PHYSICAL REVIEW C VOLUME 50, NUMBER 6 DECEMBER 1994

Effects of $N^*(1440)$ resonance on particle production in heavy-ion collisions at subthreshold energies

Bao-An Li, C. M. Ko, and G. Q. Li
Cyclotron Institute and Department of Physics, Texas A&M University, College Station, Texas 77843

(Received 7 September 1994)

We study quantitatively the effects of the $N^*(1440)$ resonance on the production of kaons, antikaons, and antiprotons in heavy-ion collisions at subthreshold energies. It is found that baryon-baryon collisions involving the N^* have minor effects on the production of kaons and antikaons. For the production of antiprotons—considerably different from the previous finding that baryon-baryon collisions involving the $\Delta(1232)$ dominate—we found that collisions involving the N^* are at least equally important as those involving the Δ. Medium effects such as the broadened resonance widths and decreased masses of nucleons and antinucleons are also discussed.

PACS number(s): 25.70.Lm, 24.30.Gd, 14.20.Gk

Particle production, especially at subthreshold energies, provides valuable information about the high density phase of relativistic heavy-ion collisions [1,2]. For a recent review, see Refs. [3,4]. Experimental data accumulated at several laboratories during the last decade together with those obtained more recently at SIS/GSI on the production of kaons, antikaons, antiprotons, and etas as well as pions indicate that a gradual transition to resonance matter occurs in the participant region of heavy-ion collisions at beam energies of 1 to 2 GeV/nucleon [5]. The resonance matter is characterized by a high baryon density with about 1/3 of the nucleons excited to the resonance states. To study in detail the properties of this new form of matter, it is important to first determine its baryonic composition, i.e., the relative abundance of nucleons and various baryon resonances.

In the beam-energy range of 1–2 GeV/nucleon, the important baryonic resonances are $\Delta(1232)$, $N^*(1440)$, $N^*(1520)$, and $N^*(1535)$. The excitation of the $\Delta(1232)$ resonance in heavy-ion collisions has been extensively studied through pion production, and its effects on the production of kaons, antikaons as well as antiprotons at subthreshold energies have been stressed frequently in the literature. While the excitation of $N^*(1535)$ resonance has been studied through eta mesons [6,7], no detailed study on the excitation of $N^*(1440)$ resonance has been carried out although it is the second most easily populated resonance, and its effects on subthreshold particle production are still unclear.

Resonances are produced in heavy-ion collisions from energetic hadron-hadron collisions. Subsequent collisions or decays of these high energy resonances can produce particles that cannot be produced in the first-chance nucleon-nucleon interactions. From energy consideration, one expects that the effects of baryon resonances on particle production strongly depend on the threshold energies of the particles to be produced, the mass of resonances, and the excitation functions of resonances in hadron-hadron collisions.

Also, the properties of hadrons, including the baryon resonances, in hot and dense matter may be different from those in free space [8–11]. To study the properties of hadrons in the hot and dense matter has been one of the motivations for relativistic heavy-ion research. It has been shown recently via the relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) transport model and the quantum molecular dynamics (QMD) model that the attractive scalar mean-field potential, which leads to a reduction of particle production thresholds in a medium, is required to account for the measured yields of kaons [12], antikaons [13], and antiprotons [14–16] from heavy-ion collisions at subthreshold energies. In these studies, however, higher resonances other than the delta have been ignored. To extract more quantitatively information of the scalar mean-field potential for kaons, antikaons, and antiprotons from heavy-ion collisions, it is important to know the contribution of higher resonances to their production.

