Rare $\Phi$ Decays and Exotic Hadrons

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1 Introduction

Exotic hadrons are named those hadrons, which structure is different from ordinary $q_{1}\bar{q}_{2}$ structure for mesons and $q_{1}q_{2}q_{3}$ for baryons. Their exotic nature could reveal itself in unusual properties of these hadrons like some suppressed or enhanced decays, too wide or too narrow widths, quantum numbers, forbidden in conventional structure, etc. Up to now among huge variety of hadrons about 10 candidates were found, which look like exotic states. In scalar meson sector such candidates are the lowest lying states $f_{0}(980)$ and $a_{0}(980)$. The main reasons, which lead to the conclusion on possible exotic structure of $f_{0}(980)$ and $a_{0}(980)$, are their suppressed production in $J/\Psi$ decays, low values of $\gamma\gamma$-width, too low masses.

Three models are used to describe $f_{0}$ and $a_{0}$ mesons [1] - conventional $q\bar{q}$ model, molecular model ($K\bar{K}$) and 4-quark model ($qq\bar{q}\bar{q}$). The $q\bar{q}$ model is hardly consistent with experimental data. More than 10 years ago the radiative decays $\phi \rightarrow f_{0}\gamma, a_{0}\gamma$ were proposed as a new sensitive test of $f_{0}$ and $a_{0}$ structure [2].

These decays were studied recently in the reactions:

\[ e^{+}e^{-} \rightarrow \phi \rightarrow \pi^{0}\pi^{0}\gamma, \pi^{+}\pi^{-}\gamma \]  \[ (1) \]
\[ e^{+}e^{-} \rightarrow \phi \rightarrow \eta\pi^{0}\gamma \]  \[ (2) \]

which could proceed via radiative decay $\phi(1020) \rightarrow f_{0}\gamma, a_{0}\gamma$. We measured the branching ratios of these decays and of other rare decays of $\phi$ and $\rho(770), \omega(783)$. Other experimental data from Novosibirsk and conference contribution from IHEP, Protvino are reviewed in this talk.

2 Experiment

The experiments to study the reactions [1], [2] have been carried out at VEPP-2M collider in the energy range 2E from 0.4 to 1.4 GeV. VEPP-2M is the lowest energy $e^{+}e^{-}$ collider, operating in Novosibirsk since 1974. The collider luminosity $L$ sharply
depends on its energy $L \sim E^4$. At the energy of $2E = M_\phi$ the maximum luminosity $L_{max} = 5 \cdot 10^{30} \text{cm}^{-2}\text{s}^{-1}$.

At present two detectors CMD-2 and SND, located opposite each other, take data. CMD-2 is a magnetic detector (fig.1) with superconductive solenoid and 20 layer drift chamber with jet cell structure. Electromagnetic calorimeter consists of 892 CsI(Tl) crystals in barrel and of 680 BGO crystals in endcaps. The muon identification is provided by 4 layers of streamer tubes inside the yoke. The CMD-2 detectors operates at VEPP-2M since 1992 with $\approx 27 \text{pb}^{-1}$ of collected luminosity.

SND is a general purpose nonmagnetic detector (fig.2). The main part of SND is three-layer spherical electromagnetic calorimeter with 1625 NaI(Tl) crystals of 3.6 t total weight. Detector includes also a 10-layer drift chamber and outer muon system, consisting of streamer tubes and plastic scintillation counters. SND resembles famous Crystal Ball detector constructed in SLAC, but unlike Crystal Ball it has a 3-layer crystal calorimeter, which provides better particle recognition $e/\pi/\mu$ and $\gamma/K_L$. The integrated luminosity accumulated by SND since 1995 is about $27 \text{pb}^{-1}$.

Both detectors take data in parallel. Total number of produced resonances is $N_\phi \approx 4.5 \cdot 10^7$, $N_\rho \approx 4 \cdot 10^6$, $N_\omega \approx 2.5 \cdot 10^6$. About half of the total time was used for scanning the energy range between resonances with the goal of the precise measurement of the quantity $R = \frac{\sigma(e^+e^-\rightarrow\text{hadrons})}{\sigma(e^+e^-\rightarrow\mu^+\mu^-)}$ and study particular channels of
Evidence of the decays $\phi \rightarrow f_0 \gamma, a_0 \gamma$

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

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

$$e^+e^- \rightarrow \phi \rightarrow \pi^0 \pi^0 \gamma$$

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

$$e^+e^- \rightarrow \phi \rightarrow \eta \gamma \rightarrow 3\pi^0 \gamma$$

$$e^+e^- \rightarrow \omega \pi^0 \rightarrow \pi^0 \pi^0 \gamma$$

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

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

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

The study the $\pi^0\pi^0$ and $\eta\pi^0$ mass spectra was important for the interpretation of the data. Figs. 3,4 show the obtained mass spectra after background subtraction and detection efficiency corrections. Both pictures show the considerable rise in the spectra at higher masses. The visible location of the peak in spectra is near 960 MeV. The table with numerical values of $\pi^0\pi^0$ mass spectrum can be found in [10].

