SEARCH FOR A DARK PHOTON WITH THE WASA DETECTOR AT COSY

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We present recent results on the search for the U boson based on the data collected by means of the WASA detector and the Cooler Synchrotron COSY

1 Introduction

Many astrophysical observations indicate existence of dark matter. One of the best example is delivered by the Chandra X-Ray Observatory which established that only a part of the colliding galactics (1E 0657-56) emits X rays whereas the presence of the much larger galactic mass is deduced only based on the gravitational lensing [1,2]. If the dark matter is utterly different from the "Standard Model" matter then from the known interactions it will feel only gravitational force.

Other experiments indicate that the present astrophysical models cannot explain magnitude and energy distributions of electrons and positrons [3,4,5,6] and a signal from 511 keV gamma quanta coming from the center of our Galaxy [7]. The origin of these phenomena may be explained assuming that positrons are created in the annihilation of the dark matter particles into e^+e^- pairs, and that this process is mediated by the U boson with the mass in the order of 1 GeV, which may mix with the virtual photon [8]. The existence of such a hypothetical boson would affect the value of the branching ratios for the decays such as e.g.: $\pi^0 \to e^+e^-$ or $\eta \to e^+e^-$.

The $\eta \to e^+e^-$ decay branching ratio has not yet been determined experimentally, and on the basis of the Standard Model it is expected [9] to be of the order of about 10^{-9}. Low probability of this decay makes it sensitive to the hypothetical new forces that may indicate physics beyond the Standard Model. This is a very interesting opportunity to search for such effects at relatively low energies of the order of 1 GeV. The $\eta \to e^+e^-$ decay is not forbidden in the Standard Model but it has to proceed through an intermediate state with two virtual photons. Therefore, it is suppressed with respect to the $\eta \to \gamma\gamma$ decay by a factor α^2 and the mass ratio $(m_e/m_\eta)^2$. Theoretical lower limit on the branching fraction $\mathrm{BR}(\eta \to e^+e^-) > 1.78 \times 10^{-9}$ results from the experimental value of the partial decay width $\Gamma(\eta \to \gamma\gamma)$ [10].

The interest in decays into lepton-antilepton pair is also due to the results of the KTeV group which determined the value of $\mathrm{BR}(\pi^0 \to e^+e^-) = (\ 6.44 \pm 0.25 \pm 0.22\ )\ 10^{-8}$ [11], which

is by about 3.3 σ larger from the theoretical value obtained based on the Standard Model [12]. This result sparked speculations about a possible signature of physics beyond the Standard Model [13,14].

The U boson would manifest itself also as a maximum in the e^+e^- invariant mass distribution from the reactions such as e.g. $\eta \to e^+e^-\gamma$ or $\pi^0 \to e^+e^-\gamma$. Assuming the hypothetical coupling between the photon and the U boson ($\gamma^* \to U$), such a decay can proceed via a following reaction chain: $\pi^0 \to \gamma\gamma^* \to \gamma U \to \gamma e^+e^-$ as it is illustrated in Figure 1.

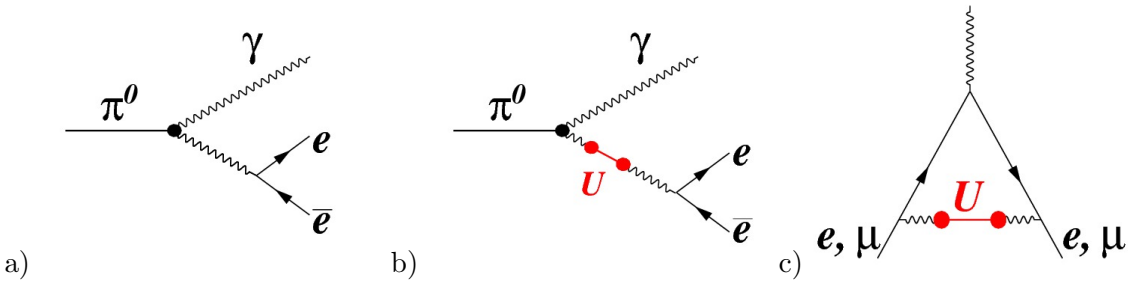

Figure 1 – Feynman diagrams for a) the lowest order electromagnetic $\pi^0 \to e^+e^-\gamma$ decay and possible contributions of U vector boson to: b) $\pi^0 \to e^+e^-\gamma$ and c) lepton $g-2$. The figure and caption is adapted from reference [15]

Diagram presented in Figure 1 c indicates a mechanism which may contribute to the g-2 anomaly and therefore an existence of U boson may be also considered as a possible source of discrepancy between a g-2 value measured [16], and predicted based on the Standard Model [17,18,19,20,21,22].

WASA-at-COSY experiment has gathered the world largest statistics of the η and π^0 mesons. In this presentation a newest preliminary results obtained based on about 10% of the data sample are presented and discussed.

2 The WASA-at-COSY experiment

The design of the WASA detector has been optimized for the study of the $\eta \to e^+e^-$ and $\pi^0 \to e^+e^-$ decays [24]. Therefore, data collected with this detector, together with the world's biggest statistics, create advantageous capabilities for studies of these rare decays. In addition, η and π^0 mesons were produced in hadronic collisions near the threshold for their production which significantly reduces background of the electromagnetic processes.

