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DIFFERENCES IN LEADING BARYON PRODUCTION FROM $p\bar{p}$ & pp
COLLISIONS WITH $\sqrt{s} = 31$ GEV AT THE CERN-ISR

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Abstract: Significant differences are observed between forward-produced $\Delta^{++}(1232)$ and Λ^0 's in pp interactions and their corresponding anti-particles in $p\bar{p}$ interactions, as expected from quark counting and single $q\bar{q}$ annihilation. A possible relationship between these results and the $p\bar{p}$ - pp total cross section difference is discussed.

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Since the introduction of the $p\bar{p}$ colliding beam capability to the CERN Intersecting Storage Rings in April 1981 and the subsequent observation of the small (1-4%) differences between the pp and $p\bar{p}$ total cross sections^[1], considerable effort has been devoted to looking for differences in final state particle spectra. Such differences have proved to be very elusive. The observed agreement^[2,3] between final state spectra reflects a near identical nature of high energy pp and $p\bar{p}$ interactions.

In the present Letter, we consider the possibility of specific types of differences between pp and $p\bar{p}$ interactions, which may be attributable to single $u\bar{u}$ or $d\bar{d}$ valence quark annihilation. Because there are 4 $u\bar{u}$ and 1 $d\bar{d}$ combinations in the $p\bar{p}$ system, the di-quark^[4] system remaining after a $q\bar{q}$ annihilation is four times more likely to be a ud system than a uu system. When annihilation does not occur, the ratio ud/uu should be 2/1 (or less) in both $p\bar{p}$ and pp interactions. Thus, the ud/uu di-quark ratio is increased by the annihilation process. This increase should, in turn, be reflected in a larger production of $\Lambda^0(uds)$ and smaller production of $\Delta^{++}(uuu)$ in $p\bar{p}$ interactions than in pp interactions. We have looked for these effects and observed them.

The results reported here were obtained with the CERN-Los Angeles-Saclay forward spectrometer^[5] at the ISR. The magnetic spectrometer, shown in Figure 1, is installed on the downstream $\bar{p}$ arm and is sensitive to particles produced with CM angles in the range $23 < \theta < 150$ mradian.

We compare particle production data from p fragmentation in pp interactions with the corresponding anti-particle production data from $\bar{p}$ fragmentation in $p\bar{p}$ interactions. With C-invariance in $p\bar{p}$ interactions, our comparison is equivalent to comparing $p \rightarrow A$ in $p\bar{p}$ interactions with $p \rightarrow A$ in pp interactions. This comparison tests whether a proton fragments in the same way when it scatters on another proton or on an antiproton. The $q\bar{q}$ valence annihilation process violates this factorization.

The data sample used in the present analysis consists of 3.2×10^6 $p\bar{p}$ and 1.8×10^6 pp interactions with colliding beam energies of 15.4 GeV on 15.4 GeV^[6]. The data represent the entire sample recorded by our experiment during a 222 hour run with 4.2 milliamperes antiproton current and about 10 amperes proton current. The pp comparison data were recorded during a run with 5 amperes current in each ring.

In both cases, the data were recorded with a minimum-bias trigger, which required that one or more tracks traverse the spectrometer (signaled by appropriate wire chamber multiplicity requirements and by a coincidence between the front and back scintillation counter systems in the spectrometer arm; F2•B in Fig. 1). To obtain a pure inclusive sample of Λ^0 and Δ^{++} data, the trigger made no requirements in the arm opposite the

spectrometer. Off-line event reconstruction yields background-free vertex distributions in the beam-beam crossing region. There are 684,796 $p\bar{p}$ events and 391,082 pp events that have a primary vertex of 2 or more tracks.

