Some Dates : Reminder

Term Paper or Filmlet due	:	Wed. 8th April 2021
Open Book MCQ Test 2	:	Wed. 7th April 2021
Scope of Test 2	:	from Lecture 9 onwards
Luminus Zoom Test	:	Wednesday, Lecture slot

2 MCQ Term Tests

Test 1: Wednesday, 3rd Mar 2021 (7th week)

Test 2: Wednesday, 7th April 2021 (12th week)

Duration: 1 Hour plus (Please do not be late)
~ 30-35 MCQ + ~ 5-10 short Questions

(10am to 12pm lecture slot)

Mode: LumiNus Quizzes, short Questions; require short Answers

Assessment

Tutorials (CAs):	35 %	(start: 3rd week)
MCQ Test 1:	20 %	(7th week)
Term Project:	25 %	(due: 12th week, short ppt Presentations/Vivas)
MCQ Test 2:	20 %	(12th week)
Final Grade:	100 %	
Notes:	No Examination (only 2 MCQ Tests)	
	Tutorials begin on week 3	
CAs :	Tutorial Attendance (Active !) / Assignments)	
	Forum participation (Active !)	

Lecture 13

What is ***Real*** then ?

Are you upset ?

… tarassei tous anthropous ou ta pragmata alla ta peri ton pragmaton dogmata …

… what upsets people is not things themselves, but their theories about things …

Epictetus,
Greek & Stoic Philosopher,
55-135 AD

What is a Scientific Theory ?

Ontology & Epistemology

A Scientific Theory

All scientific theories begin from basic assumptions or postulates (conjectures).

All Physical (Physics) theories see to develop a mathematical structure that is also logically consistent. Then the theory is ready for use.

Example : 2 postulates of Special Relativity.

What is a Good Scientific Theory ?

Must not only explains quantitatively all known physical phenomena of the kind it is supposed to deal with.

Makes successful predictions about new phenomena not known before.

The predictions are verified later by experiment.

Example : General Relativity predicts bending of light by gravity and subsequently verified by experiment.

But what really, is a Theory ?

It is a ***model*** for Reality.

The word reality seems deceptively simple but lurking behind it lies many subtle complications.

Example: Ptolemy, Copernicus sort to explain sunrise, sunset and eclipses etc ...

Reiterate: theories of physics essentially attempt a mathematical description of physical reality. Which theory eventually survives depends on which one provides the best description of reality.

What is the reality that quantum theory is trying to describe ?

Epistemology: A branch of Philosophy that deals with the theory of knowledge … simply means Our knowledge or conception about a physical system.

Caveat Emptor : Our knowledge about the system might in fact be quite different from what the system actually is.

What is the reality that the quantum theory is trying to describe ?

Ontology: A branch of Philosophy that deals with the nature of being … it simply means the nature of the system as it actually exists.

What is the difference ?

Epistemology deals with knowledge built up from observation where as Ontology refers to attributes the system has, independent of whether one observes them or not.

Ontic and Epistemic

One can argue that it could be a Higher Order Being (God) would know all about it although we are ignorant.

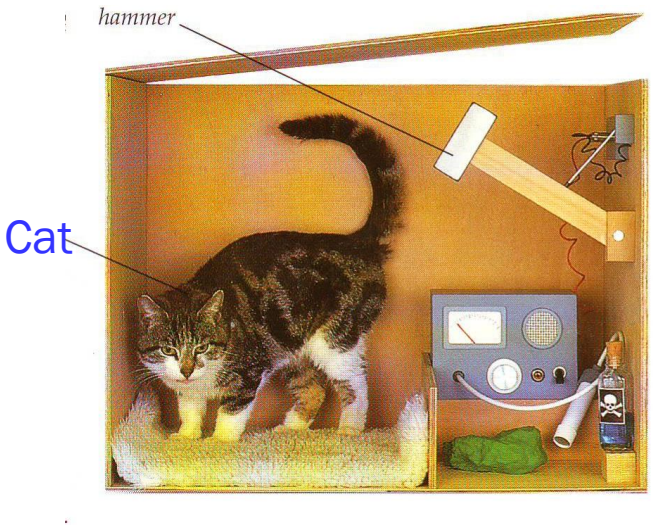
So this Being (so to speak, God) can predict (determine) accurately whereas we can only assign probabilities.

Summary: the system of study is intrinsically deterministic but Our knowledge of it is probabilistic.

We have ontic determinism but epistemic indeterminism.

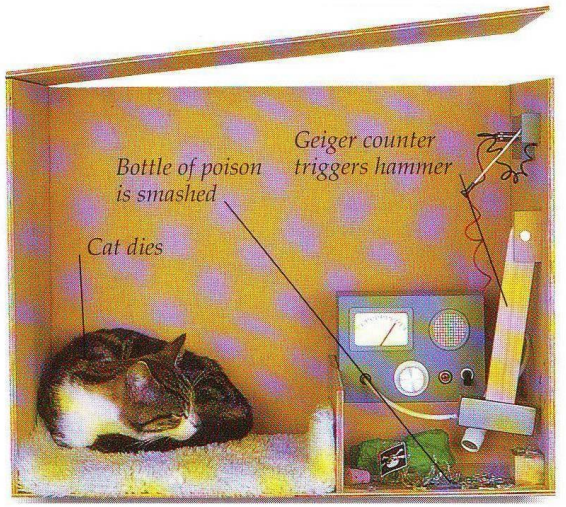
We are ready to discuss the famous Schrodinger Cat !

The Schrodinger Cat



$$\Psi =$$

$$\Psi = \; ? \; +$$

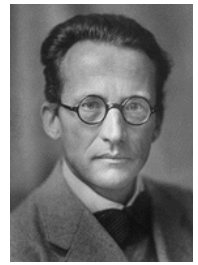


Without opening the lid i.e. we would like to know whether the cat is alive or dead ?

