FERMILAB-FN-0827-T

Respect for Symmetry

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German version published as "Respekt für Symmetrie"
in *Physik-Journal* **7** (12), 19–21 (December 2008)

The award of the 2008 Nobel Prize in Physics to Yoichiro Nambu of the University of Chicago "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics" was greeted with warm appreciation by colleagues around the world, for whom he has long been an icon. Nambu's contributions constitute an essential element of an aspiring theorist's education, especially in particle physics. From early studies of dispersion relations encapsulating the analytic properties of scattering amplitudes [1], through the origins of quantum chromodynamics as the theory of the strong interactions, to the birth of string theory and beyond, Nambu has been consistently prescient. His ideas and his way of thinking pervade the standard model of particle physics. The study of Nambu–Goldstone modes, spin waves, second sound, and their damping in magnets, superfluids, and liquid crystals was one of the central areas of condensed-matter research in the second half of the twentieth century.

After earning his doctorate from the University of Tokyo under the supervision of Shinichiro Tomonaga, Nambu spent two years as a member of the Institute for Advanced Study in Princeton. He joined the University of Chicago in 1954, at the end of the Fermi era, and became Professor Emeritus in 1991.

Nambu's research shows him to be a meticulous thinker attuned to taking lessons won in one setting and applying them elsewhere in unexpected and revealing ways. His deftness with mathematical analysis is coupled with an acute physical intuition. Nambu in person is tidy, a bit formal, placid, and understated—all leavened with a subtle sense of humor. It is common for him to thank younger colleagues for discussing his most advanced ideas with him. His long-time colleague Peter Freund has written an engaging short portrait [2]. Nambu himself has written for a general audience [3], and a volume of selected works is available [4].

We physicists have learned to pay close attention to the symmetries of physical situations, and we are particularly attentive to symmetries of the laws of nature. We have learned through experience that symmetries of the laws are not necessarily manifested in the outcome of those laws. The electromagnetic laws that govern the arrangement of molecules in a drop of water are invariant under three-dimensional rotations, but at temperatures below the freezing point the water crystallizes into a snowflake—a roughly planar structure with sixfold symmetry. Only a subgroup of the original SO(3) symmetry remains: a discrete set C_6 of $\pi/3$ rotations about a single symmetry axis perpendicular to the center of the snowflake. When, by circumstance, a physical system does not exhibit all the symmetries of the laws that govern it, the symmetry is said to be hidden, or spontaneously broken. A phase transition is typically correlated with the spontaneous breaking of a symmetry.

The Nobel Committee cited Nambu for discovering the far-reaching implications of hidden symmetries in the subatomic realm described by relativistic quantum field theories. His opening insight emerged from the apparently distant arena of superconductivity. The superconducting ground state in the microscopic Bardeen–Cooper–Schrieffer theory [5] does not exhibit the gauge invariance of the underlying interaction, electrodynamics. Nambu found that this lack of gauge invariance was not a disease of the BCS theory, but the key to understanding the properties of superconductors [6]. The superconducting ground state is a consequence of the spontaneous breaking of the gauge symmetry of quantum electrodynamics—the freedom to change the phase of the electron wave function independently at each point in space. He showed that the miraculous properties of a superconductor, including exactly zero-resistance current flow and the Meissner-effect exclusion of magnetic flux, follow from the spontaneous breaking of the continuous phase symmetry SO(2) down to the subgroup C_2 (phase rotations by π) that changes the sign of the electron wave function.

Nambu noted that the spontaneous breaking of the gauge symmetry gives rise to collective excitations that, in the limit of long wavelength, have vanishing frequency, and so correspond to massless particles. His speculation that such massless spin-zero particles must arise when any continuous symmetry is spontaneously broken gave rise to the Goldstone theorem [7], which finds application in many areas of physics. Such massless scalars are now known as Nambu–Goldstone bosons.

For familiar examples of hidden symmetries in the everyday world, including the spontaneous magnetization of a lump of iron, crystal formation, and superconductivity, the circumstances that provoke spontaneous symmetry breaking have to do with properties of the substance. Nambu realized that the vacuum—the state of lowest energy—could itself manifest a broken symmetry [8]. He applied this idea to the weak interaction responsible for nuclear beta decay, which had just been determined—following the discovery of parity violation—to result from the action of vector and axial vector currents. Like the familiar electromagnetic current, the weak vector current was known to be conserved (to satisfy a continuity equation). Nambu began by asking whether the weak axial vector current might also be conserved.

