Deuterons and space-momentum correlations in high energy nuclear collisions

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

Relativistic heavy ion collisions seem to be the only opportunity to study hot and dense elementary matter in the laboratory [1,?]. However, the information obtained from the particle momentum distributions do not directly reveal the initial dense state of the system that created in the collisions. Therefore it was interesting when it was found that for a given colliding system and within the same kinematic region, one observes [1,3] that the slope parameter [1] T depends on the particle type: 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 [3].

A related observation is that the size parameter $R_{T,Long}$ (R_{Long} and R_T are the size parameters in the beam direction and perpendicular to the beam direction, respectively), which is extracted from the two-particle correlation function measurement, depends on the transverse momentum of the pair. The higher the momentum, the smaller the size parameter [4,5]. This dependence, like the slope parameter dependence, is strongest (in R_{Long}) in heavy systems, although it is still observed in elementary collisions [6].

In any collision, the space-time structure and its correlation with momentum are determined by the underlying dynamics. The above observations are interpreted by considering hydro-type collective flow, which clearly leads to space-momentum correlations [7–9]. Note that hydro is not the only form of such correlation. An example might be string fragmentation (as Bowler argued) that leads to space-momentum correlations [10].

Some insight into transverse collective flow can be gained from studying the mean $\langle p_T \rangle$ of single particles like kaons, protons and pions: specifically, by observing how does the mean $\langle p_T \rangle$ vary with particle mass. But the full space-momentum structure of the collision cannot be extracted from single-particle momentum spectra along. To shed more light on this physics, we report the results of using deuteron distributions to probe nucleon freeze-out properties. The deuteron transverse momentum distribution as well as the ratio of the proton distribution to that of the deuteron were used to extract information on space-momentum correlations and flow at RHIC energies. In this study, we focus on central 100A·GeV Au + 100A·GeV Au collisions with the impact parameter $b \leq 3.0$ (fm).

The transport model RQMD [11,12] was used. The model has been used successfully to describe many observables measured at AGS and SPS bombarding energies over a wide range of projectile-target combinations. RQMD [11] 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). It is a complete 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 [13–15] is used for deuteron yields. More details of the coalescence type calculations can be found in [14,16] and references therein.

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

The deuteron is a bound state of a proton and a neutron. Its binding energy ($\sim$ 2.2 MeV) is small compared with the characteristic freeze-out temperature ($\sim$ 140 MeV) of the collisions we are studying. Therefore, deuterons can not survive rescattering. Since there are many rescatterings inside the fireball, 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 space-time structure and its correlation with momentum are determined by the collision dynamics. In other words, the way the particles are distributed in phase-space at freeze-out should reflect 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 the space-time evolution of the collisions [17]. In particular, we would like to stress: (i) Both proton-proton correlation and deuteron formation are due to final state interaction [18], (except the Coulomb effect). The sensitivity of the two particle correlation measurement decreases when the source size (and/or duration of the emission) becomes large. Deuterons have no such loss of sensitivity although yields will decrease due to larger distance between the two nucleons; (ii) Along with deuterons, a systematic study of transverse momentum distributions can be done with lighter mass particles (pions, kaons, and protons). This is a powerful tool to study any variation in phase-space structure due to possible change of the equation of state, as discussed by Hong and Shuryak [22].

Assuming a Gaussian form for the nucleon source [19,20], a radius parameter R_g can be extracted from the single particle distributions of proton and deuteron [21]:

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

The invariant cross sections are evaluated in the same velocity frame for protons and deuterons. In addition, 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. The second part of the assumption can only be true in a small phase-space cell Δp. In turn, the space-momentum correlation could be studied by inspecting the distribution of the R_g as a function of the transverse momentum p_T.

The Gaussian size parameters R_g as a function of nucleon transverse mass m_T are shown in figure 1. Here, the filled circles represent the results from standard RQMD events. The squares and triangles represent events with altered space-momentum correlation.[2] The squares represent events where, for each nucleon, the transverse momentum vector $\vec{p_T}$ is aligned with the space vector $\vec{r_T}$; and the triangles represent events where the angle between $\vec{p_T}$ and $\vec{r_T}$ has been randomized. The solid line represents the function $9.25 \cdot (m_T)^{0.5}$.

