Meson spectroscopy with the Lepton facility

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Hadron-spectroscopy experiments carried out with the Lepton facility are reviewed. These experiments led to the discovery and investigation of the new vector meson $C(1480)$, which is a candidate for an exotic state; searches have been made for radiative decays of mesons, and the decay $D(1285)\to\varphi\gamma$ has been discovered; and data have been obtained on the extent to which the OZI rule is satisfied in hadron reactions and decays. The results of investigations of rare electromagnetic leptonic decays of the η, η', and ω mesons are also given. The general picture of the development of the physics of exotic hadrons is described in an appendix.

INTRODUCTION

In recent years, the spectroscopy of "light" hadrons, which has already been carried on for more than a quarter of a century, has advanced to a qualitatively new level and undergone a second burst. This progress is to a large degree associated with the general development of experimental techniques and the construction of multichannel hodoscope γ spectrometers for the detection of hard photons. Experimentalists have constructed complex, high-luminosity facilities capable of operating in intense hadron and photon beams and detecting all secondary particles—both charged and neutral. Thus, it has become possible to separate certain exclusive reactions for investigated states and to reconstruct completely events with additional kinematic redeterminations. All this permits a very significant lowering of the background and the investigation of rare processes in the region of nanobarn cross sections.

In experiments with colliding e^+e^- beams there have also been some very interesting results for new classes of phenomena associated with the production of hadrons in decays of J/ψ particles and in $\gamma\gamma$ collisions (both for almost real and for virtual photons).

The new experiments have led to significant successes in developing the systematics of "ordinary" hadrons, which have the simplest quark structure ($q\bar{q}$ for mesons and qqq for baryons). Some rare electromagnetic decays of strongly interacting particles have also been discovered, and important information about their internal structure and other properties has been obtained. However, the most serious successes of modern hadron spectroscopy are probably those associated with searches for new forms of hadronic matter—exotic hadrons. These unusual particles can include multiquark formations ($qq\bar{q}\bar{q}$ mesons, $qqqq\bar{q}$ baryons), hybrid states with valence quarks and gluons ($q\bar{q}g$ mesons, $qqqg$ baryons), or glueballs, i.e., particles consisting solely of valence gluons (gg, ggg). The results of such investigations have far-reaching consequences for quantum chromodyamics, for the concept of confinement, and for specific models of hadron structure (lattice, string, and bag models).

During the last few years, the Lepton-F facility at the Institute of High Energy Physics (IHEP) at Serpukhov[1)] has been used in a series of experiments associated with searches for exotic mesons and other related aspects of meson spectroscopy [the properties of axial mesons and the E/iota problem, the nature of the $E(1420)$ meson, the OZI rule[2)] and the properties of exotic states, etc.]. It is these investigations that are discussed in the present review. Basically, it is devoted to the following questions.

1. $C(1480)\to\varphi\pi^0$, a new vector meson and a candidate for an exotic state.[1–6]
2. Searches for the decay $B(1235)\to\varphi\pi^0$, the OZI rule, and decays of exotic mesons.[5]
3. The reaction $\pi^-p\to\varphi n$ at $p_{\pi^-}=32.5$ GeV and the OZI rule in hadronic processes.
4. Searches for the radiative decays $D(1285)\to\varphi\gamma$, $E(1420)\to\varphi\gamma$ and the nature of the $E(1420)$ meson.[5,7–9]

In order to compare the experimental results obtained with the Lepton facility with the general picture of investigations of exotic states, we have added to the review an appendix in which we briefly describe the modern development of the physics of exotic mesons. This appendix is to a large degree based on the proceedings of the Working Symposium on Hybrids, Glueballs, and Exotic Hadrons held at BNL in August 1988: Glueballs-88. The data given in this review were discussed in detail at that symposium. For completeness, the review also covers briefly the experiments performed with the facility[10–14] Lepton-G,[3)] which led to the discovery of rare electromagnetic decays of the η, η', and ω mesons and yielded data on the internal electromagnetic structure of these particles. The results of the investigations of Refs. 10–14 were discussed in more detail in Ref. 15.

It should be emphasized that, quite generally, investigations of electromagnetic decays of hadrons play an important part in elementary-particle physics. These processes, determined by the interaction of real or virtual photons with the electric charges of the quark fields, yield unique information about the various quark configurations in hadrons, about the mixing mechanism, about the electromagnetic structure of the strongly interacting particles, and about a number of their phenomenological properties, such as the magnetic moments, form factors, etc. It is a pleasure to note that many important experimental results in this field have been obtained at the Institute of Theoretical and Experimental Physics (discovery of the $\omega\to\pi^0\gamma$ decay), at JINR (discovery of the decays $\rho\to e^+e^-$ and $\varphi\to e^+e^-$, searches for rare decays of η mesons), at IHEP (discovery of a number of rare electromagnetic decays of light mesons), and at the Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences (discovery of the resonance reaction $e^+e^-\to\rho\to\pi^+\pi^-$, investigation of radiative decays of the φ^- and η mesons). These data were considered in the reviews of Refs. 15 and 16, which also give a detailed bibliography (see also Refs. 17 and 18).

1. THE NEW VECTOR MESON C(1480): A CANDIDATE FOR AN EXOTIC STATE

In this section, we shall consider the results of investigation of the $\varphi\pi^0$ system, formed in the exclusive charge-exchange reaction

$$\pi^- p \to (\varphi\pi^0)\, n. \tag{1}$$

The $\varphi\pi^0$ system possesses unique properties, which make it particularly promising for searches for exotic hadrons.[19] The isotopic spin of such a system is equal to unity, i.e., it contains the isospin "carriers," the u and d quarks [in the combination $(1/\sqrt{2})(u\bar{u} - d\bar{d})$]. At the same time, the φ meson is characterized by hidden strangeness and consists of $s\bar{s}$ quarks. The coupling between the $u\bar{u}$ and $d\bar{d}$ quarkonium states and $s\bar{s}$ system is suppressed by the OZI rule. Therefore, the states strongly coupled to $\varphi\pi^0$ must have a complicated quark valence structure different from that of the "ordinary" $q\bar{q}$ mesons.

An experimental study of the reaction (1) was made with the 70-GeV accelerator at IHEP with the facility Lepton-F during 1983–1986. The first data on the process (1), which gave weighty indications of the existence of a resonance C state (decaying through the channel $C \to \varphi\pi^0$) with mass around 1.5 GeV and properties that did not fit into the picture of meson states of the ordinary type,[1] stimulated further investigations with an improved facility, and these culminated in the discovery of the new vector meson $C(1480)$, a candidate for an exotic state.[2-4] Further discussions of the properties of $C(1480)$ are contained in Refs. 5 and 6 and in the present review.

1.1. Experiments with the facility Lepton-F

The combined facility Lepton-F (Fig. 1), which permits effective detection of charged particles and γ rays, included a magnetic spectrometer with proportional chambers and a hodoscope γ spectrometer. The charged particles in the initial and final states were defined by means of gas threshold Cherenkov counters. Measurements were made in a beam of negatively charged particles with momentum 32.5 GeV.

