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First Observation of Beamstrahlung*

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ABSTRACT

Collisions of electron and positron bunches at the interaction point of the SLC (the linear collider at SLAC) have led to the first detected emission of beamstrahlung. This radiation, caused by the collective electromagnetic fields of one beam deflecting particles of the other, is a potential tool for optimizing collisions in linear colliders.

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With the advent of the linear collider[1] as a tool for the study of high energy elementary particle physics, there has developed a strong interest in the physics of the beams in such machines. Of particular interest is the interaction point (IP), where the two beams must be brought to superimposed foci, with transverse sizes in the micron range or smaller. New methods are needed for the measurement and monitoring of these beams in collision. We describe here the first observation of beamstrahlung —an electromagnetic radiation from the collision of the beams. The phenomenon promises to be a valuable operating tool for linear colliders and very high energy storage rings.[2]

There is a considerable body of theoretical work on beamstrahlung in the literature, covering various energy regimes and beam parameters,[3] and the topic continues to develop at a lively pace. It has not been possible to observe the radiation, however, until the SLC at SLAC began to collide high energy electron and positron beams with exceptionally intense focal spots. For the data reported here, typical beam energies were 46 GeV (Lorentz factor $\gamma = 9 \times 10^4$), with bunches of about 10^{10} electrons and 6×10^9 positrons. At collision, the bunches were approximately Gaussian along all three axes, with RMS length about 750 microns, and transverse RMS sizes typically below 5 microns.

The magnetic fields around one of these dense bunches can approach 10 T. Consequently each particle trajectory is deflected (equally by the magnetic and electric fields), and emits synchrotron radiation. It is this radiation which is termed beamstrahlung. Until conditions are such that its energy is comparable with the energy of the beam, it may be treated classically.

The charge density distributions of each beam have Gaussian lengths λ, and, in the simplified case of round cross sections, Gaussian radius σ. N is the bunch

3. The proton must have a distance of closest approach to the interaction region of greater than 0.6 mm in the x–y plane.
4. At their x–y vertex, the two tracks must have a z difference of less than 4 cm.
5. The Λ candidate must have a momentum of at least 1.5 GeV/c. Λ candidates with lower momenta are unlikely to come from Λ_c^+ decays.

The proton and pion momenta are adjusted to compensate for dE/dx loss in the beam pipe, and the two tracks are constrained in a three dimensional vertex fit. For Λ candidates with momenta p_Λ less than 2 GeV/c, the calculated mass is required to be within 5 MeV/c^2 of the actual Λ mass. For candidates with momenta more than 2 GeV/c, the calculated mass is required to be within 4 MeV/c^2 + $0.0005 p_\Lambda$ (MeV/c) of the actual Λ mass.

These Λ candidates are paired with all lepton candidates. The lepton identification criteria and background are described in Ref. 2. Electrons are required to have p $>$ 1.5 GeV/c, while muons must have p$>$ 2 GeV/c. The leptons are required to be in the same hemisphere as the Λ , where the hemisphere is determined by a plane perpendicular to the thrust axis.

For a $\Lambda\ell^+$ pair coming from a Λ_c^+ decay, a positively charged lepton will be paired with a Λ, while a negatively charged lepton will accompany a $\overline{\Lambda}$. In both cases, the $\Lambda\ell^+$ pair invariant mass will be less than the Λ_c^+ mass. The invariant mass spectrum of the combinations are shown in Fig. 1, separately for right and wrong sign combinations. Below the Λ_c^+ mass of 2.28 GeV/c^2 , there are 19 right sign (13 electron, 6 muon) and 6 wrong sign (3 electron, 3 muon) combinations, while above the Λ_c^+ mass, there are 2 right sign (both electrons) and 3 wrong sign combinations (all electrons).

