Search for the process $e^+e^- \to \eta$

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A search for the rare decay $\eta \to e^+e^-$ is performed using the inverse process $e^+e^- \to \eta$ in the decay mode $\eta \to \pi^0\pi^0\pi^0$. We analyze data with an integrated luminosity of 654 nb^{-1} accumulated at the VEPP-2000 e^+e^- collider with the SND detector at the center-of-mass energy $E = m_\eta c^2 \approx 548$ MeV, and set the upper limit $\mathcal{B}(\eta \to e^+e^-) < 7 \times 10^{-7}$ at the 90% confidence level.

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I. INTRODUCTION

This article is devoted to the measurement of the branching ratio of the decay $\eta \to e^+e^-$ at the VEPP-2000 e^+e^- collider. The experiment was proposed in Ref. [1]. For the measurement of the decay, the inverse reaction $e^+e^- \to \eta$ is used.

Decays of pseudoscalar mesons to lepton pairs $P \to l^+l^-$ ($l = e, \mu$) are rare. In the standard model, they proceed through the two-photon intermediate state, as shown in Fig. 1. An additional suppression by a factor of $(m_l/m_P)^2$ arises from the approximate helicity conservation. Thus, the width of the decay $P \to l^+l^-$ is less than the corresponding two-photon width $\Gamma(P \to \gamma\gamma)$ by a factor proportional to $\alpha^2(m_l/m_P)^2$. Because of the small probability these decays are sensitive to contributions that are not described in the framework of the standard model [2,3]. It should be noted that the imaginary part of the decay amplitude can be calculated from the width of the $P \to \gamma\gamma$ decay. This allows us to obtain a model-independent lower boundary for the decay branching fraction, the so-called unitary limit [4]. For the $\eta \to e^+e^-$ decay it is equal to $\mathcal{B}^{\text{UL}}(\eta \to e^+e^-) = 1.78 \times 10^{-9}$. It is expected that the total $\eta \to e^+e^-$ branching fraction exceeds the unitary limit by a factor of 2.5–3 [5–7].

The decay $\eta \to e^+e^-$ was not observed. The best upper limit on the decay branching fraction $\mathcal{B}(\eta \to e^+e^-) < 2.3 \times 10^{-6}$ was set at the HADES experiment [8]. This paper presents the result of the search for the decay $\eta \to e^+e^-$ performed in the SND experiment at the VEPP-2000 e^+e^- collider.

II. DETECTOR AND EXPERIMENT

The SND detector is described in detail in Refs. [9–12]. It is a nonmagnetic detector, the main part of which is a three-layer spherical electromagnetic calorimeter consisting of 1640 NaI(Tl) crystals. The calorimeter covers a solid angle of 95% of 4π. The energy and angular resolutions for photons with energy E_γ are described by the following formulas:

$$\sigma_{E_\gamma}/E_\gamma = 4.2\%/\sqrt[4]{E_\gamma(\text{GeV})}, \quad (1)$$

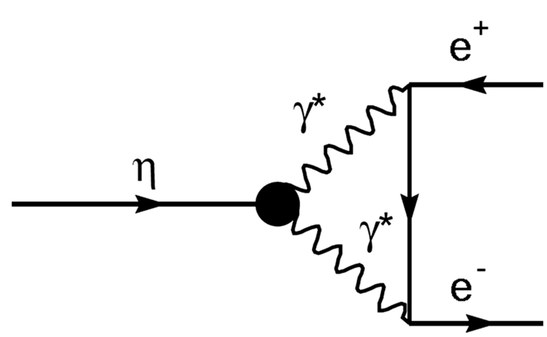

FIG. 1. The diagram for the $\eta \to e^+e^-$ decay.

$$\sigma_{\theta,\phi} = 0.82°/\sqrt{E(\mathrm{GeV})}. \tag{2}$$

Directions of charged particles are measured in a nine-layer drift chamber. The calorimeter is surrounded by an iron absorber and a muon system. In this analysis, the veto from the muon system is used for the suppression of cosmic ray background.

