

# Modern Physics (PHY 3305) Lecture Notes

## Particles and Interactions: Forces, Antiparticles, and the Building Blocks of the Universe (12.1-12.4)

SteveSekula, 19 April 2010 (created 14 April 2010)

no tags

### Review

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Last time we discussed the closing issues in nuclear physics, which today have created both technical and geo-political challenges:

- Fission
- Fusion

Today, we go one level deeper, inside the nucleus of the atom and back to a time in the universe when it was just billionths of a second old.

### The History of Human Understanding of the Universe

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The Elements: <http://www.privatehand.com/flash/elements.html>

A history of subatomic particles:

[http://www.slac.stanford.edu/~bellis/PDG\\_everything.html](http://www.slac.stanford.edu/~bellis/PDG_everything.html)

<http://spreadsheets.google.com>

[/ccc?key=0AqEmDaJ8A2rAcmVDcFdObk1Fem1mUGNvQ3ZiSmtzYWc&hl=en](http://ccc?key=0AqEmDaJ8A2rAcmVDcFdObk1Fem1mUGNvQ3ZiSmtzYWc&hl=en)

(Motion Chart Tab)

### The Nature of Forces

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How are forces transmitted? In introductory physics - and, in fact, for much of human civilization - we learned that forces are due to *contact*. Friction, collision, etc. are all contact forces. But gravity was the first example of so-called "spooky action-at-a-distance." When Newton postulated that there was a force, called gravity, that kept planets in orbit and made things fall to earth, he had to admit that he was going out on a limb by postulating a mysterious force that could act over vast distances with no obvious contact.

Electromagnetism made this concern worse, by again invoking action-at-a-distance. It was Faraday who introduced the concept of "Field Lines", or a "Field" of force that extends outward from a body to other bodies and causes action upon them.

Experiments supported this picture. See slides.

The modern understanding of forces is that they involve the exchange of **force carrier** particles between two other particles, for instance a pair of electrons or an electron and a proton (with the force carrier being the photon). This modern view is called **Quantum Field Theory**, and contains **Mediating Particles** whose job it is to convey energy from one place to another (force carriers). Rather than viewing the universe as particles moving from place to place, QFT views the universe as filled with fields - quantum fields - which can be excited to produce or annihilate particles (in a sense, like exciting a vibration on a drum head, though that is a bad picture when it comes to the mathematics). The language of QFT is particle **creation** and **annihilation** through interaction of various quantum fields (the electron field, the photon field).

Experiencing a force then merely involves an exchange of mediating particles. An analogy involves ice skaters on a pond, passing one another. One throws a snowball at the other with momentum  $+\vec{p}_{\text{snowball}}$ , changing her momentum by  $-\vec{p}_{\text{snowball}}$ . The other person catches it, and his momentum increases by  $+\vec{p}_{\text{snowball}}$ . This conveys the spirit of the force carrier picture.

However, this analogy fails in several ways:

1. how is it that attraction occurs? This picture only allows for mutual repulsion.
2. where did the snowball come from? In this classical picture, it was being carried along by the first person and caught by the second. That's not the quantum picture. For instance, when one electron emits a photon for exchange with a proton, it's not like the electron was carrying that photon around waiting to throw it.

Instead, the modern picture of force carriers relies on the Heisenberg Uncertainty Principle to explain force carriers.

## Heisenberg and Force Carriers

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The modern picture relies on the concept of "virtual particles" - particles that can have arbitrary energy (including negative momentum) so long as they themselves cannot be observed in that state. "Virtual Particles" don't have to obey the usual rules of energy and momentum conservation, so long as their existence is so fleeting that they aren't running around everywhere all the time.

This phenomenon is much like tunneling. Consider tunneling through a barrier. While the wave is in the barrier, it has **NEGATIVE KINETIC ENERGY**, a classically unacceptable concept but one which is necessitated by the wavefunction picture of quantum mechanics. However, the wider the barrier, the faster the occurrence of tunneling falls off. For sufficiently "classical" barriers, tunneling doesn't happen at all and we restore the classical picture of scattering off a boundary.

