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ON RAPIDITY-DEPENDENCE OF D AND $\bar{\mathrm{D}}$ YIELDS IN HEAVY-ION COLLISIONS

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In spite of a recognized importance of the light cluster formation, the studies – both experimental and theoretical – on the rapidity-dependent nature of D and $\bar{\mathrm{D}}$ production in the heavy-ion collisions are very sparse. In the present work we have tried to assemble the very limited data-sets available from AuAu, PbPb and some other nuclear collisions at various energies. Furthermore, within the precincts of the coalescence approach and the framework of a very recently advanced phenomenological model, we have tried to interpret the obtained data in a comprehensive manner. Besides, we have also tried to compare the performances shown by the chosen approach with those obtained by some other models extant in the field and in the heavy-ion literature.

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1. Introduction

The detection of deuteron and antideuteron in heavy-ion collisions [1], it is believed, could probe the later stages of the evolution of a quark-gluon-plasma (QGP) system supposed to be formed in the relativistic heavy-ion collisions. After the initial expansion and subsequent cooling, nucleons (antinucleons) in spatial proximity and with neighbouring momenta might coalesce to form light nucleus (antinucleus) clusters. The sensitivity of light-nucleus production to the space-time evolution of the interaction region and collision dynamics renders the studies on them signif-

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icant and relevant. However, unfortunately, the rapidity studies on deuteron (D) and antideuteron ($\bar{\mathrm{D}}$) production suffer from a degree of asymmetry, when they are compared with the availability of the vast amount of transverse-momentum-dependent studies. The dearth of rapidity-dependent studies might be attributed to the lack of feasibility of conducting experiments and some other understandable and identifiable difficulties.

One of our objectives here is primarily to collect and collate data on rapidity-dependent studies on D and $\bar{\mathrm{D}}$ production – however limited and unreliable they may be in nature – within the confines of the present studies. Secondly, we make attempts to interpret the available meager data with the simultaneous use of two models – of which one is the well known coalescence model, and the other is a combinational approach offered by the present authors in the recent past and applied to analyze data in a both extensive and intensive manner. It is a fact that our main objective here is to test whether this latest model, called Chosen Combination of Models (CCM) could accommodate the rapidity-dependent behaviour of D and $\bar{\mathrm{D}}$ production in the heavy-ion collisions. This is of special interest to us in view of the fact that the same model was successfully applied to explain the data on p_{T}-dependent studies related to D and $\bar{\mathrm{D}}$ production in a set of prior publications [2, 3, 4].

A point is to be made. This work is based on an assumption, which would be stated later and which we cannot escape for the present, due to lack of available data on deuteron rapidity spectra in PP collisions.

We proceed in the following manner. In Sect. 2 we give an outline of the basic model. The next section traces the method of arriving at the results and thereafter delivers them through the graphical plots. In the last section we present the conclusions of the present work.

2. *The basic model: an outlook*

Following Faessler [5], Peitzmann [6] and also the work of Schmidt and Schukraft [7] we propose here a generalized empirical relationship between the inclusive cross-section for production of any particle represented by Q in nucleus-nucleus collision and production of the same in nucleon-nucleon collisions in the following form:

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\Big|_{\mathrm{AB}\to\mathrm{QX}} \sim (AB)^{\epsilon(y,p_T)}\, E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\Big|_{\mathrm{PP}\to\mathrm{QX}}, \tag{1}$$

where Q is the secondary produced in high-energy nucleus-nucleus (AB) or in proton-proton (PP) collisions. The term $\epsilon(y,p_{\mathrm{T}})$ could be expressed in the factorization form $\epsilon(y,p_{\mathrm{T}}) = f(y)g(p_{\mathrm{T}})$. While investigating a specific nature of dependence of the two variables(y and p_{T}), either of them is assumed to remain averaged or with definite values. Speaking in clearer terms, if and when rapidity dependence is studied by an experimental group, the transverse momentum is integrated over certain limits and is absorbed in the normalization factor. So the effective formula for rapidity spectra turns into

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}y}\right|_{\mathrm{AB}\to\mathrm{QX}} \sim (AB)^{f(y)} \left.\frac{\mathrm{d}\sigma}{\mathrm{d}y}\right|_{\mathrm{PP}\to\mathrm{QX}}. \tag{2}$$

The main bulk of work, thus, converges to the making of an appropriate choice of form for $f(y)$. And the necessary choice is to be made on the basis of certain premises and physical considerations which do not violate the canons of high-energy interactions.

