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BARYON NUMBER TRANSFER AND CENTRAL NET BARYON DENSITY IN ELEMENTARY HADRONIC INTERACTIONS*

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New NA49 data on baryon and anti-baryon production in nucleon + proton interactions demonstrate the importance of isospin effects and asymmetric baryon pair production. Consequences for the interpretation of baryon number transfer and central net baryon density are discussed.

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1. Experimental procedure

The NA49 experiment at the CERN SPS has collected over the past five years a sample of 2.5 million events in $p+p$ interactions at $\sqrt{s} = 17.3$ GeV. For baryons the acceptance coverage is $-0.1 \le x_{\mathrm{F}} \le +0.5$ over the complete range of transverse momentum including particle identification via energy loss measurement. The resulting invariant cross sections for protons and anti-protons are shown in Fig. 1. Data from bubble chamber experiments in the range from $\sqrt{s} = 14$ to 27 GeV and ISR data are used (invoking Feynman scaling) to extend this coverage into the large x_{F} region up to the diffractive peak.

The NA49 experiment contains a forward hadronic calorimeter which allows the measurement of produced neutrons in the range of $0.2 \le x_{\mathrm{F}} \le 1.0$. In addition a low statistics data sample of 120 k events from $n+p$ collisions has been collected in a pilot run with deuteron beam. The d-beam is produced via fragmentation of Pb-ions in a C-target and subsequent selection of d-fragments. The inverse kinematics (d-beam on p-target) allows for precise tagging of the high-momentum proton spectators and the exclusion of the about 17% double interactions.

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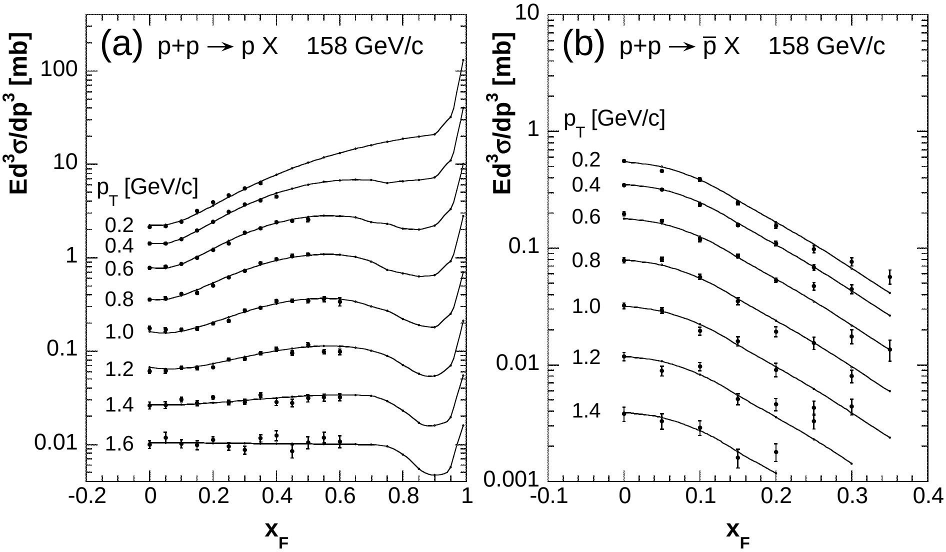

Fig. 1. Invariant inclusive cross section (before hyperon feeddown correction) of (a) protons and (b) anti-protons as a function of x_{F} in bins of transverse momentum.

2. Isospin effects in neutron and proton production

The simultaneous measurement of protons and neutrons in $p+p$ and of protons in $n+p$ interactions allows the direct control of isospin symmetry in the $I = {}^1/_2$ baryon doublet as shown in Fig. 2.

If the equality of yields for neutrons from protons and protons from neutrons comes as no surprise in this first experimental verification, it should be noted that the shape and height of the corresponding x_{F}-distributions are not calculable and have to be determined experimentally.

The distributions shown in Fig. 2 therefore constitute a basis for the construction of isospin-weighted reference baryon distributions for comparison with interactions of heavy ions which contain typically 60% neutrons. For this comparison it is mandatory to separate out the part of pair produced baryons contributing at low x_{F} in order to obtain "net" baryon densities. This procedure meets with another range of isospin problems as explained below.

