Paul Reimer showed these two slides at the Jlab User’s Group meeting: I have shamelessly copied them.....
What’s in the proton?

- Just three valence quarks?
- NO!!
Hadron Physics

Topics I will attempt to cover:

Lecture #1: The quark model, QCD, and hadron spectroscopy

Lecture #2: Internal structure of hadrons: momentum and spin

Lecture #3: Internal structure of hadrons: charge, magnetism, polarizability

Lecture #4: Hadrons as laboratories (and other miscellaneous topics)
caveats

I am an experimentalist! I will focus on what we know and how we measure it. I will not give a rigorous presentation of the theory by any stretch.

I am not an expert on most of these topics: I will borrow heavily from the work of others. In particular presentations from recent conferences and past summer schools. Recent Conferences are:

Workshop of the APS Topical Group on Hadronic Physics (GHP): Denver, 2009
 http://www.fz-juelich.de/ikp/ghp2009/Program.shtml

Conference on the Intersections between Nuclear and Particle Physics (CIPANP), San Diego 2009
 http://groups.physics.umn.edu/cipanp2009/program.html

Jefferson Lab Users Annual Meeting, June 2009
 http://conferences.jlab.org/ugm/program.html
some references

Halzen & Martin: Quarks and Leptons
F.E. Close: An Introduction to Quarks and Partons
Perkins: Introduction to High Energy Physics
Cahn and Goldhaber: The Experimental Foundations of Particle Physics

Xiangdong Ji: Graduate nuclear physics lecture notes
http://www.physics.umd.edu/courses/Phys741/xji/lecture_notes.htm

Lectures from the Hampton University Graduate School (HUGS):
http://www.jlab.org/hugs/archive/

Lectures from past Nuclear Physics Summer Schools (most are available online) and I have shamelessly borrowed material from wherever I could find it.

Special thanks to (for nice review slides)
Zein-Eddine Meziani, Temple University (spin, DIS)
Naomi Makins, University of Illinois (spin, transversity)
Volker Burkert, Jefferson Lab (N* physics)
Volker Crede, Florida State University (glueballs)
The big picture

What are the questions?

What are the connections between this topic and other areas of nuclear physics?
The Questions of the 2007 Long Range Plan

- Quantum ChromoDynamics
  - What are the phases of strongly interacting matter?
  - What is the internal landscape of nucleons?
  - What governs the transition of quarks and gluons into nucleons and pions?

- Nuclei and Nuclear Astrophysics
  - What is the nature of the nuclear force?
  - What is the origin of simple patterns in complex nuclei?
  - What is the origin of the elements in the cosmos?

- Symmetries and Neutrinos
  - What is the nature of neutrinos?
  - Why is there now more visible matter than antimatter?
  - ... and of course more....

http://www.sc.doe.gov/np/nsac/nsac.html
Jefferson Laboratory (Newport News, VA)

$E \sim 6 \text{ GeV}$

Continuous Polarized Electron Beam

$> 100 \ \mu\text{A}$

up to 85% polarization concurrent to 3 Halls
Hadron Physics

Lecture #1: The quark model, QCD, and hadron spectroscopy

Lecture #2: Internal structure of hadrons: momentum and spin

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The atom

*(slide from R. DeVita, AAAS meeting, Feb 2008)*

Our present knowledge on the atomic structure of matter was obtained through a series of experimental observations and theoretical advances:

- In 1803 J. Dalton postulated the existence of chemical elements introduced to explain the variety of known compounds.

- Discovery of the electron by J.J. Thomson in 1867 and its studies on isotopes destroy the concept of the atom as indivisible particle.

