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Study of hadronic $\Upsilon(nS)$ decays in (multi-)baryons

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A critical overview of the available experimental data on fragmentation and hadronization processes in e^+e^- annihilations, in the energy region of the first narrow Υ resonances, is presented. The possibility of producing deuterons in the inclusive decay of $\Upsilon(nS)$ $(n = 1, 2, 3)$ emerged from the data. A second interesting observation is the enhanced baryon production in the Υ decays as compared to continuum. These issues suggest to pursue further searches for multi-baryonic states, possibly with strangeness, in the data collected by the most recent experiments operating at B-factories. Ideas for possible analyses are put forward.

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1. Introduction: $\Upsilon(nS)$ spectroscopy and decays

The Υ resonances, bound states of $b\overline{b}$ quark pairs (also known as *bottomonium*), were discovered in 1977 in fixed target collisions [1] in the $\mu^+\mu^-$ decay channel. Soon after, their existence was confirmed in e^+e^- annihilations, where a number of resonances of increasing widths was observed. All these states are nearly non-relativistic ($(v/c)^2 \sim 0.08$) and, at least those below the open-beauty production threshold (10.54 GeV), long-lived.

The resonant states formed in e^+e^- annihilations have 1^{--} quantum numbers, so they correspond to the triplet $^3S_1$ $b\overline{b}$ ground state and its radial excitations. They are the most compact systems existing in nature, with a radial extension (without dressing) of less than 0.5 fm and a very large energy density, up to 200 GeV/fm^3.

The first three resonances have a very narrow width (some tens of keV), due to their suppressed strong decays. In fact, while above the open-beauty threshold strong decays are dominant and proceed through connected quark lines processes via $b\overline{b} \rightarrow (b\overline{q})(q\overline{b})$ (where q is a light quark), below threshold strong decays producing hadrons can proceed only through gluon exchange via disconnected quark line diagrams. According to the well known and experimentally well verified OZI rule [2], the latter processes are suppressed, so different decay modes, such as radiative transitions, can become competitive. Then, while above the open-beauty threshold the resonance widths are on the order of 10 MeV and are saturated by the strong decays into beauty hadrons, for the first three bottomonium states a few narrow partial widths contribute to the total one, from 1 to 10 keV each. The accessible decay modes depend, finally, on the quantum number of the resonant state. For instance, for spin triplet resonances, like $\Upsilon(nS)$ and $\Upsilon(nD)$, the total width may be written as:

$$\Gamma_{tot} = \Gamma_{ggg} + \Gamma_{gg\gamma} + (3+R)\Gamma_{ll} + \Gamma_{\gamma} + \Gamma_{\pi\pi} \tag{1.1}$$

where the first two term constitute the so-called *direct* decay channel (which does not proceed through a virtual photon, but just through gluons), the third term includes the leptonic decay mode (whose width is independent on the lepton flavor, due to universality) and the decay to $q\overline{q}$ hadrons via a virtual photon, being R the ratio between the hadronic and the muonic e^+e^- cross-sections. The fourth and the fifth term, respectively, give the radiative and the dipion decay contributions. Conversely, for the $\chi_{bJ}(nP)$ P-wave resonances, the direct part is played only by Γ_{ggg} if the resonance spin is even ($J = 0,2$) or $\Gamma_{q\overline{q}\gamma}$ if $J = 1$, and no annihilation through a virtual photon is possible. Of all the terms of formula (1.1), the hadronic decays dominate over the leptonic ones, whose width is very small and often below the experimental sensitivity thresholds. The direct width is assumed to be constant for all radial excitations of the same bottomonium resonance, but the relative weight of the two gluonic channels can be different: for instance, for $\Upsilon(1S)$ the branching fraction for decays via three gluons is about 80%, while it decreases to 60% for $\Upsilon(2S)$.

