". . . Three quarks for Muster Mark!
Sure he hasn't got much of a bark
And sure any he has it's all beside the mark."
James Joyce, *Finnegan's Wake*, p. 383

"Hark . . . (it can't be) sax
Hork . . . (it must be) twelve".
ibid., p. 403

Musings in the Museyroom

By Laurie M. Brown

"Symmetry Principles at High Energy" can be read either as a caption or a headline; the double meaning might have pleased the great Irish novelist whose quarks have, in one form or another, dominated this year's conference. The Coral Gables Conference*, meeting again in the University of Miami's Lowe Art Gallery (the "museyroom" of the title), between January 20 and 22 of this year, heard a number of contributions dealing with relativistic extensions of the static SU (6) quark model, itself an extension of the SU (3) octet model; these extensions invariably led to a symmetry group called either $\tilde{U}$(12) or M (12) based on twelve fundamental generators or "objects". The reward for enlarging the symmetry group consists of larger supermultiplets, for example, the pseudoscalar octet is united with the nine vector mesons, and the baryon octet with the decuplet. Having a formally relativistic theory makes possible the writing of $\tilde{U}$ (12) invariant interactions among these thirty-five mesons and baryons which involve only two independent (and known) coupling constants! The theory is also simple enough that important new consequences can be derived with relative ease. Some of these will be mentioned below, and others will undoubtedly, within a short time, begin to fill the pages of the physics journals. But, it should be emphasized that this is only a beginning and that the present forms of U (12) are incomplete; they may also have other difficulties, which will be mentioned subsequently.

After an address of welcome by B. Kursunoglu (University of Miami), who was the principal organizer of the conference, J. Robert Oppenheimer gave an over-all view of the problems facing the symmetry theories, providing a prospectus for what was to follow. As he noted, the first insight into the symmetry properties of the strong interactions was the recognition of the charge independence of nuclear forces; this led, through Kemmer's isospin formalism, to SU (2) symmetric meson couplings when these forces were realized in terms of Yukawa meson exchange. SU (2) symmetry was, from the outset, recognized to be broken by electromagnetic and weak interactions, as are the higher symmetries, beginning with SU(3). But the large mass differences between members of supermultiplets show that the higher symmetries are broken in a more serious way. Oppenheimer also reported on work carried out at the Institute for Advanced Study dealing with SU(6) predictions of cross-section and resonance widths, which appear to be in good agreement with experiment, and reported on bootstrap calculations which support the higher symmetries. He underlined the problem of combining SU (6) symmetry with relativity or, more accurately, of framing a relativistic theory which gives SU (6) theory as its static limit, and I shall proceed to discuss the papers which dealt with this problem.

The first exposition of this subject at the conference was given by A. Salam (University of London and International Center for Theoretical Physics, Trieste) who reported on work done in collaboration with his Trieste colleagues, R. Delbourgo and J. Strathdee. They invoke a group U (12) which can best be visualized as the symmetry possessed by a triplet of quarks, each described by a four component Dirac spinor. There are thus twelve independent building blocks, each described by a twelve component multispinor, from which the observed "elementary" particles can be

* For a report on the First Coral Gables Conference see *Tyger Hunting in the Everglades*, Physics Today, April 1964, p. 36. Laurie M. Brown, the author of both reports, is professor of physics at Northwestern University.

The audience enjoys a joke. This and other sessions of the Second Coral Gables Conference on Symmetry Principles at High Energy were held in the Lowe Art Gallery of the University of Miami.

built. If a meson supermultiplet, for example, consisted of quark-antiquark compounds in the $1S$ state, there could be 144 of them, but requiring them to obey free particle equations of motion one ends up with a mere 135, not all independent. In fact, so many restrictive supplementary conditions result that these turn out to be nine 0^- mesons and nine 1^- mesons described respectively by five- and ten-component Kemmer-Duffin spinors $(9 \times 5 + 9 \times 10 = 135)$. A similar miracle occurs for the baryon octet and decuplet. Furthermore, the symmetry becomes exactly that of SU (6) in the static limit. (Note, if it helps, that in this way of counting $1S$ positronium counts as 15 states—five singlet and ten triplet).

Before turning to some of the unsolved difficulties of this approach, let me mention those on the program who arrived at substantially similar conclusions. B. W. Lee was the spokesman for a group consisting of K. Bardakci, J. M. Cornwall, P.G.O. Freund, and himself (all from the Institute for Advanced Study, Princeton). Since SU (6) symmetry, like the analogous Wigner supermultiplet theory which inspired it, conserves spin angular momentum, it follows that orbital angular momentum is also conserved. Thus, for example,

The principal organizer of the conference, Behram Kursunoglu of the University of Miami, at the speaker's podium.

$\rho \rightarrow 2\pi$ decay is forbidden! However, the relativistic extension of SU (6) to M (12) [Salam's $\tilde{U}$ (12)] introduces, via the non-SU (6)-invariant kinetic energy, a spin-orbit interaction which gives a strong $\rho \rightarrow 2\pi$.

