Status of experiments and recent results from CMD-2 detector at VEPP-2M

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Presented by G.V.Fedotovitch

The Cryogenic Magnetic Detector (CMD-2) is shortly described. Preliminary results for the cross sections of e^+e^- annihilation into hadrons and leptons are presented in the c.m. energy range from 0.37 to 1.39 GeV. The total integrated luminosity of about 26 pb^{-1} has been collected. The new results for the ρ and ω meson parameters are reported. The major decay modes of the ϕ meson as well as its rare decays have been observed. The tagged kaons and η mesons in ϕ meson decays were used to look for some decay modes of K^0_S and η mesons.

1. INTRODUCTION

Despite thirty years of experimental studies e^+e^- annihilation into hadrons at low energies is still rather far from the complete understanding. More precise measurements are needed to determine ρ, ω and ϕmeson parameters as well as continuum properties providing the unique information about interactions of light quarks.

Exact data on the pion form factor is necessary for the precise determination of the ratio R = $\sigma(e^+e^- \to \text{hadrons})/\ \sigma(e^+e^- \to \mu^+\mu^-)$, which in the VEPP-2M energy range is dominated by the $e^+e^- \to \pi^+\pi^-$ channel. Knowledge of R with high accuracy is required to evaluate the hadronic contribution to the (g-2) of muon and to the running electromagnetic constant $\alpha(M_Z^2)$. In case of the muon (g-2) the energy range of VEPP-2M gives the major contribution both to the hadronic contribution itself and to its uncertainty.

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These physical tasks became the goal of CMD-2 detector running at the VEPP-2M e^+e^- collider in Novosibirsk since 1992 in the c.m. energy range from 0.36 to 1.4 GeV. The integrated luminosity of about 26 pb^{-1} has been collected. A short description of the most interesting results is presented in this paper.

2. CMD-2 DETECTOR

The CMD-2 detector is described in detail elsewhere [1]. It is a general purpose detector consisting of a drift chamber (DC) [2] with about 250 μ resolution in the plane transverse to the beam axis and multiwire proportional chamber (ZC) [3] with an accurate measurement (~0.5 mm) of the z-coordinate of particle track along the beam direction. Both chambers are inside a thin (0.38 X_0) superconducting solenoid with a field of 1 T.

The barrel calorimeter placed outside of the solenoid and consists of 892 CsI crystals [4] of $6 \times 6 \times 15$ cm^3 size. The crystals are arranged in eight octants. The light readout is performed by PMTs. The energy resolution is about 8% for photons with the energy more than 100 MeV. Both azimuthal and polar angle resolution is about 0.02 radian.

The endcap calorimeter [5] consists of 680 BGO crystals of $2.5 \times 2.5 \times 15$ cm^3 size. The light readout is performed by vacuum phototriodes placed on the crystals. The energy and angular resolution were found to be $\sigma_E/E = 4.6\%/\sqrt{E(\mathrm{GeV})}$ and $\sigma_{\phi,\theta} = 2 \cdot 10^{-2}/\sqrt{E(\mathrm{GeV})}$ radians respectively. The solid angle covered by both parts of the calorimeter is about 96% of 4π.

The muon range system [6] consists of two double layers of the streamer tubes operating in a self-quenching mode and is aimed to separate pions and muons. The inner and outer parts of this system are arranged in 8 modules each and cover 55% and 48% of the solid angle respectively.

3. MEASUREMENT OF THE PION FORM FACTOR AND ρ, ω MESON PARAMETERS

A large data sample of about 2 million $e^+e^- \to \pi^+\pi^-$ events was collected by CMD-2 detector in the whole VEPP-2M energy range. Analysis is completed for 10% of the data only. The beam energy was measured by the resonance depolarization technique at almost all energies. The pion form factor presented in Fig. 1 is based on the data sample at 53 energy points in the energy range from 0.37 to 0.96 MeV. The obtained ρ meson parameters based on Gounaris-Sakurai parameterization were found to be:

$M_\rho = 775.28 \pm 0.61 \pm 0.20$ **MeV,** $\Gamma_\rho = 147.70 \pm 1.29 \pm 0.40$ **MeV,**
$\Gamma_{\rho \to e^+e^-} = 6.93 \pm 0.11 \pm 0.10$ **keV,** $Br(\omega \to \pi^+\pi^-) = (1.31 \pm 0.23 \pm 0.02)\%$**.**

Here and below the first errors are statistical and the second are systematic. More details about the pion form factor can be found in [7].

