New for 2025?

(rev 2025)
(but not presented)

Quark model

- ∃ many other supermultiplets (see table)
- can't all be elementary ??
- prop. composite states, [illegible] for elts are made of p, n, + composite can be in an excited state

[To explain the observed patterns of hadrons (baryons & mesons), in 1964]

1964 Murray Gell-Mann and George Zweig independently proposed the existence of 3 types (flavors) of spin-$\frac{1}{2}$ particles from which hadrons are composed

Zweig called them "aces"
Gell-Mann called them "quarks"

		inferred!	
u	up	~2 MeV	} isodoublet
d	down	~5 MeV	
s	strange	~100 MeV	} isosinglet

[Finnegan's Wake: "three quarks for Muster Mark"]

Later there would be other flavors

Baryons consist of various combinations of 3 quarks

⇒ Quarks have $A = \frac{1}{3}$

⇒ baryon # conserved = quark # conserved

Q

FINNEGANS WAKE

James Joyce

New York: The Viking Press

1939

riverrun, past Eve and Adam's, from swerve of shore to bend of bay, brings us by a commodius vicus of recirculation back to Howth Castle and Environs.

Sir Tristram, violer d'amores, fr'over the short sea, had passencore rearrived from North Armorica on this side the scraggy isthmus of Europe Minor to wielderfight his penisolate war: nor had topsawyer's rocks by the stream Oconee exaggerated themselse to Laurens County's gorgios while they went doublin their mumper all the time: nor avoice from afire bellowsed mishe mishe to tauftauf thuartpeatrick: not yet, though venissoon after, had a kidscad buttended a bland old isaac: not yet, though all's fair in vanessy, were sosie sesthers wroth with twone nathandjoe. Rot a peck of pa's malt had Jhem or Shen brewed by arclight and rory end to the regginbrow was to be seen ringsome on the aquaface.

The fall (bababadalgharaghtakamminarronnkonnbronntonnerronntuonnthunntrovarrhounawnskawntoohoohoordenenthurnuk!) of a once wallstrait oldparr is retaled early in bed and later on life down through all christian minstrelsy. The great fall of the offwall entailed at such short notice the pftjschute of Finnegan, erse solid man, that the humptyhillhead of humself prumptly sends an unquiring one well to the west in quest of his tumptytumtoes: and their upturnpikepointandplace is at the knock out in the park where oranges have been laid to rust upon the green since devlinsfirst loved livvy.

— 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.
But O, Wreneagle Almighty, wouldn't un be a sky of a lark
To see that old buzzard whooping about for uns shirt in the dark
And he hunting round for uns speckled trousers around by Palmerstown Park?
Hohohoho, moulty Mark!
You're the rummest old rooster ever flopped out of a Noah's ark
And you think you're cock of the wark.
Fowls, up! Tristy's the spry young spark
That'll tread her and wed her and bed her and red her
Without ever winking the tail of a feather
And that's how that chap's going to make his money and mark!

Overhoved, shrillgleescreaming. That song sang seaswans. The winging ones. Seahawk, seagull, curlew and plover, kestrel and capercallzie. All the birds of the sea they trolled out rightbold when they smacked the big kuss of Trustan with Usolde.

And there they were too, when it was dark, whilest the wildcaps was circling, as slow their ship, the winds aslight, upborne the fates, the wardorse moved, by courtesy of Mr Deaubaleau Downbellow Kaempersally, listening in, as hard as they could, in Dubbeldorp, the donker, by the tourneyold of the wattarfalls, with their vuoxens and they kemin in so hattajocky (only a

sad and weary I go back to you, my cold father, my cold mad father, my cold mad feary father, till the near sight of the mere size of him, the moyles and moyles of it, moananoaning, makes me seasilt saltsick and I rush, my only, into your arms. I see them rising! Save me from those therrble prongs! Two more. Onetwo moremens more. So. Avelaval. My leaves have drifted from me. All. But one clings still. I'll bear it on me. To remind me of. Lff! So soft this morning ours. Yes. Carry me along, taddy, like you done through the toy fair. If I seen him bearing down on me now under whitespread wings like he'd come from Arkangels, I sink I'd die down over his feet, humbly dumbly, only to washup. Yes, tid. There's where. First. We pass through gràss behush the bush to. Whish! A gull. Gulls. Far calls. Coming, far! End here. Us then. Finn, again! Take. Bussoftlhee, mememormee! Till thousendsthee. Lps. The keys to. Given! A way a lone a last a loved a long the

PARIS,
1922-1939.

