ELECTROMAGNETIC EFFECTS ON CHARGED PION SPECTRA AT SPS ENERGIES*

M. Kiełbowicz

for the NA61/SHINE Collaboration

Institute of Nuclear Physics Polish Academy of Sciences, 31-342 Kraków, Poland

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One of the main goals of the NA61/SHINE experiment at the CERN SPS is to study the properties of strongly interacting matter by a two-dimensional scan of elementary and nuclear reactions as a function of system size and collision energy. This paper presents new results on a new observable relevant to this part of the NA61/SHINE programme, which is the modification of positively (negatively) charged particle spectra by the electromagnetic repulsion (attraction) of final-state particles by the charged nuclear remnant, the spectator system. Preliminary measurements of π^+/π^- ratios in central and intermediate Ar+Sc collisions at beam momentum of 150 A GeV/c are shown, and compared to NA49 data in peripheral Pb+Pb collisions at 158 A GeV/c as a function of longitudinal and transverse pion momentum. In spite of a dramatic decrease in the magnitude of spectator charge, spectator-induced electromagnetic effects remain clearly visible in Ar+Sc reactions. This is the first measurement of these effects in the Ar+Sc system at SPS energies. Moreover, a comparison with electromagnetic Monte Carlo simulations is made, and conclusions on the space-time evolution of pion production in Ar+Sc and Pb+Pb collisions are presented.

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1. Introduction

This article will be dedicated to the results of our experimental study of electromagnetic (EM) effects, which were measured in nuclear collisions at the top CERN SPS energy. The main reason for this study is to provide new information on the space-time evolution of the collision [1]. The new measurements were recently obtained in Ar+Sc collisions and they will be compared to Pb+Pb reactions in this paper.

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The measurements were conducted as a part of the two-dimensional scan, in terms of beam momentum and the size of the colliding system, performed by the NA61/SHINE experiment [2]. Different projectile–target collision configurations measured within the NA61/SHINE programme are presented in Fig. 1.

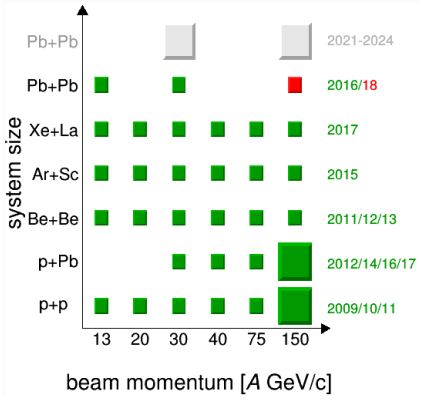

Fig. 1. Reactions collected by NA61/SHINE and proposed after CERN Long Shutdown 2. The size of the squares visualizes amount of data with the small squares corresponding typically to few million events.

2. Electromagnetic effects in Ar+Sc collisions

The spectator-induced electromagnetic distortion of the charged pion ratio was observed before in the NA49 experiment [3] in peripheral Pb+Pb collisions at 158 A GeV/c beam momentum (Fig. 3 (a)). A large charge asymmetry was found there, caused by the final-state electromagnetic repulsion (attraction) of positive (negative) pions by the highly charged spectator system.

At present, this effect is measured also in Ar+Sc collisions at 150 A GeV/c beam momentum, that is, $\sqrt{s_{NN}} = 16.8$ GeV, providing the first observation of this distortion in such a small system at the SPS. Centrality for Ar+Sc collisions was defined by the energy deposited in the Projectile Spectator Detector (PSD), essentially a forward rapidity calorimeter. On that basis, the information on centrality is obtained from dedicated Glauber simulations. To obtain information on charged particles emerging from the collision, the ionization in the Time Projection Chamber (TPC) is used (Fig. 2, left). Pion identification is achieved by ±5% cuts around the effective pion Bethe–Bloch curve (see Fig. 2, left and right). The uncertainties inherent in this analysis were studied in detail, including, in particular, kaon contamination, pion Bethe–Bloch determination precision and the contribution by

feed-down from weak decays. The overall stability of the π^+/π^- ratio appeared superior than that of π^+ or π^- spectra taken separately. The overall resulting biases on the latter ratio were estimated to remain below ± 0.06 (in absolute scale).

