Observation in *BABAR* of a narrow resonance in the $D_s\pi^0$ system at 2317 MeV/c^2

Roger Barlow
Department of Physics and Astronomy
The University of Manchester
Manchester M13 9PL, UK

The *BABAR* collaboration has observed a state of mass 2317 MeV/c^2 which decays to $D_s\pi^0$, using 91 fb^{-1} of data from asymmetric e^+e^- collisions of energy around 10.6 GeV produced by the PEP-II storage ring. The observed width is compatible with the experimental resolution, indicating that the state is narrow, with $\Gamma < 10\,\mathrm{MeV}$. Properties of the state are presented, and implications are discussed.

1 Introduction

Although the *BABAR* detector, like the asymmetric PEP-II B factory at which it runs, was built for the prime purpose of studying CP violation in B mesons produced by the $\Upsilon(4S)$, it also has many other possibilities for physics studies. We present here the observation of a new meson in the charm-strange system, provisionally named the $D^*_{sJ}(2317)$. The analysis was performed on 91 fb^{-1} of data taken during the period 1999 to 2002, with centre of mass energy equal or close to the mass of the $\Upsilon(4S)$. An account is given in [1].

2 Candidate Selection

We look for mass combinations in the $D_s\pi^0$ system. As preliminary selections for good events we require at least 3 charged tracks in the tracking chambers, at least 2 clusters in the electromagnetic calorimeter, and the ratio of Fox Wolfram moments H_2/H_1 below 0.9. (This removes many of the isotropically decaying $\Upsilon(4S) \rightarrow B\overline{B}$ events.)

The mass plot of photon pairs in Figure 1a shows a clear π^0 signal. π^0 candidates are formed from clusters above 100 MeV, with a probability for the kinematic and geometric fit to the π^0 hypothesis above 0.1%, and neither photon associated with another possible π^0 candidate.

The D_s is identified through its decay to $K^+K^-\pi^\pm$. Particle identification is done using information from the Čerenkov detector combined, using a neural network, with $\frac{dE}{dx}$ measurements from the tracking chambers. The 3 tracks are required to have a vertex fit probability greater than 0.1%. The mass spectrum (shown in Figure 1b) shows the D_s peak at 1.97 GeV/c^2, together with peaks from the Cabibbo-suppressed decay of the $D^\pm$ at 1.87 and from the $D^{*\pm}$ at 2.01 through its decay to $D^0\pi^\pm$. Although the signal peak is clear, the background is large. It is reduced by a further set of cuts.

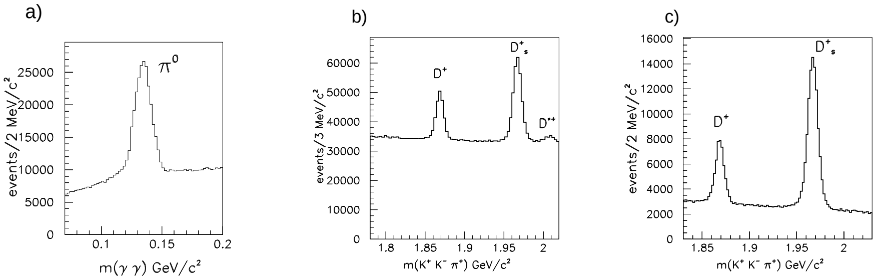

Figure 1: Mass distributions for (a) photon pairs, and for $KK\pi^{\pm}$ combinations before (b) and after (c) the cuts described

- We require the K^+K^- mass to be less than $1.84\,\mathrm{GeV/c^2}$, to eliminate the D^{*+}.
- As this D_s decay is known to proceed mostly through the two body states $\phi\pi$ and K^*K, we require that either the K^+K^- mass lie between 1.010 and $1.030\,\mathrm{GeV/c^2}$ or that the $K^{\mp}\pi^{\pm}$ mass lie between 0.842 and $0.942\,\mathrm{GeV/c^2}$.
- In both of these channels (for which the regions do not overlap) the decay of a scalar meson to scalar + vector requires the vector particle (ϕ or K^*) to decay with a distribution in the helicity angle θ_h proportional to $\cos^2\theta_h$. We therefore require that $|\cos\theta_h| \geq 0.5$.
- We require a total cms momentum of the combined $K^+K^-\pi^{\pm}\pi^0$ system above $2.5\,\mathrm{GeV/c}$.

The mass distribution after these cuts is shown in Figure 1c, and candidates are accepted as D_s if the mass lies between 1955 and $1979\,\mathrm{MeV/c^2}$. In subsequent analysis the measured mass of accepted D_s candidates is replaced by the standard value [2].

Having found clean π^0 and D_s particles - the cuts above have been given in detail to show their simplicity - we plot the invariant mass of the $D_s\pi^0$ combination in Figure 2. This shows a large, narrow and completely unexpected peak around $2320\,\mathrm{MeV/c^2}$. (The spike on the left is produced by decays of the $D_s^*(2112)$, for which this decay is just above threshold.)

