

Elementary Particle Physics: Spontaneous Broken Symmetry (Nobel Lecture)**

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I will begin with a short story about my background. I studied physics at the University of Tokyo. I was attracted to particle physics because of the three famous names, Nishina, Tomonaga and Yukawa, who were the founders of particle physics in Japan. But these people were at different institutions than mine. On the other hand, condensed matter physics was pretty good at Tokyo. I got into particle physics only when I came back to Tokyo after the war. In hindsight, though, I must say that my early exposure to condensed matter physics has been quite beneficial to me.

Particle physics is an outgrowth of nuclear physics which began in the early 1930s with the discovery of the neutron by Chadwick, the invention of the cyclotron by Lawrence, and the "invention" of meson theory by Yukawa.^[1] The appearance of an ever increasing array of new particles in the subsequent decades, and the advances in quantum-field theory gradually led to our understanding of the basic laws of nature, culminating in the present standard model.

When we faced those new particles, our first attempts were to make sense out of them by finding some regularities in their properties. They invoked the symmetry principle to classify them. A symmetry in physics leads to a conservation law. Some conservation laws are exact, like energy and electric charge, but these attempts were based on approximate similarities of masses and interactions.

Nevertheless, seeing similarities is a natural and very useful trait of the human mind. The near equality of proton and neutron masses and their interactions led to the concept of isospin SU(2) symmetry.^[2] On the other hand, one could also go in the opposite direction, and elevate a symmetry to a more elaborate gauged symmetry. Then symmetry will determine the dynamics as well, a most attractive possibility. Thus the beautiful properties of electromagnetism was extended to the SU(2) non-Abelian gauge field.^[3] But strong interactions are short range. Giving a mass to a gauge field destroys gauge invariance.

Spontaneous symmetry breaking (SSB), which is the main subject of my talk, is a phenomenon where symmetry, in the basic laws of physics, appears to be broken. In fact, it is a very familiar one in our daily life, although the name SSB is not.^[4] For example, consider a elastic straight rod standing vertically. It has a rotational symmetry; it looks the same from any horizontal direction. But if one applies increasing pressure to squeeze it, it will bend in some direction, and the symmetry is lost. The bending can occur in principle in any direction since all directions are equivalent. But you do not see it unless you repeat the experiment many times. This is SSB.

The SSB in quantum mechanics occurs typically in a uniform medium consisting of a large number of elements. It is a dynamical effect. The symmetry allows some freedom of action to each of them but the interaction among them forces them, figuratively speaking, to line up like a crowd of people looking into the same direction. It is not easy to change the direction of the whole ensemble—even if it is allowed by symmetry, hence it does not take energy—because the action is not a local operator. So the symmetry *appears* to be lost. It is still possible to recover the lost symmetry by a global operation, but it would amount to a kind of phase transition. Some examples are given in Table 1.

Table 1. Physical systems of broken symmetry.

Physical system	Broken symmetry
Ferromagnets	Rotational invariance (with respect to spin)
Crystals	Translational and rotational invariance (modulo discrete values)
Superconductors	Local gauge invariance (particle number)

SSB in a medium has the following characteristic properties:

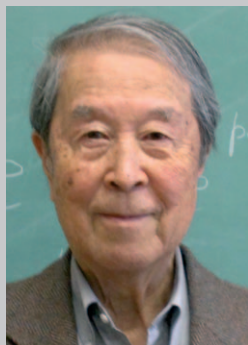
1. The ground state has a huge degeneracy. A symmetry operation takes one ground state to another.
2. Only one of the ground states and a set of excited states (arising from the chosen ground state) are realized in a given situation.
3. SSB is in general lost at sufficiently high temperatures.

In relativistic quantum-field theory, this phenomenon becomes also possible for the entire space-time, for the "vacuum" is not void, but has many intrinsic degrees of freedom. In this context, it may play an important role in cosmology. As the universe expands and cools down, it may undergo one or more SSB phase transitions from states of higher sym-

