Particle Physics for Doodlers

SPLASH Spring 2012, Kiel Howe

Introduction

This is a class on particle physics. The goal of particle physics is to explain everything we observe in terms of fundamental particles & their interactions (I'll explain what exactly I mean by that in a bit)

What do I mean by "explain everything?"

→ billiard balls example

PART I: QED

1. Electrons & photons –

Let me remind you a few things about electrons & photons.

Everything you see around you is made up of atoms. Inside of an atom there is a nucleus and ~~an~~ electrons.

The electrons ~~is~~ are attracted to the nucleus & repel eachother.

We can see that electrons & protons attract each other in an experiment you've probably all tried before – rub a balloon on your head & some electrons from your hair get knocked out & stuck to the balloon. When you hold the balloon near your head, what happens?

How do I know that there's something called an electron inside the atom to be shaken out & transferred any way?

If you heat up a piece of metal to around 1000°C, some of the electrons from the metal atoms will start to get knocked out. [Show video]

If you turned the temperature down, you would see a single electron at a time. Flashing when it hits the screen.

If you study them carefully, you'd find that the balloon you rubbed on your hair would repel them, just like the magnet did. Every electron always is repelled by the same amount, and you never observe a "3/4" electron repelled by "3/4" the amount, so we call it a "particle".

Now, what exactly do I mean by a particle?

- Position in space
- Countable
- Distinct properties - charge, mass, ...

Now let's move on to photons.
What is a photon?

Light is made up of discrete packets of energy called photons.

In most cases, you can't tell that light comes in chunks because in most cases there are so many - when you look at a 60W lightbulb, $\sim 10^{14}$ (100,000 billion) photons hit your eye each second.

However, if you keep making a light dimmer & dimmer, eventually it will start producing photons one at a time. If you could see a light this dim, you would find that at this point it no longer gets dimmer. Instead, if you tried to make it dimmer, you would start to see ~~intermittent~~ periods of total darkness w/ intermittent flashes of the light.

Unfortunately, your eyes aren't quite sensitive enough to see a single photon (they are actually very nearly able to!) But, we can make cameras that observe this effect!

Now I'm going to tell you something quite remarkable – All the phenomena and observations of how electrons behave, in atoms, when getting stuck into balloons, or being shot through your TV, can be understood just by understanding how a single electron emits & absorbs a single photon!

For hundreds of years, these phenomena seemed completely unrelated to each other, so it was an incredible discovery that visible light & the interactions between electrons (& thus all matter) have a common description.

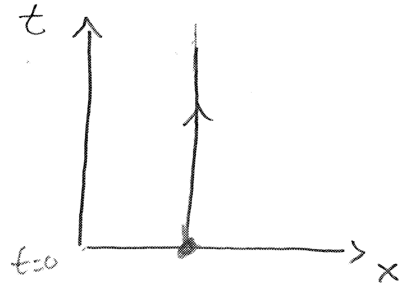
(You may have heard this expressed in the statement "light is an electromagnetic wave" – this idea was first understood before it was clear that light behave like a particle (photons),)

Our next step is to make this statement more precise. In the end, we'll find that the whole of chemistry and all the interactions of matter can be reduced to a few doodles & simple rules called Feynman diagrams

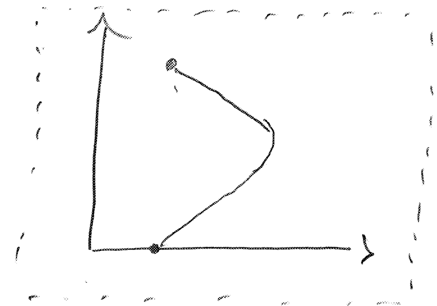
2. Space-time diagrams

We want to describe how electrons & photons move through space. A space-time diagram is a useful tool:

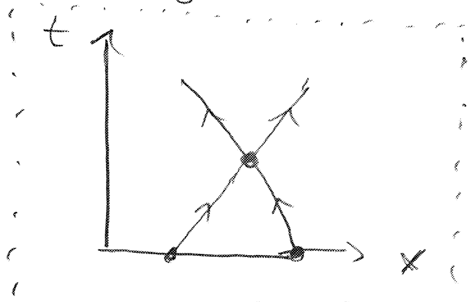
This is me standing still here:



Ex. Draw me running across the room!

