*** Disclaimer: This article is intended to lend a more intuitive understanding of the quantum vacuum state. The ideas presented are at the forefront of modern physics and the interpretation of the quantum vacuum state is still a topic of discussion. While we held as close to the facts as possible, certain aspects were generalized or glazed over for brevity and to avoid confusing the subject. ***

The Quantum Vacuum

By Sean Minster, Inside Sales Engineer

It could be argued that the ultimate, and ultimately unattainable goal of a vacuum technician is to reach pure vacuum: a chamber with zero gas particles inside. Practically speaking anyone in the industry knows this to be an impossible task. That is the direction we head, not a destination to actually reach.

When asked to describe such an idealized vacuum state the simple answer would be to say that it is, well, nothing. If you take everything away then nothing remains. Perhaps the most counterintuitive result of modern physics is that that answer is in fact wrong. Taking away all the gas particles does not leave you with nothing, not exactly anyway. If you are anything like me you would be very skeptical of that statement, and I could never ask that it be taken at face value. So, let us construct our ideal vacuum chamber and see what we find inside.

Picture a section of our universe that has only a handful of gas particles within it, perhaps thinly spread out. Now let us choose a segment within that section where there are currently no particles and construct a box out of the most perfect metal in existence. We did it! The ideal vacuum chamber has been made. Before we look inside however we need to look at some regular matter - one of the particles whizzing around outside of the chamber for instance, to understand something of the nature of our universe.

There is a concept in physics most people have heard of called the Heisenberg uncertainty principle. This amazingly impactful principle is something that no matter how hard we try we simply cannot refute, and it has been accepted as one of the fundamental truths in our universe. What this principle says is that we cannot know both a particle’s position and speed (really momentum) to perfect accuracy. We can know them both to an incredible degree of accuracy, but if you look really really close at a particle's position, you become more unsure about the value of its speed. The reverse is also true: the better you measure a particle's speed, the blurrier its location becomes. We will not go into why this is, but suffice it to say there are copious amounts of experiments that prove the effect.

Now let us think about temperature. The hotter the temperature, the more energy a particle has and the faster it moves. Cooling down a particle slows it, and cooling it down to absolute zero would bring that particle to a complete stop. Well, not quite. If that were the case we would know exactly 100% the speed of the particle, which is zero, and exactly 100% the position of the particle, because it stopped moving somewhere. This is a violation of the Heisenberg uncertainty principle, and above all that is not allowed. That brings us to the concept of zero-point energy.

Zero-point energy can be thought of as the energy of the vacuum. We do not know its depth but some calculations would lead us to believe it is immense. At the very least this background energy is enough that even at zero temperature a particle may jiggle just enough to satisfy the Heisenberg uncertainty principle. It could also be said this is why we cannot actually reach absolute zero, because the vacuum is always lending a little bit of energy, and thus a little bit of temperature, to ensure the uncertainty principle is upheld.

Energy in general comes in many forms and is said to be both a particle and a wave. The most familiar form to us is light energy, which is the same type as microwave, radio, and X-ray. This is the energy that interacts with electricity and magnetism and, to me anyway, makes up almost everything I would call familiar energy exchanges. The other types are more exotic, having to do with fusion and decay of atoms and what holds an atomic nucleus together. All of that energy can occupy the exact same space in the universe at the same time. Matter is another form of energy; the main difference being, to put it simply, no matter how hard you press two rocks together they cannot occupy the same space at the same time. Specifically, they cannot occupy the same quantum state at the same time.

We are almost ready to look inside our chamber, the last thing we must address is the what is meant by energy (or matter) being a particle and a wave at the same time. We say it is a particle because energy comes in definite sizes or packets. You do not get a little extra or a little less, you always absorb one full light particle at a time gaining exactly as much energy. The reason it is a wave goes back to the Heisenberg uncertainty principle.

We cannot know exactly where a particle is, but we can know the probability that it will be in a specific spot. If you look at the probabilities across all spots, their distribution looks like a wave. If you contain this particle within a box those waves also have to fit within the box. They may be the entire length of the box, or it might take two or three or ten thousand waves to stretch across the box. The only rule is the waves must cover the entire box and they must be whole; you cannot end with a third of a wave for instance (see figure 1). With all this in mind, let us now peer into our perfect vacuum chamber.

Humming away in the background is the zero-point energy, the very fabric of existence. If this is still not to be believed we can run an experiment. You could place two moveable plates within the chamber so that they are very close to each other but not touching, maybe a micrometer apart. Now think of what we said about waves: they must fit between the walls of the box you place them in. Think of the plates as two walls of a box. Any wave that is longer than their separation distance will not fit and cannot be between them. They will fit outside of the plates however. This creates a sort of imbalance, because adding up the "allowed" waves there is more energy outside of the plates than there is between them. The effect is that the exterior energy overcomes the internal energy, and the plates are forced together. This result, known as the Casimir effect, is nothing short of astounding.

This zero-point energy which we have shown to be within our chamber is able to bubble up into all forms of energy. For example, a Higgs boson, one of those "exotic" types of energy, might pop up from seemingly nowhere. It might then decay into an electron and positron (or anti-electron, the antimatter version of an electron). Suddenly we have particles in our perfect vacuum.

