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Search for the decays $\eta\to\mu e$ and $\eta\to e^+e^-$

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A search for the lepton-family-violating decay $\eta\to\mu e$ and the rare decay $\eta\to e^+e^-$ yields the following branching ratio (B) upper limits at a 90% confidence level: $B(\eta\to\mu e)<6\times10^{-6}$ and $B(\eta\to e^+e^-)<2\times10^{-4}$. This is the first direct search for $\eta\to\mu e$. The measurements were carried out at the SPES2 tagged η facility at Laboratoire National Saturne in the course of a measurement of $B(\eta\to\mu^+\mu^-)$. [S0556-2821(96)04211-7]

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I. THE SEARCH FOR $\eta\to\mu e$

Considerable experimental effort is under way to test the conservation of lepton flavor, since a breakdown would point to physics beyond the standard model such as the existence of massive neutrinos, leptoquarks, new gauge bosons, or supersymmetric particles. Impressive limits have already been obtained for the branching ratios of $\mu\to e\gamma$, $\mu\to 3e$, $K_L\to\mu e$, and $K\to\pi\mu e$ [1,2]. The quark structure of the η meson, $|\eta\rangle\simeq(1/\sqrt{3})|u\bar{u}+d\bar{d}-s\bar{s}\rangle$, allows testing for lepton family-violating μe couplings to an $s\bar{s}$ quark pair, which are not directly possible in the other decays.

A model-dependent upper limit to the branching ratio of order 10^{-10} can be inferred from $\mu-e$ conversion on complex nuclei [3]. The present result is a by-product of an experiment which measured the branching ratio (B) of $\eta\to\mu^+\mu^-$ [4].

The data were taken at the Saturne η facility [5]. A diagram of the detector arrangement is shown in Fig. 1. The magnetic spectrometer SPES2 detected the ^{3}He from the reaction $pd\to{}^3\mathrm{He}\,\eta$ as a tag for η production. The η decay products were detected using two identical counter telescopes optimized for muons. Each consisted of (in order from the target) an iron wedge degrader W, a position hodoscope P consisting of 16 horizontal segments and 16 vertical segments of plastic scintillator to measure the angle of the charged particle with resolutions $\theta_X\sim14$ mrad and $\theta_Y\sim17$ mrad, a 5-cm thick lead degrader D, a trigger hodoscope T, and a set of 12 plastic range scintillators S for identifying the muons. The degraders eliminated the pionic background from $pd\to{}^3\mathrm{He}\,\pi^+\pi^-$, but they also reduced the efficiency for detection of the electron from $\eta\to\mu e$.

The trigger was a fivefold coincidence between the ^{3}He signal from SPES2 and the P and T hodoscopes in each detector arm. The range counters S were not part of the trigger, but were used in the off-line analysis to identify muons

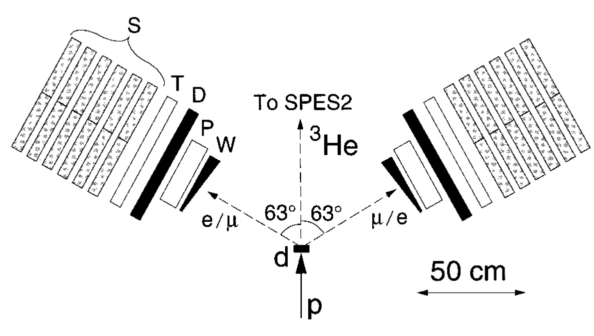

FIG. 1. Top view of the experimental arrangement. The spectrometer SPES2 detected the ^{3}He from the reaction $pd\to{}^3\mathrm{He}\,\eta$ as a tag for η production. The η decay products were detected using two identical telescopes each consisting of an iron degrader W, a position hodoscope P, a lead degrader D, a trigger hodoscope T, and a set of range scintillators S. The setup for $\eta\to e^+e^-$ used only the P hodoscope; i.e., W was removed and T was removed from the trigger.