The pp and $p\bar{p}$ data samples used for this analysis have nearly indistinguishable charged particle multiplicity distributions (for those tracks within the acceptance of our spectrometer). Events with 2, 3, 4, 5 and 6 tracks are found in the $p\bar{p}$ sample with percentages 81.1%, 17.0%, 1.73%, 0.12% and .006% and in the pp sample with percentages 81.7%, 16.5%, 1.65%, 0.12% and .006%. This agreement, as well as the agreement between invariant mass spectra and momentum spectra measured in our apparatus, implies that the same fraction of the $p\bar{p}$ and pp total cross sections is accepted by the spectrometer. Thus, in comparisons of $p\bar{p}$ and pp rates, the two data samples are normalized to the total number of $p\bar{p}$ and pp events, respectively, such that the normalized ratio of $p\bar{p} \rightarrow \bar{\Delta}^{++}$ events to $pp \rightarrow \Delta^{++}$ events is equal to the cross section ratio $[\sigma(p\bar{p} \rightarrow \bar{\Delta}^{++})/\sigma(pp \rightarrow \Delta^{++})]$ multiplied by the total cross section ratio $[\sigma_{pp}/\sigma_{p\bar{p}}]_{\text{TOTAL}}$.

Figs. 2(a,b) shows the $p\pi^+$ and $\bar{p}\pi^-$ invariant mass distributions for data with Feynman- $x(x_F) > 0.8$ and transverse momentum(p_t) < 1.0 Gev/c. The histograms represent the raw data, while the points show these data after corrections for geometric acceptance losses^[7]. In all cases, a small number of events in which the higher momentum track is a pion have been excluded by the Cerenkov information. However, the effect of the Cerenkov selection on the final results presented below is negligible. A clear Δ^{++} signal is seen with negligible background. The solid curves are the results of fits to the corrected data of a p-wave Breit-Wigner function added to a polynomial background term [dashed lines in Figs. 2(a,b)]. In the remainder of this Letter, Δ^{++} are selected as those events with invariant mass in the range 1.16-1.32 Gev. Corrections for background in the data with $0.6 < x_F < 0.8$ are included in the results given below, but do not significantly affect the ratios.

In the case of Λ^0 production, a primary vertex is not required, but the reconstructed Λ^0 momentum vector is found to intersect the beam-beam crossing plane with a background-free distribution corresponding to the primary vertex distribution discussed above. A Λ^0 is selected by demanding that its Vee vertex lies at least 20 cm downstream from the point at which its momentum vector crosses the horizontal beam-beam median plane. The $p\pi^-$ and $\bar{p}\pi^+$ mass distributions for Vee's selected in this way are shown in Figs. 2(c,d) when $x_F > 0.8$ and $p_t < 1.0$ Gev/c. Λ^0 's and $\bar{\Lambda}^0$'s are selected for the final data sample if their invariant mass lies in a 12 Mev wide interval centered at the Λ^0 mass. There are a total of 3211 $p \rightarrow$

Λ^0 events and 5677 $\bar{p} \rightarrow \bar{\Lambda}^0$ events with $x_F > 0.60$.

Figs. 3(a,b) contain the observed dependences on x_F for Δ^{++} and Λ^0 production, respectively, with transverse momentum $p_t < 1.0$ Gev/c. The lower data set in each figure is the uncorrected raw data distribution and the upper set shows the result of correcting for geometric acceptance losses^[7]. Henceforth we only use the corrected distributions, although none of the ratio results presented below depend on the corrections or are modified appreciably by them. The $p\bar{p}$ and pp data sets have the same overall characteristics, although there are differences between the two sets of data that increase as x_F approaches 1. In particular, $p\bar{p} \rightarrow \bar{\Delta}^{++}$ is consistently smaller than $pp \rightarrow \Delta^{++}$. The opposite effect is seen for Λ^0 , although the statistical significance is less.

The effects are seen more clearly in Fig. 4, which shows the Δ^{++} and Λ^0 ratios of the $p\bar{p}$ and pp data plotted vs. x_F . In plotting these points, the ratios of the normalized data from Figs. 3 are multiplied by the $p\bar{p}/pp$ total cross section ratio^[1] 1.04. Thus, as discussed above, the points in Fig. 4 are the ratios of absolute cross sections [e.g.: $\sigma(p\bar{p} \rightarrow \bar{\Delta}^{++})/\sigma(pp \rightarrow \Delta^{++})$]. The ratio for the Δ^{++} data with $x_F > 0.95$, which shows the largest effect in Fig. 4, is plotted vs. p_t in Fig. 5(a). Although its average value is approximately 0.8, the ratio is seen to decrease almost to 0.6 as p_t approaches 0.

