ANTIBARYON PRODUCTION IN THE CENTRAL REGION AT THE ISR

(The Axial Field Spectrometer Collaboration)

T. Åkesson⁵, M.G. Albrow¹¹, S. Almehed⁷, E. Anassontzis¹,
 R. Batley⁵, O. Benary¹², H. Bøggild⁶, O. Botner⁶, H. Breuker⁵,
 H. Brody⁸, V. Burkert², R. Carosi⁵⁺, A.A. Carter¹⁰,
 J.R. Carter⁵, P.C. Cecil⁵, W.E. Cleland⁹, D. Cockerill¹¹,
 S. Dagan¹², E. Dahl-Jensen⁶, I. Dahl-Jensen⁶, P. Dam⁶,
 G. Damgaard⁶, W.M. Evans¹¹, C.W. Fabjan⁵, T. Ferbel⁵⁺⁺,
 P. Frandsen⁵, W. Frati⁸, M.D. Gibson¹¹, U. Goerlach⁵,
 H. Gordon⁵, A. Hallgren⁵, K.H. Hansen⁶, B. Heck⁵, V. Hedberg⁷,
 J.W. Hiddleston¹¹, H.J. Hilke⁵, J.E. Hooper⁶, G. Jarlskog⁷,
 P. Jeffreys¹¹, T. Jensen⁵, G. Kessler⁵, T. Killian³,
 C. Kourkouvelis¹, R. Kroeger⁹, K. Kulka⁷, J. v.d. Lans⁵,
 J. Lindsay⁵, D. Lissauer¹², B. Lörstad⁷, T. Ludlam³,
 I. Mannelli⁵, A. Markou¹, N.A. McCubbin¹¹, U. Mjörnmark⁷,
 R. Möller⁶, W. Molzon⁸, A. Nappi⁵⁺, B.S. Nielsen⁵, A. Nilsson⁷,
 L.H. Olsen⁵, Y. Oren¹², R.B. Palmer³, D.C. Rahm³, P. Rehak³,
 L.K. Resvanis¹, L. Rosselet⁵, E. Rosso⁵, A. Rudge⁵,
 R.H. Schindler⁵, I. Stumer³, M. Sullivan⁹, G. Thorstenson⁷,
 E. Vella⁸, J. Williamson¹¹, W.J. Willis⁵, M. Winik³,
 W. Witzeling⁵, C. Woody³, W.A. Zajc⁸

- ¹ University of Athens, Greece
- ² Physikalisches Institut, Univ. Bonn, Fed. Rep. Germany
- ³ Brookhaven National Laboratory, Upton, N.Y., USA
- ⁴ Cambridge University, Cambridge, UK
- ⁵ CERN, Geneva, Switzerland
- ⁶ Niels Bohr Institute, Univ. of Copenhagen, Denmark
- ⁷ University of Lund, Sweden
- ⁸ University of Pennsylvania, Philadelphia PA, USA
- ⁹ University of Pittsburgh, PA, USA
- ¹⁰ Queen Mary College, London, UK
- ¹¹ Rutherford Appleton Laboratory, Didcot, UK
- ¹² University of Tel Aviv, Israel

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- + On leave of absence from Institute of Fisica, Università di Pisa and INFN Pisa, Italy
 - ++ On leave of absence from Rochester University, Rochester N.Y., USA

ABSTRACT

Using annihilation in a calorimeter as a trigger on antiprotons, we have measured the relative production cross-sections of $\bar{p}$, $\bar{\Lambda}$ and $\bar{\Xi}$ at $y \sim 0$ in the transverse momentum range 1 to 2 GeV/c in pp collisions at $\sqrt{s} = 63$ GeV. We investigate correlations between the antibaryons and associated produced particles, and find evidence for local baryon number conservation.

1. INTRODUCTION

In recent years Quantum Chromodynamics (QCD) has been successful in explaining and predicting many features of deep inelastic scattering and high p_T processes. However, the evolution of a partonic system into hadrons (hadronization) rests on much weaker theoretical ground; several models exist [1-3], some of which are inspired by QCD. The refinement of these models depends on detailed comparisons with data on e^+e^- , lepton-hadron and hadron-hadron collisions. The production of baryons and antibaryons ($B, \bar{B}$) has a special interest in this context. Many years ago surprisingly high levels of antibaryon production at high p_T were found at the ISR [4]. Nevertheless $B, \bar{B}$ production was generally ignored in hadronization models until similarly high levels ($\bar{p}/\pi^- \sim 10\%$) were found in e^+e^- collisions. Its incorporation in the models is usually rather ad hoc. For example in the Field, Fox and Wolfram parton cascade models [3] baryons play no role until final colour singlet clusters have formed; these may then decay to mesons or $B\bar{B}$ pairs. In the Lund string model [2] an arbitrary probability is put in for a diquark-antidiquark pair to be created at a string break. An alternative mechanism [5] forms baryons from three-quark recombination after a $q, \bar{q}$ cascade. Other models exist, but these examples serve to illustrate the lack of understanding of the basic physics involved.

