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Λ_c^+ PRODUCTION AND SEMILEPTONIC DECAY IN 29 GEV e^+e^- ANNIHILATION*

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ABSTRACT

We present results on Λ_c^+ production in 29 GeV e^+e^- annihilation. The Λ_c^+ are observed via their semileptonic decays to Λe^+X and $\Lambda\mu^+X$. With radiative corrections, we find $\sigma(e^+e^- \to \Lambda_c^+X) \cdot \mathrm{Br}(\Lambda_c^+ \to e\Lambda X) = 1.5 \pm 0.6 \pm 0.5$ pb or $0.0038 \pm 0.0015 \pm 0.0012$ per hadronic event, and $\sigma(e^+e^- \to \Lambda_c^+X) \cdot \mathrm{Br}(\Lambda_c^+ \to \mu\Lambda X) = 1.4 \pm 1.4 \pm 0.4$ pb or $0.0035 \pm 0.0035 \pm 0.0011$ per hadronic event. These results can be used to place constraints on the predictions of various production models.

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As the lightest charmed baryon, the Λ_c^+ is of great interest. However, fairly little is known about it. In particular, its semileptonic decays, which are the most accessible theoretically,[1] are almost unstudied experimentally. Also, although Λ_c^+ production rates are a strong test of e^+e^- fragmentation models, no previous results on Λ_c^+ production have been reported at PEP/PETRA energies. We describe here the observation of a Λ_c^+ signal in e^+e^- annihilation at 29 GeV. The Λ_c^+ is observed via its decays to a final state containing a Λ plus a lepton.[2]

This analysis is based on an integrated luminosity of 207 pb^{-1} of data, collected over a period of three years with the original Mark II/PEP 5 detector at PEP. The detector has been described elsewhere.[3] Charged particles are tracked in a 16-layer cylindrical drift chamber and a 7-layer precision drift chamber in a 2.3 kG magnetic field. Charged particle momenta p (GeV/c) are measured with a resolution of $\delta p/p = [(0.010p)^2 + (0.025)^2]^{1/2}$. Electrons are identified by their energy deposition pattern in a lead–liquid argon calorimeter, which covers 64% of the 4π solid angle. Muons are identified over 45% of the 4π solid angle by their penetration of a 4-layer steel absorber stack.

Hadronic events are selected with a standard set of cuts described elsewhere.[4] The tracks used in this analysis are required to have a momentum perpendicular to the beam axis, p_{xy}, greater than 100 MeV/c, and have $|\cos(\theta)| < 0.8$, where θ is the angle between the particle track and the beam axis.

Λ candidates are selected by finding vertices for all oppositely charged track pairs in the plane perpendicular to the beam (the x–y plane). The higher momentum particle in each pair is assumed to be the proton. This assignment is always correct for Λ with momenta over 250 MeV/c. Pairs which meet the following criteria are considered to be Λ candidates:

1. The distance from the reconstructed decay vertex to the center of the interaction region in the x– 10 mm.
2. The pion must have a distance of closest approach to the interaction region of greater than 1 mm in the x–y plane.

population, and subscripts 1 and 2 refer respectively to the beam whose radiation is being calculated and to the target beam. The impact parameter between beam centers is d. The energy radiated is

$$U_1 = \frac{8}{3\sqrt{\pi}} \frac{N_1 N_2^2 r_e^3 m c^2 \gamma^2}{\sigma_1^2 \lambda_2} F,$$

$$F = \int_0^\infty \frac{1}{x} \left(1 - e^{\left(-B^2 x^2\right)}\right)^2 e^{-\left(x^2+l^2\right)} I_0\left(2lx\right) dx.$$

Here, r_e is the electron classical radius, m its mass, c the velocity of light, B is σ_1/σ_2, and l is $d/\sqrt{2}\sigma_1$. The transverse spatial integral F, involving the modified Bessel function I_0, in general is evaluated numerically.

The energy scale of synchrotron radiation is characterized by the "critical energy",[4] E_c. In beamstrahlung, there is a range of critical energies. An expression for the energy weighted mean critical energy, under the above assumptions, is

$$\langle E_c \rangle = \sqrt{\left(\frac{6}{\pi}\right)} \left(\frac{N_2 r_e^2 m c^2 \gamma^2}{\alpha \sigma_1 \lambda_2}\right) \frac{G}{F},$$

$$G = \int_0^\infty \frac{1}{x^2} \left(1 - e^{\left(-B^2 x^2\right)}\right)^3 e^{-\left(x^2+l^2\right)} I_0\left(2lx\right) dx,$$

where α is the fine structure constant. G is also evaluated numerically. In the work reported here, $\langle E_c \rangle$ has been in the range 10–15 MeV.

