附録 I：関連原論文

素粒子の群論的研究

素粒子模型

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A Possible Symmetry in Sakata's Model for Bosons-Baryons System

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In this paper we study a possible symmetry in Sakata's model for the strongly interacting particles. In the limiting case in which the basic particles, proton, p, neutron, n and Λ-particle, Λ, have an equal mass, our theory holds the invariance under the exchange of p and Λ or n and Λ in addition to the usual charge independence and the conservation of electrical and hyperonic charge.

From our theory the following are obtained: (a) iso-singlet π_0'-meson state, which is a pseudo-scalar, exists, (b) the spin of Ξ particle may be $(3/2)^+$ and (c) several resonating states in K- and π-nucleon scattering are anticipated to exist.

§ 1. Introduction

Through the analysis of the various particles existing in nature and mutual interactions among them, we have obtained the useful concepts of family[1] and universality[2] of the interactions to clarify the complicated situation of the particle physics. For the Boson- and baryon-families which have a kind of universal interaction, e. g., the strong interaction, the well-known rule of Nakano, Nishijima and Gell-Mann[3] is valid. The complete understanding of the more fundamental origin of this rule is far from us at present, but a possible way of its realistic grasp has been proposed by Sakata.[4] Although many objections will be brought against this theory, we shall in this paper follow the idea of Sakata for its prospective insight on the present situation of the theory of elementary particles.

Now, following this idea we assume proton, p, neutron, n and Λ-particle, Λ to be the basic particles which compose other baryons and Bosons in Fermi-Yang's sense[5]. The strong interaction is characterized by the following selection rule,

$$\Delta N_p + \Delta N_n + \Delta N_\Lambda = 0, \qquad \text{(A)}$$

where ΔN_i means the change of i-th particle's number.

According to the relation (A) and from the similarity of the nature of these three particles (mass, spin, etc.) and of their role in the strong interaction, we are tempted to regard the three particles as standing on an equal footing. In fact when

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Note on Unitary Symmetry in Strong Interactions*

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Assuming invariance of theory under three-dimensional unitary group, various consequences have been investigated. Both Sakata's and Gell-Mann's scheme can be treated in the same fashion and in a simpler way. Mass formula for particles belonging to the same irreducible representation has been derived and compared with experiments.

§ 1. Introduction

The purpose of this note is to investigate consequences of the three-dimensional unitary group (denoted as U_3 hereafter), which is a certain generalization of the usual isotopic space group. Though many authors[1),2),3)] have examined this problem, our procedure is simpler and some new results have been obtained. Also, we can treat different schemes of U_3 such as Sakata's[1),2)] or Gell-Mann's[3)] on the same footing by our method.

First of all, we shall give some motivations for introducing U_3. All known interactions obey certain symmetries, i.e. they are subject to the corresponding transformation groups. We can classify all known groups appearing in the studies of elementary particles into the following three categories.

(I) *Space-group*
  (i) Lorentz group (ii) Charge conjugation
(II) *Isotopic-groups*
  (i) Isotopic spin rotation $R_3^{(I)}$
  (ii) Baryon gauge transformation $R_2^{(B)}$
  (iii) Charge gauge transformation $R_2^{(Q)}$
  (iv) Strangeness gauge transformation $R_2^{(S)}$
  (v) Leptonic gauge transformation $R_2^{(L)}$
(III) *Gauge-transformation of the 2nd kind*
  (i) Electro-magnetic field
  (ii) Yang-Mills field

[*)] A part of this paper has been presented at the La-Jolla Conference held at La-Jolla, California, June 12, 1961.

