

## Measurement of the Branching Ratio for the Decay $\eta \rightarrow \mu^+ \mu^-$

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(Received 29 September 1992)

The branching ratio ( $B$ ) for  $\eta \rightarrow \mu^+ \mu^-$  has been measured at the SATURNE tagged- $\eta$  facility using the reaction  $pd \rightarrow {}^3\text{He} \eta$  as a source of  $\sim 10^8$  tagged  $\eta$ 's per day. A sample of 100  $\eta \rightarrow \mu^+ \mu^-$  decays on a background of 8 events yielded  $B(\eta \rightarrow \mu^+ \mu^-) = [5.6 \pm 0.8(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-6}$ . This value is  $1.3 \pm 0.2$  times the unitarity (lower) bound of  $4.3 \times 10^{-6}$ , in agreement with most quark and vector meson dominance model predictions.

PACS numbers: 13.20.Jf

The decay of a neutral pseudoscalar meson into a pair of charged leptons is expected to proceed predominantly via a two-photon intermediate state. The rate for this fourth-order electromagnetic process is predicted to be very small, and therefore an exotic interaction outside the framework of the standard model may be observable. The decays  $\eta \rightarrow \mu^+ \mu^-$ ,  $\pi^0 \rightarrow e^+ e^-$  [1,2], and the flavor-changing neutral current process  $K_L \rightarrow \mu^+ \mu^-$  [3–5] are the only examples which have been observed.

QED relates the imaginary part of the  $\eta \rightarrow \mu^+ \mu^-$  decay amplitude to the known amplitude for the decay  $\eta \rightarrow \gamma \gamma$ . This on-shell contribution ( $\eta \rightarrow \gamma \gamma \rightarrow \mu^+ \mu^-$ ) gives the unitarity (lower) bound  $B(\eta \rightarrow \mu^+ \mu^-) \geq 4.3 \times 10^{-6}$  [6–9]. The *real* part of the amplitude depends on the  $\eta \gamma \gamma$  vertex form factor. Various calculations using quark and vector meson dominance models for the form factor suggest that the branching ratio is less than 1.5 times the unitarity bound [10]. A precision measurement of  $B(\eta \rightarrow \mu^+ \mu^-)$  can therefore constrain models of the  $\eta \gamma \gamma$  form factor. A measured  $B$  in excess of twice the unitarity bound (or below unitarity) might be a signal for new physics, such as the existence of leptoquark gauge bosons [11]. The weak decay  $K_L \rightarrow \mu^+ \mu^-$  is sensitive to gauge bosons of much greater mass, but involves a flavor change; the decay  $\eta \rightarrow \mu^+ \mu^-$  is a probe for flavor-conserving transitions.

The first search for  $\eta \rightarrow \mu^+ \mu^-$  at Brookhaven National Laboratory in 1968 [12] resulted in an upper bound of  $20 \times 10^{-6}$  (90% C.L.). A year later at CERN [13] the first observation of the decay  $\eta \rightarrow \mu^+ \mu^-$  was made yielding a branching ratio of  $(23 \pm 9) \times 10^{-6}$ . This value is significantly higher than the unitarity bound, and suggested that an exotic interaction might contribute. It

should be noted, however, that the  $\eta$  flux was based on calculations of  $\sigma(\pi^- p \rightarrow \eta + \text{anything})$ , which gave a large systematic uncertainty. The most recent result from Serpukhov gave  $(6.5 \pm 2.1) \times 10^{-6}$  [14], which is consistent with theoretical expectations, but it differs from the CERN measurement by nearly 2 standard deviations. The Serpukhov data suffered from a very large background coming from the tail of  $\rho \rightarrow \mu^+ \mu^-$ , and the normalization was based on the Dalitz decay  $\eta \rightarrow \mu^+ \mu^- \gamma$ .

