The idea of elements

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Elements

The complexity of the material world required the notion that things are built of other things. Many cultures have notions of one, two, three, four or five elements.

Modern notions distinguish different levels of structure. The lowest level known at any time is called elementary.

Today's theory of the elements of matter is called the Standard Model of particle physics. It is based on a few particles and their properties and interactions captured within a relativistic quantum field theory. Murray Gell-Mann's contributions are part of its foundations.

Atoms: from elementary to complex

- In 1661 Boyle postulated corpuscles as leading to the properties of gases. (Reality of atoms proven by Einstein's work on diffusion in 1905).
- In 1789 Lavoisier recognized the modern notion of chemical elements. Notion of molecules and atoms slowly clarified. Berzelius reported extensive determination of atomic weights A, in 1818.
- In 1869 Dimitri Mendeleev classifies elements into periods by A. More successful than earlier attempts, including an attempt by Meyer to classify by valence (1864).
- In 1897 Thomson discovered the electron: charged particles with negligible mass in atomic units. In 1911 Rutherford discovered the atomic nucleus. In 1912 Thomson found isotopes. In 1913 Bohr made the first quantum mechanical model of the atom as a composite system.

Nuclei: not quite elementary

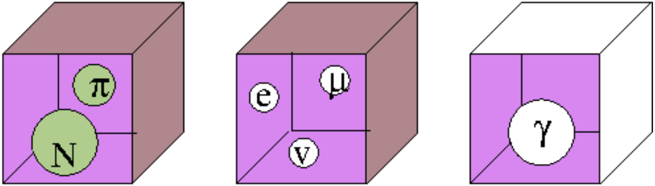
- In 1911 Rutherford (Geiger, Marsden) discovered that the atomic nucleus was nearly point like in units of atomic dimensions, and postulated that its charge was half of the atomic weight A.
- In 1911 van den Broek postulated that the charge of the nucleus Z was independent of A and was exactly correlated with the position of an element in the periodic table. Values of Z for many elements was inferred by Moseley from x-ray spectroscopy.
- The nucleus of H contained a single proton. The masses of heavier nuclei then suggested the existence of neutrons (discovered eventually in 1932 by Chadwick). The difference in masses of isotopes could be explained in terms of the number of neutrons.

The nearly strong interactions

- In 1932 Heisenberg introduced the notion of isotopic spin I. His picture was that the neutron and proton were two different quantum states of the same particle. The charge of each state of the the nucleon was given by $Z = 1/2 + I_3$.
- Yukawa hypothesized that the interactions between nucleons (then called the strong interaction) was due to a particle. This particle was identified in 1947 (Powell and Occhialini). Soon it was found that there are three charge states of the pion: π^+, π^-, and π^0. The relation between charge and isospin here was $Z = I_3$.
- Pais introduced the notion of a baryon number B. This was 1 for the nucleon and 0 for mesons. The general formula for charge was therefore $Z = B/2 + I_3$.
- Another part of the story began to unfold with the discovery of neutrinos (in the decay of the $I_3 = -1/2$ state of the nucleon to the $I_3 = +1/2$ state), and the discovery of the muon.

The new elements

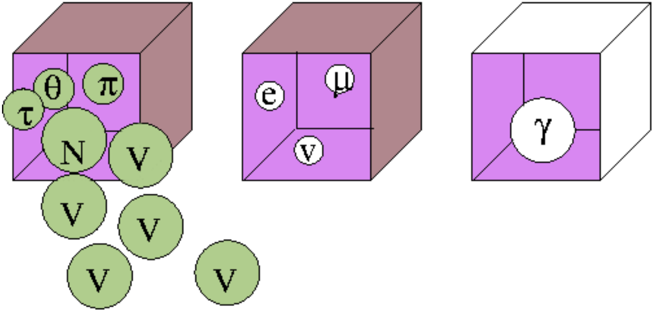
At the beginning of the 1950s a great simplification seemed to have occurred. Over a hundred chemical elements had been reduced to simpler and more elementary particles.



