What is the Physics in this Century?

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What should we do next ?

- I spent the golden time in particle physics when I was young

- I will show you what happened around me in the golden time

To find our answer to the question

The Golden Time Started

- **Discovery of neutral currents** at CERN ---1973

v_bar + e → v_bar + e   3 events

A sharped-eye's graduate student found them from 100,000 pictures scanned in Gargamelle heavy-liquid bubble chamber

The new paradigm based on gauge theories started after this NC discovery (Weinberg-Salam model had been only one of many options)

In the beginning of my graduate student period

- Discovery of the charm quark Niu… (1971)

Long lived particles were discovered in cosmic rays

X → pi^0 + pi^¥pm

M_X ~1.8 GeV, T_X~10^{-14} sec

X=(cq_bar) ….. m_c ~1.5 GeV Ogawa…(1972)

I predicted Phi(cc_bar) of mass ~3 GeV, but I did not publish it, since I did not trust my advisor …..

Ogawa and Yanagida (1973)

BUT !!!

- The Phi (cc_bar) was discovered in SLAC and Brookhaven Lab ….. (1974) They received Nobel Prize

m_Phi = 3.1 GeV

Kobayashi and Maskawa wrote the CKM theory for the CP violation believing the Niu event and the presence of the charm quark

Kabayashi and Maskawa (1973) They got Nobel Prize

You should trust your advisor sometimes !

- Bjorken scaling Bjorken (1968)

Bjorken proposed scaling law in the deep inelastic scattering of electrons and nucleon

The experimental discovery of the scaling law indicated that elementary particles (Feynman's partons) form nucleon behave like free particles deep inside of nucleon

This inspired the idea of asymptotic freedom of fundamental forces

The asymptotic freedom was discovered in QCD Gross, Wilzcek and Politzer (1973)

- By 1973 the standard model (SM) based on SU(3)xSU(2)xU(1) gauge symmetry was completed
- But we had many questions
- One of them was the charge quantization

The U(1) charges are:

Q(1/6), u(2/3), d(-1/3)

L(-1/2), e(-1)

This is one of ugly parts of the SM

Who ordered such ugly charges ?

- That is Grand Unification (GUT) ; SU(5)

Georgi and Glashow (1974)

The SM SU(3)xSU(2)xU(1) is a maximal subgroup of the GUT SU(5);

Quarks and Leptons belong **5* +10** representations of the SU(5)

And the U(1) charges are determined as required values.

It is NOT ugly but **even beautiful** !

Massless neutrinos are predicted

- The **GUT paradigm** started from 1974 and I was a PHD graduate student
- From 1967-1973 (~5 years) we have 5 works which received the Nobel Prizes in particle physics

- I thought it was **too late** for me to join the GUT paradigm
- I started to consider some different direction from the GUT, which motivated me to the idea of *the seesaw mechanism*

GUT Paradigm **form 1974**

- The GUT breaks down to the standard model at very high energies M ~10^{15} GeV

SU(5) → SU(3)xSU(2)xU(1)

We strongly believed unifications of interactions and matters at very high energies !!!

I started to consider a unification of matters

when I was a PHD student

Unification of Families

Maehara, Yanagida （1977）
Wilzeck, Zee （1978）

$$q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \quad \begin{matrix} u_R^i \\ d_R^i \end{matrix} \quad ; \quad l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \quad e_R^i \qquad (i = 1 - 3)$$

←SU(3)→ ←SU(3)→

Horizontal Gauge Symmetry

I considered that the horizontal SU(3) symmetry is broken down at very high energies

M~10^{15} GeV

- But we had **a serious problem**

There is a gauge anomaly and we can not quantize the SU(3) gauge symmetry

We need to introduce **three right-handed neutrinos** to cancel the gauge anomaly

Yanagida (1979)

$$\nu_R^i$$

$$q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \quad \begin{matrix} u_R^i \\ d_R^i \end{matrix} \quad ; \quad l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \quad e_R^i \qquad (i = 1-3)$$

- Go to the Madrid File

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- Come back from the Madrid File

I found the seesaw mechanism

m(neutrino) = m^2/M

predictes very small masses O(1) eV in 1979

The neutrino masses were discovered in the super-Kamiokande experiments in 1998,

m(v)=0.05 eV… Nobel prize in 2015

New paradigm in high energy physics (1974-1986)

- It produced many new ideas
- 1974; Grand Unification Georgi, Glashow
- 1977; Axion Peccei, Quinn; Weinberg, Wilczek
- 1979; Seesaw Yanagida, Gell-Man …
- 1980; Supersymmetry Maiani, Veltman
- 1981; Inflation Guth
- 1983; Dark Matter …..
- 1986; Leptogenesis Fukugita, Yanagida

1990 ~ present

- Deep understanding on quantum field theories
- Details about the new ideas created in the GUT paradigm
- String theories
- Detection of CMB temperature fluctuations (1992)
- Confirmation of the neutrino oscillation (1998)
- Discovery of the cosmological constant (1998)
- ……
- Higgs boson discovery (2013) ………. present

Question to Us Now

What should we do next ?

