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BABAR Results on the D_s System

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Abstract. The surprising discovery by the *BABAR* Collaboration of a narrow state with a mass of 2317 MeV decaying to $D_s\pi^0$ has been followed by other spectroscopic revelations. We focus on the *BABAR* results for the second state, at 2458 MeV, but mention related work from other experiments.

Introduction

The discovery [1] of a narrow state decaying into $D_s\pi^0$ was a surprise because it contradicted the expectations of apparently well established theory. The spectroscopy of systems of two heavy quarks is quite well understood after years of study in the ψ and Υ systems. Soon after the discovery of the charmonium system, DeRujula, Georgi, and Glashow proposed [2] that systems with one heavy quark and one light quark could be understood as analogs of the hydrogen atom, with spin-orbit couplings and hyperfine structure. This approach has been very successful in explaining the spectroscopy of heavy-quark light-quark systems.[3, 4, 5, 6].

A particularly impressive result is the understanding of p-wave states in the D ($c\bar{s}$) system. By analogy with the hydrogen atom, we successively add interactions that break large symmetries down to smaller ones. Thus with only a spin-independent potential, all first level of p-wave states are degenerate. If we write $\boldsymbol{\ell}$ for the orbital angular momentum and $\boldsymbol{s}$ for the spin of the light quark, their sum $\boldsymbol{j} = \boldsymbol{\ell} + \boldsymbol{s}$ is still a good quantum number when the spin-orbit interaction is included but hyperfine interactions are neglected. For p states we have $\ell = 1$ and thus $j = 1/2, 3/2$. The total angular momentum is obtained by adding the spin $\boldsymbol{s}'$ of the heavy quark: $\boldsymbol{J} = \boldsymbol{j} + \boldsymbol{s}'$. Thus both the $j = 1/2$ and $j = 3/2$ states contribute to $J = 1$. In the limit of a very heavy quark (for which c is not an especially good candidate) the $j = 1/2$ and $j = 3/2$ states do not mix. In considering the emission of a pion by the $j = 3/2$ state with $J^P = 1^+$ to the s-wave ground states, $J^P = 0^-, 1^-$ we see that parity forbids decay to the D but allows decay to the D^*. The $D^*\pi$ can be in either s wave or d wave. However, since the s-wave ground states have $j = 1/2$, s-wave pion emission cannot reach them from the $j = 3/2$ p-wave state. The decay is instead by d-wave emission and is suppressed by the angular momentum barrier. As a result we predict a narrow $J = 1$ state in the D system. This is precisely what is seen. The other $J = 1$ state (with $j = 1/2$) should be broad and it is.

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An entirely analogous prediction held for the D_s system except that there the decay was by K emission in order to conserve both strangeness and isospin in the strong decay: $D_s(j=3/2) \to D^*K$. This is indeed observed and is narrow. The second $J=1$ state and the $J=0$ state were expected to be broad as a consequence of s-wave K emission.

This last prediction failed because the the $J=0$ state turned out to be 160 MeV lower in mass than models indicated and thus was below threshold for decay to DK. This striking failure of theoretical models has spurred both experimental and theoretical re-examination of the D_s system and heavy-quark light-quark systems, generally.

Discovery of the $D_{sJ}(2317)$

While *BABAR* detector[7] generally runs with PEP-II set at the $\Upsilon(4S)$ resonance to produce B-$\overline{B}$ pairs, there is necessarily a substantial production of $c\overline{c}$ continuum in the 91 fb^{-1} of integrated luminosity considered here.

Candidates for $D_s^+ \to K^+K^-\pi^+$ (throughout, we imply charge conjugate processes and states, as well) are isolated using particle identification information from dE/dx measurements in the drift chamber and silicon vertex tracker and especially from the DIRC, a Cerenkov detector that measures with precision the Cerenkov angle of emitted photons. Candidates for D_s are required to have masses within the range 1.955 GeV to 1.979 GeV and to form a vertex with a fit probability greater than 0.1%. The signal is further refined by requiring that the D_s decay be into one of the quasi-two-body modes, $\phi\pi$ or $K^*\overline{K}$. We obtain additional discrimination by using the unique angular distribution for these decays by requiring that $|cos\theta_h| > 0.5$, where θ_h is the helicity angle of the vector particle's decay. Sideband regions, used for comparisons, are defined by the mass ranges (1.912 GeV, 1.934 GeV) and (1.998 GeV, 2.20 GeV).