Isospin $I = {}^1/_2$		
Projectiles	n	p
Produced particles	n	p
I_3	$-{}^1/_2$	$+{}^1/_2$

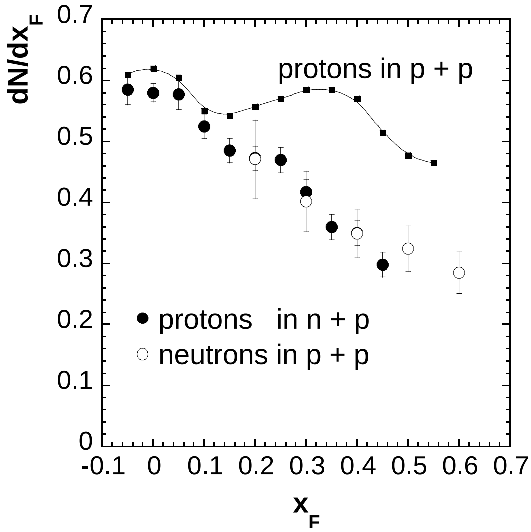

Fig. 2. p_{T} integrated x_{F} distributions of protons and neutrons from $p+p$ as well as protons from $n+p$ interactions.

3. Net baryon density and baryon number conservation

The sum rule of baryon number conservation in $p+p$ collisions may be written down as follows in the forward hemisphere:

$$\int_{x_{\mathrm{F}}=0}^{1} \left[\frac{dn}{dx_{\mathrm{F}}}(p-\bar{p}) + \frac{dn}{dx_{\mathrm{F}}}(n-\bar{n}) + \frac{dn}{dx_{\mathrm{F}}}(Y-\bar{Y}) + \cdots\right] dx_{\mathrm{F}} = 1.0\,.$$

The difference $p-\bar{p}$ is usually defined as the number of "net" protons, *i.e.* the number of leading, non-pair-produced protons. This notion is misleading as pair produced protons may be created together with anti-neutrons and anti-hyperons:

$$\sum \text{(pair-produced protons)} = p\bar{p} + p\bar{n} + p\bar{Y}\ \ldots\,.$$

A similar sum can be written down for anti-protons:

$$\sum \text{anti-protons} = \bar{p}p + \bar{p}n + \bar{p}Y \ldots .$$

The above definition of "net" protons is only valid if either the yield of asymmetric pair production of the type $p\bar{n}$ or $\bar{p}n$ is zero or if these two terms (to quote only the first contributions) are exactly equal. Both conditions are not fulfilled. A first notion of this problem may be obtained from Fig. 3 which shows the attempt to obtain "net" proton densities at three c.m.s. energies by the subtraction of the $\bar{p}$-densities from the p-densities.

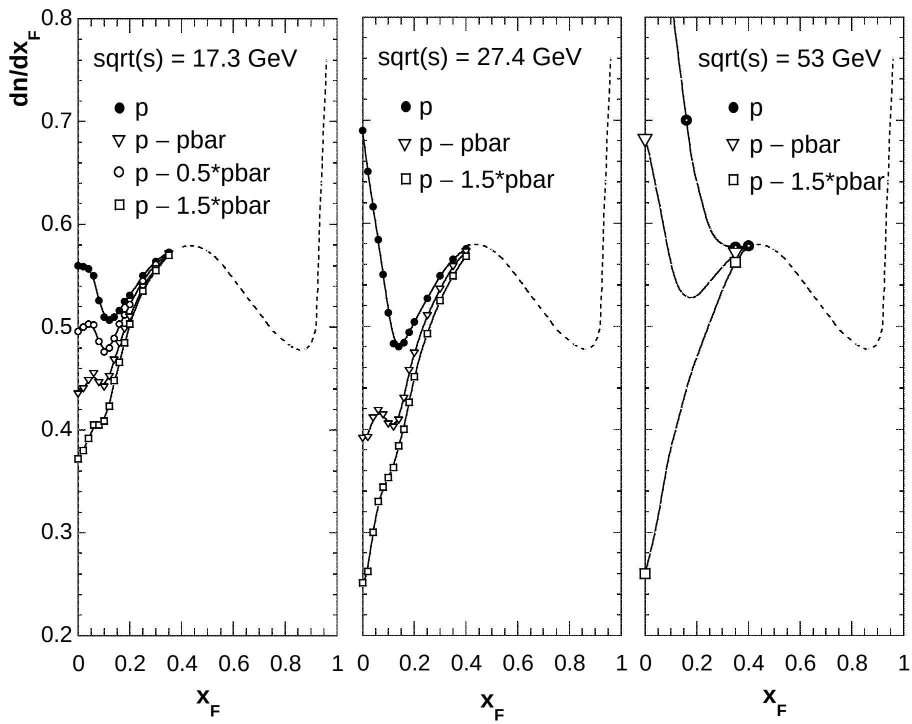

Fig. 3. Net proton distributions as a function of x_{F} for three c.m.s. energies, subtracting different fractions of anti-proton densities from proton densities.