It is very clear now!

Century View

We had two very important breakthroughs in the beginning of the last century

- ***Special Relativity (1905)***
- ***Quantum Mechanics (~1925-26)***

- *Quantum Field Theory (~1943) unifying the two theories, which is very successful*
- *The Standard Model is based on the QFT(1960~....)*

But we have a serious problem

General Relativity Einstein (1935)

- Quantum Gravity has unremovable divergences General Relativity is **inconsistent** with Quantum Mechanics
- Construction of String Theories began from 1980th However they are not completed
- But we have a hope that a string theory will open the next stage of fundamental physics, unifying the General Relativity and Quantum Mechanics

What is the Physics ?

String theories predict

1. **Ten (9+1) dimension space time**

2. **Supersymmetry**

3. **Multiverse**

   10^{500-1000} universes

all @ #107

Appendix

Masses and mixing angles for neutrinos

The recent global analysis gives

T. Schwetz, M. Tortola, J.W.F. Valle (2011)

$$\Delta m_{21}^2 = 7.59^{+0.20}_{-0.18} \times 10^{-5}\mathrm{eV}^2$$

$$\Delta m_{31}^2 = 2.50^{+0.09}_{-0.16} \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}$$

$$\sin^2\theta_{23} = 0.52^{+0.06}_{-0.07}$$

$$\sin^2\theta_{13} = 0.013^{+0.007}_{-0.005}$$

$$\delta_{CP} = (-0.61^{+0.75}_{-0.65})\pi$$

$m_3 > m_2 > m_1$ ⇒ $m_3 \simeq 0.05\mathrm{eV}$, $m_2 \simeq 0.009\mathrm{eV}$

cf. $m_{\mathrm{top}} \simeq 173\mathrm{GeV}$, $m_\tau \simeq 1.7\mathrm{GeV}$

Why are neutrino masses so small ?

Discovery of the Seesaw Mechanism

A Puzzle in the Weinberg-Salam model:

Gauge group = SU(3)xSU(2)xU(1)

1. U(1) hypercharges ?

$$q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \text{(1/6)} \qquad u_R^i \text{ (2/3)} \qquad d_R^i \text{ (-1/3)}$$

$$l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \text{(-1/2)} \qquad e_R^i \text{ (-1)}$$

The theory is anomaly free with these awkward charges !

An example; 6x(1/6)^3 + 3x(-2/3)^3 + 3x(1/3)^3 +2x(-1/2)^3 +(+1)^3 =0

The hypercharges are naturally explained in a grand unification

SU(3)xSU(2)xU(1) is embedded in **SU(5)**

Georgi, Glashow (1974)

All quarks and leptons belong to **5* + 10** of the SU(5) !
The hypercharges are given by an SU(5) generator

But, the quarks and leptons are not completely unified

SO(10) contains the SU(5) and is more attractive, since it unifies all quarks and leptons in 16

$$\textbf{16=} \quad q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \quad \begin{matrix} u_R^i \\ d_R^i \end{matrix} \quad ; \quad l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \quad \begin{matrix} \nu_R^i \\ e_R^i \end{matrix}$$

We had a big problem

The neutrino has a large Dirac mass

$$y_\nu \bar{\nu}_R l_L \langle H \rangle \quad ; \quad y_t \bar{t}_R q_L \langle H \rangle$$

$y_\nu = y_t$ ⟶ m(neutrino) = m(top) ???

But, we found the right-handed neutrino get a huge Majorana mass when the SO(10) breaks down to the Standard Model

$$\frac{1}{2} M \bar{\nu}_R^C \nu_R$$

The neutrino mass becomes $m_\nu \simeq \frac{m^2}{M}$; $M_N \simeq M$

Yanagida (1979)
Gell-Mann, Ramond, Slansky (1979)

Seesaw Mechanism