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Resonance properties in nuclear matter

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We analyze the formation and decay properties of nucleon resonances formed in heavy-ion collisions at 1–2 GeV/u within a microscopic transport approach. In case of Au+Au reactions the density of Δ resonances reaches 0.15 fm^{-3} in the central cell for a time period of the order of 10 fm/c such that one can legitimately speak about *resonance matter.* The lifetime of the Δ's is found to be shortened at high density by only 20% due to the in-medium channel $\Delta + N \rightarrow N + N$.

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In heavy-ion reactions at bombarding energies of a few GeV/u pions are copiously produced. It is nowadays well known that they are created in individual nucleon-nucleon collisions [1–3]. Detailed analyses have shown that at these energies the probability for producing a pion in a nucleon-nucleon collision is about 30% [4]. The production of pions, except for the very low-energetic ones, proceeds dominantly via the Δ resonance, at least for pion kinetic energies up to about 300 MeV. This process between free nucleons has been investigated for a long time and is well understood.

However, if pion production happens inside the nuclear medium, as in the case of a heavy-ion collision, then two basically new phenomena appear. First, the final state of the nucleon—that is created in the decay $\Delta \rightarrow N\pi$—may be Pauli blocked and, second, a new decay channel opens for the Δ, i.e., the process $\Delta N \rightarrow NN$. Both are typical "in-medium" processes, which are well known from studies of pion interactions with nuclei [5]. The first effect leads to a decrease of the in-medium width of the Δ, the second to an increase.

At normal nuclear matter density $\rho_0 \approx 0.16$ fm^{-3} the two processes largely counterbalance each other as shown by photoabsorption experiments [5]. The latter experimental studies also indicate that the resonance position is not significantly changed and that the potential, with which the Δ is bound, is nearly the same as that of a nucleon, possibly somewhat less attractive.

It would, therefore, be very interesting to see if this cancellation also works at higher densities as produced in heavy-ion collisions above 1 GeV/u. Furthermore, according to predictions by Brown *et al.* [6], precursor phenomena of the chiral symmetry restoration (at very high densities) should show up already at densities of 2–3ρ_0. These densities actually are expected to be accessible in heavy-ion collisions, for example at the SIS accelerator ($\leq$ 2 GeV/u).

We have, therefore, performed calculations of the resonance population during such a collision within the transport approach described in Refs. [7,8]; in this BUU calculation nucleons, Δ's, $N(1440)$'s and $N(1535)$'s are propagated explicitly with their isospin degrees of freedom as well as pions and η's. As an example we show in Fig. 1 the baryonic decomposition for the highest density region (maximal resonance/nucleon ratio) in the central cell ($\approx$ 33 fm^3) of the reaction volume for central Ne+Ne and Au+Au reactions as a function of the bombarding energy per nucleon. It is clearly seen that about 30% of all baryons are Δ's for both systems around 2 GeV/u, whereas the population of the higher-lying resonances is small. Since the maximum density in this cell is about 3 times that of ground state nuclear matter (ρ_0), this result indicates a Δ density of about 0.8–1ρ_0. Figure 2,

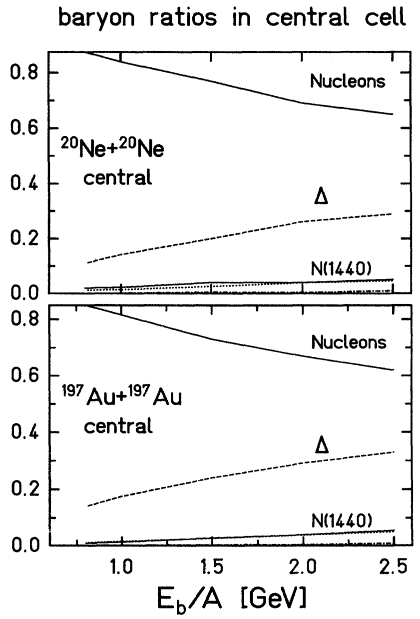

FIG. 1. Baryon decomposition at the highest densities in a central cell of volume 33 fm^3 for head-on collisions of Ne+Ne and Au+Au as a function of the bombarding energy per nucleon.

