Deuterons and space-momentum correlations in high energy nuclear collisions

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Using a microscopic transport model together with a coalescence after-burner, we study the formation of deuterons in Au+Au central collisions at $\sqrt{s} = 200AGeV$. It is found that the deuteron transverse momentum distributions are strongly affected by the nucleon space-momentum correlations, at the moment of freeze-out, which are mostly determined by the number of rescatterings. This feathur is useful for studying collision dynamics at relativistic bombarding energies.

Relativistic heavy ion collisions offer the unique opportunity to study hot and dense hadronic matter under controlled laboratory conditions (for recent reviews, see [1–4]). However, the particle momentum distributions do not directly reveal the properties of the initial dense state of the system created in these collisions. The system undergoes logitudinal and transvere expansion which greatly affects particle momentum distributions. Therefore the observation that for a given colliding system and within the same kinematic region, the slope parameter [1] T depends on the particle type [5] is of great interest and can be exploited to extract information about the reaction dynamics prior to the freeze-out stage. It has been found that the higher the particle mass, the larger the slope parameter. This mass dependence is the strongest for the heaviest systems (Pb + Pb), and vanishes altogether in p+p collisions at similar energies [5].

A related observation is that the size parameters $R_{T,Long}$ (R_{Long} and R_T are the size parameters in the beam direction and perpendicular to the beam direction, respectively), which are extracted from two-particle correlation function measurements, depend on the transverse momentum of the pair. The higher the momentum, the smaller the size parameter [6,7]. This dependence, like the slope parameter dependence, is strongest (in R_{Long}) in heavy systems, although it is also observed in elementary collisions [8].

In any heavy-ion collision, the space-time freeze-out distribution and its correlation with momentum are determined by the underlying dynamics. The above observations are interpreted by considering nuclear fluid dynamics (NFD) type collective flow, which clearly leads to space-momentum correlations [9–11]. Note that NFD is not the only model for the interpretation of such correlation. Another example might be string fragmentation [12].

Further insight into transverse collective flow can be gained from studying the mean $\langle p_T \rangle$ of single particles like pions, kaons, and protons: specifically, by observing how the mean $\langle p_T \rangle$ varies with particle mass. Unfortunately, the full space-momentum structure of the collision cannot be extracted from single-particle momentum spectra alone. To shed more light on this issue, we propose to utilize deuteron distributions to investigate nucleon freeze-out properties. In this letter we use the deuteron transverse momentum distribution as well as the ratio of the proton distribution to that of the deuteron, to extract information on space-momentum correlations and flow at RHIC energies. In this study, we focus on central (impact parameter $b \leq 3.0$ fm) Au + Au collisions at $\sqrt{s} = 200AGeV$.

For our investigation we have employed the microscopic Relativistic Quantum Molecular Dynamics model (RQMD) [13,14]. The model is well established and has been used successfully to describe many observables measured at AGS and SPS bombarding energies over a wide range of projectile-target combinations. RQMD [13] is a semi-classical microscopic approach which combines classical propagation with stochastic interactions. Color strings and hadronic resonances can be excited in elementary collisions. Their fragmentation and decay leads to production of particles. Overlapping strings do not fragment independently from each other but form 'ropes', chromoelectric flux-tubes whose sources are charge states in higher dimensional representations of color SU(3).

[1] The slope parameter is extracted from the fitting of the transverse mass distribution $\frac{1}{m_T}\frac{dN}{dm_T}$ with an exponential function $A \cdot exp(-m_T/T)$. A is a normalization parameter.

RQMD is a full transport theoretical approach to reactions between nuclei (and elementary hadrons) starting from the initial state before overlap to the final state after the strong interactions have ceased (freeze-out). The model does not include light cluster productions. Therefore an after-burner, described in [15–18] is used for deuteron yields calculations. More details of the coalescence type calculations can be found in [16,18] and references therein.

The binding energy of the deuteron ($\sim$ 2.2 MeV) [19] is small compared with the characteristic freeze-out temperature ($\sim$ 140 MeV) of ultra-relativistic heavy-ion collisions we are studying. Therefore, deuterons cannot survive rescattering. Since many rescatterings occur within the hot and dense reaction phase, the only deuterons that survive and escape are those formed near the freeze-out stage, either on the surface of the fireball or at a later collision time when the environment is dilute.

The Particle phase-space distribution at freeze-out reflects physics at earlier stage of the collision. Similar to the two-particle correlation functions, the probabilities of bound state (deuterons and heavier clusters) formations are determined by this distribution [20].

The sensitivity of the two particle correlation measurement to the source size decreases when the source size (and/or duration of the emission) becomes large. The analysis of the deuteron yield realtive to the proton yield has no such loss in sensitivity although the value of the deuteron yield will decrease due to larger distance between the two nucleons.