In this Rapid Communication, we shall study the excitation of the $N^*(1440)$ resonance in the hot and dense hadronic matter formed in the initial compression stage of heavy-ion collisions at beam energies around 1–2 GeV/nucleon. In particular, the effects of the $N^*(1440)$ resonance on the production of kaons, antikaons, and antiprotons in heavy-ion collisions at subthreshold energies will be investigated. Our study is based on the hadronic transport model for heavy-ion collisions, as described in detail in Refs. [17,18]. Similar models have been developed in Refs. [19–21]. This model includes both $\Delta(1232)$ and $N^*(1440)$ resonances. For ease of comparison with other studies, in this study we use a constant width of 200 MeV for the N^* resonance although a momentum-dependent width is available. For the Δ resonance a momentum-dependent width is used as in our early studies. Although the $N^*(1520)$ and $N^*(1535)$ resonance are not in the model, their effects have been partially included by the large N^* widths, and moreover, in the Ver West parametrization [22], as we used in the model, the nucleon-nucleon inelastic cross section is assumed to be saturated by the $\Delta(1232)$ and $N^*(1440)$ resonances in the energy range considered here.

$N^*(1440)$ resonances are mainly produced in high energy πN and NN collisions. Using the isospin decomposition of the pion production cross section in nucleon-nucleon collisions [22], one can see that the $N^*(1440)$ resonance starts being excited significantly at $E_{\mathrm{c.m.}}^{nn} \approx 2.5$ GeV and increases rapidly with increasing nucleon-nucleon center-of-mass energy. As the excitation of the $\Delta(1232)$ resonance decreases with energy in this energy range, the N^* resonance becomes more important than the Δ resonance at $E_{\mathrm{c.m.}}^{nn} \approx 3.0$ GeV.

0556-2813/94/50(6)/2675(5)/$06.00

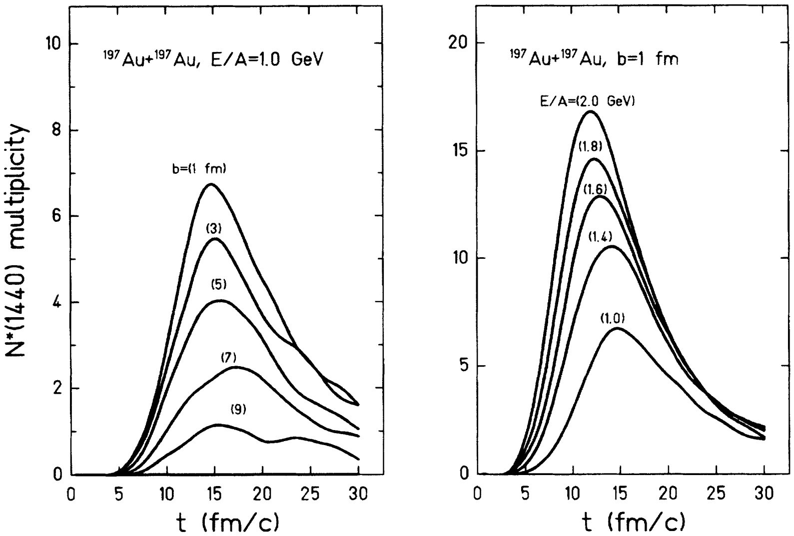

FIG. 1. Time evolution of the $N^*(1440)$ population in Au+Au collisions. (left) Impact parameter dependence. (right) Beam energy dependence.

We first show in Fig. 1 the multiplicity of $N^*(1440)$ resonance from Au+Au collisions at beam energies between 1 and 2 GeV/nucleon and impact parameters between 1 and 9 fm. The abundance of $N^*(1440)$ resonance strongly depends on the impact parameter and the beam energy. In central collisions, the maximum number of $N^*(1440)$ resonance increases from 7 to 17 as the beam energy increases from 1 to 2 GeV/nucleon. For comparisons, it should be mentioned that the maximum number of $\Delta(1232)$ resonance increases from 52 to 89 in the same collision, and therefore the ratio of the abundance for the N^* and the Δ resonance increases from 14% to 19% as the beam energy increases from 1 to 2 GeV/nucleon. Densities of the delta and $N^*(1440)$ resonances in the central cell of Au+Au reactions were recently studied in Ref. [23], a similarly important population of the $N^*(1440)$ was found.

