ω and η (η′) mesons from NN and ND collisions at intermediate energies

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Abstract

The production of pseudo scalar, η, η′, and vector, ω, ρ, φ, mesons in NN collisions at threshold-near energies is analyzed within a covariant effective meson-nucleon theory. It is shown that a good description of cross sections and angular distributions, for vector meson production, can be accomplished by considering meson and nucleon currents only, while for pseudo scalar production an inclusion of nucleon resonances is needed. The di-electron production from subsequent Dalitz decay of the produced mesons, η′ → γγ* → γe+e− and ω → πγ* → πe+e− is also considered and numerical results are presented for intermediate energies and kinematics of possible experiments with HADES, CLAS and KEK-PS. We argue that the transition form factor ω → γ*π as well as η′ → γ*γ can be defined in a fairly model independent way and the feasibility of an experimental access to transition form factors is discussed.

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I. Introduction

A theoretical analysis of light pseudoscalar and vector meson production in \( pp \rightarrow ppM, \ pn \rightarrow pnM, \ pn \rightarrow dM \) and \( dp \rightarrow p_{sp} npe^+e^- \) processes (here \( M \) denotes a meson, pseudoscalar \( \eta \) and \( \eta' \), or vector, \( \omega \) or \( \phi \); \( p \) (\( n \)) denotes the proton (neutron), \( p_{sp} \) is the spectator proton, \( d \) stands for the deuteron, and \( e^+e^- \) for a di-electron pair) at threshold-near energies is interesting for different aspects of contemporary particle and nuclear physics. It is known that the effective \( NN \) forces at short distances are governed by exchanges of \( \rho \) and \( \omega \) so that a study of their contribution to the \( NN \) elastic amplitude and to the Meson Exchange Currents in elastic scattering from light nuclei (e.g., the deuteron) can substantially augment the knowledge of the short-range part of the potential. Another important issue is the di-electron emission in \( NN \) collisions which supplies additional information on production of vector mesons with similar quantum numbers but rather different quark contents, in particular \( \omega \) and \( \phi \) mesons, which is interesting in respect to the Okubo-Zweig-Iizuka (OZI) rule and study of hidden strangeness in the nucleon. According to the OZI rule the production of \( \phi \) mesons in nucleon-nucleon collisions should be strongly suppressed relative to \( \omega \) production. An enhanced \( \phi \) production would imply some exotic (e.g., hidden strangeness) components in the nucleon wave function.

The pseudo-scalar mesons \( \eta \) and \( \eta' \) represent a subject of considerable interest since some time (cf. \cite{1} for reports). Investigations of various aspects \( \eta \) and \( \eta' \) mesons are tightly related with several theoretical challenges and can augment the experimental information on different phenomenological model parameters. Also, near the threshold the invariant mass of the \( NN\eta' \) system in such reactions is in the region of heavy nucleon resonances, i.e. resonances with isospin 1/2, including the so-called ”missing resonances”, can be investigated via these processes. Another aspect of \( \eta \) and \( \eta' \) production is that they constitute important sources of di-electrons in \( NN \) reactions. It is, in particular, the \( \eta \) which is significant source of \( e^+e^- \) pairs, competing at invariant masses of 150 - 400 MeV with \( \Delta \) Dalitz decays and bremsstrahlung \cite{2}, as the analysis \cite{3} of HADES data \cite{4} shows. One of the primary aims of the HADES experiments \cite{4} is to seek for signal of chiral symmetry restoration in compressed nuclear matter. For such an endeavor one needs a good control of the background processes, including the Dalitz decay, in particular at higher beam energies, as becoming accessible at SIS100 within the FAIR project \cite{5}. The Dalitz decays of mesons depend on the transition, ”vector-to-pseudoscalar” or ”pseudoscalar-to-vector”, form factors (FF)
which encode hadronic information accessible in first-principle QCD calculations or QCD sum rules. The Dalitz decay process of a meson (pseudo scalar "$ps$" or vector "$V$") can be presented as $ps(V) \rightarrow \gamma(ps) + \gamma^* \rightarrow \gamma(ps) + e^- + e^+$. Obviously, the probability of emitting a virtual photon is governed by the dynamical electromagnetic structure of the "dressed" transition vertex $ps \rightarrow \gamma \gamma^* (V \rightarrow ps \gamma^*)$ which is encoded in the transition form factors. If the decaying particle were point like, then calculations of mass distributions and decay widths would be straightforwardly given by QED. Deviations of the measured quantities from the QED predictions directly reflect the effects of the form factors and thus the internal hadron structure.

