MULTIPLICITY AND TRANSVERSE ENERGY DISTRIBUTIONS IN p+A AND A+A COLLISIONS

By J. L. Kacperski

Institute of Physics, University of Łódź

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Multiplicity and transverse energy distributions in the midrapidity region in p + nucleus and nucleus + nucleus collisions are reconstructed on the basis of independent nucleon + + nucleon interactions in wide range of beam energies.

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Introduction

There are several observables suggested as possible signatures for the quark-gluon plasma (QGP) formation, e.g. large fluctuations in multiplicities of produced particles and a strong increase of transverse momentum per particle with a change in the slope near the phase transition [1]. From this point of view it is interesting to investigate multiplicity distributions and closely connected with them transverse energy distributions in ultra-relativistic heavy ion collisions. The collective effects like QGP formation could then be seen as an excess above the "conventional" back-ground built on the basis of convoluted p+p distributions. The model predictions for $A+A$ collisions are in the simplest case just the straightforward extrapolation of characteristics known from the analysis of the "less complicated" p+p interactions — the resulting distribution in p+A and $A+A$ collisions being built up as a sum of many independent contributions from soft final state hadrons (see e.g. [2, 3]). In this article the p+A and $A+A$ multiplicity and transverse energy distributions are calculated in a purely phenomenological way on the basis of the simple parametrization of the transverse momentum distribution in p+p collisions, without any model assumptions on elementary (*quark* + *quark*) interactions.

The p+A collision with p+p as input

It is well known that single particle transverse momentum distribution dN/dp_T^2 approximates at fixed value of the scaling variable x an exponential $\sim \exp(-2p_T/\langle p_T\rangle)$ with $\langle p_T\rangle = 0.35$ GeV/c, at least for p_T smaller than 1.5 GeV/c. If so, then the dN/Ndp_T distribu-

* Address: Instytut Fizyki, Uniwersytet Łódzki, Pomorska 149/153, 90-236 Łódź, Poland.

tion, and, approximately, also the dN/NdE_T one, is described by the "linear-exponential" formula:

$$dN/Ndp_T = p_T \exp(-p_T/p_0)/p_0^2, \tag{1}$$

where $E_T = (m_\pi^2 + p_T^2)^{1/2} \cong p_T$; $p_0 = \langle p_T \rangle/2 = 0.175$ GeV/c.

The transverse momentum distribution is in our scheme independent of incident energy, longitudinal momentum and nuclear size. The formula (1) represents the gamma-distribution $\Gamma(p_T)_{\alpha,\nu} = \alpha^\nu p_T^{\nu-1} \exp(-\alpha p_T)/\Gamma(\nu)$, with $\nu = 2$ and $\alpha = p_0^{-1}$. The distribution of the transverse energy of k produced particles has still the form of the gamma-distribution as a k-fold convolution of the last one ($\Gamma_{\alpha,\nu} * \Gamma_{\alpha,\mu} = \Gamma_{\alpha,\mu+\nu}$, where we have used the symbol "*" for the operation of folding):

$$f_k(E_T) = p_0^{-2k} p_T^{2k-1} \exp(-p_T/p_0)/\Gamma(2k), \tag{2}$$

where $\Gamma(2k) = (2k-1)!$

The total transverse energy distribution is then a weighted sum of distributions (2):

$$f(E_T) = \sum_1^\infty P_k f_k(E_T). \tag{3}$$

Where P_k is the multiplicity distribution in p+p collisions, e.g. negative binomial distribution, with parameter values depending on the accepted phase-space volume. In our *Monte-Carlo* scheme the multiplicity of produced particles is determined by the mass of the central cluster:

$$M^* = \sum_{k=1}^{n} E_k^* = \sum_{k=1}^{n} E_{T,k} \cosh(y_k^*), \tag{4}$$

with

$$M^* = K_{in}(s^{1/2} - 2m_N), \tag{5}$$

where K_{in}, $s^{1/2}$ and m_N are the coefficient of inelasticity, total available centre-of-mass energy and nucleon mass. E_k^*, $E_{T,k} = (m_k^2 + p_{T,k}^2)^{1/2}$ and y_k^* are the cms-energy, transverse energy and cms-rapidity of the k-th particle, respectively.