In view of the significant excitation of the N^* resonance in the 1–2 GeV/nucleon energy range, we now study the effects of N^* resonance on the production of kaons, antikaons, and antiprotons in heavy-ion collisions at subthreshold energies. The production probabilities of these particles are calculated perturbatively in the hadronic transport model as in other model calculations [12–16]. Since we are only interested in studying the effects of N^* resonance relative to the Δ resonance, no final-state interaction for the produced particles is taken into account. Therefore, the calculated particle production probabilities should be regarded as primordial ones. Elementary cross sections for the production of kaons, antikaons, and antiprotons are taken as those commonly used in the literature (e.g., [12,13,15]). It should be noted that in the calculation for kaons we have assumed that the kaon production cross sections in baryon-baryon colli-

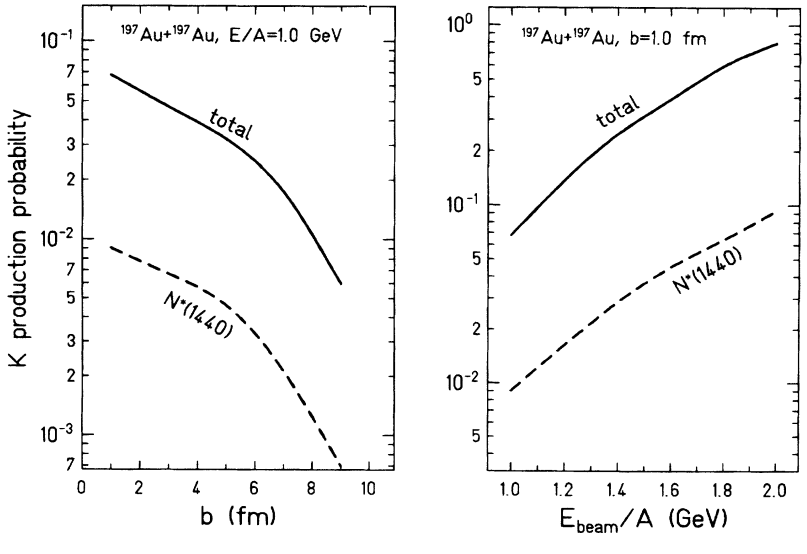

FIG. 2. Total (solid) and $N^*(1440)$ induced (dashed) kaon production probability in the Au+Au collisions. (left) Impact parameter dependence. (right) Beam energy dependence.

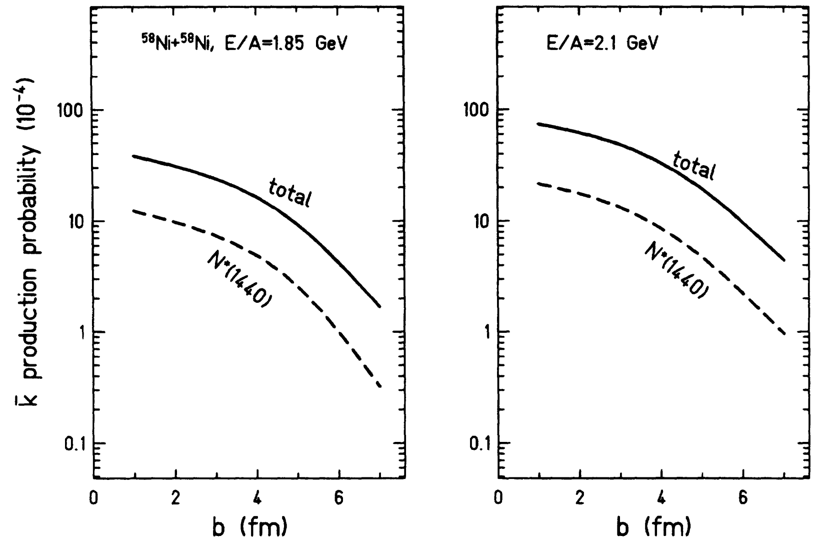

FIG. 3. Total (solid) and $N^*(1440)$ induced (dashed) antikaon production probability in Ni+Ni collisions at 1.85 GeV and 2.1 GeV/nucleon.

sions involving the N^* resonance are the same as that in collisions involving the Δ. For antikaons and antiprotons, we assume as in the literature that the production cross sections in collisions involving the baryon resonances are the same as that in *pp* collisions.

