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) experiments studies how electrons behave in magnetic fields.

Illustrates how electrons behave in another context

and in thereby further develops 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 experiment or what question we are asking.

Electrons can exhibit particle-like properties during measurements

if that how set up experiment or what question we are asking.

Context of experiment will determine experimental results

quantum theory of microworld is **contextual** in nature.

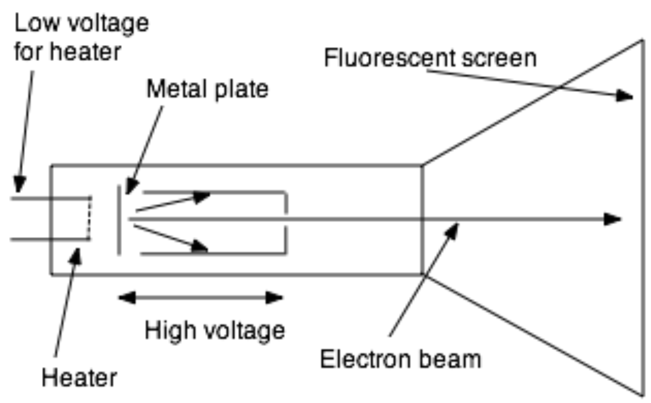
Classic Stern-Gerlach Experiment

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

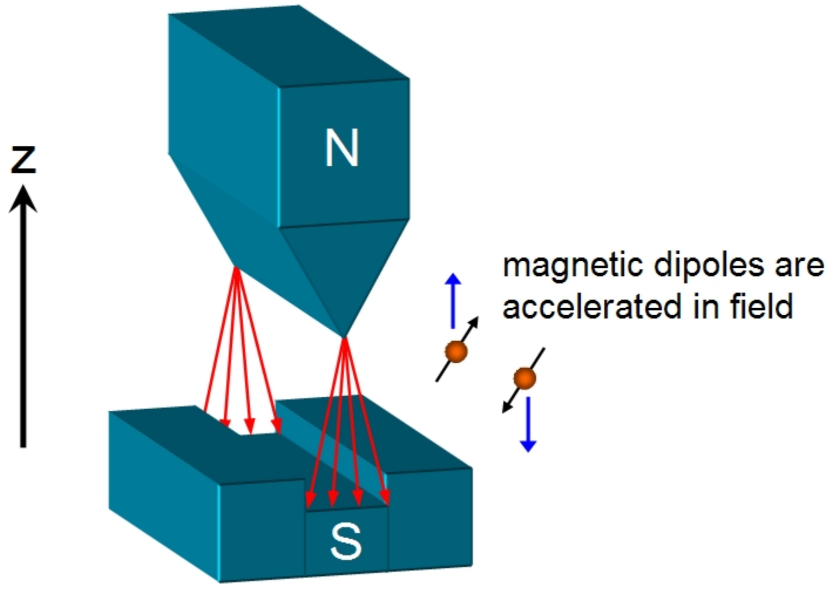
Electrons behave like tiny bar magnets when sent into magnetic field,

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.



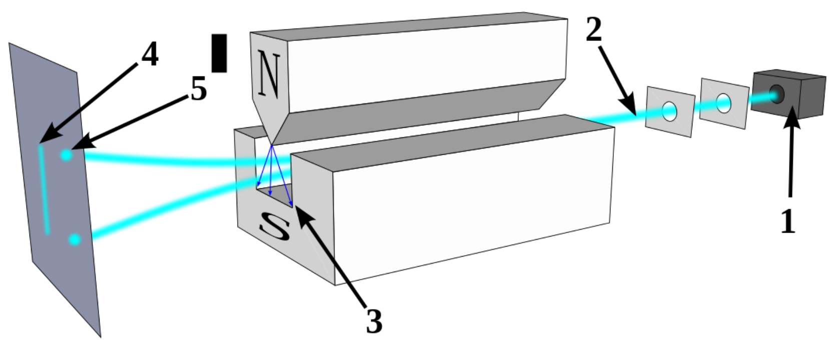
non-uniform magnetic field (red arrows) generated between magnets

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



expecting to see spread —> 4

see only 2 spots —>5

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⟩/|D⟩ 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.