Summing data from the mass spectra in figs 3,4 and CMD-2 data one can obtain the branching ratios for particular mass ranges:

![SND](image1.png)

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

![SND](image2.png)

**Figure 4:** The $\eta\pi^0$ mass distribution in the process $e^+e^- \rightarrow \eta\pi^0\gamma$
1 - SND result for $m_{\pi\pi} > 900$ MeV \[10\]:

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

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

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

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

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

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

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

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

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

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

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

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

All results listed above are practically model independent, because they do not use an assumption about $f_0$ or $a_0$ contributions into the final state. Then, assuming $f_0$ and $a_0$ dominance in the final state, using relation based on isotopic invariance $B(\phi \to \pi^+\pi^-) = 2B(\phi \to \pi^0\pi^0)$, and neglecting the decay $\phi \to KK\gamma$, we can obtain for the decay $\phi \to f^0\gamma$ and $\phi \to a^0\gamma$:

7 - SND result \[10\]:

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

8 - SND result \[13\]:

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

9 - CMD-2 result \[12\]:

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

The analysis of the $\pi^0\pi^0$ mass spectrum was done on the base of the work \[2\]. The spectrum was described by a sum of contributions from $f_0$ and $\sigma$ mesons \[14\].
The width of $f_0$ meson in the approximation of "broad resonance" depends on the product of coupling constants $g_{\phi KK} \cdot g_{f KK}$. The $f_0$ fit parameters were mass $m_f$, coupling constant $\frac{g_{f KK}^2}{4\pi}$ and the ratio of coupling constants $\frac{g_{f KK}^2}{g_{f \pi \pi}^2}$. The optimal fit parameters were obtained [14]:

$$m_f = 971 \pm 6 \text{ MeV}, \quad \Gamma_f = 188^{+48}_{-33} \text{ MeV}, \quad \frac{g_{f KK}^2}{4\pi} = 2.10^{0.88}_{0.56} \text{ GeV}^2, \quad \frac{g_{f KK}^2}{g_{f \pi \pi}^2} = 4.1 \pm 0.9. \quad (16)$$

The statistical accuracy did not allow to define the contribution of $\sigma$ in the fit, so in (16) $\sigma$ was excluded from the fit.

The $\eta\pi^0$ mass spectrum was fitted also by the formulae from [2], but because of lower statistics the ratio of coupling constants was fixed $\frac{g_{a KK}}{g_{a \pi \pi}} = 0.85$ [2]. The following $a_0$ optimal parameters were obtained:

$$m_a = 992^{+22}_{-7} \text{ MeV}, \quad \frac{g_{a KK}^2}{4\pi} = 1.09^{+0.33}_{-0.24} \text{ GeV}^2 \quad (17)$$

The obtained value of $a_0$ mass does not contradict to the PDG Table value. If the $a_0$ mass is fixed, one could obtain more accurate value of coupling constant:

$$\frac{g_{a KK}^2}{4\pi} = 0.83 \pm 0.13 \text{ GeV}^2 \quad (18)$$

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

$$e^+e^- \rightarrow \phi \rightarrow \pi^+\pi^-\gamma \quad (19)$$

with the goal to find a contribution of the $f_0 \rightarrow \pi^+\pi^-$ channel in the final state. On the contrary to the neutral channel $f_0 \rightarrow \pi^0\pi^0$, there is a significant background from the nonresonant process $e^+e^- \rightarrow \rho\gamma \rightarrow \pi^+\pi^-\gamma$ and interference with the processes $e^+e^- \rightarrow \phi \rightarrow \pi^+\pi^-\gamma$ and $e^+e^- \rightarrow \rho \rightarrow \pi^+\pi^-\gamma$. It was found, that the process [19] cross section energy dependence exhibits interference wave near point $2E = M_\phi$.