The data used in this analysis were recorded with the SND detector at the e^+e^- collider VEPP-2000 [13] in 2018 at the center-of-mass (c.m.) energy E near the η-meson mass $m_\eta c^2 = 547.862 \pm 0.017$ MeV [14]. The integrated luminosity of 654 nb^{-1} corresponding to this data set is measured using $e^+e^- \to \gamma\gamma$ events with an accuracy of 2% [15].

III. ENERGY MEASUREMENT

The η-meson width $\Gamma_\eta = 1.31 \pm 0.05$ keV [14] is much less than the c.m. energy spread $\sigma_E \approx 200$ keV. In this case the visible cross section for the reaction $e^+e^- \to \eta$ is proportional to the ratio Γ_η/σ_E. The knowledge of σ_E is needed to measure the Born $e^+e^- \to \eta$ cross section and to extract the $\eta \to e^+e^-$ branching fraction. Also, it is necessary to be able to control the collider energy with an accuracy much better than σ_E.

At the VEPP-2000 collider there is a beam-energy-measurement system using the Compton back-scattering of laser photons on the electron beam [16]. The energy spectrum of scattered photons is measured by a high-purity germanium (HPGe) detector. The energy $E_{\gamma,\mathrm{CBS}}$ corresponding to the edge of the spectrum is related to the beam energy E_b:

$$E_{\gamma,\mathrm{CBS}} \approx \frac{4\omega_0 E_b^2}{m_e^2 c^4}, \tag{3}$$

where ω_0 is the laser-photon energy, and m_e is the electron mass. The sharp edge of the Compton spectrum is smeared due to the beam-energy spread and the energy resolution of the HPGe detector. The energy calibration of the detector and the measurement of its resolution is performed using well-known sources of γ-radiation [17]. In Ref. [16] a system based on a CO laser with a wavelength of 5.426463 μm is described. For this laser at $E_b = 510$ MeV, the maximum energy of scattered photons is $E_{\gamma,\mathrm{CBS}} = 0.90$ MeV, and the width of the Compton spectrum edge due to the energy spread is 1.3 keV. The latter value is comparable with the energy resolution of the HPGe photon detector (0.9 keV). Below 500 MeV, the accuracy of the measurements of the beam energy and especially the energy spread in the system with the CO laser rapidly falls with decreasing the beam energy. Therefore, for experiments at $E_b < 500$ MeV, a second, ytterbium fiber laser with a wavelength of 1.064966 μm, is used. The comparison of the beam-energy measurements with these two lasers has been performed at $E_b = 512$ MeV. Two measurements are consistent within the statistical uncertainties (10 keV).

The systematic uncertainty of the beam-energy determination with the CO laser was estimated in Ref. [16] by comparison with the energy measurement by the resonance depolarization method [18] at $E_b = 510$ and 460 MeV ($E_{\gamma,\mathrm{CBS}} = 0.73$ MeV). It was estimated to be $\Delta E_b/E_b = 6 \times 10^{-5}$. In the measurement with the ytterbium laser, $E_{\gamma,\mathrm{CBS}} = 0.73$ MeV corresponds to $E_b = 200$ MeV. Therefore, we conclude that the above estimation $\Delta E_b/E_b = 6 \times 10^{-5}$ is valid for the ytterbium laser in the beam-energy range from 200 to 500 MeV. The systematic uncertainty in the c.m. energy determination at $E \approx m_\eta c^2$ is 33 keV.

