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Authors

Vella, E
Trilling, GH
Abrams, GS
et al.

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Observation of Semileptonic Decays of Charmed Baryons

E. Vella, G. H. Trilling, G. S. Abrams, M. S. Alam,[a] C. A. Blocker,[b] A. Blondel,[c] A. M. Boyarski,
M. Breidenbach, D. L. Burke, W. C. Carithers, W. Chinowsky, M. W. Coles,[d] S. Cooper,[e]
W. E. Dieterle, J. B. Dillon, J. Dorenbosch,[f] J. M. Dorfan, M. W. Eaton, G. J. Feldman,
M. E. B. Franklin, G. Gidal, G. Goldhaber, G. Hanson, K. G. Hayes,[f] T. Himel,[f]
D. G. Hitlin,[g] R. J. Hollebeek, W. R. Innes, J. A. Jaros, P. Jenni,[f] A. D. Johnson,
J. A. Kadyk, A. J. Lankford, R. R. Larsen, V. Lüth, R. E. Millikan, M. E. Nelson,
C. Y. Pang, J. F. Patrick, M. L. Perl, B. Richter, A. Roussarie,[h] D. L. Scharre,
R. H. Schindler,[f] R. F. Schwitters,[h] J. L. Siegrist,[f] J. Strait, H. Taureg,[f]
M. Tonutti,[i] R. A. Vidal, I. Videau,[g] J. M. Weiss, and H. Zaccone[h]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Lawrence
Berkeley Laboratory and Department of Physics, University of California,
Berkeley, California 94720

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Direct electrons are observed in baryon events produced in e^+e^- annihilation at center-of-mass energies above the $\Lambda_c\overline{\Lambda}_c$ threshold. These events are attributed to charmed-baryon pair production and subsequent Λ_c semileptonic decay. Various semileptonic branching ratios of the Λ_c are determined, including $B(\Lambda_c \to e^+X) = (4.5 \pm 1.7)\%$.

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The production of the charmed baryon Λ_c in e^+e^- annihilation and its decay into several hadronic modes have been clearly established.[1] In the present paper, the first evidence for the observation of Λ_c semileptonic decay is reported. This evidence is based on measurements of direct-electron production in baryon events at center-of-mass energies above and below the threshold for charmed-baryon pair production.

The Mark II detector at the Stanford Linear Accelerator Center e^+e^- colliding-beam facility SPEAR has been described elsewhere,[2] and we mention here only those elements essential to the present analysis. A cylindrical drift chamber (DC) system in an axial magnetic field is used to reconstruct and measure the momenta of charged tracks within a solid angle of 85% of 4π sr. Charged-particle identification is obtained with a system of time-of-flight (TOF) counters covering 75% of 4π sr. The TOF timing resolution of 300 ps provides 1σ separation of protons from kaons up to 2 GeV/c and 1σ separation of electrons from pions up to 300 MeV/c. A lead-liquid-argon (LA) electromagnetic calorimeter, covering 64% of 4π sr, is used to measure the energy deposited by electrons and to separate electrons from pions at momenta above 300 MeV/c.

The data sample was taken at center-of-mass energies from 4.5 to 6.8 GeV and represents an integrated luminosity of 13 700 nb^{-1}. Data taken at lower energies [primarily at the $\psi'(3685)$], representing an integrated luminosity of 4300 nb^{-1}, are used to verify the absence of baryon-associated direct electrons below the Λ_c threshold. Two separate baryon event samples are used—events containing an antiproton and events containing a Λ or $\overline{\Lambda}$. Events containing a proton and not an antiproton are excluded to reduce the background from beam-gas interactions. The p and $\bar{p}$ are identified by TOF, with a somewhat looser cut for those baryons which are Λ or $\overline{\Lambda}$ decay products. The background of pions and kaons misidentified as baryons is estimated to be less than 5%. The Λ ($\overline{\Lambda}$) are identified from reconstruction of their $p\pi^-$ ($\bar{p}\pi^+$) decay modes. Background under the Λ peak due to beam-gas protons is reduced to the 20% level with a cut ($Q \leqslant 0$) on the total charge of those Λ events which do not contain an identified $\bar{p}$. The background under the $\overline{\Lambda}$ peak is very small. The overall $\bar{p}$ and Λ, $\overline{\Lambda}$ detection efficiencies are 60% and 15% (including the $p\pi$ branching ratio), respectively.