More experimental measurements, particularly on the relative production of different baryons and antibaryons and on $B\bar{B}$ correlations, should help to clarify the problem. In this experiment we have measured the relative production cross-sections of $\bar{p}$, $\bar{\Lambda}$ and $\bar{\Xi}$ in the central region ($y \sim 0$) of pp collisions at $\sqrt{s} = 63$ GeV, and studied some correlations with an associated proton. For this we developed an antiproton trigger based on annihilation energy in an electromagnetic calorimeter. The experimental apparatus and the trigger are described in section 2, followed in section 3 by the event selection and data reduction. The relative antibaryon production cross-sections and the correlations with associated particles are presented in sections 4 and 5 respectively.

2. EXPERIMENTAL APPARATUS

Low momentum antiprotons entering an electromagnetic calorimeter have a high probability of annihilating, and depositing up to 2 GeV of energy (partly in the form of neutral pions) in excess of their kinetic energy. In a situation where the kinetic energy spectrum of all particles is rapidly falling, with a scale ≤ 1 GeV, as is the case at 90° at a colliding beam machine like the ISR, this process can be used to advantage in forming an antiproton trigger. We have formed such a trigger based on ≥ 1 GeV energy deposition in a liquid argon shower counter in coincidence with a charged track candidate, and collected a large sample of events containing antiprotons.

The Axial Field Spectrometer is described in Ref. [6]. The central vacuum chamber is surrounded by a scintillation counter hodoscope (Inner Hodoscope) with 44 elements of $\Delta\phi=8^\circ$ covering $40^\circ \leq \theta \leq 140^\circ$ from the centre of the intersection region. The downstream beam pipes were also surrounded by scintillator hodoscopes (Beam-Beam counters) covering $2^\circ \leq \theta \leq 20^\circ$. All these scintillators were used as elements of the trigger and for precise event-time measurement.

The inner hodoscope is surrounded by a cylindrical drift chamber situated in an axially symmetric magnetic field of 0.56 T. This drift chamber [6] is 1.4 m long and extends radially from 0.2 to 0.8 m from the centre of the intersection. It is segmented azimuthally in 4° sections, each with 42 radially distributed sense wires from which both time and pulse height signals are recorded. The r, ϕ position is measured by drift time and the z -position using charge division. The drift chamber extends over 2π in azimuth except for two blind 16° wedges up and down used for mechanical support. The spatial resolution of the chamber is $230 \mu\text{m}$ (rms) in the azimuthal direction and 1.5 cm in the axial coordinate (charge division direction). The transverse momentum resolution for tracks in the central region $45^\circ \leq \theta \leq 135^\circ$ is given approximately by $(\Delta p/p)^2 = [(0.025p)^2 + (0.01)^2]$, where p is in GeV/c. The first term arises from measurement error and the second from multiple scattering in the chamber gas and wires. Particle identification in the non-relativistic region is obtained from multiple ionization sampling (dE/dx) using the pulse height

on the drift chamber wires. Signals from radial groups of wires were put in coincidence and could be used in the trigger logic to signify the presence in a given azimuthal interval of a charged track with $p_T > 0.6$ GeV/c.

A liquid argon electromagnetic calorimeter module [7] is located at 2.1 m from the intersection region at $\theta \sim 90^\circ$. It has an entrance aperture of 1.6m x 0.64m, with a fiducial c.m. solid angle of 0.14 sr. The calorimeter is divided into three sections longitudinally, and read out by means of 20 mm wide strips with four directions (θ, ϕ, U, V), allowing the reconstruction of individual showers.

The trigger for these data required a coincidence between at least two Inner Hodoscope counter elements or a coincidence between the Beam-Beam counters, a track in the drift chamber pointing to the liquid argon calorimeter, and a localized energy deposition exceeding ~ 1 GeV in that calorimeter.