Report CTSL-20

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THE EIGHTFOLD WAY:
A THEORY OF STRONG INTERACTION SYMMETRY*

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Symmetries of Baryons and Mesons*

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The system of strongly interacting particles is discussed, with electromagnetism, weak interactions, and gravitation considered as perturbations. The electric current j_α, the weak current J_α, and the gravitational tensor $\theta_{\alpha\beta}$ are all well-defined operators, with finite matrix elements obeying dispersion relations. To the extent that the dispersion relations for matrix elements of these operators between the vacuum and other states are highly convergent and dominated by contributions from intermediate one-meson states, we have relations like the Goldberger-Treiman formula and universality principles like that of Sakurai according to which the ρ meson is coupled approximately to the isotopic spin. Homogeneous linear dispersion relations, even without subtractions, do not suffice to fix the scale of these matrix elements; in particular, for the nonconserved currents, the renormalization factors cannot be calculated, and the universality of strength of the weak interactions is undefined. More information than just the dispersion relations must be supplied, for example, by field-theoretic models; we consider, in fact, the equal-time commutation relations of the various parts of j_4 and J_4. These nonlinear relations define an algebraic system (or a group) that underlies the structure of baryons and mesons. It is suggested that the group is in fact $U(3)\times U(3)$, exemplified by the symmetrical Sakata model. The Hamiltonian density θ_{44} is not completely invariant under the group; the noninvariant part transforms according to a particular representation of the group; it is possible that this information also is given correctly by the symmetrical Sakata model. Various exact relations among form factors follow from the algebraic structure. In addition, it may be worthwhile to consider the approximate situation in which the strangeness-changing vector currents are conserved and the Hamiltonian is invariant under $U(3)$; we refer to this limiting case as "unitary symmetry." In the limit, the baryons and mesons form degenerate supermultiplets, which break up into isotopic multiplets when the symmetry-breaking term in the Hamiltonian is "turned on." The mesons are expected to form unitary singlets and octets; each octet breaks up into a triplet, a singlet, and a pair of strange doublets. The known pseudoscalar and vector mesons fit this pattern if there exists also an isotopic singlet pseudoscalar meson χ^0. If we consider unitary symmetry in the abstract rather than in connection with a field theory, then we find, as an attractive alternative to the Sakata model, the scheme of Ne'eman and Gell-Mann, which we call the "eightfold way"; the baryons N, Λ, Σ, and Ξ form an octet, like the vector and pseudoscalar meson octets, in the limit of unitary symmetry. Although the violations of unitary symmetry must be quite large, there is some hope of relating certain violations to others. As an example of the methods advocated, we present a rough calculation of the rate of $K^+\rightarrow\mu^++\nu$ in terms of that of $\pi^+\rightarrow\mu^++\nu$.

I. INTRODUCTION

IN connection with the system of strongly interacting particles, there has been a great deal of discussion of possible approximate symmetries,[1] which would be violated by large effects but still have some physical consequences, such as approximate universality of meson couplings, approximate degeneracy of baryon or meson supermultiplets, and "partial conservation" of currents for the weak interactions.

In this article we shall try to clarify the meaning of such possible symmetries, for both strong and weak interactions. We shall show that a broken symmetry, even though it is badly violated, may give rise to certain exact relations among measurable quantities. Furthermore, we shall suggest a particular symmetry group as the one most likely to underlie the structure of the system of baryons and mesons.

We shall treat the strong interactions without approximation, but consider the electromagnetic, weak, and gravitational interactions only in first order.

The electromagnetic coupling is described by the matrix elements of the electromagnetic current operator $ej_\alpha(x)$. Likewise, the gravitational coupling is specified by the matrix elements of the stress-energy-momentum tensor $\theta_{\alpha\beta}(x)$, particularly the component $\theta_{44}=H$, the Hamiltonian density.

The weak interactions of baryons and mesons with leptons are assumed to be given (ignoring possible nonlocality) by the interaction term[2]

$$GJ_\alpha^\dagger J_\alpha^{(l)}/\sqrt{2}+\text{H.c.},\tag{1.1}$$

where the leptonic weak current $J_\alpha^{(l)}$ has the form

$$J_\alpha^{(l)}=i\bar{\nu}\gamma_\alpha(1+\gamma_5)e+i\bar{\nu}\gamma_\alpha(1+\gamma_5)\mu.\tag{1.2}$$

We shall refer to $J_\alpha(x)$ as the weak current of baryons and mesons. Its matrix elements specify completely the weak interactions with leptons.