Electrons are identified by TOF in the momentum range 100–300 MeV/c, by TOF and LA in the range 300–500 MeV/c, and by LA alone in the range 500–1200 MeV/c. The electron selection criteria are chosen to give clean electron identification, with as little contamination by misidentified pions as possible, at the expense of a relatively low electron detection efficiency. This efficiency is deduced in two independent ways: (1) from a sample of real electrons arising from photon pair conversion, and (2) from a sample of Monte Carlo–generated electron showers. The results are in reasonable agreement and lead to an efficiency versus momentum dependence shown in Fig. 1(a). The fractional uncertainty in the electron detection efficiency is estimated to be less than 5%.

The major background is the misidentification of charged pions as electrons. Samples of real pions, taken from reconstructed ψ and ψ' events [$\psi' \to \psi\pi^+\pi^-$ and $\psi \to 2(\pi^+\pi^-)\pi^0$ or $3(\pi^+\pi^-)\pi^0$], are used to determine the momentum-dependent probabilities of misidentifying π^+ and π^- as electrons. These probabilities, shown in Fig. 1(b), are used to calculate the number of misidentified pions included in the electron sample. The π^+-π^- difference in Fig. 1(b) is due to misidentifications arising from π^+n and π^-p charge exchange in the LA calorimeter lead plates, which contain more neutrons than protons. Uncertainties in the pion misidentification probabilities are estimated at 7% overall, on the basis of the statistics of the samples of known pions from which they are determined.

The only other significant background arises from electron-positron pairs, produced either by photon conversions in the material between the beam and the drift chamber or by Dalitz decays of π^0's. Most e^+e^- pairs are easily identifiable, either from their small invariant mass or by a visual scan if one of the electrons was detected but not tracked by the drift chamber. These electrons are removed on an event-by-event basis. A statistical subtraction is necessary to correct for the remaining e^+e^- pairs in which one electron is completely undetected. The number of electrons from this source was calculated by a Monte Carlo program, with the π^0 population taken as half of the $\pi^\pm$ population at each momentum. Unidentified e^+e^- pairs are the dominant background at very low electron momenta, but are a negligible background above 300 MeV/c.

TABLE I. Direct-electron signal in baryon events.

	$E_{\text{c.m.}} < 4.5$ GeV		$E_{\text{c.m.}} < 4.5$ GeV	
	$9992\bar{p}$	$1499\Lambda, \bar{\Lambda}$	$5209\bar{p}$	$757\Lambda, \bar{\Lambda}$
raw $e^\pm$	613 ± 25	58 ± 8	440 ± 21	73 ± 9
$\pi^\pm$ background	424 ± 22	51 ± 3	287 ± 14	39 ± 2
$e^\pm$ background	144 ± 16	19 ± 2	84 ± 8	12 ± 1
net $e^\pm$	45 ± 37	-12 ± 8	69 ± 26	22 ± 9
corrected $e^\pm$	105 ± 86	-32 ± 23	170 ± 64	52 ± 21

The results of the search for direct electrons below and above the Λ_c threshold are shown in Table I. The raw $e^\pm$ count excludes those electrons from recognized γ conversions and π^0 Dalitz decays. The backgrounds from misidentified pions and from unidentified electron pairs are listed separately. The net electron signals, after efficiency corrections, are shown in Fig. 2 as a function of center-of-mass energy. Table I and Fig. 2 show the electron rate in baryon events to be consistent with zero below the Λ_c threshold. Above threshold, independent signals are present at the 2.6σ level in both the $\bar{p}$ and the $\Lambda, \bar{\Lambda}$ samples. The probability of obtaining such signals if there is actually no direct-electron contribution is less than 10^{-4}.

The measured rates of production of electrons in association with baryons, averaged over en-

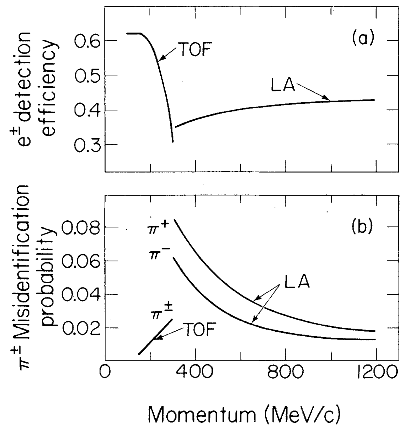

FIG. 1. (a) Electron detection efficiency, and (b) pion misidentification probability.

