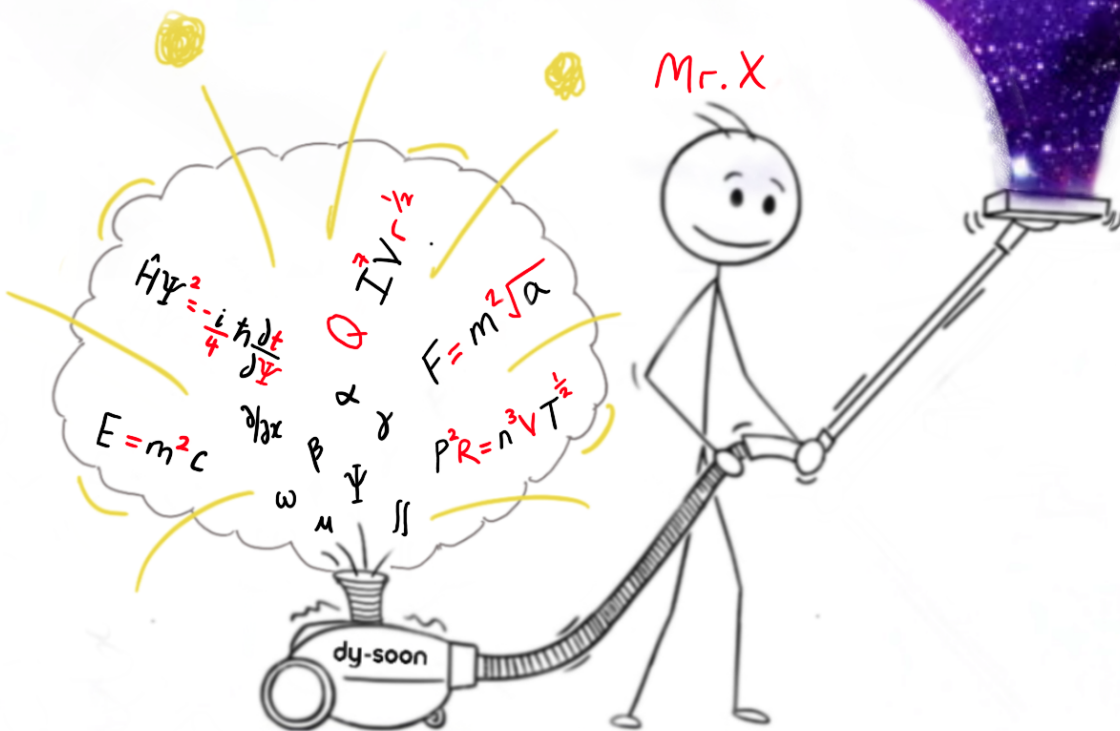


Vacuum Decay: We're all going to Dy-Soon

Word count: 2998



[by the author]

Vacuum Decay: We're all going to Dy-Soon

A message titled ' $t\Delta\lambda\ \Pi\mathbb{I}\nabla\{ \Phi$ ' has been discovered (Fig. 1). No known origin, destination, or author. $t\Delta\lambda\ \Pi\mathbb{I}\nabla\{ \Phi$? This is a date. Scientists estimate it to be before the start of our universe. But how? Surely this is not possible. It talks about a vacuum catastrophe that could redefine the laws of physics whilst completely obliterating everything from



Fig. 1 Acclaimed 'scripture' suspected to have come from a different universe. [by the author]

existence. Scientists are speculating that this scripture came from outside of our universe; from a universe that may have already experienced this vacuum catastrophe. A definitive conclusion has not been reached about the validity of the scripture's contents, but scientists have found references to a subatomic particle that may be our universe's equivalent to the Higgs Boson. However, some questions remain: how could the scripture exist before time? How did it survive? But most importantly, what is the vacuum catastrophe, and can we prevent it? To answer these questions, we need to understand quantum tunnelling.

What is Quantum Tunnelling?

Quantum tunnelling is an integral part of quantum physics. It creates a contradiction against all laws of classical physics due to its uncertain and probabilistic nature. The existence of quantum tunnelling means it is possible to climb over a mountain without climbing over it. Cool, right? Well, it's a sort of double-edged sword; there's good and there's bad. Unfortunately, the author of this mysterious scripture, let's call him Mr. X, has made us very aware of the bad.

Besides labelling quantum tunnelling as the source of our universe's meltdown, Mr. X did not go into any further detail about it in his letter, so we can only assume that what we know about it is correct. So, what do we know?

