Experiments to detect Higgs bosons

24 May 2010

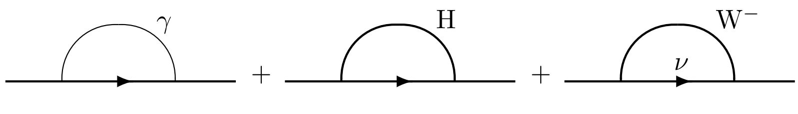
Theoretical physicists have for some time predicted the existence of a spinless elementary particle, the so-called Higgs boson, which they suggest should have a very high mass. To date, experimentalists trying to verify this prediction have failed to observe any spinless elementary particles.

A way of trying to refute the prediction that the Higgs particle should be heavy would be to systematically search for it in the low end of the mass spectrum. Surprisingly, it appears that no such search has been seriously attempted.

A new theoretical prediction of a "flyweight" Higgs boson should inspire experimentalists to fine-comb the low parts of the mass spectrum for a spinless neutral elementary particle.

Calculations in standard model (SM) theory

In pure QED theory, the lepton mass m (with m standing for m_e, m_μ, or m_τ) derives from virtual photons. In electroweak theory, this QED mass is corrected downward by virtual Higgs bosons and again slightly upward by virtual neutrinos appearing in lepton self-mass diagrams. That is, the lepton's mass is a sum of three terms, $m = m(\gamma) + m(H) + m(\nu)$, with $m(H) < 0$.



The figure shows the Feynman diagrams that to lowest (second) order contribute to the lepton's mass: $\delta m^{(2)} = \delta m^{(2)}(\gamma) + \delta m^{(2)}(H) + \delta m^{(2)}(\nu)$.

Application of standard electroweak theory gives for the sum of the first two terms the expression

$$\delta m^{(2)}(\gamma) + \delta m^{(2)}(H) = \frac{3}{2}\left(\frac{\alpha}{\pi}\right)\ln\frac{\Lambda}{m}\left[1 - \frac{G_F(mc^2)^2/(\hbar c)^3}{4\sqrt{2}\pi\alpha}\right]m, \tag{1}$$

where Λ is a UV cutoff mass. In elementary-particle perturbation theory (PT), the Higgs diagrams exactly parallel the photon diagrams. Therefore, one may expect that the ratio between the Higgs and photon contributions to the lepton mass should remain the same as in Eq. (1) also when higher-order diagrams are considered. In other words,

$$\frac{m(H)}{m(\gamma)} = -\frac{G_F(mc^2)^2/(\hbar c)^3}{4\sqrt{2}\pi\alpha} \tag{2}$$

should hold exactly.

Since the Higgs and neutrino corrections are small in comparison with the photon's contribution to the lepton mass, one may set $m(\gamma)$ equal to m in the denominator of Eq. (2). This gives

$$m(H) = -(4\sqrt{2}\pi\alpha)^{-1} G_F (\hbar c)^{-3} (mc^2)^2 m \tag{3}$$

for the contribution of the Higgs boson to the lepton mass.

What the extended standard model (xSM) predicts

For the standard model of particle physics (SM) to be logically consistent, the existence of a massive Higgs boson is a prerequisite. However, SM says nothing about the actual mass of the particle.

Still, cosmological considerations have led physicists to assume that the Higgs boson might be even heavier than the charged W and neutral Z bosons, which have masses of about 80 and 91 GeV/c^2, respectively (see table on page 20).

Recently, however, there has been an attempt to merge cosmology with SM. The result is an extended standard model of particle physics (xSM) that adds a previously missing piece to the established standard particle model.

The prediction of this complemented standard theory is straightforward and unambiguous: the Higgs mass equals the (negative) Higgs correction to the lepton's self-mass. In other words, xSM predicts

$$m_H = (4\sqrt{2}\pi\alpha)^{-1} G_F (\hbar c)^{-3} (mc^2)^2 m \tag{4}$$

for the Higgs mass. As indicated previously, m represents the lepton mass of m_e, m_μ, or m_τ, and m_H is the corresponding Higgs mass associated with each type of lepton.

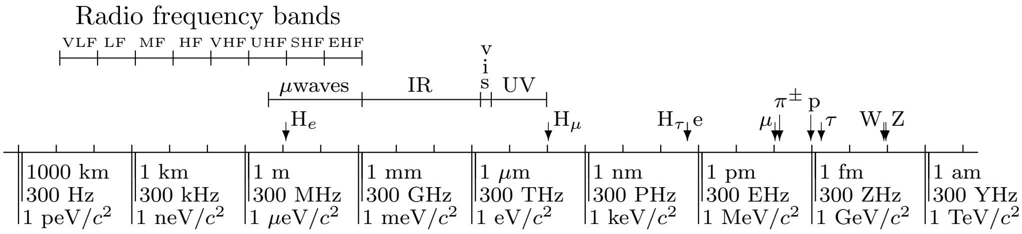
Predicted values for the Higgs mass

Using the values on page 20, the Higgs mass (m_H) may be calculated from Eq. (4). For a Higgs boson emitted by an electron, muon, and tauon, respectively, one obtains (see, however, page 19)

$m_{H_e}/m_e = 2.348\ 476(20)\times10^{-11}$	$m_{H_e} = 12.000\ 69(10)\ \mu\text{eV}/c^2$	$\nu_{H_e} = 2.901\ 753(25)\times10^{9}\ \text{s}^{-1}$
$m_{H_\mu}/m_\mu = 1.004\ 047(9)\times10^{-6}$	$m_{H_\mu} = 106.0859(9)\ \text{eV}/c^2$	$\nu_{H_\mu} = 2.565\ 147(22)\times10^{16}\ \text{s}^{-1}$
$m_{H_\tau}/m_\tau = 2.8400(6)\times10^{-4}$	$m_{H_\tau} = 0.504\ 67(14)\ \text{MeV}/c^2$	$\nu_{H_\tau} = 1.220\ 28(34)\times10^{20}\ \text{s}^{-1}$

A photon possessing the same energy as a Higgs boson at rest has frequency $\nu = m_H c^2/h$. This photon frequency is shown in the third column above.

The figure indicates the masses of the predicted Higgs boson (H_e, H_μ, or H_τ) relative to the masses of the charged leptons (e, μ, and τ), the charged and neutral weakly interacting spin-1 bosons (W and Z), and the charged pion and proton ($\pi^\pm$ and p), which are composite particles built from two and three quarks, respectively.



