Meson Transition Form Factor studies at WASA-at-COSY

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Abstract: Status of the light neutral meson (π^0, η and ω) studies carried out by the WASA-at-COSY collaboration is presented. The emphasis is on the processes related to the light meson transition form factors. The recent results on the η meson branching ratios are presented.

Key words: light meson decays

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1 Introduction

Meson transition form factors for the lightest neutral pseudoscalar mesons $P=\pi^0,\eta$ and η' are the scalar functions describing the vertex consisting of the meson and two photons $P\gamma^*\gamma^*$. They are relevant for the description of processes such as radiative decays, $P\to\gamma\gamma$, single and double Dalitz decays, $P\to\ell^+\ell^-\gamma$ and $P\to\ell^+\ell^-\ell^+\ell^-$, meson production processes, $e^+e^-\to P\gamma$ and $e^\pm\gamma\to e^\pm P$ [1]. The main features of such processes are relatively well described within approaches based on the Vector Meson Dominance (VMD) model. However, the VMD model does not match with QCD predictions for the asymptotic region.

The transition form factors studies are a field of hadronic physics where high-precision measurements are possible and several theoretical calculations are becoming available which could match the experimental precision. Recently they are subject to intensive studies [2] and one of the motivation was their relation to the dark photon searches and to the muon anomalous magnetic moment, a_μ, measurement. The $P\gamma^*\gamma^*$ vertex is the key ingredient of the hadronic light-by-light (HLbL) component for the Standard Model prediction of the a_μ [3–6]. Moreover the precise knowledge of the lepton pair mass spectra is mandatory in searches for the quark-gluon plasma and in studies of hadron properties modifications in heavy ion collisions [7].

The information about transition form factors are obtained from production processes in e^+e^- colliders or in two photon processes. They could be also studied in decay processes involving lepton antilepton pair (Dalitz decays). The transition form factors are also closely related to the anomalous hadronic process involving odd number of pseudoscalar fields. Two examples of such processes are: $\eta\to\pi^+\pi^-\gamma$ are $\omega\to\pi^+\pi^-\pi^0$. The mesons for the decay studies could be produced at many facilities in the world including *e.g.* photoproduction and hadroproduction experiments.

2 WASA-at-COSY experiment

WASA-at-COSY experiment has collected data between 2006 and 2014 at the Cooler Synchrotron (COSY) ring at Forschungszentrum Jülich in Germany. COSY can provide deuteron or proton beams with momentum up to 3.7 GeV/c. The experimental facility includes WASA detector optimized for the study of interactions and decays of the light mesons and a fixed internal target using hydrogen or deuterium 30 μm frozen pellets [8].

The WASA detector consists of a forward part arranged to measure baryonic ejectiles and a central section to detect light mesons or their decay products (leptons and photons). The forward part consists of plastic scintillators layers of various thickness and drift chambers covering full azimuthal angle. The central part consists of a CsI(Na) electromagnetic calorimeter with 1012 elements and a mini drift chamber surrounded by plastic scintillator barrel both inside of a superconducting solenoid. A detailed description of the WASA detector is found in Ref. [8, 9].

The mesons for the decay studies are produced using two complementary hadronic reactions in pp or pd collisions. The two reaction types for the production of a neutral meson X are $pd\to{}^3\mathrm{He}X$ or $pp\to ppX$.

The first group of the reactions are characterized by initially fast rising cross section which reaches plateau. The optimal signal to background ratio is reached at energies close to the reaction threshold. The two body final state includes ^{3}He which enables easy identification of the meson production process by reconstructing very clean signal in the forward part of the WASA detector. It allows to collect a data sample without bias on the decay channel of the studied meson. However, the drawback is large total cross section of the pd interactions which limits the useful luminosities (due to pile-up

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processes which are most significant for the calorimeter and for the drift chamber). At the same time the maximum cross section of the meson production in the ^{3}He fusion is rather low. For example for the $pd \to {}^3\mathrm{He}\eta$ it is 0.40(3) μb [10, 11], meaning that few η-mesons are produced per second at typical luminosity of 2×10^{31} cm^{-2}s^{-1}. The $pd \to {}^3\mathrm{He}X$ fusion reaction could therefore provide unbiased data sample suitable for determination of the branching ratios and for searches of invisible decay modes. This reaction could be also used for high precision studies of the decay distributions for the more common decays.

