Study of Baryon Correlations in e^+e^- Annihilation at 29 GeV

H. Aihara, M. Alston-Garnjost, R. E. Avery, A. Barbaro-Galtieri, A. R. Barker, A. V. Barnes, B. A. Barnett, D. A. Bauer, H.-U. Bengtsson, D. L. Bintinger, G. J. Bobbink, T. S. Bolognese, A. D. Bross, C. D. Buchanan, A. Buijs, D. O. Caldwell, A. R. Clark, G. D. Cowan, D. A. Crane, O. I. Dahl, K. A. Derby, J. J. Eastman, P. H. Eberhard, T. K. Edberg, A. M. Eisner, R. Enomoto, F. C. Erné, T. Fujii, J. W. Gary, W. Gorn, J. M. Hauptman, W. Hofmann, J. E. Huth, J. Hylen, T. Kamae, H. S. Kaye, K. H. Kees, R. W. Kenney, L. T. Kerth, Winston Ko, R. I. Koda, R. R. Kofler, K. K. Kwong, R. L. Lander, W. G. J. Langeveld, J. G. Layter, F. L. Linde, C. S. Lindsey, S. C. Loken, A. Lu, X.-Q. Lu, G. R. Lynch, R. J. Madaras, K. Maeshima, B. D. Magnuson, J. N. Marx, G. E. Masek, L. G. Mathis, J. A. J. Matthews, S. J. Maxfield, S. O. Melnikoff, E. S. Miller, W. Moses, R. R. McNeil, P. Nemethy, D. R. Nygren, P. J. Oddone, H. P. Paar, D. A. Park, S. K. Park, D. E. Pellet, M. Pripstein, M. T. Ronan, R. R. Ross, F. R. Rouse, K. A. Schwitkis, J. C. Sens, G. Shapiro, M. D. Shapiro, B. C. Shen, W. E. Slater, J. R. Smith, J. S. Steinman, M. L. Stevenson, D. H. Stork, M. G. Strauss, M. K. Sullivan, T. Takahashi, J. R. Thompson, N. Toge, S. Toutounchi, R. van Tyen, B. van Uitert, G. J. VanDalen, R. F. van Daalen Wetters, W. Vernon, W. Wagner, E. M. Wang, Y. X. Wang, M. R. Wayne, W. A. Wenzel, J. T. White, M. C. S. Williams, Z. R. Wolf, H. Yamamoto, S. J. Yellin, C. Zeitlin, and W.-M. Zhang
(TPC/Two-Gamma Collaboration)

Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
University of California, Davis, Davis, California 95616
University of California Institute for Research at Particle Accelerators, Stanford, California 94305
University of California, Los Angeles, Los Angeles, California 90024
University of California, Riverside, Riverside, California 92521
University of California, San Diego, La Jolla, California 92093
University of California, Santa Barbara, Santa Barbara, California 93106
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
Ames Laboratory, Iowa State University, Ames, Iowa 50011
Johns Hopkins University, Baltimore, Maryland 21218
University of Massachusetts, Amherst, Massachusetts 01003
New York University, New York, New York 10003
National Institute for Nuclear and High Energy Physics, Amsterdam, The Netherlands
University of Tokyo, Tokyo, Japan
(Received 14 October 1986)

We report measurements of two-particle correlations in rapidity space between a $\bar{p}$ or $\bar{\Lambda}$ and an additional p, $\bar{p}$, Λ, or $\bar{\Lambda}$. We find evidence for local conservation of baryon number, and for the first time we observe a pronounced anticorrelation between baryons with the same value of baryon number. Such an anticorrelation is expected in fragmentation models where the rapidity order of particles closely reflects their "color order," as is the case, for example, in recent versions of the Lund string model.

PACS numbers: 13.65.+i, 13.87.Fh

Baryon production in e^+e^- annihilation events provides a tool to investigate the process of quark fragmentation into hadrons. Not only is the process of baryon production itself interesting and the subject of much speculation,[1] but also, because baryons are heavy and suffer relatively little momentum smearing due to resonance decays, they provide a convenient probe to study the dynamics governing the production of primary hadrons from the color field of the initial quarks.[2] In this paper, we present data on baryon-baryon and baryon-antibaryon correlations, based on the analysis of events containing two or more p, $\bar{p}$, Λ, or $\bar{\Lambda}$.