A new opportunity to study rare  $\eta$  decays arose with the discovery of a copious source of  $\eta$ 's from the reaction  $pd \rightarrow {}^3\text{He} \eta$  very close to the reaction threshold [15]. The unique aspect of the present measurement is that the  $\eta$ 's were tagged by detecting the recoil  ${}^3\text{He}$ . This provided a normalization independent of other  $\eta$  decay channels, and eliminated most of the systematic uncertainties that plagued the previous experiments. The SATURNE synchrotron at Saclay provided a proton beam with an energy 1.5 MeV above the  $pd \rightarrow {}^3\text{He} \eta$  threshold ( $T_p \approx 893$  MeV). At this energy the total production cross section is  $\sigma(pd \rightarrow {}^3\text{He} \eta) \approx 0.4 \mu\text{b}$ , which is about 90% of its maximum value. The recoil  ${}^3\text{He}$  from  $pd \rightarrow {}^3\text{He} \eta$  were emitted at laboratory angles less than  $1.3^\circ$ , and the total momentum range was  $\pm 2.5\%$ . With the SPES II spectrometer [16] placed at  $0^\circ$ , the acceptance for the  $\eta$ -tagging reaction was 100% as a consequence of the small phase space. The proton beam of  $10^{11} \text{ s}^{-1}$  incident on the 7 mm thick liquid deuterium target yielded about  $10^8$  tagged  $\eta$ 's per day.

The SPES II spectrometer consists of a quadrupole and two dipoles which separated the proton beam from the momentum-analyzed  ${}^3\text{He}$ . The  ${}^3\text{He}$  were identified by

pulse height and time of flight using two scintillator planes behind the focal plane. Three focal-plane wire chambers with  $x$  and  $y$  readout gave a trajectory reconstruction efficiency of 97%. The recoil  ${}^3\text{He}$  momentum spectrum in Fig. 1 shows that the background under the signal peak was 8%, half of which came from the target walls.

The muons from the decay  $\eta \rightarrow \mu^+ \mu^-$  were detected by a pair of identical range telescopes (Fig. 2) located symmetrically about the target at  $63^\circ$  with respect to the incident proton beam. Each of the horizontal and vertical position hodoscope planes (P) consisted of 16 narrow scintillator elements, giving an angular resolution of 20 mrad (FWHM), and time resolution of  $\sim 0.5$  ns (FWHM). The iron and lead moderators greatly reduced the high flux of pions, protons, and deuterons produced in the target. The  $11^\circ$  slope for the iron wedge was chosen so that the average energy for the decay muons after this moderator was independent of the emission angle. The trigger hodoscope (T) consisted of horizontal and vertical scintillator arrays, and was used to

trigger on particles that penetrated the lead moderator. The stop counters (S) consisted of six 5.1 cm thick scintillator planes, and were used to measure energy loss and range. Details of the experiment are given in Ref. [17], and will be published elsewhere.

Three data streams were recorded: (i) a pre-scaled sample of  ${}^3\text{He}$  detected by SPES II, providing the total number of  $pd \rightarrow {}^3\text{He} \eta$  events; (ii) the triple coincidences between the  ${}^3\text{He}$  and the two muon detectors, yielding the fraction of  $\eta$ 's that decayed into a  $\mu^+ \mu^-$  pair; and (iii) pulser events generating artificial triple coincidences at a rate proportional to the instantaneous beam intensity, to study the effect of accidentals on the analysis efficiency. Since these three data streams were recorded *simultaneously*, the determination of the branching ratio is independent of systematic uncertainties in proton beam intensity, target thickness,  $\eta$ -tagging efficiency, total cross section for  $\sigma(pd \rightarrow {}^3\text{He} \eta)$ , and computer dead time. The limitation of the experiment came from the high singles rates in the muon detectors (about 1 MHz per counter).