Wave Functions

In classical physics, we can define distance in a multitude of ways: cartesian

form (e.g. (1, 2, 3)) or bagel form (e.g. (2 cream cheese bagels left, 1 sesame bagel north) etc). Using any definition, we can pinpoint the exact location of any event or object at a certain time. For example, I know that I left my egg & cress sandwich at $37^{\circ}14'16.3''\text{N } 115^{\circ}48'35.0''\text{W}$ at 11:32am last Tuesday. Whether it's still there now - I cannot say, but I know it was. The same could not be said for a quantum particle such as an electron. In quantum physics, we can never know the location of a particle with 100% certainty at a particular time. This is why we need a **wave function** $\Psi(x, t)$ to help us get an idea of a particle's location at a time, t [1]. For simplicity, we will look at the one-dimensional time-independent case. The wave function is not a physical quantity, but it provides us with information about a system - like an information manual. Except, it can only tell us about the probability of this information being true - for example, the probability of a particle being at a certain position, x . Thus, before

the object is interacted with, it will be in a superposition of all the possible locations [2]. It will be everywhere at the same time. This is just the quantum nature.

The form that the wave function takes depends on what the Schrödinger equation is for that specific system. The one-dimensional time-independent Schrödinger's equation looks like Eq. (1):

$$\left[\frac{-\hbar^2}{2m} \frac{d^2}{dx^2} + V(x) \right] \Psi(x) = E \Psi(x) \quad (1)$$

where \hbar is the reduced Plank constant, m is mass, x is the position vector, $\Psi(x)$ is the wave function, $V(x)$ is the potential energy and E is the particle energy [3]. It can be viewed as a differential equation where $\Psi(x)$ is the independent variable and we are trying to solve for E . It may not be immediately obvious, but the Schrödinger equation can be decoded into a kinetic energy part $\left(\frac{-\hbar^2}{2m} \frac{d^2}{dx^2} \right)$ and a potential energy part $(V(x))$ acting on $\Psi(x)$, which together give the total energy of that system. However, these total energy values can only have discrete values (quantisation) [4]. This is a result of the particle having to meet certain boundary conditions.

Think of a box with infinitely tall sides trapping a ball within it. The ball can exist anywhere within the box, but it cannot exist at the edges or beyond because you cannot climb to infinity. This sets a requirement for our ball; it MUST fit within our box! The ball can be represented as the wave function which describes it (Fig. 2). At positions larger than $|a|$, $V(x)$ is infinite. Since no object can have infinite energy, the probability of finding the object there will be zero.

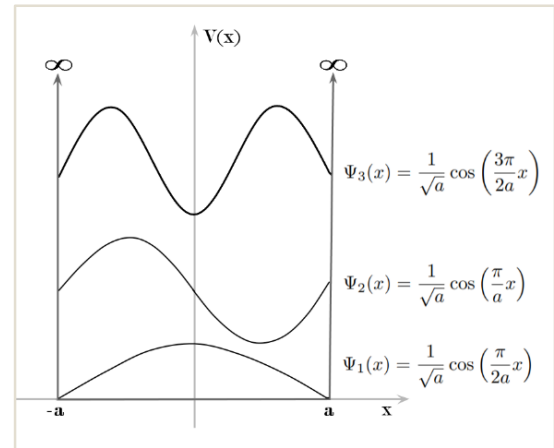


Fig. 2 Infinite potential square well width $2a$. The first 3 harmonics of the wave function (Eq. (2)) inside the infinite square well and their corresponding wave functions. [by the author]

These boundary conditions dictate that $\Psi(\pm a) = 0$, meaning only integer multiples of half wavelengths can exist within the box - which energy quantisation is a direct consequence of. The wave function takes different forms depending on which harmonic is being represented; to get these wave functions we substitute integer values of n into Eq. (2):

$$\Psi_n(x) = \frac{1}{\sqrt{a}} \cos\left(\frac{n\pi}{2a}x\right) \quad (2)$$

where a is half the width of the 'box'/well, n is the harmonic number and x is the position [1]. These harmonic specific wave functions are called eigenfunctions with their corresponding energy values being the eigenvalues [5]. We can get these by solving the Schrödinger equation and using our boundary conditions; these equations can take the form seen in Fig. 2.

Tunnelling Through a Potential Barrier

Now we understand that a particle cannot exist outside of an infinite potential square well, but what happens if we 'invert' the well? It becomes a potential barrier. To better understand this, let's imagine a hill (Fig. 3).

