Excited Hyperons and their Decays [1]

F. Myhrer

University of South Carolina

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Quark models have been extended to include exotic mesons and baryons

$\mathbf{QQ}\bar{Q}\bar{Q}$, $\mathbf{QQQQ}\bar{Q}$, $\mathbf{Q}\bar{Q}$**glue**, **glueballs** $\cdots$

Do these states exist?

What can the simple quark model teach us about the ordinary baryon structure?

The hyperons Λ^* and Σ^* have one "heavy" and two very light quarks.

Will this feature tell us something extra?

This baryon spectroscopy talk presents a few general quark-model arguments.

The focus will be on the first excited
Λ^* and Σ^* states.

These observations and arguments can be transferred to
Ξ^* and Ω^* and higher excited states.

Strange-baryon spectroscopy has made slow experimental progress
during the last decades.

Much of the talk is based on the extensive work of
Nathan Isgur and Gabriel Karl and coworkers.

^{3}H and ^{3}He have wave functions which are a linear combination of
spatial S, S$'$ and D states.

The baryons have three valence quarks.

Baryon states are mixtures of states.

These admixtures affects strongly some hyperon decays

The hadronic wave function is

$$\Psi = \Psi_{color}\ \Psi_{flavor}\ \Psi_{spin}\ \Psi_{space}$$

In this talk we assume that isospin is a good symmetry.
The masses $m_u = m_d = m_q$.
The s quark has mass $m_s > m_q$.
[In the (cloudy or MIT) bag model the u and d quarks are massless.]

The SU$_F$(3) is a broken symmetry.

Other assumptions:
(1) All hadrons are $SU(3)$-color singlets, i.e. Ψ_{color} is antisymmetric.

(2) Confinement between quarks is universal. It is the same for all quark flavors.

(3) Pauli says: Two identical quarks must have an anti-symmetric wave function.

(4) The non-relativistic quarks interact via gluon exchange, a la DeRujula et al. (1975).
This spin-spin interaction makes the *decuplet* baryons heavier than the *octet* baryons.

We adopt the one-gluon exchange (OGE) between quarks i and j:

$$H_{hyp}^{ij} = A_{ij}\left\{\frac{8\pi}{3}\vec{S}_i\cdot\vec{S}_j\delta^3(\vec{r}_{ij}) + \frac{1}{r_{ij}^3}\left(\frac{3(\vec{S}_i\cdot\vec{r}_{ij})(\vec{S}_j\cdot\vec{r}_{ij})}{r_{ij}^2} - \vec{S}_i\cdot\vec{S}_j\right)\right\}$$

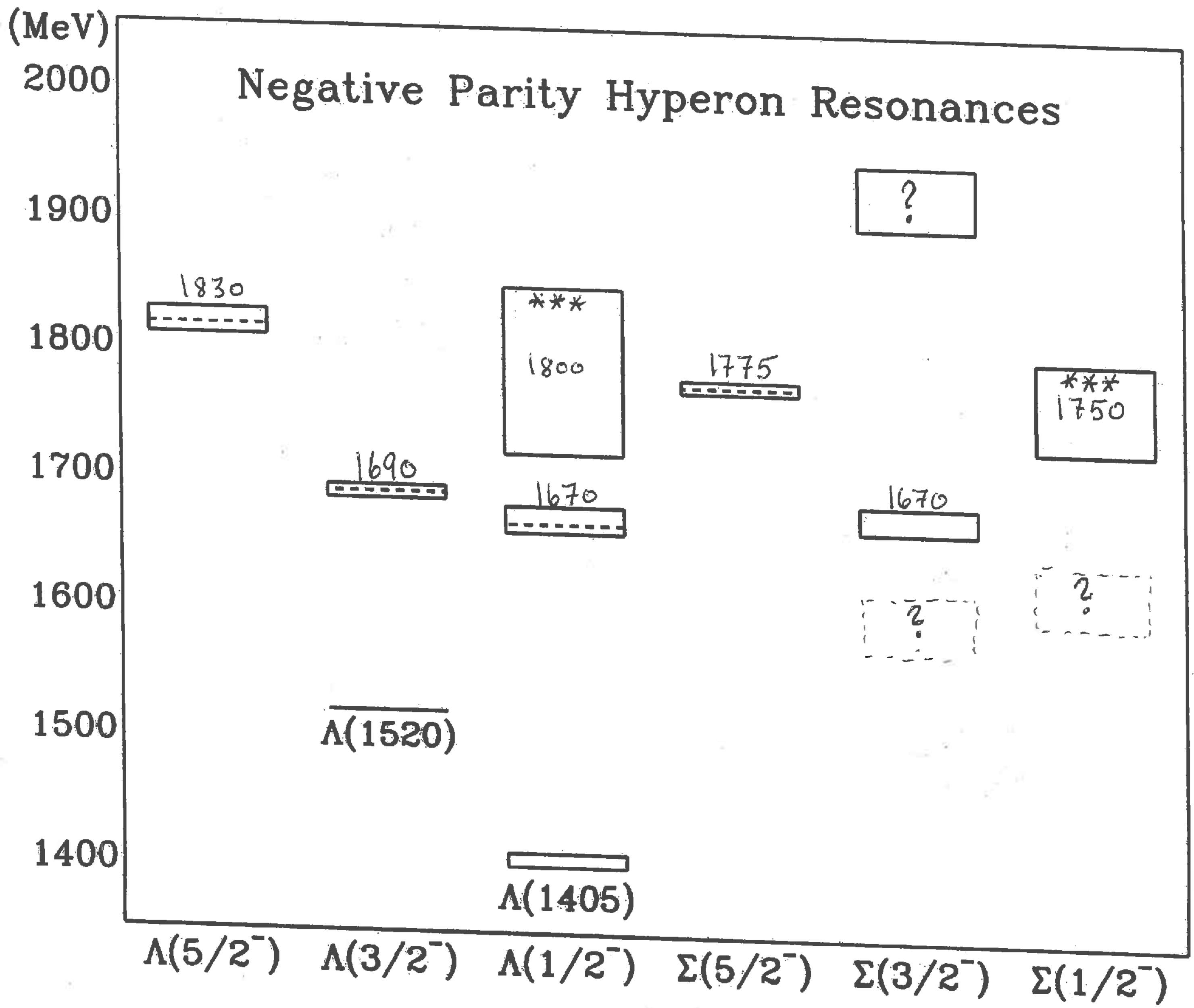
The spin-spin and the tensor interaction are closely related.

