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RAPID COMMUNICATIONS

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Dilepton production at intermediate-energy heavy-ion collisions

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Dilepton production is studied in heavy-ion collisions at bombarding energies from 60 to 400 MeV/nucleon. The dynamical evolution of the nucleus-nucleus collisions is described by a transport equation of the Vlasov-Uehling-Uhlenbeck type including explicitly pion and $\Delta(1232)$ degrees of freedom and considering free on-shell production processes. We calculate the contribution of proton-neutron bremsstrahlung, π^0 and Δ Dalitz decay, and $\pi^+\pi^-$ annihilation. At 60 MeV/nucleon bombarding energy proton-neutron bremsstrahlung dominates while around 100 MeV/nucleon most of the e^+e^- cross section arises from π^0 decay. At 400 MeV/nucleon, however, the Δ Dalitz decay is the most important dilepton source for invariant masses $M > 140$ MeV thus offering the possibility to study in-medium properties of this resonance.

Electromagnetic observables can provide important information about the dense, hot phase of nucleus-nucleus collisions since they do not suffer from final-state interactions. However, about 100–200 MeV/nucleon bombarding energy the direct γ radiation is very much swamped by the background of π^0 photon decay.[1] A natural choice at these energies is to study dilepton production since—by measuring the invariant mass—the π^0 background can be separated from the spectra. The disadvantage of dileptons is that their production is of second order in the electromagnetic interaction, and therefore the cross section for e^+e^- pairs is by 2 orders of magnitude smaller than that for direct γ production.

Whereas the original suggestion that dileptons probe the pionic self-energies in dense nuclear matter[2] has not been substantiated in later studies,[3] dileptons from *pn* bremsstrahlung can yield valuable information on the phase-space dynamics of heavy-ion collisions in a similar way as real photons.[4] In addition, our previous studies[5–7] as well as those by Xiong and co-workers[8,9] have shown that the Dilepton Spectrometer (DLS) data[10,11] obtained at the Bevalac (Lawrence Berkeley Laboratory) exhibit sizable contributions from Δ Dalitz decay thus opening the way to an experimental study of nucleon resonances in dense nuclear matter.

Recently it has been pointed out that the new generation of photon spectrometers based on BaF_2 crystals can also be used for a spectroscopy of dileptons at bombarding energies up to about 400 MeV/nucleon.[12,13] It is therefore of interest to see what the behavior of the various dilepton spectral components, i.e., π^0 decay, bremsstrahlung, Δ decay, and pion annihilation are at these lower energies. In this Rapid Communication we report on results of such calculations.

The detailed description of our approach is given in Ref. 6. Here we only briefly mention the basic properties. We use a transport approach of the Boltzmann-Uehling-Uhlenbeck type for nucleons, Δ's, and π's with their isospin degrees of freedom and solve these equations by the test-particle method.[14] The baryons move in a mean-field potential of the Skyrme type and in the Coulomb field, whereas the pions propagate only in the Coulomb field. They are assumed to be produced via Δ-resonance formation; the direct mechanism $NN \rightarrow NN\pi$ is neglected. The distribution of Δ's is calculated from all nucleon-nucleon collisions perturbatively using the known cross sections from VerWest and Arndt.[15] Δ-resonances decay according to their experimental widths. ΔN scattering and reabsorption as well as pion reabsorption are taken into account as described in Ref. 6.

At low bombarding energies (≤ 400 MeV/nucleon) we use a perturbative method[4] to calculate the Δ and pion distribution function. In this method one calculates the probability for producing a given particle with a given momentum in each baryon-baryon collision, without, however, taking its energy out of the nucleus-nucleus simulation; this does not cause a problem at low energies since only very few pions and Δ's are produced during the reaction. A shortcoming of this method is that particle reabsorption cannot be taken into account properly. At 400 MeV/nucleon, where both descriptions are applicable, the perturbative method—after including pion reabsorption with a mean free path of 5 fm (Ref. 4)—yields the same pion spectra as the nonperturbative one. We note that both calculations reproduce the differential π^- data at this energy.[6]

In the energy range considered here the following sources may contribute to dilepton production: proton-neutron bremsstrahlung, pion and Δ Dalitz decay, and $\pi^+\pi^-$ annihilation. Physically interesting information is provided by each source except for π^0 decay, since the decay width to e^+e^- is very small. Consequently the π^0's decay outside the medium and thus their dilepton decay reflects only the final π^0 cross section known from former experimental studies.[16,17]

For the proton-neutron bremsstrahlung we use a phase-space corrected soft-photon approximation,[18] which was found to agree quite well with the more sophisticated Feynman-graph calculations.[19,20]

The probability of a Δ decay to a given invariant dilepton mass M is taken as

$$\frac{\Gamma^{\Delta\rightarrow Ne^+e^-}(M)}{\Gamma^{\Delta}_{\rm total}} . \qquad (1)$$

The perturbative approach used here neglects the collisional Δ decay: $\Delta+N\rightarrow N+N$; we thus overestimate the Δ contribution by about 20–30% at bombarding energies of 60 and 100 MeV/nucleon, respectively (the results shown for 400 MeV/nucleon were obtained with the nonperturbative method). The differential decay width is given in Ref. 6.