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I was born in 1921 in Tokyo and grew up in the countryside city of Fukui. I studied physics at the Imperial University of Tokyo from 1940 to 1942, graduating at the level of MS. Then I was drafted into an army radar laboratory. After the end of the war, in 1946, I returned to the University of Tokyo as a research associate. I received a doctorate in 1952. In 1950 I became professor at the newly created Osaka City University, a position which I held until 1956. From 1952 to 1954 I stayed at the Institute for Advanced Study in Princeton (USA), as a member, and from 1954 to 1956 at the University of Chicago as a research associate. I was made Associate Professor at the University of Chicago in 1956, Professor in 1958, and Distinguished Service Professor in 1971. From 1973 to 1976 I served as chairman of the Department of Physics. In 1976 I became the Henry Judson Distinguished Professor, and after retirement in 1991, became Emeritus. I married Chieko Hida in 1945, and have a son, Jun-ichi. I am a citizen of the United States of America since 1970. I hold honorary degrees from Osaka City University (1980), Northwestern University (1985), and Osaka University (1997). I am a member of the United States National Academy of Sciences and the American Academy of Arts and Sciences since 1971, and an honorary member of Japan Academy since 1984. A partial list of the prizes I received in the past are: *Dannie Heineman Prize* American Physical Society (1970); *Order of Culture* Government of Japan (1978); *United States National Medal of Science* (1982); *Max Planck Medal* German Physical Society (1985); *Dirac Medal* International Centre for Theoretical Physics, Trieste (1986); *Sakurai Prize* American Physical Society (1994); *Wolf Prize* Government of Israel (1995); *Gian Carlo Wick Medal* World Federation of Scientists, Lausanne (1996); *Bogoliubov Prize* Joint Institute for Nuclear Research, Dubna (2003); *Benjamin Franklin Medal* Franklin Inst., Philadelphia (2005); *Pomeranchuk Prize* Inst. Theoretical and Experimental Physics, Moscow (2007). My interests in physics have been mainly on the theoretical side. The University of Tokyo was renowned for condensed-matter physics, but I was more attracted to nuclear and particle physics in which Nishina, Tomonaga, and Yukawa were making great contributions. As a student I attended seminars held by Nishina and Tomonaga at their laboratory and they spurred my interest in cosmic ray and particle physics. I started my research career at the time when Tomonaga was developing his theory of renormalization, for which he would receive the Nobel Prize. I was able to approach his group and start working on his theory and other topics in particle physics. At his recommendation I obtained the position at Osaka City University and later was invited to the Institute for Advanced Study. I owe my move to Chicago to M. L. Goldberger. My work on spontaneous symmetry breaking (SSB), for which I am receiving the Nobel Prize, started around 1959. It is a result of my experience in both condensed matter and particle physics. The BCS theory of superconductivity in 1957 led me to the idea of SSB as a general phenomenon in physics. My work on its specific application to particle physics as a mechanism for generation of the nucleon mass and the pion was first published in 1960. Since then I have pursued the subject in various areas.



metries to lower ones, which change the governing laws of physics.

I will now recall the chain of events which led me to the idea of SSB and its application to particle physics. One day in 1956, R. Schrieffer gave us a seminar on what would come to be called the BCS theory^[5] of superconductivity. I was impressed by the boldness of their ansatz for the state vector, but at the same time I became worried about the fact that it did not appear to respect gauge invariance. Soon thereafter Bogoliubov^[6] and Valatin^[7] independently introduced the concept of quasiparticles as fermionic excitations in the BCS medium. The quasiparticles did not carry a definite charge as they were a superposition of electron and hole, with their proportion depending on the momentum. How can one then trust the BCS theory for discussing the electromagnetic properties like the Meissner effect? It actually took two years for me to resolve the problem to my satisfaction. There were a number of people who also addressed the same problem, but I wanted to understand it in my own way. Essentially it is the presence of a massless collective mode, now known by the generic name of Nambu-Goldstone (NG) boson, that saves charge conservation or gauge invariance.

The Bogoliubov-Valatin (BV) quasiparticles are described by the Equations (1a), (1b) and (1c).^[8]

$$E\psi_{\mathbf{p},+} = \varepsilon_{\mathbf{p}}\psi_{\mathbf{p},+} + \Delta\psi_{-\mathbf{p},-}^* \quad (1a)$$

$$E\psi_{-\mathbf{p},-}^* = -\varepsilon_{\mathbf{p}}\psi_{-\mathbf{p},-}^* + \Delta\psi_{\mathbf{p},+} \quad (1b)$$

$$E = \sqrt{\varepsilon_{\mathbf{p}}^2 + \Delta^2} \quad (1c)$$

Here, $\psi_{\mathbf{p},+}$ and $\psi_{-\mathbf{p},-}^*$ are the wavefunctions for an electron and a hole of momentum \mathbf{p} and spin $+$ or $-$, $\varepsilon_{\mathbf{p}}$ is the kinetic energy relative to the Fermi energy, and 2Δ is the energy gap. In terms of spinlike matrices τ_i , the corresponding Hamiltonian and the charge-current are given by Equations (2a), (2b) and (2c):

