

# Phasespace Correlations of Antideuterons in Heavy Ion Collisions\*

M. Bleicher, C. Spieles, A. Jahns, R. Mattiello,

H. Sorge, H. Stöcker and W. Greiner

Institut für Theoretische Physik

Johann Wolfgang Goethe Universität

Frankfurt am Main, Germany

## Abstract

In the framework of the relativistic quantum molecular dynamics approach (RQMD) we investigate antideuteron ( $\bar{d}$ ) observables in Au+Au collisions at 10.7 AGeV. The impact parameter dependence of the formation ratios  $\bar{d}/\bar{p}^2$  and  $d/p^2$  is calculated. In central collisions, the antideuteron formation ratio is predicted to be two orders of magnitude lower than the deuteron formation ratio. The  $\bar{d}$  yield in central Au+Au collisions is one order of magnitude lower than in Si+Al collisions. In semicentral collisions different configuration space distributions of  $\bar{p}$ 's and  $\bar{d}$ 's lead to a large “squeeze-out” effect for antideuterons, which is not predicted for the  $\bar{p}$ 's.

---

\*Work supported by Bundesministerium für Forschung und Technik, Deutsche Forschungsgemeinschaft, Gesellschaft für Schwerionenforschung

To understand recent measurements of the antideuteron formation ratio (multiplicity of  $\bar{d}$  divided by the  $\bar{p}$  multiplicity squared, both at the same momentum per nucleon) in Si+Au collisions at the AGS, it has been suggested that the shape and size of the antinucleon source, which is different from the nucleon source, has to be taken into account [1, 2, 3]. Enhanced production of antibaryons and antimatter clusters has been proposed as potential signature of a quark–gluon plasma [4, 5]. The yield of light (anti–)nuclei is connected to baryon density [6] and its spatial distribution in the later stages of the collision. This can be used to extract source sizes in an alternative way to the HBT–analysis [7].

Production processes which enhance the  $\bar{p}$  yield can be counter–balanced by the annihilation in the baryon rich environment [6, 8]. This should be observable via the “anti–flow” correlation between matter and antimatter [8].

Strong annihilation distorts the configuration space distribution of antibaryons and strongly affects the antideuteron production as shown below. The strong suppression of antimatter cluster formation and their characteristic phasespace distribution of antideuterons for finite impact parameters is discussed. These phenomena can be experimentally scrutinized to differentiate between annihilation assumptions. It can also reveal details of the structure of the eventshape inaccessible by  $\bar{p}$  or p data.

The calculations presented here are based on a microscopic phase space approach, the relativistic quantum molecular dynamics model (RQMD 1.07–cascade mode)[9]. This model is based on the propagation of all hadrons on classical trajectories in the framework of Hamilton constraint dynamics. RQMD includes secondary interactions, e.g. the annihilation of produced mesons on baryons, which may lead to the formation of  $s$  channel resonances or strings. The absorption probability for  $\bar{p}$ 's in the baryonic medium is determined by the free  $p\bar{p}$  annihilation cross section.

Since RQMD does not include the production of light (anti–)nuclei dynamically, cluster formation is added after strong freeze–out. We calculate the deuteron and antideuteron formation probability by projecting the (anti–)nucleon pair phasespace on

the (anti-)deuteron wave function via the Wigner-function method as described in [10, 11]. The Hulthén parametrization [12] is used to describe the relative part of the (anti-)deuteron wavefunction. The yield of antideuterons (and deuterons, resp.) is given by

$$dN_{\bar{d}} = \frac{1}{2} \frac{3}{4} \langle \sum_{i,j} \rho_d^w(\Delta\vec{R}, \Delta\vec{P}) \rangle d^3(p_{i\bar{p}} + p_{j\bar{n}}).$$

The sum goes over all  $\bar{n}$  and  $\bar{p}$  pairs, whose relative distance ( $\Delta\vec{R}$ ) and relative momentum ( $\Delta\vec{P}$ ) are calculated in their rest frame at the earliest time after both nucleons have ceased to interact. The factors  $\frac{1}{2}$  and  $\frac{3}{4}$  account for the statistical spin and isospin projection on the (anti-)deuteron state. The calculation of the  $\bar{t}$  is straight forward, by exchanging the Hulthén parametrization of the  $\bar{d}$  wavefunction with a 3-body harmonic oscillator wavefunction to describe the  $\bar{t}$  [10]. We use the event mixing technique to improve statistics.

It has been shown that the RQMD/C-Model describes the Si(14.6AGeV)+Au antideuteron data reasonably well [3].