It is possible that the full weak interaction may be given simply by the term

$$G(J_\alpha+J_\alpha^{(l)})^\dagger(J_\alpha+J_\alpha^{(l)})/\sqrt{2},\tag{1.3}$$

although this form provides no explanation of the approximate rule $|\Delta I|=\frac{1}{2}$ in the nonleptonic decays of strange particles. If we can find no *dynamical* explanation of the predominance of the $|\Delta I|=\frac{1}{2}$ amplitude in these decays, we may be forced to assume that in addition to (1.3) there is a weak interaction involving the product

$$GJ_{n\alpha}^\dagger J_{n\alpha}/\sqrt{2},\tag{1.4}$$

of charge-retention currents (presumably not involving leptons); or else we may be compelled to abandon (1.3)

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[1] For example, see the "global symmetry" scheme of M. Gell-Mann, Phys. Rev. **106**, 1296 (1957) and J. Schwinger, Ann. Phys. **2**, 407 (1957).

[2] We use $\hbar=c=1$. The Lorentz index α takes on the values 1, 2, 3, 4. For each value of α, the Dirac matrix γ_α is Hermitian; so is the matrix γ_5.

$T_{\mu\nu}$ and (f, f_4) are not gauge invariant, nevertheless (3) and (4) will be used to show the possibility of constructing a stable electron, because we do not know a general method of construction of $T_{\mu\nu}$ which is gauge invariant. To do this, the fields are assumed to be time-independent and spherically symmetric around the centre of the electron. To satisfy the relation $f_4=0$, it is enough to set $\rho\neq 0$, $\boldsymbol{j}\neq 0$, $\boldsymbol{i}=\sigma=0$. Then the stability condition is,

$$\boldsymbol{f}=(1/4\pi)\{-\rho\boldsymbol{E}^{(1)}-\boldsymbol{B}\Delta h\}=0.$$

This equation imposes a restriction to two source functions $\rho(r)$ and $\boldsymbol{j}(r)$, and can be satisfied with variety of the choice of the pair $(\rho, \boldsymbol{j})$. It will be shown below that, if source functions vanish outside the electron, h-field also vanishes outside the electron. We first notice the relation

$$\operatorname{div}\boldsymbol{j}=-\Delta h. \tag{5}$$

Integrating eq. (5) with the boundary condition: $h(\boldsymbol{r})\to 0$ $(|\boldsymbol{r}|\to\infty)$, it follows that

$$h(\boldsymbol{r})=(1/4\pi)\times \int\{\operatorname{div}\boldsymbol{j}(\boldsymbol{r}')/|\boldsymbol{r}-\boldsymbol{r}'|\}d\boldsymbol{r}'. \tag{6}$$

Although the proper character of $\boldsymbol{j}$ is not yet known, we assume that $\operatorname{div}\boldsymbol{j}$ (which is spherically symmetric) is not zero only inside the electron. The integral appearing in the right side of eq. (6) has just the the same form when we calculate the gravitational potential around a spherical material. Then the macroscopic conservation law: $\int\operatorname{div}\boldsymbol{j}(\boldsymbol{r})d\boldsymbol{r}=0$ leads to the result that $h(\boldsymbol{r})$ vanishes outside the electron, and does not propagate far away as a wave. However, in the high energy phenomena the h-field quanta will be emitted and will give rise to the longitudinal photon. It will be interesting to test experimentally whether the γ-ray keeps on its transverse property even in the high energy region (for instance, more than 100 Mev) as derived from the Maxwell theory or it does not as predicted from our hypothesis.

The total electric plus scalar field energy can be adjusted to be equal to the corresponding electron mass, assuming a suitable diameter for the electron.

