# NEUTRINOS AND SAKATA

## — A Personal View —

Masami Nakagawa
Department of Physics, Meijo University, Nagoya 468, Japan

This conference, a workshop for the neutrino mass, is to require real contributions to Today's and Future's problems on the neutrinos, so it might not be the place to mention past history. But it may, I believe, be worth presenting some historical review of researches on neutrinos in Japan, especially of those guided by the late Professor Shoichi Sakata, since he had continuously been taking great leadership at least twenty years from the proposal of two meson-two neutrino theory (1942) to the proposal of mixture theory of massive neutrinos (1962/3)*). I must apologize for not mentioning the whole feature of the development including works done in places other than Japan because I do not like to bother you any more by my dull presentation of the well-known part of the history.

## PROPOSAL OF $\mu$ AND $\nu_\mu$ (1942)

After many pioneering works on meson theory with collabolation of Yukawa and others, Sakata and Inoue proposed the two meson-two neutrino theory in 1942 (paper written in English was published in 1946)[1]. Their two meson-two neutrino theory means that it claims the existence of another pair of leptons

$$m^-(=\mu^-),\ n(=\nu_\mu) \text{ in addition to } e^-,\ \nu(=\nu_e), \qquad (1)$$

where m and n are new fermion pair corresponding to e and $\nu$ (original meaning of the two meson theory was for the assumption of $\pi$ and $\mu$ mesons). It is to be noted that the 'neutrino' n was assumed as a particle different from $\nu(=\nu_e)$, and was not necessarily considered as massless particle. The new leptons were proposed to account for a discrepancy between predicted properties of Yukawa meson(pion) and observed properties of the hard component of cosmic rays — small scattering cross section and long lifetime — namely, muon's large penetrability in matter and its decay lifetime. Practically the masses of neutrinos were found to be very small, and afterward the neutrinos were taken essentially as massless entities and more-over as identical ($\nu_e = \nu_\mu$) from the convenience and economy principles.

Sakata had been sceptical to this conventional assumption and had repeatedly warned us that the principles of convenience and economy were dangerous and often missleaded physicists. A work of Ogawa and Kamefuchi (1950)[2], they say, under the suggestion of Sakata was to clarify phenomenological consequences of the assumption $\nu_e = \nu_\mu$. They pointed out the occurence of $\mu \leftrightarrow e$ conversion in Coulomb field via annihilation of $\nu$ and $\bar{\nu}$ in muon decay interaction if $\nu_e = \nu_\mu \equiv \nu$, and calculated the probability for one electron decay of mumesic atom in K-orbit and the probability for muon scattering under Coulomb field of nucleus associated by $\mu \to e$ conversion.

*) The leadership with his genius had lasted to the date of death, October 1970.

## A CRITIQUE (1955)

In 1955 Sakata wrote a paper[3] in Japanese with a shocking title 'Superstition around Majorana Neutrino'. He says it should not be adequate to question whether a neutrino is a Dirac or Majorana particle in an alternative judgment, and it is nothing but a superstition to believe that the answer to the question be obtained by experiment of double beta decay and so on. His point is that such a question making the Majorana theory in sharp conflict with the Dirac theory arises from choosing the interaction within unnecessarily narrow variety. Two sorts of interactions for beta decay are introduced with a Dirac neutrino $\nu$ as

$$H = \sum_i G_i(\bar{\Psi}_p\, O_i\, \Psi_n)(\bar{\Psi}_e\, O_i\, \Psi_\nu) + \text{h.c.} \qquad (2)$$

and

$$H^c = \sum_i G_i'(\bar{\Psi}_p\, O_i\, \Psi_n)(\bar{\Psi}_e\, O_i\, \Psi_\nu^c) + \text{h.c.}, \qquad (3)$$

where $\Psi_\nu^c$ means a charge conjugated field of $\Psi_\nu$. As far as the neutrino is massless, these interactions are completely equivalent, and the Dirac neutrino can be defined from either of interactions. If, however, the beta interaction most generally consists of both interactions as

$$H_\beta = H + H^c$$
$$= \sum_i(\bar{\Psi}_p\, O_i\, \Psi_n)[\,\bar{\Psi}_e\, O_i\, (G_i\Psi_\nu + G_i'\Psi_\nu^c)\,] + \text{h.c.}, \qquad (4)$$

the physical situation changes drastically. When the coupling constants satisfy an equality

$$G_i = G_i', \qquad (5)$$

the interaction can be transfered to the one described in terms of Majorana field. However as a matter of experiment, a confirmation of neutrinoless double beta decay, if it is, would yield only a constraint on the coupling constants, say, in a form as

$$G_i \simeq G_i'. \qquad (6)$$

Conversely, eq.(6) leads to the results almost equivalent to those of the Majorana theory on the phenomenological level. Furthermore, to confirm the Majorana theory literally, one should establish experimentally the relation (5) for all the processes involving neutrino.