Since the emission of the gamma rays is tangential within microradians to the emitting trajectory,[5] the radiation forms a neutral beam with the same angular divergence as the charged beam, broadened by the range of angles through which the charged beam is deflected during the collision.

At the SLC interaction point, beam bunches collide at a rate of up to 120 Hz, and so each collision can be observed individually. The bunches leaving the interaction point travel approximately 38 meters before magnetic dipoles deflect the charged beams by approximately 1°. At 41 meters along both e^+ and e^- beam lines there is sufficient separation between the charged and neutral trajectories to permit the installation of a detector for the gamma rays. However, the radiation environment, particularly the synchrotron radiation from the nearby dipole with potentially 10^3 rads per pulse and a critical energy of 2.3 MeV, strongly influenced the design and operation of the detectors, which are described in detail elsewhere.[6] For gamma ray energies $E \gg E_c$, the synchrotron (and beamstrahlung) spectrum falls as $E^{-1/2} \exp(-E/E_c)$, and so an energy threshold in the range of 20-30 MeV suppresses synchrotron radiation and other low energy backgrounds while retaining sensitivity to some of the beamstrahlung. This has been accomplished by using a plate to convert approximately 3% of the gamma rays to e^+e^- pairs, and using a gas Čerenkov counter to measure the flux of $e^\pm$ above the Čerenkov threshold. In practice, synchrotron radiation backgrounds have been too small to measure, even when thresholds were tested as low as 16 MeV.

The Čerenkov counters measure the amount of light from individual tracks within their energy and geometric acceptance, and this is not proportional to the total beamstrahlung energy. With the help of a Monte Carlo study, the response of the counter has been tabulated for a set of spectra characterized by values of $\langle E_c \rangle$, ignoring small differences in spectrum at a given $\langle E_c \rangle$ under different collision conditions. Thus an evaluation of $\langle E_c \rangle$ and U from the expressions above allows the yield of the counter to be interpolated and scaled for the beam parameters of interest.

The counters are also used for measuring Bremsstrahlung from fine carbon fiber targets inserted at the IP to probe the size and shape of the beam spots.[7] The signal is normally amplified in this case by moving a 3.3 radiation length converter plate in front of the counter. For purposes of this note, the Bremsstrahlung signals afford a calibration for the counters —the digitized pulse height is measured for a known flux of Bremsstrahlung gamma rays. The sensitivity for the lower energy beamstrahlung spectrum is then inferred with the help of the electron-photon shower code, EGS.[8]

One of the actions carried out in studying and tuning the colliding beams involves steering one beam spot across the other in steps typically of two microns. Between steps, the beams are held stable for a selected number of pulses, frequently three, to allow data from these pulses to be averaged. The influence of their fields is strong enough that the beams deflect each other, and results from beam position monitors are used to measure the deflections and set the steering for head-on collisions.[9]

An illustration is given in Fig.1(a) of the signals obtained from the counters as the positron beam spot was stepped vertically across the electron spot. The step size was two microns, and the results were averaged for three pulses between steps. The peaks rising a few counts above the signal digitizer (ADC) pedestal levels, which have been subtracted, indicate that radiation was detected along both beam lines only while the beam bunches were in very close proximity. Signals like this have been seen during numerous beam scans. With well focussed beams the radiation is consistently detectable.

There has been nothing similar to the characteristic appearance of the intensity peaks in several months of operation with single beams. Occasionally there are backgrounds, both from the nearby showering of off-axis beam particles, and from a flux of higher energy neutrals in the beam pipe from more distant beam scraping. However, such beam losses are not consistent with the tuning standards necessary for the work being reported, and also are not correlated with micron-level positioning of single beams. As a further test, one beam was stopped far upstream, and the radiation from the remaining beam immediately ceased. The radiation clearly comes from a true beam-beam interaction, and at least for the conditions of this test, remaining single-beam backgrounds were at least an order of magnitude lower in amplitude.

The radiation has also been observed with the 3.3 radiation length additional converter in front of the detector. The signal was attenuated by about 25%. Had it been caused by a high energy background, the signal would have been amplified by up to a factor of 100, depending on the energy of the rays. A background originating from synchrotron radiation —with its energies below a few MeV —would be strongly attenuated by the converter. The observed decrease in signal is, however, consistent with what would be expected for the tail of a beamstrahlung spectrum just above the Čerenkov threshold of 25 MeV.

