Symmetries and Quarks Raise More Questions than Solutions

The "Rochester" series of biennial conferences on high-energy physics leaves gaps in odd-numbered years that are being filled with greater thoroughness as time goes on. This year, although the principal out-of-season conference was at Lund, Sweden (drawing most of its participants from Europe), one North American counterpart was the International Conference on Symmetries and Quark Models, which took place in Detroit at Wayne State University, 18–20 June. In this report I have imposed some artificial unity on material whose initial presentations at the conference were quite diverse. This diversity of approaches indicates that the field in which quarks and symmetry models are used is expanding and is in an agreeably healthy state—that is, more questions are being raised than can be answered at present.

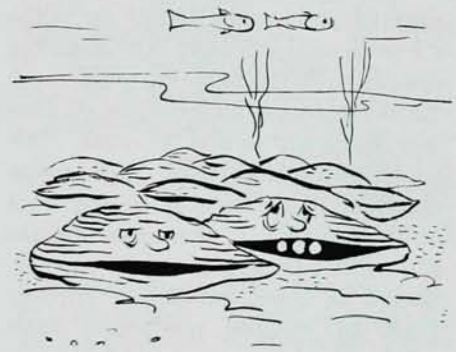
Quarks. The simplest group symmetry of interest to high-energy physicists is the well known SU(3). Quark models enter discussion at this simple level when spin states are temporarily ignored, if it is assumed that there are three genuine particles that can be assigned to the basic three-dimensional irreducible representation of SU(3). The distinctive property of the quarks in most models is that they have fractional electric charge (absolute values $e/3$ or $2e/3$, where e is the electronic charge). Therefore in principle they are easy to detect by such means as Millikan oil-drop experiments or experiments in which they leave an observable track by causing ionization in the detecting medium. However, apart from an unsupported rumor relayed to the conference from unidentified journalists in Australia, there was no news of the detection of quarks. [See page 55 for recent developments.]

Lawrence W. Jones (University of Michigan) presented a summary of experiments that set upper limits to the number of quarks per nucleon present in various materials. The lowest of these limits is currently 3×10^{-29} quarks per nucleon in sea water, a material which has been used in several experiments in the past few years. Other substances have associated limits that are not yet so stringent. For example, Millikan oil-drop experiments on animal, vegetable and mineral oils that are readily obtainable in Michigan produce an upper limit of 10^{-20} quarks per nucleon. Chemically-based speculation suggests that quarks may be concentrated in places where there are also concentrations of the most chemically active elements, such as members of either Group I or Group VII in the periodic table. Seaweed, as a representative of Group VII, and oysters, as representatives of Group I, must be concealing no more than 10^{-18} quarks per nucleon according to the present experimental evidence.

To include spin in models of particles built up from quarks and antiquarks, the quarks must have a spin of at least 1/2. As each quark then has two distinct spin states available to it, the initial symmetry group SU(3) gives way to SU(6). This symmetry group has had some notable predictive successes, such as the value of $-3/2$ for the ratio of proton and neutron magnetic moments, as well as some notable failures. If the quarks are real particles, perhaps the failures occur because they have spins greater than 1/2.

Jerrold Franklin (Temple University) discussed some of the effects of higher-spin assignments on theoretical predictions from quark models. One number that is fairly sensitive to the choice of spin and parity for the quark is the ratio of amplitudes for the two photoproduction reactions $\gamma + p \rightarrow K^+ + \Lambda$ and $\gamma + p \rightarrow K^+ + \Sigma^0$ when the K meson is produced in the forward direction. A comparison with experiment appears to rule out positive-parity spin-1/2 quarks quite sharply and tends to favor negative parity and a spin of 3/2. The magnetic moment of the Ξ hyperon is also sensitive to choices of quark spin and parity, but an accurate experimental measurement of this quantity is a long way off. It was pointed out during the discussion that many unique predictions of quark models rely implicitly on a spin-1/2 assignment, because higher-spin assignments destroy their uniqueness. In that sense, if and only if one believes in quarks, some failures of predictions based on SU(6) might imply in a roundabout way that the quarks should have spins greater than 1/2.

More predictions about other properties of quarks may be derived from models, either as a way out of problems with spin and statistics or as a consequence of the dynamical framework inside which one's model quarks are described. An example of the former type is a quark model presented by Don B. Lichtenberg (Indi-



ana University), which generates sets of particle states that have not yet been observed. It appears to be a characteristic of quark models that the number of predicted baryon and meson states significantly exceeds the number of observed particles or resonances. However, it is probably too soon to say that this characteristic is a disease of the models, because the detailed dynamics that must be added to the assumptions about "static" quark symmetries may suppress the unwanted or unobserved states. The open question is whether or not the dynamical assumptions that will limit the yield of any model to exactly those states found in experiments will be physically plausible.