Assuming a Gaussian form for the nucleon source [22,23], a size parameter R_g can be extracted from the single particle distributions of protons and deuterons [24]:

$$R_g^3 = \frac{3}{4}(\sqrt{\pi}\hbar c)^3 \frac{m_d}{m_p^2} \frac{(E_p \frac{d^3N_p}{dp^3})^2}{E_d \frac{d^3N_d}{dp^3}} \tag{0.1}$$

The above equation assumes that the deuteron energy is the sum of proton's and neutron's and that there is no space-momentum correlation in particle distributions at freeze-out. Then the space-momentum correlation could be studied by inspecting the R_g as a function of the transverse momentum p_T.

The Gaussian size parameter R_g as a function of the nucleon transverse mass m_T is shown in figure 1. Here, the filled circles represent the results from standard RQMD events. The open symbols represent events with altered space-momentum correlation. Note that in alligned and random cases, only the relative orientation of $\vec{r_T}$ to $\vec{p_T}$ is modified: momentum distributions, projections onto either r_T or p_T are not touched. The squares represent the so called alligned case where, for each nucleon, the space vector $\vec{r_T}$ is aligned with the transverse momentum vector $\vec{p_T}$; and the triangles represent the case where the angle between $\vec{p_T}$ and $\vec{r_T}$ has been randomized. In the randomized case, the amplitudes of vectors $|\vec{r_T}|$ and $|\vec{p_T}|$ are still correlated. To remove such correlation, the vectors $\vec{r_T}$ and $\vec{p_T}$ were scrambled (open circles in Fig.1). After the operation, the correlations among $\vec{r_T}$ and $\vec{p_T}$ are removed and the distribution is almost flat as a function of m_T. To some extend, the results of the scrambled case can be used as a reference. The solid line represents the function $9.25 \cdot (m_T)^{1/2}$.

While no large differences are observed between the normal and the aligned results, a dramatic effect is evident between the randomized and normal cases. This implies that nucleon momenta are already more or less radially aligned in the default calculation. It is found that the mean cosine angle between transverse space and momentum vector is about $\langle cos(\theta)\rangle \approx 0.9$ at mid-rapidity. As one can see in the figure, all distributions converge to a point where $R_g \approx 9.3$ (fm) at $m_T \to m_p$ ($p_T \to 0$), indicating that the 'true source size' can be measured at small p_T, while the size parameter is sensitive to space-momentum correlations at higher p_T region. As we mentioned above, the deuterons are sensitive to the space-time-momentum correlations in the same fashion as two particle correlation functions. Indeed, these effects were also found in the study of two pion correlation functions [25,26].

Randomizing (or aligning) the space and momentum vectors will change the phase-space structure of the collision. It will affect both the deuteron yields and momentum distributions [18]. This effect is vividly displayed in figure 2, where proton (circles) and deuteron (squares) average transverse momenta $\langle p_T\rangle$ are shown as a function of rapidity. Plots (a), (b), and (c) are for normal, randomized, and aligned cases, respectively; plot (d) is the results from a calculation without rescatterings among baryons. The solid- and dash-lines in (a) and (d) represent the values of $\langle p_T\rangle$ for kaons and pions, respectively.

At mid-rapidity, $y = 0$, the values of the average transverse momentum $\langle p_T\rangle$ for pions, kaons, and protons are $\langle p_T\rangle$= 0.4, 0.6, and 0.85 GeV/c, respectively. The value for deuterons is about 1.4 GeV/c, see Fig. 2(a). The difference in mean p_T decreases from about 550 to 150 MeV/c as one moves away from mid-rapidity to $y \geq 4$. After randomization, Fig. 2(b), the splitting between deuterons and protons in the mean transverse momentum becomes constant $\sim$ 150 MeV/c. For the aligned case, the difference changes from 580 to 280 MeV/c from mid-rapidity to $y \geq 4$. Note that the change in momentum at mid-rapidity is about 30 MeV/c, but at $y \geq 4$, the difference is about 100 MeV/c compared to the normal case. Similar to the random case, the results from calculations without baryon rescattering (Fig. 2(d)) show a constant difference between deuteron and proton of about 150 MeV.

Given the distributions shown in Fig. 1 and Fig. 2, one may already discuss the physics in terms of collectivity. To proceed, we evaluated the averaged transverse velocities for pions, kaons, and nucleons. In order to remove random motion and isolate the collective part, we use the following definition for velocity:

$$\langle\beta_T\rangle = \langle\frac{\vec{p_T}\cdot\vec{r_T}}{r_T m_T}\rangle \qquad (0.2)$$

Figure 3 (a)-(d) show the velocities as a function of rapidity for different cases and Fig, 3(e) and (f) depict the mean number of nucleon collisions as a function of rapidity.