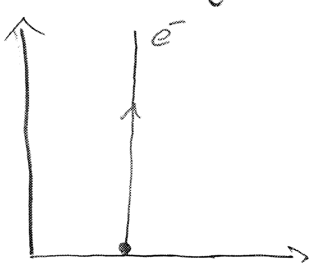


Ex. What would the diagram for two billiard balls colliding look like?

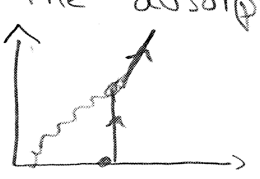


We can describe the motion of an electron in the same way:

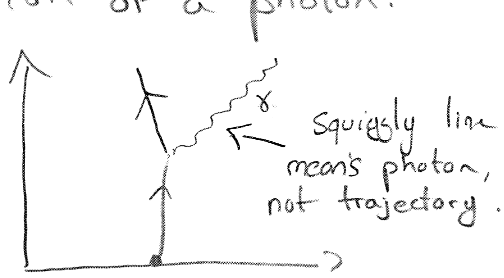
Draw all w/room For Feynman diagram



And the absorption:

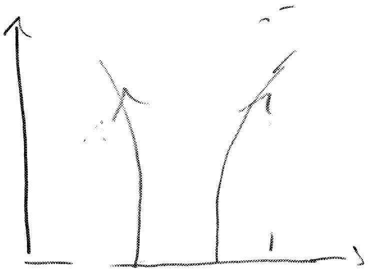


We can also describe the emission of a photon:

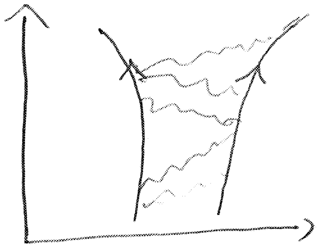


What about the interaction of two electrons?

We know electrons repel - how does it look?



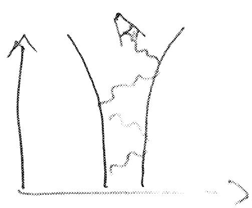
⇒ How do the electrons "know" about each other?



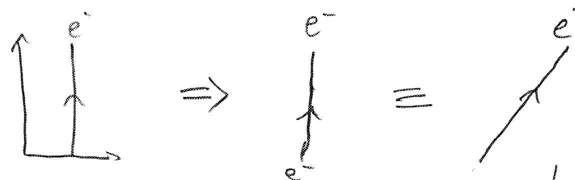
<u>Notice</u>: Interactions are "local"

⇒ Why can't we see these photons?

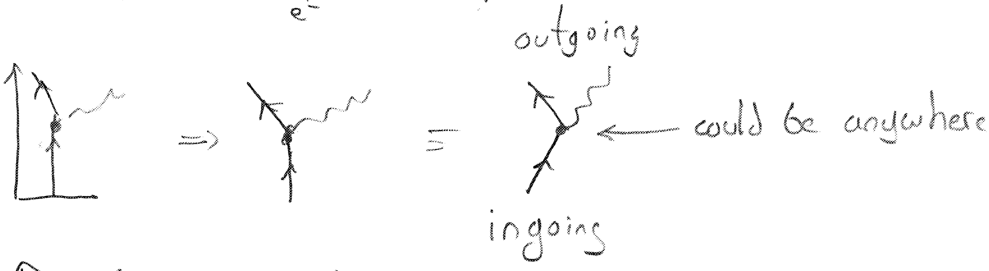
If they are far apart (weak interaction, not enough energy too) If they're close, can:



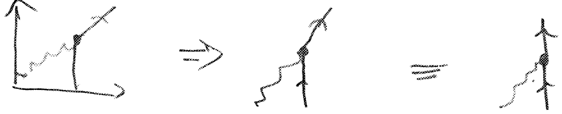
Feynman Diagrams:



