Antimatter

Transcript

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Beauty is not a word usually used to describe physics. But a physicist will tell you in a heartbeat that physics is one of the most beautiful endeavors known to humankind and no concept better illustrates the beauty of physics than does antimatter. Everything about antimatter, from its explosive power to its practical applications, is underscored by surprising symmetries and paradoxes.

The story of antimatter begins with an English theoretical physicist and mathematician named Paul Dirac. Dirac was a quiet man with an astute mathematical instinct. He believed that “If you are receptive and humble, mathematics will lead you by the hand.” Dirac let mathematics lead him to many important discoveries and his exceptional work in the field of quantum mechanics eventually earned him a Nobel Prize. In particular, Dirac developed a mathematical model of the electron.

In one of his calculations, Dirac needed to take the square root of energy squared. Performing this step actually yields two possible solutions: one of positive energy and one of negative energy. Most physicists would have thrown out this negative solution as a meaningless mathematical artifact, but Dirac had an intuition that the mathematics was leading him by the hand, as it were, and he saw it as a clue to a yet undiscovered symmetry in the laws of physics.

This led Dirac to predict the existence of a mirror twin of the electron, which he called the “anti-electron.” This particle would have the same mass as a normal electron, but the opposite electric charge (positive instead of negative). At first, Dirac thought that this particle might be the positively charged proton that can be found inside the nucleus of an atom. But the proton is much too massive for this to be possible, and it soon became clear that the anti-electron was a completely novel object — something that no one had ever observed before. And yet, in 1931, Dirac published a paper predicting that such a particle might be discovered.

Dirac’s theory was still hot off the press when an American physicist named Carl Anderson made a curious discovery. Anderson was studying cosmic rays, which are streams of exotic particles showering down on earth from space. He was performing experiments with a device called a cloud chamber that allowed him to examine the

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tracks of charged particles racing through it. In 1932, just a year after Dirac's prediction, Anderson stumbled upon a particle that looked exactly like the electron, except that it had the opposite electric charge.

This is a picture of the cloud chamber track that Carl Anderson identified. The particle's path is curved because a magnetic field causes particles to spiral in different directions, depending on their charge. The direction of this track's curvature indicates one of two possibilities. Either this was a positive particle traveling upwards or it was a negative particle traveling downwards. A negative charge would have distinguished this particle as the familiar electron.

However, on its way through the cloud chamber, this particle passed through a lead plate and it slowed down in doing so. The particle's path was straighter below the plate, indicating that the particle was traveling faster there. That tells us that this particle was traveling upwards and slowed down after passing through the plate. And therefore this particle had a positive charge. No one had ever observed a positive electron before and so the term "positron" was soon coined to describe it.

It didn't take long to realize that the "positron" that Carl Anderson had identified was exactly the "anti-electron" that Paul Dirac had predicted. The discovery of the positron is a wonderful example of the interplay between the mathematical predictions that theoretical physicists develop and the observational evidence that experimental physicists generate. It takes both theory and experiment to reveal new insights into the nature of our universe. And in the case of the positron, these insights were profound.

Paul Dirac once said that "The measure of greatness in a scientific idea is the extent to which it stimulates thought and opens up new lines of research." If this is true, then the positron is a truly great scientific idea, because it opened the door to the fascinating realm of antimatter. Today, for every known particle of matter, an equivalent particle of antimatter has also been observed. For example, the most common matter particles in the universe are the proton, the electron, and the neutron. The proton has a positive charge, and therefore the anti-proton has a negative charge. Similarly, since the electron is negative, the positron is positive. However, the neutron has no electric charge. Nonetheless, it still has a distinct antiparticle, which is usually notated with a bar to distinguish it as an antineutron.

There are some particles whose matter and anti-matter manifestations are completely identical. For example, a photon of light is neither matter nor antimatter. One way to visualize this is to consider mirror symmetry. When you look at an object in a mirror, it's flipped so that right and left are reversed. Some objects look different when they are

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reflected in a mirror, for example, the letter F. But the letter O is symmetric and so it remains exactly the same when it's viewed in a mirror. In this analogy, the letter F represents the electron, which has an antiparticle, the positron, that is fundamentally different. The letter O represents the photon, which is indistinct from its reflection. And for this reason, there's no such thing as an anti-photon, just as there's no such thing as a backwards O. The idea of symmetry extends far beyond this example, and plays a critical role in particle physics in many different forms. Studying fundamental symmetries and how they can be broken is central to understanding our universe and lies at the cutting edge of current research.

Now an interesting feature of antimatter particles is that they can annihilate with their normal matter counterparts. For example, if an electron and a positron encounter each other, they will destroy each other in a flash of light. The two particles are converted into a pair of high-energy photons. Matter-antimatter annihilation is a vivid illustration of the conversion between mass and energy. Albert Einstein's famous equation $E = mc^2$ tells us exactly how much energy is produced for a given amount of mass. Specifically, the energy of the photons produced is equal to the total mass of the particles being annihilated times the speed of light squared.

To get an idea for exactly how much energy is produced in annihilation, let's perform this calculation for one gram of matter annihilating with one gram of antimatter. The total amount of mass that's converted into energy is 2 grams — that's one gram of matter plus one gram of antimatter. We have to write that in terms of kilograms for the units to work out. The speed of light is 300,000,000 (three hundred million) meters per second. Plugging the numbers into a calculator, you would find the answer to be 180,000,000,000,000 (one hundred and eighty trillion) joules of energy. It's hard to wrap our heads around a number that big, so let's explore some examples to put it in perspective.