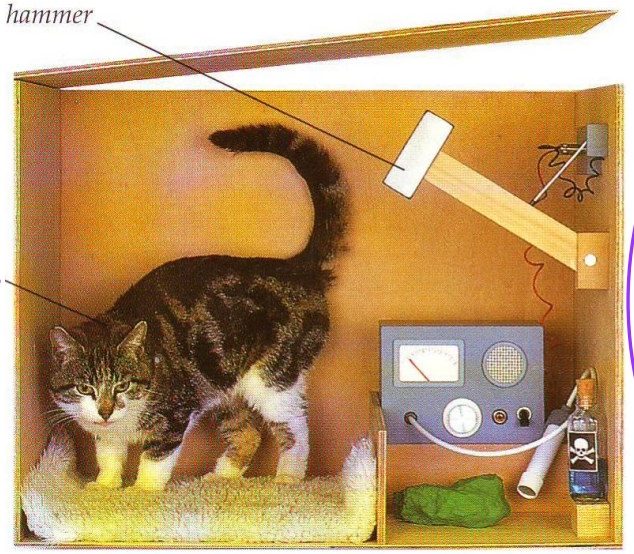
Psi alive: The radioactive atom (half life) has not randomly emitted any particle; the hammer has not fallen; the bottle is not broken; and the cat is alive.

Psi dead: The radioactive atom (half life) has randomly emitted a particle; the detector has registered a particle; the hammer has fallen; the bottle is broken; and the cat is dead.

The Schrodinger Cat

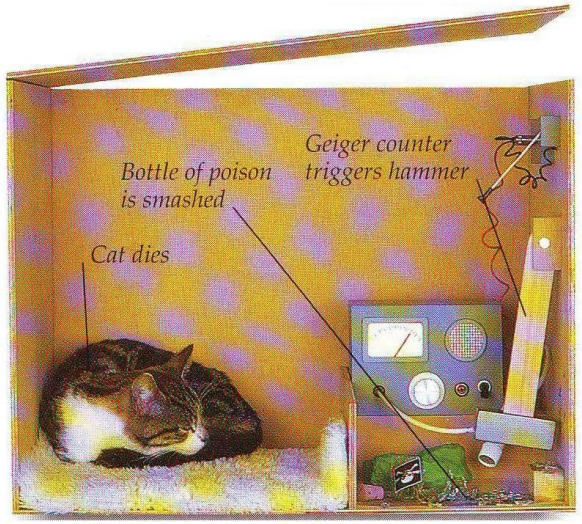


New Idea !



2 DEAD OR ALIVE
Standard theory says that as soon as someone opens the box and looks, the superposition of states collapses and one possibility becomes real. We literally do not know what is happening before we look in the box. Most physicists do not worry about what happens when nobody is looking. As long as the equations give the right answers to experiments, they are happy. It still seems strange that things only become real when people look at them.

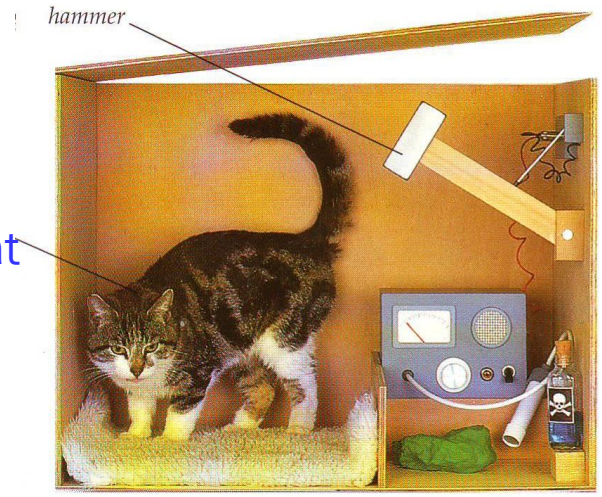
2 TWIN CATS
If the cat isn't alive on looking in the box, it must be dead. The many worlds theory says that when the radioactive material is given a choice, it takes both possibilities. It triggers the counter, and it also fails to trigger it. The Universe divides into two. In one, the cat is dead, in the other it is alive. In each Universe, someone opens the box to see what has happened. Each person thinks they live in a unique universe, unaware of other worlds.



$$\Psi = \psi_{Alive} + \psi_{Dead}$$

Schrodinger argued that this whole thing is ridiculous. "the psi function of the entire system would express this by having in it the living and the dead cat ("pardon the expression") mixed or smeared out in equal parts". This is absurd, so the standard Quantum Physics must be wrong according to Schrodinger.

The Schrodinger Cat

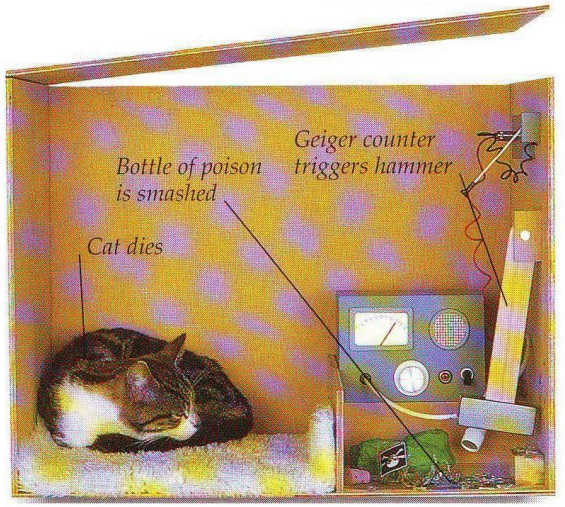


$$\Psi = \psi_{not\ decay} + \psi_{Decayed}$$

or

$$|\Psi\rangle = |\psi_{not\ decay}\rangle + |\psi_{Decayed}\rangle$$

$$\langle\Psi| = *\langle\psi_{not\ decay}| + *\langle\psi_{Decayed}|$$



Some people think that Schrodinger was wrong in trying to read too much meaning into the wave function, the way he did it.

That is : he seems to have illegally translated a microscopic uncertainty (associated with the state of the atoms) to a macroscopic uncertainty (associated with the state of the cat). But macro stuff is made of micro stuff ? Micro and macro divide is also another problem !

So measurement (observation) in Quantum Mechanics is really Weird

Atoms or elementary particles are not real; they form a world of potentialities or possibilities than one of the things or facts. W. Heisenberg

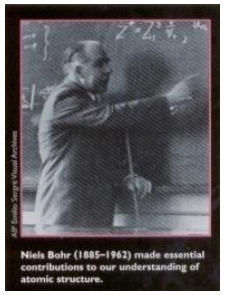
Observations not only disturb what has to be measured but in fact produce it … we ourselves produce the results of the measurement.