$$H_0 = \varepsilon_{\mathbf{p}}\Psi^\dagger\tau_3\Psi + \Delta\Psi^\dagger\tau_1\Psi \quad (2a)$$

$$\rho_0 = \Psi^\dagger\tau_3\Psi \quad (2b)$$

$$\mathbf{j}_0 = \Psi^\dagger(\mathbf{p}/m)\Psi \quad (2c)$$

The BV ground state is $\Psi_{\mathbf{p}}^\dagger|0\rangle = 0$ for all \mathbf{p} . The charge does not commute with H_0 , and the continuity equation does not hold, which is the problem. But it has turned out that the same interaction that led to the BCS–BV ground state also leads to collective excitations f , which contributes to the charge-current and restores the continuity equation. The correct expression is given by Equations (3a), (3b) and (3c):

$$\rho \simeq \rho_0 + \frac{1}{\alpha^2}\partial_t f \quad (3a)$$

$$\mathbf{j} \simeq \mathbf{j}_0 - \nabla f, \quad (3b)$$

$$\left(\nabla^2 - \frac{1}{\alpha^2 \partial_t^2}\right) f \simeq -2\Delta \Psi^\dagger \tau_2 \Psi \quad (3c)$$

where f represents the NG mode. Physically it corresponds to excitations that tend to restore the lost symmetry. Its energy goes to zero in the long wavelength limit, as it corresponds to the global symmetry operation. It also happens that the above NG mode mixes with the Coulomb interaction among the electrons because of their common long-range nature, and turns into the well-known oscillation equation for plasmons [Eq. (4)]:

$$\omega^2 = e^2 n / m \quad (4)$$

where e , n and m are, respectively, the charge, density, and mass of the electron.

The formal similarity of the BV equation to the Dirac equation naturally led me to transport the BCS theory to particle physics.^[9] The gap Δ goes over to the mass M , which breaks chirality $\sim \gamma_5$ rather than the ordinary charge ~ 1 . The axial current is the analog of the electromagnetic vector current in the BCS theory. If chirality is a broken symmetry, the matrix elements of the axial current between nucleon states of four-momentum p and p' should have the form of Equation (5):

$$\Gamma_{\mu 5}(p', p) = (\gamma_\mu \gamma_5 - 2M \gamma_5 q_\mu / q^2) F(q^2) \quad (5)$$

where $q_\mu = p'_\mu - p_\mu$.

So chiral symmetry is compatible with a finite nucleon mass M provided that there exists a massless pseudoscalar NG boson. In reality, there is a pseudoscalar pion, and the vector and axial vector interactions that appear in weak decays of the nucleons and the pion have the properties represented by Equations (6a) and (6b):

$$g_V \simeq g_A \quad (6a)$$

$$g_\pi \simeq \sqrt{2} M g_A / G \quad (6b)$$

where g_V and g_A are vector and axial vector couplings of the nucleon, g_π is axial coupling for the pion, G is the pion–nucleon coupling, and M is the nucleon mass. The second relation is known as the Goldberger-Treiman relation,^[10] and it implies that the matrix element of the axial vector part of nucleon decay is [Eq. (7)]:

$$\Gamma_{\mu A} \simeq (\gamma_\mu \gamma_5 - 2M \gamma_5 q_\mu) / (q^2 - m_\pi^2) \quad (7)$$

which differs from Equation (5) by the presence of pion mass. In view of the smallness of m_π compared to M , I made the hypothesis that the axial current is an approximately conserved quantity, the nucleon mass is generated by an SSB of chirality, and the pion is the corresponding NG boson which should become massless in the limit of exact conservation (proton and neutron masses should also become equal).