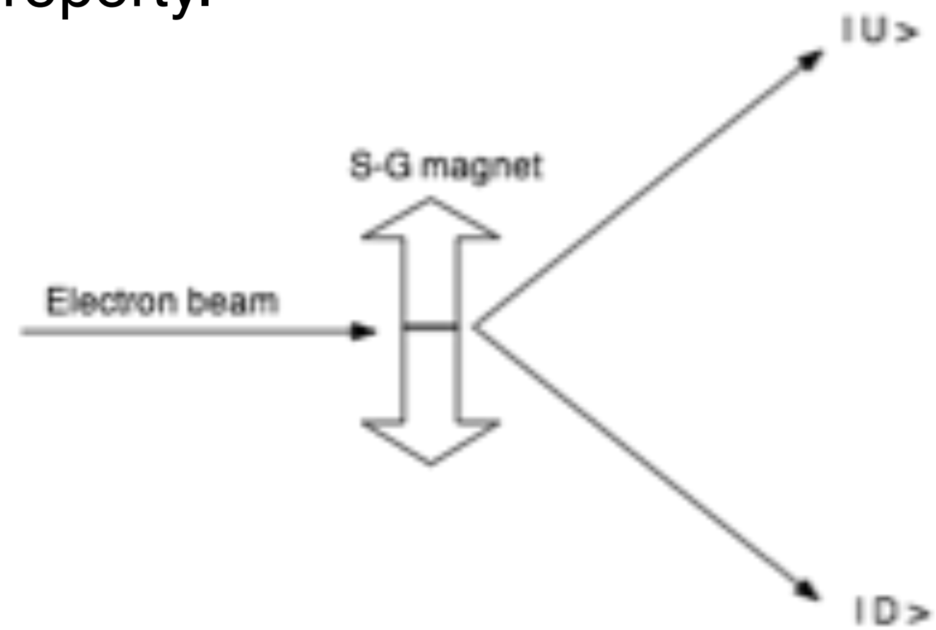
Presumably electron gun feeding experiment

producing electrons that

randomly emerge in either |U⟩ or |D⟩ state.

These Electrons pass through poles of S-G magnet

and are 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.

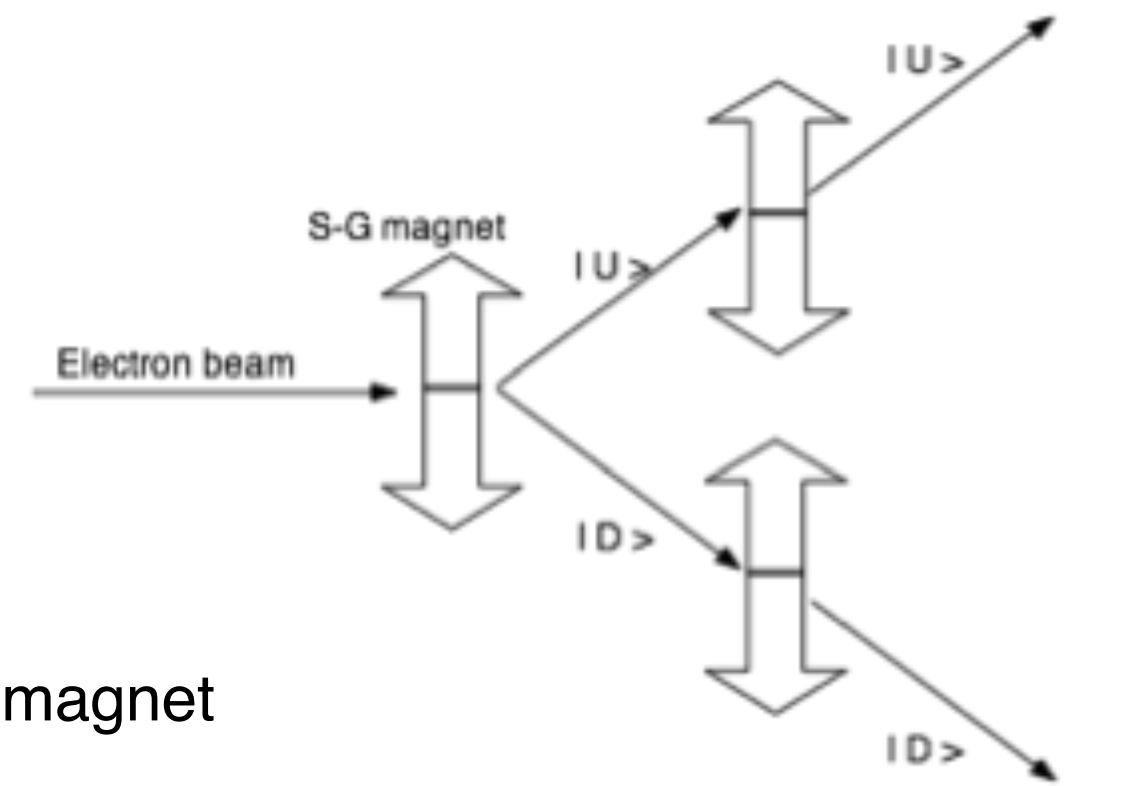
Answer question by modification of experiment