During the time of exposure of the spectrometer in the beam, 4×10^{11} π^- mesons and 8×10^{9} K^- mesons passed through its target. The facility was triggered by three types of trigger signals, which made it possible to detect the following events:

$$\pi^- p \to (K^+K^- m\gamma)\, n; \tag{2}$$

$$\to (\pi^+\pi^- m\gamma)\, n; \tag{3}$$

$$K^- N \to (K^+K^- m\gamma)\, Y \quad (m = 0, 1, 2). \tag{4}$$

These events were then used to search for and separate the processes

$$\pi^- p \to (K^+K^-\pi^0)\, n; \quad \to (\varphi\pi^0)\, n;\ \varphi \to K^+K^-; \tag{5}$$

$$\to (K^+K^-\gamma)\, n; \tag{6}$$

$$\to (\varphi\gamma)\, n;\ \varphi \to K^+K^-; \tag{7}$$

$$K^- N \to (K^+K^-\pi^0)\, Y; \tag{8}$$

$$\to (\varphi\pi^0)\, Y;\ \varphi \to K^+K^-; \tag{9}$$

$$\to (K^+K^-\gamma)\, Y. \tag{10}$$

For the calibration of the facility, study of the background, and normalization of the cross sections and decay probabilities, known processes with similar topology were used:

$$\pi^- p \to (\pi^+\pi^-\pi^0)\, n; \tag{11}$$

$$\to \eta n;\ \eta \to \pi^+\pi^-\pi^0; \tag{12}$$

$$\to \omega n;\ \omega \to \pi^+\pi^-\pi^0; \tag{13}$$

$$\to (\pi^+\pi^-\gamma)\, n; \tag{14}$$

$$\to \eta n;\ \eta \to \pi^+\pi^-\gamma; \tag{15}$$

$$\to \eta' n;\ \eta' \to \pi^+\pi^-\gamma. \tag{16}$$

To identify exclusive reactions with production of $K^+K^-\pi^0$ and $\pi^+\pi^-\pi^0$ states, the following event selection criteria were used.

1. Detection of two and only two tracks of charged particles with opposite signs of the charges, emanating from an interaction point within the target.

2. For separation of secondary π and K mesons a selec-

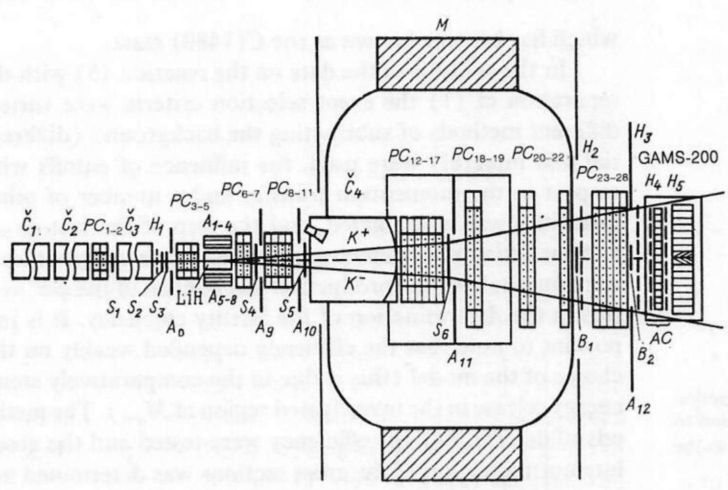


FIG. 1. Schematic diagram of the combined spectrometer Lepton-F: S_1–S_6, B_1, and B_2 are scintillation counters; H_1–H_5 are scintillation hodoscopes; A_0–A_{12} are protective scintillation counters; PC_{1-28} are proportional chambers; $\check{C}_1$–$\check{C}_4$ are gas threshold Chernkov counters; LiH is the target with protective system to separate exclusive reactions; LiH is the target with protective system to separate exclusive reactions: M is the magnet of the wide-aperture magnetic spectrometer of the secondary particles; AC is the active converter of γ rays; GAMS-200 is the γ-ray hodoscope spectrometer.

tion was, when necessary, made on the basis of a minimal momentum $p > 7.3$ GeV of the charged particles (since the threshold for π^- detection in the Cherenkov counter C_4 was $p_{\pi \text{thr}} = 5.5$ GeV).

3. Detection in the spectrometer GAMS of the decay $\pi^0 \to \gamma_1 \gamma_2$, identified in accordance with the requirements $E_{\gamma 1}, E_{\gamma 2} > 0.5$ GeV; $E_{\gamma 1} + E_{\gamma 2} > 5$ GeV; $100 < M_{\gamma 1 \gamma 2} < 180$ MeV.

4. The use of a comparatively soft requirement of "elasticity" for exclusive processes: $29 < E_{\gamma 1} + E_{\gamma 2} + E_+ + E_- < 35$ GeV (E_+ and E_- are the energies of the charged hadrons). These selection criteria made it possible to identify the reactions (5), (8), and (11) with a low background level.

The data given in Figs. 2–4 characterize the possibilities of Lepton-F for identification of well-known processes with charged particles and π^0 mesons (down to very small cross sections—see Fig. 4). Questions relating to the identification of radiative decays in (6), (7), (10), and (14)–(16) will be considered below in Sec. 3.

1.2. Separation of the reaction $\pi^- p \to (\varphi \pi^0) n$ in the analysis of $\pi^- p \to (K^+ K^- \pi^0) n$

In the mass spectrum of the K^+K^- system in the process (5) there is a clear peak corresponding to production of the φ meson in (1) (Fig. 5). Events of the reaction (1) were selected from the region of the peak ($1016 < M_{K^+K^-} < 1024$ MeV). The contribution of the background was taken into account by an integral method (by subtracting the number of events averaged over the neighboring mass intervals 1002–1010 and 1030–1038 MeV). A different, differential method of background subtraction was also used. The entire spectrum of effective masses $M_{K^+K^-\pi^0}$ for the reaction (5) was divided into intervals with $\Delta M_{K^+K^-\pi^0} = 60$ MeV, and for each interval the distribution with respect to the mass of the K^+K^- system was constructed. The number of

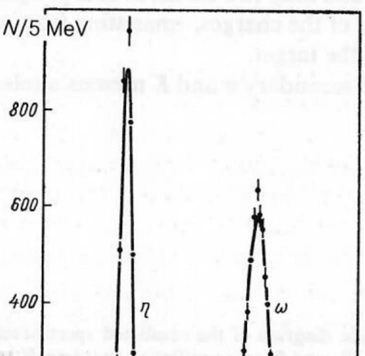


FIG. 2. Effective-mass spectrum of the $\pi^+\pi^-\pi^0$ system in the reaction $\pi^- p \to (\pi^+\pi^-\pi^0) n$ (20% of the statistics). The peaks correspond to production of η and ω mesons (the widths of the peaks are due to the resolution of the spectrometer).

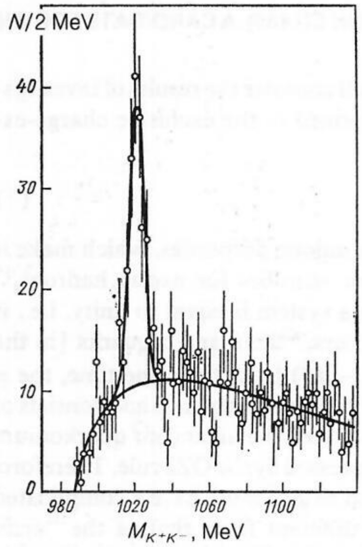


FIG. 3. Effective-mass spectrum of the K^+K^- system in the reaction $K^- N \to (K^+K^-\pi^0) Y$. The peak corresponds to production of the φ meson. The peak width $\Gamma_\varphi = 9.3 \pm 1.4$ MeV is determined by the spectrometer resolution.

φ mesons in the given interval was determined by means of a fitting procedure. Examples of the fitting are shown in Fig. 6. The differential method made it possible, in each interval of masses $\Delta M_{K^+K^-\pi^0}$, to determine the number of events of the reaction (1), i.e., to construct the spectrum of effective masses of the $\varphi\pi^0$ system. The two methods (integral and differential) gave identical results. These methods were also used to obtain all the other distributions for the $\varphi\pi^0$ system that are discussed below. The total number of detected φ mesons in the reaction (1) for different cutoffs lies in the range 350–450 events.

