

## 11.4.2: Vacuum Energy

A second consequence of this formulation of the Heisenberg Uncertainty Principle is the possibility of vacuum energy. Consider a small region of space. Suppose that it's empty; that is, you've taken out everything you can take out of it, including atoms, light (photons), dark matter, and so forth. Make sure that there are no quantum systems anywhere with non-negligible probability for being found in this region of space. Over a finite time interval  $\Delta t$ , you can't be sure exactly how much energy there is in this region of space; your uncertainty in the amount of energy must be at least  $\Delta E = \frac{\hbar}{2\Delta t}$ . As a result, there may be energy in the vacuum.

What is the expectation value of this energy? You might predict that the expectation should be 0, even though the uncertainty has to be greater than zero. Figuring it out requires going into relativistic quantum mechanics, called quantum field theory. Unfortunately, even quantum field theory can't calculate that right, for naive estimates of what you'd get (the best we can really do) gives a value of the vacuum energy density that is so high that it would prevent galaxies from ever having formed in our Universe. The fact that you are reading this indicates that this estimate cannot be right. Indeed, quantum field theory estimates a value for the vacuum energy density that is 120 orders of magnitude too big! That's pretty far off. As such, we have to say that we don't completely understand the nature of vacuum energy.

What form would this vacuum energy take? We've already seen that in a finite time interval  $\Delta t$ , we can't say with certainty that the vacuum has zero energy. In quantum field theory, it becomes possible to create and destroy particles, as long as you obey all of the conservation laws. For example, two photons can interact and create an electron/positron pair, where a positron is the antimatter partner to an electron. If you don't have to worry about conserving energy, however, you can create a positron/electron pair out of absolutely nothing. . . as long as they re-annihilate back to absolutely nothing fast enough. For every fundamental particle that exists, this sort of thing is going on around us all the time.

What is the net energy density of the vacuum as a result of all of this? For a long time, many physicists assumed that a various terms would cancel out to zero; the naive calculations indicated something absurd, and the most natural result if those calculations are wrong is that things would cancel out. However, in the last ten years, observations of the expansion of the Universe have shown that the expansion is accelerating; indeed, these astronomical observations were the source of the 2011 Nobel Prize in Physics. We don't know what is causing this, and have given the name "dark energy" to whatever it is that is causing it. The simplest explanation for dark energy is that it is vacuum energy. Measurements from cosmology indicate a vacuum energy density corresponding to about  $10^{-29}$  grams per cubic centimeter. That is, the energy density of vacuum energy is 29 orders of magnitude less than the mass-energy density of water. Obviously, we can ignore this in our every day life. However, if you look at the Universe as a whole, most of it is empty; our planet is a very special place that is, compared to most of the Universe, extremely dense with regular atoms. In the Universe as a whole, dark energy makes up three quarters of the energy density. Even though this density may be 120 orders of magnitude smaller than what naive estimates from our theory would suggest, it is coming to dominate the evolution of our Universe.

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