The π^0 candidates are constructed from pairs of photons and are constrained to be consistent with the D_s trajectory and the beam envelope, with a fit probability greater than 1%. Again a signal region (122 MeV, 148 MeV) is defined, as well as sidebands, (90 MeV, 110 MeV) and (160 MeV, 180 MeV).

The D_s and π^0 candidates are combined to look for peaks in the invariant mass distribution. To eliminate backgrounds from B-meson decays and from continuum $q\overline{q}$ events, the $D_s\pi^0$ system is required to have momentum greater than 2.5 GeV in the CM. As seen in Fig. 1, a peak is apparent at a mass near 2.32 GeV.

Using data with $p(D_s\pi^0) > 3.5$ GeV in the CM, a fit with a Gaussian distribution for the signal and a third-order polynomial for the background finds 1267 ± 53 candidates, with a mass of 2316.8 ± 0.4 MeV and a standard deviation of 8.8 ± 0.4 MeV (statistical errors only). A analogous analysis using the decay channel $D_s^+ \to K^+K^-\pi^+\pi^0$ gives similar results: a mass of (2317.6 ± 1.3) MeV and a standard deviation of (8.8 ± 1.1) MeV. The measured width is consistent with the resolution and leads to the limit on the intrinsic width $\Gamma < 10$ MeV.

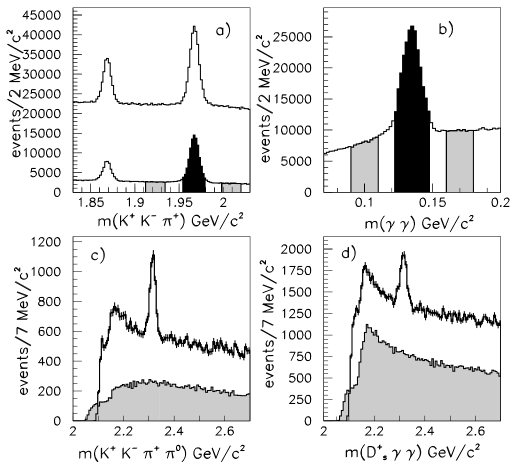

FIGURE 1. Evidence for the $D_{sJ}(2317)$. (a) Distribution of the $K^+K^-\pi^+$ mass before and after cuts described in the text that isolatethe signal. The signal region is dark, while the sidebands are shaded. The Cabibbo-suppressed decay of the D is visible. (b) The π^0 signal and sidebands. (c) The $D_s\pi^0$ mass distribution for signal π^0 with signal D_s (unshaded) and D_s sidebands (shaded). (d) The $D_s\gamma\gamma$ mass distribution for the D_s signal region and for the π^0 signal region (unshaded) and sideband region (shaded).

What is the $D_{sJ}(2317)$?

While more exotic explanation are possible, the simplest is that this is indeed the p-wave $c\bar{s}$ state with $J=0$. It falls about 160 MeV lower than anticipated [3, 4, 5, 6]. Once that is accepted, the rest fits into place. The decay to $D_s\pi^0$ is isospin violating, but still the best option available. It can be imagined to proceed through $\eta - \pi^0$ mixing [8].

If this surmise is correct, we should not find the radiative decay $D_{sJ}(2317) \to D_s\gamma$ (no $0 \to 0$ radiative transition), but could expect to find $D_{sJ}(2317) \to D_s^*\gamma$. In addition, we would expect to find a $J=1$ state, which might be too light to decay to D^*K and which might thus be narrow. Among its decays then could be those to $D_s^*\pi^0$ and to $D_{sJ}(2317)\gamma$.

A Second State

Searches for structure in the channels $D_s\gamma$ and $D_s\gamma\gamma$ reveal nothing new[1]. See Figs.2a,b. However, in the $D_s^+\pi^0\gamma$ channel, a small peak near 2460 MeV is evident, especially when the $D_s^+\gamma$ form a D_s^*. See Fig.2c. The peak occurs near the crossing of the $D_{sJ}(2317)$ and D_s^* bands in the sense that if we add a random γ to the $D_{sJ}(2317)$ in such a way that the $D_s^+\gamma$ pair has a mass near that of the D_s^*, then the mass of the total $D_s^+\pi^0\gamma$ system must be close to 2460 MeV. A similar argument holds if we add a random π^0 to a D_s^*.