There are also effects like tunneling. The walls of a chamber create a "potential barrier" that prevents particles from passing through them. A potential barrier can be very high but not infinitely so. Because of the wave nature of matter, this means there is a non-zero chance of the particle crossing said potential barrier. In this way a particle could “tunnel” through the chamber wall and thus disturb our perfect vacuum.

Then there are particles called neutrinos that are so small they can slip between the atomic lattice that makes up our chamber wall no matter how thick we make it. That being said they would likely continue on through the other side of the chamber, not interacting with anything while they passed though, but they could disrupt a “perfect” vacuum nonetheless.

These effects may appear to be of little consequence, and in large part they are for the majority of vacuum users. At room temperature and 10^{-10} Torr, which is considered ultra-high vacuum, there are on the order of a million particles per every cubic centimeter of volume. This is far from the ideal vacuum chamber we’ve been considering and many of the strange properties we discussed become lost in the wash. Still, these strange phenomena speak to the very nature of our reality.

The very fact that matter exists anywhere in the universe is cause for any vacuum to be a messy one. The only even potentially possible way around it would be to create a new universe without a single atom or observer within it, letting the nothingness make up the chamber walls which hold all the nothing inside. In truth though, that would be incredibly boring. Messy or not, I for one am glad that even when all else is removed we still live in such an exciting universe.

While the perfect vacuum chamber doesn’t exist, GNB is able to produce products that cover a full range of vacuum pressures to the extent that is practically feasible. Whether it’s polished chambers, robust gate valves, a range of vacuum pumps, or any of the components that connect them together, GNB has your vacuum solution. Though we may never get there, GNB will continue to inch ever closer to that elusive, ideal vacuum.

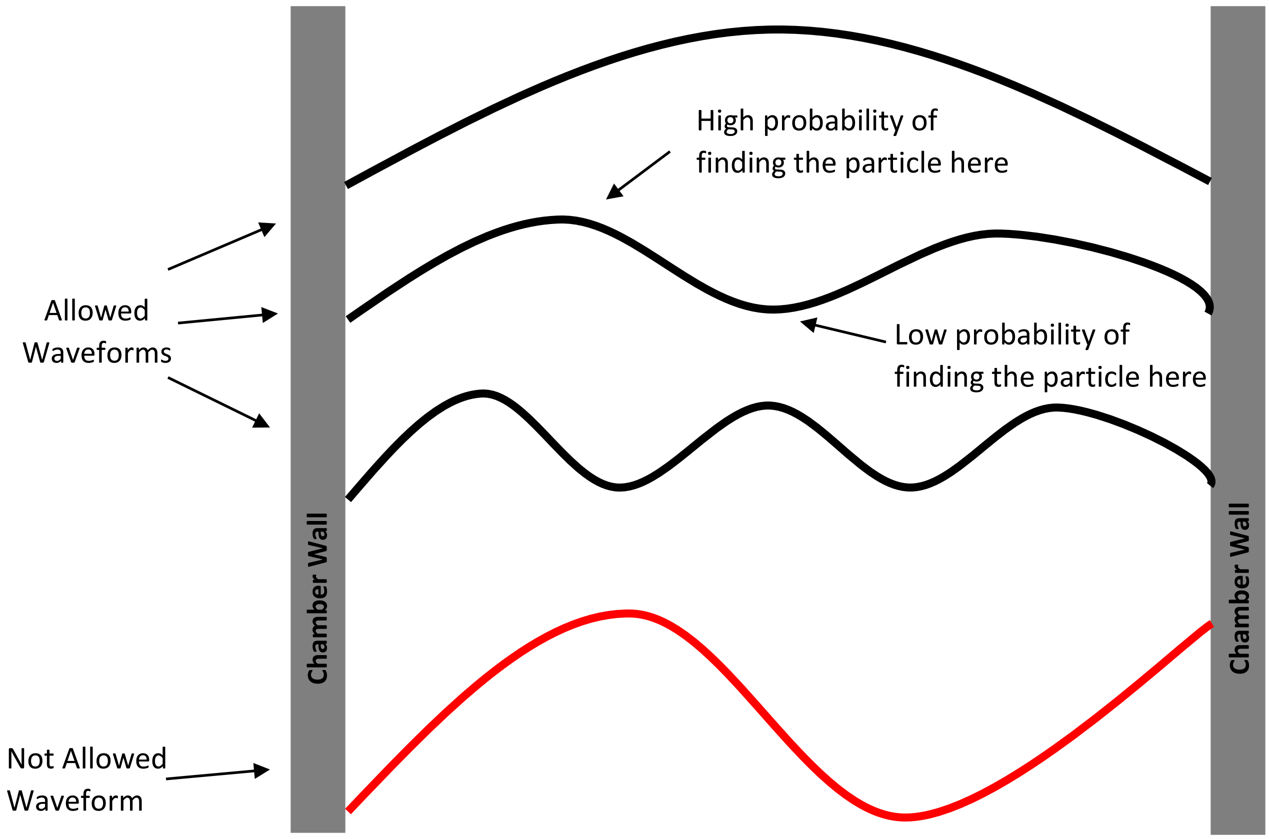

Figure 1: Three allowable waveforms of a particle inside an ideal box are shown at the top, along with an example of a waveform that is not allowed at the bottom. The amplitude (height) of these waves indicate how likely it is for the particle to be found in that location. Since the particle has to be between the walls of the box, the probability is zero at the walls of the box.