Observation of the production and decay of an excited $c\bar{s}$ state with a mass ~ 2790 MeV/c^2 in a nuclear emulsion

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A study of the interactions of neutrinos with nuclei in an emulsion has yielded the first detection of an event which is interpreted as the diffractive production of a radially excited state of a D_s^{*+} meson with a mass of 2794 ± 57 MeV/c.

The decay of an excited state of a D_s^{*+} meson has been observed in one of 194 interactions of charged-current neutrinos with nuclei in a photographic emulsion which were detected in experiment E564. In this experiment,[1] a cryogenically sensitive nuclear emulsion was positioned in the working volume of the Fermilab 15-foot bubble chamber and bombarded in a wide-spectrum neutrino beam.

CASCADE DECAY OF D^0 MESONS

The event found in the emulsion is shown schematically in Fig. 1. A two-prong star (vertex B) was found through a search along the track at a point 1029 μm from the vertex of the primary interaction, A. At vertex A there is, in addition to the recoil proton (track 3) and the muon (1), only a single relativistic particle (2), which was unambiguously identified in the emulsion as a K^+ meson. According to the measurements of the relative ionization in the emulsion and the momenta of the particles found in the bubble chamber, the negatively charged particle v.1 from vertex B is most probably a K^- meson. All that can be said regarding positively charged particle v.2, is that it is no heavier than a proton. The characteristics of all the tracks in this event are listed in Table I.

Three circumstances rule out an interpretation of vertex B as the decay of a neutral strange particle K_s^0 or Λ^0: 1) The invariant masses of particles v.1 and v.2 for the $\pi^+\pi^-$ and $\pi^- p$ mass values are 0.36 ± 0.01 and 1.17 ± 0.01 GeV/c^2, respectively. Allowing for the most probable identification of these particles, we find that the invariant mass of the $K^-\pi^+$ system is 0.908 ± 0.012 GeV/c^2, in good agreement with the mass of the $\bar{K}^{*0}$ (892) resonant state. The perpendicular component of the resultant

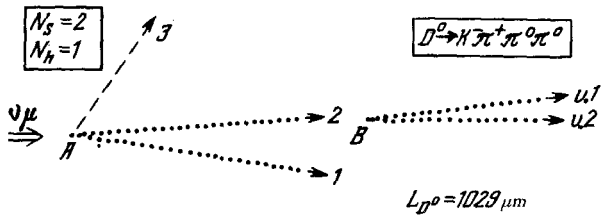


FIG. 1. Schematic diagram of the event in the emulsion. A—Vertex of the primary interaction; B—Vertex of the decay of the D^0 meson; track 3—a proton which was stopped in the emulsion. Particles 1, 2, v.1, and v.2 emerge from the emulsion. Three of them, including particle 1 (a muon), interact in the bubble chamber.

momentum of particles v.1 and v.2 with respect to the direction of the decayed particle is 0.32 ± 0.03 GeV/c. 3) At a range of 1029 μm and at a momentum greater than 3.7 GeV/c (the resultant momentum of exclusively the charged particles), the transit time before the decay of the particle with mass M (in GeV/c^2) would not exceed $9.3 \times M \times 10^{-13}$ s. The photographs taken in the bubble chamber reveal no decays of neutral strange particles. In a region close to the charged tracks emerging from the emulsion one can observe an electromagnetic shower.[11] The most probable interpretation of the two-prong star is therefore a Cabibbo-allowed decay of a charmed D^0 meson by one of the channels $D^0 \to K^-\pi^+ n\pi^0 (n = 1,2...)$.