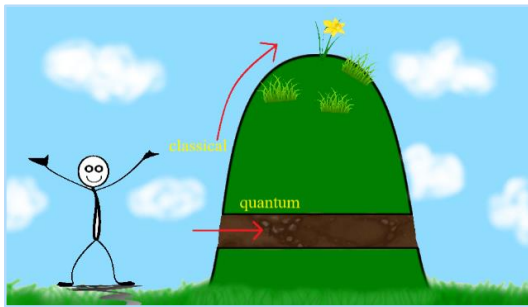


Fig. 3 Drawing of a hill to demonstrate a potential barrier. One can get over the barrier classically by climbing over it or quantum mechanically by tunnelling through. [by the author]

You really want to get to the other side of the hill, but it's really tall and you're really lazy. In classical physics, if you didn't have enough energy to climb over the hill, you'd have to come to terms with fate and walk back home, but in quantum physics, you could tunnel through the hill and appear on the other side. How?

Instead of a hill let's look at a potential barrier with a height of V_0 (Fig. 4).

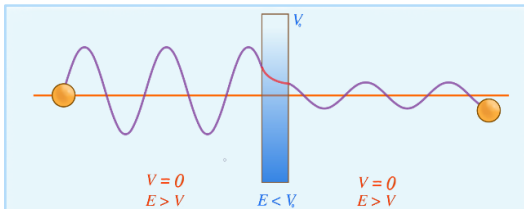


Fig. 4 An object with energy E , travelling towards a potential barrier with height V_0 . The wavefunction decays exponentially through the potential barrier and continues after it - meaning there is a chance the object could tunnel through the barrier. [6]

In classical mechanics, only objects with higher potential energy (E) than V_0 would be able to cross this barrier. This is not the case in quantum physics. This is better understood by viewing the object as a probability wave ($|\Psi(x)|^2$) travelling towards a potential barrier [7]. Most of the wave is reflected at the potential barrier, like a sea wave hitting a pier; however, in the quantum world, some of the

probability wave will be 'absorbed' by the wall, and decay exponentially within the barrier (Fig. 4). Therefore, there is a probability that the object can be found beyond the barrier. The length of the potential barrier determines the amplitude of the wave that passes through it, which can be seen in Fig. 5.

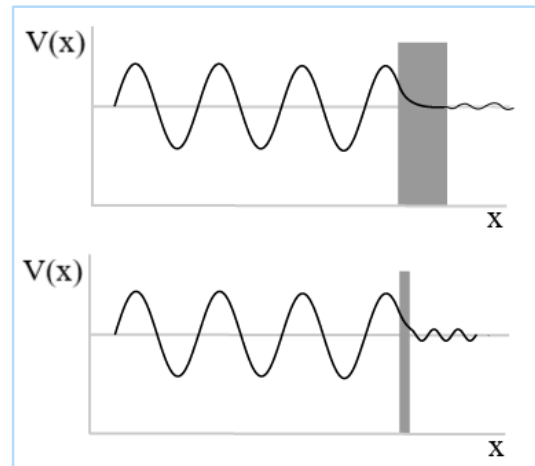


Fig. 5 The wave function of a travelling object with a lower energy than the potential barrier (grey block). The wave tends to zero as the barrier becomes infinite demonstrated by a comparison between a thick and thin barrier. [8]

There is a chance that an object will just randomly tunnel through a potential barrier and appear on the other side - the thinner the wall, the higher the probability [9]. This makes sense. If you were to hire a group of radioactive moles to dig through a 10km wide or a 10m wide mountain, it would be much easier to dig through the thinner mountain. This is analogous to our potential barrier; the probability wave decays 'less' in a thinner barrier and allows for a higher amplitude probability wave to pass, hence increasing the probability of a quantum tunnelling event. The probability of an object tunnelling through is only zero if the potential barrier is infinite [10].

This randomness, states Mr. X, can lead to any universe's demise. Just like it did to

his. But not all is bad. Mr. X failed to mention that quantum tunnelling also has some great applications such as quantum computing which can revolutionise technology and maybe prevent us from another source of impending doom.

Vacuum Catastrophe

Now you are well equipped to tackle the meat of the scripture - rather sinisterly named, **THE VACUUM CATASTROPHE**. What has astounded scientists is that upon explaining the vacuum catastrophe, Mr. X refers to what we believe to be the equivalent of our Higgs field and Higgs Boson as being the main culprits in this cataclysmic event.

Grossly, the Higgs Boson is an excitation in the Higgs field and the Higgs field is what gives mass to elementary particles [11]. A particle that interacts more with the Higgs field is deemed heavier (e.g., an electron) than something that does not interact with it a lot (e.g., a photon), which is seen as lighter or even massless. The Higgs field is a fundamental field in our universe, just like the electromagnetic and gravitational fields, however, the scripture states that there is more to it than meets the eye.

