Hadron Spectroscopy

A few introductory comments

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Self Introduction

Home town: Brooklyn, New York City
"Bay Ridge- Sunset Park" area:
from ≈1920 → ≈1970: "Little Norway"
≈1970 → now: NYC's "Chinatown #3"

BS Physics City College of New York
MS & PhD University of Wisconsin

1972-1992 Professor at U. of Rochester
1992-2009 Professor at U. of Hawaii
2009-2014 Professor at Seoul National U.

1990 → now member of the Belle Experiment
1992 → now member of the BESI, BESII, & BESIII expt

Research interests: CP violation
Hadron Spectroscopy

1984 1st time in China; started long-time collaboration
with Prof. Zheng ZhiPeng (Zheng YangHeng's father)

Spectroscopy

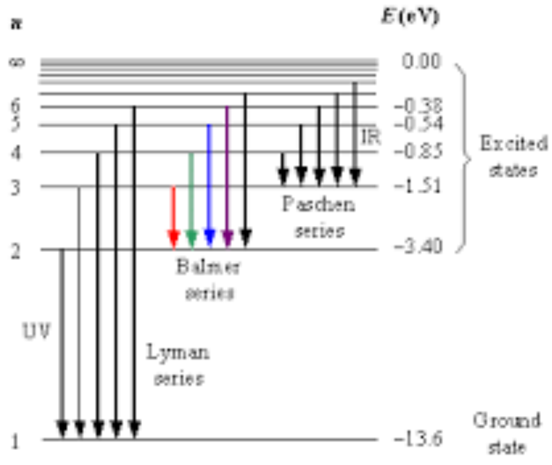
Powerful tool for understanding fundamental laws of Physics

Atomic (especially Hydrogen) spectra → Discovery of QM
& Pauli Exclusion Principle

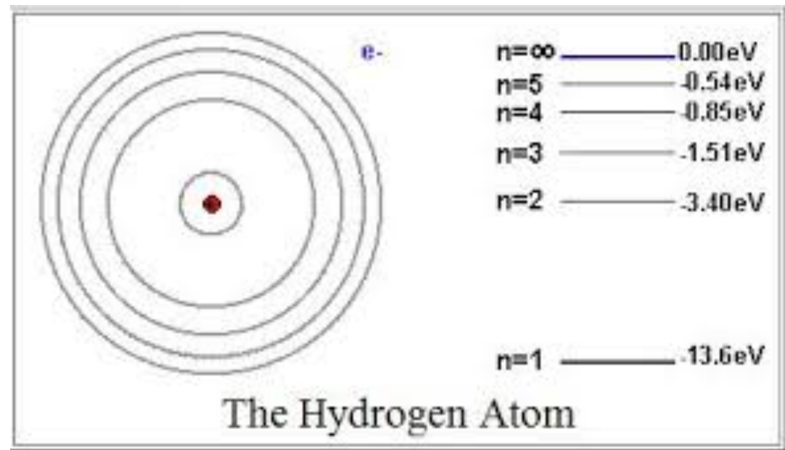
Nuclear Spectroscopy → Discovery & properties of the strong force

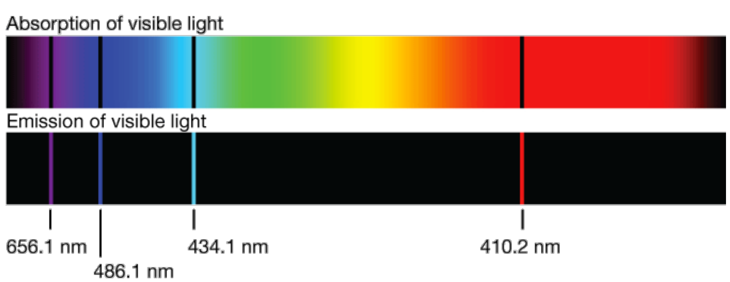
Hadron Spectroscopy → Discovery of Flavor & Quarks

