

Day 25, 05.12.2018 Quantum Mechanics 4

housekeeping

Gotta come to class

question about anything? I'll make a movie for you:

Quantum Mechanics:

Readings: Oerter, Cosmic Perspective, and Hobson

Hobson_QM1.pdf & Hobson_QM2.pdf are chapters 12 & 13 out of Hobson

Homework #11 is all from MasteringPhysics - due saturday, rather than friday

yeah. but I messed up and slipped visibility and due dates by a week... fixed last night, so due Monday, the 16th



honors project began

https://qstbb.pa.msu.edu/storage/Homework_Projects/honors_project_2018/

contains:

the first instructions: the plan & tutorial the second instructions -v2 uploaded, added a missing student the data, assigned by name in the second instructions

dates:

complete first part, March 16

analyze data by April 24 and hand in complete writeup at the final exam



Here's What You Missed About ectrons



slice through the wavefunctions

Solve Schroedinger equation probability then square them: and get wavefunctions: 1*s* (x,t)0 ons of atomic hydrogen R_{at}(r) pm 3s 3d 3p 2*s* 2s 2p r / 10⁻¹⁰ m 0 1s average radius 3*s* n=2 n=5 n=6 n=3 n=4 n=1 n=7 l = 06 0 0 0 m = 0l = 1m = 0l = 1m = 1l = 2m = 0l = 2m = 1l = 2m = 2



Heisenberg Uncertainty Relation relation alert: $\Delta x \Delta p \ge h$ & $\Delta t \Delta E \ge h$ refers to: an inherent property of Nature

lots of things!

example:

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



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

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 wavefunctions are everywhere



make a measurement....there

the electron is there with probability

Feynman's picture was one of particles: which take all possible paths

We can calculate the wavefunction at any point, very precisely...it's completely deterministic



The trajectory of a big object?

Overwhelmingly probable quantum likelihood: the classical path



Only then is it real.



so where is a quantum

before it's measured?

anywhere? everywhere?

yeah.



this is how we have to think about it:

before measurement: alive-dead state superposition state of both

after measurement: is either alive or dead

state – h or dead

OBTW: electrons are little magnets

They behave in a magnetic field as if they are little spinning current spheres The electron **itself** is *like* a spinning charge...



Electrons have an **intrinsic** angular momentum, "S": "spin"

We say "spin, plus 1/2" or "spin up" and "spin, minus 1/2" or "spin down"

$$S_z = m_s \frac{h}{2\pi}$$



jargon alert:	fermion	
	refers to:	any particle with h
	entomology:	from Fermi's theo behavior of large r
	example:	electron, proton, r

half-integer spin retical work on the numbers of Fermions

neutron

jargon alert:	boson	
	refers to:	any quantum objec
	entomology:	from Satyendra Na on the effects of m aggregates
	example:	photon, pion, Higg

ct with integer spin th Bose, who worked nultiple boson

s Boson

electron symbol: charge: mass: spin: category:

e -1*e* $m_e \neq 9.0 \times 10^{-31} \text{ kg} \sim 0.0005 \text{ p}$ 1/2 fermion, lepton

spin is a defining quality of an electron

particle:	proton	
	symbol:	p
	charge:	+1 <i>e</i>
	mass:	$m_p = 1.6726 \times 10^{-2}$
	spin:	1/2
	category:	fermion, hadron

27 kg = 1 p

photon particle: symbol: γ charge: 0 $m_{\gamma} = 0$ mass: spin: 1 category:

again, an inherent angular momentum and a defining property of photons

boson, aka Intermediate Vector Boson

66 I think I can safely say that nobody understands quantum mechanics. **Richard Feynman**

But we can calculate with Quantum Mechanics very, very well.

