Don't Underestimate the Power of Virtual Particle Exchange

W. Blaine Dowler

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1 Unanswered Questions

Our collection of questions is impressive indeed:

1. The basic building blocks of matter, called elementary particles, must all have zero volume. What, then, prevents them from piling in so closely together that the matter they form does *not* have zero volume?
2. How does a nucleus hold itself together, if the electromagnetic force trying to push the protons apart is so much stronger than gravity, and gravity is the only attractive force we know of that applies?
3. Why aren't electrons ever found in a nucleus?
4. How does information about particle positions get exchanged between particles? That would seem to violate energy conservation.
5. How are new particles created? *Answer currently incomplete.*
6. What force(s) do neutrinos experience?
7. How do we know the Heisenberg Uncertainty Principle applies to particle existence, and not merely measurement?

The answers to many of these questions depend on a surprising aspect of the Heisenberg Uncertainty Principle.

2 Information Exchange

Recall from lesson one that the biggest issue with information transmission is formed in terms of energy conservation. To quote that lesson:

> If we have an electron orbiting a nucleus, then that electron "knows" of an opposing electrical charge in the nucleus. In other words, information about that charge has been received. In order to manage that, energy needs to be transmitted away from one or the other. Where does that energy come from? How much energy does each particle have to transmit? How does the transmitted energy get replenished? It cannot balance in a direct exchange between the two particles; if that happened, that could only mean that *every* transmitted piece of energy is exactly balanced by an incoming piece of information. This, in turn, would imply that *every* transmitted piece of information reaches a destination. That is only guaranteed if the information is *only* transmitted towards particles ready to receive that information. In that case, then the transmitting particle would *already* "know" where to find the receiving particles. This creates circular logic: in order to transmit information between two particles while conserving energy, information about the two particles must already be known to both particles.
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> Nonetheless, information *does* get exchanged between particles, and yet violations of energy conservation have never been observed in an experiment. This seems to be a logical inconsistency that will need to be sorted out.

The answer to this dilemma turns out to be stranger than anticipated. You may notice some very particular phrasing in the last paragraph: "... violations of energy conservation have never been observed in an experiment." As it turns out, violations of energy conservation occur constantly, but we'll *never* observe them.

3 Conservation of Energy

As discussed in the previous lesson, the Heisenberg Uncertainty Principle is not strictly a limitation on measurement, but it is an actual property of existence. The Universe is truly "uncertain" about details within the limits of this principle. In many ways, the "it's not cheating if you don't get caught" philosophy is ingrained in nature itself. Conservation laws can be bent (or even broken) provided the process is over and done with quickly enough to be unobservable.

Just as momentum and position are related by the Heisenberg Uncertainty Principle, so are energy and time. Deviations from conservation of energy can occur if the deviation stays for no more than a certain minimum amount of time. For example, say that $\Delta E \Delta t \geq 6$ describes the limits on what we can measure (in some appropriate set of units) with ΔE representing our uncertainty in energy and Δt representing our uncertainty in elapsed time. Then the Universe has a small Heisenberg "window" in which it can fiddle, defined by $\Delta E \Delta t < 6$. So, the universe can create a particle with 2 units of energy provided the particles lives for less than 3 units of time. Because this product of energy and time is less than 6, then we'd never be able to directly measure its existence due to the Heisenberg Uncertainty Principle, and the Universe could never be "caught" with this extra energy around. If that energy hasn't somehow hidden itself from sight within 3 units of time, it vanishes as though it never existed. In many ways, it never did. If, however, it somehow becomes unobservable before that time limit expires, it can stick around indefinitely.

This is the mechanism by which electron orbits in atoms operate. The energy "transmitted" between a nucleus and an electron exists in the Heisenberg Uncertainty Principle's unobservable region. Both the nucleus and the electron orbiting around it are constantly "broadcasting" this energy, but only the energy that reaches its destination is retained to be observed. Thus, the particles sharing their orbits do not "know" in advance where the other particles are, but the energy exchanged is still 100% efficient. An electron sends out the energy in a field around itself; the energy it loses to the nucleus is exactly balanced by the energy gained by the broadcasts coming from the nucleus. Meanwhile, the energy sent out that doesn't encounter another particle fades into nothingness, and can never be observed, and is therefore not really "lost" by the electron in the end.

