NOTES ON THE VACUUM

By Bob Klauber

Main Parts of Quantum Field Theory

Four main parts:

- Free fields
- Interacting fields
- Renormalization
- Application to Experiment

Here we discuss the first two

Free Fields Analysis vs Interacting Fields Analysis

The Hamiltonian H governs elementary particle/field behavior.

Aside: Alternatively, we can say the Lagrangian L governs elementary particle/field behavior, but we can find one from the other via the Legendre transformation, so both statements are true. Here, we focus on H.

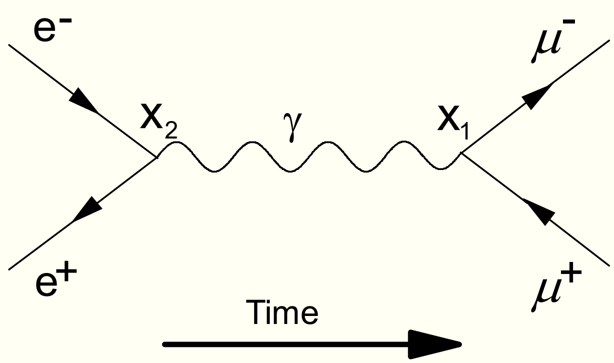
H has two parts: H_0 governs free fields and H_I governs interacting fields .

$$\text{Total } H = H_0 + H_I$$

Feynman Diagrams

Feynman diagrams are pictorial representations of the math involved in interactions.

An example:



Interactions take place at the vertices.

The form the vertices take (what particles in and out and how strongly they interact) is prescribed by the interaction Hamiltonian H_I. It has nothing to do with H_0, the free Hamiltonian.

In QFT, it turns out, there are only vertices with 3 or (occasionally) 4 particles. None with 2 particles.

Feynman Diagrams and Free vs Interacting Fields

H_0 describes fields/particles as propagating waves that just pass through other fields/particles as if they weren't there. No interactions.

- H_0 $\Longrightarrow$ Math $\Longrightarrow$ No Feynman diagrams
- H_I $\Longrightarrow$ Math $\Longrightarrow$ Feynman diagrams

Where Does Zero-Point Energy Come From?

H_0 gives rise to ZPE. See Klauber, Vol. 1, Sects. 3.4 & 3.5, pgs. 53-58.

Expectation (average measured) value of vacuum energy

$$= \langle 0 | H_0 \underbrace{|0\rangle}_{\substack{\text{vacuum}\\ \text{state}}} = \langle 0 | \sum_{\mathbf{k}} \omega_{\mathbf{k}} \left(N_a(\mathbf{k}) + \tfrac{1}{2} + N_b(\mathbf{k}) + \tfrac{1}{2} \right) | 0 \rangle$$

$$= \langle 0 | \sum_{\mathbf{k}} \omega_{\mathbf{k}} \left(\frac{1}{2} + \frac{1}{2} \right) | 0 \rangle = \sum_{\mathbf{k}} \omega_{\mathbf{k}} \left(\frac{1}{2} + \frac{1}{2} \right) \langle 0 || 0 \rangle = \sum_{\mathbf{k}} \omega_{\mathbf{k}} \left(\frac{1}{2} + \frac{1}{2} \right) = \text{ infinite energy}$$

No Feynman diagrams involved.

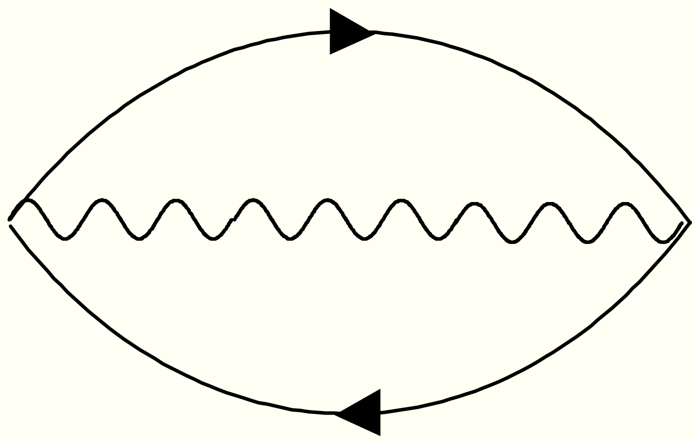
Just free particles (infinite number) propagating unhindered.

Interaction Hamiltonian H_I not involved.

Where Do Vacuum Bubbles Come From?

H_I gives rise to vacuum bubbles. See Klauber, Vol. 1, Sect. 8.4.8, pg. 234 .

Vacuum exists before. Vacuum exists after. Interactions occur in between.



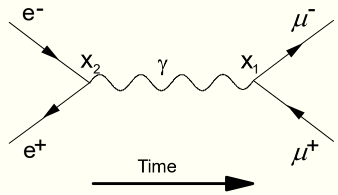
The Physics and Math Behind Vacuum Bubbles

Feynman diagrams are involved with vacuum bubbles, unlike ZPE .

