Yet another symmetry breaking to be discovered

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ABSTRACT

The discovery of spontaneous symmetry breaking in particle physics was the greatest contribution in Nambu’s achievements. There is another class of symmetries that exist in the low energy nature, yet is doomed to be broken at high energy, due to a lack of protection of the gauge symmetry. I shall review our approach to search for this class of symmetry breaking, the lepton number violation linked to generation of the matter-antimatter asymmetry in our universe.
1 My old memory of a great physicist at Chicago

Days I had frequently chances to speak to Yoichiro Nambu started at December 1967 and ended at August 1970, during which I was a graduate student at University of Chicago. Even before I went to Chicago, Nambu’s name was shining at University of Tokyo where I spent undergraduate and two graduate years. I did not know his famous superconductivity model with Jona-Lassinio, though.

The very first impression I had with Nambu was his extreme politeness. People often talk of his modesty, but I felt more than that. I was very much bewildered by his attitude, since I had expected a different impression as a type of American professors. Later I found that his attitude towards physicists is invariant, irrespective of students, postdocs and professors.

I decided to knock on the door of his office at least once a week, whether or not I have questions or something to report on. I found that he would always welcome me and started to talk of subjects he was interested in. I must say that this was unusual, because he frequently spoke of his latest ideas at that time prior to publication.

One of the works Nambu was much involved around that time was the infinite-component field theory [2]. He presumably tried to derive a mass formula for all elementary particles. This work followed his famous work with Han, Han-Nambu model and three triplet model. I studied three triplet model and found ideas fresh: especially exchange of colored vector boson to classify lowest energy hadrons was fascinating. But Nambu somehow was not satisfied with those models and he already embarked on the infinite-component field theory.

At some time during those days Streater and his young collaborator published a no-go theorem to this type of local infinite-component theory: their claim was that this approach leads to violation of unitarity or causality. Nambu immediately invited them and a young guy gave a seminar, very short one less than half an hour. Although I did not understand this seminar, Nambu immediately recognized this as a fatal block against his approach (Gell-Mann and many others were also involved in the infinite-component at that time). Thus, he very quickly abandoned his theory.

Around this time the Veneziano model and its extension, the dual resonance model, were gaining a popularity. Its particle content of infinitely many resonances and high energy Regge behavior of scattering amplitudes was also of Nambu’s interest. My opinion on Nambu’s attitude with regard to the dual resonance model was that he had a great skepticism. He thus started with P. Frampton, a postdoc then at Chicago, to check the positivity of factorized coupling at all resonance poles. What they found was that except the tachyon all resonances behave as if they are genuine objects of positive definite metric.

I believe that this was a turning point to him, and he started to search for dynamics behind dual resonance models, ultimately leading to his discovery of the string theory. Nambu’s ideas on string theory are summarized with a broad perspective in his famous undelivered lecture note [3]. When I first saw the original typed manuscript of this lecture note prepared by Nambu himself, it had only a description of the geometric construction which was very beautiful. The lecture note later presented in the final form gives a broader scope of string picture in hadron physics, and this is a good place to learn how Nambu thought, as explained by P. Ramond at this workshop.
2 Symmetry breaking: how they emerge

One of the greatest contributions of Nambu to particle physics is the discovery of spontaneous symmetry breaking. The symmetry idea in particle physics has been popular since the introduction of isospin by Heisenberg, the hyper-charge of strangeness due to Nishijima and Gell-Mann and $SU(3)$ flavor symmetry of Gell-Mann and others. All these were very useful to classify what were called elementary particles then, and to relate physical observables by a selection rule. Nambu added to this list a new class of symmetry breaking, or rather a hidden symmetry behind apparent phenomena. His original application of this general idea was directed to the $SU(2) \times SU(2)$ chiral symmetry among nucleons and pions, but it was obvious that the idea was more general.

The spontaneous symmetry breaking appears since the symmetry hidden at the fundamental level, either in the hamiltonian or in the equation of motion, is not respected by the energy minimum condition of the ground state. The conflict between the hidden symmetry and the spontaneous breaking is restored by emergence of the long range force, now called Nambu-Goldstone boson.

Needless to say, the spontaneous symmetry breaking is more restrictive than an explicit symmetry breaking introduced in the case of usual symmetry. This restriction gave rise to intricacies of our quantum world. One of these intricacies is the spontaneous symmetry breaking of gauged symmetry, known as the Higgs mechanism. The Nambu-Goldstone mode becomes the longitudinal part of otherwise purely transverse gauge bosons. This made the useless Yang-Mills non-Abelian gauge theory a leading candidate of particle physics theory.

I suspect that the $U(1)$ Higgs mechanism is well recognized in Nambu’s mind prior to the Higgs paper, due to the Meissner effect and the work of Anderson. I am reminded of Nambu’s comment on the ‘t Hooft seminal work on the renormalizability of the Weinberg model. When he mentioned ‘t Hooft’s circulating preprint to M. Suzuki and myself then at Berkeley, he confessed that he had known the work of Weinberg since its birth to our great surprise, because the model was not familiar to many of particles physicists.