Two models with a dynamical content built in at an early stage are those of Suraj N. Gupta (Wayne State University) and Herbert Jehle (George Washington University). Gupta uses a multispinor description for the quarks, which is governed by a generalization of the Dirac equation and fits certain mass formulae quite well. However, because its calculated effective mass for the quarks with the strangeness quantum number S equal to zero is about 9 MeV, whereas the effective mass for the strange ($S \neq 0$) quark is about 150 MeV, the predicted magnetic moments of strange hyperons may be significantly less than the magnetic moments of nonstrange objects such as nucleons. Jehle's model has the novel interpretation of quarks as quantized rings of magnetic flux and the accompanying drawback that calculations may be difficult.

Susumu Okubo (University of Rochester) examined several of the longer-lived models of quarks, including the original scheme of Murray Gell-Mann and George Zweig, side by side. On the basis of a comparison with experiment of their predictions for processes such as $\pi^0 \rightarrow 2\gamma$, $\eta^0 \rightarrow 2\gamma$ and the decay of a vector meson (spin 1 and negative parity) to a lepton–antilepton pair, the model to emerge with the least impaired reputation was one proposed by M. Y. Han and Yoichiro Nambu in 1965. Already it departs from the simplest type of quark model naively drawn from SU(3), because it uses nine quarks with integral charges that are arranged in three families of triplets. Thus, to improve predictions from quark models, one apparently has to give up some of the attractive simplicity that was itself a justification for the earliest models.

If pions and nucleons are composed of quarks, one should be able to construct their scattering amplitudes from amplitudes for the scattering of quarks by quarks. Multiple scattering is easy to visualize. Antonio Pagnamenta (Rutgers University) suggested that multiple scattering is responsible for the breaks that have been observed in plots of the differential cross section versus momentum transfer for pion–nucleon and nucleon–nucleon scattering. He presented the results of a calculation for pion–nucleon scattering in which all the free parameters and boundary conditions had been fixed previously by fits to nucleon–nucleon and antinucleon–nucleon scattering data. The best agreement with experiment was obtained if the ratio of the quark radius to the nucleon radius was about unity, but the results appeared to be insensitive to the number N of scattering centers present inside the nucleon provided N is greater than 2. Quark models require the presence inside the nucleon of just three centers, which are the constituent quarks themselves.

Quarks and symmetries. Several contributions to the conference fell into a region intermediate between quarks and symmetries, by having a bearing on both subjects. From the point of view of the theorist, the predicted particles with the most elusive status, or the greatest chance of agreeing with experimental findings today and disagreeing with them tomorrow, are the Ξ^* resonances, which may be regarded as excited states of the Ξ hyperon. Gaurang Yodh (University of Maryland) gave today's picture as seen by the experimentalist. This picture is that five Ξ^* resonances with masses between 1530 MeV and 2450 MeV are fairly well established but that three other candidates are presently out of favor. Richard H. Dalitz (Oxford University) commented on some predictions of a model in which quarks respecting SU(6) symmetry have orbital motions and an associated orbital quantum number L in mesons and baryons. In a model of this type it is possible to predict enough meson states with masses in the neighborhood of the A_2 meson near 1300 MeV for the apparent fine structure in the A_2 peak to result merely from the accidental degeneracy of two states with the same quantum numbers. This simple possibility contrasts well with some of the more speculative explanations for the form of the A_2 peak that have been advanced recently.

Questions involving SU(3) symmetry without quark support received some attention. Among the vector mesons, ω is placed in an octet of particles belonging to an eight-dimensional representation of the group, and ϕ is regarded as a singlet state. Because the two mesons have the same quantum numbers, we do not see the bare ω and ϕ but linear combinations of the two states with coefficients given in terms of one parameter, the "mixing angle." Michel Gourdin (Laboratoire de Physique Théorique et Hautes Energies, Orsay) considered various models of ω–ϕ mixing and their applications to processes such as the decay of a vector meson to two pseudoscalar mesons (spin 0 and negative parity). He concluded that no one model is wholly satisfactory. This observation is related to uncertainties in how SU(3) should actually be applied to such situations: For example, the formula of Gell-Mann and Okubo that connects the masses of members of the octet of vector mesons reads $4K^* = 3\omega + \rho$, but it is still not shown on rigorous grounds whether the symbols in that equation should stand for the masses of the particles, the squares of the masses or the inverse squares.