Hydrogen Atom Spectrum



Energy levels of the hydrogen atom with some of the transitions between them that give rise to the spectral lines indicated

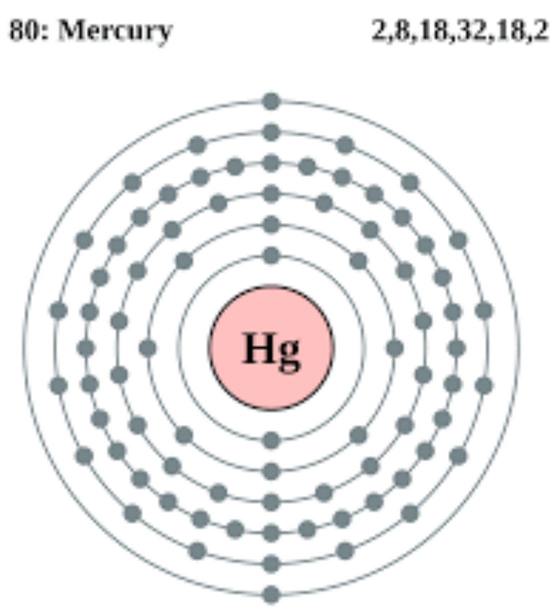


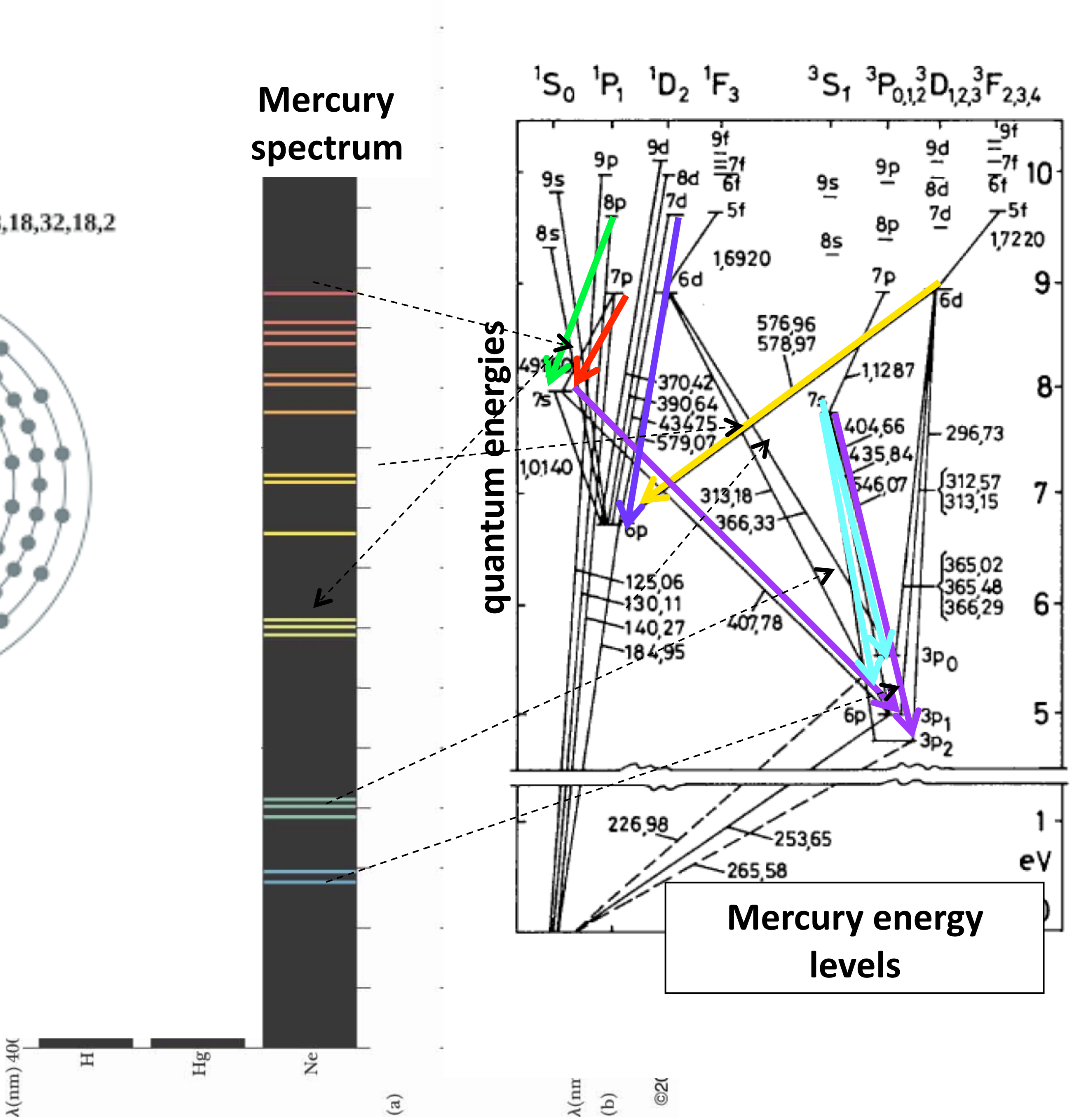


Balmer formula: $E_n = \frac{13.6eV}{n^2}$

$$13.6\text{eV} = \frac{\mu_e e^4}{2\hbar^2}$$

Decoding atomic spectra

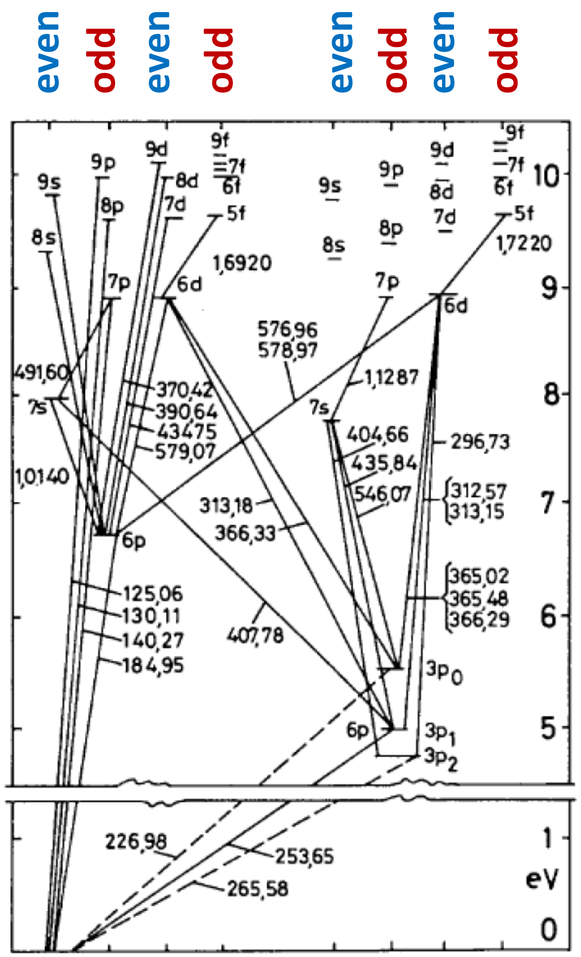




Otto Laporte
1902-1971

1924 Otto Laporte

Allowed quantum states are *either* even or odd