For production of Q in PP collisions, we apply a 3-parameter formula proposed by Thomé et al. [8], and which is given by the following expression

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}y} = C_1\left(1+\exp\frac{y-y_0}{\triangle}\right)^{-1}, \tag{3}$$

where C_1 is a normalization constant, and y_0 and $\triangle$ are two parameters. The choice of the above form made by Thomé et al. [9, 10] was intended to describe conveniently the central plateau and the fall-off in the fragmentation region by means of the parameters y_0 and $\triangle$, respectively. Had the data on deuteron/antideuteron rapidity-spectra in PP collision been available to us, we could have easily obtained the values of $\triangle$ and y_0 by fitting those data via Eqn. (3). But, at present, no data on D/$\bar{\mathrm{D}}$ rapidity spectra produced in PP collision are at hand; therefore we have had to make an assumption, as stated in the next section, on the possible values of $\triangle$ and y_0 and the adopted values are ~ 0.3 and ~ 1.0, respectively. The compulsion for this assumption is, in fact, forced on us by the circumstances and the reality.

Our next step is to explore the nature of $f(y)$ which is envisaged to be given generally by a polynomial form noted below

$$f(y) = \alpha + \beta\, y + \gamma\, y^2, \tag{4}$$

where α, β and γ are the coefficients to be chosen separately for each AB collision (and also for AA collisions when the projectile and the target are same). Before dealing with this issue in detail, let us make a point here. The suggested choice of the form in expression (5) is not altogether fortuitous. In fact, we got the clue from one of the previous works by one of the authors (SB) [11] here pertaining to the studies on the behaviour of the EMC effect related to the lepto-nuclear collisions. In the recent past, Hwa et. al. [12] also made use of this sort of relationship in a somewhat different context. Now we go back to our original discussion. Combining Eqns. (2), (3) and (4), the final working formula for $\mathrm{d}N/\mathrm{d}y$ in various AB (or AA) collisions can be expressed by the following relation

$$\begin{aligned} \frac{\mathrm{d}N}{\mathrm{d}y}\Big|_{\mathrm{AB \to QX}} &= C_2 (AB)^{\alpha+\beta y+\gamma y^2} \frac{\mathrm{d}N}{\mathrm{d}y}\Big|_{\mathrm{PP \to QX}} \\ &= C_3 \, (AB)^{\beta y+\gamma y^2} \, \left(1 + \exp \frac{y-y_0}{\triangle} \right)^{-1} , \end{aligned} \tag{5}$$

where C_3 is a constant given by $C_3 = C_2(AB)^{\alpha}$, with C_2 being the normalization constant, as α is a constant for a specific collision at a specific energy. The parameter values for different nucleus-nucleus collisions are given in Table 1.

TABLE 1. Values of different parameters for production of $\mathrm{D}/\bar{\mathrm{D}}$ *in various high-energy nucleus-nucleus collisions.*

Collision	Secondary	E_{lab}(GeV)	C_3	β	γ
Au + Au 0 − 3% Centrality	D	11.6	9.5	0.044	−0.031
Au + Au 7 − 12% Centrality		11.6	6.6	0.057	0
Au + Au 17 − 24% Centrality		11.6	6.0	−0.060	0.12
Au + Au 32 − 43% Centrality		11.6	2.4	−0.048	0.15
Au + Au 43 − 76% Centrality		11.6	0.6	−0.009	0.18
Si + Pb		14.6	0.07	−0.14	−0.013
Pb + Pb		158	0.09	−0.014	0.015
Pb + Pb	$\bar{\mathrm{D}}$	158	0.001	0.10	−0.13

3. Results and general discussion

It is quite evident from expression (5) given above that one has to obtain values for $\frac{\mathrm{d}\sigma}{\mathrm{d}y}|_{\mathrm{P+P \to D/\bar{D}+X}}$ (or $\frac{\mathrm{d}N}{\mathrm{d}y}|_{\mathrm{P+P \to D/\bar{D}+X}}$) for which we have no experimental results at hand. Our study is normally based on an analysis and understanding of the nature of production of the specific particle in PP reactions at Intersecting Storage Ring(ISR) or higher energies. Unfortunately, we have no such data right now.