Sakata's point is that the Majorana theory is equivalent to a limited form of the Dirac theory of neutrino interaction with non-conservation of lepton number, and that to choose a particular (convenient and economical) type for neutrino with no experimental confirmation implies to lose abundance in the structure of interaction simultaneously. We see such example to the assumption of two component neutrino with only one chirality for an interpretation of V-A nature of weak interaction, which seems to have long been preventing peoples from considering possibility of massive neutrinos. In this 1955, Kamefuchi and Tanaka[4] gave a consistent quantization to 'Jauch field' which in its appearance shows an intermediate nature between Dirac and Majorana fields.

### BARYON-LEPTON SYMMETRY COMPOSITE MODEL (1960)

Now after the proposal of the Sakata model, well-known composite model of hadrons, in 1955 (published in 1956)[5], lepton physics again came to Sakata in a new form of problem; how to understand the inner relation between leptons and his subhadronic fundamental particles p, n and $\lambda$*). In 1959 Gamba, Marshak and Okubo[6] pointed out a symmetry of weak interaction under the transformation

$$\nu \leftrightarrow p, \quad e^- \leftrightarrow n, \quad \mu^- \leftrightarrow \lambda, \qquad (7)$$

provided that the weak current is described only in terms of leptons and the fundamental particles. Note that the neutrino was considered as one kind at the time. In order to realize this symmetry from one more step deeper level, we (Maki, Nakagawa, Ohnuki and Sakata: 1960)[7] proposed further a composite model for the fundamental particles, namely, these are composite particles of a bosonic object

*) As is well-known, in the original 1956 paper, Sakata's fundamental particles were the physical proton, neutron and lamda particles which we here denote p, n and $\lambda$. It is, however, to be noted that the concept of fundamental triplet is evidently valid for the present-day established subhadronic particles -up to the charm realm- in the sence that it gives the correct form of weak interaction and the quark scheme only by changing the assignment of quantum numbers(baryon number and charges). In 1963, after the experimental confirmation of the eightfold way but before the proposal(Gell-Mann, Zweig: 1964) of the quark model, Sakata noted that it was not correct to compare his model with the eightfold way, but to be compared with the latter should be the U(3) symmetry realization of his model, and that his concept of fundamental triplet should be taken as subhadronic particles for eight baryons if the eightfold way got reality: a talk at the meeting on Model and Structure of Elementary Particles held at Hiroshima University, May 1963 (S.Sakata, Soryushiron-Kenkyu 27, 110 (1963)).

and leptons as

$$p = (\nu b^+), \quad n = (e^- b^+), \quad \lambda = (\mu^- b^+), \qquad (8)$$

which may be an earliest sub-quark model in the present terminology. Note that the neutrino in this model is necessarily a four component spinor.

On the lepton physics side, following to the confirmation of parity violation, lepton number conservation law was newly studied by many authors[8] in 1957-8 on the basis of separate conservation of electron- and muon-numbers. These theories can be summarized into the following currents as

$$\bar{e}\gamma_\alpha(1 + \gamma_5)\nu, \quad \text{and} \quad \bar{\mu}\gamma_\alpha(1 + \gamma_5)\omega, \qquad (9)$$

where the neutrinos are assigned in alternative ways as

$$\text{(i)} \quad \omega = \nu^c, \qquad (10)$$

$$\text{(ii)} \quad \nu = \nu_e, \quad \omega = \nu_\mu \qquad (\nu_e \neq \nu_\mu). \qquad (11)$$

Obviously these two cases lead equivalently to the separate conservation of electron- and muon-numbers as far as neutrinos are exactly massless. But once netrinos get masses, the first case (i) breaks electron-number (muon-number as well), whereas the case (ii) does not. Neutrino mixture theory we proposed (as explained in the following section) is based on the case (ii).