The mass spectrum in the figure covers the range between 10^{-12} eV/c^2 or 1 peV/c^2 and 10^{12} eV/c^2 or 1 TeV/c^2 and also indicates wavelength and frequency of photons possessing energies corresponding to rest energies of massive particles.

Note the customary abbreviations VLF = very low frequency, M = medium, H = high, U = ultra, S = super, and E = extremely and the prefixes atto, femto, pico, nano, micro, milli, kilo, mega, giga, tera, peta, exa, zetta, and yotta.

Experimental detection of Higgs bosons

One may object that, if the "flyweight" Higgs boson predicted by xSM existed, it would have been observed long ago. However, arguing in this way means ignoring the fact that very light—nearly massless—neutral spin-0 bosons are difficult to distinguish from exactly massless neutral spin-1 bosons (that is, photons). Also, it's a fact that there exist several puzzling physical phenomena that may be naturally explained by the appearance of (virtual) light Higgs bosons—that is, it appears that in various ways the Higgs boson has already revealed its existence to experimental physicists. For a comparison between photons and Higgs bosons, see page 18.

It might be possible to very accurately measure the three Higgs masses (see Experiment 5 below). Even the same 0.025 ppm precision that already has been obtained for $\hbar$, $m_e c^2$, and m_μ/m_e is conceivable. By first accurately measuring m_{H_e}, one would obtain precise values for $G_F/(\hbar c)^3$ and G_F. Next, a precision measurement of m_{H_μ} should give an independent check of the m_μ/m_e value. Finally, measurement of m_{H_τ} should yield a precise prediction for the tauon mass (or m_τ/m_μ).

Photon and Higgs optics—statements and questions (S&Q)

The electron's interaction with the Higgs is similar to its interaction with the photon. Apart from being weaker, the former interaction only differs from the latter in that its theoretical description is simpler because it does not involve polarization (see page 18).

Consequently, the theory of quantum electrodynamics (QED), which is used to calculate the interaction of electrons, muons, and tauons (the charged leptons) with the photon, may be used to calculate their interaction with the Higgs, too. Provided that the mass of the Higgs is known, these calculations will lead to precise predictions about how Higgs particles behave in various substances. Therefore, in the xSM theory with its precisely determined Higgs mass, the behavior of Higgs in matter is unambiguously predictable.

As with predicting the photon's behavior in a given material, the difficulty in predicting the behavior of the Higgs lies in understanding the atomic and molecular structure of the material. It should be a straightforward task for experts in optics and solid state physics to generalize their equations to include Higgs bosons.

In summary, the details of phenomena involving Higgs particles are predictable, and theoretical physicists should be able to (when called for) correct or improve on the statements and answer the questions (see boldface numbers) that follow:

1. The Higgs boson possesses no intrinsic angular momentum—neither spin nor orbital angular momentum. That is, it has no polarization.

2. A free photon always carries nonzero total angular momentum (see page 18). That is, unlike the Higgs, it possesses polarization.

3. A free photon travels with the speed of light (c).

4. For a free photon, the relation

$$E = pc = hc/\lambda = h\nu \tag{5}$$

holds between energy (E), momentum (p), wavelength (λ), and frequency (ν).

5. Note the correspondence between the photon wavelength $\lambda = h/p$ (where h is the Planck constant) and the wavelength

$$\lambda = h/p = (h/mv)(1 - v^2/c^2)^{1/2} \tag{6}$$

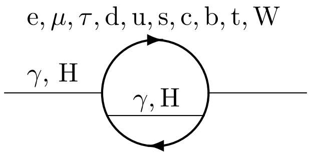
of a massive particle with mass m and velocity v (see, for instance, *Wikipedia* on "matter wave").

6. In general, the momentum and energy of a free particle are related through the equation

$$(pc)^2 = E^2 - (mc^2)^2, \tag{7}$$

which may be obtained by eliminating v from the pair of equations $E = mc^2(1 - v^2/c^2)^{-1/2}$ and $p = mv(1 - v^2/c^2)^{-1/2}$.

[The photon and the Higgs may form short-lived vacuum-polarization loops consisting of a charged particle and its antiparticle. These particles, in turn, may emit and recapture other particles, including the neutral gluons, neutrino, and Z boson. Thus, all types of elementary particles appear in the so-called photon propagator:



For these particles—and for virtual particles in general—Eq. (7) is not satisfied. Virtual particles come with all conceivable energies and momenta—between plus infinity and minus infinity—with only the restriction that four momentum (that is, energy E and the components of the momentum three vector $\boldsymbol{p}$, which together form the momentum four vector) must be conserved in every vertex of the Feynman diagram. It should be noted that, even if many massive particles appear in the photon propagator, they do not give the photon mass and so do not affect the speed of the photon.]

7. A photon moving in a transparent medium is repeatedly absorbed and reemitted by electrons.

8. The time delay between absorption and reemission of photons causes a light ray to travel slower than c in a transparent substance.

9. In general, transparent substances slow down light more at high frequencies than at low frequencies.

10. Therefore, a glass prism deviates blue light more than red light.

11. Ionized mediums slow radio waves more at low frequencies than at high frequencies.

12. Therefore, high-frequency radio waves (microwaves) that can penetrate the ionosphere are used to communicate with satellites and spacecraft.

13. The color (or wavelength λ) of light passing through a transparent substance does not change, which means that photon energy is conserved according to Eq. (5).

14. Similarly, the magnitude p of the momentum vector $\boldsymbol{p}$ is conserved (however, the vector $\boldsymbol{p}$ is not conserved because light rays may undergo both refraction and reflection, that is, change direction in a variety of ways).

15. The type or degree of polarization of light passing through a transparent material is conserved (however, the plane of polarization is not always conserved—optically active materials may rotate it in various ways).

16. Evidently, this conservation of polarization means that a photon passing through a transparent medium such as air or glass cannot transform into a (spinless or polarization-free) Higgs boson.

17. In contrast, conservation of polarization should not prevent a Higgs particle from annihilating in a medium because the Higgs may transform into two photons having opposite polarizations.

18. Does this fact imply that a Higgs traveling in a material at its first encounter with an electron almost inevitably will annihilate into electromagnetic radiation of about half the frequency of the Higgs radiation**?**

19. Or, is a medium that is transparent to photons of a given wavelength also transparent to Higgs bosons of the same wavelength (compare with Eq. (6))**?**

20. Are substances that are opaque to photons of a given wavelength also opaque to Higgs bosons of the same wavelength**?**

21. Blue light shining on a white paper colors the paper blue. This means that the energy of photons reflected from white paper is conserved.