From Fig. 3 (a), it is seen that particles of different types are moving together with a similar velocity. These model results indicate a certain amount of collectivity in Au + Au central collisions at RHIC energies.[2] The second interesting finding in Fig. 3 is that at a given rapidity, the values of the velocity are closely correlated with the number of collisions: the larger the number of collisions, the higher the value of the velocity (see Fig. 3(a) and (e)). In the case of no rescatterings (rescattering here means interaction with produced particles), the number of collisions is small, about 2.5 (see Fig. 3(f)), the velocity is about zero over the whole rapidity range (Fig. 3(d)). Recall, that, in the no-rescattering case, the splitting in the average transverse momentum p_T according to mass vanishes, see Fig. 2(d). Once the space-momentum correlation is altered, the velocity distributions behave differently. In the case of alignment, the collectivity is destroyed (Fig. 3(c)), particles of different mass have distinct distributions. In the randomized case, the velocity becomes zero (Fig. 3(d)) similar to the no-rescattering events.

It is interesting to note that within the same model, the averaged collective velocity for mid-rapidity pions, Kaons, and protons is about $0.6c$ at the RHIC energy while at the SPS ($\sqrt{s} \approx 20AGeV$) the value is about 0.4-0.45c.

In summary, using a microscopic transport model (in this case the RQMD(v2.4)) and a coalescence afterburner, we have studied the transverse momentum distributions of light hadrons (mainly nucleons and deuterons) as a function of rapidity for the central Au + Au ion collisions at $\sqrt{s} = 200AGeV$. Employing the deuteron as a probe, we demonstrated that a large number of rescatterings leads to the space-momentum correlation at freeze-out and is responsible to the collectivity observed in the ratio of $N^2(proton)/N(deuteron)$ as a function of m_T and in single particle transverse momentum distributions. Should new physics occur at RHIC energy, a modification of the space-momentum structure will manifest itself in the deuteron yields and the transverse momentum distributions. Note that these distributions can be measured in the STAR TPC and other RHIC experiments.

[2] The same model calculations, for Au+Au collisions at lower energies (few GeV per nucleon), indicate no such collective behavior although protons and light nuclear cluster distributions do show characteristics of collective motion at SIS and Bevalac energies (see [27] and references therein).

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[1] Quark Matter '96 proceedings, Nucl. Phys. **A610**, 1c (1996), and Quark Matter '97 proceedings, Nucl. Phys. **A638**, 1c(1998).
[2] J. Harris and B. Müller. Ann. Rev. Nucl. Part. Sci. **46**, 71(1996).
[3] S.A. Bass, M. Gyulassy, H. Stöcker and W. Greiner. J. Phys. **G25**, R1 (1999).
[4] A. Dumitru and D.H. Rischke, Phys. Rev. **C59**, 543(1999).
[5] I. G. Bearden *et al.*, (NA44 Collaboration), Phys. Rev. Lett **78**, 2080(1997).
[6] A. Franz *et al.*, (NA44 collaboration), Nucl. Phys. **A610**, 240c(1996).
[7] K. Kadija *et al.*, (NA49 collaboration), Nucl. Phys. **A610**, 248c(1996).
[8] (NA22 collaboration), Phys. Lett. **B407**, 33(1997).
[9] Yu. M Sinyukov, Nucl. Phys. **A498**, 151c(1989).
[10] S. Chapman, P. Scotto, and U. Heinz, Nucl. Phys. **A590**, 449c(1995).
[11] U. Heinz, K.S. Lee, and M.J. Rhoades-Brown, Phys. Rev. Lett. **58**, 2292(1987).
[12] M.G. Bowler, Z. Phys. **C29**, 617(1985).
[13] H. Sorge, //alba.physics.sunysb.edu/sorge/rqmd.html.
[14] H. Sorge, Phys. Rev. **C52**, 3291(1995).
[15] E.A. Remler and A.P.Sathe, Ann. Phys. **91**, 295(1975); M. Gyulassy, K. Frankel, E.A. Remler, Nucl. Phys. **A402**, 596(1983).
[16] J. Nagle, B. Kumar, M. Bennett, G. Diebold, J. Pope, H. Sorge, and J. Sullivan, Phys. Rev. Lett. **73**, 1219(1994).
[17] H. Sorge, Phys. Lett. **B355**, 349(1995).
[18] R. Mattiello, A. Jahns, H. Sorge, H. Stöcker, W. Greiner, Phys. Rev. Lett. **74**, 2180(1995).
[19] *Review of Particle Physics*, The Eu. Phys. J. **C3**, 1(1998).
[20] R. Lednicky and V. Lyuboshitz, Sov. J. Nucl. Phys., **136**, 370(1982); S. Mrówczński, Phys. Lett. **B277**, 43(1992).
[21] V. Lyuboshitz, Sov. J. Nucl. Phys., **48**, 956(1988);

