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REVIEW OF HEAVY QUARK SPECTROSCOPY

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ABSTRACT

After a brief introduction on the twofold aspect of heavy quark spectroscopy, a review is given of the recent results on excited states of charm and bottom mesons and baryons.

1 Introduction

Since the *invention* of the eightfold way by Murray Gell-Mann (and George Zweig, as a matter of facts) and the introduction of the quark idea, spectroscopy in particle physics became a twofold -and a two step- issue: on one side the problem arose of classifying particles and/or resonances into approximate $SU(3)_{flavour}$ multiplets; on the other side to exploit an *atomic-like* spectroscopy for the radial excited quark-antiquark states.

The first step is crucial in order to pin out the low lying *ground states* to be assumed as the *starting point* for a radial excitation *atomic like* spectroscopy.

For sake of brevity I'll call *primordial spectroscopy* the general $SU(n)_{flavour}$ classification of the particle ground states, leaving the term *spectroscopy* to the investigation of the traditional excitation processes.

Restricting, for sake of agrument, to meson spectroscopy, in the light quark sector $^{1)}$, at least tentatively, the classification of the several radial excitations spans

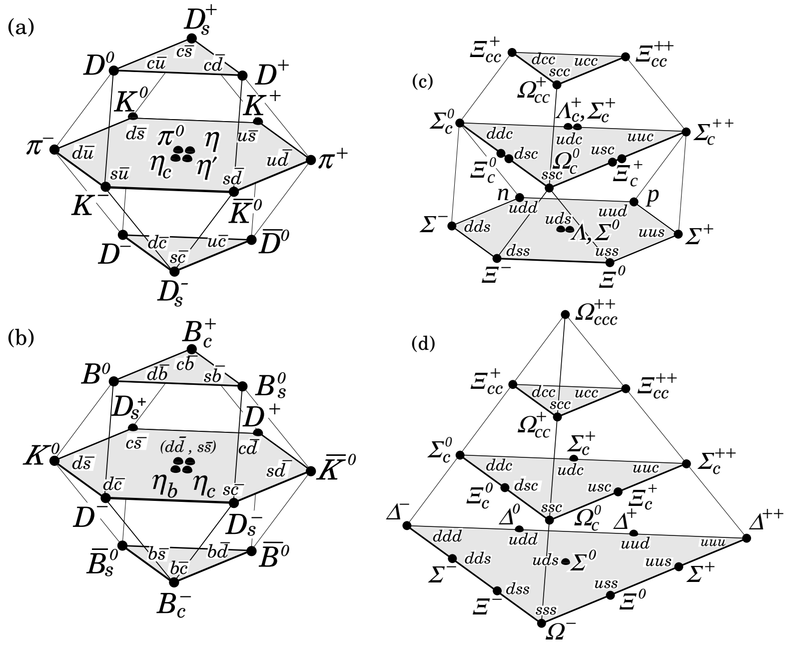

Figure 1: $SU(4)_{flavour}$ sub-multiplets for several meson and baryon states: a)- $J^P = 0^-$ mesons; b)- $SU(4)_{flavour}$ sub-multiplet in the variables s, c, b; c)- $SU(4)_{flavour}$ sub-multiplet for $J^P = \frac{1}{2}^+$ baryons; d)- $SU(4)_{flavour}$ sub-multiplet for $J^P = \frac{3}{2}^+$ baryons.

spin-parity values as high as $J^{PC} = 5^{--}$ for $I^G = 1^+$ states and $J^{PC} = 6^{++}$ for $I^G = 1^-$ states, experimentally detected, while in the strange sector, the classification may span to include $J^P = 5^-$ for $I = \frac{1}{2}$ states.

For the heavy quark sectors, on the contrary, the situation is by all means definitely different. Few $SU(n)_{flavour}$ multiplets are completed; even at this stage, the spin-parity assignments are still tentative and only very few excited states have been found so far. Fig. 1a shows the well known 0^- meson $SU(4)_{flavour}$ multiplet which includes the charm mesons. Not only: while, with the discovery of the *charm* quark, the ground states can be organized into $SU(4)_{flavour}$ multiplets and, by the use of a *triangular* representation of axes $^{2)}$, may be displayed into a 3-dimensional space, with the advent of the *beauty* quark, the approximate flavour symmetry expands into $SU(5)_{flavour}$. At this point we miss one dimension and thus run into trouble in trying to display all states in a 5-dimensional space u, d, s, c, b in one go.

