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Observation of $D_s^{**}(2536)$ meson production by neutrinos in BEBC

Big Bubble Chamber Neutrino Collaboration

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Abstract

Neutrino interactions in BEBC produce the $D_s^{**}(2536)$ charmed strange meson. The mass of this state is 2534.2±1.2 MeV. The production rate is 0.011±0.005 per neutrino charged current interaction at a mean neutrino energy of 61 GeV. An earlier claim for another $c\bar{s}$ bound state near 2565 MeV, produced in neutrino interactions, is not supported.

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1. Introduction.

The decay of the charmed strange meson $D_s^{**+}(2536)$ to D^{*+} K_s^0 has been observed in e^+e^- experiments[1],[2] and, more recently, in photoproduction[3]. This narrow state (full width less than 4.6 MeV[1]) is just above the D^*K threshold and is tentatively identified as the 1^+ state of the $c\bar{s}$ system. Earlier, an indication of D^*K decays from a heavier $c\bar{s}$ bound state near 2565 MeV had been obtained in neutrino bubble chamber data[4]. This paper now details the search for the neutrino production of these objects at a statistical level exceeding that of reference [4] by one order of magnitude. In this, one is encouraged by the relatively high rates for inclusive[5] and diffractive[6] production of the $D_s^*(2110)$ meson.

The data sample used here combines three high-statistics neutrino experiments from the bubble chamber BEBC at the CERN SPS filled with hydrogen[7], deuterium[8], and a heavy neon-hydrogen mixture[9]. The beam and bubble chamber conditions (apart from the filling) were essentially the same in the three experiments. This analysis selects the charged current interactions with muon momentum over 5 GeV and neutrino energy over 20 GeV. Some 43 630 (32 060) neutrino (antineutrino) interactions with mean neutrino energy of 61.4 (48.6) GeV pass these selections.

2. Selection of decay candidates.

This analysis searches for the decay chain $D_s^{**} \to D^* \to D$ in neutrino interactions, beginning with decays (1) or (2):

$$D_s^{**+} \to D^{*+}\ K^0 \quad (1)$$
$$\to D^{*0}\ K^+ \quad (2)$$

$$D^{*+} \to D^0\ \pi^+ \quad (3)$$
$$\to D^+\ \pi^0 \quad (4)$$

$$D^{*0} \to D^0\ \pi^0 \quad (5)$$
$$\to D^0\ \gamma \quad (6)$$

with subsequent D meson weak decays

$$D^0 \to \overline{K^0}\pi^+\pi^- \quad (7)$$
$$\to K^-\pi^+ \quad (8)$$
$$\to K^-\pi^+\pi^-\pi^+ \quad (9)$$

$$D^+ \to \overline{K^0}\pi^+ \quad (10)$$
$$\to K^-\pi^+\pi^+ \quad (11)$$

The search for D_s^{**-} production by antineutrinos uses the charge-conjugates of the above decays and of the selections below. The radiative decay $D^{*+} \to D^+\gamma$ with branching fraction near 1%[10] is not considered.

Although π^0 and γ from (4),(5) or (6) are not found efficiently in hydrogen[7] or deuterium[8] (where most gammas escape detection), D^* decays can still be selected (see below).

The neutral kaons are identified by the $K_s^0 \to \pi^+\pi^-$ decays, while the charged kaons are, generally, indistinguishable from pions. The kaon hypothesis is tried for all charged particles unless identified otherwise. A small fraction of the charged kaons decay in flight in the bubble chamber, their decay (when the target is hydrogen) is recorded as a kink on the particle track.

The mass of the D meson candidate, X, must be within 3 (computed) standard deviations of the D meson mass. The same is required of the $\gamma\gamma$ system in neon to be taken as the π^0 candidate. The D^{*+} meson candidates X^{*+} are selected by the equivalent condition applied to the mass difference $m(X^{*+}) - m(X)$. Finally, the mass of the D^*K candidate can be estimated as

$$m_1^{**} = m(X^*K) - m(X^*) + m(D^*) \tag{12}$$

with $m(D^*)$, the expected value of the D^* mass, equal to 2010.1±0.6 MeV[11].

