Open and Hidden Charm Spectroscopy and Decays: an Overview

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Abstract. An overview of charmonium and charm hadron spectroscopy is given, with a special emphasis on spin splittings, total widths, and transitions between excited states. Preliminary results from E835 and recent results from CLEO,BES and E831 are shown. After a decade of high statistics data taking, major problems remain unsolved and new results are needed.

INTRODUCTION

In recent years, the charm sector has regained attention, for many reasons:

- The failure of QCD predictions on prompt J/ψ and ψ' production at the Tevatron energies [1] triggered a number of efforts to produce a more rigorous field theoretical approach to QCD [2].
- Standard Model predictions, by dooming the D^0 system as fruitless for CP violation studies, promote it as a sensitive probe of New Physics beyond SM [3].
- The extraction of more precise values of the CKM parameters from heavy flavors is limited by systematic errors on the hadronic matrix elements.

Charm bound state dynamics is here discussed by comparing the interactions of the charm quark with its antiquark (charmonium), with light antiquarks (D-mesons) and with a pair of light quarks (C-baryons). Despite the fact that spectral patterns differ, a common feature arises: the narrow width of the excited states. This fact has two implications: it provides a clear signature of the heavy flavor, and increases the chances to use electromagnetic transitions to probe the structure of the strongly bound systems.

CHARMONIUM

Due to its clean signature, the charmonium system is the ideal arena to challenge our understanding of QCD dynamics at the boundary between perturbative and non-perturbative regime. Traditionally, the $c\bar{c}$ spectrum was studied with potential models. In recent years, theory efforts were focused on defining limits and methods for the application of non relativistic QCD (NRQCD) to the charmonium system [4, 5, 6], and on extending chiral lagrangians to heavy mesons [7]. With the increasing power of computational techniques, Lattice QCD methods are finally coming to age [8].

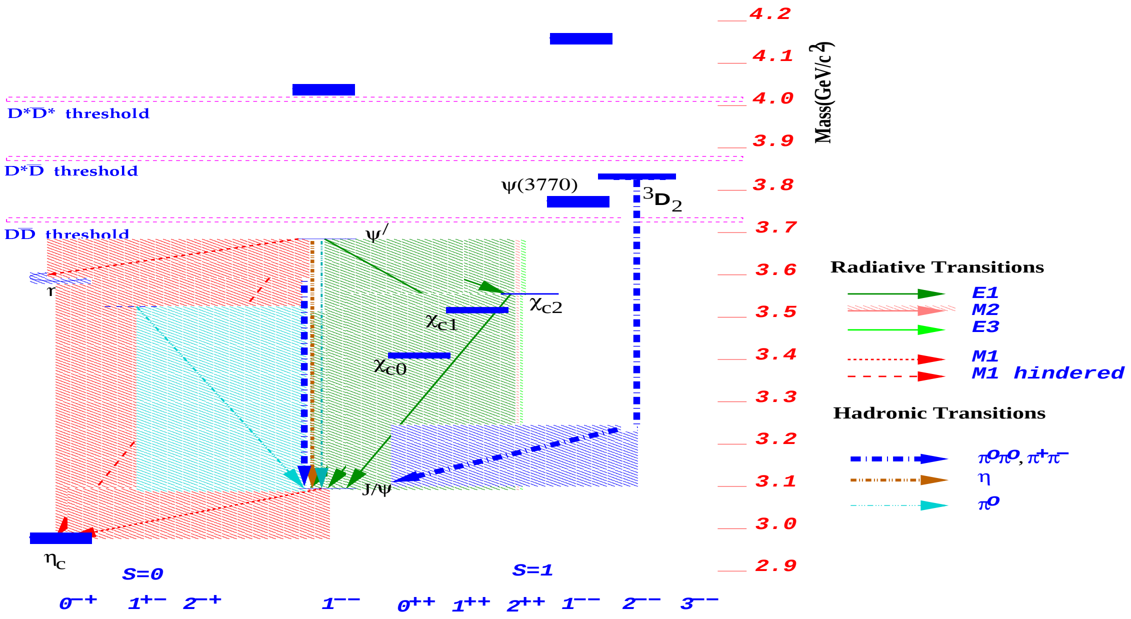

FIGURE 1. Charmonium spectrum and transitions between states.

