Rare Φ Decays and Exotic Hadrons

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1 Introduction

Exotic hadrons re those whose structure differs from the usual $q_1\overline{q_2}$ structure for mesons and $q_1q_2q_3$ for baryons. Their exotic nature could reveal itself in unusual properties, for example, suppressed or enhanced decays, too wide or too narrow decay widths, or quantum numbers forbidden in the conventional structure. Up to now, among the huge variety of hadrons, about 10 candidates were found which look like exotic states. In the scalar meson sector, the lowest lying states $f_0(980)$ and $a_0(980)$ are candidates for exotic hadrons. The main motivations for this are their suppressed production in J/Ψ decays, their low widths to $\gamma\gamma$, and their low masses.

More generally, one might describe the f_0 and a_0 mesons with one of three models [1]—a conventional $q\overline{q}$ model, a molecular model $(K\overline{K})$, and a 4-quark model $(q\overline{q}q\overline{q})$. The $q\overline{q}$ model is only barely consistent with experimental data. It was proposed more than ten years ago that the measurement of the radiative decays $\phi \to f_0\gamma$, $\phi \to a_0\gamma$ was a sensitive test that could distinguish these models [2].

These decays were studied recently in the reactions:

$$e^+e^- \to \phi \to \pi^0\pi^0\gamma\ , \quad \pi^+\pi^-\gamma \tag{1}$$

$$e^+e^- \to \phi \to \eta\pi^0\gamma\ , \tag{2}$$

which could proceed via the radiative decay $\phi(1020) \to f_0\gamma$, $a_0\gamma$. We measured the branching ratios of these decays and of other rare decays of ϕ and $\rho(770)$, $\omega(783)$. In this talk, I will report the results. Other experimental data from Novosibirsk and from IHEP, Protvino, will also be reviewed.

2 Experiment

The experiments on the reactions (1), (2) have been carried out at the VEPP-2M collider in the range of collider energy $2E$ from 0.4 to 1.4 GeV. VEPP-2M is the

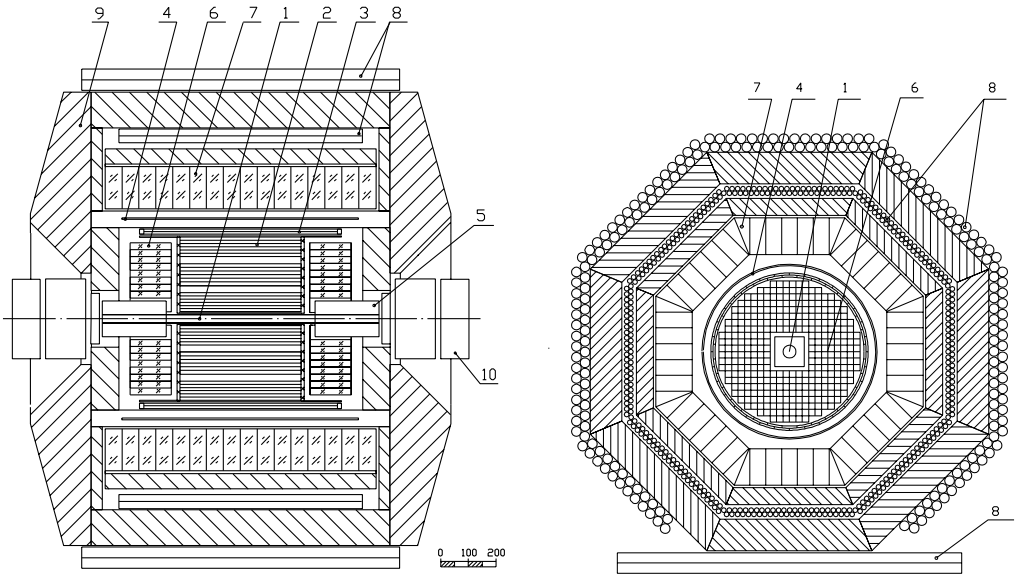

Figure 1: Layout of the CMD-2 detector; 1 - beam pipe; 2 - drift chamber; 3 - Z-chamber; 4 - superconductive solenoid; 5 - compensating magnet; 6 - endcap BGO calorimeter; 7 - barrel CsI(Tl)calorimeter; 8 - muon range system; 9 - yoke; 10 - quadrupole lenses

lowest energy e^+e^- collider at Novosibirsk, and has operated since 1974. The collider luminosity L depends sharply on the beam energy E, according to $L \sim E^4$. At the energy $2E = M_\phi$, the collider reaches its maximum luminosity $L_{\max} = 5 \cdot 10^{30} \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

At present, two detectors CMD-2 and SND, located opposite each other, are taking data. CMD-2 [3] is a magnetic detector (Fig. 1) with a superconducting solenoid and a 20-layer drift chamber with jet cell structure. Its electromagnetic calorimeter consists of 892 CsI(Tl) crystals in the barrel and of 680 BGO crystals in the endcaps. The muon identification is provided by 4-layers of streamer tubes inside the yoke. The CMD-2 detector has operated at VEPP-2M since 1992 and has collected about 27 pb^{-1} of integrated luminosity.

SND [4] is a general purpose nonmagnetic detector (Fig. 2). The main part of SND is a 3-layer spherical electromagnetic calorimeter with 1625 NaI(Tl) crystals, a total weight of 3.6 T. The detector includes also a 10-layer drift chamber and an outer muon system consisting of streamer tubes and plastic scintillation counters. SND resembles the famous Crystal Ball detector constructed at SLAC, but, unlike the Crystal Ball, it has a 3-layer crystal calorimeter, which provides better discrimination among $e/\pi/\mu$ and γ/K_L. The integrated luminosity accumulated by SND since 1995 is about 27 pb^{-1}.

The two detectors take data in parallel. The number of events collected at the vector meson resonances is: $N_\phi \simeq 4.5 \cdot 10^7$, $N_\rho \simeq 4 \cdot 10^6$, $N_\omega \simeq 2.5 \cdot 10^6$. About half of the total time was used for scanning the energy range away from the resonances with the goal of precisely measuring the quantity $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ and of studying particular channels of e^+e^--annihilation.

