Symmetries of Space, Time, and Matter

R. Cahn

Lawrence Berkeley National Laboratory

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The history of particle physics has been for the most part the history of particles, the story of their discoveries in cosmic rays and at accelerators. Yet the questions that define particle physics today are not so much about the particles themselves as about underlying patterns that they reveal, the patterns of symmetry and especially about the breaking of those patterns, which ultimately determines the nature of the world we live in.

Newton taught us that F=ma, but what are the forces - the F - of Nature? By the 1920's it was apparent that there were at least four kinds of forces. Most obvious were gravity and electromagnetism. In addition there was the strong force that held together the nucleus. There was also the weak force responsible for beta decay, one of the forms of radioactivity.

1 Isospin

When new subatomic particles were first discovered in the 1930s and 40s, the first task was taxonomy. Particles with similar properties were grouped together. The neutron, discovered in 1932, had a mass just slightly more than that of a proton. Its properties, too, were like those of a proton in that it lived in the nucleus. It differed in being electrically neutral rather than positively charged.

2: up and down electron; neutron and proton

Werner Heisenberg proposed that the neutron and proton ought to be viewed as two faces of the same entity, the nucleon. An electron spin has only two possible orientations measured relative to some direction, say up and down. Heisenberg's picture was that analogously there were two orientations possible for the nucleon: proton, nucleon up, and neutron, nucleon down.

Of course these orientations were not in real space but some hypothetical "internal" isospin space. Just as all directions in physical space are equivalent - space is isotropic - all directions in isospin space would be equivalent up to small corrections, like those responsible for the difference between the neutron's mass and the proton's mass. The strong force would be isotropic - preferring no direction in isospin space. This isospin symmetry correctly predicted regularities among the nuclides.

There are two challenges here: why is there this isospin symmetry and why is the symmetry broken, i.e. not exact? This is of more than passing interest. The neutron has more mass than an electron and proton combined, but only by a small amount. Had the breaking of

isospin worked out differently, the neutron might have been lighter than these two together, that is, lighter than a hydrogen atom. Hydrogen atoms would then have been unstable. This would have made the world a very different place.

2 Charge Conjugation

3: picture of positron discovery

Another kind of symmetry became apparent with the discovery of the positron, a particle with the mass of the electron, but with positive rather than negative charge. In the Figure we see a cloud chamber picture with a track taken in a 1.5 T magnetic field. From the direction of the curvature, the particle was either an negative electron entering from above or a positive particle entering from below. Because the track is more curved above the lead plate dividing the chamber in half, it is clear that it entered from below, lost energy in the plate and thus curled up more in the magnetic field. This picture of antimatter was taken in 1933.

As predicted by quantum theory, every particle that was subsequently found turned out to have an antiparticle with identical mass but opposite electric charge. Here the symmetry seemed exact since the masses of particle and antiparticle were truly identical. The symmetry operation that transformed particles into antiparticles is indicated by C.

3 C and P

If you watch an experiment and at the same time observe it in a mirror can you tell which is the real thing? The parity operation is equivalent to making a mirror image. If parity is a true symmetry of nature, there is no way to determine for sure which is the real thing and which is the mirror image. In the mirror image you might find a surprising number of left-handed graduate students, but would not be conclusive.

4: Lee and Yang. Wu

It wasn't until the insight of T. D. Lee and C. N. Yang that it was realized that the parity symmetry really hadn't been tested in weak interactions, the interactions responsible for beta decay. They proposed a number of experimental tests and C. S. Wu and her collaborators at the National Bureau of Standards were the first to find that parity was in fact broken and broken badly in beta decay.

5: beta decay, beta-plus decay

An especially clear manifestation of parity violation is seen in the spin of an electron emitted from a nucleus. Measurements show that such electrons are nearly entirely left-handed, i.e. rotating clockwise coming at you. But if you look in a mirror, you'll see right-handed electrons, not the real thing. Parity isn't a true symmetry – it isn't conserved – in weak interactions like beta-decay. The image with the left-handed electrons is the real one, the one with the right-handed electrons just the mirror image.

