Measurement of the $\eta \to \pi^+\pi^-e^+e^-$ decay branching ratio

CELSIUS-WASA Collaboration

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Abstract

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The reaction $pd \rightarrow ^3\mathrm{He}\,\eta$ at threshold was used to provide a clean source of η mesons for decay studies with the WASA detector at CELSIUS. The branching ratio of the decay $\eta \rightarrow \pi^+\pi^-e^+e^-$ is measured to be $(4.3\pm1.3\pm0.4)\times10^{-4}$.

Key words: eta meson decays, Dalitz decays
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1 Introduction

Radiative processes involving one or two photons are responsible for the most common decays of the lightest pseudoscalar mesons π°, η and η'. They are accompanied, as understood from Quantum Electrodynamics (QED), by a processes where a virtual photon converts into an electron-positron pair. The conversion decays are suppressed by a factor of the order of the fine structure constant α. The virtual photon probes the structure of the decaying meson and the interaction region in the time-like region of four-momentum transfer squared, q^2, which is equal to the invariant mass squared of the lepton pair. An extensive review of the conversion decays of the light mesons is given by Landsberg [1].

Experimental information on the conversion decays of η meson decays is scarce. The most frequent η decay into an e^+e^- pair is $\eta \rightarrow e^+e^-\gamma$ with a branching ratio (BR) of $(6.0 \pm 0.8)\times10^{-3}$ [2]. Only a few hundred events were collected in recent experiments [3,4]. Another decay is $\eta \rightarrow \pi^+\pi^-e^+e^-$ which is related to the radiative decay $\eta \rightarrow \pi^+\pi^-\gamma$ ($BR = (4.69 \pm 0.11)\times10^{-2}$ [2]). The first observation of one candidate event for this decay was reported from a hydrogen bubble chamber experiment by Grossman, Price and Crawford [5] in 1966. Recently semileptonic decays of the η mesons were studied by the CMD-2 Collaboration [3] using the radiative decay $\phi \rightarrow \eta\gamma$ as the source of η mesons and 4 event candidates of $\eta \rightarrow \pi^+\pi^-e^+e^-$ were identified with an estimated background of 0.5 event. The average value of the BR extracted from the two experiments is $(4.0^{+5.3}_{-2.5})\times10^{-4}$ [2].

Predicted values for $BR(\eta \rightarrow \pi^+\pi^-e^+e^-)$ are given in at least three papers. Jarlskog and Pilkuhn [6] got an upper value of 3.1×10^{-4}. Faessler et al.[7] have calculated the decay rate within the Vector Meson Dominance (VMD) model and obtained a value $(3.6 \pm 0.6)\times10^{-4}$. Picciotto and Richardson [8] got a value $(3.2 \pm 0.3)\times10^{-4}$ using a model which incorporates vector mesons

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in the chiral perturbation theory Lagrangian. In this paper the influence of an intermediate ρ meson was taken into account both for pion and lepton pairs. The calculations are similar to the ones for the $K_L \rightarrow \pi^+\pi^-e^+e^-$ decay [9,10].

Further interest in the $\eta \rightarrow \pi^+\pi^-e^+e^-$ decay comes from tests of CP violation in η decays which are often motivated by corresponding tests in K_L decays. A recent prediction (from CP violation) and observations of an asymmetry in the distribution of angles between the $\pi^+\pi^-$ and the e^+e^- production planes in $K_L \rightarrow \pi^+\pi^-e^+e^-$ [10,11,12] have triggered theoretical speculations that a similar observation in $\eta \rightarrow \pi^+\pi^-e^+e^-$ decay might reveal unexpected mechanisms of CP violation in flavor conserving processes. It appears that there could be (hypothetical) CP violating contributions which are not constrained by the limits on the $\eta \rightarrow \pi\pi$ BR or the measured limit of neutron electric dipole moment. A measurement done with a sensitivity better than 10^{-2} for the asymmetry will provide a stringent constraint for such mechanisms [13].