Thus, for mesons (and baryons, as a matter of facts) containing a b-quark, the $SU(4)_{flavour}$ sub-multiplets of $SU(5)_{flavour}$ can be displayed either disregarding the isospin third component (u,d), or by setting $s = 0$ or $c = 0$. Fig. 1b shows

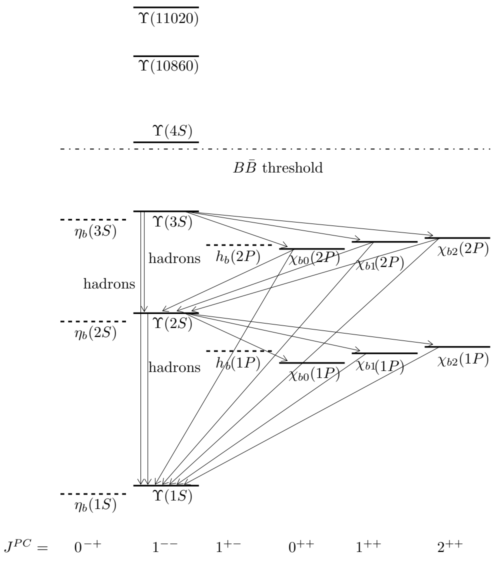

Figure 2: Level scheme of the $b\bar{b}$ states. The solid lines indicate observed states. Dashed lines indicate states non yet observed.

the sub-multiplet displayed in the variables s,c,b. In order to save space and as a reference for future considerations, fig.s 1c,d summarize also other usefull multiplets. Fig. 1c shows the $SU(4)_{flavour}$ multiplet for the $J^P = \frac{1}{2}^+$ baryons and fig. 1d the $SU(4)_{flavour}$ multiplet for the $\frac{3}{2}^+$ baryons.

To understand heavy quark baryons we may take advantage of the Heavy Quark Effective Theory 3, 4) (hereafter HQET) that provides a reasonable simplification in the description of the $Q\bar{q}$ system, where Q is a *heavy* quark, (much) heavier than the QCD scale so that charm and bottom baryons may be considered the same systems in the infinite mass limit (only at a second stage, proper corrections can be introduced to diversify charm from bottom). Similarly, HQET assumes *zero mass* light quarks in a *chiral limit.*

2 Bottomonium

The first and easiest spectroscopy case is quarkonium: the state is made of $q\bar{q}$ with identical masses, formally very similar to positronium and strangeonium, the only difference being the quark mass. Here I will cover only the bottomonium spectrum since Nadia Pastrone 5) has covered charmonium in a dedicated talk.

The status of the art in this sector -as of beginning 1998- is given in the

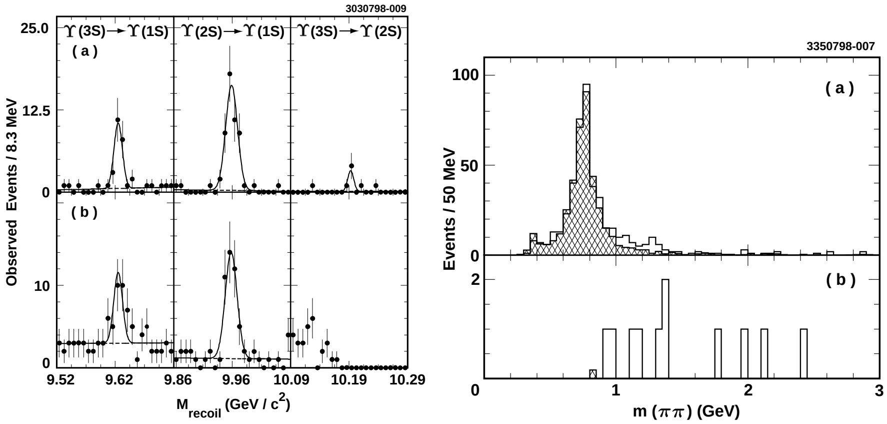

Figure 3: Bottomium states observed by Cleo-II: left- recoil mass distributions for the transitions $\Upsilon(nS) \rightarrow \Upsilon(mS)\pi^+\pi^-$ at $E_{cms} = 10.52$ GeV; a)- $\Upsilon(mS) \rightarrow \mu^+\mu^-$l; b)- $\Upsilon(mS) \rightarrow e^+e^-$; right)- Dipion invariant mass for the $\Upsilon(1S) \rightarrow \gamma 2\pi$ data, with scaled continuum data (hatched histograms) superimposed: a)- $\Upsilon(1S) \rightarrow \gamma\pi^+\pi^-$; b)- $\Upsilon(1S) \rightarrow \gamma\pi^o\pi^o$.

