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Effects of Spin-Isospin Modes in Transport Simulations†

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Abstract:

In-medium properties derived for nuclear matter in a microscopic $\pi + NN^{-1} + \Delta N^{-1}$ model are incorporated into transport simulations of nuclear collisions by means of a local-density approximation and by utilizing a local medium frame. Certain features of the transport results differ from those based on the corresponding vacuum properties. Comparisons of the π and Δ production rates, as well as pion energy spectra, are discussed in particular.

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1 Introduction

Collisions between heavy nuclei at intermediate energies produce hot and dense hadronic matter that may be probed by means of the energetic particles emitted [1, 2, 3]. The collision dynamics have been fairly well understood within microscopic transport models, such as BUU and QMD [2, 3, 4, 5], in which the hadrons are propagated in an effective one-body field while subject to direct elastic and inelastic two-body collisions. In particular, sufficiently energetic NN collisions may agitate one or both of the collision partners to a nucleon resonance. Such resonances propagate in their own mean field and may collide with nucleons or other nucleon resonances as well. Furthermore, the nucleon resonances may decay by meson emission and these decay processes constitute the main mechanisms for the production of energetic mesons [3].

Normally, the transport descriptions employ the vacuum properties of the baryon resonances and mesons, *i.e.* the cross sections, decay widths, and dispersion relations are taken as their (measured or inferred) values in vacuum [4]. However, as is well known, the strong interaction between pions, nucleons, and Δ isobars may generate spin-isospin modes in nuclear matter. While most of these modes are non-collective in their character, being dominated by a single baryon-hole excitation, others are collective and correspond to meson-like states (quasi-mesons) that may be important in the transport description.

Various incorporations of such in-medium modifications to transport simulations of nuclear collisions have already been made on the basis of a simple two-level ΔN^{-1}-model [6, 7, 8, 9, 10]. A more consistent set of in-medium quantities, suitable for implementation in transport descriptions, was derived in a refined $\pi + NN^{-1} + \Delta N^{-1}$ model [11]. These in-medium properties, and their implementation into transport models, were thoroughly discussed in refs. [11, 12], but no explicit transport simulation has yet been performed.

This work present first results from transport simulations including in-medium effects from the refined $\pi + NN^{-1} + \Delta N^{-1}$ model of ref. [11]. We aim to gain a qualitative impression of the degree to which the in-medium properties in idealized nuclear matter survive the transport simulations and lead to observable effects. To keep matters simple, we include only the most important properties of the spin-isospin modes, deferring a more rigorous treatment for later, and we consider only the π-like spin-longitudinal collective modes, since they are dominant at the energies considered (the ρ-like spin-transverse collective modes can be treated analogously).

2 Spin-isospin modes in matter

Relative to the simple two-level ΔN^{-1} model utilized in previous transport treatments [6, 7, 8, 9, 10], some features change significantly with the more rigorous treatment of the ΔN^{-1} model which includes bands of ΔN^{-1} and NN^{-1} states. The most pertinent points are briefly recalled below (a detailed discussion was given in ref. [11]).

Dispersion relations of spin-isospin modes are calculated in a non-relativistic RPA formalism, treating interactions between pion, nucleon-hole, and Δ-hole states. In such a model one should in principle treat the Δ width self-consistently, *i.e.* the Δ isobars that are used as components in the spin-isospin modes should contain the in-medium Δ width. However, such a treatment would encompasses processes like $\tilde{\pi}_j \to \Delta N^{-1} \to (N + \tilde{\pi}_k)N^{-1}$ which are already included explicitly in the transport simulations by processes like $\tilde{\pi}_j + N \to \Delta \to N + \tilde{\pi}_k$. We have therefore omitted the Δ width in the present microscopic treatment (see ref. [11] for a self-consistent treatment of the Δ width). However, we want to emphasize that this choice is not unambiguous, since the omission of the Δ width implies the omission of certain other effects, *e.g.* that the pionic modes have a Breit-Wigner-like distribution of energies, just as the Δ resonance has a Breit-Wigner like distribution of invariant masses.

Furthermore it was found in ref. [11] that the dependence on the temperature is rather weak up to moderately large temperatures. Although incorporation of in-medium effects depending on $T > 0$ into transport models is rather straightforward, the treatment in the transport formalism will depend on one more variable which makes it more cumbersome. Therefore, in the present microscopical calculations we only use properties calculated for matter at zero temperature.

