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MURRAY GELL-MANN

Selected Papers

editor

Harald Fritzsch

University of Munich, Germany

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H. Fritzsch (left) and M. Gell-Mann

Murray Gell-Mann

The American physicist Murray Gell-Mann has contributed more than anybody else to the theoretical understanding of the physics of elementary particles.

Gell-Mann, the son of Austrian immigrants, was born in New York City on September 15, 1929. His father, Arthur Gell-Mann, came from the city of Czernowitz in the Bukowina district, which is today part of the Ukraine. He studied at the University of Vienna and planned to become a high school teacher. He cut short his studies and moved to the United States so as to help his parents, who had emigrated to New York and were not doing well. He created a language school in Manhattan, which was successful for a while. When it failed, because of the new immigration laws and the Great Depression, he got a job in a bank.

Arthur Gell-Mann was very interested in science, especially in astronomy, physics and mathematics. Gell-Mann's mother, Pauline, was a housewife who had ambitions for her son Murray. She encouraged him to play the piano. She also tried to get him a scholarship to a private school. Finally it was his music teacher who succeeded in doing that. Murray Gell-Mann's brother Benedict was nine years older than Murray and taught him a great deal about plants, animals (especially birds and butterflies), and the preservation of natural ecological systems. The two brothers spent a large part of their time outdoors, studying Nature, and in museums, such as the American Museum of Natural History and the Metropolitan Museum of Art.

At the age of 14, Murray Gell-Mann graduated from high school and obtained a scholarship at Yale University, where his major subject was physics. He finished his studies in June 1948 as Bachelor of Science, when he was 18. He went to the Massachusetts Institute of Technology for his graduate studies. His Ph.D.-advisor there was Victor Weisskopf, and he obtained his doctorate in January 1951, whereupon he became a member of the Institute for Advanced Study in Princeton. The director of the Institute, Prof. Robert Oppenheimer, encouraged Gell-Mann in his work on problems in elementary particle physics. In 1952, Gell-Mann joined the Physics Department of the University of Chicago. There he worked together with Marvin Goldberger and had close contact with Enrico Fermi.

In 1955, Gell-Mann married J. Margaret Dow, who came from England and was working at the Institute in Princeton as the assistant to an archaeology professor. They had two children, a daughter Lisa, born in 1956, and a son Nicholas, born in 1963.

In the same year, Gell-Mann left Chicago and accepted a professorship at the California Institute of Technology in Pasadena, California. In 1967, Gell-Mann obtained the prestigious Robert Andrews Millikan professorship at Caltech. In 1993, he retired and went to the Santa Fe Institute in Santa Fe, New Mexico, which he had helped to found and which he regarded as one of his most satisfying achievements.

Gell-Mann obtained the Nobel Prize in Physics in 1969, mainly for his work on the classification of the hadrons, based on the approximate symmetry $SU(3)$, known as the $SU(3)$ of “flavor.”

Some of Gell-Mann’s early papers were on the newly discovered V -particles, found in cosmic ray experiments. They were copiously produced in nucleon collisions, but decayed slowly. Gell-Mann found a quantum number, strangeness, which was conserved by the strong and electromagnetic interactions. The new hadrons had nonzero strangeness, unlike the familiar ones, and so could not decay except through the weak interaction.

In 1953, Gell-Mann worked with Francis Low on problems of quantum field theory. They introduced the concept of the renormalization group and studied the behavior of the coupling constants as functions of momentum transfer. The methods of Gell-Mann and Low were very useful later in the theory of quantum chromodynamics. Also, Gell-Mann’s student Kenneth Wilson applied those methods to condensed matter physics, where the results were so important that he was awarded the Nobel Prize.

In 1956, the violation of parity symmetry in the weak interactions was discovered. Richard Feynman and Murray Gell-Mann proposed in 1957 that the weak interactions are described by left-handed currents with a $V-A$ structure (V : vector current, A : axial vector current). The same idea was published by Robert Marshak and George Sudarshan. The $V-A$ theory of the weak interactions was used later in the gauge theory of the weak interaction, developed by Sheldon Glashow, Abdus Salam, and Steven Weinberg.

In 1961, Gell-Mann succeeded in describing the new hadrons, found in cosmic ray and accelerator experiments. He used an approximate symmetry scheme based on the group $SU(3)$. This group is an extension of the isospin group $SU(2)$ and includes what amounts to the strangeness quantum number. Yuval Ne’eman in Israel also proposed this symmetry group.

The baryons were described in the $SU(3)$ scheme as an octet, consisting of the two nucleons, the three sigma baryons, the λ baryon and the two ξ baryons. Likewise the mesons formed an octet, consisting of the three π mesons, the four K mesons and the η meson. The excited baryons formed a decimet, consisting of the four δ resonances, the three σ^* resonances, the two ξ^* resonances and the ω resonance.

The group $SU(3)$ of “flavor” gives a symmetry which, in contrast to the isospin symmetry, is strongly violated. Gell-Mann and the Japanese theorist Okubo succeeded in describing the symmetry breaking in a simple way that led to formulae relating the masses of particles within each octet or decimet.

The negatively charged omega particle had not been seen in experiments when Gell-Mann predicted the existence of the particle and its mass and the search for it started. In 1964, it was found at the Brookhaven National Laboratory (BNL) in the United States. The mass of 1672 MeV corresponded accurately to the value predicted by Gell-Mann. The discovery of the ω particle was a triumph for the $SU(3)$ symmetry and was a factor in the award of the Nobel Prize to Gell-Mann in 1969.