22. Are there substances for which this rule does not hold (which, say, look yellow when they are illuminated with blue light)**?**

23. When a photon is reflected by white paper, is its type or degree of polarization conserved**?**

24. If it is conserved, are there other—more or less exotic—"white" substances which (in an arbitrary way) change the polarization of the photons it reflects (thereby sometimes transforming photons into Higgs bosons)**?**

25. Black materials absorb most of the light hitting them and turn it into heat. That is, the electrons in these materials absorb visible light and emit less energetic photons that give the molecules a higher kinetic energy. Similarly, black materials should absorb Higgs radiation and turn it into heat.

26. Does the Higgs color or blacken photographic film in the same way as photons do**?**

27. Or, does it first split into two photons (each of about half the energy of the Higgs, see S&Q 18), which may be registered on IR-sensitive film**?**

28. Because the Higgs interacts much more weakly with electrons than the photon does, it should penetrate deeper into opaque materials than photons do.

29. How big is this difference (which is expected to be material dependent, maybe small for metals and large for some other materials)**?**

30. Processes which produce photons with energy above the Higgs rest energy and with all kinds of polarization, produce Higgs bosons as well.

31. Thus, the hot filament of an incandescent light source (an electric bulb, say) should emit Higgs bosons in a broad range of frequencies.

32. What is the the ratio between the number of Higgs bosons and the number of photons emitted by the filament in an electric lamp (the discussion on page 18 suggests it lies in the vicinity of $1.04\, m_e/M_W \approx 6.6 \times 10^{-6}$)**?**

33. How does this ratio vary with energy or frequency**?**

34. A photon traveling in a transparent substance is not free. According to quantum theory, it simultaneously takes all possible paths through the substance and exits as a free photon with its direction of motion being determined by a kind of probability summation over all its paths (see Richard P. Feynman, *QED: The Strange Theory of Light and Matter*, 1985).

[This is how the behavior of photons and other elementary particles are commonly pictured in SM. Often, it is stated that these quantum phenomena are counterintuitive and impossible to understand via logical reasoning. According to xSM, however, this behavior of microscopic particles is nothing but an inevitable consequence of the fact that space, being perfectly smooth, provides no coordinate system (no coordinate points, no south or north direction) through which particles might be positioned or located in space. As long as a particle (or a system of interacting or entangled particles) hasn't been registered—and its position thereby defined—by a measuring instrument (a macroscopic assembly defining a macroscopic coordinate system), it is, in a way, "both anywhere and nowhere" from a macroscopic observer's point of view. Add to this observation the experimentally well-established fact that identical elementary particles are indistinguishable from—and exchangeable with—each other, and the conclusion can only be that the path-integral formalism of quantum theory is both logical and perfectly intuitive.]

35. Conservation of four momentum (that is, the simultaneous conservation of energy and momentum) forbids a free (massless) photon from transforming into a free (massive) Higgs boson (or even into a free Higgs-photon pair).

36. Virtual particles (particles "off mass-shell" for which energy and momentum do not obey Eq. (7)) suffer no such limitations. Therefore, a free photon that is absorbed by a charged particle (electron or quark, say) could be transmitted to a neighboring charged particle in the form of a virtual Higgs if it were not for the mismatching polarizations of the photon and the Higgs (the Higgs being, by its very nature as a spinless particle, forced to always stay in a state of zero angular momentum or no polarization, while the real photon because of its lack of rest mass is forbidden to exist in such a state).

37. Thus, conservation of polarization prevents the photon from occasionally transforming into a Higgs during its journey through a transparent substance. That is, from jumping in the shape of a Higgs from one charged particle to the next in the substance.

38. Still, nothing prevents the real photon from occasionally performing one of its jumps from one charged particle to another in the form of a particle pair consisting of a virtual Higgs (a Higgs boson not satisfying Eq. (7)) and a virtual photon.

39. Consequently, the photon takes on the shape of a virtual Higgs-photon pair during part of the time it spends in a transparent material.

40. Since massive particles move with a speed that is less than c, the appearance of the Higgs boson in the photon trajectory implies a further slowing down of the signal's actual speed of travel in a transparent substance.

41. This effect is very small for visible light because at corresponding energies the speed

of the Higgs is very close to c.

42. In contrast, for microwave photons of energy slightly below the Higgs rest energy, the effect should be readily observable.

43. Quarks have a higher probability than electrons for emitting Higgs bosons (see Martinus Veltman's *Diagrammatica*, pp. 270 and 271). Therefore, microwave photons traveling long distances in a plasma consisting of protons and electrons—such as the interplanetary plasma of the solar wind—should experience an easily observable extra delay caused by the occasional splitting of free photons into short-lived virtual Higgs-photon pairs.

44. How is Higgs radiation refracted by a prism**?** May glass prisms or prisms made from other materials be used to separate Higgs radiation from photon radiation**?**

45. Klystrons, magnetrons, and masers are used to generate microwaves. What other devices or methods are there**?**

46. Are there microwave transmitters that, sending at a given frequency, produce Higgs bosons having the same energy as the photons (and therefore lower momentum and, according to Eqs. (5) and (6), longer wavelength and lower frequency than the electromagnetic radiation)**?**

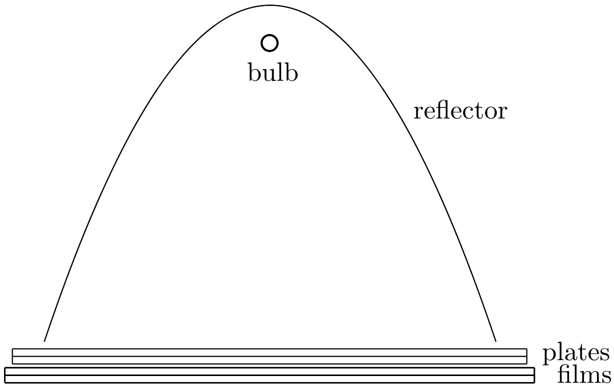
47. Are there microwave transmitters that, sending at a given frequency, produce Higgs radiation of the same frequency**?**

48. The Higgs may spontaneously split into two photons via a virtual lepton loop. What is the lifetime of the electron, muon, and tauon Higgs, respectively**?**

Experiment 1. Missing energy

Suppose that a microwave source emits photons of adjustable energy (or frequency) and Higgs bosons of the same energy (if the energy equals or exceeds the threshold value for Higgs production). Further, suppose that, before it is picked up by a receiver, the transmitted signal passes through a medium that is transparent to photons but opaque to Higgs bosons. If the frequency of the signal is gradually increased from, say, an initial 2.9017 GHz, one would expect a small discontinuity to occur in the received signal when the frequency passes the threshold for production of real (free) Higgs bosons. Below the threshold, all of the transmitter's output effect goes to production of photons. If above the threshold, one out of a million particles emitted is a Higgs boson, there should be an anomalous one ppm decrease in energy of the received signal.