Since charmonium discovery, the main road for the experimental study of these states was traced by e^+e^- colliders, both in formation, and in $\gamma\gamma$ fusion. In 1984, the CERN experiment R704 pioneered the study of $c\bar{c}$ narrow states in $p\bar{p}$ annihilation. The three techniques complement each other:

- e^+e^- annihilations give direct access only to vector $c\bar{c}$ states, and are sensitive to all decay channels;the use of crystal calorimeters greatly extends the sensitivity of these experiments to the $c\bar{c}$ states reachable through radiative transitions;
- Central production in $e^+e^- \to \gamma\gamma e^+e^-$ allows to access states with positive C-parity and is again sensitive to all decay channels;
- $p\bar{p}$ annihilations allow direct access to all the $c\bar{c}$ states, but the huge hadronic background limits the study to EM decay channels. The coupling to J=0 and S=0 states was forbidden by massless QCD. The helicity selection rule is indeed badly violated in the case of χ_{c0} and η_c states, studied during the last decade.

Mass spectroscopy

The $c\bar{c}$ bound states are charge conjugation and parity eigenstates. As in positronium, for every value of angular momentum L$\neq$ 0, we can identify a triplet of states with S=1, and C=(-1)$^{L+1}$ and a singlet with S=0 and C=(-1)^{L} (see Figure 1). Parity depends only on the angular momentum: $P = (-1)^{L+1}$. The number of expected narrow states below $D\bar{D}$ threshold is limited to eight. An additional pair of narrow states between $D\bar{D}$ and $D\bar{D}^*$ thresholds is also expected , as their quantum numbers ($J^{PC} = 2^{-+}, 2^{--}$) forbid the OZI allowed open charm decays. Two of the narrow states below open charm threshold, namely the ${}^1S_0(2s)$ (η_c') and the ${}^1P_1$ (h_c) were observed by only one experiment and need confirmation.

The spectrum of radial excitations is the first information that became available, soon after the J/ψ and Υ discoveries. The pattern of excited states is reasonably well described by an interaction kernel composed by a one gluon exchange vector term, dominant at short distances, and a long range scalar term, linearly increasing with the radial distance. However, in the case of charmonium the structure is complicated by the presence of a significant relativistic mixing between S wave and D wave vector states. Despite this, the splitting between ground state and first radial excitation in $c\overline{c}$ (589.1±0.1 MeV/c^2) is only 5% larger than in $b\underline{b}$ (563.0±0.4 MeV/c^2).

The tensor structure of the binding potential is investigated by studying the pattern of spin dependent splittings. The mass splittings between triplet P states (χ_c) have been known with excellent precision since a decade, but the theory predictions still fail by a large amount. The fine splitting is described by the mass formula:

$$M\left\{\begin{array}{c}\chi_{c0}\\ \chi_{c1}\\ \chi_{c2}\end{array}\right\} = M_{cog} + h_{LS}\left\{\begin{array}{r}-2\\ -1\\ 1\end{array}\right\} + h_T\left\{\begin{array}{r}-2\\ 1\\ -\frac{1}{5}\end{array}\right\}$$

Both the spin orbit term h_{LS} and the tensor term h_T should scale with the inverse of the heavy quark mass; table 1 shows a comparison between the relevant parameters of charmonium and bottomonium P-states.

TABLE 1. Splittings between χ_c and χ_b states

	$c\overline{c}(n=1)$	$b\overline{b}(n=1)$	$b\overline{b}(n=2)$
$\Delta M_{21} = M(\chi_2) - M(\chi_1)$ (in MeV)	45.6±0.2	19.9±0.8	13.0±0.8
$\Delta M_{10} = M(\chi_1) - M(\chi_0)$ (in MeV)	95.3±0.4	32.8±1.2	23.4±0.8
$\rho(\chi) = \Delta M_{21}/\Delta M_{10}$	0.470±0.003	0.61±0.04	0.56±0.04
h_T (in MeV)	20.2±0.1	6.3±0.4	4.7±0.3
h_{LS} (in MeV)	34.5±0.1	13.8±0.3	9.3±0.3

Lattice QCD[9, 10] still fails to fit the hyperfine and χ_c splittings : despite light quark loop effects are held responsible for this disagreement, recent unquenched lattice calculations [11] do not show any improvement.