The in-medium properties are obtained by using the Green's function technique, starting from non-interacting hadrons. Standard p-wave interactions [11, 13] are used at the $N\pi N$ and $N\pi\Delta$ vertices and effective short-range interactions at baryon-hole vertices. The strength of the short-range interactions is determined by the correlation parameters g'_{NN}, $g'_{N\Delta}$, and $g'_{\Delta\Delta}$.

The spin-isospin modes are obtained within the RPA approximation, symbolically

$$\begin{aligned} G^{\mathrm{RPA}}(\alpha,\beta;\omega) &= G_0(\alpha,\beta;\omega) \\ &+ \sum_{\gamma,\kappa} G_0(\alpha,\gamma;\omega)\ \mathcal{V}(\gamma,\kappa;\omega)\ G^{\mathrm{RPA}}(\kappa,\beta;\omega)\ . \end{aligned} \tag{1}$$

The spin-isospin modes, here represented by the Green's function G^{RPA}, are in this approximation obtained as an infinite iteration of (non-interacting) pion, nucleon-hole, and Δ-hole states, represented by the diagonal Green's function G_0, coupled by the symbolic interaction $\mathcal{V}$. A set of RPA equations equivalent to eq. (1) were derived in ref. [11] and they determine the eigenvectors and eigenenergies for the different spin-isospin modes. The eigenvectors yield the amplitudes of the different components (π, NN^{-1}, ΔN^{-1}) forming the particular spin-isospin eigenmode with the given energy. These RPA amplitudes contain important information about the nature of the different spin-isospin modes.

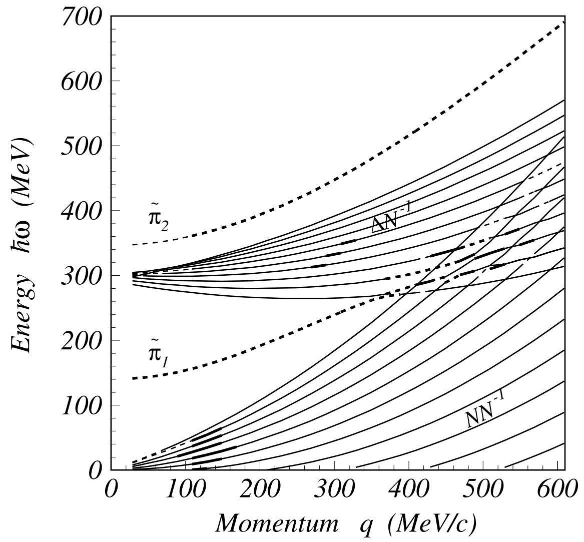

Figure 1: The spin-longitudinal spin-isospin modes in nuclear matter at normal density and zero temperature, as obtained with the $\pi + NN^{-1} + \Delta N^{-1}$ model. The solid curves represent non-collective modes, while dashed curves are used to indicate collective strength. Thick lines indicate that the pionic component is larger than 5%.

The dispersion relation[1] is shown in fig. 1 for normal nuclear density, $\rho = \rho_0$, and at zero temperature, $T=0$. There are two collective modes, corresponding to those of the simple two-level model. They are often referred to as the pion and ΔN^{-1} branch, respectively. However in their structure these modes are similar and by the collectivity they are both pion-like in the sense that many such modes may be created (in contrast to a non-collective mode that is exhausted by a single mode). Therefore the two collective spin-isospin modes should be treated on an equal footing, and they can effectively be regarded as particles of mesonic character (quasi-mesons, here denoted $\tilde{\pi}_1$ and $\tilde{\pi}_2$). In addition, a number of NN^{-1} and ΔN^{-1} like modes are obtained. These modes are mainly non-collective, each being dominated by a single NN^{-1} or ΔN^{-1} component.

The total Δ width gives the transition rate for the Δ resonance to decay to any of its decay channels. In a transport description one explicitly allows the Δ resonance to decay into specific final particles. Consequently, one needs not only the total Δ width (which is the sum of all decay channels) but also the partial widths governing the decay into specific RPA channels. These decay channels consist of a nucleon and one of the spin-isospin modes. The partial Δ width for a Δ decay to a nucleon and

[1]The dispersion relation is obtained in a finite box with periodic boundary conditions, giving a finite number of NN^{-1} and ΔN^{-1} states. Infinite nuclear matter is approached as the size of the box is increased.

