

Dilepton production in pp and np collisions at 1.25 GeV

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The inclusive reactions $pp \rightarrow e^+e^-X$ and $np \rightarrow e^+e^-X$ at the laboratory kinetic energy of 1.25 GeV are investigated in a model of dominance of nucleon and Δ resonances. Experimental data for these reactions have recently been reported by the HADES Collaboration. In the original model, the dileptons are produced either from the decays of nucleon and Δ resonances $R \rightarrow Ne^+e^-$ or from the Dalitz decays of π^0 and η mesons created in the $R \rightarrow N\pi^0$ and $R \rightarrow N\eta$ decays. We found that the distribution of dilepton invariant masses in the $pp \rightarrow e^+e^-X$ reaction is well reproduced by the contributions of $R \rightarrow Ne^+e^-$ decays and $R \rightarrow N\pi^0, \pi^0 \rightarrow \gamma e^+e^-$ decays. Among the resonances, the predominant contribution comes from the $\Delta(1232)$, which determines both the direct decay channel $R \rightarrow Ne^+e^-$ and the pion decay channel. In the collisions $np \rightarrow e^+e^-X$, additional significant contributions arise from the η -meson Dalitz decays, produced in the $np \rightarrow np\eta$ and $np \rightarrow d\eta$ reactions, the radiative capture $np \rightarrow de^+e^-$, and the $np \rightarrow npe^+e^-$ bremsstrahlung. These mechanisms may partly explain the strong excess of dileptons in the cross section for collisions of np versus pp , which ranges from 7 to 100 times for the dilepton invariant masses of 0.2 to 0.5 GeV.

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Introduction. The HADES Collaboration [1] has recently published the results of measurements of dilepton production differential cross sections in pp and dp collisions at $T_{\text{lab}} = 1.25$ GeV. Data on the np collisions were taken by recording spectator protons from breakup of the deuteron. A huge (from 7 to 100) excess of the dilepton pairs in the np collisions as compared to the pp collisions has been observed for the dilepton masses $M = 0.2$ to 0.5 GeV. Conventional sources of dileptons including η mesons produced in the np collisions are not able to explain this excess.

Bremsstrahlung of dileptons is studied by Kaptari and Kämpfer [2]. The authors conclude that bremsstrahlung of dileptons does not improve the agreement: In the pp collisions, the dilepton yield turned out to be overestimated in the entire range of the dilepton invariant masses, whereas in the np collisions, the dilepton yield was overestimated (underestimated) at lower (higher) values of M . Another attempt to describe the dilepton data at 1.25 GeV is undertaken by Shyam and Mosel [3]. The authors argue that the inclusion of electromagnetic form factors in the bremsstrahlung amplitude of Ref. [4] practically solves the problem: The distribution of invariant masses of dileptons in the np reaction is found to be consistent with the data [5,6].

In this Brief Report, the resonance model of Ref. [7], developed earlier to describe the production of dileptons in nucleon-nucleon collisions at $T_{\text{lab}} = 1$ to 6 GeV, is used for description of the HADES data. The basic mechanisms of the dilepton production are supplemented by the contribution of bremsstrahlung [3], scaled by a monopole form factor in the spirit of the vector meson dominance (VMD) model, and by the radiative capture $np \rightarrow de^+e^-$ described on the basis of experimental data on deuteron photodisintegration, with the inclusion of the monopole form factor.

Baryon resonance model. In the resonance model, the reaction is a two-stage process. First, nucleon and Δ resonances are produced in NN collisions; at the second step, resonances decay into a nucleon, a number of mesons, and a dilepton pair. The reaction scheme is shown in Fig. 1.

