AN OVERVIEW OF QUANTUM CHROMODYNAMICS

UNIVERSITY OF WASHINGTON PHYS575

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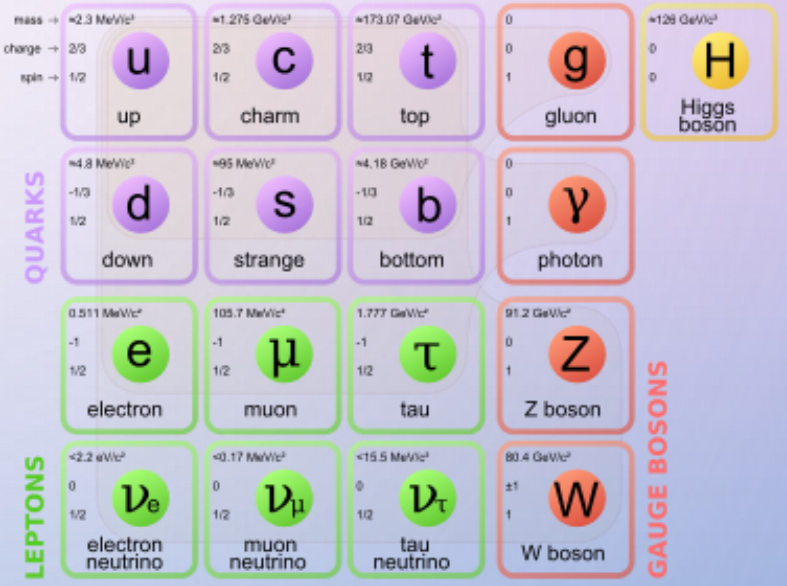
12/10/2015

AGENDA

- SOME DEFINITIONS (QCD, FUNDAMENTAL FORCES)
- SOME HISTORY (THEORY, SLAC)
- GAUGE THEORY
- FLAVORS AND COLORS
- THE STRONG INTERACTION
- COMPARISON TO QED, QUANTUM ELECTRODYNAMICS
- STRANGE PROPERTIES (CONFINEMENT, ASYMPTOTIC FREEDOM)
- QUARK DETECTION
- QUESTIONS / RESOURCES

QUANTUM CHROMODYNAMICS (QCD) IS…

- THE STUDY OF THE DYNAMICS OF COLOR-CHARGED PARTICLES AND THE STRONG INTERACTION
- A QUANTUM FIELD THEORY, GAUGE THEORY
- A MODEL FOR COLOR-CHARGED PARTICLES SUCH AS HADRONS, BARYONS, MESONS, QUARKS, AND GLUONS
- A DESCRIPTION OF HOW THE NUCLEUS IS HELD TOGETHER
- A THEORY OF THE STRONGEST FORCE OVER SMALLEST DISTANCES (FOUR FUNDAMENTAL FORCES)