### PROPOSAL OF NEUTRINO MIXTURE SCHEME FOR THE BARYON-LEPTON SYMMETRY (1962)

It was evident to modify the 'sub-quark' model (8) to harmonize with the existence of two neutrinos. In 1962, after the experimental confirmation[9] of two kinds for neutrinos, Kyoto group (Katayama, Matumoto, Tanaka and Yamada)[10] and independently we (Maki, Nakagawa and Sakata)[11] extended the baryon-lepton symmetry (7) into the four leptons scheme as follows

$$\begin{array}{lcl} \nu_1 = \cos\theta\ \nu_e + \sin\theta\ \nu_\mu & \leftrightarrow & p \\ \nu_2 = -\sin\theta\ \nu_e + \cos\theta\ \nu_\mu & \leftrightarrow & p' \\ e^- & \leftrightarrow & n \\ \mu^- & \leftrightarrow & \lambda \end{array} \qquad (12)$$

where instead of $\nu_e$ and $\nu_\mu$ the rotated states correspond to baryons. The 'sub-quark' model is now modified to

$$p = (\nu_1 b^+), \quad n = (e^- b^+), \quad \lambda = (\mu^- b^+), \quad p' = (\nu_2 b^+). \qquad (13)$$

Note that the principle of baryon-lepton symmetry implies an introduction of the fourth fundamental particle p' as a logical consequence, and the weak current satisfying (12) is given as

$$j_\alpha = \bar{e}v_\alpha \nu_e + \bar{\mu}v_\alpha \nu_\mu + \cos\theta\ \bar{p}v_\alpha n + \sin\theta\ \bar{p}v_\alpha \lambda$$
$$-\sin\theta\ \bar{p}'v_\alpha n + \cos\theta\ \bar{p}'v_\alpha \lambda, \qquad (14)$$

where $v_\alpha = \gamma_\alpha(1+\gamma_5)$. It is to be noted that the neutrino mixture is inevitable to accomodate strangeness change in the weak current satisfying the baryon-lepton symmetry. Here you can easily read off the current (14) to the present-day GIM current by putting the ordinary quarks u, d, s and c on the Sakata particles p, n, λ, and p'.

MASSIVE NEUTRINOS AND NEUTRINO OSCILLATION (1962/3)

In the paper of 1962, we (Maki, Nakagawa and Sakata)[11] put forward study of the neutrino structure. We defined $\nu_e$ and $\nu_\mu$ of the weak current (14) as 'weak neutrinos', and defined $\nu_1$ and $\nu_2$ as 'true neutrinos' which mean the particles of mass eigenstates. Then the weak neutrinos are mixing states of the true neutrinos as follows

$$\nu_e = \cos\theta\ \nu_1 - \sin\theta\ \nu_2$$
$$\nu_\mu = \sin\theta\ \nu_1 + \cos\theta\ \nu_2. \qquad (15)$$

It was also shown on the basis of a lepton model that the mixture theory provides a reasonable value to the angle θ (equal in magnitude to the Cabibbo angle proposed in 1963) as well as μ-e mass difference. Furthermore it was pointed out that the weak neutrinos are not stable due to the occurence of a virtual transmutation $\nu_e \leftrightarrow \nu_\mu$, and that the two-neutrino experiment using fast neutrino with momentum ≃GeV/c will be useful to check the two-neutrino hypothesis only when the mass difference of $\nu_1$ and $\nu_2$ is $|m_{\nu1} - m_{\nu2}| \leq 1$ eV under a conventional geometry of experiments. The other muon-number non-conserving process $\mu \to e + \gamma$ was also pointed out to occur as a consequence of the model of leptons.

In subsequent 1963, we (Nakagawa, Okonogi, Sakata and Toyoda)[12] discussed the implications of the mixture theory for the case of neutrino mass of order 1 MeV, i.e. $m_{\nu1} = 0$, $m_{\nu2} = 1$ MeV. The Brookhaven experiment was reanalyzed in terms of the neutrino oscillation initiated by $\nu_\mu$ beam, our formula for the ratio of electrons to muons was given as

$$\frac{N_e}{N_\mu} = \frac{2\sin^2\theta\cos^2\theta}{\cos^4\theta + \sin^4\theta} \qquad (16)$$

