Tachyons today

Matthew Headrick: Pappalardo research highlight

Much of my work as a Pappalardo Fellow has involved some puzzles that arise in certain string theories because of a very peculiar type of particle, called a tachyon. Here I'll explain what a tachyon is and why it's important to solve these puzzles. Along the way we'll compare and contrast string theories with conventional particle theories.

I should first clarify that when I say "theory" here I mean an abstract mathematical construct, which is *physical* in the sense that it satisfies the basic rules of physics like quantum mechanics and special relativity, but is not necessarily intended to be an accurate description of the real world. Of course, ultimately our goal is to construct a string theory that describes the real world, but in order to do so we need to understand more about the mathematical properties of string theories.

What is the difference between a string theory and a conventional particle theory? Both kinds of theories describe particles and their interactions, but in the latter case the particles are the fundamental entities, whereas in the former case they are made of something more fundamental (the string). When constructing a conventional particle theory, the theorist is more or less free to decide what types of particles to include and what properties to endow them with, such as what their masses are, whether they are bosons or fermions, and how they interact with each other. For example, the theorist might include only electrons and photons, to make a simple theory called quantum electrodynamics (one of the first modern particle theories, developed in the 1940's). Or she could add neutrinos, quarks, gluons, W and Z bosons, and Higgs bosons, to make the Standard Model of particle physics (which was developed in the 1970's and describes all the particles and interactions that have been observed up to now, except for gravity). These are examples of *realistic* theories, meaning that they describe the real world (or at least aspects of it), but there are countless other theories one can construct that are equally mathematically consistent (and also satisfy basic physical requirements like quantum mechanics and special relativity). The framework of conventional particle theories is thus extremely flexible, which can be very useful to theorists. This permissiveness, however, means we have no hope of using such theories to explain *why* the real world has the particular types of particles present in the Standard Model, when some other combination seems equally allowed by the math: the Standard Model lacks *inevitability.* There is another problem with conventional particle theories: although we can include many different types of particles in a mathematically consistent theory, we cannot include gravitons. Since the graviton is the massless particle that carries the force of gravity (just as the photon carries the electromagnetic force), using a conventional particle theory to describe this important aspect of nature is unfortunately ruled out.

Like particle theories, string theories describe the world in terms of particles and their interactions; unlike in particle theories, however, these are derived concepts. Just as in the Standard Model neutrons and protons are made of more elementary constituents—quarks and gluons—in a string theory the particles are made of a more elementary constituent, a short segment or loop of string. The string is a one-dimensional object moving in space. It has a certain mass density and tension, but otherwise is endowed with (almost) no intrinsic properties. Its tension is so large that it can exist only in very short segments or loops, which are so small that they behave essentially like particles (just as protons and neutrons can be considered particles for many purposes, even though, being composite objects, they are not strictly points but occupy some space). A segment or loop can vibrate in certain ways dictated by the rules of quantum mechanics, and depending on how it vibrates, it behaves in different ways; in other words it behaves like a different type of particle. The properties of these particles—their masses and their interactions with each other—can be calculated from the string's properties.[1] The goal of string theorists is thus to *derive*, from a small set of assumptions about the string, all of the complicated and seemingly random properties of the particles observed in nature; this is the dream of unification. Furthermore, while the different string theories predict different sets of particles, all of them include a graviton.

So far so good. But here's the problem (or rather, one of the problems). In many cases, when we calculate the masses of the different particles in a string theory, we get a crazy answer for some of them. More precisely, we calculate the *square* of the mass of each particle. Normally, the mass-squared is a positive number (if the particle is massive, like an electron) or zero (if the particle is massless, like a photon or a graviton). In some cases, however, the mass-squared turns out to be negative! Such a particle is called a "tachyon". The name *tachyon* (derived from the Greek root "tachy-", meaning "swift") comes from the following observation. According to the equations of special relativity, massive particles must travel slower than the speed of light, while massless particles must travel at the speed of light. If we apply the same equations to a tachyon, we find that it must travel *faster* than the speed of light! Needless to say, no such particle has ever been observed in nature.

At this point you might be tempted to conclude that any string theory that predicts the existence of a tachyon must be incurably sick, and should be rejected. But consider this: many conventional particle theories also contain tachyons—including the venerable Standard Model! In fact, what really happens when a theory contains a tachyon has nothing to do with particles travelling faster than light or any such nonsense. What really happens is even weirder. For such a theory, the vacuum (the state with no particles present) is *unstable*. It will spontaneously decay. The way it decays is by *filling up* with tachyons, which are spontaneously created out of nothing. Whereas creating a massive or a massless particle requires energy, creating a tachyon actually releases energy. So the vacuum is *not* the state with the lowest energy—a state that is full of tachyons has a lower energy, and the vacuum will naturally evolve to such a state (left to their own devices, systems tend to relax to their lowest energy state). The Higgs particle of the Standard Model is in fact a tachyon, and it is believed that at a time very shortly after the Big Bang the universe filled up with these particles. This sea of Higgs particles is quite important, because according to the Standard Model it is responsible for giving masses to the quarks and electrons; in their "natural state" quarks and electrons are massless and move at the speed of light, but as they move around they interact with all those Higgses, slowing them down (just as light moving through a medium like water is slowed down by interacting with the atoms that make it up).