The spin-orbit force is left out.

Isgur and Karl argued it should.

Bag models, where a $j-j$ coupling is natural,

show that spin-orbit from scalar confinement and OGE cancel (roughly).


(MeV)
2000
1900
1800
1700
1600
1500
1400
Negative Parity Hyperon Resonances
1830
***
1800
1775
?
***
1750
1690
1670
1670
?
?
Λ(1520)
Λ(1405)
Λ(5/2⁻)
Λ(3/2⁻)
Λ(1/2⁻)
Σ(5/2⁻)
Σ(3/2⁻)
Σ(1/2⁻)

We define the spatial wave function with two relative coordinates

$$\vec{\rho} = (\vec{r}_1 - \vec{r}_2)\,/\sqrt{2}$$

$$\vec{\lambda} = (\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)\,/\sqrt{6}$$

(quarks 1 and 2 are the u and d quarks, quark 3 is the s-quark).

The corresponding masses are $m_\rho = m_q$ and $m_\lambda = 3m_q m_s/(2m_q + m_s)$.

We adopt the uds basis not the SU$_F$(3) basis.

In an NRQM the harmonic oscillator confinement potential gives a difference in ρ and λ oscillating frequencies:

$$\omega_\rho - \omega_\lambda = \omega_\rho \left[1 - \left(\frac{2(m_q/m_s) + 1}{3}\right)^{1/2}\right] > 0$$

The frequency ω_ρ is the one adopted for the nucleon ground state.

The masses of the two $J^P = 5/2^-$ states are split mainly due to confinement and a broken $SU_F(3)$ $m_q < m_s$.

This mass splitting is due to the following:

Both $J^P = 5/2^-$ states have symmetric spin wave functions $S = 3/2$.

$\Lambda^*(1830)$**, an iso-singlet, has a $\vec{\rho}$-dependent spatial wave function ($\vec{\rho}$ is anti-symmetric under $1 \leftrightarrow 2$).**

$\Sigma^*(1775)$**, an iso-triplet, has a $\vec{\lambda}$-dependent spatial wave function ($\vec{\lambda}$ is symmetric under $1 \leftrightarrow 2$).**

The mass difference due to $\hbar\omega_\rho - \hbar\omega_\lambda \approx 75$ MeV.

Decay ratio consequences:

$\Lambda^*(1830)$ **couples weakly to $\bar{K}N$ since the nucleon wave function is symmetric $1 \leftrightarrow 2$, whereas $\Sigma^*(1775)$ couples easily to $\bar{K}N$.**

These findings are modified by H_{hyp}.

