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A NEUTRAL CURRENT CONSTRAINT AND GAUGE MODEL

T. Hagiwara*
The Rockefeller University; New York, New York 10021
and
Stanford Linear Accelerator Center†
Stanford University; Stanford, California 94305

E. Takasugi**
Department of Physics
The Ohio State University; Columbus, Ohio 43210
and
Stanford Linear Accelerator Center†
Stanford University; Stanford, California 94305

ABSTRACT

The experimental observation $R^{\bar{\nu}}/R^{\nu} < \sigma_C^{\nu}/\sigma_C^{\bar{\nu}}$, i.e., $\sigma_N^{\nu} > \sigma_N^{\bar{\nu}}$ where $\sigma_{C,N}^{\nu(\bar{\nu})}$ are the ν-($\bar{\nu}$-) induced charged and neutral current inclusive cross sections on an isospin 0 nucleon and $R^{\nu(\bar{\nu})} = \sigma_N^{\nu(\bar{\nu})}/\sigma_C^{\nu(\bar{\nu})}$, provides a constraint on the possible quark representations among various SU(2) × U(1) gauge models. We have examined the energy dependence of both ν-($\bar{\nu}$-) induced charged and neutral current processes in the models which respect the constraint. Some of the models contain one or a few heavy quarks with an exotic charge of Q=5/3 and/or -4/3.

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GIM-charm[1] may have been found. The recent discoveries at SPEAR of neutral and charged resonance states around 1.87 GeV[2], which decay exotically into $K+\pi$'s, strongly suggest that they may be indeed long awaited "charm" particles.[3] On the other hand, we have been informed that the GIM-charm alone cannot explain the recent experimental data on ν- and $\bar{\nu}$-induced charged current inclusive processes.[4] The data indicate that there exists another degree of freedom other than "charm". More specifically, in addition to the SU(3)-triplet quarks (u, d, s), and the GIM-charm quark (c), the data require the existence of a heavy quark (say, b).[5] The b-quark has a mass about 5 GeV and it couples to u- or d-quark in the form of right-handed charged current[6] $\bar{u}_R\gamma_\mu b_R$ or $\bar{d}_R\gamma_\mu b_R$. A charge of b-quark is either -1/3 or exotic -4/3.

If such an observation is correct, that two new flavors of quarks (i.e., c- and b-quarks), are necessary to interpret the recent experimental data consistently, then the following questions ought to be raised. (i) Is there any limit on the number of quark flavors? Can the limit be derived theoretically? (ii) Provided that the limit is known, how orderly can these quarks be incorporated into the unified theory of strong, weak and electromagnetic interactions?

As the $SU(2) \times U(1)$ gauge model[7] has been known to be successful to describe low energy phenomenology of weak interactions, we rephrase the latter question into the following: In the light of present experimental data, which quark representations of $SU(2) \times U(1)$ gauge models are acceptable?

In the following, we show that there are five classes of $SU(2) \times U(1)$ gauge models which are consistent with both ν-($\bar{\nu}$-) induced charged and neutral current inclusive data.

Classification of SU(2) × U(1) Gauge Model

Let us propose that the following quantity Δ, defined by

$$\Delta \equiv \sum_{i=u,d} C_V^i C_A^i \quad , \tag{1}$$

provides an effective way to classify various quark representations of SU(2) × U(1) gauge models. C_V^i and C_A^i are a vector and an axial-vector coupling constants of a neutral current,

$$J_\mu = \sum_{i=u,d,\ldots} \bar{q}^i \gamma_\mu \left(C_V^i + C_A^i \gamma_5\right) q^i \tag{2}$$

where i runs over u, d, and other quark flavors. We have assumed that the neutral current has the diagonal form at least for the parts involving u- and d-quarks.

Because of the very existence of ν- and $\bar{\nu}$-induced neutral current weak interactions in order of G_F and β-μ Cabibbo universality, we consider models with the following left-handed lepton and quark doublet representations:

$$\begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}_L \quad , \quad \begin{pmatrix} u \\ d_C \end{pmatrix}_L \quad \text{and} \quad \begin{pmatrix} c \\ s_C \end{pmatrix}_L \tag{3}$$

where (d_C, s_C) are Cabibbo rotated (d, s)-quarks. Then, we can identify various gauge model quark representations by specifying the 3rd components of an SU(2)-spin, for the right-handed u- and d-quarks: $\frac{\alpha}{2}$ for a u-quark and $\frac{\beta}{2}$ for a d-quark, with $\alpha, \beta = 0, \pm 1, \pm 2, \ldots$. Notice that no constraint is imposed on the possible number of quark flavors. The neutral current in the model (α, β) is now given by

$$J_\mu = \bar{u}_L \gamma_\mu u_L - d_L \gamma_\mu d_L - 2\left(Q_u \bar{u}\gamma_\mu u + Q_d \bar{d}\gamma_\mu d\right) \sin^2\theta_W$$
$$+ \alpha \bar{u}_R \gamma_\mu u_R + \beta \bar{d}_R \gamma_\mu d_R + \ldots \quad , \tag{4}$$

where $Q_u = 2/3$ and $Q_d = -1/3$ are electric charges of u- and d-quarks, respectively, and θ_W the Weinberg angle. In terms of (α, β),

$$\Delta = \frac{1}{4}\left\{2 - \alpha^2 - \beta^2 - \frac{4}{3}\sin^2\theta_W(3-2\alpha+\beta)\right\} \quad . \tag{5}$$

As is shown in Fig. 1, the sets of integer values (α, β) are classified according to $\Delta \gtreqless 0$, correspondingly inside, on, or outside of the circle, determined by the value of $\sin^2\theta_W$.

For Δ=0, there are only nine possible sets of (α, β). The model (α=1, β=-1) predicts that Δ=0, regardless of the value of $\sin^2\theta_W$. Among this class of models is the vector-like model[6] where the number of quark flavors is restricted to six. The models, (1, 1), (-1, 1) and (-1, -1) predict Δ=0 only at $\sin^2\theta_W = 0$ and Δ<0 for nonvanishing $\sin^2\theta_W$. For the rest, we observe:

for models

$$(-1, 0);\ \Delta \geq 0 \text{ for } \sin^2\theta_W \leq \frac{3}{20} \quad ,$$

$$(0, 1);\ \Delta \geq 0 \text{ for } \sin^2\theta_W \leq \frac{3}{16} \quad ,$$

$$(0, -1);\ \Delta \geq 0 \text{ for } \sin^2\theta_W \leq \frac{3}{8} \quad ,$$

$$(0, 0);\ \Delta \geq 0 \text{ for } \sin^2\theta_W \leq \frac{1}{2} \quad ,$$

$$(1, 0);\ \Delta \geq 0 \text{ for } \sin^2\theta_W \leq \frac{3}{4} \quad .$$

All other models (α, β) predict Δ<0 for any value of $\sin^2\theta_W$.