As discussed in detail in Ref.6, the counters are capable of estimating the angular distribution of the incident radiation in the horizontal plane for radiation from the electron beam, and in the vertical plane for emission from the positron beam. This is obtained from the distribution of signals among the photomultiplier tubes. To date, however, the beamstrahlung yields have been small, and the contribution of electronic noise and least-count sensitivity to the results from individual channels has been relatively large. Nonetheless, a single measurement has been made of the vertical angular divergence of the positron beam. The result, 251 ± 25

μrad, lies within the range measured using Bremsstrahlung during beam tuning operations a few hours before and after the beamstrahlung measurement.

A more quantitative examination has been attempted of the results of some of the scans. Fluctuations are to be expected from pulse-to-pulse intensity changes of the charged beams. Corrections for this have already been made in Fig.1(a), using the numerical calculations of beamstrahlung to estimate the sensitivity. The resulting plots show some remaining fluctuations, and also a tendency for left-right asymmetry. Asymmetries can be produced by beams with substantial ellipticity whose major axes are in the neighborhood of 45° askew, and where the scan passes to one side of the exact head-on position. Studies with beam deflections and with carbon fibers suggest that these circumstances are unusual. On the other hand, the effect can simply be explained by a drift in the beam transverse dimensions in the range of 5% during the scan, with possibly a contribution from intrinsic asymmetry in the beam spots. Other measuring techniques do not exclude this. To compensate partially for such effects, we fold the scan results about the common mid-point of the positron and electron peak. In Fig.1(b) are shown the results of folding the data of Fig.1(a).

Some separation of variables can be achieved, since the widths of the distributions are essentially determined by the geometry of the beams and their field shapes. We make use of the first moment of the distribution about zero offset, which is less sensitive than the RMS to pedestal fluctuations in the tails. To characterize the signal amplitude, the mean of the data points within 25% of the peak has been calculated, reducing the effect of a fluctuation at any single scan position. A set of calculations was then carried out to try to reproduce these measurements.

The calculations used the approximation of round beams, which carbon fiber measurements (usually on the order of an hour earlier) suggested would be reasonable for certain scans. A search was carried out to find the Gaussian radii of the two beams which together gave the measured values for both the first moments from the scan. Then a set of charged beam intensities and Gaussian lengths were sought which simultaneously gave the two peak intensities as defined above.

Results are illustrated in Fig.1(b). The solid curves are the best representation found for this data. In this and other cases, the charged beam intensities needed for the curves agree with values from beamline monitors within their uncertainty of $\pm15\%$. The bunch lengths required for agreement with the data have also been consistent in the cases tried, close to 0.5 mm for positrons and 0.82 mm for electrons. The extent to which uncertainties in intensity and width (considered below) affect the length values was treated by a Monte Carlo correlation analysis, giving a length uncertainty of ±0.21 mm. The results are consistent with electron bunch lengths of 0.54 ± 0.06 mm measured near the start of the linac,[10] although trajectory path length differences may modify the length slightly before the IP is reached, and small variations with time may also occur. In summary, beamstrahlung yields appear to be consistent with theory, the dominant uncertainties being those on the charged beam parameters.

The beam radii required in the calculations to make the first moments agree with the data generally have fallen within 7% of the values from carbon filament scans made within an hour or so of the beam scans. The exception is the electron beam of Fig.1, which, at 3.7 μm, is 26% narrower than the carbon fiber result, probably because of a change in beam conditions. The positron bunch radius was 4.1 μm. The effect of a 26% difference may be judged from the figure, in which the dashed curves are calculated for an electron beam only 10% wider than the best value. (With the wider beam, it was necessary to shorten the bunch length to compensate for the 40% loss in intensity.) Although it was the electron beam whose width was altered, the dominant effect is on the emission from positrons. The calculations show that, over a broad range of beam radii of interest at SLC, the first moment remains within the range 1.45 to 1.75 times the *target* beam width. This simplifies the interpretation of the results of scans used to monitor changes in the colliding beams.

In the scans we have examined, there are occasional differences in shape between data and calculation. These can be large enough that our confidence in the width measurement does not yet extend below uncertainties of 10%. They may be associated with ellipticity in the beams, for which an analysis should include major and minor axis $e^{\pm}$ beam dimensions (instead of radii), and the angles of both ellipses relative to the scan direction. In order to determine the extra geometrical parameters, a set of scans must be made along at least three directions, a procedure which remains to be tested in future SLC operation. It may be concluded, however, that the technique is ready for development as a non-destructive monitor of beam profiles. Performance should improve as beam intensity increases, into the range where carbon filament probes could not survive.[7]

A most important part of the work of obtaining the beamstrahlung signal was the effort of the people, too numerous to mention individually, who have worked hard to develop the SLC beams, both improving the collisions and reducing the background radiation. Particularly we acknowledge J.Ballam and W.Kozanecki for their continual support and interest.