2. Fragmentation and Hadronization processes in e^+e^- annihilations at 10 GeV

In high-energy e^+e^- collisions the production of hadrons is understood to schematically proceed through three steps:

- fragmentation: quarks, antiquarks and gluons (generally known as *partons*) are produced in the collision. They trigger a partonic shower, in which $q\overline{q}$ fragment into gluons, and gluons radiate other gluons or split into $q\overline{q}$ pairs. The process is complex but can be calculated fairly precisely by pQCD (the better the higher the energy), and models and simulation programs exist based on different mechanisms to phenomenologically reproduce this stage. In the most widely used simulation tools, the following approaches are followed:

HERWIG: gluons are split into $q\overline{q}$ pairs, that are subsequently combined to form colorless clusters, which then are forced to decay into primary hadrons [3];

JETSET: partons interact through semiclassical strings in a color fields. An iterative algorithm breaks the string into several pieces, which form the primary hadrons [4];

UCLA: the reactions are simulated with weights deduced from phase space considerations and proper Clebsch-Gordan factors [5];

- hadronization: in this stage the partons transform into primary hadrons, emitted in jets. The quantitative understanding of the process is still scarce, so experimental data are necessary to build appropriate models and tune them properly;
- unstable primary hadrons decay: primary hadrons are detected in experiments only for about one third of the times while, in general, the observed particles come from the decay of vector mesons and SU(3) decuplet baryons. This adds a further complication to the hadronization dynamics.

Several differences emerge when e^+e^- annihilations at the Υ peaks are compared with those off-resonance, *i.e.* in the non-resonant continuum. The first important difference concerns the geometrical shape of the events (that is, its sphericity) and the emitted particle multiplicities. Events from $\Upsilon(nS)$ decays in three gluons are more spherical than those from $q\bar{q}$, which are jet-like and have a typical $(1+\cos^2\theta)$ distribution (being θ the emission angle of the jet in the center of mass, relative to the center of mass boost direction). In fact, gluons emitted from bottomonium rarely fragment again into heavy quarks, therefore the jet vertex is located very close to the interaction point, while for $q\overline{q}$ continuum events the jet vertices may be more displaced. Thrust distributions in events from $\Upsilon(1S)$ and in χ_{bJ} decays, as well as from the continuum, were measured first by the CLEO experiment [6]. It was found that decay channels dominated by gluons, namely $\Upsilon(1S) \to ggg$ and $\chi_{b0,2} \to gg$, have a similar behavior, different from the $e^+e^- \to q\overline{q}$ reaction in the continuum or the $\chi_{b1} \to gq\overline{q}$ decay, which are similar one to each other in turn. This indicates the inherently different hadronization mechanism occurring in gluons or quark-induced hadron production.

Concerning the final state multiplicity, more partons are expected in gluon induced events, since gluons can carry eight color combinations, which enhances the counting ratio to 9/4 as compared to $q\bar{q}$. However, while this rule, which basically holds for $Q^2 \to \infty$ [7], is almost verified at the Z^0 peak as observed by experiments at LEP, in the 10 GeV region non-perturbative effects appear. In this case, only a slight dominance of the produced multiplicity in ggg, as compared to $q\overline{q}$ decays, is observed.

2.1 Hadron production in gluon versus quark fragmentations at high energies

Just a few experimental observations exist on the production rates of several hadron species in e^+e^- reactions at the Z^0 peak, performed by SLD and experiments at LEP. SLD showed that at these energies the inclusive production of pions, kaons and protons is basically equivalent in gluon or quark-induced jets [8]. The same equality was found by OPAL for the production of K_S^0 and Λ [9]. On the other hand, OPAL found that the inclusive production of charm in gluon jets is suppressed of about one order of magnitude as compared to quark jets [10]. The same was observed for beauty production by ALEPH [11] and DELPHI [12], with the 9/4 color counting rule largely violated.

2.2 Baryonic production in $\Upsilon(nS)$ decays and the continuum: experimental observations

Most of the experimental observations on hadron production rates at the Υ energies are old and date back to the late Eighties, in spite of the large wealth of data collected by more recent experiments performed at B-factories.

The first results were provided by ARGUS, operating at the DORIS ring in Hamburg, and then by CLEO at Cornell. The first ARGUS data [13] showed an enhancement of the baryon production at $\Upsilon(1S)$ as compared to continuum of a factor 2.5. The momenta of hadrons produced from the continuum were in average larger as compared to the production at the resonance. ARGUS studied the production of a variety of hadrons, showing that the enhancement observed for baryons was not a mere mass effect, since it did not involve mesons like η or ϕ. Conversely, the meson production rate from $\Upsilon(1S)$ was suppressed, as compared to baryons, of a factor of three. ARGUS added also information on strangeness as well as spin suppression. The observed suppression of strange hadron production at $\Upsilon(1S)$, which was less then half as compared to the yield of hadrons with one unit of strangeness less, affected in the same way both baryons and mesons, independently on their spin. On the other hand, a spin suppression effect reduced the spin 3/2 decuplet baryons production rate of a factor 5 compared to the spin 1/2 octet. Fig. 1a) shows the ratio r between production rates of strange baryons differing of one unit of strangeness. Fig. 1b) shows the ratio R between the production rates in Υ decays and $(q\overline{q})$ continuum for several particles (both figures are from Ref. [13]).