Experiment 2. Depth of penetration



Assume that a nearly opaque black plate lets one percent of the light hitting it pass through. Assume that the same holds for a photographic film.

1. Place two black plates between the bulb and the film (letting 100 ppm of light through). Use two layers of film. Adjust the time of exposure so that the second film is slightly blackened. Say that the exposure time is 1 ms.

2. Repeat the experiment using three black plates and an exposure time of 100 ms. The two films should blacken in the same proportions as in step 1.

3. Add one more black plate and increase the time of exposure by a factor of 100 (resulting in an exposure of ten seconds).

Repeat step 3 until there is a change in the proportion of blackening of the two films.

At a given point, practically all photons will be absorbed in the plates while a substantial portion of the much rarer—and much more weakly-interacting—Higgs bosons would still be able to pass through them. This should mean that, when compared with the first film, the second film is blacker than before (because the first film should now let more than one percent of the particles (the sum of Higgs particles plus photons) pass through it).

As an illustration, assume that the Higgs on average penetrates ten times deeper into the black plates than the photon does. Further, assume that one Higgs is emitted for every million photons. Then, for every 10^{18} photons emitted, 10^{18} photons and 10^{12} Higgs bosons should reach the first film if there are no black plates. With seven plates, 10^{4} photons and 10^{5} Higgs bosons should reach it, while 10^{2} photons and 10^{4} Higgs bosons should reach the second film.

Discussion

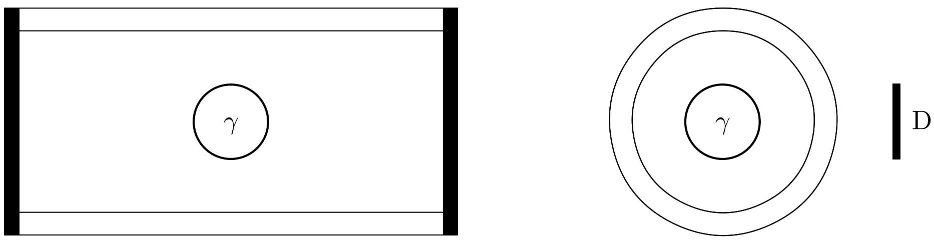
The experiment would fail: if (1) the bulb's hot filament emits no or very few Higgs bosons, (2) the Higgs particles cause no reaction in the film, or (3) there only is a small difference in depth of penetration of the two types of particles.

For the case that air or the bulb's glass or gases are opaque to Higgs particles (S&Q 18), the glass of the bulb should be removed and the region within the reflector evacuated.

In a practical experiment, the black plates might, for instance, be replaced by a metal, graphite, or other coating applied directly on the film. Also, a single sheet of film might be used and the distribution of the radiation's depth of penetration into it examined with the help of a microscope.

A successful experiment might require the use of IR-sensitive film (S&Q 27). However, after its splitting into two photons, a UV Higgs may reappear as visible light.

Experiment 3. Higgs-induced secondary microwave radiation



A hollow glass cylinder is sealed at its ends by metal plates. The inner surface of the cylinder's glass wall is coated with a thin layer of metal. A photon source in the middle of the cylinder may emit microwave radiation of two different frequencies, 2.8 GHz and 3.0 GHz, say. The cylinder is evacuated to almost total vacuum. The metal layer should be thick enough to prevent photons from penetrating into the glass wall, but thin enough for a substantial portion of possibly appearing Higgs bosons to pass through it.

If Higgs bosons are produced, part of them should be trapped by electrons in the glass and reemitted as secondary photon radiation hitting the detector D. The threshold frequency above which Higgs bosons are predicted to show up is $\nu_{H_e} = 2.901\ 753(25)$ GHz. See, however, discussion below.

The photon source may be a magnetron similar to the type used in microwave ovens. However, standard microwave ovens operate at a frequency of 2.45 GHz (wavelength 12.24 cm), which is below the treshold frequency (but see discussion below). Possibly, the detector may be an ordinary leakage tester. It should be sensitive to microwaves of half the original frequency (S&Q 18). Preferably, the experiment should be performed in a so-called Faraday cage to ensure that the result of the experiment is not corrupted by background radiation.

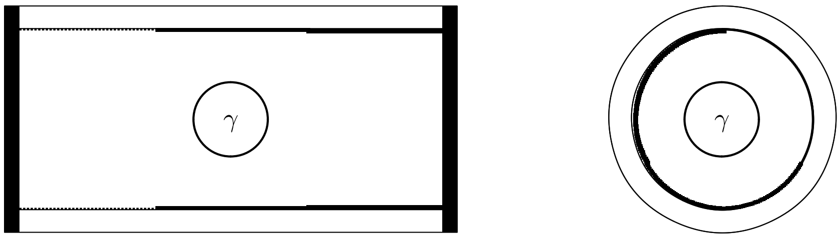
Discussion

For the experiment to succeed, the photon source must be capable of emitting spinless particles. One would expect an emitter that produces randomly polarized photons to also produce (spinless) Higgs particles.

A question is how the photon source functions. If, instead of having the same energy, the Higgs bosons and the photons produced by the transmitter have the same frequency, Higgs radiation will be produced also for frequencies below the mentioned “threshold frequency” (see S&Q 47).

Another question concerns the opacity of glass to Higgs radiation. If it is transparent to the Higgs, maybe some other material may be found that is opaque to the Higgs while being transparent to the photon. See S&Q 19.