The  $\eta \rightarrow \mu^+ \mu^-$  branching ratio was obtained from the relation

$$B(\eta \rightarrow \mu^+ \mu^-) = \frac{N(\eta \rightarrow \mu^+ \mu^-)}{N(pd \rightarrow {}^3\text{He} \eta)} \times \frac{1}{\mathcal{A}_{\eta \rightarrow \mu^+ \mu^-} \times \epsilon_{\mu^+ \mu^-}^{\text{analysis}} \times \epsilon_{\mu^+ \mu^-}^{\text{electronic}}}, \quad (1)$$

where  $N(\eta \rightarrow \mu^+ \mu^-)$  is the number of  $\eta \rightarrow \mu^+ \mu^-$  events observed,  $N(pd \rightarrow {}^3\text{He} \eta) = (1.22 \pm 0.01) \times 10^9$  is the number of tagged  $\eta$ 's,  $\mathcal{A}_{\eta \rightarrow \mu^+ \mu^-}$  is the acceptance for the decay  $\eta \rightarrow \mu^+ \mu^-$ ,  $\epsilon_{\mu^+ \mu^-}^{\text{analysis}}$  is the analysis efficiency, and  $\epsilon_{\mu^+ \mu^-}^{\text{electronic}}$  is the electronics efficiency for  $\eta \rightarrow \mu^+ \mu^-$  events.

The three essential features of the  $\eta \rightarrow \mu^+ \mu^-$  event selection were (i) good time resolution to reject accidentals, (ii) the measurement of each decay product's emission angle and range to provide kinematic constraints, and (iii) stop-counter pulse heights to reject background from  $\eta \rightarrow \gamma\gamma$  ( $B \approx 0.4$ ) and  $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$  ( $B \approx 0.3$ ). The background from neutral  $\eta$  decays came mainly from photons that showered in the iron wedge.

An angle correlation function  $\Delta\theta_{LR} \equiv \theta_{LR}^{\text{calc}} - \theta_{LR}^{\text{measured}}$  was defined, where  $\theta_{LR}^{\text{calc}}$  is the  $\mu^+ \mu^-$  opening angle calculated for the  $\eta$  momentum inferred from the tagged  ${}^3\text{He}$ , and  $\theta_{LR}^{\text{measured}}$  is the opening angle measured by the left and right muon detectors. Figure 3 shows the angle

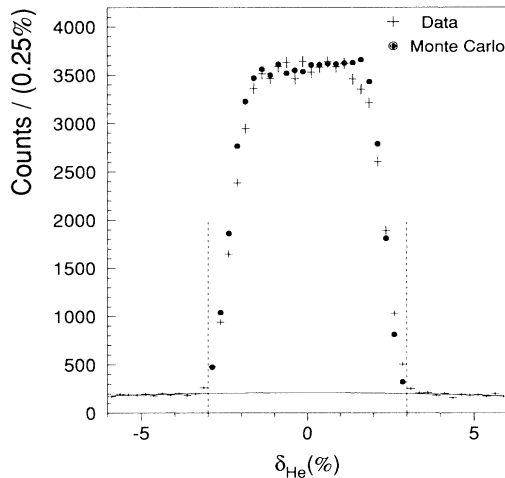


FIG. 1. The  ${}^3\text{He}$  momentum ( $\delta_{\text{He}}$ ) relative to the central value of 1320 MeV/c, as measured at the SPES II focal plane. The large peak in the interval  $-3 < \delta_{\text{He}} < 3\%$  is due to the reaction  $pd \rightarrow {}^3\text{He} \eta$ . The solid line is a fit to the background, and the dashed vertical lines show the window used to select  $pd \rightarrow {}^3\text{He} \eta$  events. The dots are the result of a Monte Carlo simulation.

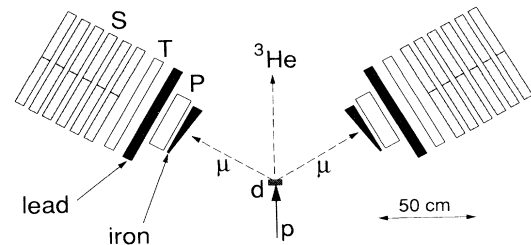


FIG. 2. Muon detectors for  $\eta \rightarrow \mu^+ \mu^-$ . The basic elements of each detector are horizontal and vertical position hodoscopes (P), iron and lead moderators, horizontal and vertical trigger hodoscopes (T), and six stop-counter planes (S). The proton ( $p$ ) beam is incident on the deuterium target ( $d$ ), and the recoil  ${}^3\text{He}$  is detected in the SPES II spectrometer (not shown).