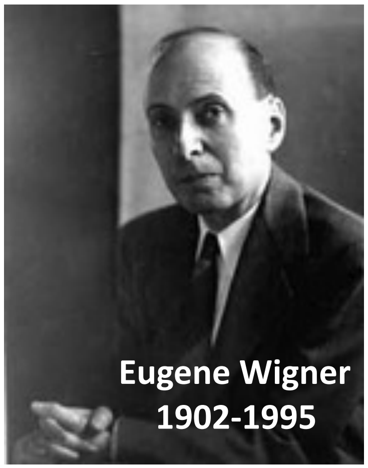


Laporte rule

even → odd
odd → even
OK

even ↛ even
odd ↛ odd
not allowed

Wigner: Laporte rule is a consequence of Left-Right symmetry of Nature



Left ⟷ Right symmetry
= “Parity” symmetry

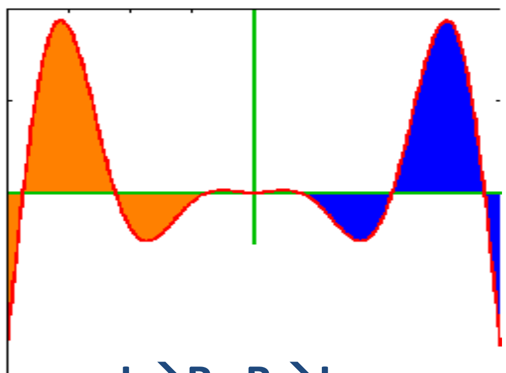
Rules governing Atomic Physics (E&M) are L⟷R symmetric:

i.e., they “Conserve” Parity

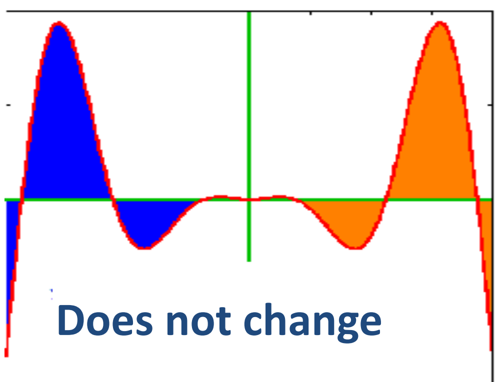
1963 Nobel Physics prize “for the discovery and application of fundamental symmetry principles”