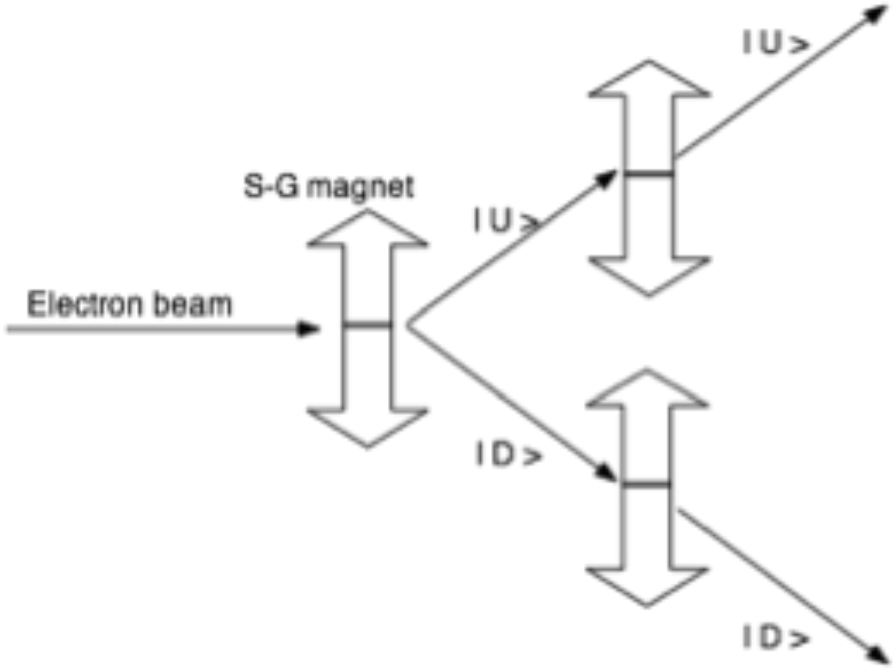
electron detector removed/replaced

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 arguments suggest

there are two possible states for electron $|R\rangle$ and $|L\rangle$,

and magnet sorts them.

Thus, 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?

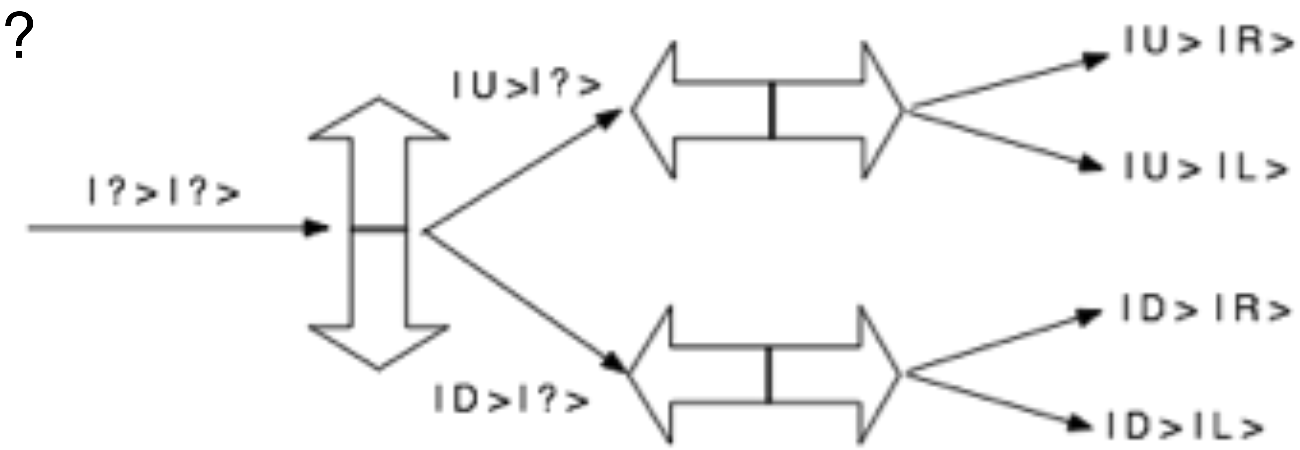
Easy to check by constructing experiment

