PARTICLE PRODUCTION IN NUCLEAR MATTER: HIGHLIGHTS FROM $\boldsymbol{h+p}$ AND $\boldsymbol{h+A}$ DATA AT SPS ENERGIES*

Andrzej Rybicki

Henryk Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland
and
CERN, Geneva, Switzerland

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Various phenomena observed in $A+A$ collisions can be traced back to more elementary $h+h$ and $h+A$ reactions.

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1. Introduction

In the study of $A+A$ reactions, mainly driven by the search for the quark–gluon plasma, a critical issue is that of correct interpretation of the observed phenomena. Before any observed effect can be interpreted as signature of QGP formation in $A+A$ collisions, it has to be verified that it cannot be caused by "standard" processes, present already in hadron + hadron $(h+h)$ and hadron+nucleus $(h+A)$ reactions.

The new experimental results provided by the NA49 experiment open new ways for studying any potential connections between $h+h$, $h+A$, and $A+A$ interactions. In the present paper, it is demonstrated that several effects observed in $A+A$ can in fact be traced back to phenomena seen in more elementary reactions. Some of them can be attributed to the mixed proton/neutron content of the nucleus, others to multiple collisions undergone by the projectile in nuclear matter. The discussion includes the behaviour of π^+/π^- ratios, the strangeness enhancement phenomenon, the energy dependence of the strangeness over pion ratio, and baryon stopping.

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2. The role of the valence structure of the projectile

Fig. 1(a) shows a set of p_{T} distributions, corresponding to the production of positive and negative pions in $p+p$ and $n+p$ interactions[1]. The complete "flip" of π^+ and π^- spectra with the change of projectile can be regarded as a "trivial" result of isospin symmetry. However it has important consequences for the understanding of $A+A$ reactions. This is exemplified in Fig. 2. In panel (a), the x_{F}-dependence of the π^+/π^- (π^-/π^+) ratio in $p+p$ ($n+p$) collisions is shown. This data is used to construct a direct prediction for $A+A$ reactions, defined by the relative proton/neutron proportion in a given nucleus (see [1] for a detailed discussion). This prediction, panel (b), is closely fulfilled by data on Si + Si and central Pb + Pb collisions. The data on peripheral Pb + Pb reactions suggest a relative excess of neutrons over protons at the edge of the nucleus, an effect well known from nuclear physics.

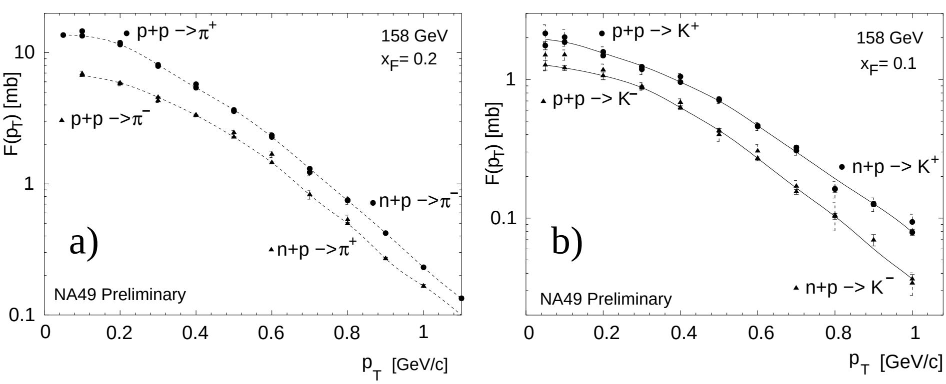

Fig. 1. (a) Invariant pion p_{T} distributions. Note the equalities $p+p \rightarrow \pi^+ = n+p \rightarrow \pi^-$ and $p+p \rightarrow \pi^- = n+p \rightarrow \pi^+$. (b) Invariant kaon p_{T} distributions. Note the equalities: $p+p \rightarrow K^+ = n+p \rightarrow K^+$ and $p+p \rightarrow K^- = n+p \rightarrow K^-$.

The second example is the $\sqrt{s}$-dependence of the mid-rapidity π^+/π^- ratio. The curve shown in Fig. 2(c) illustrates a compilation of experimental results on this ratio in $p+p$ collisions. The corresponding prediction for heavy ion reactions, shown in Fig. 2(d), is again closely fulfilled by the data.