Charles Sommerfield, Murray Gell-Mann and Barton Zwiebach

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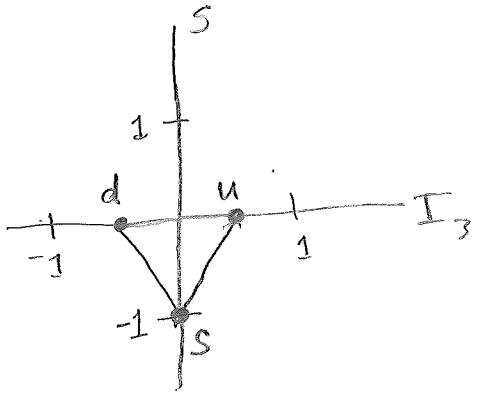
Flavor quantum numbers

- strangeness S
- Isospin I_3

s quark has property of strangeness. $S = -1$

u + d quarks have isospin $I_3 = \pm \frac{1}{2}$

weight diagram



	A	S	I_3	$q = \frac{1}{2}(A+S) + I_3$
u	1/3	0	1/2	2/3
d	1/3	0	-1/2	-1/3
s	1/3	-1	0	-1/3

Gell-Mann Nishijima formula for electric charge

$$q = \frac{1}{2}(A + S) + I_3$$

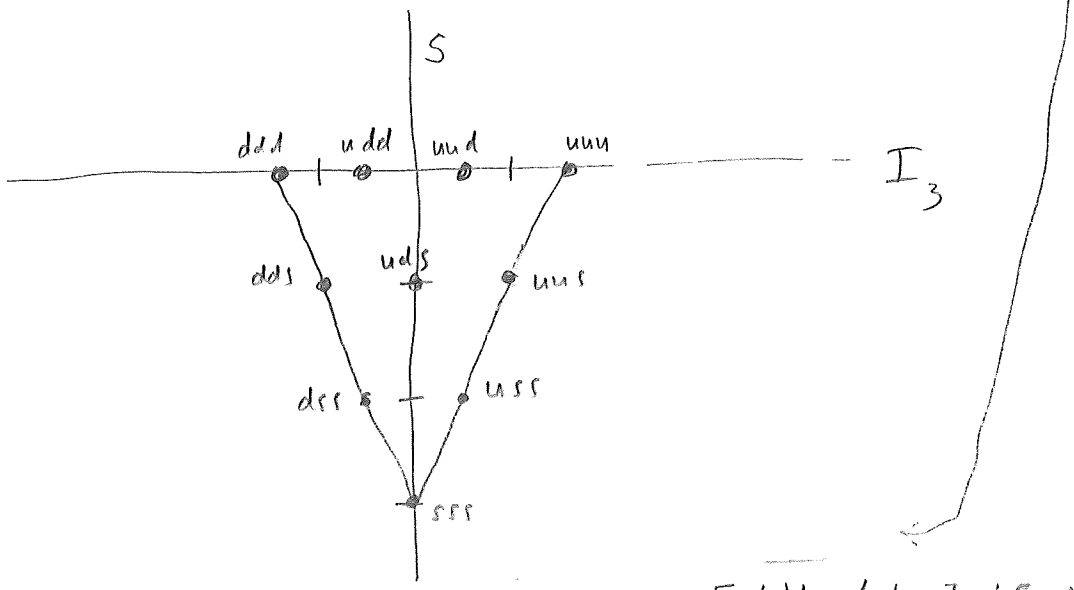
obeyed by quarks & any particle composed of quarks ——→