ν- and $\bar{\nu}$-Induced Neutral Currents Inclusive Processes

The significance of Δ lies in its relation to the experimentally observable quantity, i.e., the difference between ν- and $\bar{\nu}$-induced neutral current inclusive cross sections on an isospin 0 nucleon:

$$\delta\sigma_N = \left(\sigma_N^{\nu} - \sigma_N^{\bar{\nu}}\right) \Big/ \frac{G_F^2 ME}{\pi} = \frac{2}{3}\eta\,\Delta V \quad , \tag{6}$$

where we have assumed the quark-parton model[8] with the slow-rescaling assumption.[9] V is the valence contribution defined by

$$V = \int_0^1 dx\, x\, v(x) = \int_0^1 dx\, x\left[u(x) + d(x) - \bar{u}(x) - \bar{d}(x)\right] \tag{7}$$

and u(x), d(x), ($\bar{u}(x)$, $\bar{d}(x)$) are the u, d quark (antiquark) distributions in a proton where x is a scaling variable $x = Q^2/2p \cdot q$. The parameter η is defined by

$$\eta = \left(M_W/M_Z \cos\theta_W\right)^4 \tag{8}$$

where M_W and M_Z are masses of charged and neutral intermediate bosons. η determines the relative strength of the neutral current weak interaction with respect to the charged current interaction. The sea contributions are also taken into account to derive Eq. (6). The remarkable facts in Eq. (6) are that $\delta\sigma_N$ is free from heavy quark contributions and is also independent of the incident (anti-) neutrino energy E. The signature of $\delta\sigma_N$ is determined solely by that of Δ, for the valence term V is positive. Thus, the experimental observation of σ_N^ν, $\sigma_N^{\bar{\nu}}$ and therefore of $\delta\sigma_N$, renders a way to choose a particular class of SU(2) × U(1) gauge models, as well as to determine weak interaction parameters $\sin^2\theta_W$ and η.

Experimentally the data on ν- and $\bar{\nu}$-induced neutral current processes are taken as the neutral current inclusive cross sections normalized by the charged current inclusive cross sections;

$$R^{\nu(\bar{\nu})} = \frac{\sigma_N^{\nu(\bar{\nu})}}{\sigma_C^{\nu(\bar{\nu})}} \tag{9}$$

Comparison of the data to theoretical predictions for each model then should be made in two quantities.[10] (i) Energy dependence of R^ν and $R^{\bar{\nu}}$: If a new quark flavor excitation is visible in the energy dependence of $\sigma_C^{\nu(\bar{\nu})}$ then it should be reflected in $R^{\nu(\bar{\nu})}$. (ii) $R^{\bar{\nu}}/R^{\nu}$: This ratio is a function of energy and is dependent on $\sin^2\theta_W$, but independent of another parameter η. At the extremely high energies where thresholds for all flavors of quark freedom are open or at the extremely low energy where no other than u-, d-, and s-quark freedoms are excited, $R^{\bar{\nu}}/R^{\nu}$ takes a constant value. However, at the intermediate energies, where we suspect that recent ν-($\bar{\nu}$-) experimental data are being taken, some heavy-quark freedoms can be excited while production channel for some heavier quarks remain closed. The charge current cross section ratio, $\sigma_C^{\bar{\nu}}/\sigma_C^{\nu}$, is no longer a constant.

The signature of Δ is obtained simply by comparison of $R^{\bar{\nu}}/R^{\nu}$ with $\sigma_C^{\bar{\nu}}/\sigma_C^{\nu}$. Namely, we observe[11]:

$$R^{\bar{\nu}}/R^{\nu} = \frac{\sigma_N^{\bar{\nu}}}{\sigma_C^{\bar{\nu}}} \Big/ \frac{\sigma_N^{\nu}}{\sigma_C^{\nu}}$$

$$\lesseqqgtr \frac{\sigma_C^{\nu}}{\sigma_C^{\bar{\nu}}} \qquad \text{for} \quad \Delta \gtreqqless 0 \tag{10}$$

Recall that the signature of Δ is independent of energy.[12] So is the relationship

$$R^{\bar{\nu}}/R^{\nu} \gtreqqless \frac{\sigma_C^{\nu}}{\sigma_C^{\bar{\nu}}}$$

Indeed the experimental data published so far are consistent with $\Delta > 0$ [13]:

Gargamelle: $\qquad R^{\bar{\nu}}/R^{\nu} = \dfrac{0.43\pm0.12}{0.22\pm0.02} = 1.95\pm0.33$

at $E \simeq 2$ GeV $\qquad \sigma_C^{\nu}/\sigma_C^{\bar{\nu}} = 2.78\pm0.06$

HPWF Collaboration: $\qquad R^{\bar{\nu}}/R^{\nu} = \dfrac{0.39\pm0.10}{0.29\pm0.04} = 1.34\pm0.32$

at $E_{\bar{\nu}} \simeq 41$ GeV

at $E_{\nu} \simeq 53$ GeV $\qquad \sigma_C^{\nu}/\sigma_C^{\bar{\nu}} \approx 2.0$

CITF Collaboration: at $E \simeq 50$ GeV

$$R^{\bar{\nu}}/R^{\nu} = \frac{0.35\pm0.11}{0.241\pm0.034} = 1.45\pm0.38 \quad .$$

SU(2) × U(1) Gauge Models with $\Delta>0$

There are five classes of gauge models which satisfy $\Delta>0$, since $\nu_\mu e$, $\nu_e e$-neutral current elastic scattering experimental data do not set any meaningful restriction on the value of $\sin^2\theta_W$.[14] Among various models for each set of (α,β), corresponding to $\Delta>0$, we present only the models which possess the following characters with a minimum number of quark flavors:

1) The low energy phenomenology suggests that there is no right-handed charge current $\bar{u}_R\gamma_\mu d_R$ (or s_R) among SU(3) triplet quarks.

2) If V and A currents contribute dominantly to both $\Delta I=1/2$ and $\Delta I=3/2$ weak interactions governing nonleptonic decays, then $\bar{c}_R\gamma_\mu d_R$ current is not favorable.[15]

3) In order to explain recent experimental data[4,5] on charged current inclusive cross sections, there should exist $\bar{u}_R\gamma_\mu b_R$ and/or $d_R\gamma_\mu b_R$ currents where a mass of a heavy b-quark is around 5 GeV.

