Proton distributions in $dp$ dielectron production within Regge theory

A.P. Jerusalimov, G.I. Lykasov

JINR, Dubna, Moscow region, 141980, Russia

Abstract

The processes of dielectron production in deuteron-proton collisions at intermediate incident deuteron beam energies are analyzed in the spectator model within the one-pion exchange reggeized approach. We focus mainly on the momentum and angle distributions of the proton-spectator and the proton emitted in quasi-free $NN$ processes at small angles in the laboratory frame. It is shown that the inclusion of many channels in quasi-free $NN$ interaction allows us to describe the HADES data quite satisfactorily at incident deuteron kinetic energies of about 2.5 GeV.

1. Introduction

As it is well known, the Regge theory [1] is well applied in the analysis of inclusive hadron production in nucleon-nucleon and pion-nucleon collisions at high energies and not large transfers. For analysis of the exclusive production of one or two pions in $NN$ or $\pi N$ interactions the one-pion exchange reggeized (OPER) model was suggested [2]. For example, recently the OPER was successfully applied [3, 4] to describe the experimental data on two-pion production in $np$ collisions at incident kinetic energies $E_{\text{kin}}$ of about 1-5 GeV [3, 5, 6, 7] and the HADES data at $E_{\text{kin}} = 1.25$ GeV [4]. One of the most interesting goals in the HADES program is the study of $e^+e^-$-pair production in $np$ interactions. But there are no pure narrow neutron beams in the world. Thus, this process can only be studied using the $dp$ or $pd$-interactions.

The HADES [8] (High Aacceptance Di-Electron Spectrometer) is designed at GSI (Darmstead, Germany) and operated at the SIS synchrotron at nuclear ($A$) beam energies of about 1-2 $A$ GeV. It is a magnetic spectrometer capable of registering both hadrons ($p, K$- and $\pi$-mesons) and $e^+/e^-$ pairs within the range of polar angles from 17° up to 85° and exhibits a nearly full azimuth coverage. The main goal of the HADES experiments is the study of hadron properties inside the hot and dense nuclear medium via their di-electron decays. One specific aspect of heavy-ion reactions in the 1-2 $A$GeV range is the important role of baryonic resonances produced, that propagate due to the long lifetime of the dense hadronic
matter phase. A detailed description of resonance excitation and its coupling to the pseudo-scalar and vector mesons is significant for interpretation of the di-electron spectra measured by HADES.

The broad experimental program includes the study of $e^+e^-$-pair production in nucleus-nucleus collisions, elementary reactions ($pp$, $np$, $\pi p$) as well as $pA$, $\pi A$ collisions with the emphasis on properties of vector mesons at finite baryonic densities.

2. Calculation procedure

2.1 Spectator mechanism for dielectron production in the $dp$ reaction

If the proton is emitted in the forward direction, i.e., at small angles relative to the beam in the reaction $dp \rightarrow pe^+e^-X$, then one can use the so-called spectator diagram to analyze spectra of the hadrons and dielectrons produced. Here the system $X$ can contain two nucleons and a few pions. This diagram is presented in Fig. 1, where $p_s$ is the spectator proton. In this case the dielectron pair is produced in the quasi-free $np \rightarrow e^+e^-X$ reaction. In principle, the neutron can also be treated as a spectator, $(n_s)$, then dielectrons are produced in the quasi-free $pp \rightarrow e^+e^-X$ process. To resolve the spectator neutron problem the HADES set-up

![Spectator diagram](image)

Figure 1: The spectator diagram for the process $dp \rightarrow p_s e^+e^-X$. Here $P_d$, $P_t$, $P_s$ and $\vec{P}_{12}$ stand for the momenta of the deuteron, proton-target, proton-spectator and of the three-momentum of the final proton ($p$) and neutron ($n$), respectively; $X$ represents one or two pions.