Even & Odd quantum functions

Even Function



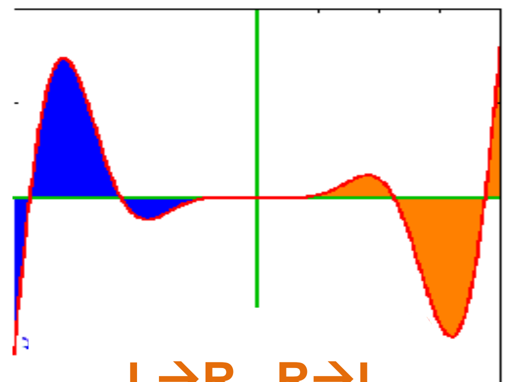
L→R R→L



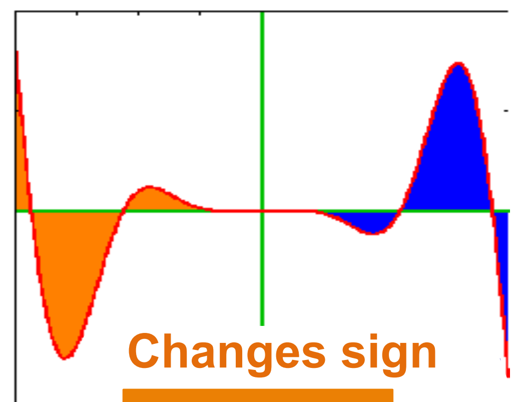
Does not change

Parity = +1

Odd Function



L→R R→L



Changes sign

Parity = -1

Parity Conservation in QM

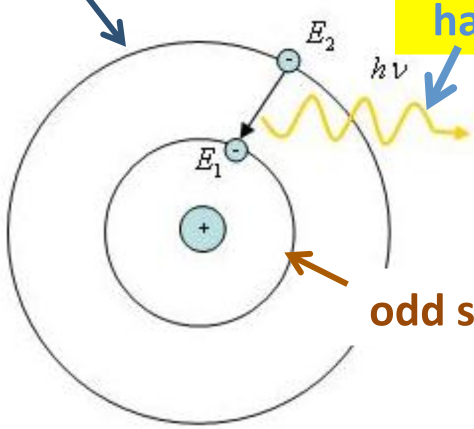
Left ↔ Right symmetry of Nature

⇓

Conservation of Parity

even state

photon has P=-1



odd state

initially:

even state (P_{even}=+1)

finally:

odd state + (P_{odd}=-1)