Data Particle Book 1) and depitched in fig. 2. The $\eta_b, 0^{-+}$ states are still missing. The Cleo-II collaboration 6)a,b observes several $\Upsilon(nS)$ states and several $\Upsilon(nS) \rightarrow \Upsilon(mS)$ transitions, including 6)b the first observation for the $\Upsilon(1S) \rightarrow \gamma 2\pi$ decay. Running at energies $E_{cms} = 10.58$ GeV and $E_{cms} = 10.52$ GeV, close respectively to the threshold for the $\Upsilon(4S)$ or the $\Upsilon(3S)$ production, they obtain several results:

a- they give two 90% confidence level upper limits for the $\Upsilon(4S)$ branching fractions: $B.F.[\Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^-] < 1.2 \times 10^{-4}$ and $B.F.[\Upsilon(4S) \rightarrow \Upsilon(2S)\pi^+\pi^-]$ $< 3.9 \times 10^{-4}$;

b- they observe three intermediate transitions, i.e.: $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$; $\Upsilon(3S) \rightarrow \Upsilon(2S)\pi^+\pi^-$ and $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$.

The data at $E_{cms} = 10.52$ GeV are shown in the left part of fig. 3.

The analysis is simplified by selecting only the dilepton decay modes of the *daughter* $\Upsilon(mS)$ states and then adding two pions to calculate the 4-body invariant mass. The new observations improve the data in the 1998 Review of Particle Data 1). The same data provide also very interesting information on the radiative production of the Υ particles which are not relevant for our limited purposes. Fig.s 3 (left) keep separated the $\mu^+\mu^-$ (fig. 3a) and the e^+e^- channels (fig. 3b).

The same collaboration 6)b published also the first observation of the radiative decays $\Upsilon(1S) \rightarrow \gamma\pi^+\pi^-$ and $\Upsilon \rightarrow \gamma\ 2\pi^o$. The data are shown in the right part of fig. 3. The evidence for $\Upsilon \rightarrow \gamma 2\pi^o$ is weak, although important:

B.F.$[\Upsilon(1S) \rightarrow \gamma 2\pi^o] = (1.6 \pm 0.6 \pm 0.3) \times 10^{-5}$ for dipion masses > 1.0 GeV, while the branching fraction -in the same conditions- $[B.F.(\Upsilon(1S) \rightarrow \gamma\pi^+\pi^-) = (6.3 \pm 1.2 \pm 1.3) \times 10^{-5}]$ provides a new relevant measurement. By fitting the dipion mass spectrum, after subtraction of the continuum contribution, they estimate for the decay $\Upsilon(1S) \rightarrow \gamma f_2(1270)$ -barely visible (in fig. 3a, right part)- a relative branching ratio $B.R.[\Upsilon(1S) \rightarrow \gamma f_2(1270)] \times B.R.[f_2(1270)\pi^+\pi^-] = (4.6 \pm 1.3^{+1.6}_{-1.5}) \times 10^{-5}$. The data on the $\Upsilon(1S) \rightarrow \gamma 2\pi^o$ channel are, at present, only *consistent* with the above value.

3 Heavy quark mesons

The 0^- multiplet, shown in fig. 1a, including the charmed mesons, has been fully observed and it is well established. The primordial spectroscopy of the multiplet is completed by the $D^+(1869)$, $D^o(1864)$ and $D_s^+(1969)$ mesons. The vector charmed meson 1^- multiplet, on the contrary, is still not completed. Well established are the charmed states $D^{*o}(2007)$ and $D^{*+}(2010)$, but the spin parity assignement of the $D_s^{*+}(2112)$ is still tentative.