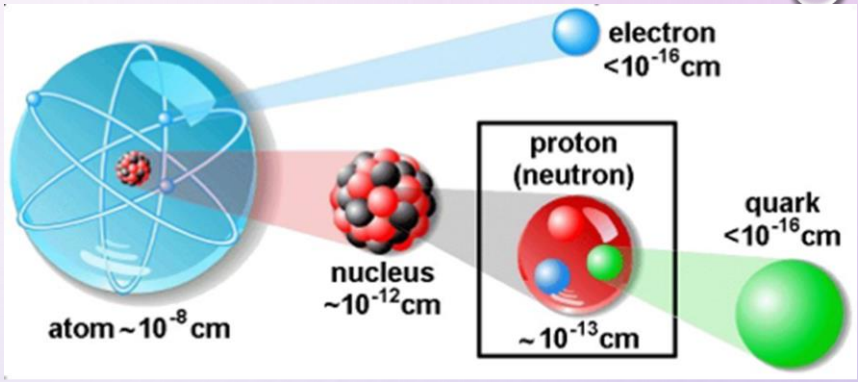


FOUR FUNDAMENTAL FORCES

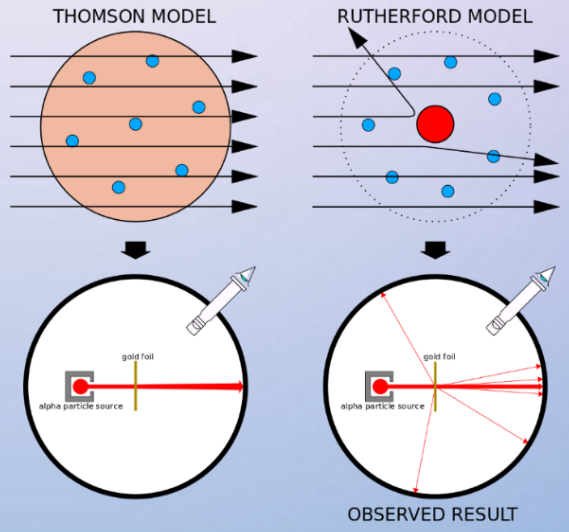
FORCE	Strong	Weak	Electromagnetism	Gravity
OBJECTS AFFECTED	Quarks, Objects with Color Charge	Objects with Flavor	Objects with Electric Charge	Objects with Mass - Energy
FORCE CARRIERS	Gluons	W & Z Bosons	Photons	Gravitons
THEORY	Quantum Chromodynamics	Quantum Fluorodynamics	Quantum Electrodynamics	Quantum Gravity, General Relativity
FORCE RANGE	10^{-15} m	10^{-18} m	Infinite	Infinite
RELATIVE FORCE STRENGTH	10^{38}	10^{25}	10^{36}	1
		Electroweak Theory		
Grand Unified Theory (GUD)				
Theory of Everything (TOE)				

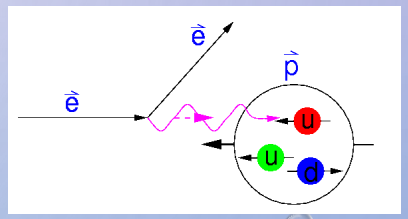
SOME HISTORY

- THE FIRST QUARKS WERE DISCOVERED IN DEEP INELASTIC SCATTERING EXPERIMENTS AT SLAC IN 1970
- QCD THEORY WAS FINALIZED BY THE END OF 1974 (MURRAY GELL-MANN, OTHERS)
  - MESONS (PIONS) WERE FIRST THEORIZED TO BE RESPONSIBLE FOR THE STRONG FORCE BY HIDEKI YUKAWA
  - GLUONS WERE FOUND TO BE RESPONSIBLE FOR THE FUNDAMENTAL STRONG FORCE
  - YANG-MILLS FIELD THEORY GENERALIZED ABELIAN FIELD THEORY TO NON-ABELIAN