For the dilepton production in pN collision at 1.25 GeV, we distinguish generally between three different channels,

$$\begin{aligned} pN &\rightarrow NR \rightarrow NN\pi^0, \pi^0 \rightarrow \gamma e^+e^-, \\ pN &\rightarrow NR \rightarrow NN\eta, \eta \rightarrow \gamma e^+e^-, \\ pN &\rightarrow NR \rightarrow NNe^+e^-, \end{aligned}$$

where R is either a nucleon resonance N^* or a Δ resonance. The last channel contains all the contributions of the intermediate ρ and ω mesons. For the first channel, we use here the following isotopic relations for two-nucleon final states: $pp : pn = 1 : 1$ for all intermediate resonance N^* except $N^*(1535)$, $pp : pn = 1 : 5$ for $N^*(1535)$, and $pp : pn = 1 : 2$ for $R = \Delta$ [8]. $N^*(1535)$ is the only one resonance giving a significant contribution to the η -meson production. The isotopic ratio for η , as a result, becomes $pp : pn = 1 : 5$ [8]. The third channel has the same isotopic ratio as the first channel if one neglects the interference of the intermediate ρ and ω mesons. This approximation is justified when the contribution of one of the interfering mesons considerably exceeds the contribution of the partner. The lack of interference means, in our case, that in the reactions $pn \rightarrow pR^0$ and $pn \rightarrow nR^+$ the radiative decays of R^0 and R^+ are not coherent and their probabilities are summed up. Accordingly, the intermediate vector mesons in the R^0 and R^+ decays do not interfere, although in each of these decays the coherence of ρ and ω is preserved.

The Fermi motion of the constituents inside the deuteron is taken into account using the momentum distribution of the

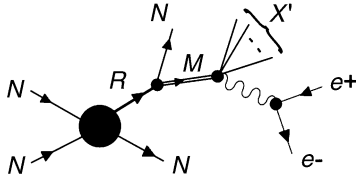


FIG. 1. Two-step mechanism for the creation of dilepton pairs in NN collisions. N are nucleons, R is nucleon or Δ resonance, M is meson arising in the nucleon resonance decay. X' are mesons and photons. $X' = \emptyset$ corresponds to the direct channel of vector meson decays $M \rightarrow e^+e^-$.

bound proton extracted from the experimental data on the electron scattering cross section on deuteron [9].

At the energy of $T_{\text{lab}} = 1.25$ GeV the threshold effects for the η production become extremely important. In the pp case, the excess of energy over the threshold in the center-of-mass coordinate system equals $\epsilon = -1$ MeV, so the η meson is not produced. In the np case, the value of ϵ is positive for both $d\eta$ and $np\eta$ channels. It is further known from the experiment [10] that close to the threshold the $np \rightarrow d\eta$ cross section is greater by a factor of 3 to 4 than the $np \rightarrow np\eta$ cross section, which in turn is greater than the $pp \rightarrow pp\eta$ cross section by a factor of 6.5. To describe the production of η mesons in the resonance models, the channels $pp \rightarrow pp\eta$ and $np \rightarrow np\eta$ are usually considered. However, near the threshold it is necessary to take into account the channel $np \rightarrow d\eta$, whose cross section is dominant over the others. We thus add the reaction $np \rightarrow d\eta$ to the list of reactions involved in the production of the η meson. Below, a parametrization of Ref. [10] for the experimental $np \rightarrow d\eta$ cross section is used.

Bremsstrahlung and radiative capture. The situation with bremsstrahlung is rather indefinite. Two calculations [2] and [3] that use different vortices for pion coupling to nucleon give different results. For pseudovector coupling [2], there is an uncertainty of the contact term appearing under the gauging of pion-nucleon interaction; for pseudoscalar coupling [3], there is an uncertainty of electromagnetic form factors of photon coupling to pion and nucleons. Nevertheless, we will include bremsstrahlung contribution to our dilepton data. For this, we will take the results of Ref. [3] available also without electromagnetic form factors and scale them by VMD form factor $1/(1 - M^2/m_\rho^2)$.

