Elementary Hadronic Interactions at the CERN SPS

H.G. Fischer [a] for the NA49 Collaboration

[a]CERN, Geneva

1. Introduction

An extensive set of new data concerning elementary hadron+hadron and hadron+nucleus interactions has been accumulated over the past few years at the CERN SPS at $\sqrt{s} = 17.2$ GeV, using the NA49 detector. These data, summarized in Table 1, contain more than 9 million events with wide acceptance coverage and particle identification using energy loss measurements in a Time Projection Chamber tracking system [1].

Reaction	Events [M]
p + p	5.000
n + p	0.120
$\pi^+ + $ p	0.640
$\pi^- + $ p	0.450
p + Pb	2.200
$\pi^+ + $ Pb	0.500
$\pi^- + $ Pb	0.480

Table 1

A few general features of these data appear noteworthy:

- All hadron+nucleus reactions have centrality control via detection of grey protons.
- Complementary data samples with non-baryonic projectiles, e.g. π-beams, allow for the separation of target contributions as far as net baryon number is concerned; in particular these data are obtained with opposite projectile charge such that proper isospin averages may be performed.
- A small but clean sample of n+p interactions with inverse kinematics (neutron projectile) permits a first study of neutron fragmentation into identified charged hadrons.

This new effort in a field that had been practically abandoned since many years, is aimed at establishing an improved experimental basis for the study of the evolution from elementary to nuclear hadronic interactions, in a model independent fashion. For this aim, good phase-space coverage and particle identification, completeness and complementarity with respect to reaction channels are necessary pre-requisites. This is especially valid for a renewed scrutiny of hadron+nucleus interactions which constitute the only laboratory for elementary multiple collision processes.

In this short review, evidently only a very limited range of subjects can be touched upon. Longitudinal and transverse momentum distributions of baryons, the effects of isospin symmetry in neutron fragmentation, and the yields of strange mesons and baryons will be discussed. Whenever relevant, results from Pb+Pb collisions obtained with the same detector will be shown for comparison.

2. The Evolution of Longitudinal Baryon Density and Hadronic Factorization

The longitudinal transfer of baryon number in hadronic collisions from target and projectile momenta to the central region constitutes one of the most important observables as it has to do with final state energy density ("stopping"). A central argument in this context will be the factorization between target and projectile components, i.e. the way how these contributions superimpose, how they may be experimentally separated and put together again in the more complex, asymmetric case of hadron+nucleus collisions.

To this intent in Fig. 1a the net proton density as a function of Feynman x_F for proton+proton collisions is tentatively separated into a target and a projectile component meeting by symmetry at half-height at $x_F = 0$. Using now isospin-averaged pion projectiles the net proton density as a function of x_F can be obtained for a net baryon number zero projectile (Fig. 1b). The ratio of the pion-induced to proton-induced densities (Fig. 1c) should be 1 in the target hemisphere and pass through 0.5 at $x_F = 0$ if factorization, and herewith independence of baryon transfer on projectile type, holds.
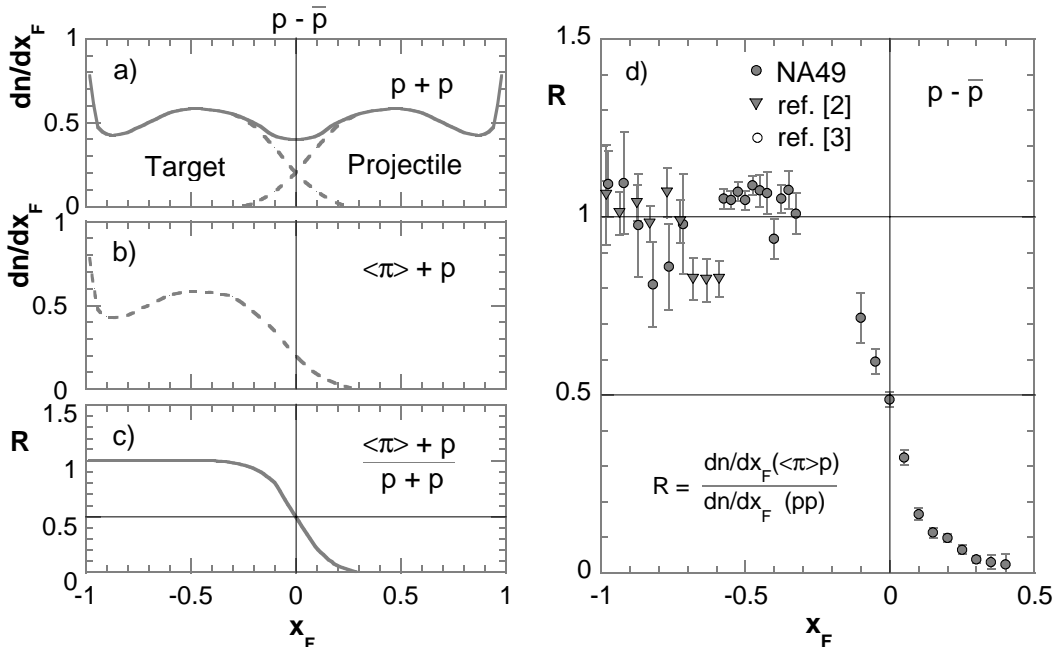