As emphasized by Isgur and Karl even the ground state baryons have a complicated spatial wave function (a la ^{3}He?) due to H_{hyp}.

For example, the nucleon state is evaluated to be:

$$|N\rangle \simeq 0.90|^2S_S\rangle - 0.34|^2S'_S\rangle - 0.27|^2S_M\rangle - 0.06|^2D_M\rangle$$

Isgur and Karl find the $\Lambda(1116)$ to be:

$$|\Lambda\rangle \simeq 0.93|^2S_S\rangle - 0.30|^2S'_S\rangle - 0.20|^2S_M\rangle - 0.03|^4D_M\rangle - 0.05|\mathbf{1},^2S_M\rangle$$

(Isgur and Karl argue that the D-states can be ignored.)

These expressions indicates that the ground state baryons are not pure $|^2S_S\rangle$ states.

The other components will modify (sometimes strongly) the excited baryon to ground states <u>decay widths</u>.

Adding the mixed symmetric component $|^2S_M\rangle$ of the nucleon state gives the ratio of decay amplitudes (PRL 41, 1271):

$$\frac{\mathrm{A}(\Lambda(1830) \to \bar{K}N)}{\mathrm{A}(\Sigma(1775) \to \bar{K}N)} \simeq -0.28$$

The excited Λ^* and Σ^* states have similar mixed states.

Assume: one quark is in a P-state.
The two others are in S-states.

For a decay to the ground state it is the P-state quark which couples to the photon or the outgoing meson (π, $\bar{K}$ or η).

For example, the $\Lambda(1520)$ state is well established and is found to be:

$$|\Lambda(1520)\rangle \simeq a|^2\mathbf{1}\rangle + b|^4\mathbf{8}\rangle + c|^2\mathbf{8}\rangle$$

Different models give different a, b and c coefficients:
The harmonic oscillator NRQM of Isgur and Karl:
$a = 0.92$, $b = -0.04$ **and** $c = 0.39$.

A cloudy bag model gives:
$a = 0.95$, $b = -0.09$ **and** $c = 0.30$.

The decay widths of the two models are:

NRQM: $\Gamma[\Lambda(1520) \to \Lambda\gamma] = 96$ **keV,** $\Gamma[\Lambda(1520) \to \Sigma^0\gamma] = 74$ **keV**

Cloudy bag: $\Gamma[\Lambda(1520) \to \Lambda\gamma] = 32$ **keV,** $\Gamma[\Lambda(1520) \to \Sigma^0\gamma] = 49$ **keV**

Comparing several different model calculations of the decay rate Γ_γ:

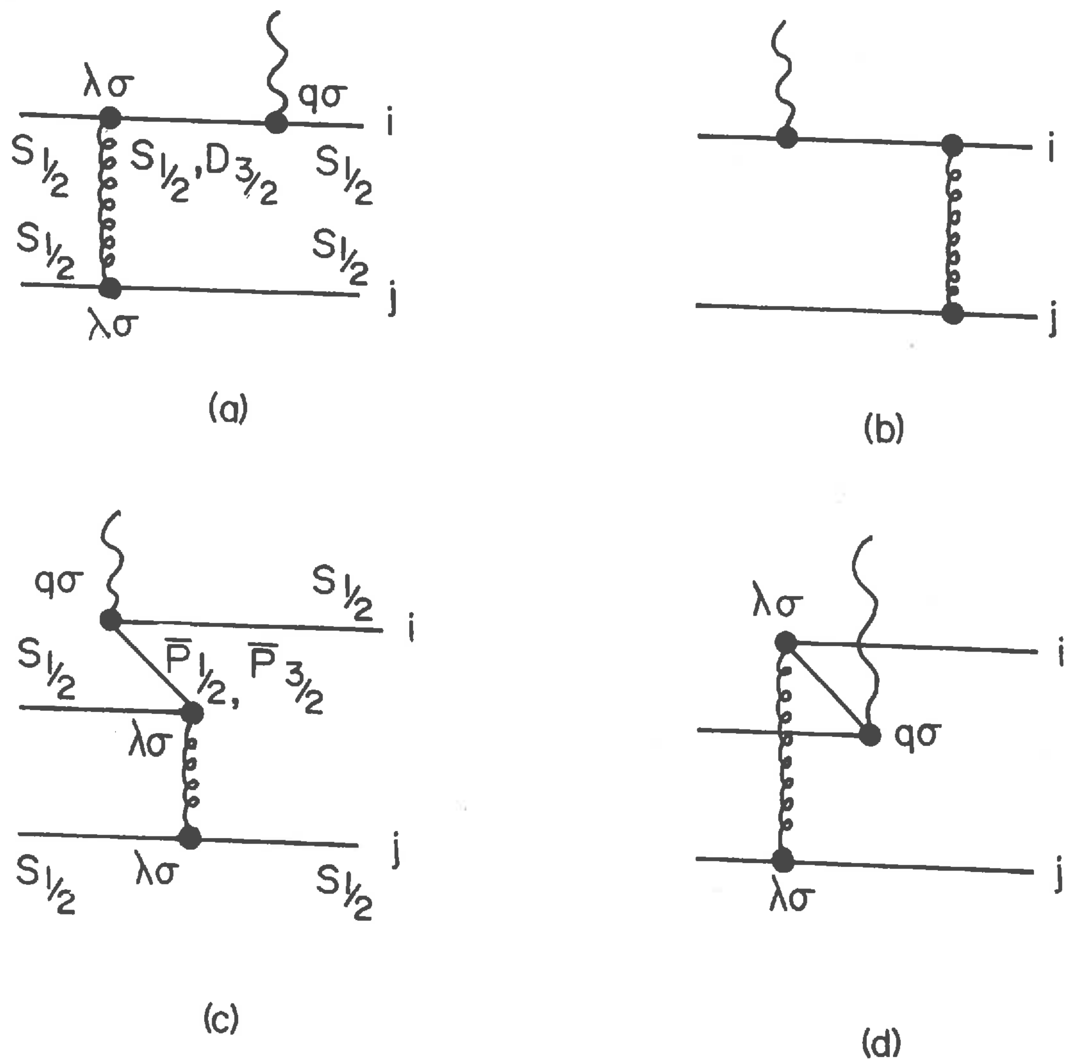
$$\Lambda(1520) \to \Lambda(1116) + \gamma$$