We're all highly skilled Quantum *Mechanics*





shifting gears

antimatter



here's a number:



zero

the # of successfully combined models of

Quantum Mechanics and Relativity

prior to 1928

odels of ivity

remember the relativistic energy relationship

and compare it to the nonrelativistic one

Classical

$$E = \frac{1}{2}mv^2 \qquad p$$

Relativistic

 $E^2 = (m_0 c^2)^2 + (pc)^2$

that square is problematic since it suggests:

$$E = \pm \sqrt{(m_0 c^2)^2 + (m_0 c^2)^2} + \frac{1}{2}$$

translated to Schroedinger QM: negative energies for freely moving electrons

v = mv $v = \frac{p}{2}$

 $-(pc)^{2}$

negative energies for unbound systems a disaster

any additional E is kinetic

F

 $m_0 c^2$

negative energies for unbound systems

a disaster

negative energies for unbound systems

a disaster

there's no bottom!

worse!

Quantum Mechanics using Relativity: required not only negative energies negative probabilities!

1928



Paul Dirac

1902 - 1984





At the question period after a Dirac lecture at the University of Toronto, somebody in the audience remarked: "Professor Dirac, I do not understand how you derived the formula on the top left side of the blackboard." "This is not a question," snapped Dirac, "it is a statement."

hilarious interview with the Wisconsin State Journal from 1929 on the blog.

Dirac's Mathematical Imagination

Dirac embraced the negative energy

Dirac set out to find an equation that would solve both problems

> **Dirac's** imagination

The "Dirac Equation" is the correct equation for electrons: Probabilities turn out okay, but required interpretation of negative energies

Solved the negative probability



negative electric charge + Energy

positive electric charge – Energy

Dirac's result

required: 4 quantum fields, rather than 1 $\psi_{\mu}(E,\psi)(E,\psi)(+E)$ 2 have positive energy, 2 have negative energy each pair is related precisely to spin

Dirac showed that spin is a wholly relativistic effect ... it just popped out of his equation.

 $\psi(\overline{D}(EE))/\psi(\overline{D})n(-E)$

still negative energies?

"solved" it with Pauli's Exclusion Principle

 His vacuum is

 full of negative

 energy

 electrons

positive energy







negative energy

 mc^2

 $-mc^2$

0

e-

start with nothing

 $E_{\gamma} > 2 m_e c^2$



+







Dirac began this discussion

which continues today

in particle physics

and in cosmology





what is this?

 $\psi(-E)$ a positively charged object with negative energy?

At first, he thought: "proton"

nah. A bolder idea: an anti-electron. The Positron.

Us...antimatter.



modern intepretat

a photon poof-disappears








The antimatter story has a happy ending:

1932





protons from space

~2 per minute per fingernail



Cosmic Rays very high energy

Carl Anderson

clever...put in a lead plate to cause particles to lose energy

DOWN and negative?

Right on schedule: 1932

UP and positive?



B field <u>in</u>



sharper curvature at top

"antiparticle"

anti-electron, aka "positron" symbol: \overline{e} or e^+ charge: +1e $m_e = 9.0 \times 10^{-31} \text{ kg} \simeq 0.0005 \text{ p}$ mass: 1/2 spin: anti-fermion, anti-lepton category:

the bar over the top will mean

antimatter

is a fact of life

every particle has it's anti-particle partner

same mass, different electrical charge

e partner sharge

Dirac Nobel

at the age of 31

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Carl Anderson and Victor Hess

Anderson was 31

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Alfred Nobel

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Victor F. Hess

Carl D. Anderson



Victor Franz Hess

The Nobel Prize in Physics 19 "for his discovery of cosmic rate

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Carl David Anderso	n
1936 was divided equal radiation" and Carl Day	lly between Victor Franz Hess vid Anderson "for his discovery
belprize.org. 20 l ureates/1936/	Mar 2013

this is where it gets interesting we need to establish a language for Dirac-like reactions

"Relativistic Quantum Field Theory" essentially invented by Paul Dirac

notice a couple of things about what appears in Dirac's equation

1. it's about more than one thing: two electrons and a photon

"regular" Quantum Mechanics is about single objects only

2. stuff appears and stuff disappears



what's

nothing.

what's nothing

you'd maybe say:

no objects (particles...quanta)

zero energy



47

the Heisenberg Uncertainty Principle:

there's no state of Nature that can possess any precise value of, say, energy

and that includes Zero.

the Heisenberg Uncertainty Principle

will not allow a **void**.