1.3. Spectrum of effective masses for the $\varphi\pi^0$ system in the reaction $\pi^- p \to (\varphi\pi^0) n$

Figure 7a gives the spectrum of effective masses of the $\varphi\pi^0$ system in the reaction (1), obtained after subtraction of the background under the φ peak; it is weighted with allowance for the acceptance of the facility (Fig. 7b). The dominant feature in the spectrum is a resonance peak with parameters

$$M = (1480 \pm 40)\,\text{MeV and } \Gamma = (130 \pm 60)\ \text{MeV}, \quad (17)$$

which has become known as the $C(1480)$ state.

In the analysis of the data on the reaction (5) with the separation of (1) the event selection criteria were varied, different methods of subtracting the background (differential and integral) were used, the influence of cutoffs with respect to the momentum transfer and a number of other quantities was investigated, and the step of the histogram and the fitting parameters were varied. Various hypotheses were made about the production mechanism of the $\varphi\pi^0$ system in the determination of the facility efficiency. It is important to note that the efficiency depended weakly on the choice of the model (this is due to the comparatively small energy release in the investigated region of $M_{\varphi\pi}$). The methods of determining the efficiency were tested and the absolute normalization of the cross sections was determined us-

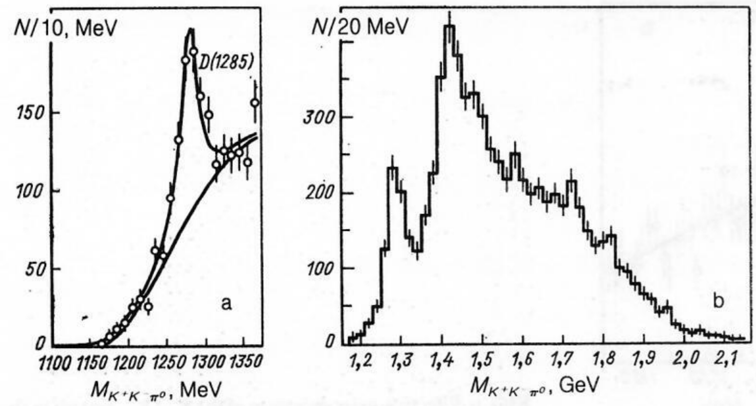


FIG. 4. Investigation of the reaction $\pi^- p \to (K^+K^-\pi^0)n$ at momentum $p_\pi = 32.5$ GeV: a) effective-mass spectrum of the $K^+K^-\pi^0$ system in the region $M < 1375$ MeV. The peak corresponds to production of the $D(1285)$ meson. The cross section of the reaction $\pi^- p \to D(1285)n$, $D(1285) \to K^+K^-\pi^0$ is 30×10^{-33} cm^2; b) the same spectrum in the complete investigated range of masses for $|t| > 0.1$ GeV^2.

ing the known reactions $\pi^- p \to \eta n$, $\eta \to \pi^+\pi^-\pi^0$ and $\pi^- p \to \omega n$, $\omega \to \pi^+\pi^-\pi^0$ with nearly the same kinematic properties (see Fig. 2).

The spectrum of the masses $M_{\varphi\pi^0}$ obtained by the different methods were found to be very similar. The small differences between them were used to estimate the systematic errors. Thus, the results [Fig. 7a and the parameters (17)] are stable with respect to appreciable variations in the procedure for the analysis. The cross section for production of the $C(1480)$ state is

$$\sigma\,[\pi^- p \to C\,(1480)\,n]\,BR\,[C\,(1480) \to \varphi\pi^0]$$

$$= (40 \pm 15)\cdot 10^{-33}\ \text{cm}^2. \qquad (18)$$

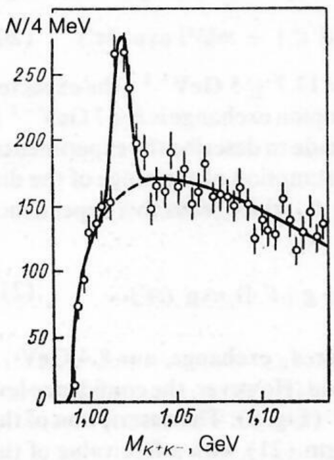


FIG. 5. Effective-mass spectrum of the K^+K^- system in the reaction $\pi^- p \to (K^+K^-\pi^0)n$. The peak corresponds to production of the φ meson. The parameters of the fit (Gaussian distribution and smooth background) are $M_\varphi = 1019.7 \pm 0.7$ MeV, $\Gamma_\varphi = 10.6 \pm 1.6$ MeV, $N_\varphi = 349 \pm 46$. The peak width corresponds to the spectrometer resolution.

The uncertainties in the values of (17) and (18) include both the statistical and the systematic errors.

A test of the procedure for subtracting the background under the φ peak in the separation of the $\varphi\pi^0$ system is the absence of a signal from the $D(1285)$ meson in the $M_{\varphi\pi^0}$ mass spectrum. The $D(1285)$ meson is clearly manifested for $K^+K^-\pi^0$ states in the reaction (5) (see Fig. 4) and can be seen even for events from the region of the φ peak, $1016 < M_{K^+K^-} < 1024$ MeV [because of the background, since the decay $D\,(1285) \to \varphi\pi^0$ is forbidden by C parity and isotopic invariance]. Having determined the suppression of the signal from the $D(1285)$ meson in the spectrum of the $\varphi\pi^0$ system and used the upper limit for the ratio $E(1420)/D(1285)$ in the reaction (5), we can show that the background from the $E(1420)$ meson did not exceed a few percent of the total number of $\varphi\pi^0$ events.

A study was made of the effect of incorrect identification of K mesons in the reaction (5), particularly of the possible background from kinematic "reflections" of η, $\omega \to \pi^+\pi^-\pi^0$ events from the reactions (12) and (13). This background was readily monitored; it was assumed that the investigated $K^+K^-\pi^0$ events for the region of the φ meson and for the background intervals were "$\pi^+\pi^-\pi^0$ events," and the corresponding effective-mass spectra were constructed. The investigation showed that for the selection criteria used in the analysis of the data the background from the kinematic η and ω reflections was very small— its contribution to the total number of $\varphi\pi^0$ events was less than 2%.

For an additional global verification of the entire procedure for separating the $\varphi\pi^0$ system, a special "background experiment" was performed; in it, to imitate the φ mesons the mass region $1044 < M_{K^+K^-} < 1052$ MeV (i.e., outside the φ peak) was chosen, and, as "neighboring intervals," the $M_{K^+K^-}$ regions 1030–1038 and 1058–1066 MeV. A spurious mass spectrum of the "φ" π^0 system was determined with the same event selection criteria and the same integral method for subtracting the background that was used to separate the true $\varphi\pi^0$ system. This spurious spectrum, weighted with the facility acceptance, is shown in Fig. 7c. The total number of events in the spurious spectrum did not exceed 20% of the true $\varphi\pi^0$ events. Resonance peaks are not observed in the spurious spectrum. The background experiment confirmed the correctness of the procedure for the analysis and the reliability of the data on the $C(1480)$ peak in the mass spectrum of the $\varphi\pi^0$ system.