http://www.davidschaich.net/research/lattice_QCD.html

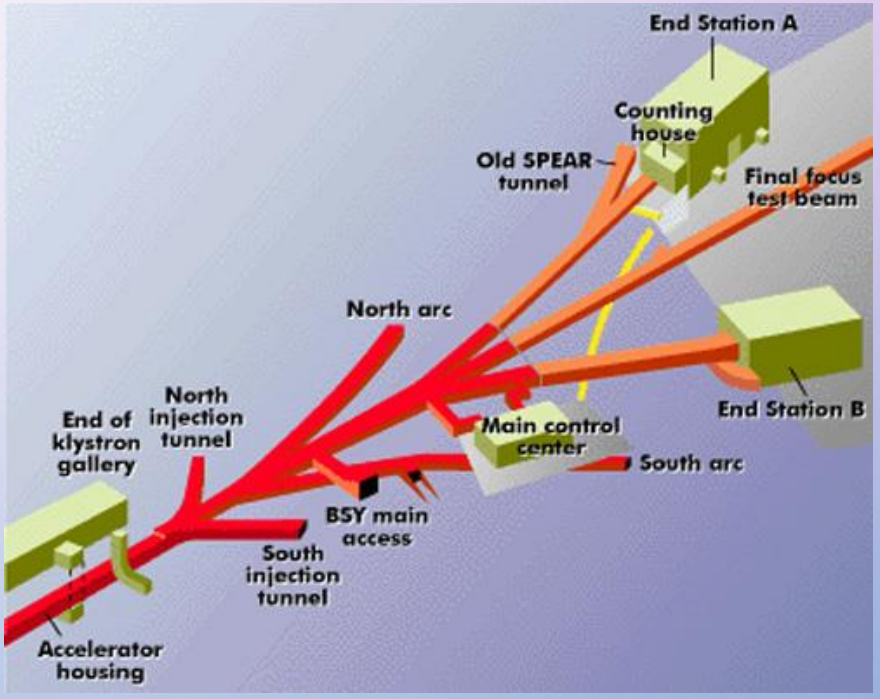




https://en.wikipedia.org/wiki/Rutherford_backscattering_spectrometry

MORE ABOUT SLAC
(STANFORD LINEAR ACCELERATOR CENTER)

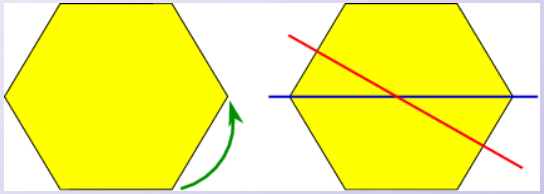
- AN ENORMOUS VERSION OF RUTHERFORD'S SCATTERING EXPERIMENT ACCELERATED INTENSE BEAMS OF ELECTRONS UP TO 20 GEV AT LIQUID HYDROGEN AND DEUTERIUM TARGETS IN END STATION A
- RESEARCHERS OBSERVED ELECTRONS SCATTERING AT WIDE ANGLES MUCH MORE FREQUENTLY THAN EXPECTED. ANALYSES OF THE DISTRIBUTION OF THE SCATTERED ELECTRONS MEASURED IN THE MAGNETIC SPECTROMETERS IN END STATION A REVEALED THREE SCATTERING CENTERS WITHIN THE NUCLEON



https://www.learner.org/courses/physics/unit/text.html?unit=1&secNum=5

WHAT IS GAUGE THEORY?

- A FIELD THEORY IN WHICH A CONTINUOUS GROUP OF SYMMETRIC LOCAL TRANSFORMATIONS EXIST THAT DO NOT CHANGE VARIOUS PHYSICAL QUANTITIES OF INTEREST
  - GIVES RISE TO LAWS OF CONSERVATION (MOMENTUM, ENERGY, ELECTRIC CHARGE, AND COLOR CHARGE)
  - (NOETHER'S THEOREM)

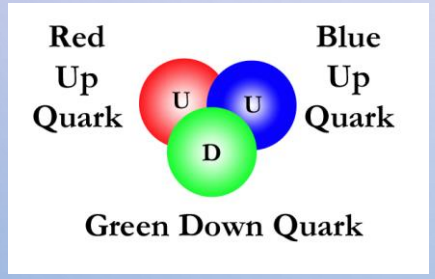


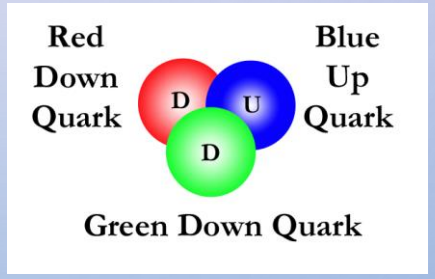
- MORE ABOUT TRANSFORMATIONS
  - CAN BE REPRESENTED BY MATRICES
  - SU(N) – SPECIAL UNITARY GROUP OF NTH DEGREE IS A GROUP OF N X N MATRICES WITH A DETERMINANT OF 1
- LOCAL SYMMETRIES ARE NOT DIRECTLY OBSERVABLE, AND DO NOT HAVE IMMEDIATE CONSEQUENCES. THEY ALLOW FOR A MATHEMATICALLY CONSISTENT AND SIMPLE FORMULATION OF THE THEORIES, AND IN THE END PREDICT EXCHANGED PARTICLES – THE GAUGE BOSONS
- QCD SYMMETRY – CHIRAL, CONFORMAL

