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HEAVY FLAVOR SPECTROSCOPY

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Abstract

I review and discuss the status of heavy-flavor spectroscopy.

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1 Introduction

The topic of heavy flavor spectroscopy refers to hadrons containing one quark, whose mass can be considered large compared to the QCD scale. In this limit, a flavor and spin symmetry arises and the underlying dynamics is independent from the heavy quark mass. The properties of mesons and baryons with charm or beauty reflect this symmetry.

For decades after the charm and beauty discoveries, experimental efforts were mainly devoted to identify the ground states of mesons and baryons which contain heavy quarks and to investigate their weak decays. From the studies on lifetimes, Cabibbo-favored, singly- and doubly-Cabibbo-suppressed decays, leptonic and semileptonic decays, we have learned about the structure of the CKM matrix, weak interactions, and quark interactions. In recent years, identification of excited charm- and beauty-flavored states, mainly mesons, has gained experimental relevance. Predictions of mature models inspired by heavy-quark symmetry can now be compared with experimental results which have very high statistics and excellent mass resolution.

2 Heavy-quark symmetry

In a meson composed of a heavy and a light quark ($Q\bar{q}$) as the mass (m_Q) of the heavy quark increases, its motion progressively decreases and the properties of the system should be more and more determined by the dynamics of the light quark only. Finally, for a heavy quark of infinite mass the system will reach a universal limit¹⁾.

Actually, in a heavy-light meson, when the mass of the heavy quark is large compared to the QCD scale ($m_Q > \Lambda_{QCD}$), quantum chromodynamics manifests a new flavor-symmetry. One effect of this symmetry is that the total spin of the system is not a good quantum number. In the heavy-quark limit, the spin of the heavy quark \bar{s}_Q and the total angular momentum of the light quark $\bar{j}_q = \bar{L} + \bar{s}_q$ (orbital + spin) are, indeed, separately conserved. Each level of the meson excitation spectrum is then composed of a degenerate pair of states with the same j_q and total angular momentum $J = j_q \pm 1/2$. In *S-wave* the level ($L = 0$), the spin of the light and of the heavy quark couple to form the pseudoscalar ($J^P=0^-$) and the vector ($J^P=1^-$) states, which, in the heavy-quark limit, are degenerate. For *P-wave* ($L = 1$) orbitally excited mesons, we have two distinct doublets with $j_q = \frac{3}{2}$ ($J^P=2^+$ and $J^P=1^+$ degenerate states) and $j_q = \frac{1}{2}$ ($J^P = 0^+$, $J^P = 1^+$ degenerate states)¹⁾.

In heavy-quark symmetry, to compute the excitation spectrum of a heavy-light meson, all references to the mass of the heavy quark are removed. The excitation spectra of the ($c\bar{q}$), ($c\bar{s}$), ($b\bar{q}$) and ($b\bar{s}$) mesons are in first approximation the same, although the overall mass scales are different²⁾. Corrections are in terms of $1/m_Q$ and $1/m_Q^2$ which are systematically computable in the heavy-quark effective theory (*HQET*). Heavy-quark symmetry also implies that the decay to

¹⁾ In a meson formed from equal mass quarks (as, for example, the quarkonia $c\bar{c}$ and $b\bar{b}$) the total spin is, instead, a good quantum number. It can have a value of 1 or 0 and couples to the angular momentum $L = 1$ to form a singlet (1S) and a triplet (3P) of states. Here, we can see an analogy to LS coupling in atomic physics, while in a heavy-light quark meson the analogy is to JJ coupling.

J_q	J^P	Charmed Mesons	Mass (MeV) exp.	Mass (MeV) theory	Width (MeV) exp.	Width (MeV) theory	Dominant Decay Mode	Beauty Mesons	Mass (MeV) exp.	Mass (MeV) theory	Width (MeV) exp.	Width Theory theory	Dominant Decay Mode
1/2	0^+	D_0^*		$\sim 2360^a$		$> 170^a$	$D\pi$ S-wave	B_0^*		5659^b 5238^c		~ 1.50	$B\pi$ S-wave
1/2	1^+	D_1	$\sim 2461^0_{-35} +42$ (CLEO)	$\sim 2432^a$	$\sim 290^0_{-83} +104$	$> 250^a$	$D^*\pi$ S-wave	B_1	~ 5670 (L3)	5671^b 5757^c	$70^{\pm 21st}_{\pm 25sy}$	~ 1.50	$B^*\pi$ S-wave
3/2	1^+	D_1	$2422^0, 2427^\pm$		$19^0 28^\pm$		$D^*\pi$ D-wave	B_1	5739(ALEPH)	5759^b 5719^c		~ 2.1	$B^*\pi$ D-wave
3/2	2^+	D_2^*	$2459^0 2459^\pm$		$23^0 25^\pm$		$D\pi, D^*\pi$ D-wave	B_2^*	~ 5768 (L3)	5771^b 5733^c	$24^{\pm 19st}_{\pm 24sy}$	~ 2.5	$B\pi, B^*\pi$ D-wave

