PHYSICAL REVIEW LETTERS

VOLUME 42 22 JANUARY 1979 NUMBER 4

Observation of the Kaonic Decay of the $\Lambda_c{}^+$ Charmed Baryon

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(Received 3 November 1978)

We have observed 34 events with visible strange-particle production out of a total charged-current sample of 4500 events in a wide-band neutrino exposure of the Brookhaven National Laboratory 7-ft bubble chamber filled with H_2 or D_2. Three events were uniquely identified as having single–strange-particle production, two with $\Delta S = -\Delta Q$. In both $\Delta S = -\Delta Q$ events we observe the $\Lambda_c{}^+(2260)$, which in one case decays to $\Lambda\pi^+\pi^+\pi^-$ and in the second case to $p\bar{K}^0\pi^-\pi^+$. Production rates are given.

The discovery of a high-mass narrow resonance, the J/ψ,[1] indicated the existence of a new flavor (charm) beyond strangeness. Using the mass of this state De Rújula, Georgi, and Glashow[2] predicted that the lowest baryon state with this flavor, the $\Lambda_c{}^+$, should have a mass near 2200 MeV with the next higher state, the Σ_c, being more massive by about 160 MeV. The first evidence of such charmed-baryon production arose from the study[3] of a neutrino interaction in the Brookhaven National Laboratory (BNL) 7-ft bubble chamber. The event had a clear $\Delta S = -\Delta Q$ charm signature and was consistent with the production of $\Sigma_c{}^{++}$ (with mass 2426 ± 12) followed by the decay to $\Lambda_c{}^+$ (mass 2260 ± 10). The subsequent observations[4] of $\bar{\Lambda}_c(2260)$ in a photoproduction experiment confirmed both the interpretation and the mass. In this Letter we report on a second event in the Brookhaven National Laboratory (BNL) 7-ft bubble chamber which is identified as production followed by the kaonic decay of the $\Lambda_c{}^+(2260)$, the reaction being

$$\begin{aligned}\nu n \to\ & \mu^-\Lambda_c{}^+ \\ & \quad \llcorner\!\to pK^{*-}\pi^+ \\ & \qquad\quad \llcorner\!\to \bar{K}^0\pi^- . \end{aligned} \qquad (1)$$

The $\Lambda_c{}^+$ mass obtained is 2254 ± 12 MeV.

The data come from an exposure of the BNL 7-ft cryogenic bubble chamber to a broadband neutrino beam. The neutrino energy spectrum peaks at about 1.5 GeV with 14% of all events having energies greater than 4 GeV. A total of 4500 charged-current events, of which 34 have visible strange particles, have been accumulated to date. This has involved exposures with either hydrogen or deuterium in the chamber. The relevant volume is 9 m^3, of which 25% is occupied by four 2-in.-thick stainless steel plates inserted for neutral-current investigations. All pictures are scanned for events containing two or more charged tracks. Cosmic-ray events were effectively removed by requiring that the vector sum of the visible momentum be greater than 150 MeV/c and make a polar angle $\theta_{\text{vis}} \leq 50°$ with respect to the beam direction. All events were measured and kinematically fitted with the appropriate final states. In this manner 80% of the 4500 events were uniquely identified. In this same sample there were 34 events containing identified strange particles (1 event with Σ^+ and 33 events with visible neutral strange particles). Of these, 22 events (or 65%) have no missing neutrals and, for all but one of the final states, have been uniquely determined; see Table I.

All events but three[5] are consistent with being associated strange-particle production, the remaining three being examples of single-strange-particle production. The first has been published[3] as the first example of charmed-baryon production and decay, with a $\Delta S = -\Delta Q$ signature. The second corresponds to the reaction $\nu p \rightarrow \mu^- K_s^0 \pi^+ p$. The $K_s^0 \pi^+$ effective mass is in the region of the well-known $K^*(892)$, implying that the strangeness of the K_s^0 is +1, thus favoring the interpretation for this event as $\Delta S = \Delta Q = +1$. In addition, the value of the scaling variable $x = q^2/2m\nu$ [$q^2 = 2E_\nu E_\mu(1-\cos\theta_\mu)$, m is the target-nucleon mass, and $\nu = E_\nu - E_\mu$] is 0.11 and therefore consistent with $\Delta S = +1$ production off the quark sea. The third event is the main subject of this Letter and is shown in Fig. 1. It consists of four charged tracks, two negative and two positive, and a single V^0 pointing to the vertex. The V^0 is clearly a K_s^0 associated with the primary vertex (χ^2 probability 27% for K^0 compared with less than 10^{-4} for Λ). Track 1 is negative and is consistent with penetrating three plates and then leaving the chamber. Track 2, the second negative track, goes through two plates, and enters and fails to emerge from the third, marking it as a hadron. Track 3 leaves the chamber without entering any of the plates. Track 4 leaves the chamber, its momentum and range clearly identifying it as a π^+. Transverse momentum is balanced to better than 90 MeV/c, the longitudinal momentum is 3.9 GeV/c, and the vector momentum of the visible tracks is within 1.3° of the beam direction. The