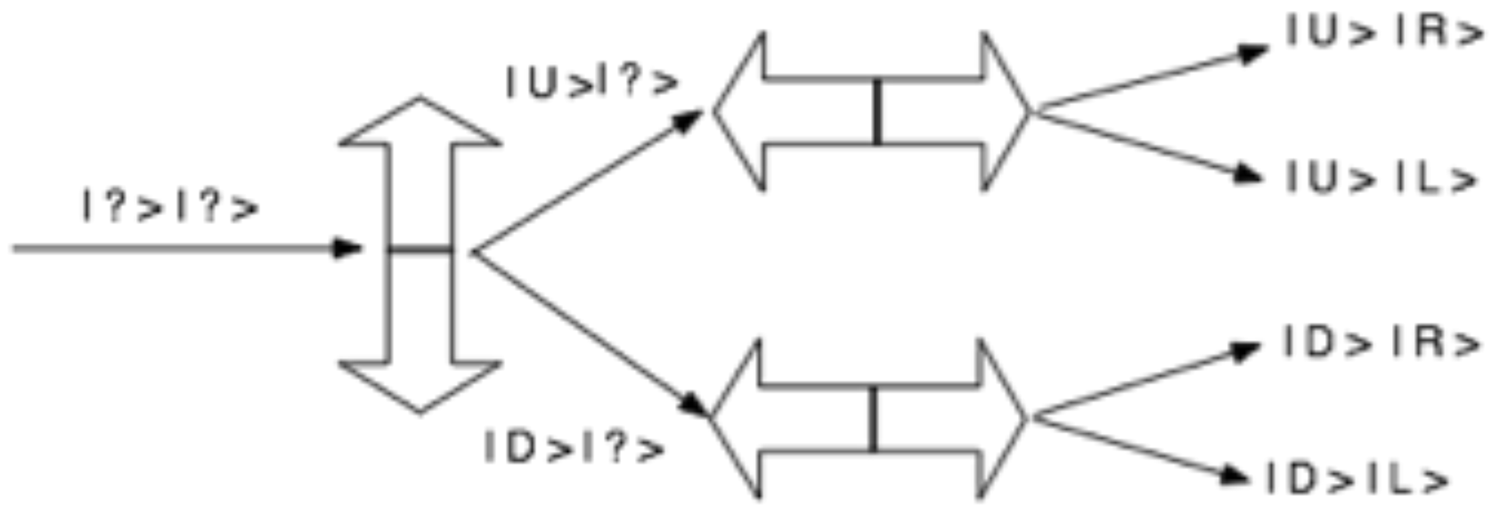
that uses an (UP,DOWN) S-G magnet

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⟩.





Results of experiment interesting.

$|D\rangle$ passing into (LEFT, RIGHT) magnet

-> out either channel;

also same for $|U\rangle$ 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 $|U\rangle$ could also be in either state $|L\rangle$ or state $|R\rangle$.

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 |?〉|?〉.

