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η AND η' PRODUCTION IN NUCLEON–NUCLEON COLLISIONS NEAR THRESHOLDS*

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The production of η and η' mesons in nucleon–nucleon collisions near thresholds is considered within an one-boson exchange model. We show the feasibility of an experimental access to transition form factors.

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1. Introduction

The pseudo-scalar mesons η and η' have represented a subject of considerable interest for some time (*cf.* [1] for reports). Investigations of various aspects of η and η' mesons are tightly related with several theoretical challenges and can augment the experimental information on different phenomenological model parameters. For instance, the "anomalously" large mass of the η' meson, as a member of the SU(3) nonet [2], can be directly connected with the U(1) axial anomaly in QCD. Yet, a combined phenomenological analysis of η and η' production in $N+N$ reactions together with the $\mathrm{U}_A(1)$ anomaly provides additional information on the gluon–nucleon coupling, which can be used to describe, *e.g.*, the so-called "spin crisis". Also, the knowledge of the nucleon–nucleon-η' coupling constant $g_{NN\eta'}$ allows to better understand the origin of the OZI rule violation in $N+N$ reactions. A remarkable fact is that 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 can be investigated via these processes. Furthermore, the so-called "missing resonances" can be studied.

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Another aspect of η and η' production in elementary hadron reactions is that both mesons have non-negligible Dalitz decay channels into $e^+e^-\gamma$. As such, they constitute further sources of di-electrons. It is, in particular, the η which is a significant source of e^+e^- pairs, competing at invariant masses of 150–400 MeV with Δ Dalitz decays and bremsstrahlung, as the analysis [3] of HADES data [4] shows. One of the primary aims of the HADES experiments [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 η' Dalitz decay, in particular at higher beam energies, as becoming accessible at SIS100 within the FAIR project [5].

The η' Dalitz decays depend on the pseudo-scalar transition form factor, which encodes hadronic information accessible in first-principle QCD calculations or QCD sum rules. The Dalitz decay process of a pseudo-scalar meson ps can be presented as $ps \to \gamma+\gamma^* \to \gamma+e^-+e^+$. Obviously, the probability of emitting a virtual photon is governed by the dynamical electromagnetic structure of the "dressed" transition vertex $ps \to \gamma\gamma^*$ 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.

The present paper reports parameterizations of η and η' production cross-sections in nucleon–nucleon collisions (*cf.* also [6]) near the respective thresholds within a one-boson exchange model. Emphasis is put on the accessibility of transition form factors encoding the strong-interaction η, η' structure.

2. One-boson exchange model

Cross-sections of interest are

$$d^5\sigma^{\rm tot}_{NN\to NNps} = \frac{1}{2(2\pi)^5\sqrt{\lambda(s,m^2,m^2)}} \times \frac{1}{4}\sum_{\rm spins} |T_{NN\to NNps}|^2 \, ds_{1'2'}\, dR_2^{N_1N_2\to s_{ps}s_{1'2'}}\, dR_2^{s_{1'2'}\to N_1'N_2'} \tag{1}$$

with two-particle invariant phase space $R_2^{ab\to cd} = \sqrt{\lambda(s_{ab},m_c^2,m_d^2)}/(8s_{ab})d\Omega_c^*$ for the production of $ps \equiv \eta, \eta'$ and

$$\frac{d\sigma}{ds_{ps}ds_{\gamma^*}} = \frac{d\Gamma_{ps\to\gamma e^+e^-}}{ds_{\gamma^*}} \frac{1}{4\pi\sqrt{s_{ps}}} \frac{1}{\left(\sqrt{s_{ps}}-m_{ps}\right)^2+\frac{1}{4}\Gamma_{ps}^2}\, d^5\sigma^{\rm tot}_{NN\to NNps} \tag{2}$$

for the Dalitz decay. Integrating the latter one over ds_{ps} or taking it at $s = m_{ps}^2$ is meant to access the electromagnetic form factors appearing in

$$\frac{d\Gamma_{ps\to\gamma e^+e^-}}{ds_{\gamma^*}} = \frac{2\alpha_{em}}{3\pi s_{\gamma^*}}\left(1-\frac{m_{ps}^2}{s_{\gamma^*}}\right)^3 \Gamma_{ps\to\gamma\gamma}\left|F_{ps\gamma\gamma^*}\left(s_{\gamma^*}\right)\right|^2 . \tag{3}$$

2.1. η channel

We employ here a one-boson exchange model, where the η production is described by the diagrams exhibited in Fig. 1. The sum of these diagrams generate the invariant amplitude $T_{NN\to NNps}$ via interaction Lagrangians.

