

Subthreshold antiproton production in nucleus-nucleus collisions

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Antiproton production from the secondary process $\rho\rho \rightarrow p\bar{p}$ is studied for nucleus-nucleus collisions at energies which are below the threshold for its production from the nucleon-nucleon reaction in the free space. In an expanding fireball model, we determine the ρ abundance from the fusion of pions and find that for collisions at 2.1 GeV/nucleon the antiproton to negative pion ratio is $\approx 5.5 \times 10^{-7}$ and has a similar magnitude to that of the data.

Recently, experiments¹ were carried out at the Bevalac to detect the antiproton from heavy-ion collisions at energies which are below the threshold for its production from the nucleon-nucleon reaction in the free space. The motivation for such experiments is to look for effects of dense nuclear matter formed in the early stage of the collision on antiproton production so that one can learn about the properties of such a matter. In particular, antiproton production might be a possible probe of the structure of the Dirac sea in the presence of dense nuclear matter.

The measured antiproton to negative pion ratio for the collision of two Si nuclei at an incident energy of 2.1 GeV/nucleon has a surprisingly large value of about 4.3×10^{-7} . This is 3 orders of magnitude larger than that predicted by a calculation^{1,2} incorporating internal motion of the nucleons in the colliding nuclei and is actually comparable to that from assuming that both the antiproton and the pion abundance are given by their equilibrium values. But this is not expected for antiproton due to its small production probability from the nucleon-nucleon reaction. However, a recent study by one of us³ indicates that antiproton production from the secondary process $\rho\rho \rightarrow p\bar{p}$ is appreciable if we assume that the ρ meson abundance is given by its equilibrium value. This process is important because of its appreciable cross section and the higher ρ abundance than other heavy mesons. Assuming that antiproton production occurs at the freezeout density of half the normal nuclear matter density and lasts a time limited by the lifetime of the ρ meson, i.e., 1.8 fm/c, we have found that the ratio of the antiproton number to that of the negative pion is $\approx 3.3 \times 10^{-7}$ for the reaction studied at the Bevalac and is very close to the measured value. But our assumption that the ρ abundance is given by the equilibrium value has been questioned in Ref. 1 as the ρ to π ratio in our model is about 2.6×10^{-2} and is about a factor of 4 larger than that estimated from electron-pair production in Ca+Ca collisions at the same energy.⁴ However, the limit set in Ref. 4 is unreliable due to the very large error associated with the dilepton data. Still, it is of interest to find out whether the ρ meson remains to play an important role in antiproton production if the ρ meson abundance is dynamically determined in the collision. In the following, we shall report the results from such an improved study.

As in the previous study, we assume that a fireball is formed from the participants of the two colliding nuclei

with only Δ 's being in equilibrium with the nucleons. We do not include pions in the initial fireball as the cascade model⁵ predicts that their number is small in the initial compression stage of the collisions. The expansion of the fireball is then described by the hydrodynamical model in which the fireball is assumed to be in thermal but not chemical equilibrium. The thermal energy in the fireball is converted into the collective flow energy via a simplified relativistic hydrodynamical equation. During the expansion, the particle abundance is determined from solving the kinetic equations. Details on this model can be found in Ref. 6 where it is used to study kaon production in heavy-ion collisions. In particular, ρ mesons are produced from the fireball via the fusion of two pions with the production rate calculated from the ρ meson width Γ_ρ (153 MeV) which also determines its decay rate back to pions. The ρ meson density ρ_ρ as a function of time is then determined by

$$\frac{d\rho_\rho}{dt} \approx \Gamma_\rho \left(\frac{\rho_\rho^{(0)}}{\rho_\pi^{(0)2}} \rho_\pi^2 - \rho_\rho \right). \quad (1)$$