- The “gold foil” experiment by E. Rutherford and the development of Quantum Mechanics led to the modern models of atomic structure.
### FERMIONS

**Leptons** (*spin = 1/2*)

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ (electron neutrino)</td>
<td>$&lt;1 \times 10^{-8}$</td>
<td>0</td>
</tr>
<tr>
<td>e (electron)</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\mu$ (muon neutrino)</td>
<td>$&lt;0.0002$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$ (muon)</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\tau$ (tau neutrino)</td>
<td>$&lt;0.02$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ (tau)</td>
<td>1.7771</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Quarks** (*spin = 1/2*)

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>d down</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>c charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>s strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>t top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>b bottom</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

### PROPERTIES OF THE INTERACTIONS

<table>
<thead>
<tr>
<th>Property</th>
<th>Interaction</th>
<th>Gravitational</th>
<th>Weak (Electroweak)</th>
<th>Electromagnetic</th>
<th>Strong</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles experiencing:</td>
<td></td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically charged</td>
<td>Quarks, Gluons</td>
<td>Hadrons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td></td>
<td>Graviton (not yet observed)</td>
<td></td>
<td></td>
<td>Gluons</td>
<td>Mesons</td>
</tr>
<tr>
<td>Strength relative to electromagnetic:</td>
<td>for two u quarks at:</td>
<td>$10^{-18}$ m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>for two protons in nucleus</td>
<td>$3 \times 10^{-17}$ m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
observation of hadron states

Chicago Cyclotron: beams of $\pi^+$ and $\pi^-$ from 50-180 MeV

$$\pi^+ p \rightarrow \pi^+ p$$
$$\pi^- p \rightarrow \pi^0 n$$
$$\pi^- p \rightarrow \pi^- p$$

ratio of production cross sections (9:2:1) consistent with all three processes going through a single common resonance with Isospin 3/2. The authors suggest looking at the angular distribution in order to determine the state’s total angular momentum….
angular distributions

From “phase shift analysis”, assuming only S and P waves, found that resonance was associated with \( I=3/2, J=3/2 \)

(early example of electronics diagram in a paper!)
strangeness: The V particle

Tracks observed in a cloud chamber photographs, exposed to cosmic rays

2 photographs out of 5000 showed forked tracks

Surprisingly long life time \((10^{-10} \text{ s})\) compared w/ typical production reactions: \(\rightarrow\) weak decay

masses of outgoing tracks could only be estimated, but \(<\) proton mass.

New property called *strangeness* was introduced: conserved in strong interactions but violated in weak interactions.
Experiments

Experimental requirements for hadron spectroscopy:

energy (accelerators provide the luminosity)

mass/charge measurement: magnetic field

solid angle: need to detect all the outgoing products to completely reconstruct the decays

“hermetic” detector (cloud chamber, bubble chamber)

track resolution needed both for particle ID and for vertex reconstruction
CLEO-c: charm quark spectroscopy at Cornell (CESR: $e^+e^-$ collider)

$e^+e^- \rightarrow \gamma^* \rightarrow c\bar{c}$

**Key Features of CLEO-III**
- Excellent Calorimeter
- Excellent Tracking
- RICH and $dE/dx$ for PID
-Muon Chambers
the quark model

1950-1970:
explosion of discovery of new “particles”, including antibaryons
concepts of *isospin, strangeness*, baryon number, became
useful as organizing/classification scheme

charge: \[ Q = I_3 + (B + S) / 2 \] (hypercharge = \( B + S \))

Quark hypothesis (Gell-Mann and Zweig, 1964): up, down, and strange

<table>
<thead>
<tr>
<th>Flavor</th>
<th>B</th>
<th>J</th>
<th>I</th>
<th>I3</th>
<th>S</th>
<th>charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>1/3</td>
<td>½</td>
<td>½</td>
<td>+1/2</td>
<td>0</td>
<td>2/3</td>
</tr>
<tr>
<td>d</td>
<td>1/3</td>
<td>½</td>
<td>½</td>
<td>-1/2</td>
<td>0</td>
<td>-1/3</td>
</tr>
<tr>
<td>s</td>
<td>1/3</td>
<td>½</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

*what are the quark masses? Can we understand them from the spectrum of observed particles?*
hadrons in QCD

The strong interaction is defined by the property “color”. This is required to produce bound states with the appropriate symmetry properties (fermion/boson statistics)

• The strong interaction is (approximately) flavor independent (same for all quarks, thus, e.g., same for n and p)