Experiment 4. Higgs-induced secondary light emission



A hollow glass cylinder is sealed at its ends by reflecting metal plates. The inner surface of the cylinder’s glass wall is coated with a thin layer of metal paint that prevents light from reaching the glass. The metal may vary in thickness as indicated left (with thickness greatly exaggerated). The metal coating, in turn, is painted white. The white paint may vary from thin semitransparent to thick opaque as indicated right (again with thickness greatly exaggerated).

A photon source—such as an incandescent light source in the form of an ordinary electric bulb—in the middle of the cylinder emits visible light.

Since white paint is a substance that reemits photons with a variety of polarizations, one expects that some of the photons hitting it should be reemitted as Higgs bosons. Part of these Higgs particles would penetrate the metal and be absorbed in the glass cylinder, where they should produce heat and hopefully some secondary light. This light might be detected by photomultipliers or a light-sensitive film wrapped around the glass cylinder.

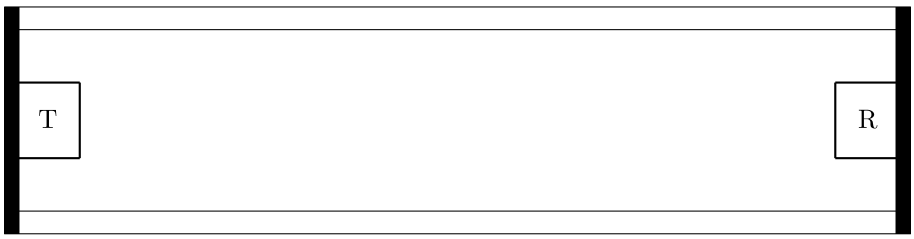
Since the probability for a Higgs created in the white paint to reach the glass depends on the thickness of both the metal and the white paint, the pattern formed by the light hitting the detectors should tell if the light (or part of it) is caused by Higgs bosons. Consequently, a single experiment should reveal the existence of Higgs bosons, provided they are produced in sufficiently large numbers.

Discussion

This experiment should work also in the case that air or the bulb’s glass or gases are opaque to Higgs particles. However, the assumptions that white paint may emit Higgs bosons and that glass is opaque to them may be wrong. See S&Q 19 and 24.

If Higgs bosons are very rarely produced in the experiment, background noise should be minimized. This may be achieved by performing the experiment deep underground in water tanks designed to detect neutrinos. (Keywords: *Super-Kamiokande* and *Cherenkov light* or *Cerenkov light*)

Experiment 5. Higgs speed in vacuum



A transmitter (T) placed at one end of an evacuated tube emits microwaves that are recorded by a receiver (R) at the other end of the tube. If L is the distance between transmitter and receiver, the travel time of the photons is $t = L/c$. For instance, a distance of $L = 1$ m is traversed by the signal in $299\ 792\ 458^{-1}$ s = 3.34 ns.

The threshold frequency for Higgs production is predicted to be $\nu_H = 2.901\ 753(25)$ GHz. Higgs bosons produced at this photon frequency have no kinetic energy and their total energy equals their rest energy, $m_H c^2$. If the frequency of the transmitter is $\nu = k\,\nu_H$, the Higgs has a total energy of $E_H = k\,m_H c^2$, and its velocity may be obtained from the relation $E = k\,m_H c^2 = m_H c^2(1 - v^2/c^2)^{-1/2}$. Solving this equation for v gives

$$v = (1 - k^{-2})^{1/2} c, \quad k \geq 1. \tag{8}$$

Imagine that in reality the threshold frequency happens to be exactly 2.901 754 GHz. If the frequency of the transmitter is chosen to be precisely $\nu = 2.901\ 764$ GHz, one obtains $k = \nu/\nu_H$ $= 2.901\ 764/2.901\ 754 = 1.000\ 003\ 446\ 19$ and $v = 0.002\ 625\ 328\,c$, which means that the Higgs bosons travel a distance of $L = 1$ m in 1270.56 ns. In other words, the second pulse carried by Higgs particles reaches the detector $\Delta t = 1267.22$ ns later than the first arriving photon pulse.

Conversely, when the frequency of the transmitter is known, and the time delay Δt has been measured, the speed v and the mass m_H of the Higgs boson may be calculated.

Discussion

If the microwave transmitter produces photons and Higgs bosons of identical frequency (see S&Q 47), the Higgs mass is related to its velocity via

$$mc^2 = h\nu(v/c)^{-1}(1 - v^2/c^2)^{1/2}, \tag{9}$$

which follows from Eq. (6) with $\lambda = c/\nu$.

For example, assume that the magnetron of a standard microwave oven is used as the source and emits Higgs bosons and photons of the standard frequency 2.45 GHz (which corresponds to a wavelength of 122 mm). Further, assume that over a distance of $L = 1$ km, a difference in travel time of $t_2 - t_1 = 1.8349$ μs is observed between photon pulse and Higgs pulse. With $t_1 = L/c$ and $t_2 = L/v$, one obtains $v/c = L/(L + c(t_2 - t_1)) = 0.645\ 124\ 172$. Using this value, together with 2.45×10^9 s^{-1} for ν, one finds from Eq. (9) that $mc^2 = 12.000\ 682$ μeV.

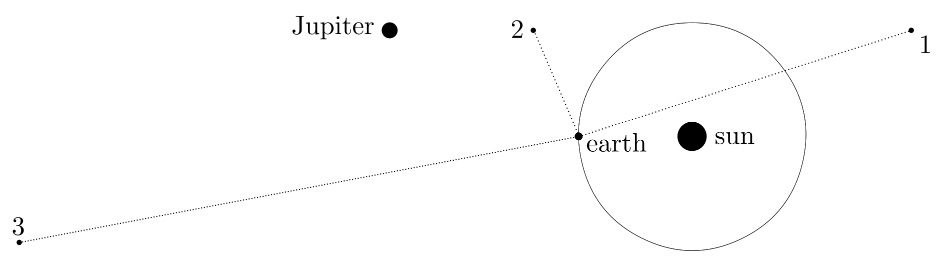
The photon threshold frequency ($2.565\ 148(22)\times10^{16}$ s^{-1} or 25 651 THz) for production of muon-type Higgs lies in the far end of the UV region (visible light ranges between roughly 400 THz and 800 THz). Since muon and tauon-type Higgs bosons cannot be emitted by electrons, they might instead be produced via bombardment of protons (e.g., hydrogen nuclei) with photons.

