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### What are we made out of? Standard Model

**QUARKS**

1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	
u (2.3 M)	c (1.27 G)	t (173.1 G)	
d (4.8 M)	s (95 M)	b (4.2 G)	g (8.3 G)

**LEPTONS**

e (0.511 M)	μ (105.7 M)	τ (1.78 G)	γ (0)
ν <sub>e</sub> (0)	ν <sub>μ</sub> (0)	ν <sub>τ</sub> (0)	W (80.4 G)
			Z (91.2 G)

**FERMIONS**      **GAUGE BOSONS**

Structure within the Atom: Quark (Size ~ 10<sup>-16</sup> m), Nucleus (Size ~ 10<sup>-14</sup> m), Atom (Size ~ 10<sup>-10</sup> m)

How small are they?

Wavelength (m): 10<sup>-2</sup> m, 10<sup>-6</sup> m, 10<sup>-9</sup> m

Micrograph of a nanowire curled into a loop in front of a strand of human hair (10<sup>-2</sup> m), Molecules of DNA (10<sup>-9</sup> m), atom (~10<sup>-8</sup> cm), nucleus (~10<sup>-12</sup> cm), quark (~10<sup>-16</sup> cm), electron (<10<sup>-16</sup> cm), proton (neutron) (~10<sup>-15</sup> cm)

A line of billion protons will be approximately the size of the diameter of a hair!!!!

### Ground state Baryons

When the configuration of three quarks have minimum energy, we call it "ground state"

We need more **quantum numbers** (labels which can have certain values) to specify baryon states

**Octet (8) Spin 1/2**      **Decuplet (10) Spin 3/2**

**SU(3) Flavor Multiplets**

Charge (Q), Isospin projection (I<sub>3</sub>), Strangeness (S)

### Baryon Masses

$$M_B = \frac{1}{\xi} N_c M_0 + \xi \frac{C_{HF}}{N_c} \hat{S}^2 + \xi \frac{C_1}{2} N_c \chi_+^0 + \left( \frac{\delta \Sigma^F - \xi^2 [\mu_1 \tilde{\chi}_+ + \delta \mu_1 \tilde{\chi}_+ + \frac{\delta C_{HF}}{N_c} \hat{S}^2 + \frac{\delta C_1}{2} \chi_+^0] - \xi^3 [\frac{\mu_2^2}{N_c} \chi_+^0 \hat{S}^2 + \frac{\mu_2}{N_c} \tilde{\chi}_+ \hat{S}^2 + \frac{\mu_3}{N_c} \tilde{\chi}_+^a S^i G^{ia}]}{1 - \xi \delta Z^F + \xi (\frac{w_1}{N_c} + \frac{w_2}{N_c} \hat{S}^2 + z_0 N_c \chi_+^0)} \right)$$

Where,  $\delta Z = \frac{\partial}{\partial p^0} \delta \Sigma$

Mapping the coefficients with their **natural sizes** (in MeV)

M <sub>0</sub>	C <sub>HF</sub>	C <sub>1</sub>	μ <sub>1</sub>	δμ <sub>1</sub>	δC <sub>HF</sub>	δC <sub>1</sub>	w <sub>1</sub>	w <sub>2</sub>	z <sub>0</sub>	μ <sub>2</sub> <sup>0</sup>	μ <sub>2</sub>	μ <sub>3</sub>
c[1]	c[2]	c[4]	c[3]	c[5]	c[6]	c[7]	c[8]	c[9]	c[10]	c[11]	c[12]	c[13]
300	300	0.002	0.002	0.002	0.002	0.002	1	1	4 × 10 <sup>-6</sup>	0.002	0.002	0.002

**Gell-Mann-Okubo (GMO) Relation**      **Equal Spacing (ES) Relation**

$$(3M_\Lambda + M_\Sigma) - (M_N + M_\Xi) = 0$$

$$M_{\Sigma^*} - M_\Delta = M_{\Xi^*} - M_{\Sigma^*} = M_\Omega - M_{\Xi^*}$$

### So, what kinds of quark combinations exist in "Nature"?

**Color**      **quantum numbers**      **flavor**

Mass: eV/c<sup>2</sup>, Charge, Spin, Name

**Mesons**      **Baryons**      **Tetra quark**      **Penta quark**

**Standard Hadrons**      **Exotic Hadrons**

### Behavior of Quarks

$$\mathcal{L}_{QCD} = \bar{\psi}_f (i \not{D} - m_f) \psi_f - \frac{1}{4} \text{tr} (GG)$$

Deep Inelastic Scattering, e<sup>+</sup>e<sup>-</sup> Annihilation, Hadron Collisions, Heavy Quarkonia