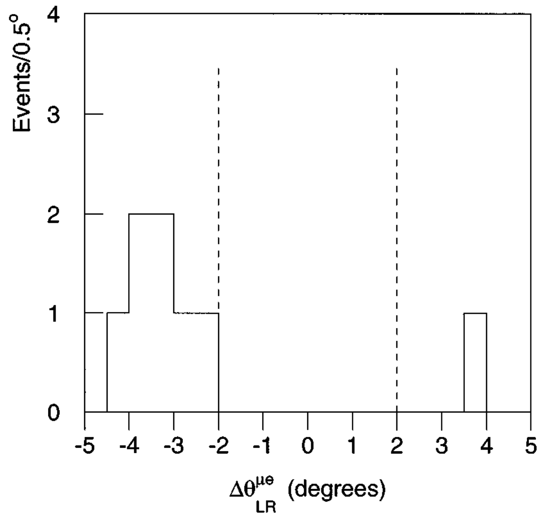

FIG. 2. Histogram of $\Delta\theta_{\mathrm{LR}}^{\mu e}$ for the final data sample in the search for $\eta\to\mu e$ after all other cuts have been applied. The dashed lines show the cut $-2°<\Delta\theta_{\mathrm{LR}}^{\mu e}<2°$ used to select $\eta\to\mu e$ candidates.

by range and energy loss. The η were identified using kinematical constraints on the ^{3}He. The total η event sample was $N_\eta=(1.22\pm0.01)\times10^9$. Further details of the apparatus, the η tagging, and the common analysis for the measurement of $B(\eta\to\mu^+\mu^-)$ are reported in [4].

The $\eta\to\mu e$ event selection used the same muon identification technique as the $\eta\to\mu^+\mu^-$ selection, except that a muon was required in one and only one detector arm. Detection of the electron in the P hodoscope was required for a measurement of its angle, but there was no particle identification in the electron arm. Cuts were applied to the pulse height in the P and T hodoscopes of the muon arm to reduce the large background originating from $\eta\to\gamma\gamma$, but no pulse height cut was used for the electron arm. Timing cuts reduced the background from random pileup, and coplanarity of the η, μ, and e was required to reduce background from three-body η decays.

The main variable used in searching for $\eta\to\mu e$ candidates was the opening angle deviation, $\Delta\theta_{\mathrm{LR}}^{\mu e}\equiv\theta_{\mathrm{LR}}^{\mathrm{calc}}-\theta_{\mathrm{LR}}^{\mathrm{meas}}$, where $\theta_{\mathrm{LR}}^{\mathrm{meas}}$ is the $\eta\to\mu e$ opening angle as measured by the P hodoscopes and $\theta_{\mathrm{LR}}^{\mathrm{calc}}$ is the expected opening angle calculated from the $pd\to{}^3$He η kinematics and the ^{3}He momentum measured in SPES2. The definition is analogous to the $\eta\to\mu^+\mu^-$ opening angle deviation defined in [4], with the appropriate adjustment for $\eta\to\mu e$ kinematics.

Figure 2 shows a histogram of $\Delta\theta_{\mathrm{LR}}^{\mu e}$ for the final data sample after all other cuts have been applied. The range $-2°\leqslant\Delta\theta_{\mathrm{LR}}^{\mu e}\leqslant2°$ includes 85% of the simulated μe events. The events at $\Delta\theta_{\mathrm{LR}}^{\mu e}<-2°$ are consistent with coming from $\eta\to\gamma\gamma$ decays, and the event at 4° is consistent with coming from $pd\to{}^3$He $\pi^+\pi^-$. There were no events detected within the region of interest.

The upper limit of the branching ratio is given by $B(\eta\to\mu e)<U/S$, where U is the upper limit to the number of $\eta\to\mu e$ events, and $S\equiv N_\eta\mathcal{A}_{\eta\to\mu e}\epsilon_{\eta\to\mu e}^{\mathrm{trigger}}\epsilon_{\eta\to\mu e}^{\mathrm{analysis}}$ is the experiment sensitivity factor, the product of the number of tagged η's, the $\eta\to\mu e$ detector acceptance, the trigger efficiency for $\eta\to\mu e$, and the $\eta\to\mu e$ selection efficiency.