Evidently there remains an instability at $x_{\mathrm{F}} = 0$ in the form of an interference pattern between the shape of the anti-proton distributions and the steeply falling "net" proton distributions which is visible both in the NA49 data and the EHS data at $\sqrt{s} = 27.4$ GeV [1]. At ISR energies [2, 3] this instability develops into a sizeable peak at $x_{\mathrm{F}} = 0$ which, if integrated together with the scaling density distribution at larger x_{F}, would indicate an increase of the total number of net protons with interaction energy and thereby a problem with baryon number conservation. In order to eliminate these problems the subtraction of more than the measured anti-proton yields seems necessary with a typical increase of around 1.5 in order to obtain "physical" net proton distributions.

4. Anti-proton production from neutron projectiles

The first ever measurement of anti-proton production from neutron projectiles shown in Fig. 4 quantifies the indications discussed above.

Isospin $I = 1$					
Projectiles		n		p	
Produced particles	$\bar{p}n$		$p\bar{p}$ $n\bar{n}$		$p\bar{n}$
I_3	-1	$-{}^1/_2$	0	${}^1/_2$	$+1$

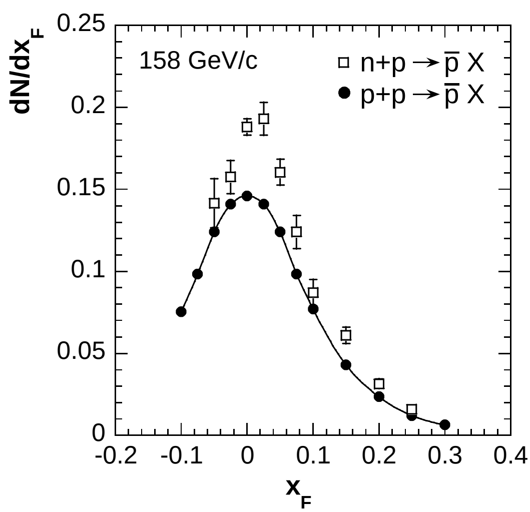

Fig. 4. Anti-proton density distribution as a function of x_{F} for $p+p$ and $n+p$ interactions.

In fact there is a sizeable increase of anti-proton production in $n+p$ collisions if compared to $p+p$ interactions. By making proper allowance for the equal target contribution in both reactions, this increase amounts to a factor of 1.5 to 1.6 at $x_{\mathrm{F}} = 0$. The underlying isospin symmetry may be understood by arranging the possible baryon/anti-baryon combinations evoked in the preceding chapter into the isospin triplet/singlet combinations presented in Fig. 4. The measured yield asymmetry between p and n projectiles corresponds to the preference of the positively charged $p\bar{n}$ combination over $\bar{p}n$ with a proton projectile and of the negatively charged $\bar{p}n$ combination over $p\bar{n}$ with a neutron projectile. In fact there is a complete correspondence of these isospin states with high mass $I = 1$ mesons with the additional feature that the measurement of $\bar{p}$ scans both the $I_3 = 0$ (symmetric $p\bar{p}$) and $I_3 = -1$ (asymmetric $\bar{p}n$) components. The observed sizeable increase factor, therefore, corresponds to a very strong asymmetric component.

5. Consequences for central net baryon density

The evolution of the invariant p_{T}-integrated proton and anti-proton cross sections at $x_{\mathrm{F}} = 0$ with $\sqrt{s}$ is presented in Fig. 5(a) for $p + p$ collisions. A sharp decrease of central proton density up to $\sqrt{s} \simeq 20$ GeV is followed by a minimum at around 25 GeV and an increase at higher energies which traces the development of the anti-proton cross section. If subtracting the anti-proton from the proton yield the invariant "net" proton density reaches a constant level above $\sqrt{s} \simeq 30$ GeV (see Fig. 5(b)) which illustrates again the problem with baryon number conservation mentioned above, as a constant invariant cross section at $x_{\mathrm{F}} = 0$ implies a central proton density which increases linearly with $\sqrt{s}$.