The data were recorded with the TPC detector facility at the SLAC e^+e^- storage ring PEP operating at 29-GeV center-of-mass energy. The Time Projection Chamber[3] (TPC) was used to track charged particles over 87% of 4π and to identify particles via their ionization energy loss. Data were taken in two different detector configurations: a 77-pb^{-1} sample with the TPC operating in the 4-kG field of a normal solenoid, and a second sample of about 70 pb^{-1} with a 13.25-kG superconducting coil. At high momentum, typical momentum resolutions are $(3.5\%\ \text{GeV}^{-1})p$ and $(0.65\%\ \text{GeV}^{-1})p$ for the first and second sets, respectively. The average ionization energy loss ("dE/dx") is calculated as the 65% truncated mean of up to 183 individual measurements per track, resulting in a resolution of 3.7% for tracks with at least eighty usable samples. Hadronic an-

© 1986 The American Physical Society

nihilation events are selected by the requirement of at least five charged hadrons in the event, a sum $\sum E$ of the energies of charged particles of at least 7.25 GeV, and a momentum imbalance $|\sum p_z|/\sum E$ along the beam (z) direction of at most 40%.[3] After additional cuts to reject annihilation events into leptons, we are left with 27880 and 24164 events from the low-field and high-field data sets, respectively.

This study of baryon correlations uses p and $\bar{p}$ identified by dE/dx, and Λ and $\bar{\Lambda}$ reconstructed by secondary-vertex-finding algorithms. In order to optimize sample purity, only p and $\bar{p}$ candidates in two distinct momentum regions are considered. At low momentum, $0.5\ \text{GeV}/c < p < 1.5\ \text{GeV}/c$, p and $\bar{p}$ can be identified on a track-by-track basis.[4] To eliminate p's produced in secondary interactions in the beam pipe from this sample, we require that the extrapolated orbit pass within 1 cm of the event vertex. Contamination of the low-momentum sample due to misidentification or p's from secondary interactions is less than 5%. At high momentum, above 3.7 GeV/c, the typical dE/dx separation between $K^{\pm}$ and $p,\bar{p}$ is 1–2 standard deviations, and >4 standard deviations between $\pi^{\pm}$ and $p,\bar{p}$; here $p,\bar{p}$ are identified on a statistical basis by means of maximum-likelihood fits to the dE/dx distribution.[3,5]

Λ ($\bar{\Lambda}$) are detected[6] by reconstruction of $\Lambda \rightarrow \pi^- p$ ($\bar{\Lambda} \rightarrow \pi^+ \bar{p}$) decay vertices. Pion and proton candidates are selected as charged tracks whose measured dE/dx is consistent within 1.5–3.5 standard deviations (depending on momentum) with the pion and proton hypotheses, respectively. If the tracks are consistent with a secondary vertex separated from the main vertex by at least 3 cm and if the confidence level of a secondary-vertex fit for the Λ ($\bar{\Lambda}$) hypothesis exceeds 1%, a pair is accepted as a Λ ($\bar{\Lambda}$). Pairs are rejected if dE/dx values and kinematics are also consistent with a $K_s^0 \rightarrow \pi^+\pi^-$ decay. Because of the superior signal-to-background ratio, only the high-field data are used for correlations involving Λ or $\bar{\Lambda}$. Depending on their momentum, the signal-to-background ratio for Λ ($\bar{\Lambda}$) candidates thus selected varies between 3:1 and 4:1.