So, what exact form does this energy take as it travels? We are used to classifying the world into two categories: particles, which are made out of "stuff," and waves, which are motions of particles. If you have ever dropped an object into a still body of water, you know that waves spread out in all directions.[1] If the broadcast energy was sent in such a wave form, it would also disperse in this fashion, and the energy would then have to find some way to redistribute itself when it encountered its target. Energy spread out over a given area would then have to suddenly rush to the point of contact, increasing the amount of time it spent subject to observation and making it less likely to escape Heisenberg limits. The alternative is much simpler: if the energy was sent in the form of a particle, then 100% of the energy would be carried in a point of zero volume, and would be delivered to the target simultaneously, minimizing the "exposure time" that it spends risking observation and nonexistence. Therefore, we can safely conclude that energy is transmitted in the form of short lived particles,

[1] If you have never dropped an object into a still body of water, go find something waterproof, fill up a bathtub and try it. Do it now; this lesson will be here when you get back.

and these particles mediate interactions between other particles, including all forces. We call these particles *virtual particles*.

This quantum mechanical picture of forces, with violations of conservation of energy that can never be observed, can be hard to stomach, particularly if you have already had a few years of physics instruction that drill conservation of energy into you to the point where you cannot imagine an alternative. The rest of this lesson will be spent studying this picture and showing how effectively it really does explain that which we see in the quantum mechanical world.

4 The Other Forces

We have already noticed that there must be other forces at work than the two we are familiar with. One force is that which holds the nucleus together; whatever it is, it must be stronger than the electromagnetic force that would push the protons apart. It must also be felt by neutrons, as they are part of the nucleus, but it does not affect electrons, which are never found in a nucleus. Moreover, it must have a limited range, because neighbouring nuclei do not fling themselves into each other overcoming the electromagnetic repulsion they experience from a distance. Similarly, the force which governs radioactive decay (which does involve electrons, and so must be a distinct force) also has a distance limit, since neighbouring nuclei have no influence over the decay of another nucleus. The first question we ask applies to both forces: what could limit the range of a force?

Our forces are mediated by virtual particles who are limited by a maximum value of $\Delta E \Delta t$. We also know that there is a maximum speed in the universe. Let us backtrack our observations and see where they lead:

- The forces in question have a limited range.
- If they have a limited range, the virtual particles mediating the force have a maximum distance they may travel. We have seen no limits on distances particles can travel, so we need to keep digging.
- With a maximum speed and a maximum range, the particle will have a maximum lifetime. We haven't seen any upper limit on the lifetime of a particle.[2] Again, we keep digging.

[2] Half lives come close to this, by predicting how long an unstable particle can stick around before decay becomes likely, but the random nature of radioactive decay means that there is no limit on an individual particle's lifetime. Thus, the force would be greatly weakened over distance if it used unstable particles, but it would not be completely cut out at a certain point as it actually is.

- If we have an upper limit on Δt, and we have a lower limit on the product $\Delta E \Delta t$, then we are forced to conclude that there is an lower limit on ΔE. In other words, if a particle's lifetime cannot be more than 2 units, and $\Delta E \Delta t$ cannot be less than 6 units, then ΔE cannot be less than 3 units.[3]

There is no reason to expect a minimum speed for virtual particles, or a minimum kinetic energy, so we are led to another seemingly inevitable conclusion: the particles mediating these two forces have mass.[4] By $E = mc^2$, if we use a virtual particle of a particular mass m, then any such virtual particle in nature must have at least mc^2 units of energy. That provides a lower limit on the energy of the created particle.

This conclusion is half right. The force governing radioactive decay, known as the weak nuclear force, (felt by neutrinos) uses mediating virtual particles[5] that have mass, and this mass is exactly enough to account for the range limit. The force that holds protons and neutrons together to form a nucleus, known as the strong nuclear force, is an entirely different beast altogether.