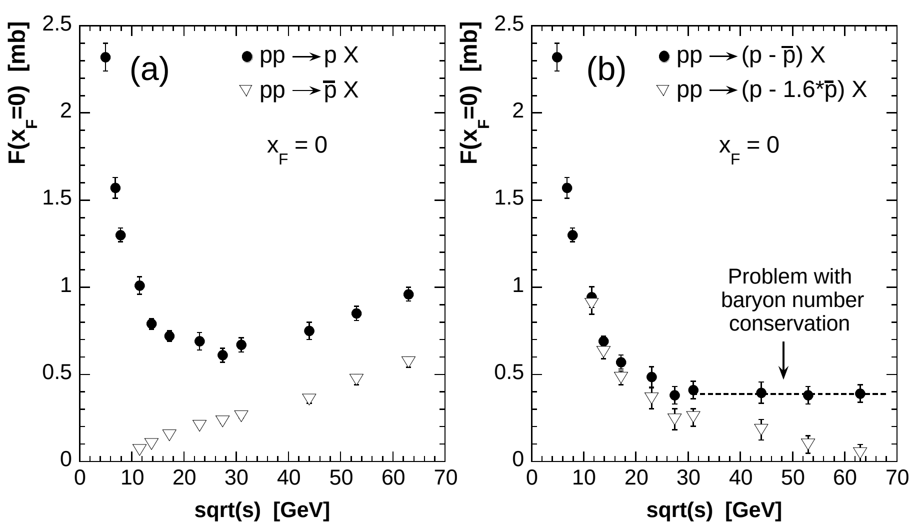

Fig. 5. (a) p_{T}-integrated invariant p and $\bar{p}$ yields at $x_{\mathrm{F}} = 0$ as a function of $\sqrt{s}$; (b) $p - \bar{p}$ and $p - 1.6 \cdot \bar{p}$ as a function of $\sqrt{s}$.

If, however, a larger amount of anti-protons is subtracted (in Fig. 5(b) 1.6 times the measured yield) the "net" proton cross section approaches zero in the upper ISR energy range thus precluding a divergence of total proton number.

6. Consequences for hyperon yields

The observed pattern of isospin dependencies for baryons may be extended to strange and double-strange hyperons noting the following isospin multiplets (making no difference in notation between Λ^0 and Σ^0 which are anyway indistinguishable in most experiments):

Isospin $I = 1$						Strangeness
Projectiles		n		p		
Produced particles	$\Lambda\bar{\Sigma}^-$ $\Sigma^-\bar{\Lambda}$		$\Lambda\bar{\Lambda}$		$\Lambda\bar{\Sigma}^+$ $\Sigma^+\bar{\Lambda}$	$-1, +1$
I_3	-1	$-^1/_2$	0	$^1/_2$	$+1$	

Isospin $I = 1$						Strangeness
Projectiles		n		p		
Produced particles	$\bar{\Xi}^0\,\Xi^-$		$\Xi^0\,\bar{\Xi}^0$ $\Xi^-\,\bar{\Xi}^+$		$\Xi^0\,\bar{\Xi}^+$	$-2, +2$
I_3	-1	$-^1/_2$	0	$^1/_2$	$+1$	

As a consequence of the possible combination of $I_3 = 0$ states (Λ^0, Σ^0) with $I_3 = \pm 1$ states $(\Sigma^\pm)$ it is apparent that there should be no dependence of Λ^0 and $\bar{\Lambda}^0$ yields on projectile charge. In other words the $\bar{\Lambda}^0$ measures the total number of pair produced Lambda's and the quantity $\Lambda^0 - \bar{\Lambda}^0$ gives the yield of "net" Lambda hyperons. This is visible in Fig. 6 where the s-dependence of invariant Λ^0 and $\bar{\Lambda}^0$ yields are given at $x_{\mathrm{F}} = 0$. Within the sizeable error bars several basic features are noteworthy:

(a) The rapid decrease of net hyperon number up to $\sqrt{s} \simeq 20$ GeV followed by a minimum at $\simeq 25$ GeV and an increase which traces the evolution of the $\bar{\Lambda}^0$ yield from a threshold at $\simeq 7$ GeV (see Fig. 5(a) for comparison).

(b) The steep decrease of net hyperon number below $\sqrt{s} \simeq 8$ GeV corresponding to the threshold cut-off in associate $(\Lambda,\, K)$ production.

(c) The much smaller difference between Λ^0 and $\bar{\Lambda}^0$ yields at $\sqrt{s}$ around and above 25 GeV if compared to p and $\bar{p}$ (Fig. 5). This leads to a rapid decrease of the "net" Λ^0 yield with $\sqrt{s}$ at ISR energies.