While not much difference is seen between the normal and 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 a normal event. 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. More importantly, all distributions converge to a point where $R_g \approx 9.3$ (fm) at $m_T \rightarrow m_p$ ($p_T \rightarrow 0$), indicating that the 'true source size' can always be measured at small p_T, while the size parameter is sensitive to space-momentum correlations at higher p_T. 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 [23,24].

Randomizing (or aligning) the space and momentum vectors will change the phase-space structure (packing of particles) of the event. It will affect both the deuteron yields and momentum distributions [16]. This effect is vividly displayed in figure 2, where proton (circles) and deuteron (squares) averaged 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 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 pion, kaon, and proton 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 550 to 150 MeV/c as one moves away from mid-rapidity to $y \geq 4$. After randomization of the space-momentum correlation, 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 about 100 MeV/c at $y \geq 4$ 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

[2]This operation is applied to the angle between $\vec{p_T}$ and $\vec{r_T}$.

Note that 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.

may already discuss the physics in terms of collectivity. To put the arguments on a solid ground and check the idea of collectivity in the heavy ion collisions, we evaluated the averaged transverse velocities for pions, kaons, and nucleons. In order to remove random motion and isolate the collective part, we used the following definition for velocity:

$$\langle \beta_T \rangle = \langle \frac{\vec{p_T} \cdot \vec{r_T}}{r_T m_T} \rangle \tag{0.2}$$

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

From Fig. 3 (a), it is clearly seen that particles of different types are moving together with a similar velocity. This model results indicate a certain amount of collectivity in the Au+Au central collisions at the RHIC energy.[3] The second interesting finding in Fig. 3 is for 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-rescattering events, 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 this 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 from the same model, the averaged collective velocity for mid-rapidity pion, Kaon, and protons is about $0.6c$ at the RHIC energy while at the SPS ($\sqrt{s} \approx 20$A·GeV) the value is about 0.4-0.45c.

In summary, using the transport model (in this case the RQMD(v2.4)) and a coalescence after-burner, we study the transverse momentum distributions of light hadrons (mainly nucleons and deuterons) as a function of rapidity for the central 100A·GeV Au + 100A·GeV Au ion collisions. Using 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. In heavy ion collisions at RHIC energy, should new physics occur which lead to a change in space-momentum structure, this change will manifest itself in the distributions in Fig. 1 and 2. Note that these distributions can be measured in the STAR TPC and other RHIC experiments.

Finally, we would like to remark that the origins of radial flow and directed flow are different and one should not mix them in terms of physics. As we have discussed, multi-scatterings in hot, dense collision zone lead to collective transverse radial flow, most pronouncedly at mid-rapidity in central collisions. On the other hand, directed flow is the strongest in semi-peripheral collisions ($b \approx 6 - 8$ fm) at beam (and target) rapidity, and is strongly affected by the geometry of the colliding system [26]. It will be interesting to use the deuteron to probe the space-time-momentum structure in such semi-peripheral collisions in order to gain more insight into the physics of directed flow.

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[3] From the same model calculations, for Au+Au collisions at lower energies (few GeV per nucleon), such collective behavior is absent although protons and light nuclear cluster distributions do show characteristics of collective motion at SIS and Bevalac energies, see [25] and references therein.

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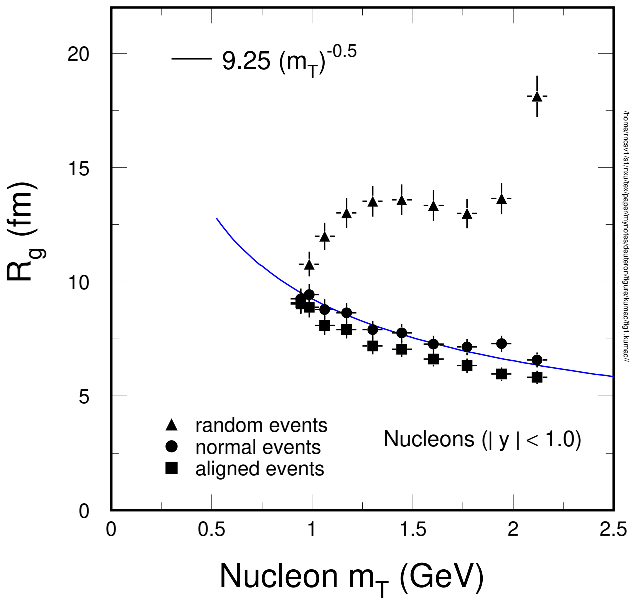