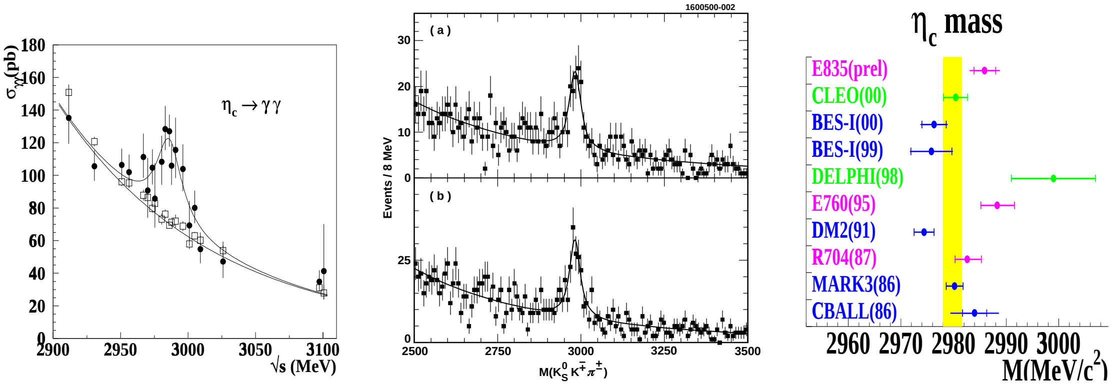

FIGURE 2. η_c mass plots by E835(left) and CLEO(center). Summary of all measures (right).

The precision on the 1S hyperfine splittings is limited by the experimental difficulty to extract the η_c signal. Recently, this state was indeed observed with the three existing techniques (see Figure 2):

a) in e^+e^-, at BES, from the radiative decay of ψ'[12] or J/ψ[13].
b) in $\bar{p}p \to \eta_c \to \gamma\gamma$, by E835; the $\gamma\gamma$ decay channel, however, is affected by a large and steep feeddown from $\pi^o\pi^o$ and $\pi^o\gamma$ continuum.
c) in $e^+e^- \to e^+e^-\gamma\gamma$, where the initial $\gamma\gamma$ flux has a steep dependence on $\sqrt{s}$, by CLEO[14] and DELPHI[17].

A few MeV systematic discrepancy between the results from different experimental techniques is not resolved at this time.

The hyperfine splitting between triplet and singlet P states yields information on the long range behaviour of the vector potential. The state h_c has been observed[18] by E760 in the reaction $p\bar{p} \to h_c \to J/\psi\pi^0$, and awaits confirmation. E835 analysis on Ldt = 97 pb^{-1} is in progress. Given a series of modifications to the machine parameters and data taking conditions, a lengthy set of cross checks on the energy measurements is crucial.

The hyperfine splitting between excited S states $\Delta M(2S) = M(\psi') - M(\eta_c')$ was measured by Crystal Ball[19]: the experiment saw a bump in the inclusive photon spectrum from $1.8{*}10^6\psi'$ decays. E835 has extensively searched [20] for the η_c' in the reaction $p\bar{p} \to (\eta_c') \to \gamma\gamma$, without confirming it. BES,CLEO-c and B-factories have a reasonable chance to find this state in the near future.

Hints for a possible evidence of the 2^{--} state above $D\bar{D}$ threshold at M=3836±13 MeV/c^2 were seen by the FNAL experiment E771 [21], in the reaction $\pi Li \to J/\psi\pi^+\pi^- + X$.

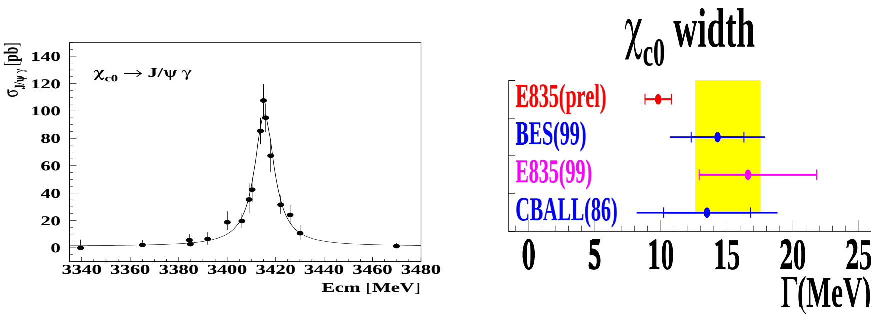

FIGURE 3. χ_{c0} resonance scan by E835 (left). χ_{c0} width measurements (right)

Radiative and Hadronic Decay Widths

The widths of the J=1 states below threshold range between 100 keV and 1 MeV. In this case electromagnetic and hadronic decays have comparable magnitude. States with J=0,2 have widths ranging between 2 and 25 MeV, due to their allowed decay to two hard gluons. The most recent measurements by CLEO[14] and E835[15] of the η_c width suggest a value close to 20 MeV, larger than the PDG value $\Gamma(\eta_c)$= $13.2^{+3.8}_{-3.2}$[22].