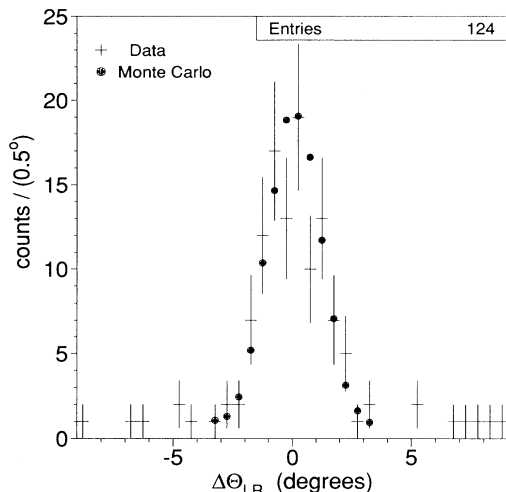


FIG. 3. The angle correlation distribution (see text for definition) of the final sample. In the signal region defined as  $-3^\circ < \Delta\theta_{LR} < 3.0^\circ$ , there are  $108 - 8 = 100 \pm 11$  events. The dots show the result of a Monte Carlo simulation normalized to the data; the reduced  $\chi^2$  of data/Monte Carlo is 0.9.

correlation for the data sample after applying cuts on the flight times, pulse heights, coplanarity, and stop-counter hit patterns of the detected decay products. After subtracting 8 background events, the peak in Fig. 3 contains  $100 \pm 11$   $pd \rightarrow {}^3\text{He}\mu^+\mu^-$  events that satisfy the  $\eta \rightarrow \mu^+\mu^-$  selection criteria.

A separate analysis was made to determine the continuum background from  $pd \rightarrow {}^3\text{He}\rho$  followed by  $\rho \rightarrow \mu^+\mu^-$ , in which the  $\rho$  mass was limited to a 2 MeV band near the  $\eta$  mass. The continuum background was analyzed for  ${}^3\text{He}$  momenta *outside* the kinematic region for  $pd \rightarrow {}^3\text{He}\eta$ , and used a simulation to determine the expected number of  $\rho \rightarrow \mu^+\mu^-$  events that satisfied the  $pd \rightarrow {}^3\text{He}\eta$  selection criteria. No  $\rho \rightarrow \mu^+\mu^-$  signal was found, and our sensitivity gave an upper limit of seven background events (90% C.L.) contributing to the peak in Fig. 3 (for comparison, in the best previous experiment [14], the background from  $\rho \rightarrow \mu^+\mu^-$  was about 50% larger than the  $\eta \rightarrow \mu^+\mu^-$  signal). A correction for the continuum background was made by adding the background upper limit at 70% confidence level (4 events) in quadrature with the lower statistical error. This resulted in an asymmetric error,  $N(\eta \rightarrow \mu^+\mu^-) = 100^{+11}_-1$ .

The production of  $pd \rightarrow {}^3\text{He}\pi^+\pi^-$  was studied using separate data sets without the iron wedge; these data, combined with a Monte Carlo simulation of the decay of one or both pions, determined the corresponding background contribution to the  $\eta \rightarrow \mu^+\mu^-$  signal to be less than 0.3 event. The background due to the muon Dalitz decay ( $\eta \rightarrow \mu^+\mu^-\gamma$ ) with soft photon emission has been calculated to be less than 0.5 event. No correction was made for the small background coming from pion and Dalitz decay.