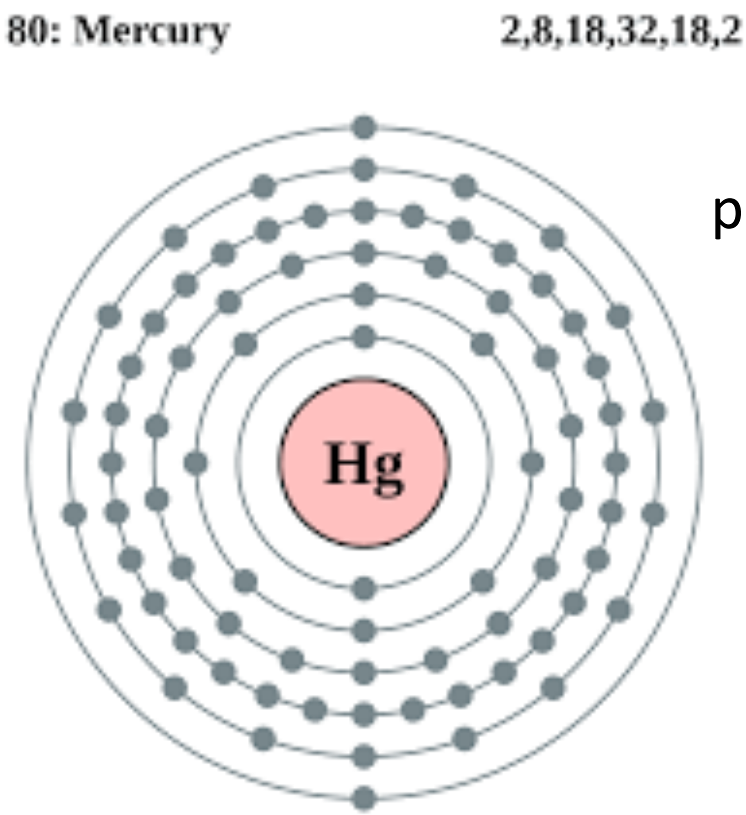
Photon (P_{phot}=-1)

$P_{initial}$=+1

P_{final}=(-1)(-1)=+1

Parity is conserved

Atomic shell structure



properties of $Y_l^m(\theta,\varphi)$ → shells

$$\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin^2\theta\frac{\partial Y}{\partial\theta}\right)+\frac{1}{\sin^2\theta}\frac{\partial^2 Y}{\partial\varphi^2}=-\lambda Y$$

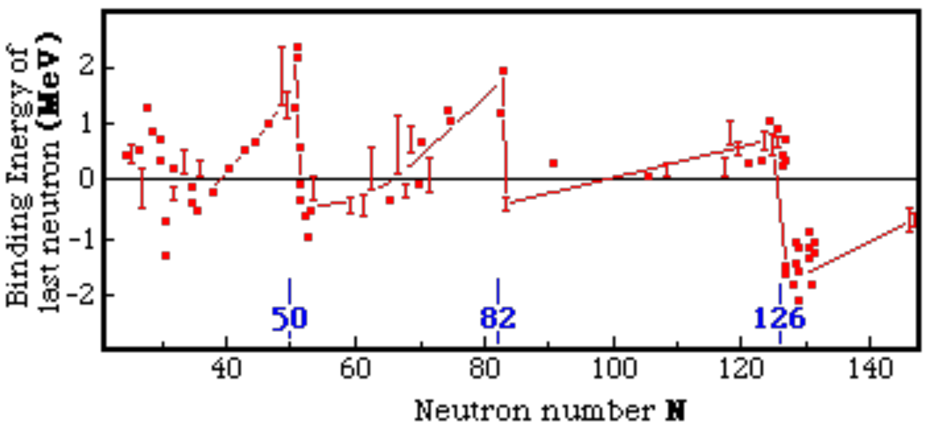
Solutions: $Y_l^m(\theta,\varphi)$; $\lambda = l(l+1)$ & $|m| \le l$

