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Antinucleon sources in heavy-ion collisions *

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As recently measured in relativistic heavy-ion collisions, the antideuteron formation rate, which is the ratio of the antideuteron production cross section to the antiproton cross section squared at the same momentum per nucleon, is substantially smaller than the formation rate of deuterons. This happens because the shape of the antinucleon source is different from the nucleon one. In the case of baryon-rich sources, the nucleons are emitted from the whole source volume while antinucleons are emitted predominantly from the surface due to antinucleon absorption in the baryon environment.

The cross section of antideuteron production in Si–Au collisions at AGS has been recently measured [1] and it has been found that the antideuteron formation rate, i.e. the ratio of the antideuteron cross section to the antiproton cross section squared both at the same momentum per nucleon, is 5–10 times smaller than the deuteron formation rate. This is hard to understand within a simple coalescence model [2], where the coalescence radius, which determines the formation rate, mainly reflects the deuteron structure and consequently should be essentially the same for deuterons and antideuterons. However, a more careful analysis presented here shows that such an experimental result should be indeed expected.

It has been argued that the formation rates of deuterons [3,4] and antideuterons [5–7] are sensitive to the space–time characteristics of particle sources in nuclear collisions. Measurements of deuterons and antideuterons can even be used to determine these characteristics in a similar manner as one studies two-particle correlations for this purpose; for a review see ref. [8]. In our earlier paper [5] the antideuteron production and two-pion correlations in p–p collisions were simultaneously considered. However, the analysis was obscured by the fact that two antinucleons are not produced independently from each other in p–p collisions and consequently one cannot approximate the cross section of nucleon pair production as a product of the single nucleon cross sections which were measured. When heavy ions collide the assumption that antinucleons and nucleons are independent of each other is well justified—every antinucleon is expected to be created in a different N–N interaction. Thus, the difference between the formation rates of deuterons and antideuterons should appear only due the different shapes and/or sizes of the nucleon and antinucleon sources. It has been suggested [1,7] that the antideuteron formation rate is smaller than the deuteron one because antinucleons (due to their large cross section) are emitted at a later stage of the source expansion, and consequently the antinucleon source is bigger than the nucleon one. As we will show below, such an explanation demands a density of the nucleon source which is about five times larger than that of the antinucleon one. Thus, we find this solution rather unacceptable and suggest another one in this note.

We start our considerations with a qualitative discussion of (anti)deuteron production in relativistic heavy-ion collisions.

The particle source is created when the colliding nuclei penetrate each other. If the size of the source is smaller than the particle mean free path, the particles immediately escape from the source. In the case

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of large sources, the particles cannot escape because they collide with each other. The source evolves towards thermodynamic equilibrium, expands a bit and then rapidly disintegrates when the particle mean free path is comparable to the fireball size. One often assumes that the source reaches equilibrium immediately or soon after it is created. In contrast to ref. [7], we do *not* adopt this far going assumption, although we assume that the antinucleons, which are produced near the center of the interaction region of the nucleus–nucleus collision, experience secondary interactions and most of them annihilate in the baryon environment. The antinucleons which are produced near the surface can escape from the source without reinteraction. Thus, the nucleons are emitted from the whole source volume while the antinucleons are emitted predominantly from the surface. As we will further show, the different shapes of antinucleon and nucleon sources can explain the difference between the formation rates.

Keeping in mind the qualitative picture presented above we can start our quantitative considerations. The cross section of (anti)deuteron production can be written as [2–6]

$$\frac{d\sigma^d}{d^3\boldsymbol{P}} = \mathcal{A}' \, \frac{d\widetilde{\sigma}^{np}}{d^3\boldsymbol{p}_1 \, d^3\boldsymbol{p}_2} , \tag{1}$$

where $\mathcal{A}'$ is the formation rate (see below) and $d\widetilde{\sigma}^{np}/(d^3\boldsymbol{p}_1 \, d^3\boldsymbol{p}_2)$ is the n–p production cross section with $\boldsymbol{p}_1 = \boldsymbol{p}_2 = \boldsymbol{P}/2$. This cross section neglects particle correlations due to the final state interactions and is usually factorized as

$$\frac{d\widetilde{\sigma}^{np}}{d^3\boldsymbol{p}_1 \, d^3\boldsymbol{p}_2} = \frac{1}{\sigma^{\rm inel}} \frac{d\sigma^n}{d^3\boldsymbol{p}_1} \frac{d\sigma^p}{d^3\boldsymbol{p}_2} , \tag{2}$$

with $\sigma^{\rm inel}$ being the total inelastic cross section. Thus, independent production of each nucleon is assumed here.