but we still have a notion of the vacuum

it's the lowest energy state in Nature

where there are no real particles

understanding whatsgoingonhere

requires some mental fortitude



remember

trying to trap an electron?

let's make it all about nothing.







make the trap smaller



remember

trying to trap an electron?

do nothing tighter







make the trap smaller to this value:

$$\Delta x \sim \frac{1}{\eta}$$

The size of a Hydrogen atom... 5 x 10^{-11} m The size of a proton... $\sim 10^{-15}$ m



or an electron, somewhere here:

- $m_e c$
- .2 x 10⁻¹² m

an important

but simple calculation about nothing



a very important "length"

Compton Wavelength

we consider this to be "the size of a particle"

 $\Delta x \ \Delta p \quad \sim \quad h$ $\frac{h}{m_e c} \Delta p \sim h$ $\frac{1}{m_e c^2} \Delta p c \sim 1$

An energy equivalent to the mass energy...all by looking closely at nothing.



remember

What's in Nothing with an electron?

electron + nothing, somewhere here:

trying to trap an electron?

do nothing tighter





make the trap smaller to this value:





$\sim 2.2 \text{ x } 10^{-12} \text{ m}$

but wait.

let's just do this in space...shrink to this critical size

the same thing happens

remember

What's in Nothing?

trying to trap an

electron?

do nothing tighter





make the trap smaller to this value:

$$\Delta x \sim \frac{1}{\eta}$$







$\sim 2.2 \text{ x } 10^{-12} \text{ m}$



the Uncertainty Principle requires

that particle-antiparticle pairs pop into and out of existence

all the time





uncertainty principle

+ the particular length of:

$$\lambda_C = \frac{h}{mc}$$

makes the vacuum very active.



they are all popped out of the same stuff the vacuum Field of the electron

electrons appear because they're coerced out of the vacuum positive

like by a photon



60

the quantum vacuum

a word about theories

let's play chess ...

my model of chess watch tons of matches





my model requires

the existence of a new entity



my model of chess only with the board do the rules make sense







remember what I see are the pieces





remember what I need to be the case...is the board







The technical description: "if it walks like a and it quacks , then it must be a likea

]]



a successful physics additional commitment!

model that requires an



what about fields?

a number in space



you know one everywhere...a number


you know one everywhere...a number



what's a particle?

it's localized wave in a field



0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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-2	2	0	-Ø	0	Ø	0	0	2	0	-2	Φ	Φ	2	Φ	0	-Ø	-Ø	2	Ø	0	-2	0	1	0	-2	0	-2
0	-2	2	0	2	0	2	1	1	2	-Ø	-Ø	-Ø	-2	2	-2	-2	0	-Ø	1	2	-2	-Ø	2	2	-Ø	2	0
2	2	0	1	-2	-2	-2	2	-2	-2	2	0	-Ø	-2	-2	2	0	1	2	0	2	0	-Ø	1	2	2	0	-Ø
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0	2	-Ø	-2	Φ	0	0	2	-0	2	-Ø	2	-0	1	-2	2	0	0	Φ	1	0	0	-2	Φ	Φ	-2	2	2
-2	0	2	-2	0	1	-0	-2	2	-2	-Ф	-0	-Ф	-2	2	Φ	1	-2	0	0	-2	-2	0	0	-0	2	-2	1
2	1	2	1	Φ	0	-2	-0	-2	1	0	1	Φ	0	Φ	Φ	2	0	2	2	1	1	-0	2	2	0	0	2
0	-0	1	-2	1	2	0	-0	-0	2	-2	-0	2	2	1	2	2	Φ	1	0	0	-2	1	-0	-0	-2	-0	-2
0	-2	-1	-0	1	1	0	0	0	0	2	1	-2	0	-0	-0	-0	0	0	-2	2	1	2	0	2	2	-0	-0
-0	2	0	1	-2	-0	-2	-2	-0	-0	1	2	2	-2	0	0	-0	-1	1	-2	-0	-2	1	2	-1	2	1	-0
-2	-2	1	1	-2	0	-0	2	-2	-0	-2	-1	2	-2	-2	-1	-2	-2	1	0	-1	2	-0	1	-2	0	2	1
0	0	0	2	-0	0	0	2	-0	-0	2	0	1	-2	1	-2	2	-0	-2	0	0	-2	-2	2	0	0	0	1
2	0	2	-2	-2	1	-0	-2	-1	0	1	1	0	-2	1	-1	-1	-2	2	1	2	2	0	-2	0	1	1	-1