• There are 3 types of “color”

• The bound states of QCD are only “color neutral”: individual constituents cannot be observed → confinement

• The exchange particles (gluons) carry the property of color (and thus can interact with themselves)

• The interaction strength decreases with increasing energy → asymptotic freedom
u and d only: SU(2) flavor symmetry

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix}
\quad q\bar{q} : \quad 2 \otimes \bar{2} = 3 \oplus 1
\]

symmetric \quad antisymmetric

\[
\left( \pi^+, \pi^0, \pi^- \right)
\]

\[
qqq : \quad 2 \otimes 2 \otimes 2 = (3 \otimes 2) \oplus (1 \otimes 2) = 4 \oplus 2 \oplus 2
\]

\[
\left( \Delta^{++}, \Delta^+, \Delta^0, \Delta^- \right)
\]

mixed symmetry: combine with spin part of wave fn to get antisymmetric state: \( p \) and \( n \)

e.g.,

\[
\left| \Delta^{++} \right> = \left| \frac{3}{2}, \frac{3}{2} \right>_I \otimes \left| \frac{3}{2}, \frac{3}{2} \right>_S \otimes \left| L = 0 \right> \otimes \psi_{color}
\]

symmetric \quad color “neutral”: antisymmetric
SU(3) and s quarks

Mesons: $\bar{q}q$

$$3 \otimes \bar{3} = 8 \oplus 1$$

Baryons: $qqq$

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$

$\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$

$\Sigma^{*-}, \Sigma^{*0}, \Sigma^{*+}$

$\Xi^{*-}, \Xi^{*0}$

$\Omega^-$

$\Omega^{3/2+}$

$\Lambda^0$

$(uds)$

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

$\eta_8 = \frac{1}{\sqrt{6}} (u\bar{u} + d\bar{d} - 2s\bar{s})$

$\eta_1 = \frac{1}{\sqrt{3}} (u\bar{u} + d\bar{d} + s\bar{s})$

figure from V. Crede, FSU
FIG. 2. Photograph and line diagram of event showing decay of Ω⁻.
masses and magnetic moments

The “constituent quark” model can predict these pretty well.

\[ M_{\Lambda} - M_N = 177 \text{ MeV} \]
\[ M_{\Sigma} - M_N = 254 \text{ MeV} \]
\[ M_{\Xi} - M_{\Lambda} = 203 \text{ MeV} \]

Similar relationships for the J^P=3/2+ baryons. These get modified a little by q-q hyperfine structure. Result in “constituent quark” masses:

\[ p, n \]
\[ \Sigma^-, \Sigma^0, \Sigma^+ \]
\[ \Xi^-, \Xi^0 \]

<table>
<thead>
<tr>
<th>Baryon</th>
<th>Magnetic Moment</th>
<th>Quark-model expression</th>
<th>fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>2.793 ± 0.000</td>
<td>( \frac{2}{3} \mu_u - \frac{1}{3} \mu_d )</td>
<td>input</td>
</tr>
<tr>
<td>( n )</td>
<td>-1.913 ± 0.000</td>
<td>( \frac{2}{3} \mu_d - \frac{1}{3} \mu_u )</td>
<td>input</td>
</tr>
<tr>
<td>( \Lambda )</td>
<td>-0.613 ± 0.004</td>
<td>( \mu_s )</td>
<td>input</td>
</tr>
<tr>
<td>( \Sigma^+ )</td>
<td>2.458 ± 0.010</td>
<td>( \frac{2}{3} \mu_u - \frac{1}{3} \mu_s )</td>
<td>2.67</td>
</tr>
<tr>
<td>( \Sigma^- )</td>
<td>-1.160 ± 0.025</td>
<td>( \frac{2}{3} \mu_d - \frac{1}{3} \mu_s )</td>
<td>-1.09</td>
</tr>
<tr>
<td>( \Sigma^0 )</td>
<td>unknown</td>
<td>( \frac{2}{3} (\mu_u + \mu_d) - \frac{1}{3} \mu_s )</td>
<td>0.79</td>
</tr>
<tr>
<td>( \Xi^0 )</td>
<td>-1.250 ± 0.014</td>
<td>( -\frac{1}{3} \mu_u + \frac{4}{3} \mu_s )</td>
<td>-1.43</td>
</tr>
<tr>
<td>( \Xi^- )</td>
<td>-0.651 ± 0.003</td>
<td>( -\frac{3}{3} \mu_d + \frac{3}{3} \mu_s )</td>
<td>-0.49</td>
</tr>
</tbody>
</table>

