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Dilepton and ϕ meson production in elementary and nuclear collisions at the NICA fixed-target experiment*

György Wolf and Miklós Zétényi[a]

Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary

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Abstract. We argue that the NICA fixed-target experiment will be able to provide very important new experimental data on dilepton and ϕ meson production in the basically undiscovered energy domain between the SIS and SPS energies. Experimental information about elementary cross sections in this energy region is an essential ingredient of models of nuclear collisions in the same energy range.

Currently, the strongly interacting matter can be accessed experimentally at low density (RHIC/Brookhaven and LHC/CERN) and at normal nuclear density (ordinary nuclear physics). Its properties at high densities, where the critical endpoint probably sits, are not known, neither experimentally nor theoretically. Therefore it is very important that new accelerators and detectors (NICA/MPD and FAIR/CBM) are going to be built to study the properties of the dense, strongly interacting matter.

Chiral symmetry is expected to be restored at high densities. The path to the restoration is not known, and may be observed by measuring meson properties, like masses and widths.

Dileptons are an important probe of relativistic nuclear collisions, because they leave the hot and dense phase of the collision unaffected by strong final-state interactions and can be used to observe vector meson properties in dense matter via their direct decays to dileptons. On the other hand, the dilepton spectrum obtained from a nuclear collision is a complicated superposition of many production channels coming from various stages of the process. Therefore, drawing any reliable conclusions based on the dilepton spectrum is difficult, and depends on understanding many aspects of the underlying physics, like elementary cross sections, in medium modification of particles, reaction dynamics, etc.

In recent years dilepton production was studied experimentally at RHIC, SPS, and at much lower energies at GSI SIS by the HADES experiment and theoretically by several theoretical groups as well, a few of them to mention here: [1–5]. The range between the SIS and SPS energies is basically undiscovered, and the NICA fixed-target experiment will give a unique opportunity to study dilepton production in this regime.

At low energies elementary hadron collisions were usually described by the resonance dominance model, where in the first step of the collision a baryon resonance is excited, which later decays —possibly in multiple steps— and creates the final-state particles. These kinds of models were used to study the dilepton spectrum of nucleon-nucleon collisions in connection with the DLS data (see refs. [6–8]). However, a more or less satisfactory agreement between theory and experiment has been reached only with the HADES data and the new calculations in terms of effective field theory (EFT) models [9–11]. A similar EFT model has been recently applied to dilepton production in pion-nucleon collisions [12].

The spectrum of baryon resonances is known only up to slightly above 2 GeV, with increasing uncertainty at high masses. The resonance model cannot be applied to collisions above the SIS energy range not only because the baryon resonance spectrum is unknown, but also because multiparticle final states become more and more important. The calculation of multiparticle production processes in EFT models is complicated by the multi-dimensional phase-space integrals, and many different Feynman diagrams contributing to the same final state. These diagrams have to be added coherently, which results in a large number of interference terms.

Heavy-ion collisions in similar energy ranges are usually described by hadronic transport models. An ingredient of such models is a description of the elementary hadronic reactions. Normally, a variant of the resonance dominance model serves this purpose in hadronic transport codes. The reason of this is that EFT model

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[a] e-mail: zetenyi.miklos@wigner.mta.hu

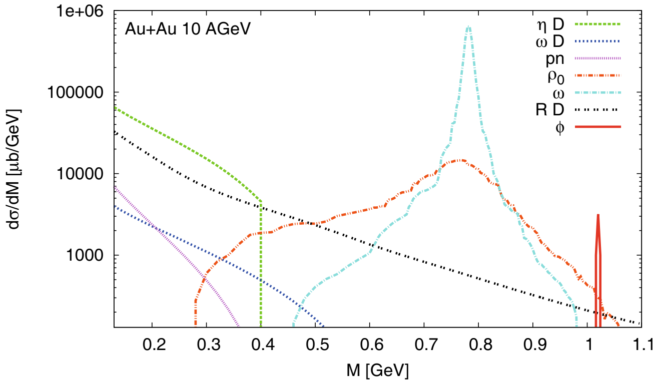

Fig. 1. Contributions of various elementary channels to the dilepton invariant-mass spectrum of Au+Au collisions, at 10 AGeV laboratory kinetic energy, as predicted by a hadronic transport model.

calculations contradict the philosophy of transport, where (baryon and meson) resonances propagate as ordinary particles. This prohibits the implementation of certain types of interference terms that appear naturally in EFT models.