To sum up, the behaviour of π^+/π^- ratios in $A+A$ reactions can be directly deduced from elementary $p+p$ and $n+p$ collisions. This inspires the extension of the above considerations to strangeness production. The kaons, Fig. 1(b), behave differently from pions: when changing the projectile no flip is observed. This has immediate consequences for collisions of nuclei, involving both protons and neutrons. A strangeness over pion ratio

[1] We always refer to the Feynman variable $x_{\mathrm{F}} = \frac{p_{\mathrm{L}}}{p_{\mathrm{L\ max}}}$ in the nucleon + nucleon c.m.s.

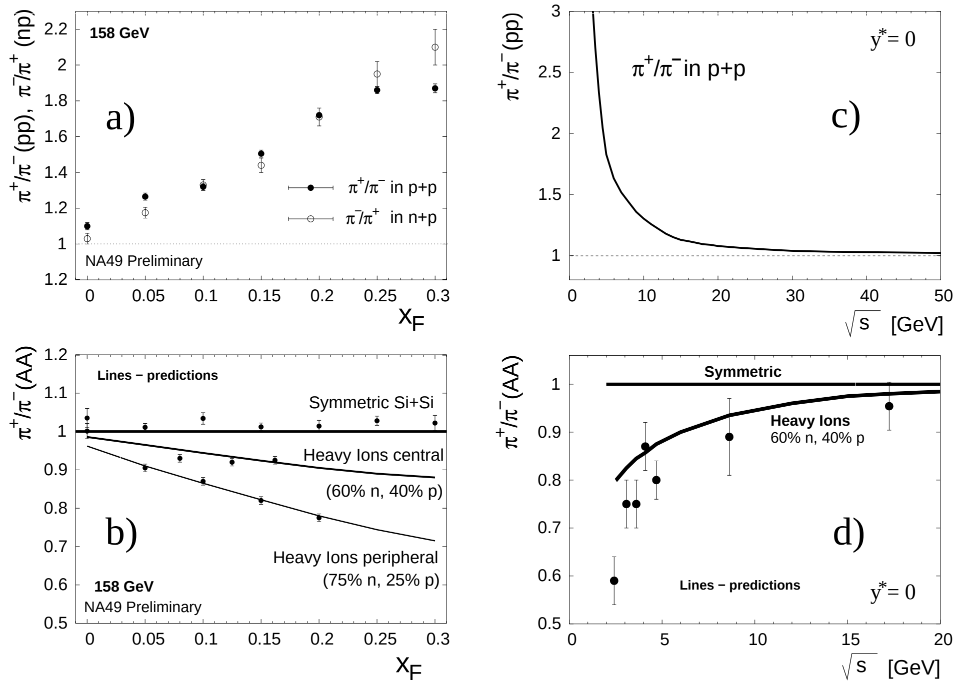

Fig. 2. (a) x_{F}-dependence of π^+/π^- (π^-/π^+) ratio in $p+p$ ($n+p$) collisions. (b) x_{F}-dependence of π^+/π^- in $A+A$ reactions, compared to the predictions described in the text. (c) $\sqrt{s}$-dependence of π^+/π^- ratio in $p+p$ reactions. (d) $\sqrt{s}$-dependence of π^+/π^- in $A+A$ collisions compared to the prediction described in the text.

like K^+/π^+ will be different for a participating neutron and proton. This difference will be given by the π^+/π^- ratio, as written below:

$$\left(\frac{K^+}{\pi^+}\right)^n = \left(\frac{K^+}{\pi^-}\right)^p = \left(\frac{K^+}{\pi^+}\right)^p \cdot \left(\frac{\pi^+}{\pi^-}\right)^p . \tag{1}$$

The importance of this observation is exemplified in Fig. 3. Panel (a) shows the x_{F}-dependence of K^+/π^+ in central Pb + Pb collisions, normalised to the same ratio in $p+p$ interactions. The analogous ratio measured in central $p+\mathrm{Pb}$ reactions is also shown in the figure; it is lower than in central Pb + Pb. However, following Eq. (1), the x_{F}-dependence of the π^+/π^- ratio in $p+p$ reactions shown in Fig. 2(a) can be used to estimate the increase of K^+/π^+ due to the presence of neutrons in the Pb nucleus. Once the K^+/π^+ ratio in Pb + Pb is corrected for this effect, it becomes similar to that observed in central $p+\mathrm{Pb}$ reactions. Thus an *enhancement* *of strangeness over pion production* does not necessitate a central Pb + Pb reaction; a proton colliding centrally with a Pb nucleus is sufficient to cause this effect [2].

