

Day 21, 04.04.2019 Quantum Mechanics 4

NCAA championship 5 days



housekeeping

Starting grading book reviews. Some tips for the second one:

- 1. "novels" are fiction. these books are not novels!
- 2. Please, please put the book title and author in the heading of your report
- 3. Many of you did not "reserve" your book, so I had to constantly edit the Googledoc.
- 4. Treat it like a university paper. Make it look decent, please? That means formatting, a title, your name, the date...
- 5. and...proofread.
- Grades to date: Projects, quizzes, notes in a pdf in the slides area the rest of your grades are in LON-CAPA or MasteringPhysics
- The "redshift homework problem."
 - this Saturday



April 2019



Honors project

How's it going?

Document #2 is uploaded

https://qstbb.pa.msu.edu/storage/QS&BB2019/Homework Projects/honors project 2019/

It assigns data files to each

Two due dates:

report on the day of the Final

text file of data by April 26

you'll see in document #2

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particle:	photon, γ	
	symbol:	γ
	charge:	0
	mass:	0
	spin:	1
	category:	an intermedi
		a messenger

ate vector boson, particle

interference of light

and diffraction at the same time



finally, 1918

Planck got his due

Nobel	Prizes	

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Prize in Economic Sciences

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Nomination and Selection of

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Nobel Prize in Literature	9	and the second						
Nobel Peace Prize								

Max Karl Ernst Ludwig Planck

The Nobel Prize in Physics 1918 was awarded to Max Planck "in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta".

Max Planck received his Nobel Prize one year later, in 1919. During the selection process in 1918, the Nobel Committee for Physics decided that none of the year's nominations met the criteria as outlined in the will of Alfred Nobel. According to the Nobel Foundation's statutes, the Nobel Prize can in such a case be reserved until the following year, and this statute was then applied. Max Planck therefore received his Nobel Prize for 1918 one year later, in 1919.

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relation alert:

Planck's Law

refers to:

E = hf

Energy of radiation comes in a

example:

photoelectric effect

discrete amount for each frequency

constant of nature:	Planck's Constant, h				
	value:	<i>h</i> = 6.62606896			
	units:	Energy - time			
	usage:	everything at at sizes			

5(33)×10-34 J-sec

comic and smaller

Nobel Prize in Chemistry

1908

which greatly amused him

and went on

to do his best work after his Nobel...very unusual

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2010
Prize category: Chemistry
908
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~
ed to Ernest Rutherford "for his
nents, and the chemistry of
ora, 8 Feb 2011
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1899: he
carefully
isolated 2
components of
radiation:

one stopped by thin aluminum

one highly penetrating

and one more

and figured out another found in 1903:

negatively charged, passes through matter relatively easily



→ electrons

 \mathcal{m}







	beta particles,				
jargon alert:	eta (old name for	an electron)			
	refers to:	the emission of a decay of some nu			
	entomology:	alpha, beta,			
	example:	Carbon-14 → Nit			

an electron in the uclei - <u>beta decay</u>

rogen-14 + e

	alpha particles, α					
jargon alert:	(old name for a F	(old name for a Helium nucleus)				
	refers to:	the emission of a decay of some nu				
	entomology:	alpha, beta,				
	example:	Uranium-238 →				

a Helium nucleus in uclei - <u>alpha decay</u>

Thorium-234 + *e*

He had the solution after 2 years of work

he found:

1911: that the Atomic Number was +Ze

and made a model of the atom...

the Rutherford Model of the atom: Matter consists of hard-cores of positive charge.

The nucleus is tiny: most alphas go right through... only direct "hits" recoil.

The **electrons**? Somewhere around the outside?





JJ Plum pudding...smear of positive charge - tiny individual deflections

- That's problematic, the electrons would
- accelerate...and
- radiate.
- a "spiral of death"

finally

the 1921 prize, given in 1922

not the Nobel's finest hour.

