Heavy baryons in quantum field approaches

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Plan

- Historical overview
  - Experimental status and classification
  - Basic trends in theory:
    - $m_Q \to \infty$ limit in QCD
    - Heavy Quark Effective Theory (HQET)
    - Single and double heavy baryons in HQET
    - Heavy Hadron Chiral Perturbation Theory (HHChPT)
    - Heavy baryons at Large N$_c$
- Three-quark model for heavy baryons
  - Framework
  - Application to weak, em and strong decays
  - Magnetic moments of single and double heavy baryons
- Summary

Historical overview

- ⋆ Discovery of J/Ψ at BNL and SLAC (1974)
- ⋆ Charmed baryons Λ_c^+, Σ_c^{++} at BNL (1975), FNAL (1976)
- ⋆ Charmed baryons confirmed (masses, decays) at FNAL (1979)
- ⋆ Further experimental progress [Λ_c^+ baryon at SLAC]:
  e^+e^- annihilation (1979), semileptonic decays (1982)
- ⋆ Discovery of Υ at FNAL (1977)
- ⋆ Bottom baryon Λ_b^0 at FNAL (1981,1986), at CERN (since 1992)
- ⋆ Doubly charmed baryons Ξ_{cc}^+ at FNAL (2002)
- ⋆ Masses, lifetimes, decay form factors and widths, asymmetry parameters:
  BNL, CERN, CLEO, DESY, FNAL, KEK, IHEP

Historical overview

⋆ Algebraic schemes, 3q and qD models:

- classification
- mass formulas
- magnetic moments
- sum rules for weak decay amplitudes

A.De Rujula, H.Georgi, S.Glashow, PRD12 (1975) 147

M.Gaillard, B.Lee, J.Rosner, RMP47 (1975) 277

D.Lichtenberg, PRD15 (1977) 345

J.Körner, G.Kramer, J.Willrodt, ZPC2 (1979) 117

Historical overview

- ⋆ SU(5) classification of baryon states $5 \otimes 5 \otimes 5 = 10_A \oplus 40_M \oplus 40_M \oplus 35_S$
  - $F^{[mnk]}$ antisymmetric 10-plet $J^P = \frac{1}{2}^-$
  - $B^{m[nk]}$ two mixed 40-plets $J^P = \frac{1}{2}^+$
  - $D^{\{mnk\}}$ symmetric 35-plet $J^P = \frac{3}{2}^+$

  Light Baryons 19 = 1 [singlet] + 8 [octet] + 10 [decuplet]

- ⋆ $F^{[123]} = \Lambda^{*0}$

- ⋆ $B^{1[23]} = \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}}$ $\quad B^{2[23]} = \Sigma^-$ $\quad B^{3[23]} = \Xi^-$

  $B^{1[13]} = \Sigma^+$ $\quad B^{2[31]} = -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}}$ $\quad B^{3[13]} = \Xi^0$

  $B^{1[12]} = p$ $\quad B^{2[12]} = n$ $\quad B^{3[12]} = -\frac{2\Lambda^0}{\sqrt{6}}$

- ⋆ $D^{\{111\}} = \Delta^{++}$ $\quad D^{\{112\}} = \frac{\Delta^+}{\sqrt{3}}$ $\quad D^{\{122\}} = \frac{\Delta^0}{\sqrt{3}}$ $\quad D^{\{222\}} = \Delta^-$

  $D^{\{113\}} = \frac{\Sigma^{*+}}{\sqrt{3}}$ $\quad D^{\{123\}} = \frac{\Sigma^{*0}}{\sqrt{6}}$ $\quad D^{\{223\}} = \frac{\Sigma^{*-}}{\sqrt{3}}$

  $D^{\{133\}} = \frac{\Xi^{*0}}{\sqrt{3}}$ $\quad D^{\{233\}} = \frac{\Xi^{*-}}{\sqrt{3}}$ $\quad D^{\{333\}} = \Omega^-$

Historical overview

Single Charm Baryons 18 = 3 + 9 + 6

$\star$ $F^{[124]} = \Lambda_c^{*+}$ $F^{[134]} = \Lambda_{cs}^{*+}$ $F^{[234]} = \Lambda_{cs}^{*0}$

$\star$ $B^{1[24]} = \frac{\Sigma_c^+}{\sqrt{2}} + \frac{\Lambda_c^+}{\sqrt{6}}$ $B^{2[41]} = -\frac{\Sigma_c^+}{\sqrt{2}} + \frac{\Lambda_c^+}{\sqrt{6}}$ $B^{4[12]} = -\frac{2\Lambda_c^+}{\sqrt{6}}$

$B^{3[14]} = \frac{\Xi_c'^+}{\sqrt{2}} + \frac{\Xi_c^+}{\sqrt{6}}$ $B^{1[43]} = -\frac{\Xi_c'^+}{\sqrt{2}} + \frac{\Xi_c^+}{\sqrt{6}}$ $B^{4[31]} = -\frac{2\Xi_c^+}{\sqrt{6}}$

$B^{3[24]} = \frac{\Xi_c'^0}{\sqrt{2}} + \frac{\Xi_c^0}{\sqrt{6}}$ $B^{2[43]} = -\frac{\Xi_c^0}{\sqrt{2}} + \frac{\Xi_c'^0}{\sqrt{6}}$ $B^{4[32]} = -\frac{2\Xi_c^0}{\sqrt{6}}$

$B^{1[14]} = \Sigma_c^{++}$ $B^{2[24]} = \Sigma_c^0$ $B^{3[34]} = \Omega_c^0$

$\star$ $D^{\{114\}} = \frac{\Sigma_c^{*++}}{\sqrt{3}}$ $D^{\{124\}} = \frac{\Sigma_c^{*+}}{\sqrt{6}}$ $D^{\{224\}} = \frac{\Sigma_c^{*0}}{\sqrt{3}}$