B. Sakita and K. C. Wali (Argonne) have developed the same theory as Salam et al., and Sakita reported it briefly. B. Kursunoglu (Miami) delivered a paper which also involved the group $\tilde{U}$ (12), first introduced by him in 1960 in an article in *Nuovo Cimento*, entitled "Relativity and Quantum Theory". (At the January 1964 New York Meeting of the APS a week later, A. Pais and M. B. Beg of the Rockefeller Institute were reported by Pais to have made a similar relativistic extension of SU (6). So have P. Roman and J. Aghassi of Boston University).

A related subject was discussed by J. Schwinger (Harvard) who asked in what manner the symmetry properties of the underlying fields (i.e., quarks or quark-like objects, viewed at the moment as "real" or as abstractions according to one's taste) determine the symmetry properties of the observed particles. Again the result was that the full underlying symmetry would not be maintained but, rather, it would be broken and in a definite way.

The recurring question of combining internal symmetries with the Lorentz group (which was largely initiated at the First Coral Gables Conference) was discussed in papers delivered by S. Okubo (Rochester), G. Sudarshan (Syracuse), and L. Michel (Institut des Hautes Etudes Scientifiques, Paris). Okubo and R. E. Marshak have considered two different quark models, one mixing parity with the internal symmetry group and one based on what they call "Casimir decomposition"; they have obtained the maximal symmetry

Mrs. Kursunoglu chats with J. Robert Oppenheimer and Abdus Salam on the University of Miami campus.

groups which apply. They emphasized the impossibility of obtaining a Lagrangian formulation of the $\tilde{U}$ (12) or M (12) theories. Sudarshan remarked that while most symmetry theories define spin in terms of the homogeneous Lorentz group, it must be defined through the inhomogeneous Lorentz group (Poincaré group), if a particle interpretation is to be meaningful. He proposed a product symmetry group of this type which, in the static limit, yields as one supermultiplet mesons of spin-parity 0^-, 1^-, and 2^- (thirty-five in all). Sudarshan also proved an extension of the McGlinn theorem, which limits severely the combining of internal symmetries with the Poincaré group. This last was also the subject of Michel's talk which covered, in an elegant and profound manner, the mathematical difficulties involved. Surprisingly, however, in later discussion Michel was unwilling to condemn the attitude taken by the physicists present who hoped to sidestep these difficulties. For this Ne'eman compared him to the biblical figure Balaam who, called upon to curse the Israelites, remained to bless them.

The other papers dealing with higher symmetry models for the strong interactions were delivered by H. J. Lipkin (Weizmann Institute), Y. Ne'eman (CIT), and Y. Nambu (Chicago). Lipkin discussed possible experimental tests of the dynamical aspects of proposed symmetry schemes, pointing out that SU (3) itself leads to few selection rules because of the great freedom available in coupling octets to octets. But this is not true of the higher representations of SU (3), nor is it generally true in the higher symmetry schemes; he gave a number of examples. Ne'eman discussed work he has been doing with M. Gell-Mann based on an algebra of SU (3) current commutators. This involves the introduction of orbital angular momentum into the quark model and leads to noncompact groups, Regge poles, and rotational bands. Nambu's talk dealt with "realistic" quark models, and he argued that the most acceptable model involves not one, but two fundamental triplets. These should carry a property (which some physicists have called "charm"), analogous to electric charge, and there should also be a heavy boson field or fields coupled to "charm". (This is reminiscent of Schwinger's *Field Theory of Matter*.) On the basis of a static model, this leads to an SU (6) $\times$ SU (6) symmetry scheme in which it is possible to place the SU (3) supermultiplets. It is supposed that the underlying triplets are very heavy and that the charm forces are correspondingly strong, so that what we are currently observing are states of zero charm (analogous to neutral, as opposed to ionized, atoms). To observe charmed particles we would need higher energy accelerators.

L. M. Brown (Northwestern) reported on some work with H. Faier bearing on the evidence for a sigma meson, this being a conjectured scalar meson of zero isospin having a mass of about 400 MeV and a width of about 100 MeV. The processes studied were decays into three pions of the pseudoscalar mesons η and K and the decay of X^0 (960) into $\eta + 2\pi$. Spectral distortions, as well as branching ratios, were satisfactorily explained tending to confirm the hypothesis first put forward by Brown and P. Singer, although no clearcut evidence for sigma has been seen in high energy production.

Symmetry, as it enters in the weak interactions, was discussed by B. d'Espagnat (Paris) who presented an elaboration of the well-known Cabibbo theory to allow for the possibility of *CP* violation. (Similar results of B. Zweig and F. Zachariasen of CIT were presented informally by Zweig, but derived from a $\tilde{U}$ (12) model which permits a number of predictions to be made.) Weak interaction currents were used by R. Dashen of CIT in a bootstrap approach to generating the symmetries of the strong interactions. His results, in general, confirmed previous work of the bootstrap school, especially that of Capps and Cutkosky.