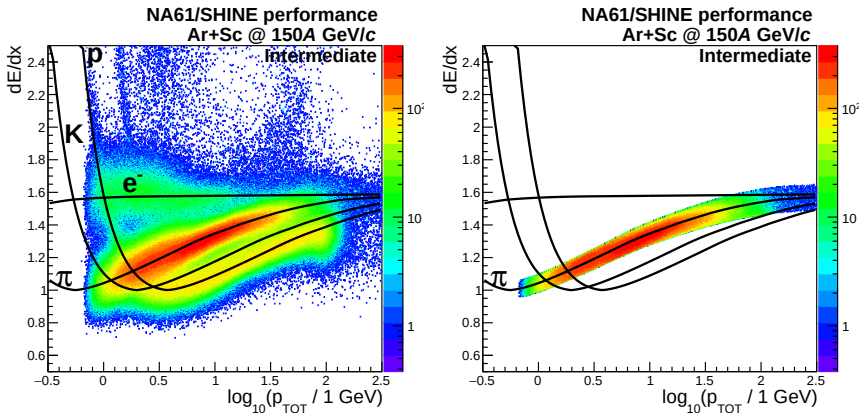

Fig. 2. Left: the ionization $\mathrm{d}E/\mathrm{d}x$ as a function of logarithm of total momentum for the negative particles in the NA61/SHINE time projection chambers for Ar+Sc collisions at 150 A GeV/c. Right: pion candidates selected by the particle identification method used in this analysis.

The results on Ar+Sc collisions are presented in Fig. 3 (b) and (c). The centrality of the two data samples is defined by the total number of wounded nucleons ($\langle N_{\mathrm{W}} \rangle$) and the number of Ar spectator nucleons ($\langle N_{\mathrm{s}}^{\mathrm{Ar}} \rangle$). The π^+/π^- ratio is drawn as a function of $x_{\mathrm{F}} = p_{\mathrm{L}}(\pi)/p_{\mathrm{L}}$ (*beam nucleon*) in the center-of-mass system of the collision. In the intermediate centrality sample (Fig. 3 (b)), this ratio shows a depletion at low transverse momenta. This effect is strongest for $x_{\mathrm{F}}(\pi) = 0.15$ which corresponds to pions close to beam rapidity ($y \approx y_{\mathrm{beam}}$). One finds that the spectator-induced EM effect is observed in intermediate centrality Ar+Sc collisions at 150 A GeV/c beam momentum. This is the first observation of this specific effect for small systems at the SPS.

The picture which emerges from the comparison (Fig. 3) of peripheral Pb+Pb reactions to intermediate and central Ar+Sc collisions is the following. For peripheral Pb+Pb reactions (Fig. 3 (a)) where the spectator charge is about 70 elementary units, one can observe a very large electromagnetic effect clearly seen as a lowering at the π^+/π^- ratio which goes down close to zero, for fast-moving pions at low transverse momentum. In intermediate centrality Ar+Sc collisions (Fig. 3 (b)) with spectator charge of about 8 elementary units, the spectator-induced electromagnetic effect is still well visible and large enough to break simple expectations imposed by isospin