a spin-longitudinal mode ν becomes

$$\begin{aligned}\Gamma^\nu_\Delta(E_\Delta,\vec{p}_\Delta) &= \frac{1}{3}\int\frac{d^3q}{(2\pi)^3}\bar{n}(\vec{p}_\Delta-\vec{q})|h^\nu_{N\Delta}|^2 \\ &\times\ 2\pi\,\delta(E_\Delta-e_N(\vec{p}_\Delta-\vec{q})-\hbar\omega_\nu)\ ,\end{aligned} \tag{2}$$

where e_N is the energy of the nucleon. The factor $h^\nu_{N\Delta}$ is obtained from the interactions at the vertex consisting the Δ, the nucleon, and the spin-isospin mode ν. The interactions to be used depend on the non-interacting states that the mode consists of and must therefore be multiplied by the amplitude of the corresponding state (for further details, see ref. [11]). Note that when this expression is to be used in transport models the Pauli blocking factor $\bar{n}_N$ should be omitted since the Pauli blocking is treated explicitly in the transport description.

The total Δ width is obtained as a sum over all modes, collective as well as non-collective,

$$\Gamma_\Delta(E_\Delta,\vec{p}_\Delta)=\sum_\nu\Gamma^\nu_\Delta(E_\Delta,\vec{p}_\Delta)\ . \tag{3}$$

(The sum contains also spin-transverse contributions [11] which are not treated explicitly here.)

Unfortunately, the available experimental data is insufficient to fully constrain the model parameters and so some choices must be made. A particular set of values was motivated in ref. [11]. It contains a density-dependent effective nucleon mass and reproduces the vacuum cross sections $p+p\to\Delta^{++}+n$ as well the imaginary part of the Δ-nucleus spreading potential of ref. [14]. In this work we incorporate the calculated medium effects into an established transport code that utilizes vacuum properties [15]. Since that code does not admit effective masses, we have taken $m^*_N=m_N$ and then readjusted $g'_{\Delta\Delta}$ (from 0.35 to 0.5) to reproduce the same data, keeping all other parameters remaining as in ref. [11].

3 Incorporation of the in-medium properties

In this section we discuss how the results from the microscopical calculations in infinite nuclear matter is incorporated in a dynamical transport simulation of a heavy ion collision. For this purpose we will compare with a simple test-particle description that propagates nucleons (N), delta isobars (Δ), and pions (π) [15]. This will be referred to as the *standard* transport description. In this standard description, the properties of the Δ's and π's (decay widths, cross sections, dispersion relations, *etc.*) are taken to be those in vacuum. In ref. [11] it was thoroughly discussed how these vacuum properties can be replaced by in-medium properties in a consistent way. Here we present a brief recapitulation of the points essential for this study.

The general idea is to employ a local-density approximation in order to incorporate the infinite-matter properties obtained by the microscopic calculations into the transport treatment of the nuclear collision dynamics. Furthermore, the microscopic calculations are performed in a system where the medium is at rest and the obtained dispersion relations and decay widths refer to this *medium frame*. When incorporating the in-medium quantities into the transport formalism, this requirement can be met by employing a local medium frame in which the current density vanishes.

In ref. [11] it was found that at all densities the spin-isospin modes (in the spin-longitudinal channel) could be well categorized as either non-collective ΔN^{-1} modes, non-collective NN^{-1} modes, or one of two different collective modes corresponding to quasi-pions. The non-collective NN^{-1} and ΔN^{-1} modes correspond to particles and processes already incorporated in standard transport models. On the other hand, the collective modes reflect the modified properties of the pion in the medium and they should therefore replace the real pions present in the standard transport treatment. Both correspond to quasi-pions, each propagating with their own Hamiltonian. In accordance with the replacement of the real pions with two different types of quasi-pions, appropriate partial Δ decay widths must be used (as will will be further discussed below).

The quasi-pions do not only have a pion component, but also NN^{-1} and ΔN^{-1} components. The strength of these components vary with the momentum of the pionic mode and with the nuclear density, and this variation is different for the two types of pionic mode. Fortunately their specific structure is irrelevant[2], as as long as these quasi-particles remain well inside the nuclear medium. When the surrounding density approaches zero (as happens if the quasi-pion escapes through the nuclear surface or as the result of an overall expansion), one of the components of the quasi-pions will automatically be realized. That is to say, it will turn into either a free pion or an unperturbed ΔN^{-1} state. The number of quasi-pions that are realized as ΔN^{-1} states is quite small, as will be discussed in section 4. Below a certain critical density, these few modes could be converted to a free Δ by absorption on a nearby nucleon, but in the present study we simply simply let also these quasi-pions be realized as free pions.