TABLE I. Characteristics of the tracks at the primary vertex A and at the vertex corresponding to the decay of the D^0 meson, B

Vertex	Track	Measurements in emulsion		Measurements in bubble chamber		Particle
		Azimuthal angle α (deg)	Immersion angle β (deg)	Momentum (GeV/c)	Charge	
	ν	-3.0 ± 0.5	-2.5 ± 0.5			
A	1	-8.4 ± 0.2	-2.6 ± 0.4	12.50 ± 0.20	$-$	μ^-
	2	2.5 ± 0.2	-2.4 ± 0.5	0.82 ± 0.04	$+$	K^+
	3	54.2 ± 0.3	-36.8 ± 0.6	0.28 ± 0.01 [12]		p
	4 [13]	-0.7 ± 0.3	-0.8 ± 0.2	1.45 ± 0.16	0	γ
	AB connecting track	2.7 ± 0.2	-2.2 ± 0.4			
B	v.1	8.5 ± 0.2	-0.4 ± 0.4	1.15 ± 0.05	$-$	K^-
	v. 2	3.3 ± 0.2	3.4 ± 0.4	2.52 ± 0.05	$+$	π^+
	v. 3 [13]	-2.0 ± 0.4	-2.8 ± 0.3	4.15 ± 0.22	0	π^0
	v.4 [13]	8.9 ± 0.3	-7.6 ± 0.3	2.84 ± 0.29	0	π^0

[12]The momentum was estimated from the range in the emulsion.
[13]The angles were reconstructed from measurements in the bubble chamber.

In the bubble chamber we detected five γ rays with momentum vectors directed either toward the vertex of the primary interaction or toward the decay vertex. The momentum of each of these γ rays was greater than 0.5 GeV/c. Their total energy was ~ 8 GeV. The momenta of the other γ rays which can be seen in the bubble chamber are small (less than 0.5 GeV/c). The distribution in conversion length and the angular characteristics indicate that their production is of a secondary nature because of the bremsstrahlung of electrons. Five combinations of invariant masses of the γ rays are close to the mass of the π^0 meson. The momenta (1C fit) of these candidate events for the decay of π^0 mesons range from ~ 2 to ~ 4 GeV/c. The reconstructed candidate events for the decay of π^0 mesons make it possible to examine the following channels for the decay of the D^0 meson.

The decay $D^0 \to K^- \pi^+ \pi^0$. In this case we need (OC fit) a π^0 meson with a momentum ~ 9.6 GeV/c. None of the reconstructed candidate events for the decay of a π^0 meson is consistent with this interpretation.

The decay $D^0 \to K^- \pi^+ \pi^0 \pi^0$. A kinematic analysis showed that of the four possible combinations with π^0 mesons only two were acceptable (with a confidence level greater than 1%). The final choice between these combinations was based on the detection of the electromagnetic decay $D^{*0} \to D^0 \gamma$. The confidence level for the decay $D^{*0} \to D^0 \gamma$ is $\sim 96\%$ (1C fit), and the corresponding decay is $D^0 \to K^- \pi^+ \pi^0 \pi^0 - 27\%$ (3C fit). The mass difference between the D^{*0} and D^0 mesons is 143 ± 16 MeV/c^2 (the tabulated value[2] is 142.5 ± 1.3 MeV/c^2). The mass of the D^0 meson is 1901 ± 50 MeV/c^2, and its flight time before decay at a momentum of 10.24 ± 0.20 GeV/c would be $(6.25 \pm 0.12).10^{-13}$ s. The tabulated values[2] of the mass and lifetime of the D^0 meson are 1864 ± 0.6 MeV/c^2 and $(4.3^{+0.5}_{-0.4}) \times 10^{-13}$ s, respectively. Questions concerning the identification of the particles and the reconstruction of the decay of the D^{*0} meson are discussed in more detail in Ref. 3.