In the following we present only right-handed quark multiplets containing a u- or a d-quark as a member. The common left-handed multiplets are already given by Eq. (3).

(a) (0, 0)-model; $\Delta>0$ for $\sin^2\theta_W < \frac{1}{2}$

$$\text{a triplet } \begin{pmatrix} g \\ u \\ b \end{pmatrix}_R \text{ and a singlet } d_R \tag{11}$$

or

$$\text{a triplet } \begin{pmatrix} t \\ d \\ q \end{pmatrix}_R \text{ and a singlet } u_R \tag{12}$$

Charges of g, b, t, and q quarks are 5/3, -1/3, 2/3 and -4/3, respectively. Both models have six quark flavors. The neutral current structure is identical to that of the standard SU(2) $\times$ U(1) model (i.e., Weinberg-Salam model with GIM-mechanism[7]). The triplet representation is necessary to accommodate with charged current data. The right-handed charged current for the multiplet, (11), given by $\sqrt{2}(\bar{g}_R\gamma_\mu u_R + \bar{u}_R\gamma_\mu b_R)$, has $\sqrt{2}$ times stronger coupling relative to the left-handed current for a doublet, say, $\bar{u}_L\gamma_\mu d_{CL}$. The threshold effect of g- and b-quarks are taken care of by the slow-rescaling[9] assumption, where the masses of g and b are fixed with $M_g > M_b$. Roughly speaking, $\sigma_C^{\bar{\nu}}/\sigma_C^{\nu}$ takes 1/3, 7/3 and 7/5 at $E \lesssim E_b$, $E_b \lesssim E \lesssim E_g$ and $E \gtrsim E_g$, respectively, where E_b and E_g are threshold energy of b- and g-quark production.

Masses of heavy quarks are estimated[15] from charged current inclusive cross section data. A parameter $\sin^2\theta_W$ is fixed by the energy dependence of $R^{\bar{\nu}}/R^{\nu}$ while η is determined from $R^{\bar{\nu}}$-R^{ν} correlation diagrams. The estimated masses, η and $\sin^2\theta_W$ are tabulated in Table I. The energy dependence of $\sigma_C^{\bar{\nu}}/\sigma_C^{\nu}$, $\langle y\rangle^{\bar{\nu}}$ and $R^{\bar{\nu}}/R^{\nu}$ are shown in Figs. 2-4 for all the models. Figure 5a-c presents $R^{\bar{\nu}}$-R^{ν} correlations at E=10, 50, and 150 GeV, respectively. Two models, (11) and (12), are distinguishable by examining induced charged current inclusive cross sections with $I\neq 0$ target. Since masses of g, b, and q quarks are assumed heavier than ~5 GeV (see Table I), it is unlikely to observe up-rising of R-value, $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$, or to detect doubly charged bosons and/or more than triply charged baryons at SPEAR energies.

(b) (1, 0) model; $\Delta>0$ for $\sin^2\theta_W < \frac{3}{4}$

$$\text{a doublet } \begin{pmatrix} u \\ b \end{pmatrix}_R \text{ and a singlet } d_R \tag{13}$$

This model consists of five quarks. With six quarks, d_R quark can be taken as a member of a triplet:

$$\text{a doublet} \begin{pmatrix} u \\ b \end{pmatrix}_R \quad \text{and a triplet} \begin{pmatrix} t \\ d \\ q \end{pmatrix}_R \tag{14}$$

The model (13) has been advocated by many authors.[5] $\sigma_C^{\bar{\nu}}/\sigma_C^{\nu}$ shows an increase roughly from 1/3 to 4/3 as E exceeds E_b.

(c) (0, 1) model; $\Delta>0$ for $\sin^2\theta_W < \frac{3}{16}$

$$\text{a doublet} \begin{pmatrix} d \\ q \end{pmatrix}_R \quad \text{and a singlet } u_R \tag{15}$$

The model requires at least five quark flavors and the existence of an exotically charged quark q, $Q_q = -4/3$. The charged current $\bar{d}_R\gamma_\mu q_R$ is indistinguishable from $\bar{u}_R\gamma_\mu b_R$ of model (b) with I=0 nucleon target.

(d) (-1, 0) model; $\Delta>0$ for $\sin^2\theta_W < \frac{3}{20}$

$$\text{a doublet} \begin{pmatrix} g \\ u \end{pmatrix}_R \quad \text{and a triplet} \begin{pmatrix} t \\ d \\ q \end{pmatrix}_R \tag{16}$$

The minimum model of this class consists of seven flavors. The right-handed triplet is necessary to explain charged current data. Two exotically charged quarks are present; $Q_g = 5/3$ and $Q_q = -4/3$ while $Q_t = 2/3$. The masses should satisfy $M_q < M_{g,t}$. $\sigma_C^{\bar{\nu}}/\sigma_C^{\nu}$ is roughly 1/3, 7/3, 7/4, (7/5), 7/6 for $E < E_q$, $E_q < E < E_{g,t}$, $E_t < E < E_g$ $(E_g < E < E_t)$, $E > E_{g,t}$, respectively, where $E_{q,g,t}$ stand for the threshold energies for q-, g-, t-quark production, respectively.

(e) (0, -1) model; $\Delta>0$ for $\sin^2\theta_W < \frac{3}{8}$

$$\text{a doublet} \begin{pmatrix} t \\ d \end{pmatrix}_R \quad \text{and a triplet} \begin{pmatrix} g \\ u \\ b \end{pmatrix}_R \tag{17}$$

Seven-quarks model is the minimal model of this class. An exotically charged g-quark, $Q_g = 5/3$, is needed to form a triplet representation. The charged current has the same structure as in the (-1, 0) model. The difference between models (d) and (e) can be detected by charged current data on $I \neq 0$ nucleon target.

A few remarks on a vector-like model[6] should be in order. The vector-like model with right-handed doublets,

$$\begin{pmatrix} u \\ b \end{pmatrix}_R \quad \text{and} \quad \begin{pmatrix} t \\ d \end{pmatrix}_R \tag{18}$$

is one of the (1, -1) models with six quarks. The choice of $M_b \simeq 5$ GeV and $M_t \simeq 10$ GeV would explain the charged current data. However, the definite prediction, $\Delta = 0$, regardless of the value of $\sin^2 \theta_W$, shows poor agreement to the present neutral current data. Estimations in the vector-like model are also shown in Figs. 2-5 as references.

