Exotic Hadrons

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Allowed hadronic states

- At the beginning of this course, we stated that there are only two allowed combinations of quarks that give bound hadronic states
  - Mesons ($q\bar{q}$)
  - Baryons (qqq)
- Both of these can be adjusted to give colour singlet states, which is the real requirement
- Other states can be made (e.g.

$gg, ggg, q\bar{q}q\bar{q}, q\bar{q}qqq$, which are also colour singlets

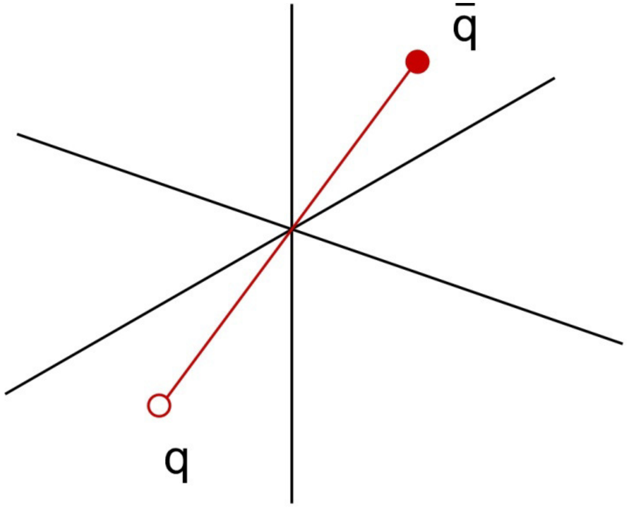
Signature for such states

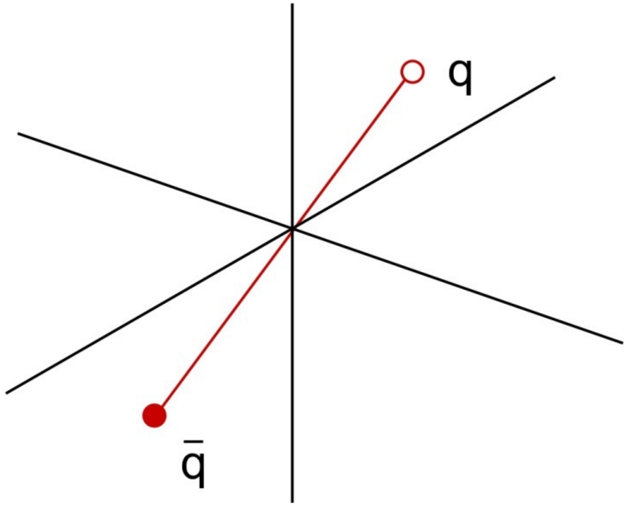
- It is often difficult to identify such states, as they can have the same quantum numbers as "standard" states, and therefore be indistinguishable from them.
- In addition to this, if a "normal" hadronic state has the same J^{PC} as an exotic state, the two states will interfere to produce, in general, two mixed states at masses different from those expected for the pure states.

Signature for such states

- In certain cases, a particular non-standard, or “exotic” state, can show characteristics that clearly cannot be produced by standard states.
- Such states are of particular interest, as they have a clear signature for an exotic nature.
- The main characteristics of interest are
  - Exotic J^{PC}. Not all configurations are possible for standard states
  - Unusual mixtures of quarks and antiquarks, e.g. baryons with evidence for both quarks and antiquarks in the valence quarks. Usually this identification is made by looking at heavy flavours, as additional antiquarks in the light (**ud**) sector would be undetectable. Additional **s** quarks are already detectable. Same remarks hold for **c** or **b** quarks

Allowed states for q$\bar{q}$ mesons





- $\mathbf{P}(\psi(\mathbf{r})) = \eta_P \psi(\mathbf{r}) = \psi(-\mathbf{r})$

  $\psi(\mathbf{r}) = \mathbf{R}(r) Y_{lm}(\theta,\phi)$

  $\psi(-\mathbf{r}) = \mathbf{R}(r) Y_{lm}(\pi-\theta,\phi+\pi) = (-1)^l R(r) Y_{lm}(\theta,\phi)$
- Fermions and anti-fermions have opposite intrinsic parity: $\eta_q \eta_{\bar{q}} = -1$
- So $P(q\bar{q}) = \eta_q \eta_{\bar{q}} (-1)^L = (-1)^{L+1}$

Allowed states for $q\bar{q}$ mesons

- C-Parity swaps quarks for anti-quarks, so is equivalent to the co-ordinate swap done by the parity operation just discussed, but it also swaps labels in the spin wavefunction.
- Interchange symmetry was positive for the S=1 state and negative for the S=0 state (the only two possibilities) giving a factor $(-1)^{S+1}$.
- Thus, overall, $C(q\bar{q}) = (-1)^{L+1}(-1)^{S+1} = (-1)^{L+S}$