The pionic modes are created in the Δ decays and governed by the Δ decay width. While the Δ in vacuum has only the single decay channel $\Delta \to N+\pi$, there are several channels available in the medium. Apart from the decay to the quasi-pions there is a contribution from the decay channels $\Delta \to N+NN^{-1}$ and $\Delta \to N+\Delta N^{-1}$. However these decay channels are already included in the standard transport treatment by the processes $\Delta + N \to N + N$ and $\Delta + N \to \Delta + N$, and these partial widths should therefore be omitted.

The in-medium partial decay width differs from the free width for mainly two reasons. First, the phase space for the decay is different, *i.e.* the pionic mode has a different energy-momentum relation, $\hbar\tilde{\omega}(q)$. Second, the pion component of the quasi-pion is no longer unity, as it has ΔN^{-1} and NN^{-1} components as well, and their strengths vary with the momentum (and density). All these effects are properly taken into account in the formalism of ref. [11], and the proper partial widths are obtained from eq. (2).

The general behavior of the partial widths to the pionic modes are that for low

[2]For secondary processes, such as dilepton production from pion annihilation, the amplitudes become important also in the medium (see, for example, ref. [16]).

invariant Δ mass (keeping p_Δ=0 for the moment) the decay to the lower pionic mode resembles the decay to a free pion. As the invariant Δ mass increases (and the pionic momentum correspondingly), the partial width becomes smaller than the free width because the pion amplitude on the lower mode decreases. For further increasing invariant mass the partial width to the lower mode starts to decrease and becomes very small. This is because the pion component vanishes and the collectivity disappears when the mode enters the band of non-collective ΔN^{-1} modes. Note that although the decay width to the band of ΔN^{-1} modes can be quite substantial, the decay to a single ΔN^{-1} mode is small and vanishes in the continuum limit (box-size $\to \infty$). Thus very few lower pionic modes ($\tilde{\pi}_1$) with large momentum (in the local medium frame) will be created, and above a certain momentum (depending on the density) no $\tilde{\pi}_1$ will be created at all. Instead, the partial decay width to the upper pionic mode is substantial for large invariant mass, where this mode takes over the role of the free pion.

Another feature for the Δ width in the medium is that it depends explicitly on the Δ momentum in the medium (in addition to the Δ energy), while in vacuum the relativistic invariant mass $m = \sqrt{E_\Delta^2 + p_\Delta^2 c^2}/c^2$ suffices to determine the width. For the total width this momentum dependence is rather weak in comparison with the dependence on the invariant mass and may be neglected in a first approximation. However, for the partial widths this is a poor approximation, especially for the decay to the lower mode (where the width becomes small for large pionic momenta in the medium frame). Thus a different treatment for the Δ decay is needed, as compared to the standard transport prescription where the decay takes place isotropically in the Δ rest frame, with the Δ decay width determined by the invariant mass. To this end we calculate and store in a large table the partial Δ decay widths to the two pionic modes, for a mass-momentum grid in the medium frame. In addition, these decay widths are obtained for a number of different densities, ρ_i. The Δ then decays in the medium frame according to linear interpolation in the table of decay widths.

4 Results and discussion

In this section we present results from BUU simulations, containing in-medium effects as discussed in section 3. The purpose of these simulations is to elucidate the role and effects of the included in-medium properties. We therefore compare our results to standard BUU simulations. Further, to make the treatment as simple as possible (and the signals as clean as possible), we have excluded some processes that may be of equal importance when comparing with experimental results. Such processes include direct pion production, N^* resonances, and impact parameter averaging, as well as other in-medium properties not treated here (though discussed to some extent).

We have performed simulations for central collisions of two different symmetric systems, one light, ^{40}Ca+^{40}Ca, and one heavy ^{197}Au+^{197}Au, each at two different energies, 500 and 1000 A GeV. All simulations were performed with 250 test particles per nucleon, utilizing a mean field $U(\rho) = -0.218\,(\rho/\rho_0) + 0.164\,(\rho/\rho_0)^{4/3}$ (GeV). Fig. 2 presents the time evolution of the pions and Δ's for the Au+Au reaction at

