What is the Higgs boson? Will it destroy the universe?

Abstract

Current measurements of the masses of the Higgs boson and top quark particles imply that the Higgs field is likely metastable and that the universe is sat in a false vacuum, which may ultimately result in the formation of a bubble of true vacuum that would grow outwards at the speed of light, destroying everything in its path. Once this "vacuum decay" were to start there would be no way of stopping it, although the expansion of the universe makes it unlikely that this bubble would ever be able to consume and destroy the universe in its entirety.

Introduction

Our universe is permeated by fields. There is evidence to suggest that one of these fields in particular, the Higgs field, may be metastable - if this is the case, a new possibility for the ultimate fate of the universe arises: vacuum decay. The Higgs field's associated particle, the Higgs boson, is a key part of determining the stability of the Higgs field. However, in some instances the vacuum decay hypothesis and the Higgs boson's role in said hypothesis have been misreported as the Higgs boson destroying the universe.[i] [ii] [iii] In actual fact it is not the Higgs boson itself that might destroy the universe – it would be more accurate to attribute this hypothetical destruction to the Higgs field, but as it stands now this destruction is just that: hypothetical. This article will detail some of the features of the Higgs boson and field and their roles in the vacuum decay hypothesis, as well as exploring some of the possibilities concerning vacuum decay and the apparent existential threat that it poses to the universe.

The Higgs boson

The Higgs boson is a fundamental particle in the Standard Model of particle physics – one of the most basic particles that cannot be broken down into any further constituent parts. The bosons are a class of fundamental particles following Bose-Einstein statistics. This means that they have integer values of spin (angular momentum), as opposed to fermions which have half integer values. This also means that bosons do not follow the Pauli Exclusion Principle,[iv] which states that identical fermions within a quantum system (e.g. two electrons in a single orbital) cannot occupy the same quantum state, and therefore must have differing quantum numbers (hence why electrons sharing an orbital will have opposite spins).[v] There have been five bosons confirmed to exist: the Higgs boson and the four vector bosons consisting of photons, gluons, the Z boson and the W bosons. The vector bosons act as force carriers or exchange particles between fermions (matter particles), making them responsible for the fundamental interactions of electromagnetism, the weak force and the strong force.[vi] In contrast, the Higgs boson is a scalar boson and is thought to give particles their mass.[vii]

The Higgs mechanism and quantum fields

According to quantum field theory, all particles are excitations of their associated quantum field – in other words, for each type of particle there exists a field, and it is excitations of these fields that gives rise to particles. Quantum fields are spread out across the entire universe and are constantly fluctuating. Highly concentrated areas of field energy form bundles or quanta – these are the field's associated particle. For example, excitations of the electron – positron field give rise to electrons and

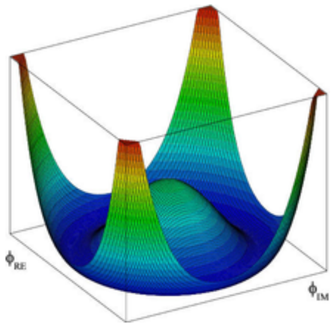

Figure 1 Mexican hat model, via https://en.wikipedia.org/wiki/Higgs_mechanism

positrons, and excitations of the electromagnetic field give rise to photons, the quanta of electromagnetic radiation.[viii] Similarly, Higgs bosons exist due to excitations of the Higgs field – this is the field responsible for a process called the Higgs mechanism that gives the W and Z bosons mass.[ix] The Higgs mechanism does so via spontaneous electroweak symmetry breaking, electroweak symmetry being the unification of the electromagnetic and weak interactions. The potential energy of the Higgs field can be plotted as a three-dimensional "Mexican hat" shape (see figure 1), in which the origin is not the minimum and so the Higgs field tries to "roll" down into the trough of the "hat", which is the true minimum. This is similar to a ball rolling down a hill – at the top of the hill the ball has high potential energy, and at the bottom it has low or minimum potential energy. As the Higgs field rolls down the hat, rotational symmetry is broken, hence electroweak symmetry is broken.[x] The top of the hat can be described as a false vacuum (see figure 2), as it is the expected but unstable value of potential energy, whereas the trough of the hat can be described as a true vacuum as this is the true ground state (lowest/most stable energy level) in which the potential energy of the field is at its true minimum value.[xi]