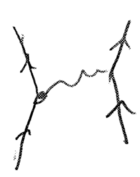
Emission



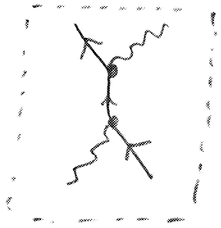
Absorption



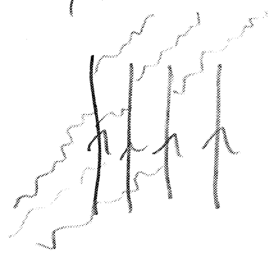
Put them together any way they fit:



Q: Draw a diagram for the scattering of a photon by an electron; $e^-\gamma \rightarrow e^-\gamma$



This diagram completely describes how light interacts w/ matter:



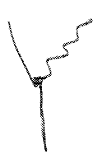
What do the diagrams mean?

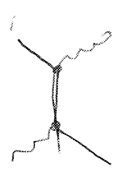
They are a recipe for answering questions of the form

I have electron 1 at $\vec{x}_1$ w/velocity $\vec{v}_1$, electron 2, photon 1, ...

what is the <u>probability</u> that I will end up with electron 1 at ... out going?

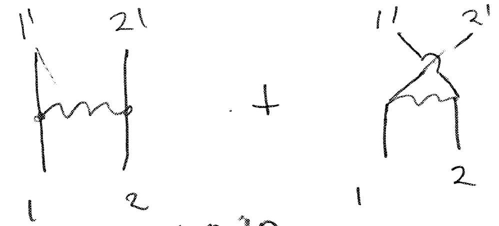
① Each diagram can be converted into a number:

e.g.  $\Rightarrow g \approx \sqrt{\frac{4\pi}{137}} \approx 0.302\ldots$

 $\Rightarrow \sim g^2 \frac{1}{V/c}$

② Draw all the diagrams that can contribute:

e.g.



$\alpha \approx 0.10$ $\quad$ $\beta \approx -0.5$

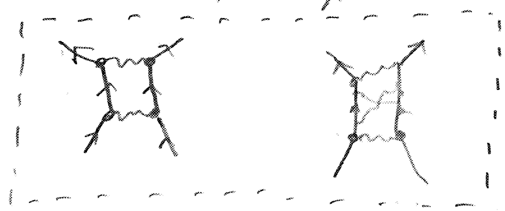
← Look up formulas in book or evaluate in computer:

⇒ Add up the numbers and square to get the probability:

$$P = (\alpha + \beta)^2 = (-0.4)^2 = 36\%$$

Note: when adding up diagrams, you also add up contributions from everywhere the interaction vertex could occur

Q: What other diagrams could contribute to $e^- e^-$ scattering?



How many power of g?

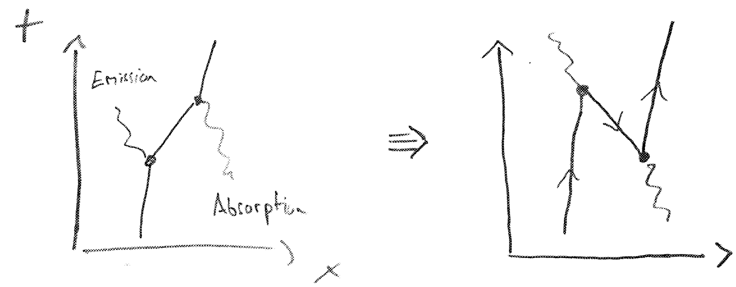
⇒ $g^2 \sim 0.1$, $g^4 \sim \frac{1}{100}$ ⇒ can stop before diagrams get too complicated

Note: diagrams must be connected ⇒

Antiparticles

Earlier I said that we should sum over all the positions in space & time that an interaction could take place.

This leads to diagrams that look like this:

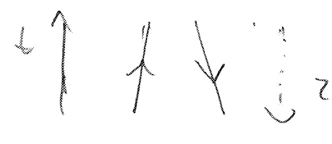


$\Rightarrow$ what does $\downarrow$ mean?

An electron "traveling back in time"

How to interpret?

Electron traveling back in time, still repelled by another electron, but in reverse direction!