The isospin splitting of the charmed mesons has been observed for both J^P mesons. Cleo [7] has measured $M(D^+) - M(D^o) = (4.76 \pm .28)$ MeV and $M(D^{*+}) - M(D^{*o}) = (2.6 \pm 1.8)$ MeV. Several spectroscopic studies have been presented at this workshop and are well summarized in fig. 4, shown by Michael Thiergen [8] in his talk. It summarize all radially excited states detected for all charmed mesons. For the D_s, three excited states have been seen so far: the isosinglets $D_s^{*+}(2112)$ with undetermined spin-parity, $D_{s1}(2536)^\pm$ with $J^P = 1^+$ strongly favoured and $D^+_{sJ=s2?}(2573)$ with undetermined spin parity but consistent with $J^P = 2^+$. The situation is visible in the right hand part of fig. 4.

In the non strange charmed meson sector an issue is controversial and still open to discussion: the transition between the two $J^P = 1^-$ states $D^{*'+}$ and D^{*+}. Delphi [9] found a radially excited state at $M = (2637 \pm 2 \pm 6)$ MeV, $\Gamma < 15$ MeV decaying into $D^*(2007)\pi^+\pi^-$ with a signal of 66 ± 14 events which is confirmed neither by Opal [8] nor by Cleo [10].

Cleo-II [10], fitting a partial wave decomposition of the decay $B^- \rightarrow D_j^o\pi^-$, finds for the first time a broad S-wave $J^P = 1^+ D_1^*$ state at a mass $M = (2461^{+41}_{-34} \pm 10 \pm 32)$ MeV and a width $\Gamma = (290^{+101}_{-79} \pm 26 \pm 36)$ MeV. In addition to the evidences presented by Cleo [10] and by Opal [8] at this workshop, new data come from a partial sample of the FOCUS data. With over 1.2 million golden mode D reconstructed, Focus shows promising evidence for the transitions of the $D_2^{*+}(2450) \rightarrow D^o\pi^+$ (fig.

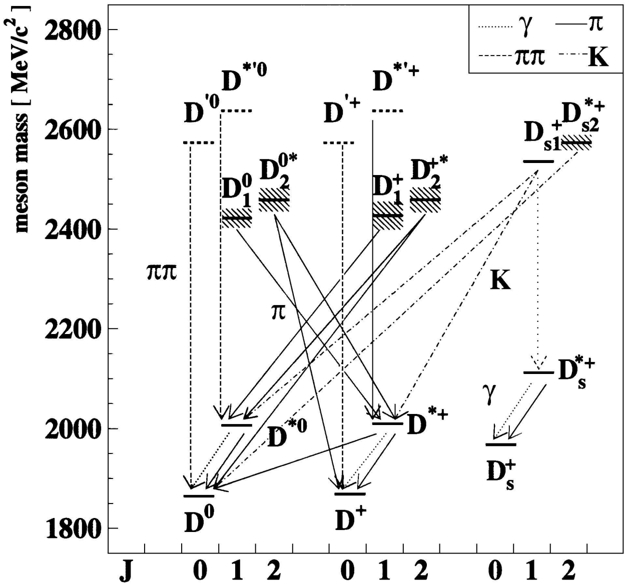

Figure 4: Orbitally excited charm states. Full lines and arrows: observed; dashed lines and arrows: not observed.

5a), and the $D_2^{*o}(2460)$ (fig. 5b) and $D_1(2420)^o$ into $D^*(2010)\pi^+$ (fig. 5c). The data refer to about 50% of the statistics. The experiment will reconstruct over 10^5 $D^{*+} \to D^o\pi^+$ events.

More limited information is available on the B mesons, but LEP and the coming B factories should bring new data very soon.

The bottom $J^P = 0^-$ multiplet is completely observed, while, in the vector $J^P = 1^-$ multiplet, the $B^*(5325)$ states have not yet been resolved in charge. Contrary to the charm case, there is no significant isospin splitting for the B meson 1): $[M(B^o) - M(B^+) = 0.34 \pm 0.32$ MeV].

Very few data are available on possible excited bottom states. The first experimental results come from the LEP experiments, where B mesons are detected as decay products of the Z^o 11, 12). Both $B\pi$ correlations and $B\pi$ resonant structures were observed, mostly based on the inclusive reconstruction of B mesons unresolved in charge and with limited mass resolution. Recently the Aleph collaboration 11)b searched for the $L = 1$ orbitally excited B states generically called B^{**} predicted by E.J. Eichten et al. 13).