Fractional charge never observed in isolation ⇒ confinement postulate

↳ deep inelastic in 1960's, until observed in deep inelastic scattering SLAC

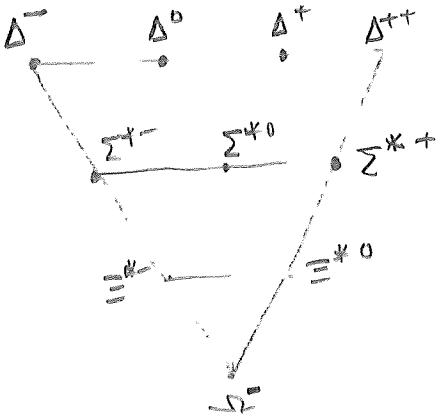
Baryons consist of 3 quarks. Can have spin $\frac{3}{2}$ or spin $\frac{1}{2}$.

All combinations of 3 u, d, s quark



This matches the pattern of [don't include I_3 + S axes]

Spin-$\frac{3}{2}$ baryon decuplet ($\underset{\sim}{10}$)



The masses of hadrons depend on kinetic energy of quarks & their strong interactions & orientations (spin)

The mass <u>difference</u> between n & p due to mass of strange quark

All particles in the $\underset{\sim}{10}$ decay strongly ($\tau \sim 10^{-23}$ s)

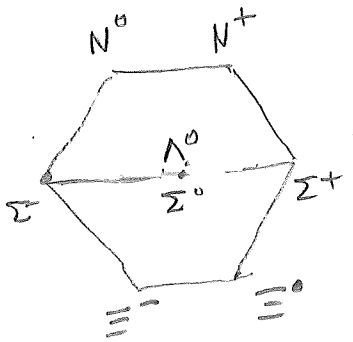
except the Ω^-, which decays weakly ($\tau \sim 10^{-10}$ s)

~~[explain later]~~

↳ HW problem later!

Quark model also describes [don't draw axes]

spin-$\frac{1}{2}$ baryon octet ($\underset{\sim}{8}$)



940 MeV

1115 MeV
1190 MeV

1315 MeV

nucleons

$N^+ = p$

$N^0 = n$

Again, mass differences due to strange quark (not quite so much)

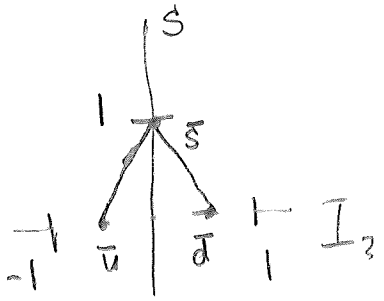
- ~~[illegible]~~ There are no spin-$\frac{1}{2}$ baryons corresponding to the corners of the triangle (uuu, ddd, sss) because violates antisymmetry of the baryon wave function

$p = N^+$ is stable (so far!)

All other particles in the $\underset{\sim}{8}$ decay weakly [discuss later]

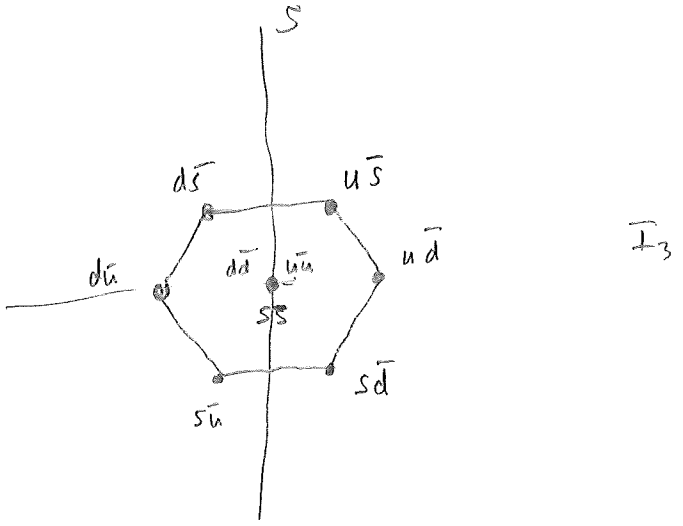
There are other patterns of baryon decuplets & octets of high mass