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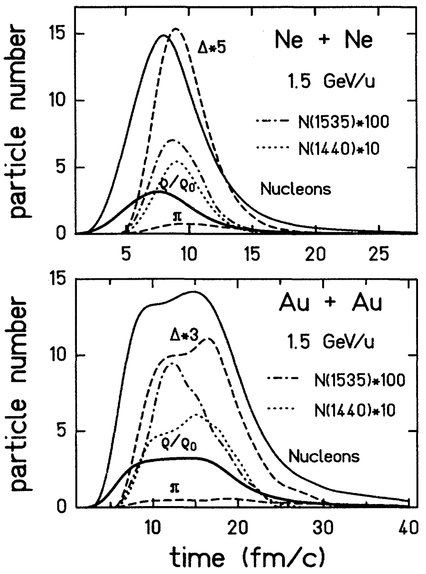

FIG. 2. Time evolution of the density ρ/ρ_0 (thick solid line) and the number of baryons in the central cell for head-on collisions of Ne+Ne and Au+Au at 1.5 GeV/u. [Nucleons: solid line; Δ's: dashed line; $N(1440)$: dotted line; $N(1535)$: dash-dotted line.]

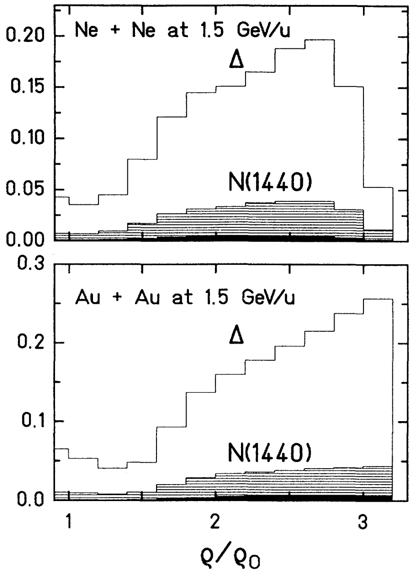

FIG. 3. The ratios of Δ's, $N(1440)$ (hatched histograms), and $N(1535)$ (full histograms) to the total baryon number as a function of density ρ/ρ_0 for central collisions of Ne+Ne and Au+Au at 1.5 GeV/u integrated over space and time of the whole collision.

which shows the time development of the density ρ/ρ_0 (thick solid line) and the various hadronic components for Ne+Ne and Au+Au at 1.5 GeV/u in the central cell, indicates that this Δ density (dashed line) is maintained for about 8–10 fm/c in case of Au+Au, i.e., over a relatively long time compared to the typical nucleon-nucleon collision time ($\approx$ 1 fm/c) at this energy. We are thus looking at a strongly interacting system of relatively dense *resonance matter*, a new form of hadronic matter. On the other hand, the abundance of the higher resonances $N(1440)$ (dotted line) and $N(1535)$ (dash-dotted line) is down by roughly one or two orders of magnitude, respectively, in comparison to the nucleons (solid line).

In fact, our transport simulations indicate a strong correlation of the Δ abundance with the total baryon density (see also Ref. [9]). This is demonstrated more closely in Fig. 3, where the Δ and $N(1440)$ ratio to the total baryon density are plotted as a function of ρ/ρ_0 for central collisions of Ne+Ne and Au+Au at 1.5 GeV/u. In order to provide an integral information the latter correlation has been obtained by integrating over space and time of the whole reaction, thus including the approach phase of the collision with average density $\rho/\rho_0 \approx 1$, however, $N_\Delta/N = 0$. As before the $N(1440)$ (hatched histogram) and $N(1535)$ (full histograms) appear to be of minor importance except when triggering on specific decay channels, e.g., $N(1535) \to \eta + N$. We note in passing that the resulting π^0 and η spectra [8] are well in line with the experimental data.

An important consequence of the high Δ abundance (especially at high baryon density) is an amplification of particle production far below the free nucleon-nucleon threshold by two-body collisions in which one of the partners is a Δ. This has been illustrated for K^+ production in Ref. [10] where it was shown that at energies around 1 GeV/u about 90% of the kaons produced are created in nucleon-Δ collisions. Furthermore, in case of antiproton production around 2 GeV/u, almost all the yield stems from $N\Delta$ or even $\Delta\Delta$ channels [11]. This amplification is essentially due to the fact that a considerable amount of energy can be stored in internal nucleon excitations, which, in a subsequent reaction, can be used for the production of heavy mesons or a $p\bar{p}$ pair.

We have also analyzed the lifetime of the Δ resonance in matter, by looking at the questions raised above, namely the Pauli quenching and the collisional broadening. In the calculational method used the width Γ_Δ for populating a resonance is usually put in from the outside, whereas the effective decay width is determined dynamically, thus neglecting the effects of possible changes on the resonance population. We have, therefore, for the first time, performed these calculations of the widths self-consistently, i.e., they have been iterated by sequential BUU simulations until the prescribed width $\Gamma_{\rm in}(M_\Delta, \rho)$ for the population is the same as the dynamically evaluated decay width $\Gamma_{\rm out}(M_\Delta, \rho)$ of the resonances.

