Nucleon resonances and the production of light vector mesons near thresholds\textsuperscript{1}

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Abstract

The production of the light vector mesons $V = \rho, \omega, \phi$ in the reactions $\pi N \rightarrow VN$ and $NN \rightarrow VNN$ near threshold is studied. The subsequent electromagnetic decay $V \rightarrow \gamma^* \rightarrow e^+e^-$ is particularly suited for exploring subthreshold $\omega N$ resonances.

1 Introduction

Baryon resonances represent an important part of the hadronic spectrum which in turn reflects the pattern of excitations above the QCD ground state. Their experimental investigation proceeds with various probes, e.g., in photo- or electro-production processes at nucleons or nuclei. Also in hadronic reactions the baryon resonances play an important role. The theoretical investigation is based on coupled channel analyses, effective field theories, chiral perturbation theory, QCD sum rules etc. The resonances once excited decay under emission of hadrons, real or virtual photons. The decay channels we here focus on are such ones where light vector mesons are emitted. An understanding of the elementary hadronic production processes of vector mesons is of utmost importance for analyzing di-electron spectra from intermediate heavy-ion reactions and hadron-nucleus reactions as well. Corresponding experiments with the HADES detector \cite{1} started recently. This is the main motivation for the present note.

To illustrate some aspects of light vector meson production in hadronic reactions let us mention three issues related to this topic.

(i) While for the processes $\pi p \rightarrow VN$ and $pp \rightarrow Vpp$ (here $V = \rho, \omega, \phi$; $N$ stands either for the proton ($p$) or for the neutron ($n$)) some experimental

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data is at our disposal, one needs often a model to deduce the corresponding reactions at the neutron. There are various examples for the ratio of the cross sections \( \sigma(pn \rightarrow Vpn)/\sigma(pp \rightarrow Vpp) \) which highlight a strong energy dependence and clearly show that there is no simple isospin factor relating these two channels.

(ii) There is a long list of various effects influenced by the hidden strangeness content in the nucleon. Among them is the dropping mass of the \( \phi \) meson in nuclear matter, as predicted by the QCD sum rule approach [2, 3]. As shown in [1], such an in-medium mass shift of the \( \phi \) meson can considerably modify the di-electron spectrum in heavy-ion collisions. This modification depends on the poorly known fraction of hidden strangeness in the nucleon. Present lattice QCD calculations do not deliver a stringent constrain of this fraction [5]. Otherwise, as the nucleon is the core of visible matter in the universe, it is challenging to understand its composition, and therefore any possible source of information is well come. Our approach to this problem is to consider the sensitivity of \( \phi \) meson production on a possible \( \bar{s}s \) component in the nucleon wave function.

(iii) Below we are going to include, within an effective Lagrangian model on tree level, resonances in the above mentioned hadronic reactions and elaborate their specific importance for several observables. Otherwise, we also demonstrate that certain reactions can be effectively parameterized without inclusion of resonances.

The present note is organized as follows. In section 2 we recapitulate the isoscalar-isovector \((\rho - \omega)\) interference near the \( \omega \) threshold and emphasize that this effect can allow a unique access to resonance properties. Section 3 is devoted to a brief description of the combined \( \omega \) and \( \phi \) production in \( \pi N \) reactions with respect to the OZI rule and its implications for the hidden strangeness content of the nucleon. In section 4 we consider \( \omega \) and \( \phi \) production in \( NN \) reactions. Our conclusions can be found in section 5.

2 Iscalar-Isovector Interferences in \( \pi N \rightarrow Ne^+e^- \) Reactions as a Probe of Nucleon Resonance Dynamics

The tree level diagrams depicted in Fig. 1 serve as basis for an exploratory study of the reaction \( \pi N \rightarrow e^+e^-N \) with interfering intermediate \( \rho \) and \( \omega \) mesons. This reaction, proposed in [6] as a suitable probe of baryon resonance dynamics, is evaluated in [7] with resonances \( N^* \) and \( \Delta^* \) up to 1720 MeV without the t-channel process displayed in the right part of Fig. 1; effective couplings are taken from [8] (cf. [7] for details). Some illustrative results of
this model exhibited in Fig. 2 agree in trends with the more sophisticated approach of [9]: a destructive (constructive) $\rho - \omega$ interference in the reaction $\pi^- p \rightarrow e^+ e^- n$ ($\pi^+ n \rightarrow e^+ e^- p$) below the $\omega$ threshold. Angular distributions and the energy ($\sqrt{s}$) dependence of the invariant mass spectra can reveal the role of individual resonances. A comparison of both isospin channels can be used to disentangle the $N\omega$ subthreshold resonances. Both reactions can be explored experimentally at GSI with the pion beams and HADES in exclusive measurements.