[8] was upgraded with the Forward scintillator hodoscope Wall (FW) [9, 10] to select quasi-free $n-p$ reactions by detecting fast spectator protons from the deuteron break-up. The FW was located 7 m downstream from the proton target covering
polar angles between 0.3° and 7.0° and provided the time-of-flight information that permitted to reconstruct the proton-spectator momentum.

The FW can register not only the proton-spectator, but also other charged particles (mainly secondary protons).

To eliminate dilepton pairs produced by γ conversion in the detector material the \(e^+e^-\)-pairs were selected at angles \(\Theta_{ee}^{LAB} > 9°\).

The spectra of nucleons and of dielectron pairs produced in the \(dp\) reaction were calculated by MC simulation inputting the nucleon momentum distribution inside the deuteron and the differential cross section of the processes \(NN \rightarrow NN{X}e^+e^-\). As for the deuteron wave function (DWF), the CD-Bonn DWF [11] was used. The differential cross section of the \(NN \rightarrow e^+e^-X\) reaction was calculated within the one-pion exchange reggeized (OPER) model [2].

### 2.2 OPER

The OPER model is based on the method of complex momenta [1]. In Fig. 2 the one-Reggeon \(R\) exchange graph in the \(t\) channel of the binary process \(a + b \rightarrow c + d\) is presented. The virtual state \(R\) has quantum numbers of a particle or a resonance with a certain spin and orbital momentum in the complex space, which corresponds to a Regge trajectory \(\alpha_R(t)\) that is a function of the transfer \(t\). The amplitude of binary processes \(a + b \rightarrow c + d\) presented in Fig. 2 is given by the following [1]:

\[
T_R(s, t) = i8\pi s_0 \ g_{ac}^{R}(t) \ \eta_R(t) \left( \frac{ss_0}{m_c^2m_d^2} \right)^{\alpha_R(t)} g_{bd}^{R}(t) . \tag{1}
\]

Here \(s\) is the initial energy squared, \(s_0\) is the energy scale factor, which is usually chosen to be about 1 GeV\(^2\), \(m_c, m_d\) are the masses of the produced hadrons \(c\) and \(d\), respectively; \(g_{ac}^{R}(t)\) \((g_{bd}^{R}(t))\) is the vertex function or the so-called Regge form factor depending on the transfer \(t\), which is usually parametrized in the simple exponential form \(g_{ac}^{R}(t) = g_{ac}^{R}(t = 0) exp(-R^2 | t |)\), where the parameter \(R\) is called the Regge radius, \(\eta_R(t)\) is the signature factor, determined as follows:

\[
\eta_R(t) = -\frac{\sigma + \exp(-i\pi \alpha_R(t))}{\sin[\pi \alpha_R(t)]} , \tag{2}
\]
where $\sigma = \pm 1$ is the signature value. If $\sigma = +1$, then

$$\eta_R(t) = i - ctg(\pi \alpha_R(t) / 2)$$

and

$$\eta_R(t) = i - tg(\pi \alpha_R(t) / 2)$$

at $\sigma = -1$.

The pion Regge trajectory, which is a linear function of $t$, can be expanded in the following approximate form, see for example [12, 13]:

$$\alpha_R(t) = \alpha_R(t=0) + \alpha'_R(t=0) \cdot t,$$

where $\alpha_R(t=0)$ is the intercept of the Regge trajectory, $\alpha'_R(t=0)$ is its derivative at $t = 0$. The diagrams of the one-pion exchange reggeized for the reaction $np \rightarrow \gamma^* np \rightarrow e^+ e^- np$ are presented in Fig. 3. The amplitude of this process within the OPER can be presented in the following form:

$$T_{NN \rightarrow NN \gamma^* \rightarrow NN e^+ e^-} = G_{\pi N}u(\pi N)\Gamma_{\pi N}u(p_N)F_{\pi N}f_{\pi N \rightarrow \gamma^* N \rightarrow e^+ e^- N}$$

where

$$F_{\pi N} = exp[(R_1^2 + \alpha'_\pi ln(s(\mu^2 + k^2_{\gamma^*})))(t - \mu^2)]$$

