Mean transverse mass of hadrons
in proton-proton reactions

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Abstract

An energy dependence of the mean transverse mass $\langle m_T \rangle$ at mid-rapidity in proton-proton ($p + p$) reactions is studied within the ultra-relativistic quantum molecular dynamics (UrQMD). The UrQMD model predicts a nonmonotonic dependence of $\langle m_T \rangle$ on collision energy for several hadron species: for $\pi^+$, $p$, $K^+$, and $\Lambda$ the mean transverse mass has a maximum at the center of mass energy region $5 \leq \sqrt{s} \leq 8$ GeV. These results are a consequence of an interplay of two contributions: 1) excitations and decays of the baryonic resonances $N^*$ and $\Delta$; 2) excitations and decays of the baryonic strings. The UrQMD results do not show any nonmonotonic dependence of $\langle m_T \rangle$ on $\sqrt{s}$ for $\pi^-$, $K^-$, and antiprotons. Whether a nonmonotonic dependence of $\langle m_T \rangle$ at mid-rapidity on the collision energy for $\pi^+$, $p$, $K^+$, and $\Lambda$ is relevant for real $p + p$ interactions will be soon checked experimentally by the NA61/SHINE Collaboration.

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Experimental data on hadron production in central Pb+Pb collisions obtained by the NA49 Collaboration [1–3] at the Super Proton Synchrotron (SPS) of the European Organization for Nuclear Research (CERN) are consistent with the onset of deconfinement in central nucleus-nucleus collisions at about $\sqrt{s_{NN}} = (7–8)$ GeV [4–6], where $\sqrt{s_{NN}}$ is the center of mass energy of two nucleons from colliding nuclei. An important experimental result in this context is an observation of a step-like behavior of a mean value of the transverse mass $m_T = \sqrt{m^2 + p_T^2}$, where $m$ is a particle mass and $p_T$ its transverse momentum. The mean transverse mass $\langle m_T \rangle$ for different hadron species ($\pi^-$, $K^\pm$, $p$, and $\bar{p}$) measured at mid-rapidity in central Pb+Pb collisions demonstrates an increase at small and large collision energies, but it remains approximately constant in the SPS energy range $\sqrt{s_{NN}} = 7.6–17.3$ GeV (see Fig. 8 in Ref. [3]). This is the energy region, where one expects the transition between confined and deconfined matter with the creation of mixed phase. Such an energy dependence of $\langle m_T \rangle$ is indeed typical for a 1st order phase transition in the mixed-phase region [7–9]. In existing up to now data, there were no indications on such type of $\langle m_T \rangle$ dependence on the center of mass energy $\sqrt{s}$ in proton-proton ($p + p$) reactions.

A further progress in understanding the effects related to the onset of deconfinement can be achieved by a new comprehensive study of hadron production in $p + p$, proton-nucleus, and nucleus-nucleus collisions. This motivated the present NA61/SHINE ion programme at the SPS CERN devoted to the system size and energy scan [10, 11] and the Beam Energy Scan (BES) programme at the Relativistic Heavy Ion Collider (RHIC) of the Brookhaven National Laboratory (BNL) [12]. These efforts will be extended by the future Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) [13, 14], which will employ high-luminosity beams and large-acceptance detectors to study system-size and energy dependence of hadron production in proton-nucleus and nucleus-nucleus collisions.

In Ref. [15], we analyzed recent NA61/SHINE data [16] on $\pi^-$ spectra in $p + p$ reactions within the ultra-relativistic quantum molecular dynamics (UrQMD) model [17, 18]. The version UrQMD-3.3p2 [19] was used in Ref. [15]. Recently a new version, UrQMD-3.4 [20], was released. It will be used in the present study. Both the data and the UrQMD simulations demonstrate a monotonous increase of $\langle m_T \rangle$ with collision energy for $\pi^-$ at mid-rapidity. This is shown in Fig. left. Unexpectedly, the UrQMD has predicted a nonmonotonous dependence of $\langle m_T \rangle$
on collision energy for $\pi^+$ in $p + p$ reactions: the mean transverse mass of positively charged pions evaluated at mid-rapidity decreases notably with the collision energy inside the region of $\sqrt{s} = 5 - 8$ GeV. This is shown in Fig. 1 right.