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Nobel Prize in Literature	
Nobel Peace Prize	
Prize in Economic Sciences	Albert Einstein
Nobel Laureates Have Their Say	Albert Einstein
Nobel Prize Award Ceremonies	The Nobel Prize in Physics 1921 was awarded to Albert Einstein "for his services to Theoretical Physics, and especially for his discovery of the law of the
Nomination and Selection of Nobel Laureates	photoelectric effect".
FRCOM Street	Albert Einstein received his Nobel Prize one year later, in 1922. During the selection process in 1921, the Nobel Committee for Physics decided that none of the year's nominations met the criteria as outlined in the will of Alfred Nobel. According to the Nobel Foundation's statutes, the Nobel Prize can in such a case be reserved until the following year, and this statute was then applied. Albert Einstein therefore received his Nobel Prize for 1921 one year later, in 1922. Photos: Copyright © The Nobel Foundation
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remember the formula

> Einstein's extension of Planck's idea to a statement about the nature of light itself

E = hf 10^{18} 10^{12} 10^{24} 10^{22} 10^{20} 10^{10} X rays UV IR γ rays 10^{-12} 10^{-8} ; 10^{-6} 10^{-16} 10^{-10} 10^{-14} 10^{-4} 10^{-2} Visible spectrum 600 500 400 remember about waves: $v = \lambda f$ $\frac{hc}{-}$

the higher the frequency the higher the energy the lower the energy the lower the frequency



- the larger the wavelength
- the smaller the energy
- the larger the energy
- the smaller the wavelength

1922 yup,

actually with Einstein's delayed prize

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Nomination and Selection of Nobel Laureates If the Nobel Frize in Frize in Frize is 522 was awarded to Nies Born Tor his Services in the investigation of the structure of atoms and of the radiation emanating from them". Photos: Copyright © The Nobel Foundation TO CITE THIS PAGE: MLA style: "The Nobel Prize in Physics 1922". Nobelprize.org. 14 Mar 2013 http://www.nobelprize.org/nobel_prizes/physics/laureates/1922/	lobel Prize Award Ceremonies	The Nobel Prize in Physic	a 1022 was awarded	to Niele Bohr "for his on	nvices in			
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Neils Bohr (1885-1962)



.

LOTTE MEITNE

Aage Bohr Nobel 1972







 10^{0} v (Hz)

 10^{8} λ (m)

Swiss HS teacher: Johann Balmer 1885 found by trial and error:

 $\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$

what Bohr 1/2 did,

two assumptions

1. There are electron states in an atom that don't radiate: "stationary states"



2. Any radiation or absorption of light corresponds to an electron making a transition between two stationary states.

 $E_{\gamma} = hf = E_i - E_f$

what Bohr 2/2did,

Newton + Maxwell + Planck

1. Plain, old Newton centripetal force plus the Coulomb force between + and - charges



2. But: he assumed that the momentum in the orbit is "quantized"

$$L = rp = rmv = n\frac{h}{2\pi} \qquad n = 1,$$

3. Solved for E, r, v and the energy difference between stationary states

provided by Coulomb's Force

 $, 2, 3, 4, 5, \dots$

results

for each orbit: a NUMBER, n FIXED radius FIXED velocity FIXED energy



$$r_n = \frac{h^2}{4\pi^2 kme^2} n^2 = a_0 n^2 \qquad a_0 = 0.05$$

$$E_n = -\frac{e^2}{2ka_0}\frac{1}{n^2} = -\frac{\mathcal{E}_1}{n^2} \qquad \mathcal{E}_1 = 13.6$$

29 nm "Bohr Radius" when n=1...lowest 3 eV the energy of H ground state 23 look at a particular transition

n -> 2



$$hf = \frac{\hbar c}{\lambda} = \left(- \right) \left(\frac{1}{hc} \right)$$

$$\frac{1}{\lambda} = \underbrace{\frac{\mathcal{E}_1}{hc}} \left(\frac{1}{2^2} - \frac{1}{n^2} \right)$$

just a number...

he didn't know!