What happens when a positron is emitted from a nucleus? Measurements show that these positrons are right-handed. If C were a real symmetry we would find that the left-handed electrons would be replaced by left-handed positrons. Instead it is the combination CP, which changes a left-handed electron into a right-handed positron, that seems to work. CP could be a true symmetry though neither C nor P is.

4 Quarks and Leptons

6: table of quarks and leptons

Starting in the 1950s, there was a tremendous proliferation of elementary particles: pions, kaons, lambdas, sigmas,... In the 1960s it was realized that they could be explained in terms of quarks. Only two quarks, the u and d, are needed to describe ordinary matter like protons and neutrons. The remaining quarks, s, c, b, and t, are found only in particles that decay rapidly, in much less than a microsecond. In addition to the six quarks, there are six particles that, like the electron, do not feel the nuclear forces enjoyed by protons and neutrons. Of the six, three are charged like the electron and three are neutral. The latter are called neutrinos.

5 Electroweak Symmetry

A free neutron lives about 15 minutes on average before decaying into a proton, an electron, and an anti-neutrino. At the level of quarks, this is the decay of a d quark to a u quark. Just as the neutron and proton form a pair, so do the d and u quarks, or rather the left-handed d quark and the left-handed u quark since it is the left-handed particles, and right-handed antiparticles, that participate in the weak interactions.

In contemporary particle physics the quarks and leptons are grouped into doublets (u, d), (c, s), (t, b), (ν_e, e), (ν_μ, μ), (ν_τ, τ). Each pair of left-handed quarks and leptons is analogous to the neutron-proton pair: it is a doublet under a "weak isospin."

7: weak isospin

This result is counterintuitive. It is one thing to say the neutron and proton are two aspects of a single entity. The neutron and proton, after all, are found together in the nucleus. How can the electron and the neutrino be two faces of the same thing? The electron is the ubiquitous substance of chemistry while the neutrino is essentially imperceptible and never encountered in everyday life.

8: z line shape

The symmetry that makes the left-handed electron the partner of the neutrino is known as electroweak symmetry. As the name suggests, it makes a single theory of electromagnetism and weak interactions. Despite its improbable pairing of an electron and a neutrino, this symmetry has been tested to high precision, especially by studying a particle called Z, which is a sort of heavy photon. We see in the Figure an example of the agreement between electroweak theory and experiment. The data agree perfectly with the expectations from three kinds of neutrinos.

Nonetheless, since the electron and the neutrino really are very different we know this symmetry is broken. What we don't know is how it is broken. To find out, we look for vestiges of the symmetry breaking. Those vestiges might consist of a new particle called the Higgs boson.

It is not the Higgs boson per se that we are after, but an understanding of how the electroweak symmetry is broken. The breaking of isospin symmetry is responsible for the small difference between the masses of the proton and neutron. The breaking of electroweak symmetry is responsible for the entirety of the masses of the quarks and leptons, and the masses of the Z boson and its charged partners, the Ws. The actual goal, then, is to learn where mass comes from.

6 CP

9: CP, Jim Cronin, Val Fitch

CP symmetry was all the could be salvaged from the failure of parity in 1956. But this symmetry, too, turned out to be inexact. This was learned through the study of K mesons, perhaps the all-time favorite plaything of particle physicists. Had CP been a good symmetry, the the neutral K meson and its antiparticle should have sorted themselves out into one particle that was CP even and another that was CP odd. Indeed, there are two neutral K mesons, one with a short lifetime, K_S and the other with a long lifetime, K_L. CP conservation would forbid the K_L, which would be CP odd, to decay into two pions, since this state is CP even. In 1964, this decay was found to occur about two times in 1000. Another symmetry turned out to be broken, if only slightly.

10: Imagining CP symmetry

We can think of parity as exchanging right and left hands. If we imagine charge conjugation, then, as interchanging black and white, then the CP image of a black hand on a white background is a white hand on a black background.