In summary, we have argued that the experimental observation, $\sigma_N^{\bar{\nu}}/\sigma_N^{\nu} < 1$, imposes a constraint on the structure of a neutral current. With this constraint, no assumption is required to examine the experimental data. In particular, in the framework of the SU(2) × U(1) gauge model, only five classes of gauge models are found to be consistent with the constraint. The leptonic sector of the model is not at stake, since experimental data are poor in providing definite information on the leptonic neutral current.

Some of the models are required to contain one or a few exotically charged quarks, whose charges are 5/3 and/or -4/3. Needless to mention, these models can be tested distinctively at high energies where exotic quark thresholds are open. There, the rise in $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ should be conspicuous. The leptonic decay width of ψ-like particle, made of an exotic quark and antiquark pair, would be accordingly large. Doubly charged bosons and/or more than triply charged baryons should be detected.

We expect the future experiments will eventually select one of these models as the correct one, if our comprehension of weak interactions in terms of $SU(2) \times U(1)$ gauge models is correct. Examination of other neutral current processes in these models is in progress.

We wish to express our deep gratitude to Professor S. Drell and other colleagues at SLAC for their hospitality and providing stimulating atmosphere. After this work had been done, we had an opportunity to learn that some of the generalizations we took have also been considered by Professor J. Bjorken; namely, considering a doublet representation for right-handed leptons. One of us (E. T.) is thankful to Professors K. Tanaka and G. Aubrecht for discussions.

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8. In the quark-parton model, the structure function $G_3^{\nu(\bar{\nu})}(x)$, corresponding to the neutral current given by Eq. (2), is evaluated as

$$G_3^{\nu(\bar{\nu})}(x) = 2 \sum_i C_V^i C_A^i \left(-q_i(x_i) + \bar{q}_i(x_i)\right)$$

where x_i is the slow-rescaling variable depicted by

$$x_i = x + \frac{m_i^2}{2MEy}$$

and m_i is the mass of q_i-quark ($\bar{q}_i$-antiquark) whose distribution is given by $q_i(x_i)(q_i(x_i))$. Because $q_i(x_i) = \bar{q}_i(x_i)$ except for u- and d-quarks in a proton we obtain $G_3^{\nu(\bar{\nu})}(x) = \left(- \sum_{i=u,d} C_V^i C_A^i\right) v(x)$ where we have taken an average of u and d to describe an isospin 0 nucleon. Equation (6) is easily derived using standard relation between $G_3^{\nu(\bar{\nu})}(x)$ and cross section. We note that $G_3^{\nu(\bar{\nu})}(x)$ depends only on x and independent of the sea-quark contributions which would bring E- and y-dependences through slow rescaling.

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11. If we are allowed to ignore sea-quarks contributions to $\sigma_N^{\nu(\bar{\nu})}$, then $\sigma_N^{\bar{\nu}}/\sigma_N^{\nu}$ becomes energy independent. Therefore we observe $R^{\bar{\nu}}/R^{\nu} \propto \sigma_C^{\nu}/\sigma_C^{\bar{\nu}}$.

12. The statement is no longer true if there exists a considerable mixture between u(d)-quark and a heavy quark. Namely, if the neutral current contains a nondiagonal part involving u- and/or d-quarks,

$$J_\mu^{\text{nondiagonal}} = \sum_{i \neq j} \bar{q}_i \gamma_\mu \left(C_V^{ij} + C_A^{ij} \gamma_5\right) q_j + \text{h.c.}$$

then the threshold effect for exciting heavy quarks should be taken into consideration. The effect will result in the energy dependence of $\delta\sigma_N$. Since such nondiagonal currents are expected only among right-handed currents, they contribute to decrease $\delta\sigma_N$. At present there is no apparent indication for the existence of nondiagonal currents.

13. The new data on the neutral current are reported at the Aachen Neutrino Conference. See, for example, B. W. Lee, Fermi-Lab-Conf.-76/61-THY.

14. Right-handed electron (muon) is a singlet in the standard $SU(2)\times U(1)$ gauge model. However, it may well be a member of doublet, triplet or a higher leptonic multiplet with heavy leptons; a doublet $\begin{pmatrix} E^o \\ e^- \end{pmatrix}_R$, a triplet $\begin{pmatrix} E^+ \\ E^o \\ e^- \end{pmatrix}_R$, etc. As is shown in Fig. 6, the range of $\sin^2\theta_W$ varies for the different representations of a right-handed electron, to satisfy currently available data on neutrino-electron neutral current elastic cross sections. For instance, with $\eta=1$, $0.05 \lesssim \sin^2\theta_W \lesssim 0.32$ for a singlet e_R, while $0.20 \lesssim \sin^2\theta_W \lesssim 0.39$ or $0.61 \lesssim \sin^2\theta_W \lesssim 0.71$ is obtained in case e_R^- is an $I_3=-1/2$ member of a doublet. The triplet representation with $I_3=-1$ for e_R^- renders $0.68 \lesssim \sin^2\theta_W \lesssim 0.96$, for which there is no model with $\Delta>0$ for hadronic neutral currents.

As is easily observed, the range of $\sin^2\theta_W$ is also dependent of η. Notice that for ν_e-e neutral current weak interaction, the vector and axial-vector coupling strengths are given as functions of η as well as of $\sin^2\theta_W$:

$$C_V^{\nu_e e} = 1+g_V = 1+\sqrt{\eta}\,\frac{1}{2}\left(-1+\beta+4\sin^2\theta_W\right)$$

$$C_A^{\nu_e e} = 1+g_A = 1-\sqrt{\eta}\,\frac{1}{2}\,(1+\beta)$$

The ranges of $\sin^2\theta_W$ for $\eta=1$ and 2/5 are shown in Fig. 6.

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16. For the valence and sea quark distributions, we take solution (3) of V. Berger et al., Nucl. Phys. B 102, 439 (1976).