2 The experimental method

In the experiment performed by the CELSIUS/WASA collaboration, the η mesons were produced in the $pd \rightarrow {}^3\mathrm{He}\,\eta$ reaction at 893 MeV incident proton kinetic energy, very close to the threshold. This reaction was first employed as an η source for decay experiments at the Saturne II synchrotron at Saclay [14]. The production of η mesons was tagged by measuring ^{3}He at 0°. The η production cross section in the reaction increases to a plateau value of 0.4 μb at about 2 MeV excess energy, where the background from prompt $pd \rightarrow {}^3\mathrm{He}\pi^+\pi^-$ reaction is at the percent level [15]. This tagging method enables to collect simultaneously an unbiased data sample of all η meson decays.

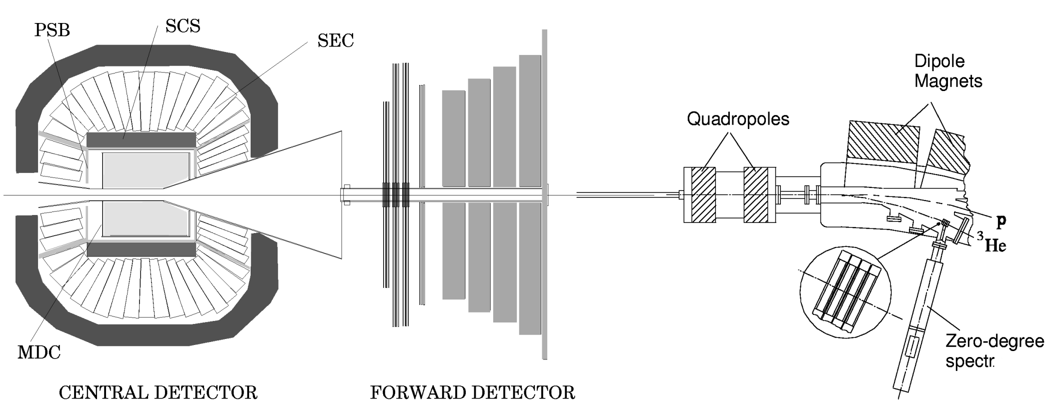

Fig. 1. Cross section of the WASA apparatus with Central Detector (CD) built around the interaction region, Forward Detector (FD) and Zero Degree spectrometer (ZD). The individual components are described in the text.

In the CELSIUS/WASA experiment an internal deuterium pellet target was used. The ^{3}He nuclei recoiling at 0° were detected in a zero-degree spectrometer (ZD) (Fig. 1). It used the accelerator quadrupole and dipole magnets to focus and deflect the ^{3}He nuclei onto a tagging telescope, which was placed inside the beam pipe 6.6 m downstream from the target [16]. The telescope, comprising two silicon detectors (total thickness 1.3 mm) and two germanium detectors (total thickness 29.4 mm), was able to stop ^{3}He nuclei up to 400 MeV. Operated at liquid nitrogen temperature, the telescope provided an energy resolution of 1.5 MeV (FWHM) at 300 MeV [17]. The ΔE-E spectrum in Fig. 2(left), where ΔE(E) is the total energy deposition in the two silicon (germanium) detectors, shows that the ^{3}He nuclei are easily separated already in the raw data. Fig. 2(right) shows the energy spectrum of ^{3}He nuclei. The pronounced distribution between 280 and 305 MeV is due to η production. The two peaks, indicated by the structure at the top of the distribution, correspond to backward and forward emission of ^{3}He, respectively, in the center-of-mass frame. The smoother distribution is mainly due to direct 2π production, yielding a background of less than 2% in the η meson tagging. The acceptance for ^{3}He nuclei from the η production is approximately 50% at 1 MeV above the threshold.