The model system^[11] I worked out subsequently with Jona-Lasinio is a concrete realization of the proposed SSB. It has the form shown in Equation (8), which is similar to the BCS model:

$$L = -\bar{\psi} \gamma^\mu \partial_\mu \psi + g[(\bar{\psi} \psi)^2 - (\psi \gamma_5 \psi)^2] \quad (8)$$

which is invariant against the particle number and chiral transformations [Eq. (9)]:

$$\begin{aligned} \psi &\rightarrow \exp(i\alpha) \psi, \quad \bar{\psi} \rightarrow \bar{\psi} \exp(-i\alpha), \\ \psi &\rightarrow \exp(i\gamma_5 \alpha) \psi, \quad \bar{\psi} \rightarrow \bar{\psi} \exp(-i\gamma_5 \alpha) \end{aligned} \quad (9)$$

After SSB, the “nucleon” acquires a mass $M \sim 2g \langle \psi \psi \rangle$. Although the model is non-renormalizable, it is easy to demonstrate the SSB mechanism. The generated mass M is determined by the “gap equation” [Eq. (10)]:

$$\frac{2\pi^2}{g\Lambda^2} = 1 - \frac{M^2}{\Lambda^2} \ln\left(1 + \frac{\Lambda^2}{M^2}\right) \quad (10)$$

where Λ is a cutoff. Bound states of nucleon–antinucleon (“meson”) and nucleon–nucleon (“dibaryon”) pairs of spin 0 and 1 were also found. In particular, the masses of 0^- , ($\sim \bar{\psi} \gamma_5 \psi$) and 0^+ , ($\sim \bar{\psi} \psi$) mesons are found to be 0 and $2M$ respectively. A more realistic two flavor model was also considered by generalizing Equation (8) to give Equation (11):

$$L = -\bar{\psi} \gamma^\mu \partial_\mu \psi + g[(\bar{\psi} \psi)^2 - \sum_i (\bar{\psi} \gamma_5 \tau_i \psi)(\bar{\psi} \gamma_5 \tau_i \psi)] \quad (11)$$

with a similar gap equation. We get an isovector 0^- pion and an isoscalar 0^+ . The actual pion mass was generated by a small explicit bare mass in the Lagrangian of the order of 5 MeV. This also induced a change of axial coupling constant g_A in the right direction.

Other examples of the BCS-type SSB are ^3He superfluidity and nucleon pairing in nuclei.^[12] In general there exists simple mass relations among the fermion and the bosons in BCS-type theories.^[13]

The BCS theory also accounts for the generation of the London mass for the electromagnetic field. This problem is made simple in terms of the Higgs scalar field.^[14] The relativistic analog of the London relation—in momentum space—are given by Equations (12a), (12b) and (12c):

$$j_\mu(q) = K_{\mu\nu}(q) \Lambda^k \quad (12a)$$

$$K_{\mu\nu} = (\delta_{\mu\nu} - q_\mu q_\nu / q^2) K(q^2) \quad (12b)$$

$$K(q^2) \simeq q^2 / (q^2 - m^2) \quad (12c)$$

The third relation [Eq. (12c)] shows the massless NG boson turning into a massive “plasmon”, a process corresponding to Equation (4). This was successfully applied to weak gauge field in the Weinberg–Salam (WS) theory^[15] of electroweak unification. The fermion masses are also generated and break chiral invariance. These so-called current masses for the up and down quarks play the role of the bare mass in the NJL model.

In the current standard model of particle physics, the NJL model may be regarded as an effective theory for the QCD with respect to generation of the so-called constituent masses. One is interested in the low-energy degrees of freedom on a

scale smaller than some cut-off $\Lambda \sim 1$ GeV. The short distance dynamics above Λ as well as the confinement may be treated as a perturbation. The problem has been extensively studied by many people. The Lagrangian adopted by Hatsuda and Kunihiro^[16] is given in Equation (13):

$$L = L_{\text{QCD}} + L_{\text{NJL}} + L_{\text{KMT}} + \delta L \quad (13)$$

L_{NJL} is for the quarks, and contains “current mass” terms. L_{KMT} refers to the Kobayashi-Maskawa–t’Hooft chiral anomaly [Eq. (14)]:

$$L_{\text{KMT}} = g_{\text{D}} (\det [\bar{q}_i (1 - \gamma_5) q_j] + \text{h.c.}) \quad (14)$$

Both contribute to the explicit breaking of chiral invariance. (δL contains the effects of confinement and one gluon exchange). The WS theory resembles the Ginzburg–Landau^[17] description of superconductivity which is shown to follow from the BCS theory by Gor’kov.^[18] In the same way the NJL model goes over to the model of Gell-Mann and Lévy.^[19] If this analogy turns out real, the Higgs field might be an effective description of underlying dynamics. Finally I will end this lecture with a comment on the mass hierarchy problem. Hierarchical structure is an outstanding feature of the universe. The masses of known fundamental fermions also make a hierarchy stretching 11 orders of magnitude. Mass is not quantized in a simple regular manner like charge and spin. Mass is a dynamical quantity since it receives contributions from interactions. But we do not see yet a pattern like those in the hydrogen atom which led to quantum mechanics, or the Regge trajectories which led to the dual string picture.

