EVIDENCE FOR LOCAL COMPENSATION OF BARYON NUMBER IN e^+e^- ANNIHILATION

TASSO Collaboration

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Received 16 January 1984

We have studied at CM energies of 14, 22 and 30–36.7 GeV e^+e^- annihilation events in which the hadronic final state contains both a proton and an antiproton in the momentum range $1.0 < p < 5.0$ GeV/c. We find that such pairs are produced predominantly in the same jet and conclude that baryon–antibaryon production is dominated by a mechanism involving local compensation of baryon number.

The observation of abundant baryon production in high energy e^+e^- annihilation into hadrons [1–6] shows that baryon formation is an important feature of quark and gluon fragmentation. Indeed, at a CM energy $W = 34$ GeV an event contains on average 0.8 ± 0.1 p, $\bar{p}$ [4]. Large baryon yields have also been observed in deep inelastic μN scattering [7].

The investigation of events in which two or more baryons are detected in the final state provides additional information on the baryon production mechanism. An analysis of events having at least two final state protons, with momenta restricted to the range 0.4–1.2 GeV/c, has already been published [4]. (Unless an explicit distinction is made, the term "proton" is used from here on to refer to either a proton or an antiproton). No evidence for anomalously large production of more than one p + $\bar{p}$ pair per event was found and – within the limited rapidity range considered – no statistically significant correlation between p and $\bar{p}$ was observed. Here we extend our analysis to events where the protons in the final state have momenta larger than 1 GeV/c, so that they can be associated with considerable certainty with a particular hadron jet.

The experiment was performed with the TASSO detector at PETRA. A sample of 26 376 hadronic events at $W = 14$, 22 and 30–36.7 GeV, with 21 552 events at $W \geq 30$ GeV, was selected using the central detector [‡1] information on charged particles as described in ref. [9]. Protons with momenta in the range $1.0 < p < 5.0$ GeV/c were identified on a particle by particle basis by using the information of the hadron arm time-of-flight (HATOF) and of the Čerenkov counters. Detailed descriptions of these components and of their performance have been given in previous publications [1,4,10] as well as in technical reports [11,12]. We briefly outline here their main characteristics: The HATOF as well as the Čerenkov counter systems are both mounted in the TASSO "hadron arms" outside the 10 cm thick aluminium magnet coil (31 g/cm^2 of material). Each hadron arm covers a solid angle of $\simeq 10\%$ of 4π on azimuthally opposite sides of the detector. The HATOF counters, equipped with photomultipliers at each end, are located at an average distance of 5.5 m from the interaction point and cover a total solid angle of 20% of 4π. Their average rms time resolution, measured for muons in $e^+e^- \to \mu^+\mu^-$ events at $W = 34$ GeV, is 0.45 ns. The HATOF system is preceded by three types of threshold Čerenkov counters, arranged sequentially and subtending a solid angle of 19% of 4π. The radiators are silica aerogel, Freon 114, and CO_2 with threshold momenta for pions of 0.7, 2.7 and 4.8 GeV/c, for kaons of 2.3, 9.5 and 17 GeV/c, and for protons of 4.4, 18 and 32 GeV/c, respectively.

Nuclear interactions in the material of the coil may falsify the particle identification signature in the HATOF and Čerenkov counters. In order to recognize such interactions, a set of horizontal (parallel to the beam axis) and vertical drift chamber tubes,

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[‡1] For a description of the TASSO central detector see ref. [8].

3 cm in diameter, are mounted directly behind the coil. The tubes cover the acceptance of the hadron arms and are arranged in successive layers (two horizontal layers followed by two vertical ones and succeeded by another horizontal and a vertical layer ‡2.

A particle was selected as a proton candidate if it satisfied the following requirements:

(i) The particle track should have $d_0 < 1.0$ cm and $|z| < 5.0$ cm, where d_0 is the distance of closest approach to the origin in the (x,y) plane and z is the coordinate at the point of closest approach to the z axis (= beam direction). These cuts, tighter than those used in ref. [9], suppress tracks coming from interactions in the beam pipe.