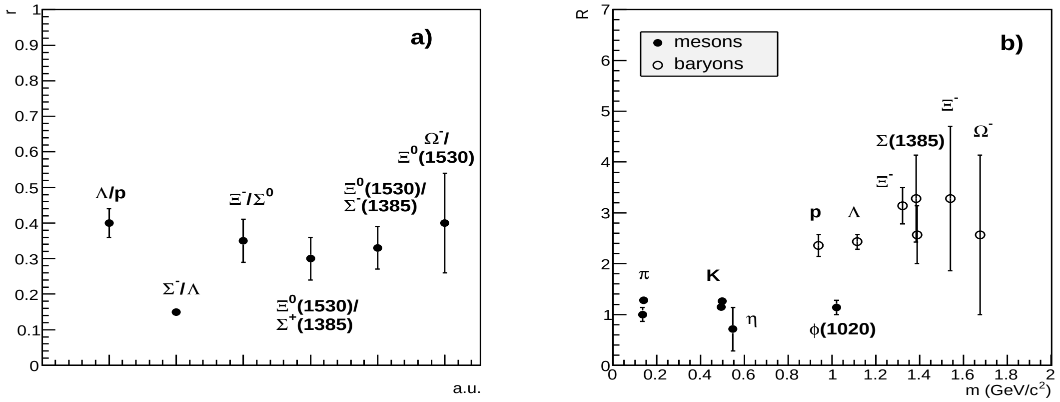

Figure 1: a): Strangeness suppression factor for baryons different of one unit of strangeness (data from ARGUS, Ref. [13]). b): Ratio of hadron production rates (data from ARGUS, Ref. [13] and references therein).

Later, CLEO studied in detail the baryon production from continuum and bottomonium decays in the two channels $\Upsilon(nS) \to ggg$ and $\Upsilon(nS) \to gg\gamma$ [14]. They show the same features and trends, though larger enhancements for all hadrons (namely, Λ, p, $\bar{p}$, ϕ and $f_2(1270)$) occur in the three gluon decay channel. Clear enhancements were observed for the production of Λ, p and $\bar{p}$, of a factor 2.5-3 comparing $\Upsilon(nS) \to ggg$ decay to $q\bar{q}$ continuum. The behaviour is similar from all the Υ radial excitations, with a hierarchical decreasing trend for hadron production from $\Upsilon(1S)$ down to $\Upsilon(3S)$. The $\Upsilon(nS) \to gg\gamma$ decay channel features basically the same pattern. Fig. 2 left (right) shows the production fractions measured by CLEO for several baryons in ggg ($gg\gamma$) as compared to $q\bar{q}$ ($q\bar{q}\gamma$) events (from Ref. [14]).