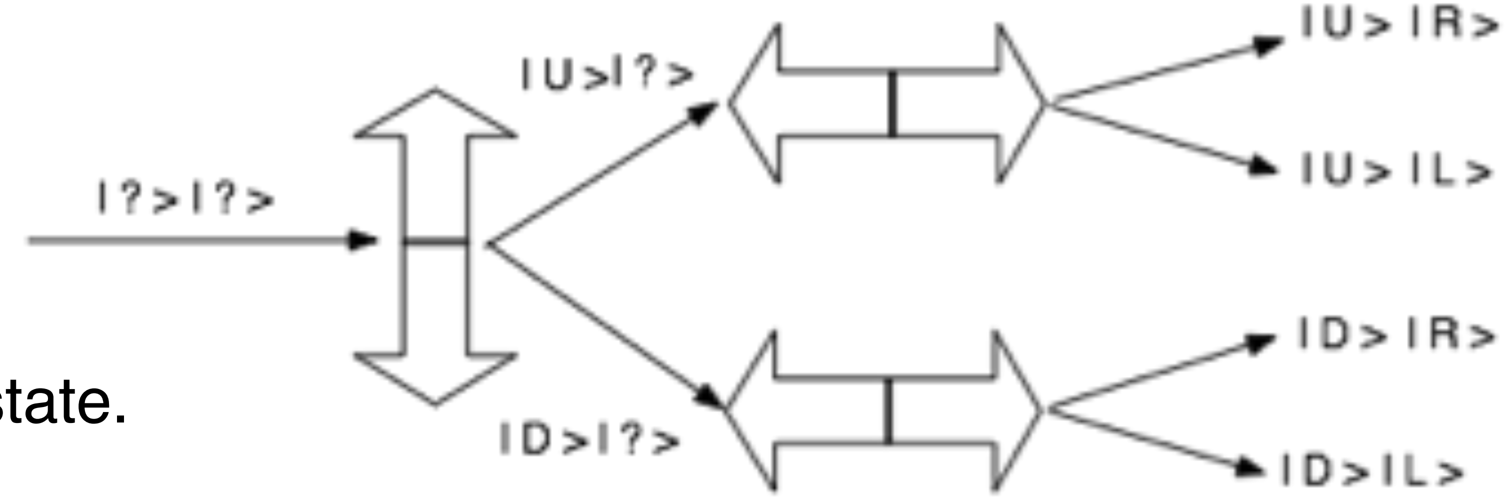
First magnet sorts into |U〉 or |D〉,

but tells nothing about |R〉 or |L〉 state.

Final pair of magnets completes sorting

-> four piles of distinct state combinations,

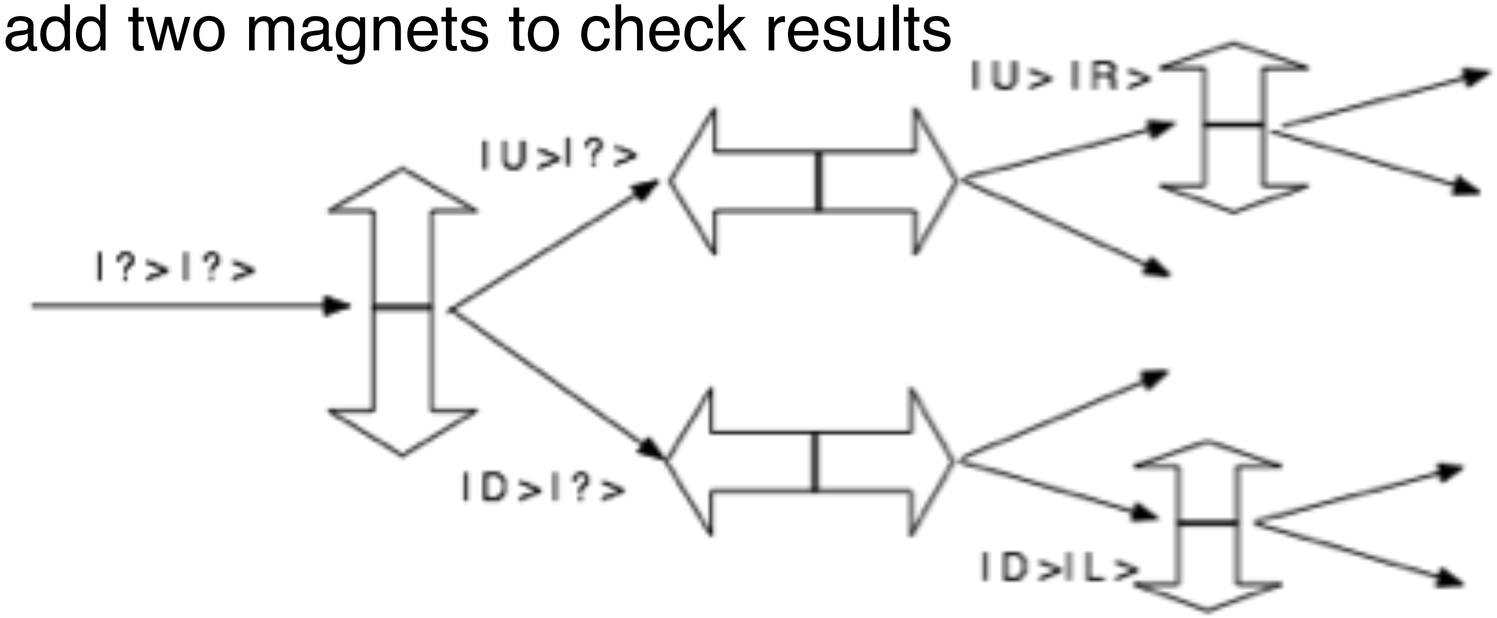
roughly equal numbers of in each.



Things Get More Puzzling

As extension to experiment,

add two magnets to check results



Results of experiment

are truly remarkable.

Electrons from beam labelled |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 $|D\rangle$ state electrons got mixed with beam thought pure $|U\rangle$,

but that 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 $|U\rangle$ state,

but perhaps after passing through (LEFT,RIGHT) magnet,

a few flipped into $|D\rangle$ state.