$D^{\{134\}} = \frac{\Xi_c^{*+}}{\sqrt{6}}$ $D^{\{234\}} = \frac{\Xi_c^{*0}}{\sqrt{6}}$ $D^{\{334\}} = \frac{\Omega_c^{*0}}{\sqrt{3}}$

Historical overview

Single Bottom Baryons   18 = 3 + 9 + 6

⋆ $F^{[125]} = \Lambda_b^{*0}$ $F^{[135]} = \Lambda_{bs}^{*0}$ $F^{[235]} = \Lambda_{bs}^{*-}$

⋆ $B^{1[25]} = \frac{\Sigma_b^0}{\sqrt{2}} + \frac{\Lambda_b^0}{\sqrt{6}}$ $B^{2[51]} = -\frac{\Sigma_b^0}{\sqrt{2}} + \frac{\Lambda_b^0}{\sqrt{6}}$ $B^{5[12]} = -\frac{2\Lambda_b^0}{\sqrt{6}}$

$B^{3[15]} = \frac{\Xi_b'^0}{\sqrt{2}} + \frac{\Xi_b^0}{\sqrt{6}}$ $B^{1[53]} = -\frac{\Xi_b'^0}{\sqrt{2}} + \frac{\Xi_b^0}{\sqrt{6}}$ $B^{5[31]} = -\frac{2\Xi_b^0}{\sqrt{6}}$

$B^{3[25]} = \frac{\Xi_b'^-}{\sqrt{2}} + \frac{\Xi_b^-}{\sqrt{6}}$ $B^{2[53]} = -\frac{\Xi_b'^-}{\sqrt{2}} + \frac{\Xi_b^-}{\sqrt{6}}$ $B^{5[32]} = -\frac{2\Xi_b^-}{\sqrt{6}}$

$B^{1[15]} = \Sigma_b^+$ $B^{2[25]} = \Sigma_b^-$ $B^{3[35]} = \Omega_b^-$

⋆ $D^{\{115\}} = \frac{\Sigma_b^{*+}}{\sqrt{3}}$ $D^{\{125\}} = \frac{\Sigma_b^{*0}}{\sqrt{6}}$ $D^{\{225\}} = \frac{\Sigma_b^{*-}}{\sqrt{3}}$

$D^{\{135\}} = \frac{\Xi_b^{*0}}{\sqrt{6}}$ $D^{\{235\}} = \frac{\Xi_b^{*-}}{\sqrt{6}}$ $D^{\{335\}} = \frac{\Omega_b^{*-}}{\sqrt{3}}$

Historical overview

Double Charm Baryons 6 = 3 + 3

- ⋆ $B^{4[41]} = \Xi_{cc}^{++}$ $B^{4[42]} = \Xi_{cc}^{+}$ $B^{4[43]} = \Omega_{cc}^{+}$
- ⋆ $D^{\{144\}} = \frac{\Xi_{cc}^{*++}}{\sqrt{3}}$ $D^{\{244\}} = \frac{\Xi_{cc}^{*+}}{\sqrt{3}}$ $D^{\{344\}} = \frac{\Omega_{cc}^{*+}}{\sqrt{3}}$

Double Bottom Baryons 6 = 3 + 3

- ⋆ $B^{5[51]} = \Xi_{bb}^{0}$ $B^{5[52]} = \Xi_{bb}^{-}$ $B^{5[53]} = \Omega_{bb}^{-}$
- ⋆ $D^{\{155\}} = \frac{\Xi_{bb}^{*0}}{\sqrt{3}}$ $D^{\{255\}} = \frac{\Xi_{bb}^{*-}}{\sqrt{3}}$ $D^{\{355\}} = \frac{\Omega_{bb}^{*-}}{\sqrt{3}}$

Historical overview

Bottom-Charm Baryons 12 = 3 + 6 + 3

⋆ $F^{[145]} = \Lambda^{*+}_{cb}$ $F^{[245]} = \Lambda^{*0}_{cb}$ $F^{[345]} = \Lambda^{*0}_{cbs}$

⋆ $B^{1[45]} = \frac{\Xi'^{+}_{cb}}{\sqrt{2}} + \frac{\Xi^{+}_{cb}}{\sqrt{6}}$ $B^{4[51]} = -\frac{\Xi'^{+}_{bc}}{\sqrt{2}} + \frac{\Xi^{+}_{cb}}{\sqrt{6}}$ $B^{5[14]} = -\frac{2\Xi^{+}_{cb}}{\sqrt{6}}$

$B^{2[45]} = \frac{\Xi'^{0}_{cb}}{\sqrt{2}} + \frac{\Xi^{0}_{cb}}{\sqrt{6}}$ $B^{4[52]} = -\frac{\Xi'^{0}_{cb}}{\sqrt{2}} + \frac{\Xi^{0}_{cb}}{\sqrt{6}}$ $B^{5[24]} = -\frac{2\Xi^{0}_{cb}}{\sqrt{6}}$

$B^{3[45]} = \frac{\Omega'^{0}_{cb}}{\sqrt{2}} + \frac{\Omega^{0}_{cb}}{\sqrt{6}}$ $B^{4[53]} = -\frac{\Omega'^{0}_{bc}}{\sqrt{2}} + \frac{\Omega^{0}_{cb}}{\sqrt{6}}$ $B^{5[34]} = -\frac{2\Omega^{0}_{cb}}{\sqrt{6}}$

⋆ $D^{\{145\}} = \frac{\Xi^{*+}_{cb}}{\sqrt{6}}$ $D^{\{245\}} = \frac{\Xi^{*0}_{cb}}{\sqrt{6}}$ $D^{\{345\}} = \frac{\Omega^{*0}_{cb}}{\sqrt{6}}$