The energy range around the ω meson has been scanned at 13 energy points with a total integrated luminosity of about 1.5 pb^{-1}, but the detailed analysis was performed for 10% of the data. The ω meson parameters were measured with high accuracy using the $\omega \to \pi^+\pi^-\pi^0$ decay mode. The following parameters have been obtained from the fit:

$M_\omega = 782.71 \pm 0.07 \pm 0.04$ **MeV,** $\sigma_0 = 1482 \pm 23 \pm 25$ **nb,**
$\Gamma_\omega = 8.68 \pm 0.23 \pm 0.10$ **MeV,** $\Gamma_{e^+e^-} = 0.605 \pm 0.014 \pm 0.010$ **keV.**

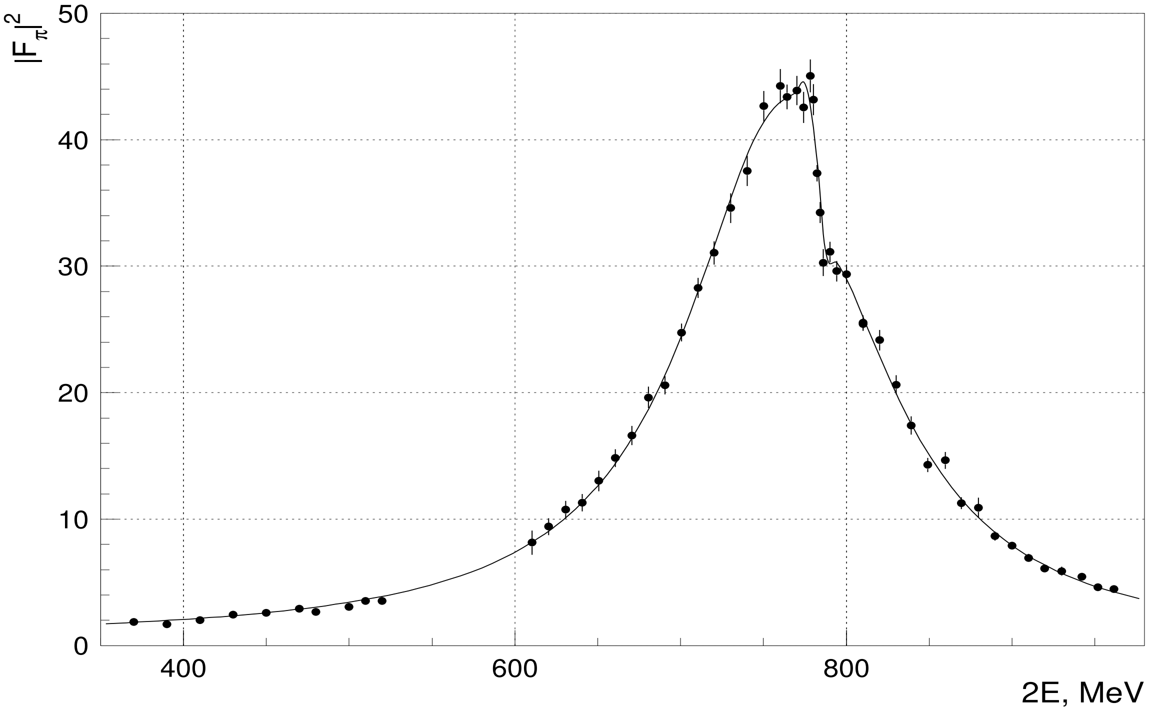


Figure 1. The pion form factor vs c.m.energy and the fit with Gounaris-Sakurai parametrisation .