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On a Composite Model for the New Particles*

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Recently, Nishijima-Gell-Mann's rule[1] for the systematization of new particles has achieved a great success to account for various facts obtained from the experiments with cosmic rays and with high energy accelerators. Nevertheless, it would be desirable from the theoretical standpoint

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* The content of this letter was read before the annual meeting of the Japanese Physical Society held in October 1955.

A note on the same supject has also been published in Bulletin de L'académie Polonaise des Sciences (Cl. III-vol. IV, No. 6, 1956) to find out a more profound meaning hidden behind this rule. The purpose of this work is concerned with this point.

It seems to me that the present state of the theory of new particles is very similar to that of the atomic nuclei 25 years ago. At that time, we had known a beautiful relation between the spin and the mass number of the atomic nuclei. Namely, the spin of the nucleus is always integer if the mass number is even, whereas the former is always half integer if the latter is odd. But unfortunately we could not understand the profound meaning for this even-odd rule. This fact together with other mysterious properties of the atomic nuclei, for instance the beta disintegration in which the conservation of energy seemd to be invalid, led us to a very pessimistic view-point that the quantum theory would not be applicable in the domain of the atomic nucleus. However the situation was entirely changed after the discovery of the neutron. Iwanenko and Heisenberg[2] proposed immediately a new model for the atomic nuclei in which neutrons and protons are considered to be their constituents. By assuming that the neutron has the spin of one half, they explained the even-odd rule for the spins of atomic nuclei as the result of the addition law for the angular momenta of the constituents. Moreover, they could reduce all the mysterious properties of atomic nuclei to those of the neutron contained in them.

Supposing that the similar situation is realized at present, I proposed a compound hypothesis for new unstable particles to account for Nishijima-Gell-Mann's rule. In our model, the new particles are considered to be composed of four kinds of fundamental particles in the true sense, that is, nucleon, antinucleon, Λ^0 and anti-Λ^0. If we assume that Λ^0 has such intrinsic properties as were assigned by Nishijima and Gell-Mann, we can easily get their even-odd rule for the composite particles as the result of the addition laws for the ordinary spin, the isotopic spin and the strangeness. In the next table, the models and the properties of the new particles are shown together with those of the fundamental particles in the true sense.

Name	Model	Isotopic Spin	Strangeness	Ordinary Spin
$\mathfrak{N}$		1/2	0	1/2
$\bar{\mathfrak{N}}$		1/2	0	1/2
Λ		0	-1	1/2 ?
$\bar{\Lambda}$		0	1	1/2 ?
π	$\mathfrak{N}+\bar{\mathfrak{N}}$	1	0	0
$\theta(\tau)$	$\mathfrak{N}+\bar{\Lambda}$	1/2	1	0 ?
$\bar{\theta}(\bar{\tau})$	$\bar{\mathfrak{N}}+\Lambda$	1/2	-1	0 ?
Σ	$\mathfrak{N}+\bar{\mathfrak{N}}+\Lambda$	1	-1	1/2 ?
Ξ	$\bar{\mathfrak{N}}+\Lambda+\Lambda$	1/2	-2	1/2 ?

Here $\mathfrak{N}$ and $\bar{\mathfrak{N}}$ denote nucleon and antinucleon respectively, whereas Λ and $\bar{\Lambda}$ denote Λ^0 and anti-Λ^0 respectively[3].

So far as the internal structure is not concerned, our model for new particles is identical with that of Nishijima and Gell-

Mann. However, it should be stressed that the curious properties of the new particles could be reduced to those of Λ^0, just like the mysterious properties of the atomic nuclei were reduced to those of neutron. Hence our theory contains less arbitrary elements than was the case for original one of Nishijima and Gell-Mann.