Figure 1: The mean transverse mass $\langle m_T \rangle - m_\pi$ of $\pi^-$ (left panel) and $\pi^+$ (right panel) in $p + p$ reactions as a function of the center of mass energy $\sqrt{s}$. The rapidity window in the center of mass system is $0 < y < 0.2$. The solid lines show the results of UrQMD-3.4 calculations. The symbols with error bars in the left panel are the data from Ref. [16].

The nonmonotonous dependence of $\langle m_T \rangle$ on $\sqrt{s}$ seen in Fig. 1 right for $\pi^+$ accepted at mid-rapidity are absent for the UrQMD results taken at all rapidities. This is in an agreement with a compilation of the old $p + p$ data in Ref. [21].

A physical origin of the nonmonotonous dependence of $\langle m_T \rangle$ on $\sqrt{s}$ for $\pi^+$ in $p + p$ reactions is connected to a presence of two different sources of pions. Main inelastic reactions at small energies are the following [17, 18]:

$$
p + p \to p + \Delta^+ , \quad p + p \to n + \Delta^{++} , \quad p + p \to \Delta^+ + \Delta^+ , \quad p + p \to \Delta^0 + \Delta^{++} , \quad p + p \to p + N^+ , \quad p + p \to N^+ + \Delta^+ , \quad p + p \to N^0 + \Delta^{++} .
$$

Specific charge states of $N^*$ and $\Delta$ emerged in Eq. (1) explain a difference in a production of $\pi^-$ and $\pi^+$: only $\Delta^0$ and $N^0$ may produce $\pi^-$ after their decays, whereas $\Delta^+$ and $N^+$ may produce only $\pi^+$, and $\Delta^{++}$ has to produce $\pi^+$.

The reactions listed in (1) give the dominant contribution to the $p + p$ inelastic cross section
at small collision energies. However, at $\sqrt{s} \geq 4$ GeV the excitations of baryonic strings,

$$p + p \rightarrow \text{String} + \text{String},$$

(2)

open the new channels of hadron production. At collision energies $\sqrt{s} \geq (6 - 8)$ GeV the string production dominates in the UrQMD description of inelastic $p + p$ cross section [17].

We can distinguish two sources contributing to hadron production in $p + p$ reactions: 1) the excitations of baryonic resonances listed in (1) and their decays to final hadrons; 2) the excitation of strings according to (2) and their decays to final hadrons. The mean transverse mass of a final hadron can be presented as

$$\langle m_T \rangle = f_B \langle m_T \rangle_B + f_S \langle m_T \rangle_S,$$

(3)

where $f_B(\sqrt{s})$ and $f_S(\sqrt{s})$ are the fractions of multiplicities for a given hadron species from excited baryons (1) and from strings (2), respectively. In Eq. (3), $\langle m_T \rangle_B$ and $\langle m_T \rangle_S$, also dependent on $\sqrt{s}$, are the values of the mean transverse mass for a hadron originating from these two sources. At SPS energies, the UrQMD gives $f_S > f_B$ for $\pi^+$. Besides, $f_S$ increases and $f_B$ decreases with $\sqrt{s}$. On the other hand, there is an opposite inequality, $\langle m_T \rangle_B > \langle m_T \rangle_S$, between the transverse masses of $\pi^+$ produced by baryons and by strings. This has a simple kinematic origin. To produce $\pi^+$ at mid-rapidity according to Eq. (1) baryonic resonances $N^*$ or $\Delta$ should be themselves created in the mid-rapidity region. Thus, with increasing $\sqrt{s}$ transverse momentum and/or mass of the baryonic resonance has to increase. This leads to an increase of $\langle m_T \rangle_B$ of final $\pi^+$ with $\sqrt{s}$. An interplay of these two contributions to $\langle m_T \rangle$ in Eq. (3) leads to a nonmonotonous dependence on $\sqrt{s}$ of the resulting mean transverse mass as it seen in Fig. 1 right (see Ref. [15] for further details).

