Physics of the
Quantum Vacuum

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1 Introduction

The classical understanding of the vacuum – in the sense of "the absence of anything" – might correspond to a system with the least amount of interesting physics.

For instance, we may consider a box and remove all matter density ϱ (gas, air, etc.) from the inside

, $\varrho \to 0$

corresponding to the "pneumatic vacuum". In such a system there is even no point in doing classical single-particle mechanics.

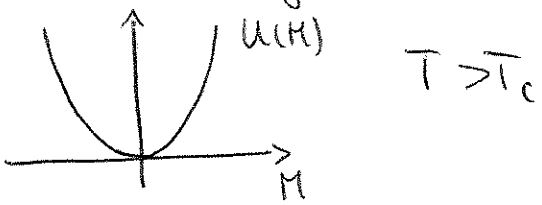
However, for a true "pure" vacuum – even in the classical sense – it requires more: in our labs, the above given vacuum would still contain blackbody radiation because of the finite temperature or other photons from electromagnetic radiation. The vacuum would also be under the influence of the gravitational field. A "true" vacuum would require to send all the corresponding parameters $T, \vec{E}, \vec{B}, \vec{g} \to 0$. This would be close to our understanding of the vacuum as the "ground state" of a system, i.e., the absence of any kind of excitation. And this seems to be close to our (naive) viewpoint that the vacuum is physically featureless (and thus maximally simple to describe or boring, depending on your point of view).

It is one of the amazing properties of quantum field theory (and even of classical field theory) that this viewpoint is completely wrong.

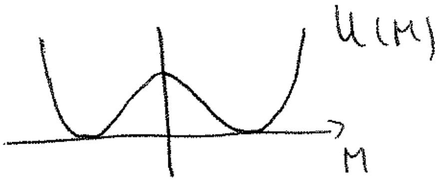
Let us try to illustrate this with some examples:

First, let us consider a ferromagnet (and ignore for a moment that the presence of a ferromagnet is, of course, no vacuum.)

At high temperatures above the Curie temperature $T > T_C$, the microscopic magnetic moments or spins are disordered and the total magnetization $\mathbf{M}$ is zero. Of course, by applying an external $\vec{B}$ field, we can induce a magnetization. But if $\vec{B}$ is switched off, the magnetization becomes zero again. Hence, the potential for the magnetization might look like this



with a minimum, i.e. ground state, at $M = 0$. By contrast, if we cool down the ferromagnet below the Curie temperature, the ferromagnet (or at least small domains of it) can exhibit ordered magnetic moments with a finite magnetization. Hence, the ground state even in the absence of an external field can be characterized by $M \neq 0$. The corresponding potential might look like this:



$T < T_c$

where the two minima indicate that the magnetization might point into two different directions.

In this example, we needed a ferromagnet (which is not "nothing"), but in field theory, we can write down systems, where no such "medium" is required, but still the ground state is characterized by a finite field amplitude with physical consequences. We will deal with such systems in the first part of the course.

As a second motivation, let us refer to a property which is specifically "quantum". Already from the harmonic oscillator in quantum mechanics, we are familiar with the fact that the ground state energy is

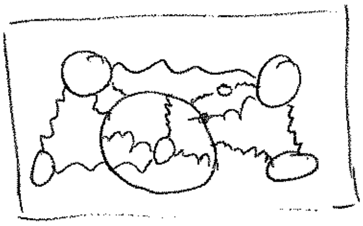
$$E_0 = \frac{1}{2} \hbar \omega > 0$$

in a harmonic potential.

This can be traced back to the uncertainty relation $\Delta x \Delta p \geq \frac{\hbar}{2}$ which forbids us to put the quantum mechanical particle into the minimum of the potential at absolute rest.

If we transfer this concept to Quantum Field Theory, this implies that we may not be able to send the amplitude of a field and its corresponding momentum to zero. Instead, we have to live with the omnipresent possibility of fluctuations enabling so-called "virtual processes".

Therefore, a more adequate picture of the quantum vacuum might be this one



where the virtual fluctuations of electrons, positrons and photons are indicated.

It is important to emphasize that this is primarily only a picture without direct observational consequences.

In order to probe this picture, we have to probe the quantum vacuum, i.e. we have to expose the quantum vacuum to external influences such as temperature, fields, boundary conditions etc. The response of the vacuum to these probes will then carry the imprint of the fluctuating fields.

The physics of probing the quantum vacuum will be part II of this lecture course.

Of course, both aspects of the quantum vacuum can show an interesting interplay. For instance, if the fluctuating fields have strong interactions (as in quantum chromodynamics), the fluctuations can

induce a nontrivial ground state.
Several of these aspects will be dealt with in this course.