As a measurement for the correlation between two baryons a and b, we define the correlation function C_{ab}:

$$C_{ab}(y_a,y_b) = \rho_{ab}(y_a,y_b)/\rho_a(y_a)\rho_b(y_b) - 1 \qquad (1)$$

Here, $\rho(y) = (1/\sigma_{\text{tot}})d\sigma/dy$ denotes a single-particle density as a function of rapidity y, and $\rho_{ab}(y_a,y_b) = (1/\sigma_{\text{tot}})d^2\sigma/dy_a\,dy_b$ is a two-particle density. σ_{tot} is the annihilation cross section into hadrons. Rapidity values refer to the sphericity axis; at 29 GeV c.m.s. energy the rapidity range for baryons is ± 3.4 units, with a plateau of about ± 1.5 units. The indices a and b refer to particle type. $C = 0$ means that two particles are not correlated; $C > 0$ implies that the two particles are produced in association with each other. Local compensation of quantum numbers such as baryon number implies that $C_{\bar{p}p}(y_{\bar{p}},y_p)$ is positive for small $|y_{\bar{p}} - y_p|$, and decreases towards 0 for larger $|y_{\bar{p}} - y_p|$. The correlation function C has the advantage that acceptance corrections cancel to first order; in our case remaining corrections are negligible compared to the statistical errors. If sample a or b contains contamination from other particle species, the raw measured C will deviate from its true value by an amount depending on the amount of contamination and on the correlations between the background particles among themselves (if both a and b are misidentified) and between background particles and correctly identified particles (if only one is misidentified). Using measured sample purities, we correct C and include a conservative estimate of the uncertainty of the correction in the errors. With the exception of $\bar{\Lambda}\Lambda$ correlations, these corrections are typically less than the statistical errors. The influence on C of radiative corrections due to initial-state radiation is negligible.

We present $C_{ab}(y_a,y_b)$ for a given combination of particle types a and b as a function of y_b, keeping y_a fixed within a certain interval. Ideally, the width of this interval should be small compared to the typical correlation length in rapidity. In our case, limited statistics does not allow such small intervals, and the two quantities are of the same order. Figure 1 shows (a) $C_{\bar{p}p}$, (b) $C_{\bar{p}\Lambda}$, (c) $C_{\bar{p}\bar{p}}$, and (d) $C_{\bar{p}\bar{\Lambda}}$. In all cases, particle a is a $\bar{p}$ with positive rapidity and a momentum between 0.5 and 1.5 GeV/c. The rapidity range of this $\bar{p}$ extends from 0 to 1.25, with a mean rapidity of 0.56 and an rms width of

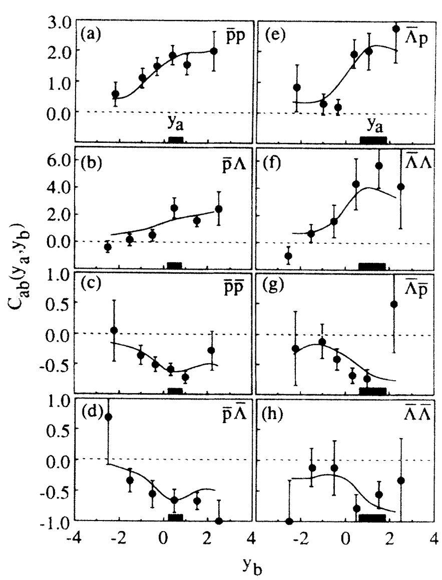

FIG. 1. (a)–(d) Correlation function $C_{ab}(y_a,y_b)$ for a $\bar{p}$ in the rapidity interval $0 < y_a < 1.25$ and an additional baryon b at rapidity y_b, for (a) p, (b) Λ, (c) $\bar{p}$, (d) $\bar{\Lambda}$. The rms width of the rapidity distribution of the $\bar{p}$ a is indicated by the black bar. (e)–(h) The corresponding correlation functions for a $\bar{\Lambda}$ in the rapidity range $y_a > 0$ as particle a. Curves indicate predictions by the Lund hadronization model (Ref. 7).

the distribution of 0.29 [indicated as a black bar in Figs. 1(a)–1(d)]. In the calculation of $C_{\bar{p}\bar{\Lambda}}$, the decay $\bar{p}$ from the $\bar{\Lambda}$ is excluded.