Figure 1. Schematic view of a) factorization of the net proton density in target and projectile components, b) net proton density for a net baryon number zero projectile, c) ratio of the pion-induced to proton-induced densities, and d) data on this ratio (NA49, [2], [3]).

The data shown in Fig. 1d clearly support this picture:

- The density ratio is 1 in the target hemisphere, i.e. for $x_F \leq -0.3$.
- The ratio passes through 0.5 at $x_F = 0$. It should be stressed that this is a non-trivial result.

- The rapid approach to zero in the projectile hemisphere – together with the integral of the distribution – does not leave room for an important "leakage" of baryon number from the target to the projectile side. This puts constraints e.g. on the applicability of the so-called "junction mechanism".

This argumentation may now be extended to nuclear data by using isospin-averaged pion+nucleus interactions at different centralities. As shown in Fig. 2a, the net proton density in the forward region – which is not affected by nuclear rescattering at SPS energy – shows a smooth and conformal increase with the mean number of collisions ν suffered by the projectile. This is direct experimental evidence for target pile-up which is demonstrated to be linear with ν at $x_F = 0$ in Fig. 2b.
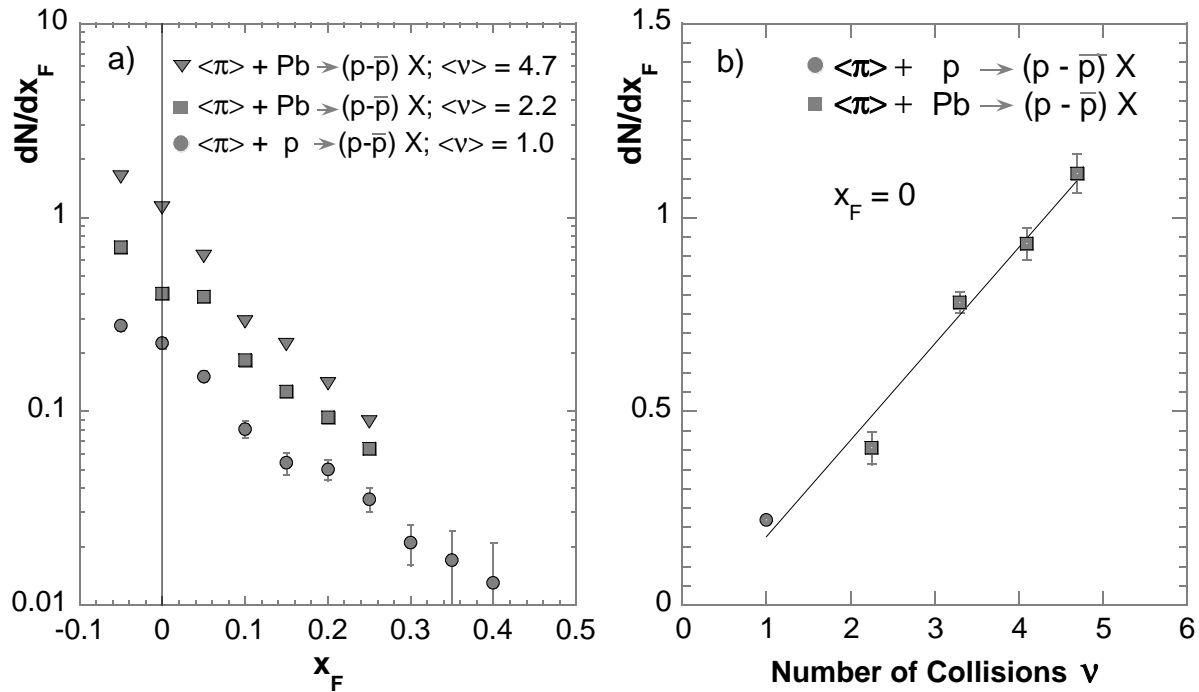

Figure 2. a) Net proton density as function of x_F for various mean numbers of collisions ν; b) net proton density at $x_F = 0$ as function of ν.

This result opens up the possibility to obtain experimentally the projectile contribution to the net baryon density in p+Pb interactions and thereby a clear picture of baryon number transfer in multiple hadronic collisions. In fact by subtracting the target component (Fig. 2a) from the total net baryon density in p+Pb collisions (Fig. 3a) for the same number of projectile collisions, the projectile component shown in Fig. 3b can be extracted (see also [4]).

