Teacher notes
Topic E

Antiparticles

We saw the existence of antiparticles in beta plus and beta minus decay. In beta plus decay we produce the positron, the antiparticle of the electron and in beta minus decay we produce an anti-neutrino, the antiparticle of the neutrino. Each particle in nature has an anti-particle which has the same mass as the particle, but all other physical characteristics are opposite. So, the positron, for example, has the same mass as an electron but opposite electric charge. Some neutral particles are their own anti-particle so that there is no way to distinguish the particle from its anti-particle. The photon falls into this category. But some neutral particles have a distinct antiparticle. For example, the anti-neutron is distinguished from a neutron by a property called baryon number. A positron and an anti-proton can combine to form an anti-hydrogen atom.

Anti-particles were predicted by one of the most significant but least well-known physicists of the 20th century, Paul Dirac. Dirac attempted to unify the quantum mechanics of the time with special relativity. The result was Dirac's equation that described electrons and their interactions with photons. The equation was peculiar, however, because it allowed for negative energy states. Therefore, nothing could stop an electron, in an atom, from making a transition to one of those negative energy states emitting photons in the process. But since the negative energy states extended to negative infinity the process would never stop and electrons would emit an infinite amount of energy. Dirac solved this problem by postulating that all the negative energy states were filled with electrons. By Pauli's principle, no electron could then make a transition to a negative energy state since no two electrons could occupy the same quantum state. However, a photon colliding with one of the negative energy electrons could give it enough energy to make the total energy of the electron positive and this electron would then appear as an ordinary electron. But the vacuum, which used to be filled with negative energy electrons, now misses one electron, there is a "hole" in the vacuum and so the charge of the vacuum is now one positive unit. Dirac originally thought that this "hole" might be the proton. It turned out to be the positron, the anti-particle of the electron, discovered by Carl Anderson in 1932. This is Dirac's hole theory of positrons.

However, every particle has an anti-particle not just electrons. Spin ½ particles obey the Pauli principle. Bosons, particles with integral spin, do not. Thus, Dirac's theory cannot prevent a boson from making a transition to a negative energy state. So, the Dirac equation, contrary to what Dirac thought, is not a relativistic generalization of the Schrödinger equation. The Dirac equation describes the quantum mechanics of relativistic spin ½ particles only.

There are other problems with Dirac's interpretation as well, for example the vacuum containing an infinite amount of negative energy electrons would have an infinite negative charge. The hole theory has now been abandoned and has been replaced by quantum field theory.

Another mystery surrounding anti-particles is this: why is the matter we observe in the Universe predominantly made of particles and not anti-particles? Since there is symmetry between particles and anti-particles we would expect equal numbers of particles and anti-particles i.e. equal numbers of matter and anti-matter. A partial solution is that the symmetry between particle and anti-particles is not a perfect symmetry. But that is not enough to explain the lack of anti-matter in the Universe and the puzzle still remains.