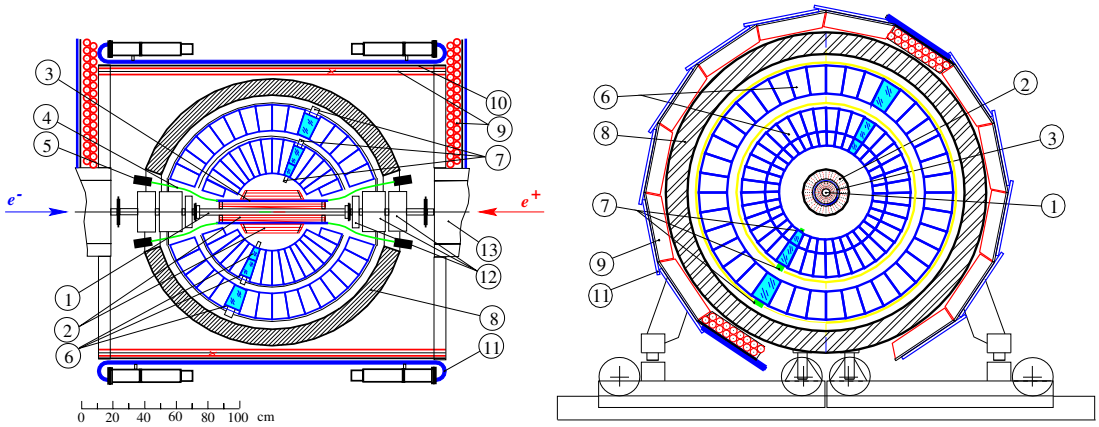

Figure 2: Layout of the SND detector; 1 - beam pipe, 2 - drift chambers, 3 - scintillation counter, 4 - light guides, 5 - PMTs, 6 - NaI(Tl) crystals, 7 - vacuum phototriodes, 8 - iron absorber, 9 - streamer tubes, 10 - iron plates, 11 - plastic scintillators, 12 and 13 - collider magnets

3 Evidence for the decays $\phi \to f_0\gamma$, $a_0\gamma$

The first search for the decays $\phi \to f_0\gamma, a_0\gamma \to \pi^0\pi^0\gamma$, $\eta\pi^0\gamma$ was carried out with the ND detector [5] at the VEPP-2M collider in 1987 [6, 7]. That early experiment placed upper limits on the decay branching ratios at a level $\sim 10^{-3}$. Later, it was shown by N. Achasov [2] that the study of these decays can provide unique information on the structure of lightest scalars f_0 and a_0. Subsequent studies verified this idea. Thus, in 1995, experiments were begun at VEPP-2M with the SND detector [4], which has photon detection capabilities much better than ND. The study of the decays $\phi \to f_0\gamma$, $a_0\gamma \to \pi^0\pi^0\gamma$, $\eta\pi^0\gamma$ was one of the important goals of the SND detector. In 1997, the first results from SND [8] were reported, giving evidence for the processes (1), (2).

The reaction (1) was studied by SND in the all-neutral final state:

$$e^+e^- \to \phi \to \pi^0\pi^0\gamma \ . \tag{3}$$

Thus, both processes (1) and (2) were studied in using the 5-photon final state. The main background comes from the following reactions:

$$e^+e^- \to \phi \to \eta\gamma \to 3\pi^0\gamma \tag{4}$$

$$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma \tag{5}$$

$$e^+e^- \to K_S K_L \to neutrals\ . \tag{6}$$

In order to suppress background, SND selected events with 5 photons satisfying energy-momentum balance. The final state was required to contain $2\pi^0$ for the process (3) or $\eta\pi^0$ for (2). The contribution of the reaction (4) in the event sample for the process (2) was suppressed by a cut on the maximum energy of the photon in an event. For suppression of the process (5), cuts were imposed on the $\pi^0\gamma$ effective mass, to exclude the region around the $\omega(783)$ mass. The processes (4) and (6) were suppressed by a cut on a parameter describing the transverse shower profile in the calorimeter [9].

Under the chosen selection criteria, the detection efficiency was determined to be 15% and 4%, respectively, for (3) and (2). In the experimental data sample with integrated luminosity 4 pb^{-1}, corresponding to $2 \cdot 10^7$ produced ϕ mesons, about 150 events of process (3) were found. This gave about 70 events of the process (2) in the full SND data sample.

The angular distributions of the processes (2) and (3) were studied in [10, 11]. It was shown that the distribution of the polar angle θ of the recoil photon is proportional to $(1 + \cos^2\theta)$. The angle ψ was defined as the angle between a pion direction in the $\pi^0\pi^0$ or $\eta\pi^0$ center of mass reference frame and the recoil photon direction. The distribution in $\cos\psi$ was found to be flat. So, the experimental data confirm the conclusion that the $\pi^0\pi^0$ and $\eta\pi^0$ systems are produced in this reaction in a scalar state.

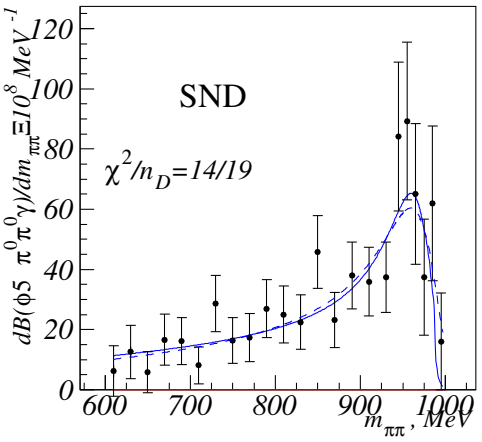

Figure 3: The $\pi^0\pi^0$ mass distribution in the process $e^+e^- \to \pi^0\pi^0\gamma$