For a reliable study of these effects one needs more experimental data and more types of processes. In particular, for further checks of the reaction mechanism it is necessary to study meson production also at neutron targets which can be be extracted, with some efforts and even mostly with some model dependent assumptions, from reactions on nuclei, mainly on the deuteron. The spectator technique represents one example how one can use a deuteron target to isolate reactions on the neutron. It is based on the idea to measure the spectator proton, $p_{sp}$, at fixed beam energy in the meson production reactions $dp \rightarrow p_{sp} npM$, thus exploiting the internal momentum spread of the neutron inside the deuteron. In such a way one gets access to quasi-free reactions $pn$.

In the present paper we present a theoretical approach within that an analysis of mentioned processes can be achieved on a common ground and the differential and total cross sections, as functions of the relevant kinematical variables and initial energy, can be parametrized with the same set of effective parameters.

II. The model

The nucleons and mesons, involved in the process are treated within a meson-nucleon theory based on effective interaction Lagrangians with scalar, pseudoscalar, and neutral ($\omega, \phi$) and charged vector ($\rho$) mesons (see e.g. [2, 6, 7]). The electromagnetic interaction Lagrangians are included into the model as well. The invariant cross section for the meson production in $NN$ collisions of the type $N_1 + N_2 \rightarrow N'_1 + N'_2 + ps(V)$ is

$$d^5\sigma = \frac{1}{2\sqrt{s(s-4m^2)}} \frac{1}{4} \sum_{s_1,s_2,s'_1,s'_2,M_V} |T_{s1s2,s'_1s'_2,M_V}|^2 d^5\tau_f \frac{1}{n_f},$$

where $m$ is the nucleon mass, $s_i$ and $M_V$ are the projections of the nucleonic and mesonic spins ($M_{ps} = 0$) on the quantization axis, $d\tau_f$ is the invariant phase space volume, $s$ is the
invariant mass squared of the initial particles and the factor $\frac{1}{n!}$ accounts for $n$ identical particles in the final state. Calculations of the amplitude $T_{s_1s_2,s_1's_2'}^M$ with the chosen Lagrangians result into a series of Feynman diagrams of two types: (i) the ones which describe the meson production from the processes of one-boson exchange (OBE) between two nucleons accompanied by the emission of a meson by a nucleon (in what follows we call these diagrams nucleon current contribution, see Fig. 1a), and (ii) production of mesons resulting from a conversion of virtual exchanges into a meson, which are called internal conversion type diagrams, Fig. 1b).

\[\begin{align*}
\text{FIG. 1: Feynman diagrams for the nucleon current (a) and internal conversion (b) contributions to meson production in } N N \text{ reactions. The thin solid lines denote incoming and outgoing nucleons, the dashed lines are for the exchanged (OBE) mesons, while the intermediate thick lines can be either a virtual nucleon or a nucleon resonance; } \mu_1 \text{ (} \mu_2 \text{) are the virtual mesons before (after) conversion, whereas the produced final meson is depicted as waved lines.}
\end{align*}\]

