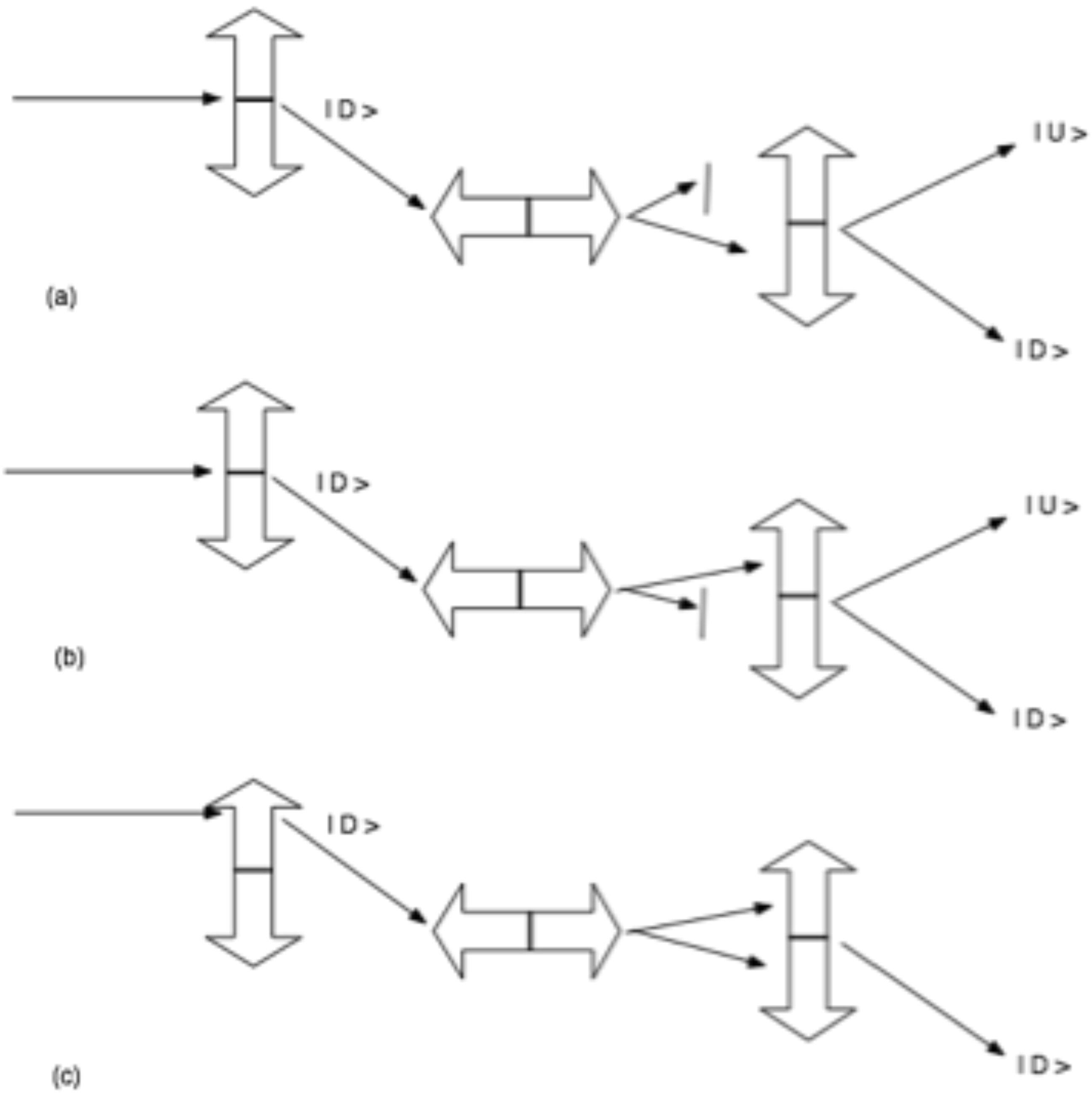
Can turn flipping on or off

by blocking one of paths and doing nothing to distance.

(Blocking RIGHT channel gives same type of result.)

Same as happened with color/hardness experiments

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 a 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 have been **assuming** that the state of electron is

fully determined **before** it enters any magnet in its path.

This is the assumption behind the classical idea of a state

i.e., that a measurement simply reveals what is already there.

Results of these experiments completely undermine this idea.

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

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

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

4. Undermines thought expressed in (1) that we can specify (UP,DOWN) and (LEFT,RIGHT) states at same time.

No $|D\rangle\,|L\rangle$ and $|D\rangle\,|R\rangle$ states exist, just $|U\rangle/|D\rangle$ OR $|R\rangle/|L\rangle$ states.

5. **Suggestion:** distance travelled by electrons on 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 reaching 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 - the question asked!!!**.

Another point makes things even stranger.

If we block LEFT channel,

then electrons passing along RIGHT channel into (UP,DOWN) magnet

emerge either $|U\rangle$ or $|D\rangle$.