The strong increase of this projectile contribution for p+Pb collisions with respect to the elementary p+p reaction is quantified in Fig. 4 as function of ν.

Similar measurements should be performed for all other types of "net baryons", e.g. Λ, Ξ, Ω, in order not to confound an increase from baryon number transfer with true nuclear enhancement factors (see chapter 4 and the contribution from M.Kreps [8] to these proceedings).

As far as the (symmetric) Pb+Pb interactions are concerned, their central net proton density may be directly compared to the (symmetric) p+p collisions in order to extract the effect of
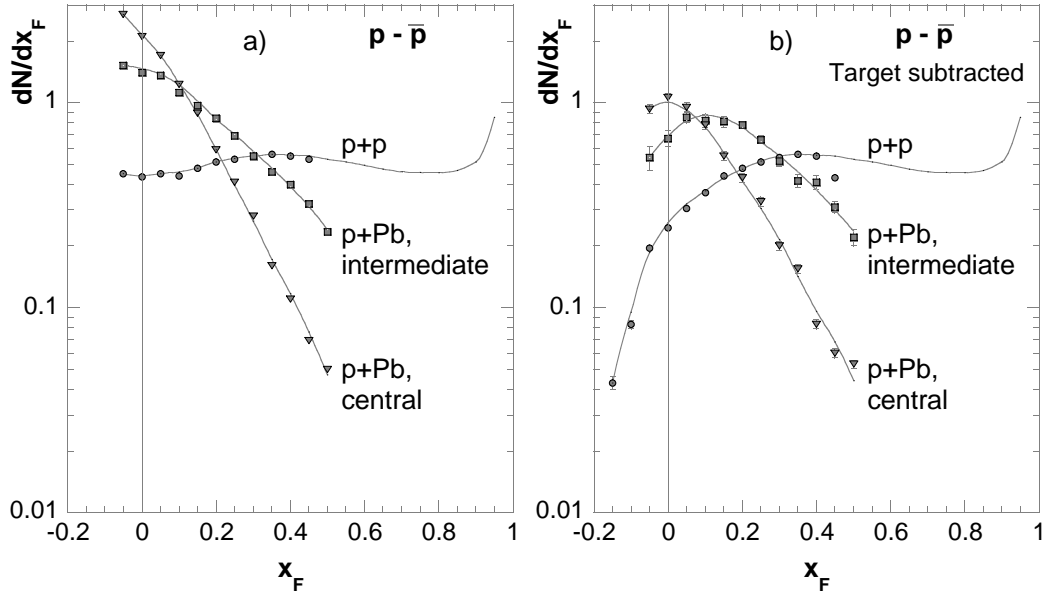
Figure 3. a) total net baryon density as function of x_F; b) projectile component of net baryon density.

baryon stopping. This is also shown for peripheral and central Pb+Pb interactions in Fig. 4 (see [4] for a more detailed argumentation). Two important results emerge:

- There is a smooth increase of central net proton density with the number of projectile collisions.
- Taking into account the uncertainty in determining ν there is no difference between p+Pb and Pb+Pb interactions.
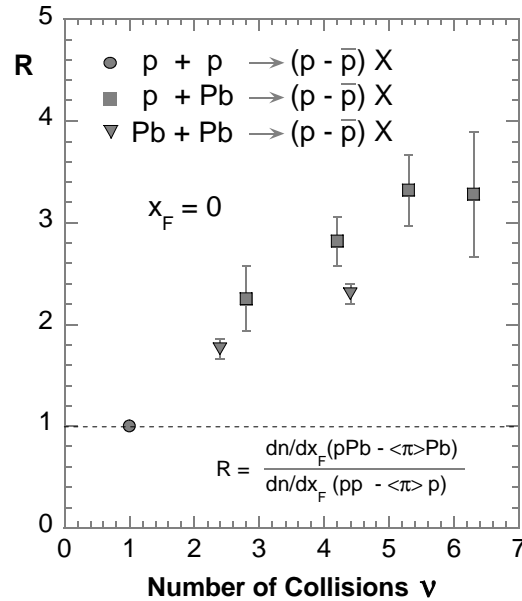

Figure 4. Projectile contribution to the net proton density at $x_F = 0$ as function of ν for p+Pb collisions normalized to p+p interactions.

3. The Evolution of Transverse Baryon Density

Given the substantial modification of longitudinal baryon distributions in multiple hadronic collisions as discussed above, it is interesting to regard also the transverse baryonic density distributions. In fact it would be rather surprising if such strong long-range longitudinal effects did not leave their trace also in the transverse dimension.