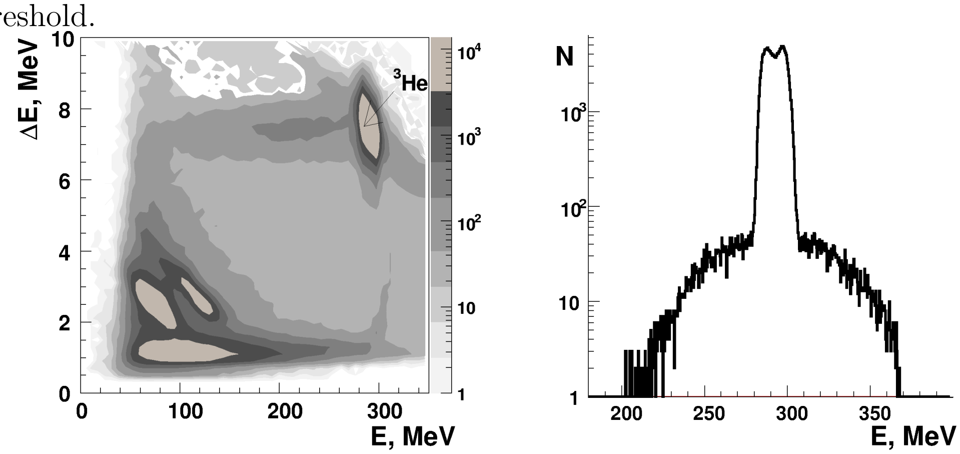

Fig. 2. (Left) ΔE-E spectrum from the ZD, where ΔE(E) is the total energy deposition in the two silicon (germanium) detectors indicating very clean ^{3}He identification. (Right) Energy spectrum of ^{3}He nuclei. The pronounced distribution around 300 MeV corresponds to the η production. The cut-off at 200 and 380 MeV in the distribution associated with 2π production is a result of the rigidity acceptance of the spectrometer.

The η decay products were detected in the central part of the WASA detector (Fig. 1) consisting of an electromagnetic calorimeter with over 1000 CsI(Na) crystals (SEC), a plastic scintillator barrel detector (PSB) and a drift chamber (MDC) made of thin–walled ($25 \mu m$) aluminized mylar straw tubes placed in a 1 Tesla magnetic field produced by a very thin walled ($0.18\ X_0$) superconducting solenoid [18] (SCS). The design of the WASA detector was optimized for measurements of decays with both electrons and photons. To minimize the probability for photon conversion it included a thin beryllium beam pipe with a wall thickness of 1.2 mm (0.0034 radiation lengths only). Fig. 3 shows an example of a candidate event for $\eta \rightarrow \pi^+\pi^-e^+e^-$decay registered in the CD.

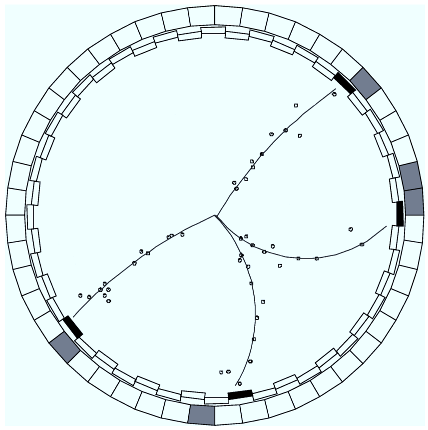

Fig. 3. Example of a candidate event for $\eta \to \pi^+\pi^-e^+e^-$ decay. Four charged tracks are measured in the MDC, all particles leave the volume of the chamber and deposit energy in the PSB and SEC (represented as the two outer rings).

3 Analysis and results

The candidate events for the η decay into $\pi^+\pi^-e^+e^-$ were selected by requiring four tracks caused by the charged particles in the central drift chamber with a possible energy deposit in the SEC and/or the PSB. Two particles should carry positive and two negative charge. A candidate event could in addition have a calorimeter hit-cluster not clearly associated with any of the tracks in the MDC (such a cluster will be referred to later in the paper as a "γ"-cluster). These events could not be discarded directly without significant loss of acceptance (in the order of 35%). *MC* studies show that small but well separated additional clusters can arise from the $\eta \to \pi^+\pi^-e^+e^-$ decay products due to secondary reactions in the calorimeter material resulting in emission of neutral particles. However, the energy deposit in such clusters is expected to be small. Only events with an energy deposit below 80 MeV in the "γ"-clusters were accepted as candidates.

