Antiproton production in Ni+Ni collisions at 1.85 GeV/nucleon

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Antiproton production in Ni+Ni collisions at 1.85 GeV/nucleon is studied in the relativistic Vlasov-Uehling-Uhlenbeck model. The self-energies of the antiproton are determined from the nucleon self-energies by the G-parity transformation. Also, the final-state interactions of the antiproton including both rescattering and annihilation are explicitly treated. With a soft nuclear equation of state, the calculated antiproton momentum spectrum is in good agreement with recent experimental data from the heavy-ion synchrotron at Gesellschaft für Schwerionenforschung Darmstadt. The effect due to the reduced nucleon and antinucleon masses in a medium is found to be more appreciable than in earlier Bevalac experiments with lighter systems and at higher energies.

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The study of antiproton production in heavy-ion collisions at subthreshold energies has been a topic of great interest both experimentally [1–4] and theoretically [5–14]. In Ref. [14], we have studied antiproton production from Si+Si collisions at 2.1 GeV/nucleon in the relativistic Vlasov-Uehling-Uhlenbeck (RVUU) model [15]. Extending the RVUU model to include the antiproton degree of freedom, we have been able to include the medium effects on antiprotons and treat consistently their production, propagation, rescattering, and annihilation. Because of the attractive scalar field, both nucleon and antinucleon masses are reduced in a medium. Assuming that the antiproton self-energies in a medium are given by the G-parity transformation of the nucleon self-energies, then the vector potential for the antiproton has an opposite sign from that for the nucleon. The vector potential therefore does not play any role in antiproton production as the antiproton is produced together with a nucleon as a result of baryon conservation. The reduction of nucleon and antinucleon masses in the medium then reduces the antiproton production threshold and enhances thus the primordial antiproton production in the dense matter formed in nucleus-nucleus collisions. In Ref. [14], our theoretical results for the antiproton momentum spectrum are found to agree with experimental data from the Bevalac at Lawrence Berkeley Laboratory [1].

Systematic measurements of antiproton production in heavier systems and at lower incident energies are being carried out at the heavy-ion synchrotron (SIS) at GSI [4]. Since the density reached in these collisions is higher and the energy deficit is larger than in the experiments at Bevalac with lighter systems and at higher energies, we expect that the medium effects discussed above will be more appreciable in these collisions. In this Brief Report, we present our calculation of antiproton production in Ni+Ni collisions at 1.85 GeV/nucleon and compare the results with recent experimental data from SIS [4].

The calculation is carried out in the same way as in Ref. [14]. We use two sets of parameters for the nuclear equation of state as given in Ref. [14]. They lead to the same binding energy and nucleon effective mass at the same saturation density but differ in the incompressibility of the nuclear matter. The one with an incompressibility of 200 MeV corresponds to the soft equation of state, while the incompressibility of the stiff equation of state is 380 MeV. We note that although the nucleon effective mass ($m_N^* = 0.83 m_N$) at saturation density is the same for the two set of parameters, it differs at higher densities and is smaller for the soft equation of state than for the stiff equation of state (see Ref. [14]).

The nucleon effective mass also depends on the temperature of the medium. In the Walecka model, the nucleon mass at finite density is slightly increasing for the temperature range encountered in heavy-ion collisions at SIS energies [16]. A similar temperature dependence of the constitutent quark mass has also been found in calculations based on the Nambu–Jona-Lasinio model [17,18]. This small change of the nucleon mass with temperature is thus not too important. It is, nevertheless, implicitly included in our transport model as we determine at each time step and for each cell the local effective mass as a function of local baryon density and average kinetic energy. The latter is related to the temperature in an equilibrium description.

Antiprotons are produced from $B_1 B_2 \to NNp\bar{p}$, where B_1 and B_2 are either a nucleon or a Δ. Higher baryon resonances are not included in our calculation. In Ref. [12], subthreshold antiproton production has also been studied using the relativistic quantum molecular dynamics where all baryon resonances with masses below 2 GeV are included. However, no specific information is given regarding the importance of the contribution from higher resonances relative to that from the Δ. It has been shown in Ref. [19] from the total photonuclear cross section that the widths of higher baryon resonances increase substantially already at normal nuclear matter density. To treat these broad and mostly overlapping baryon resonances as elementary particles in a dense matter may thus be questionable.

Antiprotons can also be produced from pion-baryon interactions. In our model pions are produced from the decay of Δ's and thus materialize at the later stage of heavy-ion collisions when the system already starts to expand and baryons have therefore less kinetic energies.