Equation 1 has also an impact on the understanding of $\sqrt{s}$-dependence of the mid-rapidity K^+/π^+ ratio. In Fig. 3(b), a compilation of the $p+p$ data is shown [3]. Within sizeable uncertainties, the data can be parametrised by a constant function at high $\sqrt{s}$, followed by a steep threshold at low energies. This parametrisation is used to construct a direct prediction for Pb + Pb reactions, including the change of K^+/π^+ due to the presence of neutrons in the nucleus. The predicted Pb + Pb curve displays a non-monotonic behaviour. It should be noted that a similar non-monotonic "horn" seen in the $\sqrt{s}$-dependence of central $A+A$ reactions has been claimed as unique to heavy ion collisions, and as a possible signature of QGP formation [4]. Clearly, the behaviour shown in Fig. 3(b) appears as a consequence of processes present already in hadron+hadron interactions, and most of all of the mixed proton/neutron content of the nucleus. A similar non-monotonic behaviour is observed for the Λ/π^+ ratio in elementary collisions [1]. Thus, such a behaviour of the strangeness over pion ratio is not unique to $A+A$ reactions; it can be deduced from $p+p$ and $n+p$ interactions.

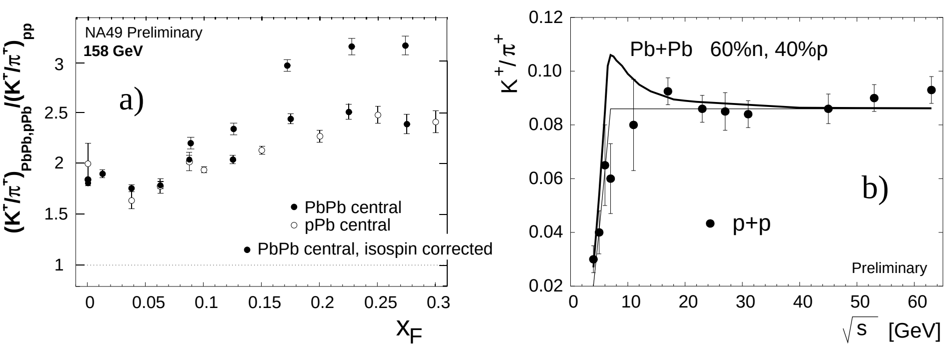

Fig. 3. (a) K^+/π^+ ratio in central Pb + Pb collisions, central $p+$ Pb reactions, and central Pb + Pb collisions corrected for the mixed isospin content of the Pb nucleus. (b) $\sqrt{s}$-dependence of the mid-rapidity K^+/π^+ ratio in $p+p$ collisions and the prediction for Pb + Pb reactions described in the text.

3. Multiple collisions

In a $p+A$ reaction, the projectile has to pass through a larger amount of nuclear matter relative to a $p+p$ collision. It can be said to undergo *multiple collisions* with several target nucleons. A similar situation can be expected to occur for each nucleon participating in an $A+A$ reaction. If