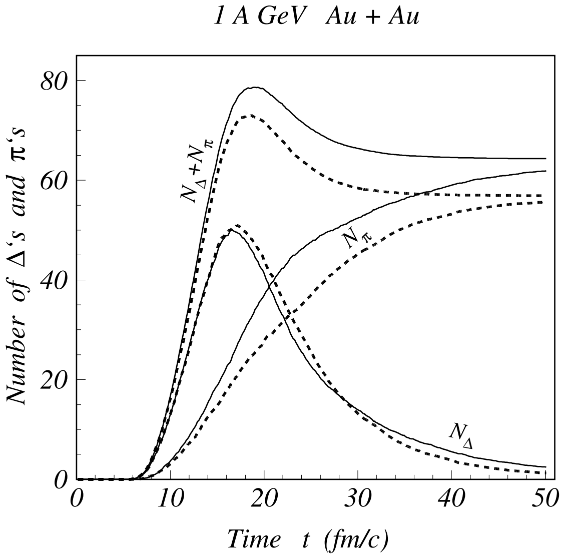

Figure 2: Time evolution of pions and Δ resonances. Solid curves represent simulations with in-medium properties included, while dashed curves correspond to standard BUU simulations.

1 A GeV. The net effect in the total number of pions escaping the collision as free is that somewhat more pions are produced in the medium-modified simulations. The difference is about 10% for both systems and bombarding energies.

For the medium-modified simulations we find that at the higher energy about 95% of the emitted pions originate from the lower pionic mode, while the lower mode is even more dominant at the lower bombarding energy, with a contribution of about 99%. For the Au system we find that 2-5% of the pionic modes are realized as (unphysical) ΔN^{-1} states, while for the Ca system the ΔN^{-1} realization amounts to 7-9%. For the upper pionic mode, though, the situation is worse since about half of these modes end up with the ΔN^{-1} realization. However, since their total contribution is very small, also the total error is small.

Fig. 3 displays the number of Δ decays ($\Delta \to N + \tilde{\pi}$) and pion reabsorption processes ($N+\tilde{\pi} \to \Delta$) per unit time, for the Au+Au reaction at 1 A GeV. Comparing the rate of decay processes ($\Delta \to N + \tilde{\pi}$) for both the heavy system and the light system, we find that they look quite similar in the two types of transport simulation. In both systems there is a tendency to a few per cent less decay during the dense phase in the medium-modified simulation at the high bombarding energy.

However, the numbers of reabsorbed quasi-pions ($N+\tilde{\pi} \to \Delta$) differ for two treatments: When the medium properties are included, there is 5-20% less reabsorption in the dense phase, while the reabsorption is slightly larger at late times when the system is dilute. The effect is largest for the Au system at 1 A GeV and smallest for the Ca system at 500 A MeV. Inspecting the time and density distributions of the reabsorbed pions, we also find that the absorption is somewhat delayed in the medium-modified simulations as compared to the standard simulations. Furthermore,

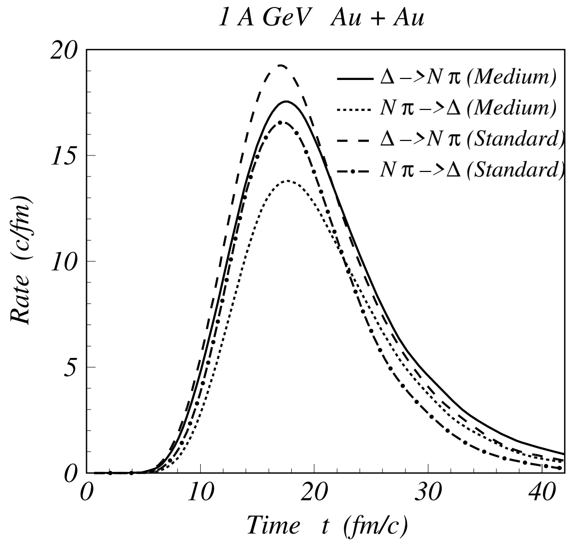

Figure 3: The time dependence of the rates for Δ decay and pion reabsorption.