Triple Heavy Baryons 6 = 2 + 4

⋆ $B^{4[45]} = \Omega^{+}_{bcc}$ $B^{5[45]} = \Omega^{0}_{bbc}$

⋆ $D^{\{444\}} = \Omega^{*++}_{ccc}$ $D^{\{445\}} = \frac{\Omega^{*+}_{ccb}}{\sqrt{3}}$ $D^{\{455\}} = \frac{\Omega^{*0}_{cbb}}{\sqrt{3}}$ $D^{\{555\}} = \Omega^{*-}_{bbb}$

Historical overview

- J.Körner, M.Krämer, D.Pirjol, PPNP33 (1994) 787

Charm $1/2^+$ and $3/2^+$ baryons

Notation	Content	J^P	SU(3)	(I, I_3)	S	C	Mass (GeV)
Λ_c^+	$c[ud]$	$1/2^+$	3^*	(0, 0)	0	1	2.285
Ξ_c^+	$c[su]$	$1/2^+$	3^*	(1/2, 1/2)	-1	1	2.466
Ξ_c^0	$c[sd]$	$1/2^+$	3^*	(1/2, -1/2)	-1	1	2.472
Σ_c^{++}	cuu	$1/2^+$	6	(1, 1)	0	1	2.453
Σ_c^+	$c\{ud\}$	$1/2^+$	6	(1, 0)	0	1	2.451
Σ_c^0	cdd	$1/2^+$	6	(1, -1)	0	1	2.452
$\Xi_c^{\prime +}$	$c\{su\}$	$1/2^+$	6	(1/2, 1/2)	-1	1	2.574
$\Xi_c^{\prime 0}$	$c\{sd\}$	$1/2^+$	6	(1/2, -1/2)	-1	1	2.579
Ω_c^0	css	$1/2^+$	6	(0, 0)	-2	1	2.698
Σ_c^{*++}	cuu	$3/2^+$	6	(1, 1)	0	1	2.519
Σ_c^{*+}	cud	$3/2^+$	6	(1, 0)	0	1	2.516
Σ_c^{*0}	cdd	$3/2^+$	6	(1, -1)	0	1	2.518
Ξ^{*+}	cus	$3/2^+$	6	(1/2, 1/2)	-1	1	2.647
Ξ^{*0}	cds	$3/2^+$	6	(1/2, -1/2)	-1	1	2.645
Ω_c^{*0}	css	$3/2^+$	6	(0, 0)	-2	1	2.74

Historical overview

Bottom $1/2^+$ and $3/2^+$ baryons

Notation	Content	J^P	SU(3)	(I, I_3)	S	B	Mass (GeV)
Λ_b	$b[ud]$	$1/2^+$	3^*	(0, 0)	0	1	5.624
Ξ_b^0	$b[su]$	$1/2^+$	3^*	(1/2, 1/2)	-1	1	5.80
Ξ_b^-	$b[sd]$	$1/2^+$	3^*	(1/2, -1/2)	-1	1	5.80
Σ_b^+	buu	$1/2^+$	6	(1, 1)	0	1	5.82
Σ_b^0	$b\{ud\}$	$1/2^+$	6	(1, 0)	0	1	5.82
Σ_b^-	bdd	$1/2^+$	6	(1, -1)	0	1	5.82
$\Xi_b^{\prime 0}$	$b\{su\}$	$1/2^+$	6	(1/2, 1/2)	-1	1	5.94
$\Xi_b^{\prime -}$	$b\{sd\}$	$1/2^+$	6	(1/2, -1/2)	-1	1	5.94
Ω_b^-	bss	$1/2^+$	6	(0, 0)	-2	1	6.04
Σ_b^{*+}	buu	$3/2^+$	6	(1, 1)	0	1	5.84
Σ_b^{*0}	bud	$3/2^+$	6	(1, 0)	0	1	5.84
Σ_b^{*-}	bdd	$3/2^+$	6	(1, -1)	0	1	5.84
Ξ_b^{*0}	bus	$3/2^+$	6	(1/2, 1/2)	-1	1	5.94
Ξ_b^{*-}	bds	$3/2^+$	6	(1/2, -1/2)	-1	1	5.94
Ω_b^{*-}	bss	$3/2^+$	6	(0, 0)	-2	1	6.06

Historical overview

- V.Kiselev, A.Likhoded, Phys.Usp.45 (2002) 455

Double heavy $1/2^+$ and $3/2^+$ baryons [$q = u$ or d]

Notation	Content	J^P	I	S	C	B	Mass (GeV)
Ξ_{cc}	$q\{cc\}$	$1/2^+$	1/2	0	2	0	3.519
Ω_{cc}^+	$s\{cc\}$	$1/2^+$	0	-1	2	0	3.59
Ξ_{cc}^*	$q\{cc\}$	$3/2^+$	1/2	0	2	0	3.61
Ω_{cc}^{*+}	$s\{cc\}$	$3/2^+$	0	-1	2	0	3.69
Ξ_{bb}	$q\{bb\}$	$1/2^+$	1/2	0	0	2	10.09
Ω_{bb}^-	$s\{bb\}$	$1/2^+$	0	-1	0	2	10.18
Ξ_{bb}^*	$q\{bb\}$	$3/2^+$	1/2	0	0	2	10.13
Ω_{bb}^{*-}	$s\{bb\}$	$3/2^+$	0	-1	0	2	10.20
Ξ_{cb}	$q[cb]$	$1/2^+$	1/2	0	1	1	6.82
Ω_{cb}^0	$s[cb]$	$1/2^+$	0	-1	1	1	6.91
Ξ_{cb}'	$q\{cb\}$	$1/2^+$	1/2	0	1	1	6.85
$\Omega_{cb}'^0$	$s\{cb\}$	$1/2^+$	0	-1	1	1	6.93
Ξ_{cb}^*	$q\{cb\}$	$3/2^+$	1/2	0	1	1	6.90
Ω_{cb}^{*0}	$s\{cb\}$	$3/2^+$	0	-1	1	1	6.99