Table 3.3: The magnetic moment of the octet baryons and quark model fit.

\[ m_u \approx m_d \approx \frac{1}{3} M_N = 300 \text{ MeV} \]
\[ m_s \approx 450 \text{ MeV} \]

\[ \mu_q \approx \frac{q_q \hbar}{2m_q c} \]
\[ \mu_u = -2 \mu_d \]
heavy quark bound states

quark analog of positronium
short range
nonrelativistic
perturbative QCD is not bad

e.g. Charmonium: \((J/\Psi)\)
states are very narrow
excellent lab to search for
exotic and hybrid bound states
(very active: BaBar, Belle, CDF, D0, …)

\[ V_{QCD}(r) \propto -\frac{4}{3} \frac{\alpha_s}{r} + kr \]

“Coulombic”

confining
Lattice QCD

Flux tubes in LQCD

Flux tube forms between $q\bar{q}$

G. Bali

ab initio computation of Baryon masses

Excited baryons

simple quark model: harmonic oscillator + some hyperfine splitting...

$$H_0 = \frac{1}{2m} \left( \vec{p}_2^2 + \vec{p}_1^2 \right) + \frac{1}{2m} \vec{p}_3^2 + \frac{1}{2} k \sum_{i<j} \left( \vec{r}_i - \vec{r}_j \right)^2 + V_{ij}$$

more states predicted than have been found. Are these the correct degrees of freedom?

- predicted
- PDG 3-4 ***
- PDG 1-2 ***

see X. Ji, U Md Phys 741
lecture notes

see also Capstick & Roberts
PRD 58 (1998) 074011
“Missing” Baryon States

Quark models with underlying SU(6)xO(3) symmetry predict many states, not observed in either hadronic experiments or in meson photo- and electro-production.

Possible solutions:

1. States don’t exist, e.g. di-quark model predicts fewer states, with different underlying symmetry group
2. States exist but have not been found.

Possible reason: they do not couple to $\pi N$ final states…

Maybe they decay to other channels:

$K\Lambda$, $K\Sigma$, $p\omega$

adapted slide from V. Burkert, JLab
Searches for resonances

2-body decay: look at the *invariant mass distribution*.

\[ W^2 = M^2 = (p_1 + p_2)^2 \]

Worse: sometimes they overlap

3-body decay: Dalitz plot

Beware of artifacts…..

*slide from V. Burkert, JLab*
Partial Wave Analysis II

\[ \psi(r, \theta, \phi) \rightarrow e^{ikz} + f(\theta, \phi) \frac{e^{ikr}}{r} \]

- **Differential cross section:**
  \[ \frac{d\sigma}{d\Omega} = |f(\theta, \phi)|^2 \]

\[ f(\theta, \phi) = \frac{-m}{2\pi\hbar^2} \int d\vec{r} e^{i\vec{q}\cdot\vec{r}/\hbar} V(\vec{r}) \]

- More generally,
  \[ \psi_s = \psi_f - \psi_i = \frac{1}{k} \sum_{l=0}^{\infty} (2l + 1) \frac{m e^{2i\delta_l}}{2i} P_l(\cos \theta) \frac{e^{ikr}}{r} \]

*See Dan Carman’s seminar from last year’s Summer School*
Partial Wave Analysis IV

Amplitude analysis:

\[ \text{beam} \times \text{decays} \quad 2 \quad \text{target} \quad \text{recoil} \]

\[ = \]

\[ \text{beam} \times_1 \text{decays} \quad + \quad \text{beam} \times_2 \text{decays} \quad 2 \]

\[ \text{target} \quad \text{recoil} \quad \text{target} \quad \text{recoil} \]

---

Caveats:

The number of counts in a given bin must account for the Poisson fluctuation probability in the number of events.

