

The 64th Compton Lecture Series

Unsolved Mysteries of the Universe: Looking for Clues in Surprising Places

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Lecture 7: Matter and Antimatter, Dancing to Different Drummers?

Isn't the Difference Obvious?

- **Electrically charged particles always have distinct antimatter counterparts, with the same mass, but opposite charge.**
- **Some neutral particles, such as the neutron, also have distinct antimatter counterparts.** (An antineutron is different from a neutron). Other neutral particles, such as the Z-boson, are their own antiparticles.
- Matter and antimatter particles annihilate each other upon collision.
- So, at first glance, it is obvious that matter and antimatter are different. Antiprotons are obviously different from protons in that they have a negative electrical charge. Even antineutrons are obviously different from neutrons in that bringing an antineutron next to a neutron will cause an annihilation, but bringing two neutrons together does not.
- **But, what if our world were made up of antimatter?** (What if normal nuclei were made of antiprotons and antineutrons, what if positrons carried the current to our light bulbs, etc.?) **Would the laws of physics be the same for that world?**
- You might immediately suspect that there is a fundamental difference in how antimatter behaves, since after all, we are made of matter and not antimatter. We have to answer the question of how this situation arose. This question is not fully resolved, and we will talk about it next week.
- Apart from the fact that our world is made mostly of matter and not antimatter, the answer to our question is not so clear—it requires experiments, and difficult ones at that, to find the answer.
- Are dark matter and antimatter the same thing? People often confuse them, but they are completely different categorizations. We regularly create and detect antimatter particles, but we have yet to detect dark matter particles.

Discrete Symmetries C, P, T

- Symmetry is one of the most important concepts in modern physics. Thinking about symmetries and how they are sometimes broken describes much of what physicists do.
- Things in front of me look different from things to my right, but processes going on at both angles appear to be following the same laws of physics. This is called **rotational symmetry**.
- Another example is **time-translation symmetry**. The world around me will look different a year from now. But, it will still appear to follow the same laws of physics.
- Rotational symmetry and time-translation symmetry are continuous symmetries. For example, I can pick any number of angles for rotation.
- **There are also either-or symmetries, or discrete symmetries.** Here, unlike for rotations where you can pick any angle, you either “transform the system” completely or you do not. We will talk about three of them: **parity inversion (P)**, **time reversal (T)**, and **charge conjugation (C)**.
- **Parity inversion (P)**
 - Under a P transformation, all vectors, such as velocity, get reversed.
 - Looking in a mirror essentially accomplishes a P transformation. (Technically, a 1-dimensional mirror doesn't accomplish a pure P transformation, since it only reverses one of the three axes. But, since a simple 180° rotation fixes this problem, the distinction is not important.)
 - If P is a good symmetry, physical processes observed in a mirror will look still look like they are obeying the laws of physics.
- **Time reversal (T)**
 - Don't confuse this with time-translation, where you are just letting some time elapse.
 - In a T-transformation, we actually reverse time.
 - If T is a good symmetry, movies played backwards in time will look like they are obeying the same laws of physics.
 - This is a little confusing, because of entropy. If I drop a glass full of water and it shatters, things will look wrong in the time-reversed movie. However, this is an issue of statistical likelihood, and not of the fundamental interactions. If we actually gave the water molecules and glass shards just the right momenta, we could in principle actually create the process that we see in the time-reversed movie. So, there is no T-violation here—real T violation is actually very difficult to observe.
- **Charge conjugation (C)**
 - Here, we exchange all particles with their antiparticles.

- Note, C also changes many neutral particles such as neutrons, so the name is a little misleading
- If C is a good symmetry, a world made of antiprotons, antineutrons, positrons, etc. will look like it is obeying the same laws of physics as ours.

Violation of C, P, T Symmetries

- We now know that none of these by themselves are good symmetries, but it was difficult to find this out.
- The first violation was seen in beta-decays of cobalt-60, in 1956. Here, both C and P symmetries are violated. It turns out that C and P are *maximally violated* in weak interactions. But, since weak interactions are so rare, it took a long time before we noticed.
- After discovery of C and P violation, most physicists assumed that CP (application of both a C and a P transformation) was still a good symmetry.
- If CP is still a good symmetry, things are really not that strange. Antiparticles would still behave exactly like particles with reversed charges, so long as you watched them in a mirror.
- However, CP violation was found in the decay of kaons (or K-mesons) in 1964.
- This shocked most physicists.
 - It was no longer possible to say that matter and antimatter followed the same rules. A clear example of this is the decay of the K_2 meson.
 - We start with a K_2 and look at a certain subset of its decay products. (Technically, we need to wait long enough for the weak interaction to turn the K_2 into its long-lived cousin the K_L , but that is just a detail). One of the decay modes for this particle gives you an electron, but a different mode gives you a positron.
 - K_2 is its own antiparticle. It looks the same when viewed in a C- or a CP-mirror. So if nature treats particles and antiparticles the same way, we expect an equal balance electrons and positrons in the decay products. Otherwise this decay process will look funny in the CP-mirror.
 - However, experiments show that we get the positron 0.3% more often than we get the electron.
 - For other neutral decays, such as for the neutron, things look funny in a C-mirror but look OK in a CP-mirror. However, the double transformation doesn't fix the K_2 asymmetry. Its decay looks wrong in both a C-mirror and in a CP-mirror.
 - So, nature treats matter and antimatter differently. Some processes create an imbalance of one over the other. The K_2 process we looked at favors antimatter, but other processes favor matter.

- **In proverbial form, matter and antimatter do indeed dance to different drummers.** But only slightly different ones.
- CP violation provides a few clear definitions, all of which are surprising to physicists who had previously thought that nature didn't play favorites.
 1. We can define matter as opposed to antimatter
 2. We can define positive charge as opposed to negative charge
 3. We can define left-handedness as opposed to right-handedness (that has not been explained here, but it is related to what we have discussed).

Time-Reversal Symmetry (T) Violation

- The CPT theorem is a general property of quantum field theories, if one makes only a few basic assumptions.
- Consequences of CPT are that many properties of particles and antiparticles are either identical or opposite. For example, CPT says that particles and antiparticles have equal mass but opposite charge. (CPT only claims this sort of symmetry for some properties, not for others like the ones we discussed above for the kaons.)
- In the kaon system, experimenters have found that some processes have a different probability to happen in the forward direction than in the reverse direction. $P(A + B \rightarrow C + D) \neq P(C + D \rightarrow A + B)$. This is an observation of T-violation.
- Other experiments are underway in attempts to observe electric dipole moments (EDMs) of neutrons, protons, or electrons. The presence of a non-zero EDM would also be a clear indication of T violation. So far, experiments have not found a non-zero EDM.