Pascual Jordan

Summary

In Quantum Mechanics, actual state of existence depends on how we observe and what we choose to observe … prior to a measurement we cannot even think that the electron has definite momentum and a definite co-ordinate.

… final show down …



Schrodinger fell ill but Bohr continued to argue with him at the bedside: probabilistic interpretation, complementarity, quantum jumps and all that … final show down …

"If we are going to stick to those damned quantum jumps, then I regret that I ever had anything to do with quantum theory."

He wrote a book "What is life ?" Cambridge U. Press.

“Question” still not settled ?

Einstein, Podolsky and Rosen, 1934

EPR Problem

Einstein, Podolsky and Rosen, 1934.

Title of the Paper: Can Quantum Mechanical Description of Physical Reality be considered complete ?

Main idea: Quantum Mechanics is at best a successful theory but not a complete one.

EPR's Criterion for Reality

Einstein, Podolsky and Rosen:

"If, without in any way disturbing a system, we can predict with certainty (i.e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

EPR Scenario

Let us denote their positions and momenta, of 2 micro particles A & B

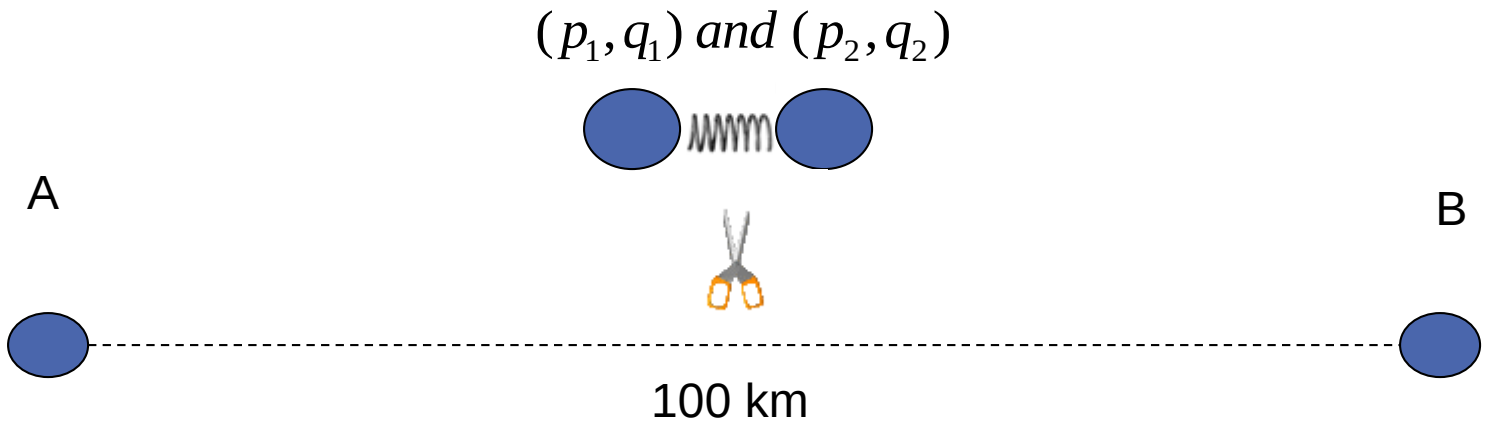
$(p_1, q_1)\ and\ (p_2, q_2) \quad [or\ \ (p_2, q_2)\ and\ (p_1, q_1)]$

$Total\ momentum\ P = p_1 + p_2$

$Separation\ (relative\ distance)\ \ Q = q_1 - q_2$

EPR Problem

Let us denote their positions and momenta (see below)

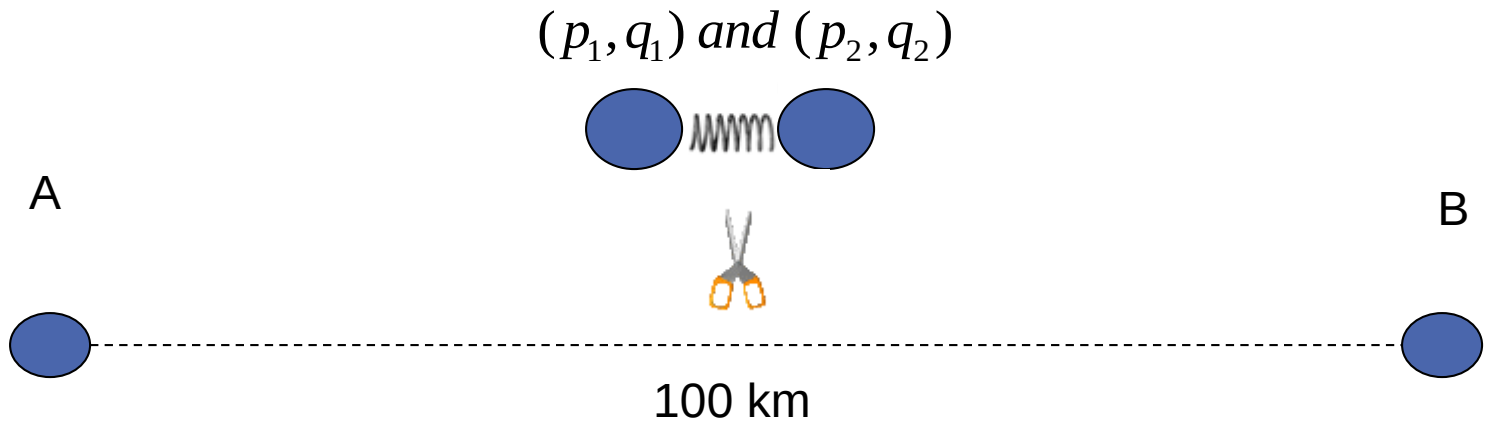


We already know P and 1st measure p_1. Then we can determine p_2 since $p_2 = P - p_1$. Thus we have been able to determine p_2 by observing particle A and without disturbing particle B. So p_2 is an element of reality.

Having taken care of p_2, we next measure Q and q_1. This then enables us to predict the value of q_2 without disturbing particle B. So q_2 is also an element of physical reality.

EPR Problem

What can we deduce ?



The net result is that we find p_2 and q_2 are simultaneous elements of reality.