(ii) The particle should penetrate the material of the coil without nuclear interaction. A central detector track was considered to have fulfilled this requirement if two out of the three horizontal and vertical drift tube layers showed a hit within an "acceptance window" covering about 3 times the average multiple scattering angle. (A similar criterion was used in the case of the single drift chamber layer; see also ref. [10].)

(iii) The particle momentum should lie within the appropriate range: For momenta $1.0 < p < 2.3$ GeV/c protons were identified by requiring that $0.6 < m^2 < 1.8$ GeV^2, where m^2 is the mass squared of the particles as reconstructed from the flight time measured in the HATOF counter system. In addition, we demanded that only one track entered a given HATOF counter and that the reconstructed vertical coordinate of the track along the counter, as determined from the relative timing of the photomultiplier signals, was consistent with the position determined by extrapolating the track from the central detector. For $3.0 < p < 5.0$ GeV/c a proton candidate was defined as a particle that did not produce light in any of the three different Čerenkov counters. Particles with momenta in the interval $2.3 < p < 3.0$ GeV/c were classified as protons if they fulfilled both the HATOF and the Čerenkov requirements. (In this momentum range m^2 was restricted to $0.7 < m^2 < 1.8$ GeV^2).

‡2 The drift chamber tube system has replaced a planar drift chamber with one layer of horizontal signal wires and vertical cathode strips. Approximately 50% of the data in the present analysis were recorded while the single layer chamber was in use.

A total of 622 events had at least one final state particle satisfying the conditions above. We obtained 362 proton and 293 antiproton candidates. After correction for the different absorption probabilities in the material of the magnet coil, we find the ratio of protons to antiprotons to be 1.12 ± 0.08. The given error is purely statistical. We estimate an additional error of ± 0.02 resulting from the uncertainty of the annihilation cross section of antiprotons in aluminum. 31 events had two proton candidates, while one event had three ($p + p + \bar{p}$).

We restricted ourselves to the sample of events with two proton candidates observed in the final state and classified these candidates as occurring within the same jet or in opposite jets according to whether they were identified in the same or in opposite hadron arms. The single event with three proton candidates was not included in our sample.

Because of the geometrical acceptance of the hadron arms, the above method of associating fast particles with jets is unambiguous for two-jet events. In the case of three-jet events it is possible that particles belonging to different jets are identidied in the same hadron arm. Using the method of generalized sphericity [13], 5 events in our sample were found to be three-jet candidates. For these events, the three-jet analysis and our scheme above resulted in the same assignment of the observed proton candidates to same/opposite jets.

Our method of assigning the proton candidates to jets gave the results shown in table 1.

A preference for protons and antiprotons to be produced together within the same jet is clearly seen in the table.

The sample of proton pairs contains background due to incorrect particle identification. We used the data themselves to obtain the total number of background events in the sample and to examine the assignment of falsely identified proton pairs to same/opposite jets. Because the main background source are events with one correctly identified proton and

Table 1

Data	In same jet	In opposite jets
$e^+e^- \to pp + X$ or $\bar{p}\bar{p} + X$	3	6
$e^+e^- \to p\bar{p} + X$	18	4

one misidentified meson, we considered the sample of 590 events with only one identified proton. In this sample we formed all pairings of the proton candidate with particles identified as mesons.

The total number of background events in the sample of proton pairs was obtained by multiplying the number of proton–meson combinations with the probability to identify falsely a meson as a proton. Since some of the proton candidates in the proton–meson pairs were misidentified, this procedure yields the sum of background events in which one or both protons were identified incorrectly.

