Chapter 5 Symmetries and Antimatter

Scientists use *symmetry* both to solve problems and to search for new understandings of the world around us. In nuclear science the concept of symmetry plays a key role in gaining an understanding of the physical laws governing the behavior of matter. It provides a shortcut based on geometry for getting at some of Nature's innermost secrets. Because the laws of physics are the same at any time (symmetry in time) and any location (symmetry in position) as another, the laws of conservation of energy and momentum apply.

Symmetry in Rotation

Consider for example the simple idea that when an object is rotated through an angle of 360° it should end in a state no different from its initial state. If we apply this simple symmetry in quantum mechanics, the physics theory of matter and energy at the smallest distances, we find that it imposes the requirement that the angular momentum of rotating objects must be quantized in units of $\hbar$ (Planck's constant, h, divided by 2). A spinning object, be it a planet, a top, or a nucleus, should only be able to have rotations such that its angular momentum comes out in "chunks" $\hbar$ in size.

Imagine, then the big surprise that swept through the world of physics when it was discovered in the 1930s that this symmetry was "broken" by particles like electrons, protons and neutrons, which were found to have "spin 1/2", or one half an $\hbar$ unit as their "built-in" angular momentum (called "intrinsic angular momentum" or simply "spin"). In nuclear science it has become standard to use $\hbar$ as the measuring stick for angular momentum and to describe the angular momentum of nuclei in units of $\hbar$. Thus, we say that a nucleus has angular momentum 0, or 2, or 7/2, in units of $\hbar$.

One consequence of the half-integer spins of neutrons and protons is that nuclei with an odd number of nucleons must have half-integer angular momentum, while nuclei having an even number of nucleons must have integer angular momentum (in $\hbar$ units). Another consequence is quite bizarre: objects with half-integer spin must be rotated by 720° (not 360°) before they return to their initial state! This peculiar behavior has been demonstrated using very slow (ultracold) spin-oriented neutrons from a reactor, which are split into two beams. In one beam the neutrons are rotated about an axis along their direction of motion through some angle, and then the beams are recombined. It is found that when the rotation angle is 360°, the combined beams are out of phase and cancel, (meaning that they are shifted away from the detector) while after 720° of rotation the beams are in phase and reinforced (meaning that they show a large signal at the detector). A rotation of 720° is needed to put the neutrons back in their original state.

Charge, Parity, and Time Reversal (CPT) Symmetry

Three other symmetry principles important in nuclear science are parity P, time reversal invariance T, and charge conjugation C. They deal with the questions, respectively,

of whether a nucleus behaves in a different way if its spatial configuration is reversed (P), if the direction of time is made to run backwards instead of forward (T), or if the matter particles of the nucleus are changed to antimatter (C). All charged particles with spin 1/2 (electrons, quarks, etc.) have antimatter counterparts of opposite charge and of opposite parity. Particle and antiparticle, when they come together, can annihilate, disappearing and releasing their total mass energy in some other form, most often gamma rays.

The changes in symmetry properties can be thought of as "mirrors" in which some property of the nucleus (space, time, or charge) is reflected or reversed. A real mirror reflection provides a concrete example of this because mirror reflection reverses the space direction perpendicular to the plane of the mirror. As a consequence, the mirror image of a right-handed glove is a left-handed glove. This is in effect a parity transformation (although a true P transformation should reverse all three spatial axes instead of only one).

Until 1957 it was believed that the laws of physics were invariant under parity transformations and that no physics experiment could show a preference for left-handedness or right-handedness. Inversion, or mirror, symmetry was expected of nature. It came as some surprise that the radioactive decay beta decay process breaks P symmetry. C. S. Wu and her collaborators found that when a specific nucleus was placed in a magnetic field, electrons from the beta decay were preferentially emitted in the direction opposite that of the aligned angular momentum of the nucleus. When it is possible to distinguish these two cases in a mirror, parity is not conserved. As a result, the world we live in is distinguishable from its mirror image.

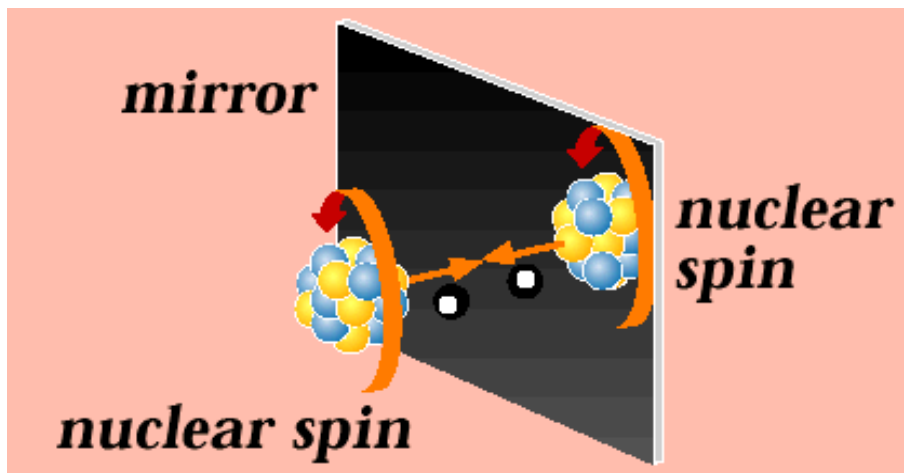Figure 5-1 illustrates this situation. The direction of the emitted electron (arrow)