On the other hand, according to Quantum Mechanics p_2 and q_2 cannot be simultaneous elements of reality because they cannot be simultaneously measured. Thus EPR is able to establish a reality that Quantum Mechanics denies. So Quantum Physics cannot be claimed to be a complete theory … **essence of EPR argument.**

EPR Scenario

Let us denote their positions and momenta, of 2 micro particles A & B

$$(p_1, q_1)\ and\ (p_2, q_2) \quad [or\ \ (p_2, q_2)\ and\ (p_1, q_1)]$$

$$Total\ momentum\ P = p_1 + p_2$$

$$Separation\ (relative\ distance)\ \ Q = q_1 - q_2$$

But Quantum Mechanics says : p and q cannot be measured simultaneous for each micro particle.

$$p_1 q_1 - q_1 p_1 = -i\hbar$$

$$p_2 q_2 - q_2 p_2 = -i\hbar$$

$$p_1 q_2 - q_2 p_1 = p_2 q_1 - q_1 p_2 = 0$$

EPR Conclusion

Einstein, Podolsky and Rosen

"the wave function (PsI ψ or state function) does not provide a complete description of the physical reality, we left open the question of whether or not such a description exits".

Till the end, Einstein still believes that mankind should be able to construct a classical theory which besides being deterministic, would provide a complete description of physical reality; objective reality.

EPR Problem Revisited

Einstein, Podolsky and Rosen :

Title of the Paper: Can Quantum Mechanical Description of Physical Reality be considered complete ?

Main idea: Quantum Mechanics was at best a successful theory but not a complete one.

Einstein viewed Quantum Physics as at most a good working recipe (prescription !) and that it was able to correctly and accurately predict the outcome of experiments in the microscopic world.

He stopped arguing that Quantum Physics was not correct, instead he now attack Quantum Physics' denial of objective reality.

Bohr's Rebuttal to EPR

Title of the Paper: Can Quantum Mechanical Description of Physical Reality be considered complete ? Same title.

Bohr's style is quite complicated.

Einstein: "Bohr though very clearly, wrote obscurely and regard himself as a prophet"

Bohr : "The opposite of a deep truth is also a deep truth ! … truth and clarity are complementary"

Bohr's Argument

$\langle \mathcal{L} | \hat{\mathcal{A}} | \mathcal{R} \rangle$

If no observations (measurement) are made, a particle cannot have physical real attributes.

To put it in a layman question.

How is physical reality realized ?

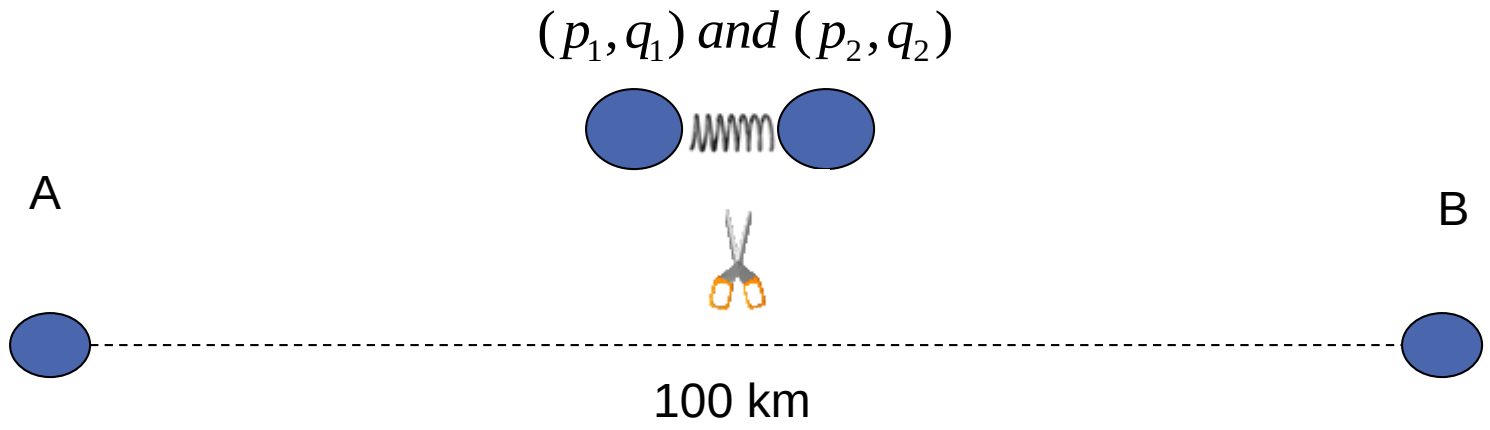
Reality happens when we look and what happens depends on how we look !

"Anyone who is not shocked by quantum theory has not understood it"

... appreciate the problem ...

EPR Problem

Let us denote their positions and momenta (see below)



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EPR Correlation Problem

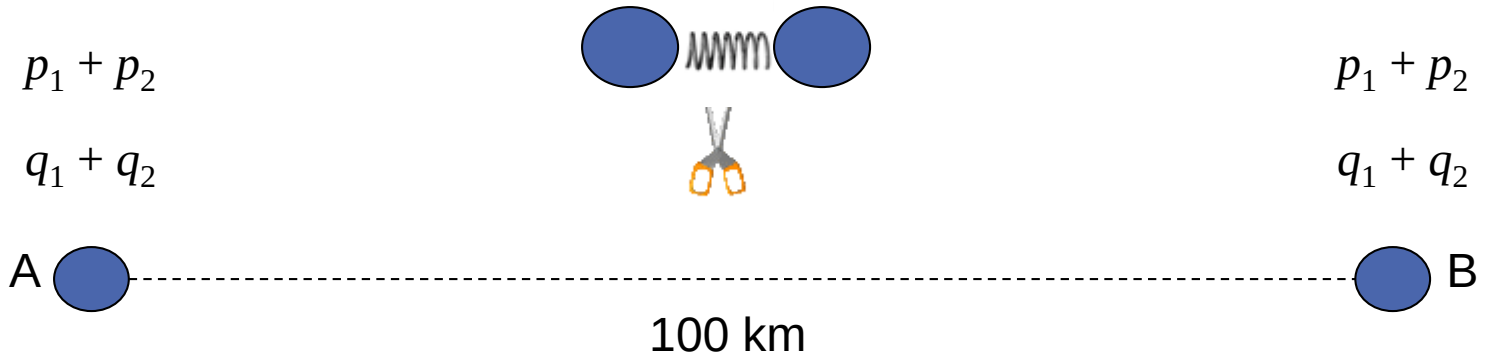
What is the problem ?