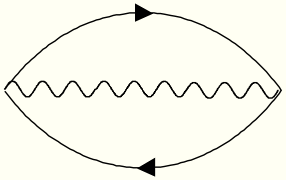
Vacuum bubbles are interactions, not free particles, as ZPE particles are.

Vacuum bubbles are a particular kind of interaction with no real particles existing before or after the interaction.

This is qualitatively different from annihilation of a real electron and a real positron (producing a virtual photon at a vertex) of earlier slide.

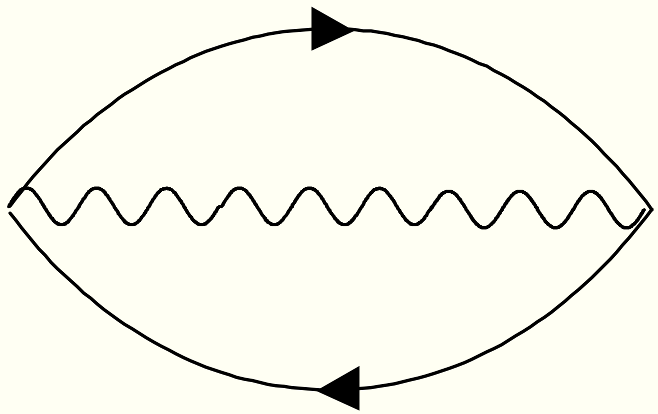


Note 3 particle vertices. None with 2 particles.



The Physics and Math Behind Vacuum Bubbles, Part 2

Note also: Energy sums to zero inside the bubble.



Energy conservation. Zero energy before. Zero energy after. Zero energy in between.

This means 1 or 2 particles in the bubble have negative energy.

This is OK for virtual particles. Unlike real particles, they can have negative energy.

The Physics and Math Behind Vacuum Bubbles, Part 3

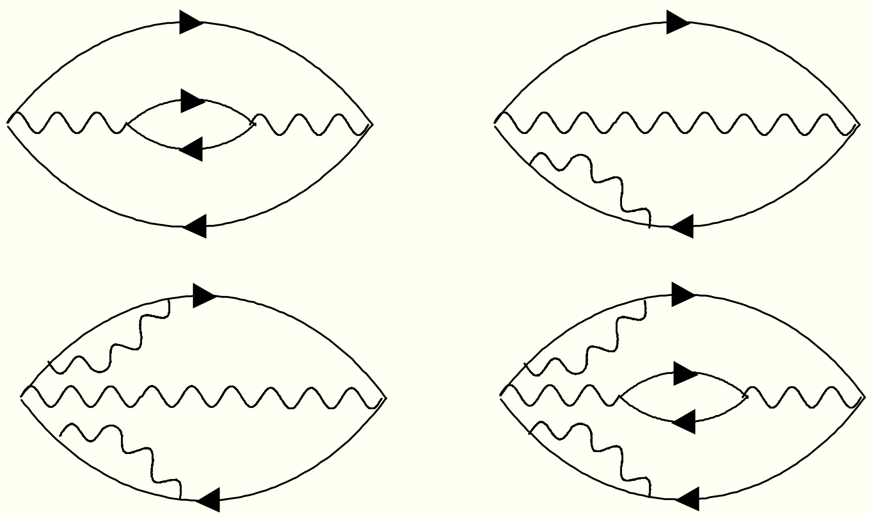
Physically: vacuum bubbles can't be the source of ZPE as they have no net energy.

Mathematically: vacuum bubbles come from interaction Hamiltonian H_I,
but ZPE comes from free Hamiltonian H_0.

Bottom line: Vacuum bubbles are not the source of zero-point energy.

The Physics and Math Behind Vacuum Bubbles, Part 4

There are higher order vacuum bubbles, too.



And many more (infinite number).

Always 3 or (occasionally in weak & strong interaction theory) 4 particles at a vertex. Never 2.

The Physics and Math Behind Vacuum Bubbles, Part 5

Experiment: vacuum bubbles have never been detected.

Theory: vacuum bubbles should not be detectable, since, by theory, they don't interact with any real particles.

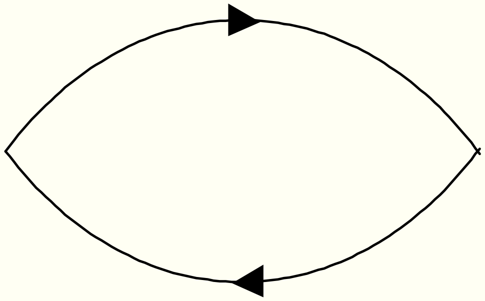
They are purely virtual particles, and such particles are not detectable.

So, as far as we are concerned, in calculations and in measurements, they play no role. For all intents and purposes, do not really exist.

Pair Popping

There are no vacuum bubbles with two particle vertices.

There are no Feynman diagrams like this.