Though the rigorous treatment of our model is a very hard task4), it is worthwhile to notice that most of the composite particles which seem to be stable against the strong interaction can be identified with the well-known new particles, and that there are possibilities of predicting some more new particles which have not been discovered up till now.5)

Finally, it should be remarked that there are some other arguments in favour of the compound hypothesis for the elementary particles. In spite of the great success achieved by the advent of Tomonaga-Schwinger's technique, it has recently become clear that we could not avoid the internal inconsistency of the quantum field theory, so far as the point model for elementary particles was adopted. Moreover, in the case of π-meson, the cut-off prescription has recently been proved to be very powerful in order to account for the experimental results. These facts indicate strongly the necessity of substantial innovations in the model for the elementary particles, though some change has already been made by the discovery of the renormalization technique. Landau pointed out that the model for the electron would possibly be changed by the effect of the gravitational field. But in the case of π-meson we must look for another effect, because the cut-off radius is found to be as large as the order of the nucleon Compton wave length in contrast to $e^2/mc^2 \cdot e^{-137} \sim 10^{-58}$ cm which appeared in the quantum electrodynamics.6)

1) T. Nakano and K. Nishijima, Prog. Theor. Phys. **10** (1953), 581; K. Nishijima, Prog. Theor. Phys. **12** (1954), 107; **13** (1955), 285; M. Gell-Mann, Phys. Rev. **92** (1953), 833.
2) D. Iwanenko, Nature **129** (1932), 798; W. Heisenberg, ZS. Phys. **77** (1932), 1.
3) Markov (Rep. Acad. Sci. USSR, 1955) proposed also a composite model which is very similar to ours. It should be remarked that our model may be considered as a generalization of the π-meson model proposed by Fermi and Yang (Phys. Rev. **76** (1948), 1739), and that it will throw a new light on Heisenberg's theory of elementary particles (Zs. Naturf. **9a** (1954), 291; **10a** (1955), 425), in which only one kind of "Urmaterie" is assumed.
4) S. Tanaka, Prog. Theor. Phys. **16** (1956), 625. Z. Maki, Prog. Theor. Phys. **16** (1956), 667.
5) K. Matsumoto, Prog. Theor. Phys. **16** (1956), 583.
6) M. A. Markov, Uspekhi Fiz. Nauk **51** (1953), 317; L. Landau et al., DAN. **95** (1954), 497, 733, 1177; **96** (1954), 261; **102** (1955), 489; S. Kamefuchi & H. Umezawa, Prog. Theor. Phys. **15** (1956), 298; Nuovo Cimento **3** (1956), 1060.

Special Theory of Relativity and the Structure of Elementary Particles

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The present field theory of elementary particles is based on both quantum mechanics and the special theory of relativity. Since we have for so long been unsuccessful

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means of dispersion theory, there are still meaningful and important questions regarding the algebraic properties of these interactions that have so far been discussed only by abstracting the properties from a formal field theory model based on fundamental entities [3] from which the baryons and mesons are built up.

If these entities were octets, we might expect the underlying symmetry group to be SU(8) instead of SU(3); it is therefore tempting to try to use unitary triplets as fundamental objects. A unitary triplet t consists of an isotopic singlet s of electric charge z (in units of e) and an isotopic doublet (u, d) with charges z+1 and z respectively. The anti-triplet $\bar{t}$ has, of course, the opposite signs of the charges. Complete symmetry among the members of the triplet gives the exact eightfold way, while a mass difference, for example, between the isotopic doublet and singlet gives the first-order violation.

For any value of z and of triplet spin, we can construct baryon octets from a basic neutral baryon singlet b by taking combinations ($bt\bar{t}$), ($btt\bar{t}\bar{t}$), etc. **. From ($bt\bar{t}$), we get the representations **1** and **8**, while from ($btt\bar{t}\bar{t}$) we get **1**, **8**, **10**, $\overline{\mathbf{10}}$, and **27**. In a similar way, meson singlets and octets can be made out of ($t\bar{t}$), ($tt\bar{t}\bar{t}$), etc. The quantum number $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), ($qqqq\bar{q}$), etc., while mesons are made out of ($q\bar{q}$), ($qq\bar{q}\bar{q}$), etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration ($q\bar{q}$) similarly gives just **1** and **8**.