(p_1, q_1) *and* (p_2, q_2),

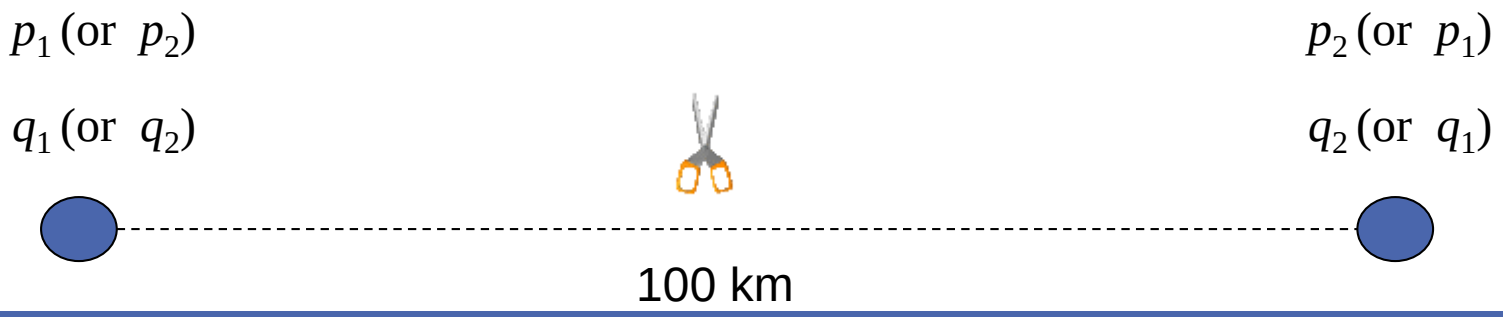
$Q = q_1 - q_2$

$P = p_1 + p_2$,

Before Measurement (together and not decided)



After Measurement



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P. Jordan

Summary

In Quantum Mechanics, actual state of existence depends on how we observe and what we choose to observe … prior to a measurement we cannot even think that the electron has definite momentum and a definite co-ordinate.

Correlation and Entanglement

Recall EPR's 2 particles.

It is always correlated (entangled), even though they might be separated by macroscopic distances.

According to Bohr, till a measurement is made we can only talk of a total wave function for the system of two particles, no matter how far apart they are.

Teleportation !

Classical Physics

Continuously varying quantities
e.g. Energy, momentum

Deterministic and gives rise to Causality (Theory of cause and effect)

The system already has a definite value for the property being measured even before the measurement is actually made.
The instrument or apparatus or observer does not affect the system.

Example: measuring the length of the table (macro system) and the table is not affected.

Classical Physics can stand all by itself.

Quantum Physics

Discrete quantities
e.g. Energy, momentum

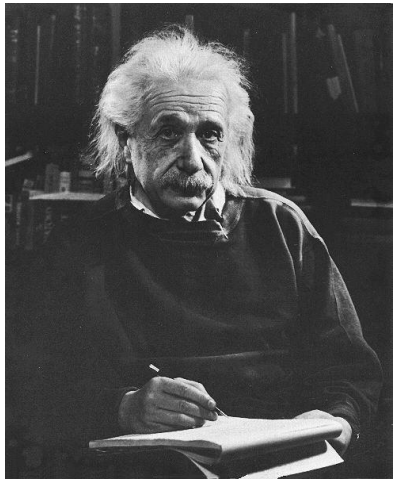
Not deterministic (indeterminism) and we can only use probabilistic ideas.

Prior to a measurement we cannot even think that the electron has a definite say momentum and a definite co-ordinate.
The instrument or apparatus or observer does affect the system.

Example: measuring or observing a micro system will disturb it.

Quantum Physics needs classical physics as a foundation.

So Einstein asked ?



Einstein asked Abraham Pais

… during one walk Einstein suddenly stopped, turned to me and asked whether I really believe that the moon exists only when I look at it ?

… I would like to think so.

A. Einstein

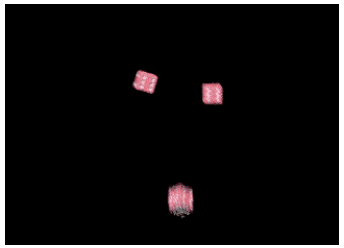
Hidden Variables !

Hidden Variables means that there are microscopic properties of fundamental particles that we are unable to observe directly by means of testing (or unknown to us).

Perhaps due to technological limitations that might exist at some future time.

EPR argues that since it is "unreasonable" to believe that these particle attributes require observation to become real, therefore Hidden Variables must exist.

Classical Probability



Why do we use probability theory in the prediction of an outcome in tossing a coin.

Since tossing a coin is a mechanical act, so why one cannot use ordinary (classical) mechanics and calculate precisely the outcome if it is a head and a tail instead of relying on a probabilistic forecast ?

Ignorance: There is almost no hope … we are forced to make a probabilistic prediction of the outcome of the toss rather than deterministic one.

If you like History and Philosophy

Quantum Mechanics is a candidate of Epistemology.

Hidden Variable Theory is a candidate for Ontology.

"I must seem like an ostrich who forever buries his head in the relativistic sand in order not to face the evil quanta"

A. Einstein

For whom the *Bell* tolls !

John Von Neumann & Albert Einstein

John Bell's Theorem

It does not really explain things; in fact the founding fathers of quantum mechanics rather pride themselves on giving up the idea of explanation. They were very proud that they dealt only phenomena: they refused to look behind the phenomena, regarding that as the price one had to pay for coming to terms with nature …

John Bell, CERN

Bell's Inequality

He (John Bell) studied the EPR problem very carefully … was not a paradox at all.

Related to Spin

1965 : Bell's inequality is $-2 < S < +2$. If his inequality could be violated by the results of experimental tests, such a violation would provide evidence in favour of quantum mechanics.