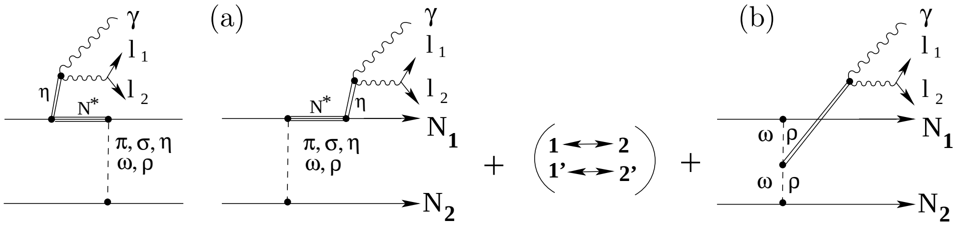

Fig. 1. Diagrams for the process $NN \to NN\eta \to NN\gamma e^+e^-$ within the one-boson exchange model. (a) Dalitz decays of η mesons from bremsstrahlung like diagrams. The intermediate baryon N^* (triple line) can be either a nucleon or a nucleon resonance. Analog diagrams for the emission from Fermion line N_2. (b) Dalitz decay of η mesons from internal meson conversion. Exchange diagrams for identical nucleons in exit channel are not displayed.

2.2. η' channel

The calculation of η' uses the same diagram topology as in Fig. 1 (with $\eta \to \eta'$) supplemented by a_0 exchange. The included resonances are $S_{11}(1650)$ with odd parity, and $P_{11}(1710)$ and $P_{13}(1720)$ with even parity.

2.3. Interaction Lagrangians

The employed interaction Lagrangians can be represented as follows.
(i) Nucleon currents:

$$\mathcal{L}_{\sigma NN} = g_{\sigma NN}\bar{\Psi}_N(x)\Psi_N(x)\Phi_\sigma(x)\,, \tag{4}$$

$$\mathcal{L}_{a_0 NN} = g_{a_0 NN}\bar{\Psi}_N(x)(\tau\Phi_{a_0})(x)\Psi_N(x)\,, \tag{5}$$

$$\mathcal{L}_{psNN} = -\frac{f_{psNN}}{m_{ps}}\bar{\Psi}_N(x)\gamma_5\gamma^\mu\partial_\mu(\Phi_{ps}(x))\Psi_N(x)\,, \tag{6}$$

$$\mathcal{L}_{VNN} = -g_{VNN}\bar{\Psi}_N(x)\left(\gamma_\mu{\Phi_V}^\mu(x) - \frac{\kappa_V}{2m}\sigma_{\mu\nu}\partial^\nu{\Phi_V}^\mu(x)\right)\Psi_N(x)\,. \tag{7}$$

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

$$\mathcal{L}^{(\pm)}_{NN^*ps}(x) = \mp\frac{g_{NN^*ps}}{m_{N^*}\pm m_N}\bar{\Psi}_R(x)\left\{\begin{array}{c}\gamma_5\\ 1\end{array}\right\}\gamma_\mu\partial^\mu\Phi_{ps}(x)\Psi_N(x)+\text{h.c.} \quad (8)$$

$$\mathcal{L}^{(\pm)}_{NN^*V}(x) = \frac{g_{NN^*V}}{2(m_{N^*}+m_N)}\bar{\Psi}_R(x)\left\{\begin{array}{c}1\\ \gamma_5\end{array}\right\}\sigma_{\mu\nu}V^{\mu\nu}(x)\Psi_N(x)+\text{h.c.} \quad (9)$$

(iii) Spin $\frac{3}{2}$ resonances (D_{13} and P_{13}):

$$\mathcal{L}^{(\pm)}_{NN^*ps}(x) = \frac{g_{NN^*ps}}{m_{ps}}\bar{\Psi}^\alpha_R(x)\left\{\begin{array}{c}1\\ \gamma_5\end{array}\right\}\partial^\alpha\Phi_{ps}(x)\Psi_N(x)+\text{h.c.} \quad (10)$$

$$\begin{aligned}\mathcal{L}^{(\pm)}_{NN^*V}(x) &= \mp i\frac{g^{(1)}_{NN^*V}}{2m_N}\bar{\Psi}^\alpha_R(x)\left\{\begin{array}{c}\gamma_5\\ 1\end{array}\right\}\gamma_\lambda V^{\lambda\alpha}(x)\Psi_N(x)\\ &\quad -\frac{g^{(2)}_{NN^*V}}{4m_N^2}\partial_\lambda\bar{\Psi}^\alpha_R(x)\left\{\begin{array}{c}\gamma_5\\ 1\end{array}\right\}V^{\lambda\alpha}\Psi_N(x)+\text{h.c.} \quad (11)\end{aligned}$$

with the abbreviations $ps \equiv \pi$ or η or η', $\Phi_{ps} \equiv (\tau\Phi_\pi(x))$ or $\Phi_{\eta'}(x)$, $V \equiv V_\omega(x)$ or $V(\tau\rho(x))$, and $V^{\alpha\beta} = \partial^\beta V^\alpha - \partial^\alpha V^\beta$. Furthermore, needed interactions, such as $\mathcal{L}_{ps\omega\omega}$, $\mathcal{L}_{ps\rho\rho}$, $\mathcal{L}_{\gamma ll}$, and $\mathcal{L}_{ps\gamma\gamma}$ are listed in [7].