The recoil photon energy spectrum (fig.5) shows a peak at $E_\gamma \simeq 220 \text{ MeV}$ due to the process $e^+e^- \rightarrow \rho\gamma$ and an enhancement at $E_\gamma \simeq 50 \text{ MeV}$ from the decay $f_0 \rightarrow \pi^+\pi^-$, which roughly corresponds to the mass difference between $\phi$ and $f_0$ mesons. To obtain the branching ratio $B(\phi \rightarrow \pi^+\pi^-\gamma)$ the fitting of photon spectra at different energy points was done using formulae from the work [16], which include contributions of the background reactions and the $f_0 \rightarrow \pi^+\pi^-$ decay. The optimal value of $f_0$ mass was $m_f = 976 \pm 5 \text{ MeV}$, the branching ratio:

$$B(\phi \rightarrow f_0\gamma) = (1.93 \pm 0.46 \pm 0.59) \cdot 10^{-4} \quad (20)$$
4 Discussion on the decays $\phi \rightarrow f_0 \gamma, a_0 \gamma$

In the list of new VEPP-2M data the results (7)-(12) are model independent, because they are based on the total number of events. Other results - (13)-(18) use different assumptions, for instance, $BR(\phi \rightarrow f_0 \gamma)$ (13),(15) is based on assumption of $f_0$ dominance in the final $\pi^0\pi^0$ state. The main parameters of $f_0$ and $a_0$ like their masses, widths, coupling constants were obtained from the description of these decays, proposed by N.Achasov [3], so these parameters are also strongly model dependent. Below we give a conclusion on the nature of $f_0$ and $a_0$ scalars, which follows from the model dependent data (13)-(18) and the work [4].

There are three main models, describing structure of $f_0$ and $a_0$ scalars: $q\bar{q}$ model ($n\bar{n}$ or $s\bar{s}$), molecular model ($K\bar{K}$) and 4-quark model ($q\bar{q}q\bar{q}$). The general accepted opinion is that $f_0$ and $a_0$ are difficult to fit into $q\bar{q}$ model. This opinion is based on the existing experimental data. For instance, the decays $J/\psi \rightarrow f_0 \gamma, f_0 \omega, a_0 \rho$ are considerably suppressed in comparison with similar decays, where instead of $f_0$ and $a_0$ the tensor mesons $f_2$ or $a_2$ are produced. If $f_0$ and $a_0$ are $q\bar{q}$ mesons, their production in $J/\psi$ decays should be of the same order as the production of tensor mesons.

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

The radiative decay $\phi \rightarrow f_0 \gamma, a_0 \gamma$ measurements were long awaited as a new test of $f_0$ and $a_0$ nature. The Table 1 shows the comparison of different models predictions with averaged experimental data at VEPP-2M (see preceding section). The accuracy
model predictions \cite{1} is about 50%. The conclusion from the Table 1 is that VEPP-2M data are in good agreement with four-quark model of $f_0$ and $a_0$. But we remind the reader, that experimental data in the 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 experimental spectra, but the present accuracy is not sufficient to exclude contributions of other scalars into the final state.

Table 1: The comparison of VEPP-2M data with different $f_0$ and $a_0$ models.

| Model | $n\bar{n}$ | $s\bar{s}$ | $K\bar{K}$ | $q\bar{q}s\bar{s}$ | Exp-t |
|-------|-----------|-----------|-----------|----------------|-------|
| $Br(\phi \to f_0\gamma) \cdot 10^4$ | 0.45 | 0.55 | 0.1 | 2.5 | 3.0 ± 0.4 |
| $Br(\phi \to a_0\gamma) \cdot 10^4$ | 0.25 | — | 0.1 | 2.0 | 0.88 ± 0.13 |

There is one remark, concerning the decay $\phi \to a_0\gamma$. Its branching ratio is close to that of $\phi \to \eta'\gamma$. So, $a_0$ should contain strange quarks like $\eta'$, which is impossible for $q\bar{q}$ isovector meson, but is quite natural if $a_0$ is a four quark $q\bar{q}s\bar{s}$ meson.

This discussion was based mainly on the work \cite{1}, where detailed analysis of existing data for $f_0$ and $a_0$ mesons, regarding their nature, is given.

