Collective versus independent annihilation of "transhydrogen" antinuclei

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Annihilation of "heavy" antinuclei, such as $\bar{d}$, $\bar{t}$, or $\bar{\alpha}$ in nuclear matter could serve to probe whether the constituent antinucleons annihilate independently of each other or whether a single fireball is formed. In the latter case the total meson multiplicity distribution should have a lower mean and a larger relative width than in the trivial case. The meson spectrum would be correspondingly harder.

With the advent of high-energy heavy ion accelerators and advanced detectors for heavy secondary fragments and antifragments,[1] one may soon expect separated beams of antinuclei heavier than hydrogen (such as $\bar{d}$, $\bar{t}$, $\bar{\alpha}$) to become available.

A recent proposal[1] has been accepted at Brookhaven National Laboratory (BNL) as a test run (expected to yield $\simeq 10^5 \bar{p}$ and $\simeq 10^2 \bar{d}$) for a more important run with $\simeq 10^3$ times higher statistics.[2] Even observation of the production and annihilation of heavier antinuclei such as $\bar{\alpha}$ will, hopefully, become possible.

Beside the intrinsic interest in the production mechanisms involved,[1] a useful by-product of such experiments might be the investigation of the annihilation process of the antinuclei produced in high-energy nucleus-nucleus collisions.

This annihilation process can be imagined within the context of two extreme scenarios:

(i) The ν initial antinucleons annihilate independently of each other; in this case (hereafter denoted by A) the multiplicity distribution (MD) of the mesons resulting from the annihilation is expected to be just the ν-fold convolution of the MD for a $p\bar{p}$ annihilation with the same laboratory Lorentz factor γ_0.

(ii) The incident antinucleus annihilates as a whole, leading to formation of a single "fireball." In this case (denoted by B) the MD is determined by the total effective center-of-mass system (c.m.s.) energy of the annihilating baryons+antibaryons.

We will show below that considerable differences between the MD's are to be expected in these two cases.

Previous theoretical studies of $p\bar{p}$ and $d\bar{d}$ (case A) annihilation at rest as well as at moderate energies have been carried out in Refs. 3–5, where the authors considered the implications of the process for the investigation of the equation of state and/or quark-gluon-plasma formation. "Independent" $d\bar{d}$ annihilation (case B) was treated within the Glauber formalism in Refs. 6 and 7. For a review of microscopic theoretical descriptions of $p\bar{p}$ annihilation in the quantum chromodynamics (QCD) context, see Ref. 8.

As long as one is interested only in the gross features of the MD of annihilation secondaries one may ignore detailed model representations and use only the property of "universality," i.e., the independence of the final state on the nature of the incident particles depositing a given effective c.m.s. energy $\sqrt{s_{\text{eff}}}$ into meson production. For this purpose direct experimental information is readily available.

For the basic data on $p\bar{p}$ annihilation we use the detailed cross-section tables of Ref. 9. Fortunately reliable measurements of MD parameters concerning hadronic particle production in pp collisions *at fixed effective c.m.s. energy* (i.e., after subtraction of the leading baryons) have come out of a hybrid hydrogen bubble chamber (HBC) spectrometer experiment,[10] up to $\sqrt{s_{\text{eff}}} \simeq 12$ GeV. Therefrom one may deduce such basic characteristics of the MD for negative secondaries (mostly pions) as the mean $\langle n^- \rangle$ and the dispersion

$$D_{n^-} \equiv [\langle (n^-)^2 \rangle - \langle n^- \rangle^2]^{1/2} , \tag{1}$$

which measures the absolute width of the distribution. The (more relevant) relative width of the MD is given by

$$\epsilon^- \equiv \frac{D_{n^-}}{\langle n^- \rangle} ; \tag{2}$$

the deviation of the MD from a Poisson distribution is measured, e.g., by the normalized second factorial cumulant:

$$\varphi_2^- \equiv (\epsilon^-)^2 - \frac{1}{\langle n^- \rangle} . \tag{3}$$

If the incident antinucleus has a lab Lorentz factor γ_0 then the effective c.m.s. energy is

$$\sqrt{s_{\text{eff}}} = \tilde{\nu}(2m_N) \left(\frac{\gamma_0 + 1}{2} \right)^{1/2} , \tag{4}$$

where $\tilde{\nu} = 1$ for $p\bar{p}$ and case A whereas $\tilde{\nu} = \nu$ for case B.