The acceptance for the detection of the electron in the P hodoscope only and full detection of the muon was determined from a GEANT-based Monte Carlo simulation to be $\mathcal{A}_{\eta\to\mu e}=0.024\pm0.001$. Electrons reached the P hodoscopes with ~80% probability. This acceptance includes neither the trigger efficiency nor the $\eta\to\mu e$ offline selection efficiency.

The trigger, which was optimized for detecting $\eta\to\mu^+\mu^-$ events, demanded a hit in both T hodoscopes. There is only a 2% probability that an electron shower from $\eta\to\mu e$ will penetrate the degraders and trigger the T hodoscope. However, because of the high probability of an accidental hit in the electron-arm T hodoscope because of pileup, the trigger efficiency was actually much higher than 2%. Two independent methods were used to determine the accidental coincidence rate between an $\eta\to\mu e$ decay and a random signal in the T hodoscope of the electron arm.

The first method used ''pulser'' events in which a generator gated the time to digital converters (TDC's) and analogue to digital converters (ADC's) and triggered the event acquisition at a rate proportional to the instantaneous beam intensity. These events provided a measurement of random pileup which was combined with simulated $\eta\to\mu e$ events; 16.5% of the simulated $\eta\to\mu e$ events had an accidental coincidence in the electron-arm T hodoscope.

The second method for determining the accidental coincidence rate used data from observed $pd\to{}^3$He $\pi^+\pi^-$ events. The two pions have a well-defined opening angle, allowing easy selection of this event type. The $pd\to{}^3$He $\pi^+\pi^-$ production rate was known from a separate measurement without the iron degrader W, and with the T hodoscope removed from the trigger. With the standard $\eta\to\mu e$ setup, 1.7% of the $pd\to{}^3$He $\pi^+\pi^-$ events were observed, whereas the Monte Carlo simulation indicated that less than 0.2% of these events should penetrate the degraders in both arms and satisfy the event trigger. The excess of observed events is attributed to a 13% probability of an accidental coincidence with each T hodoscope because of random pileup.

Averaging both results gives a probability of 0.15±0.02 for an $\eta\to\mu e$ event to be in random coincidence in the electron-arm T hodoscope. The total hardware trigger efficiency for the $\eta\to\mu e$ events is $\epsilon_{\eta\to\mu e}^{\mathrm{trigger}}=0.16\pm0.02$, which includes the 2% efficiency for the direct detection of the electron shower in the T hodoscope and accounts for the 92% live time of the P and T hodoscope electronics.

The $\eta\to\mu e$ offline selection efficiency is determined by simulation to be $\epsilon_{\eta\to\mu e}^{\mathrm{analysis}}=0.083\pm0.008$. The low efficiency is because of several factors. Pileup in the TDC's data eliminates all but approximately 40% of the data. The approximate efficiencies of the five major criteria for event selection were 80% for muon identification, 60% for coplanarity, 80% for timing, 60% for muon arm P and T hodoscope pulse height cuts, and 85% for opening angle correlation. Systematic uncertainties in the determination of this efficiency are largest for the calibrations of the time differences between the ^{3}He, μ, and e. By varying the calibration parameters used in the analysis, the systematic error is estimated to be 10%. Further details related to the analysis are given in Refs. [4,6].

The experiment sensitivity factor is $S=(3.8\pm0.6)\times10^5$. The uncertainty in S is the combined effect of the uncertainties from the acceptance (5%), the accidental trigger efficiency (13%), and the selection efficiency (10%). The upper limit for the number of $\eta\to\mu e$ events, accounting for the systematic error in S, is $U=2.4$ events [7]. This gives $B(\eta\to\mu e)<6\times10^{-6}$ at 90% confidence level.

This is the first experimental search for $\eta\to\mu e$. A dedicated experiment with more efficient detection of the electron and better identification of the electron could obtain orders of magnitude improvement.