In this circumstance, the first priority is to make sure that the state at 2317 MeV was itself real and not simply an artifact of this possible higher state. Indeed the structure that would be produced from the decay of a state at 2460 MeV would be wider than that

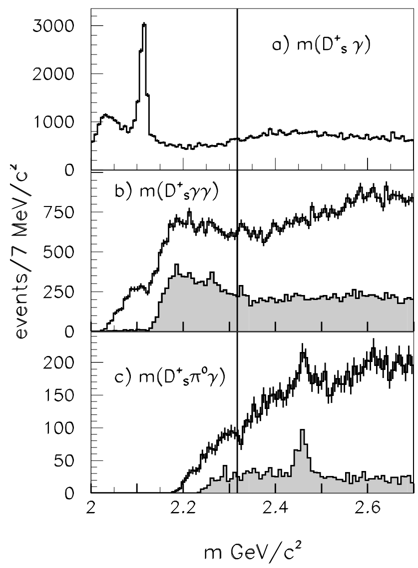

FIGURE 2. Searches for additional structure: (a) in $D_s^+\gamma$, (b) in $D_s^+\gamma\gamma$, (c) $D_s^+\pi^0\gamma$. The lower histograms of (b) and (c) correspond the $D_s^+\gamma$ masses that fall in the D_s^* signal region. The vertical line is at 2317 MeV. Taken from [1].

observed. Moreover, such decays could account for only one-sixth of the signal observed at the lower mass.

The study [1] of the 2460-MeV region in the first paper ended with the remark "...the complexity of the overlaping kinematics of the $D_s^*(2112)^+ \to D_s^+\gamma$ and $D_{sJ}(2317) \to D_s^+\pi^0$ decays requires more detailed study, currently underway, in order to arrive at a definite conclusion."

CLEO and BELLE

The CLEO and BELLE collaborations quickly confirmed the existence and narrowness of the $D_{sJ}(2317)$[9, 10, 11]. Moreover, CLEO identified the structure at 2460 MeV as a narrow state [9], as did BELLE, both in inclusive production through the $c\bar{c}$ continuum [10] and in exclusively reconstructed B decays[11].

BABAR Analysis of the Second State

BABAR did indeed carry out the detailed study. (The conference talk was given before complete results from *BABAR* on the $D_s(2458)$ were available. The *BABAR* paper on this was submitted Oct. 24, 2003.) To address the question of whether there is really a signal at a mass near 2460 MeV or whether the structure shown above is just the result of superposing two known sources, the D_s^* and $D_{sJ}(2317)$ together with random π^0s or γs, we consider the variables

$$\Delta m_\gamma \equiv m(D_s^+\gamma) - m(D_s^+) \tag{1}$$

$$\Delta m_{\pi^0} \equiv m(D_s^+\gamma\pi^0) - m(D_s^+\gamma)\,. \tag{2}$$

A scatter plot of events in these two variables displays the crossing. Using the sidebands

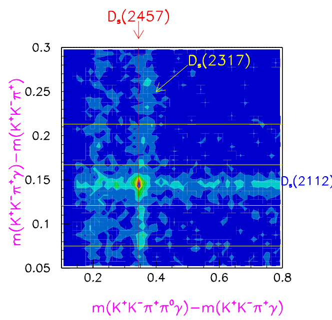

FIGURE 3. Scatter plot of $D_s^+\pi^0\gamma$ events in the variables Δm_γ and Δm_{π^0}.

indicated in Fig. 3, we can perform a subtraction to determine the distribution in the variable Δm_{π^0} This is shown in Fig. 4. The fit finds a yield of 140 ± 22 events with the

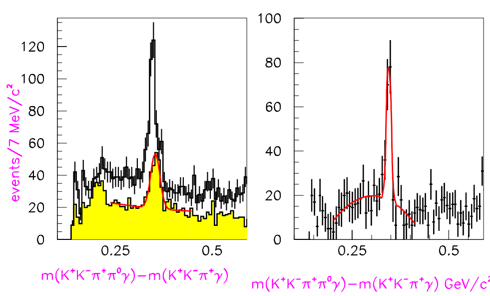

FIGURE 4. The distributions in the variable Δm_{π^0} for the (a) Δm_γ signal bands (white) and sidebands (shaded), (b) the difference between signal band and sidebands, with a Gaussian plus polynomial fit.

peak at $\Delta m_{\pi^0} = 344.6 \pm 1.2$ MeV.

While this settles the question of whether there is a state near 2460 MeV, and confirms the results of CLEO and BELLE, it does not answer the question of whether its decay path is $D_s(2458) \to D_s^{*+}\pi^0$ or $D_s(2458) \to D_{sJ}(2317)\gamma$. Of course in the first instance the distribution of $D_s\gamma$ masses will be narrowly peaked near the D_s^{*+} while in the latter, there will be a narrow peak in the $D_s\pi^0$ channel.