A modification of the full SU(6) group, called $SU(6)_w$, is free from any obvious contradictions with experiment as far as predictions for particle decays are concerned. Sydney Meshkov (National Bureau of Standards) reviewed calculations of ratios of amplitudes for various strong-scattering processes and concluded that agreement with experimental results was good to within 20%. The major disagreements here, as with disagreements in SU(3) predictions, are between predictions for reactions initiated by strange and nonstrange particles; this difficulty suggests that other potential areas of disagreement that are overshadowed by this effect should appear if one tests predictions for a group having a set of generators from which the strangeness operator is excluded. The best group for this purpose is $SU(4)_w$.

The success of dynamical models that include currents in the descriptions of weak and electromagnetic interactions has led many physicists to construct systems of currents with particular commutation relations that may apply to strong interactions. The most effective of these constructions contains equal numbers of vector and axial-vector quantities obeying the same conditions of symmetry. However, the two types can be regarded as occupying two disjoint mathematical spaces, so that, if G is the symmetry group of each type, the symmetry for the entire system is the direct product $G \otimes G$. Models in which $G = SU(2)$ and $G = SU(3)$ are quite popular in various quarters, but the question of the consistency of any direct-product symmetry with more traditional group structures like SU(6) has not been studied in general. Yuval Ne'eman (Tel-Aviv University and University of Texas at Austin) reported on a first example of such a study, which considered the consistency of SU(6) with a slightly simplified version of the algebra of fields (in which fields replace the currents mentioned above) developed by Tsung Dao Lee, Steven Weinberg and Bruno Zumino in 1967. An inconsistency was found in the classification of mesons.

Some of the simpler direct-product symmetries lead indirectly to predictions, such as the impossibility of the decay $\omega \rightarrow \pi^0 + \gamma$, that are not supported by experiment. Richard Arnowitt (Northeastern University) discussed theoretical modifications by which these difficulties might be removed. In particular, he suggested that the so-called "partial conservation of the axial-vector current" condition, in which the divergence of the axial-vector current is expressed in terms of the pion field, might have to be supplemented by further contributions in the fields of the ω and ϕ mesons.

Arno Böhm (University of Texas at Austin) presented a different type of product symmetry, which grew in a natural way out of a set of commutation relations for physical operators that included the momentum and angular-momentum operators. Dynamical group structures of this type, which have infinite-dimensional representations and are therefore not as easy to handle as groups such as SU(3) with finite-dimensional representations, have come into prominence in high-energy physics since 1965. Böhm's contribution was to make quantitative predictions about fine structure in the peaks in the meson spectrum, using the observed fine structure in the A_2 meson peak to fix the free parameters of the theory.