Historical overview

Triple heavy $1/2^+$ and $3/2^+$ baryons

Notation	Content	J^P	C	B	Mass (GeV)
Ω_{ccb}^{+}	ccb	$1/2^+$	2	1	8.0
Ω_{cbb}^{0}	cbb	$1/2^+$	1	2	11.5
Ω_{ccc}^{*++}	ccc	$3/2^+$	3	0	4.73
Ω_{ccb}^{*+}	ccb	$3/2^+$	2	1	8.0
Ω_{cbb}^{*0}	cbb	$3/2^+$	1	2	11.5
Ω_{bbb}^{*-}	bbb	$3/2^+$	0	3	15.0

Historical overview

- QCD simplifies in the $m_Q \to \infty$ limit

- E.Shuryak, PLB93 (1980) 134, NPB198 (1982) 83

  Q in hadron c.m., static center $\to$ proton in H-atom;
  masses, spin and em splittings of D, B, Σ_c and Λ_c;
  3q currents of heavy baryons

- E.Eichten, F.Feinberg, PRD23 (1981) 2724

  $1/m_Q$ expansion of heavy quark propagator;
  spin-dependent forces for $Q\bar{q}$ systems are governed by m_q

- W.Caswell, G.Lepage, PLB167 (1986) 437
  G.Lepage, B.Thacker, NPB Proc. Suppl. 4 (1988) 504

  Nonrelativistic effective Lagrangians for bound-state systems

- M.Voloshin, M.Shifman, SJNP45 (1987) 292
  H.Politzer, M.Wise, PLB206 (1988) 681
  Asymptotic behavior of $f_P \sim m_Q^{-1/2}$ at $m_Q \to \infty$

Historical overview

- Heavy Quark Symmetry (Isgur-Wise Symmetry)

  N.Isgur, M.Wise, PLB 232 (1989) 113; 237 (1990) 527

  Limit $m_Q \to \infty$ gives rise to a new spin-flavor symmetry

  Q is surrounded by a light quark (heavy meson)

  or by a light diquark cloud (heavy baryon)

  $\mu_H = \frac{m_Q\, m_l}{m_Q + m_l} \to m_l$ no dependence on m_Q [flavor symmetry]

  $H_{s_Q s_l} \sim \frac{\vec{s}_Q\, \vec{s}_l}{m_Q\, m_l} \to 0$ spins decouple [spin symmetry]

- Velocity Superselection Rule

  H.Georgi, PLB 240 (1990) 447

  Initial state $P^\mu = m_Q v^\mu \quad \to$ Final state $P'^\mu = m_Q v'^\mu + k^\mu$

  $v^\mu = v'^\mu$ at $m_Q \to \infty$ for fixed k^μ

Historical overview

⋆ <u>H</u>eavy <u>Q</u>uark <u>E</u>ffective <u>T</u>heory (HQET)

H.Politzer, M.Wise, PLB206 (1988) 681; N.Isgur, M.Wise, PLB232 (1989) 113; E.Eichten, B.Hill, PLB234 (1990) 511; B.Grinstein, NPB339 (1990) 253; H.Georgi, PLB240 (1990) 447; J.Korner, G.Thompson, PLB264 (1991) 185; T.Mannel, W.Roberts, Z.Ryzak, NPB368 (1992) 204; ...

Systematic approximation to QCD using methods of EFT

QCD $\mathcal{L}_{\rm QCD} = \bar{Q}[i\,\not{D} - m_Q]Q$

$$Q(x) = e^{-im_Q v\cdot x}\,[h_v^+(x) + h_v^-(x)), \qquad \not{v}h_v^\pm(x) = \pm h_v^\pm(x)$$

$$D_\mu = v_\mu v\cdot D + D_\mu^\perp, \qquad D_\mu^\perp = D_\mu - v_\mu v\cdot D$$

HQET Integrate out low component h_v^-

$$\mathcal{L}_{\rm HQET} = \bar{h}_v^+\, iv\cdot D h_v^+ - \lim_{\epsilon\to+0} \bar{h}_v^+\ \not{D}^\perp \frac{1}{iv\cdot D + 2m_Q - i\epsilon}\ \not{D}^\perp\, h_v^+$$

Factorization of long and short distance effects at any order in $1/m_Q$

$$G_{\rm full}(p_1 ... p_n; m_Q, \mu_0 = m_Q) = \sum_N \left(\frac{1}{m_Q}\right)^N \underbrace{Z^{(N)}(m_Q,\mu)}_{\rm short}\ \underbrace{G_{\rm eff}^{(N)}(p_1 ... p_n;\mu)}_{\rm long}$$

Review M.Neubert, PR245 (1994) 259

Introduction to HQET; SB corrections; weak decays of HL hadrons

Historical overview

⋆ Single heavy baryons in HQET

N.Isgur, M.Wise, NPB348 (1991) 276; H.Georgi, NPB348 (1990) 447;
T.Mannel, W.Roberts, Z.Ryzak, NPB355 (1991) 38;
F.Hussain, J.Körner, M.Krämer, G.Thompson, ZPC51 (1991) 321; ...