We have assumed that neutral pions constitute 1/3 of the total pion yield and that the relative yields of produced pions, kaons and nucleons are 0.88 : 0.08 : 0.04. In the case of total (or charged) E_T distribution, transverse energies of "leading" protons are taken into account. The rapidities of emitted particles are sampled from a Gaussian distribution with dispersion σ_0 proportional to y_{max}, where $y_{max} = \ln[(s^{1/2} - 2m_N)/m_\pi]$ denotes the maximum rapidity reached for given cms-energy $s^{1/2}$(m_N and m_π are the nucleon and pion masses, respectively, and $\sigma_0 = 1.36$ at 205 GeV).

The p+A collisions differ significantly from the p+p ones: particles with small rapidities are produced inside the target nucleus and they can collide with the target nucleons. We shall present a simple extension of the picture of independent p+p collisions to the p+A and A+A collisions in the central rapidity region, where the contribution of projectile and target fragmentation products can be neglected. According to the standard picture the incident hadron interacts incoherently with ν nucleons of the target in the tube of cross section $\sim\sigma_{in}^{hN}$. In the p+A collision, each nucleon in the target nucleus participates in one at most interaction, whereas the average number of inelastic collisions of the projectile is $\langle\nu\rangle = A\sigma_{in}^{pN}/\sigma_{in}^{pA}$. Further we adopt the picture of the p+A collision presented in [4], where the first collision differs clearly from the subsequent ones: only in the first collision both projectile and target nucleons can be excited. The inelasticity coefficient K_ν is connected with the mean energy of a proton after ν collisions, $\langle E_\nu\rangle$, via the relation:

$$\langle E_p\rangle_\nu = (1-K_\nu)\langle E_p\rangle_{\nu-1}. \tag{6}$$

The experimental value of K_ν, obtained from the analysis of the reaction p+A at 100 and 200 GeV, equals to about 0.5 and 0.2 for $\nu = 1$ and $\nu > 1$ respectively [4]. If the proton multiply interacts inside the nucleus with energy loss in the ν-th collision equal to K_ν, and only particles which fall into a given rapidity window, Δy, fixed in the laboratory are registered, then the average number of particles generated in successive collisions monotonically decreases. This drop follows from the total multiplicity drop, the narrowing rapidity distributions $y_{max}-y_{min} \sim \ln(s/m_N^2)$ and the shift of the CM system rapidity: $y_{CM} = \frac{1}{2}\ln[(1+\beta_{CM})/(1-\beta_{CM})]$, where β_{CM} denotes the velocity of the CM system. These effects can be easily taken into account if the rapidity distribution in p+p collisions is parametrized by the Gaussian shape (the role of the central "fire-ball" is dominant up to $y_{CM} \sim 1.5$). The distribution of proton collisions inside a target nucleus is calculated on the basis of geometrical picture of the $p+A$ collision with two parameter Woods-Saxon form describing the nuclear matter density:

$$\varrho(r) = \varrho(0)/\{1+\exp[(r-R)/a]\}, \tag{7}$$

with $\varrho(0)$ determined from the normalization condition $A = \int \varrho(r)d^3r$: $\varrho(0) = 3A/4\pi R^3(1+\pi^2a^2/R^2)$; ($R = r_0A^{1/3}+r_1$; $r_0 = 1.24$ fm; $r_1 = -0.71$ fm; $a = 0.51$ fm [5]). The mean free path of a nucleon in nuclear matter is estimated as $\lambda = 1/\varrho\sigma$, where σ denotes the p+p inelastic cross section and ϱ — the normal nuclear density. With a "non-diffractive" part of the total inelastic cross section, $\sigma = 25$ mb, and $\varrho_0 = 0.145\ \text{fm}^{-3}$, we have $\lambda = 2.76$ fm.

