Formation of antideuterons in heavy ion collisions

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Abstract

The antideuteron production rate at high-energy heavy ions collisions is calculated basing on the concept of $\bar{d}$ formation by antinucleons which move in the mean field of the fireball constituents (mainly pions). The explicit formula is presented for the coalescence parameter $B_2$ in terms of deuteron binding energy and fireball volume.

PACS numbers: 25.75.-q, 25.75.Dw, 12.38.Mh

1. Introduction. Recent measurements have reported the production of antideuterons in heavy ion collisions [1], [2], [3]. The theoretical description of this interesting effect is complicated, because the antideuterons are produced at intermediate stage of fireball evolution, when the density of hadronic matter is rather low, but the particle collisions are still important. In other words they are produced at the "dense gas" stage of the fireball evolution.

Here we present the theoretical picture of this stage and calculate the $\bar{d}$ production. The basic ideas of our approach are the following. The dominant mechanism of $\bar{d}$ production is the formation of antideuterons through the fusion reaction $\bar{p} + \bar{n} \rightarrow \bar{d}$. The fusion reaction is not possible if all participating particles are on mass shell. However, in the fireball at the "dense gas" stage of its evolution $\bar{p}$, $\bar{n}$, $\bar{d}$ are not on mass shell, since they interact with surrounding matter. The interaction with the fireball constituents leads to appearance of the mass shift and widths of all particles propagating in the medium (or width broadening for unstable ones), analogous to refraction and attenuation indices in case of photon propagation. The fusion reaction rate is strongly enhanced in comparison with the main process of $\bar{d}$ production in vacuum $\bar{p} + \bar{n} \rightarrow \bar{d} + \pi$. Another important ingredient of the theoretical picture is the balance of the deuteron formation and desintegration rates. This balance is achieved because of large number of produced pions and high rate of $\pi + \bar{d}$ collisions leading to $\bar{d}$ desintegration. The balance does not imply a statistical equilibrium, but rather a stationary process, like a balance in the isotope concentrations in a radiative chain. The formation rate $\bar{p} + \bar{n} \rightarrow \bar{d}$ vanishes, when $\bar{d}$ size increases, i.e. its binding energy $\varepsilon \rightarrow 0$. This fact explicitly manifests itself in our calculations. The previous theoretical investigations of the problem were performed in statistical models [4, 5], in the model of (anti)nucleon sources.
in the fireball [6] and in the Wigner function approach (see [7, 8] and references therein). In all these approaches the interaction of nucleons, forming \( \tilde{d} \) (or \( d \)) with the fireball constituents as well as \( \tilde{d} \) (or \( d \)) desintegration was not accounted (in [4, 5] the results do not depend on \( \varepsilon \)).

According to the dominant coalescence mechanism it is convenient to characterize \( d \) production in heavy ion collisions by the coalescence parameter:

\[
B_2 = E_d \frac{d^3 N_d}{d^3 p_d} \left( E_p \frac{d^3 N_p}{d^3 p_p} E_n \frac{d^3 N_n}{d^3 p_n} \right)^{-1},
\]

where we can put \( d^3 N_p/d^3 p_p = d^3 N_n/d^3 p_n \), \( p_p = p_n = p_\tilde{d}/2 \). In what follows, we will consider only the central heavy ion collisions.

2. Theory. Consider the ”dense gas” stage of fireball evolution, which follows after so-called ”chemical freeze-out” stage [9, 10]. Assume, that particle propagations at this stage may be described classically using kinetic equations. We use the notation \( q_i(x, p) \), \( i = \tilde{p}, \tilde{n}, \tilde{d}, \pi \ldots \) for the double densities in coordinate and momentum spaces, \( n_i(x) = \int q_i(x, p) d^3 p \) are the densities. \( \{q_i(x, p)\} \) are Lorentz invariant.) Let us work in the c.m. system of colliding ions. The kinetic equation for \( q_{\tilde{d}}(p_{\tilde{d}}, x) \) reads:

\[
\frac{m_\tilde{d}}{E_\tilde{d}} \frac{\partial q_{\tilde{d}}(p_{\tilde{d}}, x)}{\partial x_\mu} u_\mu^{\tilde{d}} + v_{\tilde{d}} \nabla q_{\tilde{d}} = \int d^3 p_{\tilde{p}} d^3 p_{\tilde{n}} q_{\tilde{p}}(p_{\tilde{p}}) q_{\tilde{n}}(p_{\tilde{n}}) \sigma_{\tilde{p}\tilde{n} \rightarrow \tilde{d}} v_{\tilde{p}\tilde{n}}^{rel} \times
\]

\[
\times \delta^3(p_{\tilde{p}} + p_{\tilde{n}} - p_{\tilde{d}}) - q_{\tilde{d}}(p_{\tilde{d}}) \left[ \int d^3 p_{\pi} q_{\pi}(p_{\pi}) \sigma_{\pi \tilde{d}} v_{\pi \tilde{d}}^{rel} + \ldots \right]
\]

where \( u_\mu^{\tilde{d}} = (1, v_{\tilde{d}})/\sqrt{1 - v_{\tilde{d}}^2} \) is the \( \tilde{d} \) 4-velocity, the ellipsis mean similar terms for collisions of \( \tilde{d} \) with other constituents of the fireball (\( p, n \) etc.) and \( v_{\tilde{p}\tilde{n}}^{rel}, v_{\pi \tilde{d}}^{rel} \) are the differences of \( \tilde{p}, \tilde{n} \) and \( \pi, \tilde{d} \) velocities \( v_{\pi \tilde{d}}^{rel} = |v_{\tilde{d}} - v_{\pi}| \) etc. The terms, when \( \tilde{d} \) appears in the momentum interval \( p_{\tilde{d}} + \Delta p_{\tilde{d}} \) due to elastic collisions are neglected. Necessary applicability condition of (2) is \( \lambda = \frac{p_{\tilde{d}}}{\Delta p_{\tilde{d}}} \ll d \), where \( d \) is the mean distance between fireball constituents.

The cross section \( \sigma_{\tilde{p}\tilde{n} \rightarrow \tilde{d}} = \sigma_{pn \rightarrow d} \) is equal to:

\[
\sigma_{pn \rightarrow d} = \frac{3}{4} \cdot \frac{\pi}{4} \frac{g^2}{E_p E_n E_d} \frac{1}{v_{pn}^{rel}} \delta(E_p + E_n - E_d),
\]

where \( E_p, E_n, E_d \) are \( p, n \) and \( d \) total energies, \( 3/4 \) is the spin factor and \( g \) is the coupling constant of low energy effective \( pnd \) interaction (in the d c.m. system). The value of \( g^2 \) was found by Landau [11] from the requirement of coincidence (at the deuteron pole) of the \( pn \) scattering amplitude in effective theory with the amplitude in the Bethe-Peierls theory of the low-energy \( pn \)-scattering [12]. In the limit of zero range of nuclear forces \( g^2 \) is

\[
g^2 = 128\pi m_N \sqrt{m_N \varepsilon},
\]

where \( m_N \) is the nucleon mass, \( \varepsilon = 2.2 \text{ MeV} \) is the deuteron binding energy. The account of non-zero range \( r_0 \) increases \( g^2 \) by a factor of \( (1 - \sqrt{m_N \varepsilon r_0})^{-1} \approx 1.6 \) [12, 13].

The mass of the particle moving in medium is shifted being compared with its vacuum value. Similarly, due to interaction with medium constituents, the width \( \Gamma \) appears (or width broadening, if the particle has its proper width). The mass shift \( \Delta m(E) \) and \( \Gamma(E) \)
are expressed through the forward scattering amplitude \( f(E) \) of the particle on medium constituent (see [14, 15] and references therein).

\[
\Delta m(E) = -2\pi \frac{n}{m} \Re f(E)
\] (5)

\[
\Gamma(E) = 4\pi \frac{n}{m} \Im f(E) = \frac{np}{m} \sigma(E),
\] (6)

where \( E, p \) and \( m \) are particle energy, momentum and mass, \( n \) is the density of the constituent in medium. Eqs. (5), (6) take place in the system, where constituents are at rest. In case of moving constituents the corresponding Lorentz boost must be done. (By definition \( \Delta m \) and \( \Gamma \) are Lorentz invariant, for details see [16]).