Note that $K^-$ and $\bar{p}$ can not appear from decays of the baryonic resonances contributed to Eq. (1). In Fig. 2 left we present the UrQMD values of $\langle m_T \rangle - m$ at mid-rapidity for these hadrons as the functions of collision energy. No nonmonotonous dependence of $\langle m_T \rangle$ on $\sqrt{s}$ are seen.

Protons are obviously produced from decays of baryonic resonances excited according to Eq. (1). Heavy $N^*$ have the following decay channel: $N^* \rightarrow \Lambda + K^+$. Therefore, Eq. (3) can be also applied to a description of $\langle m_T \rangle$ for $p$, $\Lambda$, and $K^+$ in $p + p$ reactions. These UrQMD results
are shown in Fig. 2 right. A non-monotonous dependence of $\langle m_T \rangle - m$ on $\sqrt{s}$ at mid-rapidity ($0 < y < 0.2$) are observed for these hadron species. Like in a case of $\pi^+$, it disappears if final hadrons are detected in unrestricted rapidity window.

Figure 2: The results of the UrQMD-3.4 calculations for the mean transverse masses $\langle m_T \rangle - m$ in $p + p$ reactions as a function of collision energy. The rapidity window in the center of mass system is $0 < y < 0.2$. The error bars depict statistical uncertainties. Left: $K^-$ (dashed line) and anti-protons (dotted line). Right: Protons (solid line), $\Lambda$ (dashed line), and $K^+$ (dashed-dotted line).

Figure 3: The mean transverse mass $\langle m_T \rangle - m$ of $\pi^+$ (left panel) and protons (right panel) in $p + p$ reactions as a function of collision energy. The rapidity window in the center of mass system is $0 < y < 0.2$. Solid lines correspond to the results of UrQMD-3.4, dashed ones to UrQMD-3.3, and dotted ones to HSD-2.5.
Predictions of non-monotonous energy dependence for the mid-rapidity values of $\langle m_T \rangle$ for $\pi^+$, protons, and $\Lambda$ in $p+p$ reactions is based on the UrQMD results. It is a consequence of interplay of the contributions from baryonic resonances and strings. Note, however, that the version UrQMD-3.3 \cite{19} includes the baryonic resonances $N^*$ and $\Delta$ with artificially large masses which are not listed in the Particle Data Tables. In the last version UrQMD-3.4 \cite{20} used in the present paper some of these baryonic resonances are omitted. In Figs. 3 left and right we present the results for $\pi^+$ and protons, respectively, obtained within two different versions of UrQMD, 3.3 and 3.4, as well as with the Hadron String Dynamics (HSD-2.5) \cite{22–24}. The number of baryon species in the HSD model is smaller than that in UrQMD. In fact, not all baryonic resonances from the Particle Data Tables are included. Note that inelastic $p+p$ reactions above $\sqrt{s} \approx 2.6$ GeV are described in HSD-2.5 by the FRITIOF string model \cite{25}.

As seen from Fig. 3 both UrQMD-3.3 and UrQMD-3.4 predict a non-monotonous dependence of $\langle m_T \rangle$ on $\sqrt{s}$ for $\pi^+$ and protons at mid-rapidity, whereas the HSD results give a monotonous increase of $\langle m_T \rangle$ with collision energy for both $\pi^+$ and protons.

