The Higgs boson and the origin of the electron mass

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This year's Nobel prize in physics was awarded to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles [. . .]". The particle associated with the mechanism, the Higgs boson predicted in 1964, was discovered last year by the ATLAS and CMS experiments at CERN, Geneva. The idea that the elementary constituents of matter should acquire a mass "through their interaction with the Higgs field" is perhaps the hardest to fathom for non-physicists. In this article, I explain this aspect of the mechanism by using the particle-wave duality and by viewing the Higgs field as a dispersive medium.

Light propagating through a transparent medium

Waves of all kinds – waves on the sea, on a violin string, sound waves in the air – are disturbances which typically oscillate in time at a definite frequency. Light, too, is a wave. Most of us are familiar with the fact that sunlight is a superposition of all the colors of the rainbow. Each of its colors corresponds to a different frequency: blue is a higher frequency than green, which is a higher frequency than red.

Sound propagates faster in water or along an iron rail than through air. The speed at which light propagates in water, on the other hand, is smaller than in empty space by about 30 percent. In some substances, different colors of light travel at appreciably different velocities. A prism splits up the different colors composing white light into a beautiful rainbow pattern, due to this effect called dispersion – the fact that the velocity of light depends on its frequency.

Imagine a storm surge, a bulge of water moving on the surface of the sea; in the physics of waves, a localized disturbance traveling through space is called a wave packet. A wave packet of light, such as a flash, can be used to transmit a signal. The principle of special relativity that "no signal can propagate faster than the speed of light" implies that no wave packet can be transmitted through any medium faster than the speed of light in empty space.

The wave description of elementary particles

In the cathode ray tube of an old-fashioned TV set, electrons are shot like little bullets onto a fluorescent screen. It has been known since the 1920's, however, that electrons behave under certain circumstances like waves. One such circumstance is the double-slit experiment. Thomas Young had performed this experiment with light in 1803 and thereby largely settled a century-old scientific debate on its nature, establishing that light, as we experience it in everyday life, behaves like a wave rather than like a beam of miniature bullets. When light passes through two slits in a plate, it exhibits a series of minima and maxima of intensity on a screen placed behind the plate. The same experiment performed with electrons shows that they too form this pattern characteristic of waves.

This peculiar behavior of electrons was anticipated in 1923 by the Belgian physicist Louis de Broglie in a remarkable example of physical intuition. And he went further: he formulated a specific correspondence between the 'particle' properties of the electron and its 'wave' properties. In the wave description, the electron is represented by a wave packet. A broad wave packet may be characterized by a frequency and the speed at which it propagates, while the motion of a particle is characterized by its energy and velocity. The simplest way to state de Broglie's correspondence is that (a) the wave packet velocity is equal to the velocity of the particle, and (b) the frequency of the wave is proportional to the energy of the particle. The first point seems almost indispensable for the correspondence to make sense: if the particle is used to transmit a signal, the time it takes for the signal to arrive had better be the same in the wave description. As to the second point, it seems reasonable that a high frequency wave is more energetic than a low-frequency wave.

We learn at school that the energy of a truck is equal to half its mass times its speed squared. In order to discuss the origin of the electron mass, we will adopt as a definition of mass that it is a property which fully determines the relation between the electron's energy and its velocity. A massless object is characterized by the fact that it always moves at the speed of light through empty space, no matter what its energy is. The velocity of a massive object, however, is smaller than the speed of light and depends on its energy.

An electron propagating through a dispersive medium

As described above, the speed of a light signal is reduced inside a transparent medium, and this velocity depends, in general, on the frequency of light (dispersion). The medium is characterized by a 'refractive index', a function of the frequency that determines by how much the velocity of light of a given frequency is reduced. If a light ray traverses several substances on its path, the refractive index it is subjected to varies in space.

In general, a field is the assignment of a quantity to each point in space; it may also depend on time. The notion of field is ubiquitous in physics; the earth, for instance, is the source of a gravitational field and of a magnetic field. The refractive index, too, can be thought of as a field.

Imagine that an electron of a certain energy propagates through a region of space where a field – call it H – is present. We will describe the electron as a wave packet, which is characterized by the frequency corresponding to the electron's energy through de Broglie's correspondence. Suppose that the field H acts like a refractive index on the electron's wave packet[1]. The latter then travels through the field, for the same frequency, at a different speed than it would in empty space. If the electron is massless, it moves, in empty space, at the speed of light. When it enters the region of space where the field H is present,

[1]As an example that a de Broglie wave can experience a refractive index, the forward propagation of slow neutrons in water is well described in this way.

it must be slowed down, since nothing can travel faster than light. By analogy with the dispersion of light, the velocity of the electron's wave packet now depends on its frequency. Using de Broglie's correspondence reversely, we conclude that the speed of the electron in the medium H depends on its energy. In other words, in the region of space where the H field is present, the electron behaves as if it had mass.

If we imagine extending the region where the field H is present further and further, the electron eventually appears to have mass everywhere. We may as well describe it as a particle with mass from now on. Its mass, however, is now attributed to its interaction with a background field that permeates space.

The Higgs field and its elementary excitation

We have described a mechanism that 'gives' mass to elementary particles. So what has been gained? Why could the electron not simply have mass from the beginning? There is a specific, symmetry related reason why, in the theory of particle physics, it would be inconsistent to postulate an electron mass from the beginning - this aspect could be the subject of a different article. The idea that the origin of the electron mass lies in the interaction of the electron with a background field permeating space, on the other hand, is consistent in the Standard Model of particle physics. The latter theory successfully accounts for all the results obtained hitherto in particle collider experiments. Why then do some elementary particles have larger masses than others? It is because they interact more strongly with the H field. Their mass is proportional to the interaction strength.

However, even before we discuss the necessity of this new mechanism to generate mass, we could ask, is there any new phenomenon that this mechanism implies? The observation or non-observation of this phenomenon would then allow us to distinguish experimentally between a description where the electron simply 'has' mass from the beginning and the description where the mass 'emerges' from its interaction with a background field. As a matter of fact, there is a new phenomenon. Once we introduce a new field (H), we must accept that it may have its own space and time dependence. If we think of the background field H as the surface of the sea on a windless day, the field can be 'excited' so as to exhibit waves of different amplitude and wavelength. At low amplitude however, just as light manifests itself in discrete energy packets called photons, the excitations of the H field are quantized. They can be created in a high-energy collider experiment, where they show up as particles. You may have guessed by now that the field H is the Higgs field, whose elementary excitation is the Higgs boson recently discovered at CERN's Large Hadron Collider.

There is a further prediction that follows from the mass-generating mechanism first described by Brout, Englert and Higgs in 1964: if more massive particles interact more strongly with the Higgs field, they must correspondingly interact more strongly with the Higgs boson. This implies that the short-lived Higgs boson decays much more often into heavy matter particles than into light ones. This, and all the other properties of the Higgs boson predicted by the Standard Model of particle physics, are consistent with the experimental results to date.