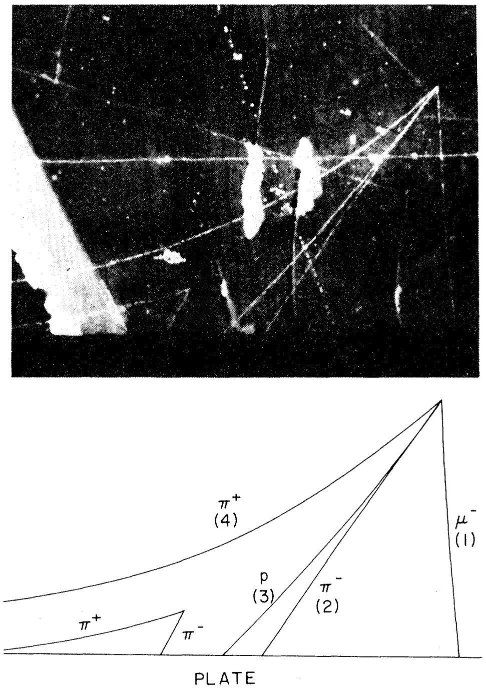

FIG. 1. View of the event as seen in camera 2.

TABLE I. Topologies of the 34 charged-current events with visible strange particles. The symbol h is used for those particles with ambiguous interpretation.

Reaction	Events observed	ΔS	Constraints	E_ν (GeV)	x	y	W (GeV)
$\nu p \rightarrow \mu^- \pi^- \pi^+ \pi^+ \pi^+ \Lambda$	1	−1	3	13.5	0.31	0.28	2.426
$\nu p \rightarrow \mu^- p \pi^+ K^0$	1	+1	3	5.2	0.11	0.39	2.059
$\nu p \rightarrow \mu^- \pi^+ K^+ \Lambda$	6	0	3				
$\nu p \rightarrow \mu^- h^- h^- h^+ h^+ \pi^+ K^0$	1	0,±1	3				
$\nu p \rightarrow \mu^- h^+ h^+ K_s^0 \ldots$	1		0				
$\nu p \rightarrow \mu^- h^+ h^+ \Lambda \ldots$	1		0				
$\nu p \rightarrow \mu^- h^- h^+ h^+ h^+ \Lambda \ldots$	1		0				
$\nu p \rightarrow \mu^- h^+ h^+ \Lambda K^0 \ldots$	1		0				
$\nu n \rightarrow \mu^- p \pi^+ \pi^- \overline{K}^0$	1	−1	3	3.9	0.23	0.74	2.254
$\nu n \rightarrow \mu^- K^+ \Lambda$	10	0	3				
$\nu n \rightarrow \mu^- \pi^- K^+ \Sigma^+$	1	0	3				
$\nu n \rightarrow \mu^- \pi^+ \Lambda K^0$	1	0	3				
$\nu n \rightarrow \mu^- h^+ K_s^0 \ldots$	3		0				
$\nu n \rightarrow \mu^- h^- h^+ h^+ K_s^0$	2		0				
$\nu n \rightarrow \mu^- h^+ \Lambda \ldots$	2		0				
$\nu n \rightarrow \mu^- h^+ \Lambda K^0 \ldots$	1		0				

kinematic variables for each particle are given in Table II.

The best kinematic fit obtained for this reaction is $\nu d \to \mu^- K_s^0 p \pi^+ \pi^- (p_s)$ with a χ^2 probability of 55% for a three-constraint (3C) fit. The standard procedure was utilized in handling the reaction in deuterium, with $P_x = P_y = P_z = 0 \pm 45$ MeV/c set for the target nucleon. This fit gave a spectator momentum of 50 ± 25 MeV/c, which would not be seen and is consistent with the lack of any visible stub at the primary vertex.

We now turn to alternative explanations of this event. Examination of all multibody effective-mass combinations of the charged tracks from the primary vertex reveal that the $\pi^+\pi^-$ combination has a mass 489 ± 6 MeV which is 1.5σ from the accepted K^0 mass. We thus have to consider the hypothesis $\nu d \to \mu^- K^0 \bar{K}^0 p (p_s)$ where one K^0 decays very near the primary vertex. Extrapolation of these two charged tracks back to the vertex indicates that their intersection lies within 1.5 mm (in space) of the primary vertex. The probability for such a 1.5-GeV/c K_s^0 decaying within this distance is 2×10^{-2} which when coupled to the mass deviation and multiplied by the number of associated production events with two V^0's (one event with a 3C fit) gives an estimated background of 3×10^{-3} events.