5 Other rare $\phi$ decays

The large number of produced $\phi$ mesons at both SND and CMD-2 detectors ($N_\phi \simeq 4.5 \cdot 10^7$) allows to carry out the search of rare $\phi$ decay. The long awaited decay $\phi \to \eta'(958)\gamma$ was first observed by CMD-2 \cite{17}. In the decay chain $\phi \to \eta'\gamma, \eta' \to \eta\pi^+\pi^-, \eta \to \gamma\gamma$ the branching ratio was $(8.2^{+2.1}_{-1.8}) \cdot 10^{-5}$. For another chain $\eta' \to \pi^+\pi^-\pi^0(\gamma)$ the CMD-2 result was $(5.8 \pm 1.8) \cdot 10^{-5}$ \cite{18}. Later SND confirmed the existence of the decay $\phi \to \eta'\gamma$ with the branching ratio of $6.7^{+3.4}_{-2.9} \cdot 10^{-5}$ \cite{19}. The clear signature of the decay $\phi \to \eta'\gamma$ is demonstrated in figs.7, 8. The averaged value of branching ratio is $BR(\phi \to \eta'\gamma) = (6.9 \pm 1.2) \cdot 10^{-5}$. The statistical significance is greater than 5 standard deviations. This result is in agreement with nonrelativistic quark model prediction of $(6 \div 10) \cdot 10^{-5}$ \cite{20}. At present level of the accuracy no significant admixture of gluonim in $\eta'$ is seen.

The $\phi \to \pi^+\pi^-,$ $\omega\pi^0$ decays are double suppressed - by isospin invariance and OZI rule. The $\phi \to \pi^+\pi^-$ decay was already observed. Its PDG Table value is $Br(\phi \to \pi^+\pi^-) = (0.8^{+0.5}_{-0.3}) \cdot 10^{-4}$, while the second decay $\phi \to \omega\pi^0$ was not observed yet. SND performed the search for this decay in the the reaction [21]:

$$e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$$

(21)

The clear interference pattern in energy dependence of the process \cite{21} was observed.
Figure 7: Two-photon invariant mass in \( \eta \rightarrow \gamma \gamma \) decay vs. recoil photon energy in a search for \( \phi \rightarrow \eta' \gamma, \eta' \rightarrow \eta \pi^+ \pi^-, \eta \rightarrow \gamma \gamma \) decay.

Figure 8: Recoil photon energy spectrum in the \( \phi \rightarrow \eta' \gamma \) decay.

The decay amplitudes and branching ratios are the following [13]:

\[
Re(Z) = 0.112 \pm 0.015, \quad Im(Z) = -0.104 \pm 0.022, \quad Br(\phi \rightarrow \omega \pi^0) = (4.6 \pm 1.2) \cdot 10^{-5}
\]

The theoretical prediction [22] for the branching ratio is about twice larger. In our case the real part \( Re(Z) \) is too low. The observed disagreement could be due to existence of direct \( \phi \rightarrow \omega \pi^0 \) transition or nonstandard mixing of light vector mesons.

In similar way was studied the cross section of the process

\[
e^+e^- \rightarrow \pi^+\pi^-
\]

The results of fitting are [13]:

\[
Re(Z) = 0.061 \pm 0.005, \quad Im(Z) = -0.042 \pm 0.006, \quad Br(\phi \rightarrow \pi^+\pi^-) = (7.1 \pm 1.0 \pm 1.0) \cdot 10^{-5}
\]

The accuracy of the measurement is about 3 times higher than in PDG Tables. But here again SND result for real part \( Re(Z) \) is lower than predicted in [22] and preliminary result of CMD-2 [23]:

\[
Br(\phi \rightarrow \pi^+\pi^-) = (18.1 \pm 2.5 \pm 1.9) \cdot 10^{-5}
\]

The disagreement between CMD-2 and SND in \( Br(\phi \rightarrow \pi^+\pi^-) \) is 3 standard deviations.
Both detectors studied the rare decay $\phi \rightarrow \mu^+\mu^-$. The result of SND is

$$Br(\phi \rightarrow \mu^+\mu^-) = (33.0 \pm 4.5 \pm 3.2) \cdot 10^{-5}$$

(26)

The result of CMD-2 is

$$Br(\phi \rightarrow \mu^+\mu^-) = (28.0 \pm 3.0 \pm 4.6) \cdot 10^{-5}$$

(27)

The full review of other $\phi$ rare decay studied at VEPP-2M can be found in refs [23, 25].