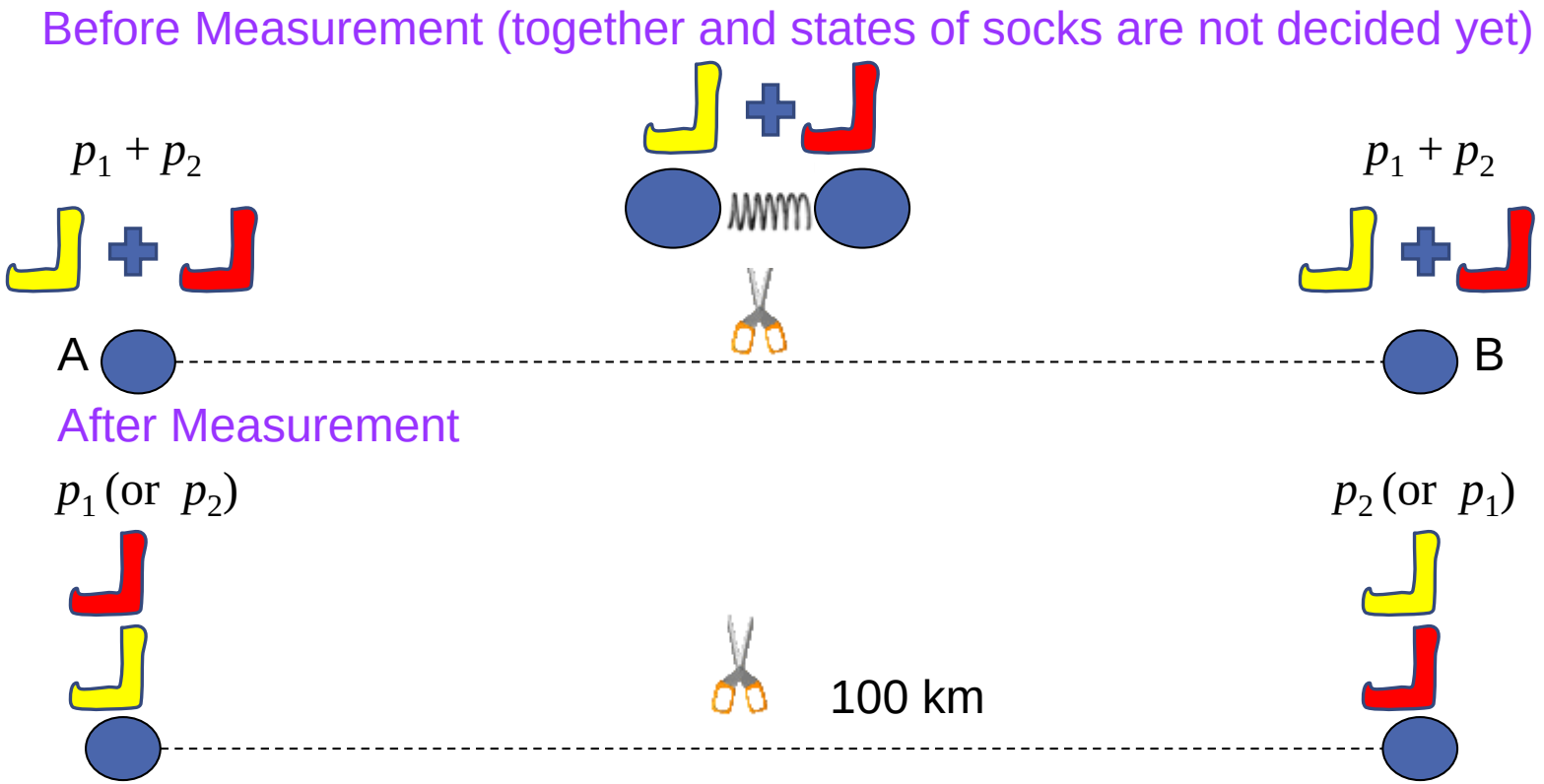
No physical theory of local Hidden Variables can ever reproduce all of the predictions of Quantum Mechanics.

This dashes Einstein's hope of finding hidden variables to restore a deterministic world and objective reality … a theory that is not probabilistic.

Alain Aspect's French team verified "spooky action" really does happen.

EPR Correlation Problem (Socks)

What is the problem? (p_1, q_1) *and* (p_2, q_2), $P = p_1 + p_2$, $Q = q_1 - q_2$

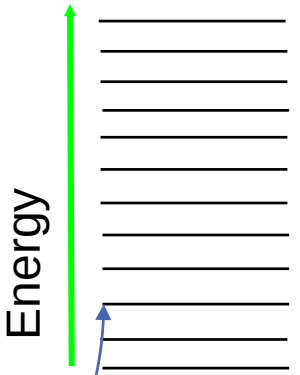


Collapse of Wave function

& *Many Worlds*

Recall Schrodinger Equation

Suppose we are studying the electron (hydrogen atom)
… we want to measure the energy of the system ?



$$\left[\left(-\frac{\hbar^2}{2m}\right)\frac{d^2}{dx^2}+V\right]\psi(x)=E\psi(x) \quad \Longrightarrow \quad H\psi=E\psi$$

$$E_1, \quad E_2, \quad E_3, \quad E_4, \quad E_5,\ldots$$

In general, we have energy labels

$$|\psi\rangle = C_1|1\rangle + C_2|2\rangle + C_3|3\rangle \ldots + C_k|k\rangle + \ldots$$

$$|\psi\rangle = C_1|1\rangle + C_2|2\rangle + C_3|3\rangle \ldots + C_n|n\rangle + \ldots$$

1) Suppose we do an experiment and measure the energy of the system.

What answer would we get ? May be $E3$

2) We repeat the experiment under the same initial conditions i.e. $|\psi\rangle$