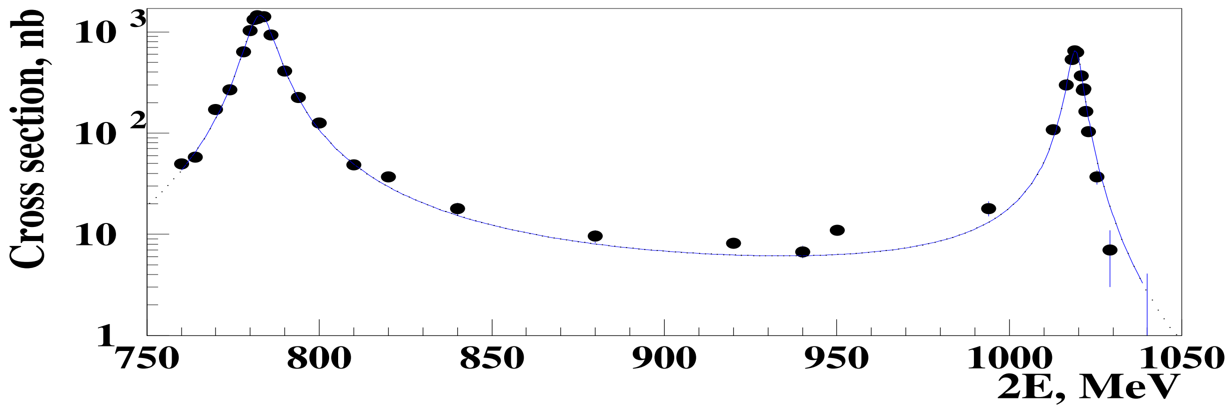
The common excitation curve for the ω and ϕ meson is presented in Fig. 2.

4. MEASUREMENTS OF ϕ MESON PARAMETERS

The ϕ-meson parameters were measured using data on the four major decay modes of $\phi \to K_S K_L$, K^+K^-, 3π, $\eta\gamma$. The first results based on a relatively small integrated luminosity of about 300 nb^{-1} were published in [8]. The new more precise results were obtained for the channel $\phi \to K_L^0 K_S^0$ when K_S^0 decays into a $\pi^+\pi^-$. The data sample was collected in four scans of the energy range from 984 to 1040 MeV with the integrated luminosity of 2.37 pb^{-1} and contains 2.97×10^5 of selected $K_L^0 K_S^0$. The following parameters have been obtained from the fit: $\sigma_0(\phi \to K_L^0 K_S^0) = 1312 \pm 7 \pm 33$ **nb,** $M_\phi = 1019.470 \pm 0.013 \pm 0.018$ **MeV,** $\Gamma_\phi = 4.51 \pm 0.04 \pm 0.02$ **MeV,** $\Gamma_{\phi\to ee} \cdot Br(\phi \to K_L^0 K_S^0) = (4.181 \pm 0.024 \pm 0.084) \times 10^{-4}$ **MeV**.

5. SEARCH FOR RARE DECAYS $\phi \to \mu^+\mu^-, \pi^+\pi^-$

The data sample with the integrated luminosity of about 1.8 pb^{-1} was analysed. The visible cross section vs c.m.energy is presented in Fig. 3 for muons and pions . The signal of the ϕ meson is clearly seen as an interference pattern in the cross sections. Assuming e-μ universality the following result for the branching ratio $\phi \to \mu^+\mu^-$ has been obtained: $Br(\phi \to \mu^+\mu^-) = (3.26 \pm 0.14 \pm 0.17) \times 10^{-4}$. The branching ratio for the $\phi \to$