All particles have electromagnetic interactions, particles in brown boxes have weak interactions (leptons), coloured particles have strong interactions (baryons and mesons).

The study of nuclei was therefore deemed important in order to understand the strong interactions.

Proliferation!



Cosmic ray experiments gave evidence of five new unstable baryons (all then called V) and two unstable mesons (originally called τ and, later, τ and θ). What happens to the simple classification? Did they have anything to do with the unstable μ?

Pais suggested that the new particles have an "orbital isotopic angular momentum" and "isotopic parity".

Enter Gell-Mann

Odd properties of new particles

Gell-Mann suggested that I_3 remains conserved even in this extended scheme and generalized the Pauli principle to say that the wave-function of these particles is anti/symmetric in space, spin and isospace. This could rule out certain processes.
Phys. Rev. 92, 833 (1952)

Gell-Mann and Pais argued that θ^0 and $\overline{\theta}^0$ do not mix under strong interactions, since they are always produced in pairs (associated production). So they must be considered distinct under charge conjugation **C**. So θ must be represented by complex fields. However, under weak interactions they can mix, and so one can decay into another. As a result, the eigenstates of **C** must be physically distinct, with different lifetimes and masses. They suggested new decay modes based on this argument.
Phys. Rev. 97, 1387 (1955)

Strangeness

Gell-Mann proposed a new quantum number such that

$$Z = \frac{B}{2} + I_3 + \frac{S}{2},$$

where S$=0$ for "ordinary" particles, *i.e.*, nucleon and pion, but S$\neq 0$ for "strange" particles such as hyperons and "K-particles". Also, since Z, I_3, and B change sign under **C** (charge conjugation), so must S.
(Footnote: "It should be emphasized that the conservation of strangeness is nothing but the conservation of I_z restated in a more convenient form.)
Nuovo Cim. 4 848 (1956) and unpublished preprint of August 1953
Gell-Mann and Pais, Proceedings of Glasgow Conference, 1954.

Attributes the term "associated production" to M.G.K. Menon.

Japanese development

Nishijima proposed an η-charge such that

$$Z = \frac{B}{2} + I_3 + \frac{\eta}{2}.$$

Net result: strong interactions independent of charge, and conserve η. Weak interactions change η. Suggests one resolution of the τ–θ puzzle (equivalent to Gell-Mann-Pais).
Prog. Theor. Phys. 13, 285 (1955) received February, published March (Thanks Pais for a copy of the proceedings of the Glasgow conference)

Sakata proposed that all particles are made of N and Λ^0. Then $\pi = \overline{N}N$, $\theta = N\overline{\Lambda}^0$, $\overline{\theta} = \overline{N}\Lambda^0$. Also, $\Sigma = \overline{N}N\Lambda^0$ and $\Xi = \overline{N}\Lambda^0\Lambda^0$.
Prog. Theor. Phys. 16, 686 (1956) (Report of talk in October 1955)

The eightfold way

Generalized the Sakata model by analyzing the structure of the symmetry groups which generate currents. Found that if one neglects mass differences then the symmetry group is SU(3). Studied representations of this group (introduced generators which are today called Gell-Mann matrices).

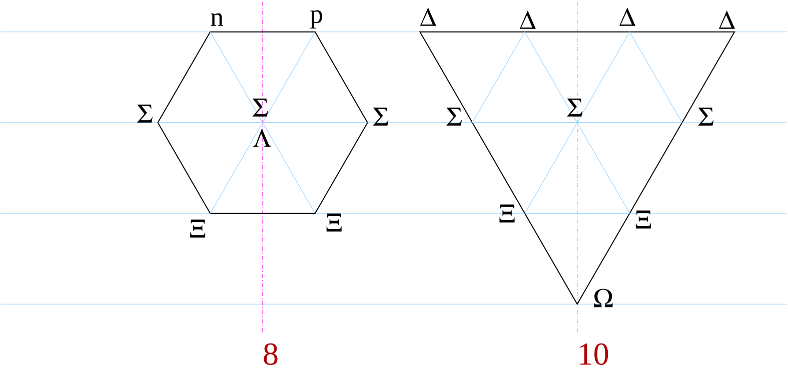
Introduced a three dimensional representation of particles b, which he called **3**. Antiparticles $\overline{b}$ belong to a representation $\mathbf{3}^*$ (not related by an unitary transformation). Mesons are formed by pairs $\overline{b}b$, and belong to the representations $\mathbf{3} \times \mathbf{3}^* = \mathbf{8} + \mathbf{1}$.
Baryons remained a problem, since $\mathbf{3} \times \mathbf{3} \times \mathbf{3}^* = \mathbf{3} + \mathbf{3} + \mathbf{6} + \mathbf{15}$, and one could not fit the known baryons, N, Λ^0, Σ, and Ξ, into these multiplets.
Phys. Rev. 125, 1067 (1962) Acknowledges Ne'eman's work in Nucl. Phys. 26, 222 (1961)