- Flavor symmetry: mass difference coincide for c and b baryons with different quantum numbers of light degrees of freedom

  $m_{\Sigma_b} - m_{\Lambda_b} = m_{\Sigma_c} - m_{\Lambda_c} \simeq 200$ MeV

  Spin symmetry: 3/2 and 1/2 states degenerate, mass splitting $\sim 1/m_Q$

  $m_{\Sigma_c^*} - m_{\Sigma_c} \simeq 75$ MeV $\ll \bar{\Lambda} = 500 - 700$ MeV

- Weak decays matrix elements

$$\langle \Lambda_{Q_2}(v_2)|\bar{h}^{Q_2}_{v_2} \Gamma h^{Q_1}_{v_1}|\Lambda_{Q_1}(v_1)\rangle = \xi(\omega)\ \bar{u}(v_2)\Gamma u(v_1)$$

$$\langle \Sigma^{(*)}_{Q_2}(v_2)|\bar{h}^{Q_2}_{v_2} \Gamma h^{Q_1}_{v_1}|\Sigma^{(*)}_{Q_1}(v_1)\rangle = [-g^{\mu\nu}\zeta_1(\omega) + v_1^\mu v_2^\nu \zeta_2(\omega)]\ \bar{u}_\mu(v_2)\Gamma u_\nu(v_1)$$

$u_\mu(v)$ for Σ^*_Q $\qquad u_\mu(v) = \frac{1}{\sqrt{3}}(\gamma_\mu + v_\mu)\gamma_5\, u(v)$ for Σ_Q

Isgur-Wise functions $\qquad \xi(\omega)\,,\ \zeta_1(\omega)\,,\ \zeta_2(\omega)$ $\qquad$ with $\omega = v_1 \cdot v_2$

Normalization $\qquad \xi(1) = \zeta_1(1) = 1$

Historical overview

⋆ Double heavy baryons in HQET
M.Savage, M.Wise, PLB248 (1990) 177; M.White, M.Savage, PLB271 (1991) 410

QQq - bound state of heavy QQ pair (pointlike object) and light quark q

Color triplet system $\varepsilon^{abc}\bar{Q}^b\bar{Q}^c \simeq T^a$

No dependence on heavy triplet mass and spin Heavy quarks move in spin-independent Coulomb potential

- Antibaryon $\bar{Q}\bar{Q}\bar{q}$ related to heavy meson $Q\bar{q}$

$$m_{\Sigma^*_{\bar{Q}_{12}}} - m_{\Sigma_{\bar{Q}_{12}}} = \frac{3}{2}\frac{m_{Q_3}}{\mu_{\bar{Q}_{12}}}[m_{P^*_{Q_3}} - m_{P_{Q_3}}]$$

- Semileptonic decay matrix elements

$$\langle\Lambda_{Q_{23}}(v_2)|\bar{Q}_2\gamma_\mu(1-\gamma_5)Q_1|\Lambda_{Q_{13}}(v_1)\rangle = \eta_{Q_{123}}(v_1,v_2)\,\frac{(v_1+v_2)_\mu}{4\tilde{m}}\,\bar{u}(v_2)u(v_1)$$

$\eta_{Q_{123}}(v_1,v_2)$ product of IW function $\xi(\omega)$ with overlap of "in" and "fin" Coulomb wf

$\tilde{m} = [(m_{Q_1}+m_{Q_3})(m_{Q_2}+m_{Q_3})]^{1/2}$

⋆ Double heavy baryons in combined approach HQET + NRQCD + pNRQCD
V.Kiselev, A.Likhoded, Phys.Usp.45 (2002) 455

Historical overview

- ⋆ Heavy Hadron Chiral Perturbation Theory (HHChPT)

  M.Wise, PRD45 (1992) R2188; G.Burdman, J.Donoghue, PLB280 (1992) 287;
  T.Yan, et al., PRD46 (1992) 1148; P.Cho, PLB285 (1992) 145;
  P.Cho, H.Georgi, PLB296 (1992) 408

- EFT based on ChPT (expansion in m_q) and HQET (expansion in $1/m_Q$)

  HH and light PS mesons $U = \xi^2 = \exp(i\hat{P}/F_\pi)$

  HH emit and absorb chiral fields without change of velocity v

- LO chiral Lagrangian for soft hadronic and em interactions of heavy baryons

$$\mathcal{L} = \bar{T}_i ivDT_i - \bar{S}_{\mu,ij} ivDS^\mu_{ij} + \Delta_{\rm ST}\bar{S}_{\mu,ij}S^\mu_{ij} + g_2\varepsilon_{\mu\nu\sigma\lambda}v^\nu\bar{S}_{\mu,ik}i\xi^\sigma_{ij}S^\rho_{jk}$$
$$+g_3\varepsilon_{ijk}\,[\,\bar{T}_i\xi^\mu_{jl}S_{\mu,kl} + \bar{S}_{\mu,kl}\xi^\mu_{lj}T_i\,]$$

$$S^\mu_{ij} = (\gamma^\mu + v^\mu)\gamma^5 S_{ij}/\sqrt{3} + S^{*\mu}_{ij} \qquad \xi_\mu = \frac{i}{2}(\xi D_\mu \xi^\dagger - \xi^\dagger D_\mu \xi)$$

$$T = \{\Xi_c^{0A}\,, -\Xi_c^{+A}\,, \Lambda_c^+\} \qquad S = \{\Sigma_c^{++}\,, \Sigma_c^+\,, \Sigma_c^0\,, \Xi_c^{0S}\,, -\Xi_c^{+S}\,, \Omega_c^0\}$$

  Corrections: long-distance $1/\Lambda_\chi$, short-distance $1/m_Q$ and chiral m_q

- ⋆ Chiral Lagrangians for heavy baryons

  Yu.Kalinovsky, V.Pervushin, N.Sarikov, PLB166 (1986) 351; PLB180 (1986) 141

Historical overview

⋆ Heavy baryons at Large N_c

C.Galan, I.Klebanov, NPB262 (1985) 365; PLB202 (1988) 269;
E.Jenkins, A.Manohar, PLB294 (1992) 273; Z.Guralnik et al., NPB390 (1993) 474;
E.Jenkins et al., NPB396 (1993) 7

- Bound states of solitons (N, Δ, etc.) and heavy mesons D , D^* , B , B^*
  Attractive harmonic oscillator potential

- Combined HQ and large-N_c limit: a new contracted symmetry exists connecting orbitally excited and ground states

- Universal relations between baryon IW functions
  Large N_c C.-K. Chow, PRD51 (1995) 1224; PRD54 (1996) 837

  Spectator quark model J.Körner, M.Krämer, D.Pirjol, PPNP33 (1994) 787;
  M.Ivanov, J.Körner, V.Lyubovitskij, A.Rusetsky, PRD59 (1999) 074016

  $\xi(\omega) = \zeta_1(\omega) = \zeta_2(\omega)(\omega+1) = f(\omega)\frac{\omega+1}{2}$ with $f(1) = 1$

  Soliton model: E.Jenkins et al., NPB396 (1993) 7
  $\xi(\omega) = \exp[-\lambda N_c^{3/2}(\omega-1)]$ with $\lambda \sim 1$

Historical overview

- ⋆ Heavy baryons in QCD motivated approaches
- Lattice QCD
- QCD sum rules
- Quark models
- Bethe-Salpeter approaches
- Soliton approaches
- . . .