S. Mrówczński, Phys. Lett. **B248**, 459(1990); P. Danielewicz and P. Schuck, Phys. Lett. **B274**, 268(1992).
[22] S. Mrówczński, Phys. Lett. **B308**, 216(1993).
[23] S. Leupold and U. Heinz, Phys. Rev. **C50**, 1110(1994).
[24] W. Llope *et al.*, Phys. Rev. **C52**, 2004(1995).
[25] S. Esumi, U. Heinz, and N. Xu, in preparation.
[26] D.E. Fields, J.P. Sullivan, J. Simon-Gillo, H. van Hecke, B.V. Jacak, and N. Xu, Phys. Rev. **C52**, 986(1995).
[27] W. Reisdorf and H.G. Ritter, Annu. Rev. Nucl. Part. Sci. **47**, 663(1997).

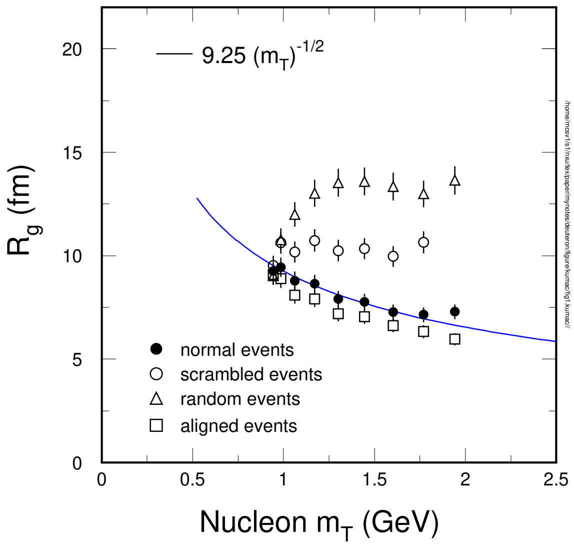

FIG. 1. The Gaussian radius parameter R_g as a function of proton transverse mass m_T from Au+Au collisions at $\sqrt{s} = 200AGeV$. Filled circles represent the results for normal RQMD events. Open symbols represent the results for the events where $\vec{p_T}$ and $\vec{r_T}$ are altered. Only mid-rapidity ($|y| \leq 1.0$) nucleons from central collisions ($b \leq 3$fm) are used for the plot.

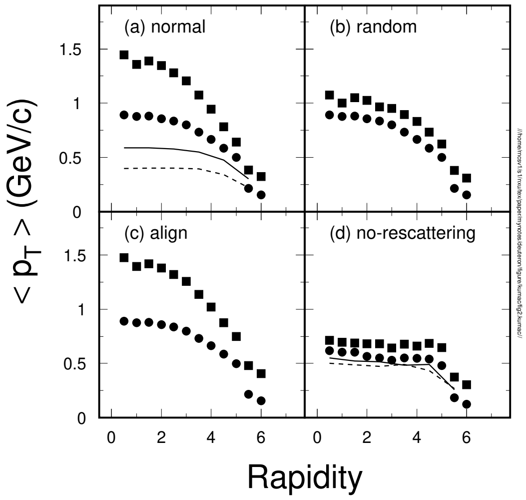

FIG. 2. Deuteron (filled square), nucleon (filled circle), kaon (solid-line), and pion (dashed-line) mean transverse momentum $\langle p_T \rangle$ as a function of rapidity.

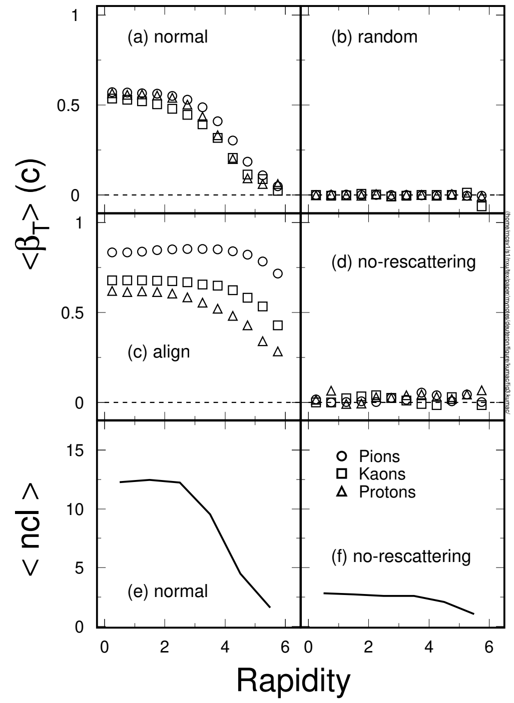

FIG. 3. RQMD mean velocities $\langle \beta_T \rangle$ of pions, kaons and nucleons and mean number of collisions $\langle ncl \rangle$ for nucleons are a function of rapidity.