The configuration mixing in $\Lambda(1116)$ may change the rate by 50% or more.

A more precise determination of this decay rate is desirable.

Table 1 : The values of Γ_γ from various models.

Models	a	b	c	$\Lambda(1116)$	Γ_γ(keV)
NRQM	0.91	0.01	0.40	$^2S_S\rangle$	96
NRQM ($SU(6)-$basis)	0.91	0.01	0.40	–	98
χQM	0.91	0.01	−0.40	$^2S_S\rangle$	85
χQM	0.91	0.01	−0.40	mixed	134
NRQM ($uds-$basis)	–	–	–	mixed	154
MIT bag	0.86	0.34	−0.37	–	46
Chiral/Cloudy bag	0.95	0.09	−0.29	$^2S_S\rangle$	32
RCQM	0.91	0.01	0.40	mixed	215
Bonn – CQM	–	–	–	–	258


λσ
qσ
i
j
S1/2
S1/2, D3/2
(a)
(b)
(c)
(d)
P̄1/2, P̄3/2

In the cloudy bag model ($m_q = 0$ MeV)

the quark P-state with j=3/2 has a lower energy than j=1/2.

The bag confinement condition introduces a spin-orbit splitting of the quark states.

Fortunately, the relativistic OGE introduces a spin-orbit force of opposite sign.

In cloudy bag model calculations the two spin-orbit contributions basically cancel.

Effectively what remains are

the spin-spin and tensor interactions

due to OGE and the pseudo-meson cloud.

These interactions strongly affects the decay rates of Λ^* and Σ^* states

to $\bar{K}N$ and $\pi\Sigma$.

We need new data to test the various quark models.

Why is $\Lambda(1405)$ about 100 MeV below $\Lambda(1520)$?

Assuming the Λ^* states are mainly three-quark states,

quark models have serious problems generating this

large spin-orbit-like mass splitting.

Dalitz and Tuan proposed in 1960 that $\Lambda(1405)$ is a K^-p bound state

(a quark molecule?).

Is it a multi-quark state?

A recent very readable arXiv paper by Molina and Döring

discusses the pole structure of $\Lambda(1405)$.

This paper refers to many publications (including lattice evaluations).

Apart from recent measurements of the K^-p atom, most data are old.

We urgently need better data to settle this and the other issues,

SUMMARY

The lowest excited J^- Λ^* and Σ^* mass spectrum should be completed.

A K_L^0 beam on a hydrogen target can access the Σ^* states.

Σ^* decays to $\bar{K}N$ or $\pi\Sigma$ or both, or $\pi\Lambda$ according to theory estimates.

The reaction $\gamma + p \to K^+\Lambda^*$ can explore better the Λ^* states.

Theory needs Λ^* and Σ^* partial decay widths to make progress.