Noname manuscript No.
(will be inserted by the editor)

Symmetry Breaking and Transition Form Factors from η and ω Decays

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Received: date / Accepted: date

Abstract The WASA-at-COSY collaboration uses meson production and the decays for the realization of the physics goals. Different rare decay channels of the mesons have to be analyzed in order to investigate symmetry breaking patterns. The combination of high intensity COSY (COoler SYnchrotron) beams and the WASA 4π detector setup allows us to study the rare decay channels of light mesons. We are analyzing different symmetry breaking decay channels of η mesons. One rare decay channel $\eta \to \pi^+\pi^-e^+e^-$ is being used to test CP violation. The asymmetry in the angle between the electron and pion planes can give insight about the degree of CP violation. The study of another rare decay channel $\eta \to \pi^0e^+e^-$ is a test of C-parity violation. Our analysis of transition form factors of different mesons via conversion decays ($\eta \to \gamma\gamma^* \to e^+e^-\gamma$, $\omega \to \pi^0e^+e^-$) provides insight about hadron structure. The transition form-factor of the ω meson provides information about the form factor in the time-like region where the two vector particles (the ω and the intermediate virtual photon) have an invariant mass squared will be discussed.

Keywords Light meson decays · Transition form factor · WASA-at-COSY

1 Introduction

WASA-at-COSY pursues the study of the strong interaction in the low energy regime via the decays of the light mesons η, ω. Moreover, rare decays of light mesons provide information beyond the Standard Model. The physics objectives of WASA particularly include the study of symmetry and symmetry

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breaking of different light mesons through rare decay modes and the electromagnetic transition factor of the mesons through their Dalitz decay.

The $\eta \to \pi^+\pi^-e^+e^-$ and $\eta \to \pi^0e^+e^-$ decays have been studied to test symmetry breaking which will be discussed in section 3. The $\eta \to \pi^+\pi^-e^+e^-$ decay allows to test flavor conserving CP violation. Theoretical studies indicated that the asymmetry of the dihedral angle between the electron and pion production planes is an observable representing the degree to which CP violation contributes to the decay [1]. C-parity conservation forbids the decay $\eta \to \pi^0\gamma^* \to \pi^0e^+e^-$. Thus, the decay is allowed to proceed only via higher order processes and is highly suppressed by the Standard Model. The transition form factor of η and ω mesons through the Dalitz decay $\eta \to \gamma e^+e^-$, $\omega \to \pi^0e^+e^-$ will be discussed in section 4.

2 Experimental Setup and Analysis Method

The COSY accelerator at Forschungszentrum Jülich provides proton and deuteron beams of maximum momentum 3.7 GeV/c. Both, polarized and unpolarized beams are accelerated. Phase space cooling enables to achieve high precision beams (momentum spread of $\Delta p/p \leq 10^{-4}$) for internal and external target experiments.

WASA is an internal target experiment with large acceptance. It employs a frozen pellet target of protons or deuterons which provides a high density and high purity of the target. Therefore, large luminosities ($10^{32} cm^{-2} s^{-1}$) can be achieved. Large luminosities and the large solid angle acceptance of the detector setup helps to study rare decays of the mesons.

WASA has been using two different reactions to produce mesons $pd \to {}^3$HeX and $pp \to ppX$. The pd reaction has a relatively smaller background and the cross-section is small whereas the pp reaction has significant multipion background and the cross-section is large. Therefore, the analysis is first trained by the pd data set whereas the p+p reaction is used to produce high statistics for the rare decays.

WASA has two detector parts - the central and the forward detector. The forward detector is a combination of several sub-detectors, used to detect the recoil particles. The central detector is also a combination of several subdetectors to identify charged and neutral final state particles of the meson decays. The straw tube tracker and the super-conducting solenoid are used for charged particle tracking in the central detector. A combination of the plastic scintillator barrel and the electromagnetic calorimeter helps to distinguish charged from neutral particles. More detailed information of the detector is available in [2], [12].

A number of techniques are used to analyze a decay process. Recoil particles are tagged by the $\Delta E - E$ method. A missing mass analysis is used to tag the produced meson using the beam parameters and the energy of the recoil particles. Charged tracks are identified by combining the energy and direction information collected from the plastic scintillator barrel detector or straw tube tracker and the deposited energy information from the electromagnetic calorimeter. Invariant masses are reconstructed from the decay products identified in the central detector. Finally, a kinematic fit is used to enhance the signal to noise ratio and improve the mass resolution. Simulations are performed to subtract the different background contributions from unwanted decays of the meson under study. Finally, polynomial fitting is used to subtract any smooth background, mostly stemming from multi-pion production.

3 Symmetry and Symmetry Violating Decay

There are many theoretical approaches to describe the $\eta \to \pi^+\pi^-e^+e^-$ decay. The Wess-Zumino-Witten Lagrangian [3] describes completely the decays $\eta \to \pi^+\pi^-\gamma$ and $\eta \to \pi^+\pi^-e^+e^-$ based on triangle and box anomalies. However, these results are far from the experiment because the decay phase space is far from the chiral limit which was the basis for the calculation. However, Vector Meson Dominance [4] which is the more realistic approach gives a partial width of 0.38 eV and a branching ratio of $(3.2 \pm 0.3) \times 10^{-4}$ for the $\eta \to \pi^+\pi^-e^+e^-$ decay. There are other theoretical approaches which are based on effective meson theory [5], chiral pertubation theory [6], anomalous Lagrangian using Wess-Zumino-Witten action [7].