3. DATA ANALYSIS

Events were first selected which contain a reconstructed shower exceeding 1 GeV in a fiducial area excluding the edges of the liquid argon calorimeter. This resulted in 240,000 events which were then fully analysed through track reconstruction programs. Negatively charged tracks were extrapolated to the calorimeter face and the hit point compared with the shower centre. The distribution of the difference ($\Delta x, \Delta y$) is shown in two projections in Fig. 1. We defined an elliptical region of $\sim 4 \sigma$ in ($\Delta x, \Delta y$) for associating a track with a shower. We then compared the deposited energy E with the track momentum p using the parameter $F = (E^2 - p^2)/2E$. For electrons, or charged pions undergoing charge exchange, $F \approx 0$ and for protons $F < 0$. For antiprotons annihilating into at least some electromagnetic energy $F > 0$; in the ideal case of no energy loss after track measurement and totally electromagnetic annihilation F is equal to the proton mass. Fig. 2 shows the observed distribution. The shaded area corresponds to positive tracks analysed in the same way, mostly e^+ and π^+ (charge exchange). Clearly most of the tracks are $\bar{p}$, with some contamination from e^- and π^- (charge exchange). Essentially all this background is for momenta > 1 GeV/c; the $\bar{p}$ spectrum extends down to the

limit ~ 600 MeV/c determined by the drift chamber track requirement and energy loss in materials in front of the calorimeter. The ionization of the track in the drift chamber was then used to clean further the $\bar{p}$ sample. The truncated (lowest 70% of the pulse height distribution) mean pulse height of the (~ 40) points on the track has $\sigma \sim 12\%$ and shows [6] clear separation between antiprotons and other particles for $p \leq 1$ GeV/c. All tracks were required to be consistent with the dE/dx of an antiproton.

The resulting $\bar{p}$ sample is background-free below 1 GeV/c; above this momentum there is an increasing contamination of e^- , and π^- charge exchange. The positive track sample selected with the same criteria was used as a measure of this background, and was subtracted to obtain a $\bar{p}$ spectrum weighted by the efficiency of the trigger and the selections. The trigger efficiency is not easily calculable as it depends critically on the details of $\bar{p}$ annihilation events, but none of the physics we present depends on this efficiency to first order. We estimated the trigger efficiency as a function of antiproton momentum by comparing the obtained $\bar{p}$ spectrum with ISR data at $y=0$ (our $\bar{p}$ sample has $|y| < 0.2$) and at the same c.m. energy [4]. The trigger is most efficient in the region of ~ 0.7 GeV/c which corresponds to $\bar{p}$'s stopping in the front part of the calorimeter. Between 0.7 and 1 GeV/c the efficiency falls to approximately 50%, and for higher momenta it is relatively constant up to ~ 2 GeV/c.

We then proceeded to use this $\bar{p}$ sample to search for $\bar{\Lambda}$, by combining the $\bar{p}$ with an associated positive track with $p > 130$ MeV/c and dE/dx energy loss consistent with that of a pion. The lower momentum cut was applied to remove pions in the range where their detection efficiency is rapidly varying. The $\bar{p}$ and π^+ were fitted to a common vertex, and their effective mass and the distance d between their vertex and the primary vertex (defined by the remaining tracks) were calculated. Fig. 3 shows the distribution of distance d for $\bar{p}\pi^+$ pairs in the mass range 1.107 to 1.127 GeV, excluding very small distances ($d < 13$ mm). The fall-off for distances exceeding ~ 20 cm results from a decreasing efficiency of the pattern recognition programs for tracks originating far from the interaction region; a cut was applied at 20 cm. Fig. 4 shows the invariant mass distribution of the $\bar{p}\pi^+$ in the $\bar{\Lambda}$ region after this distance cut. A fit to a Gaussian distribution with a polynomial background gives the peak position

(1117.1 ± 0.1) MeV with r.m.s. width (3.0 ± 0.1) MeV. The difference from the Particle Data Group value (1115.6 MeV) is consistent with systematic errors. Events with $1107 < M(\bar{p}\pi^+) < 1127$ MeV were accepted as $\bar{\Lambda}$. Fig. 5 shows the measured $\bar{\Lambda}$ lifetime distribution for $\bar{\Lambda}$ momenta between 0.8 and 1.0 GeV/c, with the line corresponding to the P.D.G. value of the lifetime, 2.632×10^{-10} sec.