If one gram of antimatter were annihilated with matter all at once, the resulting explosion would be more powerful than the combined explosive force of both atomic bombs dropped on Japan during World War II. Just imagine two cities being completely decimated by something the mass of a paperclip! If all of this energy could be harnessed for domestic use, then with just that one gram of antimatter being annihilated with one gram of matter, the electricity for the average American home could be provided for four and a half thousand years.

Clearly matter-antimatter annihilation can produce incredible amounts of energy. And the same process can be operated in reverse. Large amounts of energy can be converted back into matter and antimatter. In fact, physicists are producing antimatter

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this way all the time. Using particle accelerators, they smash matter particles into each other, producing large amounts of energy — some of that energy can then coalesce into pairs of matter and antimatter particles.

So when can we expect all of our energy problems to be solved by antimatter? Well, don't get your hopes up. We won't be able to use antimatter as an energy source. The reason is that we can never get more energy out of antimatter than we put in to begin with. If we start with some amount of energy and then convert it into antimatter, we must also create an equal amount of matter. Which means that after all of it is annihilated, we end up exactly where we started. The law of energy conservation tells us that we can't just fabricate energy out of the blue and antimatter is no exception to this rule.

But despite its limitations as an energy source, antimatter is still very useful. For example, antimatter was used an experiment at CERN laboratory in Geneva, Switzerland, which collided high-energy beams of protons and antiprotons. In 1983, this experiment resulted in the Nobel Prize winning discovery of an important collection of particles called the weak bosons. Antimatter has played a crucial role in countless experiments and remains at the forefront physics research.

In addition to helping us probe the nature of our universe, antimatter is also used in medical technology in the form of PET scans: positron emission tomography. PET scans are performed by injecting a person with a radioactive substance that emits positrons. This tracer substance is carried throughout the person's blood stream and when the positrons are emitted inside the body, they annihilate with nearby electrons, producing high-energy photons, that can be detected by the scanner. In this way, doctors can tell where certain substances are accumulating in a person's body to help them diagnose and treat their condition. In addition, antimatter may someday be used to treat cancerous tumors by selectively destroying unhealthy cells.

Beyond the realm of medicine, there has been speculation about whether antimatter may someday be used to propel rockets into space. The natural advantage of using antimatter is that it packs a lot of energy into a very small amount of fuel. But with current technologies, there's simply no way to produce enough antimatter to make this feasible. Physicists can only produce antimatter in very small quantities. Performing an experiment on a handful of tiny particles is one thing, but producing enough antimatter to power a rocket is something else entirely. Still, the possibilities are tantalizing and technologies for antimatter production, storage, and controlled annihilation are being explored.

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And regardless of its practical applications, antimatter is a beautiful idea. Matter and antimatter are very similar and yet they are fundamentally opposite. For this reason, the difference between matter and antimatter is really very subtle. If you were to construct an apple entirely out of antimatter, it would look exactly the same to you as an apple made of normal matter. It would have the same color, shape, and mass, but the particles making it up would be fundamentally different. And of course, you wouldn't want to eat it.

In this way, matter and antimatter reflect the ancient Chinese principle of yin-yang. Matter and antimatter are opposite and yet the same — they balance each other, making the laws of physics intrinsically harmonious.

But even more interesting than the symmetry of this idea is the fact that matter and antimatter are completely out of balance in our universe. If for every particle of matter, there's an equal and opposite particle of antimatter, then why is it that everything we see around us is made of matter — where's all the antimatter? In the beginning of the universe at the Big Bang, there was a tremendous amount of energy. This energy should have coalesced into equal amounts of matter and antimatter. Soon after the Big Bang, all of the matter and antimatter should have annihilated, leaving nothing but a sea of photons and no intelligent life forms to talk about it.

And yet, here we are. The earth is made of matter. The sun is made of matter. The whole solar system is made of matter. In fact, it seems that everything is made of matter. Matter-antimatter annihilations produce a recognizable signal of high energy photons, and none of these signals have been observed anywhere in outer space. Why is antimatter completely absent from our universe? This question remains one of the great mysteries of physics, but some clues have already been revealed. For one thing, although matter and antimatter are very symmetric, they aren't exactly opposites of each other, almost as though the yin-yang of the universe is slightly out of balance.

This asymmetry has been observed in the behavior of a particle called the neutral kaon. The kaon is a curious particle that can turn into its own antiparticle and back again. If matter and antimatter were perfectly symmetric, then kaons should switch between matter and antimatter at equal rates. But, quite simply, they don't. Kaons are more likely to adopt their matter form than their antimatter form. It's as if kaons slightly prefer matter over antimatter. Similar asymmetries of this kind have been identified in other particles. In a way, this violation of symmetry is somewhat troubling; it almost seems as though the laws of physics are broken. Matter and antimatter are so close to being perfectly balanced, and yet they aren't.

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And although the kaon seems to prefer matter over antimatter, this slight asymmetry isn't sufficient to explain the overwhelming majority of matter in the universe. A number of other theories have been developed in attempts to explain this conundrum, but the question remains open. How did the near perfect balance between matter and antimatter become broken in the early universe? It will be the job of the next generation of physicists to find a resolution to the antimatter paradox.

One reason that antimatter is such an interesting subject is that it has an unparalleled ability to connect very different fields. Antimatter is observed in the realm of tiny particles, but it leads us to grapple with a cosmic paradox at the scale of the entire universe. It was predicted theoretically based on abstract mathematics and yet it has been applied practically in medical imaging technologies. And although antimatter is a subject of rigorous science, it also appeals to a philosophical outlook on the universe — one of elegant harmony and symmetry, or very nearly so. In fact, it's probably not an overstatement to call antimatter one of the most beautiful ideas in all of physics.

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