A formal mathematical model based on field theory can be built up for the quarks exactly as for p, n, Λ in the old Sakata model, for example [3] with all strong interactions ascribed to a neutral vector meson field interacting symmetrically with the three particles. Within such a framework, the electromagnetic current (in units of e) is just

$$i\{\tfrac{2}{3}\,\bar{u}\,\gamma_\alpha\,u - \tfrac{1}{3}\,\bar{d}\,\gamma_\alpha\,d - \tfrac{1}{3}\,\bar{s}\,\gamma_\alpha\,s\}$$

or $\mathscr{F}_{3\alpha} + \mathscr{F}_{8\alpha}/\sqrt{3}$ in the notation of ref. [3]. For the weak current, we can take over from the Sakata model the form suggested by Gell-Mann and Lévy [7], namely $i\,\bar{p}\,\gamma_\alpha(1+\gamma_5)(n\cos\theta + \Lambda\sin\theta)$, which gives in the quark scheme the expression ***

$$i\,\bar{u}\,\gamma_\alpha(1+\gamma_5)(d\cos\theta + s\sin\theta)$$

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* Work supported in part by the U.S. Atomic Energy Commission.

** This is similar to the treatment in ref. [1]. See also ref. [5].

*** The parallel with $i\,\bar{\nu}_e\,\gamma_\alpha(1+\gamma_5)\,e$ and $i\,\bar{\nu}_\mu\,\gamma_\alpha(1+\gamma_5)\mu$ is obvious. Likewise, in the model with d^-, s^-, u^0, and b^0 discussed above, we would take the weak current to be $i(\bar{b}^0\cos\theta + \bar{u}^0\sin\theta)\,\gamma_\alpha(1+\gamma_5)\,s^- + i(\bar{u}^0\cos\theta - \bar{b}^0\sin\theta)\,\gamma_\alpha(1+\gamma_5)\,d^-$. The part with $\Delta(n_t - n_{\bar{t}}) = 0$ is just $i\,\bar{u}^0\,\gamma_\alpha(1+\gamma_5)(d^-\cos\theta + s^-\sin\theta)$.

or, in the notation of ref. 3),

$$[\mathcal{F}_{1\alpha} + \mathcal{F}^5_{1\alpha} + i(\mathcal{F}_{2\alpha} + \mathcal{F}^5_{2\alpha})] \cos\theta$$
$$+ [\mathcal{F}_{4\alpha} + \mathcal{F}^5_{4\alpha} + i(\mathcal{F}_{5\alpha} + \mathcal{F}^5_{5\alpha})] \sin\theta \, .$$

We thus obtain all the features of Cabibbo's picture 8) of the weak current, namely the rules $|\Delta I| = 1$, $\Delta Y = 0$ and $|\Delta I| = \frac{1}{2}$, $\Delta Y/\Delta Q = +1$, the conserved $\Delta Y = 0$ current with coefficient $\cos\theta$, the vector current in general as a component of the current of the F-spin, and the axial vector current transforming under SU(3) as the same component of another octet. Furthermore, we have 3) the equal-time commutation rules for the fourth components of the currents:

$$[\mathcal{F}_{j4}(x) \pm \mathcal{F}^5_{j4}(x), \; \mathcal{F}_{k4}(x') \pm \mathcal{F}^5_{k4}(x')] =$$
$$- 2 f_{jkl} \, [\mathcal{F}_{l4}(x) \pm \mathcal{F}^5_{l4}(x)] \, \delta(x-x') \, ,$$
$$[\mathcal{F}_{j4}(x) \pm \mathcal{F}^5_{j4}(x), \; \mathcal{F}_{k4}(x') \mp \mathcal{F}^5_{k4}(x')] = 0 \, ,$$

