Murray Gell-Mann (1929–2019) and the Story of Strong Interactions*

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Murray Gell-Mann, who passed away at the age of 90 years was a giant of modern particle physics. His most well-known contribution is the proposal that protons and neutrons are not indivisible but are made up of smaller particles called 'quarks'. The complete story of strong interactions of which the discovery of quarks is only a part and which is intimately connected to Gell-Mann's work is presented here in an elementary manner.

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After Ernest Rutherford discovered the proton in 1917 and James Chadwick discovered the neutron in 1932, physicists began to recognise the existence of a new force of nature called the 'strong force' that binds the protons and neutrons to form the atomic nucleus.

Sometime after the discovery of the neutron, the German physicist Werner Heisenberg introduced a concept called 'isospin symmetry' to make sense of the fact that they (proton and neutron) are so similar in many respects. This symmetry is now called the 'SU(2) symmetry' because it concerns two objects – the proton and the neutron. The mathematical object SU(2) is called a 'group'.

In 1935, the Japanese physicist Hideki Yukawa propounded a now-famous theory that the protons and neutrons were bound together inside the nucleus because they exchanged particles, later called 'mesons'. Further studies with cosmic rays confirmed the existence of these particles. They are the 'pi mesons' or 'pions'.

Keywords

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In fact, physicists began to find a variety of particles in cosmic

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rays, such as the Lambda (Λ), Sigma (Σ) and the K meson. These particles had a strange behaviour. Working independently, Kazuhiko Nishijima and Gell-Mann found in 1953 and 1956, respectively that their strange behaviour could be explained if they had a new attribute or quantum number called 'strangeness'. This explanation was encapsulated in the Gell-Mann–Nishijima formula and became an important part of particle physics.

In 1956, Shoichi Sakata and his group in Japan propounded a new idea that the proton, neutron and Lambda were fundamental particles, and all other composite particles were made of them. This idea became known as the 'SU(3) symmetry', the symmetry of three particles proton, neutron and Lambda.

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It was at this juncture, in 1961, that Gell-Mann's most influential contribution to the study of fundamental properties of matter arrived.

Gell-Mann noticed that apart from proton, neutron and Lambda, there existed five other particles similar to them. They are Σ^+, Σ^-, Σ^0, Ξ^0, Ξ^-. Gell-Mann and Yuval Neeman independently proposed that these eight particles together formed a family under SU(3). Gell-Mann called it the 'eightfold way' (taking the name from Buddhist scriptures).

Eightfold way became highly successful. Using this concept, Gell-Mann predicted the existence of another particle Ω^-. It was later discovered in 1964, and that cemented the validity of the eightfold way.

The mathematics of SU(3) group symmetry strongly suggested the existence of three particles which forms a triplet under the SU(3) group.

At this point, I would like to describe what I call the 'Bangalore event'.

In August 1961, the first summer school in theoretical physics of the Tata Institute of Fundamental Research (TIFR) was held at the Indian Institute of Science, Bangalore. The lecturers were Gell-Mann and Richard Dalitz, and the audience included Homi

Bhabha, M G K Menon, Yash Pal and other physicists and graduate students.

Gell-Mann lectured on SU(3) symmetry and eightfold way, fresh from the anvil, even before they were published! During one of those lectures, Dalitz questioned Gell-Mann about the triplets, and why he was ignoring them. Gell-Mann managed to evade a direct response despite Dalitz's repeated questioning. If Gell-Mann had answered the question, he might have predicted the existence of a new kind of particle called 'quark' in Bangalore in 1961 instead of somewhere else three years later.

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Indeed, had any of the other Indian participants succeeded in answering Dalitz's question, we would have got the quarks, and this would have been a major Indian contribution. It was a missed opportunity.

Gell-Mann and Zweig independently proposed the idea of quarks in 1964, but it took many more years before their existence was confirmed.

Gell-Mann himself was rather tentative; the title of his published paper was, 'A schematic model of baryons and mesons' (see the Classics section for a reproduction of the paper [1]). It was in this article that Gell-Mann proposed quarks as the constituents of protons and neutrons.

Since protons and neutrons make up all the atomic nuclei, we now know that all matter is made up of quarks. To him, at that stage, quarks were only mathematical, an on-paper technique to break down a complicated problem.

Three types of quarks *u*, *d* and *s*, called *up*, *down* and *strange* replaced Sakata's proton, neutron and Lambda as fundamental particles. Proton and neutron are made of three quarks each. Pions and K mesons are composed of a quark and an anti-quark.

The principal reason Gell-Mann did not accept the reality of quarks as the constituents of hadrons was the prevalent S-Matrix philosophy. The idea that some strongly interacting particles like quarks were 'more' elementary than others was repugnant to the whole scheme of the S-Matrix theory. In fact, G F Chew, the chief proponent of the S-Matrix theory, delivered a lecture at TIFR, Mumbai in the late 1960s, where he claimed he could prove that because of relativity and quantum mechanics, no particle more elementary than proton or neutron was possible.