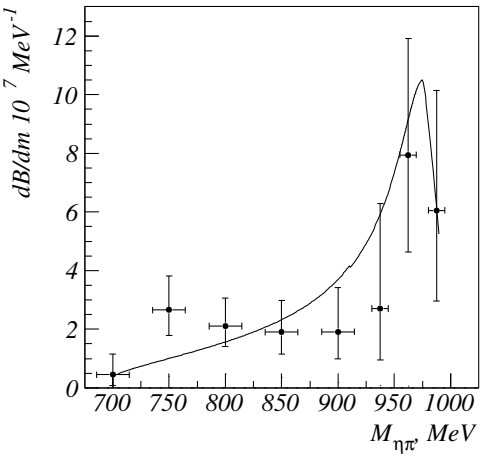

Figure 4: The $\eta\pi^0$ mass distribution in the process $e^+e^- \to \eta\pi^0\gamma$

The important information for the interpretation of the data is contained in the $\pi^0\pi^0$ and $\eta\pi^0$ mass spectra. Figs. 3 and 4 show these mass spectra after background

subtraction and detection efficiency corrections. Both pictures show a considerable rise in the spectra at higher masses. A peak is visible in both spectra near 960 MeV. A table with the numerical values of the $\pi^0\pi^0$ mass distribution can be found in [10].

Combining the data from the mass spectra in Figs. 3 and 4 and from the CMD-2 experiment, one can obtain the branching ratios for particular mass ranges:

1. SND result for $m_{\pi\pi} > 900$ MeV [10]:

$$B(\phi \to \pi^0\pi^0\gamma) = (0.50 \pm 0.06 \pm 0.06) \cdot 10^{-4} \ . \tag{7}$$

2. SND result for the whole mass spectrum [10]:

$$B(\phi \to \pi^0\pi^0\gamma) = (1.14 \pm 0.10 \pm 0.12) \cdot 10^{-4} \ . \tag{8}$$

Here and below, the first error is statistical while the second one is systematic, determined mainly by the background subtraction error, detection efficiency error and normalization error.

3. CMD-2 result for $m_{\pi\pi} > 700$ MeV [12]:

$$B(\phi \to \pi^0\pi^0\gamma) = (0.92 \pm 0.08 \pm 0.06) \cdot 10^{-4} \ . \tag{9}$$

4. SND result for $m_{\eta\pi^0} > 950$ MeV [13]:

$$B(\phi \to \eta\pi^0\gamma) = (0.36 \pm 0.11 \pm 0.03) \cdot 10^{-4} \ . \tag{10}$$

5. SND result for the whole mass spectrum [13]:

$$B(\phi \to \eta\pi^0\gamma) = (0.87 \pm 0.14 \pm 0.07) \cdot 10^{-4} \ . \tag{11}$$

6. CMD-2 result for the whole mass spectrum [12]:

$$B(\phi \to \eta\pi^0\gamma) = (0.90 \pm 0.24 \pm 0.10) \cdot 10^{-4} \ . \tag{12}$$

All of the results listed above are practically model-independent because they do not make use of any assumption about the f_0 or a_0 contributions to the final state. If we assume f_0 and a_0 dominance in the final state, make use of the relation based on isotopic invariance $B(\phi \to \pi^+\pi^-) = 2B(\phi \to \pi^0\pi^0)$, and neglect the decay $\phi \to KK\gamma$, we can obtain the branching ratios for the decays $\phi \to f^0\gamma$ and $\phi \to a^0\gamma$:

7. SND result [10]:

$$B(\phi \to f^0\gamma) = (3.42 \pm 0.30 \pm 0.36) \cdot 10^{-4} \ . \tag{13}$$

8. SND result [13]:

$$B(\phi \to a^0\gamma) = (0.87 \pm 0.14 \pm 0.07) \cdot 10^{-4} \ . \tag{14}$$

9. CMD-2 result [12]:

$$B(\phi \to f^0\gamma) = (2.90 \pm 0.21 \pm 1.54) \cdot 10^{-4} \ . \tag{15}$$

An analysis of the $\pi^0\pi^0$ mass spectrum was carried out on the basis of the theory presented in [2]. The spectrum was described by a sum of contributions from f_0 and σ mesons [14]. The width of f_0 meson in the approximation of 'broad resonance' was taken to depend on the product of coupling constants $g_{\phi KK} \cdot g_{fKK}$. The f_0 fit parameters were the mass m_f, the coupling constant $g^2_{fKK}/4\pi$, and the ratio of coupling constants $g^2_{fKK}/g^2_{f\pi\pi}$. The optimal fit parameters obtained were [14]:

$$\begin{aligned} m_f &= 971 \pm 6 \text{ MeV} \ , \qquad \Gamma_f = 188^{+48}_{-33} \text{ MeV} \ , \\ \frac{g^2_{fKK}}{4\pi} &= 2.10^{+0.88}_{-0.56} \text{ GeV}^2 \ , \qquad \frac{g^2_{fKK}}{g^2_{f\pi\pi}} = 4.1 \pm 0.9 \ . \end{aligned} \tag{16}$$

The statistical accuracy did not allow one to determine the contribution of the σ in the fit; for the fit parameters given in (16), the σ was excluded.