Therefore, \( \bar{p}, \bar{n} \) and \( \bar{d} \) in the reaction \( \bar{p} + \bar{n} \rightarrow \bar{d} \) can be considered as Breit-Wigner resonances with varying masses distributed according to the Breit-Wigner formula. In process of the fireball expansion these Breit-Wigner resonances smoothly evolve to their stable counterparts. So we integrate the first term in the r.h.s. of (2) after substituting (3) over the masses \( m' \) of the Breit-Wigner resonances:

\[
I = \int dm'_p \, dm'_n \, dm'_d \frac{\Gamma_p/2\pi}{(m'_p - m_p)^2 + \Gamma^2_p/4} \frac{\Gamma_n/2\pi}{(m'_n - m_n)^2 + \Gamma^2_n/4} \frac{\tilde{\Gamma}_d/2\pi}{(m'_d - m_d)^2 + \tilde{\Gamma}^2_d/4} \times \frac{3\pi}{16} g^2 \int \frac{d^3p_p}{E_p} \frac{d^3p_n}{E_n} \frac{d^3p_d}{E_d} q(p_p) q(p_n) \delta^3(p_p + p_n - p_d) \delta(E_p + E_n - E_d)
\] (7)

where \( E'_p = \sqrt{p_p^2 + m_p^2} \) etc. We assume that the widths \( \Gamma \ll m \) are much smaller than the typical momenta in \( \bar{p}, \bar{n} \) distributions. Than the distributions \( q(p_p) = q_p(p_p) \) can be taken out from the integral sign at the values \( p_p = p_n = p_d/2 \). The result of calculation is given by

\[
I = \frac{3\pi^2}{16} g^2 \frac{\Gamma_p + \Gamma_n + \tilde{\Gamma}_d}{m_N} q^2(p_p)
\] (8)

(the mass difference \( \Delta m = m_d - m_p - m_n \sim 30 \text{ MeV} \) is small in comparison with the width \( \Gamma \sim 300 \text{ MeV} \) and neglected in (8)). Later we assume \( \Gamma_p = \Gamma_n \equiv \Gamma \). \( \tilde{\Gamma}_d \) generally is not equal to the antideuteron width \( \Gamma_d \approx 2\Gamma \sim 600 \text{ MeV} \). The \( \bar{p}nN \) system with \( \bar{d} \) quantum numbers at high excitations will not evolve to \( \bar{d} \) in the process of fireball expansion, but may decay in other ways. One may expect \( \tilde{\Gamma}_d < \Gamma_d \). We shall keep the ratio \( a \equiv \tilde{\Gamma}_d/\Gamma_d \) as free parameter in the calculations. However, the results weakly depend on this ratio: the variation within the limits \( 0 < a < 1 \) may change the coalescence parameter \( \tilde{I} \) by at most \( \sqrt{2} \) times, but in real cases about 20%. This uncertainty is within accuracy of the whole method, estimated as 50%.

The contributions of direct processes \( \bar{p} + \bar{p} \rightarrow \bar{d} + \pi^- \), \( \bar{n} + \bar{n} \rightarrow \bar{d} + \pi^+ \) and \( \bar{p} + \bar{n} \rightarrow \bar{d} + \pi^0 \) are small, altogether about 20% in comparison with (8). If these processes were essential, the coalescence parameter \( B_2 \) (11) would be meaningless, since the antideuteron distribution \( \frac{d^3N_d}{d^3p_d} \) is given by complicated integral over the antinucleon distributions in this case.

