Antibaryon ($\bar{\rho}$, $\bar{\Lambda}$) production in relativistic nuclear collisions


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The relativistic meson field theory is used to study the effects of the in-medium interaction on the predicted antibaryon abundancy in hot hadronic matter. It is demonstrated that subthreshold production of antiprotons in high energy heavy ion collisions at $E_{\text{lab}} = 1-2$ GeV/nucleon is enhanced by 2-3 orders of magnitude as compared to a standard fireball model estimate. Furthermore, we show that after the inclusion of interactions the anti-hyperon yields, e.g. $\bar{\Lambda}/\pi^-$, are enhanced by about a factor ten. Predicted yields are in excess of the data measured by the NA35 and WA85 collaborations at CERN. The annihilation of antibaryons in surrounding matter at the final stage of the reaction may essentially reduce their abundancy.

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1. Introduction

In recent years the relativistic meson field model (RMFM) has been widely used for the description of nuclear matter, finite nuclei and nuclear dynamics (for reviews see [1]). This model is one of the possible realizations of the Quantum Hadro Dynamics (QHD) based on an effective Lagrangian of Dirac-baryons interacting with (mean) meson fields. Both QHD and QCD motivated models may describe the same observable phenomena just in different languages. In particular, Theis et al. [2] demonstrated that the RMF model exhibits a sudden change in thermodynamical behaviour around $T_c \approx 200$ MeV at zero baryon density, in analogy to quark-gluon deconfinement in lattice QCD calculations: The pressure and the internal energy become up to a constant those of a free, nearly massless fermion plasma. The scalar field in the RMF model yields this strong reduction in mass (in analogy to chiral restoration observed in lattice QCD), which in turn results in high abundance of low mass baryon-antibaryon pairs at high temperature ($\approx T_c$). A large enhancement of antiproton (and anti-lambda, anti-sigma) production in heavy ion collisions should then be observable. This is of great interest both for the subthreshold $\bar{p}$ production measurements at LBL [3, 4, 5] and at GSI [6] and also with respect to the recent observation of enhanced $\bar{\Lambda}$, $\Xi$ production in ultrarelativistic heavy ion collisions [7], which was proposed as a quark gluon plasma signal [8].

It was shown in [9] that the attractive interaction of antibaryons with the meson fields in a high density medium may lower their energy far below values of the baryon mass in vacuum and may thus significantly reduce the gap between particles and antiparticles in the Dirac spectrum. The importance of the reduction of the baryon-antibaryon gap in the normal nuclear matter as compared with vacuum was emphasized earlier [12].

2. Effective model Lagrangian

We use the following effective Lagrangian containing baryon ($\Phi_B$), scalar-meson ($\sigma$) and vector-meson ($\omega^a$) fields [1]:

$$\mathcal{L} = \sum_B \bar{\Psi}_B \left[ i \gamma^\mu \left( \partial_\mu - g_{B\nu} \omega^\nu \right) \Phi_B - \left( m_B - g_{B\sigma} \Phi_B \right) \right] \Psi_B$$

$$- \frac{i}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \omega^a \omega^a - \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - V(\sigma),$$

(1)

where the sum runs over the baryon species $B = N, \Lambda, \Lambda, \Xi, \bar{\Xi}$. Here

$$F_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu$$

(2)

is the vector field tensor and

$$V(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{b}{3} \sigma^3 + \frac{c}{4} \sigma^4$$

(3)

is the potential energy of the scalar field including nonlinear selfinteraction terms [10]. $m_B, m_\sigma, m_\omega$ are vacuum
masses of the corresponding fields and $g_{SB}$, $g_{VB}$, $b$ and $c$ are the coupling constants. The corresponding equations of motion are

\begin{align}
(i\gamma^\mu(\partial_\mu - g_{VB} \alpha_\mu) + (m_B - g_{SB} \sigma)) \psi_B &= 0, \\
(\partial^2 - V^2) \sigma + V(\sigma) &= \sum_B g_{SB} \rho_S^{(B)}, \\
(\partial^2 - V^2 + m_\omega^2) \omega &= \sum_B g_{VB} \rho_V^{(B)}. 
\end{align}

The scalar and the vector (baryon) densities are $\rho_S^{(B)} = \langle \bar{\psi}_B \psi_B \rangle$ and $\rho_V^{(B)} = \langle \bar{\psi}_B \gamma_0 \gamma_\mu \psi_B \rangle$, respectively. The total scalar and vector densities are given by

$$\rho_S = \sum_B \rho_S^{(B)}, \quad \rho_V = \sum_B \rho_V^{(B)}.$$  \hfill (7)