The configuration space distribution of midrapidity antideuterons is calculated at freezeout in a cut perpendicular to the beam axis ( $\Delta z = \pm 0.5\text{fm}$ ) for the Au(10.7 AGeV)+Au,  $b=5$  fm reaction (fig. 1). Antimatter is preferentially emitted from the surface of the fireball – i.e. the region of hot and dense matter – in clear contrast to the source of baryons, which spreads over the whole reaction volume. This can be understood as a consequence of antibaryon absorption, which produces deep holes in the momentum- (at  $p_{\text{cms}} \approx 0$  GeV/c) and even more so in the configuration space distribution (at  $x_{\text{cms}} \approx 0$  fm,  $y_{\text{cms}} \approx 0$  fm, fig. 1) of the antibaryons at freezeout [8, 1].

The antideuteron formation happens perpendicular to the reaction plane, where the observer gets an undistracted view directly into the hot and dense participant matter. The suppression of  $\bar{p}$ 's in the reaction plane is due to the fact that the baryons annihilate  $\bar{p}$ 's preferentially moving parallel to the impact parameter plane. The anticluster formation probability decreases rapidly with the relative distance of the

$\bar{p}$ ,  $\bar{n}$  constituents. The small decrease of the spatial  $\bar{p}$  density (<30%) along the football-shaped region in the  $x$ - $y$ -plane shows up very clearly in the  $\bar{d}$ 's.

The anisotropic configuration space distribution of the  $\bar{d}$ 's can be magnified via the azimuthal ( $\phi$ ) distribution of antideuterons.  $\phi$  is the angle between  $\vec{p}_T$  and the  $x$ -axis ( $\tan \phi = |p_y|/p_x$ ). Thus, a vector with  $\phi = 0$  degrees points into the direction of the  $x$ -axis.

Fig. 2 shows the azimuthal distribution of midrapidity antiprotons (full line), antideuterons (long dashed) and antitritons (short dashed) in peripheral Au(10.7A GeV)+Au collisions. The momentum distribution of  $\bar{p}$ 's in the  $p_x$ - $p_y$ -plane is slightly concave and reflects the geometry of the almond shaped reaction zone.

In contrast, the  $\bar{d}$  distribution is shifted towards  $\phi = 90^\circ$ , in line with the described configuration space distribution of the  $\bar{d}$ 's. This looks like a "squeeze-out" effect. It is expected that the effect is even more pronounced for  $\bar{t}$ 's. The asymmetry in the azimuthal angular distributions ( $d^2N_{\bar{d}}/d\phi/dy|_{y=y_{\text{mid}}}$ ) can be experimentally tested – once the reaction plane is determined. The exact reflection symmetry of fig. 2 is due to the fact that every event for the symmetric system has been reflected by  $\phi = 90^\circ$ .

Let us explore the reaction volume dependence of the (anti-)deuteron formation ratio. This can be done by varying the impact parameter  $b$  as shown in fig. 3 ( $\bar{d}/\bar{p}^2$ -ratio, full circles;  $d/p^2$ -ratio, open squares). In thermodynamic approaches the (anti-)deuteron formation rate is proportional to the inverse volume of the sources. Those rates measure the average phase-space distance of nucleons and antinucleons, respectively [8]. The  $\bar{d}$  formation ratio in central collisions (where up to 95% of the initially produced antinucleons are reabsorbed) is predicted to be roughly two orders of magnitude lower than the formation ratio of deuterons. This difference vanishes when going to higher impact parameters or small systems (like Si+Al). It has to be pointed out that this effect is so strong that the absolute yield of  $\bar{d}$  actually *decreases* from  $\approx 10^{-7}$   $\bar{d}$ 's per Si+Al event to  $\approx 10^{-8}$   $\bar{d}$ 's in central Au+Au collisions! If the antideuteron formation ratio is calculated within a momentum coalescence model with a momentum

cutoff parameter of  $\Delta p = 120$  MeV ( $\bar{d}/\bar{p}^2$ -ratio, open circles), one finds only little sensitivity to the impact parameter chosen. This strengthens the explanation of the mostly configuration space origin of this effect. For very peripheral collisions the antideuteron formation ratio must decrease rapidly (not shown in the figure), because the production of two antibaryons is not allowed due to the limited available energy. The E814 collaboration might be able to measure these dependencies as they have done for matter clusters [13].

The predicted reaction volume dependence and the squeeze-out of anti-fragments reflects mainly the spatial distribution of antibaryons. Antimatter clusters provide an exciting opportunity to measure the spatial properties of the exploding dense matter.