The true number of counts is not just what we see in the detector. We must count up everything.

account for acceptance of detector and all inefficiencies

(the larger the detector acceptance, the smaller the corrections)
The CLAS Detector at JLab
example of Dalitz Plot: $\gamma p \rightarrow pK^+K^-$

$E_\gamma = 1.6-3.5$ GeV

slide from V. Burkert, JLab

from the CLAS detector in Hall B at JLab
Differential & total cross section of $\gamma p \rightarrow K^+ \Lambda$

Needs polarization observables and measurement in other channels for more definite conclusions.
Beyond the Quark Model: Hybrids and Exotics

Quarks combine to “neutralize” color force

Quark-gluon configurations can give colorless objects

- mesons
- baryons
- molecule
- tetraquark
- glueball meson
- hybrid meson
pure glue

from V. Crede, FSU

Glueballs: \( g \otimes g = 8 \otimes 8 = 27 \oplus 10 \oplus 10 \oplus 8 \oplus 8 \oplus 1 \)

Hybrids: \( q \otimes \bar{q} \otimes g = 27 \oplus 10 \oplus 10 \oplus 8 \oplus 8 \oplus 8 \oplus 1 \rightarrow (q\bar{q})^1((q\bar{q})^3)^m(g)^n, \quad l + m \geq 1 \text{ for } n = 1 \)

States with hidden exotic properties

\( \Rightarrow \) Problem: predicted glueballs can mix with ordinary \( q\bar{q} \) states

\[ f_0(1500) \quad \{ \quad J^{PC} = 0^{++} \]

In summary: Is there evidence for glueballs?

- Lightest \( 0^{++} \) glueball: possible ... \( f_0(1370), f_0(1500), f_0(1710) \)

- Lightest \( 0^{-+} \) glueball: maybe ... \( \eta(1295), \eta(1405), \eta(1490) \)

- Lightest \( 2^{++} \) glueball: well, there is not even a candidate ...
Glue-Rich Environments

Different Production Mechanisms

1. $J/\psi$ may convert into two gluons and a photon.
2. In central production, two hadrons scatter diffractively; no valence quarks are exchanged.
3. In $p\bar{p}$ annihilation, quark-antiquark pairs annihilate into gluons forming glueballs.
The Crystal-Barrel Experiment from V. Crede, FSU

Combination of WA76 and GAMS-4000 detector...

p+p

1989 - 1996
Proton-Antiproton Physics at LEAR, CERN

The BES-II Experiment at IHEP, Beijing
Operation started in 1989...

e^+ + e^-

E. Beise, U Maryland
from V. Crede, FSU

Do glueballs exist in nature?

I don’t know … http://dx.doi.org/10.1016/j.ppnp.2009.03.001

1. The tensor glueball
   ➔ No evidence so far.

2. The pseudoscalar glueball
   ➔ Very weak evidence, not likely.

3. The scalar glueball
   ➔ Best evidence, but no clear state. Physical states can mix:

\[
\begin{pmatrix}
| f_0(1370) \rangle \\
| f_0(1500) \rangle \\
| f_0(1710) \rangle \\
\end{pmatrix}
= \begin{pmatrix}
M_{1n} & M_{1s} & M_{1g} \\
M_{2n} & M_{2s} & M_{2g} \\
M_{3n} & M_{3s} & M_{3g} \\
\end{pmatrix}
\cdot
\begin{pmatrix}
n\bar{n} \\
s\bar{s} \\
G \\
\end{pmatrix}
\]
Beyond the Quark Model: Hybrids and Exotics

Quarks combine to “neutralize” color force

Other quark-gluon configurations can give colorless objects

- mesons
- baryons
- molecule
- tetraquark
- glueball meson
- hybrid meson

*slide from R. deVita, AAAS meeting, Feb 2008*
"Ordinary" Meson Properties

Spin/angular momentum configurations and radial excitations generate the known spectrum of light quark mesons.