Here, the following notation is introduced: $\Gamma_{\pi N} = \gamma_5 g_m \gamma^m$ or $\Gamma_{\pi N} = \gamma_5$; $s = (p_n + p_p)^2$; $s_1 = (p_\pi + p_p)^2$; $s_2 = (p_n + k_{\gamma^*})^2$; $t = (p'_N - p_p)^2$; $p_n, p_p, p_\pi$ are the four-momenta of the initial neutron, proton and exchange pion, respectively; $p_N, p'_N, k_{\gamma^*}$ are the four-momenta of the final nucleon and virtual time-like photon decaying into a $e^+ e^-$ pair.

The slope of the pion trajectory $\alpha'_\pi = 0.7$ is well-known, see, for example, [2]. The parameter value $R_1^2$ = 3.3 GeV$^{-2}$ is chosen from the best description of many observables of dielectron production in the quasi-free $np$ interaction presented below. In the general case we calculated the amplitude of the process $NN \rightarrow \gamma^* np \rightarrow e^+ e^- X$, where $X$ can stand for two nucleons and one or two pions. In the next subsection we present the different channels of dielectron production in the $NN$ interaction.
\subsection{Different channels of dielectron production in quasi-free $NN$ interactions}

The following reactions were taken into account to describe the production of $e^+e^-$ pairs ($p_s$ denotes the spectator proton and $n_s$ is the spectator neutron:
\[
dp \rightarrow p_s + (np \rightarrow e^+e^- + X):
\]
\[
np \rightarrow np \pi^0, \quad \pi^0 \rightarrow e^+e^-;
np \rightarrow np \eta_0, \quad \eta_0 \rightarrow e^+e^-;
np \rightarrow np \rho_0, \quad \rho_0 \rightarrow e^+e^-;
\]
\[
dp \rightarrow n_s + (pp \rightarrow e^+e^- + X):
\]
\[
pp \rightarrow pp \pi^0, \quad \pi^0 \rightarrow e^+e^-;
pp \rightarrow pp \eta_0, \quad \eta_0 \rightarrow e^+e^-;
pp \rightarrow pp \rho_0, \quad \rho_0 \rightarrow e^+e^-;
\]

The rates of these processes to the total yield of the $np \rightarrow np \pi^0e^-X$ at the effective dielectron mass $M_{ee} < 0.140\text{GeV}/c^2$ are presented in Table 1.

\begin{table}[h]
\centering
\begin{tabular}{|c|ccccc|}
\hline
\textbf{Reaction} & $0.5^\circ < \Theta < 2.0^\circ$ & $2.0^\circ < \Theta < 4.0^\circ$ & $4.0^\circ < \Theta < 6.0^\circ$ \\
\hline
$np \rightarrow np \pi^0$ & 0.826 & 0.759 & 0.533 \\
$np \rightarrow np \eta_0$ & 0.036 & 0.064 & 0.063 \\
$np \rightarrow np \rho_0$ & 0.041 & 0.005 & 0.004 \\
$np \rightarrow npe^-$ & 0.001 & 0.001 & 0.001 \\
$np \rightarrow \Delta N$ & 0.025 & 0.013 & 0.011 \\
$np \rightarrow \Delta N\pi$ & 0.017 & 0.008 & 0.007 \\
$pp \rightarrow pp \pi^0$ & 0.045 & 0.118 & 0.212 \\
$pp \rightarrow pp \eta_0$ & 0.002 & 0.003 & 0.005 \\
$pp \rightarrow pp \rho_0$ & <0.001 & 0.001 & 0.004 \\
$pp \rightarrow \Delta N\pi$ & 0.007 & 0.028 & 0.160 \\
\hline
\end{tabular}
\caption{$M_{ee} < 0.140\text{GeV}/c^2$}
\end{table}

One can see from Table 1 that the main contribution to dielectron production in the $np$ interaction at $M_{ee} < 0.14 \text{ GeV}/c^2$ comes from the channel $np \rightarrow np\pi^0$ with
the subsequent $\pi^0 \rightarrow e^+e^-\gamma$ decay. The decay amplitudes of $\pi^0$, $\rho^0$, $\eta^0$-mesons and the $\Delta$-isobar were calculated using the PLUTO model [14, 15, 16].