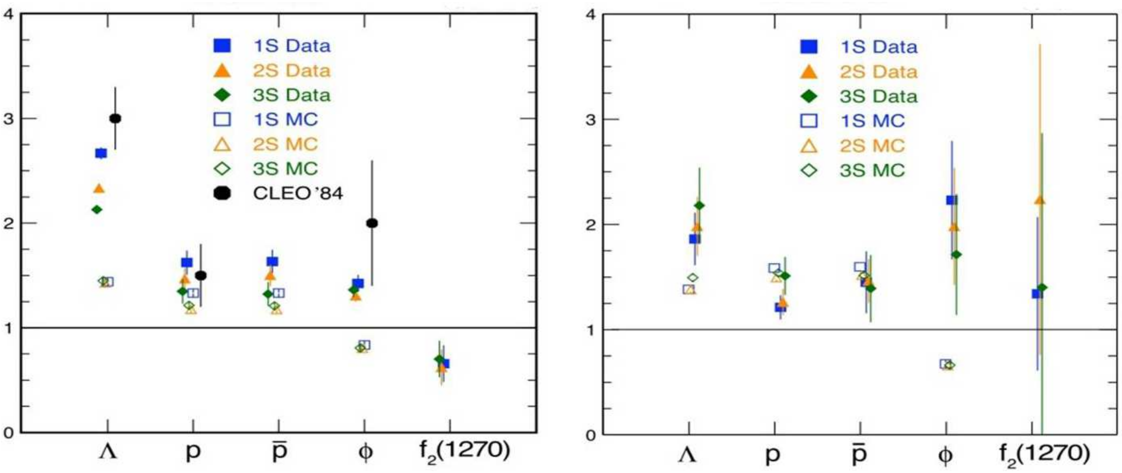

Figure 2: Compilations of momentum integrated $ggg/q\bar{q}$ enhancements for ggg (left) and $gg\gamma$ (right) decay events, for several hadrons. Full symbols are data, open symbols are from JETSET simulations. The color code is as follows: blue, data from $\Upsilon(1S)$ resonance; yellow, data from $\Upsilon(1S)$; green, data from $\Upsilon(3S)$. From Ref. [14].

All these observations favour different possible fragmentation-hadronization scenarios. Two opposite situations are 1) a completely independent fragmentation and hadronization of the gluons/quarks produced in the collision, or 2) an hadronization through quark pairs only, which would introduce correlation effects, observable in the final states, among the primary hadrons. While the strangeness suppression could be more easily explained by an independent fragmentation of each quark, the overall baryonic enhancement, as well as the spin 3/2 suppression and the same strangeness suppression of baryons and mesons would occur more naturally in case of production through di-quarks. In favour of this hypothesis also several observations exist of correlated baryon production in opposite spatial hemispheres, performed at $\Upsilon(4S)$ and in the below continuum. In case of independent fragmentation, one would expect the same production of baryons/antibaryons in opposite hemispheres, but a 3σ excess is observed for inclusive $\Lambda\bar{\Lambda}$ production at $\Upsilon(4S)$ by CLEO [15]. The same holds for $\Lambda_c\bar{\Lambda}_c$ production: an excess of a factor 3-4 in the relative $\Lambda_c/\bar{\Lambda}_c$ production was observed, respectively, at $\Upsilon(4S)$ by BaBar [17] and CLEO [16].

CLEO reported also a few results on correlations between other strange baryons [15], which however are much more difficult to measure due to the large amount of secondaries from charmed baryon decays. In general, the correlation between |S|=1 baryons ($\Sigma\bar{\Sigma}$, $\Lambda\bar{\Lambda}$) follows the pattern outlined for $\Lambda\overline{\Lambda}$. However, for $\Xi\overline{\Xi}$, the emission rate is suppressed and a small signal of correlation is observed, but this time for baryons emitted in the same hemisphere. This could be an indication of a different hadronization mechanism effective in the |S|=2 case, and of the fact that in both Λ and Ξ production the lighter quarks lead the hadronization process.

3. $\Upsilon(nS)$ decays in bound states: (anti-)deuteron production

(Anti-)deuteron production has been measured in several high energy reactions, from relativistic heavy ion collisions (where it gives a signature of the cooling into hadrons of hadronic fluid at freeze-out time), to $\bar{p}p$ collisions, to deep inelastic electron scattering, to photoproduction, and finally to Z^0 and Υ decays. Usually antideuteron rates are measured, as deuterons can also be produced in secondary interactions of beams and particles with detectors and solid materials inside the apparatuses.

The mechanisms of fragmentation and hadronization into deuterons in high energy collisions are of fundamental interest to explain a possible excess from the expected yield of cosmic (anti-) deuterons (at the level of 10^{-9} m^{-2}s^{-1}sr^{-1}GeV^{-1}), which otherwise could be due to other unknown sources, among which Dark Matter decays.

So far no quantitative prediction exists for the production of bound states (as loose as deuterons or $X(3872)$) in Υ decays. Intuitively, small cross-sections and branching fractions are expected, as the shallow binding can easily be broken at these high energies. All qualitative existing estimations have been deduced from purely phenomenological event generators [18].

