Search for the $\eta \rightarrow e^+e^-e^+e^-$ double Dalitz decay

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Abstract. The Wide Angle Shower Apparatus (WASA) operated at the Cooler Synchrotron COSY-Jülich is a $4\pi$-spectrometer to study the decay channels of light mesons ranging up into the strange quark sector. A large number of $\eta$ mesons is being produced in proton-deuteron and proton-proton reactions, permitting the study of very rare $\eta$-decay channels. One of the channels is the double Dalitz decay, where the $\eta$ meson decays via two virtual photons into two electron-positron pairs. The coupling between the $\eta$ meson and the two virtual photons can be described by the transition form factor. It depends on the squared invariant mass of the lepton pairs and allows to study the structure of the decay mechanism. Currently, there is only an experimental upper limit for the branching ratio. One objective of the WASA-at-COSY experiment is to reduce the upper limit for this decay channel or to determine a finite value of the branching ratio. The goal is to study the transition form factor. The status of the continuing analysis and preliminary results are presented.

1. Introduction
The Wide Angle Shower Apparatus (WASA) is a $4\pi$-spectrometer being operated at the Cooler Synchrotron COSY-Jülich (see figure 1).

Figure 1. The internal $4\pi$-spectrometer Wide Angle Shower Apparatus (WASA).
The key experiment is to study rare $\eta$-decay channels into charged lepton pairs with branching ratios below $10^{-4}$ \cite{1}. One of these decays is $\eta \rightarrow \pi^+\pi^-e^+e^-$ where CP-violating effects are expected to be reflected in an angular asymmetry between the emission plane of the electrons and the pions \cite{2}. The most challenging decay channel is $\eta \rightarrow e^+e^-$, where only an upper limit for the experimental branching ratio exists which is $2.7 \times 10^{-5}$ \cite{3}. Theoretical calculations based on the standard model predict a value larger or equal to $1.7 \times 10^{-9}$ \cite{4}. Any significant discrepancy from this value can be an indication for an unknown process and a sign for new physics beyond the standard model. In this report, the $\eta \rightarrow e^+e^+e^-e^-$ decay channel and its analysis is discussed.

2. The $\eta \rightarrow e^+e^+e^-e^-$ channel
In case of the $\eta \rightarrow e^+e^-e^+e^-$ double Dalitz decay, the $\eta$ meson decays at first into two off-shell photons. Subsequently, each of these virtual photons decays into an electron-positron pair. The theoretical value for the branching ratio has been calculated to be $BR(\eta \rightarrow e^+e^-e^+e^-)/BR(\eta \rightarrow \gamma\gamma) = 6.6 \times 10^{-5}$ \cite{5}. With the known branching ratio $BR(\eta \rightarrow \gamma\gamma) = 0.3938$ \cite{6}, the branching ratio $BR(\eta \rightarrow e^+e^-e^+e^-)$ can be calculated to be $2.6 \times 10^{-5}$. The current experimental upper limit is found to be $6.9 \times 10^{-5}$ \cite{7}. Therefore, as a next step an experimental value for the branching ratio should be established. Our goal is to study the transition form factor, which describes the coupling between the $\eta$ meson and the two virtual photons. The knowledge of this function would contribute to the calculation of the hadronic contribution to the anomalous magnetic moment of the muon \cite{8}. Furthermore, it is important for the calculation of the real part of the amplitude of the $\eta \rightarrow e^+e^-$ and $\eta \rightarrow \mu^+\mu^-$ decay channels \cite{9}.

3. Data sets
There are two independent analyses in progress. The data set for the first analysis comprises approximately $10^7 \eta$ mesons measured during a $pd \rightarrow \eta^3He$ beam time in 2008. The data set for the second analysis comprises $2 \times 10^7 \eta$ mesons measured during a $pd \rightarrow \eta^4He$ beam time in 2009. The 2009 data analysis is described in this report.

Figure 2 shows the $^3He$-missing mass spectrum of the collected data in 2009.

Figure 2. $^3He$-missing mass spectrum of the data collected in 2009. The signal is peaked around a mass of 547.9 MeV/$c^2$ and containing approximately $2 \times 10^7 \eta$ mesons.
The missing mass is calculated as

\[ MM(\text{He}) = \sqrt{(P_{\text{beam}} + P_{\text{target}} - P_{\text{He}})^2} = \sqrt{(E_{\text{beam}} + m_d - E_{\text{He}})^2 - (p_{\text{beam}} - p_{\text{He}})^2} \]  

where \( P_i \) is the four-vector of particle \( i \), \( E_i \) is its energy, \( p_i \) is its momentum-vector, and \( m_d \) is the deuteron mass. The \( \eta \) signal is extracted by fitting the spectrum with a Gaussian function plus a polynomial for the background coming from direct pion production. The signal is peaked around a mass of 547.9 MeV/c\(^2\) and containing approximately \( 2 \times 10^7 \) \( \eta \) mesons.

4. Analysis methods
The analysis steps are based on the production of the \( \eta \) mesons in \( p d \rightarrow ^3\text{He} \eta \) reactions. The protons have a momentum of 1.7 GeV/c and are shot on a stream of frozen deuteron droplets. The \(^3\text{He} \) nuclei are identified by their energy loss in the WASA forward detector using the \( \Delta E-E \) method. As an example, figure 3 shows the deposited energy in the trigger hodoscope, which is a thin segmented scintillator, as a function of the deposited energy in the range hodoscope.