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-1	-1	1	2	4	2	3	-2	-2	0	-2	-1	0	-1	-1	-2	-2	-1	-2	2	3	4	5	4	3	4	-2	-2	0	-1	-1	0	0	-
-1	2	3	4	5	4	3	4	-2	-2	-1	0	-2	-1	-1	-2	-2	0	-2	1	3	4	5	4	3	2	-2	-2	-2	-1	0	-1	0	-
-1	1	3	4	5	4	3	2	-2	0	-2	0	-1	0	-1	-2	-1	-2	-1	-1	-4	3	2	2	1	-1	-1	0	-2	0	-1	-2	-2	-
-2	-2	4	3	2	2	1	-2	0	-1	0	-1	-2	-2	-1	-2	-1	-2	-1	0	0	2	1	3	0	-2	-2	-1	-1	-2	-1	0	0	_
-1	-1	-1	2	1	3	-1	0	-1	-1	-2	0	0	0	-1	-1	-2	0	0	-2	-1	0	0	0	-1	-1	-1	0	-1	-2	-2	0	0	(
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0	-1	-2	-2	0	-2	-2	0	0	-1	0	-1	0	-2	-1	-2	-1	0	-1	-2	-1	-2	0	-2	-1	-1	0	-2	-2	-1 2	1		0	-
0	-2	0	-1	-2	0	-2	-1	-2	-1	-2	-2	0	-1	-2	-2	-2	-2	-2	0	0	-1	-1	-2	-2	0	0	-1	-2 ₁	12	4	. :	2	3
-1	0	-2	-1	-1	0	-1	0	-2	0	-2	-1	0	0	-2	-1	0	-2	-2	0	-1	-2	-1	0	-1	0	-1	-2 2	3	4	5	5 4	1	3
0	-1	-0	0	0	_1	-1	Δ	-?	2	1	1	-	-1			-1	0	0	-1	2	-2	0	0	-1		2	-1-	3	-				3
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-1	-2	0	-2	0	0	0	1	3	4	5	4	3	2	-2	0	-2	0	0	0	-1	-2	0	0	-1	-2	-1	-1	-1	-2	-1	-2	0	-
0	-2	-1	-2	0	0	0	-2	4	3	2	2	1	-1	0	0	-2	-2	0	-2	0	-1	0	0	-1	-1	-1	-1	0	-2	-2	-2	-1	
-1	-1	0	0	-2	-2	-1	-1	-2	-2	1	3	-1	-1	-1	-1	-2	-2	-2	-2	-2	-2	-1	0	0	0	-1	-1	-2	0	-2	-2	-1	
0	0	-2	0	-1	-2	0	-1	0	-2	-2	-2	-2	0	-2	0	0	-2	-1	-1	0	-1	0	0	-1	-2	-2	-1	0	-2	0	-2	-1	-
0	-2	0	-2	2	1	1 -1	-2	-1	-2	-1	0	0	-2	-1	-2	-2	-1	0	-1	0	-2	0	0	-2	0	-2	-1	-2	0	-1	-1	-1	-
-1	0	0 1		2	4	2	3 0	-2	0	0	-1	0	0	-2	-2	-2	-1	-2	2	1	1 0	0	-1	-2	-2	-1	-1	0	0	-1	-2	-2	-
-2	-22	2 3	3	4	5	4	3	4 1	-1	-2	0	0	-1	-1	-2	-2	-1	1	2	4	2	3)	-2	-1	0	-1	-1	0	0	-1	-1	0	-
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0	-2	-1	-2	-1	-2	-1	-1	-1	-2	-2	-2	-2	-2	-2	0	0	-2	0	2	1	31	0	-2	-1	-2	-1	-1	-2	-1	-1	-2	-1	-

here's how

stuff happens in this particle field theory model



0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	P	R			R	F		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	~7	~7	^ 7	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	- 6	, 7	, 7	7	- 6	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0	0	- 6	7	8	γ_0	8	7	- 5	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	7	9_		9	7	6	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	8	9	8	7	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		7	7	7	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