A first indication may be obtained by comparing the transverse proton density distributions $dn/dx_F dp_T$ at $x_F = 0$ for p+p and central p+Pb interactions as shown in Fig. 5a. A considerable shift to higher transverse momenta is evident in p+Pb collisions. This corresponds to the well-known Cronin effect [5], here however measured for about 5 rather than 3.7 average projectile collisions. Following the argumentation of the preceding chapter we may now extract the relative contributions of target and projectile to this effect.
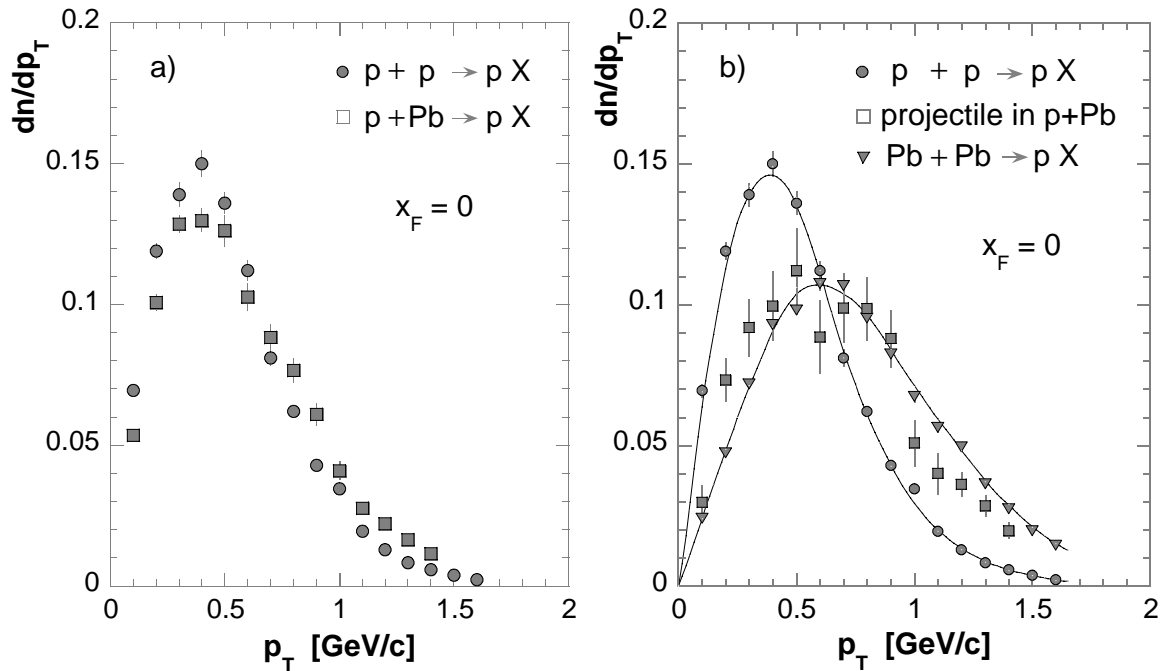

Figure 5. a) p_T distribution of protons at $x_F = 0$ for p+p and p+Pb interactions; b) p_T distribution of protons at $x_F = 0$ for p+p and projectile component to this distribution for p+Pb compared to p_T distribution for Pb+Pb interactions.

The target contribution should be represented by the transverse net proton distribution from $\langle\pi\rangle$+Pb collisions which turns out to be equal to the distribution from p+p interactions. This leaves the projectile contribution as the source of the observed p_T broadening and indeed a further substantial upward shift in transverse momentum is observed as seen in Fig. 5b (open squares). This projectile contribution approaches the proton p_T distribution obtained in central Pb+Pb collisions also shown in Fig. 5b.

Several conclusions may be drawn from this study:
- Again the results from central p+Pb and Pb+Pb collisions are very similar.
- A new interpretation of the Cronin effect as a two-component phenomenon including a transversally inert target contribution is necessary at least in the p_T range considered here.
- Major transverse activity is induced by multiple hadronic collisions already on the level of elementary p+A interactions.

The last conclusion casts some doubt on the validity of the "standard" interpretation of transverse momentum broadening in heavy ion collisions by transverse expansion of a "hot" initial partonic phase. Doubtlessly by introducing a vector field of expansion of sufficient complexity it will always be possible to map two different transverse momentum distributions onto each other. Such a vector field has however no place in p+A interactions. It should rather be asked what happens to transverse hadronization in multiple collision processes as these processes establish the link between p+A and A+A collisions.

Finally it should be mentioned here that the hierarchy of transverse momentum broadening with respect to particle mass, with pions showing practically no effect up to $p_T \simeq 1$ GeV/c, is also reproduced in p+A collisions.