To determine which is the case, we divide the region surrounding the signal area in the $m(D_s^+\gamma)$-$m(D_s^+\pi^0)$ plane into a three-by-three array of tiles, with the actual center coinciding with the peak intensity. Then by taking suitable linear combinations of tiles we can isolate a signal associated with just the $m(D_s^+\gamma)$ variable, and a signal associated with just the $m(D_s\pi^0)$ variable. We can then check whether these are broad or narrow, by comparing them with Monte Carlo generated to represent the two obvious possibilities for the decay path.

In Fig. 5 we see the sideband-subtracted distributions in $m(D_s^+\gamma)$ and $m(D_s^+\pi^0)$ compared with Monte Carlo generated assuming the decay chain is $D_s(2458) \to D_s^{*+}\pi^0$. Figure 6 shows the same data, but compared instead to Monte Carlo generated to represent the decay chain $D_s(2458) \to D_{sJ}(2317)\gamma$. It is apparent that the path $D_s(2458) \to D_s^{*+}\pi^0$ gives a far better description of the data.

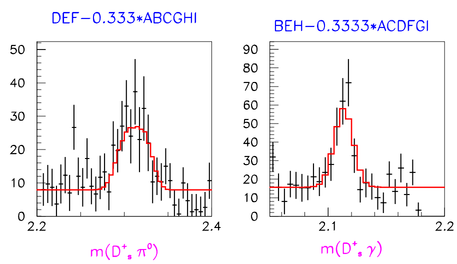

FIGURE 5. Sideband-subtracted data for the distributions in Δm_{π^0} and Δm_γ compared to Monte Carlo (shown in the histogram) based on the decay path $D_s(2458) \to D_s^{*+}\pi^0$.

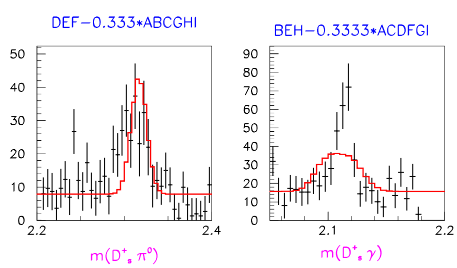

FIGURE 6. Sideband-subtracted data for the distributions in Δm_{π^0} and Δm_γ compared to Monte Carlo (shown in the histogram) based on the decay path $D_s(2458) \to D_{sJ}(2317)\gamma$.

The decay $D_s^{*+} \to D_s\gamma$ provides information on the polarization of the D_s^{*+}, and thus on the spin of its parent $D_s(2458) \to D_s^{*+}\pi^0$. If the $D_s(2458)$ is spin-zero, its parity must be odd. Otherwise, if the decay products have orbital angular momentum L, then the parity is $(-1)^L$. The total angular momentum is $J = L-1, L$, or $L+1$. In particular, if $D_s(2458)$ has natural spin-parity, then $J = L$ and there is a unique decay amplitude. For unnatural spin-parity (except $J^P = 0^-$) we have $J = L \pm 1$. With two decay amplitudes, the angular distribution of the photon relative to the line of flight of the D_s^{*+} is not uniquely determined. We find that for $J^P = 0^-$ the angular distribution is $\sin^2\theta$, while for natural spin-parity it is $1+\cos^2\theta$. Figure 7 shows our data compared to the expectations for various spin-parities. It is apparent that $J^P = 0^-$ is disfavored. This is in agreement with the BELLE result [11] obtained by studying $B \to DD_s(2357), D_s(2357) \to D_s\gamma$. The very existence of this decay excludes the assignment $J = 0$ for the $D_s(2357)$. The angular distribution excludes $J = 2$ and is consistent with $J = 1$.

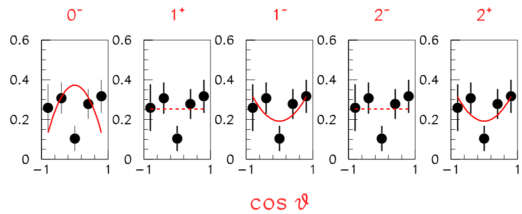

FIGURE 7. The observed angular distribution of the photon relative to the line of flight of the D_s^{*+} from the decay $D_s(2458) \to D_s^{*+}\pi^0$. The predictions for J^P of the $D_s(2458)$ are unique for 0^- and the natural spin-parity sequence $(1^-, 2^+, \ldots)$. Except for $J^P = 0^-$, for unnatural spin-parity the angular distribution is not determined a priori.

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