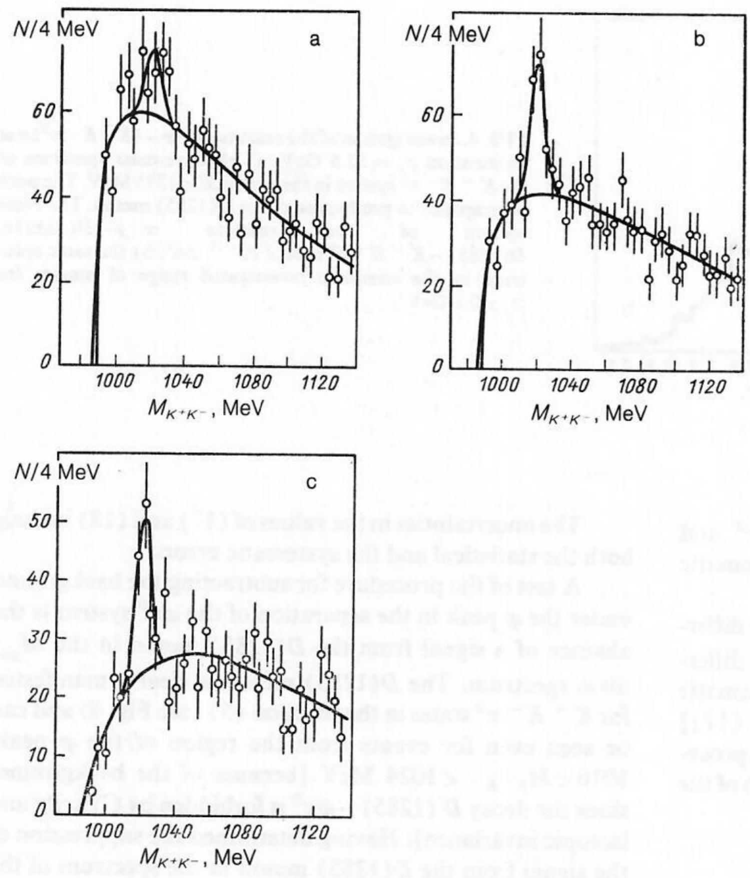


FIG. 6. Effective-mass spectrum of the K^+K^- system in the reaction $\pi^- p \to (K^+K^-\pi^0)n$ in ranges of $M_{K^+K^-\pi^0}$ masses: a) 1390–1450 MeV; b) 1450–1510 MeV; c) 1510–1570 MeV. The curves show the results of the fit. The parameters of the φ peak ($M_\varphi = 1019.8$ MeV, $\Gamma_\varphi = 9.3$ MeV) were determined from the data of Fig. 3. The background was approximated by a smooth two-parameter distribution.

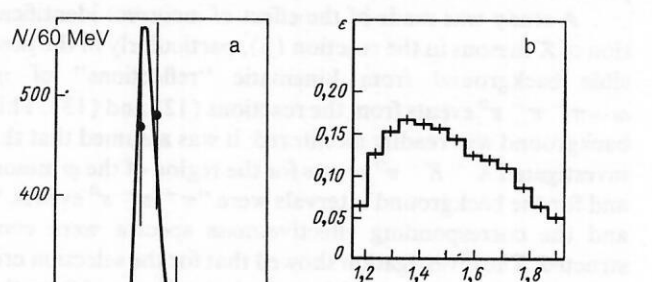


FIG. 7. Investigation of the reaction $\pi^- p \to (\varphi\pi^0)n$ at momentum $p_\pi = 32.5$ GeV: a) effective-mass spectrum of the $\varphi\pi^0$ system, weighted with the acceptance of the facility. The spectrum was approximated by the relativistic Breit–Wigner formula for orbital angular momentum $l = 1$ and a polynomial background. The experimental resolution for $M_{\varphi\pi^0}$ ~1.5 GeV is 45 MeV FWHM; b) acceptance of the spectrometer for detection of the $\varphi\pi^0$ system in the reaction (1); c) results of the "background experiment" for the spectrum of spurious "φ" π^0 events (see the text).

1.4. OPE dominance in the reaction $\pi^- p \to C(1480)n$ and the quantum numbers of the $C(1480)$ state

The distribution of the events of the reaction

$$\pi^- p \to C\ (1480)\ n \tag{19}$$

with respect to the square of the 4-momentum transfer $t' = t - t_{\min}$ was investigated. The experimental data (Fig. 8) are well described by the dependence for pion exchange

$$dN/d\mid t'\mid = \text{const}\ [\mid t'\mid/(\mid t'\mid + m_\pi^2)^2]\ \exp\ (bt') \tag{20}$$

with the free parameter $b = 13.7 \pm 5$ GeV^{-2} [the expected value of the slope in (20) for pion exchange is $b \simeq 7$ GeV^{-2}].

An attempt was also made to describe the experimental t' distribution under the assumption of exchange of the different nearest possible pole A_2, which leads to a dependence of the form

$$dN/d\mid t'\mid = \text{const}\ (1 + g\mid t'\mid)\ \exp\ (ct'). \tag{21}$$

The standard parameters for A_2 exchange, $c = 8.4$ GeV^{-2} and $g = 31$ GeV^{-2}, were used. However, the confidence level of this fit was below 10^{-5} (Fig. 8). The description of the experimental data in the form (21) with a free value of the slope parameter leads to $c = 33 \pm 5$ GeV^{-2}, i.e., to an unreasonably large slope for a reaction with elementary particles. All this suggests that the dominant mechanism in the charge-exchange reaction with production of the $C(1480)$ state is pion exchange. Since the t distribution in the case of pion exchange is concentrated in the region of small $|t'|$, the

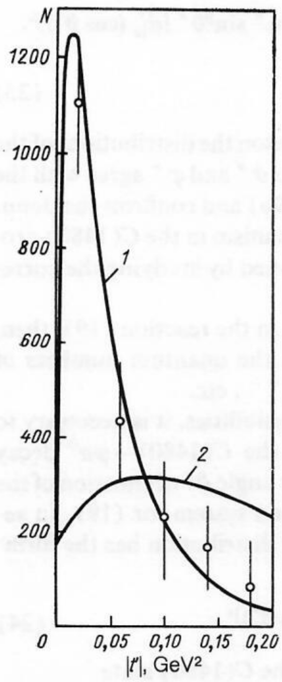


FIG. 8. Distribution of events from the $C(1480)$ peak with respect to the square of the 4-momentum transfer t', weighted with the acceptance of the facility. Curve 1 is the result of fitting the experimental data by the t' dependence expected for pion exchange [see (20)]; curve 2 is the expected form of the t' distribution for A_2 exchange [see (21)].

final mass spectra (see Figs. 5 and 7) were obtained using the additional selection criterion $|t'|<0.2\ \mathrm{GeV}^2$, which somewhat reduces the background, although it does not significantly change the results.

The distribution with respect to the momentum transfer for the reaction (19) confirms, in particular, the conclusion drawn earlier about the small contribution to the $\varphi\pi^0$ system from the background due to the processes

$$\pi^- p\to(\eta,\omega)n\to(\pi^+\pi^-\pi^0)n,$$
$$\pi^- p\to(D,E)n\to(K^+K^-\pi^0)n.$$

In these processes, pion exchange is forbidden, and their t distributions must be considerably broader than for the reaction (19) (they have the form of curve 2 in Fig. 8). On the other hand, for the control background intervals of masses $M_{K^+K^-}$ adjacent to φ, the t distribution has precisely such a gently sloping nature.

The existence of the dominant pion-exchange mechanism restricts the possible quantum numbers of the $C(1480)$ state by the condition $P=C=(-1)^J$. It follows from the $C(1480)\to\varphi\pi^0$ decay scheme that this state has isospin $I=1$ and negative charge parity.[4)] Therefore, only odd values are allowed for the total angular momentum, i.e., $J^{PC}=1^{--}, 3^{--}$, etc. We can evidently restrict ourselves to considering the first two sets of quantum numbers, since all known mesons with $J>3$ have mass greater than 2 GeV.