In the above, ρ_π is the pion density while $\rho_\pi^{(0)}$ is its value at equilibrium. The equilibrium density of the ρ meson is denoted by $\rho_\rho^{(0)}$. Equation (1) is valid as the change of the ρ density due to other processes are negligible. From ρ mesons, antiprotons are produced from the process $\rho\rho \rightarrow p\bar{p}$ with its density $\rho_{p\bar{p}}$ determined by

$$\frac{d\rho_{p\bar{p}}}{dt} \approx \langle \sigma_{p\bar{p}}^{\rho\rho} v_{p\bar{p}} \rangle \left(\frac{\rho_\rho^{(0)} \rho_{p\bar{p}}^{(0)}}{\rho_\rho^{(0)2}} \rho_\rho^2 - \rho_\rho \rho_{p\bar{p}} \right), \quad (2)$$

where ρ_ρ and $\rho_\rho^{(0)}$ are respectively the proton density and its value at equilibrium. The equilibrium density of antiproton is given by $\rho_{p\bar{p}}^{(0)}$. The thermal average of the antiproton annihilation cross section $\sigma_{p\bar{p}}^{\rho\rho}$ and the relative velocity $v_{p\bar{p}}$ between the proton and antiproton is denoted by $\langle \sigma_{p\bar{p}}^{\rho\rho} v_{p\bar{p}} \rangle$. The antiproton annihilation cross section $\sigma_{p\bar{p}}^{\rho\rho}$ is estimated to have a value of ≈ 5 mb.⁷ Again, we have neglected the small contribution from other processes in deriving Eq. (2).

The initial condition of the fireball is determined by assuming that it is formed from the overlap of two Lorentz contracted nuclei as in Ref. 6. For the reaction of two ²⁸Si nuclei at an incident energy of 2.1 GeV/nucleon, the initial density is about $3\rho_0$, where ρ_0 is the normal nuclear

matter density, and the initial temperature is about 163 MeV. In Fig. 1(a), we show the particle abundance as functions of time. The ρ meson number reaches a maximum at about 3 fm/c, which is about twice its lifetime. Most antiprotons are produced during this time interval. The final antiproton to negative pion ratio at freezeout is about 5.5×10^{-7} and is of a similar magnitude as that from our previous calculation and also the measured one. It is interesting to note that the ratio for the antiproton number to one-third of the total number of Δ and pion reaches this value at about 4 fm/c and remains essentially unchanged afterwards. The ratio of the maximum ρ number to the final pion number is $\approx 2.2 \times 10^{-2}$ and is about 60% of that predicted from assuming that both the initial ρ and π numbers are given by their equilibrium values. The ρ meson abundance, therefore, almost reaches its equilibrium value in heavy-ion collisions due to the fast decay of Δ 's into pions and the large $\pi\pi$ fusion cross section. For the latter case, the time evolution of the particle abundance is shown in Fig. 1(b). The calculated antiproton to negative pion ratio is about a factor of 5 larger than the case when there are no ρ and π mesons in the initial fireball. In both cases, the maximum ρ number to the final pion number is much larger than the limit estimated from the electron-pair production in Ca+Ca collisions at the same energies.⁴

Our results are not modified appreciably if we change by a factor of 2 both the initial fireball density and the magnitude of the cross section for the process $p\bar{p} \rightarrow \rho\rho$. The inclusion of antiproton production from the annihilation of other mesons such as pions, η 's, and ω 's does not change our results either as their contributions are negligible as in Ref. 3. Therefore, we conclude that the ρ

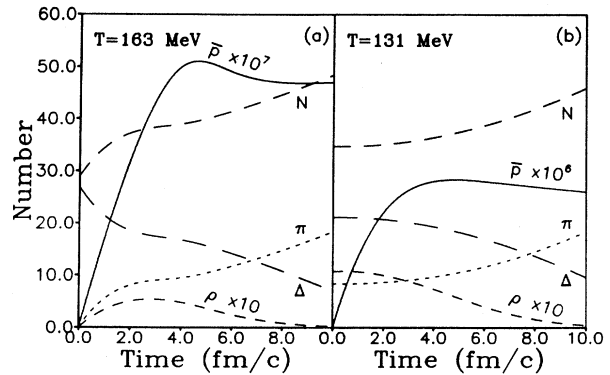


FIG. 1. The particle abundance as functions of the time for a fireball with an initial density of $3\rho_0$. The initial temperature is indicated by T . The initial π and ρ meson densities in the fireball are zero in (a) and are taken to be their equilibrium values in (b).

meson plays an important role in antiproton production from heavy-ion collisions at subthreshold energies. It is thus necessary to determine reliably the contribution to antiproton production from the process discussed here before we can hope to extract information on other exotic mechanisms. To achieve this, further work is needed to determine more reliably the cross section for $p\bar{p} \rightarrow \rho\rho$ and to implement this process in the heavy-ion transport model.

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