An excess of $B\pi$ events around 5.7 GeV is analized first in terms of a single gaussian and then in terms of a spectrum of different $J^P_{j_q}$ B^{**} states, i.e.: a $2^+_{\frac{3}{2}}$ B_2^*,

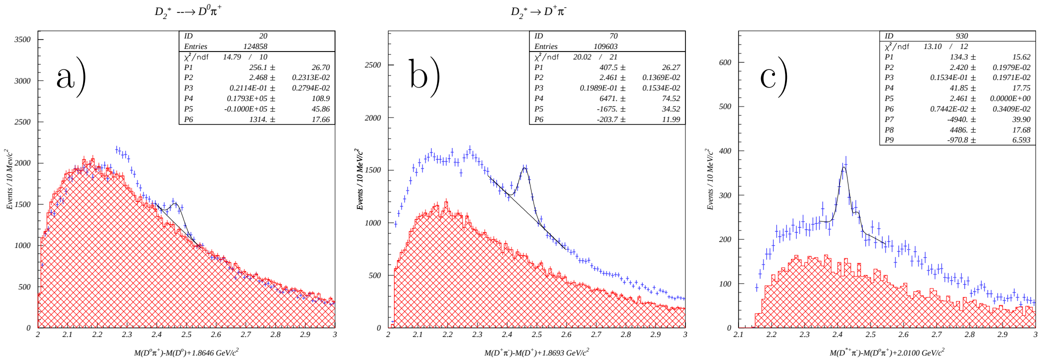

Figure 5: D^* observed on a partial sample by Focus: a)- $D_2^{*+} \to D^o\pi^+$; b- $D_2^{*o} \to D^+\pi^-$; c- D_1^o and D_2^{*o} unresolved.

a $1^+_{\frac{3}{2}}$ B_1, a $1^+_{\frac{1}{2}}$ B_1^* and a $0^+_{\frac{1}{2}}$ B_o. With the second analysis, they find a narrow and a wide state (fig. 6): a $B\pi$ resonant structure at $M = 5696^{+17}_{-19}$ MeV with a width $\Gamma = 54^{+26}_{-19}$ MeV and a state (B_2^*) at a mass $M = [5768 \pm 5(stat) \pm 6(syst)]$ MeV, with a width $\Gamma = [24 \pm 22(stat) \pm (5(syst)]$ MeV, plus a high-mass spin state or a mixture of states B' at $M = [5937 \pm 21(stat) \pm 4(syst)]$ MeV and $\sigma = [50 \pm 22(stat) \pm 5(syst)]$ MeV. Here, time is still too premature. We shall have to wait for quite a while before traditional spectroscopy will be addressed for the bottom mesons.

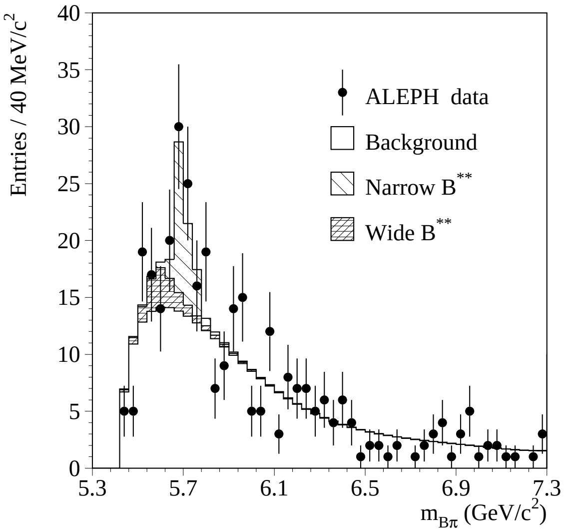

Figure 6: Narrow and broad $B\pi$ states observed by the Aleph collaboration.

4 Heavy Quark Baryons

In the heavy quark baryon sector the primordial spectroscopy situation is not so good as it is for mesons. Very few bottom baryons have been observed 1), i.e.: the isosinglet $\Lambda_b^o(5624)$ since 1991 and, since about 1996, unresolved Ξ_b strange-bottom baryons or *unresolved* b-baryons, mainly through anomalous behaviours of the semileptonic decays. The lifetime has been estimated -in the region of picoseconds- only for an admixture of all possible baryons and all possible charges.

At this workshop, Enrico Predazzi 14) has presented predictions for a series of exctited bottom baryons including cb and bb baryons. At least from the theoretical standpoint there exists a guideline to indicate where to look appriximately in their search.