Antiquarks have opposite flavor quantum numbers as quarks



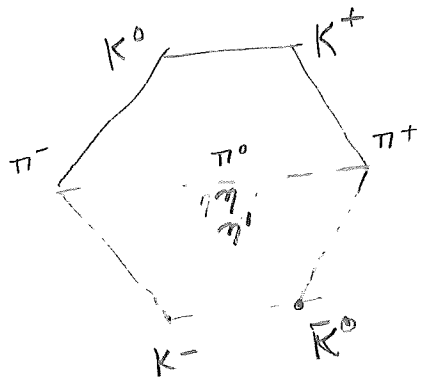
Antibaryons are composed of three antiquarks.

Mesons consist of all possible pairs of a quark & antiquark (9 possibilities)



Two spin $\frac{1}{2}$ particles can have either spin 1 or spin 0

Spin 0 (scalar) meson nonet (8_S)



495 MeV

140 MeV
548 MeV
958 MeV

495 MeV

$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$

$\eta = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$

$\eta' = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$

} admixture of strange quark partially accounts for higher mass

Again, mass not quite as simple.

All particles in scalar nonet decay weakly (or electromagnetically) [last]
except η, η' which can also decay strongly

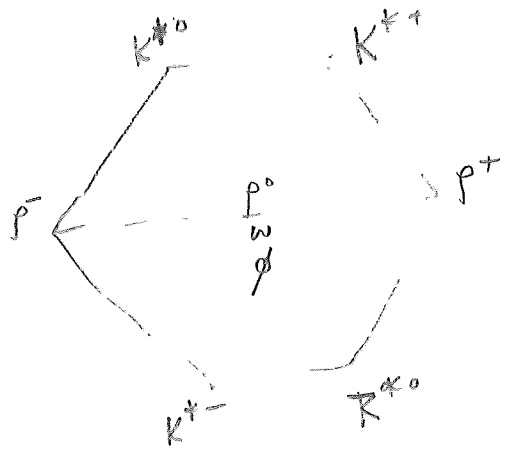
[isospin $u = |\frac{1}{2}\rangle$, $-\bar{d} = |\frac{1}{2}\rangle$ $\quad |1,1\rangle = |\frac{1}{2},\frac{1}{2}\rangle = -u\bar{d}$

$d = |-\frac{1}{2}\rangle$, $\bar{u} = |-\frac{1}{2}\rangle$ $\quad |1,0\rangle = \frac{1}{\sqrt{2}}\left(|\frac{1}{2},-\frac{1}{2}\rangle + |-\frac{1}{2},\frac{1}{2}\rangle\right) = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$

$\therefore |1,-1\rangle = |-\frac{1}{2},-\frac{1}{2}\rangle = d\bar{u}$]

The quark-antiquark pairs making the pattern of

Spin 1 (vector) meson nonet



892 MeV

770 MeV
782 MeV
1020 MeV

892 MeV

[Note: use 892 for K^* to agree w/ PDB]