TABLE I

Various SU(2) × U(1) gauge models which satisfy a neutral current constraint, $\sigma_N^{\nu} \geqq \sigma_N^{\bar{\nu}}$

model (α,β)	$\sigma_N^{\nu} > \sigma_N^{\bar{\nu}}$ if $\sin^2\theta_W <$	$\sin^2\theta_W$	η	quark masses (GeV)	Remarks
(0,0)	1/2	$\simeq .3$	1	$m_b \approx 6$ $m_g \approx 10$	W-S neutral current good agreement
(1,0)	3/4	$\simeq .4$	1	$m_b \approx 5$	good agreement
(0,1)	3/16	$\simeq 0$	2/5	$m_b \approx 5$	fair agreement
(-1,0)	3/20	$\simeq 0$	2/5	$m_b \approx 6$ $m_{g,t} \approx 10$	fair agreement
(0,-1)	3/8	$\simeq 0$	2/5	$m_b \approx 6$ $m_{g,t} \approx 10$	fair agreement
(1,-1)	$\sigma_N^{\nu} = \sigma_N^{\bar{\nu}}$	independent	1	$m_b \approx 5$ $m_{g,t} \approx 10$	vector-type neutral current poor agreement
(1,1) (-1,1) (1,-1)	$\sigma_N^{\nu} < \sigma_N^{\bar{\nu}}$ except for $\sin^2\theta_W = 0$	0			poor agreement

FIGURE CAPTIONS

1. Classification of $SU(2) \times U(1)$ gauge models according to $\Delta > 0$. $\alpha/2$ and $\beta/2$, with both α, β = integer, are the third components of SU(2) isospin for right-handed u- and d-quarks, respectively. The inside of the circle, given by $2 - \alpha^2 - \beta^2 - \frac{4}{3}\sin^2\theta_W(3-2\alpha+\beta) = 0$, corresponds to $\Delta > 0$. The circles for extreme cases, $\sin^2\theta_W = 0$ and $\sin^2\theta_W = 1$, are drawn in the figure. Following the discussion in Ref. 13, no constraint is imposed on the value of $\sin^2\theta_W$.

2. $\sigma_C^{\bar{\nu}}/\sigma_C^{\nu}$ as a function of energy. $\sigma_C^{\nu(\bar{\nu})}$, the charged current inclusive cross section, is evaluated using the slow rescaling assumption with the heavy quark masses given in Table I. The data are taken from Ref. 4.

3. Energy dependence of y-average for antineutrino cross section, $\sigma_C^{\bar{\nu}}$. The data are taken from Ref. 4.

4. Energy dependence of $R^{\bar{\nu}}/R^{\nu}$. The parameter $\sin^2\theta_W$ is taken to be 0.4, 0.5, and ~ 0.0 for $(\alpha,\beta) = (0,0)$, $(1,0)$, and all of $(0,1)$, $(-1,0)$, and $(0,-1)$ models, respectively. The shape of the curve is determined essentially by charged current inclusive cross sections, σ_C^{ν} and $\sigma_C^{\bar{\nu}}$, which are evaluated in the same way as in Fig. 2.

5a,b,c. $R^{\bar{\nu}}$-R^{ν} correlation for E = 10, 50, and 150 GeV, respectively. The energy dependence is mostly due to the threshold effect in charged current cross sections. $\eta = 1$ is taken for (0,0) and (1,0) models as well as for vector-like and GIM-W-S models, while $\eta = 2/5$ for (0,1), (-1,0), and (0,-1) models. Experimentally both (0,0) and (1,0) models are favored, but the latter three models are not excluded provided $\sin^2\theta_W \approx 0$.

6. Determination of $\sin^2\theta_W$ from neutrino-electron neutral current elastic cross sections. The experimentally allowed region is obtained from J. J.

Sakurai, CERN preprint TH.2099-CERN (1975). $\beta/2$ stands for the third component of SU(2)-spin for a right-handed electron. For example, the standard model with a singlet e_R is shown by $\beta = 0$, while the model with a doublet $\begin{pmatrix} E^o \\ e^- \end{pmatrix}_R$ by $\beta = -1$, and a triplet $\begin{pmatrix} E^+ \\ E^o \\ e^- \end{pmatrix}_R$ by $\beta = -2$. The cases for $\eta = 2/5$ are also shown for $\beta = 0, -1, -2$.