At large \( p_{\bar{p} \perp} \) the \( \bar{p} \) spectrum decreases steeply, so the approximation \( p_{\bar{p}} = p_{\bar{d}}/2 \) becomes inaccurate which leads to an underestimation of \( B_2 \). The case of large \( p_{\bar{p} \perp} > 1 \text{ GeV} \) is not considered here.
Using (6) and performing Lorentz boost to heavy ion c.m. frame, the term in square brackets in (2) can be brought to the form $(m_d/E_d) \Gamma_d$, where

$$\Gamma_d = \sum_i \int d^3 p_i \frac{1}{q_i(p_i)} v_{i\bar{d}}^{rel} \sigma_{i\bar{d}}(\bar{d} \text{ at rest})$$

(9)

Suppose, that the rate of antideuteron collisions with other constituents of the fireball resulting in antideuteron desintegration is much larger than the rate of fireball expansion. This happens at collisions of heavy nuclei at high energies, when the fireball size is large because of large number of produced pions per nucleon. In this case one may expect the balance: the first term in the r.h.s. of (2) is equal to the second one and

$$q_d(p_d) = \frac{I}{\Gamma_d(m_d/E_d)} = \frac{3\pi^2}{32m_N} \sqrt{\frac{1 + a}{2\Gamma m_N}} g^2 q_{p\bar{p}}^2(p_{\bar{p}})$$

(10)

The momentum distribution $d^3 N_{\bar{d}}/d^3 p_{\bar{d}}$ entering (1) is obtained from (10) by integration over the fireball volume

$$\frac{d^3 N_{\bar{d}}(p_{\bar{d}})}{d^3 p_{\bar{d}}} = \int d^3 x q_{\bar{d}}(p_{\bar{d}}, x)$$

(11)

Using (1), (10), (11) and (4) (with $r_0$ correction) we find for the coalescence parameter

$$B_{2}^{th} = \frac{24\pi^3}{E_{\bar{p}}} \times 1.6 \sqrt{\frac{(1 + a)\varepsilon}{2\Gamma}} \frac{\int d^3 x q_{\bar{p}}^2(p_{\bar{p}}, x)}{\left[\int d^3 x q_{\bar{p}}(p_{\bar{p}}, x)\right]^2}$$

(12)

Since the $x$-dependence of $q_{\bar{p}}(p_{\bar{p}}, x)$ is not known, we replace (12) by:

$$B_{2}^{th} = \frac{24\pi^3}{E_{\bar{p}}} \times 1.6 \sqrt{\frac{(1 + a)\varepsilon}{2\Gamma}} \frac{\bar{n}_{\bar{p}}^2}{V}$$

(13)

where $V$ is the fireball volume, $\bar{n}_{\bar{p}}$ and $\bar{n}_{\bar{p}}^2$ are the mean and mean square $\bar{p}$ densities in the fireball. (The coordinate dependence of $\sqrt{\Gamma}$ is neglected). $B_{2}^{th}$ is Lorenz invariant, as it should be. The volume $V$ may be understood as a mean value of the fireball volume at a stage, where, on one side, hadrons are already formed, i.e., mean distances between them are larger than the confinement radius $R_c \sim 1/m_\rho \sim (1/4)$ fm, but on the other side, hadron interactions are still essential. The antinucleon distributions $n_{\bar{p}}(r), n_{\bar{n}}(r)$ inside the fireball are nonuniform: at the dense gas stage and before it the antinucleons strongly annihilate in the internal part of the fireball and in much less extent in its external layer of the thickness of order $\bar{p}(\bar{n})$ annihilation length $l_{ann}$ (this effect was considered in [5]). For this reason $\bar{n}_{\bar{p}}^2/\bar{n}_{\bar{p}}^2$ may be remarkable larger than 1. For the same reason the antinucleons and antideuterons from the backside of the fireball (relative to the observer) are absorbed in the fireball and cannot reach the detector (see Fig. 1). Therefore, only one half of the fireball volume contributes to the number of registered $\bar{p}, \bar{n}$ and $\bar{d}$. The corresponding factor approximately equal to 2 is accounted in (13).

In fact, the fireball evolution after the balance may reduce the antideuteron number as $N_{\bar{d}} \rightarrow N_{\bar{d}}e^{-\Gamma_{\bar{d}}\Delta t}$, where $\Delta t$ is a typical time, required for the antideuteron to leave the interaction region. (Such $\approx 50\%$ reduction of $K^-$ mesons was observed in [17].) However,
Figure 1: Fireball at the dense gas stage. The effective volume $V_{\text{eff}}$ is the half of the outer shell of thickness $l_{\text{ann}}$, from which the antiprotons reach detector.