Fig. 5-1. Parity inversion of a nuclear decay

reverses on mirror reflection, but the direction of rotation (angular momentum) is not changed. Thus the nucleus before the mirror represents the actual directional preference, while its mirror reflection represents a directional preference not found in nature. A physics experiment can therefore distinguish between the object and its mirror image.

If we made a nucleus out of antimatter (antiprotons and antineutrons), its beta decay would behave in almost the same way. However the mirror image in Fig. 5-1 would represent the preferred direction of electron emission, while the antinucleus in front of the mirror would represent a directional preference not found in nature.

The great physicist, Richard Feynman, told a story to illustrate this point: suppose you were in two-way contact with some alien species, but only by "telegraph" (*i.e.,* light flashes or radio signals). The well known procedures of SETI (Search for Extraterrestrial Intelligence), starting with prime numbers and progressing to pictures, physics, and chemistry information could be used to develop a common language and arrive at a good level of communication. You could tell the alien how tall you are by expressing your height in mutually understood wavelengths of light. You could tell the alien how old you are as some large number of ticks of a light-frequency clock. Now you want to explain how humans shake hands when they meet, and you describe extending your right hand. "Wait a moment!" says the alien. "What do you mean by 'right'?"

Until 1957, there would have been no way of answering that question. But now you could use the parity experiment shown in Fig. 5-1. You could tell the alien to turn the experiment until the electrons come out in the upward direction (the direction opposite gravity), and the front edge of the rotating nucleus will move from right to left or clockwise to make the angular momentum. This works because the parity violation of the weak interaction allows us, at a fundamental level, to distinguish right from left.

Feynman also had a punch line to this story. Suppose, after lots of communication you finally can go into space and meet your alien counterpart. If, as you approach one another, the alien extends its left hand to shake, watch out! He's made of antimatter! This, of course, is because a parity violation experiment constructed of antimatter would give the opposite result.

If the mirror in Fig. 5-1 not only reversed spatial direction but also changed matter to antimatter, then the experiment in front of the mirror would look just like its mirror image. Changing both C and P preserves the symmetry and we call this CP symmetry. The separate violations of P symmetry and C symmetry cancel to preserve CP symmetry. These symmetry violations arise only from the weak interaction, not from the strong and electromagnetic interactions, and therefore show up strongly only in beta decay.

There are fundamental reasons for expecting that nature at a minimum has CPT symmetry—that no asymmetries will be found after reversing charge, space, and time. Therefore, CP symmetry implies T symmetry (or time-reversal invariance). One can demonstrate this symmetry by asking the following question. Suppose you had a movie of some physical process. If the movie were run backwards through the projector, could you tell from the images on the screen that the movie was running backwards? Clearly in everyday life there would be no problem in telling the difference. A movie of a street scene, an egg hitting the floor, or a dive into a swimming pool has an obvious "time arrow" pointing from the past to the future. But at the atomic level there are no obvious clues to time direction. An electron orbiting an atom or even making a quantum jump to produce a

photon looks like a valid physical process in either time direction. The everyday "arrow of time" does not seem to have a counterpart in the microscopic world—a problem for which physics currently has no answer.

Until 1964 it was thought that the combination CP was a valid symmetry of the Universe. That year, Christenson, Cronin, Fitch and Turlay observed the decay of the long-lived neutral K meson, K_L^o, to $^+ + ^-$. If CP were a good symmetry, the K_L^o would have CP = -1 and could only decay to three pions, not two. Since the experiment observed the two-pion decay, they showed that the symmetry CP could be violated. If CPT symmetry is to be preserved, the CP violation must be compensated by a violation of time reversal invariance. Indeed later experiments with K^0 systems showed direct T violations, in the sense that certain reaction processes involving K mesons have a different probability in the forward time direction (A + B   C + D) from that in the reverse time direction (C + D   A + B). Nuclear physicists have conducted many investigations searching for similar T violations in nuclear decays and reactions, but at this time none have been found.