1.5. Direct measurement of the spin and parity of the *C*(1480) state by analysis of the angular distributions of cascade decays

Direct data on the quantum numbers of the $C(1480)$ state can be obtained by analyzing the cascade decays $C(1480)\to\varphi\pi^0$, $\varphi\to K^+K^-$. To analyze the decay $C(1480)\to\varphi\pi^0$, the Gottfried–Jackson system is used for the reaction (19) [i.e., the $C(1480)$ rest system], which for the analysis of $\varphi\to K^+K^-$ the rest system of the φ meson is used. The choice of the coordinate systems is as follows: a) Gottfried–Jackson system: $\mathbf{e}_{z'}=\mathbf{p}'_{\pi^-}/|\mathbf{p}'_{\pi^-}|$; $\mathbf{e}_{y'}=(\mathbf{p}'_{\pi^-}\times\mathbf{p}'_n)/|(\mathbf{p}'_{\pi^-}\times\mathbf{p}'_n)|$; $\mathbf{e}_{x'}=(\mathbf{e}_{y'}\times\mathbf{e}_{z'})$; b) rest frame of φ: $\mathbf{e}_{z''}=\mathbf{p}''_{\pi^0}/|\mathbf{p}''_{\pi^0}|$; $\mathbf{e}_{y''}=(\mathbf{p}''_{\pi^-}\times\mathbf{p}''_{\pi^0})/|(\mathbf{p}''_{\pi^-}\times\mathbf{p}''_{\pi^0})|$; $\mathbf{e}_{x''}=(\mathbf{e}_{y''}\times\mathbf{e}_{z''})$. Here, $\mathbf{p}''_{\pi^-}$ and $\mathbf{p}''_{\pi^-}$ are the momenta of the primary meson in these systems; $\mathbf{p}'_n$ is the momentum of the recoil neutron in the Gottfried–Jackson system; $\mathbf{p}''_{\pi^0}$ is the π^0 momentum in the φ rest frame; ϑ', φ' are the polar and azimuthal angles of the π^0 meson in the Gottfried–Jackson system; and ϑ'', φ'' are the same angles for K^- in the φ rest frame.

The distribution of the events with respect to the angle ϑ'' between the K^- meson and the π^0 meson in the rest frame of the φ meson determines the helicity of the φ meson: for $\lambda_\varphi=\pm1$ it must have the form $dN/d\cos\vartheta''=\mathrm{const}\cdot\sin^2\vartheta''$, and for $\lambda_\varphi=0$ the form $dN/d\cos\vartheta''=\mathrm{const}\cdot\cos^2\vartheta''$. The experimental distribution with respect to ϑ'' is practically undistorted by the acceptance of the facility. It was described in the form $dN/d|\cos\vartheta''|=\mathrm{const}[1-(b/3)+b\cos^2\vartheta'']$. For the parameter b, the value $b=-1.36\pm0.37$ (Fig. 9a) was obtained. This means that the helicity of the φ meson is compatible with the values $\lambda_\varphi=\pm1$ ($b=-1.5$) and, in particular, reliably excludes a spin of $C(1480)$ equal to zero, for which $\lambda_\varphi=0$

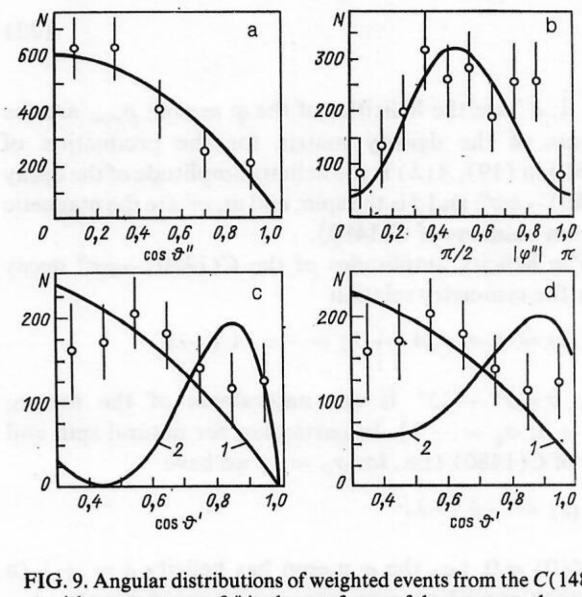


FIG. 9. Angular distributions of weighted events from the $C(1480)$ peak: a) with respect to $\cos\vartheta''$ in the rest frame of the φ meson; the curve is the result of fitting by the dependence $dN/d|\cos\varphi''|\sim1-b/3+b\cos^2\vartheta''$, $b=-1.36\pm0.37$, where ϑ'' is the angle between the K^- and π^0 in the rest frame of the φ meson; b) with respect to the azimuthal angle φ''; the curve is the result of fitting by the dependence $dN/d\varphi''\sim\sin^2\varphi''$ (the confidence level of the fit is 0.13); c) with respect to $\cos\vartheta'$ [ϑ' is the emission angle of the π^0 in the Gottfried–Jackson system for (19)]; curve 1 is the expected form of the distribution for the case $J^{PC}=1^{--}$ [see (25)]; curve 2 is for the case $J^{PC}=3^{--}$ [see (26)]; the simplest OPE model is used with density matrix for the reaction $\pi^-p\to C(1480)n$ of the form $\rho_{00}=1$, $\rho_{mm'}=0$ for $m, m'0$; d) the same distribution, but curves 1 and 2 correspond to the expected form $dN/d\cos\vartheta'$ for $C(1480)$ quantum numbers $J^{PC}=1^{--}$ and 3^{--} in the Ochs–Wagner OPE model.[23]

(i.e., $b=3$). The conclusion that the $C(1480)$ has nonzero spin follows from the form of the distribution $dN/d\,|\cos\vartheta''|$ and does not depend on the assumption of a dominant role of one-pion exchange in the reaction (19).

Figure 9b shows the distribution of the events with respect to the azimuthal angle φ'' for the emission of the K^- mesons in the rest frame of the φ meson [the angle φ'' in this system is measured from the $C(1480)\to\varphi\pi^0$ decay plane]. The azimuthal distribution has the form $dN/d\varphi'' = \text{const}\cdot\sin^2\varphi''$.

The distributions with respect to $\cos\vartheta''$ and φ'' in the background mass intervals for the K^+K^- system (for the integral method of subtracting the background under the φ peak) shows that the background is isotropic and cannot lead to serious systematic distortions of the angular distributions for the decays $C(1480)\to\varphi\pi^0$, $\varphi\to K^+K^-$.

We now turn to a complete analysis of the angular distributions of the cascade decays in (19), using for this the formalism of helicity amplitudes.[20] The general expression for the angular distribution of the secondary particles has the form (here and in what follows, see, for example, Ref. 21)

$$\left.\begin{aligned}
&W(\vartheta',\varphi';\vartheta'',\varphi'')=\sum_{\lambda,\lambda'}R(\lambda,\lambda')\,\Lambda(\lambda,\lambda');\\
&R(\lambda,\lambda')=\sum_{m,m'}\exp[i(m-m')\varphi']\,\rho_{mm'}d^J_{m\lambda}(\cos\vartheta')\\
&\qquad\times d^J_{m'\lambda'}(\cos\vartheta')A(\lambda)A^*(\lambda');\\
&\Lambda(\lambda,\lambda')=\exp[i(\lambda-\lambda')\varphi'']\,d^1_{0\lambda}(\cos\vartheta'')\,d^1_{0\lambda'}(\cos\vartheta'').
\end{aligned}\right\}\tag{22}$$

Here, λ, λ' are the helicities of the φ meson; $\rho_{mm'}$ are the elements of the density matrix for the production of $C(1480)$ in (19); $A(\lambda)$ is the helicity amplitude of the decay $C(1480)\to\varphi\pi^0$; and J is the spin, and m, m' are the magnetic quantum numbers of $C(1480)$.