The $\eta\pi^0$ mass spectrum was also fit by the formulae from [2], but because of the lower statistics, the ratio of coupling constants was fixed to be $g_{a\eta\pi}/g_{aKK} = 0.85$ [2]. The values obtained as the optimal parameters of the a_0 were:

$$m_a = 992^{+22}_{-7} \text{ MeV} \ , \qquad \frac{g^2_{aKK}}{4\pi} = 1.09^{+0.33}_{-0.24} \text{ GeV}^2 \ . \tag{17}$$

The value of a_0 mass obtained in the fit is consistent with the PDG value. If the a_0 mass is fixed at the PDG value, one obtains a more accurate value of the coupling constant:

$$\frac{g^2_{aKK}}{4\pi} = 0.83 \pm 0.13 \text{ GeV}^2 \ . \tag{18}$$

CMD-2 carried out a search for the decay $\phi \to \pi^+\pi^-\gamma$ in the reaction [15]:

$$e^+e^- \to \phi \to \pi^+\pi^-\gamma \ , \tag{19}$$

with the goal of finding a contribution of the $f_0 \to \pi^+\pi^-$ channel to the final state. In contrast to the neutral channel $f_0 \to \pi^0\pi^0$, there is a significant background from the nonresonant process $e^+e^- \to \rho\gamma \to \pi^+\pi^-\gamma$ and interference with the processes $e^+e^- \to \phi \to \pi^+\pi^-\gamma$ and $e^+e^- \to \rho \to \pi^+\pi^-\gamma$. It was found that the energy dependence of the cross section for the process (19) exhibits interference effects near the point $2E = M_\phi$. The recoil photon energy spectrum (Fig. 5) shows a peak at $E_\gamma \simeq 220$ MeV due to the process $e^+e^- \to \rho\gamma$ and an enhancement at $E_\gamma \simeq 50$ MeV from the decay $f_0 \to \pi^+\pi^-$. The value of 50 MeV roughly corresponds to the mass difference between the ϕ and the f_0 meson. To obtain the branching ratio $B(\phi \to \pi^+\pi^-\gamma)$, the fitting of photon spectra at different energy points was done

using formulae from the paper [16], which include the contributions of the background reactions and the $f_0 \to \pi^+\pi^-$ decay. The optimal value of the f_0 mass was found be $m_f = 976 \pm 5$ MeV, and the branching ratio was found to be

$$B(\phi \to f_0\gamma) = (1.93 \pm 0.46 \pm 0.59) \cdot 10^{-4} \ . \tag{20}$$

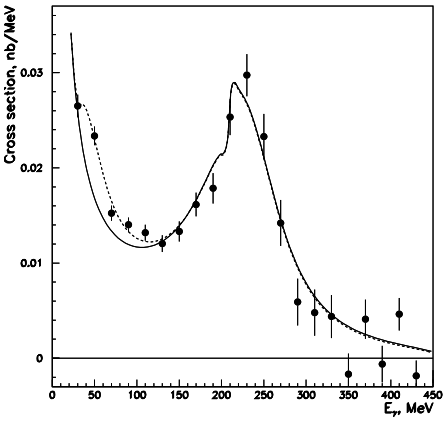

Figure 5: The recoil photon spectrum in the process $e^+e^- \to \pi^+\pi^-\gamma$

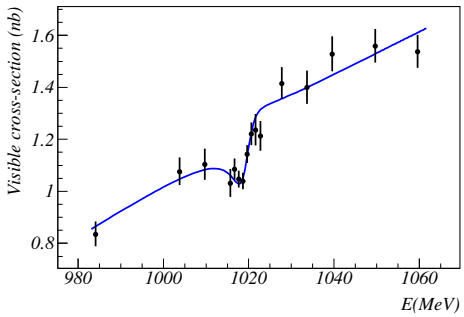

Figure 6: The detected cross section for the process $e^+e^- \to \omega\pi^0$ near the ϕ meson energy.

4 Discussion of the decays $\phi \to f_0\gamma$, $a_0\gamma$

In the list of new VEPP-2M results, (7)–(12) are model independent because they are based only on the total numbers of events in the defined samples. The results (13)–(18) depend on the use of certain theoretical assumptions. For example, the determination of $B(\phi \to f_0\gamma)$ in (13) and (15) is based on the assumption of f_0 dominance in the final $\pi^0\pi^0$ state. The main parameters of f_0 and a_0, including the masses, widths, and coupling constants, were obtained from the description of these decays proposed by Achasov [2], so these parameters are also strongly model dependent. Below we give a conclusion on the nature of the f_0 and a_0 scalars which follows from the model dependent results (13)–(18) and the considerations of [1].

There are three models that can be used to describe the structure of the f_0 and a_0 scalars: the $q\overline{q}$ model ($d\overline{d}$ or $s\overline{s}$), the molecular model ($K\overline{K}$), and the 4-quark model ($q\overline{q}q\overline{q}$). The generally accepted opinion is that f_0 and a_0 are difficult to fit into the $q\overline{q}$ model. This opinion is based on the existing experimental data. For instance, the decays $J/\psi \to f_0\gamma$, $f_0\omega$, and $a_0\rho$ are considerably suppressed in comparison with similar decays in which, instead of f_0 and a_0, the tensor mesons f_2 or a_2 are produced.

If f_0 and a_0 were $q\overline{q}$ mesons, their production in J/ψ decays would be of the same order as the production of tensor mesons.

Another example is given by the two-photon width of f_0 and a_0. The experimental value $\Gamma \simeq 0.3$ keV is smaller than the value 0.6 keV predicted for the $K\overline{K}$ model and value $0.6 - 15.$ keV for $q\overline{q}$ model. But the four-quark model prediction (0.3 keV) agrees with experiment.

Model	$d\overline{d}$	$s\overline{s}$	$K\overline{K}$	$q\overline{q}s\overline{s}$	Expt.
$B(\phi \to f_0\gamma) \cdot 10^4$	0.45	0.55	0.1	2.5	3.0 ± 0.4
$B(\phi \to a_0\gamma) \cdot 10^4$	0.25	—	0.1	2.0	0.88 ± 0.13

Table 1: Comparison of the VEPP-2M data with different f_0 and a_0 models.

The measurement of the radiative decays $\phi \to f_0\gamma$, $a_0\gamma$ were long awaited as a new test of the f_0 and a_0 nature. Table 1 shows the comparison of different model predictions with the average of the VEPP-2M experimental data reported in the previous section. The accuracy of the model predictions [1] is about 50%. The conclusion from Table 1 is that the VEPP-2M data are in good agreement with the four-quark model of f_0 and a_0. But, we remind the reader that experimental data in Table 1 assume that f_0 and a_0 dominate in the final state of the reactions (1) and (2). This assumption is in good agreement with the experimental spectra, but the present accuracy is not sufficient to exclude contributions of other scalars to the final state.