3 Yet another symmetry breaking to be discovered

My quest for the symmetry breaking is somewhat twisted. I had been much fascinated by the simple and the beautiful $SU(5)$ grand unified theory of Georgi and Glashow ever since its publication. Since the baryon number violation predicted by this model had no experimental support, I thought that this is a serious defect of the model, and attempted to recover the baryon number conservation by imposing some global symmetry [4]. After this work was finished, I began to think the other way: one should pursue physical consequences of the baryon number violation instead of a contrived idea. This led to my work on baryo-genesis in 1978 [5].

Incidentally, I wish to bring to the audience the great contribution of Hirotaka Sugawara on the birth of neutrino oscillation experiments. He recognized the importance of my baryo-genesis work with great interest, and persuaded M. Koshiba to initiate the proton decay experiment which led to Kamiokande detector. Although the group was not successful in the search of proton decay, they later converted the
detector to suit for the solar neutrino search. With completion of this upgrade, Koshiba’s group succeeded in observing supernova burst neutrino in the spring of 1987. Later the group got the money for super-Kamiokande project which was led by Y. Totsuka. This upgrade led to this year’s Nobel prize for T. Kajita. Without Sugawara’s enthusiasm the story of neutrino physics in the world would have been different. I had a fortune to meet Sugawara in my first year of Chicago where he was spending his postdoctoral year.

It is my strong belief, which I suspect also shared by many, that all accidental symmetries not protected by the gauge principle are doomed to be broken, albeit their strength not precisely known. The baryon and the lepton number conservation valid to excellent experimental resolution today belong to this class of symmetry to be broken at some high energy scale.

Fortunately there were some guides such as $SU(5)$ grand unified theory of Georgi and Glashow for the baryon number violation and $SO(10)$ model for lepton number violation. The use of lepton number violation for creating the matter-antimatter imbalance of our universe became more popular than the baryogenesis idea, hence one calls this lepto-genesis. The popularity of lepto-genesis is understandable, because one naturally expects that one of the ingredients for a successful scenario of the asymmetry generation is already there: discovery of neutrino oscillation indicates the finite neutrino mass and its mass presumably violates the lepton number according to the idea of Majorana. On the other hand, there is no experimental hint on the baryon number violation.

The Majorana nature of neutrino masses has two attractive features. We assume that the nature favors a symmetry of all quarks and leptons, and that neutral leptons are born with four components similar to all other fundamental particles. On the other hand, the electroweak interaction described by the standard theory only requires two-component neutrinos, since the right-handed component is free of quantum numbers of $SU(3) \times SU(2) \times U(1)$ gauge group. This suggests that the right-handed component has a huge mass compared to the electroweak scale given by the Fermi constant.

The presence of the right-handed component gives rise to the seesaw mechanism that explains the smallness of ordinary neutrinos, caused by a Dirac mass mixing term generated by the usual Higgs coupling. Moreover, the right-handed component may become the agent of lepton asymmetry generation at an early epoch of cosmological evolution. Using the important observation of Shaposhnikov and others that lepton and baryon numbers can be converted to a thermal equilibrium value in high temperature phase above the electroweak scale, Fukugita and Yanagida proposed the lepto-genesis idea which was further elaborated by many others later on.

The important prerequisite for a success of lepto-genesis idea is an experimental proof of the Majorana nature of ordinary neutrino. A conventional experimental method of exploring the Majorana nature of neutrinos is to look for the lepton number violating double-beta decay, the neutrino-less double beta decay. Although this is an interesting approach to directly look for the symmetry violation, the expected tiny neutrino masses below eV might be a great obstacle against experiments.
4 Towards Spectroscopy of Atomic Neutrino (SPAN)

Our method of looking for the Majorana nature of neutrinos is quite different, and it has a merit of evading the smallness of the effect.

Consider atomic de-excitation. Although tiny, it contains a decay branch into a neutrino pair if quantum number changes match. Its presence is ensured in the standard electroweak theory. Suppose then that the neutrino is of Majorana type. Two emitted neutrinos are then indistinguishable fermions, hence emitted two-particle state must satisfy the anti-symmetry under the exchange of the two. This leads to an interesting interference contribution of rates where the Majorana mass effects are large. The effect does not occur for Dirac neutrinos, hence giving a method of distinction between Majorana and Dirac neutrinos [6].

Although the method of SPAN (SPectroscopy of Atomic Neutrino) seems beautiful, there was a serious problem: the smallness of atomic processes. The weak interaction rates scale with energy to high power, usually to the fifth power, giving a hopeless rate. Fortunately, we discovered a mechanism of huge enhancement [7], [8], which I shall describe.