- ⋆ Calculated characteristics
- Isgur-Wise functions
- Mass spectrum and lifetimes
- Weak, em and strong decay amplitudes, widths, etc.

Three-quark model for heavy baryons

- Collaboration
  M.Ivanov (Dubna), J.Körner (Mainz), P.Kroll (Wuppertal), A.Rusetsky (Bonn), A.Faessler, T.Gutsche, D.Nicmorus, K.Pumsa-ard (Tübingen)

- Baryons - bound states of constituent quarks

- Int. Lagrangian of three low-lying SU(5) multiplets with their $3q$ currents

$$\mathcal{L}_{\rm int} = \mathcal{L}_{\rm int}^{1/2^-} + \mathcal{L}_{\rm int}^{1/2^+} + \mathcal{L}_{\rm int}^{3/2^+}$$

$$\mathcal{L}_{\rm int}^{1/2^-} = g_F \bar{F}^{[m_1 m_2 m_3]} J_F^{m_1 m_2 m_3} + \text{h.c.}$$

$$\mathcal{L}_{\rm int}^{1/2^+} = g_B \bar{B}^{[m_1 m_2] m_3} J_B^{m_1 m_2 m_3} + \text{h.c.}$$

$$\mathcal{L}_{\rm int}^{3/2^+} = g_D \bar{D}^{\{m_1 m_2 m_3\};\mu} J_D^{m_1 m_2 m_3;\mu} + \text{h.c.}$$

- Compositeness condition
  $Z_B = 1 - g_B^2 \Sigma'_B(m_B) = 0$

Three-quark model for heavy baryons

⋆ Three-quark currents

$$J_B(x) = \int dx_1 dx_2 dx_3 \underbrace{F_B(x; x_1 x_2 x_3)}_{\text{vertex function}} \Gamma_B^1 q^a(x_1)\, q^b(x_2)\, C\, \Gamma_B^2\, q^c(x_3)\, \varepsilon^{abc}$$

- Proton

$$J_p^V = \gamma^\mu \gamma^5 d^a u^b C \gamma_\mu u^c \varepsilon^{abc}$$

$$J_p^T = \sigma^{\mu\nu} \gamma^5 d^a u^b C \sigma_{\mu\nu} u^c \varepsilon^{abc}$$

- Λ_Q baryons

$$J_{\Lambda_Q}^P = Q^a u^b C \gamma_5 d^c \varepsilon^{abc}$$

$$J_{\Lambda_Q}^S = \gamma^5 Q^a u^b C d^c \varepsilon^{abc}$$

$$J_{\Lambda_Q}^A = \gamma^\mu Q^a u^b C \gamma_\mu \gamma_5 d^c \varepsilon^{abc}$$

- Σ_Q baryons

$$J_{\Sigma_Q}^V = \gamma^\mu \gamma^5 Q^a u^b C \gamma_\mu u^c \varepsilon^{abc}$$

$$J_{\Sigma_Q}^T = \sigma^{\mu\nu} \gamma^5 Q^a u^b C \sigma_{\mu\nu} u^c \varepsilon^{abc}$$

Three-quark model for heavy baryons

⋆ Vertex function

$$F_B(x;x_1x_2x_3) = \delta(x - \sum_{i=1}^{3} \mu_i x_i)\ \Phi_B[\sum_{i<j}(x_i - x_j)^2]$$

- Euclidean region
  $\tilde{\Phi}_B[(k_1^2 + k_2^2)/\Lambda_B^2] = \exp[-(k_1^2 + k_2^2)/\Lambda_B^2]$

- Provide UV convergense of loop integrals

⋆ Quark propagator $S_i(k) = \frac{1}{m_i - \not{k}}$ with $i = u, d, s, c, b$

- $1/m_Q$ expansion for c and b quark

$$S_v(k, \bar{\Lambda}, m_Q) = \frac{1+\not{v}}{2}\,[-\frac{1}{kv+\bar{\Lambda}} + \frac{(k+v\bar{\Lambda})^2}{2m_Q(kv+\bar{\Lambda})^2} - \frac{1}{2m_Q}]$$

$\bar{\Lambda} = M_{B_Q} - m_Q = 600$ MeV

Three-quark model for heavy baryons

⋆ Parameters

- Quark masses

m_u	m_s	m_c	m_b	
0.420	0.570	1.67	5.1	(GeV)

- Baryon size parameters Λ

Λ_{qqq}	Λ_{Qqq}	Λ_{QQq}	
1	1.25	2.5	(GeV)

Three-quark model for heavy baryons

- ⋆ Semileptonic decays $B_i \to B_f + l + \nu_l$

M.Ivanov, V.Lyubovitskij, J.Körner, P.Kroll, PRD56 (1997) 348;
M.Ivanov et al., PRD61 (2000) 114010; A.Faessler et al., PLB518 (2001) 55