$$\frac{1}{\lambda} = \underbrace{\frac{\mathcal{E}_1}{hc}} \left(\frac{1}{2^2} - \frac{1}{n^2} \right)$$

just a number... = $1.097 \times 10^7 \text{ m}^{-1}$

5 teacher:
Balmer 1885
by trial and error:
$$\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$
$$97 \times 10^7 \text{ m}^{-1}$$
$$5, \dots$$

the "Bohr
Formula"

atoms with Z protons and electrons...and one lone electron outside

the agreement with experiment

was game-changing

while simultaneously making no physical sense!

sole winner

1929

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	The Nobel Prize in Physic discovery of the wave nat	s 1929 was awarded t ture of electrons".	o Louis de Broglie "for hi	s			

the momentum of an electron

related to the wavelength of an electron

the wavelength of an electron??

electrons: photons: $\lambda_{\gamma} = \frac{h}{p_{\gamma}} \quad \lambda_e = \frac{h}{p_e} \quad \lambda_e = \frac{h}{m_e v}$ each "Bohr orbit" ... one deBroglie wavelength

this relation will be important

relating the wavelength of a quantum object to its momentum = h"deBroglie relation"

JJ's son GP

JJ got the Nobel for showing that the electron exists and is a particle

GP got the Nobel for showing that the electron is a wave

Germer lost out

Nobel rules: 3 people.

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tal discovery of the diffraction of
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deBroglie suggested how: they should exhibit diffraction

Davisson & Germer

0.071nm X-ray diffraction on a polycrystal

600 Ev electron diffraction on a polycrystal 0.057 ev neutron diffraction on a polycrystal

a "slit" appropriate for X-ray wavelengths

in one picture

ра

http://www.hqrd.hitachi.co.jp/em/doubleslit.cfm

Since electrons are detected one by one as particles, we have to conclude that each electron must have passed through at random on either side of the m, thus creating a uniform distribution, without erference when accumulated.

both the particle	biprise any in
like features of	
electrons	
the dots a dev	nonstration is u
and the wavelike	Universit
features of	
electrons	
the diffraction pattern	

electrons!

photons!

Quantum Mechanics born of some anxiety

the lack of radiation of Bohr's accelerating electrons was still a problem: Bohr knew it and figured there would be a more complete answer.

There was much that was ad hoc and not believable

both in Bohr's approach and deBroglie's

however, the experimental situation made it clear that the broad suppositions of both had to be a part of the truth.

Quantum Mechanics, proper was the child of 3+1 people:

Werner Heisenberg - 1925; invention #1

Erwin Schrödinger - 1926; invention #2

Paul Dirac - 1925; showed #1 and #2 are equivalent

Max Born - 1926; gave the modern interpretation

what in the world is an electron in deBroglie's scheme?

the breakthrough

from an unlikely source

Erwin Schrödinger

Erwin Schroedinger 1887-1961

where do you look for your keys in the dark?

Schroedinger was an expert

in the mathematics of waves

EM waves, material waves, fluids, elastic media, sound...

the quantum idea:

made use of integers

so do complicated waves

what is the "state" of a "regular" system

a function:

you give me a time and a position in space

I'll give you the "state" of the system

There can be classical states:



Let's call the "state" of the drumhead, S...which is a function of time and space.

The value of S is the height above the plane.

forces

initial state at x_0 , y_0 , t_0



& energy

at any time, all over the surface



Solutions for the vibrations of a drumhead, or a violin string, or that vibrating hoop...

Forget the details...just notice the mixing of lots of waves...the m's and k's? Integers.

Here are some of these infinite modes of vibration as described by some of the functions (white and brown are moving in opposite directions (the drum is clamped down at the edges)







these are both m=1 modes



I found these nice movies at: http://photon.phys.clemson.edu/brad/courses.dir/movies.dir/phys841-01.dir/movies.html





terrific

what's waving???

Schroedinger "solved" a drum-head-like equation for the hydrogen atom

Discrete, vibrational modes...of a something.

However, he was in for a surprise -Brave guy: worked in the alps over Christmas 1925 with

his girlfriend while his wife stayed in Zurich.

The surprise, is that the mathematics required that the **<u>state</u>** of such a system had to be

Îmagînary!!