Figure 2 False vacuum, via http://www.quantumfieldtheory.info/Electroweak_sym_breaking.pdf

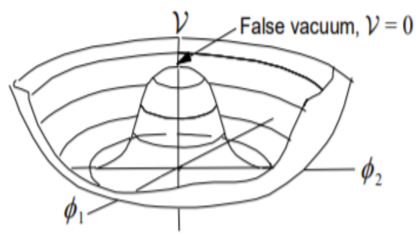

Figure 2. Higgs Field ϕ in Goldstone Model (Mexican Hat)

False vacuum and metastability of the Higgs field

It is possible that the Higgs field is currently in a false vacuum state. The true "vacuum state" of the Higgs field has as little energy as possible – the energy is at a global minimum, whereas a false vacuum state would only be at a local minimum. The true vacuum state of the Higgs field would be its most stable state – no further energy can be lost, and so no further decay can take place. A false vacuum, in contrast, is "metastable" – it will appear stable as there may be no active decay taking place for a very long period of time. A false vacuum can once again be compared to a ball at the top of a hill – the ball will have high potential energy, but may stay at the top for a long time if not given any kinetic energy, appearing "stable". However, if the ball is given just enough kinetic energy to be nudged over the edge, it will roll down the hill to the bottom where it will have much less potential energy – this is the ball's true most stable state, or its true "vacuum state". Similarly to how the ball must first be nudged over the edge, the Higgs field would have to overcome a potential barrier in order to reach its true vacuum state, e.g. via quantum tunnelling (a phenomenon in which particles are able to pass through a physical or potential barrier).[xii] [xiii] [xiv]

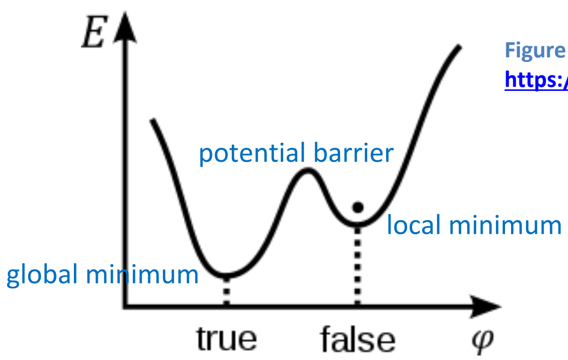

Figure 3 True and false vacuums via https://en.wikipedia.org/wiki/False_vacuum

So why is it thought that the Higgs field may be metastable? The stability of the Higgs field can be calculated as a function of the masses of the Higgs boson and the heaviest quark.[xv] [xvi] Quarks are fundamental particles in the Standard Model, like the Higgs boson, and are a type of fermion, making up matter particles like the protons and neutrons found in atomic nuclei. Currently, the heaviest observed quark is the top quark.[xvii] Data from CERN currently puts the mass of the Higgs boson at about 125-126 GeV and the mass of the top quark at about 173 GeV. These values seem to imply that the Higgs field is close to the border between stability and metastability. Taking into account experimental and theoretical errors, the central values of the Higgs boson and top quark put the Higgs field in the region of metastability, with the range of uncertainty overlapping into the region of stability at two standard deviations away from the central values.[xviii] This is illustrated below:

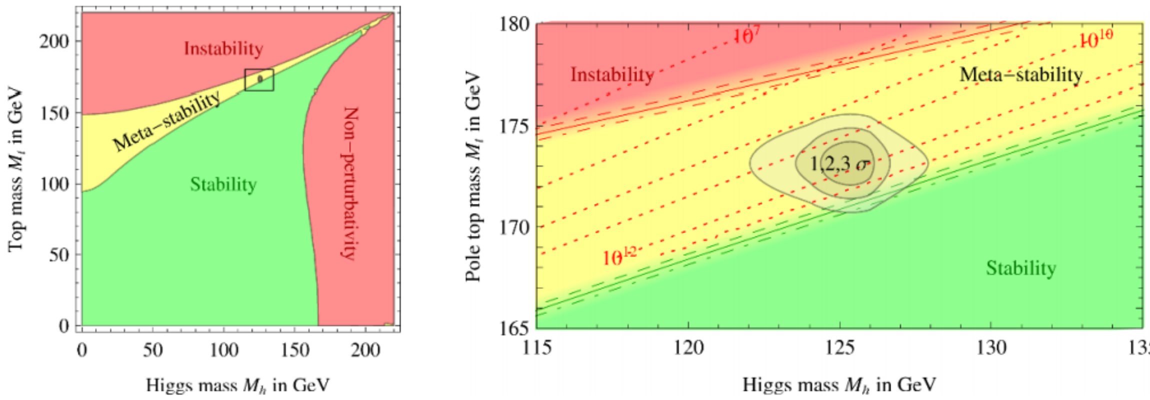

Figure 4 "Regions of absolute stability, meta-stability and instability of the SM vacuum in the Mt–Mh plane. Right: zoom in the region of the preferred experimental range of Mh and Mt (the gray areas denote the allowed region at 1, 2, and 3σ)" via [Higgs mass and vacuum stability in the Standard Model at NNLO | SpringerLink]

This implies that there is a high chance that the Higgs field – and with it, the universe as a whole, may be metastable. More accurate measures of the masses of the top quark and Higgs boson would need to be taken to be sure, but if this is true, it would mean that it is likely only a matter of time until the universe decays into its true vacuum state in a catastrophic event called vacuum decay.

Vacuum decay

If a high energy event such as quantum tunnelling were to randomly occur, this could push the Higgs field over the potential barrier and create an area or "bubble" of true vacuum. In doing so large amounts of energy would be released, pushing the space around the bubble over the barrier into the true vacuum too.[xix] The result is that the bubble would expand outwards in all directions, asymptotically accelerating towards the speed of light almost immediately upon materialisation. The effects of this vacuum decay could be devastating – the very constants of nature would be changed, resulting in a universe with completely different physics.[xx] The bubble of true vacuum would destroy everything in its path, causing the protons that make up ordinary matter to decay away,[xxi] and chemistry itself would break down, rendering life as we know it impossible.

Will vacuum decay destroy the universe?

Although the possibility of vacuum decay does sound disheartening, there may not be as much cause for concern as one may think. For a start, a metastable universe may still stay in its false vacuum state for 10^{30} years,[xxii] whereas the universe is currently only about 13.8×10^{9} or 13.8 billion years old.[xxiii] However, as mentioned earlier, there are uncertainties in our current values of the top and Higgs masses, and so until we have more precise and accurate values we cannot say for certain that this apparent doomsday scenario will even happen at all. But we should also consider that there may be other factors that determine whether or not vacuum decay will ever actually occur – indeed, it is thought that quantum fluctuations in the early universe should have already released enough energy to push the Higgs field over the edge, in which case the universe wouldn't even be here.[xxiv xxv] Clearly, our current understanding of the Standard Model may not account for all of the conditions of an unstable Higgs field.

Furthermore, even if a bubble of true vacuum were to form, or even in the case that bubbles of true vacuum have already formed somewhere in the universe, vacuum decay may never be an issue for us on Earth. There is no doubt that we wouldn't survive a true vacuum bubble that formed reasonably close to Earth, but the entirety of the universe in incomprehensibly huge. The observable universe has a diameter of 93 billion light years, and some estimates suggest that the entire universe may even be 7 trillion light years across.[xxvi] This means that even a bubble expanding at the speed of light could take millions, if not billions of years to reach Earth. What's more, the universe is currently expanding at about 70 (km/s)/Mpc or 70 kilometres per second per megaparsec, a megaparsec being the equivalent of 3.26 million light years (although the exact value of the rate of expansion, or the "Hubble constant", is still disputed).[xxvii] In other words, a galaxy one megaparsec away would be travelling away from Earth at about 70 km/s, a galaxy two megaparsecs away would be travelling away at about 140 km/s, a galaxy three megaparsecs at about 210 km/s, etc. Taking the speed of light as approximately 300,000 km/s:[xxviii]

$300{,}000\ \text{kms}^{-1} \div 70\text{kms}^{-1}\text{Mpc}^{-1} = 4000\ \text{Mpc (1sf)}$

$4000 \times 3.26\times10^{6} = 1\times10^{10}$ light years (1sf) = approx. 10 billion light years

So galaxies more than about 4000 megaparsecs or 10 billion light years away are actually accelerating away from Earth at more than the speed of light, and thus if a bubble of true vacuum were to form at these distances it would never even reach Earth at all. Furthermore, assuming that the universe will continue to expand indefinitely, for any given point in the universe there will always be a radius at beyond which space will be travelling away at more than the speed of light, and so a bubble of true vacuum would never be able to consume the entire universe.