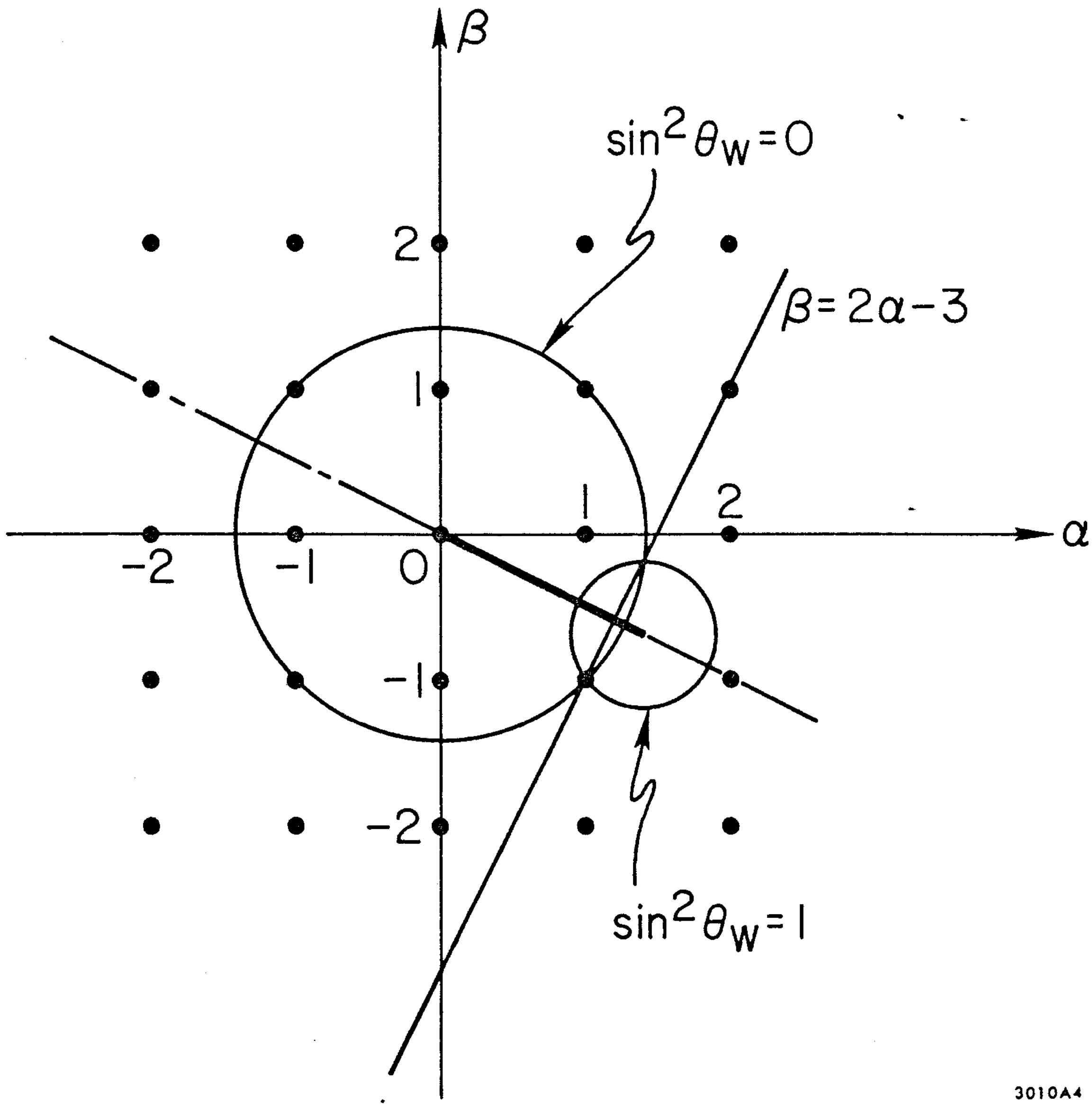

Fig. 1

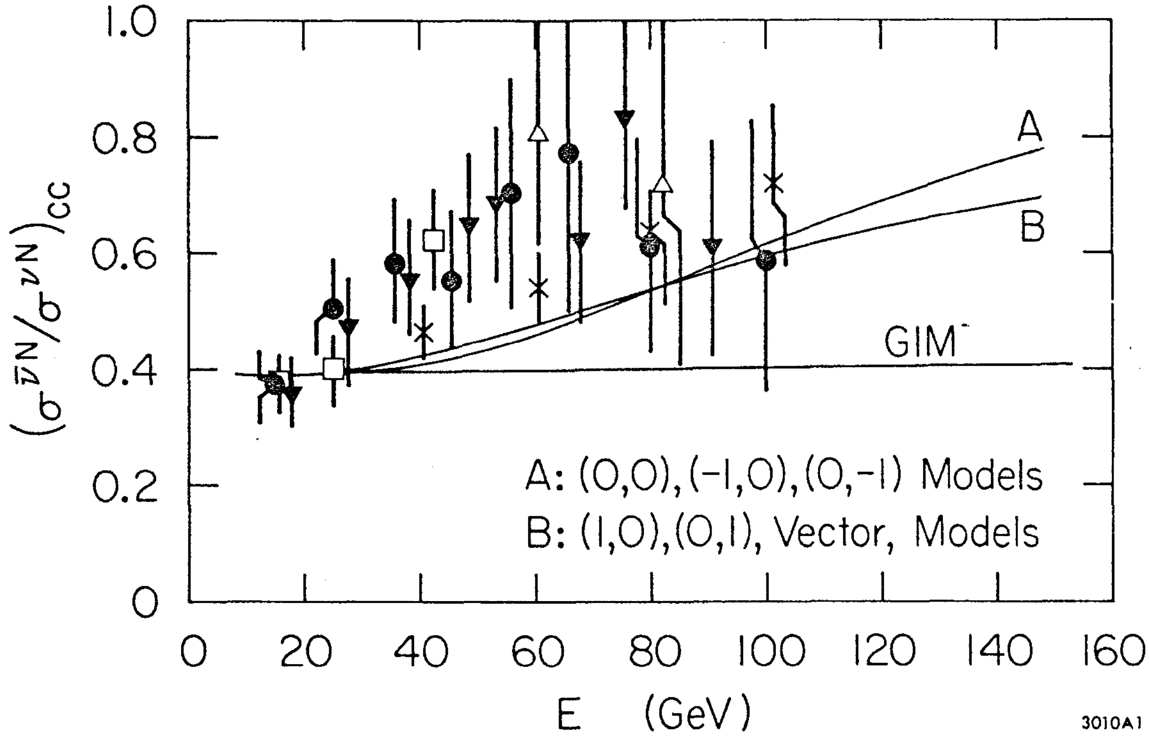
1.0
0.8
0.6
0.4
0.2
0
$(\sigma^{\bar{\nu}N}/\sigma^{\nu N})_{cc}$
A
B
GIM
A: (0,0),(-1,0),(0,-1) Models
B: (1,0),(0,1), Vector, Models
0
20
40
60
80
100
120
140
160
E (GeV)
3010A1

Fig. 2

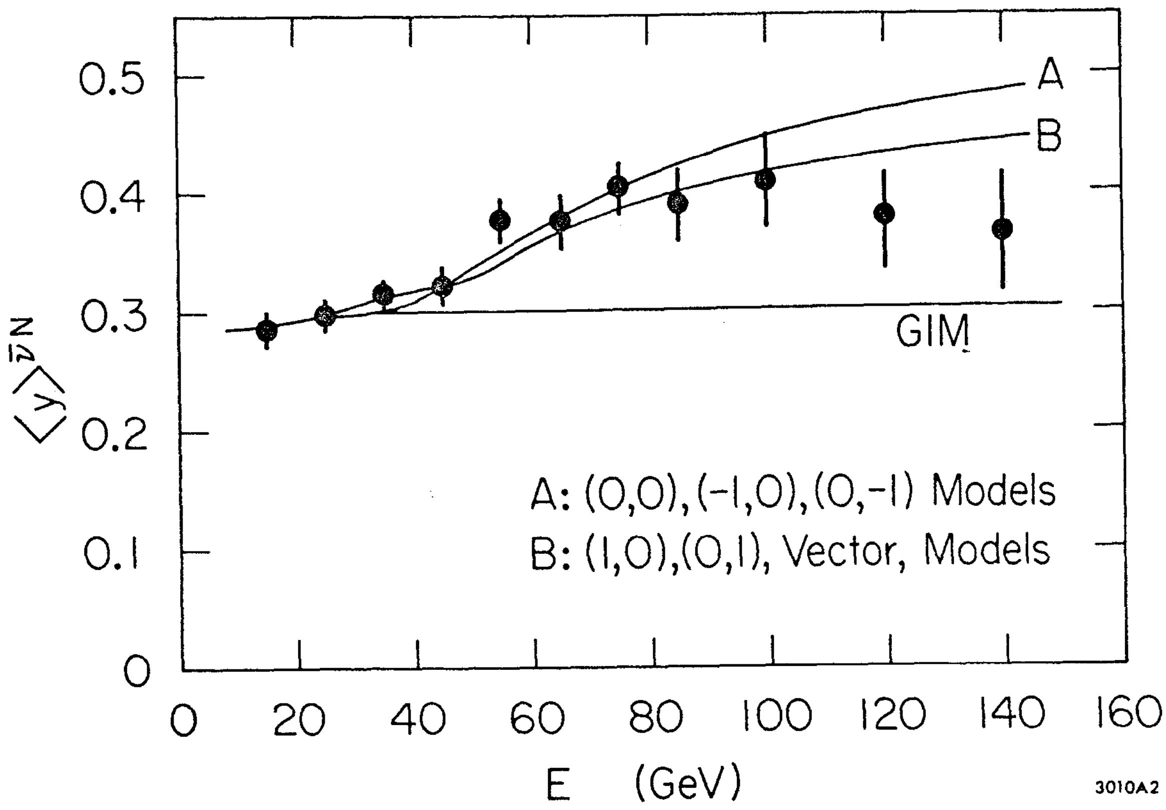
0.5
0.4
0.3
0.2
0.1
0
$\langle y \rangle^{\bar{\nu}N}$
A
B
GIM
A: (0,0),(-1,0),(0,-1) Models
B: (1,0),(0,1), Vector, Models
0
20
40
60
80
100
120
140
160
E (GeV)
3010A2