Table 1. Orbitally excited charm- and beauty-flavored mesons. In bold well established states (masses and widths from PDG98 for neutral and charged states). The ALEPH measurement refers to the mass of the narrow doublet. The L3 values are obtained from a fit which includes the four $L=1$ excited beauty-mesons and a contribution B' of a high-mass state compatible with the radial excitation (2S) of the B-meson. Predictions are: a) Godfrey et al., b) Quigg et al. and c) Erbert et al.

the ground state from $L=1$ orbitally excited states with $j_q = \frac{3}{2}$ and $j_q = \frac{1}{2}$ must proceed primarily via a D -wave and S -wave, respectively. The decay widths of the $j_q = \frac{3}{2}$ states are expected to be relatively narrow ($\Gamma \simeq 20 \text{ MeV}/c^2$), whereas the width of the $j_q = \frac{1}{2}$ states are predicted to be broad ($\Gamma \geq 400 \text{ MeV}/c^2$)³.

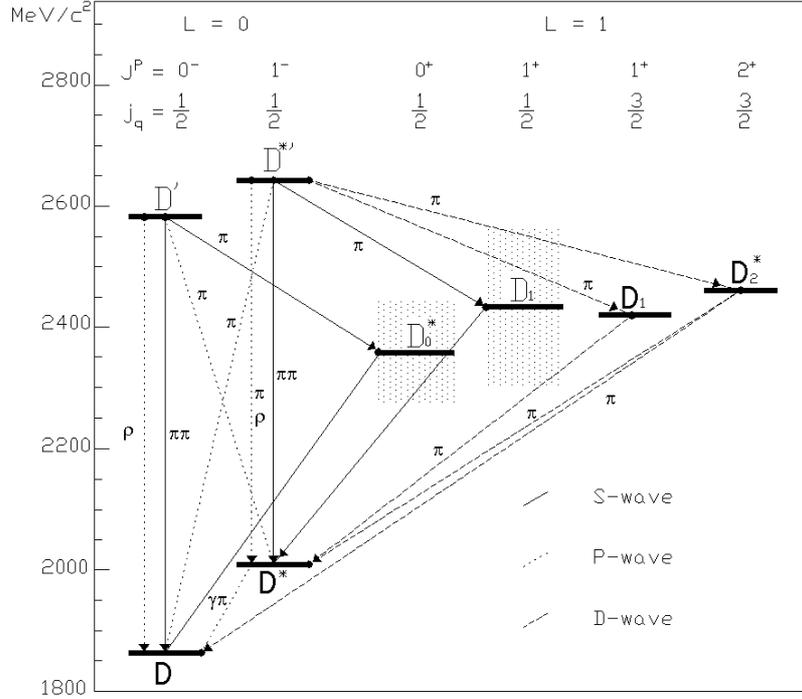


Figure 1. Charm-mesons spectroscopy chart. Masses, quantum numbers and decay modes are indicated for $L=0$ and $L=1$ non strange states. Apices indicate radial excited states. Well established states (PDG98) shown in bold. For clarity the D_1 and D_2^* decays via ρ or $\pi\pi$ are not shown. Shaded areas indicate predicted decay widths for those states.

3 Heavy-flavor spectroscopy

All the experimental groups that have contributed significantly to the heavy-flavor spectroscopy attended the workshop in Frascati and presented exhaustive, up-to-date reports on their searches.