This may change soon. Time reversal invariance implies that the neutron can have no electric dipole moment, a property implying separation of internal charges and an external electric field with its lines in loops like Earth's magnetic field. Currently ultracold neutrons are being used to make very sensitive tests of the neutron's electric dipole moment, and it is anticipated that a nonzero value may be found within the next few years.

Matter and Antimatter

Time-reversal invariance and the CP violation are connected to another asymmetry of the universe, the imbalance between matter and antimatter. At the microscopic level, matter and antimatter are always created together in 1:1 correspondence. High-energy collisions produce equal numbers of quarks and antiquarks. And yet, our universe has a conspicuous surplus of matter, of which our surroundings and we are made. How did this happen?

A clue to this deep mystery is provided by the CP violation in the K^o meson, which shows decay modes having a preference for matter over antimatter. The K^o does not have enough mass for its decay to produce protons. Its decay asymmetry suggests that some more massive particle, perhaps a B^o meson containing a bottom quark, might in the early universe have decayed preferentially into protons rather than antiprotons, leading to the present day dominance of matter. Current experiments using the B-Factory at the Stanford Linear Accelerator Center (SLAC) are investigating this problem.

Antimatter exists in nature only in the form of antiprotons present in very small numbers in cosmic rays and in *positron*s (antimatter electrons) produced in some radioactive decays. Recently, evidence has also been found for a "fountain" of positrons ejected from some object near the center of our galaxy, presumably a black hole.

However, we are getting better and better at producing and storing antimatter in the laboratory. Antiprotons, antineutrons, and even antideuterons (a nucleus consisting of an antineutron and an antiproton) are routinely produced using high-energy particle

accelerators at Fermilab in Illinois and CERN in Geneva, Switzerland. Positrons and antiprotons have been trapped in electric and magnetic fields and held under high vacuum for several months. Recently, "antihydrogen" atoms having a positron orbiting an antiproton have been formed in laboratory experiments. These researchers are looking for any indication that trapped positrons, antiprotons, and antihydrogen atoms show a behavior that differs in any way from that of their normal matter counterparts, because any such difference would represent a violation of CPT symmetry.

Antimatter nuclei are also interesting for other reasons. Special facilities at CERN and Fermilab provide beams of low energy antiprotons and permit nuclear scientists to study the interactions of antiprotons with matter. While a positron and an electron usually annihilate to form a pair of gamma-ray photons traveling in opposite directions, the annihilation of an antiproton with a proton is more complicated. Several mesons are usually produced. About a third of the mass energy of the proton-antiproton pair becomes inaccessible in the form of energetic neutrinos.

Nevertheless, antimatter can be viewed as an extremely compact form of stored energy that can be released at will by annihilation with matter. The US Air Force has commissioned design studies of antimatter-powered space vehicles that, given a supply of antimatter, look quite feasible. The problem with such schemes is that production of any significant quantity of antimatter would cost far too much right now to be economically feasible.

Other Symmetries

In addition to the symmetries described above, nuclear scientists use a number of other approximate symmetries to describe and predict the behavior of nuclei. Examples of these are charge independence, the expectation that, at the nuclear level, neutron-proton systems should behave the same as proton-proton or neutron-neutron systems; and charge symmetry, the expectation that the interactions between two neutrons should be the same as that between two protons. Charge symmetry can be demonstrated by comparing "mirror nuclei," two low-mass nuclei that have their neutron and proton numbers interchanged and which have very similar nuclear structure, for example ^{13}C (Z=6, N=7) and ^{13}N (Z=7, N=6).

A related symmetry is isospin symmetry, which is related to interchanging the roles of neutrons and protons in certain nuclei. These three symmetries are destroyed when the Coulomb force becomes sufficiently strong, but nevertheless they have proved to be useful approximations in many areas of nuclear science.

Books and Articles:

Martin Gardner, *The New Ambidextrous Universe,* W. H. Freeman & Co., New York, 1990. (Revised edition)

Richard Rhodes, *The Making of the Atomic Bomb,* Simon and Schuster, New York, 1986.

Richard P. Feynman and Stephen Weinberg, *Elementary Particles and the Laws of Physics,* Cambridge University Press, Cambridge, 1987.

Hannes Alven, *Worlds-Antiworlds: Antimatter in Cosmology.*

Web Sites:

Symmetry and Antimatter
http://athena.web.cern.ch/athena/ —Description of antihydrogen experiment at CERN and possible applications.

Antimatter Space Propulsion
http://www.engr.psu.edu/antimatter/ — Research in using antimatter for space propulsion. Please note that in the future it will be moved to http://www.synergistictech.com/

The Antimatter Factory
http://cern.web.cern.ch/livefromcern/antimatter/factory/AM-factory01.html — The site describes the antiproton decelerator of CERN. This machine produces a copious amount of antiprotons.