12 -20 -21 -2-1 0-1 0-1 22 0-2 2-2 -11 2-2 -11 2-2 11 -12 1-1 2 -1 0 0 $\mathbf{Proton} \begin{bmatrix} 0 & 0 & -12 & 1-2 & 0-2 & -11 & 10 & -2-1 & -21 & 11 \\ 0 & 0 & -1 & 1 & -1 & 1 & -1 & -2 & 1 & 1 \end{bmatrix}$



particle field theory* the best theory in history

never an incorrect prediction



*Quantum Electrodynamics



outrageously precise agreement, prediction and measurement

what's more fundamental?

a winner



fields



the particle vacuum full of fields:

·2 -2 -1 -1 -1 -1 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -1 -2 -2 -2 -2 -2 -2 ·2 -1 <mark>√2</mark>-2 ·2 -2 ·2 -2 -2 -2 -2 -2 -2 -2 -1 -2 -2 -2 -? 0 2 -2 -2 -2 -2

the particle vacuum full of fields for every "particles"

 $\sum_{i=1}^{n} (1 + 2) (1 + 2) (2 + 2) (1 + 2) (1 + 2) (2 + 1) (1 + 2) (2 + 2) (1 + 2) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1) (2 + 1)$ $\begin{array}{c} 2 - 1 \\ 2 - 2 & 2 & 0 \\ 2 - 2 & 2 & 0 \\ 1 & 2 - 2 & 0 \\ 2 & 2 & 0 \\ 2 - 2 & 0 & 1 \\ 2 - 2 & -2 & 2 \\ - 2 & -2 & 2 \\ - 2 & -2 & 2 \end{array}$



two predictions for "space"



energy in the particle vacuum is

times the energy in the dark energy vacuum



this has a name "the worst



prediction in the history of physics"



a little more specific

what the mathematics tells US



it's not like the photon is now "in" the electron

the photon pops the electron-positron pair out of the Ur electron field and itself disappears back into the Ur photon field.

but what we have to subtract the energy of the vacuum does away...because it's infinite and all we care about is the states we build above the vacuum energy mean?

it means that the vacuum is full of energy

like a reservoir

particles are created out of the vacuum



[J3h S(0) an infinite offset = Has

93

Okay. So we don't like infinity we subtract it away and worry about the difference between

infinity and finite energies of real particles

Seriously?

That seems to be the case.

This picture works with exquisite precision and accuracy.

but the vacuum

is roiling with particleantiparticle "virtual pairs" popping into and out of existence

multiple ways we know this.

A "regular" model of the hydrogen atom...needs modification to take into account the effects of the vacuum

The electron cloud is spread out by the virtual photon and the positron's effects...and that changes the emission spectrum of hydrogen: The "Lamb Shift"...measured after WWII with microwave technologies



1955 Nobel Prize

Willis E. Lamb

died just a few years ago at the University of Arizona

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Nobel Laureates Have Their





Willis Eugene Lamb Polykarp Kusch

The Nobel Prize in Physics 1955 was divided equally between Willis Eugene Lamb "for his discoveries concerning the fine structure of the hydrogen spectrum" and Polykarp Kusch "for his precision determination of the magnetic moment of the electron".

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The Nobel Prize in Physics 1958

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Willis E. Lamb

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The Nobel Priz Willis E. Lamb, Po	e in Physics 195 olykarp Kusch	55	
obel Prize in Physi	cs 1955		~
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the "Casimir Effect"

two highly polished mirrors isolated from all external effects

The vacuum has all wavelengths of virtual waves from particles and fields...but fewer can fit between the walls

...and the pressure from the outside, moves them closer together

The amount is precisely predicted...and a few years ago the experiments confirmed it convincingly in 2001



the vacuum

is a very complicated thing

as we'll see when we get back to cosmology



Feynman Diagrams

now for real.

creation and annihilation of can be embodied in Feynman Diagrams



hero worship



about as close as we come













Richard Feynman, Sin-Itiro Tomonaga, Julian Schwinger

1965 Nobel



Nobel Prize in Literature

Nobel Peace Prize

Prize in Economic Sciences

Nobel Laureates Have Their Say

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Nomination and Selection of Nobel Laureates





The Nobel Prize in Physics 1965 was Julian Schwinger and Richard P. Feyr quantum electrodynamics, with deepelementary particles".