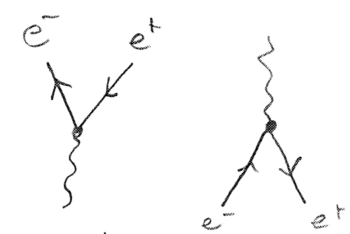
In normal time direction, looks like attracted

$\Rightarrow$ positive charge

Can show that behaves just like electron, but w/ positive charge $\Rightarrow$ "antiparticle"

"positron" = e^+

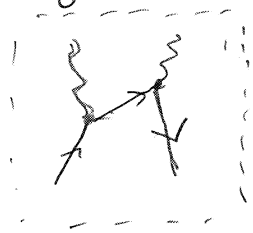
New vertices $\Rightarrow$



pair creation annihilation.

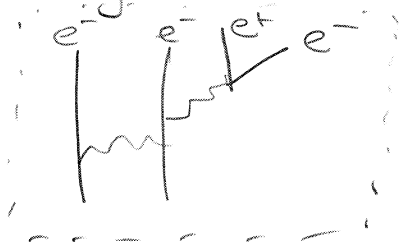
$\Rightarrow$ Must include for consistent theory.

Q: Draw a diagram for $e^+e^- \to \gamma\gamma$



If everything we see is made of electrons, how do we know there exist positrons?

Q: Draw a diagram for $e^-e^- \to e^-e^-e^+e^-$



$\Rightarrow$ produced in collisions ($\Rightarrow$ How do you tell if it's a positron?)

$\Rightarrow$ Why don't we see this all the time?
Electrons have mass $\Rightarrow$ minimum energy needed for the collision $\Rightarrow$ why we build colliders

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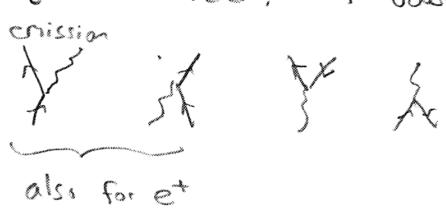
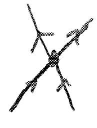
Summary: All electromagnetic phenomenon described by (chemistry, biology, light, mechanics) interaction of electrons, photons, + positrons to make the theory consistent. 4 basic processes, all inter-related:



} This called QED!

Why not



$\Rightarrow$ we don't observe it
(would actually be evidence for more models)

Intermission / Exercises:

① If you start w/one electron, can you ever end up w/ more positrons than electrons?

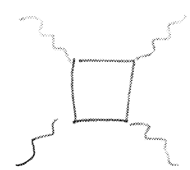
[No]

② If you start w/just an electron, is there any limit to the # of photons you can end up with?

[No limit]

③ Draw a diagram for light-by-light scattering:

$2\gamma \to 2\gamma$

[

Note: this process would not occur w/out antiparticles]

PART II: The Standard Model — "Who ordered that?"

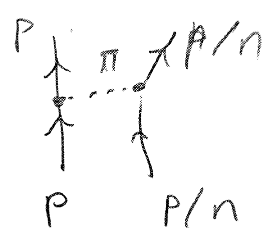
The theory of QED does not explain 2 important things:

- The behavior and components of nuclei
- Radioactivity

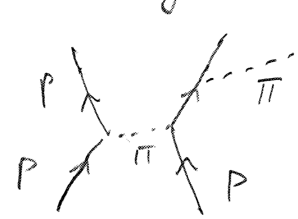
Understanding these phenomena led to the discovery of new particles & interactions.

1. The Strong Force

Nuclei are made up of protons (+ charge) and neutrons (neutral). EM wants to push the protons apart ⇒ what sticks them together? New interaction ⇒ new particle ⇒ pion



Test the theory? Collide protons (cosmic rays)

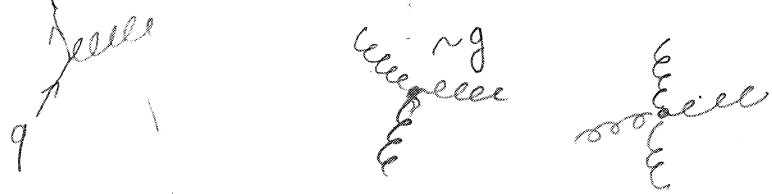


⇒ $\pi, \eta, \rho, \omega \ldots$

Zoo of new particles

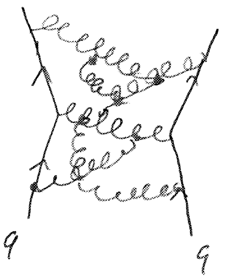
⇒ Quarks: $p = uud$, n udd, $\pi = u\bar{u}$ ...