The radiative capture $np \rightarrow de^+e^-$ was never considered as a possible source of dileptons in np collisions. Unexpectedly, its contribution is large in the region $M > 0.4$ GeV. To find the cross section of $np \rightarrow de^+e^-$ reaction, we used experimental data on deuteron photodisintegration $\gamma d \rightarrow np$ at photon energies from 139 to 832 MeV [11]. Kinetic energy of the neutron $T_{\text{lab}} = 1.25$ GeV in the reaction $np \rightarrow d\gamma$ corresponds to the photon energy $E_\gamma = 600$ MeV in deuteron photodisintegration reaction. The differential cross section of the last can be parametrized by the linear function [11]

$$\frac{d\sigma}{2\pi d \cos\theta} = 0.6 + a \cos\theta \mu\text{b/sr}. \quad (1)$$

This gives the total cross section $\sigma(\gamma d \rightarrow np) = 7.5 \mu\text{b}$. The cross section of time-reversed process $\sigma(np \rightarrow d\gamma)$ is

equal to

$$\sigma(np \rightarrow d\gamma) = \left(\frac{p_{\text{c.m.}}^2(d\gamma)}{p_{\text{c.m.}}^2(np)} \right) \frac{2 \times 3}{2 \times 2} \sigma(\gamma d \rightarrow np) \approx 5 \mu\text{b}. \quad (2)$$

The conversion of the photon to dilepton pair adds to this cross section phase space correction, form factor (which is taken in the simple VDM form), and conversion factor,

$$\frac{d\sigma(np \rightarrow de^+e^-)}{dM} = \sigma(np \rightarrow d\gamma) \frac{p_{\text{c.m.}}(d\gamma^*)}{p_{\text{c.m.}}(d\gamma)} \times \left(\frac{1}{1 - M^2/m_\rho^2} \right)^2 \frac{2\alpha}{3\pi M}. \quad (3)$$

Results and discussion. For comparison with the experimental data, we must take into account the geometrical acceptance of the HADES detector. It is used in the form given in the official website of the HADES Collaboration at <http://www-hades.gsi.de>.

In the case of $pp \rightarrow e^+e^-X$ reaction (left panel on Fig. 2), the dilepton yield is shown separately for the $\Delta(1232)$ Dalitz decay (marked by “ Δ ”), the Dalitz decays of other baryon resonances (marked by “ R ”) and π^0 (marked by “ π^0 ”), and for bremsstrahlung (dash-dotted line). In the case of $np \rightarrow e^+e^-X$ reaction (right panel), there are two additional contributions: the η -meson Dalitz decay (marked by “ η ”) and the $np \rightarrow de^+e^-$ radiative capture (dashed line).

The results shown in Fig. 2 suggest that the radiative capture is dominated at the dileptons invariant masses $M \gtrsim 400$ MeV. There exists the apparent possibility of isolating the contribution of other channels by considering the missing mass distribution of the two initial nucleons and the lepton pair in the region of $M \gtrsim 400$ MeV. The missing mass distribution should reveal a peak corresponding to the deuteron. Quantitative analysis must take into account the smearing of the peak associated with the Fermi motion of the proton spectator in the initial-state deuteron.

The excess of the dileptons in comparison with the theoretical estimates at the high invariant masses indicates a lack of understanding of the mechanism of the dilepton pair creation. Among the additional possible sources, we wish to point to a dibaryon resonance observed recently in the reaction $np \rightarrow d\pi^0\pi^0$ in the energy region of interest [12].

In the model [7], the dilepton spectrum in the direct channels $M \rightarrow e^+e^-$ is bounded from below by two electron masses. In all other models, which we know, there is a cutoff at strong thresholds, i.e., at two pion masses for the $\rho \rightarrow e^+e^-$ decay, or three pion masses for the $\omega \rightarrow e^+e^-$ decay. In the dilepton cross section, the strong meson widths are included only in the meson propagators, so they do not determine the reaction thresholds. The strong thresholds give rise to certain difficulties in the simulation of vector mesons using the Monte Carlo technique. ρ meson, e.g., is generated in accordance with the Breit-Wigner distribution,

$$dW(\mu) = \frac{1}{\pi} \frac{\mu\Gamma_\rho(\mu)d\mu^2}{(\mu^2 - m_\rho^2)^2 + [\mu\Gamma_\rho(\mu)]^2}, \quad (4)$$