Our results on the production of kaons in Au+Au collisions at beam energies between 1 and 2 GeV/nucleon and impact parameters between 1 and 9 fm are shown in Fig. 2. The total kaon production probability includes contributions from NN, $N\Delta$, NN^*, $\Delta\Delta$, N^*N^*, ΔN^*, and $N\pi$ collisions. In the figure, the total probabilities are shown with the solid lines while the contributions from collisions involving the N^* are shown with the dashed lines. It is seen that the collisions involving the N^* contribute only about 11% in the whole energy and impact parameter ranges. This result is not surprising since baryon-baryon collisions at center-of-mass energies around the kaon production threshold of 2.55 GeV are dominated by the production and absorption of Δ resonances. However, by considering the excitation functions of Δ and N^* resonances in both πN and NN collisions one expects that the $N^*(1440)$ resonance would become more effective than the $\Delta(1232)$ resonance in accumulating enough energy such that subsequent collisions of $N^*(1440)$ resonances can produce particles with higher thresholds. This is indeed seen in our calculations as we will discuss in the following.

Antikaon and antiproton production probabilities in the Ni+Ni collisions at beam energies of 1.85 and 2.1 GeV/nucleon and impact parameters between 1 and 7 fm are shown in Figs. 3 and 4, respectively. It is seen that at both

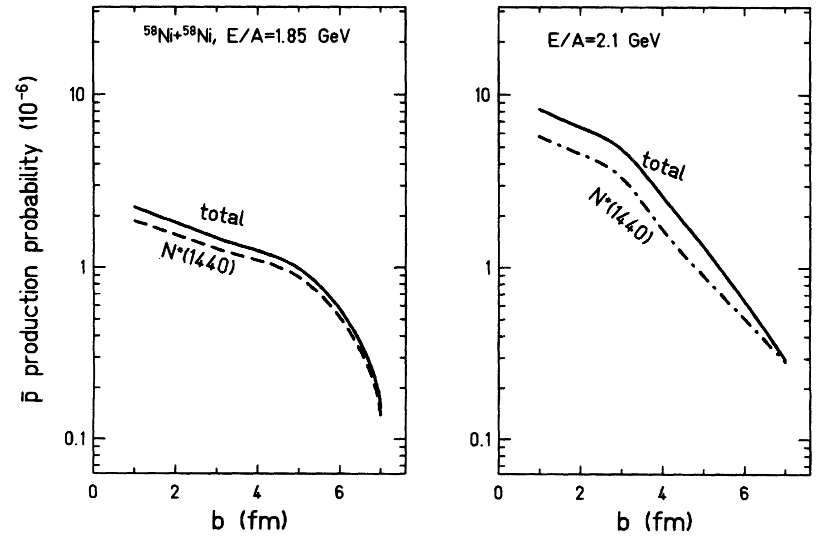

FIG. 4. Total (solid) and $N^*(1440)$ induced (dashed) antiproton production probability in Ni+Ni collisions at 1.85 GeV and 2.1 GeV/nucleon.

TABLE I. Effects of doubling the resonance widths and reducing the $\bar{p}$ production threshold.

Calculations	P_K^{total}	$P_K^{N^*}$	$P_{\bar{K}}^{\text{total}}$	$P_{\bar{K}}^{N^*}$	$P_{\bar{p}}^{\text{total}}$	$P_{\bar{p}}^{N^*}$
Free widths	0.180	0.020	0.730×10^{-2}	0.208×10^{-2}	0.827×10^{-5}	0.576×10^{-5}
Double widths	0.184	0.013	0.575×10^{-2}	0.117×10^{-2}	0.295×10^{-5}	0.190×10^{-5}
Reduced $\bar{p}$ threshold					0.346×10^{-3}	0.174×10^{-3}

beam energies collisions involving the N^* contribute about 25% to the total antikaon yields. While for antiproton production, baryon-baryon collisions involving the N^* contribute about 90% at 1.85 GeV/nucleon, this contribution decreases to about 70% at 2.1 GeV/nucleon as one would expect. This finding indicates that antiproton production at subthreshold energies may serve as a possible probe of the N^* resonances in the resonance matter formed in relativistic heavy-ion collisions.