Experiment 6. Systematic search for light Higgs bosons

The xSM theory predicts that the Higgs boson comes in three distinct masses. Even if these masses are found by experiments to have the theoretically predicted values, it does not prove that the theory is correct because these experimental results do not exclude the possibility that the Higgs boson may come in more than three masses. To check that this is not so, an extensive search through all the accessible parts of the mass spectrum should be done. See figure on page 3.

For low frequencies, the experiment may be similar to Experiment 5, but with the difference that the frequency of the photon transmitter is variable. Between the emission of each pulse, the frequency may be shifted upward a step of, say, $\Delta\nu = 0.000\ 01$ GHz. With a time delay of $\Delta t = 1$ ms between each pulse, one might, for instance, comb out the interval between 3 GHz and 4 GHz in 100 seconds.

Experiment 7. Signal speed in plasma: the Pioneer anomaly



To test the hypothesis that microwaves experience a small frequency-dependent retardation when they travel through the solar plasma, equip a spacecraft with a microwave transmitter capable of simultaneously sending two short pulses of different frequencies that may be chosen from a set of at least three available frequencies (for instance 2, 4, and 8 GHz) and measure the time difference between the arrivals of the two pulses.

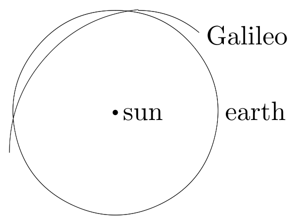
Note that in communications with spacecraft, one doesn't measure the speed of the radio signals. This means that the signals in a way "calibrate the speed of light" when the spacecraft are near the earth—in positions 1 or 2, say. That is, one implicitly uses a value for c that is slightly less than the true (and exact) value 299 792 458 m/s. When a spacecraft (in position 3) leaves the solar system and the signal speed (because of decreasing plasma density) increases and tends toward the speed of light in vacuum, it affects the computations of the spacecraft's speed and position in the same way as if c increased past the value 299 792 458 m/s.

Therefore, signals returned from the spacecraft arrive a little earlier than expected, which is taken to mean that the spacecraft is a little less distant than it should be, and that it, consequently, experiences a slight anomalous acceleration toward the sun.

Consequently, the flyweight Higgs provides a simple, natural, and easily testable explanation for the so-called Pioneer anomaly.

Experiment 8. Signal speed in plasma: the flyby anomaly

The figure shows schematically the trajectory of the Galileo spacecraft when it in December 1990 passed near the earth to pick up additional kinetic energy. Both planet and spacecraft are moving counterclockwise in the figure.



The fact that the density of the plasma of the solar wind decreases with increasing distance from the sun implies that the spacecraft moves from a region of lower density to a region of higher plasma density. Therefore, the accompanying decrease in signal speed causes an apparent anomaly that is opposite to the corresponding Pioneer anomaly.

In earth flybys, however, the situation is more complex. One reason is that the solar wind varies in intensity with solar activity (sunspots and sun flares) and may cause fluctuations in plasma density that affect the microwave signal speed.

Another possibly disturbing factor is the presence of the ionosphere, which extends to over 1000 km. Also, the magnetic field of the earth affects the distribution of solar plasma in the vicinity of the planet and, consequently, the speed of microwave signals near it. These facts, in turn, imply that spacecraft passing sufficiently near the earth might exhibit one or more additional anomalies.

Because of the presence of the earth's magnetic field, there should be significant variations in speed of microwave signals traveling between earth and satellites in polar orbit.

A way of measuring these variations would be to equip a satellite with a microwave transmitter coupled to a mirror: A laser ray hitting the mirror triggers the transmission of a microwave pulse. The time difference between the return of the reflected light signal and the arrival of the microwave pulse should vary with latitude and give information about plasma density.

By continuously measuring the speed of microwave pulses between several spacecraft and earth (and possibly between the spacecraft themselves), it should be possible to map in detail the distribution of solar plasma in the entire planetary system.

Such measurements might even find use in some kind of early warning system, monitoring variations in plasma density caused by solar eruptions.

Experiment 9. Higgs signature in gamma-ray bursts

Wikipedia notes under "Gamma-ray burst" that "While most astronomical transient sources have simple and consistent time structures (typically a rapid brightening followed by gradual fading, as in nova or supernova), the light curves of gamma-ray bursts are extremely diverse and complex. No two gamma-ray burst light curves are identical."

This diversity in the received signals may derive from an unpredictable behavior of the gamma-ray sources. However, another possibility is that the gamma-ray sources behave in a predictable manner, but the signals received from them are distorted during their journey through the universe.

Thus, a Higgs boson coming in the three masses predicted by xSM is expected to cause the light curves of gamma-ray bursts to become diverse and complex even if the process that causes the bursts is perfectly predictable.

Gamma-ray bursts are of comparatively short duration. (*Wikipedia* mentions two populations with average duration of about 0.3 and 30 seconds, respectively.) This fact suggests that photons traveling through intergalactic space experience no Higgs delay, since otherwise gamma beams that have traveled for billions of years should exhibit a much wider spread in arrival time.

However, both immediately after their emission and immediately before their arrival at an instrument such as the Fermi Gamma-ray Telescope, the gamma-ray photons should experience energy-dependent delays that may explain the complexity and diversity of the light curves.

Depending on the direction from which it comes, a gamma ray arriving from a distant object has spent more or less time in the solar-wind plasma and perhaps a considerable time—or no time at all—traversing more-or-less vast interstellar plasma clouds of varying densities.

For a Higgs particle with a total energy E that is $k \geq 1$ times its rest energy $m_H c^2$, the relativistic relation $E = k\, m_H c^2 = m_H c^2 (1 - v^2/c^2)^{-1/2}$ holds. For the velocity of the Higgs, one obtains $v = (1 - k^{-2})^{1/2} c$. The difference in travel time over a distance L between a Higgs and a photon is $\Delta t = L/v - L/c = [(1 - k^{-2})^{-1/2} - 1] L/c$. For instance, $k = 1.1$ gives $\Delta t = 1.4\, L/c$. If a gamma ray spends 10 hours traveling a distance of $L = c \times 36\ 000$ s through the solar wind, and during one millionth of this time takes on the shape of a Higgs boson, the delay it experiences is $\Delta t = 1.4 \times 36\ 000 \times 10^{-6}$ s $= 0.05$ s. For $k = 10$, one similarly obtains $\Delta t = 0.05\, L/c$ and a delay of 1.8 ms. This example suggests that the final, direction-dependent shifting of time of arrival of photons in the ray should be rather small and mainly affect photons of energy near 0.505 MeV.