A collection of particles that are all in the same quantum state, such as the "sea of tachyons" described in the previous paragraph, is technically called a "condensate". Other examples of condensates include Bose-Einstein condensates of ultracold atoms (recently discovered by MIT

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[1] A disclaimer: The properties of the particles actually depend not just on the string's intrinsic properties, but also on the shape of the six extra dimensions that the string moves in (as I discussed in my Pappalardo Symposium lecture last May). Therefore different possible shapes should be considered as defining different string theories. Since many different shapes are allowed, even if one is found which gives rise to the observed particles of nature, it is not clear how much inevitability the resulting string theory will have.

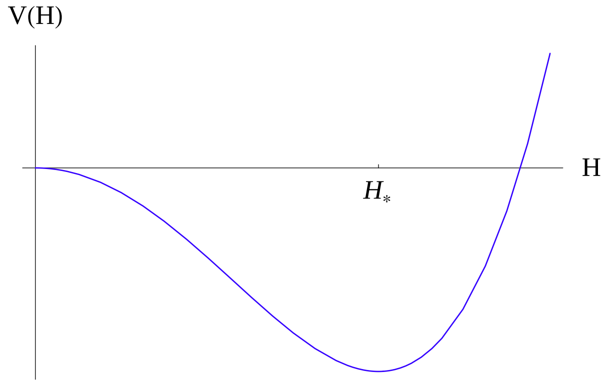

Figure 1: The potential energy density $V(H)$ as a function of the value of the Higgs field H. In the vacuum the Higgs field is zero, which as seen on the left-hand side of the plot is an unstable state. In the stable state the Higgs field takes the value H_* that minimizes its potential energy. This state is a condensate of Higgs particles.

professor Wolfgang Ketterle and others), and laser beams, which are condensates of a large number of photons. The example of the laser beam suggests another way to think about condensates of tachyons, in terms of a *field* rather than particles. I can describe a laser beam as "a condensate of photons", or equivalently as "a wave in the electomagnetic field". In fact, even a single photon is simply a very small (quantum) wave in the electromagnetic field. Two identical photons are a wave with twice the amplitude (i.e. carrying twice the energy). And a condensate of a large number of photons, as in a laser beam, is a wave with a macroscopically observable amplitude.

Let's get back to the tachyons, and the Higgs particles in particular. Just as photons are excitations of the electromagnetic field, the Higgs particles are excitations of the *Higgs field*. Whereas the electromagnetic field is made up of two vectors (the electric and magnetic fields), the Higgs field is made up of a collection of numbers—it doesn't point in any direction. For an anology, think of air pressure, which is a field in the sense that it is a physically measurable number which can vary from place to place. To simplify the discussion, we'll pretend that the Higgs field is a single number H that can vary from place to place. In the figure above, I've plotted the energy density $V(H)$ associated with the Higgs field as a function of H. It's pretty obvious from the picture that the vacuum, in which $H = 0$, is unstable, and that the field prefers to sit at the minimum $H = H_*$. This state is precisely the condensate of Higgs particles discussed above, but expressed in the language of fields rather than particles. So we are bathed not just in air pressure, but also in this Higgs field (which, unlike air pressure, is present and constant throughout the universe).

In a conventional particle theory, for every type of particle there is a corresponding field—in addition to the electromagnetic and Higgs fields, there are quark fields, an electron field, and so on. (In fact conventional particle theories are technically called "quantum field theories".) What about in a string theory? Are there "string fields"? Indeed there are, but they are mathematically far more complicated than conventional fields. MIT is one of the world leaders in the subject of string field theory, thanks to the work of professors Barton Zwiebach and Washington Taylor, as well as visiting professor Ashoke Sen.

Recall that there are two types of strings: segments and loops. In string jargon, segments are called "open strings" and loops "closed strings". It turns out that the string fields (and therefore the tachyons) corresponding to open strings are quite a bit more tractable than their closed string counterparts. Thanks largely to the work of the MIT professors mentioned above, the process of open string tachyon condensation is by now reasonably well understood, and it turns out to be basically a more complicated version of the Higgs phenomenon described above. On the other hand, closed string fields (and tachyons) involve some profound conceptual difficulties. To understand the difference, you need to know one simple fact: the graviton, which as I mentioned above appears in every string theory, is a closed string. The graviton's field (the gravitational field) is nothing more or less than the geometry of spacetime itself. A condensate of closed string tachyons—unlike a condensate of open strings—can excite its cousins the gravitons, potentially dramatically altering the shape—even the very existence—of spacetime. For this reason, closed string tachyons have been a source of fascination to me for many years now. They have also been a major theme of my work, which has succeeded in unravelling several "little puzzles" concerning them.

I hope I've convinced you that tachyons give rise to fascinating and important physical phenomena, and that unravelling these phenomena in the context of string theory is vital for fulfilling its promise.