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Also, at the expansional stage, the effect of reduced nucleon mass is less significant because the density is not high. The chance that a proton-antiproton pair is produced from the pion-baryon interaction is thus smaller than that from the energetic baryon-baryon collisions occurring at the compressional stage of heavy-ion collisions. In Ref. [12], the situation is different as mesons (including higher mass ones in addition to pions) are produced from string breaking and thus are present already at the early stage of heavy-ion collisions. The meson-baryon contribution in Ref. [12] is about 50% of the total antiproton yield. We expect that the pion-baryon contribution in our approach is about 20–30% of the total antiproton yield, similar to the pion-baryon contribution to subthreshold kaon production [20,21]. As the medium effects discussed in this paper are more significant than the pion-baryon contribution, we shall neglect the latter in present work.

In the free space, the antiproton production cross section from the process $B_1B_2 \to NNp\bar{p}$ has been parametrized in Refs. [9,14] by $\sigma^{\bar{p}}_{B_1B_2}(\sqrt{s}) = 0.012\ (\sqrt{s}-\sqrt{s_0})^{1.846}$, where $\sqrt{s}$ is the center-of-mass energy of the colliding baryons and $\sqrt{s_0} = 4m$ is the antiproton production threshold energy. In a medium, the reduced nucleon and antinucleon masses should enter in the antiproton production cross section not only into $\sqrt{s}$ and $\sqrt{s_0}$ but also into other parameters. Due to the lack of knowledge of the process in a nuclear medium and for an exploratory study of antiproton production in heavy-ion collisions, we assume that the cross section has the same form as that in free space, with corresponding energy and threshold replaced by the medium-dependent ones, i.e.,

$$\sigma^{\bar{p}}_{B_1B_2}(\sqrt{s^*}) = 0.012\ (\sqrt{s^*} - \sqrt{s_0^*})^{1.846}. \quad (1)$$

We note that, within the mean-field approximation and under the G-parity transformation, the vector potential energy is the same in both the initial and the final state of the reaction $B_1B_2 \to NNp\bar{p}$, and thus does not play any role in antiproton production. The total center-of-mass energy $\sqrt{s^*}$ of the colliding pair of baryons is thus given by

$$\sqrt{s^*} = (\mathbf{p}_1^* + m_1^*)^{1/2} + (\mathbf{p}_2^* + m_2^*)^{1/2}, \quad (2)$$

where m_i^* and $\mathbf{p}_i^*$ (i=1,2) are, respectively, the effective mass and kinetic momentum of the colliding baryons. The antiproton production threshold in the medium is

$$\sqrt{s_0^*} = 4m^*. \quad (3)$$

In the reaction $B_1B_2 \to NNp\bar{p}$, about twice nucleon effective mass [Eq. (2)] is involved in the initial state, while four times nucleon effective mass [Eq. (3)] appears in the final state; the decrease of the nucleon and antinucleon masses in dense medium leads to a reduction of the threshold and thus an enhanced production of antiprotons from heavy-ion collisions.

In writing down Eqs. (2) and (3) we include only mean-field contributions to the antiproton self-energies. In principle, the dispersive correction due to both antiproton elastic scattering and annihilation by a nucleon should be added to the mean-field contribution. In Ref. [13], the dispersive correction from antiproton annihilation has been evaluated and is found to be appreciable. However, the dispersive correction, which involves higher order loop diagrams, is expected to be somewhat suppressed in heavy-ion collisions due to the highly nonequilibrium nature of the dynamics. As an exploratory study and since no dispersive corrections have been added to either the nucleon or the pion mean-field potential in the transport model, we neglect thus the dispersive contribution to the antiproton potential in the present calculation and plan to address this question in the future.

The final-state interactions of primordial antiprotons with baryons are explicitly treated in our calculation. These include the propagation of antiprotons in the mean-field potential and their elastic rescattering and annihilation by baryons. The mean-field potential is determined from the self-energies of the antiproton. For both elastic scattering and annihilation, the cross sections in free space as parametrized in Ref. [22] are used in the calculation.

The theoretical results shown below are obtained with the soft equation of state and including all medium effects, unless otherwise explicitly stated. In Fig. 1 we show the antiproton abundance as a function of time for a head-on (b=0 fm) Ni+Ni collision at 1.85 GeV/nucleon. The dashed and the solid curves give the primordial and the final antiproton (after taking into account annihilation) abundance, respectively. The primordial antiproton abundance is about 1.7×10^{-5} but is reduced to about 2.2×10^{-7} due to annihilation. So only about 1.3% of primordial antiprotons can escape from the dense hadronic matter and be detected. Comparing with the results from the Si+Si collision [14], we find that the annihilation effect is more appreciable in a heavier system like Ni+Ni.