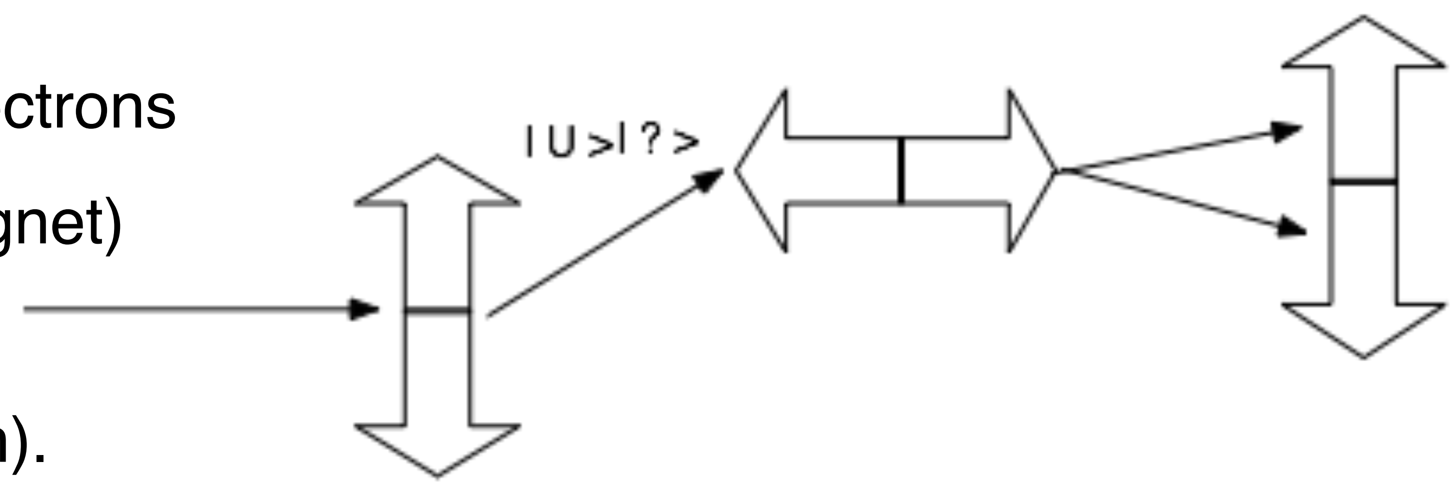
Answer from new experiment:

Experiment starts with pure beam of $|U\rangle$ 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 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 $|U\rangle$ and $|D\rangle$.

4. 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?

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.

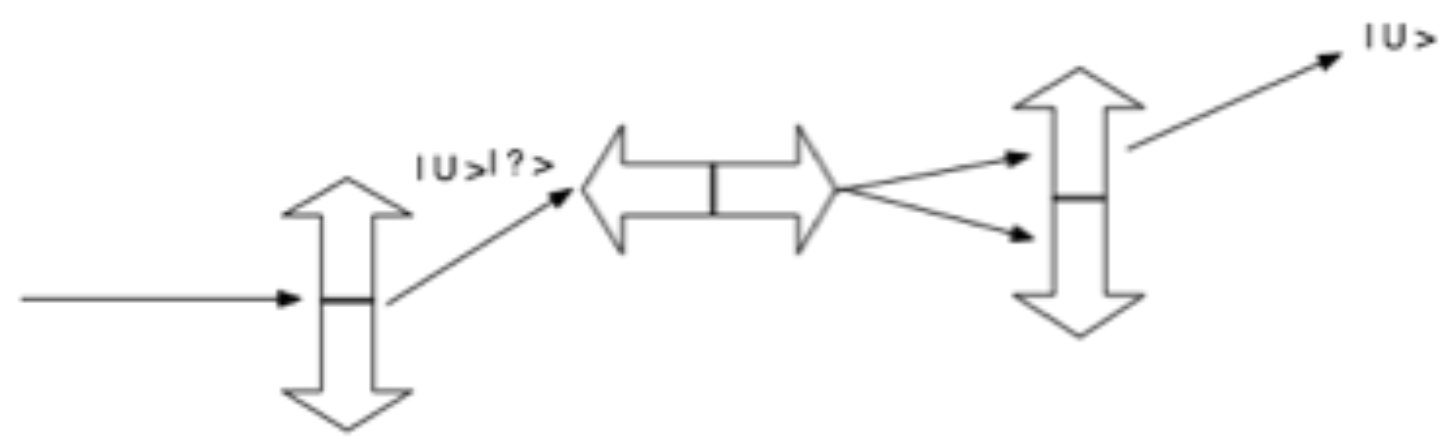
Of course we get an unexpected result!