Higgs delay in the Milky Way's interstellar plasma clouds might induce considerably more diversity in the received gamma beams.

In the same way as the geometry of the Milky Way and the planetary system affects the degree of delay of photons during the final part of their journey, the (probably rather random) distribution of plasma clouds in the surroundings of the gamma-ray source should affect the photons' Higgs delay during the initial part of their journey.

For very distant gamma-ray sources, the initial and final disturbances should be clearly distinguishable from each other. If the redshift caused by the expansion of the universe has deprived a photon beam of, say, 90 percent of its energy, the initial disturbances should predominantly be seen at photon energies in the vicinity of 0.0505 MeV (versus 0.505 MeV for disturbances induced during the last few thousand years).

Via statistical methods, using existing data, and assuming that certain gamma-ray bursts produce consistent photon energy spectra, it might be possible to separate the random Higgs-induced distortion from the original, undistorted signal. If that is so, one should be able to identify the Higgs signature in gamma-ray bursts and obtain an estimate for the Higgs masses from astrophysical observations.

Prediction

Gamma-ray bursts arriving from a direction opposite to the direction of the sun and the center of the Milky Way should exhibit less complex and diverse light curves than gamma-ray bursts that have traversed most of the galaxy and the planetary system. The difference is expected to be most marked for short gamma-ray bursts (events of duration less than about two seconds).

Note on evaporating black holes

The xSM theory predicts the existence of twice as much matter in the universe as traditional models do. Also, it requires that practically all of the so-called missing dark matter comes in the form of black holes populating intergalactic space. Still, evaporations of low-mass black holes may be rare events. The reason is that presently existing black holes are expected to be comparatively heavy and, in fact, appear to be "Jupiter-mass bodies" that reveal themselves through their gravitational microlensing of distant quasars—a conclusion that Micahel Hawkins was compelled to draw in 1993 after he had been studying long-term quasar variations for 16 years (see pages 159-163 in Hawkins' book *Hunting down the Universe: The Missing Mass, Primordial Black Holes, and other Dark Matters*, 1997). On 10 April 2010 *New Scientist* reported that "Mike Hawkins of the Royal Observatory in Edinburgh, UK" had found that measurements of time dilation in quasar light curves support the conclusion that variations in these curves are caused by microlensing of the quasars by black holes.

Note the parallel between quasar light and gamma-ray bursts. In both instances there appear seemingly random variations in the received photon signal. And in both cases, SM in combination with traditional cosmology fails to explain the variations. But in both cases, xSM provides simple and natural explanations for the variations.

Experiment 10. Higgs delay in pulsar signals

By studying gamma rays from a pulsar lying in a plane defined by the orbit of the earth, it should be possible to see the Higgs-delay effect. The distortion of the pulsar's light curve should reach its maximum when the rays pass near the sun and fall to its minimum during the next six months.

Higgs radiation versus photon radiation

The reduced Planck constant, $\hbar = h/2\pi = 6.582\,118\,99(16) \times 10^{-16}$ eV s, is the basic quantum of action exchanged between particles interacting with each other.

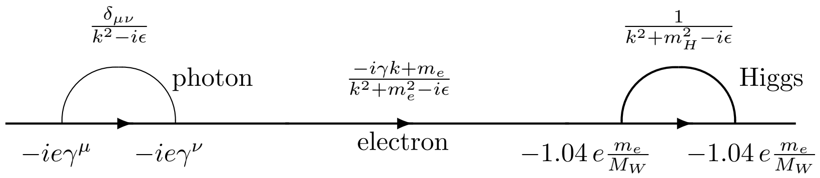
Particles are either bosons that carry integer spin or fermions that carry half-integer spin. The massless photon and the eight massless gluons are spin-1 bosons. That is, they have a spin of $\hbar$.

The massive elementary particles have spin zero (the Higgs boson), spin $\frac{1}{2}\hbar$ (quarks, charged leptons, and the neutral lepton or neutrino), or spin $\hbar$ (the neutral Z and charged W bosons).

A massive spin-1 boson may be in any of three possible spin states or states of polarization; +1, 0, or −1. By changing its spin state, the charged W boson may emit a spin-1 photon. Similarly, a quark or a charged lepton—the electron, say—may be in one of two spin states or states of polarization; $+\frac{1}{2}$ or $-\frac{1}{2}$. By flipping its half-integer spin state, the electron may emit a photon carrying integer spin $(\frac{1}{2} - (-\frac{1}{2}) = 1)$.

The familiar massless photon—mediator of the electromagnetic force—is a more complex particle than the massive Z and W bosons. Thus, in addition to its spin angular momentum, it possesses an intrinsic orbital angular momentum about itself. This means that the photon's polarization—the conserved quantity that physicists actually measure—is not the photon's spin angular momentum, but a combination of its spin and orbital angular momenta.

The self-mass diagrams in the figure illustrate the difference between the massless spin-1 photon and the massive spin-0 Higgs.



The notation follows Martinus Veltman's *Diagrammatica*. The respective propagator for the photon, electron, and Higgs is shown above the corresponding particle line. The expressions for the electron-photon and electron-Higgs vertices are shown below the electron line. (See *Diagrammatica* pages 258, 259, and 271. Note on page 253 that $gs_w = (4\pi\alpha)^{1/2} = e$ with the numerical value of s_w given as $s_w^2 = 0.2337$–0.2310, and M_W stated to be $M = 80.22 \pm 0.26$ GeV, which gives $m_e/M_W \approx 6.4 \times 10^{-6}$.)

The photon polarization reveals itself in the μ and ν indices of the delta function δ and the four-component matrix γ. To calculate the self-mass due to the massless spin-1 photon, summation over μ and ν must be performed. The calculation of the self-mass due to the massive spin-0 Higgs is a simpler task, since no polarizations with accompanying summation appear.

Due to the photon's lack of mass, the dynamics of a free photon forbids it to exist in a state of zero total angular momentum. This state, in turn, is the only possible state the Higgs may be in. Therefore, the nearly massless Higgs fills a gap left by the photon in the spectrum of massless or nearly massless real elementary particles, and may be regarded as a complement to the exactly massless photon.

Precise calculation of Higgs masses

Eqs. (3) and (4) are obtained from Eq. (2) via the approximation $m(\gamma) = m$. In a more precise calculation of the Higgs masses, $m(\gamma)$ must be corrected.