New baryons and their representations

Lot of work on alternative groups and representation theory.
for example: Rev. Mod. Phys. 34, 3 (1962).

Glashow and Sakurai predicted a **27**-plet of baryons with spin $3/2$ based on the eightfold way. Many states not seen; "predicted" them.
Nuovo Cim. 25, 337 (1962)
Huge effort to find more particles: many predicted by Sakata model and eightfold way. After some more discoveries, Glashow and Sakurai arranged the the spin $3/2$ baryons into a **10**: pure phenomenology.
Nuovo Cim. 26, 622 (1962)
Samios and group published the observation of a single bubble chamber event of a S$= -3$ baryon which they called Ω^- (after Gell-Mann).
Phys. Rev. Lett. 12, 204 (1964)

The **8** and **10** of Baryons



Periodic table: the vertical line corresponds to $I_3 = 0$. The horizontal lines to different S, from 0 on top to -3 at the bottom.

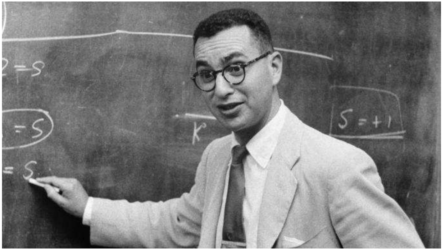
Quarks

Gell-Mann's proposal of quarks had been talked about since 1962. Samios refers to a talk given in CERN in 1962 where the Ω^- had been proposed. The first published reference to quarks came after the Brookhaven experiment.

Proposed the alternative that the $\mathbf{3}$ has B$= 1/3$. Then mesons are made of $\overline{q}q$ (so that $\mathbf{3}\times\mathbf{3}^* = \mathbf{8}+\mathbf{1}$). But then baryons are made of qqq so that $\mathbf{3}\times\mathbf{3}\times\mathbf{3} = \mathbf{1}+\mathbf{8}+\mathbf{8}+\mathbf{10}$. Only one $\mathbf{8}$ and the $\mathbf{10}$ appear when spins are considered.

"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)." Proposed a search for fractionally charge particles. Phys. Lett. 8, 214 (1964) (Acknowledges discussion with Serber, ascribes the word quark to James Joyce).

The Nobel Prize



The Nobel Prize in Physics 1969 is awarded to Murray Gell-Mann "for his contributions and discoveries concerning the classification of elementary particles and their interactions."

Quantum chromodynamics

Fritzsch and Gell-Mann introduced a new quantum number for quarks called colour. Quarks come in three colours (needed to get correct amplitude for π^0 decay). All baryon states are colourless, colour and fractional electric charge is never seen in experiments.

Add a colour octet of neutral vector bosons (named gluons) and make a Yang-Mills theory of interacting quarks and gluons. Discussed the kinds of observations that such a theory may support.
ICHEP Chicago, 1972

Fritzsch, Gell-Mann Leutwyler state "infrared divergencies could provide a mechanism for confining all color nonsinglets permanently". Give reasons for using octet gluons (connection to parton model made using renormalization group equations of Gell-Mann and Low).
Phys. Lett. 47 B, 365 (1973)