The charmed baryon primordial spectrometry is largely incomplete. For both $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$ multiplets (see fig.s 1c,d), no *doubly charmed* states have been observed; no Ω_c^{*o} has been detected yet. Furthermore, no spin-parity values have been measured but for the *canonical* Λ_c^+.

The Cleo collaboration presented at this workshop 10) a wealth of good results on $L = 1$ charmed baryons. They provide new and preliminary evidence for two narrow Ξ_{c1}. The new states are consitent with theoretical predictions of $(\frac{3}{2})^-$ baryons decaying, either, via 2π, directly into the Ξ_c ground state or through the intermediate Ξ_c^*. The evidence is for a $\Xi_{c1}^o \rightarrow \Xi_c^{*+}\pi^-$ at a mass difference $\Delta M = (348.6 \pm .6 \pm 1.0)$ MeV and a width $\Gamma < 3.5$ MeV and for a $\Xi_{c1}^+ \rightarrow \Xi_c^{*o}\pi^+$ at a mass difference $\Delta M = (347.2 \pm .7 \pm 2.0)$ MeV and a width $\Gamma < 8.1$ MeV.

In addition, Cleo provided evidence for both positive and neutral Ξ_c''s decaying into $\Xi_c\gamma$ at preliminary mass differences $\Delta M(\Xi_c'^+) = (107.8 \pm 1.7 \pm 2.5)$ MeV and $\Delta M(\Xi_c'^o) = (107.0 \pm 1.4 \pm 2.5)$ MeV.

The E687 collaboration 15) recently published new evidence for the narrow Ξ_c^{*+} at $\Delta M = (177.1 \pm .5 \pm 1.1)$ MeV.

In total, four ground states have been clearly observed: the Λ_c^+, the two Ξ_c's and the Ω_c^o, states for which the lifetimes have also been measured 16); a dozen excited states have been observed with rather uncertain attributions to possible multiplets (for instance either $J^P = \frac{1}{2}^-$, or $J^P = \frac{3}{2}^+$, or $J^P = \frac{3}{2}^-$. A tentative situation is schematically summarized in fig. 7. The vertical scale gives the mass of the states, the horizontal axis gives the absolute value of the strangeness number listing then the several states of the $c = 1$ sextuplet (see fig. 1c,d). None of the states is provided with a spin-parity assigned experimentally. All numbers given are tentative guesses. The E687 17) collaboration and Cleo-II 10) provided most of the

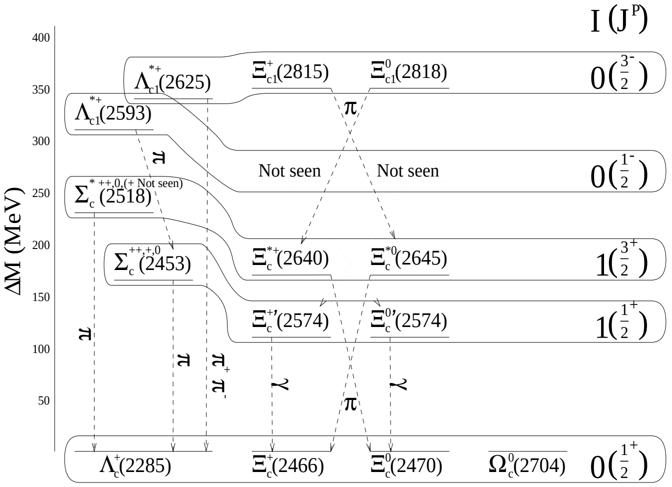

Figure 7: Possible orbitally excited charm baryon states. Full lines and arrows: observed; dashed lines and arrows: not observed before this workshop.

data in this sector.

Focus has analysed partial data samples looking for excited charmed baryons. An example is given in fig.s 8 which collects the evidence for: Σ_c^o (top left histogram), Σ_c^{++} (top right histogram), Σ_c^+ (bottom left histogram), and Λ_c^* (bottom left histogram) in fig. 8. At the end they should come up with a total statistics of close to 30,000 Λ_c^+ to associate to pions in the search of excited charmed baryons.