This effect does not change the coalescence parameter $B_2$. Indeed, in this case $B_2$ should be multiplied on the factor $e^{-\Gamma_\bar{d}\Delta t}/(e^{-\Gamma_\bar{d}\Delta t})^2$; the time $\Delta t$ is the same both for antideuteron and antiproton in consideration, because they move with equal velocities. But since $\Gamma_{\bar{d}} = 2\Gamma_{\bar{p}}$ with good accuracy (we checked it explicitly by eq (19)), this factor is close to 1 regardless of the evolution details.

$\Gamma$ may be calculated if the spectrum and densities of the fireball constituents at hadronic gas stage are known. At high energy of heavy ion collisions (SPS, RHIC) the main contributions to $\Gamma_{\bar{p}}$, $\Gamma_{\bar{n}}$, $\Gamma_{\bar{d}}$ come from the collisions of $\bar{p}$, $\bar{n}$, $\bar{d}$ with pions. Therefore $\Gamma_{\bar{p}}$, $\Gamma_{\bar{n}}$, $\Gamma_{\bar{d}}$ essentially depend on pionic density in the fireball, the dependence of $\Gamma$ on the densities of other fireball constituents is much weaker. Also weak is the dependence of $\Gamma$ on the spectrum of the fireball constituents, since the main contribution to $\Gamma_{\bar{p}}$ ($\Gamma_{\bar{n}}$, $\Gamma_{\bar{d}}$) arises from the collisions at high energies in c.m. system of $\bar{p}(\bar{n}, \bar{d}) + \pi$, where the cross sections are approximately constant. For this reason, without a serious error, for the calculation of $\Gamma$ we can take the spectra from the experimental data, i.e. corresponding to the final stage of the fireball evolution. Moreover, since the width enters as $\sqrt{\Gamma}$ in (13), the errors are reduced twice. If $\Gamma$ is known, then by comparison with the data the parameter $V^{-1}(n_{\bar{p}}/n_{\bar{p}}^2)$ can be found, what would allow to check various models of fireball evolution.

3. Comparison with the data. Consider the NA44 experiment at SPS (CERN): $\text{Pb} + \text{Pb}$ collisions at $\sqrt{s} = 17A$ GeV [1]. Antideuterons were observed at $0.6 < p_{\bar{d}t} < 1.6$ GeV and in the rapidity interval 1.9 to 2.1 in lab. system, which corresponds to $p_{\bar{d}t} = 0.55$ GeV, $(E_{\bar{p}})_{\text{c.m.}} = 1.5$ GeV. The spectra and particle yields at such collisions are given in [18].

The number of active nucleons, participating in collision ("wounded" nucleons) $N_N$ and the number of produced pions are presented in [19]: $N_N = 362$, $N_\pi = 1890$, $Q_\pi = N_\pi/N_N = 5.2$ (see also [20] for the review of the data on heavy ion collisions).

We accept the following model for the dense gas stage of fireball evolution [15]. (A related model had been suggested long ago [21, 22]: it may be called Fermi–Pomeranahuk model). Neglect for a moment contributions of all particles except for nucleons and pions. Assume that any participant – nucleon or pion occupies the volume $v_N$ or $v_\pi$, respectively. Then

$$n_N = \frac{N_N}{V} = \frac{n_N^0}{1 + Q_\pi \beta}, \quad n_\pi = \frac{N_\pi}{V} = \frac{n_\pi^0 Q_\pi}{1 + Q_\pi \beta} \tag{14}$$

where $n_N^0 = 1/v_N$, $\beta = v_\pi/v_N$. For numerical estimations we take $n_N^0 = 0.26$ fm$^{-3}$, 1.5 times standard nucleus density and $\beta = (r_\pi/r_N)^3 \approx 0.55$, where $r_\pi = 0.66$ fm and $r_N = 0.81$ fm are pion and nucleon electric radii. It must be stressed, that $n_N^0$ is the only essential uncertain
parameter in our approach. Even if $Q_\pi$ at dense gas stage differs from ones at the final stage, the arising error is essentially compensated by the appearance of $Q_\pi$ both in numerator and denominator in (14). (As was already mentioned, the nucleon contribution to $\Gamma$ is small.)