Figure 1 shows the predictions of a BUU-type transport model (for some of the details see [1,2,13,14]) for the various contributions to the dilepton invariant-mass spectrum of a central Au+Au collision in the NICA energy range of 10 AGeV. Above 0.6 GeV dilepton mass the spectrum is dominated by the direct decay of the neutral vector mesons ρ, ω and ϕ. For lower dilepton masses the Dalitz decays are the most important source of dileptons. In particular, around 0.4–0.5 GeV the Dalitz decay of baryon resonances is expected to be very important. This is because at these higher energies a large fraction of the nucleons are excited to the resonance states.

Since the spectrum of higher baryon resonances is poorly known, the predictions for contributions of their Dalitz decay are also rather uncertain (see [15]). These resonances also participate in the production of the vector mesons, which brings in uncertainties in the vector meson channels of dilepton production. Furthermore, the highest baryon densities (approximately 6 times the normal nuclear density at 10 AGeV) are expected to be reached in heavy-ion collisions in the energy range studied at NICA. Dilepton spectra will be influenced by the modification of hadron spectral functions in the dense medium. In addition, multiparticle final states will contribution to dilepton production as well. These are usually described in transport codes in terms of string fragmentation models.

This shows that there must be a transition in the applied theoretical models just above the SIS energy range, with probably a pure EFT model (or in transport codes a resonance dominace model) for lower energies, supplemented by a string fragmentation model the importance of which is increasing with energy. It is clear that experimental input about elementary cross sections is needed in order to test and calibrate the theoretical models at this regime of transition. The NICA fixed-target experiment is

Table 1. The probability of creating a ϕ meson for various channels in a Au+Au central collison at 10 AGeV bombarding energy (B and N denote a non-strange baryon and a nucleon, respectively).

Channel	Contribution
BB $\to$ NN ϕ	8.910^{-3}
π B $\to$ N ϕ	1.4410^{-3}
(ρ, ω) B $\to$ N ϕ	6.3010^{-4}
$\mathrm{K^+K^-} \to \phi$	8.5710^{-2}

an ideal possibility to provide these important experimental data.

Another reason why the energy range of the NICA fixed-target experiment is interesting is ϕ meson production. ϕ, as a neutral vector meson is interesting because it decays directly to the dilepton channel and, therefore, its spectral function can be studied on the dilepton invariant mass spectrum. Furthermore, as a particle containing hidden strangeness, it decays dominantly to the kaon-antikaon channel. The simultaneous study of both decay channels can contribute to a deeper understanding of the underlying physics. In medium modification of antikaon mass can lead to a broadening of the ϕ. At low-energy heavy-ion reactions, collision of secondary particles plays an important role in the production of ϕ mesons (see [16, 17]), therefore it is sensitive to the reaction dynamics, the EOS etc.

In a hadronic fireball created in moderate energy heavy-ion collisions, ϕ mesons can be created in baryon-baryon, meson-baryon, and in meson-meson collisions. Of the latter, obviously kaon-antikaon collisions are the most important. The contributions of these channels to ϕ meson production in central Au+Au collisions at 10 AGeV laboratory kinetic energyare shown in table 1. The elementary cross sections are obtained from one-boson-exchange models. Contributions of higher baryon resonances are included, too. They actually dominate the baryon-baryon contributons. Their cross section is not known, can only be extrapolated from nucleon-nucleon cross sections. Most of the ϕ mesons originates from $\mathrm{K^+K^-}$ annihilations. Therefore any in-medium effects on the kaon and antikaon properties, *e.g.* on the masses, heavily influences the dilepton spectra.

The energy at SIS was not high enough to study the ϕ meson in detail. In particular, it was not seen in the dilepton channel. Only a few measurements have been performed at SIS to study ϕ production via the $\mathrm{K^+K^-}$ channel in subthreshold heavy-ion collisions [18,19]. These results by the FOPI collaboration indicate a large ϕ production cross section, which is not explained by the transport calculations of ref. [16,17].

At higher energies the ϕ meson peak in the dilepton spectrum is expected to be more pronounced, which can be seen in the BUU predictions of fig. 1. This means, that the NICA fixed target experiment would be able to study the ϕ meson in both decay channels and, therefore, could contribute to a better understanding of ϕ production around the kinematical threshold. Since the ϕ meson production is dominated by K^+K^-, experiments at NICA energies would enable us to study uniquely kaon and antikaon properties in a very dense medium (6–10 times nuclear matter density), which may help us understand the interior of a neutron star [20].

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