New results on energy and momentum conservation in meson production for A+A collisions at SPS energies

A. Rybicki^{1,*}, A. Szczurek^{1,2}, M. Kiełbowicz¹, K. Mazurek¹, and V. Ozvenchuk¹

¹H.Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, 31-342 Kraków, Poland

²University of Rzeszów, Rejtana 16, 35-959 Rzeszów, Poland

Abstract. We review our recent findings on electromagnetic (EM) effects in Ar+Sc and Pb+Pb collisions at CERN SPS energies, and discuss them in the context of our earlier results on the EM splitting of π^+/π^- meson directed flow. A specific space-time picture emerges, on the basis of which we construct a simple model of the collision. Starting from local energy and momentum conservation, we nicely describe the centrality dependence of π meson rapidity distributions in Pb+Pb collisions at $\sqrt{s_{NN}}=17.3$ GeV. We discuss the resulting implications on the role of energy and momentum conservation for the dynamics of meson production in A+A collisions. We present our conclusions on the link between the initial stages of the nuclear collision and the final state observables connected to strong and electromagnetic phenomena in charged meson emission. We also discuss the possibility to use the latter EM phenomena to obtain new insight into the spectator space-time evolution and excitation energy.

1 Introduction

Below we discuss the recent results of our research programme of phenomenological and experimental studies of electromagnetic (EM) effects, obtained in nuclear collisions in the CERN SPS and RHIC BES energy regime. The aim of this programme is to provide new information on the space-time evolution of the reaction by studying the spectator-induced EM effects on charged meson emission (see, e.g., [1]). In this context, new information has recently been obtained on EM effects in Ar+Sc collisions, on the role of energy-momentum conservation in the longitudinal evolution of the system in Pb+Pb collisions, and on the fragmentation of the spectator system in both reactions.

2 Electromagnetic effects in Ar+Sc collisions

First data on the spectator-induced electromagnetic (EM) distortion [2] of charged pion ratios have been obtained for Ar+Sc collisions at 150A GeV/c beam momentum, that is, $\sqrt{s_{NN}}=16.8$ GeV [3]. These are presented in Fig. 1(a). For Ar+Sc collisions at intermediate centrality, the π^+/π^- ratio drawn as a function of $x_F = p_L(\text{pion})/p_L(\text{beam nucleon})$ in the collision c.m.s., shows a significant depletion at low transverse momenta. The largest effect is observed for $x_F = 0.15 = m_\pi/m_p$, which corresponds to pions moving at spectator rapidity.

*e-mail: andrzej.rybicki@ifj.edu.pl

Figure 1. (a) π^+/π^- ratio in intermediate Ar+Sc collisions [3], (b),(c),(d) π^+/π^- ratio compared to model simulations described in the text, with the distance between the spectator and the pion at freeze-out set to $d_E = 0, 0.5$, and 1 fm. The optimal description of exp. data is indicated by the yellow line [3]. (e) Dependence of the distance d_E on pion rapidity [1], obtained on the basis of exp. heavy ion data [4–6] and compared to the value presently estimated for Ar+Sc collisions. (f) Sketch of our model [7]. (g) Comparison of our model predictions to experimental π^- rapidity spectra in Pb+Pb collisions [8]. For peripheral reactions, both exp. data and model are scaled up by an arbitrary factor (from [7]).

This distortion of the π^+/π^- ratio is caused by the final state electromagnetic repulsion (attraction) of positive (negative) pions by the spectator system. This is the first observation of this effect in small systems at the SPS.

It is known that spectator-induced EM effects bring information on the space-time evolution of the reaction [9]. Figs 1(c-e) show the results of a Monte Carlo model simulation of charged pion propagation in the EM field of the Ar spectator system. The model applied is similar to that described in [2]. The assumption of a stable spectator system ($\beta=0$) cannot describe the experimental data. The optimal description corresponds to the spectator expansion surface velocity of $\beta = 0.3$ in its own c.m.s., in combination with the distance $d_E = 0.5$ fm in collision c.m.s. between pions emitted at freeze-out and the Ar spectator. The former suggests a significant effect of spectator fragmentation; this will be further discussed below. The latter indicates that fast pions in Ar+Sc reactions are emitted at a small distance behind the spectator. This is quantified in Fig. 1(e) where the above pion emission distance d_E is drawn as a function of emitted pion rapidity. The distance estimated for intermediate Ar+Sc collisions appears comparable to that obtained for heavy ion reactions on the basis of EM-splitting of directed flow [2, 10] and of the distortion of π^+/π^- ratios [11]. Taken together with information obtained from heavy ion data, the distance between the π meson emitted at freeze-out and the spectator system decreases rapidly with increasing pion rapidity.