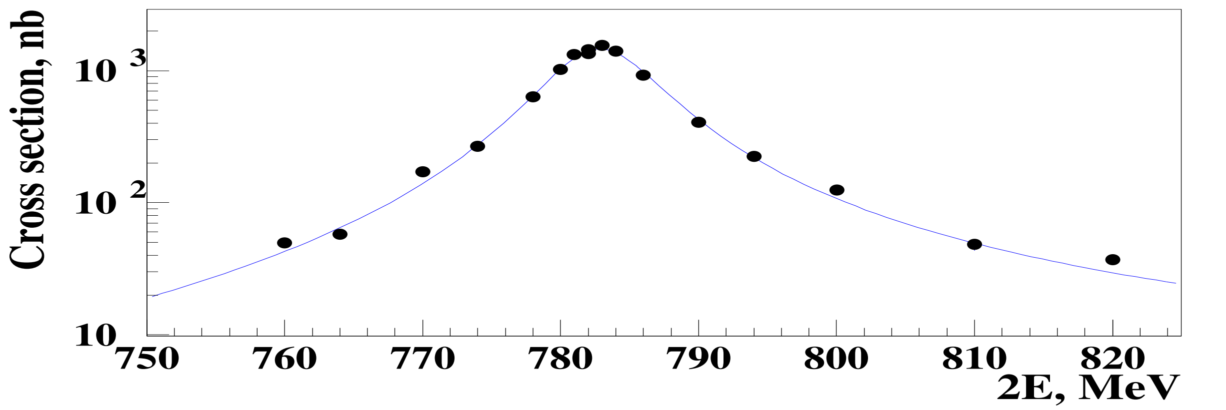


Figure 2. The upper figure - cross section vs c.m.energy and common fit for the ω, ϕ mesons. The lower figure - cross section in the energy range around ω-meson.

$\pi^+\pi^-$ decay was found to be: $Br(\phi \to \pi^+\pi^-) = (2.01 \pm 0.22 \pm 0.25) \times 10^{-4}$. The main sources of systematic errors are the luminosity measurement, muon-pion separation and uncertainty in energy measurement.

6. STUDY OF $\phi \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma$ DECAY

The radiative magnetic dipole transition of ϕ into η has been studied with the integrated luminosity of about 1.9 pb^{-1}. Events with two charged particles and one recoil photon with the energy more than 250 MeV were selected. The direction of the recoil photon should be close to the opposite direction of two charged pions. The reconstructed invariant mass of all other photons in this system forms a peak near the π^0 mass or near zero corresponding to the events of the η decay into $\pi^+\pi^-\gamma$. The small fraction of the background comes from ϕ decays into $\pi^+\pi^-\pi^0, \omega\pi^0$, $K_L^0 K_S^0$ and was subtracted according to the simulation results. Using the branching ratio for the $\phi \to e^+e^-$ decay from PDG [9], the following value for branching ratio has been determined: $Br(\phi \to \eta\gamma) = (1.18 \pm 0.03 \pm 0.06) \times 10^{-4}$.