FLAVORS AND COLORS

Quark Flavor	Mass (Approx.)	Spin	Charge	Found	Lab
Up (u)	4 MeV	½	+2/3 e	1968	SLAC
Down (d)	7 MeV	½	-1/3 e	1968	SLAC
Charm (c)	1.35 GeV	½	+2/3 e	1974	SLAC / BNL
Strange (s)	150 MeV	½	-1/3 e	1968	SLAC
Top (t)	170 GeV	½	+2/3 e	1995	Fermilab
Bottom (b)	4.8 GeV	½	-1/3 e	1977	Fermilab

PROTON



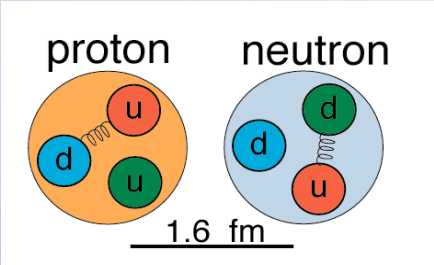


NEUTRON

http://www.historyoftheuniverse.com/?p=hadronEpoch.htm

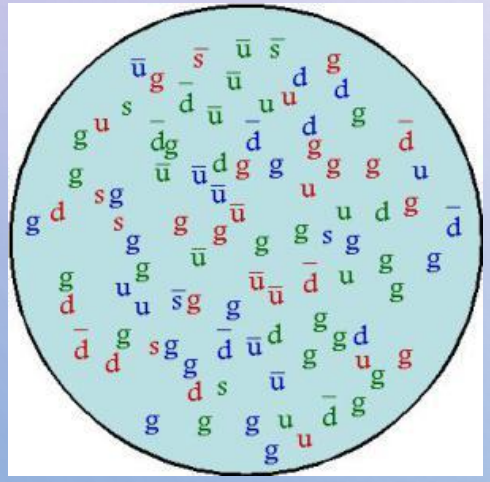
THE STRONG INTERACTION – TWO TYPES

FUNDAMENTAL STRONG FORCE



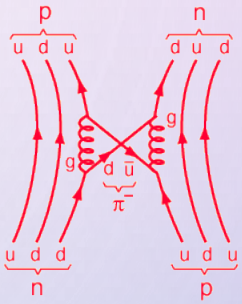
QCD Coupling Constant
Defines the Strength of
One Strong Interaction

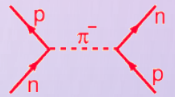
α_s



http://physics.stackexchange.com/questions/166407/why-do-the-quarks-constantly-change-colors