We replace the meson field operators by their expectation values in the mean field approximation. The model has four adjustable parameters for infinite nuclear matter (without other baryons)

$$C_S = g_{SN} \frac{m_n}{m_\omega}, \quad C_V = g_{VN} \frac{m_n}{m_\omega}, \quad C_3 = \frac{b}{m_N g_{SN}}, \quad C_4 = \frac{c}{g_{SN}},$$  \hfill (8)

plus $g_{VA}/g_{VN}$ and $g_{SA}/g_{SN}$ for hyperons, where $m_n = 938$ MeV is the vacuum nucleon mass. These parameters can be fixed by the binding energy $E_B$, baryon density $\rho_B$, effective mass $m^*_B$ and incompressibility modulus $K$ of isospin-symmetric nuclear matter in equilibrium. The simplest realization of the model ($C_3 = C_4 = 0$) leads to an effective mass which is too small ($m^*_B = 0.56m_\omega$) and to an incompressibility which is too high ($K = 540$ MeV). One can get more realistic values of $m^*_B$ and $K$ by using the nonlinear terms in $V(\sigma)$ introduced in [10]. The coupling constants used are taken from a fit to the properties of eight spherical finite nuclei [1] with an effective mass of $m^*_B = 0.75m_\omega$ given by the values below: $g_{SN} = 7.51141$, $g_{VN} = 9.51541$, $b = -9.57568$ fm$^{-1}$, $c = 1.97056$, $m_\omega = 454.871$ MeV, and $m_n = 780$ MeV. The coupling constants of the $A$ relatively to the nucleon coupling constants are fixed by a fit to recent hypernuclear data [13] and chosen to be $g_{SA}/g_{SN} = g_{VA}/g_{VN} = 0.43$ so that the potential depth of the $A$ in nuclear matter is about 27 MeV. This parameter set reproduces the properties of normal nuclei and of hypernuclei. For simplicity we adopt the same coupling ratio for the other strange baryons of the baryon octet in agreement with the recent knowledge of hypernuclei.

3. The spectrum of the Dirac equation in relativistic mean fields

Let us consider now a finite region of space occupied by nuclear matter and characterized by a spatial dimension $R$. We assume that the baryon densities are uniform inside this region and that they decrease rapidly to zero in the thin surface layer. When $R$ is large enough, the single particle states can be classified by the 3-momenta $p$, i.e. the internal baryon wave functions may be well approximated by plane waves. In the static case $\omega = 0$ and the Dirac equation for baryons (4) leads to the following single particle energy spectrum:

$$E^\pm(p) = U_{VB} \pm \sqrt{p^2 + m_B^2},$$  \hfill (9)

where

$$m_B^2 = m_B^2 - U_{SB}$$  \hfill (10)

is the effective baryon mass and

$$U_{SB} = g_{SB} \sigma,$$  \hfill (11)

$$U_{VB} = g_{VB} \omega_0$$  \hfill (12)

are the effective scalar and vector potentials generated by the mean meson fields. These fields are determined selfconsistently from the equations of motion (5, 6) after substituting $\rho_S$ and $\rho_V$ as functions of $\sigma$ and $\omega$.

The scalar and vector densities are expressed as

$$\rho_S = \int_{p \leq p_F} \frac{d^3p}{(2\pi)^3} \frac{v_N p^2}{6\pi^2},$$  \hfill (13)

$$\rho_V = \int_{p \leq p_F} \frac{d^3p}{(2\pi)^3} \frac{m_N^2}{\sqrt{p^2 + m_N^2}} = \frac{v_N m_N^2 p^2}{4\pi^2} \Phi \left( \frac{m_N^2}{p_F^2} \right),$$  \hfill (14)

where

$$\Phi(x) = \sqrt{1 + x^2} - \frac{x^2}{2} \ln \left( \frac{\sqrt{1 + x^2} + 1}{\sqrt{1 + x^2} - 1} \right)$$  \hfill (15)

and $v_\sigma$ is the spin-isospin degeneracy factor of the baryon $B$ (for nucleons $v_N = 4$). It has been demonstrated that the RMF model based on the nonlinear Lagrangian (1) reproduces well the main properties of atomic nuclei [1]. The qualitative picture is a follows: the mean meson fields generate the selfconsistent potential $U_N$ for the nucleons which – in turn – are the sources of these fields. It is important to point out that the relativistic Dirac equation (4) describes simultaneously the baryons (nucleons) with energies $E_N(p) = E^+(p)$ and the antibaryons (antinucleons) with the energies $E_B(p) = -E^-(p)$. The corresponding mean potentials acting on the baryons and the antibaryons at $p = 0$ are

$$U_B = E_B(0) - m_B = + U_{VB} - U_{SB},$$

$$U_B = E_B(0) - m_B = - U_{VB} - U_{SB}.$$  \hfill (16)

Note that the mean potential for baryons induced by the vector field is repulsive, while it is attractive for antibaryons. The tremendous vector and scalar potentials for nucleons (magnitudes of several hundred MeV are involved!) nearly cancel each other at normal nuclear density, resulting in the rather shallow nuclear potential well of about 60 MeV. However, the antinucleons feel a much deeper potential of about 800 MeV at the same positive baryon density (in the case $C_3 = C_4 = 0$). Note