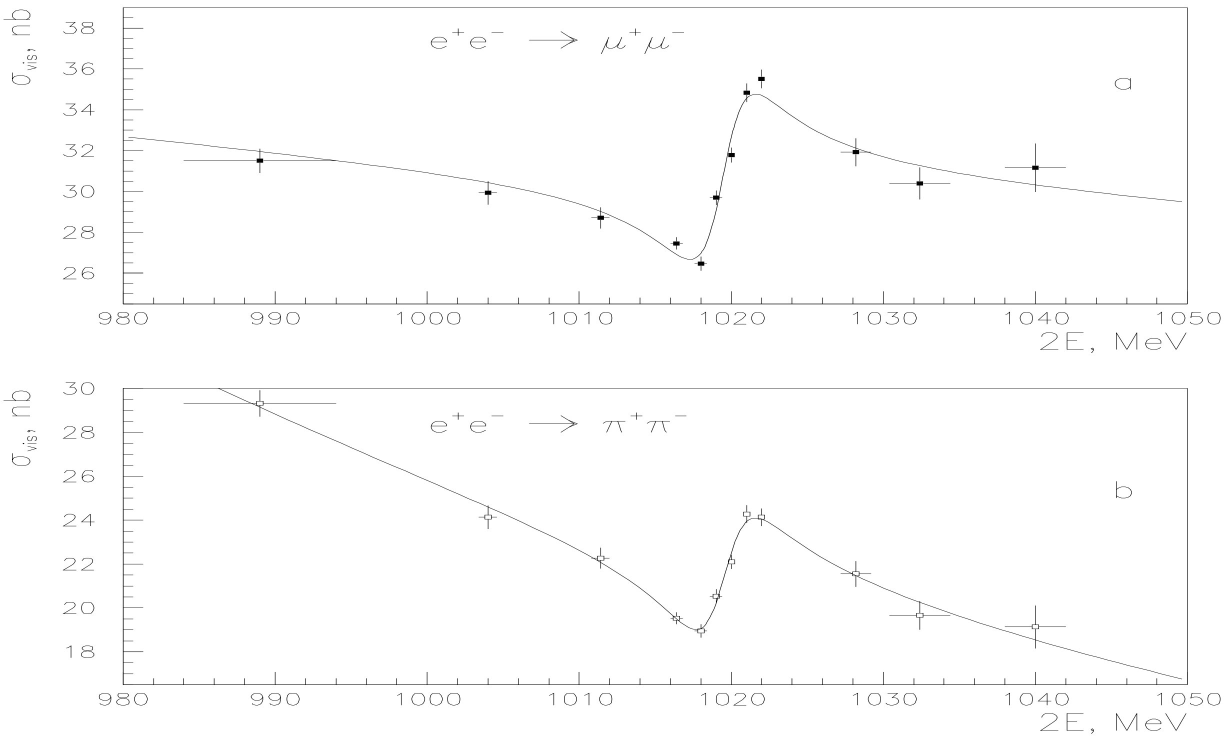


Figure 3. The upper and lower figures - cross section data and fit vs energy range around ϕ peak for the channels $e^+e^- \to \mu^+\mu^-$, $\pi^+\pi^-$ respectively.

7. STUDY OF $\phi \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$ DECAY

The data analysis was done with the integrated luminosity of about 14 pb^{-1}. It is a pure neutral channel with seven photons in the final state. Of these seven photons there is one monochromatic with the energy 362 MeV. Other photons have been pairing to form π^0 by combinatorial way and the combination with the best χ^2 was chosen. The constrained fit with the requirement of energy-momentum conservation was applied to events. The detection efficiency was obtained by simulation and was found to be (10.8±0.1)%. After background subtraction, mostly coming when $K_L^0K_S^0$ events decaying into neutrals, 8826±101 signal events were selected and the following branching ratio has been obtained: $Br(\phi \to \eta\gamma) = (1.24 \pm 0.02 \pm 0.06) \times 10^{-4}$.

8. OBSERVATION OF $\phi \to \eta'\gamma$ DECAY

A search of this rare radiative decay was performed with the integrated luminosity of about 14 pb^{-1} at 14 energy points around the ϕ meson when η' decays into $\pi^+\pi^-\eta$. The analysis of events has been performed using three different decay modes of η: a. $\eta \to \gamma\gamma$, b. $\eta \to \pi^+\pi^-\gamma$ and c. $\eta \to \pi^+\pi^-\pi^0$.

For the first case (a), there are two charged pions and three photons in the final state. The monochromatic recoil photon has a fixed energy of 60 MeV. The invariant mass of two other (more hard) photons should equal M_η. The main source of the background comes from the decay $\phi \to \eta\gamma$ when η decay into $\pi^+\pi^-\pi^0$. In this case the final state has the same particles but their kinematics is drastically different. The hardest photon is monochromatic with the energy 362 MeV and the invariant mass of two others is M_{π^0}. The decay $\phi \to \eta\gamma$ is two orders of magnitude more probable and it is a source of main background. The branching ratio of $Br(\phi \to \eta'\gamma)$ was calculated relative to $Br(\phi \to \eta\gamma)$. This ratio is not sensitive to systematic uncertainties from luminosity, detector inefficiency, resolution and so on. Using the values of the all needed branching ratios from PDG [9] the following result has been obtained: $Br(\phi \to \eta'\gamma) = (0.82^{+0.21}_{-0.19} \pm 0.10) \times 10^{-4}$.

For the second(b) and third(c) decay modes of η there are four charged particles and two or three photons in the final state. The softest photon is monochromatic with the energy of 60 MeV. One of the combinations of two particles with opposite charges has to form a missing mass to M_{π^0} or zero. The kinematic constrained fit with additional angular cuts was applied to select events with the best χ^2. The main source of the background comes from decays: $\phi \to K^0_S K^0_L$ when $K^0_S \to \pi^+\pi^-$ and $K_L \to \pi^+\pi^-\pi^0$. The number of these background events was subtracted according to the simulation results. The following result has been obtained : $Br(\phi \to \eta'\gamma) = (0.58 \pm 0.18 \pm 0.15) \times 10^{-4}$.