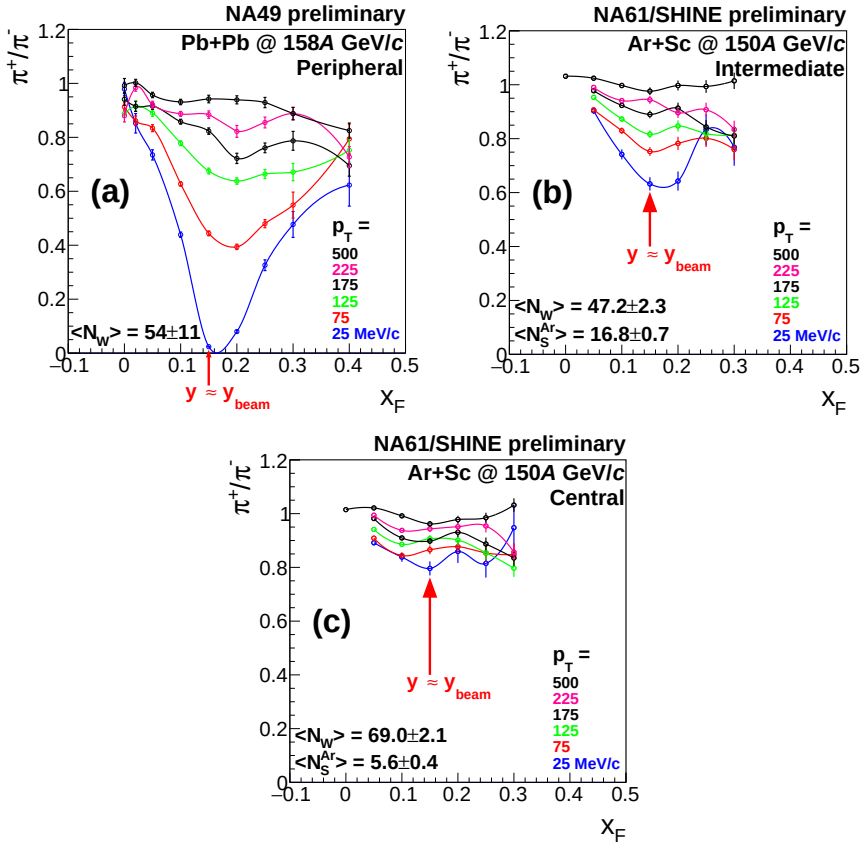

Fig. 3. Characteristic electromagnetic distortion for peripheral Pb+Pb (a), intermediate (b) and central (c) Ar+Sc collisions. The π^+/π^- ratios are presented as a function of x_F for six different values of transverse momentum p_T. Only statistical uncertainties are shown. Systematic biases of the Ar+Sc data are discussed in the text. $\langle N_\mathrm{W}\rangle$ and $\langle N_\mathrm{s}^\mathrm{Ar}\rangle$ are explained in the text.

symmetry with the $\frac{p}{n}$ ratio being equal to 0.82 in the $^{40}_{18}$Ar projectile. Interestingly, for the case of central Ar+Sc collisions (Fig. 3 (c)), some lowering of the ratio at beam rapidity can still be observed, suggesting a shadow of the EM distortion even for such a low spectator charge (about 3 e.u.).

It is known that the spectator-induced EM effects bring information on the space-time evolution of the reaction [4]. The new results presented here allow to obtain such information for Ar+Sc collisions along with a possible insight into the process of break-up of the spectator system [5]. Figure 4 (a), (b), (c) shows the results of a Monte Carlo model simulation of charged pion propagation in the EM field of the argon spectator. We underline that Fig. 4 overrides the erroneous MC result presented during this Workshop.