On the contrary, the first 10% measurement of the χ_{c0} width, $\Gamma(\chi_{c0})$= 9.8±1.0 ± 0.1, done by E835[16] in 2000, shifts the central PDG value 30% below the current average.

Below open charm threshold, charmonium states' decays can be grouped in seven different classes, as summarized in Table 2. Most partial widths of charmonium states are known with a precision not better than 10%, barely sufficient to distinguish among different theoretical approaches.

TABLE 2. Charmonium decays (LH stands for *light hadrons).*

Decay mode	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
a - $(c\overline{c}) \to gg, gg^* \to LH$	100%	0	99%	73%	87%	0
b - $(c\overline{c}) \to ggg \to LH$		70%				7%
c - $(c\overline{c}) \to \gamma gg \to \gamma + LH$	0		0	0	0	
d - $(c\overline{c}) \to \gamma^* \to LH$	0	17%	0	0	0	
e - $(c\overline{c}) \to e^+e^- + \mu^+\mu^-, \gamma\gamma$	$3 \cdot 10^{-4}$	12%	$\sim 10^{-4}$	0	$\sim 10^{-4}$	2%
f - $(c\overline{c}) \to \gamma + (c\overline{c})$	0	1%	0.6%	27%	13%	30%
g - $(c\overline{c}) \to LH + (c\overline{c})$	0	0	?	?	?	58%

Electromagnetic transitions between charmonium states probe the long range behaviour of the wavefunction. Relativistic corrections are expected to give first order effects on $\psi' \to \chi_c\gamma$ and on $\psi', J/\psi \to \eta_c\gamma$ transitions. E1 Radiative widths have been known at ~ 15% level during the last decade. Equal contributions to the statistical error came from the branching ratios (measured by Crystal Ball) and from the total width (E760). The study of angular distributions allows to access the suppressed M2 amplitudes through the M2-E1 interference terms in radiative decays. A recent result from E835[23] hints at a 2σ discrepancy between theory and experiment on the χ_c radiative decay. A global refitting of all the radiative transition rates, correctly accounting for correlations between different measurements can be found in ref.[24]. Table 3 summarizes the current experimental situation. The new fit value of $\Gamma_{rad}(\chi_{c0})$ incorporates the recent E835 fit of the χ_{c0} total width.

TABLE 3. Radiative decays between charmonium states. Partial widths (with relative errors) from ref.[22] are compared with the results of a new fit from ref.[24]

Transition	E_γ,MeV	Γ_{rad}^{PDG},keV	$\frac{\delta\Gamma_{tot}}{\Gamma_{tot}} \oplus \frac{\delta BR}{BR}$	$\frac{\delta\Gamma_{rad}}{\Gamma_{rad}}$	Γ_{rad}^{newfit},keV	M2/E1
$\psi' \to \chi_{c2}\gamma$	127.5	22±3	11% ⊕ 10%	= 15%	19±3	(8±5)%
$\psi' \to \chi_{c1}\gamma$	171.3	24±4	11% ⊕ 9%	= 14%	23±4	(13±9)%
$\psi' \to \chi_{c0}\gamma$	260.8	26±4	11% ⊕ 10%	= 15%	19±4	0
$\chi_{c2} \to J/\psi\gamma$	429.6	270±32	9% ⊕ 8%	= 12%	374±62	-(9±4)%
$\chi_{c1} \to J/\psi\gamma$	389.2	240±41	16% ⊕ 6%	= 17%	282±52	(0±2)%
$\chi_{c0} \to J/\psi\gamma$	303.6	98±32	17% ⊕ 27%	= 32%	118±32	0
$\psi' \to \eta_c\gamma$	638	0.78±0.19	11%⊕ 21%	= 24%		0
$J/\psi \to \eta_c\gamma$	115	1.13±0.35	6%⊕ 31%	= 31%		0

Very few hadronic transitions between charmonia were observed so far, namely $\psi' \to J/\psi\pi\pi, J/\psi\eta, J/\psi\pi^0$, and the unconfirmed $h_c \to J/\psi\pi^0$. The analysis of a high statistics sample of $\psi' \to J/\psi\pi^+\pi^-$ decays [25] recently yielded the evidence of a 18% D-wave contribution in the dipion. Due to the isospin violation, $c\overline{c} \to c\overline{c}\pi^0$ transitions (BR=9.7±2.1*10^{-4}) are suppressed by more than one order of magnitude with respect to $c\bar{c} \to c\bar{c}\eta$(BR=2.2±0.4%). χ_c transitions to $J/\psi + \pi, \pi\pi$ are suppressed by C-parity conservation, which forbids purely hadronic transitions. E835 is sensitive to $\Gamma(\chi_{c1,2} \to J/\psi + LH)$ at $\sim 10^{-4}$ level, in $\chi_{c1,2}$ decays. No $(c\bar{c}) \to \eta_c + LH$ transitions have been detected so far.