However, if they passed along RIGHT channel,

how can they have known that LEFT channel closed?

(poor question)

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 $|D\rangle$ 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 with each other.

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 be made a coherent whole as follows.

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 old 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.

Having 1 path blocked after 2nd magnet

-> electron entering (UP,DOWN) magnet

clearly either |L⟩ or |R⟩ state

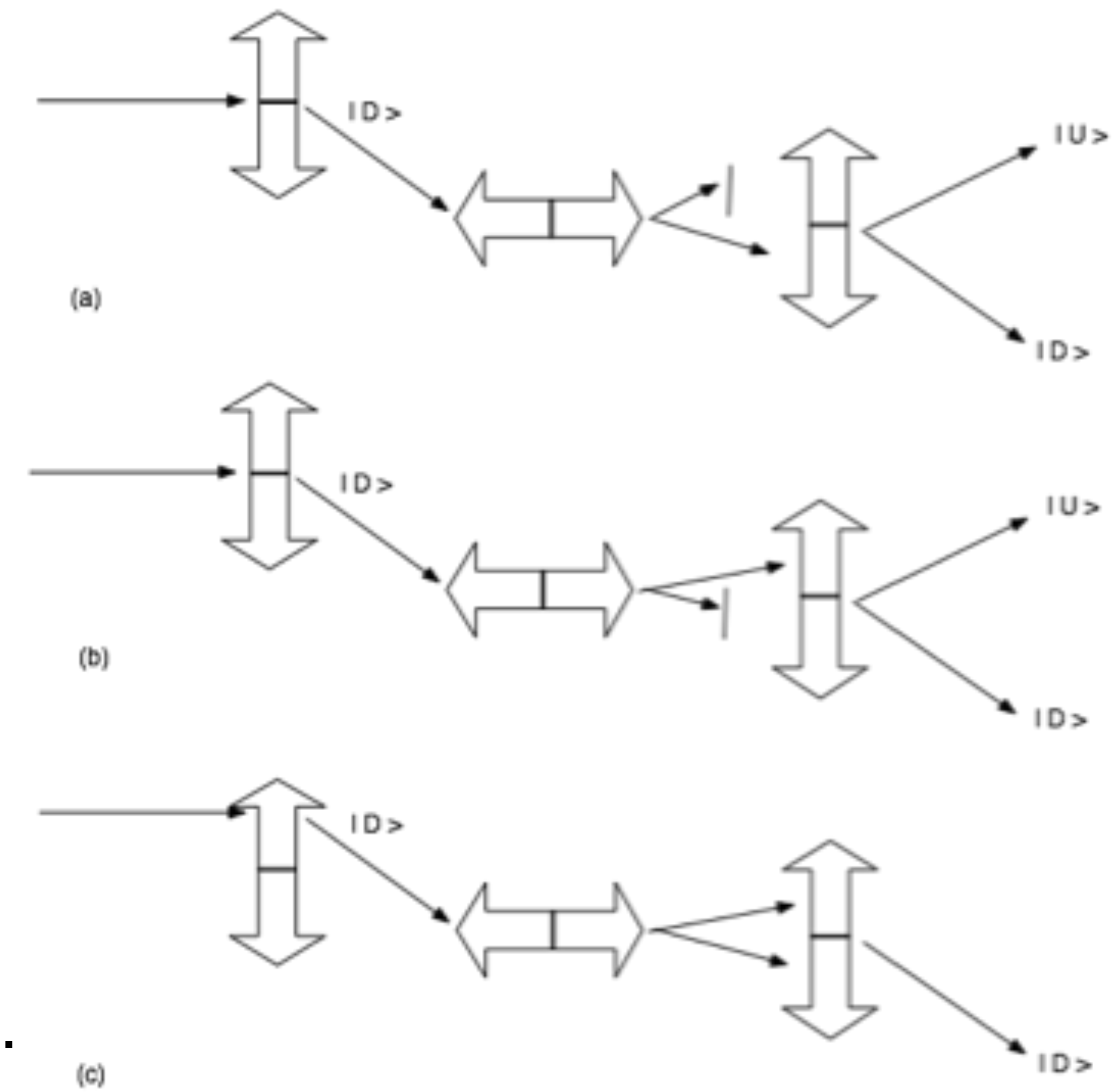
-> lose any idea of being |U⟩ or |D⟩.

Both paths open

-> no information from experiment

tells us about |L⟩/|R⟩ state of electrons.

Then, can retain some information about |U⟩/|D⟩ state.



Interpretation is not required by results of experiments discussed so far.

Must look at other quantum experiments to see consistency of approach.

Earlier color/hardness showed getting different results
depended on not being able to tell which path electrons were using.

Here we can tell if it is $|U\rangle / |D\rangle$ **as long as we cannot tell** if is $|L\rangle / |R\rangle$.

Results are showing us something important about nature of quantum state.