Figure 4 shows the results of such a study for various bins in the baryon density ρ/ρ_0 for a central collision of ^{40}Ca+^{40}Ca at 1.5 GeV/u. It is seen that the iterated width of the Δ's (dashed lines) indeed gets somewhat larger at higher densities than the free width (solid line), but that this increase never amounts to more than 20%. Thus even at densities between 2 and 3 times ρ_0 Pauli quenching and collisional broadening cancel each other to a large extent. We also find that, contrary to earlier expectations, the self-consistency in the treatment of the resonance widths has only a very small effect.

Whereas the width or inverse lifetime of the Δ's varies

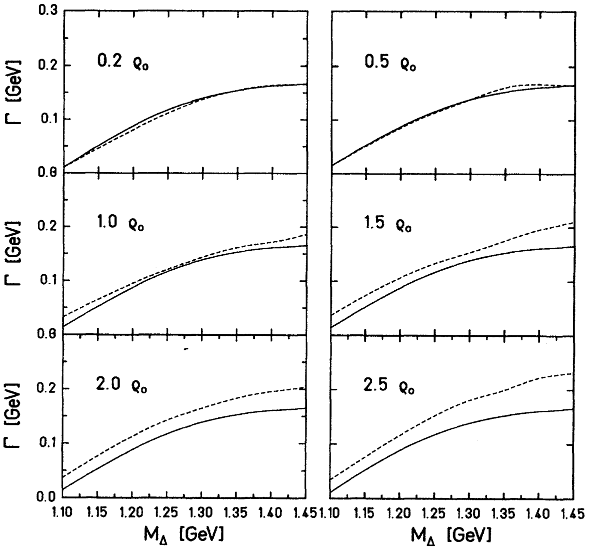

FIG. 4. The iterated Δ width $\Gamma(M_\Delta,\rho)$ (dashed lines) as a function of mass and density in comparison to the free Δ width (solid lines) for a central collision of Ca+Ca at 1.5 GeV/u.

only moderately with baryon density, we find a more significant shift of the Δ mass distribution as a function of the Δ generation. This is demonstrated in Fig. 5 (by the dotted lines) for central collisions of Ne+Ne and Au+Au at 1.5 GeV/u. Whereas the first generation of Δ resonances—that are created in primary collisions—shows a distribution centered slightly below $M_\Delta = 1.232$ GeV (dashed line labeled 1), the sequential Δ generations are shifted downwards in mass due to Δ decay and pion reabsorption; this is the same effect as that discussed by Li and Bauer in Ref. [12]. The Δ mass distribution, which finally generates the asymptotically free pions, is shown in Fig. 5 in terms of the thick solid lines. The experimentally seen Δ mass distribution is only very moderately downward shifted for light Ne+Ne systems; for the heavier Au+Au the shift is more significant and amounts to about 50 MeV. These results are relatively insensitive to the self-energies of pions and Δ's if both are treated consistently [13].

In summary, our calculations indicate that Δ resonance matter does indeed exist in the central zone of the reaction volume in heavy-ion collision at energies around 2 GeV/u. Observable consequences are a strong enhancement of the far-subthreshold particle production cross sections [10,11]; also the observed high pion production probabilities per nucleon-nucleon collision, extracted from heavy-ion reaction data in Ref. [4], point into that direction. Furthermore, the transverse pion spectra reflect the average Δ mass distribution and thus the average number of pion emission and reabsorption events.

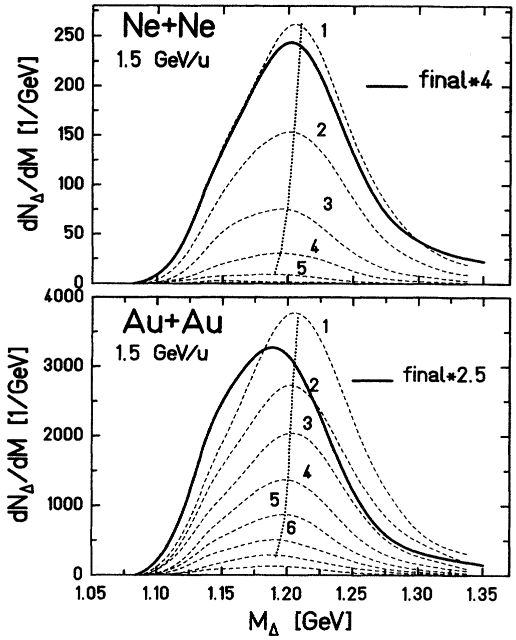

FIG. 5. The Δ mass distribution for different Δ generations (labels 1–5). The dotted lines indicate the shift of the individual peak positions with the generation number. The thick solid line reflects the Δ mass distribution that decays into asymptotically observed pions.

We conclude that heavy-ion reactions in the energy regime about 1–2 GeV/u should indeed be a good testing ground for in-medium modifications of hadronic properties.

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