Nadia Pastrone in a mini-review summarized the recent data in charmonium obtained by E835, OPAL, and BES. Vladimir Ivanchenko proposed the use of hard-photon emission by an electron or a positron for $\Upsilon(4S)$ spectroscopy studies. Steven Timm reviewed the results on charm-flavored mesons and baryons obtained from CLEO, which observes charmed states both from B -meson decays, and from continuum. Daniel Bloch for DELPHI reported on search for narrow and wide charmed mesons in B -meson semileptonic decays, and on observation of the radial excited state D^{*1} . Michael Thierghen presented the OPAL results on production of χ_2 via photon-photon collisions and on unsuccessful searches for radially excited charmed mesons. Stephane Monteil for ALEPH reported on a search for excited beauty mesons in which candidate B -mesons have been, for the first time, fully reconstructed. Steven Goldfarb presented instead a new analysis done by L3 on excited beauty mesons which makes use of B -mesons

reconstructed inclusively. Sergio Ratti gave an interesting review on hadron spectroscopy and presented preliminary results from the FOCUS collaboration, the E687 successor, which studies charmed states obtained in photoproduction at Fermilab.

3.1 Charmed mesons

The first charmed meson was discovered in 1976 ⁴⁾. It took nearly a decade to find all six *S*-wave charmed mesons: the pseudoscalar states D^0, D^+, D_s^+ and the vector states D^{*0}, D^{*+}, D_s^{*+} . In the following years, six more narrow mesons the $L=1, j_q = \frac{3}{2}$ states for each quark content ($c\bar{u}$), ($c\bar{d}$), ($c\bar{s}$) were well established, their decay channels were seen and studied. Their masses, widths and quantum numbers are quite established, their production rates in $Z \rightarrow c\bar{c}$ and in $Z \rightarrow b\bar{b}$ are measured. The wide states $L=1, j_q = 1/2$ instead, have been, so far, very difficult to identify. None of the higher ($L > 1$) excited states have been detected.

A report on an observation of a broad excited charmed meson was reported at the workshop by the CLEO collaboration. The previously unseen state $D_J(1/2)$ has a mass of $\sim 2461 \text{ MeV}/c^2$ with a width of $290_{-83}^{+104} \text{ MeV}/c^2$. This is the first of the charm-meson broad states foreseen by the heavy-quark symmetry prescription, which has been observed.

At the workshop the puzzle concerning the $D^{*'}$, the first radial excitation of the vector state D^* , remains unsolved. Models inspired by QCD and relativistic quark models ⁵⁾ predict the radial excitation of the D and D^* mesons respectively around $2580 \text{ MeV}/c^2$ and $2640 \text{ MeV}/c^2$. Both should decay to their ground states emitting two pions in the *S*-wave. Predictions for the widths of these states range from 40 to $200 \text{ MeV}/c^2$. The DELPHI collaboration discussed at the workshop the evidence for an excited charmed state already presented at recent conferences: a $15 \text{ MeV}/c^2$ wide peak in the $D^*\pi\pi$ mass spectrum at $2637 \pm 2 \pm 6 \text{ MeV}/c^2$ compatible with the radial excitation of the D^* . Although OPAL and CLEO searched intensively for this state, they obtained only upper limits which are not consistent with the DELPHI signal. Moreover, theoretical considerations claim that such a narrow width is hardly compatible with expectation for a radial excitation ⁶⁾. New data are needed to solve this contradiction. The FOCUS collaboration should be one of the providers, with a stream of new information on charmed excited mesons. The experiment has collected $\sim 1.3 \cdot 10^6$ charmed mesons in the pseudoscalar ground states and, at the end of data analysis, promises us $\sim 1.3 \cdot 10^4 D^*$ and ~ 7000 excited charmed mesons (orbital + radial). Clean D_{SJ} states were also shown recently by FOCUS ⁷⁾.