So we proceed with the building up of an ansatz for which we have some indirect clues to be pointed out hereafter. We assume that the qualitative nature of the deuteron rapidity spectra in PP reaction would be exactly or very nearly the same as that of the proton(or antiproton) rapidity spectra in PP interactions at higher energies. The indirect evidence which prompt us to make this assumption and prediction are as follows: (i) the qualitative similarity between antiproton rapidity dependence and antideuteron rapidity dependence in Au+Pb collisions at AGS energies, though the orders of magnitude are distinctly different in the two cases [13]. (ii) Though the orders of magnitude are largely different, the near qualitative identity in the slope-behaviour of the invariant cross sections vs. p_T plots for proton and deuteron production in S+Pb collisions at 200 GeV/A [14]. The observed qualitative similarities are, observed in both the cases, for two nuclear collisions with entirely different sets of projectile-target combinations. So our hunch is: the basis of similarity lies in the exact or the approximate similarity of production of them in basic PP reactions. This provides the rationale for our assumption stated earlier. Thus, the stated assumption has been put to practice here on the arguments of parallelism. Once it is adopted, the procedural pattern would be the same as of some of our prior works [9, 10]. It is to be noted that the differences in the quantitative values in such an approach are absorbed by the normalization terms lying outside the y-dependent terms.

The results obtained by Eqn. (5) on production of deuteron(D) and antideuteron ($\bar{\text{D}}$) are shown in several diagrams. The plots of rapidity-density of multiplicity vs. the c.m. rapidity for various centralities of the collisions are shown in Fig. 1. The

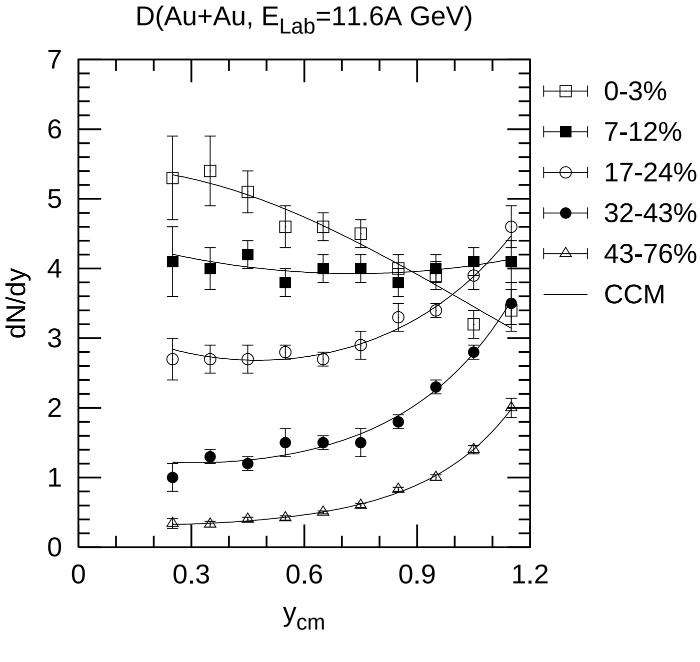

Fig. 1. Plot of rapidity spectra for production of secondary deuterons in AuAu *collisions at an energy* E_{lab} = 11.6A GeV *in three different centrality-bins. The experimental data are taken from Ref. [16] while the solid curves are for CCM-based results.*

solid curves demonstrate the model-based values against the data. The data for each of the centrality values have been labelled separately. In fact, the plots on the same observable for other different collisions have been depicted in Figs. 2 and 3. And the same for the $\bar{\mathrm{D}}$ production in Pb+Pb collision at CERN-SPS is

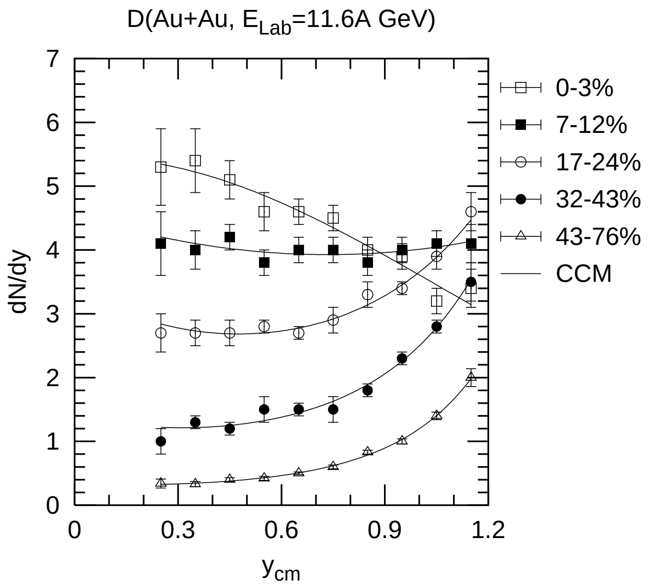

Fig. 2. Nature of rapidity spectra for secondary D *produced in* SiPb *interaction at* $E_{\mathrm{lab}} = 14.6A$ GeV. *The experimental data are taken from Ref.[17]. The solid curve provides the CCM-based results.*