3 The longitudinal evolution of the system

The observation made in Fig. 1(e) inspired the construction of a simple model of the initial stage of the A+A collision, local in the impact parameter plane, with some degree of similarity to the “fire-streak” approach [12, 13]. This model [7] assumes the formation of longitudinal elements of excited matter as shown in Fig. 1(f). Starting from local energy and momentum conservation, we nicely describe the complete centrality dependence of the absolutely normalized π^- rapidity distribution in Pb+Pb collisions at $\sqrt{s_{NN}}=17.3$ GeV, and in particular also the broadening of this distribution from central to peripheral collisions as shown in Fig. 1(g). This indicates that the longitudinal evolution of the system created in the collision is largely dominated by energy and momentum conservation, with consequent impact on longitudinal spectra and yields of produced π mesons.

4 Spectator fragmentation

The results on Ar+Sc reactions described above inspired a new analysis of EM effects in Pb+Pb collisions at $\sqrt{s_{NN}}=17.3$ GeV, more refined than our earlier study [9]. Fig. 2(a) shows

Figure 2. (a) π^+/π^- ratio in peripheral Pb+Pb reactions [11], compared to model simulations described in the text, with the distance d_E set to 0.75 fm and different values assumed for the spectator expansion surface velocity β . (b) Theoretical calculations of spectator excitation energy [14], compared to the kinetic energy of the expanding sphere described in the text.

the comparison between the π^+/π^- ratio measured in peripheral Pb+Pb reactions and our new electromagnetic Monte Carlo simulation which allows for the radial expansion of the spherical spectator with a given surface velocity β in its own c.m.s. Similarly to Ar+Sc collisions, a stable spectator ($\beta=0$) does not provide the optimal description of the data. The latter is provided by $\beta \approx 0.2 \pm 0.05$ (the error is tentatively estimated from the curves shown in the Figure). In order to get a first idea of what this could correspond to in terms of energy, in Fig. 2(b) this value of β is recalculated into kinetic energy under the simplest assumption of a radially expanding sphere. The comparison of this result to recent theoretical calculations [14] based on LSD [15, 16] and ABRABLA models [17, 18] displays some degree of consistency, at least with the excitation energy obtained from ABRABLA. To draw definite conclusions would be, at the present moment, clearly premature. However, it seems that spectator-induced EM effects on charged meson spectra, Figs 1(a), 2(a), can provide new insight into the space time evolution not only of the *participant*, but also of the *spectator* system.

5 Summary

New experimental and phenomenological results on spectator-induced EM effects in the final state of intermediate ion (Ar+Sc) and heavy ion (Pb+Pb) collisions have recently been obtained in the SPS energy regime. These provide new information on the space-time evolution of the reaction. On one hand, the presented results suggest a specific picture of the longitudinal evolution of the participant system at the initial stage of the collision, largely governed by energy-momentum conservation. On the other hand, they offer the possibility to obtain new, independent information on the fragmentation of the spectator system.

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References

- [1] A. Rybicki *et al.*, EPJ Web Conf. **130**, 05016 (2016)
- [2] A. Rybicki and A. Szczurek, Phys. Rev. C **87**, 054909 (2013)
- [3] M. Kielbowicz [NA61/SHINE Collaboration], talk at the XIII Workshop on Particle Correlations and Femtoscopy (WPCF2018), Kraków, Poland, to appear in Acta Phys. Pol. B Proc. Suppl.
- [4] L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **112**, 162301 (2014)
- [5] H. Schlagheck [WA98 Collaboration], Nucl. Phys. A **663**, 725 (2000)
- [6] A. Rybicki, PoS (**EPS-HEP2009**), 031 (2009)
- [7] A. Szczurek, M. Kielbowicz and A. Rybicki, Phys. Rev. C **95**, 024908 (2017)
- [8] T. Anticic *et al.*, Phys. Rev. C **86**, 054903 (2012)
- [9] A. Rybicki, A. Szczurek, Phys. Rev. C **75**, 054903 (2007)
- [10] A. Rybicki *et al.*, Acta Phys. Polon. B **46**, 737 (2015)
- [11] A. Rybicki *et al.*, Acta Phys. Polon. Supp. **9**, 303 (2016), and references therein
- [12] W. D. Myers, Nucl. Phys. A **296**, 177 (1978)
- [13] R. Hagedorn, doi:10.5170/CERN-1971-012
- [14] K. Mazurek *et al.*, Phys. Rev. C **97**, 024604 (2018)
- [15] K. Pomorski, J. Dudek, Phys. Rev. C **67**, 044316 (2003)
- [16] J. Dudek *et al.*, Eur. Phys. J. A **20**, 165 (2004)
- [17] J. Gaimard, K. Schmidt, Nucl. Phys. A **531**, 709 (1991)
- [18] A. Kelic *et al.*, arXiv:0906.4193 [nucl-th]