The background was studied with a Monte Carlo simulation, and compared with the wrong sign candidates.[5] In decreasing order of importance, the major background sources are: K_s and random track combinations misidentified as Λ (roughly 70% of the background), fake leptons, as discussed in Ref. 4 (roughly 25% of the background), and random lepton–Λ combinations (roughly 5%). All of these sources populate the right and wrong sign plots equally. There are two small additional sources which can produce only wrong sign pairs. The first is semileptonic B decays, where a B meson or baryon decays to a lepton plus a Λ_c^+, and the Λ_c^+ subsequently decays to a Λ. The estimated background from this source is negligible, as can be seen by examining the excess of wrong events above the Λ_c^+ mass, where most decays of this type will appear. Secondly, if an antiproton is produced in association with a Λ , and the antiproton annihilates in the liquid argon calorimeter to mimic an electron, this can produce a wrong sign pair. The possible background from this source is included as a systematic error.

The wrong sign combinations should therefore be a good measure of the background. After background subtraction, the signal is 10 $\pm$ 4 electron and 3 $\pm$ 3 muon events.

Measuring the production cross section times branching ratio requires a knowledge of the detection efficiency, which, along with the shapes of many interesting distributions, depends heavily on which specific decay modes are dominant. To determine which modes are most likely to be important, we are forced to rely on theoretical arguments, and allow for uncertainties as a systematic error. Some possible modes are: $\Lambda\ell^+\nu$, $\Sigma^0\ell^+\nu$, $\Sigma^{*0}\ell^+\nu$, $\Lambda\pi^0\ell^+\nu$, $\Sigma^0\pi^0\ell^+\nu$, and $\Lambda(\pi\pi)^0\ell^+\nu$. Other modes are Cabbibo suppressed, or have little phase space.

Theory predicts that most of the above modes are suppressed. Since the Λ_c^+ is an isosinglet, the final state hadrons should have isospin 0, suppressing the isospin 1 modes $\Sigma^0\ell^+\nu$, $\Sigma^{*0}\ell^+\nu$, and $\Lambda\pi^0\ell^+\nu$. Another restriction comes from the dynamics of the decay. When the $c \to s\ell^+\nu$ decay occurs, the strange quark gets a perpendicular momentum kick from the W, while the u and d quarks are spectators. If additional quark–antiquark pairs are created, they should appear between the s quark and the u and d quarks. The baryon producing ud diquark will be separated from the strange quark, reducing the probability of a final state Λ in modes involving extra pions. We can also compare the Λ_c^+ with the charmed meson sector, where semileptonic D meson decays generally lead to a charged lepton, a neutrino, and a single hadron.[6]

Two final arguments come from the data. We searched for the final state $\Lambda\pi^+\pi^-\ell^+X$ and found no candidates. Since the acceptance for this mode is quite good, compared with the acceptance for $\Lambda\ell^+X$, we conclude that this mode should be negligible. Finally, the Monte Carlo prediction for the $\Lambda\ell^+$ mass spectrum from $\Lambda_c^+ \to \Lambda\ell^+\nu$, shown in Fig. 1, agrees with the data. So, we will therefore assume that $\Lambda_c^+ \to \Lambda\ell^+\nu$ dominates and include the possibility of other Λ containing decays as a systematic error in the efficiency.

Another important consideration in calculating the efficiency is the momentum spectrum. Figure 1 compares the observed momentum spectrum of the $\Lambda\ell^+$ combination with the Lund model prediction. Because of the limited momentum range and statistics, it is not possible to extract the original Λ_c^+ momentum spectrum.

By using the Monte Carlo determined efficiency, it is possible to calculate the Λ_c^+ production cross section rate times $\mathrm{Br}(\Lambda_c^+ \to \Lambda\ell^+X)$. The major systematic errors come from the uncertainties in the Λ_c^+ momentum spectrum and decay modes (25%). The reasonable agreement shown in Fig. 2, together with the ARGUS[7] and CLEO[8] observations that the Λ_c^+ fragmentation function is similar to the D fragmentation function limit the error due to uncertainty in the momentum spectrum. The uncertainty due to decay modes is estimated from a comparison of the efficiencies for the modes $\Lambda\ell^+\nu$ and $\Lambda\pi^0\ell^+\nu$. Other sources of systematic uncertainty are in the tracking efficiency (3% per track, or 9% overall), detector variations over time (10%), luminosity (2%), Monte Carlo simulation (10%), and Monte Carlo statistics (8%). The electron measurement has an additional 14% systematic uncertainty due to the possibility of antiproton electron misidentification.