The total data set for the η meson decay studies includes $3 \cdot 10^7$ tagged mesons produced in the pd collisions. The $pd \to {}^3\mathrm{He}\eta$ reaction was used with a proton beam of 1 GeV. The published analyses includes studies of reaction mechanism of the common decays such as $\eta \to \pi^+\pi^-\pi^0$ [14] and $\eta \to \pi^+\pi^-\gamma$ [15]. The recently finished measurement of the branching ratios is reported in the next section [16]. $pd \to {}^3\mathrm{He}\omega$ reaction at 1.45 and at 1.5 GeV was used for studies of $\omega \to \pi^+\pi^-\pi^0$ Dalitz plot and for studies of other hadronic decays of the ω meson. The analysis of the ω decays is ongoing and the status was presented in Ref. [17].

The meson production in the $pp \to ppX$ reaction has larger cross sections. In addition lower total cross section for the proton-proton interactions allows for larger luminosities to be used. However, more restrictive trigger conditions have to be used to limit number of the rates of the collected events. The conditions include information on the decay channel *i.e.* separate chains for charged and neutral decay channels. For example η mesons have been produced in protonproton interactions at beam kinetic energy of 1.4 GeV, corresponding to the excess energy of 56 MeV and cross section 9.8±1.0 μb [12]. The collected data sample corresponds to more than $5 \cdot 10^8$ η mesons produced. The ω mesons were produced in proton-proton interactions at beam kinetic energies 2.06 GeV and 2.54 GeV with the corresponding cross sections of 5.7 μb and 35 μb.

The WASA detector was in fact designed and optimized for studies of rare π^0 meson decays produced in $pp \to pp\pi^0$ reaction at CELSIUS storage ring in Uppsala at the kinetic beam energy of 550 MeV. This corresponds to the excess energy of 122 MeV with respect to $pp\pi^0$ threshold (*i.e.* below two pion production thresholds) with a cross section of 1.12 mb [13]. In the series of runs WASA-at-COSY has collected few millions of $\pi^0 \to \gamma e^+e^-$ events for dark photon searches, π^0 transition form factor studies and for measurement of $\pi^0 \to e^+e^-$ branching ratio. The results based on about 10% of the collected data sample were published in 2013 [18].

3 Branching ratios of the η meson decays

The η meson data sample collected from pd collisions was used to determine branching ratios of the η meson decay modes [16]. The following four decay modes are considered: $\eta \to \pi^+\pi^-\gamma$, $\eta \to e^+e^-\gamma$, $\eta \to \pi^+\pi^-e^+e^-$ and $\eta \to e^+e^-e^+e^-$. The branching ratios are normalized to the $\eta \to \pi^+\pi^-\pi^0$ decay. In addition a CP-violating asymmetry in $\eta \to \pi^+\pi^-e^+e^-$ is measured.

The absolute branching ratios were obtained by using the world average from Ref. [19] for the $BR(\eta \to \pi^+\pi^-\pi^0) = (2.292 \pm 0.028) \times 10^{-1}$. The results are presented in Table 1.

The value for the $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$ is $0.208 \pm 0.003_{stat/fit} \pm 0.008_{sys}$. It is in a good agreement with the older experiments [20, 21] but is 2.6 and 2.5 standard deviations above the recent values from CLEO [22] and KLOE [23] respectively.

The branching ratio for $\eta \to e^+e^-\gamma$ is consistent with the most recent Particle Data Group fit $(6.9\pm0.4)\times10^{-3}$ but it is more precise. The absolute branching ratios for $\eta \to \pi^+\pi^-e^+e^-$ and $\eta \to e^+e^-e^+e^-$ decays are in good agreement with the values reported by KLOE [24, 25]

The uncertainties for $\eta \to \pi^+\pi^-\gamma$ and $\eta \to e^+e^-\gamma$ are dominated by the systematic effects and the largest contribution comes from a comparison of two data sets corresponding to the experimental runs with different luminosities and accelerator settings and which was separated by more than one year.

The CP violating asymmetry, A_ϕ, determined from the distribution of the angle ϕ between the $\pi^+\pi^-$ and e^+e^- decay planes for $\eta \to \pi^+\pi^-e^+e^-$ has been also determined and found to be consistent with zero: $A_\phi = (-1.1 \pm 6.6_{stat} \pm 0.2_{sys}) \times 10^{-2}$.

Table 1. Summary of the η meson branching ratios measured by WASA-at-COSY.

Channel	Branching Ratio
$\eta \to \pi^+\pi^-\gamma$	$(4.67 \pm 0.07_{stat/fit} \pm 0.19_{sys}) \times 10^{-2}$
$\eta \to e^+e^-\gamma$	$(6.72 \pm 0.07_{stat/fit} \pm 0.31_{sys}) \times 10^{-3}$
$\eta \to \pi^+\pi^-e^+e^-$	$(2.7 \pm 0.2_{stat} \pm 0.2_{sys}) \times 10^{-4}$
$\eta \to e^+e^-e^+e^-$	$(3.2 \pm 0.9_{stat} \pm 0.5_{sys}) \times 10^{-5}$

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