For independent annihilation (case A) the ν-fold convolution yields

$$\langle n^- \rangle_{X\bar{X},\ \text{indep}} = \nu \langle n^- \rangle_{p\bar{p}(\sqrt{s_{\text{eff}}})} , \tag{5}$$

TABLE I. Characteristics of the multiplicity distributions of negative secondaries from the annihilation of antiprotons and heavier antinuclei.

Annihilation	γ_0	$\sqrt{S_{\rm eff}}$ (GeV)	$\langle n^- \rangle$	D_{n^-}	ϵ^-	φ_2^-
$p\bar{p}$	1	1.88	1.52	0.68	0.45	−0.46
$d\bar{d}$ (indep)	1	1.88	3.04	0.96	0.32	−0.33
$d\bar{d}$ (collect)	1	3.75	1.75	0.81	0.46	−0.36
$t\bar{t}$ (indep)	1	1.88	4.56	1.18	0.26	−0.22
$t\bar{t}$ (collect)	1	5.63	2.16	1.03	0.48	−0.24
$\alpha\bar{\alpha}$ (indep)	1	1.88	6.08	1.35	0.22	−0.16
$\alpha\bar{\alpha}$ (collect)	1	7.50	2.51	1.83	0.47	−0.18
$p\bar{p}$	12	4.93	2.76	0.99	0.36	−0.23
$d\bar{d}$ (indep)	12	4.93	5.52	1.40	0.25	−0.18
$d\bar{d}$ (collect)	12	9.86	2.85	1.31	0.46	−0.14
$t\bar{t}$ (indep)	12	4.93	8.28	1.71	0.21	−0.12
$t\bar{t}$ (collect)	12	14.79	3.52	1.53	0.44	−0.10
$\alpha\bar{\alpha}$ (indep)	12	4.93	11.05	1.97	0.18	−0.09
$\alpha\bar{\alpha}$ (collect)	12	19.72	4.08	1.68	0.41	−0.07

where X $(\bar{X})$ stands for any complex nucleus (antinucleus), and

$$(D_{n^-})_{X\bar{X},\,\rm indep} = \sqrt{\nu}(D_{n^-})_{p\bar{p}(\sqrt{s_{\rm eff}})} \,. \tag{6}$$

For "collective" annihilation one expects

$$\langle n^- \rangle_{X\bar{X},\,\rm collect} = \langle n^- \rangle_{pp(\sqrt{s_{\rm eff}})} \,, \tag{7}$$

and

$$(D_{n^-})_{X\bar{X},\,\rm collect} = (D_{n^-})_{pp(\sqrt{s_{\rm eff}})} \,. \tag{8}$$

The results of Ref. 10 are best given in terms of the (very good) fits:

$$\langle n^- \rangle = 0.88\,(\sqrt{s_{\rm eff}})^{0.52} \tag{9}$$

and

$$D_{n^-} = 0.105 + 0.535\,\ln\sqrt{s_{\rm eff}} \,. \tag{10}$$

We now consider the cases of annihilation at rest (γ_0=1) as well as in flight at $\gamma_0 \approx 12$, for which detailed experimental data are provided in Ref. 9.

For incident $\bar{d}$, $\bar{t}$, and $\bar{\alpha}$ (i.e., ν = 2–4) the numbers turn out as presented in Table I. As can be seen (at both incident energies), if case B is realized, the mean multiplicity is smaller by factors between 1.7 and 2.5 than in case A. Obviously since energy is conserved, the mean meson energy would be higher by the same factor. As to the relative widths of the MD's (which are both "sub-Poisson" since $\varphi_2^- < 0$), they also differ by factors close to 2, the MD being narrower in the "independent" case and closer to a Poisson distribution. Such large differences in the MD should be easily detectable even with the limited statistics available in the early phases of new experiments.

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