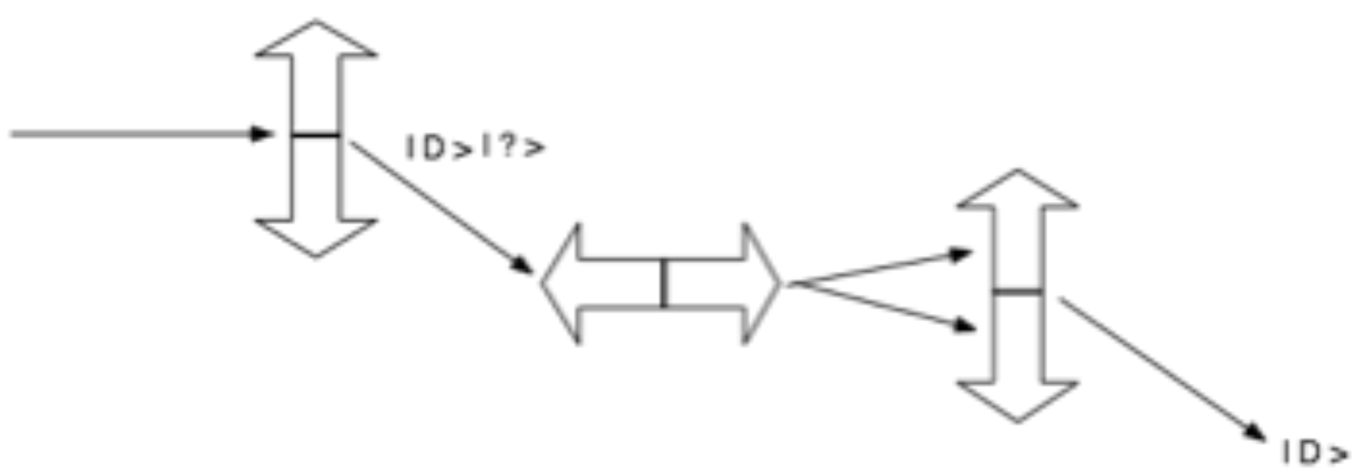
Using 1 magnet to catch both emerging beams

produces just single beam of pure $|U\rangle$

electrons (and for lower beam also).

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 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.

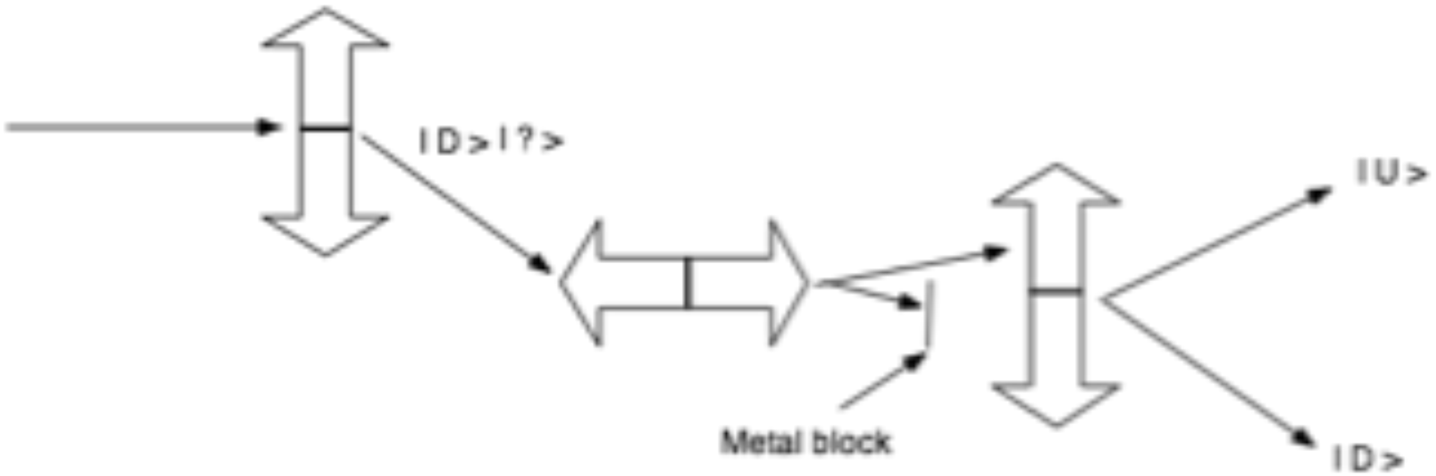
Moving (UP,DOWN) S-G magnet closer

has 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 |D⟩|L⟩ electrons will presumably,

