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Deuterons and space-momentum correlations in high energy nuclear collisions

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Using a microscopic transport model together with a coalescence afterburner, we study the formation of deuterons in Au+Au central collisions at $\sqrt{s}=200A$ GeV. 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 feature is useful for studying collision dynamics at ultrarelativistic energies. [S0556-2813(99)50309-9]

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Relativistic heavy-ion collisions (RHIC) offer the unique opportunity to study hot and dense 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 longitudinal and transverse expansion which greatly affects the 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 mass [5] is of great interest and can be exploited to extract information about the reaction dynamics prior to the freeze-out stage. It was 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 and R_{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 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 the strongest (in R_{long}) in the heaviest systems, although it is also observed in elementary collisions [8].

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

Further insight into transverse collective flow can be gained from studying the mean transverse momentum $\langle p_T\rangle$ of different particles such as pions, kaons, and protons: specifically, analyzing the mean p_T variation with particle mass. Unfortunately, the full space-momentum structure of the collision cannot be extracted from single-particle momentum spectra alone [13,14]. To shed more light on this issue, we propose to utilize deuteron distributions to investigate nucleon freeze-out properties. In this Rapid Communication we use the deuteron transverse momentum distribution, as well as the ratio of the proton distribution to that of the deuteron [15], to extract information on space-momentum correlations and flow at RHIC energies. In this study, we focus on central (impact parameter $b \leqslant 3.0$ fm) Au+Au collisions at $\sqrt{s}=200A$ GeV.

For our investigation we employ the relativistic quantum molecular dynamics model (RQMD) [16,17]. The model is well established and has been used successfully to describe many observables measured at Alternating Gradient Synchroton (AGS) and CERN Super Proton Synchrotron (SPS) bombarding energies over a wide range of projectile-target combinations. RQMD [16] is a semiclassical microscopic approach which combines classical propagation with stochastic interactions. Color strings and hadronic resonances can be excited in elementary collisions. Their fragmentation and decay lead 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). 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

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

not include light cluster productions. Therefore an afterburner, described in [18–21], is used for deuteron yield calculations. More details of the coalescence type calculations can be found in [19,21,22], and references therein.

The deuteron binding energy ($\sim$2.2 MeV) [23] is small compared to the characteristic freeze-out temperature ($\sim$140 MeV) of ultrarelativistic heavy-ion collisions we are studying. Hence, 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 time when the environment is dilute.

The particle phase-space distribution at freeze-out reflects physics at an earlier stage of the collision. Similar to the two-particle correlation functions, the probabilities of bound state (deuterons and heavier clusters) formation are determined by this distribution [24,25].

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 relative to the proton yield has no such loss in sensitivity although the value of the deuteron yield decreases due to larger distances between the two nucleons.

Assuming a Gaussian form for the nucleon source [26,27], a size parameter R_g can be extracted from the single particle distributions of protons and deuterons [28]:

$$R_g^3=\frac{3}{4}(\sqrt{\pi}\hbar c)^3\frac{m_d}{m_p^2}\frac{\left(E_p\dfrac{d^3N_p}{d^3p}\right)^2}{E_d\dfrac{d^3N_d}{d^3p}}, \tag{1}$$

where m_p, m_d are the proton and the deuteron masses, respectively. The invariant distribution is $E_i d^3N_i/d^3p$ with ($i = proton, deuteron$). The above equation assumes that the deuteron energy is the sum of the proton and the neutron energies and that there is no space-momentum correlation in particle distributions at freeze-out. Then the space-momentum correlation can 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 Fig. 1. Here, the filled circles represent the results from original (default) RQMD events. The open symbols represent events with altered space-momentum correlation. The squares represent the so-called aligned case, where for each nucleon the space vector $\vec{r}_T$ is aligned with the transverse momentum vector $\vec{p}_T$. The triangles represent the case where the angle between $\vec{p}_T$ and $\vec{r}_T$ has been randomized. Note that in the aligned and random cases only the relative orientation of $\vec{r}_T$ to $\vec{p}_T$ is modified: momentum distributions and projections onto either r_T or p_T are not touched. In the randomized case, the amplitudes of vectors $|\vec{r}_T|$ and $|\vec{p}_T|$ are still correlated. To remove such a correlation, the vectors $\vec{r}_T$ and $\vec{p}_T$ were scrambled (open circles in Fig. 1). After the operation, the