The simplest hypothesis for the formation of (anti-)deuterons is that a coalescence process occurs which binds a proton-neutron (or $\overline{n}\overline{p}$) pair emitted nearby in phase space, that is with a relative momentum on the order of the deuteron binding energy ($\sim$ 2 MeV) [19]. In this scenario, the rate of (anti)-deuteron production is related to the square of the production rates of the single nucleons, so the yield is expected to be suppressed by at least two orders of magnitude as compared to the production yield of protons or neutrons. The momentum spectrum of the emitted (anti-) deuterons is assumed to follow a thermal distribution, typical of a fireball: the data collected by ARGUS [20, 21] and later on by CLEO [22] can indeed be fitted by a Maxwellian distribution with a temperature of 160 MeV, a common value in nuclear collisions. An important parameter deduced from the Maxwellian distribution is the coalescence radius, which defines the (spherical) phase-space volume in which the (anti-)deuteron wave function develops, and is related to the size of the fragmentation region. The analysis of CLEO data finds for this radius $p_0 \sim 200$ MeV/c, a value roughly in agreement with the typical radius of low-energy proton-nucleus collisions.

ARGUS measured the antideuteron inclusive yield in $\Upsilon(1S,2S,4S)$ decays and in the continuum in two data sets with small statistics (respectively, 6 [20] and 21 candidate events [21]). However, it was enough to point out a strong suppression of antideuteron production as compared to the antiproton yield, and an unexpectedly large rate from the resonance events as compared to continuum. CLEO [22] repeated the observation with the purpose of measuring also the direct part of the Υ decay branching fraction, which, as mentioned in Sec. 1, is only due to gluon exchange and is assumed to be the same for every radial excitation. By means of specific energy loss measurements, 338, 69 and 3 $\bar{d}$ candidate events were found [22] from the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ samples respectively, from which the following branching fractions per resonant (or $q\overline{q}$) event were obtained (statistical and systematic uncertainties are here added in quadrature for the sake of conciseness):

$$\begin{aligned} B.R.^{dir}(\Upsilon(1S) \to \bar{d}X) &= (3.36 \pm 0.34) \times 10^{-5} \\ B.R.(\Upsilon(1S) \to \bar{d}X) &= (2.86 \pm 0.28) \times 10^{-5} \\ B.R.(\Upsilon(2S) \to \bar{d}X) &= (3.37 \pm 0.56) \times 10^{-5} \\ B.R.(\Upsilon(4S) \to \gamma^{*} \to q\bar{q} \to \bar{d}X) &< 1.3 \times 10^{-5}. \end{aligned}$$

These figures show again an enhancement of (anti-)deuteron production in ggg, $gg\gamma$ decays of at least three times as compared to the production from $q\bar{q}$.

In all the candidate events the baryonic quantum number is almost exactly compensated against nucleon uncorrelated pairs. On the other hand, the compensation against deuterons is largely suppressed: $R(e^+e^- \to \bar{d}dX)/R(e^+e^- \to \bar{d}NNX) \sim 1\%$. This implies, not unexpectedly, that a double coalescence is very unlikely. A much larger ratio would indicate the presence of a mechanism different from coalescence acting during the hadronization phase, or even at the beginning of fragmentation.

Updates of these measurements are currently being pursued, with much larger statistics, both by Belle and BaBar.

4. From nuclear to strange bound states

A straightforward extension of the existing observations could be the search of bound states with strangeness in Υ decays. The simplest strange bound state could be the $\Lambda(1405)$ baryon, whose nature, though, is still unclear. In fact, it could be a simple radial (uds) excitation of the $\Lambda(1115)$ baryon, but its particular production and decay patterns suggest that it might likely be a quasi-molecular $\overline{K}N$ state, were the $\overline{K}N$ potential so strong to provide a deep enough binding. Studies on $\Lambda(1405)$ are currently being pursued by several experiments; so far, the cleanest observation has been provided by CLAS [23]. Remarkably, the state has always been observed in its $\Sigma\pi$ decay channel, but it is produced through a $\overline{K}N$ interaction, therefore it could be generated dynamically through the interplay of two poles in two different sheets of the Riemann space.

According to some $\overline{K}N$ potential models, the $\Lambda(1405)$ can be seen as the "doorway" for the composition of even more complex strange baryonic aggregates, the antikaon-nuclear bound states [24]. Contrary to the $\Lambda(1405)$ case, these states have not been observed steadily yet, and the possibility of their existence is still a controversial issue from the theoretical point of view. Ref. [24] suggests them to be very dense systems (with a density of a least three times that of ordinary nuclei), bound by as much as 100-200 MeV as a consequence of the strength of the $\overline{K}N$ attractive potential. This large binding energy would only allow their non-mesonic decay into a hyperon and nucleons, therefore their width should be narrow enough, on the order of some tens of MeV, to observe them experimentally. The existence of such systems could have implications on the composition of astrophysical objects like compact stars. In fact, in highly dense baryonic matter the onset of kaon condensation is crucial to provide gravitational stability [25]; so, a strong relationship exists between dense nuclear systems and strangeness, and the existence of (relatively) long-lived bound kaonic systems could account for it.