But in spite of this quark-phobia, a few bold souls took the idea seriously and worked out the consequences. They included A N Mitra, G Morpurgo and Dalitz.

Dalitz in particular, perhaps as a response to the Bangalore event, began working on the quark idea. He surprised everyone at the Rochester Conference in 1966 when he claimed that all the properties of the hadrons came out correctly if one assumed that they were made of quarks. Nonetheless, although these calculations provided compelling evidence for their correctness, there was no clinching evidence for quarks yet.

In the meantime, Gell-Mann was making steady progress on his programme to exploit the mathematical quarks to glean more information about strong interactions, through what he called 'current algebra'.

Quarks eventually became 'real' after two important experimental discoveries. The first was the use of high-energy electrons at the Stanford Linear Accelerator Center to probe the internal structure of protons in the late 1960s, and the second was the discovery of the psi particle, with an extraordinarily long lifetime of decay.

Quarks eventually became 'real' after two important experimental discoveries. The first was when, in the late 1960s, high-energy electrons were used at the Stanford Linear Accelerator Center (SLAC) to probe the internal structure of protons. We will say more about it later. The second was the discovery of the psi particle, which had an extraordinarily long lifetime of decay. It was as if anthropologists stumbled upon a group of humans living for 10,000 years in some remote corner of the world!

This puzzle was solved by the invention of a new quark *c* with a new quantum number *charm*. Most sceptics started believing in quarks after these developments. The success of the quark model has a parallel in the history of atoms.

Sceptics like Ernest Mach, Wilhelm Ostwald and others did not believe in the reality of atoms, while Ludwig Boltzmann waged a heroic battle against their conservative notions. He emerged triumphant after Jean-Baptise Perrin experimentally verified Einstein's formula for Brownian motion, which was based on the idea that atoms and molecules exist.

How were the quarks made visible? In the SLAC experiments, protons were bombarded with very high-energy electrons, and some of the electrons rebounded since they struck point particles inside the proton. These point particles were identified as quarks.

This Stanford experiment was very similar to Rutherford's experiment in 1911. He shot alpha particles at gold atoms, and some of the alpha particles bounced back since they struck point nuclei inside the atoms. That's how the atomic nucleus was discovered.

Further, the Stanford experiments showed that as seen by the high-energy electrons, quarks inside the proton behaved like non-interacting free particles. This was called 'asymptotic freedom'. Soon, the theory which had the asymptotic freedom was identified as the theory of gluons based on a new quantum number called 'colour'.

Gell-Mann along with Harald Fritzch and Heinrich Leutwyler proposed this as the 'theory of strong interactions'. Quarks interact by exchanging gluons just as electrons interact by exchanging photons. This is a generalisation of electrodynamics and is called 'chromodynamics'. Gell-Mann had a knack for coining new words: *strangeness*, *quark*, *colour* and *chromodynamics* were all coined by him.

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Including the charmed quark, there were four quarks: u, d, s and c. Two more quarks were discovered later: t and b; t was discovered only in 1995. Therefore, we have six quarks in total and their anti-particles. A summary of the composition of different particles in terms of quarks is given in *Table* 1.

One would have thought that the physics of strong interactions was complete. But, not really. There was another problem. If you smash an atom with high-energy particles, electrons pop out. If you smash a nucleus, protons and neutrons pop out. But if you smash a proton, quarks don't pop out. This is because quarks are

Table 1. The quark composition of the strongly interacting particles. u, d, s, c are quarks and $\bar{u}$, $\bar{d}$, $\bar{s}$ and $\bar{c}$ are anti-quarks.

Proton	p	uud
Neutron	n	ddu
Pi mesons	π^+	$u\bar{d}$
	π^0	$u\bar{u}, d\bar{d}$
	π^-	$d\bar{u}$
K mesons	K^+	$u\bar{s}$
	K^0	$d\bar{s}$
	K^-	$s\bar{u}$
	$\bar{K}^0$	$s\bar{d}$
Hyperons	Λ	$(ud - du)s$
	Σ^+	uus
	Σ^0	$(ud + du)s$
	Σ^-	dds
	Ξ^0	uss
	Ξ^-	dss
	Ω^-	sss
Psi mesons	ψ	$c\bar{c}$

said to be permanently confined within a volume of space, the size of the proton. Physicists believe that this confinement is a consequence of chromodynamics, but is yet to be proven. Many of the world's brightest minds and biggest computers are working on it but the answer remains elusive till date.

Gell-Mann was awarded the Nobel Prize for Physics in 1969. From 1955 to 1999, he was working at the California Institute of Technology. In his later years, he devoted himself to studies of complexity theory at the Santa Fe Institute, which he had co-founded along with other scientists in 1984.

Note: An earlier version of this article was published in *The Wire*.

Suggested Reading

[1] Murray Gell-Mann, A Schematic Model of Baryons and Mesons, *Phys.Lett.*, Vol.8, No.3, pp.214–215, 1964.

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