4. Consequences of Isospin Symmetry on Kaon and Baryon Production

In view of the fact that neutrons constitute 60% of the baryonic participants in heavy ion interactions, the almost complete absence of experimental information on neutron fragmentation constitutes a major flaw. Although isospin invariance is of course uncontested in hadronic interactions, its consequences for final state hadronization depend on details of production mechanisms and are as such incalculable; they have to be extracted experimentally.

A first measurement of charged pion and kaon yields from neutrons in the projectile hemisphere, see Fig. 6, may illustrate these problems.
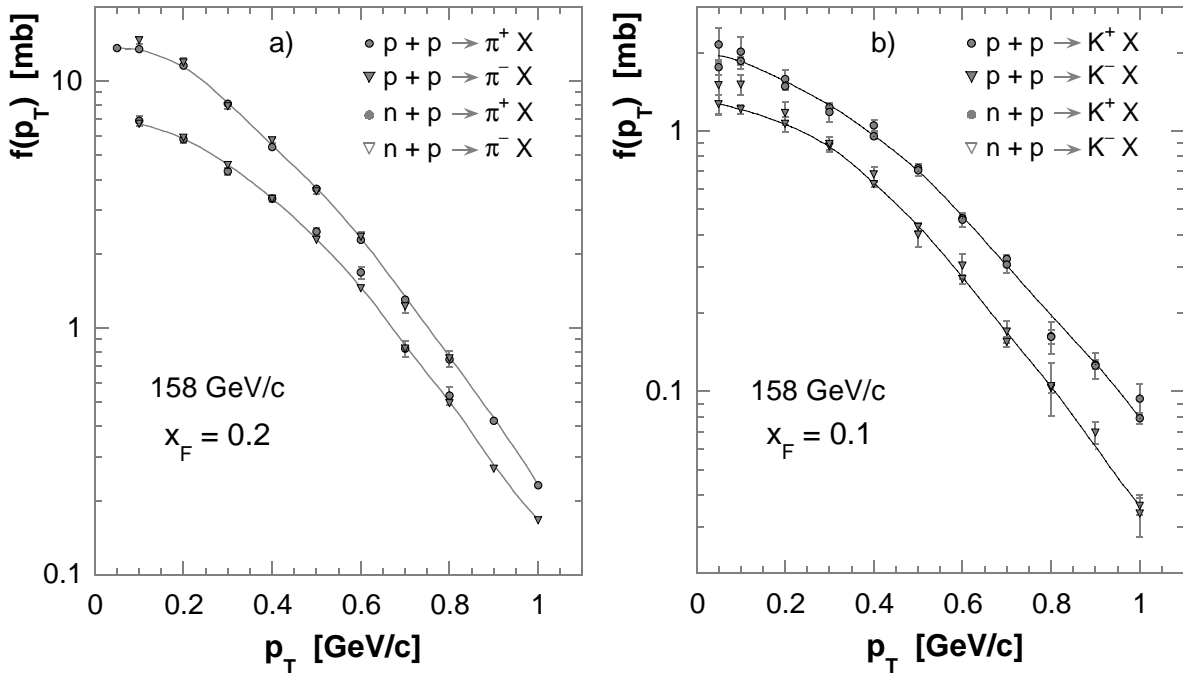

Figure 6. Differential invariant cross section as function of p_T for a) π^+ and π^- b) K^+ and K^- produced in p+p and n+p interactions.

Apparently π^+ and π^- change their place when switching from p to n projectile, but K^+ and K^- do not (within error bars). Whereas the first fact may be expected from the relevant isospin multiplets given in Table 2, the latter one can only be understood by the prevalence of associate

K-hyperon production at SPS energy, and even so only by invoking important high-mass N*, Y* and K* formation and subsequent decay.

Isospin $I = 1$					
Projectiles			n		p
Produced particles	π^-		π^0		π^+
I_3	-1	-1/2	0	1/2	+1

Isospin $I = 1/2$			Strangeness
Projectiles	n	p	
Produced particles	K^0	K^+	1
(associate)	K^-	$\overline{K}^0$	-1
I_3	-1/2	+1/2	

Isospin $I = 1$					Strangeness
Projectiles		n		p	
Produced particles (in pairs)	$K^- K^0$		$K^+ K^-$ $K^0 \overline{K}^0$		$K^+ \overline{K}^0$	0
I_3	-1	-1/2	0	1/2	+1	