After corrections for acceptance and initial state radiation, we find

$$\sigma(e^+e^- \to \Lambda_c X) \cdot \mathrm{Br}(\Lambda_c^+ \to \Lambda e^+ X) = 1.5 \pm 0.6 \pm 0.5\mathrm{pb}$$

or $0.0038 \pm 0.0015 \pm 0.0012$ per hadronic event, and

$$\sigma(e^+e^- \to \Lambda_c X) \cdot \mathrm{Br}(\Lambda_c^+ \to \Lambda\mu^+ X) = 1.4 \pm 1.4 \pm 0.4\mathrm{pb}$$

or $0.0035 \pm 0.0035 \pm 0.0011$ per hadronic event.

To put this in perspective, we need to consider the Λ_c^+ branching ratios. Mark II at SPEAR measured[9] $\mathrm{Br}(\Lambda_c^+ \to e^+X) = 4.5 \pm 1.7\%$ and $\mathrm{Br}(\Lambda_c^+ \to \Lambda e^+ X) = 1.1 \pm 0.8\%$. A Fermilab neutrino beam experiment also measured[10] $\mathrm{Br}(\Lambda_c^+ \to \Lambda e^+ X) < 2.2\%$ at a 90% confidence level.

Using this upper limit, we get a lower limit on the production rate of $0.17 \pm 0.07 \pm 0.05$ Λ_c^+ per hadronic event, neglecting uncertainty from the branching ratio limit. This limit can be compared with the predictions of various models.

The Lund model[11] predicts 0.06 Λ_c^+ per hadronic event. The UCLA model[12] bases hadron production rates on their mass, and since the Λ_c^+ mass is high, the predicted rate is much lower, 0.018 Λ_c^+ per hadronic event, somewhat lower than the data indicate. The Webber model[13] predicts 0.026 Λ_c^+ per hadronic event, also somewhat lower than the data indicate.

We have also searched for hadronic decays of the Λ_c^+. The final states $\mathrm{p}K^-\pi^+$, $\Lambda\pi^+$, $\Lambda 3\pi$, $\mathrm{p}K_s$, and $\mathrm{p}K_s\pi^+\pi^-$ were studied. No evidence for any of these states was found. The most interesting upper limit was for the decay to $\Lambda 3\pi$. The cuts used in the search were chosen to match the semileptonic analysis cuts as closely as possible. The Λ_c^+ were required to have a momentum of at least 5.5 GeV/c, chosen to match the 4 GeV/c $\Lambda\ell^+$ momentum requirement as closely as possible. The same Λ selection criteria were used. Each of the three pions were required to have a momentum of at least 400 MeV/c. The resulting mass spectrum is shown in Fig. 3. To find an upper limit on the rate, the invariant mass spectrum was fit to a Gaussian, with fixed width determined by Monte Carlo simulation, plus a linear background. The position of the Gaussian was allowed to vary within the systematic mass uncertainty; the position that gave the worst upper limit was used. This led to a 90% confidence level upper limit of

$$\frac{Br(\Lambda_c \rightarrow \Lambda 3\pi)}{Br(\Lambda_c^+ \rightarrow \Lambda e^+ X)} < 1.7 \quad .$$

We have also searched for the Σ_c, via the decay chain $\Sigma_c \rightarrow \Lambda_c^+\pi$, by studying the mass difference, $\Delta m = m(\Sigma_c) - m(\Lambda_c)$ for Σ_c candidates. Because of the missing ν momentum, the Δm resolution is poor, about 60 MeV/c^2. There are one Σ_c^{++} and two Σ_c^0 candidates, which are completely compatible with background. With these candidates, and assuming that all Σ_c decay to $\Lambda_c^+\pi$, we find $\sigma(\Sigma_c^{++})$ / $\sigma(\Lambda_c^+) < 0.48$ and $\sigma(\Sigma_c^0)$ / $\sigma(\Lambda_c^+) < 0.67$, both at a 90% confidence level.

To conclude, we have observed semileptonic Λ_c^+ decays in 29 GeV e^+e^- annihilation. The Λ_c^+ are identified by their decays to a final state containing a Λ plus a lepton with an invariant mass below the Λ_c^+ mass. Using previous measurements of the Λ_c^+ semileptonic branching ratios, we find that the UCLA and Weber models predict too little Λ_c^+ production, while the Lund model gives reasonable agreement with the data.