5 The Strong Nuclear Force

When researchers first looked for the particle that mediates the strong nuclear force, they expected a particle with mass to account for the limited range of the force. As the strong nuclear force appears to have a more limited range than the weak nuclear force,[6] it stood to reason that the mediating particle would have even greater mass than that which mediates the weak nuclear force.

The particle which mediates the strong nuclear force and glues the nucleus together, called the gluon, has no mass at all.

This appears to be a problem. The only explanation we have so far for the limited range of a force is a virtual particle with mass. Well, upon closer inspection, there is a property of virtual particles that is unique to the gluon.

The (as yet unobserved, and therefore technically theoretical) particle which mediates gravity, called the graviton, has no mass. This means that the graviton

[3] If $\Delta t = 2$ and $\Delta E = 1$, then $\Delta E \Delta t = 2$ which is below its lower limit.

[4] Conversely, the electromagnetic and gravitational forces must use massless virtual particles, as they do not seem to have any range limit at all.

[5] There are actually three particles that mediate this one, named W^+, W^- and Z^0, where the superscripts refer to their electric charges.

[6] The weak nuclear force can, on rare occasion, mediate interactions between electrons and the nuclei they orbit. On the other hand, protons and neutrons that slip into an atom as comparable distances from the nucleus as orbiting electrons do not experience a strong nuclear force.

itself does not feel a gravitational force. The photon, which mediates the electromagnetic force, has no electric charge, and does not feel the electromagnetic force itself. The gluon, however, *does* carry the charge for the strong nuclear force. This discovery gave researchers a lot of hope: a unique property of a particle means unique behaviour can be expected. They looked into how this property impacts the strength of the force over increasing distances, and found something similarly unique.

As you increase the distance between two particles attracted by the strong force, the gluons mediating the force between them start interacting with each other, creating even more virtual particles along the line separating the two particles. In short, the attractive force between them *increases*.

Suddenly, explaining why two neighbouring nuclei fail to attract each other is not nearly as difficult as explaining why the strong nuclear force fails to pull the Earth into the Sun with an acceleration that puts any amusement park to shame.

The Heisenberg Uncertainty Principle solves this problem, too. As you start to pull particles which feel this force apart, they pull against each other more strongly. It takes more energy to keep them apart. When they are far enough apart, the energy required to hold them apart becomes greater than the energy required to make new particles through $E = mc^2$. That's exactly what happens.

Virtual particles are created between our original two particles. There is enough potential energy between our original pair to account for the virtual particles, so they can become real, permanent, observable particles without violating conservation of energy, and so they do. Because the increased force between the original two particles is confined to the line connecting them, the original pair and the new pair break apart into smaller, enclosed "cells." This not only explains the range limit on the strong nuclear force, but it explains why we haven't seen exactly what makes up the internal structure of the protons and neutrons (which we have known was there since lesson two.) The particles protons and neutrons are made of, which are called quarks, are confined to small, complete groups. These groups form protons, neutrons, and less common, more exotic particles we will not discuss in these lessons.

This process works for many forces. The most common way for researchers to create new particles is to impart large amounts of kinetic energy to a small number of particles, and then collide these high energy particles into each other, providing the opportunity for this energy to convert into mass in the form of new particles.

6 A New Question

So, our new picture of forces involves the exchange of particles that only get anywhere if they reach their targets. We can almost picture this as though each particle carried around paddles with rubber balls tied to the middle by elastics. Higher energy balls have shorter elastics. If the ball is thrust from the particle without hitting anything, it comes back as though it had never left. If it does reach another particle, it collides, transfers its energy and momentum, and falls limp without returning to the paddle.

However, the particles carrying the balls and paddles, the balls themselves, and the particles that are getting hit by the balls all have zero volume. They are, in essence, impossibly small bullseyes to hit. How do they ever reach their targets?

7 Next Lesson

In our next lesson, we will look at the quantum mechanical behaviour of light itself, and in doing so, pave the way to delve more deeply into the properties of one of the new particles introduced in this lesson.