

## Wrapping up the Standard Model

The award of the Nobel prize in equal shares to Prof. Yoichiro Nambu of the University of Chicago, Profs. Makoto Kobayashi of the KEK laboratory in Tsukuba and Toshihide Maskawa of Kyoto University, nearly completes the series of Nobel Prizes recognizing the development of the Standard Model of Particle Physics. This model is a simple and coherent picture of fundamental particles and forces based upon the mathematical formalism of Relativistic Quantum (Gauge) Field theory(RQFT) developed between 1960 and 1979. It successfully describes the underlying physics of all material reality (except gravitational forces) in terms of just three families of Quark-Lepton matter particles and three types of force particles (photons, gluons and W-Z bosons, responsible for Electromagnetic, Strong subnuclear and Weak subnuclear forces respectively). The quark pairs of the three generations are called up-down, charm-strange and top-bottom, while the lepton pairs are the electron, muon and tau leptons along with their partner neutrinos.

Of the three families, the first, lightest, family comprising the up and down quark 'doublet' and the electron-neutrino lepton doublet is the constituent of all stable nuclear and electronic matter. The other two families contain short lived particles that can decay to the lighter particles via emission of Weak charged (or W) force particles. Three Nobel Prizes recognizing *theoreticians* who built the Standard Model have already been given : in 1979 ( S.Glashow, A.Salam and S.Weinberg for the Electro-Weak and lepton sector ), 1999 ('t Hooft and Veltman , for proving 'renormalizability' of the SM i.e it's mathematical consistency using only a limited number of experimentally determined quantities) and finally in 2004 (D.Gross, H.D. Politzer and F.Wilczek for the discovery of the 'asymptotic freedom' or weakness at high energies of the gluon mediated force between quarks or QCD ). Similarly no less than 7 Nobel prizes have recognized the experimental confirmation of various components of the SM such as the discovery of the Charm quark(1976), CP violation in K mesons (1978), W-Z bosons(1984), mu-neutrino(1988), Deep inelastic scattering(1990), tau lepton(1995) and neutrino physics(1995).

Quantum Field Theory(QFT) sees the material world at the subatomic level as a restless cauldron in which continual creation and destruction of particles plays out against the backdrop of the vacuum, reference or ground state. The vacuum is now thought of as a 'sea' rather than as an emptiness since modern physics has shown it is a fullness (of fleeting but uncontrollably violent) quantum fluctuations rather than the emptiness that is the colloquial, but out dated, classical sense of the word vacuum.

The significance of Nambu's contributions is twofold. On the one hand, he is known as a physicist's physicist (a sort of Yoda of the Particle Physics Galaxy!) who (in the fabled beginning i.e 1960) germinated the very concept of 'spontaneously broken symmetry'. Proceeding by analogy with the Theory of Superconductivity in metals which had then just been invented, he transposed its ideas to the framework of QFT. For elementary particle physics. *This was the fundamental intuition that permitted the*

*construction of the Standard Model.* By symmetry we mean changes (such as rotations) that leave unchanged (or symmetric : just as a ball appears unchanged after a rotation) the Lagrange function. The Lagrange function is basic because it gives the equations of motion (or "Newton's Laws") of the theory. The catch is that the symmetry operations do *not* leave the vacuum unchanged. As a result the symmetry of the Lagrange function is manifested to us (in experimental measurements) in a hidden or 'broken' way. This is the so called Nambu-Goldstone mode of symmetry realization (the only other mode is the trivial or so called Wigner-Weyl mode where both the equations of motion and the vacuum are unchanged by the symmetry operations).

The insight of Nambu paved the way for the consistent introduction, by Salam and Weinberg in 1967, of (large) masses for the W-Z bosons which are responsible for the extremely short range Weak sub-nuclear force. Equally importantly, it is at the basis of the idea of *Chiral Perturbation Theory* which is used for the description of the composite Hadrons (Baryons and Mesons) which are bound states of the quarks and which are what is actually observed directly in Nature by us. The basic idea of Nambu was that there is a nearly exact "*Chiral symmetry*" due to the extreme lightness of the stable up and down quarks relative to the mass of the proton and neutron (the basic Baryons). This symmetry is broken, i.e is not respected, by the vacuum or ground state which forms under the domination of the strong nuclear force. As a result there exist very light particles, the so called pseudo- Nambu-Goldstone(NG) bosons of this symmetry breaking. They are identified with the Pi-Mesons which are mainly responsible for the (relatively long ranged) forces between hadrons. The word pseudo refers to the fact that the original chiral symmetry is only approximate due to the small but not zero masses of the underlying quarks, so that the pi-mesons are light but not massless as they would be- as shown in 1961 by J.Goldstone - if the symmetry was exact. Such NG bosons are also a third part of each of the massive force particles(W-Z) of the Weak force. Thus both in the Electro-Weak and in the Strong (or QCD) sectors of the SM the contributions of Nambu were fundamental and seminal and it would have been ironic and unjust had he not received recognition for them.