$i = 1, \ldots 8$, yielding the group SU(3) × SU(3). We can also look at the behaviour of the energy density $\theta_{44}(x)$ (in the gravitational interaction) under equal-time commutation with the operators $\mathcal{F}_{j4}(x') \pm \mathcal{F}_{j4}{}^5(x')$. That part which is non-invariant under the group will transform like particular representations of SU(3) × SU(3), for example like $(3, \bar{3})$ and $(\bar{3}, 3)$ if it comes just from the masses of the quarks.

All these relations can now be abstracted from the field theory model and used in a dispersion theory treatment. The scattering amplitudes for strongly interacting particles on the mass shell are assumed known; there is then a system of linear dispersion relations for the matrix elements of the weak currents (and also the electromagnetic and gravitational interactions) to lowest order in these interactions. These dispersion relations, unsubtracted and supplemented by the non-linear commutation rules abstracted from the field theory, may be powerful enough to determine all the matrix elements of the weak currents, including the effective strengths of the axial vector current matrix elements compared with those of the vector current.

It is fun to speculate about the way quarks would behave if they were physical particles of finite mass (instead of purely mathematical entities as they would be in the limit of infinite mass). Since charge and baryon number are exactly conserved, one of the quarks (presumably $u^{\frac{2}{3}}$ or $d^{-\frac{1}{3}}$) would be absolutely stable *, while the other member of the doublet would go into the first member very slowly by β-decay or K-capture. The isotopic singlet quark would presumably decay into the doublet by weak interactions, much as Λ goes into N. Ordinary matter near the earth's surface would be contaminated by stable quarks as a result of high energy cosmic ray events throughout the earth's history, but the contamination is estimated to be so small that it would never have been detected. A search for stable quarks of charge $-\frac{1}{3}$ or $+\frac{2}{3}$ and/or stable di-quarks of charge $-\frac{2}{3}$ or $+\frac{1}{3}$ or $+\frac{4}{3}$ at the highest energy accelerators would help to reassure us of the non-existence of real quarks.

These ideas were developed during a visit to Columbia University in March 1963; the author would like to thank Professor Robert Serber for stimulating them.

References

1) M. Gell-Mann, California Institute of Technology Synchrotron Laboratory Report CTSL-20 (1961).
2) Y. Ne'eman, Nuclear Phys. 26 (1961) 222.
3) M. Gell-Mann, Phys. Rev. 125 (1962) 1067.
4) E.g.: R. H. Capps, Phys. Rev. Letters 10 (1963) 312;
R. E. Cutkosky, J. Kalckar and P. Tarjanne, Physics Letters 1 (1962) 93;
E. Abers, F. Zachariasen and A. C. Zemach, Phys. Rev. 132 (1963) 1831;
S. Glashow, Phys. Rev. 130 (1963) 2132;
R. E. Cutkosky and P. Tarjanne, Phys. Rev. 132 (1963) 1354.
5) P. Tarjanne and V. L. Teplitz, Phys. Rev. Letters 11 (1963) 447.
6) James Joyce, Finnegan's Wake (Viking Press, New York, 1939) p. 383.
7) M. Gell-Mann and M. Lévy, Nuovo Cimento 16 (1960) 705.
8) N. Cabibbo, Phys. Rev. Letters 10 (1963) 531.

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* There is the alternative possibility that the quarks are unstable under decay into baryon plus anti-di-quark or anti-baryon plus quadri-quark. In any case, some particle of fractional charge would have to be absolutely stable.

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AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

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ABSTRACT

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number 1/3 and is fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time and group theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. Quantitative speculations are presented concerning resonances that have not as yet been definitively classified into representations of SU_3. A weak interaction theory based on right and left handed aces is used to predict rates for $|\Delta S| = 1$ baryon leptonic decays. An experimental search for the aces is suggested.

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