Conservation laws are linked by Noether's theorem to continuous (global) symmetries, and this link holds even if the symmetry is spontaneously broken. In the case of electromagnetism, as we have already remarked, the symmetry is electromagnetic gauge invariance; the conserved vector current in beta decay follows from the isospin symmetry of nuclear physics. A symmetry known as a chiral symmetry, mandating invariance under independent global transformations on the left-handed and right-handed nucleons, would imply a conserved axial current. But an exact chiral symmetry immediately runs afoul of experimental reality: if the chiral symmetry were manifest, the proton and neutron would have to be massless, and if the chiral symmetry were spontaneously broken, there should be an isospin triplet of massless spinless particles with odd parity. Neither possibility describes the real world.

Nambu cunningly observed that if in addition to being spontaneously broken, the chiral symmetry were inexact, then the triplet of pseudoscalar particles would be not massless, but much lighter than the other strongly interacting particles such as the proton and neutron. The three pions,

π^+, π^0, π^-, Yukawa's carriers of the nuclear force, weighing about one-seventh of the proton mass, fit the description perfectly. Today we call the light particles arising from the spontaneous breaking of an approximate symmetry pseudo-Nambu–Goldstone bosons. They appear in settings as diverse as cosmology and "little Higgs" models of electroweak symmetry breaking.

In a pair of papers with Giovanni Jona-Lasinio [9, 10], Nambu formulated an explicit toy model in which the nucleon mass arises essentially as a self-energy in analogy with the appearance of the mass gap in superconductivity. The pions arose as light nucleon-antinucleon bound states, following the introduction of a tiny "bare" nucleon mass and spontaneous chiral-symmetry breaking. This construction, three years before the invention of quarks, prefigured our current understanding of the masses of strongly interacting particles in quantum chromodynamics. The Nambu–Jona-Lasinio model has served as a template for many subsequent theoretical developments.

A further evolution, central to developing the standard model of particle physics, was the discovery by François Englert & Robert Brout [11], Peter Higgs [12], and Gerald Guralnik, Richard Hagen, & Tom Kibble [13] of a crucial evasion to the Goldstone theorem. If a local gauge symmetry is spontaneously broken, the would-be Nambu–Goldstone bosons become the third polarization states of massive spin-1 gauge bosons. The massive photon within a superconducting medium, which explains the Meissner effect, is the very prototype. Steven Weinberg [14] and Abdus Salam [15] exploited this insight in creating the essence of the electroweak theory that today focuses our attention on the Large Hadron Collider at CERN and the coming exploration of the TeV scale.

A little-known side of Nambu's relationship with experiments was revealed to one of us when Winstein, as a beginning assistant professor in the mid-1970s, taught a summer course in waves and optics. In one of the laboratory exercises, students used a Michelson interferometer to repeat the Michelson–Morley experiment and test for the luminiferous ether. Winstein worked out the transfer function of the instrument for himself, then went to test his understanding in the lab. When he tuned the path length of the laser light toward destructive interference, a weird aberration caused the beam spot to sprout lobes.

The strange observation drove him to look for a colleague to consult; only Yoichiro Nambu was in his office on that summer day. Nambu agreed with Winstein's analysis of the apparatus, and that something was strange, and promised to think further. True to his word, he telephoned his junior colleague at home in the evening. A few rounds of discussion led them to the hypothesis that multiple reflections from the surfaces of the beam splitter were important, and that a beam splitter of different thickness would provide a check. The people in charge of the lab equipment did not have an alternative splitter. The fast-paced course moved on, and there was no time to follow up.

A month after the course ended, an unexpected package appeared in Winstein's mailbox—a new beam splitter. He took it to the lab, verified the expected behavior, and went to inform Nambu, who was out of town. When he went to thank the lab personnel for the new beam splitter, they denied any knowledge. Some time later, Nambu surprised Winstein by asking whether he had received the beam splitter. He responded that he had, and that its effect was what they had expected. How did Nambu know about the new equipment? *He* had put it into Winstein's mailbox! He obtained it from a scientific surplus store he knew from building a laser with his son, in a basement lab in his house. Unknown even to long-time colleagues, the famous theorist was an amateur experimenter.

Yoichiro Nambu's seminal work on broken symmetries is but a part of his scientific legacy. His influence is all around us, and all physicists are the richer for it.

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