Check first the applicability conditions of our approach. We have: $n = n_N + n_\pi \approx 0.42 \text{fm}^{-3}$ and the mean distance between the fireball constituents is $d = 1/n^{1/3} = 1.3 \text{fm}$. Evidently, the condition $\lambda_\bar{p} = 1/p_\bar{p} \ll d$ is well satisfied. The calculation of $\Gamma$ according to (9) ($\Gamma = \Gamma_{\bar{q}}/2$) gives $\Gamma \approx 300 \text{MeV}$. (Only inelastic cross sections were accounted, the pion contribution comprises about 75%, the nucleon one about 25%. Note, that the value of $\Gamma$ is close to the momentum integration interval in the Wigner function approach, $\Delta P \approx 200 - 300 \text{MeV}$, found in [8].) Check now the balance condition – that the probability of deuteron desintegration exceeds the fireball expansion rate. The former is given by $2\Gamma(m_N/E_{\bar{p}})$. The estimation for the escape rate (or fireball expansion) is $w \sim (1/4) \text{fm}^{-1}$. We have: $2\Gamma(m_N/E_{\bar{p}}) \approx 2.0 \text{fm}^{-1} \gg 0.25 \text{fm}^{-1}$. So, this condition is also fulfilled. Even more, the balance condition would be fullfilled at much lower hadronic densities than chosen above, up to $n_0^0 \approx 0.05 \text{fm}^3$, i.e. up to densities not much higher, than supposed for thermal freeze-out [10, 23, 24]. However, such low densities would lead to much lower values of $B_2$, than ones obtained in experiments. Eq.6 is legitimate, if $\text{Imf}(E) \ll d$ [14, 15]. Since $\text{Imf} f \approx 1 \text{fm}$, this condition is not well satisfied. For this reason the value of $\Gamma$, presented above, has a large (may be 50%) uncertainty, and, probably, is overestimated (the effect of screening). This fact, however, does not influence too much the value $B_2^{th}$, since $\sqrt{\Gamma}$ enters (12). One may expect, that because of their slightly larger velocities in comparison with nucleons, pions form a halo around the fireball. This effect also may lead to an overestimation of $\Gamma$.

At the parameters used above the fireball volume comes out to be: $V = 6.2 \times 10^3 \text{fm}^3$ (15% correction for other particles, except for pions and nucleons were accounted). This value is about 2 times larger, than the ones found in [9] at chemical freeze-out and about 2 times smaller, than at thermal freeze-out [23, 24]. (Note, that the dense gas stage is an intermediate between these two.) In the case of sphere its radius is equal to $R = 11.4 \text{fm}$. If we assume, that antiprotons are mainly concentrated in the outer shell of the fireball of the thickness of $l_{ann} \approx 3 \text{fm}$, then $\bar{n}^2/n^2 \approx 2$ and we get for the coalescence parameter

$$B_2^{th} = 3.0 \times 10^{-4} \text{GeV}^2$$

(We put $\bar{\lambda}_q = \Gamma$, or $a = 1/2$.) Experimentally [1], for the average value of the most central 10% events it was found: $B_2^{exp} = (4.4 \pm 1.3) \times 10^{-4} \text{GeV}^2$. However, $B_2^{exp}$ strongly depends on centrality: the results for $0 - 5\%$ centrality are about 1.5 times lower. Taking in mind all uncertainties – theoretical and experimental, we believe, that the NA44 data for coalescence parameter are not in contradiction with theoretical expectation.