There is one further remark on the decay $\phi \to a_0\gamma$. The branching ratio for this decay is close to that of $\phi \to \eta'\gamma$. This means that a_0 should contain strange quarks, as the η' does. This is impossible for a $q\overline{q}$ isovector meson, but it is quite natural if the a_0 is a four-quark $q\overline{q}s\overline{s}$ meson.

This discussion was based mainly on the work [1], where more detailed analyses of the existing data for f_0 and a_0 mesons may be found.

5 Other rare ϕ decays

The large number of produced ϕ mesons at both the SND and CMD-2 detectors ($N_\phi \simeq 4.5 \cdot 10^7$) allows us to carry out searches for rare ϕ decays. The long awaited decay $\phi \to \eta'(958)\gamma$ was observed for the first time by CMD-2 [17]. Using the decay chain $\phi \to \eta'\gamma$, $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$. The branching ratio was found to be $(8.2^{+2.1}_{-1.9}) \cdot 10^{-5}$. For another chain, with $\eta' \to \pi^+\pi^-\pi^0(\gamma)$, the CMD-2 result for the branching ratio was $(5.8 \pm 1.8) \cdot 10^{-5}$ [18]. Later, SND confirmed the existence of the decay $\phi \to \eta'\gamma$, giving the branching ratio of $6.7^{+3.4}_{-2.9} \cdot 10^{-5}$ [19]. The clear signature of the decay $\phi \to \eta'\gamma$ is demonstrated in Figs. 7 and 8. The averaged value of the branching ratio is $B(\phi \to \eta'\gamma) = (6.9 \pm 1.2) \cdot 10^{-5}$. The statistical significance is greater than 5

standard deviations. This result is in agreement with the nonrelativistic quark model prediction of $(6-10)\cdot 10^{-5}$ [20]. At the present level of the accuracy, no significant admixture of gluonium in the η' is seen.

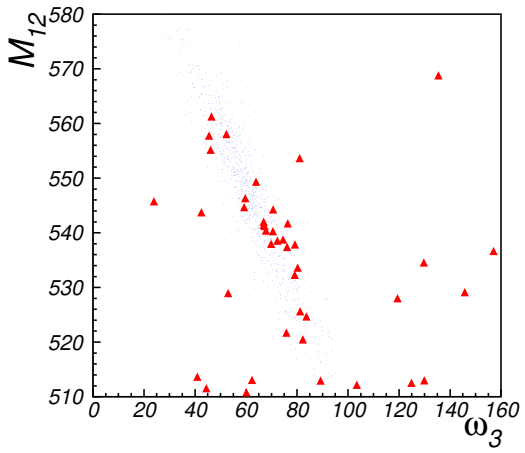

Figure 7: Two-photon invariant mass in $\eta \to \gamma\gamma$ decay vs. recoil photon energy in a search for $\phi \to \eta'\gamma, \eta' \to \eta\pi^+\pi^-, \eta \to \gamma\gamma$ decay.

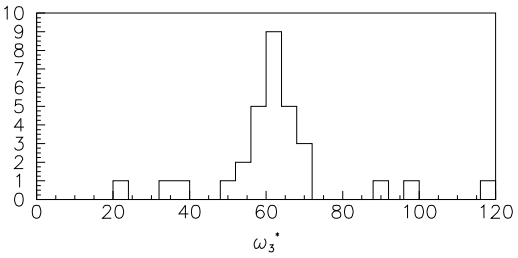

Figure 8: Recoil photon energy spectrum in the $\phi \to \eta'\gamma$ decay.

The decays $\phi \to \pi^+\pi^-, \omega\pi^0$ are double suppressed, by isospin invariance and by the OZI rule. The $\phi \to \pi^+\pi^-$ decay has already been observed. The PDG value for the branching ratio is $B(\phi \to \pi^+\pi^-) = (0.8^{+0.5}_{-0.4})\cdot 10^{-4}$. The second decay $\phi \to \omega\pi^0$ has not previously been observed. SND performed a search for this decay in the reaction [21]

$$e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0 \tag{21}$$

and found a clear interference pattern in the energy dependence of this process, shown in Fig. 6. The decay amplitudes and branching ratios were found to be [13]

$$\begin{aligned} \mathrm{Re}(Z) &= 0.112 \pm 0.015\ , \qquad B(\phi \to \omega\pi^0) = (4.6 \pm 1.2)\cdot 10^{-5} \\ \mathrm{Im}(Z) &= -0.104 \pm 0.022\ . \end{aligned} \tag{22}$$

The theoretical prediction [22] for the branching ratio is about two times larger. In particular, the real part $\mathrm{Re}(Z)$ in (22) is too low. The disagreement could be due to the existence of a direct $\phi \to \omega\pi^0$ transition or to nonstandard mixing of the light vector mesons.

In similar way, SND has studied the cross section for the process

$$e^+e^- \to \pi^+\pi^-\ . \tag{23}$$

The results of their fit are [13]:

$$\begin{aligned} \mathrm{Re}(Z) &= 0.061 \pm 0.005 \ , \qquad B(\phi \to \pi^+\pi^-) = (7.1 \pm 1.0 \pm 1.0) \cdot 10^{-5} \\ \mathrm{Im}(Z) &= -0.042 \pm 0.006 \ . \end{aligned} \tag{24}$$

The accuracy of this measurement is about three times better than that of the PDG value. But here again the SND result for the real part $\mathrm{Re}(Z)$ is lower than that predicted in [22]. The measurement also disagrees with the preliminary result of CMD-2 [23]:

$$B(\phi \to \pi^+\pi^-) = (18.1 \pm 2.5 \pm 1.9) \cdot 10^{-5} \ . \tag{25}$$

The level of the disagreement between CMD-2 and SND in $B(\phi \to \pi^+\pi^-)$ is 3 standard deviations.