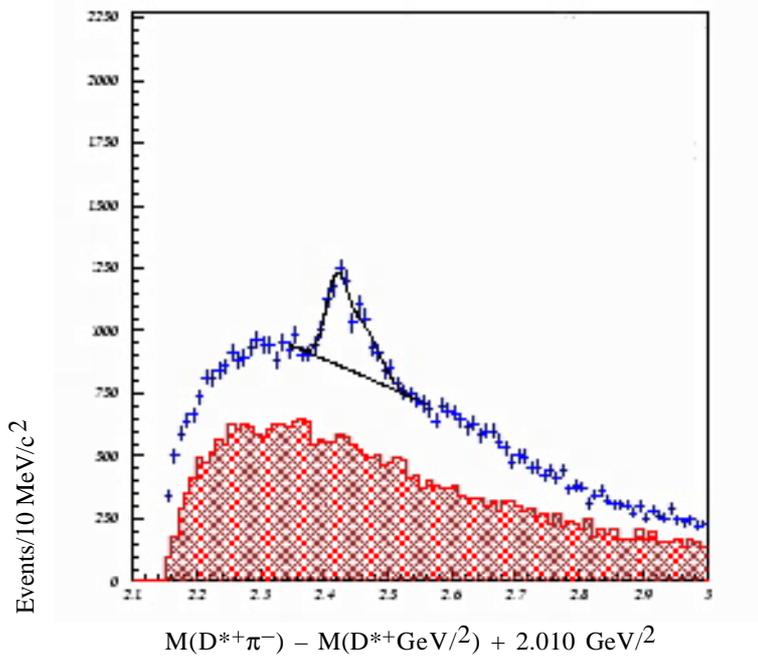


Figure 2: $D^{*+}\pi^-$ mass plot (50% of total FOCUS data set). The quantity histogrammed is the mass difference between $D^{*+}\pi^-$ and D^{*+} to which a constant $2.010 \text{ GeV}/c^2$ is added (PDG value of D^{*+} mass). The enhancement near 2.4 GeV^2 can have contributions from $D_1(j=3/2)$, and D_2^* . The superimposed curve is a sum of two Gaussians and a second order polynomial background. While fitting, the mass of D_2^* is fixed to $2.461 \text{ GeV} c^2$ as obtained from $D\pi$ mass distribution.

3.2 Beauty mesons

The first observation of a $L=1$ orbitally excited beauty meson was reported in 1995 by the OPAL collaboration ⁶⁾ and later confirmed by DELPHI and ALEPH. In these measurements the ground state B -mesons are reconstructed inclusively. The excess of events is fitted with a single Breit–Wigner including all the contributions from the different excited beauty mesons.

The only search for excited beauty mesons in which B -meson decay chains are fully reconstructed ($B \rightarrow D^* + (\pi, \rho, a_1)$ and $J/\psi(\psi') + (K^*, K^\pm)$) has been recently performed by ALEPH and presented at the Frascati workshop. An excess of 45 ± 13 events in the $B\pi$ mass right–sign sample compared to the wrong–sign sample is found to accumulate at $5695_{-19}^{+15} \text{ MeV}/c^2$. This result is in agreement with respect to the previous inclusive studies. The structure is fitted with five Breit–Wigner functions. The relative masses of the excited states, their widths, and the production rates of the different channels have been fixed to the HQET predictions. Finally, the mass of the narrow doublet $j_q=3/2$ is measured to be $5739_{-12}^{+8} \text{ MeV}/c^2$.

The L3 collaboration presented instead a new inclusive method. Several approaches are used to unfold the component signals. The fitting procedure, *HQET* guided, provides a measurement of the masses and decay widths of the $B_2^*(3/2)$ and $B_1(1/2)$ mesons. A remarkable result is that, together with the contributions of two narrow $B_1(3/2)$, $B_2^*(3/2)$ and two wide $B_0^*(1/2)$, $B_1(1/2)$ states, a B' ($\sim 5940 \text{ MeV}/c^2$, $50 \text{ MeV}/c^2$ wide) state is necessary to get good agreement with the data. The mass of the narrow doublet found by ALEPH is somewhat low with respect to the heavy–quark symmetry expectation which, instead, the value found by L3 of $\sim 5768 \pm 5 \pm 6 \text{ MeV}/c^2$ for the $B_2^*(3/2)$ meson agrees with.

3.3 Charmed Baryons

In the framework of $SU(4)$ we expected twenty baryon ground states with $J^P = 1/2^+$, twelve of which charmed, and twenty with $J^P = 3/2^+$, ten of which charmed. Only thirteen out of twenty-two charmed states have been clearly identified. Most of the single-charmed baryons have been observed. At present all the nine single-charmed baryons (cqq) in $J^P = 1/2^+$ have been detected, while the three (ccq) $J^P = 1/2^+$ double-charmed baryons are still missing. In the $J^P = 3/2^+$, sector, six single-charmed baryons have been identified (Σ_c^{*+} and Ω_c^* missing), while all the four multiple-charmed baryons (three double- and one triple-charmed) have not been seen yet. Masses and widths of the identified baryons have been measured, the measurements of their isospin mass splitting and branching ratios are advanced. Only a few of the orbitally excited states have been observed.