The rates of these processes to the total yield of the $np \rightarrow np e^+e^-X$ at the effective dielectron mass $M_{ee} > 0.140\text{GeV}/c^2$ are presented in Table 2. One can see from Table 2 that at $M_{ee} > 0.14$ GeV/c$^2$ the main contribution to the dielectron production in the $np$ interaction comes from the channel $np \rightarrow np e^+e^-$, which was calculated in [17].

### Table 2: $M_{ee} > 0.140\text{GeV}/c^2$

| Reaction                  | $0.5^\circ < \Theta < 2.0^\circ$ | $2.0^\circ < \Theta < 4.0^\circ$ | $4.0^\circ < \Theta < 6.0^\circ$ |
|---------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| $np \rightarrow np e^+e^-$| 0.463                             | 0.292                             | 0.259                             |
| $np \rightarrow \Delta N$ | 0.146                             | 0.127                             | 0.138                             |
| $np \rightarrow \Delta N\pi$ | 0.104                             | 0.110                             | 0.137                             |
| $np \rightarrow np\eta^0$   | 0.139                             | 0.195                             | 0.211                             |
| $np \rightarrow np\rho^0$   | 0.032                             | 0.032                             | 0.037                             |
| $pp \rightarrow \Delta^+p$   | 0.054                             | 0.066                             | 0.121                             |
| $pp \rightarrow \Delta^+N\pi$ | 0.062                             | 0.178                             | 0.097                             |

Fig. 4 presents the momentum distributions of charged particles (protons) calculated within the OPER including the possible channels (see table 1 and Table 2) and their comparison to the HADES data [18]. At the top of Fig. 4, the distributions are presented as functions of the proton momentum $p_{FW}$ registered by the FW at $M_{ee} < 140$ MeV/c within three intervals of the angle $\Theta_{FW}$ between the proton and the incident deuteron beam. At the bottom of Fig. 4, the same distributions are presented for $M_{ee} > 140$ MeV/c. The solid lines in Fig. 4 correspond to our total calculation including the contributions of channels presented in Table 1 and Table 2; the dashed lines are the contributions due to the spectator proton, the dash-dotted curves correspond to the background, which is the contribution of protons produced in the reaction $Np \rightarrow pX$ illustrated by the bottom vertex in Fig. 1. All the results presented in Fig. 4 were obtained including the possible $np$ and $pp$ channels listed in Tables (1,2). Note that the channels $pp \rightarrow pp\pi^0$, $pp \rightarrow pp\pi^0\pi^0$, $pp \rightarrow \Delta^+p$, $pp \rightarrow \Delta^+N\pi$ correspond to the contribution of the spectator neutron. One can see from Fig. 4 that the background contribution is visible in the $p_{FW}$-spectrum only at large angles $2.0^\circ < \Theta_{FW} < 4.0^\circ$ and it is sizable at $4.0^\circ < \Theta_{FW} < 6.0^\circ$. The description of the HADES data within the OPER and one-baryon exchange (OBE) [19] model is satisfactory except in the region of $4.0^\circ < \Theta_{FW} < 6.0^\circ$ at $M_{ee} > 140$ MeV and at $p_{FW} > 2000$ MeV/c, where the error bars are large.

Fig. 5 presents the angular distributions of protons registered by the FW. The experimental data were taken from [18]. The dashed line is the contribution of the spectator proton registered by the FW, the dash-dotted curve corresponds to the background, which is due to the non spectator protons registered by the FW. One
Figure 4: The momentum spectra of protons registered by the FW within two ranges of di-electron masses and three ranges of $\Theta_{FW}$. Black squares are experimental data [18], the solid line represents the total description, the dashed curve is the contribution of a true spectator proton, the dash-dotted line corresponds to the background, when the proton produced in reaction $Np \rightarrow pX$ is registered by the FW.

can see the description of the HADES data to be satisfactory within the OPER+one-boson exchange (OBE) model. Unfortunately, at $M_{ee} > 140$ MeV/$c^2$ and $4.0^\circ < \Theta_{FW} < 6.0^\circ$ the statistics is very poor.