Both detectors studied the rare decay $\phi \to \mu^+\mu^-$. The result of SND is [24]

$$B(\phi \to \mu^+\mu^-) = (33.0 \pm 4.5 \pm 3.2) \cdot 10^{-5} \ , \tag{26}$$

while the result of CMD-2 is [23]

$$B(\phi \to \mu^+\mu^-) = (28.0 \pm 3.0 \pm 4.6) \cdot 10^{-5} \ . \tag{27}$$

A full review of other ϕ rare decay studied at VEPP-2M can be found in [23, 25].

6 The decays $\rho, \omega \to \pi^0\pi^0\gamma$

The decays $\rho, \omega \to \pi^0\pi^0\gamma$ are of interest for the study of the possible low-mass scalar resonance σ, which should decay to $\pi\pi$. Some contributions are expected also from the decays $\rho, \omega \to \omega\pi^0$, and $\rho\pi \to \pi^0\pi^0\gamma$. In our work [7], where the $\rho \to \pi^+\pi^-\gamma$ decay was studied, an enhancement was observed at the high end of the photon bremsstrahlung spectrum. This can be interpreted as a manifestation of a light bound state, possibly the σ resonance. Later, in Protvino, the decay $\omega \to \pi^0\pi^0\gamma$ was observed with the branching ratio $(7.2 \pm 2.5) \cdot 10^{-5}$, which is about three times larger than expected in Vector Dominance Model (VDM).

In the recent paper [13], we studied the all-neutral final state in the reaction $e^+e^- \to \rho, \omega \to \pi^0\pi^0\gamma \to 5\gamma$. Figure 9 shows a 2-dimensional scatter plot of the best neutral pion candidates found in the 5-photon final state. The measured cross section was fit with a sum of the Breit-Wigner contributions from the ω and ρ resonances. The Born cross section and the fit curves are shown in Fig. 10. One can see that the measured cross section considerably exceeds the VDM prediction. The fit parameters are found to be

$$B(\omega \to \pi^0\pi^0\gamma) = (8.4^{+4.9}_{-3.1} \pm 3.5) \cdot 10^{-5} \ , \qquad \Gamma_{\omega\pi^0\pi^0\gamma} \simeq 0.7 keV \tag{28}$$

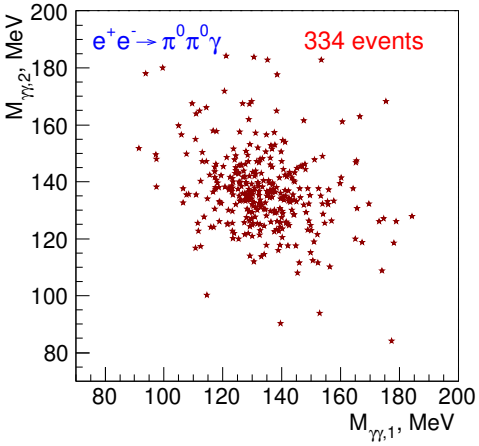

Figure 9: Two-dimensional scatter plot of the best neutral pion candidates in the search for the process $e^+e^- \to \pi^0\pi^0\gamma$.

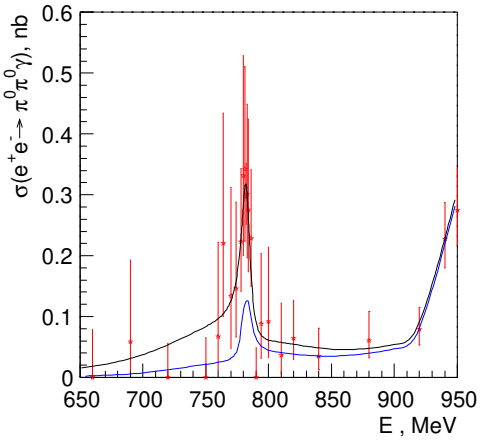

Figure 10: Born cross section for the process $e^+e^- \to \pi^0\pi^0\gamma$. The upper curve is a fit to the data; the lower curve is the VDM prediction.

$$B(\rho \to \pi^0\pi^0\gamma) = (4.2^{+2.9}_{-2.0} \pm 1.0) \cdot 10^{-5} \ , \quad \Gamma_{\rho\pi^0\pi^0\gamma} \simeq 6 \text{ keV (without } \omega\pi^0) \ . \qquad (29)$$

The result (28) confirms the PDG value of $B(\omega \to \pi^0\pi^0\gamma)$. Both branching ratios (28) and (29) are considerably higher than VDM estimates, by about a factor of 4. A possible explanation of this enhancement could be the contribution of a light scalar σ decaying into $\pi^0\pi^0$. It was suggested by Jaffe [26] that the σ could be the lightest member of the four-quark nonet with the structure $u\overline{u}d\overline{d}$. Because of the superallowed $\sigma \to \pi\pi$ decay, the σ would be very broad. The $f_0(980)$ and $a_0(980)$ would also belong to this nonet. These particles have a superallowed, but phase space suppressed decay into $K\overline{K}$. So, both $f_0(980)$ and $a_0(980)$ should have a narrow width, of order 50–100 MeV. Further investigation of the decays ϕ, ρ, $\omega \to \pi^0\pi^0\gamma$, and in particular study of the $\pi^0\pi^0$ decay mass spectra, could clarify the nature of the light scalar mesons.