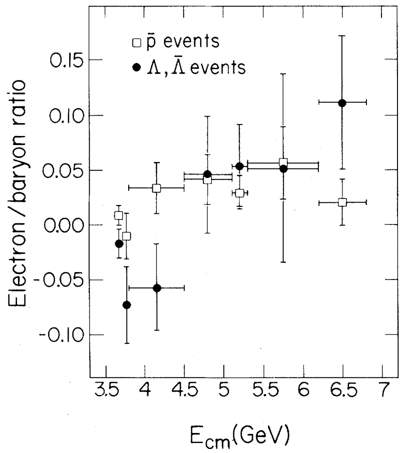

FIG. 2. Electron signal vs $E_{\text{c.m.}}$.

ergies between 4.5 and 6.8 GeV, are as follows:

$$N(\bar{p}e^+)/N(\bar{p}) = (1.9 \pm 0.9)\%,$$

$$N(\bar{p}e^-)/N(\bar{p}) = (1.4 \pm 0.6)\%,$$

$$\frac{N(\bar{\Lambda}e^+)+N(\Lambda e^-)}{N(\bar{\Lambda})+N(\Lambda)} = (3.2 \pm 1.8)\%,$$

$$\frac{N(\bar{\Lambda}e^-)+N(\Lambda e^+)}{N(\bar{\Lambda})+N(\Lambda)} = (3.8 \pm 2.0)\%,$$

where $\bar{p}$ from $\bar{\Lambda}$ decay are included in the first two entries.

We attribute the baryon-electron events to charmed-baryon pair production and subsequent semileptonic decay. Charmed-baryon–charmed-meson associated production is assumed to be negligible.[3] Events with misidentified baryons in which the electrons actually arise from charmed-meson semileptonic decay contribute at most 10% of the observed signal in the $\bar{p}$ events, and much less in the Λ, $\bar{\Lambda}$ events.

The branching-ratio determinations require estimates of the charmed-baryon content of the proton and lambda data samples. These estimates are provided by previous measurements of inclusive p and Λ production, $R(p)$ and $R(\Lambda)$, as functions of energy,[4] which show definite steps near the charmed-baryon threshold. The fraction of p or Λ events due to charmed-baryon production is taken as the increase in $R(p)$ or $R(\Lambda)$ relative to the base value of $R(p)$ or $R(\Lambda)$ below the charmed-baryon threshold. Averaged over the center-of-mass energy distributions of the baryon data samples, the resulting fractions are $\Delta R(p)/R(p) = 0.45 \pm 0.07$ and $\Delta R(\Lambda)/R(\Lambda) = 0.57 \pm 0.14$. The fraction of charmed-baryon decays leading to a proton (rather than a neutron) in the final state is taken to be $F(p) = 0.6 \pm 0.1$.[5] The fraction of charmed-baryon decays leading to a lambda in the final state is then $F(\Lambda) = [\Delta R(\Lambda)/\Delta R(p)]F(p) = 0.17 \pm 0.06$. The above numbers are based on the assumption that the observed increases in $R(p)$ and $R(\Lambda)$ above the charmed-baryon threshold are due entirely to charmed-baryon production. If part of the increases are unassociated with charm, the true branching ratios will be correspondingly larger than those calculated below.

Since charmed baryons emit positrons, the inclusive branching ratio $B(\Lambda_c \to eX)$ can be obtained from baryon-electron events, with the observed baryon serving only as a tag for a charmed-baryon event. Semi-inclusive branching ratios $B(\Lambda_c \to peX)$ and $B(\Lambda_c \to \Lambda^0 eX)$ can be obtained from baryon-positron events. The same statements apply to the charge conjugate combinations.

The calculations of the various semileptonic branching ratios of the charmed baryon proceed as follows:

$$B(\Lambda_c \to e^+X) = \frac{N(\bar{p}e^+)}{N(\bar{p})}\left(\frac{\Delta R(p)}{R(p)}\right)^{-1} = (4.2 \pm 2.0)\%;$$

$$B(\Lambda_c \to e^+X) = \frac{N(\bar{\Lambda}e^+)+N(\Lambda e^-)}{N(\bar{\Lambda})+N(\Lambda)}\left(\frac{\Delta R(\Lambda)}{R(\Lambda)}\right)^{-1} = (5.5 \pm 3.5)\%.$$

Averaging these two results gives $B(\Lambda_c \to e^+X) = (4.5 \pm 1.7)\%$.