Fig. 2: Top: Differential cross section as a function of the $e^+e^-$ invariant mass below (left) and above threshold (right) [the polar angle of the $e^+e^-$ pair is 30$^\circ$ in the $\pi N$ center-of-mass system]. Bottom: Phase space averaged squared matrix elements for the individual resonances in the partial channels with an intermediate $\rho$ (left) and $\omega$ (right) meson as a function of the energy.
Fig. 3: Tree level diagrams for the reaction $NN \to VNN$.

3 Combined Analysis of $\omega$ and $\phi$ Production: OZI Rule

A combined analysis of the $\omega$ and $\phi$ production in the reaction $\pi N \to VN$ shows that the experimental data can be well described by including s-, u- and t-channels. The contribution of the meson current dominates [10]. Therefore, there is no need to introduce an anomalously large coupling $g_{\phi NN}$ which could be interpreted, in the spirit of [11], as a hint to a substantial hidden strangeness fraction in the nucleon. The standard OZI rule violation comes in this description from the $\phi\rho\pi$ vertex, see [12] for a discussion of this issue.

Further investigations of photo-production of $\omega$ and $\phi$ mesons at the nucleon [13] do also not allow to deduce hints to a sizeable admixture of hidden strangeness in the nucleon wave function.

4 The Reactions $NN \to \omega NN$ and $NN \to \phi NN$

The tree level diagrams exhibited in Fig. 1 serve as building blocks of diagrams for the corresponding processes $NN \to VNN$ in Fig. 3. Therefore, one could expect that with adjusting the parameters of effective Lagrangians to the reactions $\pi N \to VN$ a substantial part of the ambiguities of in the parameter space is removed. However, additionally exchanged mesons and form factors ruin this expectation. Rather, a combined analysis of both reactions can reduce ambiguities, cf. [16].
4.1 $\phi$ Meson Production

Fig. 4 exhibits a calculation [16] of the reaction $pp \rightarrow \phi pp$ within the described framework. To show the ambiguities inherent in the tree level effective Lagrangian approach two different parameter sets are used. One parameter set delivers a dominating meson current for the sub-reaction $\pi^- p \rightarrow \phi n$ (Fig. 4 bottom left), while the other employs a dominating nucleon current (Fig. 4 bottom right). Correspondingly the interferences in the reaction $pp \rightarrow \phi pp$ are quite different (see Fig. 4 top).

The model for the reaction $pp \rightarrow \phi pp$ is used to deduce a parameterization of the cross section $pn \rightarrow \phi pn$ which serves as input of a calculation [17] of the reaction $pd \rightarrow d\phi p_{\text{spec}}$, where $p_{\text{spec}}$ is a tagged spectator proton. A corresponding measurement is feasible at COSY-ANKE [18].
Fig. 5: Energy dependence of the total cross section for the reactions $pp \rightarrow \omega pp$ and $pn \rightarrow \omega pn$ (top, data compilation from [19]) and their ratio (left bottom). The parameters are adjusted to the angular distribution at excess energy of 170 MeV (right bottom, data from [20]). "MEC" denotes the contribution from the meson current (bottom right diagram in Fig. 3, while "Brem" depicts the contribution from the other diagrams. Final state interaction (FSI) among the nucleons is included along the lines of [10].

4.2 $\omega$ Meson Production

The previous framework can be extended to study the production of $\omega$ mesons. A preliminary parameter adjustment to the angular distribution at an excess energy of 170 MeV (Fig. 5 bottom right) describes the energy dependence of the total cross section in fairly large range (Fig. 5 top left). (A similar approach is used in [19]. Note that present model does not yet include nucleon resonances.) The isospin rotated reaction $pn \rightarrow \omega pn$ (Fig. 5 top right) which results in a strongly energy dependent ratio of cross sections (Fig. 5 bottom left) is presently used to study the reaction $pd \rightarrow d\omega p_{\text{spec}}$ for which already first results from COSY-ANKE are at our disposal [21].
5 Summary

In summary we present a few selected examples of calculations of near-threshold vector meson production in $\pi N$ and $NN$ reactions. In doing so we employ tree level effective Lagrangians to accomplish simple parameterizations of the elementary cross sections. The role of baryon resonances in the reaction $\pi N \rightarrow e^+ e^- N$ is highlighted within a s-u-channel model with coupling strengths deduced from a chiral quark model. A combined study of of $\omega$ and $\phi$ meson production is mentioned not to reveal the need of a noticeable $\bar{s}s$ shake-off the nucleon. The role of baryon resonances for the reaction $pp \rightarrow \omega pp$ is presently under consideration.

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