We've just started work on the technology to power a Star-Trek style replicator

June 30 2015, by Gianluca Sarri

Credit: AI-generated image (disclaimer)

Who has never dreamt of having a machine that can materialise any object we need out of thin air at the push of a button? Such machines only exist in the minds of science fiction enthusiasts and the film industry. The most obvious example is the "replicator" that Star Trek characters routinely use to generate a diverse range of objects, helping them escape from even the most impossible of plotlines.

However, scientists might have found a way to build such a dream-like machine. The trick will be to exploit the ever-famous $E=mc^2$ equation, known as Einstein's energy-matter equivalence principle. This equation tells us that mass (the amount of matter a body is made of) is just another form of energy. This means it should be possible to take some mass and directly convert it into pure energy.

This phenomenon is supported by uncountable experimental evidence. For instance, it provides the energy that keeps atomic nuclei together. If you "weigh" the nucleus of an atom, you will find that it is slightly lighter than the sum of its components. The missing mass is converted into energy, which holds everything together. So far so good, but the equals sign in the equation tells us something even more exciting. We can, in principle, take pure energy and materialise it into mass.

Vacuum – not so empty

How might that be possible? In order to grasp this idea, we need to change our concept of pure vacuum. Classically, vacuum is nothing but a completely empty (and rather boring) region of space. Quantum mechanics instead tells us that vacuum is an extremely busy region of space, where ultra-tiny particles come into existence for extremely short periods of time (shorter than 10^{-21} s, or a thousandth of a billionth of a billionth of a second).

The particles are quickly annihilated when they collide with a corresponding (anti)particle made from antimatter. Together, these particles and antiparticles, usually referred to as "virtual particles" because they exist for such short periods of time, are a direct consequence of Heisenberg's Uncertainty Principle.

Now, imagine sending a super-intense laser beam (which is pure electromagnetic energy) into a vacuum. If the laser is intense enough, it could rip these virtual particles away from their antiparticles to such a distance that they will not collide and annihilate. This means you have sent energy into a void region and end up with some real particles with mass.

There's only one drawback: you would need to send enough energy to separate the virtual particle-antiparticle pair before they would naturally annihilate each other (remember the 10^{-21} s?). This appears to be a Herculean task, but recent developments in laser technology are now giving us the opportunity to do so.

Lasers are now able to produce bursts of light that last for tiny periods of time, periods comparable to the time it takes an electron to perform one revolution around the nucleus in the atom. They can also be focused on a region of space smaller than the width of a human hair. To bring things into a bit more perspective, these laser bursts are thousands and thousands of times more powerful than the whole UK electrical grid (although they require relatively small amounts of energy) and billions and billions of times more intense than solar irradiation on Earth.

Ramping up the power

Scientists are notoriously never satisfied, however, and are pushing this limit even further. A major European project is now building the most powerful laser ever generated, the Extreme Light Infrastructure (ELI). This unprecedented project will result, in the next few years, in the creation of a laser system that provides beams with a power of 10 PW (10,000,000,000,000,000 watts). That's 10 times more powerful than existing state-of-the-art laser facilities.

Theoretical calculations indicate that such a laser is able to "produce" a handful of particles out of a pure vacuum and provide the first experimental evidence that energy can be directly transformed into tangible matter.

We might still be a long way from producing a polished finished object from vacuum but the first step is now being taken. Once the wheel is set in motion, it will only be a matter of time before a replicator will be an essential appliance in every household. The only problem remaining then will be what to do with the anti-objects that will unavoidably be generated beside the requested objects?

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Citation: We've just started work on the technology to power a Star-Trek style replicator (2015, June 30) retrieved 19 April 2024 from https://phys.org/news/2015-06-weve-technology-power-star-trek-style.html