Turn now to the STAR experiment at RHIC: $Au + Au$ collisions at $\sqrt{s} = 130A \text{GeV}$ [2]. Antideuterons were measured at $0.5 < p_t < 0.8 \text{GeV}$ and in the rapidity interval $|\Delta y_{c.m.}| < 0.3$, 18% of central collisions were collected. We take $E_{\bar{p},c.m.} = 1.05 \text{GeV}$. The number of ”wounded” nucleons in the 18% central $Au + Au$ collisions can be estimated as $N_N = 320$ [25]. Multiplicity of negative hadrons $\bar{h}$ (mainly, pions) was measured in [26] at pseudorapidity $\eta = 0$ only and it was found an increasing of $dh^-\eta |_{\eta=0}$ by 52% comparing with the SPS data at $\sqrt{s} = 17A \text{GeV}$. But it is known that $dh/d\eta |_{\eta=0}$ increase faster with energy than the total multiplicity. We estimate $Q_\pi = N_\pi/N_N \approx 7 \pm 1$. (A value close to the presented above, can be found from the data compilation [27]). At $N_N = 320$ with account of 20% correction
for $K$-mesons and hyperons $V = 7.2 \times 10^3 \text{fm}^3$. The coalescence parameter is equal to

$$B_2^{th} = 3.8 \times 10^{-4} \text{GeV}^2$$

(16)

($\Gamma = 320 \text{MeV}$, $\bar{n}^2/(\bar{n})^2$ was put to be 2). Experimentally, STAR found $B_2^{exp} = (4.5 \pm 0.3 \pm 1.0) \times 10^{-4} \text{GeV}^2$.

The main uncertainty of $B_2^{th}$ comes from the fireball volume $V$ which was calculated by (14). However, the width $\Gamma$ also depends on the fireball volume, so that $B_2^{th} \sim 1/\sqrt{V}$, which suppresses this uncertainty twice. We expect the accuracy of our estimations (15), (16) to be about 50%.

In E864 experiment [3] at AGS the antideuterons were observed in $Au + Pt$ collisions at $\sqrt{s} = 4.8 \text{A GeV}$. 10% of central collisions we selected. From the data we take: $p_{\mu} = 0.17 \text{GeV}$, $E_{\bar{p},c.m.} = 0.99 \text{GeV}$. The number of "wounded" nucleons and $\pi/N$ ratio are $N_N = 350$, $Q_\pi = 1.6$ (see [20] and references herein). In the same way as before, we find: $V = 2.8 \times 10^3 \text{fm}^3$, $\Gamma = 220 \text{MeV}$, $l_{ann} = 1.2 \text{fm}$. In this case the validity conditions of our approach are at the edge of their applicability. So, the theoretical expectations for $B_2$ are valid only by the order of magnitude:

$$B_2^{th} \sim 1.5 \times 10^{-3} \text{GeV}^2$$

in comparison with $B_2^{exp} = (4.1 \pm 2.9 \pm 2.3) \times 10^{-3} \text{GeV}^2$.

4. Summary and Acknowledgements. The coalescence parameter $B_2$ for the antideuteron production in heavy ions collisions was calculated. It was supposed, that the $\bar{d}$ production proceeds at the stage, when the fireball may be treated as a dense gas of interacting hadrons. The $\bar{d}$ production is described as the formation process $\bar{p} + \bar{n} \rightarrow \bar{d}$, where $\bar{p}$, $\bar{n}$, $\bar{d}$ are moving in the mean field of the fireball constituents (mainly pions). It was shown, that in case of large $N_\pi/N_N$ ratio one may expect a balance: the number of produced antideuterons is equal to the number of desintegrated $\bar{d}$ due to collisions with pions. The balance condition determines $\bar{d}$ production rate and the value of coalescence parameter $B_2$. The later is expressed in terms of deuteron binding energy and mean fireball volume at this stage. The comparison with data demonstrates, that $\bar{d}$-production proceeds at the stage intermediate between chemical and thermal freeze-out – the dense gas stage of the fireball evolution. The theoretical values of $B_2$ are in satisfactory agreement with experimental data at SPS, RHIC and AGS but more data at various nuclei and various energies of collision and $\bar{d}$ energies would be very desirable. The comparison of the data with theory would allow to check various models of fireball evolution.

We are thankful to G.Brown, L.McLerran, E.Shuryak for discussions and S.Kiselev, Yu.Kiselev, A.Smirnitsky, N.Rabin for information about experimental data. This work was supported in part by INTAS grant 2000-587 and RFBR grant 03-02-16209.
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