Solutions: the Bohr atom bang-on. but with a twist.



the "quantum field"

"psi"...also called the "wavefunction" the "state" of something. The "Schroedinger Equation" predicts its behavior in space and time



what is the ''state'' of a quantum system

forces forces initial state at x_0 , y_0 , t_0

Schroedinger didn't know what it was

but he could solve the equation



& energy at any time, all over the volume

forces can be of two types forces

attractive, bound forces...

initial state at x₀, y₀, t₀

with negative energies - atoms

free forces

with positive energies...often the forces of other particles - particle physics



what is
the
''state'' of
a system
for an electron

and proton

coupled by the Coulomb's Force? Coulomb's Law

initial state at x_0 , y_0 , t_0





The prize

with Paul Dirac

about whom I will swoon soon!

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WHAT'S WAVING??

"wavefunctions"

...but they're imaginary!



Schroedinger had to work with real quantities

built from the imaginary quantum field function

With only a half-baked clue of what he was doing.

Remember what imaginary quantities are?

$$i = \sqrt{-1} \longrightarrow A$$

Nature... does "Real."

So, Schroedinger created a real number out of $|\psi|$

The "complex conjugate" of A is: $A^* = a - ib$

And a real combination of them is the "norm" $|A|^2$

$$AA^* = (a+ib)(a-ib)$$

Schroedinger thought that $|\psi|^2$ might refer to the distribution of electrons' electrical charge.

4 = a + ib

has both real and imaginary parts



Sandy: Oh Danny, is this the end? Danny: No Sandy. It's only the beginning.



probably, it's probability

Where Max Born (Olivia Newton-John's grand-dad) comes in

$|\psi|^2$ is the **probability of finding the electron**

a measure of the likelihood that an electron will be at a given place at a given time...that's all we can know

then: no radiation problem...since the electron is not actually orbiting

We calculate the shape of its probability density

a probability

The concept of normal matter disappears, never to return





finally

in 1954

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of quantum mechanics





I'm now uncertain.

This probabilistic interpretation stresses your intuition

intensely pursued by Heisenberg, who in the best Einsteinian tradition, asked a simple question:

what's involved in measuring something...?

this relation will be important relating the wavelength of a quantum object

to its momentum



it was hard enough

for photons

but for an electron?

A particle is HERE:



A wave is EVERYWHERE:

The deBroglie hypothesis:

of given momentum

<u>also</u> has

a single wavelength

immediate implications

wavelength and momentum are inversely linked

 $p_1 = \frac{h}{\lambda_1}$



immediate implications



 $p_2 = \frac{h}{\lambda_2}$ $p_2 < p_1$

long wavelength: low momentum

immediate implications

 $p_3 = \frac{h}{\lambda_3}$

 $p_3 > p_1$

short wavelength: high momentum

but a pure momentum: one wavelength, one definitive momentum



suppose we trap

an electron

Where's the electron?

somewhere here:

how to locate it better?



suppose trap We

Where's the electron?

somewhere here:

an electron

make the trap smaller



suppose trap We

an electron



how to locate it better?

suppose trap We

an electron

Where's the electron?

somewhere here:

VVV

make the trap smaller

 $p = \frac{h}{\lambda}$





The wavelength is shorter... So the momentum is higher! an inevitable trade-off in order to make the location more precise you pay the price that its **speed is higher**



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Heisenberg Uncertainty Principle

the Heisenberg Uncertainty Principle was from 26 year old Werner Heisenberg an enigma inventor of many important concepts

did he save the west from a German nuclear bomb?

or the opposite?



Werner Heisenberg 1901-1976

measuring something ... you have to "look" at it by eye or some external, intermediate probe remember for waves what determines the scale? wavelength

What if the object is atomic sized or smaller? ... what is it to "look"??

66

Heisenberg Uncertainty really!

how do you measure the trajectory of an object?

look at it in Time

→ bounce light off it

Sweet spot for identifying an object: need $\lambda \sim$ size of the object



uncertainty - sometimes called "indeterminancy"

Try to "see" and electron. Electrons are small. So...need light wavelength small.