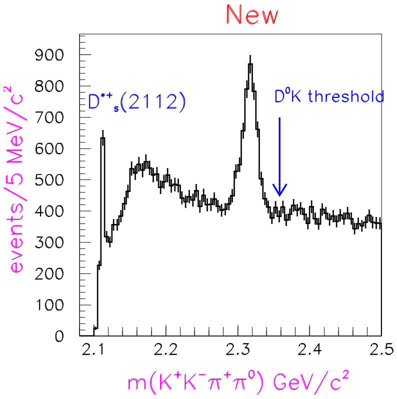

Figure 2: The $D_s\pi^0$ mass combination

3 Checks and Properties

To check that this peak is not an artefact produced by known particle decays, we examine the Monte Carlo simulation of the process $e^+e^- \to c\bar{c}$ including the effects of detector simulation. The mass plot (Figure 3) does not display any peak in this region, though it does provide a good description of the $K^+K^-\pi^\pm$ mass combinations.

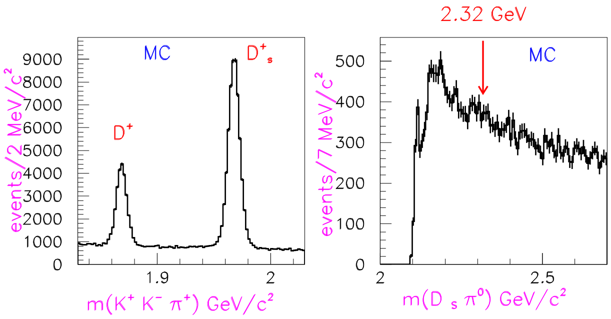

Figure 3: Monte Carlo simulation of the $K^+K^-\pi^\pm$ and $D_s\pi^0$ mass combination

We make many further checks. There is no sign of this peak if events are selected from sidebands in either the π^0 or the D_s combinations. We see the same peak in both the $\phi\pi^\pm$ and the $K^\pm K^{*0}$ decay modes of the D_s. We also observe it in the decay $D_s \to K^+K^-\pi^\pm\pi^0$, i.e. in the $K^+K^-\pi^\pm\pi^0\pi^0$ configuration, with a consistent value for the mass.

We check that this is not an artefact produced by known resonances with a pion misidentified as a kaon: if we take events in the signal peak and reassign one of the identified $K^\pm$ particles as a $\pi^\pm$ there is no sign of a peak at the mass of the D^+, D^0, D^* or elsewhere. Nor is it produced by the $D_s^*(2112) \to D_s\gamma$ decay with an extra γ: if we remove events for which the mass of a $D_s\gamma$ combination is in the region of 2112 MeV/c² the peak at 2317 MeV/c² is actually enhanced.

Having verified that the peak is genuinely a new particle, we now investigate its properties.

The production of the state is studied by examining the mass plot in different regions of p^*, the cms momentum of the $K^+K^-\pi^\pm\pi^0$ system, shown in Figure 4. The significance of the peak rises with increasing p^*. This is what would be expected if the particle is produced in $e^+e^- \to c\bar{c}$ interactions, as opposed to arising in $b \to c$ decays of the $\Upsilon(4S)$.

We select the region $p^* > 3.5$ GeV/c as providing high statistics and good signal to noise, and fit the mass as 2316.8 ± 0.4 MeV/c², using a single Gaussian and a polynomial background, shown in the large plot of Figure 4. We therefore give it the provisional name of $D^*_{sJ}(2317)$. (The fit gives 1267 ± 53 events in the peak - so it is established with a statistical significance of 24 standard deviations.) From comparison of other mass measurements with their standard values we conservatively estimate the systematic uncertainty on this as better than 3 MeV/c².

The single Gaussian provides a good fit to the data with an acceptable χ^2. It fits the width as $\sigma = 8.6 \pm 0.4$ MeV/c². From Monte Carlo simulation, and from the width in the data of the $D_s \to K^+K^-\pi^\pm\pi^0$ peak, we find this to be compatible with our experimental resolution. We are thus unable to measure it, and can only say that it must be narrow: $\Gamma \leq 10$ MeV/c².

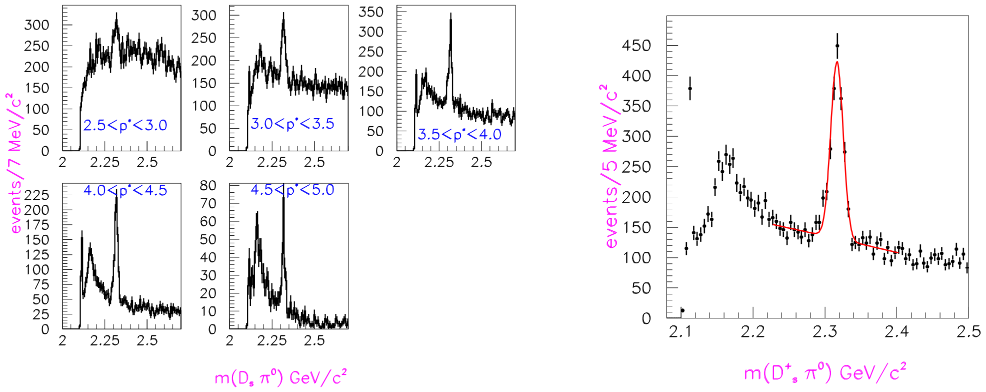

Figure 4: The $D_s\pi^0$ mass in bins of p^* and for $p^* > 3.5\,\mathrm{GeV/c}$ showing the fit to the peak plus background