We then searched for $\bar{\Xi}$ candidates by intersecting in space the trajectory of the selected $\bar{\Lambda}$ with other positive tracks which had dE/dx identification consistent with π^+ and $p > 130$ MeV/c. The intersection distance was required to be between 0.8 and 15 cm from the main vertex, the lower limit being chosen (as for the $\bar{\Lambda}$ selection) to minimize combinatorial background and the upper limit by acceptance considerations. The invariant $\bar{\Lambda}\pi^+$ mass distribution is shown in Fig. 6 and exhibits a clear $\bar{\Xi}$ signal on a flat background. This background was estimated by applying the same criteria to $\bar{\Lambda}\pi^-$ combinations; the shaded area in Fig. 6 shows the result of subtracting this background. The peak has a mass consistent with the P.D.G. value (1321 MeV) and a cut of $1312 < M(\bar{\Lambda}\pi^+) < 1338$ MeV was applied for $\bar{\Xi}$ candidates.

We also searched for $\bar{\Omega}$ decaying to $\bar{\Lambda}K^+$, taking all associated positive tracks to the $\bar{\Lambda}$ consistent with being K^+ and calculating the $\bar{\Lambda}K^+$ invariant mass. The spectrum does not show any significant $\bar{\Omega}$ signal, but allows us to place an upper limit on $\bar{\Omega}$ production.

4. RESULTS ON ANTIBARYON PRODUCTION

We present here results on the inclusive production ratios $\bar{\Lambda}/\bar{p}$ and $\bar{\Xi}/\bar{\Lambda}$ and an upper limit on $\bar{\Omega}/\bar{\Xi}$. For the $\bar{\Lambda}/\bar{p}$ ratio, corrections were made for the applied cuts on decay distances, for the π^+ detection efficiency (which was checked by studying the $\bar{\Lambda}$ decay angular distributions), for the estimated p_T dependence of the $\bar{p}$ detection efficiency (which enters into both the $\bar{p}$ and $\bar{\Lambda}$ spectrum and cancels to first order) and for neutral $\bar{\Lambda}$ decays. We present the ratio in the p_T range 1-2 GeV/c, the region of least sensitivity to the cuts, and for $|y| < 0.2$. The number of $\bar{\Lambda}$ candidates is 6700. The ratio of the $\bar{\Lambda}$ to $\bar{p}$ inclusive production cross-

section is shown as a function of p_T in Fig. 7. Systematic errors due to the uncertainty of the $\bar{p}$ detection efficiency are included; they dominate the errors at lower p_T values and are comparable to the statistical errors in the highest p_T bin. The $\bar{\Lambda}/\bar{p}$ ratio in this p_T range is consistent with being constant at a value 0.27 ± 0.02 , in agreement with an earlier measurement [8].

For the $\bar{\Xi}/\bar{\Lambda}$ ratio a similar procedure was applied to correct for acceptance after the cuts and for background subtraction. We present the ratio for the region $1.2 < p_T < 2.4$ GeV/c in the rapidity range $|y| < 0.2$, corresponding to 182 $\bar{\Xi}$ candidates. The ratio of inclusive cross-sections is $\bar{\Xi}/\bar{\Lambda} = 0.06 \pm 0.02$, with the error dominated by statistics, which are too limited to study the p_T dependence within this range.

From the absence of a significant $\bar{\Omega}$ peak in the $\bar{\Lambda}K^+$ sample we obtain an upper limit in the region $1.4 < p_T < 2.4$ GeV/c, $|y| < 0.2$ of $\bar{\Omega}/\bar{\Xi} < 0.15$ with 90% confidence level.

5. CORRELATIONS WITH ASSOCIATED PARTICLES

Important constraints on models for antibaryon production result from investigating where in phase space the associated baryon is likely to be found. In most models, eg. the decay of high mass mesonic clusters or diquark-antidiquark string-breaking, a high p_T antibaryon will generally be followed, in the same jet, by its associated baryon.