Allowed states for $q\bar{q}$ mesons

- G-parity extends the notion of C-parity to charged particles (only neutral particles can be C-parity eigenstates) by adding a rotation by π about the y-axis in Isospin space, giving, by similar arguments an additional factor $(-1)^I$.

$$G = \eta_q \eta_{\bar{q}} (-1)^{\mathbf{L+S+I}}$$

Allowed states for $q\bar{q}$ mesons

- Summary:

$$\mathbf{J} = \mathbf{L} \oplus \mathbf{S}$$

$$\mathbf{P} = (-\mathbf{1})^{\mathbf{L}+\mathbf{1}}$$

$$\mathbf{C} = (-\mathbf{1})^{\mathbf{L}+\mathbf{S}}$$

$$\mathbf{G} = (-\mathbf{1})^{\mathbf{L}+\mathbf{S}+\mathbf{I}}$$

Consequences for Meson Spectrum

- If we use the equations we have just obtained to work out the allowed J^{PC} states for $q\bar{q}$ mesons, we find the following states (up to J=3)
  - $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{--}, 2^{-+}, 2^{++}, 3^{--}, 3^{+-}, 3^{—}$

which are arranged as follows (up to J=2)

Meson multiplet J^{PC} Assignment

State	S	L	J	P	C	J^{PC}	Mesons	Name
$^1S_0$	0	0	0	-	+	0^{-+}	π η η' K	Pseudoscalar
$^3S_1$	1	0	0	-	-	1^{--}	ρ ω ϕ K^*	Vector
$^1P_1$	0	1	1	-	-	1^{+-}	b_1 h_1 h_1' K_1	Pseudovector
$^3P_0$	1	1	0	+	+	0^{++}	a_0 f_0 f_0' K^*_0	Scalar
$^3P_1$	1	1	1	+	+	1^{++}	a_1 f_1 f_1' K_1	Axial vector
$^3P_2$	1	1	2	+	+	2^{++}	a_2 f_2 f_2' K^*_2	Tensor

Exotic States

- Some JPC assignments are missing from this table, indicating that they cannot be made from a $q\bar{q}$ pair.
  - 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, …
- These are the so-called exotic states.

Glueballs

- In principle glueballs can be made from any number of gluons (≥2) provided the resultant state is a colour singlet.
- Restrictions only apply for gg glueballs, as for greater numbers of gluons all spin parities can be accommodated by suitable coupling of spins.

gg Glueballs

- Restrictions come about because of the restrictions on the gluons, as vector particles analogous to photons.
- The main restriction is that two gluons cannot form a C=- state.
- If the gluons are massless, the same restrictions as for photons apply (think of Yang's theorem) forbidding all spin one states (1^{--}, 1^{++}, 1^{-+}), but if gluons are off mass shell, as would be required in a more realistic model of bound states, Yang's theorem no longer applies.
    - NB. C=- states remain forbidden.

Allowed J^{PC} states

J^{PC}	$q\bar{q}$	GG	GGG	$q\bar{q}G$	$q\bar{q}q\bar{q}$
0^{++}	✓	✓	✓	✓	✓
0^{+-}			✓	✓	✓
0^{-+}	✓	✓	✓	✓	✓
0^{--}			✓	✓	✓
1^{++}	✓	*	✓	✓	✓
1^{+-}	✓		✓	✓	✓
1^{-+}		*	✓	✓	✓
1^{--}	✓		✓	✓	✓
2^{++}	✓	✓	✓	✓	✓
2^{+-}			✓	✓	✓
2^{-+}	✓	✓	✓	✓	✓
2^{--}	✓		✓	✓	✓

* Forbidden for massless gluons

More realistic Assignments

- The table shown in the previous slide summarizes the situation for pure states. However, in reality, states with the same J^{PC} can mix, so actual states can have both normal and non-standard components.
- Thus, exotic J^{PC}s remain very interesting, as these cannot mix with standard mesons.
- No restrictions on tetraquarks, or (within constraints of baryon sector, pentaquarks)

Summary

- The establishment of the quark model owes a lot to the observation of meson and baryon states displaying the SU(3) symmetries expected for states made up from quark-antiquark or three quark states.
- This was backed up by evidence from (mainly) lepton-proton scattering experiments (see next term)
- However, QCD suggests other states should exist, and these are slowly being found.
- We may already have found some, as problem is to distinguish them from “normal” states in the case where the quantum numbers can be the same.
- Hence the interest in “exotic” states, and in states decaying to a large number of heavy flavour particles, which give indications of an origin that cannot be accommodated in the normal quark model of hadrons.