In our calculations we use the following Lagrangians: (i) Nucleon currents:

\[\begin{align*}
\mathcal{L}_{\sigma NN} &= g_{\sigma NN} \bar{\Psi}_N(x)\Psi_N(x)\Phi_\sigma(x), \\
\mathcal{L}_{a_0NN} &= g_{a_0NN} \bar{\Psi}_N(x)(\tau\Phi_{a_0})(x)\Psi_N(x), \\
\mathcal{L}_{psNN} &= -\frac{f_{psNN}}{m_{ps}} \bar{\Psi}_N(x)\gamma_5\gamma^\mu\partial_\mu(\Phi_{ps}(x))\Psi_N(x), \\
\mathcal{L}_{VNN} &= -g_{VNN} \bar{\Psi}_N(x) \left(\gamma_\mu\Phi_V^\mu(x) - \frac{\kappa_V}{2m}\sigma_\mu\nu\partial_\nu(\Phi_V^\mu(x))\right)\Psi_N(x)
\end{align*}\]

(ii) Spin $\frac{1}{2}$ resonances ($S_{11}$ and $P_{11}$):

\[\begin{align*}
\mathcal{L}_{NN^*ps}^{(\pm)}(x) &= \mp \frac{g_{NN^*ps}}{m_{N^*} \pm m_N} \bar{\Psi}_R(x) \begin{cases} \gamma_5 \\ 1 \end{cases} \gamma^\mu\partial_\mu(\Phi_{ps}(x))\Psi_N(x) + h.c., \\
\mathcal{L}_{NN^*V}^{(\pm)}(x) &= \frac{g_{NN^*V}}{2(m_{N^*} + m_N)} \bar{\Psi}_R(x) \begin{cases} 1 \\ \gamma_5 \end{cases} \sigma_\mu\nu V^{\mu\nu}(x)\Psi_N(x) + h.c.
\end{align*}\]
with the abbreviations \( ps \equiv \pi \) or \( \eta \), \( \Phi_{ps} \equiv (\tau \Phi_{\pi}(x)) \) or \( \Phi_{\eta'}(x) \), \( V \equiv V_{\omega}(x) \) or \( V(\tau \rho(x)) \), and \( V^{\alpha \beta} = \partial^\beta V^\alpha - \partial^\alpha V^\beta \). Similar expressions hold for the spin \( \frac{3}{2} \) resonances \( (D_{13} \text{ and } P_{13}) \) which contribute mainly to the \( \eta' \) meson production. Furthermore needed for internal conversion interactions, such as \( L_{\rho\pi V} \), \( L_{psVV} \), \( L_{\gamma\eta} \), and \( L_{ps\gamma\gamma} \) are listed in [8]. All the nucleon – nucleon (resonance) – meson vertices are dressed with cut-off form factors of the form reported in [8, 9].

### III. Results

These seemingly many ingredients (coupling strengths, form factors and their cut-offs, see [8, 9]) may cause the impression that the one-boson exchange approach to hadronic observables contains too many free parameters and does not have too much predictive power. However, a bulk of these apparently free parameters are constrained by independent experiments and can be fixed from independent data, e.g. from fitting the elastic \( NN \) phase shifts or from known decay widths of mesons into different partial channels etc. Details of fixing parameters can be found, e.g. in Refs. [2, 7, 8, 9].

In Fig. 2 the results of calculations of the total cross sections (upper panel) and angular distributions (lower panel) for vector meson production \( (\omega \text{ and } \phi) \) [6, 10] are exhibited together with available experimental data. It should be stressed that an overall good description of data has been achieved by taking into account contributions from nucleonic current and internal conversion only, without implementing any excitations of nucleon resonances. Also, as input into the calculations we used the coupled constants for free \( NNV \) vertices which do not contradict the OZI rule. The obtained relatively high cross sections for \( \phi \) production demonstrate, that the observed enhancement is solely governed by dynamic effects (OBE interaction, interference of many different diagrams, isospin effects etc.) and does not favour any OZI rule violation and the presence of hidden strangeness in nucleons.

In Figs. 3 and 4 results of calculations of \( \eta \) and \( \eta' \) mesons in \( pp \) and \( pn \) reactions are displayed. Contrarily to the case of vector mesons, excitations of intermediate resonances here are rather important. This mainly concerns \( \eta \) meson production, which occurs primarily due to excitations of the \( N_{1535} \) nucleon resonance.