May be $E7$

3) So patiently we accumulate a large number N of such readings and

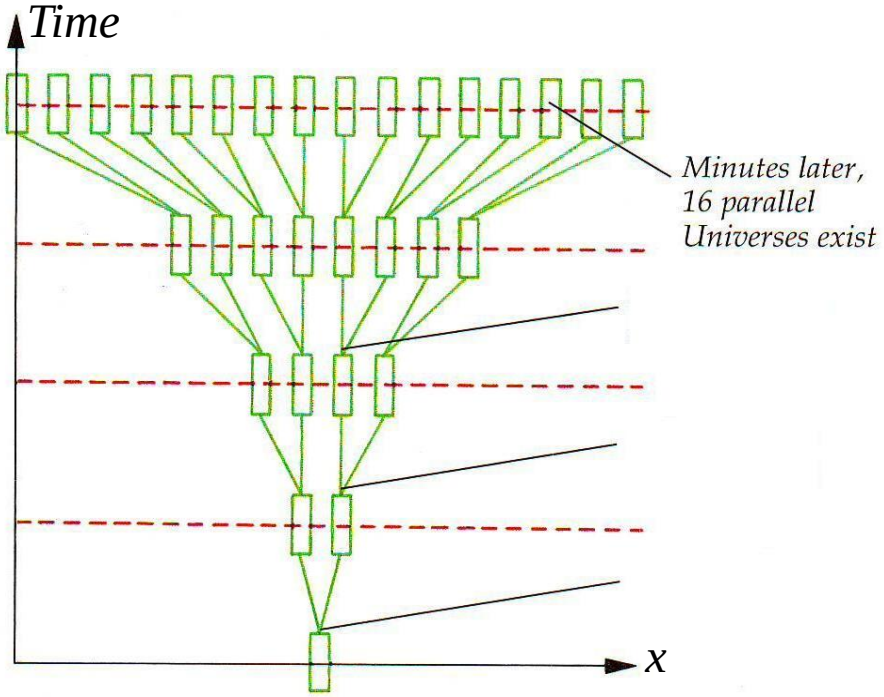
enumerate how many times we have $E3$, how many times we get $E7$, etc

4) In fact, if we keep on trying, our log book would end up with a sequence of

entries as in $E3$, $E7$, $E1$, … $E10$, $E3$ … i.e. completely random

$$Note: \quad N = n_3 + n_7 + n_2 + n_4 + \ldots$$

Many World Interpretations



Instead it just split up into 2 parts one of which remains in our universe and the other wanders off to another universe to oblige another observer spying at the other slit.

As for the Schrodinger cat scenerio, the wave function is $|\text{dead}\rangle + |\text{alive}\rangle$, till we open it. The moment we open the lid, the wave function does not collapse but split into two.

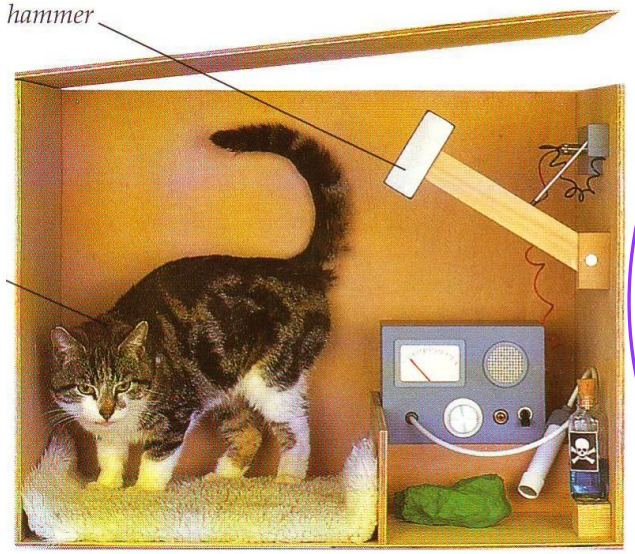
1950 Hugh Everett (student of Wheeler)

If we find that the cat is $|\text{alive}\rangle$, the part alive stays in our universe while the part $|\text{dead}\rangle$, appears in another universe. So what does it mean ?

It means that to an observer in that universe, the cat would be dead ! Weird ! Weird and Morbid ! !

The Schrodinger Cat

New Idea !



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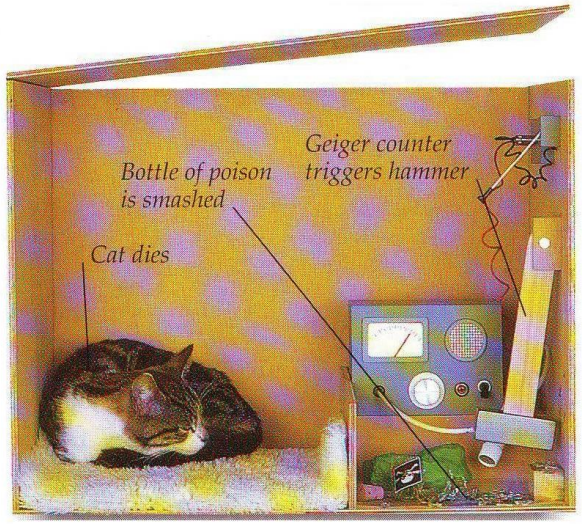

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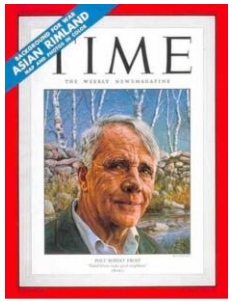
The Road Not Taken !



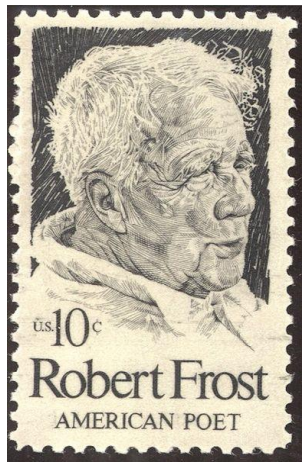
*Two roads diverged in a **yellow** wood*

and sorry I could not travel both

And be one traveller, long I stood

And looked down one as long as I could

To where it bents in the under growth;



Is there any *Logic* ?

in Quantum Phenomena

Boolean Logic (Set Theory)