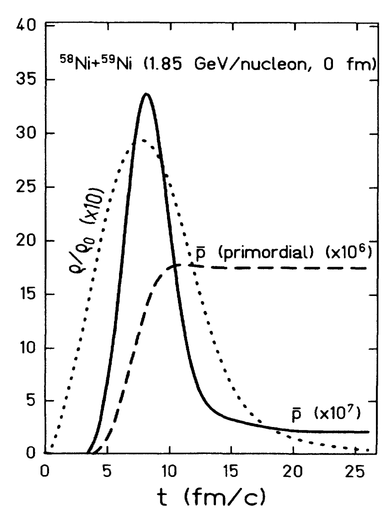

FIG. 1. Time evolution of antiproton abundance and central density. The dashed and the solid curves correspond to the primordial and the final (with antiproton annihilation effect included) antiproton abundance, respectively. The dotted curve gives the central density.

We also show in this figure by the dotted curve the time evolution of the central density ρ/ρ_0 ($\rho_0 = 0.17$ fm^{-3}). It is clearly seen that antiprotons are produced in the high density region where the reduction of the production threshold is most appreciable. As in the Si+Si collision [14], antiprotons are mainly produced from the nucleon-delta interaction.

The comparison of our theoretical results with the experimental data is given in Fig. 2, where the antiproton production cross section is plotted as a function of the antiproton momentum in the laboratory. The dashed curve gives the results for the primordial antiprotons, while the solid curve is the final antiproton spectrum with all final-state interactions (propagation in the mean-field potential, elastic rescattering, and annihilation) taken into account. The recent experimental data from SIS [4] are shown in the figure by solid circles. It is seen that the theoretical results are in reasonable agreement with the data [4]. The calculated cross section at $p_{\rm lab} = 1.0$ GeV/c is somewhat below the experimental value which has, however, a large error.

The effect of the nuclear equation of state on antiproton production is shown in Fig. 3. It is seen that the antiproton production cross section with the stiff equation of state is about a factor of 2–3 smaller than that with the soft equation of state and is thus below the experimental data by the same factor. This is due to the larger incompressibility (thus a larger compressional energy) and effective mass at high densities (thus a higher threshold) in a stiff equation of state than those in a soft equation of state. The effect due to the equation of state is more significant than in the Si+Si collision at 2.1 GeV/nucleon where we have found that the antiproton yield using a soft equation of state is only about 50% larger than that using a stiff equation of state [14]. Given the uncertainties in the antiproton production and annihilation cross sections in a medium, it is, however, premature to conclude that the soft equation of state is favored by the antiproton data from heavy-ion collisions at subthreshold energies.

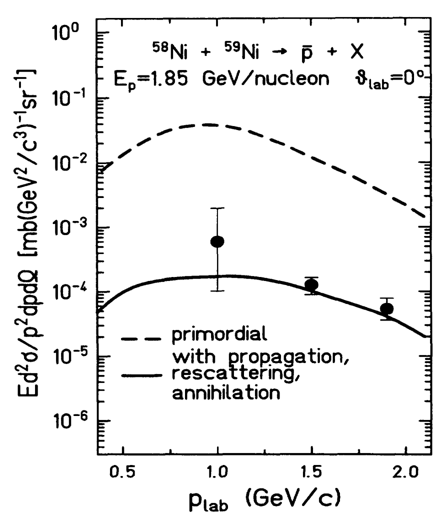

FIG. 2. Antiproton momentum spectrum at $\theta_{\rm lab} = 0°$ in a Ni+Ni collision at 1.85 GeV/nucleon. The dashed curve is for the primordial antiprotons, while the solid curve is the final result obtained with antiproton propagation, elastic rescattering, and annihilation. The experimental data are taken from Ref. [4].