For the pion Dalitz decay we obtain

$$\frac{d\Gamma(\pi^0\rightarrow \gamma e^+e^-)}{dM}=\frac{4\alpha}{3\pi}\frac{\Gamma_0(M^2)}{M} , \qquad (2)$$

where M is the virtual photon or dilepton mass,

$$\Gamma_0^{\pi^0\rightarrow 2\gamma}(M^2)=\frac{\alpha^2 m_\pi}{16\pi^3}\left(1-\frac{M^2}{m_\pi^2}\right)^3 f^2 . \qquad (3)$$

Here m_π is the pion mass and $f(=0.726)$ is a coupling constant fitted to the experimentally known $\Gamma_0^{\pi^0\rightarrow 2\gamma}(0)$ photonic decay width of the π^0. For $\pi^+\pi^-$ annihilation we assume vector meson dominance; the cross section is given in Refs. 2 and 6. Since at low energies the $\pi^+\pi^-$ annihilation is negligible, we include this process only at 400 MeV/nucleon within the nonperturbative approach.

We have calculated the dilepton production in ^{40}Ca + ^{40}Ca collisions at 60, 100, and 400 MeV/nucleon bombarding energies (Fig. 1). At these intermediate energies one is free from the uncertainties of the baryonic electromagnetic form factors arising at higher energies (see the discussion in Ref. 6). At 60 MeV/nucleon the bremsstrahlung contribution dominates at all invariant masses. At 100 MeV/nucleon, however, the π^0 Dalitz decay dominates as one might have expected from direct γ to π^0 ratios.[4] At 400 MeV/nucleon for $M > 140$ MeV the Δ Dalitz decay gives the most relevant contribution. It is about a factor of 2 larger than the bremsstrahlung process. Since the relative dileptonic decay width of the Δ is very sensitive to mass and width of the Δ, the dilepton pro-

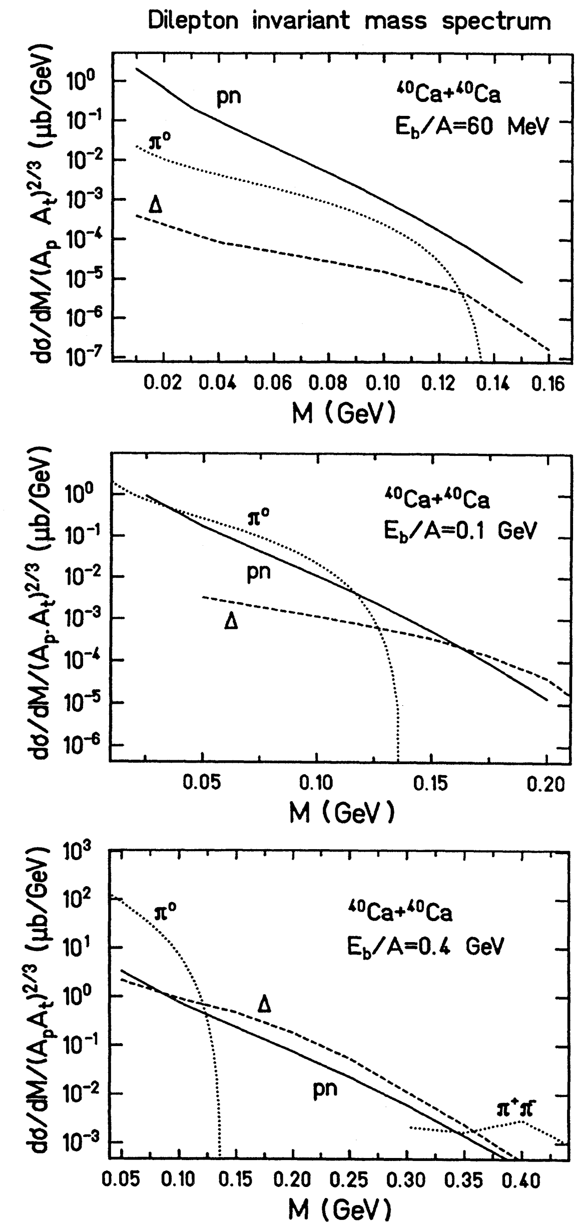

FIG. 1. Dilepton invariant mass spectra for ^{40}Ca + ^{40}Ca at 60, 100, and 400 MeV/nucleon, respectively. Solid line: *pn* bremsstrahlung; dashed line: Δ Dalitz decay; dotted line: π^0 decay. Also at 0.4 GeV/nucleon the $\pi^+\pi^-$ annihilation component is shown by a dotted line.

duction provides a possibility to study the properties —mass distribution and width—of the Δ in the medium.

It is also worth mentioning that at 400 MeV/nucleon about half of the Δ Dalitz-decay contribution arises from Δ's that were created in the high-density phase of the reaction ($\rho > 1.5\rho_0$); however, due to the finite Δ decay time and the expansion of the compressed nuclear system, the Δ's decay into dileptons on average at lower densities. Nevertheless, we find that abut 50% of the dilepton yield from Δ Dalitz decay arises at densities $\rho > \rho_0$. Furthermore, for invariant masses $M > 2m_\pi$ there is a contribution from $\pi^+\pi^-$ annihilation. It is not as pronounced as at 1 GeV/nucleon (Ref. 6) since the pion density is significantly lower at 400 MeV/nucleon.

To summarize the results, below about 100 MeV/nucleon bombarding energy the *pn* bremsstrahlung dominates the dilepton production. Above this energy, the π^0 Dalitz decay dominates the dilepton invariant mass spectrum up to the pion mass. For $M > m_\pi$ the Δ Dalitz-decay contribution is much larger than the bremsstrahlung yield; however, to obtain a reasonably large cross section for invariant masses $M > m_\pi$ one should perform experiments at several hundred MeV/nucleon bombarding energy. The energy regime from 400 MeV/nucleon to 1 GeV/nucleon (where the Δ contribution is a factor of 2–3 larger than *pn* bremsstrahlung[6]) offers a promising perspective to study Δ properties in the nuclear medium.

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