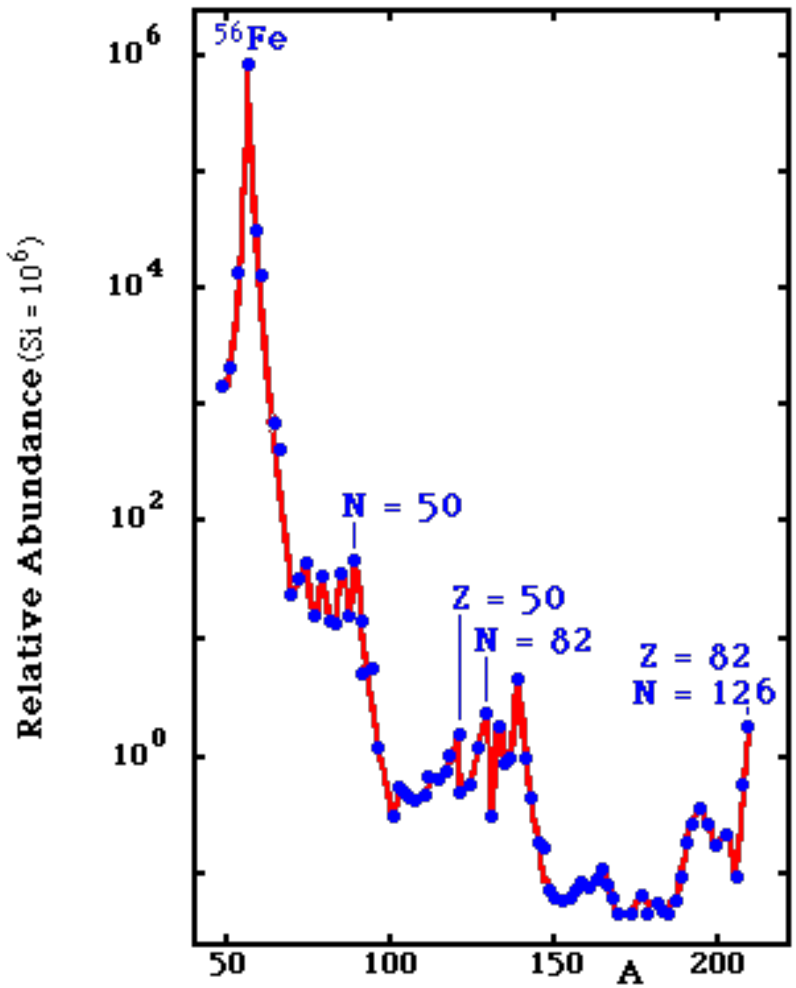
m & l are integers

Same for all spherically symmetric systems

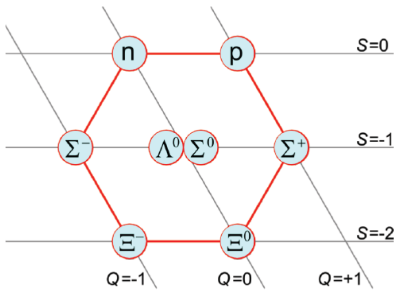
Nuclear Spectroscopy

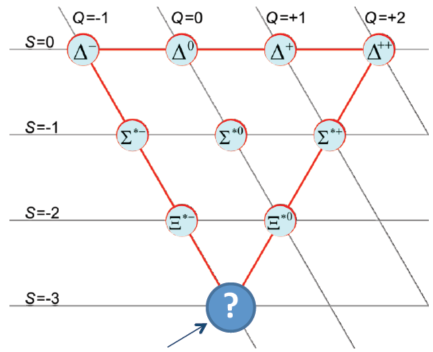
Shell structure in nuclei





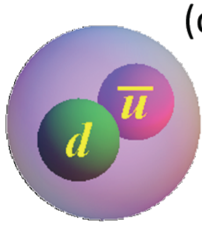
Hadron Spectroscopy





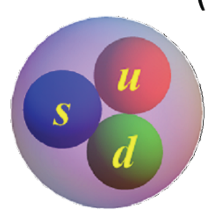
SU(3)

$(q\bar{q})$



$\pi^- = (d\bar{u})$

(qqq)



