Test of charge conjugation invariance in the decay of the η meson into $\pi^+\pi^-\pi^0$

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Abstract. In this work we present the preliminary results of the analysis of the $pp \rightarrow pp\eta \rightarrow pp\pi^+\pi^-\pi^0$ reaction aiming to test the charge conjugation symmetry C in strong interactions. Based on approximately 10^5 identified $\eta \rightarrow \pi^+\pi^-\pi^0$ decay events we have extracted asymmetry parameters sensitive to C symmetry violation for different isospin values of the final state and we have established that all are consistent with zero within the obtained accuracy.

1 Introduction

In the Standard Model of particles and fields, the charge conjugation C along with the spatial parity P and time reversal T, is one of the most fundamental symmetries. The C operator in quantum field theory applied to a particle state $|\psi\rangle$, changes all additive quantum numbers of this particle to opposite sign, leaving the mass, momentum and spin unchanged, and making it an antiparticle state:

$$C|\psi\rangle = |\bar{\psi}\rangle. \tag{1}$$

In the Quantum Electrodynamics (QED) and Quantum Chromodynamics (QCD) it is postulated that C holds in all electromagnetic and strong interactions on the level smaller than 10^{-8}. Therefore the C-invariance should imply the balance between the matter and antimatter, however experimental observations of the Universe shows that there is significantly larger abundance of matter over antimatter [1]. The known CP breaking effect is insufficient to explain this phenomenon, but it is hoped that investigations of the charge conjugation invariance may help in clarification of this problem.

Difficulties in studies of the charge conjugation arise from the fact that there are only few known particles in nature which are the eigenstates of the C operator. The most suitable candidates are neutral and flavorless mesons and the particle-antiparticle systems. The particularly interesting appears the η meson, which plays a crucial role for understanding of the low energy Quantum Chromodynamics, and can be also used to tests of the fundamental symmetries.

In the hadronic decay $\eta \rightarrow \pi^+\pi^-\pi^0$, the C invariance violation can manifest itself as an asymmetry between energy distribution of the π^+ and π^- mesons in the rest frame of the η meson. The convenient way to study this invariance is to use Dalitz plot described by the Mandelstam variables defined as:

$$s_i = (p_\eta - p_i)^2 = (m_\eta - m_i)^2 - 2 \cdot m_\eta T_i, \tag{2}$$

where p_i and m_i denote the four-momentum vectors and masses of final state particles, and T_i stands for the kinetic energy in the rest frame of the η meson. For the $\pi^+\pi^-\pi^0$ final state where $m_{\pi^+} = m_{\pi^-}$, one can use the symmetrized and dimensionless variables defined as:

$$X = \sqrt{3}\left(\frac{T_+ - T_-}{Q}\right), \quad Y = \frac{3T_0}{Q} - 1, \tag{3}$$

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where $Q = T_+ + T_- + T_0$ is the excess energy. The Dalitz plot distribution inside the kinematic boundaries is symmetric and flat when the transition matrix element is constant. However, in general the density distribution is given by the matrix element squared which can be described by expanding the amplitude in the powers of X and Y:

$$|M|^2 = A_0^2(1 + aY + bY^2 + cX + dX^2 + fY^3 + ...),\tag{4}$$

where $a, b, c, d, f, ...$ are the parameters which can be obtained phenomenologically or on the ground of theory, and A_0 stands for the normalization factor.

The amplitude mixing between $\lambda_C = -1$ and $\lambda_C = +1$, describing the transition into isospin state $I = 1$ and $I = 0, 2$, respectively, can be investigated by studying of the symmetries of population in different parts of the Dalitz plot. In particular the possible presence of C violation could be observed in three parameters: (i) left-right asymmetry – A_{LR}, (ii) quadrant asymmetry – A_Q, and (iii) sextant asymmetry – A_S. Each of these parameters depends on different isospin states of the final three pions. The asymmetries are defined as number of events observed in different sectors of the Dalitz plot. The left-right asymmetry is defined as:

$$A_{LR} = \frac{N_R - N_L}{N_R + N_L},\tag{5}$$

where the N_L stands for the number of events where π^- has a larger energy than π^+ and and N_R denotes the number of events where the π^+ has greater energy than π^-. It is sensitive to C violation averaged over all isospin states. However, it is possible to test the charge conjugation invariance in given I state. For this, one uses the quadrant and sextant asymmetries which are defined as:

$$A_Q = \frac{N_1 + N_3 - N_2 - N_4}{N_1 + N_2 + N_3 + N_4},\tag{6}$$

$$A_S = \frac{N_1 + N_3 + N_5 - N_2 - N_4 - N_6}{N_1 + N_2 + N_3 + N_4 + N_5 + N_6},\tag{7}$$

where N_i denotes the number of observed events in i-th sector of the Dalitz plot. The quadrant asymmetry tests the C invariance in transition into the 3π final state with $I = 2$, and the sextant asymmetry is sensitive to the $I = 1$ [2].