The contributions of Kobayashi and Masakawa (KM) may also be seen within the general framework of broken symmetries but they concern a quite different (discrete as opposed to continuous) symmetry respected by all but a small piece of the Lagrange function of the SM. In a way, the work of KM could be called the capstone of the SM as opposed to the foundation stone laid by Nambu. The story below will also bring out the poignancy of the *omission* of N. Cabibbo and perhaps others from this years Nobel awards, since their contributions precede and underlie those of KM.

In the SM the *only* way in which one *type* of particle can change into another type (say an up type quark into a down type quark or a charged lepton (electron, muon, tau) into its corresponding Neutrino –or vice versa) is by emitting or absorbing the charged Weak force carriers (W particles). Furthermore, the *only* way that quarks (leptons

never do so in the SM) from one family can change into those of *another* family( e.g the strange quark into the up quark) is again via this process of emitting W force particles. The small extent to which this change of strange into up quark happens is described by the small value of the so called Cabbibo mixing angle. This angle was introduced by N. Cabbibo well before the advent of the modern Standard Model. In 1970 S.Glashow, J.Illiopoulos and L.Maiani(GIM) proposed that certain unobserved strangeness changing processes could be understood via the existence of a fourth (or “Charm”) quark analogous to the up quark of the first family (as the strange is analogous to the down quark). Such a quark was triumphantly discovered in 1974(and rewarded by a Nobel prize to B. Richter and S. Ting in 1976).

In 1972 Kobayashi and Maskawa extended the idea of the Cabbibo mixing angle (all that would be needed if there were only two families) to a fundamental quantity called the Cabbibo-Kobayashi-Maskawa(CKM) matrix by introducing *three* new quarks beyond the up, down and strange quarks already known. The CKM matrix depends on three Cabbibo type mixing angles (between the 1-2,2-3 and 1-3 generation pairs) and a KM “phase angle”. This KM phase angle first appears for three families and describes the extent to which the symmetry of reversal of time direction (T) -or equivalently the symmetry of successive particle-antiparticle and Left-Right interchanges (CP symmetry operation)- is broken in Nature. The equivalence of the T and CP violation is the consequence of a very fundamental and general result called the CPT theorem which inserts that the succession of the three operations C,P,T is always a symmetry.

In fact KM hit upon their model by investigating , *in the context of the SM*, the conditions required for introducing CP(or equivalently T) violation into the Lagrange function of the SM. They showed that this was not possible without (at least ) an additional family over and above the one completed by GIM. *Their work thus motivated the conception of a SM with three families of matter fermions well before the actual discovery of the charm(1974), bottom(1975) and top(1994) quarks and tau lepton(1977).*

Violation of CP/T symmetry had already been observed in the inter-transformations of K mesons and their antiparticles in 1964 (and recognized by a Nobel prize to Cronin and Fitch in 1978). Although other sources for this type of symmetry violation are conceivable it has now been confirmed that all the CP violation observed so far (in the K, B meson systems) is well described by the CKM framework alone. Since the work of A.Sakharov (of Nobel peace prize and Hydrogen Bomb fame) , CP violation is known to be essential for the creation of a Universe like ours (where matter dominates over antimatter). The discovery and successful description of CP violation is thus of truly fundamental importance for our very existence.

The Standard Model is now nearly “wrapped up”. The only major component as yet unconfirmed by experiment is the existence of the Higgs particle predicted by the SM as the residuum of the symmetry breaking mechanism that gives rise to the mass of

Quarks and Leptons and W-Z force particles. The enormous investment, gargantuan dimensions and mind boggling technical achievements, as well as media doomsday hype, of the Large Hadron Collider(LHC) at CERN in Geneva has the entire world agog to see the next act in the unfolding story of the fundamental constituents of the universe. Whatever is discovered will have a vital bearing on the continuing quest to discover the even deeper levels of reality behind the beautiful broken symmetries of the Standard Model. Besides the tremendous intellectual and technical achievements of the theoretical and experimental edifices erected for the SM and its confirmation by experiment, we have already benefited enormously from spin-off technologies such as the World Wide Web and Grid/Cloud Computing which were invented to handle the unprecedented information processing demands of High Energy Physics. Yet most of all the rigour and precision of this fundamental science engages the drive that is our deepest and noblest characteristic : namely our curiosity and need to know what lies beyond any limit, and our need to give symbolic expression to what our curiosity uncovers. Thus we celebrate once again with these Nobels our highest common humanity.

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