Starting with u, d, s quarks, we expect to find mesons grouped in nonets, each characterized by a given \( J, P, \) and \( C \).

\[
\begin{align*}
S &= S_1 + S_2 \\
J &= L + S \\
P &= (-1)^{L+1} \\
C &= (-1)^{L+S}
\end{align*}
\]

\( q\bar{q} \) color singlet bound states

\[ J^{PC} = 0^- + 0^{++} 1^{--} 1^{+-} 2^{++} \ldots \]
Allowed combinations

\[ J^{PC} = 0^{--} 0^{+-} 1^{--} 1^{+-} 2^{--} \ldots \]
Not-allowed: exotic

No need for gluons here!
Hybrid Mesons

Hybrids are quark–antiquark states with excitation energy in the gluonic flux tube.

Flux tube excitation (and parallel quark spins) lead to exotic $J^{PC}$
Exotic Mesons

Data Set Overview

Existing data for the evidence of exotic mesons has come from a number of sources.

1). Brookhaven National Laboratory: E852 - 18 GeV $\pi^- p$ reactions

2). Crystal Barrel at CERN: $\bar{p}p$, $\bar{p}d$ reactions at 1–2 GeV

3). VES at IHEP: $\pi^- p$ at 37 GeV

4). GAMS at Serpukhov: $\pi^- p$ at 40 GeV

5). KEK at Japan: $\pi^- p$ at 6 GeV

6). Smattering of photoproduction data: SLAC (old) and JLab/CLAS

Each experiment has its own limitations, not the least of which is relatively small statistics!
The GlueX Experiment (w/ JLab 12 GeV upgrade)

GlueX Detector

diamond wafer

electron beam

electron-diversion magnet

electron beam

photon beam

excited flux tube

lead-glass detector

barrel calorimeter

target

Čerenkov counter

wire tracking chambers

superconducting magnet

Curtis Meyer NNPSS 2006
Photoproduction Experiment

Quark spins anti-aligned

A pion or kaon beam, when scattering occurs, can have its flux tube excited

Much data in hand but little evidence for gluonic excitations (and not expected)

Quark spins aligned

Almost no data in hand in the mass region where we expect to find exotic hybrids when flux tube is excited

GROSS SECTIONS SHOULD BE SIZEABLE!

See Dan Carman’s seminar from last year’s Summer School
GSI Helmholtz Center and FAIR
PANDA Physics Program at the FAIR Facility in Germany

Charmonium spectroscopy

Exotics: charmed hybrids & heavy glueballs

Medium modifications of charmed mesons

CP-violation (D & Λ - sector)

Time-like form factors

Drell-Yan processes

Hard exclusive processes

Hypernuclei

D. Bettoni, GHP 2009
PANDA detector

Detector Requirements

• (Nearly) $4\pi$ solid angle coverage (partial wave analysis)
• High-rate capability ($2 \times 10^7$ annihilations/s)
• Good PID ($\gamma$, e, $\mu$, $\pi$, K, p)
• Momentum resolution ($\approx 1\%$)
• Vertex reconstruction for D, $K^0_s$, $\Lambda$
• Efficient trigger
• Modular design
• Pointlike interaction region
• Lepton identification
• Excellent calorimetry
  • Energy resolution
  • Sensitivity to low-energy photons

http://www.gsi.de/panda
Summary of this section

The quark model laid the groundwork for QCD.

The basic spectroscopy of the more easily identifiable bound states of meson and baryon can be characterized by a set of quantum #'s described by the quark model.

Searching for new bound states tests the limits, perhaps revealing something deeper about QCD and confinement.

Difficult task! Need lots of data taken together with close connection to theory.

Opportunities are abundant!
Hadron Physics

Lecture #1: The quark model, QCD, and hadron spectroscopy

Lecture #2: Internal structure of hadrons: momentum and spin

Lecture #3: Internal structure of hadrons: charge, magnetism, polarizability

Lecture #4: Hadrons as laboratories (and other miscellaneous topics)