A second possibility is that the negative hadron track is a K^- and the final state is $\mu^- K^0 K^- p \pi^+$ which yields a 3C fit probability of 7%. This fit requires a recoil-proton stub of 3.5 mm in space which is not observed. The viability of this hypothesis is further reduced by the improbability of a $K^0 K^-$ system forming a $K^*(892)$ when the K^- is interpreted as a π^-. We calculate the background due to this reaction to be 5×10^{-3} events.[6]

There are also the possibilities of missing neutral final states, the most likely being (a) $\mu^- \bar{K}^0 K^+ \pi^+ \pi^- (n)$, and (b) $\mu^- \bar{K}^0 p \pi^+ \pi^- (K^0)$. In case (a) the neutron is required to have a momentum of between 1.1 and 1.7 GeV/c and be emitted in the forward direction such that $P_T < 100$ MeV/c. Further, track 3 must be a K^+ instead of a proton, a possibility which is disfavored but not excluded by ionization measurements.[7] We calculate this background to be 2×10^{-3} events.[6] Similarly, for case (b) the K^0 must have a momentum greater than 2.0 GeV/c and have $P_T < 100$ MeV/c, yielding a background of 4×10^{-3} events. We have also considered backgrounds from incoming K^0's, $\bar{\nu}$'s, and neutrons. All contribute less than 2×10^{-3} events.

The favored hypothesis is therefore single-strange-particle production with a total background of about 1.6%. This event could be either single-strange-particle production off a sea quark ($\Delta S = +\Delta Q$), or $\Delta S = -\Delta Q$ indicating charm production off a valence quark and its subsequent decay ($\nu + d \to \mu^- + c$, $c \to s +$ etc.). The latter is favored on two grounds. First, an examination of the two-body effective masses gives a $K_s^0 \pi^-$ mass of 913 ± 8 MeV, strongly suggesting a $K^{*-}(892)$ ($\Gamma = 50$ MeV) and thus favoring a negative strangeness for the K_s^0, i.e., $\bar{K}^0$. Examination of other K_s^0 events indicates that the random probability of a $K_s^0 \pi^-$ having an effective mass within the width of the K^* is 10%. Second, a consideration of the quark kinematics[8] favors valence charm production over $\Delta S = +\Delta Q$ production off the sea by a factor of 3:1. This, combined with the observed K^{*-}, indicates only a 3% probability that the event is $\Delta S = +\Delta Q$.

We now examine the masses of particle combinations with the Λ_c^+ quantum numbers. Two values are obtained: $M(\bar{K}^0 p) = 1520 \pm 6$ MeV and $M(\bar{K}^0 p \pi^+ \pi^-) = 2254 \pm 12$ MeV. This latter value is in good agreement with the Λ_c^+ mass of 2260 ± 10 MeV both for the original BNL event and from the photoproduction experiments. We estimate that the probability of obtaining such agreement by coincidence is less than 2%. This, when combined with the evidence against the presence of a second strange particle and against the $\Delta S = +\Delta Q$

TABLE II. The measured kinematic variables for each particle.

Track	Momentum (MeV/c)	Azimuthal angle (degrees)	Dip angle (degrees)	Identification
1	1009 ± 21	-26.24 ± 0.10	19.71 ± 0.10	μ^-
2	1309 ± 28	1.77 ± 0.10	-11.03 ± 0.10	π^-
3	755 ± 19	8.86 ± 0.10	4.17 ± 0.13	p
4	205 ± 3	-7.95 ± 0.53	-42.39 ± 0.60	π^+
V^0	935 ± 10	22.87 ± 0.10	2.17 ± 0.10	K_s^0

interpretation, identifies the event as Λ_c^+ production with a confidence of better than $10^3{:}1$, and establishes the decay mode $\Lambda_c^+ \to K^{*-} p\pi^+$. The observation of a kaonic decay mode of the Λ_c^+ is consistent with the observed[9] increase of $p\bar{p}$ yields in e^+e^- annihilation between 4.4- and 5.5-GeV c.m. energies at SPEAR. The event also confirms, though at a lower confidence level (95%), the existence and mass of the Λ_c^+ itself.