So how does Heisenberg help us understand forces mediated by force carriers? Well, consider the energy-time relationship:

$$\Delta E \Delta t \geq \hbar/2$$

Let's be a little hand-waving so that we can make some progress on this. Imagine that the mediating particle is created in a state such that:

$$\Delta E \Delta t \approx \hbar$$

It is existing very close to the Heisenberg limit in this case. How long can it live?

$$\Delta t \approx \hbar / \Delta E = \hbar / mc^2$$

Let's assume the particle is traveling as fast as it can - the speed of light. How far will it go before it has to disappear again?

$$\Delta x \approx c \Delta t = \hbar / mc$$

So we now have a relationship between the range of a force carrier (the range of the force) and the mass of the particle. Consider light. There appears to be no upper limit on the range over which electromagnetism can act (consider light reaching us from billions of light-years away). This suggests that the range of light is unlimited, and so its force carrier (the photon) should be massless. Of course, we also know this to be the case based on relativity, but quantum physics can also teach us about light.

This approach, though a gross approximation, has proven VERY fruitful on several occasions, predicting the mass of force carriers BEFORE they were discovered. This is what makes quantum theory so powerful - it's ability to create new knowledge. That's what distinguishes it from any competing ideas.

## **Discussion: the mass of the carrier of the nuclear force**

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Before we discovered that the proton and neutron were not fundamental particles, there was a serious question about what particle might carry the strong nuclear force and bind together nucleons. You can use the relationship between the range of the nuclear force, Planck's constant, the speed of light, and the mass of the force carrier to estimate the mass of the carrier of the strong nuclear force.

The range of the nuclear force is 2fm. Based on that, the mass of the force carrier should be:

$$m \approx \hbar / (c \cdot R) = (1.0552 \times 10^{-34} \text{ J} \cdot \text{s}) / ((2.998 \times 10^8 \text{ m/s}) \cdot (2 \times 10^{-15} \text{ m})) = 1.6 \times 10^{-11} \text{ kg} \approx 100 \text{ MeV}/c^2$$

Based on that, what particle (do you think) was identified as the carrier of the strong nuclear force?

## Antiparticles

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Before we can discuss in detail the fundamental building blocks of the universe, and the fundamental forces that weave them together, we need to discuss antiparticles. What are they?

Antiparticles are simply partners of particles, like the electron, whose properties appear to be all the same with the exception of the reversed electron charge. The positron, for example, has the same mass and spin as the electron but carries positive electric charge.

When particles and antiparticles meet, pair annihilation can occur and leads to the production of pairs of photons. Mass energy is converted to photon energy. You might think that the antineutron has no properties that distinguish it from its antiparticle, but antineutrons have been produced and do, in fact, annihilate with neutrons. This is explained by the fact that the neutron and proton are not fundamental, and the underlying building blocks - the quarks - do have distinct opposing properties from their antiparticles.

What is the theoretical basis for antiparticles? In fact, they were theorized before they were discovered. In order to predict antiparticles, you have to do something that physicists tried to do in the 1920s: marry special relativity and quantum mechanics.

The quantum mechanics we've been discussing, embodied in the SWE, is *NON-RELATIVISTIC*. This, you recall, is encoded in the free-particle formula:

$$-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} \Psi(x, t) = i\hbar \frac{\partial}{\partial t} \Psi(x, t)$$

Which we can short-hand as:

$$\hat{K}E \frac{\partial^2}{\partial x^2} \Psi(x, t) = \hat{E} \Psi(x, t)$$

by recognizing that the derivatives are OPERATORS that act on the wave function and RETURN THESE PROPERTIES OF KINETIC AND TOTAL ENERGY. The SWE is fundamentally an expression of energy conservation, albeit *classical energy conservation*.