⇒ color & strong force



very hard to calculate because $g > 1$

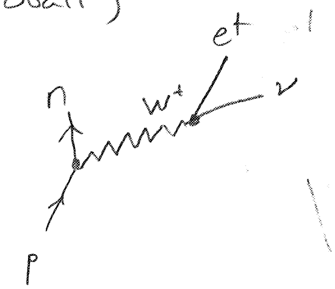
=> more complicated diagrams are <u>more</u> important



(& the Weak force)

② Radioactivity: $p \to n + e^+ + \cdots$

(e.g. Cobalt)

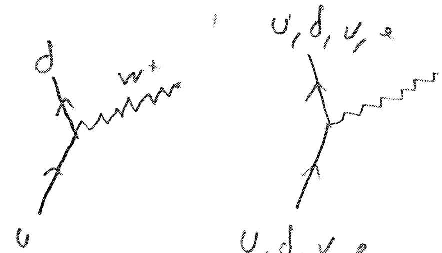


=> new particles: $W^+, W^-, Z,$ ν

(W^+, W^-, Z: Heavy; ν: neutral & not heavy)

=> "Weak" interactions

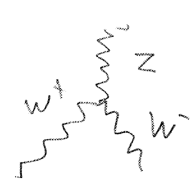
In terms of quarks



<u>Q</u>: Draw a diagram for the production of a W^+ in a u-$\bar{d}$ collision?

<u>Problem</u>: WWZ scattering:

there is a vertex



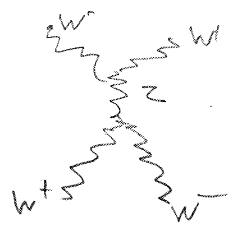
<u>Q</u>: Draw a diagram for $W^+W^- \to W^+W^-$

Problem: needed W to heavy to make radioactive decay slow.

But W w/a mass breaks down

(other gauge bosons γ, g are massless so don't have this problem)

Probability of

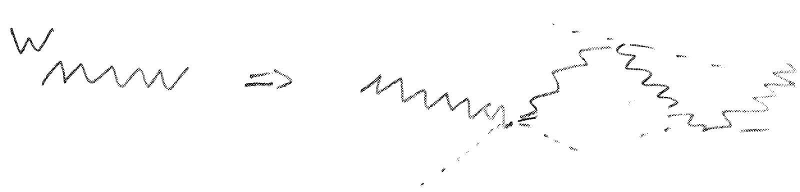


> 100%

⇒ theory not consistent

One appealing solution — Higgs Boson

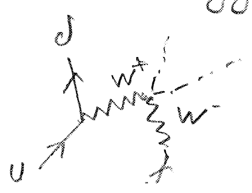
'' — Universe filled w/ Higgs field ⇒ many Higgs bosons



⇒ "drags on W" - makes it heavy

This theory self consistent ⇒ should see Higgs Boson

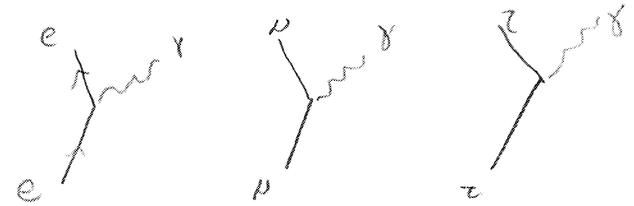
Q: How can a Higgs be made in a u-d collision?



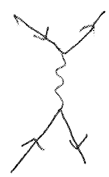
⇒ This is what the LHC is looking for

3. Many Families?

2 extra copies of electron; just heavier: μ, τ



<u>Q</u>: Draw a diagram for $e^+e^- \to \mu^+\mu^-$



Likewise for neutrinos, quarks

Who knows why?