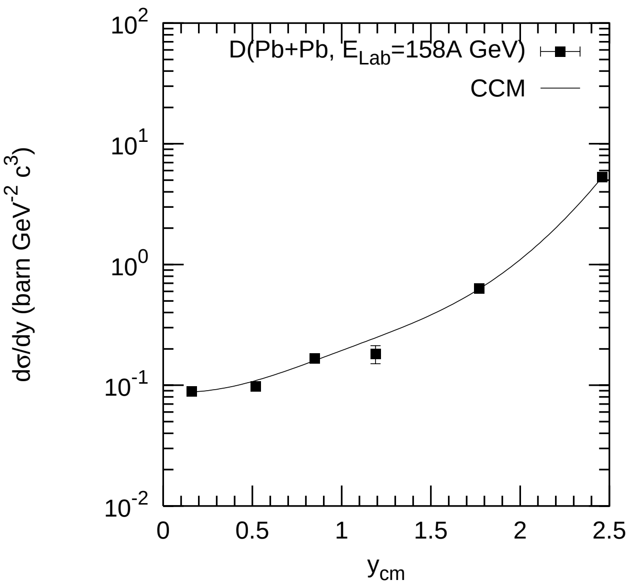

Fig. 3. Rapidity spectra for production of secondary deuterons in PbPb *collisions at an energy* $E_{\mathrm{lab}} = 158A$ GeV. *The experimental data are taken from Ref. [18] while the solid curve is on the basis of CCM.*

shown in Fig. 4. The values for ratio of the multiplicity-densities at various c.m. rapidities reveal results consistent with measurements — both qualitatively and quantitatively (Fig. 5). In Fig. 6 we have presented comparison of our model-based

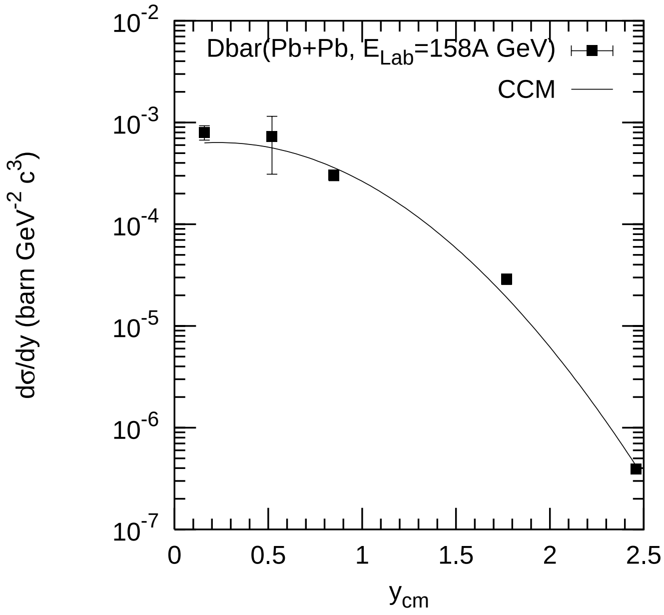

Fig. 4. Rapidity spectra for production of secondary antideuterons in PbPb *collisions at an energy* $E_{\rm lab}$ = 158A GeV. *The experimental data are taken from Ref. [18] while the solid curve is on the basis of CCM.*

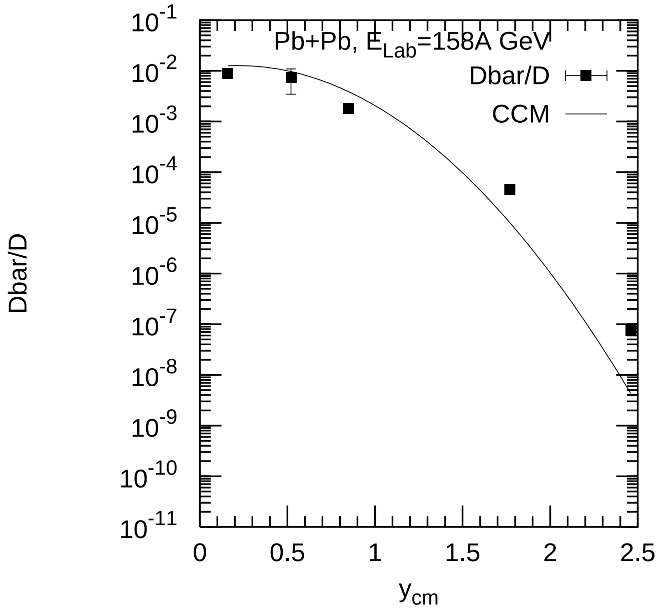

Fig. 5. Nature of $\bar{\rm D}/{\rm D}$ *ratio as a function of c.m. rapidity. The experimental data are for* PbPb *collisions at* $E_{\rm lab}$ = 158A GeV *[18]. The solid curvilinear line depicts the CCM-based results.*