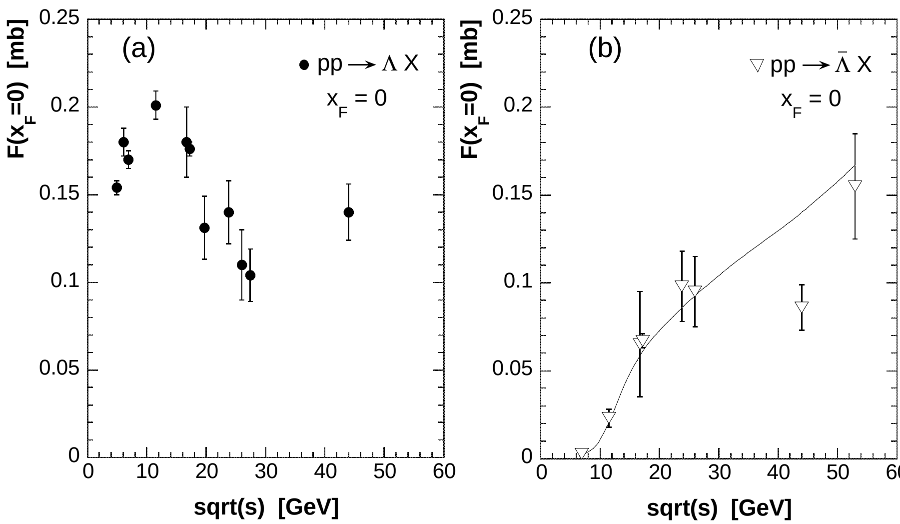

Fig. 6. $p_{\rm T}$ integrated invariant cross sections at $x_{\rm F} = 0$ for (a) Lambda and (b) Anti-Lambda as a function of $\sqrt{s}$. The line in Fig. 6(b) gives the scaled s-dependence of anti-protons.

Concerning the cascade baryons and anti-baryons, their isospin triplet is in complete charge-antisymmetry to the triplet of protons and anti-protons. Therefore, the number of pair produced Ξ^- is smaller than the number of $\bar{\Xi}^+$ in $p+p$ interactions in opposition to the case of pair produced protons and anti-protons. Consequently in passing to neutron-induced interactions one should predict an increase of Ξ^- and a decrease of $\bar{\Xi}^+$ yields with important consequences for the interpretation of the enhanced production of these particles in $A+A$ collisions. Proceeding to Ω-hyperon production NA49 has obtained a first clear signal of Ω^- in $p+p$ interactions whereas there is — with the present event statistics — no $\bar{\Omega}^+$ visible. Nevertheless this allows to establish an upper limit of the $\bar{\Omega}^+/\Omega^-$ ratio of 0.5 with 95% confidence level.

The combined situation of anti-baryon/baryon ratios as a function of strangeness content is given in Fig. 7.

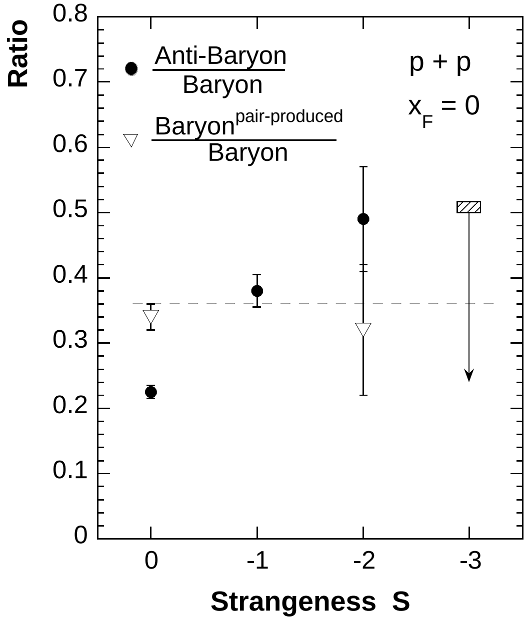

Fig. 7. Anti-baryon/baryon and pair-produced-baryon/baryon ratios at $x_{\mathrm{F}} = 0$ in $p + p$ interactions as a function of strangeness content.

The apparent increase of this ratio with strangeness content can, based on the above discussion, be traced to isospin effects which have to and can be corrected for. This leads to the redefinition of the ratio as pair-produced-baryons/baryons. If applying the measured isospin correction to anti-protons and the predicted (and opposite) correction to $\bar{\Xi}^+$ one obtains within error bars a flat dependence of this redefined ratio on strangeness as indicated in Fig. 7.

7. Conclusion

New data from the CERN SPS concerning baryon and baryon pair production in $p + p$ and $n + p$ collisions have been discussed. Their exploitation offers improved insight into the detailed mechanisms of isospin symmetry, baryon number transfer and the evolution of net baryon density. Such studies form the indispensable basis for the understanding of the more complex nucleon + nucleus and nucleus + nucleus interactions. As such the experimental scrutiny of elementary hadronic collisions should be vigorously pursued.

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Note concerning Ref. [2] and [3]: as the ISR data are not corrected for hyperon feeddown, this correction (using data of Fig. 6 plus an assumption on the Σ-yield) has been performed to obtain the values shown in Fig. 5.