Due to the clean tagging in $pd \to ^3\mathrm{He}\,\eta$, as discussed in the previous section, the only major background for the $\eta \to \pi^+\pi^-e^+e^-$ decay can be due to other η decays into two charged pions. A source of background could be the $\eta \to \pi^+\pi^-\pi^0$ decay with $\pi^0 \to e^+e^-\gamma$ and the $\eta \to \pi^+\pi^-\gamma$ decay with the photon undergoing conversion in the detector material. In order to reduce the latter background a vertex position constraint (Δx,Δy $=\pm 5$ mm and Δz $=\pm 50$ mm) was used to ensure that all particles originated from the interaction region. That constraint removes more than 94% of $\eta \to \pi^+\pi^-\gamma$ events with photon conversion.

The two-lepton invariant mass distribution $d\Gamma/dq^2(\eta \to \pi^+\pi^-\,\mathrm{e}^+\,\mathrm{e}^-)$ can be expressed approximately as $d\Gamma/dq^2 = \Gamma(\eta \to \pi^+\pi^-\gamma)\,[QED]\,|F(q^2)|^2$. The QED term ($[QED]$) is given by [1]:

$$[QED] = \frac{\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{q^2}}\left[1+\frac{2m_e^2}{q^2}\right]\frac{1}{q^2}\left[\left(1+\frac{q^2}{m_\eta^2 - M_{\pi\pi}^2}\right)^2 - \frac{4m_\eta^2 q^2}{(m_\eta^2 - M_{\pi\pi}^2)^2}\right]^{\frac{3}{2}}$$

where m_e, m_η are the electron and η masses and $M_{\pi\pi}$ is the invariant mass of the two-pion system. The q should be in the range $2m_e < q < m_\eta - 2m_{\pi^\pm}$. The QED term leads to a strong enhancement in the $d\Gamma/dq^2$ distribution at the lowest possible q values. The form-factor $F(q^2)$ modifies the distribution mainly at large q. The most common assumption for the form-factor for η and π^o conversion decays is a dipole parametrization justified by ρ^0 dominance.

The invariant mass is closely correlated to the opening angle between the leptons leading to a sharp peak at small opening angles. This feature of the process is used for particle identification. In order to distinguish between pions and electrons, the opening angle between two particles with opposite charges is calculated. The pair with the smallest opening angle is most likely the positron-electron pair. The efficiency of such a separation is demonstrated in Fig. 4 (left) using Monte Carlo (MC) simulation with the $\eta \to \pi^+\pi^-e^+e^-$ mechanism given by the above formula. In addition an energy-momentum (E-P) method of particle identification is applied for all the particles which did not stop in the MDC. The energy deposit (dE) in the SEC and/or the PSB (E $=$ dE$_{SEC}$ $+$ dE$_{PSB}$) is combined with the momentum (P) calculated from the track curvature (the sign gives the charge of the particle). Fig. 4 (right) shows the simulated E-P distributions for all reconstructed tracks with associated energy deposition in the SEC. In that case the pion and electron bands, which are well separated, can be used to check and improve the identification based on the opening angle. The overall identification is correct in 90% of the cases for all tracks in the MC event.