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Sin-Itiro Tomonaga

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the symbols of Feynman Diagrams

each line represents an entire "history" of trajectories

to go from A to B, represent all histories with a single line.



Feynman's lines include rules on how to calculate the possibilities in a relativistically consistent way.

very efficient

avoids lots of technicalities.

When I teach these techniques to second year graduate students, I first do the calculation of Compton Scattering and do it without Feynman's tools.

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4 (7) Do the standard Earn), at (m) i - ture

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> TT) 3 2E S(P-P,) Srs Spr N: Ym tions can be

> > ip'x, -ipx Life (p) e e

- twice (which cancels the Friday minus night). A* (x,) 1Y>= JdK, Z Evil (h,) e (IT) 32W, Six, S(E-E,) 107 and we can do the momentum nit equals giving Y(11'x) 1: Ap(4.1 Ar(x)): 18(4x) >= $\epsilon_{\mu(\lambda')}(\omega') \epsilon_{\tau(\lambda)}(\omega) e e + \epsilon_{\tau(\lambda')}(\omega) \epsilon_{\mu(\lambda)}(\omega) e e^{i\omega' x_{\lambda} - ih \cdot x_{\lambda}}$ thingue, & terms merale (+ex) = -e' [d4x. f. P(p) un (p) e e

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Earliev, I attesched a graphical meaning to the which expansion terms, let's recorp that according to what we've calculated.

p) uppe pe

平(x)+(y) = COIT[平(x)+(y)]10>

× ?

14(x) y + +(y) St A(x)

So, the trist (O or () graph would be

Ar(x) -> A+(x) -> a generally: ¥(4) ¥(4) for our poster

and Dor @

 $A(x_{i}) \rightarrow A^{+} \rightarrow a$ $5 A(x_{i}) \rightarrow A^{-} \rightarrow a^{+}$



his rules eliminate all of that

and I can just write down the "answer"

appropriately labeled, each line tells us what to put into a long equation for further solving



325 Now let's do the comptan calculation as it we have the rules all clong. I want the cross section for T(L) + e(p) → T(L) + e(p) to 2th order p+4-m (-ies TE un -ied) Evin u \$+4+m ++++2p.6-0
but the pictures themselves are visually...informative

and I'm going to try to tell you how to do this without the geeky mathematics

theoretical papers each diagram is a complicated calculation



 m_{π_T} smaller than 260 GeV. The parameter ϵ refers to the proportion of the top quark mass generated by the extended technicolor which is taken in the range of $\epsilon \sim (0.01, 0.1)$.







By using the laser back-scattering technique on electron beam, an e^+e^- LC which has the c.m. energy of hundreds of $\,{\rm GeV}$ to several TeV can be transformed to be a photon collider.^[19-21] By integrating over the photon luminosity in an e^+e^- linear collider, the total cross section for the process $e^+e^- \rightarrow t\bar{b}\pi_t^-$ can be obtained in the form

$$\sigma(s) = \int_{\frac{E_0}{\sqrt{s}}}^{x_{\max}} dz \frac{d\mathcal{L}_{\gamma\gamma}}{dz} \hat{\sigma}(\gamma\gamma \to t\bar{b}\pi_t^-, \text{ at } \hat{s} = z^2 s),$$
(12)

where $E_0 = m_t + m_b + m_{\pi_T}$, $\sqrt{s}(\sqrt{\hat{s}})$ is the $e^+e^-(\gamma\gamma)$ c.m. energy, and $\frac{d\mathcal{L}_{\gamma\gamma}}{dz}$ is the distribution function of photon luminosity, which is defined as