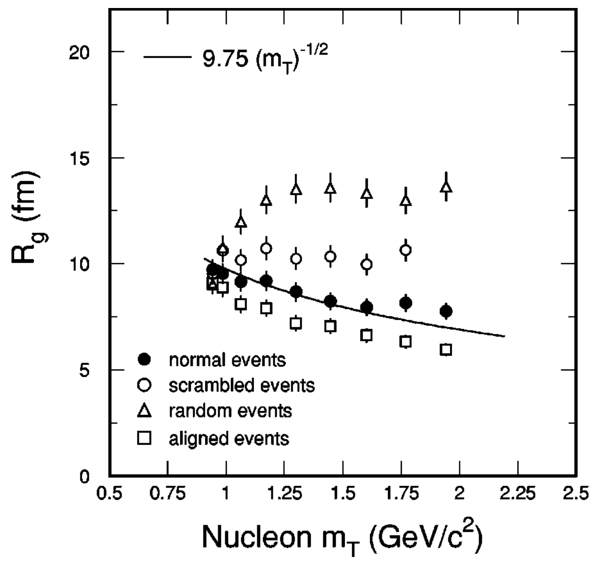

FIG. 1. Gaussian radius parameter R_g as a function of proton transverse mass m_T for Au+Au central collisions ($b \leqslant 3$ fm) at $\sqrt{s}=200A$ GeV. Filled circles represent the results for original RQMD events. Open symbols represent the results for the events where the correlation between $\vec{p}_T$ and $\vec{r}_T$ has been altered. Only midrapidity ($|y| \leqslant 1.0$) nucleons are used for the plot.

correlations among $\vec{r}_T$ and $\vec{p}_T$ are removed and, as expected, the distribution is almost flat as a function of m_T. To guide the eye, the solid line represents the function $9.75\times(m_T)^{1/2}$.

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 largely aligned in the real events. The calculated mean cosine of the angle between transverse space and momentum vector is about $\langle\cos(\theta)\rangle \approx 0.9$ at midrapidity. As one can see in the figure, all distributions converge to a point where $R_g \approx 9.5$ (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 at higher p_T the size parameter is found to be sensitive to space-momentum correlations. As it was mentioned above, the deuterons are sensitive to the space-time-momentum correlations in the same fashion as the two-particle correlation function. Indeed, these effects were also found in the study of two-pion correlation functions [29,30].

Randomizing (or aligning) the nucleon space and momentum vectors changes the space-momentum correlations. It affects both the deuteron yields and momentum distributions [21]. This effect is vividly displayed in Fig. 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 result from a calculation without rescatterings among baryons (rescattering here means interaction with produced particles). The solid and dashed lines in (a) and (d) represent the values of $\langle p_T\rangle$ for kaons and pions, respectively.

At midrapidity the values of the average transverse momentum $\langle p_T\rangle$ of 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). These values are very similar to the results in references of [4,14]. The difference in mean p_T between proton and deuteron decreases from about 550 to 150 MeV/c as one moves away from midrapidity to $y \geqslant 4$. 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 midrapidity to $y \geqslant 4$. The change in transverse momentum at midrapidity is about 30 MeV/c, but at $y \geqslant 4$, the difference is about 100 MeV/c compared to the normal case. Similar to the random case, the results of calculations without baryon rescattering [Fig. 2(d)] show a constant difference between deuteron and proton transverse momentum of about 150 MeV.

Given the distributions shown in Fig. 1 and Fig. 2, one may discuss the physics in terms of collectivity. To proceed, we evaluate the average transverse velocities of pions, kaons, and nucleons. In the following analysis, the collective velocity is defined as

$$\langle \beta_T \rangle = \left\langle \frac{\vec{p}_T \cdot \vec{r}_T}{r_T m_T} \right\rangle. \tag{2}$$