The energy spreads measured with the CO and ytterbium lasers at $E_b = 512$ MeV were also compared. They coincided within the 10% statistical errors. For the CO laser at $E_b = 512$ MeV, the detector resolution and the beam-energy spread give comparable contributions to the width of the Compton-spectrum edge, whereas for the ytterbium laser ($E_{\gamma,\mathrm{CBS}} = 4.6$ MeV) the detector resolution practically does not affect the beam-energy spread determination. The coincidence of σ_E obtained with the two lasers means that the detector resolution measured using radioactive sources is taken into account correctly in the fit to the spectrum edge. At $E_b > 500$ MeV the beam-energy spread can be evaluated using the formula [19]

$$\sigma_{E_b} = 4.05\sigma_Z\sqrt{V_{\mathrm{cav}} E_b \sin(\arccos(63.2 E_b^4 V_{\mathrm{cav}}))}, \tag{4}$$

where σ_{E_b} is measured in keV, E_b in GeV, the longitudinal beam size σ_Z in mm, and the rf cavity voltage V_{cav} in kV. The length of the beam σ_Z is measured using detected events of elastic e^+e^- scattering. Data collected at $E_b = 511$, 550, 575, and 600 MeV are used, in which

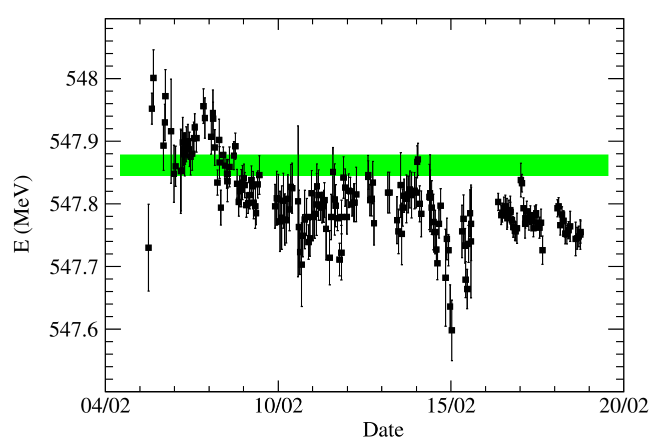

FIG. 2. The measurements of the c.m. energy during data taking. The errors are statistical. The band indicates the $\pm 1\sigma$ range for $E = m_\eta c^2$ [14].

the beam energy was measured with the ytterbium laser. The beam-energy spread obtained by Eq. (4) is found to be 10%–15% lower than that measured on the Compton spectrum. This difference (15%) is taken as an estimation of the systematic uncertainty on σ_{E_b}.

The beam-energy measurements is performed with a period of about 1 hour during data taking. These are presented in Fig. 2. The beam-energy spread was determined in every measurement. We do not observe nonstatistical deviations in the energy spread during the experiment. Therefore, the average value $\sigma_E = 226 \pm 7 \pm 34$ keV is used in the analysis, where the first error is statistical, and the second is systematic.

IV. CALCULATION OF THE $e^+e^- \to \eta$ CROSS SECTION

The Born cross section for the reaction $e^+e^- \to \eta$ is described by the Breit-Wigner formula:

$$\sigma_0 = \frac{4\pi}{E^2}\mathcal{B}(\eta \to e^+e^-)\frac{m_\eta^2\Gamma_\eta^2}{(m_\eta^2 - E^2)^2 + m_\eta^2\Gamma_\eta^2}. \qquad (5)$$

In analyses of experimental data it is necessary to take into account the radiative corrections, arising, e.g., from the emission of additional photons from the initial state. To do this, we need to convolve the cross section (5) with the so-called radiator function $W(s,x)$ [20,21]

$$\sigma(s) = \int_0^{x_{\max}} W(x,s)\sigma_0(s(1-x))dx, \qquad (6)$$

where $s = E^2$, and $x_{\max} = 1 - (3m_{\pi^0})^2/s$ for the decay $\eta \to 3\pi^0$. The theoretical accuracy of the cross section (6) is better than 1% [20,21]. For the unitary limit $\mathcal{B}^{\mathrm{UL}}(\eta \to e^+e^-) = 1.78 \times 10^{-9}$, the Born cross section in the resonance maximum is $\sigma_0(m_\eta c^2) = 29$ pb. The radiative corrections decrease this cross section up to $\sigma(m_\eta c^2) = 14$ pb.