6 Decays $\rho, \omega \rightarrow \pi^0\pi^0\gamma$

The decays $\rho, \omega \rightarrow \pi^0\pi^0\gamma$ are of interest for the study of the possible low-mass scalar resonance $\sigma$, decaying into $\pi\pi$ final state. Some contributions are expected also from the $\rho, \omega \rightarrow \omega\pi^0, \rho\pi \rightarrow \pi^0\pi^0\gamma$ decays. In our work [7], where the $\rho \rightarrow \pi^+\pi^-\gamma$ decay was studied, an enhancement was observed in the high end of the photon bremsstrahlung spectrum, which can be interpreted as a manifestation of a light bound state, possibly $\sigma$ resonance. Later in Protvino, the decay $\omega \rightarrow \pi^0\pi^0\gamma$ was observed with the branching ratio $(7.2 \pm 2.5) \cdot 10^{-5}$, which is $\sim 3$ times larger, than expected in Vector Dominance Model (VDM).

![Figure 9: 2-dim. scatter plot of the best neutral pion candidates in the search for the process $e^+e^- \rightarrow \pi^0\pi^0\gamma$.](image)

![Figure 10: Born cross section of the process $e^+e^- \rightarrow \pi^0\pi^0\gamma$; upper curve is a fit, lower curve - VDM prediction.](image)

In the recent work [13] we studied neutral final state in the reaction $e^+e^- \rightarrow \rho, \omega \rightarrow \pi^0\pi^0\gamma \rightarrow 5\gamma$. Fig. 5 shows a 2-dimensional plot of the best neutral pion candidates, found in 5-photon final state. The measured cross section was fitted by the sum of the Breit–Wigner contributions from $\omega$ and $\rho$ resonances. The Born cross section and
fitting curves are shown on the fig.[10]. One can see, that the measured cross section considerably exceeds VDM prediction. The fit parameters are the following:

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

\[
BR(\rho \to \pi^0\pi^0\gamma) = (4.2^{+2.9}_{-2.0} \pm 1.0) \cdot 10^{-5}, \; \Gamma_{\rho\pi^0\pi^0\gamma} \simeq 6 keV, \text{ (without } \omega\pi^0) \tag{29}
\]

So, the result (28) confirms the PDG value of \(BR(\omega \to \pi^0\pi^0\gamma)\). Both branching ratios (28) and (29) are considerably (~4 times) higher than VDM estimates. The possible explanation of this enhancement could be a contribution of light scalar \(\sigma\), decaying into \(\pi^0\pi^0\). It was suggested by Jaffe [26], that \(\sigma\) could be lightest member of the four-quark nonet with the structure \(u\bar{d}u\bar{d}\). Because of superallowed \(\sigma \to \pi\pi\) decay, \(\sigma\) is very broad. Among other members of four-quark nonet there are \(f_0(980)\) and \(a_0(980)\) - the particles with also superallowed but phase space suppressed decay into \(K\bar{K}\). So, both \(f_0(980)\) and \(a_0(980)\) have a narrow width 50–100 MeV. The further investigation of the decays \(\phi, \rho, \omega \to \pi^0\pi^0\gamma\) and in particular study of the \(\pi^0\pi^0\) decay mass spectra could clarify the nature of light scalar mesons.

7 The process \(e^+e^- \to \pi^+\pi^-\pi^0\) above \(\phi\) resonance

![Figure 11: Born cross section of the process \(e^+e^- \to \pi^+\pi^-\pi^0\) (linear scale)](image)

![Figure 12: Born cross section of the process \(e^+e^- \to \pi^+\pi^-\pi^0\) (logarithmic scale)](image)

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

\[
e^+e^- \to \pi^+\pi^-\pi^0 \tag{30}
\]
is of particular interest, because earlier it was measured with poor accuracy and new possible isoscalar vector resonances could be found here. The study of the process (30) was done by SND detector in the energy range 2E=1.04–1.38 GeV [27].

The measured cross section, shown in fig.11,12 is in agreement with previous data from ND experiment [7] and well matches DM2 measurements at higher energies [28]. The systematic error in the cross section is \(\sim 10\%\), but it grows up to 50\% closer to \(\phi\) because of radiative corrections. The Born cross section in fig.11 shows a broad peak with the visible position at \(2E \simeq 1200\) MeV. To describe the cross section in terms of sum of vector mesons, the fit was done including \(\omega(783), \phi(1020), \omega(1600)\) and an additional \(\omega\)-like state, named \(\omega(1200)\), with its mass and width set free. For two latter resonances the widths were assumed independent of energy. The optimal fit parameters strongly depended on interference phases choice. The best fit occurs at the following phase set: \(\phi_{\omega(783)} = 0, \phi_{\phi(1020)} = \pi, \phi_{\omega(1200)} = \pi, \phi_{\omega(1600)} = 0\). The \(\omega(1200)\) parameters are:

\[
M_{\text{eff}} = 1170 \pm 10 \text{MeV}, \quad \Gamma_{\text{eff}} = 187 \pm 15 \text{MeV}, \quad \sigma_{\text{max}} = 7.8 \pm 1.0\text{nb},
\]