Figures 3(a)–(d) show the velocities as a function of rapidity for different cases and Figs. 3(e) and 3(f) depict the mean number of nucleon collisions as a function of rapidity. Fig. 3(a) shows that on average particles of different types are moving together with a similar velocity. These results indicate a certain amount of collectivity in Au+Au central collisions at RHIC energies.[2] On the other hand, the RQMD calculations predict the charged pion ($\pi^+ + \pi^-$) to nucleon ($p+n$) ratio to be about 10 near midrapidity for the central Au+Au collisions at the RHIC energy. Lévai and Müller argue that in such a baryon-poor region the equal magnitude of pion and nucleon flow velocities can be established only at an earlier deconfined phase [32]. Such a deconfined phase, of course, was not included in the present calculation. The other interesting observation in Fig. 3 is that at a given rapidity, the values of the velocity are closely correlated with the number of rescatterings: the larger the number of collisions, the higher the velocity [see Figs. 3(a) and 3(e)]. In the case of the no-rescattering calculation [see Fig. 3(f)], the number of collisions is about 2.5 and 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 according to mass vanishes, see Fig. 2(d). Once the space-momentum correlation is altered, the collectivity is destroyed [Fig. 3(c)].

[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 GSI Schwerionen-Synchrotron (SIS) and Bevalac energies (see [31], and references therein).

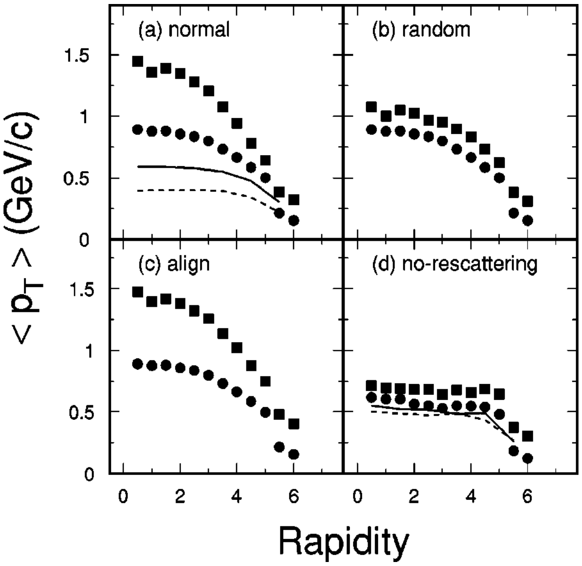

FIG. 2. Deuteron (filled square), nucleon (filled circle), kaon (solid line), and pion (dashed line) mean transverse momentum as a function of rapidity.

Note that RQMD predicts the averaged transverse collective velocity of midrapidity about 0.6 at the RHIC energy [Fig. 3(a)] while at the SPS ($\sqrt{s} \approx 20A$ GeV) the value is about 0.4–0.45c.

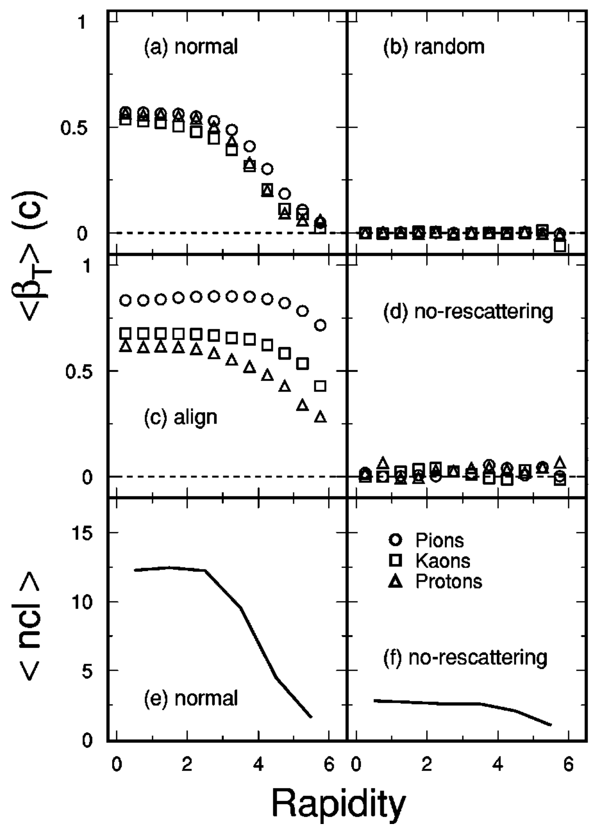

FIG. 3. RQMD mean velocities $\langle \beta_T \rangle$ of pions, kaons, and, nucleons and mean number of collisions $\langle ncl \rangle$ for nucleons as a function of rapidity.

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

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