BES has recently published papers concerning exclusive light meson decay channels for J/ψ and ψ' states: these show that baryon-antibaryon and vector-pseudoscalar decays are consistent with the rule [26]:

$$\frac{BR(\psi' \to X_h)}{BR(J/\psi \to X_h)} = \left[\frac{\alpha_s(\psi')}{\alpha_s(J/\psi)}\right]^3 \frac{BR(\psi' \to e^+e^-)}{BR(J/\psi \to e^+e^-)} = 11.6 \pm 2.2\%$$

However, since many years, some exclusive channels ($\rho\pi$ being the most dramatic one) were found to violate the rule. The systematic study of these regularities and anomalies will eventually be of great help in the understanding of charmonium dynamics.

Recent observations of hadronic exclusive decays of χ_c states with charged final products were reported by BES[12]. e^+e^- experiments can only measure the products BR($J/\psi, \psi' \to \gamma R_{c\bar{c}}$)*BR($R_{c\bar{c}} \to X_h$), therefore only the ratios (e.g. BR($R_{c\bar{c}} \to J/\psi\gamma$)/BR($R_{c\bar{c}} \to p\bar{p}$)) will not depend on BR($J/\psi, \psi' \to \gamma R_{c\bar{c}}$), which is currently the dominant source of systematic error on the hadronic branching ratios from η_c, χ_c states. On the contrary, the $p\bar{p}$ experiments only allowed us to measure the products BR($R_{c\bar{c}} \to p\bar{p}$)*BR($R_{c\bar{c}} \to J/\psi\gamma$). The measurement of BR($R_{c\bar{c}} \to p\bar{p}$) at BES has a special interest, because it finally allows to complement $p\bar{p}$ and e^+e^- data, and remove the dependence from the radiative BR's.

CHARMED HADRONS

From the experimental point of view, while charmonium can be formed, D-mesons and c-baryons can only be produced , and the measurement of the widths of narrow states strongly depend on the ability to deconvolute the detector resolution on final product energies and momenta. The extraction of a clean signal with respect to the combinatorial background relies upon three factors: low multiplicity of the final state, good particle identification and good vertex resolution. In the last decade, most results on charm hadron spectroscopy came either from photoproduction experiments (E687 and E831 at FNAL), or from e^+e^- colliders (LEP and CESR).

D-meson spectroscopy

If charmonium is the positronium of QCD , we can say that D-mesons are the analogue of the hydrogen atom. In the case of the excited D-mesons , the charge conjugation symmetry is no longer useful, and the mass asymmetry between the constituents suggests to split the total angular momentum $\vec{J} = \vec{s_q} + \vec{s_c} + \vec{L}$ in the angular momentum $\vec{j_q} = \vec{s_q} + \vec{L}$ of the light orbiting quark and the spin $\vec{s_c}$ if the heavy, quasi-static, quark.

Theoretical predictions on the dynamics of excited heavy-light mesons have been made in the framework of the Heavy Quark Effective Theory (HQET) or the low energy chiral effective theory. Both approaches do not aim to give accurate results: lattice gauge theory is the ultimate candidate for more detailed predictions.