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dz} = 2z \int_{z^2/x_{\text{max}}}^{x_{\text{max}}} \frac{dx}{x} F_{\gamma/e}(x) F_{\gamma/e}\left(\frac{z^2}{x}\right).$$
(13)

For the initial unpolarized electrons and laser photon beams, the energy spectrum of the back scattered

photon is given by [22]

$$F_{\frac{\gamma}{e}} = \frac{1}{D(\xi)} \left[1 - x + \frac{1}{1 - x} - \frac{4x}{\xi(1 - x)} + \frac{4x^2}{\xi^2(1 - x)^2} \right],$$
(14)

 $= 2\omega/\sqrt{s}$ is the fraction of the energy of the incident electron carried by the back-scattered photon, the maximum fraction of energy carried by the backscattered photon is $x_{\text{max}} = 2\omega_{\text{max}}/\sqrt{s} = \xi/(1+\xi),$ and

$$\begin{aligned} \mathcal{D}(\xi) &= \left(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\right) \ln\left(1 + \xi\right) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2}, \\ (15)\\ \xi &= \frac{2\sqrt{s\omega_0}}{m_e^2}, \end{aligned}$$

where m_e and $\sqrt{s}/2$ are the mass and energy of the electron, ω_0 is the laser photon energy. In our evaluation, we choose ω_0 such that it maximizes the backscattered photon energy without spoiling the luminosity through e^+e^- pair creation. Then we have $\xi = 2(1 + \sqrt{2}), x_{\text{max}} \simeq 0.83, \text{ and } D(\xi) \approx 1.84, \text{ as used}$ in Ref. [23].

The processes $\gamma \gamma \rightarrow t \bar{b} \pi_t^- (\bar{t} b \pi_t^+)$ occurs through the u- and t-channel involving charged top-pion bremsstrahlungs originated from different positions on quark lines. The Feynman diagrams are drawn in Fig. 3, but the corresponding diagrams with interchange of the two incoming photons are not shown.



Fig. 3. Diagrams for $\gamma \gamma \rightarrow t \bar{b} \pi_t^-$



Fig. 4. Dependence of the cross section for $e^+e^- \rightarrow \gamma\gamma \rightarrow$ $t\bar{b}\pi_t^-(\bar{t}b\pi_t^+)$ on the top-pion mass m_{π_t} at the ILC with energy of 500 GeV.

We show the cross section for $e^+e^- \rightarrow \gamma\gamma \rightarrow$ $t\bar{b}\pi_t^-(\bar{t}b\pi_t^+)$ at the ILC with energy of 500 GeV as a

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2.1.1 Lepton and heavy quark pair decays of the SM Higgs particle

$$\Gamma[H \to l^{+}]$$

unimportant.



Figure 3: Typical diagrams contributing to $H \to Q\bar{Q}$ at lowest order and one-, two- and three-loop QCD.

depicted in Fig. 3] by the well-known expression [38–40]

$$\Gamma[H \to Q\overline{Q}] = \frac{3C}{4}$$

In lowest order the leptonic decay width of the SM Higgs boson is given by [10, 37]

$$l^{-}] = \frac{G_F M_H}{4\sqrt{2}\pi} \ m_l^2 \beta^3 \tag{6}$$

with $\beta = (1 - 4m_l^2/M_H^2)^{1/2}$ being the velocity of the leptons. The branching ratio of decays into τ leptons amounts to about 10% in the intermediate mass range. Muonic decays can reach a level of a few 10^{-4} , and all other leptonic decay modes are phenomenologically

For large Higgs masses the particle width for decays to b, c quarks [directly coupling] to the SM Higgs particle] is given up to three-loop QCD corrections [typical diagrams are

$$\frac{FM_H}{2\pi} \overline{m}_Q^2(M_H) \left[\Delta_{\rm QCD} + \Delta_t\right] \tag{7}$$

we really do use Feynman Diagrams





Feynman's approach is really sneaky and really cute

energy and time appear together in the equations:

In essence, this: $(\pm E)(t)$ either energy solution: (-E)(t)just the -E solution: (E)(-t)move the – sign:

Get a whole new interpretation of antimatter