9. SEARCH FOR $\phi \to \pi^+\pi^-\gamma$, $\pi^0\pi^0\gamma$, $\eta\pi^0\gamma$ DECAYS

The data with the integrated luminosity of 14.8 pb^{-1} corresponding to about 20 million ϕ decays were used for this analysis. The events with two charged particles and one photon, as well as only five photons in the final state were selected. The signal from $\phi \to \pi^+\pi^-\gamma$ decay was studied as an interference pattern with the dominated bremsstrahlung background in the energy dependence cross section as well as in the photon spectra around 50 MeV region. The analysis of these spectra indicates some enhancement of events over bremsstrahlung spectra. Under the assumption that the intermediate $f_0(980)\gamma$ state dominates in $\phi \to \pi^+\pi^-\gamma$ decay [10], the corresponding branching ratio was found: $\mathbf{Br}(\phi \to f_0\gamma) = (1.93 \pm 0.46 \pm 0.50) \times 10^{-4}$.

The $\phi \to \pi^0\pi^0\gamma$ decay with the intermediate $f_0(980)\gamma$ mechanism can help to understand the f_0 structure. The constrained fit with the requirement of energy-momentum and conservation removes the background from the decays: $e^+e^- \to K^0_L K^0_S$ with $K_S \to \pi^0\pi^0$ decay, $e^+e^- \to \omega\pi^0$ with $\omega \to \pi_0\gamma$ decay and $e^+e^- \to \eta\gamma$ when η decay into $3\pi^0$ with two lost photons. 268 ± 27 $\pi^0\pi^0\gamma$ events have been found after background subtraction. If $\phi \to \pi^0\pi^0\gamma$ decay goes only through the f_0 intermediate state [10], the following branching ratio can be obtained: $\mathbf{Br}(\phi \to f_0\gamma) = (2.90 \pm 0.21 \pm 1.54) \times 10^{-4}$.

The same five photons event sample was used to search for the $\phi \to \eta\pi^0\gamma$ decay when η decays into two photons. Two of the softest photons have to pair into the π^0 mass and two other remaining most energetic photons have to pair into the η mass. The constrained fit, finding the best combination of the photon pairs, was performed. The number of $\eta\pi^0\gamma$ events was found to be: 80 ± 22 after background subtraction. Under the assumption that the intermediate $a_0(980)\gamma$ state dominates in this decay [10], the corresponding branching ratio is: $\mathbf{Br}(\phi \to a_0\gamma) = (0.90 \pm 0.24 \pm 0.10) \times 10^{-4}$. The systematic error comes from the uncertainty of the background subtraction and of the number of $\phi's$ taken for normalisation.

10. DIRECT OBSERVATION OF $K_S^0 \to \pi e \nu$ DECAY

While the semileptonic decays of K_L^0 have been well measured, the information on the similar decays of K_S^0 is extremely scarce. PDG evaluates the corresponding decay rate indirectly using the K_L^0 semileptonic decays and assuming the rule: ΔS=ΔQ.

We present results of the direct measurement of the branching ratio for $K_S^0 \to \pi e \nu$ decay using the unique opportunity to study events containing a pure $K_L^0 K_S^0$ system in the final state produced in the reaction: $e^+e^- \to \phi \to K_L^0 K_S^0$. The data with the integrated luminosity of 14.8 pb^{-1} were used for this analysis. After applying selection criteria and background subtraction the corresponding number of the events was found to be: $N = 75 \pm 13$. Using the $K_S^0 \to \pi^+\pi^-$ decay for normalisation, the following branching ratio was obtained: $Br(K_S^0 \to \pi e \nu) = (7.19 \pm 1.35) \times 10^{-4}$. This result is consistent with the PDG value obtained by recalculation from K_L^0 semileptonic rates.

11. STUDY OF THE CONVERSION DECAYS

Conversion decays, when a virtual photon is converted into a lepton pair, are closely related to corresponding radiative decays. The branching ratios for conversion decays $\phi \to \eta e^+e^-$, $\phi \to \pi^0 e^+e^-$ as well as Dalitz decay $\eta \to e^+e^-\gamma$ were determined using a data sample with the integrated luminosity of $15.5 pb^{-1}$.

The decay $\phi \to \eta e^+e^-$ was detected via the mode $\eta \to \gamma\gamma$ and the $\eta \to 3\pi^0$, the decay $\phi \to \pi^0 e^+e^-$ – via the $\pi^0 \to \gamma\gamma$ and the decay $\eta \to e^+e^-\gamma$ – via the mode $\phi \to \eta\gamma$. The process $\phi \to \eta\gamma$, $\eta \to \pi^+\pi^-\gamma$ was used to determine the number of ϕ-mesons.