An alternative estimate of the D^*K mass for which the momentum of the D^{*+} decay pion is not required exploits the smallness of the phase space in the D^* decays. Since the D^* decay pion (charged or neutral) is virtually at rest in the D^* rest frame, the 4-momenta of the D^* and D mesons are simply scaled by the ratio of their masses. Therefore the mass of the D^*K system can also be estimated as

$$m_2^{**} = m(X^{*'}K) \tag{13}$$

where the 4-momentum of $X^{*'}$ is obtained from that of the D meson candidate X by rescaling the latter with a factor $m(D^*)/m(X)$.

A Monte Carlo simulation of $D_s^{**}(2536)$ decays shows that m_2^{**} is an unbiased estimate of the true mass, with an uncertainty of ±1.8, ±1.8, and ±2.3 MeV for the chain decays (1,3), (1,4) and (2,5), respectively. For (2,6) involving the radiative D^* decay with a bigger phase space, the m_2^{**} distribution around the true mass value is broader, ±7.0 MeV. For (2,5) and (2,6) mixed in the proportion of the two D^{*0} branching fractions[11], the deviation of m_2^{**} from the true D^{**} mass is ±4.6 MeV.

Selecting the candidate events for (1,4) with a missing π^0, we additionally require that the K^- in (11) be identified in the bubble chamber by its decay. Unlike D^{**} decay (1), decay (2) produces a charged kaon which is usually unidentified so there are many background combinations. In the decay chains (2,5) and (2,6) where a D^0 is always produced:
(i) any $D^0 \to \overline{K^0}\pi^+\pi^-$ must include a K^{*-},defined as any $m(K_s^0\pi^-)$ within 60 MeV of $m(K^*)$, with $|cos\beta|$ above 0.7 (where β is the angle between the π^+ and π^- directions in the K^* rest frame; the angular distribution of the P-wave decay $D \to K^*\pi$ follows $cos^2\beta$);
(ii) for $D^0 \to K^-\pi^+$, either the K^- or the K^+ from the D^{**} decay must be identified through its decay in the bubble chamber;
(iii) $D^0 \to K^-\pi^+\pi^-\pi^+$ is not used as there are too many possible combinations.

All D meson decays (7 to 11) must have $|cos\theta|$ below 0.9, where θ is the angle between the D boost direction (from the laboratory system) and the kaon, as measured in the D meson rest frame. (The $cos\theta$ distribution is uniform for spinless D meson decays, while the forward-backward topologies, with $|cos\theta|$ near 1, are typical for the combinatorial background).

3. Results.

The m_2^{**} distributions of the selected $D^{*+}K^0$ and $D^{*0}K^+$ candidate combinations are shown in figure 1a and figure 1b, respectively; figure 1c is the sum. The unhatched entries everywhere are the antineutrino contribution. Figure 1d is the wrong sign background where the decays (1 to 11) and their charge conjugates are selected in the antineutrino and neutrino data, respectively. Another background distribution, with the mass of the D meson combination in the D mass wings (between 3 and 6 standard deviations), is shown in figure 1e. A narrow cluster formed by 9 events is observed in figure 1c near 2535 MeV. Two events in this cluster