if guess about distance

being needed correct,

stay in |D⟩ 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,

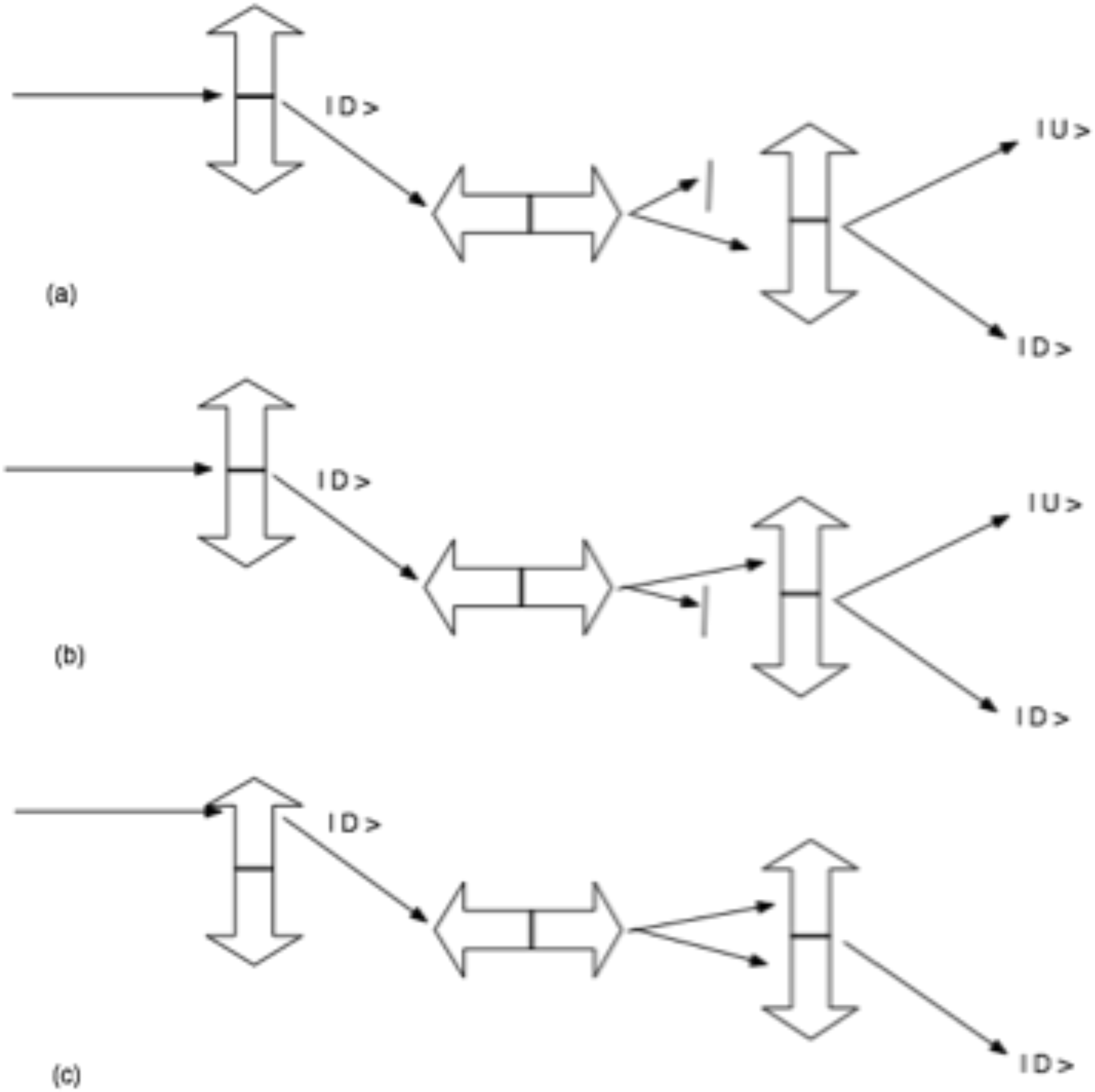
have eliminated argument based on flipping needing certain distance to work.

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⟩/|D⟩ states in electrons that pass through LEFT channel.

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

(c) Having both LEFT and RIGHT channels open produces only |D⟩ 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⟩ state and some in |D⟩ state,

and when electrons are formed into beam,

|U⟩ and |D⟩ 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 $|D\rangle$ 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 can specify (UP,DOWN) and (LEFT,RIGHT) states at same time. No $|D\rangle$ $|L\rangle$ and $|D\rangle$ $|R\rangle$ states, just $|U\rangle/|D\rangle$ OR $|R\rangle/|L\rangle$ 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.

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.