Since the η-meson width is much less than the c.m. energy spread, the cross section observed in the experiment is significantly smaller than the cross section calculated above. It is calculated as a convolution of the cross section (6) with a Gaussian function describing the energy spread:

$$\sigma_{\mathrm{vis}}(E_0) = \frac{1}{\sqrt{2\pi}\sigma_E}\int_{-\infty}^{+\infty} e^{-\frac{(E-E_0)^2}{2\sigma_E^2}}\sigma(E)dE \qquad (7)$$

where E_0 is the average collider c.m. energy. For $\sigma_E = 226$ keV, $E_0 = m_\eta c^2$, and $\mathcal{B}^{\mathrm{UL}}(\eta \to e^+e^-) = 1.78 \times 10^{-9}$ the visible cross section (7) is equal to

$$\sigma_{\mathrm{vis}}^{\mathrm{UL}}(m_\eta c^2) = 72 \pm 11 \text{ fb}. \qquad (8)$$

The quoted uncertainty is due to the uncertainties in σ_E and Γ_η.

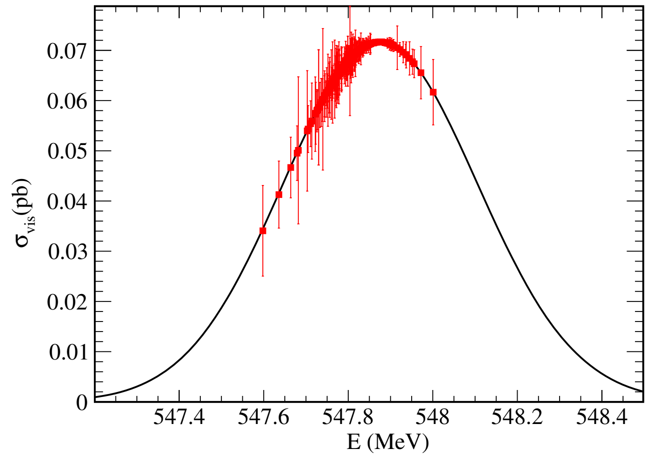

FIG. 3. The visible $e^+e^- \to \eta$ cross section evaluated for $\mathcal{B}^{\mathrm{UL}}(\eta \to e^+e^-) = 1.78 \times 10^{-9}$ and $\sigma_E = 226$ keV. The points with error bars represent the cross section values at the energy points where data were recorded. The errors of the cross section are determined by the statistical errors in the measurement of the beam energy.

The η-meson excitation curve obtained using Eq. (7) is shown in Fig. 3. The points with error bars in Fig. 3 represent the cross section values at the energy points, where data were recorded. The errors of the cross section are determined by the statistical errors in the measurement of the beam energy. The expected η-meson production cross section is calculated as follows:

$$\sigma_{\mathrm{vis}}^{\mathrm{UL}} = \frac{\sum_i L_i\sigma(E_i)}{\sum_i L_i} = 65 \pm 9 \text{ fb}, \qquad (9)$$

where L_i is the integrated luminosity for the ith energy point E_i, $\sigma(E_i)$ is the cross-section calculated using Eq. (7). The error of $\sigma_{\mathrm{vis}}^{\mathrm{UL}}$ includes contributions from the statistical errors in the beam-energy measurements (0.4 fb), uncertainties on σ_E (7.9 fb), Γ_η (0.3 fb), and m_η (0.2 fb), and the systematic uncertainty of the energy measurement (3 fb).

V. EVENT SELECTION

The preferred η decay mode for the search for the process $e^+e^- \to \eta$ with SND, for which physical background is small [1], is $\eta \to \pi^0\pi^0\pi^0 \to 6\gamma$. The main source of the background is cosmic rays. We select events with exactly six photons and energy deposition in the calorimeter greater than $0.6E$. Background from events with charged particles is rejected by the requirement that the number of fired wires in the drift chamber is less than four. The cosmic ray background is suppressed by the veto from the muon detector.