Gedankenexperiment

Photon diffracts by the electron "barrier" and blurs the electron position by about the amount of the photon wavelength





So, make λ small to reduce Δx



 $\Delta p \Delta x \sim h$

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there is no way to beat this:

one cannot make a simultaneous arbitrarily precise measurement of position and momentum

the inverse relation between p and λ messes with you every time



but here's the hard part

this inability to determine position or momentum to arbitrary precision

is not about poor instruments

It. Is. About. Nature.

Heisenberg Uncertainty Relation relation alert: refers to:

example:

 $\Delta x \Delta p \ge h$ & $\Delta t \Delta E \ge h$ an inherent property of Nature objects to not possess precise position and precise velocity at the

same time.

1932 Nobel

31 years old

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Werner Heisenberg

The Nobel Prize in Physics 1932

Werner Heisenberg



Werner Karl Heisenberg

The Nobel Prize in Physics 1932 was awarde creation of quantum mechanics, the applicati discovery of the allotropic forms of hydrogen'

Werner Heisenberg received his Nobel Prize selection process in 1932, the Nobel Commit the year's nominations met the criteria as out According to the Nobel Foundation's statutes be reserved until the following year, and this Heisenberg therefore received his Nobel Prize

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a new way

A measurement cannot be made of both precise position and precise momentum: Objects in Nature dont possess those properties.

Of thinking and doing science

we lose another classical, unchallenged scenario

there is no such thing as a precise trajectory

and a measurement is not isolated from the thing being measured

which is where new-age-y analyses of physics go off the rails



get real

I got pulled over for doing 105 mph* The state police use radar ~20 GHz, λ ~ 14cm

How uncertain was my position?



* it was a different black Bimmer that had passed me a while back.

 $\Delta p \Delta x \sim h$ about 6 x 10⁻³³ m

instead of midlife-crisis sports cars

how about:

a proton at 0.9c

what's its position uncertainty?

 $\Delta p \Delta x \sim h$

about 1/3 the size of a nucleus



$\Delta x = \frac{h}{n} \sim \frac{h}{m \gamma w} \sim 10^{-15} \text{ m}$ $p m\gamma v$

the whole story

for technical reasons, we use:



plus

the other form:



$\Delta x \Delta p \ge \frac{h}{4\pi}$

 $\Delta t \Delta E \ge \frac{h}{4\pi}$

one more...

from the Bohr model, the speed of the electron is ~ 2 x 10⁶ m/s – let's use non-relativistic momentum: for Δp for an electron: $\Delta x \Delta p \ge \frac{h}{4\pi}$ $\Delta x \sim \frac{h}{4\pi \Delta p} \sim 3 \times 10^{-11} m$

> So, the size of the atom is consistent with the electron being smeared all over the "fixed" **Bohr radius.**

just about the Bohr radius!



The "electron cloud" in a bound system is sort of...visualizable

I'm dancing around a tough question But, if particles are waves and if waves are "everywhere" ...what's the "particle" in Particle Physics?



But, remember that what's real about the quantum fields is the square: $|\psi(x,t)|^2$



(I've changed the heights)

notice the peaking

add quantum field functions - more





peaking is even more pronounced

(I've changed the heights)

add quantum field functions -





peaking is even more pronounced

(I've changed the heights)

a classical particle (dot) and its wavefunction

waves of different wavelengths? different momenta



Heisenberg Uncertainty Relation at work again

called "wavepackets"

the wave combinations localize the state...with some spread in x



all of the wave combinations means all of the momenta contribute: an spread in *p*.

the larger the momentum spread the smaller the localization "particles" are more particle-like at large momentum

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the lathat's why weiced IT the smarticle PHYSICS" and not "particles" are more particle-like at large momentum Wave physics"

The Schroedinger Equation is precisely, predictive

There is no ambiguity in how the quantum field evolves the only measurable is its probabilistic feature... Is the quantum field function - the wavefunction - real? I don't know. It cannot be observed...so moot. Does it work as a description of Nature?

absolutely...to exquisite precision

1911 Solvay Conference





Einstein: "God does not play dice." Bohr: "Einstein, stop telling God what to do." snap.

Nature's little joke

is encapsulated in a famous Feynman-description

a Gedankenexperiment...

e joke