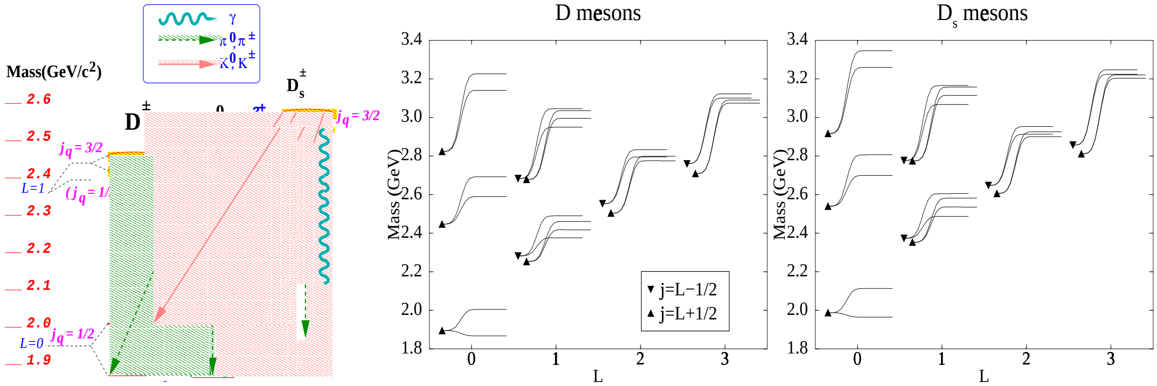

FIGURE 4. D-meson experimental spectrum and theory expectations (from ref.[27])

The hyperfine splitting $M(D^*) - M(D)$ is expected to depend on the inverse mass of the heavy quark, and should not depend on the light quark flavor. The agreement with experiment is at 3% level, as shown in Table 4.

TABLE 4. $1/M_Q$ dependence of the hyperfine splitting.

	$c\bar{u}$	$c\bar{d}$	$c\bar{s}$	$b\bar{u},b\bar{d}$	$b\bar{s}$
M(1^-)-M(0^-),MeV/c^2	142.12 ± 0.07	140.64±0.10	143.8±0.4	45.78±0.35	47.0±2.6

The four possible P states are grouped in two doublets because of parity conservation in the hadronic decay:

- The one with $j_q^P = 3/2^-$ ($J^P = 1^+, 2^+$) can decay to $D\pi$ only via the D-wave , and will have narrower width (about 20 MeV). Parity conservation forbids $D(1^+) \to D(0^-)\pi$.
- The one with $j_q^P = 1/2^-$ ($J^P = 0^+, 1^+$) decays to $D\pi$ via S-wave, therefore will be much wider (about 200 MeV). Parity conservation allows only $D(1^+) \to D(1^-)\pi$ and $D(0^+) \to D(0^-)\pi$.

A mixing between the two 1^+ states is expected. The same rules apply also on the D_s states, after replacing the pion with the kaon. The observation of broad structures is obstacled by the large combinatorial background. Recently, E831 showed that a broad 0^+ bump, overlapping the narrow $D^{**}(2^+)$ peak, can provide a better fit to the $D^+\pi^-$ mass distribution.

It is worth to notice that the flavor independence (within 2%) of the splitting between 1^- and 2^+ states is valid also for the heavy quarkonia (see Table 5), in agreement with

TABLE 5. Flavor independence of the tensor-vector splitting.

	$c\bar{u}$	$c\bar{d}$	$c\bar{s}$	$c\bar{c}$	$b\bar{b}$
M(2^+)-M(1^-), in MeV/c^2	452 ± 2	449±4	461±2	458.3±0.1	452.3±0.6

the $m_Q \to \infty$ limit [28]. These are the states having the highest level of simmetry with respect to SU(2)$_{spin}$, in the two cases L=0 and 1.

The orbital excitation of the D^* state was seen only by DELPHI [29], and was not confirmed by OPAL [30] and CLEO [31]. The state was seen in the channel $D^*\pi^+\pi^-$ at $M = 2637 \pm 2 \pm 6 MeV/c^2$, but theoretical predictions expect it about 50 MeV above. The same signal is being searched for by E831.

D-meson decays

The dynamics of hadronic transitions between D mesons, involving slow pions or kaons, is fully in the non perturbative QCD regime. The hyperfine splitting $M(D^*) - M(D)$ is very close to the π mass. Therefore all the D^* states have very little phase space for the hadronic decay, and are expected to be very narrow, below 100 keV. Recently, CLEO has published the first measurement of the D^{*+} width [32]:$\Gamma(D^{*\pm}) = (96 \pm 4_{stat} \pm 22_{syst}) keV$. This remarkable result is unlikely to be repeated in the near future on the widths of the D^*_s and the D^{0*}.

In the framework of the chiral quark model, all the partial widths $\Gamma(M \to M' + \pi, K)$ are related through Clebsch-Gordan coefficients, and are proportional to the effective coupling constant $g^8_A = 0.82 \pm 0.09$, as obtained [27] from the measurement of the D^* width. All the available measurements in the D-meson sector are consistent with this result. The lattice calculation of g^8_A is $\sim$ 30% below this value.