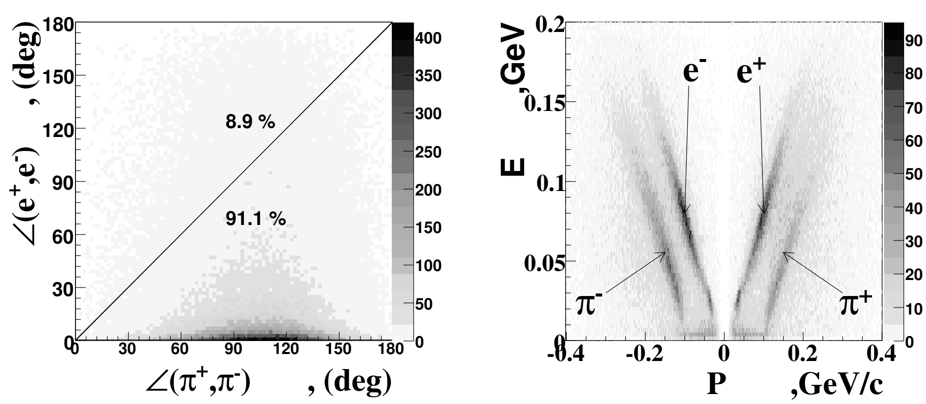

Fig. 4. Particle identification for the MC sample of $\eta \to \pi^+\pi^-e^+e^-$ decay. (Left) Angle between the two pions (X-axis) versus the angle between the two leptons (Y-axis). The latter angle is smaller in 90% of cases. (Right) E-P distributions for all tracks with energy released in the SEC versus reconstructed particle momentum. The bands due to pions and electrons are well separated.

In order to suppress the background from the $\eta \to \pi^+\pi^-\pi^0$ decays two constraints optimized by the MC studies were used. The missing mass of the pions and leptons was constrained around the ^{3}He mass (in the range from 2.6 GeV/c^2 to 2.85 GeV/c^2). This reduces the number of $\eta \to \pi^+\pi^-e^+e^-$ and $\eta \to \pi^+\pi^-\pi^0$ events by 10% and 47% repectively according to the MC studies. Some of the remaining events had so-called "γ"-clusters in the calorimeter present (hit-clusters unassociated with a track in the MDC). Fig. 5 presents the invariant mass of the e^+e^-"γ" system for the experimental sample with four charged particles and a neutral cluster in the final state. We find a clear peak around π^0 mass in accordance with the simulation of the $\eta \to \pi^+\pi^-\pi^0$ decay (with $\pi^0 \to e^+e^-\gamma$). Thus, for the class of events with a "γ"-cluster, the invariant mass of the e^+e^-"γ" system was calculated and an event was identified as a background event, if the mass was greater than 120 MeV/c^2.

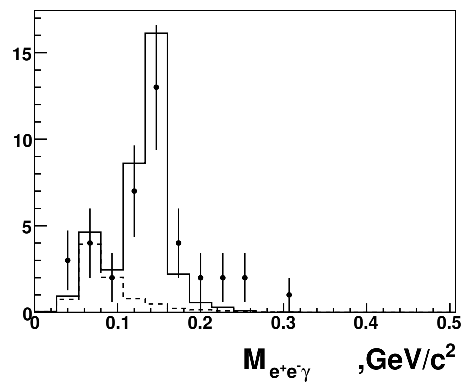

Fig. 5. The experimental invariant mass of e^+e^-"γ" for the events with the "γ"-cluster. The pronounced π^0 peak in the experimental mass spectrum (black points) indicates a significant admixture of the background events. Superimposed are: a sum of the appropriately weighted MC simulation of $\eta \to \pi^+\pi^-e^+e^-$, $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ decays (full line) and $\eta \to \pi^+\pi^-e^+e^-$ decay (dashed line).

The invariant mass distribution, $M_{\pi^+\pi^-e^+e^-}$, is plotted in Fig. 6 for the final data sample, first only for events without the "γ"-clusters (left) and later using all events (right). The experimental distribution is compared in both cases to the MC prediction taking into account the dominant background channels ($\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$) and the shape of the signal distribution. The contribution of the background events to the peak is estimated to be 4.6 and 7.7 events (in the left and right plot respectively) by taking into account the known BR and acceptance from the MC studies. (The background contributions are represented in the figures by the broken lines). The remaining events in the plots are attributed to the $\eta \to \pi^+\pi^-e^+e^-$ decay. This gives a number of reconstructed $\eta \to \pi^+\pi^-e^+e^-$ events for the right plot in Fig. 6 equal to $16.3\pm5.0_{stat}\pm2.0_{syst}$ (the systematic error includes the ambiguity of the background contribution). The overall detection efficiency for $\eta \to \pi^+\pi^-e^+e^-$ was estimated to be 16.5±0.2% where the error is dominated by the uncertainty in acceptance calculation due to extrapolation using different reaction models.