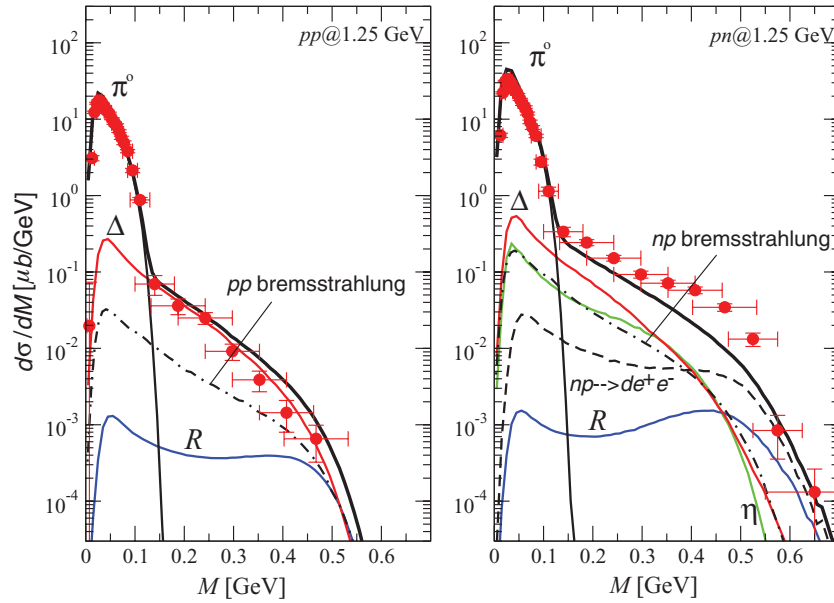


FIG. 2. (Color online) Left panel: Dilepton spectrum of the $pp \rightarrow e^+e^-X$ reaction. Contributions of π^0 -mesons, $\Delta(1232)$, and other baryon resonances are marked by the symbols π^0 , Δ , and R , respectively. Bremsstrahlung contribution is shown by the dash-dotted line. All contributions are summed up incoherently (extra bold solid line). Right panel: Dilepton spectrum of the $np \rightarrow e^+e^-X$ reaction. In comparison to the dilepton spectrum of the $pp \rightarrow e^+e^-X$ reaction, additional contributions of the η -meson Dalitz decay (marked by " η ") and the radiative capture $np \rightarrow de^+e^-$ (dashed line) are added.

where $\Gamma_\rho(\mu)$ is the strong width. When the ρ -meson invariant mass μ approaches the two-pion threshold, $\Gamma_\rho(\mu)$ decreases and the number of the generated ρ mesons decreases, too. However, in the dilepton cross section the distribution (4) is then multiplied by the differential branching ratio of the $\rho \rightarrow e^+e^-$ decay,

$$\frac{dB(\mu, M)}{dM^2} = \frac{1}{\Gamma_\rho(\mu)} \frac{d\Gamma_{\rho \rightarrow e^+e^-}(\mu, M)}{dM^2}, \quad (5)$$

that contains the strong width in the denominator. The result is a numerical instability, although there is a simple cancellation of the two terms.

In order to consistently simulate the subthreshold ρ mesons, it is sufficient to replace $\Gamma_\rho(\mu)$ both in the numerator of Eq. (4) and in the denominator of Eq. (5) by any function $f(\mu)$ that is strictly positive above the two-electron threshold. The cross section does not depend on the choice of $f(\mu)$. This feature can be used to check self-consistency of the code.

The subthreshold contribution of vector mesons to the dilepton yield can be observed experimentally by measuring the

exclusive cross section $pp \rightarrow ppe^+e^-$. Such measurements are planned by the HADES Collaboration. Only the direct decay channels $\rho, \omega \rightarrow e^+e^-$ contribute to this reaction. The experimental data in the subthreshold domain will allow one to constrain the coupling constants of far off-shell vector mesons with the photon.

Conclusion. In this Brief Report, we showed that the HADES data on the distribution of invariant masses of dileptons in the pp collisions at the beam kinetic energy of 1.25 GeV are well reproduced by our resonance model and are mainly explained by the $R \rightarrow Ne^+e^-$ decays and $\pi^0 \rightarrow \gamma e^+e^-$ decays. Moreover, the decays of resonances are dominated by $\Delta(1232)$. In the np collisions, an important role is attributed to the η -meson Dalitz decays, the radiative capture $np \rightarrow de^+e^-$, and the bremsstrahlung. These additional sources provide a partial explanation of the observed excess of dileptons in the np collisions.

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