![Figure 3](image)

**Figure 3.** Deposited energy in the first layer of the trigger hodoscope as a function of the deposited energy in the first layer of the range hodoscope (data from 2009 WASA-at-COSY beam time).

As a consequence of the two-body kinematics and the rather small Q-value of the fusion reaction, the \(^3\text{He} \) nuclei have to stop in the first layer of the range hodoscope. Thus, the deposited energy in the first layer of the range hodoscope must be equal to the total energy loss in the range hodoscope. Since the kinematic parameters of the initial state are known, the kinematic properties of the \( \eta \) meson can be determined by measuring the \(^3\text{He} \) kinematics in the forward detector.

The \( \eta \)-decay products are measured in the WASA central detector. In the center of this detector is a straw chamber – Mini Drift Chamber (MDC) – permeated by a magnetic field of up to 1 T. This detector element consists of 1738 straw tubes arranged in 17 layers. Nine layers consist of tubes, which are orientated along the beam line. The other eight layers consist of skewed tubes. This sequence of parallel and skewed tubes gives the three dimensional information about the particle tracks. Since only charged particles are registered by the MDC, double Dalitz decay candidates must have at least two positively charged and two negatively charged tracks in the MDC. The distinction between positively and negatively charged particles is achieved by using the curvature information of the tracks in the magnetic field.
At this stage of the analysis, the accepted events have one $^3\text{He}$ nucleus in the forward detector and at least two positively and two negatively charged particles in the central detector. In the next analysis step, each charged central detector track is tested for its energy loss in the Plastic Scintillator Barrel (PSB) and the Scintillator Electromagnetic Calorimeter (SEC). The expected deposited energy of electrons and pions in these detector elements as a function of the momentum times the sign of the charge can be seen in figures 4 and 5. These plots are obtained by Monte Carlo simulations. Cuts on electrons and positrons are chosen according to the simulated distribution.

Figure 4. Simulated energy deposit in the Plastic Scintillator Barrel (PSB) as a function of the particle momenta times charge.

Figure 5. Simulated energy deposit in the Scintillator Electromagnetic Calorimeter (SEC) as a function of the particle momenta times charge.

The single Dalitz decay $\eta \rightarrow e^+e^−\gamma$ or the decay $\eta \rightarrow \gamma\gamma$ with conversion of one respectively two photons have the same particles in the finale state as the double Dalitz decay. The conversion probability in the 3 mm thick beryllium beam tube is $3 \times 10^{-3}$. Assuming a branching ratio for the double Dalitz decay to be $2.6 \times 10^{-5}$, which is the theoretical prediction based on pure QED calculations, the background from $\eta \rightarrow e^+e^−\gamma$ with conversion of the photon relative to the double Dalitz decay is 80.8% and 13.6% for $\eta \rightarrow \gamma\gamma$ with conversion of the two photons. To reduce events from conversion decays, it is cut on the closest approach of the particles’ trajectories in $xy$-plane.

The following cuts consider the decay-specific kinematics and the opening angles of the electrons and positrons, respectively. At first, the momentum vectors of the two virtual photons, which are calculated from the momenta of the electrons and positrons, are transformed into the center-of-mass system (CM system) of the $\eta$ meson. Due to the two body decay $\eta \rightarrow \gamma^*\gamma^*$, the two virtual photons must be emitted back-to-back in the CM system. Accordingly, the sum of their momenta must be zero and their opening angle must be $180^\circ$. In the laboratory system, the opening angle between the electron and the positron from the same virtual photon peaks at small values, whereas the opening angle between the virtual photons is the most populated in the range of large values.

5. Results
The analysis of the data set from the 2008 $pd \rightarrow ^3\text{He}\eta$ beam time with approximately $10^7$ $\eta$ mesons found $30 \pm 10$ double Dalitz decay event candidates [10]. This number is consistent with the current experimental upper limit.
The analysis of the data set from the 2009 $pd \rightarrow ^{3}\text{He}\eta$ beam time with approximately $2 \times 10^{7}$ $\eta$ mesons is in progress and the first double Dalitz decay event candidates have been found. Figure 6 shows three $\eta \rightarrow e^{+}e^{-}e^{+}e^{-}$ event candidates. The tracks of the four leptons have been measured with the WASA MDC, which is permeated by a magnetic field. The charge of the particles can be determined by their curvatures.

In the following, the background contribution has to be studied in more detail and systematic effects have to be investigated.

![Figure 6. Front view of the WASA MDC as seen along the beam pipe. The reconstructed curves show electrons and positrons, which have been identified to come from a $\eta \rightarrow e^{+}e^{-}e^{+}e^{-}$ double Dalitz decay event. The charge of the particles can be determined by their curvatures in the magnetic field, which is parallel to the z-axis.](image)

6. Outlook

In the future, the statistics will be significantly improved by a large amount of $\eta$ mesons from $pp \rightarrow pp\eta$ reactions. Although this production reaction brings along more background from prompt multi-pion production ($\sigma(2\pi^{0})/\sigma(\eta) \approx 20$), it enables to study the rare $\eta$-decays with larger statistics. The cross section for $\eta$-production is $10 \mu b$ at 60 MeV excess energy compared with $0.4 \mu b$ for the $\eta$ production in $pd$-reactions.

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