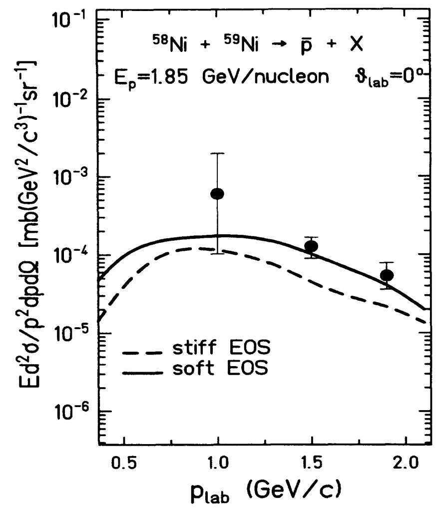

FIG. 3. Same as Fig. 2. The solid and the dashed curve are the results obtained with the soft and the stiff equation of state, respectively.

The reduction of in-medium nucleon and antiproton masses is expected to lead to an enhancement of primordial antiproton production as a result of the decreasing production threshold. To see this explicitly, we have carried out three calculations for the antiproton production cross section. The first calculation is done in the usual nonrelativistic VUU model, using a soft Skyrme parametrization for the equation of state ($K = 200$ MeV) [23]. In this case, baryon masses do not change with density as the mean-field potential is momentum independent. Bare nucleon and antiproton masses are thus used in Eqs. (1)–(3). The result is shown in Fig. 4 by the dotted curve. The other two calculations are carried out in the RVUU model. In one calculation, the bare antiproton mass is used, i.e., only the nucleon mass decreases with density. The threshold in this case is thus $3m^* + m$. The result of this calculation is shown in Fig. 4 by the dashed curve. The antiproton production cross section in this case (dashed curve) is enhanced by about a factor of 12 over the result with the bare nucleon mass (dotted curve). In the final calculation, both the nucleon and the antiproton effective mass are used and the threshold is therefore $4m^*$. The result is shown in Fig. 4 by the solid curve. It is seen that the antiproton production cross section is further enhanced by about a factor of 8 as compared to the second case. Overall, the antiproton production cross section is enhanced by about two orders of magnitude due to the reduction of baryon masses in a medium. In Ref. [14], we have found that for Si+Si collisions at 2.1 GeV/nucleon, the overall enhancement factor of antiproton yield due to dropping nucleon and antinucleon masses in a medium is about 20. The medium effects are thus more clearly seen in heavy-ion collisions with heavier systems and at lower incident energies.

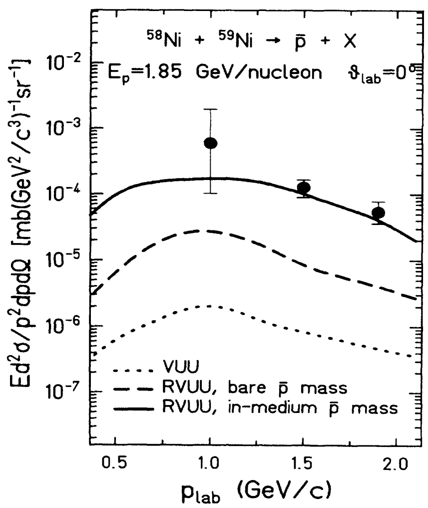

FIG. 4. Same as Fig. 2. The dotted curve gives the results obtained from the nonrelativistic VUU calculation. The results obtained from the RVUU calculation with the bare antiproton mass are given by the dashed curve. The solid curve gives the results of the RVUU calculation with both the nucleon and the antiproton in-medium mass.

Antiproton production in the Ni+Ni collision at 1.85 GeV/nucleon has also been studied by Teis *et al.* [13] based on a relativistic transport model that is similar to ours. They need, however, only a moderate attractive antiproton potential to account for the experimental data. This is due to the smaller nucleon effective mass in their calculation than in ours as a result of a stronger attractive scalar potential at high densities. Since the properties of a nucleon at high densities have not been well determined, whether the antiproton has a strong attractive potential in dense medium is still an open question, and more theoretical study is therefore needed.

In summary, we have calculated the antiproton production cross section in the Ni+Ni collision at 1.85 GeV/nucleon within the relativistic Vlasov-Uehling-Uhlenbeck model that has been extended to include the antiproton degree of freedom. The nucleon self-energies have been calculated in the nonlinear σ-ω model, while the antiproton self-energies are obtained from the nucleon self-energies by the G-parity transformation. Because of the attractive scalar potential, both nucleon and antiproton masses decrease with increasing density. The antiproton final-state interactions with baryons have been explicitly treated in the calculation. With a soft equation of state, our theoretical results are in good agreement with recent experimental data from the SIS at GSI [4]. Our study confirms thus the conclusion of Ref. [14] that it is essential to include the attractive scalar potentials for both nucleon and antinucleon in accounting for the measured antiproton yield.