This conference, though primarily theoretical, was blessed, like the first Coral Cables Conference, with the presence of a number of first-rate experimentalists. G. Goldhaber (Berkeley) reviewed the latest information on strong particle resonances, while S. Lindenbaum (Brookhaven) gave the present status of very high energy elastic scattering, this being an important test of assumptions frequently made in using dispersion relations. With regard to the Regge-pole theorists, Lindenbaum concluded that the energy regime at which single Regge poles dominate, a region

Session chairman Gregory Breit of Yale assists speaker Laurie M. Brown of Northwestern with the microphone.

he names "Asymptopia", has as yet not been attained.

Ne'eman gave an excellent summary talk touching on the various problems and solutions which had been proposed. After this Marshak, speaking for all of us, thanked our hosts and was moved to compare this conference in significance with the Shelter Island Conference, which gave birth to the triumph of renormalized quantum electrodynamics.

In organization and amenity this year's conference surpassed even that of the previous year. In addition to the principal sponsorship, that of the University of Miami, support was given by the National Science Foundation, the Air Force Office of Scientific Research, the National Aeronautics and Space Administration, and the Atomic Energy Commission. We look forward with pleasure to the Third Coral Gables Conference and to still higher symmetry groups!

Why $\tilde{U}(12)$?

The currently fashionable emphasis on group theoretical methods in elementary-particle physics may leave the nonspecialist with the uncomfortable feeling that his physical foundations are in need of repair. However, what has been achieved so far in explaining the gross features of the strongly interacting particles (or hadrons, as they are now often called), brilliant and spectacular as some of the insights have been, can be easily grasped by anyone who understands, for example, the positronium atom. In an article[1] entitled "Are Mesons Elementary Particles?", Fermi and Yang pointed out in 1949 that a tightly bound system of nucleon and antinucleon in the $^1S_0$ state would behave like a Yukawa meson (the pion). After the discovery of the strange particles, and after the definition of strangeness in terms of charge, baryon number, and isospin was given by Gell-Mann and Nishijima, Sakata[2] pointed out that a more general composite model, based on combining proton, neutron, and lambda particles with their antiparticles would yield the Gell-Mann–Nishijima relation; in this picture conservation of strangeness in strong interactions is nothing more than the conservation of lambda hyperons. The lowest states of the Fermi-Yang-Sakata model are mesons with odd parity which can be identified with the eighteen pseudoscalar and vector mesons, ranging from the pion to the phi meson.

The difficulty with the Sakata theory arises in connection with the baryons. To make baryons it is necessary to combine two particles of the p, n, Λ triplet with one of their antiparticles. In this way one easily makes Ξ and Σ baryons of the right properties, but also three new objects p′, n′, Λ'. Which of the objects p, n, Λ or p′, n′, Λ' are to be identified with the physical proton, neutron, and lambda? It is on this rock that the Sakata theory founders.

Attempts to treat the eight lightest baryons on an equal basis as four originally degenerate isospin doublets led to an unsuccessful scheme known as "global symmetry." It remained for Gell-Mann[3] and Ne'eman, in 1961, to generalize the isospin group SU(2) to the "eightfold way" or SU(3), emphasizing the group-theoretical structure and not being greatly concerned about the reality or nonreality of the underlying elements, which again formed a Sakata triplet.

All recent attempts to treat SU(3) in terms of a realistic composite model have renounced the physical p, n, Λ particles and assumed the fundamental triplet to have unusual properties such as very large mass, fractional strangeness, or fractional charge. The latter particles have been called "quarks" by Gell-Mann.

The SU(3) supermultiplets of 1, 8, 10, 27 (etc.) particles each belong to a given "unitary spin", just as the three pions belong to an isospin multiplet; and, analogously, they contain particles of the same spin and parity. Recent efforts, such as those described in the accompanying conference report, have been concerned with enlarging the symmetry group to obtain larger supermultiplets; the motivation being twofold; first, the identification of a larger approximate symmetry allows a reduction in the number of arbitrary coupling constants, just as isospin symmetry requires a *single* pion-nucleon coupling constant. Secondly, in incorporating space-time symmetries, such as angular momentum, into the symmetry scheme one is actually entering the realm of dynamics, the ultimate aim of physics.

The SU(6) scheme of Gürsey, Radicati, Pais, and Sakita was the first to treat the SU (2) spin group and the SU(3) unitary spin group on an equal footing. (In terms of a composite model the members of an SU(6) supermultiplet have a common internal orbital angular momentum structure.) However, the spin can only be isolated from the rest of the Lorentz group in a static framework, and to make a fully covariant theory it is necessary to include general Lorentz transformations. Hence $\tilde{U}(12)$.

References

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2 S. Sakata, Progr. Theoret. Phys. **16**, 686 (1956).
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