The meson candidates used in forming the proton–meson combinations were required to fulfill the same acceptance conditions used for selecting protons. For momenta $1.0 < p < 2.3$ GeV/c (HATOF region) a "meson" was defined as a particle having $m^2 < 0.6$ GeV^2. For $2.3 < p < 3.0$ GeV/c (Mixed region) all particles with $m^2 < 1.8$ GeV^2 that produced light in any of the three Čerenkov counters, as well as all particles with $m^2 < 0.7$ GeV^2, were classified as "mesons". In the Čerenkov region ($3.0 < p < 5.0$ GeV/c), the particles incorrectly identified as proton are almost exclusively kaons, since the combined efficiency for a pion to produce light in either the aerogel or the Freon counters exceeds 99% [4,14]. We therefore selected a sample of predominantly kaons by defining as "mesons" in this region all particles having light in the aerogel counters only. In the 590 events with only one identified proton we found a total of 235, 56 and 29 proton–meson pairs with the meson in the HATOF, Mixed and Čerenkov regions, respectively.

The probability to misidentify a meson as a proton was determined for the (a) HATOF, (b) Mixed and (c) Čerenkov regions separately:

(a) For the HATOF region it was obtained from the observed mass squared distribution of particles satisfying the acceptance requirements used in selecting proton candidates in the sample of 26 376 hadronic events. Figs. 1a–c show the observed m^2 spectra after subtraction of particles whose timing information could have been falsified by electromagnetic showers produced in the coil. The solid curves show fits with $\pi^{\pm}$, $K^{\pm}$ and p, $\bar{p}$ contributions. They describe the data well, particularly in the region $m^2 > 0.4$ GeV^2. The proton fractions found in the fits are in agreement with our published results [4]. The probability of a meson to be identified incorrectly as a proton was calculated from the fraction of mesons predicted by the fits to have $m^2 > 0.6$ GeV^2. It amounts to 0.1% for $1.0 < p < 1.5$ GeV/c, 2.6% for $1.5 < p < 2.0$ GeV/c and 4.4% for $2.0 < p < 2.3$ GeV/c. Averaged over the momentum spectrum of the mesons occurring in proton–meson pairs it is 1.8% implying a background of 4.3 ± 1.5 events in our proton pair sample. The error is dominated by systematic uncertainties.

(b) For the Mixed region, we show in fig. 1d the mass squared distribution of all particles with momenta $2.3 < p < 3.0$ GeV/c that did not produce light in any of the three Čerenkov counters. The proton yield resulting from a fit as in (a) above is in good agreement with an interpolation of our previous measurements [4]. The efficiency of pions (kaons) in this momentum interval to produce light in the Čerenkov counters is ~90% (30%) [14]. Combining these efficiencies with the measured particle fractions [4], we estimate that about 30% of all mesons in the Mixed region will not produce light in any Čerenkov counter. From this and from the fraction of mesons predicted by the fit to have $m^2 > 0.7$ GeV^2 (4.8%), we estimate a probability of 1.5% to misidentify a meson as a proton. The corresponding number of background events in our sample of proton pairs is $0.9^{+1.0}_{-0.4}$. The errors include the uncertainty of the fit as well as the systematic uncertainties.

(c) In the Čerenkov region only kaons have to be considered as a source of misidentified protons. Following the method outlined in ref. [4], we obtained the probability to misidentify a kaon as a proton from the measured particle yields [4] and found a background of 4.1 ± 1.2 events.

Adding the contributions of the three regions we found the total background in our sample of proton pairs to be 9.3 ± 2.2 events. We estimated that in at most 2 of these events both protons may have been misidentified.

To examine how the background pairs are assigned to jets, we classified the observed proton–"meson" combinations in the same way as in the case of proton pairs (table 2). In contrast to the sample of proton pairs, the class of oppositely charged hadrons in the same jet has approximately the same population as the classes referring to hadrons in opposite jets. For hadrons inside the same jet, the number of pairs having net charge zero is significantly larger than that of pairs with net charge ±2, in agreement with the observation of strong local charge compensation [15].

Subtraction of the total number of background events (9.3 ± 2.2) according to the distribution of proton–meson pairs above, results in yields shown in table 3. The only statistically significant signal remaining is for events with a proton and an antiproton produced in the same jet. We conclude that high momentum protons and antiprotons are produced preferentially together in the same jet. This suggests that baryon number is compensated locally.