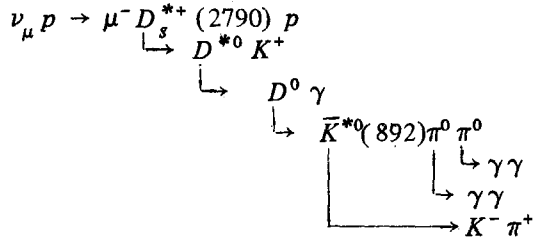
RADIALLY EXCITED STATE OF THE D_s^{*+} MESON

All the charged tracks which could be seen in the bubble chamber emerging from the emulsion and the γ rays which were detected were used in interpreting this event. At the vertex of the primary interaction, the transverse momentum of the particles with respect to the direction of the neutrino beam was 0.23 ± 0.23 GeV/c. The absence of additional tracts in the bubble chamber and the transverse-momentum balance at vertex A indicate that this event corresponds to a completely reconstructed reaction $\nu_\mu p \to \mu^- D^{*0} K^+ p$. The energy of the primary neutrino was 25 GeV. The square 4-momentum transfer Q^2 in the event was ~ 2.6 (GeV/c)^2. The event which we analyzed has several clearly defined properties which are characteristic[4] of a diffractive interaction of a neutrino with a proton. Among these characteristics are the small multiplicity of the secondary particles, the presence of only a single highly ionizing particle (the recoil proton, with a momentum of 280 MeV/c), and the small value of Q^2.

The diffractive production of charmed particles means that the intermediate W boson undergoes a virtual conversion into a D meson (cq pair), which interacts elastically with a proton. Primarily ($\sim 95\%$) cs states should be produced, since the $W^+ \to c\bar{d}$ is Cabibbo-suppressed. If the decay by the strong interaction is allowed from the

energy standpoint, the excited $c\bar{s}$ decay[5,6] into a charmed nonstrange D meson and a K meson. The invariant mass of the D^{*0} and K^+ mesons which were detected is 2794 ± 57 MeV/c^2. In view of the expected widths $\sim$50–100 MeV, we see that this value is close to the theoretically predicted[5] masses of orbitally excited 1^3D_1 and radially excited 2^3S_1 and 2^1S_0 $c\bar{s}$ states. Their masses are expected to be $\sim$2900, $\sim$2730, and $\sim$2670 MeV/c^2. The production of 1^3D_1 and 2^1S_0 states is suppressed with respect to the production of the radially excited 2^3S_1 state of the D_s^{*+} meson. The reasons are the small value of the coupling constant of the W boson and the $c\bar{s}$ state, with an orbital angular momentum of 2 (Ref. 7), and the V–A structure of the weak current.

In summary, the event detected here is interpreted most probably as the diffractive production of the first radially excited state (2^3S_1) of a vector D_s^{*+} meson which has decayed through the $D^{*0}K^+$ channel:



So far, the literature reveals no other experimental data on the observation of candidate events for the production and decay of radially excited $c\bar{s}$ states. Several candidate events for the production and decay of orbitally excited $c\bar{s}$ states were detected in Ref. 8: 1^1P_1 and 1^3P_1.

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[11)]The bubble chamber was filled with a heavy neon-hydrogen mixture. The nuclear interaction length in the mixture was 125 cm, and the radiation length was 39 cm.

[1]W. Smart *et al.*, Acta Phys. Polon. **B17**, 41 (1986).
[2]"Review of particle properties," Phys. Lett. **B170**, 1986.
[3]Yu. A. Batusov *et al.*, Preprint R1-88-120, Joint Institute for Nuclear Research, Dubna, 1988.
[4]E. D. Zhizhin, A. B. Krebs, and Yu. P. Nikitino, Neutrino Production of Charmed Hadrons (Lectures), MIFI, Moscow, 1984, p. 35 (and references to this work).

[5]S. Godfrey and N. Isgur, Phys. Rev. **D32**, 189 (1985).
[6]M. A. Shifman, Usp. Fiz. Nauk, **151**, 193 (1987) [Sov. Phys. Usp. **30**, 91 (1987).
[7]V. A. Khoze and M. A. Shifman, Usp. Fiz. Nauk **140**, 3 (1983) [Sov. Phys. Usp. **1**, 26 (1983)].
[8]A. E. Asratyan *et al.*, Preprint ITEP 87-214, Moscow.

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