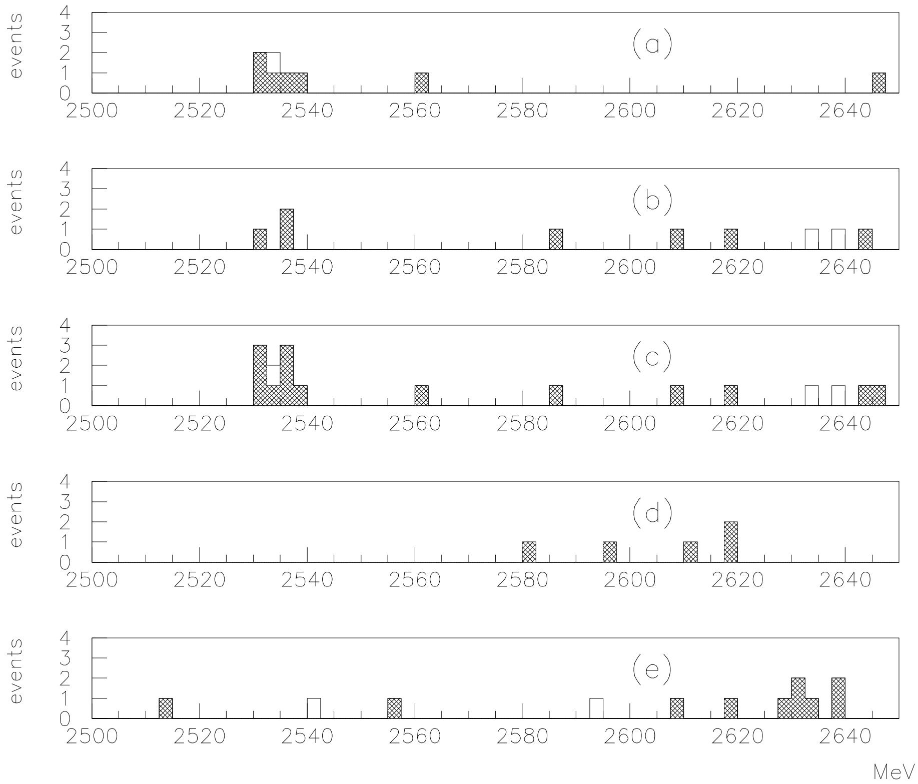

Figure 1: Mass distribution of the selected D^*K combinations (unhatched shows charge-conjugate entries for antineutrinos): (a) $D^{*+}K^0$ signal; (b) $D^{*0}K^+$ signal; (c) $D^{*+}K^0$ and $D^{*0}K^+$ signal; (d) background $D^{*-}K^0$ and $\bar{D}^{*0}K^-$ wrong sign combinations; (e) background $D^{*+}K^0$ and $D^{*0}K^+$ right sign, but with the wrong D mass (see text).

give an additional entry (using a different final state particle), at 2562 MeV and at 2643 MeV. There are no events that contribute both to the cluster in figure 1c and to the background distributions in figures 1d and 1e. Interpreting the event at 2562 MeV as a reflection of the cluster at 2536 MeV, then no enhancement is seen near 2565 MeV in figure 1c.

The cluster events are detailed in Table 1. The composition of the D meson candidates is shown in round brackets. For the events with observed D^* decay pion (the first four), the two D^*K mass estimates (12) and (13) are compatible within errors. (The second uncertainty on m_2^{**} is the systematic uncertainty evaluated by the simulation. The systematic error from the D^{*+}/D^{*0} mass uncertainty[11] is not shown). In events 5 (with a missing π^0) and 6 (with a missing π^0/γ) the K^- was identified through a decay in hydrogen. A single peak event is contributed by antineutrinos (the first in table 1).

The 9 clustered events have their energy estimated with an energy correction based on transverse momentum balance[12]. The mean fractional hadronic energy carried by the D^*K system is 0.55±0.06. The mean values for neutrino energy and other kinematic variables are E_ν = 66.6±10.0 GeV, Q^2 = 14.9±7.0 $(GeV)^2$, x_{Bj} = 0.18±0.06 and y_{Bj} = 0.49±0.05. For comparison, the corresponding mean variables for all selected charged current neutrino (an-

Table 1 The $D^{**} \to D^*K$ candidates in the cluster on figure 1. Here $\delta = m(D^*) - m(D) - m_\pi$ and π^0_u (γ_u) indicates that final state gammas are not detected, see text.