II. THE SEARCH FOR $\eta\to e^+e^-$

The decay $\eta\to e^+e^-$ is an example of a transition between a pseudoscalar meson and a pair of charged leptons. Within the framework of the minimal standard model, this process is dominated by the two-photon intermediate state. The small probability of this fourth-order electromagnetic transition makes the decay sensitive to hypothetical interactions that arise from physics beyond the standard model, such as the existence of leptoquark bosons carrying both quark and lepton flavors. The imaginary part of the amplitude for $\eta\to e^+e^-$ proceeding through the two-photon intermediate state is fixed by QED, and the real part is related to the $\eta\to\mu^+\mu^-$ amplitude in an almost model-independent way [8]. Using the measured $B(\eta\to\mu^+\mu^-)$, one expects $B(\eta\to e^+e^-)\sim(5-6)\times10^{-9}$ [4]. This is in agreement with various model calculations [9]. A branching ratio much larger than this would suggest contributions from exotic decay mechanisms.

The previous limit $B(\eta\to e^+e^-)<3\times10^{-4}$ at 90% confidence level was determined from a 1974 analysis of a bubble chamber exposure performed in 1966 [10]. In that experiment, the sample of 1.2×10^4 η's were produced in the reaction $\pi^+n\to\eta p$. The two electron-positron pairs found with an invariant mass in the vicinity of the η mass were attributed to background from $\pi^+n\to e^+e^-p$.

The present search for $\eta\to e^+e^-$ is based on a small, special data set from the $B(\eta\to\mu^+\mu^-)$ experiment which was taken without the degraders W and with the T hodoscopes removed from the trigger (Fig. 1). The detector acceptance $\mathcal{A}_{\eta\to e^+e^-}=0.030$ was determined from GEANT-based Monte Carlo simulations.

Pions from $pd\to{}^3\mathrm{He}\ \pi^+\pi^-$ were used to calibrate the P hodoscope timing to 50 ps and pulse heights to 6.5%. About two-thirds of the $pd\to{}^3\mathrm{He}\ \pi^+\pi^-$ background were removed with timing and pulse-height cuts in the P hodoscopes. All events were tested for coplanarity to select two-body η decays. The main variable used in the final selection process was again the opening angle deviation $\Delta\theta_{\mathrm{LR}}^{ee}$.

Figure 3(a) shows a histogram of $\Delta\theta_{\mathrm{LR}}^{ee}$ for the final sample after all other cuts have been applied. There are nine candidates in the S (signal) region $-2°<\Delta\theta_{\mathrm{LR}}^{ee}<2°$, where the expected background is 6.6 ± 1.8 events, with 5.9 ± 1.8 background events from the continuum, 0.7 ± 0.3 background events coming from $\eta\to\gamma\gamma$, and a negligible amount from $pd\to{}^3\mathrm{He}\ \pi^+\pi^-$.

The continuum background consists of three-body η decays, and was estimated by noting the number of events, 35, in the background region N of Fig. 3(a) and extrapolating into the S region. The N region extends beyond the displayed histogram range, to include the histogram underflows and overflows. The shape of the continuum background spectrum was assumed to be the same as for noncoplanar events. Figure 3(b) shows a histogram of $\Delta\theta_{\mathrm{LR}}^{ee}$ for noncoplanar events. The ratio of the number of such events in the S region to the number in the N region is 17/101. Hence, the estimated continuum background is $35\times17/101=5.9\pm1.8$ events.