## Discussion: Energy Conservation and the Relativistic SWE

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What is the correct form for full-blown energy conservation? Consider relativity.

Answer:

$$p^2 c^2 + m^2 c^4 = E^2$$

How might we get at the Relativistic SWE (RSWE)?

Try the operator form:

$$\hat{p}^2 c^2 \Psi(x, t) + m^2 c^4 \Psi(x, t) = \hat{E}^2 \Psi(x, t)$$

which we can expand into:

$$-c^2 \frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} \Psi(x, t) + m^2 c^4 \Psi(x, t) = -i\hbar \frac{\partial}{\partial t} \Psi(x, t)$$

This is the **Klein-Gordon Equation**. It has been shown to correctly predict the behavior of spin-less (spin-0) particles at all speeds. It was Paul Dirac who then recognized that spin had to be added to this equation in order to describe useful things like electrons.

In non-rel. QM, we treat spin as a separate property that we add to the wave function but which is not dealt with in the SWE. However, in the Dirac Equation, spin is directly included in the wave function from the beginning. This allows rel. QM to treat electrons at all speeds. The study of the Dirac Equation is in the domain of a future physics course, but we can discuss its implications.

The main difficulty with basing a relativistic matter wave equation on the **Klein-Gordon** equation is that energy appears *squared*, which means that negative energies are allowed by the equation. Either positive or negative energy solutions equally well satisfy this equation.

Another problem with the solutions to the **K-G** equation is that the probability density is not conserved over a volume - the particle can appear or disappear! It takes work, but you CAN form a probability density that doesn't change in time, but then a new problem arises: you can't interpret it as a probability density since it can be either a positive or a negative number.

A conspicuous feature here is that the probability density is correlated with the sign of the energy. Positive energy solutions correspond to one sign of the density, negative energy to the other. Instead, it was interpreted not as a probability density, but a CHARGE DENSITY, which can change sign. This led to an interpretation of the Dirac or **K-G** equations that then predicted the existence of antiparticles.

The charge density must be constant over all space and time, but its sign need not be positive. A negative energy solution, then, describes a charge density whose mass-properties are equal to those of the positive energy solution, but whose charge density sign is opposite that of the positive energy solution. This is an antiparticle.

One interpretation of this picture is to imagine that the universe is like a potential well with closely-spaced energy levels. An electron can only drop into a lower-energy state if one is vacant - a hole, or an "antiparticle". When the hole and the electron meet, energy is released - just like a light-emitting diode. The hole is a state of negative energy, and when the particle falls into it it ceases to participate in interactions (and the hole disappears) and light is emitted.

Another interpretation, which Harris doesn't discuss, is actually a more modern view of these states and was proposed by Stuckelberg and Feynman (in the 1940s). Free particle solutions have a time component that looks like:

$$\Psi(t) \propto e^{-i\omega t} = Ae^{-i(E/\hbar)t}$$

This state has total energy +E.

Imagine a positive energy particle - an electron - that instead of going forward in time goes backward in time:

$$\Psi(t) \propto e^{-i\omega t} = Ae^{-i(E/\hbar)(-t)}$$

Now you get a negative energy solution. This is the *Feynman-Stuckelberg* interpretation of negative energy states: as positive energy states traveling backward in time. This is not the only moment when the idea of "things going backward in time" appears in fundamental particle physics. In fact, time reversal is a common topic of investigation in particle physics.

## Forces and Particles: meet the families

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### The Forces

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In the modern picture, there are three independent forces that have been observed to act on fundamental particles:

- Gravitation
- Electroweak
- Strong

The Electroweak force is the unification of Electromagnetism and the Weak force at high energies, much like those believed to exist early in the universe (less than a millionth of a second after the big bang).