Fig. 1 presents the calculated multiplicity distributions of charged particles in 200 GeV p+p, p+Ar and p+Xe collisions, registered in different rapidity intervals. The inelasticity coefficients were sampled from rectangular distributions $\langle 0.1, 0.9\rangle$ and $\langle 0.1, 0.3\rangle$ for $\nu = 1$ and $\nu > 1$ respectively (uniformly distributed inelasticity agrees satisfactorily for $\nu = 1$ with rapidity loss distribution for the leading positive particle in 200 GeV p+p collisions [14], except for the largest rapidity losses).

We assume that the "survived" proton transverse momentum is independent of the number of collisions ν [4]. The relative yields of p+p and p+n collisions are determined by the Z/A ratio of the target nucleus. The intranuclear cascading process is not taken into account. The description of the data is good, except for high multiplicity tails of the distributions in the widest rapidity intervals for the heaviest target (Xe) where experimental errors are anyway rather large.

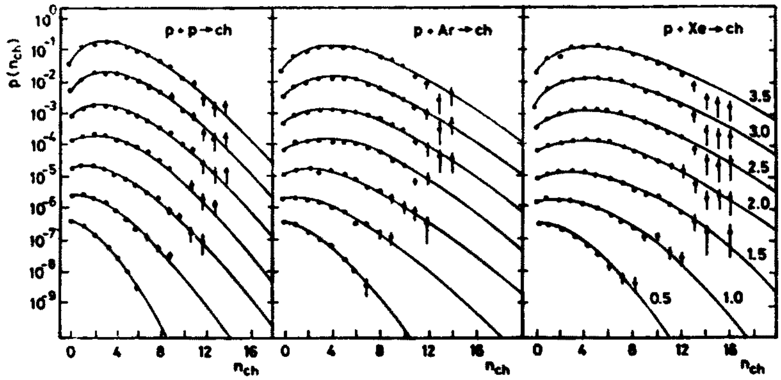

Fig. 1. Multiplicity distributions of charged particles in p+p, p+Ar, and p+Xe collisions at 200 GeV, registered in different rapidity intervals, Δy, located above the p+N center-of-mass rapidity $y_{cms} = 3.028$: $\Delta y = 0.4, 1.0, \ldots 3.5$. Experimental results are from Ref. [6]

The A+A collisions

For $A+A$ collisions it is assumed that nucleons in the projectile and target nuclei are distributed according to the Woods-Saxon density distribution (7). Each nucleon takes part in 0, 1 or more collisions with coefficients of inelasticity depending on specific configuration of the colliding pair — N+N, N′+N, N′+N′, where the apostrophe denotes "wounded" nucleon. Results are displayed in Figs. 2–4 and compared with experimental distributions for ^{16}O collisions with various targets at 14.5 A, 60 A and 200 A GeV [7, 8, 9]. The description of the data is again satisfactory, except for the target fragmentation region, where the role of intranuclear cascading may be sufficient. One should, however keep in mind that the presented data have been selected rather arbitrarily from a rich but not very homogeneous material (for a recent review of experimental data see e.g. Ref. [12]).

An interesting problem is the estimation of the energy density which can be reached in *nucleus + nucleus* collisions. In our scheme the sum of wounded projectile and target

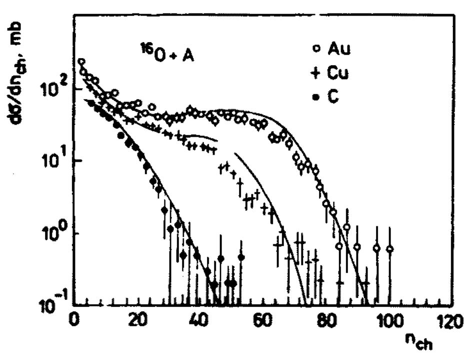

Fig. 2. Charged multiplicity distributions in 14.5 A GeV/c O+A (Au, Cu, C) collisions in the rapidity range $1.1 \leqslant y \leqslant 2.8$. Experimental points are from Ref. [7]