11: Sakharov

Symmetry breaking makes the world what it is. Indeed, in 1967 Andrei Sakharov pointed out that without the breaking of CP there would likely be no matter at all in the Universe. It is CP violation that allows unequal numbers of nucleons (neutrons plus protons) and antinucleons (antineutrons plus antiprotons) to emerge from the Big Bang. Matching images of black and white hands, when folded over on each other, would just cancel each other out. The same way, matter and anti-matter would annihilate and cancel each other after the Big Bang if CP is conserved, that is, a true symmetry of nature. For matter to survive the earliest moments of the universe we need a small mismatch, breaking the CP symmetry.

How can we study CP violation without re-enacting the Big Bang? CP violation always involves the phenomenon of interference. Optical interference occurs when there are two paths light can follow to reach the same point. Quantum mechanical interference occurs when there are two pathways for a particle to follow to arrive at the same circumstance.

11: oscillation, decays

A B meson is a souped-up version of a K meson, with the s quark replaced by a b. B mesons are ideal for studying CP violation because they come with built-in interference opportunities. A particle that begins as a B^0 will oscillate back and forth between its B^0 form and the $\overline{B}^0$ form. At any particular moment, the particle is partly B^0 and partly $\overline{B}^0$. Only the B^0 form can decay so as to produce a positron, while the $\overline{B}^0$ form can give an electron. This, and some other analogous signatures, enable us to distinguish between the B^0 and $\overline{B}^0$.

12: oscillation patterns

If we watch for positron we see only the B^0 portion. We can imagine this experiment as an analog of an interference pattern formed when light passes through two slits. The two slits are the B^0 and $\overline{B}^0$. When we observe positrons we are closing off the slit for $\overline{B}^0$. We see an oscillation because the amount of B^0 present oscillates in time as the meson goes back and forth between its B^0 and $\overline{B}^0$ forms.

13: mixing patterns

Watching for positrons when we start with a B^0 gives the same pattern as watching for electrons when we start with a $\overline{B}^0$. This is consistent with CP conservation because we have taken the CP conjugate of the starting arrangement and looked for the CP conjugate in the final arrangement. We see oscillations here, but no CP violation. To see CP violation we need interference. We see interference when a particular decay can proceed through both the B^0 and $\overline{B}^0$ paths.

14: $B \to \psi K_S$

The best way to do this is to look for the decay into $J/\psi K_S$. The J/ψ has a double name because it was discovered simultaneously at the Stanford Linear Accelerator Center and at Brookhaven National Laboratory. Brookhaven's J and SLAC's ψ is made of a charmed quark and its antiparticle. Under the combined operations CP, the J/ψ turns into itself.

The K_S is essentially CP-even, up to the very small deviation discovered in 1964. Altogether the $J/\psi K_S$ state remains $J/\psi K_S$ after the action of CP.

Now if we see a difference between the decay of a B^0 into $J/\psi K_S$ and its CP-mirror-image $\overline{B}^0$ into $J/\psi K_S$ this will show a violation of CP. The likely source of this CP violation is at the point where the B^0 becomes a $\overline{B}^0$, or vice versa.

A difference would appear as an oscillation, but making opposite contributions to the B^0 and $\overline{B}^0$ patterns. What is especially attractive here is that the amplitude of these oscillations is determined by the pattern of the pairs of quarks that are joined by the weak interactions. By measuring other weak decays that have nothing to do with CP violation, we can predict what we will find in the CP measurements.

This is such a beautiful idea and attractive experimental possibility that several groups are actively pursuing it. Some results have already been announced, though with rather limited statistics. Experiments at the KEK accelerator in Japan and at PEP-II at the Stanford Linear Accelerator Center are on-going.

7 Supersymmetry

Particles are no longer the central issue of particle physics. It is symmetries and how they are broken that have taken center stage. These symmetries can challenge our understanding of space-time itself. From Einstein we learned that we need to form a picture of nature that works for all observers, stationary or moving. Physical laws must accommodate switching from one observer's frame to another's. This symmetry is known as Lorentz invariance. Over the past two decades physicists have investigated whether there might be a larger symmetry – supersymmetry. If so, there must be partner particles for all the known particles. The status of supersymmetry was summarized succinctly by one of my colleagues while introducing one of the originators of supersymmetry: "Supersymmetry has withstood the test of time, though there is no evidence to support it."