and the ratio was ≃1/20 for $\sin\theta \simeq 0.16$; we heard Brookhaven had 29$\mu^-$ at that time! We also computed the decay processes $\mu \to e + \gamma$ and $\nu_2 \to \nu_1 + \gamma$ with now well-known diagrams involving weak boson W. We realized these processes can occur only through mass(squared) difference of virtual leptons on account of cancellation of highest divergent terms due to the rotation (15). The decay amplitudes are controlled by factors $(m_{\nu1}^2 - m_{\nu2}^2)/M_W^2$ for $\mu \to e + \gamma$, and $(m_e^2 - m_\mu^2)/M_W^2$ for $\nu_2 \to \nu_1 + \gamma$ up to the Feynman integral factors. The results are $Br(\mu^- \to e + \gamma) \simeq 10^{-17}$, and $\tau(\nu_2 \to \nu_1 + \gamma) \simeq 10^{10}$ sec for the lifetime of $\nu_2$ under $M_W = 1$ GeV. The reason for our choice of 1 MeV for neutrino mass was -now maybe an episode- due to (it must be, our wrong understanding of) experimental data about beta decays. We attempted to explain an anomaly at low (electron) energy side on Kurie plot and a slightly increasing values of coupling constant $G_V$ (effective strength of Fermi transition) with increasing Q-values. But these experiments have prompted us to put forward the idea of mixture theory of massive neutrinos into the phenomenology of oscillation and decay of massive neutrinos, and of muon-number non-conservation.

I have presented historical development of theory of neutrinos promoted by Sakata and his group which covers the proposal of $\mu^-$ and $\nu_\mu$ (two meson-two neutrino theory) to the proposal of neutrino mixture and oscilltion between different flavors. The latter was born from an attempt of unified description of leptons and sub-hadronic particles. Today also the neutrino structure is in a key position to the organization of grand unified theories. It seems there are still many problems to be clarified: What is the origin of neutrino masses and mixtures? Does it afford a consistent basis for our understanding of the old problem of electron-muon difference, of Cabibbo-Kobayashi-Maskawa angles, and of generation patterns of quarks and leptons? I would like to conclude this presentation by citing Sakata's words written in 1961 just before the discovery of two kinds for neutrinos[13]

> Even behind the neutrino, we should have to seek for the causa formalis of its mode of existence.

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# MEASUREMENT OF THE β-SPECTRUM OF $^3$H WITH A Si(Li) DETECTOR FOR DETERMINING $M_{\bar{\nu}_e}$


J. J. Simpson
Dept. of Physics, University of Guelph
Guelph, Ontario, Canada N1G 2W1



## ABSTRACT

An experiment to measure the β-energy spectrum of tritium implanted in a Si(Li) X-ray detector has been investigated as a method to determine the mass of the electron anti-neutrino and the $^3$H-$^3$He atomic mass difference. Present results imply a mass < 65 eV with 95% confidence and an end-point energy of 18567 ± 5 eV.


## INTRODUCTION

An experiment has been carried out using tritium implanted in a Si(Li) X-ray detector to determine the mass $m_{\bar{\nu}}$ of the electron anti-neutrino in tritium β-decay and the atomic mass difference between $^3$H and $^3$He. Compared to magnetic spectrometer methods of determining the same quantities[1,2], this method has the advantage that the whole β-energy spectrum can be recorded simultaneously and at the same time as calibration spectra, and that final state effects do not complicate the analysis as much. This advantage is paid for by the rather worse energy resolution of the Si(Li) detector than of a magnetic spectrometer. However, the measurement of a large part of the β-spectrum permits an analysis procedure which can compensate for the worsened resolution. (This work was first reported at Neutrino '79, Bergen[3].)

## EXPERIMENT

The experimental details are briefly as follows. (A full report will be published in Physical Review D.) A defocussed beam of tritons (0.25 nA) from the McMaster FN tandem accelerator was implanted into a commercially obtained Si(Li) detector (80 mm$^2$ in area) in steps of 100 keV from 8 MeV to 9.1 MeV as shown in fig. 1. Implantation was stopped when a worsening of resolution became apparent.

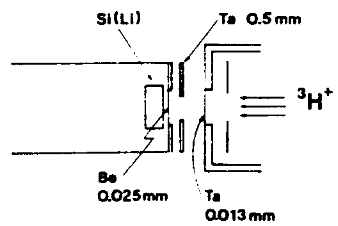


Fig. 1. Implantation of $^3$H into a Si(Li) detector.

The energy spectrum of the β-particles was routed into one half of a multi-channel analyzer memory and a spectrum including Cu, Mo and Ag X-rays which were intermittently shone on the detector every