The systematic error in the measured branching ratio is dominated by uncertainties in the efficiency and acceptance factors appearing in Eq. (1). The  $\mu^+\mu^-$  acceptance was determined from a Monte Carlo simulation to be  $(2.9 \pm 0.1)\%$ . To properly simulate losses due to accidental hits in the muon detectors, the analysis efficiency was evaluated by combining each simulated  $\eta \rightarrow \mu^+\mu^-$  event with one event from the "random" (pulsar) trigger. The losses can be summarized as follows: (i) 20% of the  $\eta \rightarrow \mu^+\mu^-$  events were lost due to accidental hits, which either corrupted the time and pulse height information, or resulted in an ambiguous event. The sensitivity to the simulated timing and pulse height calibrations resulted in  $\pm 4\%$  systematic uncertainty in  $B$ . (ii) 15% of the events were lost because one of the decay muons scattered out of the detector before stopping. Based on the sensitivity to the details of the multiple scattering algorithm used in the simulation, the corresponding systematic uncertainty in  $B$  was estimated to be  $\pm 3\%$ . (iii) 20% of the events were discarded by the software selection criteria, which introduced a  $\pm 6\%$  systematic uncertainty to  $B$ . The overall analysis efficiency [ $\epsilon_{\mu^+\mu^-}^{\text{analysis}}$  in Eq. (1)] was  $0.54 \pm 0.05$ , where the various systematic uncertainties have been added in quadrature.

The electronics efficiency was monitored by pulser events generated with light-emitting diodes attached to some of the muon and SPES II scintillators. The fraction of pulser-generated triple coincidences that produced an electronic event trigger was used to obtain the electronics efficiency, and gave  $\epsilon_{\mu^+\mu^-}^{\text{electronic}} = 0.92 \pm 0.03$ . The 3% computer dead time was not included in  $\epsilon_{\mu^+\mu^-}^{\text{electronic}}$  because it was the same for the  $pd \rightarrow {}^3\text{He}\eta$  and the triple coincidence data streams, and therefore cancels when calculating the branching ratio from Eq. (1).

The result of the analysis is

$$B(\eta \rightarrow \mu^+\mu^-) = [5.6 \pm 0.9(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-6}, \quad (2)$$

and it is compared with the previous measurements in Fig. 4. Adding the statistical and systematic uncertainties in quadrature, the ratio ( $\mathcal{R}$ ) of our measured  $B$  with respect to the unitarity bound is  $\mathcal{R} \equiv B(\eta \rightarrow \mu^+\mu^-)/B_{\text{unit}} = 1.3 \pm 0.2$ . This improves upon the previous Serpukhov measurement [14] of  $\mathcal{R} = 1.5 \pm 0.5$ , and does not support the earlier CERN value of  $\mathcal{R} = 5.3 \pm 2.1$  [13].

In conclusion, the decay mechanism for  $\eta \rightarrow \mu^+\mu^-$  is well described by a two-photon intermediate state,  $\eta \rightarrow \gamma\gamma \rightarrow \mu^+\mu^-$ . The real part of the decay amplitude, which describes the off-shell behavior of the intermediate state, contributes less than the imaginary part as predicted by most standard model calculations using quark and vector meson dominance models [10]. There is no indication of an exotic contribution to the  $\eta \rightarrow \mu^+\mu^-$  decay rate.

The authors wish to thank the SATURNE staff for the high quality beam, and for the technical support received

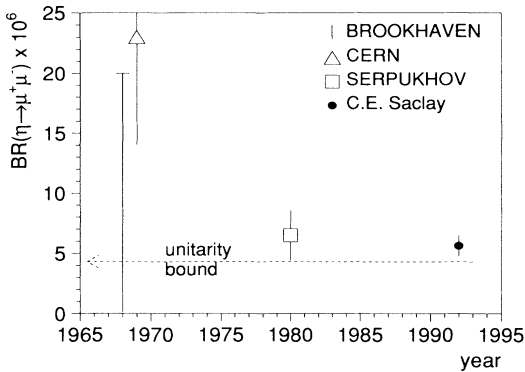


FIG. 4. The result of the present experiment compared with previous results [12–14]. The dashed line shows the unitarity (lower) bound.

in the course of the experiment. This research was supported in part by the Commissariat à l’Energie Atomique, the Paul Scherrer Institute, the Swiss National Science Foundation, the U.S. Department of Energy, the U.S. National Science Foundation, and the North Atlantic Treaty Organization.

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