The WASA detector system (shown schematically in Figure 2) consists of the Forward Detector used for tagging of meson production, the Central Detector used for the registration of the decay products, and the pellet target system. The proton-proton reactions occurs in the middle of the Central Detector in the intersection of COSY beam with the vertical beam of pellets. The interaction region is surrounded by the multi-layer cylindrical drift chamber immersed in the axial magnetic field produced by the superconducting solenoid. The outermost sensitive part of the Central Detector is the electromagnetic calorimeter covering 96 percent of the whole solid angle. Particles flying in forward direction were registered in 14 scintillating layers and 16 layers of straw tubes detectors, while decay products of short-lived mesons η and π^0 were measured in the cylindrical straw tube chamber, thin scintillator strips, and scintillating crystals of electromagnetic calorimeter. In order to identify the investigated reactions the technique of reconstruction of four-momenta of all particles in the final state and application of kinematic constraints are used. Leptons e^+e^- and charged $\pi^+\pi^-$ mesons are identified based on the spectra of energy losses in the scintillator strips as a function of momentum determined from the trajectory curvature measured by means of straw tube chambers. Relation between the particle momentum and the energy deposited in the calorimeter is also applied. Gamma quanta produced in the π^0 meson decay are registered in the electromagnetic calorimeter and

the identification of π^0 relays on the reconstruction of their invariant mass. Identification of protons and ^{3}He ions scattered in forward direction is based on energy losses in the scintillating layers of forward detector and measurement of their trajectories in the straw tube chambers. After selection of events with appropriate particles in the final state the kinematic constrains are optimally used by application of kinematic fit with the methods of least squares and Lagrange multipliers. The χ^2 test allows for optimal selection of investigated process and improvement of accuracy of four-momentum determination. Number of events corresponding to the production of desirable final state in the decay of η or π^0 mesons is determined from the integration of the signal at the spectrum of the invariant mass of this set of particles.

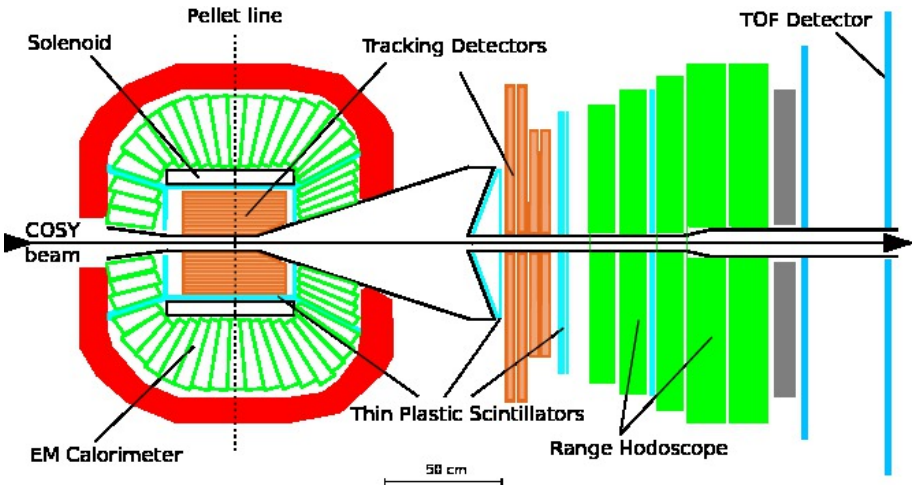

Figure 2 – Scheme of the WASA detector setup installed at COSY accelerator

As a result of experiments conducted with WASA-at-COSY we have collected a data sample of about 10^9 events with η meson and about 10^{11} with π^0 meson. These mesons were produced in the $pp \to pp\eta$ and $pp \to pp\pi^0$ reactions where proton beam collided with hydrogen pellet target.

3 Results

Using the data collected with the WASA-at-COSY experiment for the $pp \to pp\pi^0$ reaction we have determined an upper limit for the square of the $U-\gamma$ mixing strength parameter ϵ^2. Based on the 10% of the collected statistics we set an upper limit of 5×10^{-6} at 90% CL in the M_U mass range from 20 MeV to 100 MeV. This result significantly reduces the M_U vs. ϵ^2 parameter space which could explain the deviation between the Standard Model prediction and the direct measurement of the anomalous magnetic moment of the muon. For detailes the interested reader is referred to the recent WASA-at-COSY article [15].

It is important to stress that currently, several experimental groups [25,26,27,28,29] carry out investigations searching for the signal from the U boson. This year a new more stringent result was published by the HADES collaboration [30] and there are three other analysis reported on the arXive by the KLOE-2 [31], MAMI [32] and BABAR [33] experiments. These new results significantly reduce upper limits of the ϵ^2 in the range between 20 MeV and 10 GeV leaving only a small space in the low mass range from 15 MeV to 30 MeV in which a U boson can explain the discrepancy between predictions based on the Standard Model and measurements of the g-2 muon anomaly. For other mass region this explanation is excluded.

Concerning the search for the $\eta \to e^+e^-$ signal the best published experimental upper limit was set by the HADES experiment BR($\eta \to e^+e^-$) $< 5.6 \times 10^{-6}$ at 90% CL [23]. So far the WASA-at-COSY collaboration, based on 5% of the collected statistics, has reported a preliminary upper limit of 4.6×10^{-6} at 90% CL [34]. The analysis of the remaining data sample is in progress.

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