$\Lambda_b \to \Lambda_c$

$$\xi(\omega) = (\frac{2}{1+\omega})^{1.7+1/\omega}$$

$$\rho_\xi = -\xi'(1) = 1.05 \pm 0.3$$

$$\mathrm{Br}(\Lambda_b \to \Lambda_c e \nu_e) = (7.8 \pm 1.1)\%$$

DELPHI Coll., PLB585 (2004) 63

$$\rho_\xi = 2.03 \pm 0.46(\mathrm{stat})$$

$$\mathrm{Br}(\Lambda_b \to \Lambda_c e \nu_e) = (5.0^{+1.1}_{-0.8}(\mathrm{stat}))\%$$

ρ_ξ = 0.65 (QCD SR, Dai et al, 96); 0.65-0.85 (QCD SR, Grozin,Yakovlev, 92/99)

= $1.2^{+0.8}_{-1.1}$ (Lattice QCD, Bowler et al, 98); 1.3 (Skyrme model, Jenkins et al, 93)

= 1.44 (IMF QM, König et al, 97); 2.35 (MIT Bag, Sadzikowski, Zalewski, 93)

Three-quark model for heavy baryons

- Nonleptonic decays $B_i \to B_f + M$

M.Ivanov, J.Körner, V.Lyubovitskij, A.Rusetsky, PRD57 (1998) 5632

Branchings (in %) for heavy-light transitions

Process	Our	Experiment
$\Lambda_c^+ \to \Lambda\pi^+$	0.79	0.90$\pm$ 0.28
$\Lambda_c^+ \to \Sigma^0\pi^+$	0.88	0.99$\pm$ 0.32
$\Lambda_c^+ \to \Sigma^+\pi^0$	0.88	1.00 $\pm$ 0.34
$\Lambda_c^+ \to p\bar{K}^0$	2.06	2.3$\pm$ 0.6
$\Lambda_c^+ \to \Xi^0 K^+$	0.31	0.39$\pm$ 0.14
$\Lambda_c^+ \to p\phi$	0.14	0.082$\pm$ 0.027
$\Xi_c^0 \to \Xi^0\pi^0$	0.04	
$\Xi_c^0 \to \Sigma^+ K^-$	0.27	
$\Omega_c^0 \to \Xi^0\bar{K}^0$	0.02	
$\Lambda_b^0 \to \Lambda\pi^0$	4.92 $\times 10^{-5}$	
$\Lambda_b^0 \to pK^-$	2.1 $\times 10^{-4}$	< 5 $\times 10^{-3}$
$\Lambda_b^0 \to J/\psi\Lambda$	0.06	0.047 $\pm$ 0.028

Three-quark model for heavy baryons

Decay widths Γ (in 10^{10} s^{-1}) for heavy-heavy transitions

Process	Γ	Process	Γ
$\Lambda_b^0 \to \Lambda_c^+ \pi^-$	0.382	$\Xi_b^0 \to \Xi_c^{\prime 0} \pi^0$	0.014
$\Lambda_b^0 \to \Sigma_c^+ \pi^-$	0.039	$\Xi_b^0 \to \Xi_c^{\prime 0} \eta$	0.015
$\Lambda_b^0 \to \Sigma_c^0 \pi^0$	0.039	$\Xi_b^0 \to \Xi_c^{\prime 0} \eta^\prime$	0.021
$\Lambda_b^0 \to \Sigma_c^0 \eta$	0.023	$\Xi_b^0 \to \Lambda_c^+ K^-$	0.010
$\Lambda_b^0 \to \Sigma_c^0 \eta^\prime$	0.029	$\Xi_b^0 \to \Sigma_c^+ K^-$	0.030
$\Lambda_b^0 \to \Xi_c^0 K^0$	0.021	$\Xi_b^0 \to \Sigma_c^0 \bar{K}^0$	0.021
$\Lambda_b^0 \to \Xi_c^{\prime 0} K^0$	0.032	$\Xi_b^0 \to \Omega_c^0 K^0$	0.023
$\Xi_b^0 \to \Xi_c^+ \pi^-$	0.479	$\Xi_b^- \to \Xi_c^0 \pi^-$	0.645
$\Xi_b^0 \to \Xi_c^{\prime +} \pi^-$	0.018	$\Xi_b^- \to \Xi_c^{\prime 0} \pi^-$	0.007
$\Xi_b^0 \to \Xi_c^0 \pi^0$	0.002	$\Xi_b^- \to \Sigma_c^0 K^-$	0.016
$\Xi_b^0 \to \Xi_c^0 \eta$	0.012	$\Omega_b^- \to \Omega_c^0 \pi^-$	0.352

Three-quark model for heavy baryons

⋆ Strong decays $B_i \to B_f + M$

One-pion decay widths (in MeV):

M.Ivanov, J.Korner, V.Lyubovitskij, A.Rusetsky, PRD60 (1999) 094002

Process	Our	Experiment
P-wave transitions		
$\Sigma_c^+ \to \Lambda_c \pi^0$	3.63 ± 0.27	
$\Sigma_c^0 \to \Lambda_c \pi^-$	2.65 ± 0.19	$\Gamma_{\Sigma_c^0} = 2.5 \pm 0.2 \pm 0.3$
$\Sigma_c^{++} \to \Lambda_c \pi^+$	2.85 ± 0.19	$\Gamma_{\Sigma_c^{++}} = 2.3 \pm 0.2 \pm 0.3$
$\Sigma_c^{*0} \to \Lambda_c \pi^-$	21.21 ± 0.81	$13.0^{+3.7}_{-3.0}$
$\Sigma_c^{*++} \to \Lambda_c \pi^+$	21.99 ± 0.87	$17.9^{+3.8}_{-3.2}$
$\Xi_c^{*0} \to \Xi_c^0 \pi^0$	1.01 ± 0.15	
$\Xi_c^{*0} \to \Xi_c^+ \pi^-$	2.11 ± 0.29	$\Gamma_{\Xi^{*0}} < 5.5$
$\Xi_c^{*+} \to \Xi_c^0 \pi^+$	1.78 ± 0.33	
$\Xi_c^{*+} \to \Xi_c^+ \pi^0$	1.26 ± 0.17	$\Gamma_{\Xi^{*+}} < 3.1$
S-wave transitions		
$\Lambda_{c1;S} \to \Sigma_c^0 \pi^+$	0.83 ± 0.09	0.86 ± 0.25
$\Lambda_{c1;S} \to \Sigma_c^+ \pi^0$	0.98 ± 0.12	
$\Lambda_{c1;S} \to \Sigma_c^{++} \pi^-$	0.79 ± 0.09	0.86 ± 0.25
$\Xi_{c1;S}^* \to \Xi_c^{*0} \pi^+$	0.46 ± 0.03	
$\Xi_{c1;S}^* \to \Xi_c^{*+} \pi^0$	0.24 ± 0.02	$\Gamma_{\Xi_{c1;S}^*} < 2.4$
$\Sigma_{c1;A}^0 \to \Sigma_c^+ \pi^-$	0.11 ± 0.001	