p : I love this GEM

q : I love to DANCE

$\wedge$ means **and ("intersection")**

$\vee$ means **or ("union")**

Mathematicians and Engineers use truth tables

p	q	$p \wedge q$
T	T	T
T	F	F
F	T	F
F	F	F

p	q	$p \vee q$
T	T	T
T	F	T
F	T	T
F	F	F

Consider this

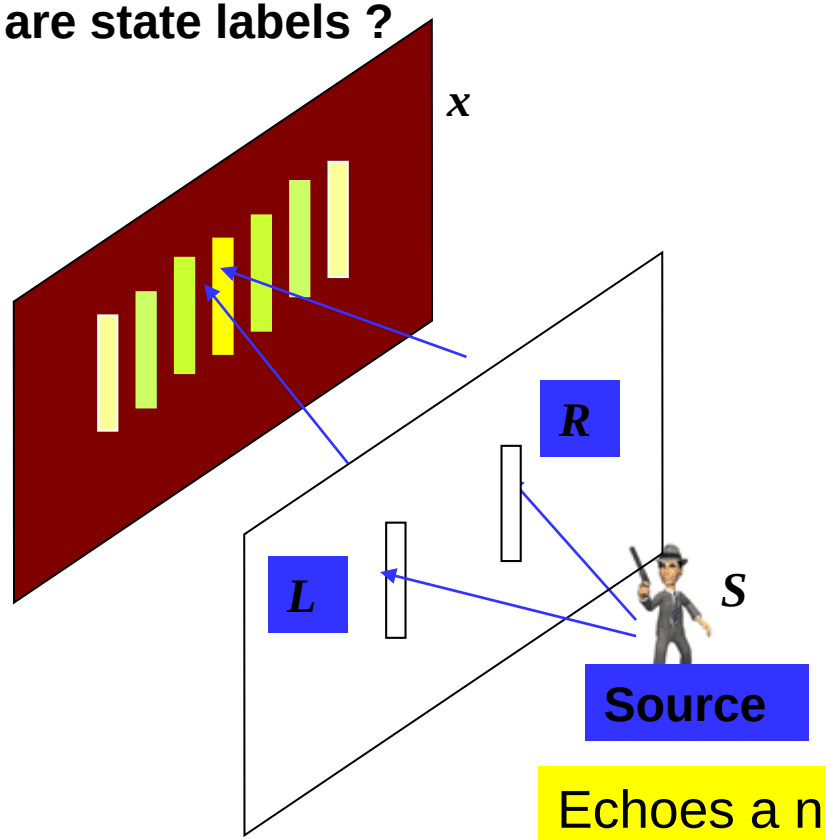
$$A \wedge (B \vee C) = (A \wedge B) \vee (A \wedge C)$$

We've learned before in Sec. School

$$A \times (B + C) = (A \times B) + (A \times C)$$

What is ψ in our 2 Slits ?

What good are state labels ?



$$\langle x|s\rangle = \langle x|s\rangle_L + \langle x|s\rangle_R$$

But we can also write

$$\langle x|s\rangle_L = \langle x|L\rangle\langle L|s\rangle$$

$$\langle x|s\rangle_R = \langle x|R\rangle\langle R|s\rangle$$

In General

$$\langle x|s\rangle = \sum_{i=1}^{n} \langle x|i\rangle\langle i|s\rangle$$

Echoes a new idea: Principle of Superposition !

No trajectory in discussion, + is AND ... more explicitly ... 2 places at the same time !

Quantum "Logic"

Consider Double Slit Experiment again

A: The electron hits the screen

B: The electron goes through slit 1

C: The electron goes through slit 2

Consider this well known equation again

$$A \wedge (B \vee C) = (A \wedge B) \vee (A \wedge C)$$

The electron hits the screen and the electron has gone through at least one of the 2 slits. i.e. slit 1 or slit 2

=

The electron hits the screen and the electron has gone through slit 1

or

The electron hits the screen and the electron has gone through slit 2

But In Quantum Mechanics, the 2 sides are not equal. Can you see why ?

Are you upset ?

… tarassei tous anthropous ou ta pragmata alla ta peri ton pragmaton dogmata …

… what upsets people is not things themselves, but their theories about things …

Epictetus,
Greek & Stoic Philosopher,
55-135 AD

Grand Summary

$$|\psi\rangle = C_1|1\rangle + C_2|2\rangle + C_3|3\rangle \ldots + C_i|i\rangle + \ldots$$

In Quantum Mechanics

To describe a micro-system, we can only talk about ψ states, possibilities or potentials.

Only $\psi^*\psi$ has meaning … probability of finding a particular state or possibility.

Measurements and Observers are part of the quantum system … see the break down of Cartesian philosophy that we are so used to i.e. the mind and nature dichotomy.

Bohr's Argument

$\langle \mathcal{L} | \hat{\mathcal{A}} | \mathcal{R} \rangle$

• If no observations (measurement) are made, a particle can physical real attributes.

• To put it in a layman question.

• How is physical reality realized ?

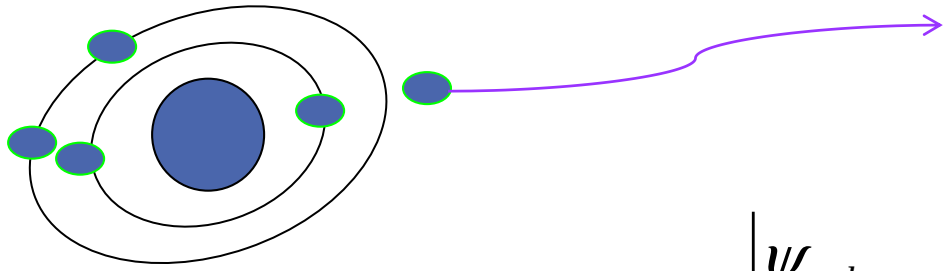
• Reality happens when we look and what happens depends on how we look !

• "Anyone who is not shocked by quantum theory has not understood it"

... appreciate the problem ...

How should you describe an electron ?

$$\left[\left(-\frac{\hbar^2}{2m}\right)\frac{d^2}{dx^2}+V\right]\psi(x)=E\psi(x)$$



$$|\psi\rangle = C_1|\psi_1\rangle + C_2|\psi_2\rangle + C_3|\psi_3\rangle \ldots + C_i|\psi_i\rangle + \ldots$$

$$|\psi_{n,l,m_l,m_s}\rangle$$

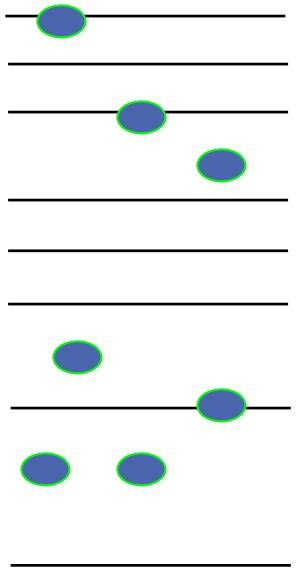
$$|n, l, m_l, m_s\rangle$$

Psi is the state of the electron

The Psi description for the electron is complex … cannot be measured

$$|\psi_{n,l,m_l,m_s}|^2$$

$$\psi^*\psi = |\psi|^2$$



Only Psi*Psi is meaningful because it is a real number and can be measured … it is the probability of finding the electron.