Table 2

This experimental observation has strong consequences for the interpretation of K/π ratios when comparing elementary to nuclear collisions. The necessary isospin correction factors for a 60/40% n/p mixture with respect to p+p interactions are presented in Fig. 7a, the corresponding isospin-corrected K^+ enhancement factors in Fig. 7b for central p+Pb and Pb+Pb collisions, as a function of x_F. Again one finds, together with a smooth dependence on the number of collisions (not shown here), no apparent difference between p+A and A+A interaction. A similar result applies to K^- production.
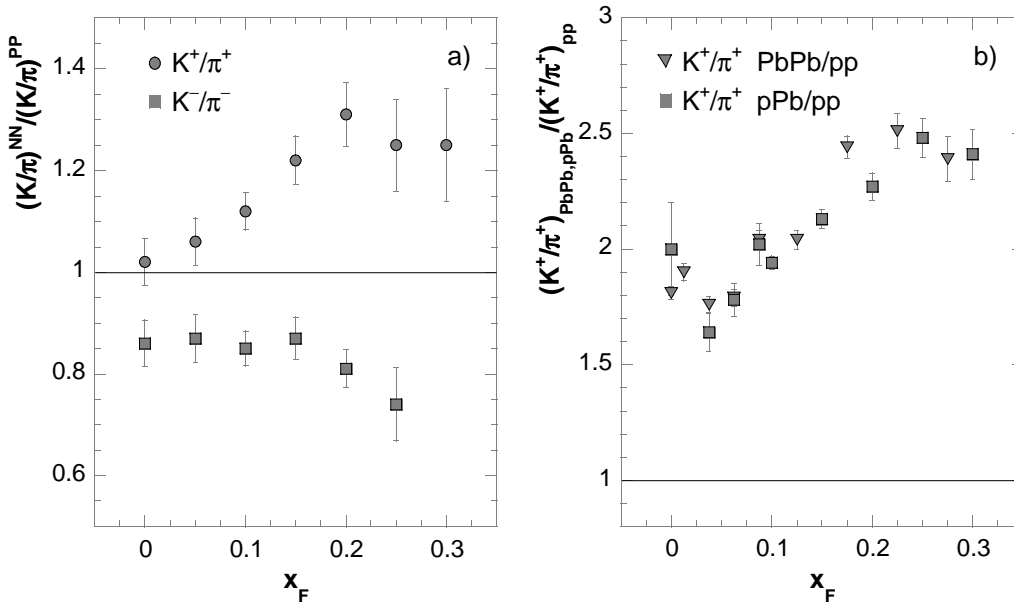
Figure 7. a) K/π ratio as function of x_F for N+N collisions, N standing for a 60/40% neutron/proton mixture, normalized to p+p interactions; b) isospin corrected K^+/π^+ ratio as function of x_F for p+Pb and Pb+Pb collisions, each normalized to p+p interactions.

Concerning baryon pair production, the anti-proton yield from n+p as compared to p+p collisions, shown in Fig. 8a, constitutes yet another non-trivial consequence of isospin symmetry. In fact there is a sizeable increase of anti-proton production from neutrons which amounts to about a factor of 1.5 if taking proper account of the equal target in both reactions.

This increase would be difficult to hide in any (symmetric) sea contribution to baryon pair production. Instead one has to allow for an important yield of asymmetric baryon pairs of the type $p\bar{n}$ or $\bar{p}n$ following from the the corresponding isospin triplet, shown in Table 3.

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

Table 3

This indicates production via high mass mesonic states which seems the only way to understand the very large correlation with projectile isospin observed, as such states might be generated in a more primordial hadronization phase.

Asymmetric baryon pair production has immediate consequences for the definition of "net" baryon yields. Evidently the usual difference p–$\bar{p}$ is not the correct measure: In p-fragmentation the $\bar{p}$ yield under-estimates the number of pair produced protons, in n-fragmentation it over-estimates it. Indeed the usual p–$\bar{p}$ difference in the invariant, p_T integrated cross section at $x_F = 0$, shown in Fig. 8b as function of $\sqrt{s}$, flattens out in the ISR energy range. This contradicts baryon number conservation. Taking account of the proper number of pair produced protons by subtracting 1.6 times the $\bar{p}$ yield, also shown in Fig. 8b, this contradiction is lifted and the "net" baryon yield approaches zero at the highest ISR energies.
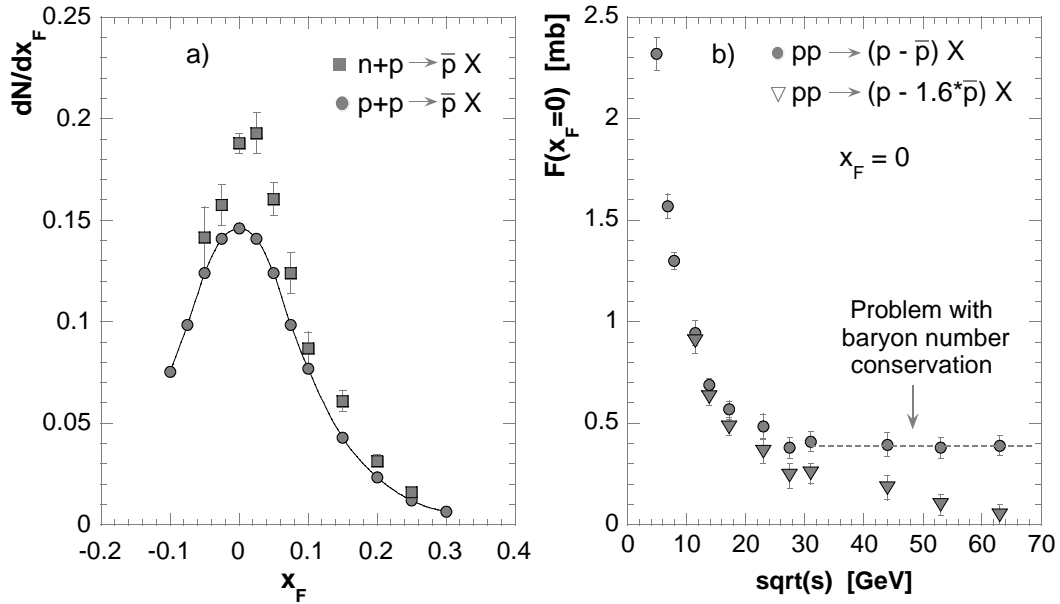