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FIGURE CAPTIONS

1. Invariant mass spectra for (a) $\Lambda\ell^+$ and (b) $\Lambda\ell^-$. The solid line in (a) is the Lund model prediction for $\Lambda_c^+ \to \Lambda\ell^+\nu$, with arbitrary normalization.
2. The background subtracted momentum spectra for the $\Lambda\ell^+$. The solid line is the Lund model prediction for $\Lambda_c^+ \to \Lambda\ell^+\nu$, normalized to agree with the data in the 3–12 GeV.c region.
3. The invariant mass spectra for $\Lambda\pi^+\pi^-\pi^+$. No Λ_c^+ signal is visible.

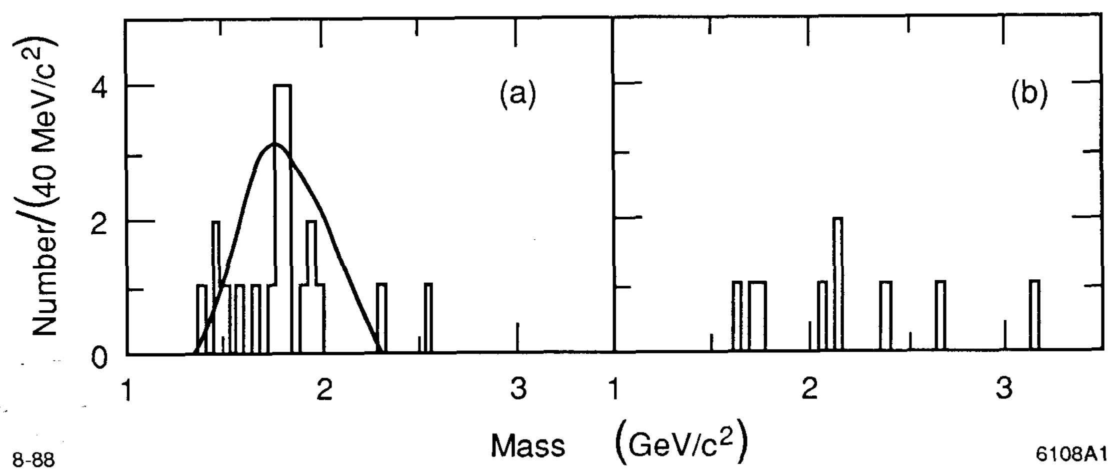

Fig. 1

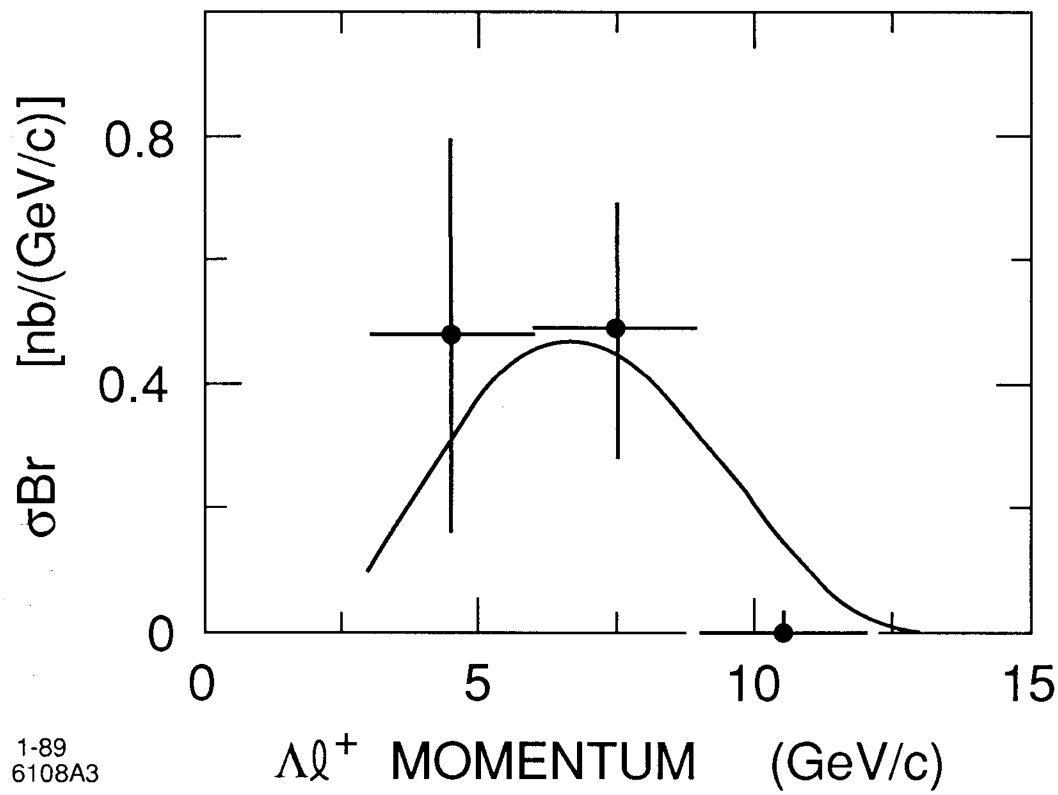

Fig. 2

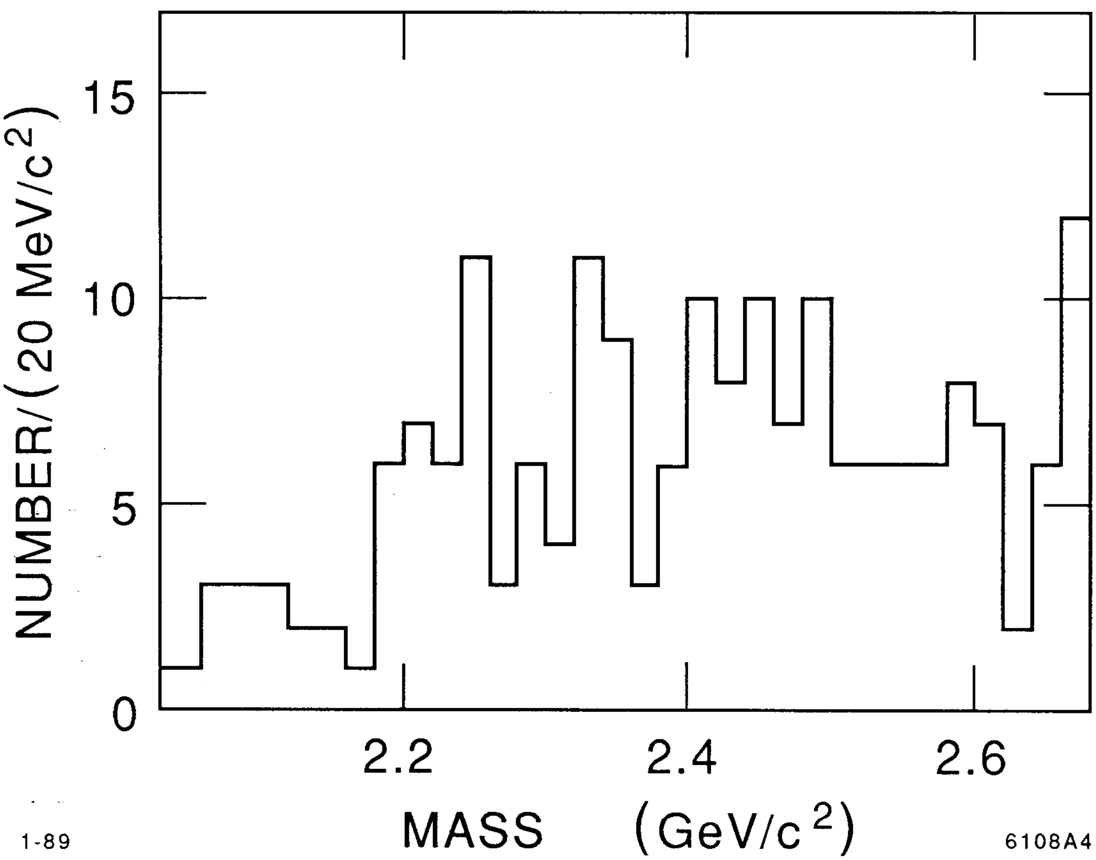

Fig. 3