Events were selected with two charged particles in DC and photons in the calorimeter. These events were subject to the kinematic fit with energy-momentum conservation. The conversion decays have a peculiar feature of their kinematics: the angle between e^+ and e^- is as a rule close to zero.

The significant background for these events comes from the γ-quantum conversion in the detector material. The detection efficiencies for these processes were determined by simulation. The decay $\phi \to \pi^0 e^+e^-$ has background from $\phi \to \pi^+\pi^-\pi^0$ via the same final state. This background was suppressed by using the information about energy deposition by electrons and pions in the calorimeter. As a result the following branching ratios were obtained:

$Br(\phi \to \eta e^+e^-) = (1.01 \pm 0.14 \pm 0.15) \times 10^{-4}$ when $\eta \to \gamma\gamma$,

$Br(\phi \to \eta e^+e^-) = (1.20 \pm 0.22 \pm 0.18) \times 10^{-4}$ when $\eta \to \pi^0\pi^0\pi^0$,

$Br(\phi \to \pi^0 e^+e^-) = (1.23 \pm 0.33 \pm 0.20) \times 10^{-5}$, $Br(\eta \to e^+e^-\gamma) = (6.85 \pm 0.60 \pm 1.00) \times 10^{-3}$. The obtained results are in agreement with the theoretical predictions and have better statistical accuracy than previous measurements quoted by PDG.

12. CONCLUSION

For the first time the rare $\phi \to \eta'\gamma$ decay was measured in three different channels. This measurement complete a list of the magnetic dipole transitions between vector and pseudoscalar mesons and it is a milestone for the theory of radiative decays. Our results on the electric dipole transitions confirm earlier observations of the decay modes $\phi \to \pi^0\pi^0\gamma$, $\eta\pi^0\gamma$ by SND [11] while the $\phi \to \pi^+\pi^-\gamma$ decay was observed for the first time. New results, not mentioned in this paper, were obtained using the tagged kaons and η mesons. Some of them are outlined in the Table.

13. TABLE - RESULTS OF CMD-2 EXPERIMENTS

	CMD-2 Data	PDG'98
$Br(\phi \to \mu^+\mu^-\gamma)$	$(1.43 \pm 0.45 \pm 0.14) \cdot 10^{-5}$	$(2.3 \pm 1.0) \cdot 10^{-5}$
$Br(\phi \to \rho\gamma)$	$< 1.2 \cdot 10^{-5}$	$< 7 \cdot 10^{-4}$
$Br(\phi \to \rho\gamma\gamma)$	$< 5 \cdot 10^{-4}$	no data
$Br(\phi \to \eta\pi^+\pi^-)$	$< 3 \cdot 10^{-4}$	no data
$Br(\phi \to \pi^+\pi^-\pi^+\pi^-)$	$(5.4 \pm 1.6 \pm 2.0) \cdot 10^{-6}$	$< 8.7 \cdot 10^{-4}$
$Br(\rho \to e^+e^-)$	$(4.67 \pm 0.15) \cdot 10^{-5}$	$(4.49 \pm 0.22) \cdot 10^{-5}$
$Br(\rho \to \pi^+\pi^-\pi^+\pi^-)$	$< 2 \cdot 10^{-5}$	$< 2 \cdot 10^{-4}$
$Br(K^+ \to \pi^+\pi^0)$	$(21.69 \pm 0.48 \pm 1.03)\%$	$(21.16 \pm 0.14)\%$
$Br(K^+ \to \pi^0 e^+\nu)$	$(4.89 \pm 0.17 \pm 0.17)\%$	$(4.82 \pm 0.06)\%$
$Br(\eta \to \pi^+\pi^- e^+e^-)$	$(3.5 \pm 2.0) \cdot 10^{-4}$	$(13^{+12}_{-8}) \cdot 10^{-4}$
$Br(\eta \to \pi^+\pi^-)$	$< 3.3 \cdot 10^{-4}$	$< 9 \cdot 10^{-4}$
$Br(\eta \to \pi^0\pi^0)$	$< 5 \cdot 10^{-4}$	no data

This work is supported in part by the grants: RFBR-98-02-17851, RFBR-99-02-17053, RFBR-99-02-17119, INTAS 96-0624.

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