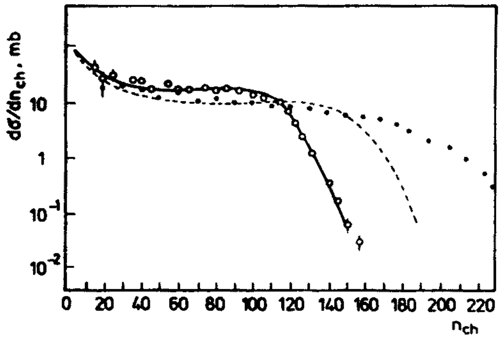

Fig. 3. Charged multiplicity distribution in 200 GeV O+W collisions in two different rapidity intervals: a) $2.9 \leqslant y \leqslant 4.9$ (full line) and b) $0.9 \leqslant y \leqslant 2.9$ (dashed line). Experimental points are from Ref. [8]

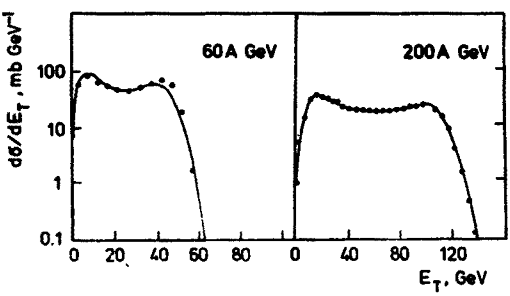

Fig. 4. Transverse energy distribution in O+Au collisions at 60 A GeV and 200 A GeV registered in the rapidity interval $2.4 \leqslant y \leqslant 5.5$. Experimental points are from Ref. [9]

nucleons is practically identical with the average number of participants calculated in Ref. [9] for A+Au collisions. The Bjorken formula, commonly used for the estimation of the energy density ε:

$$\varepsilon = (1/\tau_0 \pi R^2)(dE_T/d\eta), \tag{8}$$

where $\tau_0 = 1$ fm/c, and R denotes the radius of the interaction area, gives only very slow increase of ε with projectile mass number, if the transverse energy is proportional to the number of participants, as in our scheme in the pionization region ($2.2 \leqslant y < 3.6$) in central $O+A_t$ collisions. In 3.2 TeV $O+A_t$ collisions the average energy for one participant is about 1 GeV in a wide range of target masses: $A_t = 12$, 27, 64, 108 and 197 (for projectile momentum 0.96 TeV/c, the transverse energy per participant partly "saturates" for Ag and Au targets). For the simplest case of uniformly distributed nuclear matter the number of participants, N, is proportional to the interaction volume of both the colliding nuclei and equals, as it follows from elementary geometrical considerations in the case of central collisions:

$$N = A_p + A_t - A, \tag{9}$$

where $A = (A_t^{2/3} - A_p^{2/3})^{3/2}$.

The average numbers of participants in O+Au, S+Au, and Au+Au collisions, are 69, 113, and 394, respectively. Glauber calculations give 70, 115, and 390 [9]. If the average transverse energy per one participant remains constant for different projectile masses then the rise of the total E_T obtained from relation (9) exceeds only slightly an increase of the area S of the interaction zone ($S \sim A_p^{2/3}$ for $A_p \leqslant A_t$). Between the reactions O+Au and Au+Au this gives an increase of about 10% and, consequently, equally small increment of the energy density ε, as estimated from Eq. (8). The detailed *Monte-Carlo* calculations give however a faster energy density growth with projectile mass number A_p in the central rapidity region (see Fig. 6). The observed difference betwen the two cases: A_p+A (fixed projectile mass) and $A+A_t$ (fixed target mass) may be simply explained in the picture of independent N+N collisions. In the first case there is a slow rise of the thickness of nuclear matter penetrated by projectile participants with relatively low energies