We observe a strong positive correlation between baryons and antibaryons [Figs. 1(a) and 1(b)], with evidence for local compensation of baryon number, in confirmation of earlier results.[6,8] Furthermore, we find a pronounced local anticorrelation between two particles with the same baryon number [Figs. 1(c) and 1(d)]. We will later return to this second point. Included in Fig. 1 are predictions for C based on the Lund hadronization model,[7] which reproduces the data reasonably well. The corresponding set of correlations for a $\bar{\Lambda}$ as particle a is displayed in Figs. 1(e)–1(h). In this case, any detected $\bar{\Lambda}$ with positive rapidity is used as a. The distribution of those $\bar{\Lambda}$ is roughly Gaussian in y, with $\langle y_a \rangle = 1.29$ and an rms width of 0.55 units, still (marginally) smaller than a typical correlation length. Again, we observe clear evidence for local conservation of baryon number and find evidence for an anticorrelation between particles with the same value of baryon number.

Whereas local conservation of baryon number appears natural, given that charge and strangeness are conserved locally in the hadronization process,[5,9] the dynamical origin of the anticorrelation between particles with the same baryon number is less obvious. The production of another heavy negative object besides the $\bar{p}$ a [Figs. 1(a)–1(d)] may be suppressed somewhat because of constraints due to energy-momentum conservation and charge conservation. However, the antiproton a has energies between 1 and 1.8 GeV and drains only a small fraction of the c.m.s. energy of 29 GeV. We can estimate the maximum suppression of production rates for a second heavy object from the correlation between a $\bar{p}$ and a three-pion system of net charge -1 (like an additional $\bar{p}$) and a mass in the 2–3-GeV range (like the mass of a baryon-antibaryon pair produced in addition to the $\bar{p}$ a). The $\bar{p}(3\pi)$ correlation data are shown in Fig. 2; we do not observe an anticorrelation comparable in strength to that seen for the $\bar{p}\bar{p}$ case. Another possible explanation is that we are seeing the effects of Fermi-Dirac statistics. However, with use of the usual effective source size of about 1 fm,[12] the repulsive effects of Fermi-Dirac statistics should be limited to baryon pairs with momentum differences less than 200 MeV/c—far too short a range to explain our observations. Also, the effect should then not be visible in the $\bar{p}\bar{\Lambda}$ correlation.

The manner in which most fragmentation models describe particle production indicates another, more likely source of the anticorrelation: It is assumed that new quark-antiquark pairs are created in the color field of the initial quarks. Quarks and antiquarks then recombine into mesons; occasional production of diquark-antidiquark pairs accounts for baryon production. In the $1/N_{\text{color}} \to 0$ approximation—the limit used implicitly both in the Lund string model and in QCD shower

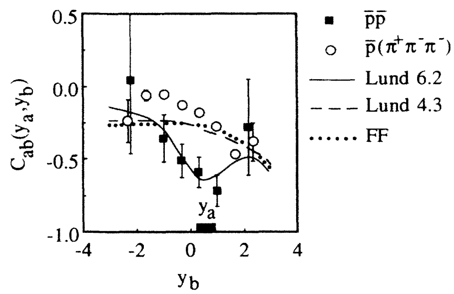

FIG. 2. Comparison of the measured $\bar{p}\bar{p}$ correlation function [see Fig. 1(c)] with the correlation observed between a $\bar{p}$ and a $\pi^+\pi^-\pi^-$ system in the 2–3-GeV mass range. Also shown are predictions of $C_{\bar{p}\bar{p}}$ from the "symmetric" Lund fragmentation model (Ref. 7) (solid line), the "standard" Lund model (Ref. 10) (dashed line), and the Lund model (Ref. 7) with Feynman-Field fragmentation functions (Ref. 11) (dotted line).