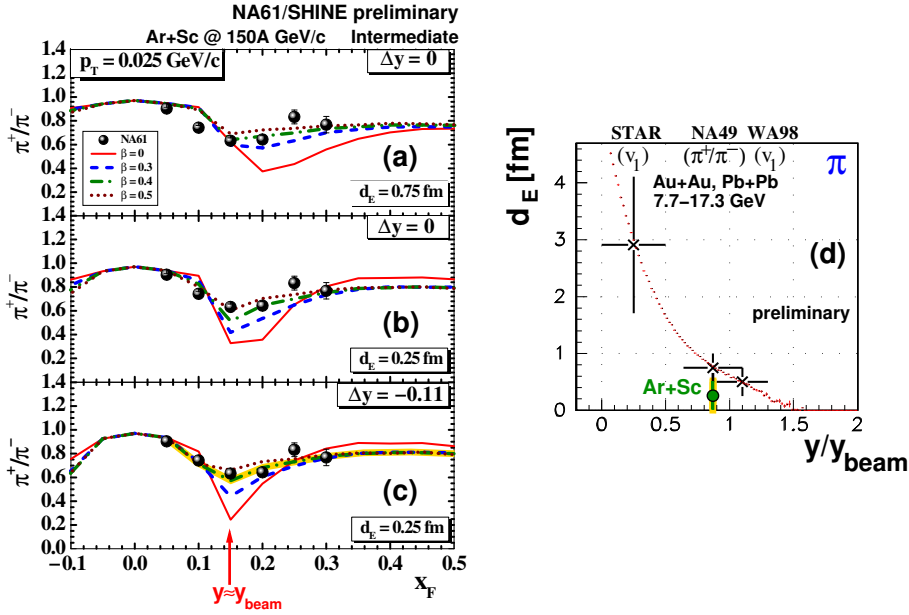

Fig. 4. (Colour on-line) (a), (b), (c) π^+/π^- ratio compared to model simulations, obtained for different combinations of the parameters d_{E}, β, and Δy described in the text. The optimal description of exp. data is indicated by the thick solid grey/yellow line. (d) The dependence of the pion emission distance d_{E} as a function of pion rapidity [3], obtained on the basis of exp. heavy-ion data [3, 6, 7] and compared to the value which corresponds to the present optimal description of Ar+Sc collisions.

The Monte Carlo model applied here is partially similar to that described in Ref. [8], with important modifications which will be explained below. The quantity d_{E} marked in Fig. 4 is the assumed distance between the pion emission zone at freeze-out and the Lorentz-contracted charged sphere, at the moment of pion emission taken in collision c.m.s. The parameter β is the assumed surface expansion velocity of the latter charged sphere, taken in its own c.m.s. Δy is the assumed rapidity shift of this sphere with respect to the original beam rapidity. As one can see in the figure, the assumption of a stable charged sphere ($\beta = 0$) does not describe the experimental data. A better description is achieved once a significant surface expansion velocity ($\beta \approx 0.4$) is assumed, see Fig. 4 (b). We note that the optimal description is obtained when an additional decrease in the rapidity of the expanding charged sphere, $\Delta y = -0.11$, is included in the model as shown in Fig. 4 (c). We interpret this as an indication for the sensitivity of EM effects on fast charged pion trajectories to the effective charge cloud composed of both

the full spectator and the faster part of participant matter, in intermediate Ar+Sc reactions. We note that such a behavior would be natural in the model of the longitudinal evolution of the system which was also presented at this Workshop (see Fig. 5 (a) in Ref. [10]).

An important conclusion from this study is that fast-moving pions in Ar+Sc collisions are emitted at a relatively small distance behind the spectator (or the corresponding effective charge cloud). This is quantified in Fig. 4 (d). The distance d_{E} which at present gives the optimal description of the intermediate Ar+Sc data is put in comparison to what was deduced from heavy-ion reactions on the basis of electromagnetic splitting of directed flow [1, 8] and of the distortion of π^+/π^- ratios [9]. At high pion rapidity, all the values of d_{E} appear roughly comparable and remain below 1 fm. As such, our new data fit the overall trend of a rapid decrease of the distance between the π meson emitted at freeze-out and the spectator charge with increasing pion rapidity. The emerging picture of the space-time evolution of pion production will be further discussed in [10] (see also [11]).

3. Summary

A selection of recent results on charged pion production measured by the NA61/SHINE experiment has been presented. New experimental data on the spectator-induced electromagnetic effect were shown for intermediate Ar+Sc collisions at 150 $A\,\mathrm{GeV}/c$ beam momentum. This is the first observation of this effect in such a small system at the CERN SPS.

The experimental data on intermediate and central Ar+Sc collisions presented in this paper bring new information on the space-time evolution of the reaction, and of charged π-meson production. The comparison of a dedicated Monte Carlo simulation to experimental data shows that a stable spectator ($\beta = 0$) cannot describe the data. The optimal description of the experimentally observed π^+/π^- ratio at low p_{T} requires both the expansion and the decrease in the average rapidity of the effective charge cloud seen by fast pions, pointing at the presence of both the spectator system and of the faster part of participant charge.

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