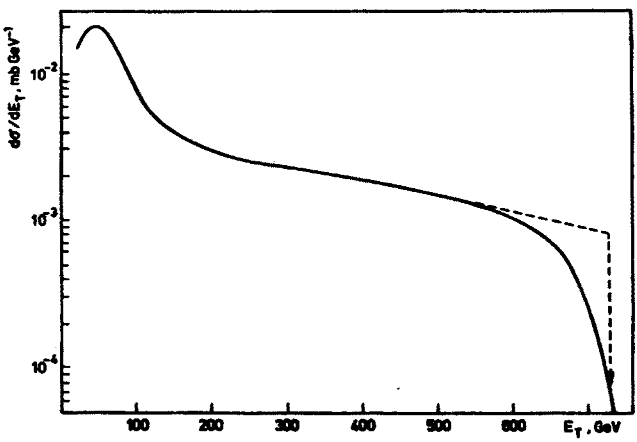

Fig. 5. Transverse energy distribution in 200 A GeV Pb+Pb collisions calculated for the NA35 rapidity acceptance region $2.2 \leqslant y \leqslant 3.6$

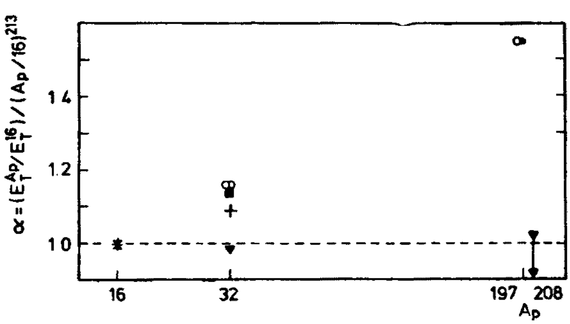

Fig. 6. Calculated values of the maximal transverse energy E^{max} registered in central A_p+Au collisions in the midrapidity region $2.2 \leqslant y \leqslant 3.6$ at 200 A GeV (full circles) and 60 A GeV (open circles). Calculations for Pb+Pb collisions are from Ref. [13] (triangles). Experimental points are from Ref. [10] (crosses, electromagnetic component only) and Ref. [11] (squares)

(after few collisions) and in the second one, there increases a number of "fresh" nucleons with considerable contribution to the total E_T, especially in the central rapidity region.

The transverse energy spectrum can be roughly divided into two parts: a central "plateau" and a high-energy tail, with approximately Gaussian shape [3], i.e. parabolic shape in the commonly used semi logarithmic scale.

In order to compare our calculated E_T distributions for central A_p+A_t collisions with "minimum bias trigger" experimental distributions, we naively estimate the maximal experimentally measured transverse energy as the value at which the linear approximation of the plateau breaks down, and the differential cross section falls to 10% of the "extrapolated" level (see Fig. 5). E_T^{max}, so roughly evaluated, rises with the projectile mass number faster than $\sim A^{2/3}$, like *Monte-Carlo* expectations. Consequently, we obtain considerably higher energy densities for Pb+Pb collisions than for O+Pb, contrary to the results obtained from the multisource model [13] (see Fig. 6).

Summary

We present the multiplicity and transverse energy distributions in nuclear collisions, calculated for the central region on the basis of the independent N+N collision scheme, for Gaussian rapidity shape, uniformly distributed inelasticity and exponential p_T distribution of newly produced particles. The description of experimental data from several BNL and CERN experiments is satisfactory. These results can be treated as a conventional no-plasma background, on which possible new effects, especially in collisions of very heavy nuclei (Au+Au or Pb+Pb), can be discovered.

The calculated energy density for such collisions at 200 A GeV is predicted to reach about 3.3–3.5 GeV/fm^3.

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