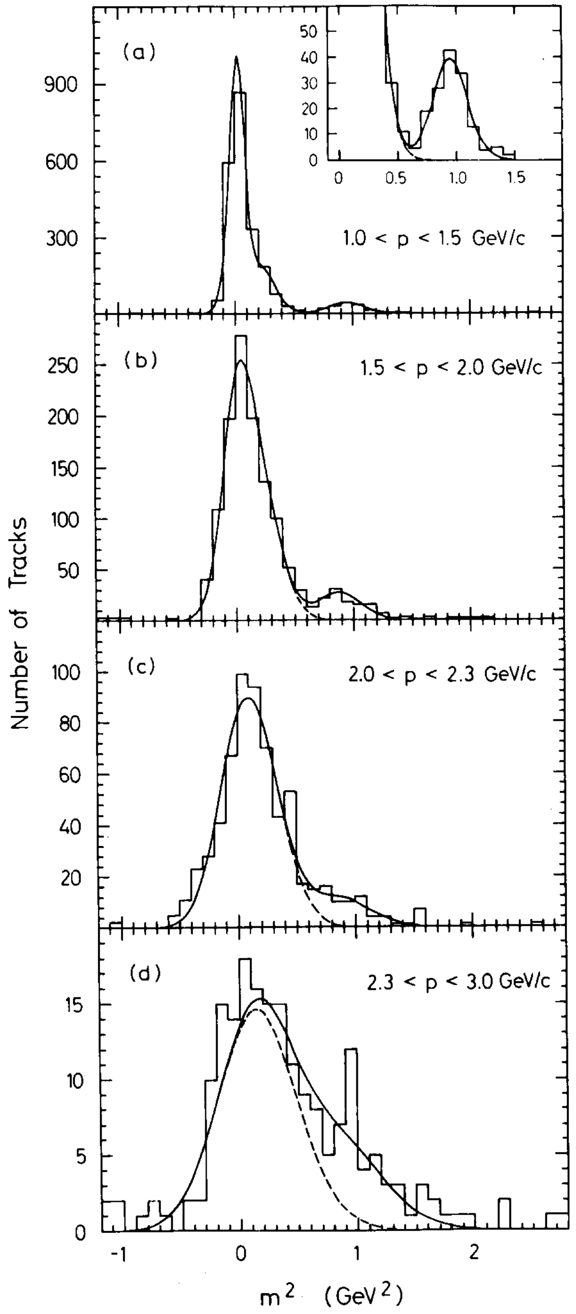

Table 2

Number of proton–meson pairs	In same jet	In opposite jets
Number of pairs with net charge ±2	49	88
Number of pairs with net charge 0	87	96

We used the $p\bar{p}$, pp and $\bar{p}\bar{p}$ correlations as measured above to investigate the dynamics of baryon–antibaryon production in e^+e^- annihilation. To proceed we made use of models, which have baryon production explicitly built into the fragmentation chain [‡3]. The Meyer model [17] allows for two mechanisms: (a) a baryon and an antibaryon are produced close together in rapidity ("local baryon number compensation") or (b) they are produced as leading par-

‡3 The contribution from B-mesons decaying to baryons is only about 1% of the measured p, $\bar{p}$ rate [16].

Fig. 1. (a) The observed mass squared distribution of particles with momenta $1.0 < p < 1.5$ GeV/c that fulfilled the acceptance criteria used for selecting protons in the HATOF analysis. Not included are particles accompanied by light in all three Čerenkov counters (more than 6 photoelectrons in the aerogel counters). The m^2 spectrum of these "shower contaminated" events was subtracted from that of all events after normalization in the region $m^2 < -0.3$ GeV^2. The solid curve was obtained by fitting $\pi^{\pm}$, $K^{\pm}$ and p, $\bar{p}$ contributions to the data. The dashed curve shows the extrapolation of the fitted meson contribution into the proton mass region ($m^2 > 0.6$ GeV^2). The insert shows the proton region in greater detail. (b,c) Same as (a) for particles with momenta $1.5 < p < 2.0$ and $2.0 < p < 2.3$ GeV/c, respectively. For the purpose of the subtraction discussed above, the "shower contaminated" distributions were normalized in the region $m^2 < -0.5$ and $m^2 < -0.7$ GeV^2, respectively. Curves as in (a). (d) The observed mass squared distribution of all particles with momenta $2.3 < p < 3.0$ GeV/c that fulfilled the acceptance criteria used in selecting protons in the HATOF and in the Čerenkov analyses and did not produce light in any of the three Čerenkov counters. Curves as in (a).