$$B(\Lambda_c \to pe^+X) = \frac{N(\bar{p}e^-)}{N(\bar{p})}F(p)\left(\frac{\Delta R(p)}{R(p)}\right)^{-1} = (1.8 \pm 0.9)\%;$$

$$B(\Lambda_c \to \Lambda^0 e^+X) = \frac{N(\bar{\Lambda}e^-)+N(\Lambda e^+)}{N(\bar{\Lambda})+N(\Lambda)}F(\Lambda)\left(\frac{\Delta R(\Lambda)}{R(\Lambda)}\right)^{-1} = (1.1 \pm 0.8)\%.$$

Protons from Λ^0 decay are included in $B(\Lambda_c \to peX)$, and lambdas from Σ^0 decay are included in $B(\Lambda_c \to \Lambda^0 eX)$. The Cabibbo-favored semileptonic charm decay has the isospin selection rule $|\Delta\vec{I}| = 0$, and hence the hadronic decay products are expected to have isospin 0. The simplest way in which this might occur, namely through the mode $\Lambda^0 e^+\nu$, does not seem to be dominant.

The inclusive semileptonic branching ratio of the Λ_c can be related to the Λ_c lifetime if the Λ_c semileptonic decay rate is known. A theoretical calculation of the semileptonic width of charmed particles gives $\Gamma_{SL} = (1.9 \pm 0.5) \times 10^{11}$ sec^{-1}.[6] Combined with the present inclusive semileptonic branching-ratio measurement, this leads to a lifetime $\tau(\Lambda_c) = B(\Lambda_c \to eX)/\Gamma_{SL} = (2.4 \pm 1.1) \times 10^{-13}$ sec. This value is in good agreement with recent direct measurements of the Λ_c lifetime,[7] which give $\tau(\Lambda_c) = (2.3^{+1.1}_{-0.7}) \times 10^{-13}$ sec.

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Institute for Basic Research in Science, University of California, Berkeley, 1980–1981.

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[a] Present address: Vanderbilt University, Nashville, Tenn. 37235.

[b] Present address: Harvard University, Cambridge, Mass. 02138.

[c] Present address: Laboratoire de Physique Nucléaire et Hautes Enérgies, Ecole Polytechnique, F-91128 Palaiseau, France.

[d] Present address: Carnegie-Mellon University, Pittsburgh, Penn. 15213.

[e] Present address: DESY, D-2000 Hamburg-52, Federal Republic of Germany.

[f] Present address: CERN, CH-1211 Geneva 23, Switzerland.

[g] Present address: California Institute of Technology, Pasadena, Cal. 91125.

[h] Present address: Centre d'Etudes Nucléaires Saclay, F-91190 Gif-sur-Yvette, France.

[i] Present address: Universitat Bonn, D-53 Bonn, Federal Republic of Germany.

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[5] This value is based on a simple isospin statistical model.

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Fractionally Charged Heavy Leptons: Cosmological Implications of Their Existence, and a Prediction of Their Abundance

H. Goldberg
Department of Physics, Northeastern University, Boston, Massachusetts 02115

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Charge $\pm\frac{1}{3}$ heavy leptons can annihilate in heavy stars down to an abundance of 10^{-19}, without generating an isotropic γ-ray background. Observation of such leptons with this abundance, and the observed flux of cosmic neutrinos imply that (1) there is no primordial hydrogen on earth, (a) the first stars were heavy ($M \gtrsim 15 M_\odot$), and (3) their formation took place at a red shift $1+z \gtrsim 20$.

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Experiments by LaRue, Phillips, and Fairbank[1] continue to show fractional charges residing on niobium balls, with an abundance of $\gtrsim 10^{-20}$. If these results are confirmed, then the first obvious possibility is that liberated quarks are being observed. However, in the context of a recently proposed[2] SU(7) grand unified theory, two other options exist: that the fractional charges are color-singlet $q\bar{q}$ or qqq composites (since the theory contains quarks with nonconventional charges), or that they are leptons. There is an attractiveness to the leptonic alternative: In the experiment the fractional charges seem to move on and off the niobium rather easily, suggesting leptons rather than hadrons.[3] Examining some not obviously wrong possibilities has proven productive in the past in particle physics, so that there would seem to be ample motivation to follow up the possibility of charge $\pm\frac{1}{3}$ leptons. (The charge $\pm\frac{2}{3}$ possibility is not discussed, for reasons that will become clear later.) In this note, I present a synopsis of some of the salient points of such an investigation. A complete version will be published elsewhere.[4]