In conclusion, within the UrQMD simulations we have observed an unexpected dependence on the collision energy of the mean transverse mass $\langle m_T \rangle$ at mid-rapidity in inelastic $p+p$ collisions: a drop for $\pi^+$ at $5 \leq \sqrt{s} \leq 8$ GeV, a drop for $K^+$ at $4 \leq \sqrt{s} \leq 7$ GeV, a decrease for protons at $5 \leq \sqrt{s} \leq 17.3$ GeV and a decrease for $\Lambda$ at $8 \leq \sqrt{s} \leq 17.3$ GeV. These results are the specific feature of UrQMD with its overpopulated spectrum of baryonic resonances $N^*$ and $\Delta$. A nonmonotonous dependence of $\langle m_T \rangle$ on $\sqrt{s}$ for both $\pi^+$ and protons are not found in the HSD model, where the baryonic spectrum is underpopulated. Whether a non-monotonous dependence of $\langle m_T \rangle$ on $\sqrt{s}$ at mid-rapidity for $\pi^+$, protons, $K^+$, and $\Lambda$ is relevant for real $p+p$ interactions will be checked soon experimentally by the NA61/SHINE Collaboration.

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[1] S.V. Afanasiev et al. [NA49 collaboration], Phys. Rev. C 66, 054902 (2002).
[2] C. Alt et al. [NA49 collaboration], Phys. Rev. C 73, 044910 (2006).
[3] C. Alt et al. [NA49 collaboration], Phys. Rev. C 77, 024903 (2008).
[4] M. Gazdzicki and M. I. Gorenstein, Acta Phys. Polon. B30, 2705 (1999);
[5] M. Gazdzicki, M. I. Gorenstein, and P. Seyboth, Acta Phys. Polon. B 42, 307 (2011).
[6] M. Gazdzicki, M. I. Gorenstein, and P. Seyboth, Int. Journ. Mod. Phys. E 23, 1430008 (2014).
[7] L. Van Hove, Phys. Lett. B118, 138 (1982).
[8] C. Hung and E. Shuryak, Phys. Rev. Lett. 75, 4003 (1995).
[9] M. I. Gorenstein, M. Gazdzicki, and K. A. Bugaev, Phys. Lett. B 567, 175 (2003).
[10] M. Gazdzicki [NA61/SHINE Collaboration], J. Phys. G 36, 064039 (2009).
[11] N. Abgrall et al. [NA61 Collaboration], JINST 9, P06005 (2014).
[12] G. S. F. Stephans, J. Phys. G 32, S447 (2006); G. Odyniec, PoS CPOD 2013, 043 (2013).
[13] B. Friman, C. Hohne, J. Knoll, S. Leupold, J. Randrup, R. Rapp, and P. Senger, Lect. Notes Phys. 814, 1 (2011).
[14] P. Senger [CBM Collaboration], Cent. Eur. J. Phys., 10, 1289 (2012); see also http://www.fair-center.eu/for-users/experiments/cbm.html.
[15] V.Yu. Vovchenko, D.V. Anchishkin, and M.I. Gorenstein, arXiv:1407.0629 [nucl-th], Phys. Rev. C, in print.
[16] N. Abgrall et al. [NA61 Collaboration], Eur. Phys. J. C 74, 2794 (2014).
[17] S.A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998).
[18] M. Bleicher et al., J. Phys. G 25, 1859 (1999).
[19] H. Petersen, M. Bleicher, S.A. Bass, and H. Stöcker, arXiv:0805.0567 [hep-ph].
[20] UrQMD-3.4 code is available at http://urqmd.org/
[21] A.M. Rossi et al., Nucl. Phys. B 84, 269 (1975).
[22] W. Ehehalt and W. Cassing, Nucl. Phys. A 602, 449 (1996).
[23] J. Geiss, W. Cassing, and C. Greiner, Nucl. Phys. A 644, 107 (1998).
[24] W. Cassing and E.L. Bratkovskaya, Phys. Rept. 308, 65 (1999).

[25] B. Nilsson-Almqvist and E. Stenlund, Comput. Phys. Commun. 43, 387 (1987).