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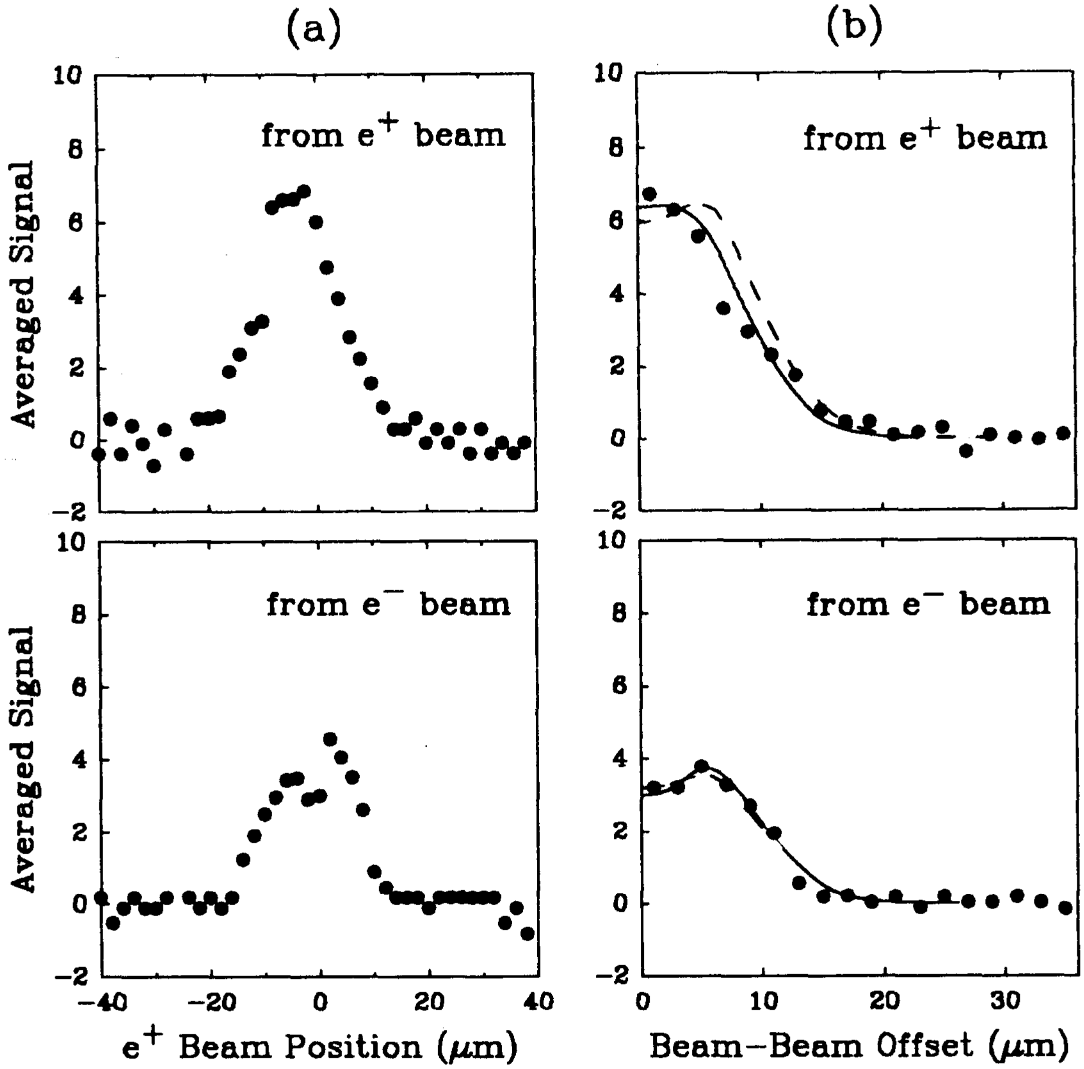
Figure Caption

1(a) Response of the two counters as the positron beam spot is stepped at 2 micron intervals across the electron spot, with three pulses averaged at each step. Pedestal subtraction and $e^{\pm}$ intensity corrections have been made. The symbol diameter represents the uncertainty from the digitizer least-count, averaged for three pulses. (b) The same data folded about the common midpoint. The continuous curves are the best representation of the data as defined in the text. For the dashed curves, the electron bunch radius is increased by 10%.



(a)
(b)
from e+ beam
from e+ beam
from e− beam
from e− beam
Averaged Signal
Averaged Signal
e+ Beam Position (μm)
Beam−Beam Offset (μm)

Fig. 1