2 Experiment

We investigated the $\eta \to \pi^+\pi^-\pi^0$ decay which may violate charge conjugation, by means of the WASA-at-COSY detector. The η meson was produced via $pp \to pp\eta$ reaction at the proton beam momentum of 2.14 GeV/c. The tagging of the η meson was done by means of the missing mass technique and the decay products were identified by the invariant mass reconstruction.

Two scattered protons were registered in the Forward Detector using the scintillator detectors (FRH and FTH) and straw tube tracker (FPC), and identified by means of the energy loss method: $\Delta E - E$. Charged pions π^+ and π^- were registered in Central Detector using the Mini Drift Chamber (MDC) and the four-momenta vectors were reconstructed based on the track curvature in the magnetic field of the Superconducting Solenoid. The gamma quanta originating from the π^0 decay were registered in the Scintillating Electromagnetic Calorimeter (SEC). Furthermore, based on the reconstruction of the invariant mass of two γ quanta, the neutral pion was identified.

The background originating from the direct two pion production and other η meson decays has been reduced to negligible level by applying the momentum and energy conservation laws, and by using conditions on the missing and invariant mass distributions. The remaining physical background for the $\eta \to \pi^+\pi^-\pi^0$ decay originating from the direct production of three pions via $pp \to pp\pi^+\pi^-\pi^0$ was subtracted for each studied phase space interval separately.
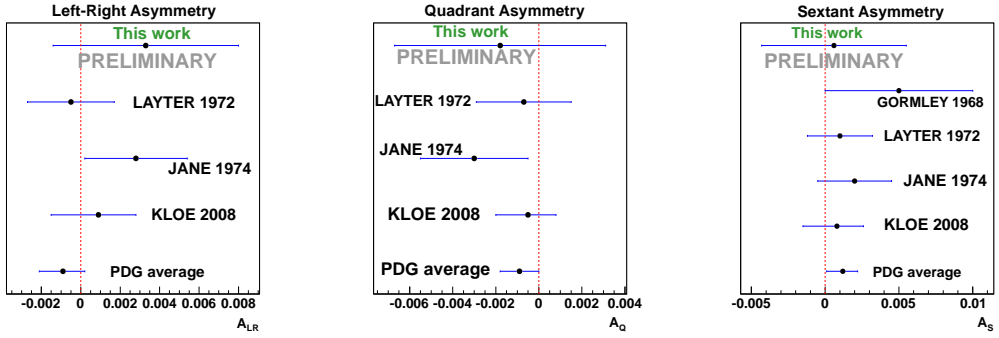
Fig. 1. Comparison of obtained values of asymmetries [7] with results determined by previous experiments [3–5], and a value given by PDG [6].

3 Results

The asymmetry parameters were determined by dividing the Dalitz plot into regions according to the formulas (5), (6) and (7). The events were summed up separately for odd and even regions and a corresponding missing mass for the $pp \rightarrow pp\eta$ reaction was reconstructed for each region. Furthermore, to determine the number of events corresponding to the $\eta \rightarrow \pi^+\pi^-\pi^0$ decay in each region the background was subtracted using the polynomial fit method, and the correction for acceptance and efficiency obtained based on the simulations of signal reaction, was applied. The preliminary estimated values of the asymmetries are shown in Fig. 1. Established values of the asymmetry parameters are consistent with zero within the range of the statistical and systematic uncertainty, which allows to conclude that the charge conjugation symmetry C is conserved in strong interactions on the level of the achieved accuracy. Obtained results are also in agreement with previously measured values [3–5] and the average of the Particle Data Group [6] (see Fig. 1).

4 Outlook

The WASA-at-COSY currently collected around 10^9 η mesons in proton-proton collisions, which is one of the world's largest data sample for the η meson, therefore the studies on the charge conjugation invariance in the pp interactions will be continued. Available statistics should enable to lower the statistical uncertainties for the determination of the asymmetry parameters by a factor of five in future analysis.

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