THE LEFTOVERS OF NOTHING

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NOTHINGS ain't what they used to be. By using his air pump -- one of the high points of seventeenth-century technology -- to remove all the air from a cavity, Sir Robert Boyle made it clear to restoration England what a vacuum was. It was what was left when you took everything away: emptiness. In the early twentieth century, quantum mechanics made everything more complicated. A vacuum is still what is left over when everything is taken away; but that no longer means that it is emptiness. The non-empty vacuum plays a fundamental role in the way physicists think about matter.

Descendants of Boyle's air pump now produce vacuums that are, to all intents and purposes, completely free of matter. But they can never be completely free of energy. According to quantum theory, it is impossible to remove all the energy from any system. As in a tin of sardines, there is always a little bit in the corner that you cannot get out. The magnitude of this "zero-point energy" is tiny; as far as everyday uses go, it can be ignored. Nobody can measure the zero-point jiggling of a pendulum caused by the mote of energy remaining in the system when nothing else is left. But not all such effects are negligible. Electromagnetic fields also have zero-point energies. In the vacuum, every electromagnetic mode--that is, every way in which an electromagnetic field could vibrate, if there was one there--has its zero-point energy. The energy for each mode is tiny, but there are an awful lot of modes. Adding them together reveals a vacuum crammed with energy.

It is surprisingly hard to find evidence of this sea of energy--largely because the level of the energy is the lowest that can be reached. There is no lower level with which it can be compared. Like sea-level for land maps, the vacuum energy is the reference point above which all else is measured. Zero-point effects do turn up, though, when matter and vacuum interact. The first to be recorded was the atomic Lamb shift. Atoms are surrounded by electrons which can have various different levels of energy. When an electron moves from a higher level to a lower one, it emits a burst of light at a particular wavelength: a photon. The wavelength can be predicted precisely from theory. In some cases, though, the wavelength observed is different from that predicted. The difference turns out to be exactly what one would expect from the effects of lots of tiny electromagnetic fields working on the electrons--the effect of the vacuum field.

Not only is the wavelength of the photon dependent on vacuum effects, so is the fact that it appeared at all. There are two ways for an electron to unburden itself of a photon and come down from a higher energy level. If the electron is hit by a photon of the right wavelength, it will be knocked down, and there will be two photons where there was one before. That is stimulated emission, the principle behind the laser. Alternatively you can wait for the electron to jump down on its own, giving up its photon by spontaneous emission. When the vacuum energy is taken into account, the distinction between these two breaks down. Spontaneous emission can be seen as stimulated emission, with the zero-point energy of the vacuum providing the stimulation. So the emission of light does not depend just on the atom--it depends on the way that the atom and the vacuum interact. By changing the vacuum, you can change the way the atom emits light.

A vacuum between two sheets of metal is not the same as one that is unconstrained. Some of the modes of the electromagnetic field are suppressed--the modes which represent waves in the field that are too big to fit into the cavity. By changing the size of the cavity, you can lose certain modes. Groups of scientists around the world have built cavities that rule out certain modes of vacuum energy, and thus stop atoms from emitting photons at various wavelengths. Using a related technique, they have designed and built cavities that enhance the radiation by allowing the atom to "see" more modes of the vacuum radiation than it would if there was no cavity. The results of such experiments allow scientists to explore otherwise inaccessible areas of quantum electrodynamics, the theory of electromagnetic fields.

An intriguing theoretical point about the way that atoms interact with vacuum has been made by Dr Hal Puthoff of the Institute for Advanced Studies in Austin, Texas. For every atom there is an energy level below which the electrons cannot sink. Dr Puthoff suggests that this is because, at the low energy levels, electrons cannot lose energy any faster than they pick it up from a vacuum. It is the vacuum energy that buoys them up, stopping them from losing all their energy and collapsing into the atomic nucleus. That means that the vacuum underpins the stability of every atom--and thus of almost all matter in the universe.

Force from nowhere

Vacuum zero-point energies can explain effects on a larger scale as well. The vacuum energy exerts a pressure on everything. Normally, this pressure has little effect, since it comes from all directions at once and almost cancels out. But if two atoms are reasonably close to each other, each will shield the other from some of the pressure. There will be slightly less pressure FROM the direction of the neighbouring atom than there is from every other direction--so the atoms will tend to move together.

This is the Van der Waals force. Though it is weak, it is strong enough to hold atoms and molecules together in gases and liquids. There are other ways to describe Van der Waals forces, in terms of the way the electrons jitter around the atoms, but they also depend on the vacuum; they just come at it in a different way.

An analogous force can be measured between parallel metal plates which are placed close together--say a few thousandths of a millimetre apart. Because the distance between the plates limits the wavelengths available for the zero-point energy, there are fewer modes available in the vacuum between the plates than in the vacuum outside. So the pressure from outside is greater, and becomes greater still as the plates are pulled together and yet more modes are ruled out. This "Casimir effect" may prove an obstacle for people who want to build machinery ever smaller, since it will tend to stick surfaces together.

On the other hand, it may be an opportunity. Dr Robert Forward, a physicist who is always ready to speculate on the outlandish--from antimatter-driven spaceships to life on the surfaces of collapsed stars--has suggested a simple, impractical machine that could remove energy from the vacuum using the Casimir effect. It is farfetched, but getting the Casimir effect to do useful work by holding things together is theoretically possible.

There are further reaches to vacuum energy ideas which are controversial, but still intriguing. Over many years, Dr Timothy Boyer of the City University of New York has tried to show that many of the results of quantum physics can be achieved using none of its assumptions, provided that zero-point energy is allowed. Dr Puthoff has recently revived an idea mooted by Dr Andrei Sakharov in the 1960s that gravity itself can be explained by vacuum effects, more or less as a very long-range version of the Van der Waals force between atoms and molecules. That goes against the grain of modern theory, but some broad-minded colleagues see it as an intriguing speculation.

And there is the question of the other sorts of energy in the vacuum. Interest has focused on the residual electromagnetic fields because there is a successful theory with which to discuss them. But there are other types of field--those associated with the nuclear forces--that are less well known. The way that quarks are bundled together in nuclei may have to do with vacuum pressure. There may still be a lot of mileage for physicists in thinking about nothing at all.