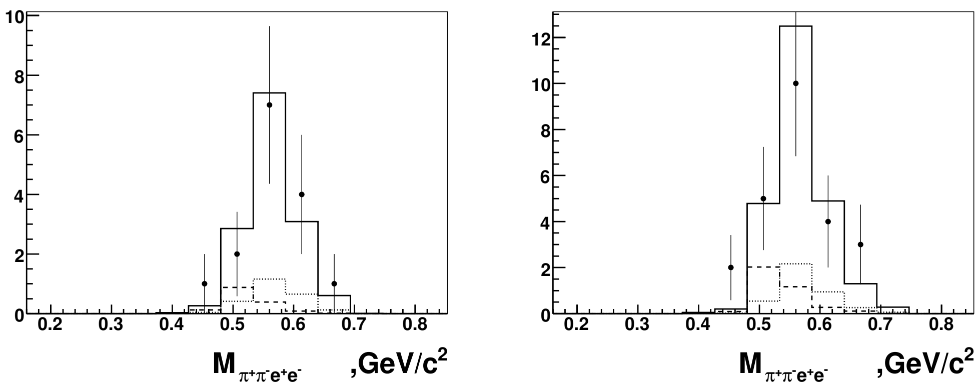

Fig. 6. The invariant mass distribution, $M_{\pi^+\pi^-e^+e^-}$, plotted for events without the "γ"-clusters unassociated with the MDC tracks (left) and for all events (right) (black points in both figures). The thick line represents the MC distribution corresponding to the sum of the signal ($\eta \to \pi^+\pi^-e^+e^-$) and the background decays. In addition the contributions of the background from $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ decays are given by the dashed and dotted line respectively.

The BR of $\eta \to \pi^+\pi^-e^+e^-$ was obtained by normalizing to a sample of $\eta \to \pi^+\pi^-\pi^0$ decays ($BR = (2.27 \pm 0.04)\times 10^{-1}$[2]) and $\eta \to e^+e^-\gamma$ decays ($BR = (6.0 \pm 0.4)\times 10^{-3}$[2]) collected simultaneously. The data were analyzed using the same track finding processing and compatible cuts. This assures that many sources of errors, like uncertainties in particle identification and track finding efficiency, will be reduced or cancel.

The selection criteria for the process $\eta \to \pi^+\pi^-\pi^0$ include requirement of two tracks with opposite charges identified as pions by the E-P method, two neutral clusters with energy E> 50 MeV each and an invariant mass of the two photons to be within the range 90 to 170 MeV/c^2. Systematical uncertainties of the normalization were estimated by varying the constraints during sample selection. This lead to a change of the normalization factor within a 5% interval, what was included in the systematic error. The number of the identified events for this process was 17100±130 and the acceptance was estimated to be (33.4±1.9)% (the error is a cumulative systematic error of the normalization and includes the MC model dependence, the background and the sample selection).

A cross-check of the normalization with the $\eta \to e^+e^-\gamma$ decay was done to test the MC predictions for the electron reconstruction efficiency. In the collected sample a clear peak of 270 events of the $\eta \to e^+e^-\gamma$ decay has been observed after application of cuts on the charge balance, the overall missing mass and the invariant mass of the two leptons. Taking into account the calculated acceptance (20%) and assuming $BR = (6.0 \pm 0.8) \times 10^{-3}$ [2] for the decay we got a normalization factor smaller by 5% from the one obtained with $\eta \to \pi^+\pi^-\pi^0$ decay, which is within the error of the given BR. The variation of cuts on the $e^+e^-\gamma$ missing mass and/or replacing the cut on the lepton pair invariant mass by the cut on their relative angle lead to a variation of the normalization factor within 8% which is within one standard deviation of the number of $\eta \to e^+e^-\gamma$ events.

Taking the obtained normalization factors and their statistical and systematical uncertainties the result for the BR of the $\eta \to \pi^+\pi^-e^+e^-$ decay is $(4.3 \pm 1.3 \pm 0.4) \times 10^{-4}$ based on $16.3 \pm 4.9_{stat} \pm 2.0_{syst}$ identified events.

It has been demonstrated that with the applied data selection the background channels are well understood. Our result increases notably the experimental information available for this η decay channel. The search for CP violation mechanism of [13], however, clearly requires much more data than what has been collected so far.

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