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[1] J. Carroll, S. Carlson, J. Gordon, T. Hallman, G. Igo, P. Kirk, G. F. Krebs, P. Lindstrom, M. A. McMahan, V. Perez-Mendez, A. Shor, S. Trentalange, and Z. F. Wang, Phys. Rev. Lett. **62**, 1829 (1989); A. Shor, E. F. Barasch, J. B. Carroll, T. Hallman, G. Igo, G. Kalnins, P. Kirk, G. F. Krebs, P. Lindstrom, M. A. McKahan, V. Perez-Mendez, S. Trantalange, F. J. Urban, and Z. F. Wang, *ibid.* **63**, 2192 (1989).

[2] A. A. Baldin *et al.,* JETP Lett. **48**, 137 (1988); A. A. Baldin, Yu. K. Gavrilov, F. F. Guber, A. B. Kurepin, V. S. Pantuev, M. A. Prokhvatilov, V. I. Razin, A. I. Reshetin, and S. N. Filippov, Nucl. Phys. **A519**, 407c (1990).

[3] J. Chiba, D. Ashery, H. Ito, K. Kimura, Yu. T. Kiselev, S. Koda, K. Miyano, T. Murakami, T. Nagae, Y. Nakai, M. Nomachi, S. Sawada, M. Sekimoto, T. Suzuki, K. H. Tanaka, M. K. Vlasov, and Y. Yoshimura, Nucl. Phys. **A553**, 771c (1993).

[4] A. Schröter, E. Berdermann, H. Geissel, A. Gillitzer, J. Homolka, P. Kienle, W. Koenig, B. Povh, F. Schumacher, and H. Ströher, Nucl. Phys. **A553**, 775c (1993); A. Schröter, Gesellschaft für Schwerionforschung Report No. GSI-93-33, 1993.

[5] P. Koch and C. B. Dover, Phys. Rev. C **40**, 145 (1989).

[6] C. M. Ko and X. Ge, Phys. Lett. B **205**, 195 (1988); C. M. Ko and L. H. Xia, Phys. Rev. C **40**, R1118 (1989).

[7] A. Shor, V. Perez-Mendez, and K. Ganezer, Nucl. Phys. **A514**, 717 (1990).

[8] P. Danielewicz, Phys. Rev. C **42**, 1564 (1990).

[9] G. Batko, W. Cassing, U. Mosel, K. Niita, and Gy. Wolf, Phys. Lett. B **256**, 331 (1991).

[10] S. W. Huang, G. Q. Li, T. Maruyama, and A. Faessler, Nucl. Phys. **A547**, 653 (1992).

[11] G. Q. Li, A. Faessler, and S. W. Huang, Prog. Part. Nucl. Phys. **31**, 159 (1993).

[12] C. Spieles, A. Jahns, H. Stöcker, and W. Greiner, Mod. Phys. Lett. **27**, 2547 (1993)

[13] S. Teis, W. Cassing, T. Maruyama, and U. Mosel, Phys. Lett. B **319**, 47 (1993)

[14] G. Q. Li, C. M. Ko, X. S. Fang, and Y. M. Zheng, Phys. Rev. C **49**, 1139 (1994).

[15] C. M. Ko, Q. Li, and R. Wang, Phys. Rev. Lett. **59**, 1084 (1987); C. M. Ko and Q. Li, Phys. Rev. C **37**, 2270 (1988); Q. Li, J. Q. Wu, and C. M. Ko, *ibid.* **39**, 849 (1989); C. M. Ko, Nucl. Phys. **A495**, 321c (1989).

[16] K. Saito, T. Maruyama, and K. Soutome, Phys. Rev. C **40**, 407 (1989).

[17] S. Klimt, M. Lutz, and W. Weise, Phys. Lett. B **249**, 386 (1990).

[18] G. Batko, A. Faessler, S. W. Huang, E. Lehmann, and R. K. Puri, J. Phys. G **20**, 461 (1994).

[19] W. M. Alberico, G. Gervino, and A. Lavagno, Phys. Lett. B **321**, 177 (1994).

[20] L. Xiong, C. M. Ko, and J. Q. Wu, Phys. Rev. C **42**, 2231 (1990).

[21] B. A. Li, C. M. Ko, and G. Q. Li, Phys. Lett. B (submitted).

[22] J. Cugnon and J. Vandermeulen, Ann. Phys. (Paris) **14**, 49 (1989).

[23] J. Aichelin, Phys. Rep. **202**, 235 (1991).