As mentioned above, no doubly charmed baryons have been observed yet. J.M Richard 18) predicted mass values in the range 3.63 − 3.70 GeV for $M(\Xi_{cc}^{++})$ and $M(\Xi_{cc}^+)$ and values in the range 3.72 − 3.80 GeV for the $M(\Omega_{cc}^+)$. Predazzi 14) predicts for $M(\Xi_{cc})$'s or $M(\Xi_{cc}^*)$'s -assuming a symmetric spin wave function for the two light quarks, but depending upon whether the ground-state baryon has spin 1/2 or spin 3/2- values in the range $(3.66 \pm .07) - (3.74 \pm .05)$ GeV as well as values in the range $(3.74 \pm .08) - (3.82 \pm .08)$ GeV for $M(\Omega_{cc})$ or $M(\Omega_{cc}^*)$. Possible decay modes of a $M(\Xi_{cc}^{+;++})$ could be $D^+\Sigma^+$ or $D^+\Lambda^o$, but there is still a long way to go before we face the problem of their finding.

5 Conclusions

There are no real conclusions to draw. The field is at the very beginning of a flourishing development. Experiments whose data collection has been completed, but with analyses still in progress, as well as experiments which are in the process of

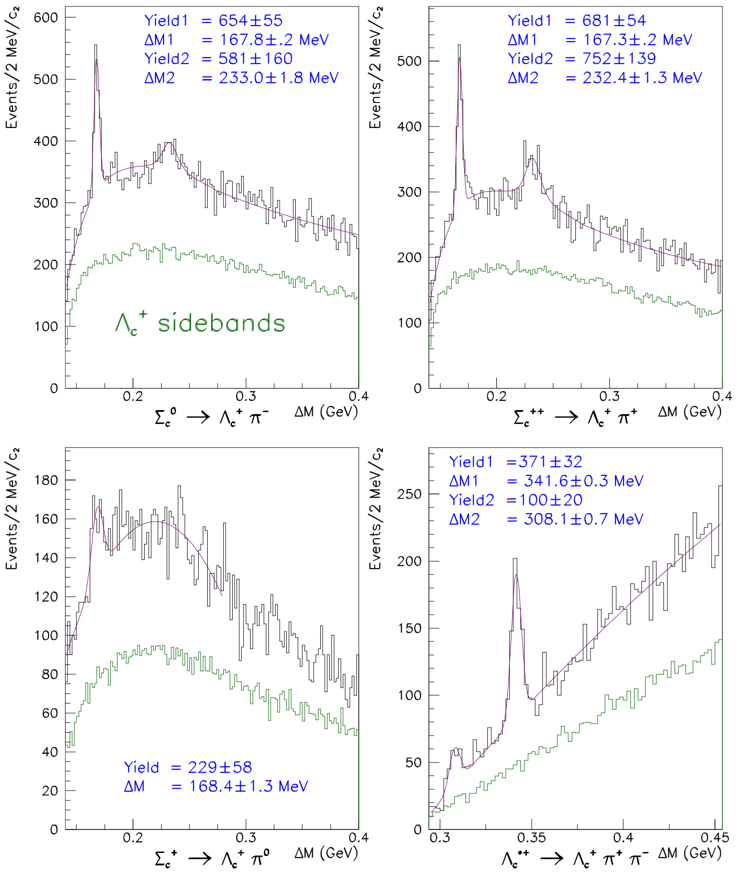

Figure 8: Preliminary evidence of charmed Λ's and Σ's from the Focus collaboration on a partial statistics.

collecting new data, will make this particular field of physics very active in the near future. There are however other interesting issues that might come up together with the high statistics experiments. Among these, the issue of the charmed fragments or supernuclei. From the theoretical standpoint it has been put forward since the very beginning of charm history.

A.A. Tyapkin [19], already in 1975, suggested the possible existence of bound states of charmed baryons to ordinary nuclei with lifetimes approximately equivalent to those of the free charmed baryons. These speculations were inherited by S. Iwao and sevearl others [20]. They investigated the nuclear potentials, calculated the energies of the ground and the excited states, finding their number more limited than in the case of hypernuclei; they calculated the binding energies using one boson exchange potential models and SU(4) symmetry.

There has been also an experimental investigation [21] to search for their production in nuclear emulsions exposed to 70 GeV and 250 GeV protons, providing upper limits for the production of Λ_c-nucleus states in Ag, Br respectively of 3.1×10^{-5} and 3.1×10^{-6} per inelastic interaction at a 90% confidence level. Tiny probabilities that might become manageable as soon as the data will become plenty.

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