Figure 8. a) Anti-proton density as function of x_F for n+p and p+p interactions; b) invariant cross section at $x_F = 0$ as function of $\sqrt{s}$ for net protons produced in p+p interactions.

5. A Comment on Strange and Multistrange Baryon Poduction

In the realm of "signatures" for "new" physics in heavy ion collisions, strange and multi-strange baryons occupy a special position: Enhancement factors of about 3 for Λ, 10 for Ξ^- and 20 for Ω with respect to "elementary" interactions have been reported. In view of the above discussion, these evidences have to be scrutinized very carefully for different systematic effects:

- It is a necessity to measure reference cross sections for elementary baryon+baryon interactions: p+Be e.g. is in this sense not a reference.
- It is a necessity to take proper account of isospin effects as shown above.
- It is a necessity to quantify and subtract effects induced by baryon number transfer. This needs wide acceptance coverage far beyond the standard range close to central rapidity.
- It is a necessity to study the elementary hadron+nucleus reaction as this is the only way to get access to the effect of multiple collisions in "cold" hadronic matter. This should be done with controlled centrality.
- In this latter case it is a necessity to learn how to disentangle target and projectile contributions which are here highly asymmetric compared to central nucleus+nucleus collisions.

In the case of cascade production, at least part of this experimental program has been fulfilled by the NA49 experiment [9]. Cross sections for p+p collisions have been measured as well as for p+Pb and Pb+Pb interactions. Due to the premature closure of the SPS fixed target program it will not be possible to work up the rest of the straight-forward experimental list presented above. Here one has to take refuge to some (reasonable) assumptions. A more detailed account of this approach is given in [6,7] and the contribution of M. Kreps [8] to this conference.

The key to a proper understanding of nuclear enhancement of cascade baryons is the last point quoted above. From the experience gained with target and projectile contributions it seems more natural to blame a measured enhancement in p+Pb on the projectile, which has undergone multiple collisions, rather than on the target which has been shown to pile up with elementary cross section at least for protons.

In doing so one arrives at the enhancement factors E at central rapidity (for definition see [8]) shown in Fig. 9 for p+A collisions as function of the number of projectile collisions, including data from WA97 [10] for minimum bias p+Be and p+Pb interactions. If compared to the enhancement factors extracted from Pb+Pb reactions one sees again, within reasonable error bars (especially on the scales concerning the number of collisions in both reactions), a very similar behaviour between the two types of nuclear collisions.

Another reasonable assumption may be made concerning isospin effects. In writing down the isospin triplet of $\Xi\bar{\Xi}$ states, Table 4, it appears that this triplet is charge-antisymmetric to the triplet of $S = 0$ baryons (see Table 3).