Three-quark model for heavy baryons

One-pion decay widths (in MeV)

Process	Our	Experiment
D-wave transitions		
$\Lambda^*_{c1;S} \to \Sigma_c^0 \pi^+$	0.08 ± 0.01	< 0.13
$\Lambda^*_{c1;S} \to \Sigma_c^+ \pi^0$	0.10 ± 0.01	$\Gamma_{\Lambda^*_{c1}} < 1.9$
$\Lambda^*_{c1;S} \to \Sigma_c^{++} \pi^-$	0.08 ± 0.01	< 0.15
$\Xi^*_{c1;S} \to \Xi_c^{0\prime} \pi^+$	0.35 ± 0.05	
$\Xi^*_{c1;S} \to \Xi_c^{+\prime} \pi^0$	0.21 ± 0.03	$\Gamma_{\Xi^*_{c1}} < 2.4$
$\Sigma^{*0}_{c1;A} \to \Sigma_c^+ \pi^-$	$\approx$ 0.001	

Three-quark model for heavy baryons

- ⋆ Electromagnetic decays $B_i \to B_f + \gamma$

Radiative decay widths (in KeV):

M.Ivanov, J.Körner, V.Lyubovitskij, PLB448 (1999) 143

Process	Decay width	Process	Decay width
$\Sigma_c^+ \to \Lambda_c^+ \gamma$	60.7 ± 1.5	$\Lambda_{c1;S} \to \Lambda_c^+ \gamma$	120 ± 1 M
$\Lambda^*_{c1;S} \to \Sigma_c^+ \gamma$	40 ± 0.5	$\Lambda^*_{c1;S} \to \Sigma_c^{*+} \gamma$	50 ± 6
$\Xi^{*+}_{c1;S} \to \Xi_c^+ \gamma$	200 ± 5	$\Lambda_{c1;S} \to \Sigma_c^+ \gamma$	80 ± 1
$\Xi^{*0}_{c1;S} \to \Xi_c^0 \gamma$	500 ± 10	$\Lambda_{c1;S} \to \Sigma_c^{*+} \gamma$	6 ± 0.1
$\Lambda_{b1;S} \to \Lambda_b^0 \gamma$	130 ± 20	$\Lambda^*_{b1;S} \to \Lambda_b^0 \gamma$	170 ± 30
$\Sigma_c^{*+} \to \Lambda_c^+ \gamma$	151 ± 4	$\Sigma_c^{*+} \to \Sigma_c^+ \gamma$	0.14 ± 0.004
$\Xi_c^{\prime +} \to \Xi_c^+ \gamma$	12.7 ± 1.5	$\Xi_c^{\prime 0} \to \Xi_c^0 \gamma$	0.17 ± 0.02
$\Xi_c^{*+} \to \Xi_c^+ \gamma$	54 ± 3	$\Xi_c^{*0} \to \Xi_c^0 \gamma$	0.68 ± 0.04

Three-quark model for heavy baryons

⋆ Magnetic moments of single and double heavy baryons

- Magnetic moments of light baryons

Baryon	3q	Meson cloud	Total	Experiment
p	2.582	0.211	2.793	2.793
n	-1.593	-0.32	-1.913	-1.913
Λ	-0.561	-0.052	-0.613	-0.613
Σ^+	2.327	-0.131	2.458	2.458
Σ^-	-0.939	-0.221	-1.16	-1.16
Ξ^0	-1.205	-0.045	-1.25	-1.25
Ξ^-	-0.611	-0.040	-0.6507	-0.6507

- Magnetic moments of single heavy baryons

Reproduce the model-indenependent structrure dictated by HHChPT: M.Savage, PLB326 (1994) 203; M.Banuls et al, PRD61 (2000) 074007

$$\mu_{\Lambda_Q} = \frac{e_Q}{m_Q} + \frac{\alpha_\Lambda}{m_Q \Lambda_\chi} + \ldots$$

$$\mu_{\Sigma_Q} = \frac{\alpha_\Sigma}{\Lambda_\chi} + \frac{e_Q}{m_Q} + \ldots$$

Three-quark model for heavy baryons

- Results for heavy baryons

Baryon	Our	HHChPTT
Λ_c^+	0.381	0.37
Ξ_c^+	0.378	0.42
Ξ_c^0	0.375	0.32
Λ_b^0	-0.062	
Ξ_b^0	-0.062	
Ξ_b^-	-0.062	
Σ_c^{++}	0.46	
Σ_c^+	0.025	
Σ_c^{+0}	-0.41	
Σ_b^+	0.51	
Σ_b^0	0.14	
Σ_b^0	-0.22	
Ξ_{cc}^{++}	0.25	
Ξ_{cc}^+	0.64	
Ξ_{bb}^0	-0.38	
Ξ_{bb}^-	0.070	

Conclusions

- HQET combined with ChPT, Large N$_c$, NRQCD, etc. is powerful method to study heavy baryons
- To investigate the long-distance effects we need to apply the model approaches
- Three-quark model of baryons works in the world of light and heavy baryons