From the experimental point of view the existing observations of bound kaonic systems are still elusive. Indications were provided by FINUDA in kaon induced interactions on light nuclear targets [26], by DISTO in pp scattering [27] and by FOPI in nucleus-nucleus scattering [28]; for comprehensive summaries of the topic see, *e.g.,* Ref. [29]. All these experiments searched for enhancements in the Λp system. The cleanest issue was provided by FINUDA, that observed a relatively narrow ($\Gamma = 67$ MeV) mass excess in the (Λp) invariant mass spectrum below the threshold of the quasi-free $K^-(pp) \to \Lambda p$ reaction, corresponding to a binding energy of 115 MeV. A marked back-to-back angular correlation between the Λ and the proton could be due to the decay at rest of an intermediate composite object. The observation was based on K^- interactions in a mixture of light targets (^{6}Li, ^{7}Li, ^{12}C), and more detailed studies are currently being performed on single nuclear species [30]. Unfortunately, in the medium further effects can add, like conversion reactions or rescattering of the particles emitted in the final state, which spoil the cleanliness of the signature. Especially, final state interactions (FSI's) were suggested to provide a huge distorting effect to the experimental observations [31]. Of course, it would be desirable to perform such studies in very light media (or, even better, in the vacuum) to limit as much as possible the blurring effect of FSI's.

4.1 Bound states with strangeness (and charm) in $\Upsilon(nS)$ decays?

$\Upsilon(nS)$ decays provide a favourable environment for the observation of possible strange (multi-) baryons, given the very high energy density of the bottomonium system and the mentioned abundance of baryons and deuterons in the decay processes. This hadronic environment can also profit from the absence of FSI's. So far, the search of inclusive decays of $\Upsilon(nS)$ resonances in strange (multi-)baryons was never pursued. A few paths that could be explored with dedicated analyses of the data collected, for instance, by BaBar and Belle are listed in the following [32]:

- search for inclusive decays into $\Lambda(1405)$, in particular exploiting its $\Sigma^0\pi^0$ decay channel which is not shared, as $\Sigma^\pm\pi^\mp$, by $\Sigma(1385)$, a well known Σ radial excitation which lies in the same mass region; also the $\Lambda(1405)$ radiative decays, studied very rarely so far, could be helpful and interesting;

- search of the $K^-(NN)$ bound system studying (Λp), $(\Sigma^0 p)$ and $(\Sigma^- p)$ pairs and their angular correlations, if any.

With a tentative production rate of some fractions of 10^{-5} per Υ decay (the level of anti-deuteron production), the statistics collected by Belle and BaBar could be at limit for such observations. It is likely that more successful searches could be performed in the charm sector, to look for charmed bound states, as suggested by Ref. [33] which claims for a larger probability for their formation as compared to those with strangeness:

- search for inclusive decays in $\Lambda_c(2595)$. $\Lambda_c(2595)$ is the charmed counterpart of $\Lambda(1405)$, and could be interpreted as a DN bound state;

- search for more complex DNN bound states, decaying for instance into $\Lambda_c N$ or $\Lambda_c \pi N$.

5. Conclusions and Outlook

Rather dated studies on hadronic decays of $^3S_1$ bottomonium resonances have evidenced interesting effects, related to basic fragmentation and hadronization mechanisms, which still wait for a comprehensive explanation. A systematic study of the production of single particle species in the decay processes, for which just a few sparse measurements exist so far, could improve the understanding of these phenomena. The unexpected observation of antideuterons suggests, moreover, that it could be worthwhile to look for the emission in Υ decays of strange (or even charmed) bound baryons. This study could provide information on some still unclear processes, like the strangeness production and the di-quark evolution in fragmentation, the coalescence mechanism (if effective) at the basis of bound states formation, and the production of bound states in reactions free from rescatterings. BaBar and Belle (and future BelleII) data have the potentiality for such studies.

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