However, before deliberating further on the effects of N^* resonance on subthreshold particle production it is necessary to add a few cautions. In the above calculations, free-space properties of baryon resonances, i.e., their masses and widths, are used. In nuclei the decreasing mass and broadening width of Δ resonance are well known [24] and have been a subject of much interest. On the contrary, little is known about the in-medium behavior of higher resonances. The very recent analysis of photoabsorption cross sections on nuclei for photon energies between 500 and 1500 MeV has shown that widths of higher resonances in medium are almost twice as large as that in free space [25], and thus there is a large overlapping between resonances. To see how the broadening of baryon resonances may change the effects of N^* resonance discussed above, we have performed calculations by doubling the widths of Δ and N^* resonance. These calculations can, however, only be regarded as schematic since it is not reliably known how the widths may depend on the density of the nuclear medium, and moreover it is highly doubtful that one can still treat resonances with such large widths as quasiparticles as usually done in transport models. Results of these calculations for the Ni+Ni collision at a beam energy of 2.1 GeV/nucleon and an impact parameter of 1.0 fm are listed in Table I.

It is seen that by doubling the widths of the resonances the total kaon production probability is slightly increased and the contribution from collisions involving the N^* decreases to about 7%. This is understandable as the resonances decay faster contributions to kaon production from higher resonances become less important. The overall reduction of the kaon production probability in the collisions involving the resonances is, however, almost completely compensated by the increase of that in the πN collisions. For antikaons the N^* contribution decreases from 28% to 20%. For antiprotons, doubling the resonance widths results in a reduction of both the total production probability and the N^* contribution by about a factor of 3. More specifically, the N^* contribution is reduced from 70% to 65%. Nevertheless, we need to be cautious in stressing the total change of the antikaon and antiproton yields as contributions to antikaon and antiproton production from pion induced reactions are almost unknown and have been neglected in the present calculations.

Another important in-medium effect is the changing masses of hadrons in a dense medium. This effect on the production of subthreshold kaons, antikaons, and antiprotons has been studied extensively [12,13,15]. As the N^* resonance is found to have the most important effect on subthreshold antiproton production, we now study schematically how this effect may change if in-medium masses of hadrons are used. For this purpose, we use the empirical density-dependent nucleon effective mass in a medium as proposed in Refs. [8,11] for the two produced particles in the reaction $BB\rightarrow NNp\bar{p}$. Consequently, the density-dependent threshold for antiproton production in a nuclear medium can be written as

$$T_{\bar{p}}=2m_n[1+1/(1+0.25\rho/\rho_0)],$$

here m_n is the free nucleon mass and ρ_0 is the normal nuclear matter density. Using the reduced, density-dependent threshold we have found that the total antiproton yield and the N^* contribution to the yield increase by a factor of 35 and 27, respectively, in the Ni+Ni collision at a beam energy of 2.1 GeV/nucleon and an impact parameter of 1.0 fm. The contribution of collisions involving the N^* decreases to about 50% of the total probability. Numerical results of this calculation are listed in the last row of Table I.