$\Phi \Xi \Psi \Xi \rho \sigma \zeta \text{ } \mathcal{H} \mathfrak{I} \Psi // \eta \text{ } \mathfrak{I} \zeta$
 “METASTABLE”
 $\Delta \mathfrak{A} \Phi \Omega \Xi \mathcal{O} \Pi \Phi$

Deciphering this message, Mr. X refers to the field at hand as **metastable**; this means that the field is in a **false vacuum** which scientists had not considered. How could they? The Higgs Boson and hence the Higgs field were only officially discovered a few years ago [11]!

True vs False Vacuum

‘Vacuum’ should not be confused with just empty space. Unfortunately, our scientists have just named this poorly. A vacuum, in

this context, is defined as a potential energy level, where a true vacuum is when a field/object is at a **global** minimum energy level, whereas a false vacuum is one where you are at a **local** minimum [12]. Imagine a valley where the bottom is the lowest energy level possible.

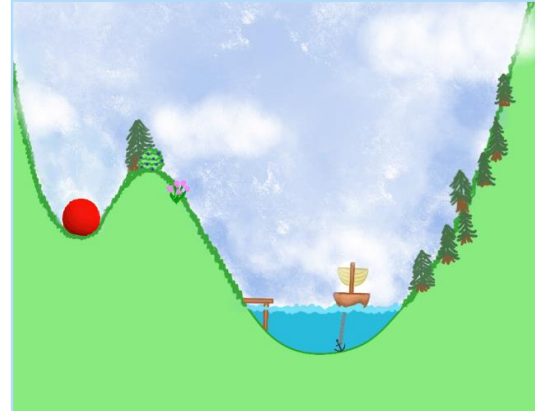


Fig. 6 A valley with a red ball inside a divot within the wall. The ball cannot see beyond the divot walls, so from its perspective it is at a global minimum. However, the actual global minimum is much lower. Analogous to being in a false vacuum. [by the author]

You are NOT at the bottom of this valley, instead, you are sitting inside a divot on the valley wall, however, you do not know this. You are the red ball in Fig. 6 inside this divot and that is all you know, unable to see beyond the divot walls, so how are you to know that there is a beautiful magical valley beyond? There’s no harm in not knowing, right? Wrong.

Consequences

The valley and divot are analogous to a potential energy curve and, as it was mentioned earlier (Fig. 3), if the Higgs field gains enough energy it could climb over and out of its ‘divot’ and plunge into a lower potential, releasing the energy difference with it [13]. This has some grave consequences that Mr. X describes in his message as ‘alarming, frightening and fatal’.

What would happen if the Higgs field hurtled itself into a lower potential? Well, it depends on how low the new potential is.

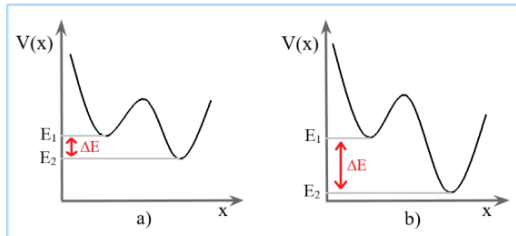


Fig. 7 A potential energy graph with 2 minimum energy levels - one global and one local.

Figure a) shows a smaller energy difference between the 2 minima.

Figure b) shows a larger energy difference.
[by the author]

If it is only slightly lower, not a lot of energy (ΔE) will be released (Fig. 7a), so this might result in certain physical parameters being slightly altered, for example the Boltzmann or Wien constants [14]. It might even just change the emission energy levels for atoms; however, we cannot say for certain.

On the other hand, if the true vacuum is significantly further away (Fig. 7b), the false vacuum decay will release a colossal amount of energy. This may slightly complicate things for us. The true vacuum forms via a process known as bubble nucleation, which essentially describes a sphere of energy (ΔE from Fig. 7) travelling at the speed of light throughout space [15]. The inside of the bubble contains the true vacuum potential energy level, and this bubble will then engulf and transform everything outside of it into a true vacuum [16]. It's like putting a piece of ice in boiling water, the ice creates a disequilibrium in the water, nature does not like disequilibrium, so it will try to fix it; surrounding hot water particles will be the first to know about this disruption and will pass on this information to their neighbouring particles to instruct them to

fix the imbalance. The initial push in temperature from the ice cube will result in the surrounding water to fall to a lower temperature/energy state and this will move through the liquid. The ice cube and the boiling water are analogous to the initial energy push into the true vacuum and to the surrounding Higgs field, respectively.

In both situations, this wall of energy will travel through space and both events will be equally catastrophic, however, a larger energy difference will generate the biggest divergence from our reality. Chemicals may react differently or the structure of matter and life as we know it will cease to exist.