The heavy-quark symmetry suggests to consider a heavy-light-light baryon as formed of a heavy quark and a light diquark. As for mesons, in baryons the heavy quark spin \bar{s}_Q and the diquark angular momentum $\bar{j}_{qq'} = \bar{L} + \bar{S}_{qq'}$ respect to the heavy quark (where \bar{L} is the diquark orbital momentum and $\bar{S}_{qq'} = s_q + s_{q'} + l'$ the diquark total momentum) are separately conserved. The lowest charmed baryons excited states are expected to be those in which the two light quarks are in S -wave ($l' = 0$) and their spins antiparallel. This gives origin to a doublet of $j_{qq'}=1$ degenerate states $J^P = 1/2^-, J^P = 3/2^-$, for each quark content: Λ_{cl}^{***} (cud), Ξ_{cl}^{**0} (csd), and Ξ_{cl}^{**0} (csu).

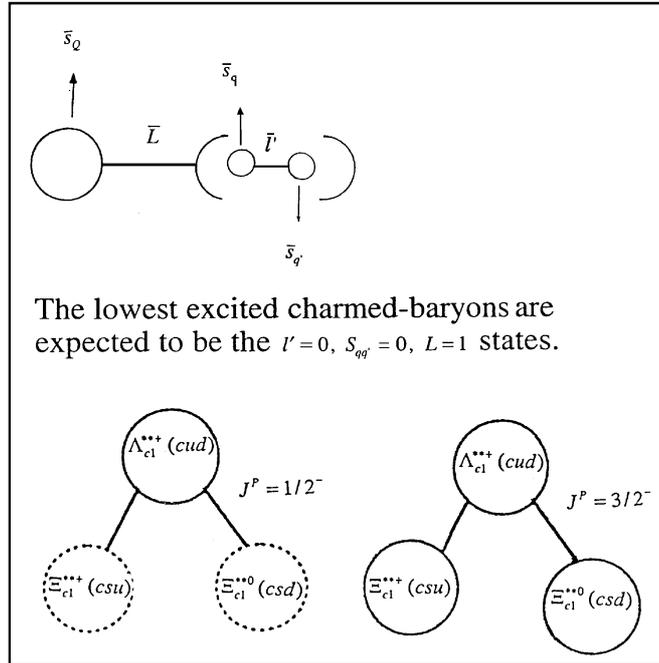


Figure 3: $SU(3)$ triplets for the lowest mass states of excited charm-baryon. At present there are two more states (dotted circles) to be discovered in this pair of triplets.

The first observation of a heavy-flavor baryon excited state, the $\Lambda_{cl}^{***} \neq (J^P = 3/2^-)$ was done by ARGUS ⁷⁾ and E687 ⁸⁾. Later CLEO ⁹⁾ found the $\Lambda_{cl}^{***} = (J^P = 1/2^-)$ partner of this doublet. At the workshop Steven Timm reported on impressive contributions of CLEO to the charmed baryon spectroscopy, including the recent mass and width measurements of the

orbitally excited baryons Ξ_{cl}^{**0} ($J^P = 3/2^-$) and Ξ_{cl}^{**+} ($J^P = 3/2^-$). The measured mass difference between the excited state and the corresponding Λ_c and Ξ_c ground states are found, as predicted by heavy-quark symmetry, to be very similar. At present there are two more (Ξ_{cl}^{**0} ($J^P = 1/2^-$) and (Ξ_{cl}^{**+} ($J^P = 1/2^-$)) states to be discovered in this pair of SU(3) triplets.

The opening of the multiple-charmed baryon sector remains an experimental challenge. The discovery of these baryons is important, not only to complete our spectroscopy chart, but also to validate our theoretical models and mass computation techniques. Two contributions were presented at the conference concerning hadron-mass predictions. Yogi Srivastava discussed a Regge-trajectory approach which has the advantage of being unique for all (light or heavy) hadrons. The agreement in prediction for ρ^- , ω^- , σ^- , ϕ^- , K^- , N^- , and Δ^- -families masses is very good, while the application to heavy-flavored hadrons is in progress. Enrico Predazzi described a nearly model-independent approach to compute heavy-flavor hadron masses in their ground states based on the Feynman-Hellman theorem and general properties of the Hamiltonian. The predictions are in very good agreement with the existing measured values. A validation/confutation test of this approach would be given by comparing predicted and measured masses of double-charmed baryons when detected. The discovery of a double-charmed baryon will also be very important for validating the extrapolation of the *HQET* from heavy-light and heavy-light-light systems, where it is a decent predictive technique, to the heavy-heavy-light configuration of quarks¹⁰). Actually, the discovery of multiple-charmed baryon seems beyond the possibilities of CLEO, as well as those of its present competitors, and will be left, probably, to future experiments.