target	event	$(D)^*$ K	$m(D)$ MeV	δ MeV	m_1^{**} MeV	m_2^{**} MeV
Ne	8711474	$(K^+\pi^-\pi^-)$ π^0 K^0	1903.1±22.2	72.6±29.0	2528.9±4.4	2533.3±4.9±1.8
H_2	9294596	$(K^-\pi^+\pi^-\pi^+)$ π^+ K^0	1884.4± 7.3	4.1±0.6	2539.9±1.1	2538.4±1.1±1.8
H_2	12111379	$(K^-\pi^+\pi^-\pi^+)$ π^+ K^0	1834.9±23.6	7.0±0.6	2533.3±2.2	2531.1±2.2±1.8
D_2	11845387	$(K^-\pi^+)$ π^+ K^0	1848.1±10.6	5.5±0.9	2534.1±1.5	2531.7±1.4±1.8
H_2	9133897	$(K^-\pi^+\pi^+)$ π^0_u K^0	1858.9±13.5	-	-	2533.7±1.1±1.8
H_2	3203321	$(K^-\pi^+)$ π^0_u/γ_u K^+	2005.7±73.9	-	-	2531.9±5.0±4.6
H_2	12113161	$(K^{*-}\pi^+)$ π^0_u/γ_u K^+	1825.1±45.5	-	-	2536.7±4.4±4.6
Ne	8783426	$(K^0_s\pi^+)$ π^0_u K^0	1855.7±29.8	-	-	2535.9±6.8±1.8
Ne	8794619	$(K^{*-}\pi^+)$ π^0_u/γ_u K^+	1828.0±52.1	-	-	2535.5±5.4±4.6

tineutrino) events are 61.4(48.6) GeV, 9.3(5.5) $(\mathrm{GeV})^2$, 0.25(0.24) and 0.41(0.32) (here, the statistical hadron energy correction[13],[14] is used).

The weighted average of m_2^{**} over the 9 peak events, with D^{*0} and D^{*+} mass uncertainties[11] taken into account, is 2534.2±1.2 MeV. A similar mass value, 2534.2±0.9 MeV, is obtained through a fit of Fig 1c with a Gaussian (to represent the experimental resolution) plus a linear background in the 2500-2650 m_2^{**} interval. (In the latter estimate, the almost uncorrelated D^{*+} and D^{*0} mass uncertainties are not taken into account). The fitted r.m.s. width of the peak is 2.4±0.8 MeV, while the mean m_2^{**} measurement uncertainty of the 9 peak combinations is 4.6 MeV.

The production rate of the $D_s^{**}(2536)$ mesons per charged current neutrino interaction with E_ν above 20 GeV is 0.011±0.005. (In this estimate, the events with the identified charged kaon decays and one with observed π^0 decay are not taken into account as their detection efficiencies are poorly known.) The CLEO[10] and PDG[11] values are used for the D^* and D branching fractions, respectively). The antineutrino production rate is less than 0.006 at the 90% confidence level.

The smallness of the $D_s^{**}(2536)$ production cross section by antineutrinos is an argument against (axial)Vector Meson Dominance[15] as a dominant production mechanism: in this case, some 1.5 times more D_s^{**} would be produced by antineutrinos than by neutrinos in our conditions.

4. Conclusions.

From the combination of data from three high-statistics neutrino experiments using BEBC we conclude:
– Some 9 $D_s^{**}(2536)$ mesons are found, on a background of less than 1 event;
– the measured mass of this state is 2534.2±1.2 MeV, the observed width is compatible with the experimental resolution;
– the production rate is 0.011±0.005 per charged current neutrino interaction with E_ν above 20 GeV, and less than 0.006 (90% confidence level) per antineutrino interaction which suggests (axial)Vector Meson Dominance is not the main production mechanism;

– no evidence is found for another $c\bar{s}$ state near 2565 MeV as claimed in an earlier publication with fewer statistics.

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