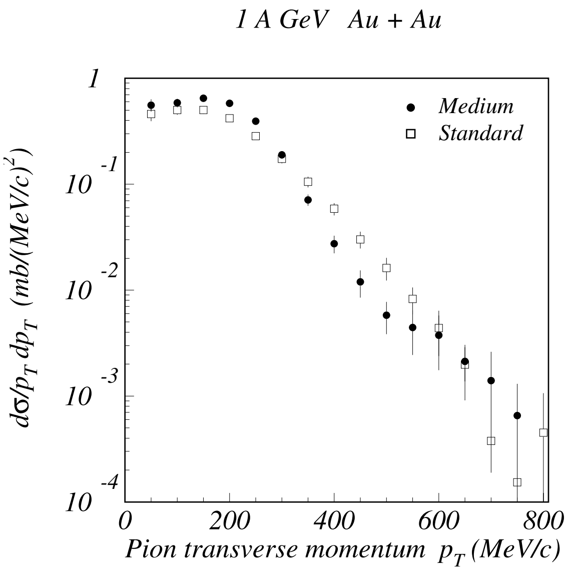

Figure 4: Transverse momentum spectrum for neutral pions in the central rapidity interval $-0.16 < y_{\rm cm} < 0.16$. Filled circles represents simulations with medium properties included, while open squares correspond to the standard simulations. The error bars represent the statistical errors.

when the medium effects are incorporated, the pionic population (and consequently the absorption) is smaller in the dense regions, while the reabsorption is enhanced at low densities ($\rho < 0.5\rho_0$).

In our work, the reabsorption is modified only by the in-medium pionic dispersion relation, $\hbar\tilde{\omega}$, which is used to determine the energy of the produced Δ. As discussed in ref. [11], the full medium corrections to the $\tilde{\pi} + N \rightarrow \Delta$ cross section should also contain a modification of the interaction factor due to the decrease of the pion component on the pionic mode in favor of the NN^{-1} and ΔN^{-1} components, as well as the total in-medium Δ decay width in the Breit-Wigner factor. Since the reabsorption cross section has a rather sharp resonance peak, relatively moderate changes in the Δ energy can produce rather large effects in the number of absorbed pions. The reabsorption cross section is expected to be reduced when taking into account the full in-medium effects. Therefore we expect the reabsorption effect to be even stronger in a simulation taking into account also these in-medium effects. However, the net reabsorption depends strongly on the energy distribution of the pionic modes which may affect such an expectation.

Fig. 4 presents the transverse momentum spectrum $d\sigma/p_T dp_T$ for the Au+Au reaction at 1 A GeV. Only zero impact parameter has been used and the cross sections have been obtained by assuming that all collisions with an impact parameter up to $b_{\max}{=}2\, r_0 A_{\rm Au}^{1/3}$ contribute equally. Thus this cross section represents an upper estimate. The effect seen in the simulations incorporating the in-medium properties, as compared to the standard simulations, is a modest but significant enhancement at low transverse momenta ($p_T \sim$100–250 MeV/c) and a reduction at higher momenta ($p_T >$350 MeV/c), corresponding to a reduction of the effective transverse temperature. This effect is seen in all four simulations, but is naturally most pronounced at the higher energy and the heavier system. This effect is due to the lower pionic mode and the partial width for Δ decay to this mode. As discussed in sect. 3, very few $\tilde{\pi}_1$ modes are created at high momentum in the local medium frame. The upper mode $\tilde{\pi}_2$ which may be created at arbitrary high momentum comes higher in Δ energy and thus not many of these modes are created either.

We finally wish to emphasize that the spectra presented in fig. 4 are not entirely suitable for quantitative comparison with experimental spectra, partly because of the simple impact-parameter averaging employed, and partly because the incorporation of higher nucleon resonances and additional medium effects might be of importance. Still comparing to the experimental spectrum in fig. 1 of ref. [17], we find that the in-medium modifications in this Letter can not explain the enhancement seen at the very low transverse momenta ($p_T <$100 MeV/c). However, there are additional in-medium effects that could be important for the production of such low energy pions. For example, the Δ mass distribution will be modified by utilizing the total *in-medium* Δ width for the production of Δ's from nucleon-nucleon collisions. This in-medium effect will modify the total number of emitted pions as well, so it could bring also the results of fig. 2 in closer agreement with the experimental results of ref. [18]. Transport simulations containing this and other additional in-medium effects are in progress. However, we expect that the enhancement of low-energy pions ($p_T \sim$100–250 MeV/c) reported here, would survive such a more complete simulation.

In summary, we have performed exploratory simulations with an existing transport code into which we have incorporated in-medium spin-isospin properties calculated in a microscopic model that is more consistent than those employed in earlier studies. The effects on the dynamical evolution of pions and Δ isobars have been elucidated and, in particular, it appears that the medium-modified treatment of dispersion relations and partial Δ widths leads to a lowering of the effective temperature of the transverse pion spectra. Our results suggest that at the quantitative level it is important to take account of these in-medium effects and, furthermore, it appears that additional in-medium effects may play a role as well.

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