4 Charmonium

Up to the 1980's, charmonium states were produced at e^+e^- storage rings. The e^+e^- annihilation proceeds, at the first order, via a virtual photon and only vectors $J^{PC} = 1^{--}$ states can be directly formed. The $J^{PC} = 1^{--}$ states, *i.e.* the χ_J states, can be observed only through radiative transitions in a two step process such as $e^+e^- \rightarrow \psi' \rightarrow (c\bar{c}) + \gamma$.

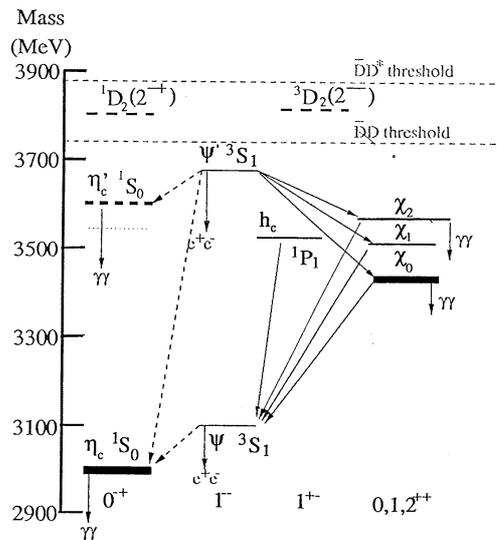


Figure 4: The spectrum of charmonium states.

In this way, masses and widths resolutions are limited by the photon detectors performances. Precise spectroscopy of charmonium is, instead, very helpful in testing quantitative predictions in the non-perturbative QCD regime. The alternative, to study $C=+1$ charmonium states at e^+e^- , is to make use of a second order process as the photon-photon collisions.

The E835 collaboration studies charmonium spectroscopy through $p\bar{p}$ annihilation. This line of experimentation was pioneered by R704 at CERN and by E760 at Fermilab. Its merit is that all J^{PC} quantum numbers are directly accessible because the $p\bar{p}$ annihilation can proceed via two ($C=+1$) or three ($C=-1$) gluons. Consequently, once the beam characteristics and parameters are well understood, a very precise determination of the masses and the widths of the studied resonance is obtained. The dramatic improvement in data quality is shown in figure by comparing the same state as seen at e^+e^- and $p\bar{p}$ facilities.

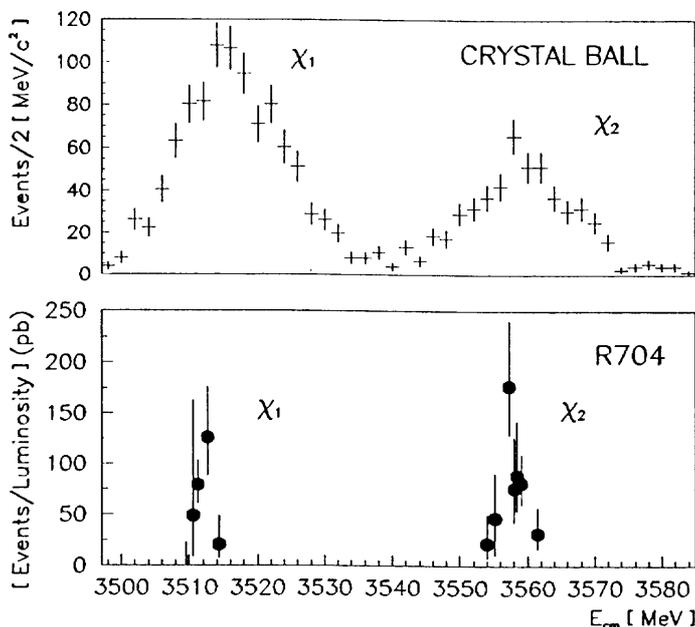


Figure 5: Charmonium states as seen at e^+e^- storage rings in radiative transition processes, and via $p\bar{p}$ annihilation.