RESIDUAL STRONG FORCE

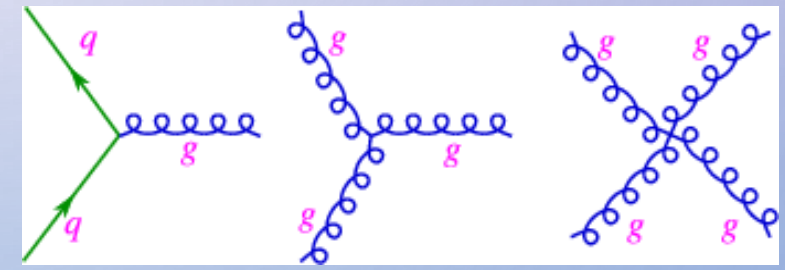




EXCHANGE OF PIONS BETWEEN NUCLEONS

http://hyperphysics.phy-astr.gsu.edu/hbase/forces/funfor.html

GLUEBALLS



http://oer.physics.manchester.ac.uk/NP/Notes/Notes/Notesse54.xht

QCD VS. QED

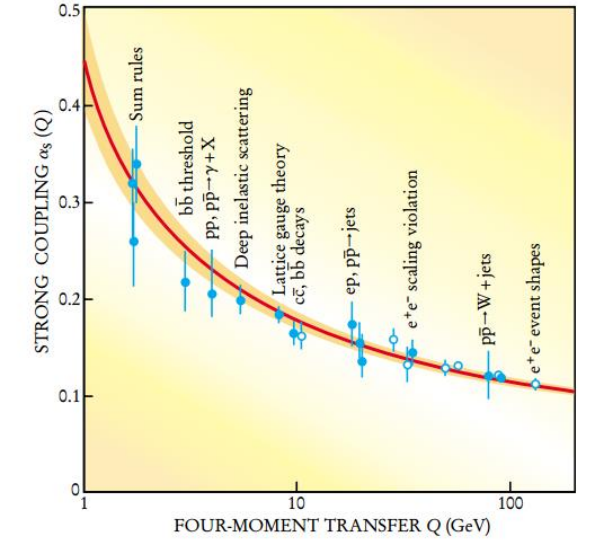
- THERE ARE TWO KEY FEATURES THAT DISTINGUISH QCD FROM QED
- QUARKS INTERACT MORE STRONGLY THE FURTHER THEY ARE APART, AND MORE WEAKLY AS THEY ARE CLOSE BY – ASYMPTOTIC FREEDOM
  - NO OTHER FORCE DOES THIS!
    - THINK BACK TO THE EQUATIONS FOR GRAVITY AND ELECTROMAGNETISM
    - $1/R^2$ TERMS WHERE R IS THE DISTANCE BETWEEN THE OBJECTS
- GLUONS INTERACT WITH THEMSELVES BECAUSE THEY ALSO CARRY COLOR CHARGE
  - PHOTONS ARE NOT ELECTRICALLY CHARGED AND DO NOT INTERACT WITH EACH OTHER
  - IF THEY DID – THINK ABOUT THE CONSEQUENCES!
- IN ADDITION
  - QED HAS TWO TYPES OF CHARGE – ELECTRIC (POSITIVE, NEGATIVE)
  - QCD HAS THREE TYPES OF CHARGE – COLOR (RED, BLUE, GREEN)

QCD Coupling Constant
Defines the Strength of One Strong Interaction

α_s

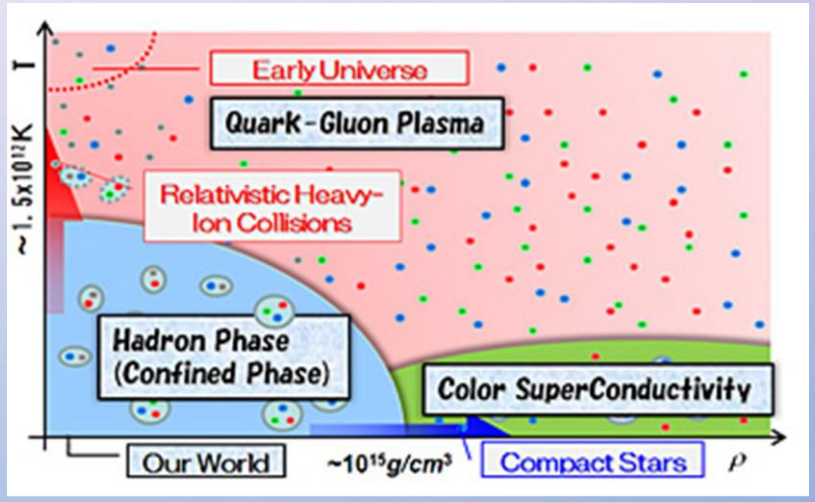
STRANGE PROPERTIES

- **CONFINEMENT** – THE STRENGTH OF THE STRONG INTERACTION INCREASES AS QUARKS ARE PULLED FARTHER AWAY FROM EACH OTHER. ONLY COLORLESS STATES OF QUARKS EXIST.
- **ASYMPTOTIC FREEDOM** – THE STRENGTH OF THE STRONG INTERACTION DECREASES AS QUARKS ARE PUSHED CLOSER TOGETHER



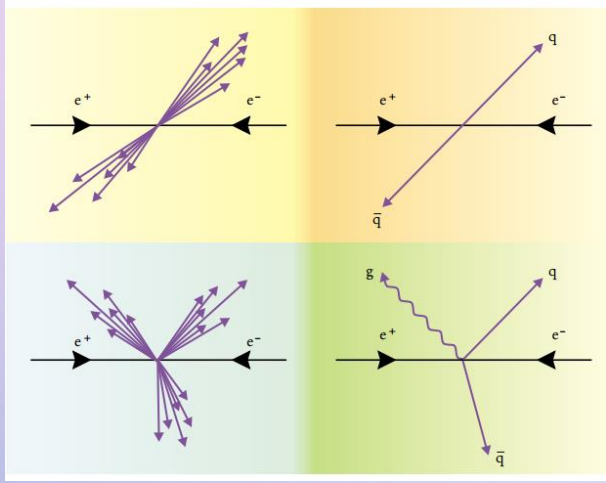
http://frankwilczek.com/Wilczek_Easy_Pieces/298_QCD_Made_Simple.pdf