results with those obtained by three fire ball model (TFM) [15]. Quite intentionally, we have not introduced the data-sets in Fig. 6, as their presence would disturb our purpose of comparing the functions of the two models, viz. TFM and CCM. The source provides also the results for thermalized cylinder model (TCM) [15] which are calculationally coincident in most of the rapidity values with TFM. Besides, as the plots of TCM are too hazy in print, we have also deliberately not included the TCM-based results in Fig. 6. However, the plots in Fig. 6 show striking agreement between two sets of model-based results for the data on most central collisions. But the agreements tend to gradually diminish for the non-central (peripheral) collisions.

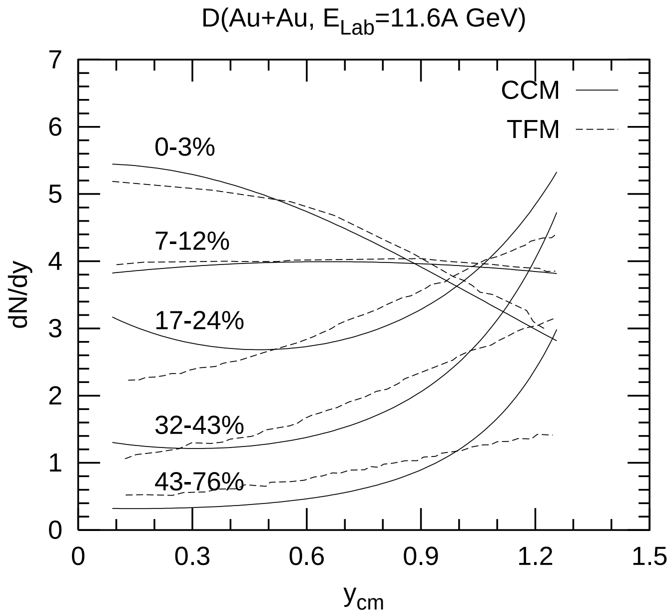

Fig. 6. Comparison of CCM-based and TFM-based[15] results on D *production in* AuAu *collisions at* $E_{\mathrm{lab}} = 11.6A$ GeV *in three different centrality bins.*

4. Concluding remarks

In so far as deuteron production is concerned on an overall basis, the model under consideration (CCM) here has a modestly satisfactory rating on its performance-appraisal for the wide energy intervals from $E_{\mathrm{lab}} = 11.6A$ GeV to $E_{\mathrm{lab}} = 158A$ GeV and for three separate heavy-ion collisions at different energies of which two lie in the relatively lower domain. The features of the multiplicity-density vs. c.m. rapidity of antideuteron in PbPb reaction at CERN-SPS and the ratio of $\bar{\mathrm{D}}/\mathrm{D}$ production in the same interaction are reproduced fairly satisfactorily. The comparison with the performance by TFM (or, for that matter, by TCM) reveals that the present one is in no hopeless condition, especially for the most central collisions. But, for the non-central collisions, the present model predicts, in general, higher values than those by TFM and the predicted rise here is also more drastic than those by TFM. But, one can and must not take such comparisons too seriously, because (i) the basis of comparison is not very sound; (ii) the measured data are too sparse and, at times, they suffer from large uncertainties; (iii) neither the TFM nor the TCM is generally entrenched in multiparticle production scenario; whereas, on the contrary, the CCM has been tried, tested and checked with data on production of all major categories of the secondaries in particle and nuclear collisions.

Let us come to the end by stating that our model is fairly successful in explaining rapidity distribution of deuteron-antideuteron yields in some heavy-ion collisions. This is so despite the very basic assumption made at the start.

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OVISNOST PRINOSA D I $\bar{\mathrm{D}}$ O RAPIDITETU U SUDARIMA TEŠKIH IONA

Usprkos uočavanja važnosti tvorbe lakih nakupina, kako eksperimentalna, tako i teorijska proučavanja naravi ovisnosti tvorbe D i $\bar{\mathrm{D}}$ o rapiditetu u sudarima teških iona premalo su zastupljena. U ovom smo radu prvo pokušali sakupiti oskudne podatke koji su dostupni za AuAu, PbPb i neke druge nuklearne sudare na različitim energijama. Nadalje, u okviru modela stapanja i nedavno razvijenog poboljšanog fenomenološkog modela, pokušali smo objasniti poznate podatke na shvatljiv način. Osim toga, načinili smo usporedbe ishoda računa u tom pristupu s postojećim modelima za teško-ionske reakcije.