In summary, we have studied the excitation of the $N^*(1440)$ resonance in heavy-ion collisions at beam energies from 1 to 2 GeV/nucleon. It is found that the contribution of N^* resonance to subthreshold kaon and antikaon production is small compared with that from the delta resonance. The results of Refs. [12,13] obtained without the N^* resonance are therefore not much affected. On the other hand, the N^* resonance does contribute appreciably to antiproton production in heavy-ion collisions at subthreshold energies. Since the medium effects due to the attractive scalar mean field are much larger than the effect from the N^* resonance, the conclusion of Ref. [15] that the observed antiproton yield in subthreshold heavy-ion collisions is consistent with a reduced threshold as a result of the reduction in the in-medium antiproton mass remains valid. However, to study more quantitatively the in-medium effects on antiproton production, one needs to include in the future the N^* resonance. We therefore conclude that antiproton production from heavy-ion collisions at subthreshold energies not only provides information on the in-medium properties of the antiproton but also serve as a possible probe of the $N^*(1440)$ resonance in the resonance matter.

This research was supported in part by the NSF Grant No. PHY-9212209 and the Welch Foundation Grant No. A-1110.

[1] J. Randrup and C.M. Ko, Nucl. Phys. **A343**, 519 (1980); **A411**, 537 (1983).
[2] J. Aichelin and C. M. Ko, Phys. Rev. Lett. **55**, 2661 (1985).
[3] U. Mosel, Annu. Rev. Nucl. Part. Sci. **41**, 29 (1991).
[4] W. Bauer, summary talk at the 9th High Energy Heavy Ion Study (Report No. MSUCL-917, 1994).
[5] V. Metag, Prog. Part. Nucl. Phys. **30**, 75 (1993); Nucl. Phys. **A553**, 283c (1993).
[6] Gy. Wolf *et al.*, Nucl. Phys. **A552**, 549 (1993).
[7] F.D. Berg *et al.*, Phys. Rev. Lett. **72**, 977 (1994).
[8] G.E. Brown, Nucl. Phys. **A522**, 397c (1991); G.E. Brown and M. Rho, Phys. Rev. Lett. **66**, 2720 (1991).
[9] D.B. Kaplan and A.E. Nelson, Phys. Lett. B **175**, 57 (1986); A.E. Nelson and D.B. Kaplan, Phys. Lett. B **192**, 193 (1987).
[10] T. Hatsuda and S.H. Lee, Phys. Rev. C **46**, R34 (1992).
[11] M. Asakawa, C.M. Ko, P. Lévai, and X.J. Qiu, Phys. Rev. C **46**, R1159 (1992); M. Asakawa and C.M. Ko, Nucl. Phys. **A560**, 399 (1993).
[12] X.S. Fang, C.M. Ko, and Y.M. Zheng, Nucl. Phys. **A556**, 499 (1993); X.S. Fang, C.M. Ko, G.Q. Li, and Y.M. Zheng, Phys. Rev. C **49**, R608 (1994).
[13] G.Q. Li, C.M. Ko, and X.S. Fang, Phys. Lett. B **329**, 149 (1994).
[14] S. Teis *et al.*, Phys. Lett. B **319**, 47 (1993).
[15] G.Q. Li, C.M. Ko, X.S. Fang, and Y.M. Zheng, Phys. Rev. C **49**, 1139 (1994).
[16] G. Batko *et al.*, J. Phys. G **20**, 461 (1994).
[17] B.A. Li and W. Bauer, Phys. Lett. B **254**, 335 (1991); Phys. Rev. C **44**, 450 (1991).
[18] B.A. Li, W. Bauer, and G.F. Bertsch, Phys. Rev. C **44**, 2095 (1991).
[19] Gy. Wolf *et al.*, Nucl. Phys. **A517**, 615 (1990).
[20] P. Danielewicz and G.F. Bertsch, Nucl. Phys. **A533**, 712 (1991).
[21] P. Danielewicz, Report No. MSUCL-946, 1994.
[22] B.J. VerWest and R.A. Arndt, Phys. Rev. C **25**, 1979 (1980).
[23] W. Ehehalt *et al.*, Phys. Rev. C **47**, R2467 (1993).
[24] E. Oset, H. Toki, and W. Weise, Phys. Rep. **83**, 282 (1982).
[25] W.M. Alberico, G. Gervino, and A. Lavagno, Phys. Lett. B **321**, 177 (1994).