For this study we consider separately the $\bar{p}$'s (excluding those which came from $\bar{\Lambda}^0$ decay) and the $\bar{\Lambda}$'s. Associated positive particles are required to have $|y| < 0.8$ and to have a good primary vertex fit. They are assigned as pions or protons using the dE/dx identification. Due to the limited range of this identification we use only the following regions of phase space for the associated particles:

(a) SAME SIDE: $0.56 < p_T$ (c.m.) < 0.76 GeV/c, $\Delta\phi < 90^\circ$, $|y| < 0.8$

(b) AWAY SIDE: $0.44 < p_T$ (c.m.) < 0.64 GeV/c, $\Delta\phi > 90^\circ$, $|y| < 0.8$

The different p_T intervals are due to the motion of the c.m. frame in the ISR frame. The number of particles per event in these two regions differs

both because of the different p_T bins but also because, as is well known, the particle density is higher opposite a high p_T trigger particle than near to it. We therefore consider only the ratios $R = N_p/N_\pi$ in the two regions. For $\bar{p}$ triggers we find R (SAME SIDE) = 0.213 ± 0.005 and R (AWAY SIDE) = 0.141 ± 0.003 . For $\bar{\Lambda}$ triggers we find R (SAME SIDE) = 0.211 ± 0.017 and R (AWAY SIDE) = 0.163 ± 0.011 , not significantly different from $\bar{p}$ triggers. In the same p_T range the corresponding ratio for typical inelastic collisions ("minimum bias") is [4]: $R \sim 0.08$, while from our background sample the ratio is R (SAME SIDE) = 0.096 ± 0.008 and R (AWAY SIDE) = 0.092 ± 0.005 . We therefore find a positive correlation between triggering $\bar{p}$ (or $\bar{\Lambda}$) and associated protons in the central region on both the same side and the away (recoil side); it is however significantly stronger on the same side.

DISCUSSION AND CONCLUSIONS

We have measured in pp collisions at $\sqrt{s}=63$ GeV around $y=0$ and at p_T -values $\sim 1-2$ GeV/c, the production ratios $\bar{\Lambda}/\bar{p}$ and $\bar{E}/\bar{\Lambda}$ and placed an upper limit on $\bar{\Lambda}/\bar{E}$. These ratios are respectively 0.27 ± 0.02 , 0.06 ± 0.02 and < 0.15 .

We note that the $\bar{\Lambda}/\bar{p}$ ratio obtained in this experiment is very similar to the value 0.30 ± 0.11 measured [9] in e^+e^- collisions at cm energy $W=34$ GeV. Noting that $\bar{\Lambda} = (\bar{s} \bar{u} \bar{d})$ while $\bar{p} = (\bar{u} \bar{u} \bar{d})$ their ratio can be naively expressed as $\bar{s}/\bar{u} \sim 0.3$ representing a strangeness suppression factor in producing the heavier strange quark. It is similar to the ratio at high p_T of $K^+/\pi^+ \sim u\bar{s}/u\bar{d} \sim \bar{s}/\bar{d}$. On the other hand $\bar{E} = (\bar{s}\bar{s}\bar{d})$, and the same argument would lead to $\bar{E}/\bar{\Lambda} = \bar{s}/\bar{u}$ which is inconsistent with the much lower result 0.06 ± 0.02 . A similar low value ~ 0.09 is also found in e^+e^- collisions [9]. Clearly the simplest "factorization" argument is invalid, and one would expect these ratios to be quite sensitive to models of antibaryon production processes.

We also find a positive correlation between $\bar{p}$ or $\bar{\Lambda}$ in the above p_T range and associated protons in the central region, both when the associated proton is on the same azimuthal side as the $\bar{p}$ ($\bar{\Lambda}$) and when it is on the recoil side. The correlation is stronger in the former region, indicating a tendency for the baryon number to be compensated within the trigger hemisphere.

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FIGURES CAPTIONS

- Fig. 1 Distribution of the difference Δx and Δy between the spatial position of the reconstructed shower and the projection of a negative track.
- Fig. 2 Distributions of the parameter $F = (E^2 - p^2)/2E$ for negative tracks (shaded area: positive tracks) projecting to a shower.
- Fig. 3 Distribution of decay distances d for $\bar{\Lambda}$ candidates.
- Fig. 4 Invariant mass distribution of $\bar{p}\pi^+$ pairs after a decay distance cut $1.3 < d < 20$ cm.
- Fig. 5 Measured distribution of $\bar{\Lambda}$ lifetimes for $0.8 < p(\bar{\Lambda}) < 1.0$ GeV/c. The line corresponds to the standard lifetime value 2.632×10^{-10} sec.
- Fig. 6 Invariant mass distribution of $\bar{\Lambda}\pi^+$ pairs and (shaded area) after subtracting the estimated background, showing the $\bar{\Xi}$.
- Fig. 7 Ratio of $\bar{\Lambda}/\bar{p}$ inclusive production cross-sections vs p_T , for $|y| < 0.2$.

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