In order to "observe" charmed baryons in this experiment we require a 3C fit and thus there may be no neutral pions present among the neutrino reaction products nor may the baryon decay products include π^0's and/or a neutron. Assuming a threshold behavior as predicted by Schrock and Lee[10] and correcting for the detection efficiency and unseen decay modes of the neutral strange particles, we find that this "observed" charmed-baryon production rate compared to charged-current events (above charm production threshold) is $(1.0 \pm 0.7)\%$. The losses due to "unobserved" $\Lambda_c^+(2260)$ baryons are difficult to estimate but should increase the total Λ_c^+ production rate to the level to 3–5%, quite compatible with the 6% Cabibbo rate for charm production expected by the Glashow-Iliopoulos-Maiani mechanism.[11]

We are grateful to the operating crew of the 7-ft bubble chamber, Ms. Fern M. Coyle who helped in editing the data, and the scanning/measuring personnel at BNL for their dedicated efforts. This research was supported by the U. S. Department of Energy under Contract No. EY-76-C-02-0016.

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[3] E. G. Cazzoli *et al.*, Phys. Rev. Lett. 34, 1125–1128 (1975).

[4] B. Knapp *et al.*, Phys. Rev. Lett. 37, 882 (1976); W. Lee, in Proceedings of the Nineteenth International Conference on High Energy Physics, Tokyo, August 1978 (to be published).

[5] The one three-constraint event whose final state was not uniquely determined has been assigned as a case of associated production in view of the larger overall number of such events.

[6] The backgrounds are obtained by multiplying the calculated probabilities by the number of events with a K_s^0 and a K^+, K^-, or K_L^0 as appropriate. Based on the observed number of zero-constraint events with a K_s^0 (6) and the number of ΛK^0 events (see Table I), we estimate the number of events for each topology class to be $K^0\Lambda$, 2.2; $\bar{K}^0K^0$, 1.7; $\bar{K}^0K^+$, 1.7; and K^0K^-, 0.4.

[7] Ionization measurements were obtained for all tracks by the gap-length distribution method. The bubble density of track 3 was found to be 2.1 ± 0.5 (the statistical error dominates) compared to the predicted values of 1.0/1.4/2.5 for $\pi^+/K^+/p$, respectively.

[8] R. M. Barnett, Phys. Rev. Lett. 36, 1163 (1976); H. Georgi and H. D. Politzer, Phys. Rev. Lett. 36, 1281 (1976), and 37, 68(E) (1976). The fraction of the target nucleon's momentum carried by the struck quark is $Z = x + m_q^2/2mEy$, where m_q is the mass of the produced quark. For this event, charm production yields $Z = 0.64$, while for strange-particle production $Z = 0.23$.

[9] M. Piccolo *et al.*, Phys. Rev. Lett. 39, 1503 (1977).

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[11] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

Solitons of Coupled Scalar Field Theories in Two Dimensions

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(Received 30 October 1978)

This work offers a method for finding some exact soliton solutions to coupled relativistic scalar field theories in 1+1 dimensions. The method can yield static solutions as well as quasistatic "charged" solutions for a variety of Lagrangians. Explicit solutions are derived as examples. A particularly interesting class of solutions is nontopological without being either charged or time dependent.

The importance of classical soliton (localized finite-energy) solutions to the corresponding quantum field theories is now well established.[1] A major problem, however, is finding exact classical solutions in the first place, particularly for coupled fields. This problem is shared by many branches of physics. Individual solutions, such as the Prasad-Sommerfeld monopole,[2] or Montonen's solution[3] (see below), had to be obtained by ingenuity combined with trial and error,

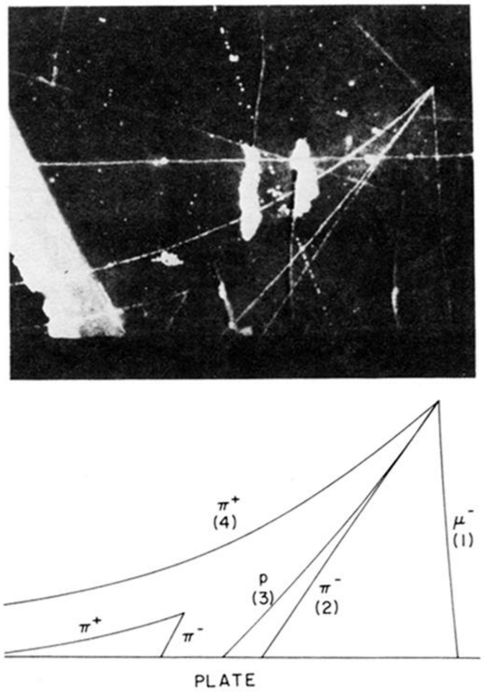

FIG. 1. View of the event as seen in camera 2.