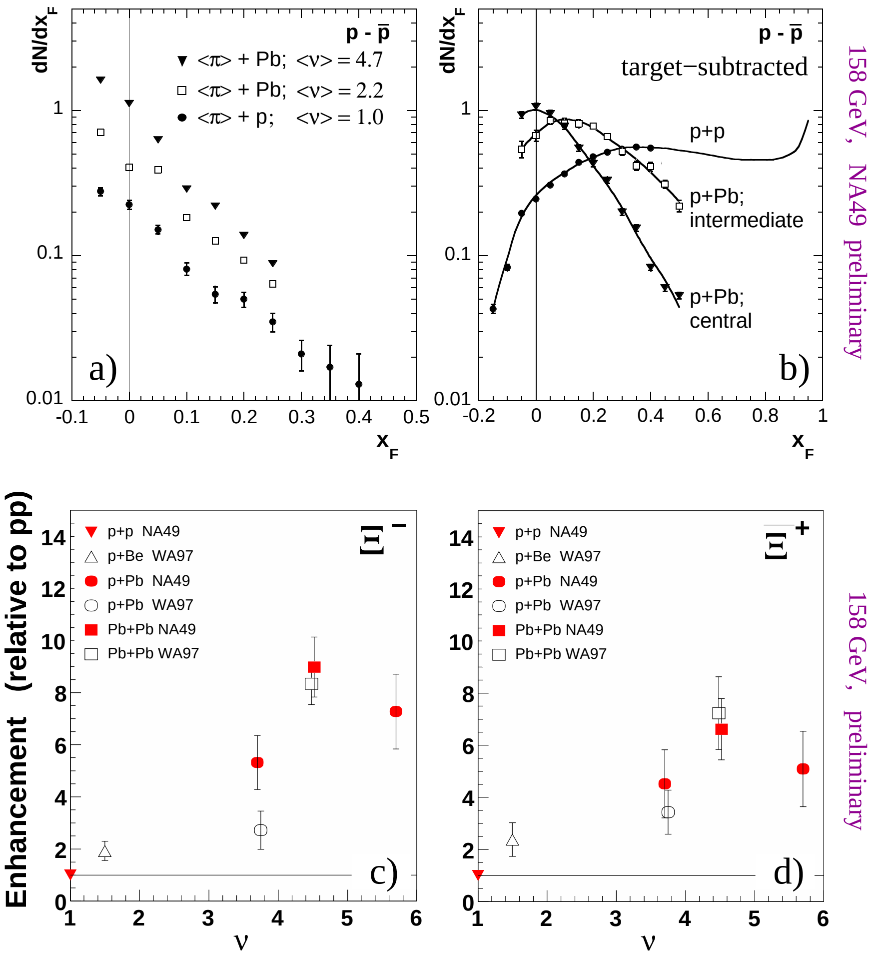

Fig. 4. Panels (a), (b): target and projectile components of net proton spectra. Panels (c), (d): mid-rapidity strangeness enhancement in $p+\mathrm{Pb}$ and central $\mathrm{Pb}+\mathrm{Pb}$ reactions relative to $p+p$ collisions, obtained for Ξ^- and $\overline{\Xi}^+$ baryons.

the contribution of the projectile to the $p+A$ reaction can be separated from that of the target, the role of multiple collisions in $p+A$ and $A+A$ can be compared directly. This problem of projectile-target separation has been studied on the basis of $p+p$ and $\pi+p$ data. It has been demonstrated that the net proton (p–$\bar{p}$) spectrum in $p+p$ collisions can be separated into independent target and projectile components. The target component can be isolated by means of isospin-averaged $\langle\pi\rangle+p$ data while the projectile component can be extracted by subtracting the $\langle\pi\rangle+p$ distribution from the $p+p$ spectrum [2].

Following this, net proton spectra in $p+\mathrm{Pb}$ reactions are split into target and projectile components, shown in Figs 4(a), (b). The centrality dependence of the target component ($\langle\pi\rangle+\mathrm{Pb}$ distribution in panel (a)) can be approximately described as a linear pile-up with the mean number ν of elementary collisions suffered by the projectile. This *passive* behaviour is expected for target nucleons hit *once* by the projectile and thus participating in a single elementary collision. The projectile component (target-subtracted spectrum in panel (b)) displays a very different, *active* behaviour known as the baryon stopping effect. An analogous analysis of Pb + Pb data [5] has shown a very similar behaviour of net proton spectra, suggesting a similar role of multiple collisions in $p+\mathrm{Pb}$ and Pb + Pb reactions.

The above findings have consequences for understanding of strange baryon production. A comparison of strange hyperon mid-rapidity yields in $p+p$, $p+\mathrm{Be}$, and $p+\mathrm{Pb}$ interactions [6] clearly shows that Wounded Nucleon Scaling underpredicts the $p+A$ data. In the presence of a *passive target* and *active projectile* seen above for $p+A$ reactions, it is natural to assume that the observed enhancement of strangeness production is solely due to the projectile [2]. Under this assumption, the strangeness enhancement in $p+A$ relative to $p+p$ reactions can be extracted. It is shown in Figs 4(c), (d) as function of ν. It appears comparable to strangeness enhancement observed in central Pb + Pb collisions, suggesting a similar origin for both effects.

4. Summary

The NA49 experiment provides a large, versatile dataset. The analysis of this dataset shows a non-trivial dependence of particle production on projectile isospin and on multiple collisions of the projectile. These effects can account for various phenomena seen in $A+A$ reactions. Extreme caution is therefore mandatory in the interpretation of $A+A$ data in a situation where a detailed experimental knowledge and theoretical understanding of more elementary reactions is still missing. This is particularly important in the case of claims of new physics like QGP formation in $A+A$ reactions.

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Note: for $\sqrt{s} < 12$ GeV, we approximate K^+/π^+ ratios at $y^* = 0$ by full phase space ratios deduced from Antinucci *et al.* Within 10%, this approximation is correct at SPS energies (where it underestimates the mid-rapidity ratio).

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