models—each colored quark has a well-defined partner carrying the corresponding anticolor, with which it forms a color-singlet hadron (or hadronic "cluster"). We can now assign each particle a rank,[11,13] going along the "color connection" from the initial quark to the antiquark. Two primary hadrons with the same baryon number (or, for that matter, with the same charge or strangeness) are separated by at least two steps in rank. Provided that the order of particles in rapidity closely reflects their order in rank, we are not likely to find two baryons or two antibaryons at the same rapidity. In iterative fragmentation models such as the Lund scheme,[13] this condition is fulfilled for appropriate choices of the momentum-sharing function $f(x)$ describing the distribution in the fraction x of parton momentum carried by the hadron in the basic process parton $\to$ hadron(x) + parton$'(1-x)$. The shape of $f(x)$ determines the distribution $g(\Delta y)$ in the rapidity difference Δy between two hadrons adjacent in rank. If the width of $g(\Delta y)$ is smaller than or comparable to the average spacing $\langle \Delta y \rangle$ of particles in rapidity, the rapidity order will closely reflect the order in rank. For example, the shape $f(x) \sim x^{-1}(1-x)^a \exp(-\beta m^2/x)$ of the "symmetric" Lund model[13] results (for 1-GeV hadrons and typical values of the parameters a,β) in a width of the Δy distribution of about 0.9 units, and an average Δy of 0.8 units. By contrast, the shapes used in earlier versions of the Lund model ("standard Lund"[10,13]), $f(x) = (1-x)^a$, and in the Feynman-Field model,[11] $f(x) = (1-a) + 3a(1-x)^2$, peak at $x = 0$ and their Δy distributions are rather wide (1.7–1.8 units rms) compared to the typical Δy. In the latter case, there is obviously no one-to-one correspondence between rank and rapidity. Indeed, the symmetric Lund model reproduces the anticorrelation effect, whereas models using the standard Lund or Feynman-Field fragmentation functions do not (Fig. 2). We note in passing that fragmentation models based on angle-ordered QCD parton showers[14] also predict a close relation between rank and rapidity order.

In summary, we find strong local rapidity correlations between baryons and antibaryons, and a significant anticorrelation between two baryons. The latter effect can be interpreted as evidence for a close correspondence between the order in which particles are created in rank, and their rapidity order; the effect is obscured in ordinary correlation studies with use of light hadrons such as pions, mainly because of the positive correlations and the rapidity smearing induced by resonance decays. By contrast, baryons provide a more direct probe of the primary production processes, revealing the observed color-ordering effects.

We acknowledge the efforts of the PEP staff, and the engineers, programmers, and technicians who made this work possible. This work was supported by the U.S. Department of Energy, by the National Science Foundation, and by the Joint Japan–U.S. Collaboration in High Energy Physics. One of us (W.H.) acknowledges receipt of an A.P. Sloan Fellowship.

[1]G. Schierholz and M. Teper, Z. Phys. C **13**, 53 (1982); K. W. Bell *et al.*, Rutherford Laboratory Report No. RL-82-011, 1982 (unpublished); see also H. Aihara *et al.*, Phys. Rev. Lett. **55**, 1047 (1985), for more recent references.

[2]This point was first brought to our attention by B. Andersson, private communication. In principle, heavy mesons such as ρ, K^*, or ϕ could serve the same purpose; in practice, such samples suffer from low statistics (ϕ) or bad signal-to-background ratios (ρ, K^*).

[3]H. Aihara *et al.*, Phys. Rev. Lett. **52**, 577 (1984).

[4]Aihara *et al.*, Ref. 1.

[5]H. Aihara *et al.*, Phys. Rev. Lett. **53**, 2199 (1984).

[6]H. Aihara *et al.*, Phys. Rev. Lett. **54**, 274 (1985).

[7]T. Sjöstrand, Comput. Phys. Commun. **39**, 347 (1986). We use version 6.2.

[8]M. Althoff *et al.*, Phys. Lett. **139B**, 126 (1983).

[9]R. Brandelik *et al.*, Phys. Lett. **100B**, 357 (1981).

[10]We use version 4.3 of the Lund Monte Carlo program as an implementation of the "standard Lund" scheme; see T. Sjöstrand, Comput. Phys. Commun. **27**, 243 (1982), and **28**, 229 (1983).

[11]R. D. Field and R. P. Feynman, Nucl. Phys. **B136**, 1 (1978).

[12]G. Goldhaber, in *Proceedings of the First International Workshop on Local Equilibrium in Strong Interaction Physics, Bad Honnef, West Germany, 1984,* edited by D. K. Scott and R. M. Weiner (World Scientific, Singapore, 1985), p. 115.

[13]B. Andersson *et al.*, Phys. Rep. **97**, 31 (1983).

[14]G. Marchesini and B. R. Webber, Nucl. Phys. **B238**, 1 (1984).