Fig. 3

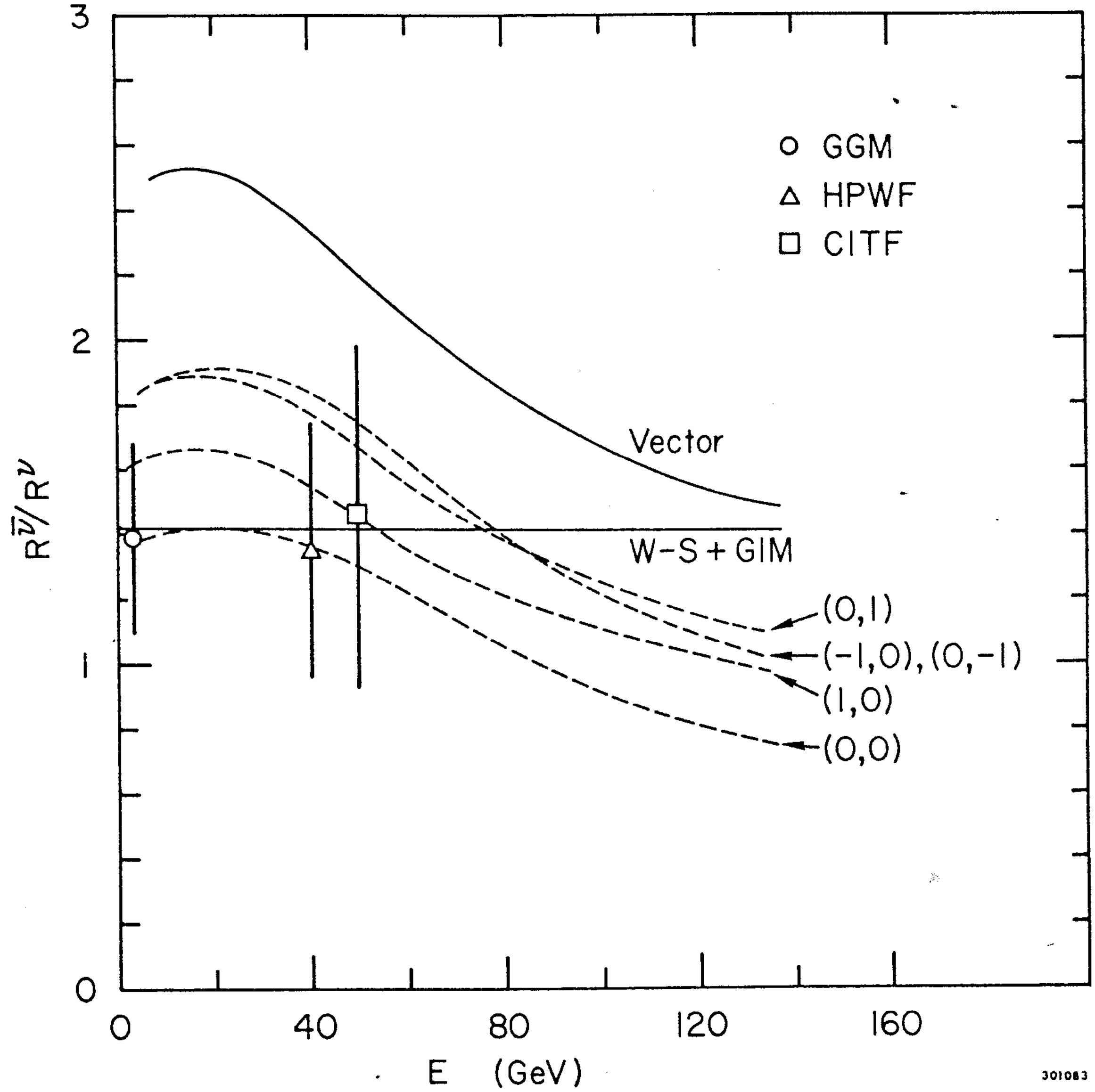
3
2
1
0
0
40
80
120
160
E (GeV)
$R^{\bar{\nu}}/R^{\nu}$
GGM
HPWF
CITF
Vector
W-S + GIM
(0,1)
(-1,0), (0,-1)
(1,0)
(0,0)
301083