Finally, Fig. 5(b) shows $d\sigma/dp_t^2$ for the $x_F > 0.95$, Δ^{++} data of Fig. 4, with the pp data normalized to the results of Lockman et al.^[8] at $\sqrt{s} = 31$ Gev. These results have the shape $\exp(-bp_t^2)$, with $b = (15.1 \pm 1.5)$ Gev⁻² for $p_t^2 < 0.1$ (Gev/c)² and $b = (5.4 \pm 0.9)$ at higher p_t . Our present pp data are seen to agree with Lockman et al.^[8], but the $p\bar{p}$ data have a different dependence on p_t at smaller values of p_t .

The results in Figs. 4 and 5 can be interpreted as evidence for the single $q\bar{q}$ annihilation process, as explained in the introduction. The departures of the ratios from unity are seen to be largest as $x_F \rightarrow 1$ and as $p_t \rightarrow 0$, corresponding to the smallest average $q\bar{q}$ invariant mass, where the cross section for this process should be largest.

An alternative view which does not refer explicitly to quark constituents, but which is nonetheless related, is that of one-meson-exchange (π and K in Δ^{++} and Λ^0 production, respectively). If one-meson-exchange dominates inclusive Δ^{++} production in both pp and $p\bar{p}$ interactions, the inclusive cross sections should be proportional to the π^+p and π^-p total cross sections at πp center-of-mass energies corresponding to the mass of system X in $pp \rightarrow \Delta^{++} + X$. That is, the ratios of $[\sigma_{\pi^+p}/\sigma_{\pi^-p}]_{TOTAL}$, and $[\sigma_{K^+p}/\sigma_{K^-p}]_{TOTAL}$, respectively, should be equal to the ratios in Fig. 4. The curves^[9] in Fig. 4 show these ratios plotted vs. x_F for both

cases and are seen to be in remarkable overall agreement with our results. However, in the statistically more significant Δ^{++} case, there is a clear disagreement at large x_F . This disagreement is related to the observed different p_t dependences seen in in Figs. 5 and presumably indicates that the one-meson-exchange picture is inappropriate to describe leading baryon production at very large x_F in $p\bar{p}$ interactions, where $q\bar{q}$ annihilation dominates. On the other hand, quark counting in the simple annihilation picture described in the introduction may account for the effect. For example, with 100% annihilation in the process $p\bar{p} \rightarrow \bar{\Delta}^{++}$ at very large x_F , the Δ^{++} ratio in Fig. 5(a) is predicted to be $(1/5)/(1/3) = 0.6$ multiplied by $[\sigma_{p\bar{p}}/\sigma_{pp}]_{\text{TOTAL}}$, in agreement with our result for $x_F > 0.95$ and $p_t < 0.2$ GeV/c.

We may ask how much of the $p\bar{p}$ - pp total cross section difference at $\sqrt{s} = 30.8$ GeV can be accounted for with the annihilation mechanism discussed here. Of the 5 possible ground state leading-baryons that can result from uu and ud di-quarks, Δ^{++} , Λ^0 , Σ^+ , p and n , we have considered only the first two in this Letter. By combining the ratios in Fig. 4 with the absolute Δ^{++} and Λ^0 cross sections measured by Lockman et al.^[8] and Erhan et al.^[10], respectively, in pp interactions at the ISR, we calculate the following contributions to the total cross section difference (including correction for the 2 hemispheres): $\Delta\sigma(\Delta^{++}) = -(0.140 \pm 0.020)$ mb. and $\Delta\sigma(\Lambda^0) = +(0.063 \pm 0.021)$ mb for $x_F > 0.75$ and $x_F > 0.6$, respectively. If the ratios in Fig. 4 do not grow at smaller x_F , the total $\Delta\sigma(\Lambda^0)$ for all x_F can not be appreciably larger. The Σ^+ contribution should be considerably smaller than the Δ^{++} contribution and presumably is not significant in these considerations.