Fig. 6 presents the effective mass distribution of $e^+e^-$-pairs produced in the quasi-free $np$ reaction. To achieve a satisfactory description of the HADES data the following reactions were taken into account [9, 20]:

\[ dp \rightarrow p_s + (np \rightarrow e^+e^- + X) \]
\[ np \rightarrow np\rho^0, (\rho^0 \rightarrow e^+e^-) \]
\[ np \rightarrow np\eta^0, (\eta^0 \rightarrow e^+e^-\gamma) \]

The matrix elements squared of the $\rho^0$ and $\eta^0$ Dalitz decays were calculated according to the PLUTO model, see [15, 16]. One can see from Fig. 6 that the main contribution to the $M_{ee}$ spectrum comes from the reaction $np \rightarrow \pi^0X$ with the subsequent $\pi^0 \rightarrow e^+e^-\gamma$ decay, whereas at large $M_{ee} > 0.3$ GeV/$c^2$ the $\rho^0$ and $\eta$ meson production in the $np$ interaction contributes significantly and its inclusion allows us to describe the high effective mass behavior of the spectrum. Inclusion of
the channels listed in Table 1 and Table 2 results in a satisfactory description of the $M_{ee}$ spectrum in the whole kinematical interval, except the very high region of $M_{ee} > 0.6 \text{ GeV}/c^2$. In Fig. 7 the $p_T$-spectrum of dielectrons is presented for $M_{ee} \leq 0.15 \text{ GeV}/c^2$ (left) and $M_{ee} > 0.15 \text{ GeV}/c^2$ (right). The notation of lines in Fig. 7 is the same as in Fig. 6. One can see from Fig. 7 that inclusion of the contributions of the $np$ channels mentioned above allows us to describe the transverse momentum spectrum of dielectrons more or less satisfactorily at $p_T \leq 0.4 \text{ GeV}/c$.

3. Conclusion

The successful description of the proton spectra in FW (PFW) of HADES was obtained by taking into account the various $np$ reactions and $pp$ processes, as a background.

The reaction $np \rightarrow npn^0 \rightarrow npe^+e^-\gamma$ provides the main contribution to the spectator momentum spectra at small dielectron effective masses $M_{ee} < 140 \text{ MeV}/c$. The reaction $np \rightarrow npe^+e^-$ results in a significant contribution at $M_{ee} > 140 \text{ MeV}/c^2$ and $0.5^\circ < \Theta_{p,FW} < 6^\circ$ as compared to other channels.

At larger angles ($2.0^\circ < \Theta_{p,FW} < 4^\circ$) and PFW $< 2000 \text{ MeV}/c$, one should also take into account the spectator neutron case as well as $pp \rightarrow e^+e^- + X$ reactions.

For a satisfactory description of the $M_{ee}$ spectrum it is also necessary to take into account the reactions $np \rightarrow np\eta^0$ and $np \rightarrow np\rho^0$ with subsequent decays ($\eta^0 \rightarrow e^+e^-\gamma$ and $\rho^0 \rightarrow e^+e^-$ respectively) in addition to the reaction used for the description of PFW spectra.
Figure 6: The effective mass spectrum of $e^+e^-$-pairs. The black squares represent experimental the smooth curves result from calculations using the (OPER+OBE)-model involving the contributions of different $np$ channels.

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Figure 7: Left: the $p_T$ distribution of dielectrons at $M_{ee} \leq 0.15$ GeV/c$^2$. Right: the same distribution at $M_{ee} > 0.15$ GeV/c$^2$. The black squares are experimental data [20]. The solid line is our total calculation involving all the $np$ channels mentioned in Table 1 and Table 2.

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