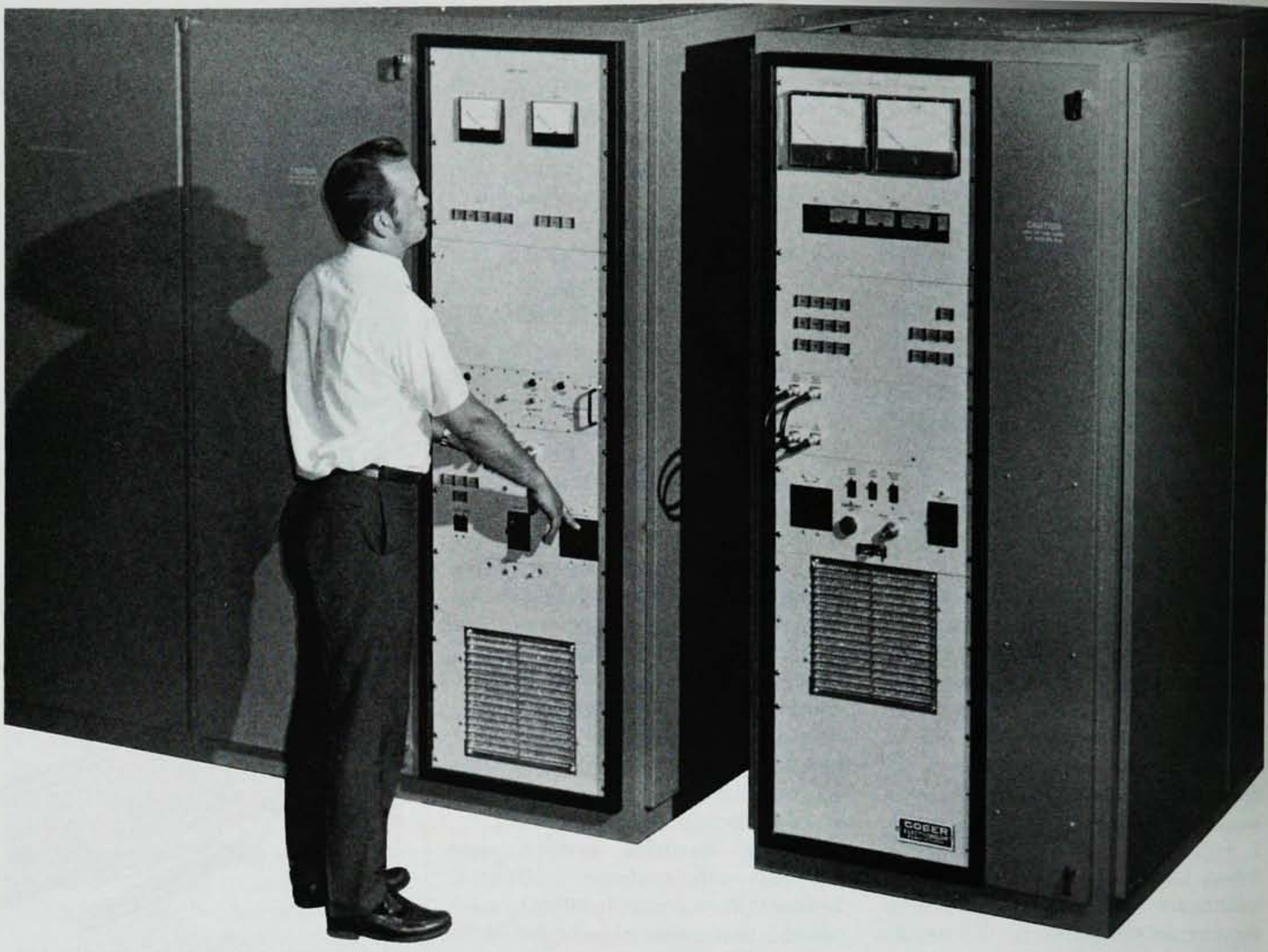
Some of the well separated, narrow, high-mass peaks that have been observed (for example S, T and U mesons) are tied together in the theory as fine structure of a very broad feature in the spectrum. Two present experiments, one at CERN and one in the US, will have a sufficiently good resolution to detect other fine structure if it exists. Other parts of the theory are applicable to weak decay processes. George Sudarshan (Syracuse University) gave a survey of some of its predictions, together with a description of the chief weak-interaction features of his own theory of universal primary interactions of particles, with which it is capable of coexistence.

Fine structure in the meson mass spectrum is also easy to predict in Dalitz's quark model with SU(6) symmetry plus orbital motions, provided that the Hamiltonian for the bound quark system that makes up the mesons contains an $L{\cdot}S$ term in exact analogy to spin–orbit coupling in atomic physics. The common characteristic of the two models, and of others that can be proposed, is that fine structure, once observed in one place, is very difficult to keep out of peaks higher in the mass spectrum. It will be a source of some theoretical confusion if future experiments find no substructure in higher-mass peaks—unless, of course, the present experimental confusion about what the A_2 peak consists of is eventually resolved by an agreement that there is no substructure at all. But that result appears to be highly unlikely.

The isospin quantum number I changes in weak decays, predominantly by steps of 1/2. If this is the only type of isospin change, the $|\Delta I| = 1/2$ rule is established. It is of importance to physicists using the methods of group theory to know whether or not operators that effect isospin changes with $|\Delta I| \geq 3/2$ can be left out of their sets of generators of groups. Oliver E. Overseth (University of Michigan) quoted recent experimental results, particularly on the decays $\Sigma^- \rightarrow n + \pi^-$, $\Sigma^0 \rightarrow n + \pi^0$ and $\Sigma^+ \rightarrow p + \pi^0$, that allow the decay amplitudes to contain up to 5% of components with $|\Delta I| \geq 3/2$.

"Exotic" particles received some publicity at the conference. Harry J. Lipkin (Weizmann Institute) commented that exotic objects should be separated into two classes, objects with quantum numbers for which there is no space in conventional group-theoretic classifications (for example particles with baryon number B satisfying $|B| > 1$), and objects with combinations of spin, parity and charge-conjugation quantum number C that can not be built up out of two or three quarks in the model of Gell-Mann and Zweig. Nominations for exotic states included: a suspicious object or quasi-object in data from the Argonne National Laboratory on the scattering of K^+ mesons from protons when the momentum of the K^+ times the velocity of light is 1950 MeV; a meson state F with a spin of 2, negative parity, $I = 1$, and a mass of 1540 MeV, which decays into K and K*; and an object at 1289 MeV, which may otherwise be a part of the A_2 peak. The nominations in each case are subject to the availability of better experimental data.