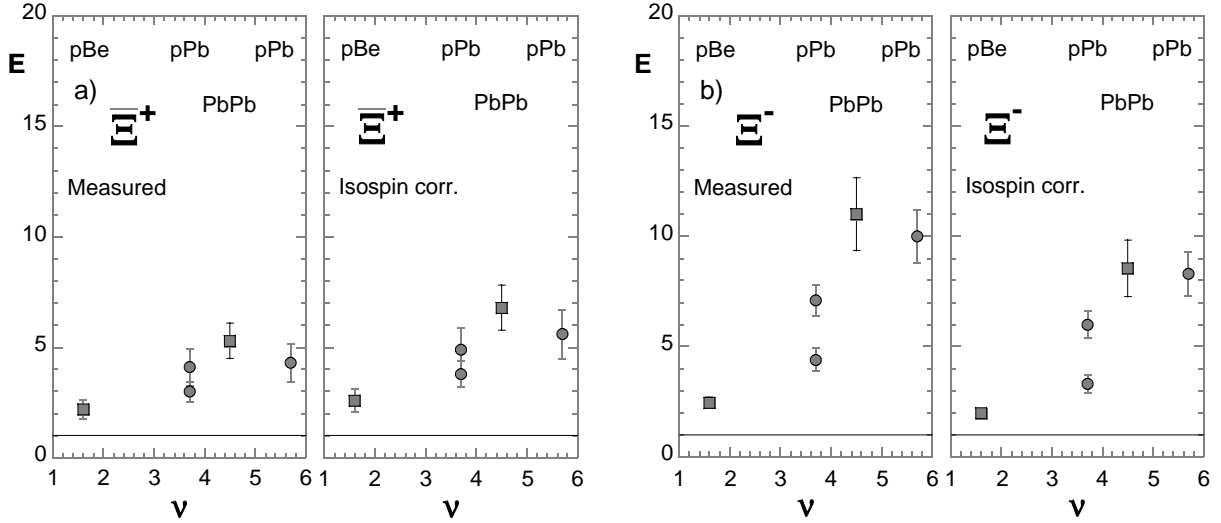| Isospin $I = 1$						Strangeness
Projectiles		n		p		
Produced particles	$\bar{\Xi}^0\Xi^-$		$\Xi^0\bar{\Xi}^0$ $\Xi^-\bar{\Xi}^+$		$\Xi^0\bar{\Xi}^+$	-2, +2
I_3	-1	-1/2	0	1/2	+1	

Table 4

Figure 9. a) Enhancement factor E at central rapidity for $\overline{\Xi}^+$ production as function of ν in p+Be, p+Pb and Pb+Pb collisions normalized to p+p interactions and next to it the isospin corrected E as decribed in text; b) same for Ξ^-.

A correspondingly opposite dependence on projectile isospin has therefore to be expected in the sense that $\overline{\Xi}^+$ production should be enhanced in p-fragmentation as opposed to n-fragmentation. The opposite trend should be valid for Ξ^- production. Assuming this asymmetry to be of the same size as the one observed for $S = 0$ baryons one arrives at the isospin-corrected comparison of p+p, p+A and A+A interactions shown in Fig. 9. Apparently the difference in enhancement of about a factor of 2 observed between Ξ^- and $\overline{\Xi}^+$ is now much reduced and the remaining effect might well be attributed to stopping, see chapter 2 above [8].

6. Conclusion

Some features of an extensive set of new data in elementary hadron+nucleon and hadron+nucleus interactions have been presented and compared to nucleus+nucleus collisions. Except for the use of very fundamental properties of hadronic reactions like baryon number conservation and isospin invariance the main aim of this study is to provide a model independent approach based exclusively on completeness and internal consistency and complementarity of the data. Several conclusions may be drawn:

- Momentum distributions and yields of hadrons follow a smooth evolution from elementary to nuclear collisions. In particular, nucleus+nucleus collisions comply well with this evolution and do not occupy a special place.

- Multiple hadronic collision processes are at the origin of this evolution; the essential physics variable is the number of collisions per participant or – in a more general sense – the depth of nuclear matter traversed by the participant hadron.

- Projectile isospin plays an important role; hence the necessity to study especially neutron fragmentation in more detail.

- Complete, high quality and high statistics data sets on elementary hadronic interactions are indispensible in order to gain model independent understanding of the more complex nuclear collisions. In the absence of reliable theoretical approaches in the field of non-perturbative QCD a better experimental basis has to be established. The present study has hopefully demonstrated that such a basis may be obtained. In this sense the detailed scrutiny of elementary hadronic collisions should be vigorously pursued.

REFERENCES

1. S. Afanasiev et al., NA49 Collaboration, Nucl. Instr. Meth. **A430** (1999) 210.
2. I.V. Ajinenko et al., Z. Phys. **C44** (1989) 573.
3. J. Whitmore, Phys. Rep. **10**, no. 5 (1974) 273.
4. A. Rybicki, Proc. Cracow Epiph. Conf., Act. Phys. Pol. **33** (2002) 1483.
5. J.W. Cronin et al., Phys. Rev. **D11** (1975) 3105.
6. H.G. Fischer, Proc. Cracow Epiph. Conf., Act. Phys. Pol. **33** (2002) 1473.
7. H.G. Fischer, Proc. Budapest'02 Workshop on Quark and Hadron Dynamics, to be published in Heavy Ion Phys., Sept. 2002.
8. M. Kreps, *Baryon and Antibaryon Production*, these proceedings.
9. T. Susa et al., NA49 Collaboration, Nucl. Phys. **A698** (2002) 491c.
10. F. Antinori et al., WA97 Collaboration, Nucl. Phys. **A661** (1999) 130c.