Radiative decays between D-mesons are detectable only for those states whose width is very narrow: the three vector D^* and the $D_s(1^+)$, limited by the phase space of the $D_s(1^+) \to D^*K$ transition. By combining $BR(D^{*\pm} \to D^\pm\gamma)$ with the above measurement of $\Gamma(D^{*\pm})$ we obtain the first measurement of the M1 radiative width, $\Gamma(D^{*\pm} \to D^\pm\gamma) = (1.6 \pm 0.5)$ keV, statistically consistent with $\Gamma(J/\psi \to \eta_c\gamma)$= 1.13±0.35 keV.

Charmed Baryon Spectra and Decays

In recent years there has been great progress in the spectroscopy of excited charm baryons, from both e^+e^- colliders at Υ energies (ARGUS,CLEO), and photoproduction experiments (E687,E831 at Fermilab). The most recent discoveries were done by CLEO and concern the spectroscopy of charmed strange baryons. As in the case of D-mesons, the assignment of quantum numbers is tightly related to the decay channel by which a state has been observed.

In the baryon spectrum, we classify the states according to the symmetry of the light quark pair:

- In the Λ_c (cud), the light quark pair has spin S=0 and isospin I=0, therefore $\vec{J}(\Lambda_c) = \vec{l} + \vec{s_c}$. Three states have been observed so far.
- The Σ_c states ($cqq, qq = uu, ud, dd$) come in triplets, as the light quark pair has S=1 and I=1; in the two lower triplets observed so far, the mass splitting is due to the relative orientation of the charm quark's and light diquark's spins.
- In the case of the Ξ_c baryon doublets ($csq, q = u, d$), the nomenclature is misleading: in this case the semi-light diquark sq can be both spin symmetric and antisymmetric. The state with a symmetric light diquark is identified by a prime, Ξ_c'. Two Ξ_c and two Ξ_c' doublets have been observed so far.

An updated summary of mass splittings and widths concerning the charmed non-strange baryon states is given in Table 6. In the Λ_c sector, the observation of the first doublet of orbitally excited states allows to compare both orbital and fine splittings with their analogues in the strange hyperon sector. For what concerns the orbital motion, the ratio between the $M(\frac{3}{2}^-) - M(\frac{1}{2}^+)$ splitting and the $M(2^+) - M(1^-)$ meson splitting is constant, and roughly equal to 3/4 [35]:

$$\frac{\Lambda_c(\frac{3}{2}^-) - \Lambda_c(\frac{1}{2}^+)}{D(2^+) - D^*(1^-)} = \frac{342}{455} = 0.752 \qquad ; \qquad \frac{\Lambda(\frac{3}{2}^-) - \Lambda(\frac{1}{2}^+)}{K(2^+) - K^*(1^-)} = \frac{404}{538} = 0.759$$

Recently, both CLEO[34] and E831 [33] have measured the masses and narrow widths of the $\Sigma_c(2455)$ resonances, as well as the masses of the three $\Sigma_c^*(2520)$ states. CLEO has also put an upper limit (at 17 MeV) for the width of the $\Sigma_c^{*+}(2520)$[36].

The spin-orbit splitting $\Delta_{LS} = M(\frac{3}{2}^-) - M(\frac{1}{2}^-)$ between the two excited states scales with the inverse mass of the heavy quark, as $\Delta_{LS}(cdu) = 32.8 \pm 1.6$ MeV/c^2 and $\Delta_{LS}(sdu) = 113.5 \pm 4.0$ MeV/c^2. The hyperfine splitting $\Delta^B_{hf} = M(\frac{3}{2}^+) - M(\frac{1}{2}^+)$ between the two lower Σ_c states is due to the coupling of the spin of the charm quark with the spin of the vector diquark, in analogy to the hyperfine splitting Δ^M_{hf} between vector and pseudoscalar mesons. In this case, due to the symmetry of the diquark wave func-