In the reference frame where a particle source is at rest, the deuteron formation rate $\mathcal{A}' = \gamma\mathcal{A}$ with γ being the Lorentz factor of the deuteron motion with respect to the source and

$$\mathcal{A} = \tfrac{3}{4}(2\pi)^3 \times \int d^3r_1 \, d^3r_2 \, \mathcal{D}(\boldsymbol{r}_1)\mathcal{D}(\boldsymbol{r}_2) \mid \psi_d(\boldsymbol{r}_1, \boldsymbol{r}_2) \mid^2 , \tag{3}$$

where the source function $\mathcal{D}(\boldsymbol{r})$, which is normalized as $\int d^3r \, \mathcal{D}(\boldsymbol{r}) = 1$, gives the probability to emit a nucleon from a space–time point $\boldsymbol{r}$; ψ_d is the deuteron wave function. The emitted nucleons are assumed unpolarized and consequently, the weight coefficient 3/4 appears.

For simplicity the time dependence is suppressed in eq. (3). This does not mean that the source is static, but that the particles are emitted simultaneously. Such an assumption leads to a slight overestimate of the source size. The point is that the effect of the time separation between the emission acts is well imitated by an increase of the space separation (see, e.g., ref. [4]). In fact, it is very hard to disentangle the two dependences. Let us also note that most (anti)nucleons are emitted during a short period of the source disintegration; thus, the (anti)deuteron formation rates, such as the correlation functions, carry information only about this last state of the source.

Eq. (1) is often written in an explicitly Lorentz invariant form as

$$E\frac{d\sigma^d}{d^3\boldsymbol{P}} = B\left(\frac{E}{2}\frac{d\sigma^p}{d^3(\boldsymbol{P}/2)}\right)^2 , \tag{4}$$

where E and $E/2$ are the energies of the deuteron and nucleons, respectively, and

$$B \equiv \frac{2}{m\sigma^{\rm inel}} \mathcal{A} , \tag{5}$$

with m being the nucleon mass. Eq. (4) assumes the factorization (2) and the approximate equality of the neutron and proton cross sections. In the case of a neutron surplus in the colliding projectile–target system, one includes an extra combinatorial factor in eq. (4).

The parameterization of a nucleon source is usually chosen in the gaussian form

$$\mathcal{D}(\boldsymbol{r}) = \frac{1}{(2\pi)^{3/2}r_0^3} \exp(-\boldsymbol{r}^2/2r_0^2) , \tag{6a}$$

which gives the mean radius squared of a source $\langle \boldsymbol{r}^2 \rangle = 3r_0^2$.

We choose the parameterization of an antinucleon source as

$$\overline{\mathcal{D}}(\boldsymbol{r}) = \frac{1}{(2\pi)^{3/2}(r_0^3 - r_*^3)} \times [\exp(-\boldsymbol{r}^2/2r_0^2) - \exp(-\boldsymbol{r}^2/2r_*^2)] , \tag{6b}$$

where r_* measures the zone where the emission of antinucleons is strongly damped.

Let us note that the parameterization (6b) is *not* singular at $r_* = r_0$. Indeed, the function (6b) in this case reads

$$\overline{\mathcal{D}}(\boldsymbol{r}) = \frac{1}{3(2\pi)^{3/2}} \frac{r^2}{r_*^5} \exp(-r^2/2r_*^2) \ . \tag{6c}$$

The parameterizations (6) allow one to factorize the integrals over the center-of-mass and relative coordinates, which are defined as $\boldsymbol{R} = \frac{1}{2}(\boldsymbol{r}_1 + \boldsymbol{r}_2)$, $\boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2$, $\boldsymbol{P} = \boldsymbol{p}_1 + \boldsymbol{p}_2$, $\boldsymbol{q} = \frac{1}{2}(\boldsymbol{p}_1 - \boldsymbol{p}_2)$. The deuteron wave function is then written down in the form

$$\psi_d(\boldsymbol{r}_1, \boldsymbol{r}_2) = e^{i\boldsymbol{P}\cdot\boldsymbol{R}} \phi_d(\boldsymbol{r}) \ . \tag{7}$$

Substituting eqs. (6) and (7) into eqs. (3) one gets after the integration over $\boldsymbol{R}$

$$\mathcal{A} = \tfrac{3}{4}(2\pi)^3 \int d^3r \, \mathcal{D}_r(\boldsymbol{r}) \, | \phi_d(\boldsymbol{r}) |^2 \ , \tag{8}$$

where $\mathcal{D}_r(\boldsymbol{r})$ describes the relative position of the emission points with

$$\mathcal{D}_r(\boldsymbol{r}) = \frac{1}{(4\pi)^{3/2} r_0^3} \exp(-r^2/4r_0^2) \ ,$$

$$\overline{\mathcal{D}}_r(\boldsymbol{r}) = \frac{1}{(4\pi)^{3/2}(r_0^3 - r_*^3)} \times [\exp(-r^2/4r_0^2) - \exp(-r^2/4r_*^2)] \ .$$

We use in further calculations the deuteron wave function in the Hulthén form

$$\phi_d(\boldsymbol{r}) = \left(\frac{\alpha\beta(\alpha+\beta)}{2\pi(\alpha-\beta)^2} \right)^{1/2} \frac{e^{-\alpha r} - e^{-\beta r}}{r} \ ,$$

with $\alpha = 0.23 \text{ fm}^{-1}$ and $\beta = 1.61 \text{ fm}^{-1}$ [9].