The helicity amplitudes of the $C(1480)\to\varphi\pi^0$ decay satisfy the symmetry relation

$$A(\lambda)=\sigma_C\sigma_\varphi\sigma_\pi A(-\lambda)=-\sigma_C A(-\lambda)$$

[here, $\sigma=P(-1)^J$ is the naturalness of the meson; $\sigma_\varphi=+1$; $\sigma_\pi=-1$]. In particular, for natural spin and parity of $C(1480)$ (i.e., for $\sigma_C=1$) we have

$$A(\lambda)=-A(-\lambda)$$

And $A(0)=0$, i.e., the φ meson has helicity $\lambda=\pm1$ (a result that, as we have seen, agrees with experiment).

The angular distributions of the decay particles for the cascade process $\pi^-p\to C(1480)n$, $C(1480)\to\varphi\pi^0$, $\varphi\to K^+K^-$ can be obtained from (22) if certain assumptions are made about the reaction mechanism and the well-known symmetry relations for the Wigner d functions and the elements $\rho_{mm'}$ of the density matrix of the reaction (19) are taken into account. In the simplest model of one-pion exchange, the density matrix $\rho_{mm'}$, has the form $\rho_{00}=1$, $\rho_{mm'}=0$ for m, $m'\neq0$. In this case, the angular distributions of the decay particles are determined by the expression

$$W(\vartheta',\varphi';\vartheta'',\varphi'')=\text{const}\cdot\sin^2\varphi''\sin^2\vartheta''\,[d^J_{10}(\cos\vartheta')]^2.\tag{23}$$

Thus, in the rest frame of the φ meson the distributions of the decay K^- mesons with respect to ϑ'' and φ'' agree with the experimental data (Figs. 9a and 9b) and confirms the dominance of the pion-exchange mechanism in the $C(1480)$ production process that was established by studying the corresponding t distribution (Fig. 8).

If pion exchange dominates in the reaction (19), then, as was already said in Sec. 1.4, the quantum numbers of $C(1480)$ must be $J^{PC}=1^{--}, 3^{--}$, etc.

To choose between these possibilities, it is necessary to investigate the distributions of the $C(1480)\to\varphi\pi^0$ decay products with respect to the polar angle ϑ' of emission of the π^0 meson in the Gottfried–Jackson system for (19). In accordance with (23), this angular distribution has the form

$$dN/d\cos\vartheta'=\text{const}\,[d^J_{10}(\cos\vartheta')]^2.\tag{24}$$

Hence, for the possible spins of the $C(1480)$ state

$$dN/d\cos\vartheta'=\text{const}\sin^2\vartheta'\ (J=1)\tag{25}$$

or

$$dN/d\cos\vartheta'=\text{const}\sin^2\vartheta'\,(5\cos^2\vartheta'-1)^2\ (J=3).\tag{26}$$

The distribution of the $C(1480)\to\varphi\pi^0$ decay events with respect to the polar angle ϑ' is shown in Fig. 9c. Here, the spectrometer acceptance has been taken into account; it restricts the effective range of angles to the interval $0.3<\cos\vartheta'<1$.

As can be seen from Fig. 9c, the investigated angular distribution agrees with the $C(1480)$ quantum numbers $J^{PC}=1^{--}$ [i.e., with (25)] and rules out $J^{PC}=3^{--}$ (26); the corresponding confidence levels are 0.2 and 10^{-7}. For the higher spin values $J^{PC}=5^{--}$, etc., the confidence levels for the description of the experimental angular distribution with respect to $\cos\vartheta'$ are even lower than for $J^{PC}=3^{--}$.

Thus, analysis of the decay angular distributions (22) for $C(1480)\to\varphi\pi^0$, $\varphi\to K^+K^-$ in (19) has permitted a model-free elimination of the $C(1480)$ spin value $J=0$ and, in the one-pion exchange (OPE) model for the reaction (19), has made it possible to establish the quantum numbers $J^{PC}=1^{--}$ for the $C(1480)$ state.

This conclusion is stable and is not changed by modifications of the OPE model that take into account absorption effects. In this case, the density matrix that describes the $C(1480)$ production in the reaction (19) is more complicated, and the form of the angular distributions (25) and (26) is somewhat changed. An additional analysis was made on the basis of the one-pion exchange model with Ochs–Wagner absorption,[23] which agrees well with the experiments for all investigated OPE processes. It can be seen from Fig. 9d that in this case too the angular distributions in the Gottfried–Jackson system agree with the quantum numbers of the $C(1480)$ state $J^{PC}=1^{--}$ and rule out $J^{PC}=3^{--}$ (the confidence levels are 0.27 and 3×10^{-4}; for more details, see Ref. 22).

1.6. The $C(1480)$ state: a new vector meson

As is well known, resonance behavior of a physical system can be imitated by a threshold Deck effect. Figure 10 shows some diagrams in which such near-threshold singularities can be manifested. The corresponding matrix elements decrease fairly rapidly with increasing mass $m(V\pi)$ near the threshold, and this may lead to a resonance-like behavior of the spectrum of the effective masses of the $V\pi$ system in the reactions $\pi^- p \to (V\pi^0)n$ $(V \equiv \rho^0; \omega; \varphi)$.

Attempts to explain the mass spectrum of the $\varphi\pi^0$ system in the reaction (1) by means of the threshold Deck effect showed that the probability of such a description is negligibly small—the $C(1480)$ peak was separated above the "theoretical background" from the Deck effect,[24] normalized outside this peak, i.e., outside the two channels with the maximal number of events in Fig. 7a), by more than 10 standard deviations. Other estimates associated with a comparative analysis of the $\varphi\pi^0$ and $\omega\pi^0$ states with nearly equal energy release Q in the reactions $\pi^- p \to \varphi\pi^0 n$ and $\pi^- p \to \omega\pi^0 n$ showed that with allowance for the OZI prohibition on the production of a nonresonance $\varphi\pi^0$ system the contribution of the Deck effect to the cross section (19) does not exceed 10^{-33} cm^2 in order of magnitude.

Thus, the $\varphi\pi^0$ state with mass 1480 MeV has quantum numbers $I = 1$ and $J^{PC} = 1^{--}$. It cannot be explained by threshold effects and is a new resonance—the $C(1480)$ meson. The conclusions about the spin and parity of the $C(1480)$ meson follow from the data on the dominant role of pion exchange in the reaction (19) and from analysis of the angular distributions for the cascade decays $C(1480) \to \varphi\pi^0$ and $\varphi \to K^+K^-$ in this reaction.

The existence of a resonance in the $\varphi\pi$ system in the investigated region of masses is also confirmed by data of an experiment with the SIGMA spectrometer,[25] in which a peak was found in the inclusive process $\pi^- p \to (\varphi\pi^-)X$, $\varphi \to \mu^+\mu^-$ in the mass spectrum of the $\varphi\pi$ system, with parameters close to those of the $C(1480)$ meson (Fig. 11).

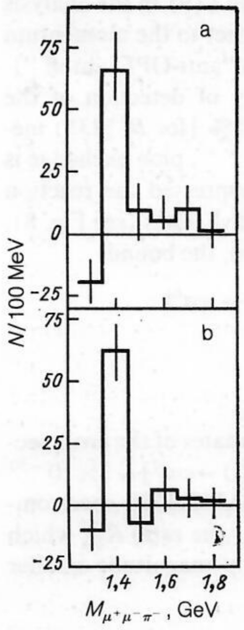


FIG. 11. Spectrum of effective masses of the $\mu^+\mu^-\pi^0$ system in the inclusive reaction $\pi^- p \to (\varphi\pi^-) + X$, $\varphi \to \mu^+\mu^-$ (after subtraction of the background below the φ peak) for initial momentum $p_{\pi^-} = 50$ GeV: a) all events detected by the spectrometer; b) events for which the total momentum of the $\mu^+\mu^-\pi^-$ system satisfies the condition $p_{\mu^-} + p_{\mu^+} + p_{\pi^-} < 45$ GeV.