2.4. Form factors

Strong form factor are needed to dress the nucleon–nucleon (resonance) and nucleon–meson vertices. These are listed in detail in [7, 8].

The electromagnetic form factors encode non-perturbative transition matrix elements $F_{ps\gamma\gamma*}$ in (3), basically accessible within QCD. Here, however, we contrast a few parameterizations: *(i)* so-called QED form factor meaning a structure-less particle with $\left|F_{\eta'\gamma\gamma^*}(s_{\gamma^*})\right|^2 = 1$, *(ii)* a parametrization suggested by the vector meson dominance model (VDM)

$$F^{\rm VMD}_{\eta'\gamma\gamma^*}(s_{\gamma^*}) = \sum_{V=\rho,\omega,\phi} C_V\frac{m_V^2}{\hat{m}_V^2 - s_{\gamma^*}}\,, \quad (12)$$

with $F_{\eta'\gamma\gamma^*}(s_{\gamma^*}=0)=1$, $\sum_V C_V = 1$ and $\hat{m}_V = m_V - i\Gamma_V/2$. The values of C_V are quoted in [7]. For the case of η, the kinematically accessible region is restricted and, as a consequence, the ρ contribution is sufficient. *(iii)* For η', a monopole fit $F_{\eta'\gamma\gamma^*}(Q^2) = (1-Q^2/\Lambda_{\eta'})^{-1}$ [7] may be used, which does not differ too much from the VDM parametrization.

2.5. Initial state and final state interactions

Initial state interactions are accounted for by the effective reduction factors for ${}^3P_0$, ${}^1P_1$ waves: $\zeta = 0.277\,(pp)$, $0.243\,(np, pp)$ [9]. Final state interactions are treated by Jost function formalism, see [10] for details.

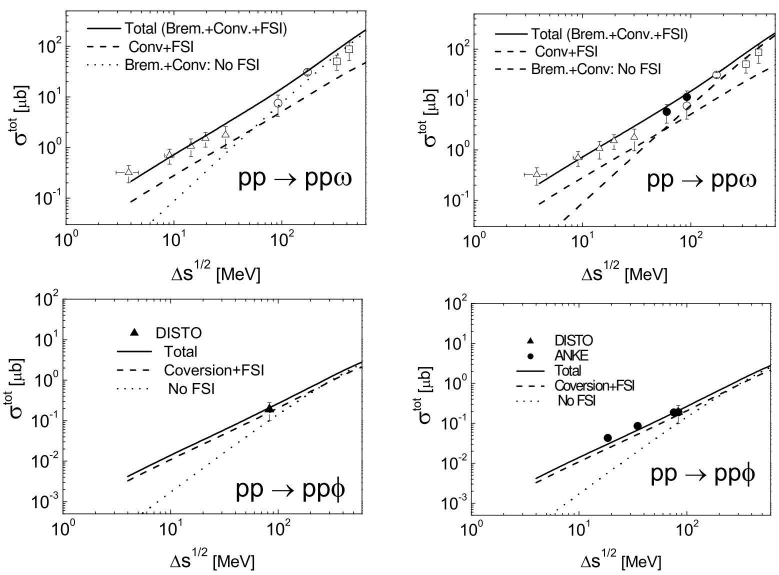

Fig. 2. Cross-sections for ω (top) and ϕ (bottom) production from [11, 12] (left). The new data situation confirms these predictions (right). Experimental data for ω are from [13] (open circles), [14] (triangles) and [15] (squares), while for ϕ from [15,16]. The new data (from ANKE for ω [17] and for ϕ [18]) are depicted as closed circles.

2.6. One-boson model at work

These seemingly many ingredients (coupling strengths, form factors and their cut-offs, see [7, 8]) may cause the impression that the one-boson exchange approach to hadronic observables near threshold do not have too much predictive power. Two counterexamples may lend more credibility to the approach. In Fig. 2 the model results of [11, 12] are exhibited (left panels). Later on the data basis has been improved confirming the model predictions (right panels). Further applications of the present approach to ω and ϕ production involving a final deuteron, including polarization observables, have been presented in [19], while [20] extends the formalism to virtual bremsstrahlung in $NN \to NN\gamma* \to NNe^+e^-$ reactions.