The helicity angle (of the π^0 in the $D_s^*(2317)$ frame) is, after correcting for efficiency, consistent with being flat. (The efficiency varies strongly with angle due to the loss of slow π^0 particles.) This suggests that this is a $J = 0$ zero-spin particle, although it is consistent with any spin assignment if the particle is produced in an unpolarised state.

We have searched for the $D_{sJ}(2317)$ in other decay modes: $D_s\gamma$, $D_s^*(2112)\gamma$, $D_s\gamma\gamma$, $D_s\pi^0\gamma$ and $D_s\pi^0\pi^0$. In no case do we see a significant signal in the $D_{sJ}(2317)$ region.

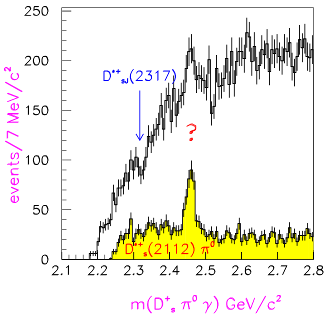

Figure 5: The $D_s\gamma$ mass

The $D_s\pi^0\gamma$ mode needs further comment. The mass distribution for the combination is shown in Figure 5. There is no sign of any peak at 2317 MeV/c^2 but a strong suggestion of one at 2460. This is enhanced if one requires the $D_s\gamma$ mass combination to be in the range 2096 to 2128 MeV/c^2, the D_s^* region, giving the shaded histogram, which shows a very clear peak.

This needs careful interpretation. In this three body system there are known to be peaks in the $D_s\pi^0$ combination at 2317 and in the $D_s\gamma$ combination at 2112. The coincidence of these peaks corresponds to a total mass of around 2460. So there is certainly a contribution to this peak from a reflection of the 2317 and 2112. (Also, a state at 2460 will produce a peak in the $D_s\pi^0$ mass around 2317. But we have verified that this cannot account for the entire signal.)

If the 2460 peak does indeed contain a contribution from another new state, then this cross-feeding means that a careful analysis is required to establish the production ratio and detailed properties of the two particles [3]

4 Conclusions and Implications

The *BABAR* discovery [1] has now been confirmed by CLEO and BELLE [4, 5]. The natural interpretation of this particle is as a $c\overline{s}$ $L = 1$ orbital excitation, with $J = 0$.

The two lowest-lying ($L = 0$) $c\overline{s}$ states are well known: the $D_s(1969)$ is the $S = J = 0$ spin-opposed state and the $D_s^*(2112)$ is the $S = J = 1$ spin-aligned state. It is believed that the most appropriate quantum number description is through the total angular momentum j of the s quark about the heavier c quark (i.e. using jj coupling rather than LS coupling). For the $L = 1$ excitation, there should thus be one doublet with $j = \frac{1}{2}$ and $J = 0$, $J = 1$, and a second with $j = \frac{3}{2}$ and $J = 1$, $J = 2$. The second doublet has been provisionally identified with masses of 2536 and 2573 MeV/c^2 respectively [2]. There is thus good reason, supported by theoretical predictions [6], to suppose that the masses of the two $j = \frac{1}{2}$ states would be similar. Such a state is thus expected to be broad, appearing only through a phase shift analysis. But if this is the $L = 1, J = 0$ state at a mass of only 2317 MeV/c^2, it cannot undergo a normal strong decay to DK, but can only access the isospin-violating mode $D_s\pi$. The unexpectedly narrow width is explained by the unexpectedly low mass.

That this state appears with such a low mass indicates either that it has some different (unconventional) quark content or that the mass splittings in the $c\overline{s}$ system are very different from what was generally expected: in either case this provides an illustration of the importance for experimenters of looking at every channel they can for interesting new phenomena, not just at the ones favoured by theorists.

References

[1] The *BABAR* collaboration (B. Aubert *et al.*) Phys. Rev. Lett. **90** 242001 (2003).

[2] K. Hagiwara *et al.*, "Review of Particle Physics" Physical Review **D66**, 010001 (2002).

[3] In the time between giving this talk and writing it up for the proceedings such an analysis has of course been done. An account can be found in F. Porter, "The New Narrow D_s states - a Mini Review" Int. Europhysics Conf., Aachen, 17 July 2003.

[4] S. Stone "New narrow $c\overline{s}$ states from CLEO" *these proceedings*
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[5] T. Browder "FPCP Experimental Summary" *these proceedings*

[6] S. Godfrey and N. Isgur, Phys. Rev. **D32**, 189 (1985).
S. Godfrey and R. Kokoski, Phys. Rev. **D43**, 1679(1991).