16: Supersymmetry

Though not yet observed, the super partners already have names, for the electron, the selectron, for quarks, squarks, for the photon, the photino.

Since we haven't seen them their masses must be much greater than those of the known particles. Supersymmetry must be quite broken. The search for supersymmetric particles will continue at the Fermi National Accelerator Lab when the highest energy accelerator in the world begins taking data this year. A much higher energy machine, the replacement for the SSC, will first operate in Geneva around 2005, and there supersymmetry should show its face if it ever will.

If there is a supersymmetry, it is fortunate that its breaking leaves as the lightest charged particle the spin-one-half electron rather than its spin-zero partner, the selectron. A world of selectrons wouldn't give us chemistry, which depends on the exclusion principle for spin-one-half particles. All the selectrons would quickly find their way into the lowest orbital around, regardless of how many other selectrons were already occupying it. All molecules would fuse together. Chemistry and biology disappear as everything contracts into an undifferentiated single blob.

8 Extra Dimensions

17: Extra dimensions

Space might be stranger still. We know there are three spatial dimensions. Or do we? The violation of parity was startling because everyone knew that a mirror image was just as good as the original. In the last three years, our prejudices have been challenged by the recognition that extra dimensions might have gone unnoticed. This could happen if we're stuck in the usual three dimensions, but gravity leaks out into the extra ones. If this happens, we might see bizarre events in high-energy collisions.

9 Accelerating Universe

18: Accelerating Universe

Particle physics is joined to cosmology because in the Big Bang all elementary particles were produced and it was their interactions that governed the first instants of existence. In the last few years we've learned that we need particle physics to understand the future as well as the past of the entire universe.

Even the present is a challenge to particle physics. A variety of measurements indicate that most of the mass of the universe is not accounted for. It isn't in the stars or even in ordinary matter made of atoms. We know this from the motion of visible stars and galaxies and from the abundances of the elements. We can't see this dark matter, but it is the majority shareholder of substance. From the known or hypothesized particles we can identify some candidates for dark matter: neutrinos or supersymmetric particles. Even more exotic possibilities are hypothesized, but we won't know the answer until some experiment tracks it down.

But dark matter has turned out to be only the beginning of the story. A group in Berkeley demonstrated that it was possible to discover and study very distant supernovae. By measuring their brightness and their redshift they hoped to learn whether there was enough mass in the universe to make it finally fall back onto itself in a final Big Crunch or whether gravity would slow but never actually halt it. When the supernova were found, the result that came back astonished them and their competitors who both saw signs that the expansion was not slowing at all, but rather speeding up, thumbing its nose at the power of gravity.

The most conservative interpretation restores Einstein's abandoned cosmological constant, anathema to particle physics. The supernova data indicate that the cosmological constant, in appropriate units, is somewhere around 1.0, say 0.7. Particle theory is comfortable with two values, zero and 10^{120}. More radical than the cosmological constant is the possibility that all space is pervaded by something stranger even than dark matter, termed dark energy.

10 Conclusion

The symmetries of space, time, and matter are the primary issues for fundamental physics today. What breaks electroweak symmetry and gives mass to the particles? What accounts for the breaking of CP and explains why any residual matter emerged from the Big Bang? Are the symmetries of space-time part of a larger supersymmetry? Do we live in a world with more than three space dimensions? What particles account for dark matter? Is the universe pervaded by a vacuum energy that accounts for a cosmological constant, or by something even more bizarre? Only experiment can tell.

The task of particle physics is not to explore exotica but rather to understand the ordinary. The ordinary world has some very light particles, electrons, and some much heavier particles, neutrons and protons, which together make this such an interesting place. The idealized, symmetric world, has massless quarks and leptons, elegant, but without the possibilities of differentiation that make the ordinary world extraordinary. Love may make the world go 'round, but symmetry breaking makes the world.

The task of understanding why there is anything here at all lies behind the intense competition to study CP violation. Without CP violation, the promise of the material world provided by electroweak symmetry breaking would not have been fulfilled. The twin challenges of the breaking of CP and of electroweak symmetry will drive particle physics research over the next decade.