For the events passing the preliminary selection, a kinematic fit to the hypothesis $e^+e^- \to \pi^0\pi^0\pi^0 \to 6\gamma$ is performed with a requirement of total energy and momentum conservation and a condition that the invariant masses

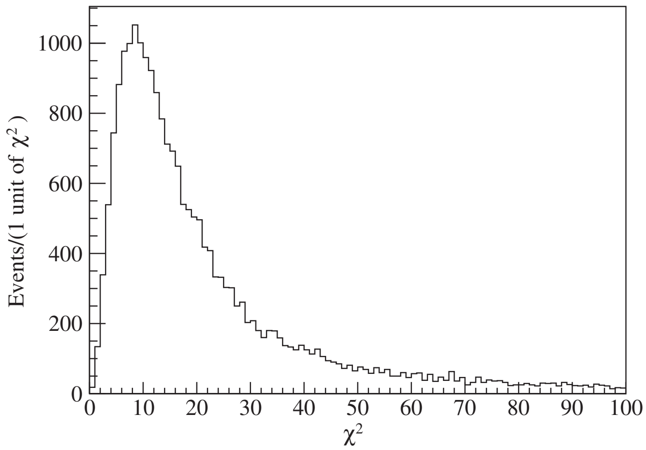

FIG. 4. The χ^2 distribution for simulated $e^+e^- \to \eta$ events passed the selection criteria of six-photon events.

of the 3 pairs of photons are equal to the π^0 mass. The invariant mass of the π^0 candidate is required to be in the range $m_{\pi^0} \pm 50$ MeV$/c^2$. The quality of the kinematic fit is characterized by the χ^2 parameter. During the fit, all possible combinations of two-photon pairs are checked and a combination with the smallest value of χ^2 is selected. The χ^2 distribution for simulated $e^+e^- \to \eta$ events passed the selection conditions described above is shown in Fig. 4. The condition $\chi^2 < 100$ is used.

The detection efficiency for $e^+e^- \to \eta$ events determined using simulation is equal to $\varepsilon = (14.1 \pm 0.7)\%$. The quoted error is systematic. It is estimated using results of Ref. [15], where data and simulated χ^2 distributions were compared for five-photon events from the process $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$.

No signal events passed the selection criteria described above are found in the data sample recorded with the SND detector at $E \approx m_\eta c^2$.

The visible cross section for the process $e^+e^- \to \eta$ and the $\eta \to e^+e^-$ branching fraction are determined as

$$\sigma_{\rm vis} = \frac{N_s}{\varepsilon L}, \qquad \mathcal{B}(\eta \to e^+e^-) = \mathcal{B}^{\rm UL}(\eta \to e^+e^-)\frac{\sigma_{\rm vis}}{\sigma_{\rm vis}^{\rm UL}}, \tag{10}$$

where N_s is the number of selected events, ε is the detection efficiency, and L is the integrated luminosity. Since no events of the process under study are found, we set the upper limit on the branching fraction

$$\mathcal{B}(\eta \to e^+e^-) < 7 \times 10^{-7} \tag{11}$$

at the 90% confidence level [22]. This result is more than 3 times lower than the previous limit $\mathcal{B}(\eta \to e^+e^-) < 2.3 \times 10^{-6}$ [8].

VI. SUMMARY

The search for the process $e^+e^- \to \eta$ has been carried out with the SND detector at the VEPP-2000 e^+e^- collider in the decay mode $\eta \to \pi^0\pi^0\pi^0$. No candidate events for the process $e^+e^- \to \eta$ have been found. Since the visible $e^+e^- \to \eta$ cross section is proportional to the branching fraction $\mathcal{B}(\eta \to e^+e^-)$, the upper limit has been set

$$\mathcal{B}(\eta \to e^+e^-) < 7 \times 10^{-7} \tag{12}$$

at the 90% confidence level.

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