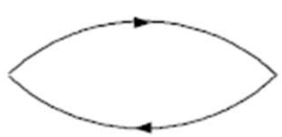
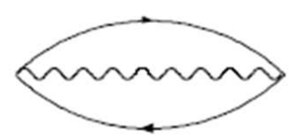
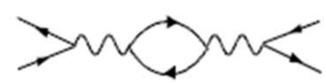
Even if there were, their energy would sum to zero and could not be ZPE.

Bottom line: Pair popping is a myth.

Summary of What Are Often Called "Vacuum Fluctuations"

See Klauber, Vol. 1, pg. 278, for entire chart. First few rows below.

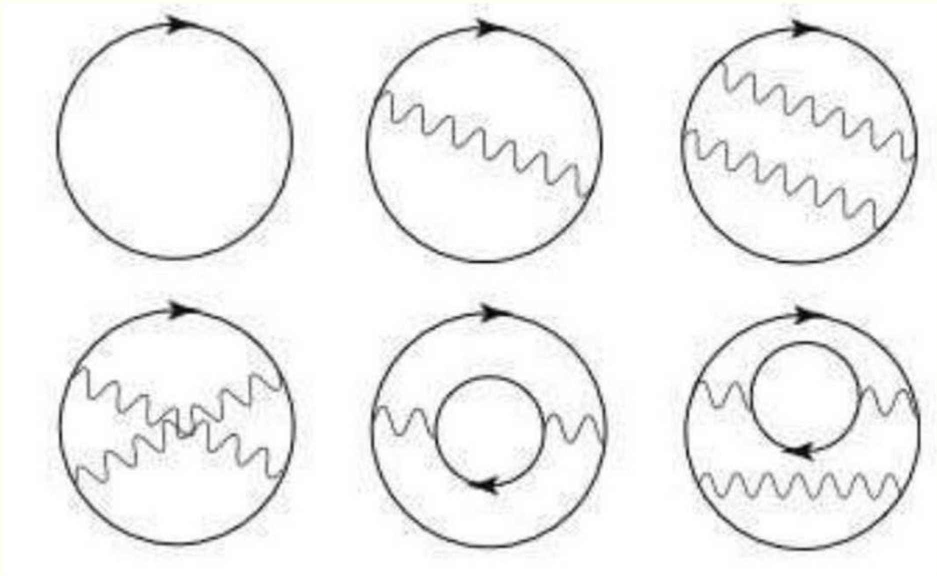
Wholeness Chart 10-1. Comparison of Vacuum Fluctuation Scenarios

	Pair Production	**½ Quanta, Zero Point Energy (ZPE)**	**Virtual Bubbles**	**Radiative Corrections**
Basic Description	Particle and anti-particle pairs continually popping in and out of vacuum	Quanta of $\frac{1}{2}\omega_{\mathbf{k}}$ sitting in vacuum, particles and anti-particles	Three virtual particles arise from and dissolve into vacuum	Higher order virtual particle corrections to lowest order interaction
Chapter in this book	This chapter.	Chaps. 3,4,5	Chap. 8	Chap. 9
How Proposed to Arise?	Uncertainty principle for states	2nd quantization	Interaction terms in Hamiltonian	Interaction terms in Hamiltonian
Typical Feynman diagram		None		
Does such a Feynman diagram exist in QFT?	No	N/A	Yes	Yes

Excerpts from Online Article

See https://www.patreon.com/posts/ask-ethan-how-98125725 .

ZPE is said to be due to vacuum bubbles, like those below.



Question: What is wrong with this? There are two things, wrong not just one.

Conclusions

- Pair popping does not exist in QFT (in its current form) and even if it did, it would have zero net energy.
- ZPE arises (in theory) from the free Hamiltonian part of QFT, and its energy is immense.
- Vacuum bubbles arise (in theory) from the interaction Hamiltonian part and have zero net energy.
- Radiative corrections (virtual particles mediating interactions of real particles) have nothing to do with the vacuum.

Conclusions, Part 2

- Only ZPE can be said to be vacuum energy.
- But its particles don't fluctuate in and out of existence.
- Only vacuum bubbles could be called "vacuum fluctuations" and be literally correct (in sense of particles popping in and out of existence).
- But ZPE particles, though not popping in and out, would oscillate like any wave. This could be labeled "vacuum fluctuations".
- But, the term is commonly used for any of the four cases above.

Final Notes

Despite what is sometimes alleged, no experimental proof of ZPE exists.

If it did, we should be able to easily see the visible spectrum part.

If it did, the mass-energy involved would curve the universe so much the light from your finger would curve back to your finger immediately and never reach your eyes.

And the universe would never have produced stars, planets, and us.

As I have shown, if one includes all the solutions to the QFT field equations (including those that are typically ignored because they appear non-physical), ZPE equals zero.

See R. D. Klauber, “Mechanism for Resolving Gauge Hierarchy and Large Vacuum Energy” (2018) http://arxiv.org/abs/1802.03277