TABLE 6. Masses and widths of Λ_c, Σ_c baryons

state	J^P	M-M(Λ_c^+),MeV	Γ,MeV	ref.
$\Sigma_c^0(2455)$	$\frac{1}{2}^+$	167.32±0.15	2.4±0.5	[22, 33, 34]
$\Sigma_c^+(2455)$	$\frac{1}{2}^+$	166.4±0.4	<4.6 (90%CL)	[22, 33, 34]
$\Sigma_c^{++}(2455)$	$\frac{1}{2}^+$	167.67±0.15	2.5±0.5	[22, 33, 34]
$\Sigma_c^{*0}(2520)$	$\frac{3}{2}^+$	232.6±1.3	17.9±5.3	[22, 34]
$\Sigma_c^{*+}(2520)$	$\frac{3}{2}^+$	231.0±2.3	<17 (90%CL)	[34]
$\Sigma_c^{*++}(2520)$	$\frac{3}{2}^+$	234.5±1.4	13.0±5.2	[22, 34]
$\Lambda_c^+(2593)$	$\frac{1}{2}^-$	308.9±0.6	$3.6^{+2.0}_{-1.3}$	[22]
$\Lambda_c^+(2625)$	$\frac{3}{2}^-$	341.7±0.6	<1.9 (90%CL)	[22]

tion, the comparison can be extended to the light baryons. The ratio $\Delta^B_{hf}/\Delta^M_{hf}$ shows little dependence on the quark mass, as shown in table 7.

TABLE 7. Hyperfine splitting in mesons and baryons

ΔM	$q\bar{q},qqq$	$s\bar{q},sqq$	$c\bar{q},cqq$	$c\bar{s},csq$
Δ^B_{hf},MeV	(Δ-N) 294	(Σ)191	(Σ_c) 66	(Ξ_c) 69
Δ^M_{hf},MeV	($\rho-\pi$) 635	(K^*-K) 397	(D^*-D) 142	($D_s^*-D_s$) 144
ratio	0.446	0.481	0.465	0.480

The first Ξ_c excited states were observed by CLEO in 1995. Recently, CLEO reported the observation of other two doublets:

- the Ξ_c', which can only decay to $\Xi_c\gamma$ [37]; its width is then extremely narrow.
- the $\Xi_c'(2645)(\frac{3}{2}^+)$, which decays to the ground state Ξ_c mostly through the double cascade $\Xi_c'(2645) \to \pi\Xi_c(2576) \to \pi\pi\Xi_c$[38]. HQET explains the suppression of the direct decay to $\pi\Xi_c$ by totally decoupling the heavy quark motion from the light diquark degrees of freedom.

TABLE 8. Masses and widths of excited Ξ_c baryons

state	J^P	M-M(Ξ_c^+),MeV	Γ,MeV	ref.
$\Xi_c'^0$	$\frac{1}{2}^+$	112.5±3.2		[37]
$\Xi_c'^+$	$\frac{1}{2}^+$	107.8±3.3		[37]
$\Xi_c'^0(2645)$	$\frac{3}{2}^+$	178.2±1.8	<5.5 (90%CL)	[22]
$\Xi_c'^+(2645)$	$\frac{3}{2}^+$	181.1±2.0	<3.1 (90%CL)	[22]
$\Xi_c^{*0}(2815)$	$\frac{3}{2}^-$	352.7±2.5	<6.5 (90%CL)	[38]
$\Xi_c^{*+}(2815)$	$\frac{3}{2}^-$	348.6±1.8	<3.5 (90%CL)	[38]

All the widths of the strange c-baryons observed so far are very narrow (see Table 8). The $\Xi_c(\frac{1}{2}^-)$ and all the excited states of the $\Omega_c(ssc)$ are still unobserved.

CONCLUSIONS

In this overview, I summarized the recent experimental results in the charm sector, and the unsolved issues concerning spectroscopy and decay of heavy hadrons.

In spectroscopy, the precision of experimental data, when available, is ahead of theory; the missing narrow states of charmonium, if confirmed, can shed light on many issues. While lattice experts are focusing on the rôle of light quark pairs in the still unexplained spin splittings, a few simple experimental patterns, consistent with valence quark approximations and with the $m_Q \to \infty$ limit, arise from the comparison of all bound systems containing charm quarks. The experimental pattern of charmed mesons and baryons up to the first radial excitation is approaching completion. The narrow width is the most powerful tag of bound states containing a charm quark: when this signature is missing, like for the $j_q = 1/2^-$ D-mesons, the identification is much harder.

On the other side, the experimental knowledge on decay widths is not yet sufficient, to challenge theoretical predictions. The hidden charm decay patterns are by far more instructive than open charm ones (both annihilations and hadronic transitions are OZI suppressed, and provide access to pure glue dynamics) but larger statistics are needed, to stimulate theory calculations at higher order. EM transitions probe details of the wavefunctions in all bound systems containing a charm quark.

In the near future, new experimental results in the charm sector are expected from BES, E831, E835, and the B-factories. The conversion of the CESR ring in a charm factory [39] will provide an unvaluable source of interesting new high statistics data.

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