7 The process $e^+e^- \to \pi^+\pi^-\pi^0$ above the ϕ resonance

The energy region above the ϕ was scanned with the goal of measuring the e^+e^--annihilation cross sections and the quantity R, the ratio of the total hadronic cross section to the muon pair production cross section. Among the processes under study, the process

$$e^+e^- \to \pi^+\pi^-\pi^0 \qquad (30)$$

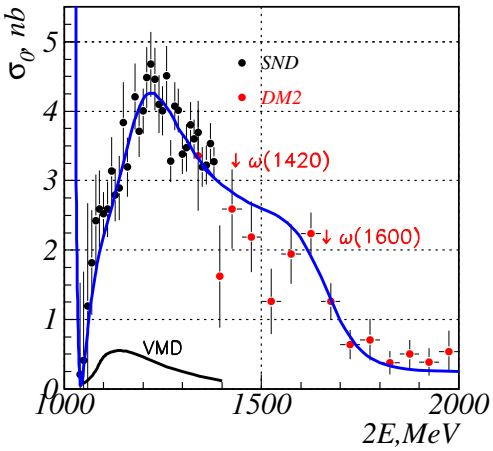

Figure 11: Born cross section for the process $e^+e^- \to \pi^+\pi^-\pi^0$ (on a linear scale)

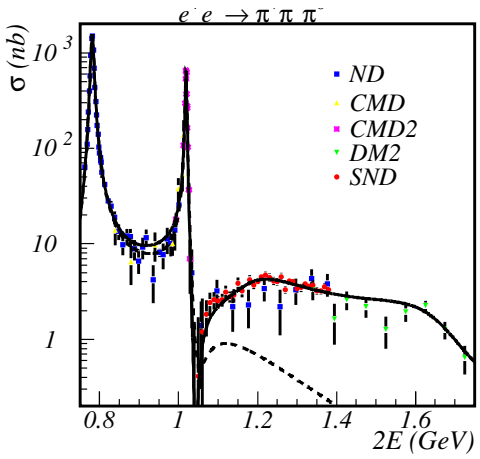

Figure 12: Born cross section for the process $e^+e^- \to \pi^+\pi^-\pi^0$ (on a logarithmic scale)

is of particular interest, because earlier it was measured with poor accuracy and because possible new isoscalar vector resonances could be found there. The study of the process (30) was done by the SND detector in the energy range $2E = 1.04$–1.38 GeV [27] .

The measured cross section, shown in Figs. 11 and 12, is in agreement with previous data from the ND experiment [7] and matches well to the DM2 measurements at higher energies [28]. The systematic error in the cross section is $\sim 10\%$, but it grows to 50% close to the ϕ because of radiative corrections. The Born cross section in Fig. 11 shows a broad peak which seems to lie at $2E \simeq 1200$ MeV. To describe the cross section in terms of a sum of vector meson contributions, a fit was done which included $\omega(783)$, $\phi(1020)$, $\omega(1600)$, and an additional ω-like state, named $\omega(1200)$, with its mass and width allowed to vary freely. For two latter resonances the widths were assumed to be independent of energy. The optimal fit parameters strongly depended on the choices for the interference phases. The best fit occurred for the following set of phases: $\phi_{\omega(783)} = 0$, $\phi_{\phi(1020)} = \pi$, $\phi_{\omega(1200)} = \pi$, $\phi_{\omega(1600)} = 0$. The parameters found for the $\omega(1200)$ are :

$$M_{eff} = 1170 \pm 10 \text{ MeV} , \quad \Gamma_{eff} = 187 \pm 15 \text{ MeV} , \quad \sigma_{\max} = 7.8 \pm 1.0 \text{ nb} . \qquad (31)$$

The parameters of the resonance $\omega(1600)$ are confirmed by the fit, but another resonance $\omega(1420)$ is not seen in our fit. If the existence of $\omega(1200)$ is confirmed, the question of its nature arises. It could be either first radial excitation 2^3S_1 of the $\omega(783)$ or a radial (D-wave) excitation 1^3D_1. In any case, new analyses of isoscalar cross section data are needed to clarify the problem of the ω family of excitations.

8 Project VEPP-2000

A new project is under study now in Novosibirsk. It is planned to replace the VEPP-2M ring, which has a maximum center of mass energy of $2E$ =1400 MeV, by a new one with the higher energy up to $2E$ =2000 MeV. Figure 13 shows the location of the new and the old rings in the VEPP-2M hall. A remarkable feature of the new collider is its round beam optics, for which, instead of conventional quadrupole lenses, superconducting solenoids are used. The beam itself has equal horizontal and vertical size, which promises higher luminosity in a single bunch mode. The future collider is named VEPP-2000. Its design luminosity is $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $2E$ = 2000 MeV and $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $2E$ = 1000 MeV.

The design and construction of VEPP-2000 is planned to start in 2000. The physics program is aimed at a detailed study of e^+e^- annihilation processes in the energy range $2E$ =1–2 GeV.

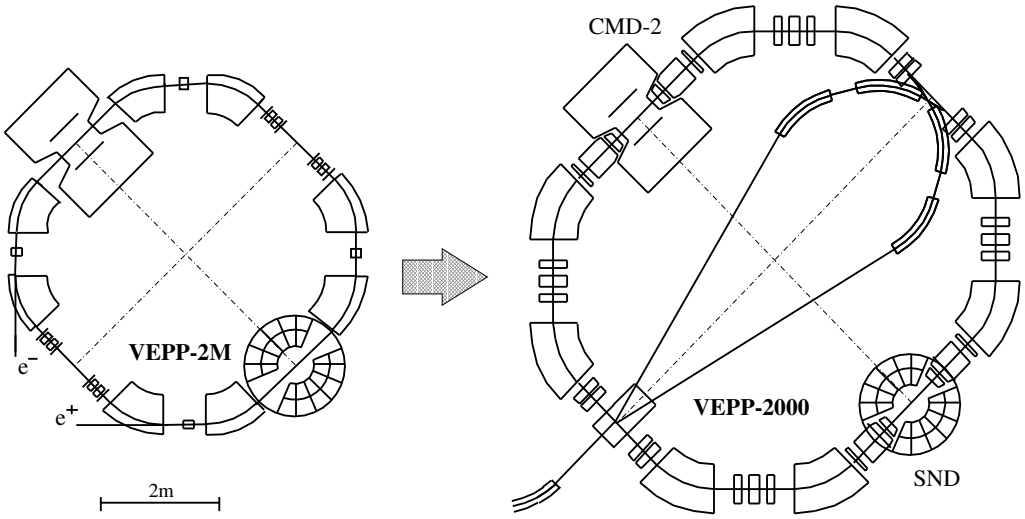

Figure 13: VEPP-2000 project. The left side depicts the existing VEPP-2M ring. The right side shows the newly proposed VEPP-2000 ring. Two collider detectors CMD-2 and SND, located opposite each other, are shown as well.