Table 3

Background subtracted data	In same jet	In opposite jets
$e^+e^- \to pp + X$ or $\bar{p}\bar{p} + X$	1.5 ± 2.1	3.5 ± 2.9
$e^+e^- \to p\bar{p} + X$	15.5 ± 4.5	1.2 ± 2.6

ticles in opposite jets. In the latter case the primary $q\bar{q}$ pair picks up virtual $q\bar{q}$ pairs aligned in such a way that the baryon and antibaryon are far apart in rapidity ("long range baryon number compensation"). There are other models, which have only the first mechanism [18,19]. The model of ref. [20] includes the first mechanism, but also allows the baryon and antibaryon to be separated in rank by mesons.

We compared our data to the predictions of the Meyer model, since it includes the possibility of long range baryon number compensation. We varied the fragmentation parameters but kept consistency with the measured charged multiplicity and the $\Lambda/\bar{\Lambda}$ and $p/\bar{p}$ inclusive rates [3,4]. The results were found to be stable against changes in the model assumptions and against variations of the inclusive $p/\bar{p}$ rate within one standard deviation of the measured value. Using only the local baryon number compensation mechanism in the model, typical results, normalized to the observed number of $\bar{p}p$, pp and $\bar{p}\bar{p}$ pairs, are as shown in table 4.

Similar predictions were obtained with the Lund model [18] and, since these numbers are in good agreement with our results, we conlcude that the correlation data among fast protons and antiprotons are consistent with models in which baryon number is compensated locally.

The long range baryon number compensation mechanism in the Meyer model leads only to unlike sign pairs with the proton and the antiproton in opposite jets. The total number of such events, as estimated by comparing the Monte Carlo results with the data, is -2.5 ± 2.6. We conclude that this mechanism is not required by the data. To set an upper limit on this process, we assumed a flat fragmentation function. (A significant contribution from a very hard fragmentation function is excluded by our measured inclusive spectra [4].) We find that at 95% confidence less than 0.12 $p/\bar{p}$ per event, or less than 15% of all $p/\bar{p}$, can be attributed to this mechanism. This limit is not inconsistent with the rate of baryons and antibaryons occurring in opposite jets as predicted by the authors of ref. [21]. We also note that the diquark production model in ref. [22] predicts only a small contribution of opposite jet baryon–antibaryon pairs at the CM energies of our experiment.

Table 4

Model predictions	In same jet	In opposite jets
$e^+e^- \to pp + X$ or $\bar{p}\bar{p} + X$	1.2	3.3
$e^+e^- \to p\bar{p} + X$	13.4	3.7

To summarize, we have observed a clear preference for fast protons and antiprotons being produced together in the same jet. Our data are in good agreement with models which do not require a process leading to long range baryon number compensation. Together with our previous result [4], which ruled out certain quark recombination models [23] and excluded the dominance of multibaryon events, we conclude that the mechanism for baryon–antibaryon production in e^+e^- annihilation is dominated by local compensation of baryon number.

We wish to thank all persons at DESY, the Technische Hochschule of Aachen and the Universities of Bonn and Hamburg, who contributed to the design, construction, testing and installation of the system of drift chamber tubes. We are particularly indebted to G. Krohn and T. Stötzer for the construction of the system and to J. Bengtsson for a large part of the associated electronics. We gratefully acknowledge the tremendous efforts of the PETRA machine group for the sustained high luminosity running. Those of us from abroad wish to thank the DESY directorate for the hospitality extended to us while working at DESY.

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