Recent E835 data include improved measurements of the η_c and χ_2 , and the first evidence of the χ_0 in $p\bar{p}$ annihilation. From the total and the partial widths of the η_c and χ_2 the E835 collaboration determines the strong coupling $\alpha_s(m_c = 1.5 \text{ GeV}/c^2)$ which agrees with the value previously obtained from the τ decay. In photon-photon collisions at LEP, the width of η_c in $\gamma\gamma$ has been measured by L3, the width of χ_2 by OPAL (reported at the workshop) and L3. The $\Gamma(\eta_c \rightarrow \gamma\gamma)$ measured by E835 appears nearly a factor of two narrower than the PDG world average, which, instead, the recent data from CERN agree with. New data on the charmonium system have also been recently submitted for publication by the BES collaboration including: the study of the P -wave charmonium state χ_J in $\psi(2S)$ decays and the J/ψ leptonic branching ratio via $\psi' \rightarrow \pi^+\pi^-J/\psi$, from which an $\alpha_s(m_c = 1.5 \text{ GeV}/c^2)$ value 20% lower than E835 is obtained.

Despite these new searches and the excellent resolutions achieved, the puzzle of the pseudoscalar radial excitation $\eta'_c(2^1S_0)$ remains unsolved. In late 1982 the Crystal Ball¹¹⁾

collaboration reported having identified the η'_c at a mass of 3594 MeV/c². The mass value, however, did not satisfy most theoreticians because, when compared with QCD prediction, it appeared too different from the ψ' mass. So far, a signal for the η'_c has been reported only by Crystal Ball. Recent DELPHI data in photon–photon collisions at LEP did not show any trace of the claimed signal. Also the E835 collaboration, during an intensive search ($\sim 30 \text{ pb}^{-1}$) in a region from 3660 MeV/c² to 3575 MeV/c², failed to find any evidence of such a state. Hence, the Crystal Ball signal should be considered ruled out quite definitively, and the η'_c still eludes us. We expect the new E835 run planned for this year, with the search for η'_c approved as priority, to finally uncover this state, which is needed to complete our understanding of the charmonium system.

5 Conclusions and shopping list

The heavy–flavor spectroscopy session of the Frascati Workshop provided us with a good and fairly complete review of the progress recently made on several aspects of one of the most active fields in quark physics. We reviewed significant results on beauty– and charmed–flavored mesons, charmed baryons and charmonium. At the end of the workshop my shopping list for experimentalists would be:

- Excited charm– and beauty–flavored mesons
 - Clarify the $D^{*'}$ puzzle.
 - Confirm the $D_1 (1/2)$ wide state and study its parameters.
 - Observe (or infer from total and know partial widths) the $D_0^*(1/2)$ state.
 - Discover $L=2$ charm–flavored mesons.
 - Confirm the $L=1$ B –mesons and study their parameters.
 - Confirm the B' –meson and clarify its nature.
- Charmed baryons
 - Discover the Σ_c^{*+} and the Ω_c^* .
 - Discover multiple–charmed baryons.
 - Observe the two, $L = 1, l' = 0$ $S_{qq'} = 0$ states still missing.
- Charmonium
 - Solve the η'_c puzzle.
 - Confirm the 1P_1 state and measure its parameters.

6 Acknowledgments

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References

1. A. De Rúyula, H. Georgi and S.L. Glashow, Phys. Rev. Lett. **37**, (1976)785.
2. E. J. Eichten, C. T. Hill, and C. Quigg Fermilab–Conf–94/118T.
3. S. Goffrey and R. Koloski, Phys. Rev. **D43**, (1991)1679.
4. I.Peruzzi and al. Phys. Rev. Lett. **37**, (1976)569.
5. S. Godfrey and N. Isgur, Phys. Rev. **D32**, (1985)189;
D. Erbert, R. N. Faustov and V. O. Galkin, HUB–EP–97/90, hep–ph/9712318.
6. D. Melikov and O. Pene, Phys. Lett. **B446**, (1999)336.
7. S. Bianco, "Charm Overview", Proc. XIX Conf. Physis. in Collision, Ann Arbor (Michigan) October 1999, hep-ex/9911034, Frascati Preprint LNF-99/029(P).
8. OPAL Collaboration Z.Phis **C69**, (1966)393.
9. ARGUS Collaboration Phys Letts. **B317**, (1993)227.
10. E687 Collaboration Phys. Rev. Letts. **B338**, (1994)106.
11. CLEO Collaboration Phys. Rev. Letts. **B74**, (1995)3331.
12. E. J. Eichten, talk at "Heavy Quarks at Fixed Target"Conference, Fermilab, 1998.
13. C. Edwards et al. Phys. Rev. Lett. **70**, (1993)2988.