1.7. The decays $C(1480) \to \varphi\pi^0$ and $C(1480) \to \omega\pi^0$

A very important quantity that characterizes the quark structure of the $C(1480)$ meson is the ratio of the decay probabilities

$$R_C = BR\,[C\,(1480) \to \varphi\pi^0]/BR\,[C\,(1480) \to \omega\pi^0], \quad (27)$$

i.e., for processes forbidden and allowed by the OZI rule for mesons consisting of u and d quarks. In Refs. 2–4 the determination of R_C was based on not only (18) but also data on the reaction

$$\pi^- p \to (\omega\pi^0)\,n, \quad (28)$$

obtained at momentum $p_{\pi^-} = 38$ GeV in experiments with the GAMS-2000 spectrometer.[26] The mass spectrum of the $\omega\pi^0$ system in (28) was found to contain peaks from the mesons $B(1235) \to \omega\pi^0$ and $g(1680) \to \omega\pi^0$, and no statistically significant structures were observed in the region of 1.5 GeV. This gave the bound

$$R_C > 0{,}5 \ (95\ \%\text{- confidence level}). \quad (29)$$

The anomalous nature of this ratio for the $C(1480)$ meson can be seen clearly from a comparison with data on the analogous decays of the well-known "ordinary" meson $B(1235)$ $(J^{PC} = 1^{+-})$:

$$R_B = BR\,[B\,(1235) \to \varphi\pi^0]/BR\,[B\,(1235) \to \omega\pi^0]$$

$$< 5 \cdot 10^{-3} \quad (30)$$

The upper limit (30) for R_B is obtained by comparing data on the spectra of the effective masses of the $\varphi\pi^0$ system in the reaction (1) (Lepton-F) and of the $\omega\pi^0$ system in the reaction (28) (GAMS-2000) in the region of masses of the $B(1235)$ meson.[5]

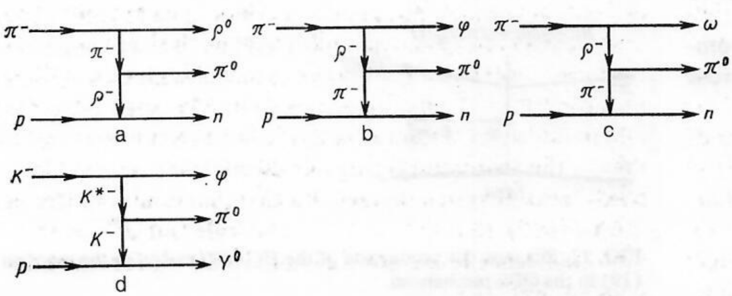


FIG. 10. Diagrams for near-threshold singularities in exclusive reactions with production of a $V\pi^0$ system ($V\pi^0 \equiv \rho\pi^0$, $\varphi\pi^0$, $\omega\pi^0$): a) $\pi^- p \to \rho\pi^0 n$; b) $\pi^- p \to \varphi\pi^0 n$; c) $\pi^- p \to \omega\pi^0 n$; d) $K^- p \to \varphi\pi^0 Y^0$.

To suppress the background from (19) in the analysis of the $\varphi\pi^0$ system, selection with respect to the momentum transfer was used: $|t'| > 0.1$ GeV^2 ("anti-OPE cutoff"). This selection reduced the efficiency of detection of the $B(1235)$ mesons by not more than 25% [for $B(1235)$ mesons with quantum numbers $J^{PC} = 1^{+-}$, pion exchange is forbidden] and at the same time suppressed the reaction (19) with $C(1480)$ mesons by about five times (see Fig. 8). After the introduction of this selection, the bound

$$\sigma\,[\pi^- p \to B\,(1235)^0\,n]\,BR\,[B\,(1235) \to \varphi\pi^0]$$

$$< 5\cdot 10^{-33}\ \text{cm}^2$$

(95% confidence level) was obtained.

These data together with the estimates of the cross section $\sigma[\pi^- p \to B(1235)n]BR[B(1235) \to \omega\pi^0] \simeq 1\times 10^{-30}$ cm^2 (from experiments with the GAMS-2000 spectrometer) led to the upper bound (30) for the ratio R_B, which was found to be at least two orders of magnitude smaller than the ratio R_C [see (29)].

1.8. Searches for other decay channels of the $C(1480)$ meson

In the analysis of the reaction (5) in the region $|t'| < 0.1$ GeV^2, searches were made for decays of the C mesons through other channels not associated with the production of φ mesons: $C(1480) \to K^*\bar{K}$ and $C(1480) \to K^+K^-\pi^0$. The upper bounds obtained for the branching ratios of these decays were

$$BR\,[C\,(1480) \to K^{*+}K^- + K^{*-}K^+]/$$
$$BR\,[C\,(1480) \to \varphi\pi^0] < 0{,}8; \qquad (31)$$
$$BR\,[C\,(1480) \to K^+K^-\pi^0]/$$
$$BR\,[C\,(1480) \to \varphi\pi^0] < 1{,}5 \qquad (32)$$

(95% confidence level).

On the basis of isotopic invariance, we can obtain from (31)

$$BR\,[C\,(1480) \to K^{*-}K^+ + K^{*+}K^-]/$$
$$BR\,[C\,(1480) \to \varphi\pi^0] < 2{,}4; \qquad (33)$$
$$BR\,[C\,(1480) \to K^*\bar{K} + \bar{K}^*K]/$$
$$BR\,[C\,(1480) \to \varphi\pi^0] < 4{,}8$$

(95%) confidence level).

Assuming the OPE model for the reaction (19), and using (18) we can show that

$$BR\,[C\,(1480) \to \pi^+\pi^-]\,BR\,[C\,(1480) \to \varphi\pi^0]$$

$$\simeq (1-2)\cdot 10^{-3} \qquad (34)$$

(S. N. Grudtsin and A. Yu. Khodzhamiryan, private communications). Indeed, from the diagram of Fig. 12 the cross section of the OPE process is found to be

$$\sigma\,[\pi^- p \to C\,(1480)\,n]$$

$$= \int dt' \frac{\sum |N\,[C\,(1480) \to \pi^+\pi^-]|^2\, g^2_{\pi NN}}{(t' - m_\pi^2)^2}\,|F_\pi\,(t')|^2.$$

The form factor $F_\pi(t')$ is determined by the "departure" of the virtual pion from the mass shell and can be estimated from data on production of the ρ meson in the reaction $\pi^- p \to \rho n$ [for primary momentum $p_{\pi^-} = 32.5$ GeV, the form factor $F_\pi(t')$ depends weakly on the difference between the masses of the $\rho(770)$ and $C(1480)$ mesons]. The square of the matrix element of the transition $C(1480) \to \pi^+\pi^-$ (the upper vertex in the diagram of Fig. 12), summed over the $C(1480)$ spin states $(\Sigma|N[C(1480) \to \pi^+\pi^-]|^2)$, determines the decay width:

$$\Gamma\,[C\,(1480) \to \pi^+\pi^-]$$
$$= \Gamma_C BR\,[C\,(1480) \to \pi^+\pi^-] = \frac{q_C\left(\sum |N\,[C\,(1480) \to \pi^+\pi^-]|^2\right)}{8\pi M_C^2\,(2J_C+1)}.$$