9 Evidence for a possible exotic baryon $X(2000)$

Among the contributed papers, there is one, presented by L. Landsberg, IHEP, Protvino [29], related to the subject of exotic hadrons. In this work, the diffractive production of baryon resonances was studied with the SPHINX detector in the reaction:

$$p + N \to YK + N \ , \quad Y = [\Sigma^0 K^+] \ , \quad \Sigma^0 \to \Lambda\gamma \ . \tag{32}$$

The mass spectrum of $\Sigma^0 K^+$ shows a clear peak close to 2000 MeV, which is referred to below as $X(2000)$. The fit gives more accurate values: $M_X = 1989 \pm 6$ MeV, $\Gamma_X = 91 \pm 20$ MeV. The statistical significance is more than 10 standard deviations. The production cross section is 95 ± 20 nb. The unusual dynamical properties of the $X(2000)$ are the following: 1. $R = B(X \to \Sigma K)/Br(X \to \text{nonstrange}) \geq 1$, while for typical qqq isobar states $R \sim 10^{-2}$; 2. $\Gamma_X \leq 100$ MeV, which is considerably less than the typical isobar widths of 300–400 MeV.

These properties of the $X(2000)$ make it a serious candidate for a pentaquark exotic baryon with hidden strangeness ($uuds\overline{s}$). The latest data from the SPHINX experiment confirmed the existence of the $X(2000)$ in another final state $Y = [\Sigma^+ K^0]$, $\Sigma \to p\pi^0$, $K^0 \to \pi^+\pi^-$. New preliminary data from the SELEX experiment at Fermilab also supports the existence of the $X(2000)$. In their analysis of the reaction $\Sigma^- + N \to \Sigma^- K^+ K^- + N$, SELEX observed a mass peak in the $Y = [\Sigma^- K^+]$ system, with parameters close to those of the $X(2000)$: $M_X = 1962 \pm 12$ MeV, $\Gamma_X = 96 \pm 32$ MeV.

Recently, the upgraded SPHINX detector has accumulated a large amount of new data on tape. The analysis of the new data is in progress.

10 General conclusions

1. Experiments were carried out in Novosibirsk at the VEPP-2M e^+e^- collider with two detectors SND and CMD-2, with total integrated luminosity $\simeq 50$ pb^{-1}. The total number of produced ϕ mesons was about $4.5 \cdot 10^7$.

2. The electric dipole radiative decays $\phi \to \pi\pi\gamma$, $\eta\pi^0\gamma$ were observed with branching ratios $\sim 10^{-4}$, indicating an exotic 4-quark structure for the lightest scalars $f_0(980)$, $a_0(980)$.

3. Several new rare ϕ-meson decays were observed with branching fractions of order $10^{-4} - 10^{-5}$, *e. g.*, $\phi \to \omega\pi^0$, $\phi \to \eta'\gamma$, $\phi \to 4\pi$, $\phi \to \pi^0 e^+ e^-$.

4. A resonance-like structure was observed in the $e^+e^- \to \pi^+\pi^-\pi^0$ cross section near $2E = 1.2$ GeV. This might be a manifestation of the lightest excited ω state.

5. The decays $\rho, \omega \to \pi^0\pi^0\gamma$ were seen. Their rates exceed the VMD level, and this might be a manifestation of the lightest scalar state σ(400-1200) decaying into $\pi^0\pi^0$.

6. The design and construction of a new VEPP-2000 e^+e^- machine with round beams, to replace the existing VEPP-2M ring, is planned for Novosibirsk. The

maximum design energy of the new machine is $2E$=2000 MeV; the design luminosity is $L = 1 \cdot 10^{32}$.

7. In the SPHINX experiment at Protvino, a narrow $X(2000)$ state with a width $\Gamma \simeq 90$ MeV was observed. It is proposed as a candidate for a pentaquark exotic baryon $qqqs\overline{s}$ with hidden strangeness.

The author is grateful to Nikolai Achasov, Vladimir Golubev, and Evgeny Solodov for numerous fruitful discussions.

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Discussion

L. G. Landsberg (IHEP, Protvino): What can you say about the two-photon production of the a_0 and f_0 mesons? Are these data in agreement with the $qq\overline{qq}$ or $q\overline{q}$ models for these mesons?

Serednyakov: The measured two photon widths of a_0 and $f_0 \simeq 0.3$ KeV are significantly lower than predictions of $q\overline{q}$ model and agree with $qq\overline{qq}$ model.

Norbert Wermes (Bonn University): Are the two detectors at VEPP-2M capable of measuring $R_{\rm had}$? Will they be able to perform a scan in energy?

Serednyakov: Both detectors have already accumulated $50\,pb^{-1}$ of data and continue data taking in the energy range from 0.4 to 1.4 GeV. The measurement of R is one of the major goals of these experiments.

B.F.L. Ward (University of Tennessee): In your table of model predictions vs. experiment, why do you say that value 2.5, for the $q\overline{q}$ model, is farther than 20, for the 4-quark model, from the experimental value of 9?

Serednyakov: Because the accuracy of the theoretical prediction is about $40-50\%$, the 4-quark value 20 ± 10 is in considerably better agreement with the experimental value 9 than the 2-quark value 2.5 ± 1.3.

Harry Lipkin (Weizmann Institute): There are very beautiful data on $D_s \to f^0\pi \to 3\pi$ from Fermilab and on $\overline{p}p \to f^-\pi \to 3\pi$ from CERN. Dalitz plot analyses of these reactions should be available soon.

Serednyakov: The data on $D_s \to f^0\pi$ decay show that the f_0 should include s-quarks. The $d\overline{d}$ structure of f_0 is not supported in $D_s \to f^0\pi$ decay.