However, there is a handful of experimental approaches[[8], [9], [10], [11]] to measure the branching ratio. Among them the KLOE collaboration [11] measured the branching ratio. Their measured branching ratio is $(2.68 \pm 0.09_{stat} \pm 0.07_{syst}) \times 10^{-4}$ with 1555 signal events. Due to the very high statistics, they could determine an upper limit on the decay plane asymmetry of $A_\phi = (-0.6 \pm 2.5_{stat} \pm 1.8_{sys}) \times 10^{-2}$.

The relative branching ratio of the decay $\eta \to \pi^+\pi^-e^+e^-$ has been determined from the WASA-at-COSY experiment with the help of another decay $\eta \to \pi^+\pi^-\pi^0[\gamma e^+e^-]$ which helps to reduce the systematic effects. The preliminary measurement of the branching ratio from the WASA-at-COSY experiment is in good agreement with theoretical predictions and the CP symmetry observable has been calculated. However, these measurements are only based on the pd data which serve to establish our analysis method [12]. Currently analyses of the branching ratio and an observable for CP violation are going on with the pp data.

After collecting the large data set of η meson decays, we aim at lowering the existing upper limit [13] of the C-violating decay $\eta \to \pi^0e^+e^-$. The analysis has been started with part of the pd data set and we have optimized the set of conditions through Monte Carlo simulations to reduce the background. In agreement with the simulations, one event candidate remains in the experimental data set after applying all cuts [14].

4 Transition Form Factor

Here, we report on our analysis to determine the transition form factor of η and ω mesons through the Dalitz decay $\eta \rightarrow \gamma(*)e^+e^-$ and $\omega \rightarrow \pi^0 e^+e^-$. The transition form factor describes the electromagnetic structure of the decaying neutral meson at, e.g., $\eta \rightarrow \gamma\gamma^*$. The virtual photon decays into a lepton pair. In such decays the invariant mass squared of the lepton pair is equal to the four momentum transfer squared ($q^2 = m^2_{l_+l_-}$) [15], that can serve as a probe of the spatial structure of the meson. Further insight can be gained if we compare the experimental results on q^2-dependency of the transition form factor with some of the theoretical models such as the Vector Meson Dominance Model (VMD). However, the transition form factor of the ω meson does not agree with Vector Meson Dominance while pseudoscalar meson decays involving dileptons like $\eta \rightarrow \gamma\mu^+\mu^-$ are consistent.

The transition form factor of η from the Dalitz decay ($\eta \rightarrow \gamma e^+e^-$) has been observed from two different production mechanisms in pp and pd interactions [16], [17]. The difficulty in selecting decay candidates is the identification of electrons and positrons and the discrimination against the dominant pion background. e^+e^- candidates are selected by using the reconstructed momentum and charge state of the particle from the tracking information. For the large invariant masses of e^+e^- pairs, the main background comes from channels with pions in the final state, like the $\eta \rightarrow \pi^+\pi^-\gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ decay channels. Also, $\eta \rightarrow \gamma\gamma$ has a significant contribution where one of the photon undergoes external conversion. Applying particle identification and kinematic constraints, the background can be reduced significantly. In order to improve the signal to background ratio a kinematic fit is been used. We are expecting to publish our results of the transition form factor of the η meson from both the reactions.

Data on ω decays have been collected with a 4 week $pd \rightarrow {}^3\text{He}\,\omega$ experiment and a 1 week p+p pilot run. The main motivation is to measure the transition form factor of $\omega\pi$ through $\omega \rightarrow \pi^0 e^+e^-$. The NA60 experiment has measured the transition form factor of the different meson [18], [19]. Also, there is a systematic theoretical study by Terschulsen and Leopold [20], [21]. However, the theoretical predictions do not agree with the NA60 experiment at the last three points at the end of the invariant dilepton mass spectrum. This motivates us to measure the transition form factor of the omega meson. The analysis has been started with a prominent decay $\omega \rightarrow \pi^0\gamma$ from both pp and pd data which is a reference channel with real photon. A missing mass peak for the ω meson has already been observed. We further aim to compare the data quality of pd and pp and background study for the analysis of $\omega \rightarrow \pi^0 e^+e^-$.

5 Summary and Outlook

The goal of the WASA-at-COSY experiment is to study rare decays of the light mesons. We have produced 3×10^7 η mesons in the reaction $pd \rightarrow {}^3\text{He}\,\eta$ and collected 10^9 η decays in $pp \to pp\eta$. Another goal is a precise determination of the $\omega\pi$ transition form factor. We have taken data from two pilot experiments with pp and pd reactions for ω decays and the analysis has been started. The final aim is to accumulate large data set for ω before 2015 to measure the transition form factor precisely.

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