Fig. 4

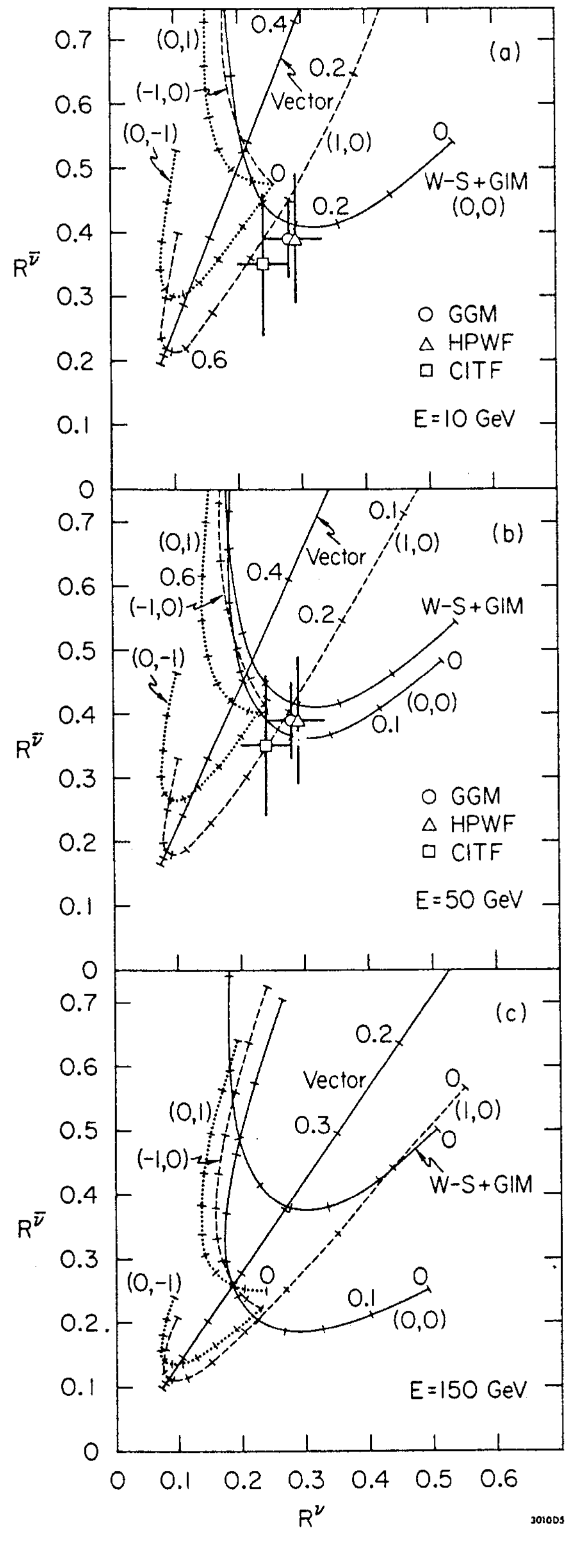
(a)
(0,1)
(-1,0)
(0,-1)
0.4
0.2
Vector
(1,0)
0
W-S+GIM
(0,0)
0.6
GGM
HPWF
CITF
E=10 GeV
(b)
(0,1)
0.6
(-1,0)
(0,-1)
0.4
Vector
0.1
(1,0)
0.2
W-S+GIM
(0,0)
E=50 GeV
(c)
0.2
Vector
0.3
(0,1)
(-1,0)
(1,0)
W-S+GIM
(0,-1)
0.1
(0,0)
E=150 GeV
$R^{\bar{\nu}}$
R^{ν}
3010D5

Fig. 5

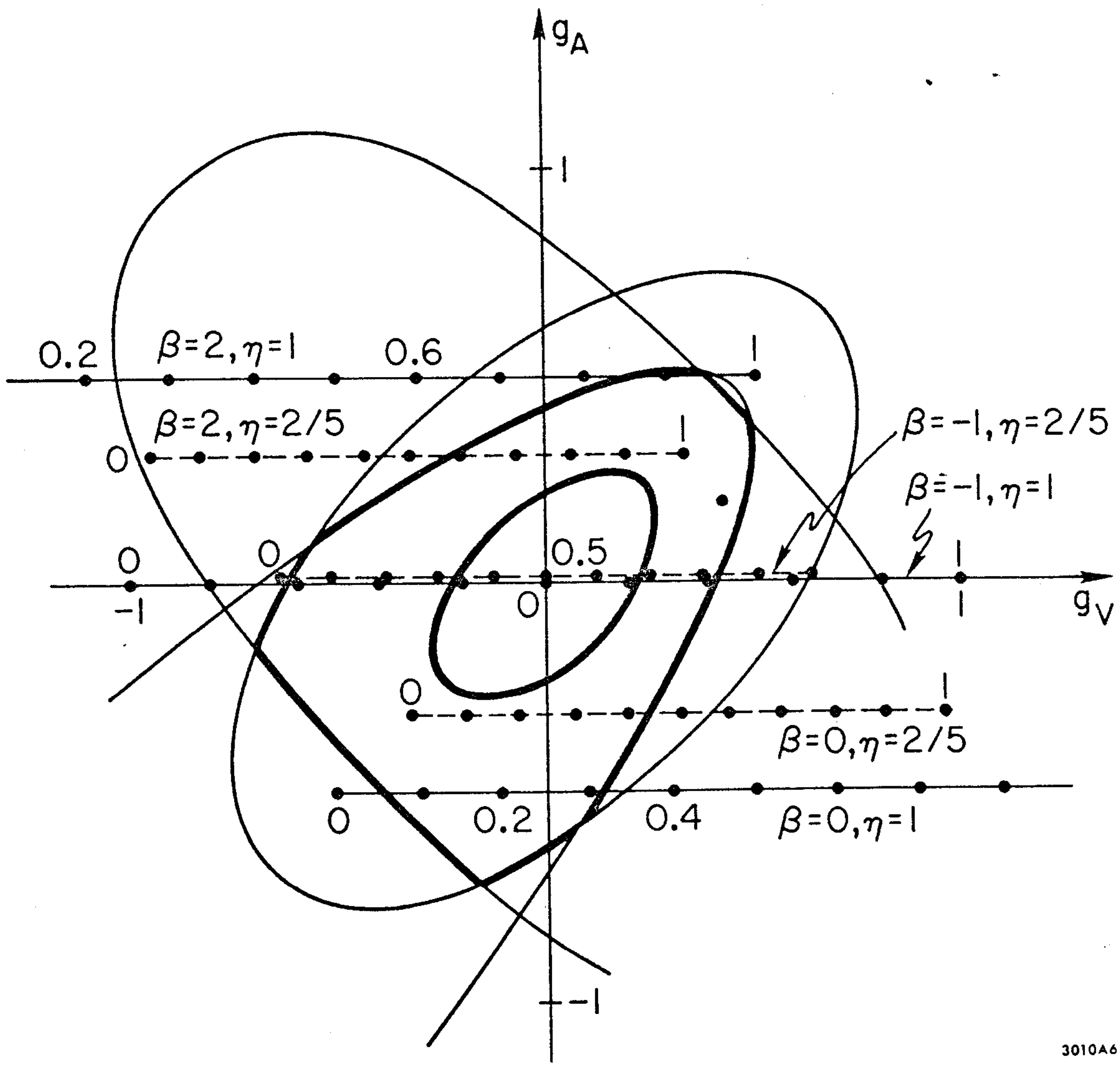
g_A
1
-1
g_V
0.2
$\beta=2, \eta=1$
0.6
1
$\beta=2, \eta=2/5$
0
1
$\beta=-1, \eta=2/5$
$\beta=-1, \eta=1$
0
0
0.5
-1
0
1
1
0
1
$\beta=0, \eta=2/5$
0
0.2
0.4
$\beta=0, \eta=1$
3010A6

Fig. 6