The BCS mechanism seems relevant to the problem, as was remarked earlier. It generates a mass gap for fermions, plus the Goldstone and Higgs modes as low-lying bosons. The bosons may act in turn as an agent for further SSB, leading to the possibility of hierarchical SSB or “tumbling”^[20]. In fact we already have examples of it:^[21]

1. The chain atoms–crystal–phonon–superconductivity. The NG mode for crystal formation is the phonon which induces the Cooper pairing of electrons to cause superconductivity.
2. The chain QCD–chiral SSB of quarks and baryons– π , σ and other mesons–nuclei formation and nucleon pairing–nuclear collective modes. No further elaboration would be required.^[22]

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- [1] See, for example, Y. Nambu, *J. Phys. Soc. Jpn.* **2007**, *76*, 111002.
- [2] W. Heisenberg, *Zeitschr. Phys.* **1932**, *77*, 1.
- [3] C. N. Yang, R. L. Mills, *Phys. Rev.* **1954**, *96*, 191.
- [4] The name is due to M. Baker and S. Glashow, *Phys. Rev.* **1962**, *128*, 2462.
- [5] J. Bardeen, L. N. Cooper, J. R. Schrieffer, *Phys. Rev.* **1957**, *108*, 1175.
- [6] N. N. Bogoliubov, *J. Exp. Theor. Phys.* **1958**, *34*, 33. This is a fermionic version of a transformation which he first introduced in a description of superfluidity, N. N. Bogoliubov, *J. Phys.* **1947**, *11*, 23–32.
- [7] G. Valatin, *Nuovo Cimento* **1958**, *7*, 843.
- [8] Y. Nambu, *Phys. Rev.* **1960**, *117*, 648.
- [9] Y. Nambu, *Phys. Rev. Lett.* **1960**, *4*, 380.
- [10] M. L. Goldberger, S. Treiman, *Phys. Rev.* **1958**, *110*, 117.
- [11] Y. Nambu, G. Jona-Lasinio, *Phys. Rev.* **1961**, *122*, 345; Y. Nambu, G. Jona-Lasinio, *Phys. Rev.* **1961**, *124*, 246. The first presentation of the model was made at the Midwest Conference on Theoretical Physics: *A Superconductor Model of Elementary Particles and its Consequences* in the *Proceedings* (Eds.: F. J. Biedenhahn et al.), Purdue University, **1960**, p. 1.
- [12] A. Arima, F. Iachello, *Phys. Rev. Lett.* **1975**, *35*, 1069; A. Arima, F. Iachello, *Ann. Phys.* **1976**, *99*, 253.
- [13] For example, Y. Nambu, *Phys. D* **1985**, *15*, 147; Y. Nambu, *Phys. Lett. A* **1988**, *201*, 1.
- [14] P. W. Anderson, *Phys. Rev.* **1963**, *130*, 439; F. Englert, R. Brout, *Phys. Rev. Lett.* **1964**, *13*, 321; P. W. Higgs, *Phys. Rev. Lett.* **1964**, *13*, 508.
- [15] S. Weinberg, *Phys. Rev. Lett.* **1967**, *19*, 1264; A. Salam in *Elementary Particles*, Almquist Forlag AB, Stockholm, **1968**, p. 167.
- [16] T. Hatsuda, T. Kunihiro, *Phys. Rep.* **1994**, *247*, 221.
- [17] V. I. Ginzburg, L. D. Landau, *J. Exp. Theor. Phys.* **1950**, *20*, 1064.
- [18] L. P. Gor’kov, *J. Exp. Theor. Phys.* **1959**, *36*, 1918.
- [19] M. Gell-Mann, M. Lévy, *Nuovo Cimento* **1960**, *16*, 705.
- [20] S. Dimopoulos, S. Raby, L. Susskind, *Nucl. Phys. B* **1980**, *B169*, 373.
- [21] Y. Nambu, *Masses as a Problem and as a Clue*, presented at the International Centre for Theoretical Physics, Trieste, **2004**.
- [22] The Nobel lectures of Makoto Kobayashi and Toshihide Maskawa are published in: M. Kobayashi, *ChemPhysChem* **2009**, *10*, DOI: 10.1002/cphc.200900215 and T. Maskawa, *ChemPhysChem* **2009**, *10*, DOI: 10.1002/cphc.200900214.

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