The idea dates back to Dicke’s super-radiance (SR). Dicke proposed that single photon emission, when it occurs within the wavelength region of emitted photon, may be enhanced. Instead of the usual stochastic decay of individual atoms a cooperative phenomena may occur after some delay: after several spontaneous emission along a long target direction atoms in target acquire a coherent phase within the wavelength region, and all of sudden essentially all atoms in the upper level decay to the lower level. This is an explosive process and one may view this as an enhanced decay process.

We discovered [7], [8], [9] that this enhancement can be made much stronger if more than two particles are involved in the final state. In Dicke’s SR the emitted photon had a phase factor $e^{i\vec{k} \cdot \vec{x}}$ and this phase may differ at atomic site $\vec{x}$. The limitation to the wavelength is due to this different phase at different atomic site. But if one considers two-photon emission, the phase factor becomes $e^{i(\vec{k}_1 + \vec{k}_2) \cdot \vec{x}}$, and at the special phase space point of $\vec{k}_1 + \vec{k}_2 = 0$ there is no restriction to the wavelength. This condition implies that both the energy and the momentum are conserved among emitted particle. (In atomic physics the momentum recoil of atom is negligibly small and one usually speaks of no momentum conservation for the usual decay.)

We may call this new type of coherence the macro-coherence. If atoms maintain the macro-coherence, radiative emission of neutrino pair (RENP), $|e\rangle \rightarrow |g\rangle + \gamma + \nu_i \nu_j$, may also benefit the huge enhancement. We worked out consequences of the macro-coherence to RENP [9], [10], [11]. There are interesting possibilities to explore almost all important questions left in neutrino physics: (1) determination of absolute neutrino mass, (2) distinction of normal vs inverted mass hierarchies, (3) distinction of Majorana vs Dirac neutrinos, (4) measurement of three CP violating phases including the Majorana phase, (5) possibility of detecting relic neutrino of 1.9 K [12].

There are however many experimental problems to overcome before we write a serious proposal for the neutrino mass spectroscopy (SPAN). Some of these problems are already discussed and I shall not discuss these here. One thing which was obvious to us is that the macro-coherence idea may work for much stronger process than RENP. We decided to embark on experimental project of verifying the macro-coherent amplification in weak QED processes.
The process we chose is two-photon emission just mentioned. The macro-coherently amplified two-photon emission may be called paired super-radiance (PSR). In our experiment we used the vibrational transition of para-hydrogen molecule, pH$_2$, because this process is electric dipole forbidden and its calculated two-photon decay rate is small, $\sim 10^{12}$ sec, almost impossible to measure in laboratories. We developed the coherence between two states of the first excited vibrational state $v = 1$ and the ground state $v = 0$ by irradiation of two Raman-type of lasers of frequencies $\omega_i$, $i = 1, 2$ with $\omega_1 - \omega_2 = 0.52$ eV, the vibrational level spacing. Two lasers of blue $\omega_1$ and red $\omega_2$ frequencies have been irradiated from the same direction. One expects many side bands due to multi-photon processes if the coherence of lasers is good. These side band photons result from higher order multiple-photon processes generated by two Raman lasers. We observed many side bands both in the blue and the red regions, more than $O(10)$ [13]. The existence of many side bands means that we have achieved a good coherence. Our estimate of macro-coherence is roughly 0.08 of the maximum allowed value over the macroscopic body of 15 cm long.

We observed PSR in two ways. One of the paired photons is generated by one of the side bands whose frequency happens to lie between the level interval [13]. The other method [14] used an external trigger different from the side band frequency. Results of [13], [14] show clear evidences of PSR phenomena. The amount of enhancement is estimated more than $10^{18}$.

The next important step towards SPAN is to form an ideal target state for RENP. This is the state in which there is a minimum photon emission from QED processes. PSR itself may become a serious background, but there exists an analogue of stopped light extended to two-photon process in which one expects that photon emission occurs only from edges of the target and not from the bulk. If this state is realized, one can minimize the PSR background. We call this ideal state two-photon soliton and its solutions have been found [15].

Clearly, there are many experimental and theoretical works before we write a serious RENP proposal. We are advancing this step steadily in Okayama.

5 Epilogue

Nambu had versatile interests in all areas of physics and basic sciences. He seemed to convey all the time that physicists should enjoy scientific achievements using benefits as a physicist. He also showed his interest in people who created the greatest achievements in science. I learned lots on these from interaction with Nambu.

Since I left Chicago, I fortunately had many occasions to talk with him, in particular the chances when I could communicate my own works were very valuable. When I spoke of the baryo-genesis idea at Sendai in 1978 where he happened to attend the annual meeting of Japan Physical Society, he showed an immediate and a great interest in my work. Later at Osaka I had many chances to talk about our SPAN project which he encouraged very much.

I learned from Nambu that one should be brave in creating and developing new ideas, but at the same time one should study physics achievements as a whole. What I could not learn from Nambu is to foster ideas for a very long time over more than ten years. Some of his bold ideas goes back to his school days. This
is something truly amazing. He has certainly left to his closest friends great impressions of how outstanding ideas can be developed. I hope that the Nambu way is also appreciated by many.

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