(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 \(2^2S_1\) or radial excitation (D-wave) \(1^3D_1\) of \(\omega(783)\). In any case, new analyses of isoscalar cross sections data are needed to clarify the problem of \(\omega\) family excitations.

8 Project VEPP-2000

A new project is studied now in Novosibirsk. It is planned to replace 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. Fig. 13 shows the location of the new and the old rings in the VEPP-2M hall. A remarkable feature of the new collider is a round beam optics, where instead of conventional quadrupole lenses the superconductive solenoids are used. The beam itself has equal horizontal and vertical size, which promises the higher luminosity in single bunch mode. The future collider is named VEPP-2000. Its designed luminosity is \(10^{32}\text{cm}^{-2}\text{s}^{-1}\) at \(2E =2000\) MeV and \(10^{31}\text{cm}^{-2}\text{s}^{-1}\) at \(2E =1000\) MeV.

The design and construction of VEPP-2000 is planned to start in 2000. The physical program is aimed to detailed study of \(e^+e^-\) annihilation processes in the energy range \(2E =1–2\) GeV.
9 Evidence of possible exotic baryon $X(2000)$

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

$$p + N \rightarrow YK + N, \quad Y = [\Sigma^0 K^+]^+, \quad \Sigma^0 \rightarrow \Lambda \gamma$$

(32)

The mass spectrum of $\Sigma^0 K^+$ shows a clear peak at $\simeq 2000$ MeV, which is referred below as $X(2000)$. The fitting 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 $95 \pm 20$ nb. The unusual dynamic properties of $X(2000)$ are the following: 1 - the value $R = \frac{Br(X \rightarrow \Sigma K)}{Br(X \rightarrow \text{nonstrange})} \geq 1$, while for usual $qqq$ isobar $R \sim 10^{-2}$; 2 - the width of $X(2000)$ $\Gamma_X \leq 100$ MeV, which is considerably less than for isobars - $300 \div 400$ MeV.

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

Figure 13: VEPP-2000 project. Left chart depicts existing VEPP-2M ring. The right one is the newly proposed VEPP-2000 ring. Two collider detectors CMD-2 and SND, located opposite each other, are shown as well.
Now a lot of statistics is accumulated on tapes with upgraded SPHINX detector. The analysis of new data is in progress.

10 General Conclusions

• Experiments were carried out in Novosibirsk at VEPP-2M $e^+e^-$ collider with two detectors SND and CMD-2 with total integrated luminosity $\simeq 50pb^{-1}$ and total number of produced $\phi$ mesons $\sim 4 \cdot 10^7$.

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

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

• A resonance-like structure in $e^+e^- \to \pi^+\pi^-\pi^0$ cross section near $2E \simeq 1.2$ GeV was observed, which might be a manifestation of the lightest excited $\omega$ state,

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

• Design and construction of a new VEPP-2000 $e^+e^-$ machine with round beams to replace existing VEPP-2M ring are started in Novosibirsk. The maximum designed energy of the new machine is $2E=2000$ MeV, designed luminosity $L = 1 \cdot 10^{32}$.

• In SPHINX experiment, Protvino, a narrow $X(2000)$ state with a width $\Gamma \simeq 90$ MeV was observed. It is proposed as a candidate for pentaquark exotic baryon $qqqs$ 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 $qqar{q}ar{q}$ or $qar{q}$ 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 $qar{q}$ model and agree with $qqar{q}ar{q}$ model.

Norbert Wermes (Bonn University): Are the two detectors at VEPP-2M capable of measuring $R_{\text{had}}$? 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 $qar{q}$ model, is farther than 20, for the 4-quark model, from the experimental value of 9?

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

Harry Lipkin (Weizmann Institute): There are very beautiful data on $D_s \to f^0\pi \to 3\pi$ from Fermilab and on $p\bar{p} \to f^-\pi \to 3\pi$ 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 $f_0$ should include $s$-quarks. The $n\bar{n}$ structure of $f_0$ is not supported in $D_s \to f^0\pi$ decay.