Further applications of the present approach to \( \omega \) and \( \phi \) production involving a final deuteron, including polarization observables, have been presented in [11], while [2] extends the formalism to virtual bremsstrahlung in \( NN \rightarrow NN\gamma^* \rightarrow NN e^+ e^- \) reactions.

### IV. Dalitz decay and transition form factors
FIG. 2: Cross sections for $\omega$ (left) and $\phi$ (right) production from $[6, 10]$. Experimental data for $\omega$ are from $[12, 13]$ (open circles), $[14]$ (triangles) and $[15]$ (squares), while for $\phi$ from $[15, 16, 17]$.

The subsequent Dalitz decay of the produced (virtual) meson into a di-electron pair and another particle can be also described within the presented approach. In the tree-level approximation the process $N_1 + N_2 \rightarrow N_1' + N_2' + ps(V) \rightarrow N_1' + N_2' + \gamma(ps) + \gamma^* \rightarrow N_1' + N_2' + \gamma(ps) + e^- + e^+$ is described by the same set of Feynman diagrams as in Fig. 1 except that now the produced meson (waved lines) is virtual and decays into the considered channel. The corresponding cross section then reads as

$$\frac{d^2\sigma}{ds_{\gamma^*} ds_M} = \sigma^{tot} (NN \rightarrow NN M) \frac{\sqrt{s_M/\pi}}{(s_M - M^2)^2} \frac{d\Gamma_{ps(V)\rightarrow\gamma(ps)e^+e^-}}{ds_{\gamma^*}}, \quad (8)$$

$$\frac{d\Gamma_{ps(V)\rightarrow\gamma(ps)e^+e^-}}{ds_{\gamma^*}} = \xi \frac{\alpha_{em} \chi^{3/2}(s_M, s_{\gamma^*}, \mu_f^2)}{3\pi s_{\gamma^*} \lambda^{3/2}(s_M, 0, \mu_f^2)} \Gamma_{ps(V)\rightarrow\gamma\gamma(ps)} F_{ps(V)\gamma^*\gamma(ps)}(s_{\gamma^*})^2, \quad (9)$$

where $s_M$ is the square of the invariant mass of the produced off-mass shell meson with $M = \mu - i\Gamma^{tot}/2$ as its pole mass and total decay width $\Gamma^{tot}$; $\mu_f^2 = 0$, $\xi = 2$ in case of
FIG. 3: Total cross sections for $\eta$ and $\eta'$ production as a function of the energy excess in $p + p$ (left) and invariant mass distribution of $\eta$ production as a function of the invariant mass $s_{12}$ of the outgoing nucleons (right). For data quotation consult [8, 9, 18, 19].

FIG. 4: Total cross section for $\eta$ and $\eta'$ production in $pn$ reactions. Experimental data are quoted in [8, 9, 18, 19]; the most recent results for $\eta$ production in $pn$ reactions [20] are depicted as squares (left). The role of different contributions, nucleonic current, internal conversion (MEC) and resonances, is also displayed.

The electromagnetic form factors encode non-perturbative transition matrix elements $F_{ps(V)\gamma\gamma^*}(ps)$ in (9), basically accessible within QCD. Here, however, we contrast a few parameterizations: (i) so-called QED form factor meaning a structure-less particle with $|F_{\eta'\gamma\gamma^*}(s_{\gamma'})|^2 = 1$, (ii) a parametrization suggested by the vector meson dominance (VDM) model

$$F_{ps(V)\gamma\gamma^*(ps)}^{VMD}(s_{\gamma'}) = \sum_{V=p,\omega,\phi} C_V \frac{m_V^2}{\hat{m}_V^2 - s_{\gamma'}},$$

with $F(s_{\gamma'} = 0) = 1$, $\sum C_V = 1$ and $\hat{m}_V = m_V - i\Gamma_V/2$. The values of $C_V$ are quoted
in [8]. For the case of light mesons ($\eta$ and $\omega$), the kinematically accessible region is below the vector mesons pole masses and, as a consequence, the $\rho$ contribution is sufficient. (iii) For $\eta'$, a monopole fit $F_{\eta'\gamma\gamma^*}(Q^2) = (1 - Q^2/\Lambda_{\eta'})^{-1}$ may be used, which does not differ too much from the VDM parametrization which, in this case, includes $\omega$, $\rho$ and $\phi$ mesons.