FIG. 1. The Gaussian radius parameter R_g as a function of proton transverse mass m_T from Au+Au collisions at $\sqrt{s} = 200$AGeV. Filled circle, square, and triangle symbols represent the results for normal RQMD events, in the events where p_T and r_T aligned and the direction of $\vec{p_T}$ and $\vec{r_T}$ randomized, respectively. Only mid-rapidity nucleons from central collisions are used for the plot.

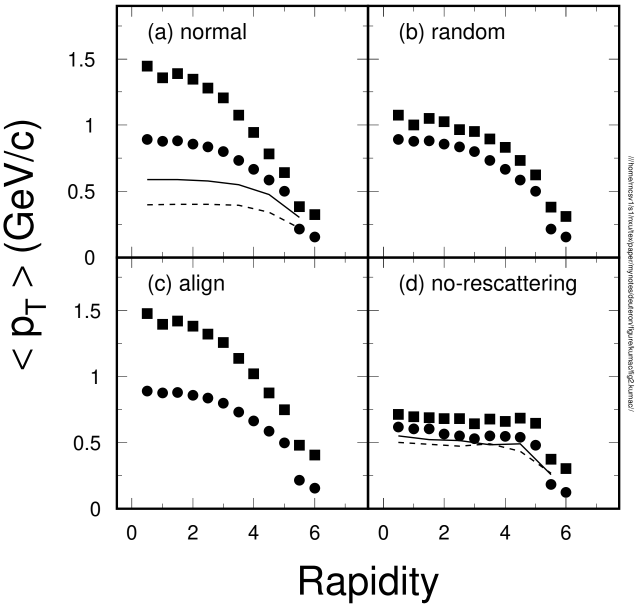

FIG. 2. Deuteron (filled square), nucleon (filled circle), kaon (solid-line), and pion (dashed-line) mean transverse momentum $\langle p_T \rangle$ as a function of rapidity. The RQMD calculation is for Au+Au central collisions at $\sqrt{s} = 200$AGeV.

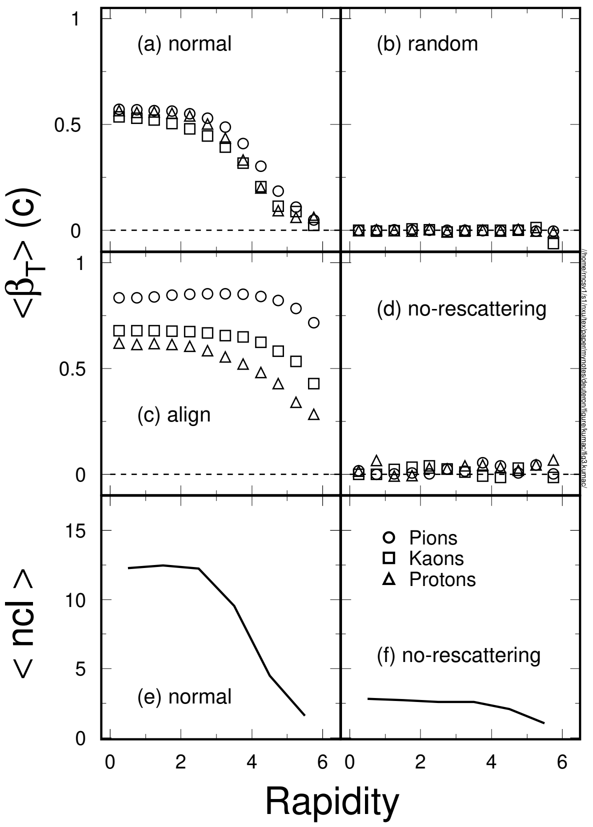

FIG. 3. RQMD mean velocities $\langle \beta_T \rangle$ of pions, kaons and nucleons and mean number of collisions $\langle ncl \rangle$ for nucleons are a function of rapidity. Same as for Figure 1 and 2, the RQMD calculation is for Au+Au central collisions at $\sqrt{s} = 200$AGeV.