PHASE DIAGRAM OF OUR UNIVERSE



http://www.phys.sci.osaka-u.ac.jp/en/research_groups/group/02-3_asakawa/

QUARK DETECTION



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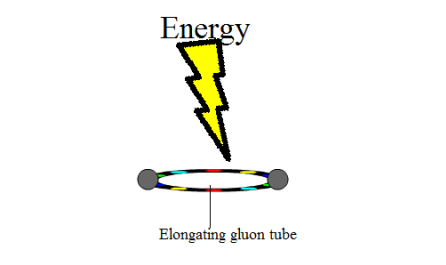
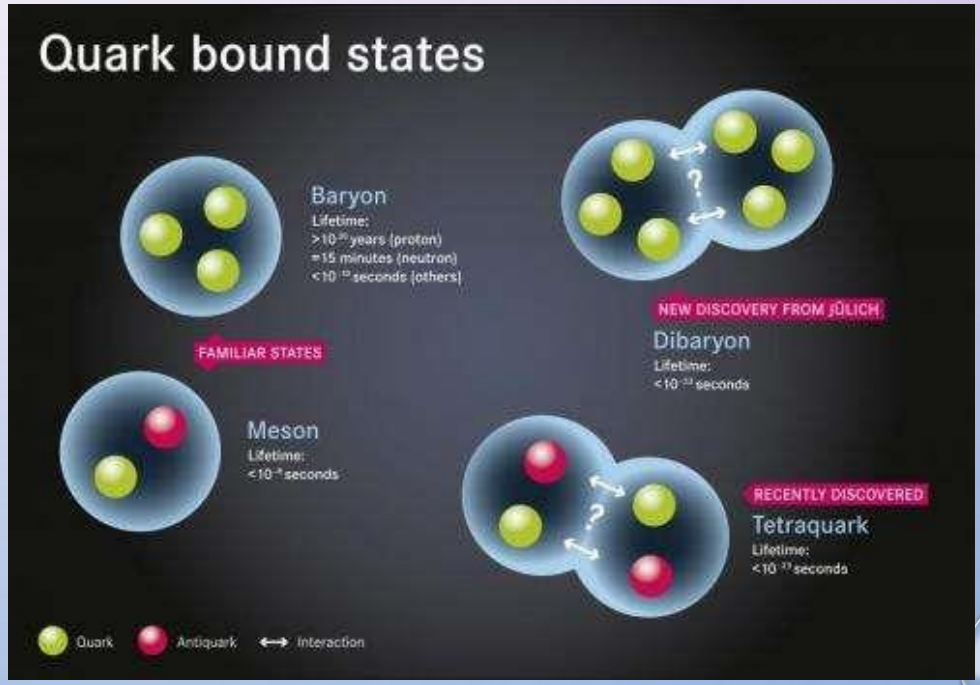
During collider experiments, any fragmented colored particles created cannot exist in isolated, free form due to confinement. Hence they must create other colored objects around them to neutralize the net color charge. These culminate in the "jets" we see in detectors.



Discovery of 4-quark hadron in 2007 proves we still don't fully understand our universe.



http://phys.org/news/2014-06-quarks-six-packs-exotic-particle.html

QUESTIONS? READ THESE RESOURCES!

Creutz, Michael. *Quarks, Gluons, and Lattices.* New York: Cambridge University Press. 1983. Print.

Feynman, P. Richard. *QED: The Strange Theory of Light and Matter.* Princeton: Princeton University Press. 2006. Print.

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"The Eightfold Way." *Wikipedia: The Free Encyclopedia.* Wikimedia Foundation, Inc., 19 Nov. 2015. <https://en.wikipedia.org/wiki/Eightfold_Way_(physics)>

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