![Graph](image)

**FIG. 5:** Transition form factors for Dalitz decay of $\omega \rightarrow \pi e^+e^-$ (left) and $\eta' \rightarrow \gamma e^+e^-$ (right).

In Fig. 5 we present results of calculations of the form factors defined by eq. (9) for transitions of a vector mesons ($\omega$) into a pion and a di-electron pair (left) and transitions of $\eta'$ into a real photon and a di-electron pair (right). The solid lines correspond to the VDM calculations, eq. (10), while the phenomenological fit is presented by the dashed lines. It is seen, that since for $\omega$ decay the kinematically allowed values of $s_{\gamma^*}$ (the argument of the transition FF) are below the vector meson pole masses, the corresponding FF exhibits a smooth behavior. A completely different situation occurs in case of $\eta'$ meson, for which $s_{\gamma^*}$ can be far beyond the the vector meson pole masses and, correspondingly, the transition FF displays a sharp maximum near that poles. Such a behavior can serve as a test of validity of VDM at large values of invariant masses.

**VI. Reactions with the deuteron**

Eventually, herebelow we present the cross section of di-electron production in $d + p \rightarrow p_{sp} + n + p + e^+e^-$ reactions within the spectator mechanism, i.e. when the fast proton is detected in forward direction with the velocity not too different from the one of the incoming
deuteron. The cross section is evaluated within the same effective meson nucleon theory, the deuteron now being treated within the Bethe-Salpeter formalism with the same effective parameters as in reactions with nucleons (details can be found in [2]).

\[
2E_{sp} \frac{d\sigma}{dp_{sp}d\gamma^*} = 2M_{D} \sqrt{\lambda(s_{NN}, m^2, m^2)} \frac{n_D(|p_{sp}|)}{\lambda(s_0, m^2, M_{D}^2)} \frac{d\sigma^{np}}{ds_{\gamma^*}},
\]

(11)

where \(n_D(|p_{sp}|)\) is the deuteron momentum distribution in the deuteron center of mass system, \(s_0\) is the initial invariant energy of the colliding particles, \(s_{NN}\) is the effective invariant energy of the target proton and the neutron within the deuteron. It is seen that the desired cross section \(d\sigma^{np}/ds_{\gamma^*}\) at the neutron target can be obtained from the experimentally measured cross section \(2E_{sp} \frac{d\sigma}{dp_{sp}d\gamma^*}\) by normalizing the latter with known kinematical factors \(\lambda(s_{NN}, m^2, m^2)\) and known deuteron momentum distribution \(n_D(|p_{sp}|)\). Note, that eq. (11) has been obtained strictly within the spectator mechanism and can not be valid at large angles and/or low velocities of the spectator proton.

**VII. Summary**

In summary we report on calculations of the reaction \(NN \rightarrow NN M\) with \(M\) as a pseudoscalar \(\eta, \eta'\) or vector \(\omega, \rho, \phi\) meson and subsequent Dalitz decay of the produced meson within a one-boson exchange model. We point out that isolating \(\omega, \eta\) and \(\eta'\) contributions, e.g., in \(p + p\) collisions, allows for an experimental determination of the corresponding transition form factors. In particular, for \(\eta'\) the vector meson dominance hypothesis would be testable. On the other hand, the \(\omega\) and \(\eta\) Dalitz decay channel are strong sources of \(e^+e^-\) pairs in medium-energy heavy-ion collisions which need to be understood before firm conclusions on possible in-medium modifications of hadrons can be made. We emphasize that, once the model parameters are adjusted in the \(p + p\) channel, the \(n + p\) channel is accessible without further parameters. The spectator technique with deuterons can allow for an experimental tagging of reactions at the neutron target, provided the spectator proton is detected in the forward direction with the same velocity as the incoming deuteron.

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