The ratio (r) between the mass $m_{\nu_\tau} + m_{\nu_\mu} + m_{\nu_e}$ transported by the neutrino and the mass $m_{H_\tau} + m_{H_\mu} + m_{H_e}$ transported by the Higgs is

$$r = \frac{m_{\nu_\tau} + m_{\nu_\mu} + m_{\nu_e}}{m_{H_\tau} + m_{H_\mu} + m_{H_e}} = 3 - \frac{2m_p - 2m_{\pi^\pm}}{4m_{\pi^\pm} - 4m_e} = 0.128\ 1945(85). \tag{10}$$

The Higgs mass is proportional to the third power of the mass of the lepton that emits it. That is, $m_{H_\mu} = (m_\mu/m_\tau)^3 m_{H_\tau}$ and $m_{H_e} = (m_e/m_\tau)^3 m_{H_\tau}$.

From the calculation of m_μ/m_e, it is deduced that $m_{\nu_\mu} = (m_\mu/m_\tau)^3 \log(m_\tau/m_\mu) m_{\nu_\tau}$—a result that awaits theoretical verification.

The order of magnitude of the electron mass corrections ($m_e(H) = -m_{H_e}$ and $m_e(\nu) = m_{\nu_e}$) is $10^{-11} m_e$, which means that these corrections are too small to affect the present calculation.

Ignoring the electron mass corrections, and starting with $m_\tau(\gamma) = m_\tau$, $m_\mu(\gamma) = m_\mu$, and $m_{\nu_\mu} = 0$, the Higgs masses and the corresponding corrections to the tauon and muon masses may be iteratively calculated from the relations

$$\begin{aligned}
m_{H_\tau} &= (4\sqrt{2}\pi\alpha)^{-1} G_F (\hbar c)^{-3} (m_\tau c^2)^2\, m_\tau(\gamma), \\
m_{H_\mu} &= (4\sqrt{2}\pi\alpha)^{-1} G_F (\hbar c)^{-3} (m_\mu c^2)^2\, m_\mu(\gamma), \\
m_{\nu_\tau} &= r(m_{H_\tau} + m_{H_\mu} - m_{\nu_\mu}), \\
m_{\nu_\mu} &= (m_\mu/m_\tau)^3 \log(m_\tau/m_\mu) m_{\nu_\tau}, \\
m_\tau(H) &= -m_{H_\tau}, \\
m_\mu(H) &= -m_{H_\mu}, \\
m_\tau(\nu) &= m_{\nu_\tau}, \\
m_\mu(\nu) &= m_{\nu_\mu}, \\
m_\tau(\gamma) &= m_\tau - m_\tau(H) - m_\tau(\nu), \\
m_\mu(\gamma) &= m_\mu - m_\mu(H) - m_\mu(\nu).
\end{aligned} \tag{11}$$

For Higgs bosons emitted by electrons, muons, and tauons, respectively, one now has

$m_{H_e}/m_e = 2.348\ 476(20)\times10^{-11}$	$m_{H_e} = 12.000\ 69(10)\ \mu\text{eV}/c^2$	$\nu_{H_e} = 2.901\ 753(25)\times10^{9}\ \text{s}^{-1}$
$m_{H_\mu}/m_\mu = 1.004\ 047(9)\times10^{-6}$	$m_{H_\mu} = 106.0860(9)\ \text{eV}/c^2$	$\nu_{H_\mu} = 2.565\ 148(22)\times10^{16}\ \text{s}^{-1}$
$m_{H_\tau}/m_\tau = 2.8407(6)\ \times10^{-4}$	$m_{H_\tau} = 0.504\ 79(14)\ \text{MeV}/c^2$	$\nu_{H_\tau} = 1.220\ 58(34)\times10^{20}\ \text{s}^{-1}$

with insignificant deviations from the values on page 2.

Some physical constants

Symbol	Numerical value	Unit	Error	Source
c	299 792 458	$\mathrm{m\,s^{-1}}$	0	
α^{-1}	137.035 999 084(51)		0.000 37	PRD 78, 053005 (2008-09)
α^{-1}	137.035 999 679(94)		0.000 68	RMP 2008-06 p. 708 (CODATA 2006)
h	4.135 667 33(10)$\times10^{-15}$	eV s	0.025	RMP 2008-06 p. 709 (CODATA 2006)
$\hbar$	6.582 118 99(16)$\times10^{-16}$	eV s	0.025	RMP 2008-06 p. 709 (CODATA 2006)
$G_F/(\hbar c)^3$	1.166 37(1)$\times10^{-11}$	$\mathrm{MeV^{-2}}$	8.6	RMP 2008-06 p. 710 (CODATA 2006)
m_μ/m_e	206.768 283 185(78)		0.000 38	xSM (physicsideas.com)
m_μ/m_e	206.768 2823(52)		0.025	RMP 2008-06 p. 711 (CODATA 2006)
m_τ/m_μ	16.8183(27)		160	RMP 2008-06 p. 711 (CODATA 2006)
m_p/m_e	1836.152 672 47(80)		0.000 43	RMP 2008-06 p. 708 (CODATA 2006)
$m_e c^2$	0.510 998 910(13)	MeV	0.025	RMP 2008-06 p. 710 (CODATA 2006)
$m_\mu c^2$	105.658 369(9)	MeV	0.085	PLB 2004-07 p. 33 (Particle Review)
$m_{\pi^0} c^2$	134.9766(6)	MeV	4.5	PLB 2004-07 p. 38 (Particle Review)
$m_{\pi^\pm} c^2$	139.570 18(35)	MeV	2.5	PLB 2004-07 p. 38 (Particle Review)
$m_p c^2$	938.272 013(23)	MeV	0.025	RMP 2008-06 p. 711 (CODATA 2006)
$m_n c^2$	939.565 346(23)	MeV	0.025	RMP 2008-06 p. 712 (CODATA 2006)
$m_\tau c^2$	1777.00(28)	MeV	160	PLB 2004-07 p. 33 (Particle Review)
$m_W c^2$	80.425(38)	GeV	480	PLB 2004-07 p. 91 (Particle Review)
$m_Z c^2$	91.1876(21)	GeV	23	PLB 2004-07 p. 91 (Particle Review)

Error: relative uncertainty in ppm (10^{-6}). Source: abbreviations used are
PLB = Physics Letters B,
PRD = Physical Review D,
RMP = Reviews of Modern Physics.