Gell-Mann described the electromagnetic and weak interactions of the hadrons by the

electromagnetic and weak currents, which could be classified in terms of the $SU(3)$ symmetry. He proposed that the commutators of these currents at equal times had simple properties, given by a current algebra. The predictions that could be derived from the current algebra agreed with experimental results.

The $SU(3)$ symmetry had a strange feature. The observed particles could be classified into octets or decimets, but the simplest representation, the triplet, was not observed. Gell-Mann and also his student George Zweig, who worked in 1964 at CERN in Geneva, noticed that the baryon octets and decimet could be constructed by multiplying three triplet representations. Likewise the meson octet could be constructed by multiplying a triplet by an antitriplet. The electric charges of these triplet objects, derivable from the electric charges of the observed particles, came out to be $2/3$ and $-1/3$. Thus the triplet objects could not be known, directly observable particles, which have integral charges. In this sense the triplet particles were not “real.” They could be described as confined inside known particles, with three of them, roughly speaking, constituting a neutron or proton.

Gell-Mann published a short letter in *Physics Letters* with the title “A Schematic Model of Baryons and Mesons.” He called the triplets quarks. The three objects were named u (for up), d (for down) and s (for strange). They were assumed to be fermions with spin $1/2$. The proton had the structure (uud) , the neutron (udd) . The strange particles contained one, two or three s -quarks corresponding to strangeness -1 , -2 , and -3 respectively. The λ baryon had the structure (uds) . The ω particle consisted of three s -quarks: (sss) . In his paper in *Physics Letters* Gell-Mann also mentioned a quark–gluon field theory, analogous to quantum electrodynamics, as a model for a possible theory of the strong interactions.

In 1968, the scaling behavior of the cross section for electron–proton scattering was discovered. Richard Feynman speculated that inside the proton were pointlike objects, which he called partons. Gell-Mann and his German collaborator Harald Fritzsch instead worked out a generalization of the current algebra to lightlike distances, the light-cone current algebra. They assumed that the commutators of the currents could be abstracted approximately from the free quark model at large momentum transfers. In that case they could derive the observed scaling behavior. The partons were, of course, quarks, antiquarks, and gluons behaving more or less like free particles at large momentum transfers.

The hypothesis of the quarks had a problem, which can be seen, for example, by considering the omega particle with the structure (sss) . The spin wave function of the state is completely symmetric in the three s -quarks. Since these s -quarks are in the ground state, the space wave function must also be symmetric. This violates the Pauli principle, which states that under the exchange of two fermions the wave function must be antisymmetric.

In 1971, Gell-Mann proposed, together with William Bardeen and Harald Fritzsch, that the quarks have a new, exactly conserved quantum number, which they called color. Each quark has an index, running from 1 to 3. The transformations among these indices lead to a new symmetry group, the color group $SU(3)$. The observed hadrons have to be singlets under this color symmetry. This implies that the wave function of a baryon is totally antisymmetric with respect to the color indices of the quarks, and the Pauli principle is not

violated. Bardeen, Fritzsch, and Gell-Mann showed that the electromagnetic decay rate of the neutral π meson is correctly described by the color scheme, but that if one were to leave out the color index in the quark picture, the theoretical decay rate would disagree with the experimental result by a factor of 9. The quarks are color triplets. The assumption that the observable hadrons are color singlets requires that the quarks be permanently confined inside the hadrons.

In 1972, Fritzsch and Gell-Mann (as well as Gross and Wilczek) constructed a new field theory of the quarks. They postulated that the color group $SU(3)$ is a gauge group, which yields a Yang–Mills theory of the quarks, interacting through massless vector gluons. Fritzsch, Gell-Mann, and Heinrich Leutwyler discussed in 1973 several interesting properties of such a theory in a paper in *Physics Letters* with the title: *Advantages of the Color Octet Gluon Picture*. Fritzsch and Gell-Mann later named this theory “Quantum Chromodynamics” (QCD).

The QCD theory has the property that it is asymptotically free, as emphasized by Gross and Wilczek and by Politzer. This means that the effective coupling constant describing the interaction of the quarks and gluons gets smaller at small distances. Thus the quarks behave as nearly pointlike particles in the lepton–hadron scattering at very high momentum transfers, and the observed scaling behavior follows from that. At small momentum transfers or large distances the interaction becomes strong, and the confinement of the quarks and gluons is a consequence.

Gell-Mann strongly supported the emerging string theory in particle physics. He thought that superstring theory might lead to a theory of all particles and forces.

Together with James Hartle, Gell-Mann has been working for some years on the interpretation of quantum mechanics, especially in the light of quantum cosmology. They have nearly completed their project, which emphasizes decoherent alternative coarse-grained histories of the universe, and the result is a view of quantum mechanics in which there is little “weirdness” and a greatly reduced role for a human observer. The universe “measures” itself.

Gell-Mann is interested in many areas outside physics, e.g. in problems of historical linguistics and in policy studies of sustainability. He is also an active bird watcher. For many years he worked as a director of the J. D. and C. T. MacArthur Foundation, where he supported initiatives to improve the preservation of biological diversity, to foster peace and international cooperation, and to promote scientific work relevant to mental health and human development.

The physics research of Murray Gell-Mann contributed greatly to the successful Standard Model of particle physics. The development of the Standard Model was the main result of fundamental physics in the second part of the 20th century.

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