Lipkin also made a distinction that will probably find its way into the folklore of theoretical high-energy physics: according to the distinction, one is either an *s-t-u* physicist or an *I-B-Y* physicist. The first three letters refer to the Lorentz-invariant variables



in terms of which a scattering amplitude is expressed by people who wish to examine its analytic properties, while *I, B* and *Y* are the discrete quantum numbers for isospin, baryon number and hypercharge that arise almost as first predictions from any group symmetry of particles. The suggestion is that physicists of the first kind practise only analysis, physicists of the second kind practise only algebra, and the intersection of the two sets is empty. Although it is my own bias that this is not true, it is true enough to be memorable.

The assumption of invariance of scattering amplitudes under certain interchanges of the three variables *s, t* and *u* is the assumption of crossing symmetry. This is hardly a symmetry in the spirit of the title of the conference, but it is a preoccupation of many physicists in connection with the Veneziano representation (PHYSICS TODAY, March 1969, page 59). In its original form, Veneziano's expression is an amplitude for the scattering of

"What's wrong with yours?"

two particles into a final state that also contains two particles. The sole contribution dealing with the mathematical properties of the Veneziano representation was by Nambu (University of Chicago). He gave an elegant extension of the amplitude to a many-particle situation, with a formalism of creation and annihilation operators, in a manner that resembled their use in statistical mechanics. Pressing the analogy with statistical mechanics a little further, it is possible to say that the formalism pictures particles made up of quarks with many degrees of freedom.

Unitarity. Despite the fact that the Veneziano representation was not officially on the agenda at the conference, there was some vigorous underground discussion of its properties. One outstanding negative property of the representation is that it is not unitary. The degree to which the problem has been considered, or solved, or both, may be deduced from the following exchange of conversation, which was heard several times during the breaks for coffee between papers:

A: "I've just made a Veneziano model that is unitary."

B: "So have I. What's wrong with yours?"

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Amorphous Semiconductors Stimulate Fundamental and Applied Research

The science and technology of amorphous semiconductors runs the gamut from analysis of the fundamental electronic-energy spectrum of disordered solids, through the physics or phenomenology of transport and switching in films, to the incorporation of actual devices in circuits. These topics were all covered in a timely symposium, held at Picatinny Arsenal 14–17 May, which attracted a representative audience of scientists and engineers either active in the field or holding a watching brief on it. Apart from short sessions on switching effects at earlier conferences (see, for example, Cyril Hilsum's report on the conference on instabilities in semiconductors held at IBM, PHYSICS TODAY, August, page 89) this was the first time the many people attracted to the field had met to discuss its health. Whether intentional or not, the inclusion by the organizers of some marginal papers was a justifiable risk, because in this new field the unusual may be correct and the largely wrong can still provide inspiration.

Fundamental properties. With a few exceptions to which I shall refer, the papers provided more fundamental questions than answers. As was emphasized by Alton H. Clark (University of Maine) for elemental amorphous semiconductors, the basic questions of the definition of the structure of the amorphous phase, the relation of the electronic band structure to the crystalline band structure, the nature (especially the localization) of the electronic states introduced by the disorder, and the transport mechanism remain only partially answered.

The most noteworthy contribution to the fundamental theory was made by Morrel Cohen (Chicago), who provided more theoretical justification for the model presented by him in collaboration with Hellmut Fritzsche and Stanford Ovshinsky in a recent *Physical Review* Letter. For readers new to the field, this letter is a succinct statement of the present theoretical idea for the energy spectrum and transport properties of an amorphous semiconductor having almost complete atomic valence satisfaction, but no additional order. There is a clear need for more basic theoretical work of this kind. However, the applicability of the structural aspects of this model to the actual experimental samples for which results are reported in the literature is an open question, because it is often not established that the atomic arrangement does not possess some local order. At the same time it is well known that the measured properties are very sensitive to the thermal history. It appears to be essential for structural or density measurements, or both, to be performed on all samples whose transport, optical or thermal properties are also being studied. Otherwise experimenters may find themselves comparing apples and oranges.

An example of the problem is provided by the early observation that the optical properties of amorphous germanium bore a strong resemblance to those of crystalline germanium, and the deduction therefrom that the band structure was not much changed in the passage from the crystalline to the amorphous phase. More recent studies showing that the density of some "amorphous germanium" may be very close to that of the crystals invite the interpretation that the "amorphous germanium" is composed of very small crystallites, small enough to escape detection as ordered arrays in x-ray examination, but large enough to yield