Whether or not the universe will in fact continue to expand indefinitely is still up for debate, although it does seem likely. In another possible scenario, the "Big Crunch", the effects of gravity would eventually stop expansion and cause the universe to collapse back in on itself into a point, similar to how the universe was right before the Big Bang.[xxix xxx] Of course, a Big Crunch scenario would result in the destruction of the universe regardless of vacuum decay.

Conclusion

The thought of the Earth suddenly being swept away at any moment and without warning is no doubt a frightening one, and current measurements of the Higgs boson and top quark masses certainly seem to imply that this is not yet a possibility that can be completely ruled out. But taking into account the uncertainties in our current measurements, as well as the fact that the universe is still here despite the high-energy environment of the early universe, it cannot yet be conclusively decided whether or not vacuum decay is inevitable for the universe. What's more, if we truly are living in a metastable vacuum that is ultimately fated to decay, the incredibly long possible lifetime of this metastable vacuum, as well as the sheer scale of the universe, means that vacuum decay is likely no more of an existential threat to humanity than the eventual expansion of the sun. Even if humanity was unfortunate enough to find itself in the path of a bubble of true vacuum, perhaps one could find comfort in the fact that the expansion of the universe will likely prevent vacuum decay from ever reaching the entirety of the universe, and that elsewhere in distant galaxies, life may continue.

References

[i] Universe Has Finite Lifespan, Higgs Boson Calculations Suggest | HuffPost 27/01/2021
[ii] Higgs boson will aid in creation of the universe - and how it will end - Technology - Catholic Online (archive.org) 27/01/2021
[iii] Higgs Boson Will Destroy The Universe Eventually : Physics : Science World Report 27/01/2021
[iv] https://en.wikipedia.org/wiki/Bose%E2%80%93Einstein_statistics 24/12/2020
[v] https://en.wikipedia.org/wiki/Pauli_exclusion_principle 24/12/2020
[vi] https://en.wikipedia.org/wiki/Boson#Types 24/12/2020
[vii] https://en.wikipedia.org/wiki/Higgs_boson 24/12/2020
[viii] https://blog.oup.com/2017/02/quantum-fields/ 24/12/2020
[ix] https://en.wikipedia.org/wiki/Higgs_mechanism 24/12/2020
[x] https://www.quantumdiaries.org/2011/11/21/why-do-we-expect-a-higgs-boson-part-i-electroweak-symmetry-breaking/ 24/12/20
[xi] http://www.quantumfieldtheory.info/Electroweak_sym_breaking.pdf 24/12/2020
[xii] False vacuum - Wikipedia 10/01/2021
[xiii] Vacuum decay: the ultimate catastrophe - Cosmos Magazine 10/01/2021
[xiv] https://www.azoquantum.com/article.aspx?ArticleId=12 10/01/2021
[xv] Physics - Are We on the Brink of the Higgs Abyss? (aps.org) 10/01/2021
[xvi] https://cds.cern.ch/record/133331/files/197907145.pdf 30/01/2021
[xvii] https://www.britannica.com/science/quark 30/01/2021
[xviii] Higgs mass and vacuum stability in the Standard Model at NNLO | SpringerLink 10/01/2021
[xix] (18) The Most Efficient Way to Destroy the Universe – False Vacuum - YouTube 25/01/2021
[xx] Gravitational effects on and of vacuum decay (ias.edu) 25/01/2021
[xxi] (72)vacuum_metastable.pdf (mit.edu) 25/01/2021
[xxii] (72)vacuum_metastable.pdf (mit.edu) 27/01/2021
[xxiii] Astronomy - Cosmology | Britannica 27/01/2021
[xxiv] Say What? Higgs Boson Theorist Claims Universe Shouldn't Exist (nbcnews.com)27/01/2021
[xxv] Vacuum decay: the ultimate catastrophe - Cosmos Magazine 27/01/2021
[xxvi] How Big is the Universe? | Size, Why So Big, Infinite & Facts (nineplanets.org) 26/01/2021
[xxvii] What Is the Hubble Constant? | Live Science 26/01/2021
[xxviii] speed of light | Definition & Equation | Britannica 27/01/2021
[xxix] Ultimate fate of the universe - Wikipedia 27/01/2021
[xxx] WMAP- Shape of the Universe (nasa.gov) 27/01/2021