3. Results

Numerical evaluations of the given formalism result in the total cross-sections exhibited in Fig. 3. Available data (*cf.* [7, 8] for quotations) are fairly nicely reproduced in the $p + p$ channel (a concern could be the region of excess energy $\Delta s^{1/2} \sim 10$ MeV for η). Since now new parameters enter, the channel n+p represents a prediction, in agreement with data in case of η; no data are available for η'.

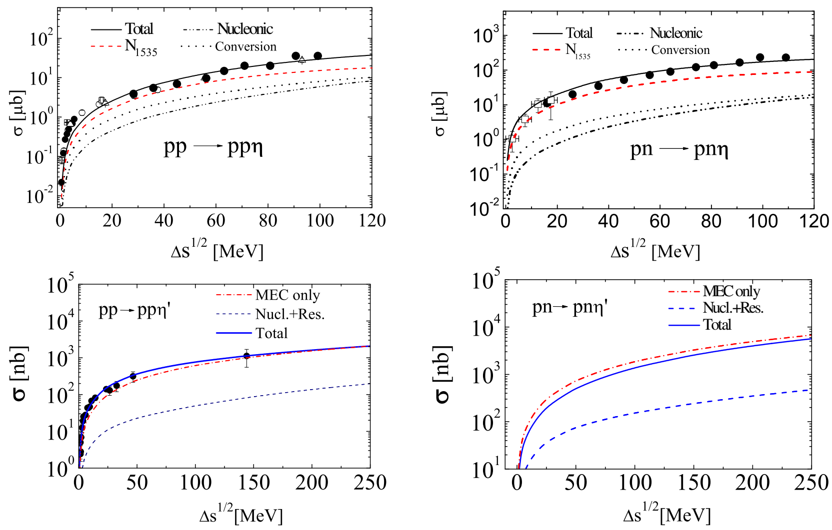

Fig. 3. Total cross-sections for η (top) and η' (bottom) production as a function of the energy excess in $p+p$ (left) and $n+p$ reactions (right). For data quotation consult [7, 8, 21, 22]; recent data [23] for η production in pn reactions are depicted as squares (right top).

The cross-sections $d\sigma/ds_{\gamma*}^{1/2}$, resulting from the integration of (2) over s_{ps}, are exhibited in Fig. 4. There is a tiny difference when neglecting the internal strong interaction structure of η ("QED form factor") or when using the VMD form factor, see left panel of Fig. 4. The situation changes drastically for η'. Here, the account of the internal structure becomes important, see right panel of Fig. 4. Precision data would even allow for a test of the VMD hypothesis. As has been shown in [7, 8] the form factors can be deduced from given cross-section $d\sigma/ds_{\gamma*}^{1/2}$.

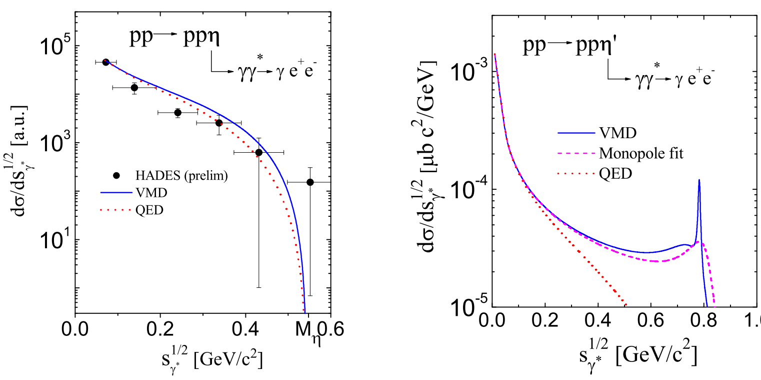

Fig. 4. Differential cross-sections for η (left, HADES data from [24], for $T_p = 2.2\,\text{GeV}$) and η' (right, for $T_p = 2.5$ GeV) which give access to the form factors.

4. Summary

In summary we report on calculations of the reaction $NN \to NNps$ with $ps = \eta, \eta'$ and subsequent Dalitz decay $ps \to \gamma e^+e^-$ within a one-boson exchange model. We point out that isolating η and η' contributions, *e.g.*, in $p+p$ collisions, allows for an experimental determination of the transition form factors $F_{ps\gamma\gamma *}$. In particular, for η' the vector meson dominance hypothesis would be testable. On the other hand, the η Dalitz decay channel is a strong source 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.

For further improvements of the presented formalism we refer the interested reader to [25], where $N+N$ collisions and η, η' photo-production are considered on a common footing.

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