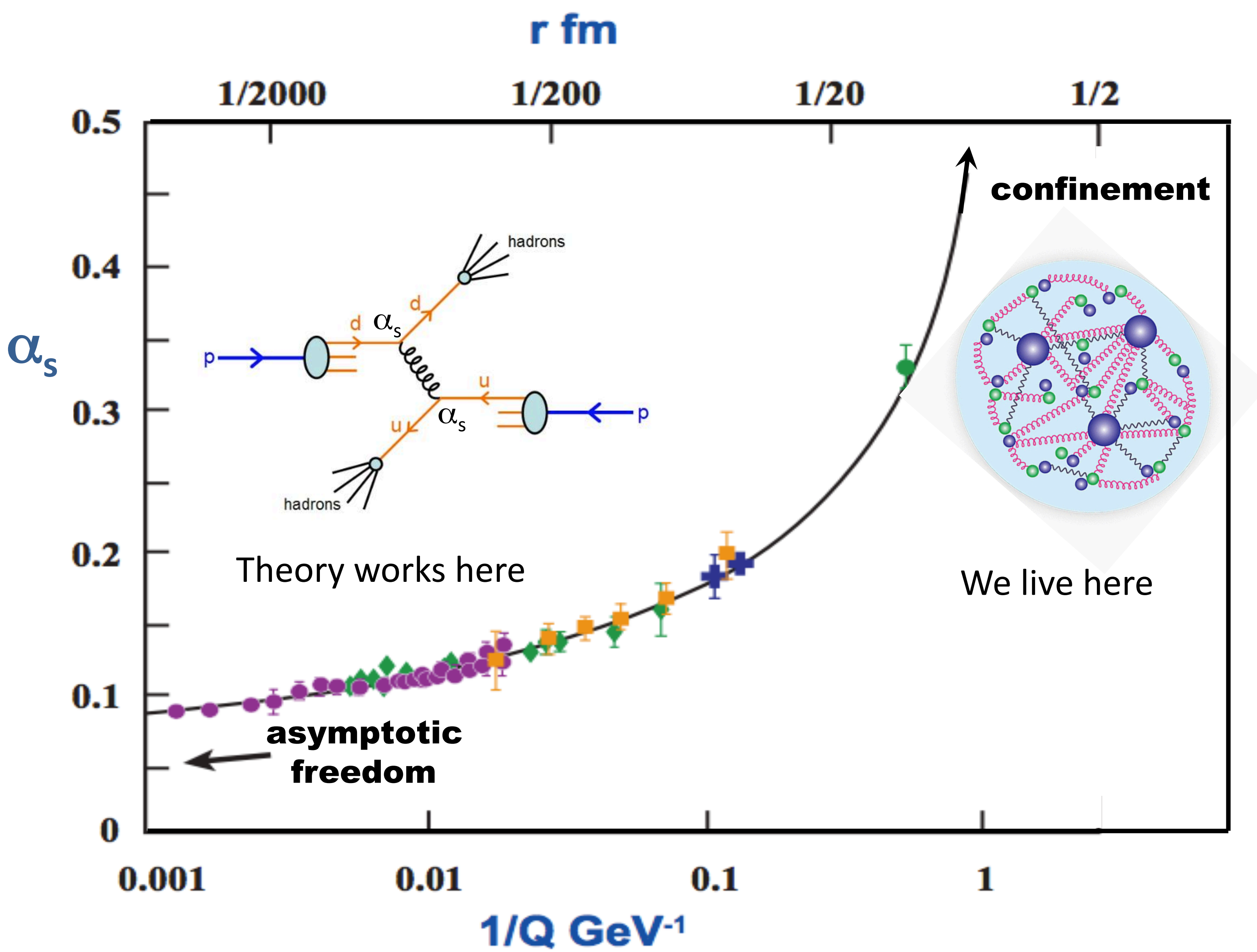
$\Lambda = (uds)$

Quarks

Atomic- vs Nuclear- vs Hadron-spectroscopy

	Constituent particles	Interparticle force
Atoms	electrons/protons well understood	Coulombic well understood
Nuclei	protons/neutrons well understood	Nuclear potential empirical models
Hadrons	quarks/antquarks/gluons NOT well understood	Long-range QCD color force NOT well understood

The QCD “dilemma”



QCD Lagrangian

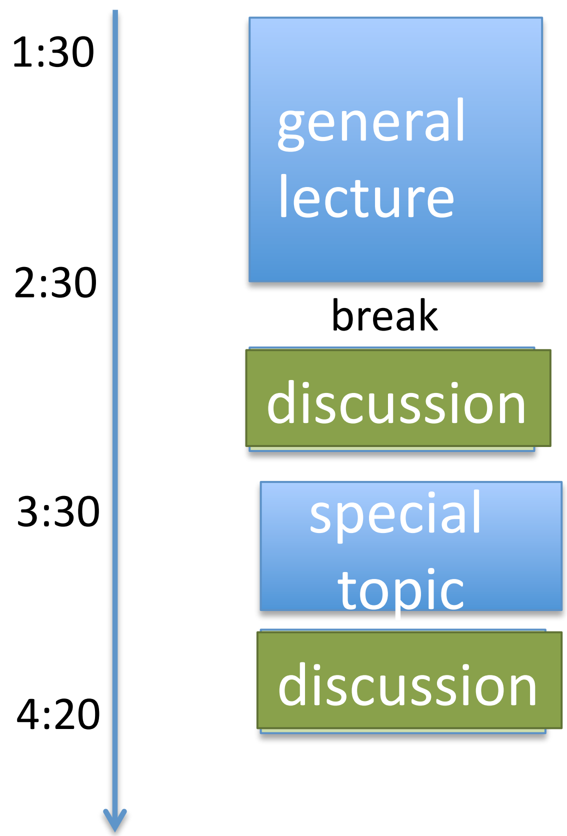
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g f^{abc} \mathcal{A}^b_\mu \mathcal{A}^c_\nu$$

A^a_μ, a=1, ..., 8, are the gluon fields

- In principle, all details of hadron spectroscopy are contained in this Lagrangian
- For distances the size of hadrons (or nuclei), it is hopelessly difficult to solve
- No useful mathematical expressions relevant to hadron spectroscopy that are based on first principle QCD calculations have ever been realized.
- Maybe a better understanding of the hadron spectrum will translate into a better understanding of long-distance QCD

Plan for these classes



Plan for the course

Main Lectures

1ST hadrons, quantum numbers, notation
-- octets and decuplets –

SU(3) and quarks light-quark spectroscopy
-- discovery of QCD---

Charmonium mesons, QCD's "hydrogen atom"

tetra-quarks, pentaquarks, hadronic molecules, …

special topics

Dalitz plots

angular distributions

multi-dimensional analyses