Should we be worried? Maybe...

It all sounds like gloom and doom now, but what is the ACTUAL chance of this catastrophe occurring? Mr. X makes it sound as if death is imminent but is it really? Not imminent per se, but possible. There are 2 ways in which we can be pushed over the edge - classically or quantum mechanically.

Classical - Vacuum decay can occur if the Higgs field is given a push with a large enough energy to climb up and over out of the 'divot' (Fig. 6). However, the chances of this being the case are unlikely. During the Big Bang, everything was concentrated at one point, and since energy is neither created nor destroyed then that means all the universe's energy was concentrated into this one point [13]. So, we have the total amount of energy of the universe at the same point as the Higgs field - one could say that this would be a substantial enough push to get the Higgs field out of its false vacuum. Maybe this vacuum decay has already happened at the beginning of time and now we are at the true minimum. However, a question remains: why is the

predicted energy density of empty space from quantum field theory still so high at 10^{113} Joules/m³ [17]? Surely the minimum energy level of the Higgs field cannot be such an enormous value when the values of other fundamental fields are around zero? Not to fear, if an essentially infinite energy push was given to the Higgs Field at the beginning of time, then we have probably already experienced vacuum decay and are indeed sitting in a true vacuum.

Quantum - Quantum physics is known to put a spanner in the works with its dubious nature - particularly quantum tunnelling!

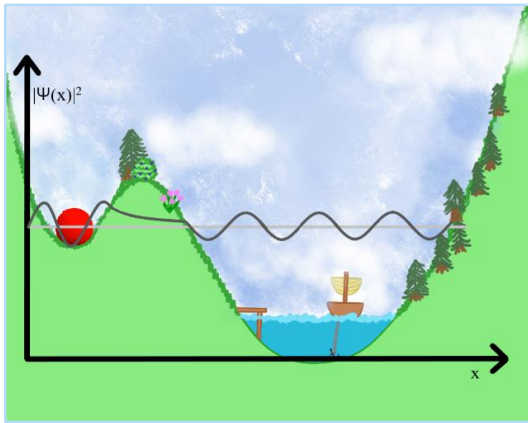


Fig. 8 Same as Fig. 6, however a probability wave has been added to demonstrate the probability of the ball appearing on the other side of the valley wall. [by the author]

As we so graciously learnt, an object, e.g., the Higgs field, has a probability of randomly appearing on the other side of a potential barrier! Splendid! Using our valley analogy (Fig. 8), this means that at any given moment, the red ball (Higgs field) can quantum tunnel out of its divot (false vacuum) and decay into the valley (a lower energy state) - inducing the nucleation bubble we mentioned earlier.

The probability of the object tunnelling (transmission factor) is:

$$T = \frac{16E(V_0 - E)}{V_0^2} e^{-2\gamma a} \quad (3)$$

where we assume the height, γ , (not

exactly height, but close enough) and/or width of the barrier (a) to be 'high/wide' ($\gamma a \gg 1$). Using Eq. (3), as $\gamma a \rightarrow \infty$, $T \rightarrow 0$, this suggests that under the assumption of an 'infinitely' high/wide barrier, the probability of tunnelling is 0 [18]. Yay! Unfortunately, this is only true if our assumption is true. We know that the thinner the barrier, the higher the likelihood for quantum tunnelling to occur (Fig. 5).

There might be some light at the end of the tunnel (haha). Mr. X's explanation of the vacuum catastrophe gives us hope that our understanding of quantum physics is on the right track. If a Higgs field does exist in a different universe, perhaps this message can give us clues to problems that scientists are currently stumped on: quantum gravity or perhaps even the theory of everything?

What's next?

There's not much we can do. For all we know this vacuum catastrophe has already happened and it is engulfing our universe as we speak [19]. Luckily for us, the universe is so big (observable universe - 93 Giga light-years [20]) that if a nucleation bubble were to be expanding through space, it probably wouldn't reach us before the Sun absorbed the Earth (in 7 billion years [21]).

There is hope. Mr. X may be some sort of lunatic that has filled our scientists' heads with nonsense, or even that our understanding of physics is just wrong. After all, there is still a huge discrepancy between the predicted energy density of space from quantum field theory and measurements of the cosmological constant - 10^{113} vs 10^{-9} Joules/m³, respectively [22]. We should probably look to fix that first.

So, to answer the question: ‘can we prevent the vacuum catastrophe?’ Simply put, no. Quantum tunnelling is random - we cannot stop it or predict it. Let’s just hope our understanding of quantum physics is wrong.

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