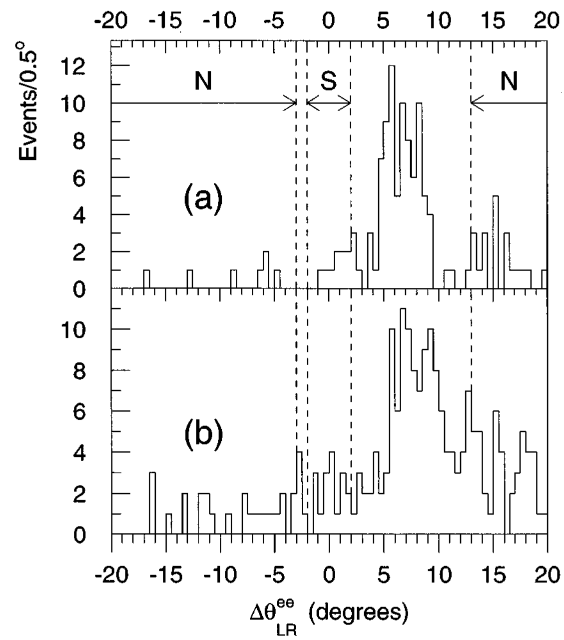

FIG. 3. (a) Histogram of $\Delta\theta_{\mathrm{LR}}^{ee}$ for the final data sample in the search for $\eta\to e^+e^-$ after all other cuts have been applied. The S region, $-2°<\Delta\theta_{\mathrm{LR}}^{ee}<2°$, was used to select $\eta\to e^+e^-$ candidates, while the N region was used to estimate continuum background. The N region includes histogram underflows and overflows. The peak at $\Delta\theta_{\mathrm{LR}}^{ee}\sim7°$ is from $pd\to{}^3\mathrm{He}\ \pi^+\pi^-$. (b) Histogram of $\Delta\theta_{\mathrm{LR}}^{ee}$ for noncoplanar events. In regions S and N, these events are from three-body η decays.

The $\eta\to\gamma\gamma$ background has the same kinematics as $\eta\to e^+e^-$ and therefore peaks at $\Delta\theta_{\mathrm{LR}}^{ee}=0$. The amount of $\eta\to\gamma\gamma$ background was calculated from Monte Carlo simulations. The absence of the degraders W increased the contribution to the background from $pd\to{}^3\mathrm{He}\ \pi^+\pi^-$ at $\Delta\theta_{\mathrm{LR}}^{ee}\sim7°$; however, it also reduced the $\eta\to\gamma\gamma$ background because of less photon conversion. The background region N was chosen to exclude $pd\to{}^3\mathrm{He}\ \pi^+\pi^-$.

The upper limit to the branching ratio is expressed as $B(\eta\to e^+e^-)<U/S$, where

$$S\equiv N_\eta\mathcal{A}_{\eta\to e^+e^-}\epsilon_{\eta\to e^+e^-}^{\mathrm{trigger}}\epsilon_{\eta\to e^+e^-}^{\mathrm{analysis}}$$
$$=[(2.71\pm0.05)\times10^6]\times(0.0302\pm0.0005)$$
$$\times(0.95\pm0.02)(0.51\pm0.11)$$
$$=(3.9\pm0.9)\times10^4$$

is the experiment sensitivity factor. The trigger efficiency $\epsilon_{\eta\to e^+e^-}^{\mathrm{trigger}}$ and analysis efficiency $\epsilon_{\eta\to e^+e^-}^{\mathrm{analysis}}$ are analogous to those defined for $\eta\rightarrow\mu e$ in Sec. I. The uncertainty in S is dominated by the resolution and the calibration uncertainty of the P hodoscope amplitudes. Further details on the event selection, the background estimate, and the sensitivity factor S are given in [11].

An upper limit of U=7.9 events ($\eta\rightarrow e^+e^-$) at 90% confidence level is determined using Eq. (17.35) of Ref. [1]. However, the uncertainties in the sensitivity factor and in the background estimate effectively increase this upper limit to $U=9.1$ events [7]. The 90% confidence level upper limit on the branching ratio is $B(\eta\rightarrow e^+e^-)<2\times10^{-4}$. A dedicated experiment with better identification of the electrons could obtain orders of magnitude improvement.

III. CONCLUSION

No evidence for the lepton-family-violating decay $\eta\rightarrow\mu e$ and the rare decay $\eta\rightarrow e^+e^-$ was observed. The 90% confidence level upper limits for the branching ratios are $B(\eta\rightarrow\mu e)<6\times10^{-6}$ and $B(\eta\rightarrow e^+e^-)<2\times10^{-4}$.

ACKNOWLEDGMENTS

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