# References

- [1] St. Mrowczynski: Phys. Lett. B308 (1993)216
- [2] A. Aoki *et al.*: Phys. Rev. Lett. 69 (1992)2345
- [3] J.L. Nagle, B.S. Kumar, M.J. Bennet, S.D. Coe, G.E. Diebold, J.K. Pope, A. Jahns, H. Sorge: Phys. Rev. Lett. 73 (1994)2417
- [4] U. Heinz, P.R. Subramanian, H. Stöcker, W. Greiner: J. Phys. G: Nucl. Phys. 12 (1986)1237
- [5] D. H. Rischke *et al.*: Phys. Rev. D41 (1990)111
- [6] S. Gavin, M. Gyulassy, M. Plümer, R. Venugoplan: Phys. Lett. B234 (1990)175
- [7] J.L. Nagle, B.S. Kumar, M.J. Bennet, G.E. Diebold, J.K. Pope, H. Sorge, J.P. Sullivan: Phys. Rev. Lett. 73 (1994)1219
- [8] A. Jahns, C. Spieles, H. Sorge, H. Stöcker, W. Greiner: Phys. Rev. Lett. 22 (1994); A. Jahns, C. Spieles, R. Mattiello, H. Sorge, H. Stöcker, W. Greiner: Phys. Lett. B308 (1994)3464
- [9] H. Sorge, H. Stöcker, W. Greiner: Ann. Phys. (N.Y.) 192 (1989) 266;
- [10] R. Mattiello, A. Jahns, H. Sorge, H. Stöcker, W. Greiner: Phys. Rev. Lett. 74 (1995)2180
- [11] M. Gyulassy, K. Frankel, E.A. Remler: Nucl. Phys. A402 (1983)596
- [12] L. Hulthen: Ark. Mat. Ast. Fys. 28, No.5
- [13] J. Barrette *et al.* (E814 collab): Phys. Rev. C50 (1994)1077

## Figure Captions :

### Figure 1

Configuration space distribution of midrapidity antideuterons in the reaction Au(10.7 AGeV)+Au,  $b=5\text{fm}$  at freezeout in a cut perpendicular to the reaction plane. The initial shapes of the colliding nuclei are also plotted.

### Figure 2

Correlations of antiprotons lead to a “squeeze-out” for  $\bar{d}$  and  $\bar{t}$  in peripheral Au(10.7AGeV)+Au reactions due to a lower anticluster formation probability in the reaction plane.

### Figure 3

Impact parameter dependence of the (anti-)deuteron to the (anti-)proton ratio squared ( $\bar{d}/\bar{p}^2$ , full circles;  $d/p^2$ , open squares). Open circles: the result of a simple momentum coalescence model. The lines are to the eye.