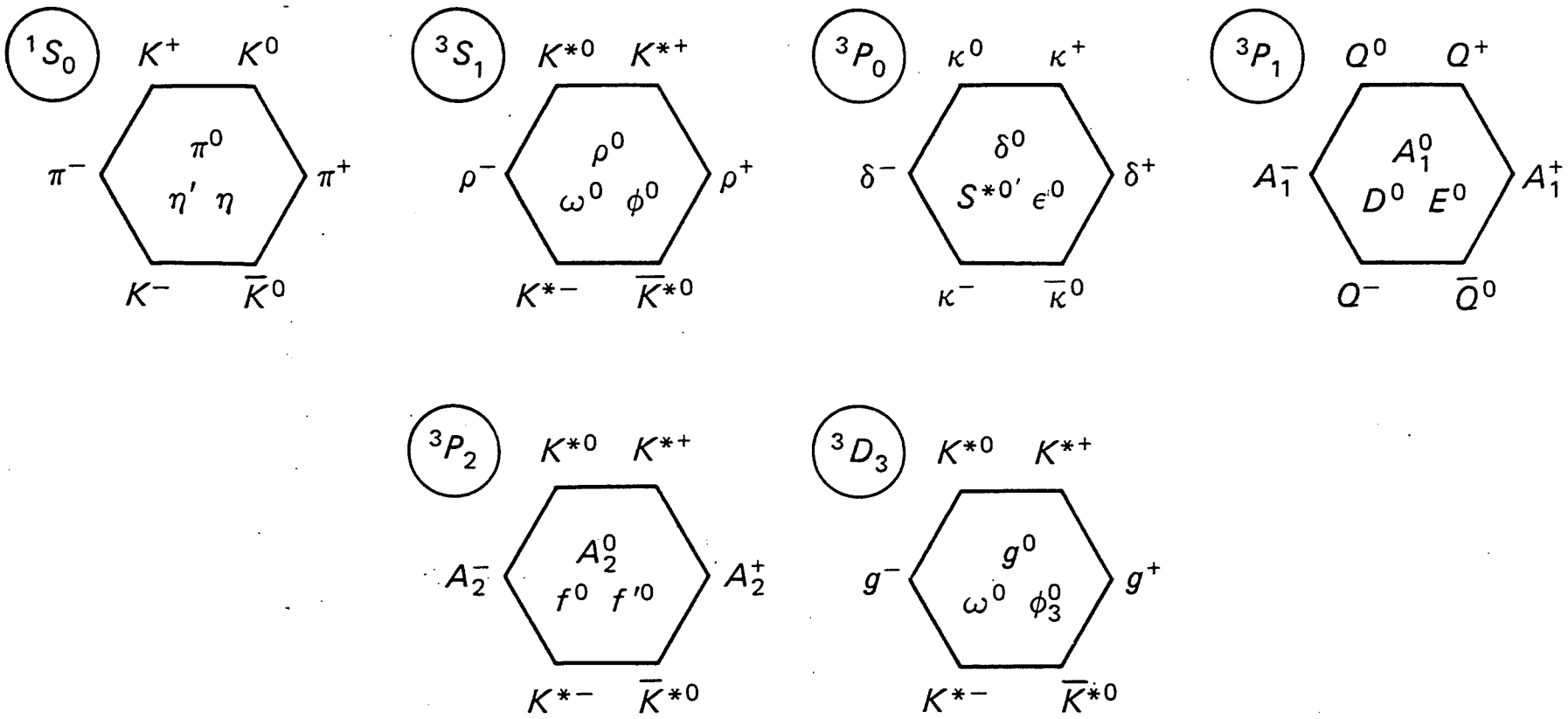
$\rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$

$\omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ → so $m_\omega \approx m_\rho$

$\phi : s\bar{s}$

Again mass difference nicely explained by $m_s \sim 100$ MeV

- All particle in vector nonet decay strongly into spin 0 mesons, which also fall into a nonet


$^1S_0$
K^+ K^0
π^- π^0 η' η π^+
K^- $\overline{K}^0$
$^3S_1$
K^{*0} K^{*+}
ρ^- ρ^0 ω^0 ϕ^0 ρ^+
K^{*-} $\overline{K}^{*0}$
$^3P_0$
κ^0 κ^+
δ^- δ^0 $S^{*0'}$ ϵ^0 δ^+
κ^- $\overline{\kappa}^0$
$^3P_1$
Q^0 Q^+
A_1^- A_1^0 D^0 E^0 A_1^+
Q^- $\overline{Q}^0$
$^3P_2$
K^{*0} K^{*+}
A_2^- A_2^0 f^0 f'^0 A_2^+
K^{*-} $\overline{K}^{*0}$
$^3D_3$
K^{*0} K^{*+}
g^- g^0 ω^0 ϕ_3^0 g^+
K^{*-} $\overline{K}^{*0}$