Performing the integration in eq. (8) one finds

$$\mathcal{A} = \frac{3\pi^2}{2r_0^2} \frac{\alpha\beta(\alpha+\beta)}{(\alpha-\beta)^2} \times \Big[F(2\alpha r_0) - 2F((\alpha+\beta)r_0) + F(2\beta r_0) \Big] \ ,$$

$$\overline{\mathcal{A}} = \frac{3\pi^2}{2(r_0^3 - r_*^3)} \frac{\alpha\beta(\alpha+\beta)}{(\alpha-\beta)^2} \times \Bigg[r_0 \Big[F(2\alpha r_0) - 2F((\alpha+\beta)r_0) + F(2\beta r_0) \Big] - r_* \Big[F(2\alpha r_*) - 2F((\alpha+\beta)r_*) + F(2\beta r_*) \Big] \Bigg] \ ,$$

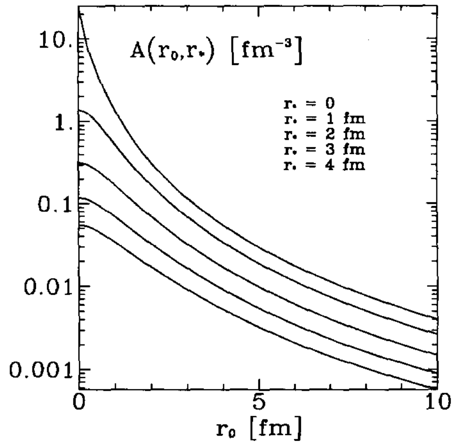

Fig. 1. The antideuteron formation rate as a function of r_0 for several values of r_*.

where

$$F(x) \equiv e^{x^2} \operatorname{erfc}(x) \ , \qquad \operatorname{erfc}(x) \equiv \frac{2}{\sqrt{\pi}} \int_x^\infty dt \, e^{-t^2} \ .$$

One observes that $\overline{\mathcal{A}}(r_0, r_*) = \overline{\mathcal{A}}(r_*, r_0)$, $\overline{\mathcal{A}}(r_0, r_* = 0) = \mathcal{A}(r_0)$.

In fig. 1 we show the formation rate $\overline{\mathcal{A}}$ as a function of r_0 for several values of r_*.

The experimental cross sections of antideuterons and antiprotons given in ref. [1] provide the value of the parameter $\overline{B}$ [defined by eq. (4)] as 7×10^{-7} GeV^2/mb [#1]. The value of B for deuterons for a similar projectile-target system is about 4×10^{-6} GeV^2/mb [10]. Estimating the cross section σ^{inel} as 3650 mb for Si–Au collisions the above values of $\overline{B}$ and B give the formation rates

$$\overline{\mathcal{A}} = 0.15 \text{ fm}^{-3} \ , \qquad \mathcal{A} = 0.90 \text{ fm}^{-3} \ .$$

Now one can find in fig. 1 the parameters r_0 and r_* corresponding to these formation rates. Then, $r_0 \cong 1.5$ fm, which corresponds to $\langle r^2 \rangle^{1/2} = \sqrt{3} r_0 \cong 2.5$ fm for the nucleon source. Therefore, the average nucleon source is somewhat smaller than the Si nucleus, the radius of which is about 3.3 fm. The value of the antideuteron formation rate can be reproduced with $r_* = 0$ and $r_0 \cong 2.5$ fm, which gives $\langle r^2 \rangle^{1/2} \cong$

[#1] The value of $\overline{B}$ given in ref. [1] is inconsistent with the cross sections listed there. The units of $\overline{B}$ are also incorrect.

4.3 fm. Then, the antinucleon source is substantially larger than the nucleon one, with the baryon density 5 times(!) smaller. The antideuteron formation rate is also reproduced with $r_0 \cong r_* \cong 1.5$ fm. In this case the antinucleon source is of the same size as the nucleon one but the antinucleons originate from the surface. Obviously, $\overline{\mathcal{A}}$ can be fitted with r_0 and r_* ranging from 1.5 fm to 2.5 fm and 0 to 1.5 fm, respectively. The most plausible case assumes, in our opinion, similar values of r_0 for the deuterons and antideuterons and a finite value of r_* for the latter.

It would be very interesting to measure $\overline{\mathcal{A}}$ and $\mathcal{A}$ as a function of (anti)deuteron momentum. The role of antinucleon absorption should decrease with increasing antideuteron momentum measured with respect to the source and then $\overline{\mathcal{A}}$ should tend to $\mathcal{A}$.

In conclusion, the experimentally observed [1] difference between the deuteron and antideuteron formation rates can be easily explained if one assumes that the nucleons are emitted from the whole volume of the source while the antinucleons are emitted predominantly from the surface.

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