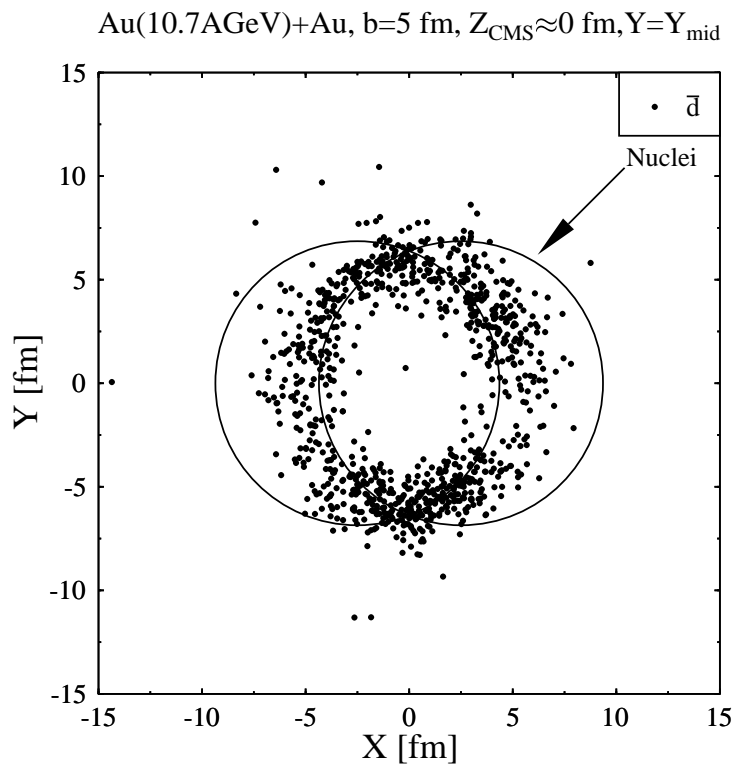


Figure 1



# Anti-Cluster Squeeze-Out

Au(10.7A GeV)+Au, b=5fm, Y=Y<sub>mid</sub>

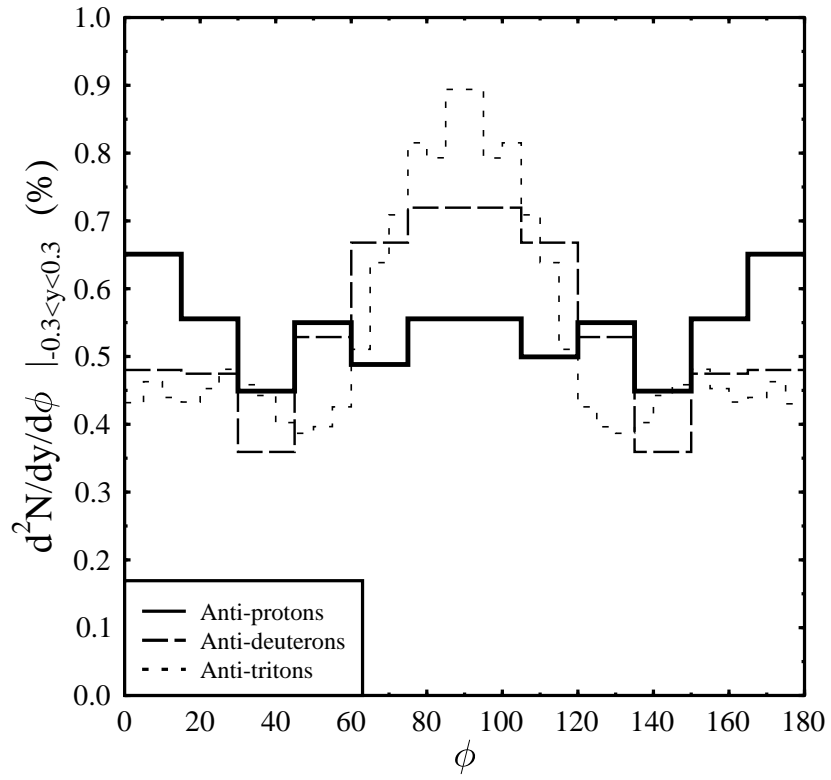


Figure 2

# Au(10.7A GeV)+Au

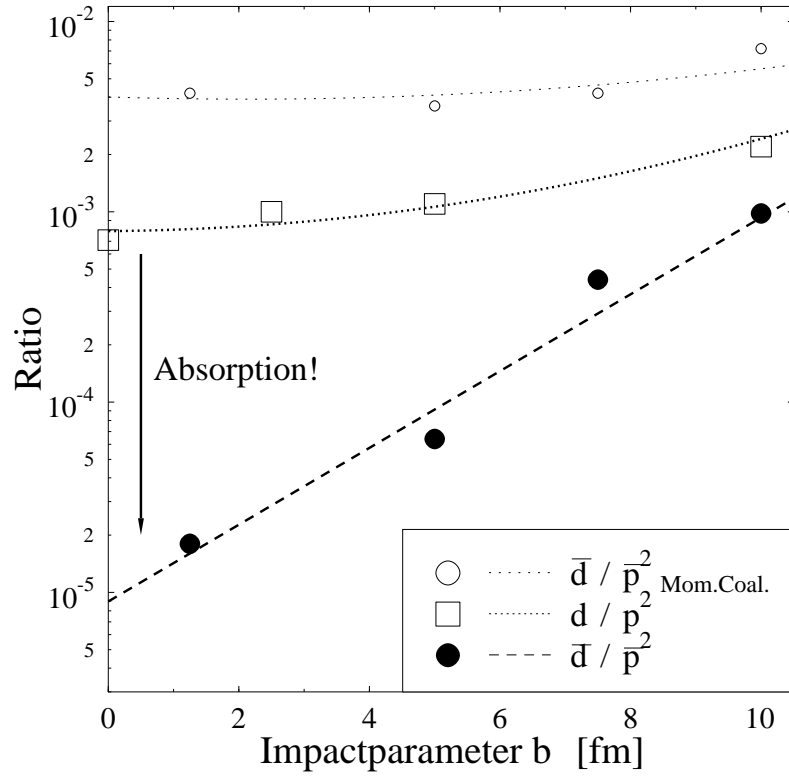


Figure 3