$\alpha_s(Q) \approx 0.1189 + 0.0010$

**Perturbative expansion in QCD gauge coupling is only possible at high energies**

**Asymptotic freedom!!!**

The Nobel Prize in Physics 2004: David Gross, H. David Politzer, Frank Wilczek

### Preliminary Results

M <sub>0</sub>	C <sub>HF</sub>	C <sub>1</sub>	μ <sub>1</sub>	δμ <sub>1</sub>	δC <sub>HF</sub>	δC <sub>1</sub>	w <sub>1</sub>	w <sub>2</sub>	z <sub>0</sub>	μ <sub>2</sub> <sup>0</sup>	μ <sub>2</sub>	μ <sub>3</sub>
c[1]	c[2]	c[4]	c[3]	c[5]	c[6]	c[7]	c[8]	c[9]	c[10]	c[11]	c[12]	c[13]
300	300	0.002	0.002	0.002	0.002	0.002	1	1	4 × 10 <sup>-6</sup>	0.002	0.002	0.002
318.87	247.03	0	0.00015	0	0	-0.00083	0	-1.85	6.35 × 10 <sup>-6</sup>	-0.0018	-0.00089	-0.00029

**Fitted masses with partial contributions**

χ<sup>2</sup> = 31.89, Pion mass = 139 MeV, Kaon Mass = 250 MeV

Baryon	Mass [MeV]	Fitted Mass [MeV]	δΣ <sup>F</sup>	δΣ <sup>F</sup> + ct.	C <sub>1Σ</sub>	δZ <sup>F</sup>	δZ <sup>F</sup> + ct.	C <sub>1ΣZ</sub>
N	938	931.35	-3.21	61.09	64.30	-0.96	0.40	1.36
Λ	1116	1126.05	-80.05	22.46	102.51	-0.77	0.59	1.36
Σ	1189	1192.32	-168.80	-100.79	68.01	-0.76	0.59	1.36
Ξ	1315	1308.27	-202.64	-79.16	123.47	-0.58	0.78	1.36
Δ	1228 - 50i	1227.25 - 44.93i	-72.80 - 30.33i	-18.26 - 30.33i	54.54	0.10 - 0.54i	-0.38 - 0.54i	-0.48
Σ*	1383 - 18i	1384.92 - 24.13i	-90.94 - 25.27i	174.17 - 25.27i	265.11	0.37 - 0.45i	-0.11 - 0.45i	-0.48
Ξ*	1532 - 5i	1530.4 - 4.75i	-109.48 - 15.16i	366.20 - 15.16i	475.69	0.53 - 0.27i	0.05 - 0.27i	-0.48
Ω	1672	1672.43	-128.44	557.81	686.26	0.58	0.10	-0.48
GMO	31	91.23	2.74	0	0.005	0.005	0	0
ES1	155	157.67	-18.13	192.43	210.57	0.27	0.27	0
ES2	149	145.48	-18.54	192.02	210.57	0.16	0.16	0
ES3	140	142.02	-18.95	191.61	210.57	0.05	0.05	0
ES1-ES2	6	12.18	0.41	0	0	0.11	0.11	0
ES2-ES3	9	3.45	0.41	0	0	0.11	0.11	0

**Fits to Lattice QCD masses**

### Baryons

What is a "Baryon" or "Baryon State"?

A configuration of quarks which consists of 3 quarks

Let's build some baryons

eg: Proton (uud), Neutron (udd)

Spin:  $\frac{1}{2} + \frac{1}{2} - \frac{1}{2} = \frac{1}{2}$        $-\frac{1}{2} + \frac{1}{2} + \frac{1}{2} = \frac{1}{2}$

Charge:  $+\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1$        $+\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$

has to be color "singlet"

**Colorless**

Color: Red, Blue, Green

### So, how do we solve this?

$\mathcal{L}_{QCD} = \bar{\psi}_f (i \not{D} - m_f) \psi_f - \frac{1}{4} \text{tr} (GG)$

**Effective Theories**

ChPT, HQET, Lattice QCD

Virginia's biggest and fastest supercomputer @ Jefferson Lab

$L(\text{Lagrangian}) = x^0 L_{LO} + x^1 L_{NLO} + x^2 L_{NNLO} + x^3 L_{NNNNLO} + \dots$

All of them have their own expansion parameters

Degree of freedom: Hadrons      Baryon Fields

Meson Fields

$$L_B = B^\dagger (i \not{D}_0 + g_A u^a G^{ia} - \frac{C_{HF}}{N_c} \hat{S}^2 - \frac{c_1}{2} N_c \chi_+) B$$

$$u = \exp(\frac{i \Pi}{2 F_\pi})$$

$$L_B(\xi), L_B(\xi^2), L_B(\xi^3)$$

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