Electromagnetism was put into a fully relativistic quantum mechanical form in the 1940s and 1950s, and the theory is called Quantum Electrodynamics, or QED. "QED: The Strange Theory of Matter and Light" by Richard Feynman, is an interesting read to understand more about this theory. It has proven so-far resilient against all experimental tests, and makes predictions to ridiculous decimal places.

QED and the theory of the weak interactions were assembled into a single theoretical framework by Abdus Salam, Sheldon Glashow, and Steven Weinberg in the 1960s. This was only possible because of advanced mathematics and experiment that made it clear that fundamental forces obey SYMMETRY rules - that is, they behave in ways that can be described by the same math as rotations which leave a system invariant (except the rotations are not necessarily in space, but in other variables). This "Era of Symmetry" led to the recognition that QED and the weak force shared common bonds through symmetry, a symmetry which is broken (not respected) at low energy but as high energy becomes respected again. Particle accelerators capable of producing energies up to 1-2 hundred  $GeV$  were required to test these ideas.

For instance, the Electroweak theory predicted that the force is transmitted by four particles - the massless photon, and three massive bosons called the  $W^+$ ,  $W^-$ , and  $Z$ . Can you estimate the mass of these bosons?

### **Discussion: estimate the mass of the weak bosons**

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In Harris, Table 11.2 (pg. 478), the range of the weak nuclear force is listed as  $10^{-3}$  fm. This leads to a prediction that the masses of the weak bosons are around 100-200  $GeV/c^2$ . In 1983, and in years after that, the electroweak bosons were found and characterized, and their properties found to confirm the Electroweak Theory of Salam, Glashow, and Weinberg. This was a stunning triumph for theoretical physics.

What about the strong force? By the 1970s, many experiments had been carried out and demonstrated not only that protons and neutrons (and mesons and baryons) were made from quarks, but that these particles behaved in a mysterious way:

1. no experiment ever found a "free quark" - a quark not bound to other quarks
2. quarks only appears to come in bindings of 2 and three, and carried their own kind of "charge." This charge was called "Color," and comes in three kinds: red, green, and blue (and the "negative" versions: anti-red, anti-green, and anti-blue). They're not really colors, but the colors are a convenient handle for understanding their binding:
  - a. triplets of quarks - red, green, and blue - form a "white" state that is colorless, and thus carries no net color charge.
  - b. pairs of quarks are always a quark and an anti-quark - a color and anti-color. This is also "colorless," and carries no net color charge

3. quarks carry FRACTIONAL electric charge: either  $\pm 2/3$  or  $\pm 1/3$ . The proton, for instance, is two up quarks ( $+2/3 + +2/3$ ) and a down quark ( $-1/3$ ), for a total charge of  $+1$ . Neutrons are two downs and an up, for net zero charge. The only difference between a proton and a neutron is that one up quark is instead a down quark.
4. quarks appeared to be "confined" - that is, rather than falling off with distance, the strong force between them INCREASED in strength with distance

The strong force yields nuclear stability. Decay of states made from pairs or triplets of quarks are not favorable, given the strong binding of the force. What, then, allows for beta decay? How is it that a neutron ever becomes a proton? We'll discuss this more next time.

Can gluons be observed directly? They, too, cannot be freed from their strong bonds to quarks. However, the fact that they are such a perfect glue has implications, that allow us to predict phenomena. Discuss the phenomena of "jets".

The theory of the strong force is Quantum Chromodynamics, QCD, and was developed in the 1970s. Measuring quark masses is very difficult, since they are never alone and are constantly surrounded by clouds of gluons, "dressing" the quarks. Quark masses are estimates, based on combinations of theory and experiment.

Table of properties of the forces:

<b>Force</b>	<b>Carrier</b>	<b>Corresponding Charge (Kinds)</b>
Electromagnetism	Photon	Electric Charge (2)
Weak	Weak Bosons	Weak Hypercharge (2)
Strong	Gluons	Color (3)

## **Tools of the Trade: colliders and detectors**

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See slides for images of subatomic particles in particle detectors.