Because protons can be created with approximately the same probability from either uu or ud di-quark systems, annihilation in $p\bar{p}$ interactions should not significantly change the average number of protons per event from what it is in pp interactions. However, since n and Λ^0 both contain ud but not uu di-quarks, the ratio $(p\bar{p} \rightarrow \bar{n})/(pp \rightarrow n)$ should be similar to the Λ^0 ratio in Fig. 4. When combined with the large single arm neutron inclusive cross section (about 11 mb) measured by J. Engler et al.^[11] for $x_F > 0.1$ in pp interactions at the ISR, it follows that neutron production could be the major contributor to the $p\bar{p}$ - pp total cross section difference. A comparative measurement of neutron production in $p\bar{p}$ and pp interactions is in order. However, the decay of higher mass baryon states into neutrons and protons presumably confuses the issue at smaller x_F , and should be studied in some detail.

The annihilation process has many potentially interesting features. For example, $q\bar{q}$ annihilation implies the existence of long-range correlations in

$p\bar{p}$ interactions. Observation of these correlations would then open the possibility of large- x_F $n-\bar{n}$ tagging in $p\bar{p}$ interactions, allowing the study of $u\bar{u}$ annihilation in the central region. Moreover, effects analogous to those reported in this Letter should be observable in comparisons of π^+p and π^-p interactions.

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- [6] The magnet field polarity was reversed when recording $p\bar{p}$ data in order to have the same acceptance for $\bar{p} \rightarrow \bar{X}$ as for $p \rightarrow X$ in pp interactions.
- [7] Monte Carlo events are generated on a grid of x_F - p_t points in the ranges: $0.6 < x_F < 1.0$ and $0 < p_t < 1.0$ GeV. The weight for an individual event is then calculated by interpolating from its four nearest-neighbor grid-point acceptance values. An observed 2.5 cm shift between the mean vertex positions in the $p\bar{p}$ and pp data, due to slightly different beam conditions, is included in the calculations, but does not affect any of the physics results.
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FIGURE CAPTIONS

1. Plan view of the R608 spectrometer. Ring-2 is filled with anti-protons or protons. Cerenkov counters C_1 and C_2 contain CO_2 and Freon-114, respectively. F1 and F2 are lumosity monitor scintillation counters. P, X, Y1 and Y2 are other counters not used for the data presented here.
2. $p\pi$ and $\bar{p}\pi$ invariant mass spectra with $p_t < 1.0$ GeV/c and $x_F > 0.8$ from $p\bar{p}$ and pp interactions, as indicated; (a,b) $\bar{p}\pi^-$ and $p\pi^+$; (c,d) $\bar{p}\pi^+$ and $p\pi^-$ with Vee vertex and selection discussed in text. Points are acceptance-corrected data. The solid curve is a fit by p-wave Breit-Wigner function added to polynomial background term (dashed line).
3. x_F distributions (a) Δ^{++} ; (b) Λ^0 ; both for $p_t < 1.0$ GeV/c. Lower points are raw uncorrected data. Upper points with geometrical acceptance corrections. Dashed line in (b) shows the Λ^0 data after additional corrections for unseen angular region below 23 mrad. Scale shows the true number of $p\bar{p}$ events.
4. Ratios of $\sigma(p\bar{p} \rightarrow \bar{\Delta}^{++})/\sigma(pp \rightarrow \Delta^{++})$ and $\sigma(p\bar{p} \rightarrow \bar{\Lambda}^0)/\sigma(pp \rightarrow \Lambda^0)$ for $p_t < 1.0$ GeV/c as described in text. Dashed curves are ratios of πp and Kp total cross sections^[9].
5. Δ^{++} data with $x_F > 0.95$; (a) ratio as in Fig. 4 plotted vs. p_t ; (b) pp and $p\bar{p}$ data of (a) normalized to Lockman et al.^[8] pp result as discussed in text.

Fig 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5