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 \( \Delta \) 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 \( \Delta \) resonances \( R \rightarrow Ne^+e^- \) or from the Dalitz decays of \( \pi^0 \) and \( \eta \)-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 \( R \rightarrow Ne^+e^- \) and \( R \rightarrow N\pi^0 \), \( \pi^0 \rightarrow \gamma e^+e^- \) decays. Among the resonances, the predominant contribution comes from the \( (1232) \) reaction, 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 \( \eta \)-meson Dalitz decays, produced in the \( np \rightarrow np\eta \) reactions, and \( np \rightarrow dp \) 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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I. INTRODUCTION

The HADES Collaboration\(^1 \) has recently published the results of measurements of dilepton production differential cross sections in \( pp \) and \( dp \) collisions at \( T_{LAB} = 1.25 \) 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 \( \eta \)-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.\(^2 \)

In this paper the resonance model of Ref.\(^2 \), developed earlier to describe the production of dileptons in nucleon-nucleon collisions at \( T_{LAB} = 1 \) 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\(^2 \), scaled by a monopole form factor in the spirit of 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.

II. BARYON RESONANCE MODEL

In the resonance model, the reaction is a two-stage process. First, nucleon and \( \Delta \) 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 shown in Fig.\(^7 \).

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

\[
\begin{align*}
\text{pN} & \rightarrow \text{NR} \rightarrow \text{NN}\pi^0, \quad \pi^0 \rightarrow \gamma e^+e^-; \\
\text{pN} & \rightarrow \text{NR} \rightarrow \text{NN}\eta, \quad \eta \rightarrow \gamma e^+e^-; \\
\text{pN} & \rightarrow \text{NR} \rightarrow \text{NN}e^+e^-,
\end{align*}
\]

where \( R \) is either a nucleon resonance \( N^* \) or a \( \Delta \) resonance. The last channel contains all the contributions of the intermediate \( \rho \) and \( \omega \) mesons. For the first channel we use here the following isotopic relations for two-nucleon final states: \( pp : pm = 1 : 1 \) for all intermediate resonance \( N^*(1535) \), \( pp : pm = 1 : 5 \) for \( N^*(1535) \), and \( pp : pm = 1 : 2 \) for \( R = \Delta \).\(^8 \) \( N^*(1535) \) is the only one resonance giving a significant contribution to the \( \eta \)-meson production. The isotopic ratio for \( \eta \), as a result, becomes \( pp : pm = 1 : 5 \).\(^8 \) The third channel has the
same isotopic ratio as the first channel if one neglects the interference of the intermediate \( \rho \) - and \( \omega \)-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 each of these decays the coherence of \( \rho \) and \( \omega \) is preserved.

The Fermi motion of the constituents inside the deuteron is taken into account using the momentum distribution of the bound proton extracted from the experimental data on the electron scattering cross section on deuteron [9].

At the energy of \( T_{LAB} = 1.25 \text{ GeV} \) the threshold effects for the \( \eta \) production become extremely important. In the \( pp \) case, the excess of energy over the threshold in the center-of-mass coordinate system equals \( \epsilon = -1 \text{ MeV} \), so the \( \eta \)-meson is not produced. In the \( np \) case, the value of \( \epsilon \) is positive for both \( dn \) and \( np \eta \) channels. It is further known from the experiment [10] that close to the threshold the \( np \rightarrow dn \) 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 \( \eta \)-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 \( np \rightarrow dn \eta \), whose cross section is dominant over the others. We thus add the reaction \( np \rightarrow dn \eta \) to the list of reactions involved in the production of \( \eta \)-meson. Below, a parameterization of Ref. [10] for the experimental \( np \rightarrow dn \eta \) cross section is used.

### III. BREMSSTRALUNG AND RADIATIVE CAPTURE

The situation with bremsstrahlung in 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 the results of Ref. [2] available also without electromagnetic form factors and scale them by VMD formfactor \( 1/(1 - M^2/m_p^2) \).

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 \( M > 0.4 \text{ GeV} \). To find the cross section of \( np \rightarrow de^+e^- \) reaction we used experimental data on deuteron photo-disintegration \( \gamma d \rightarrow np \) at photon energies from 139 to 832 MeV [11]. Kinetic energy of the neutron \( T_{LAB} = 1.25 \text{ GeV} \) in the reaction \( np \rightarrow d\gamma \) correspond to the photon energy \( E_\gamma = 600 \text{ MeV} \) in deuteron photo-disintegration reaction. The differential cross section of the last can be parameterized by the linear function [11]

\[
\frac{d\sigma}{2\pi d\cos \theta} = 0.6 + a \cdot \cos \theta \quad \mu b/\text{sr}. \tag{1}
\]

This gives the total cross section \( \sigma(\gamma d \rightarrow np) = 7.5 \mu b \). The cross section of time reversed process \( \sigma(np \rightarrow d\gamma) \) is equal to

\[
\sigma(np \rightarrow d\gamma) = \left( \frac{p_{cm}^2(d\gamma)}{p_{cm}^2(np)} \right) \frac{2 \cdot 3}{2 \cdot 2} \cdot \frac{\sigma(\gamma d \rightarrow np)}{\sigma(np \rightarrow d\gamma)} \approx 5 \mu b. \tag{2}
\]

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

\[
\frac{d\sigma(np \rightarrow de^+e^-)}{dM} = \sigma(np \rightarrow d\gamma) \frac{p_{cm}(d\gamma^*)}{p_{cm}(d\gamma)} \times \left( \frac{1}{1 - M^2/m_p^2} \right)^2 \frac{2\alpha}{3\pi M}. \tag{3}
\]

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

In the case of $pp \to e^+e^-X$ reaction (left panel on Fig. 2), the dilepton yield is shown separately for the $\Delta(1232)$ Dalitz decay (marked by "$\Delta$"), the Dalitz decays of other baryon resonances (marked by "$R$") and $\pi^0$ (marked by "$\pi^0$"), and for bremsstrahlung (dash-dotted line). In the case of $np \to e^+e^-X$ reaction (right panel), there are two additional contributions: the $\eta$-meson Dalitz decay (marked by "$\eta$") and the $np \to de^+e^-$ 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 to isolate 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 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 $np \to d\pi^0\pi^0$ in the energy region of interest [12].

In the model [7], the dilepton spectrum in the direct channels $M \to e^+e^-$ 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 $\rho \to e^+e^-$ decay, or three pion masses for the $\omega \to e^+e^-$ 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. $\rho$-meson, e.g., is generated in accordance with the Breit-Wigner distribution

$$dW(\mu) = \frac{1}{\pi} \frac{\mu \Gamma(\mu) d\mu^2}{(\mu^2 - m_\rho^2)^2 + (\mu \Gamma(\mu))^2},$$

(4)

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

$$\frac{dB(\mu, M)}{dM^2} = \frac{1}{\Gamma(\mu)} \frac{d \Gamma(\rho \to e^+e^-)(\mu, M)}{dM^2},$$

(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 $\rho$-mesons, it is sufficient to replace $\Gamma(\mu)$ 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 selfconsistency of the code.

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

V. CONCLUSION

In this paper 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 $R \to N e^+e^-$ decays and $\pi^0 \to \gamma e^+e^-$ decays. Moreover, the decays of resonances are dominated by $\Delta(1232)$. In the $np$ collisions, an important role is attributed to the $\eta$-meson Dalitz decays, the radiative capture $np \to de^+e^-$, and the bremsstrahlung. These additional sources provide a partial explanation of the observed excess of dileptons in the $np$ collisions.

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