Comparing the processes of OPE production and dipion decays of the vector $C(1480)$ and ρ mesons, we can readily find a relation for the decay widths of the $C(1480)$ meson:

$$BR\,[C\,(1480) \to \varphi\pi^0]\,BR\,[C\,(1480) \to \pi^+\pi^-] = \left[\frac{\Gamma_\rho q_C m_\rho^2}{\Gamma_C q_\rho M_C^2}\right]$$
$$\times \frac{\sigma\,[\pi^- p \to C\,(1480)\,n]\,BR\,[C\,(1480) \to \varphi\pi^0]}{\sigma\,[\pi^- p \to \rho n]}. \qquad (35)$$

Here, M_C and Γ_C are the mass and total width of the $C(1480)$ meson; q_C is the pion momentum in the decay $C(1480) \to \pi^+\pi^-$ [in the rest frame of the $C(1480)$ meson], etc. Using in (35) the properties (17) and (18) of the $C(1480)$ meson, the tabulated parameters of the ρ meson, and the cross section $\sigma[\pi^- p \to \rho n]|_{p\pi^- = 32.5\,\text{GeV}} \simeq 13\times 10^{-30}$ cm^2 (extrapolation from the region of lower energies), we can obtain the estimate for the decay widths (34) given above.

1.9. Searches for production of $C(1480)$ mesons in $K^- p$ interactions

As was already said in Sec. 1.1, in the Lepton-F experiments a fairly intense effective flux of K^- mesons (0.8×10^{10} particles) was passed through the target of the facility, and 3×10^3 events from the $K^- N \to (K^+K^-\pi^0)Y$ reaction were detected.

Production of the $\varphi\pi^0$ system in $K^- p$ interactions was also investigated. As can be seen in Fig. 3, which gives the spectrum of effective masses of the K^+K^- system in the reaction (8), the contribution of the process $K^- N \to (\varphi\pi^0)Y$ is here clearly revealed. However, the spectrum of effective masses of the $\varphi\pi^0$ system in (9) (Fig. 13) differs strongly from the analogous spectrum for the reaction (1), and a signal from the $C(1480)$ meson was not

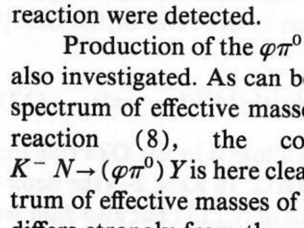


FIG. 12. Diagram for production of the $C(1480)$ meson in the reaction (19) in the OPE mechanism.

found here. An upper limit was determined for the cross-section ratio:

$$\sigma\,[K^-N \to C\ (1480)\ Y]/\sigma\,[\pi^-p \to C\ (1480)\ n] < 12 \qquad (36)$$

(95% confidence level). This ratio is two orders of magnitude lower than the ratio of the cross sections for the analogous two-particle exclusive processes of φ-meson production in $K^- N$ and $\pi^- p$ interactions at the same energy.

1.10. The nature of the C(1480) meson

In principle, there are three possibilities for interpreting data[1-4] on the vector $C(1480)$ meson.

1. The meson $C(1480)$ has the usual quark structure of a meson with isotopic spin $I = 1$: $|C(1480)\rangle = |(1/\sqrt{2})(u\bar{u} - d\bar{d})\rangle$. Then what is experimentally observed is a rare decay $C(1480) \to \varphi\pi^0$, which is strongly suppressed by the OZI rule and takes place with a very low probability ($< 1\%$ or even $\ll 1\%$).

2. The $C(1480)$ meson is an isotopically scalar particle of the type φ' with quark composition $|C(1480)\rangle_{I=0} = |s\bar{s}\rangle$ (with hidden strangeness), and, since the state $\varphi\pi^0$ is characterized by isospin $I = 1$, the decay $C(1480) \to \varphi\pi^0$ is due to breaking of isotopic invariance.

3. The $C(1480)$ meson is an exotic state, i.e., a multiquark or hybrid meson. Such a hadron could be strongly coupled to the $\varphi\pi^0$ system.[19]

We now consider these three possibilities successively.

1.10.1. Could the C(1480) meson be an ordinary vector meson of the type ρ'?

If the $C(1480)$ meson has the quark structure $(u\bar{u} - d\bar{d})/\sqrt{2}$ and in the experiments[1-4] a rare OZI-suppressed decay $C(1480) \to \varphi\pi^0$, is observed, then it appears rather natural to attempt to identify it with the already known vector ρ' meson. Although these states do differ in the tabulated values of the masses and widths, it should be borne in mind that the current data on the ρ' meson are extremely contradictory, and the masses and widths of these states in different studies lie in the ranges $1430 < m(\rho') < 1780$ MeV and $100 < \Gamma(\rho') < 850$ MeV.[27] It appears difficult to explain all these results by the existence

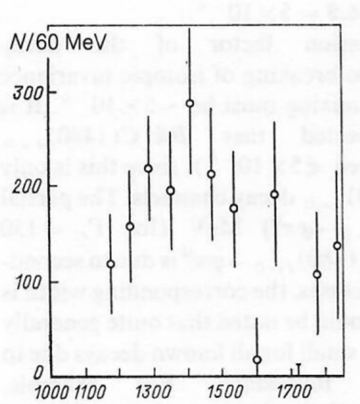


FIG. 13. Effective-mass spectrum of the $\varphi\pi^0$ system in the reaction $K^- N \to (\varphi\pi^0)\,Y$, weighted with the acceptance of the facility.

of a single ρ' meson. The analysis made in Ref. 28 suggests the existence of two such states, with $m(\rho_1') = 1465 \pm 25$ MeV, $\Gamma(\rho_1') = 235 \pm 25$ MeV and $m(\rho_2') = 1700 \pm 25$ MeV, $\Gamma(\rho_2') = 220 \pm 25$ MeV. Then $C(1480) \to \varphi\pi^0$ could be a new rare decay of the vector ρ_1' meson, and the experiments of Refs. 1–4 should be regarded as the first direct experimental discovery of the ρ_1' meson and determination of its parameters (the study of Ref. 28 appeared later and was based, not on direct measurements, but on an analysis of a set of data for several reactions in which ρ' mesons were observed).

A similar interpretation of the $C(1480)$ state can be found, for example, in Refs. 29 and 30, in which the ρ' meson was taken to have parameters $m(\rho')$ and $\Gamma(\rho')$ close to those of $C(1480)$ or ρ_1', and the decay $\rho' \to \varphi\pi^0$ with branching ratio $\simeq 0.005$ was taken to arise from dynamical breaking of the OZI rule through intermediate processes $\bar{\rho}' \to K^*\bar{K} + K^*\bar{K} \to \varphi\pi^0$. As was shown in Ref. 29, such a model makes it possible to describe, to within a factor ~ 2, the data on the reaction (1) and on the value of the cross section (18).

However, both in this model and in any other known mechanism of OZI breaking for $|C\rangle \equiv |(u\bar{u} - d\bar{d})/\sqrt{2}\rangle$ a serious difficulty arises. It is true that the low probability of OZI-forbidden processes [i.e., the smallness of $BR(C(1480) \to \varphi\pi^0)$ makes it easy to explain the small value of $\sigma[\pi^- p \to C(1480)n]\ BR[C(1480) \to \varphi\pi^0]$ [see (18)], but the complete description of the experimental data of Refs. 1–4 also requires an explanation of the anomalously large value of R_C [see (29)]. Indeed, it is precisely the ratio of probabilities of the processes with φ and ω mesons that is used to analyze the extent to which the OZI rule for particles with light quarks holds. From the data for a number known processes [comparison of the reactions $\pi^- p \to \varphi n$ and $\pi^- p \to \omega n$ (see Sec. 2) and of the widths of the decays $\varphi \to \pi^0\gamma$ and $\omega \to \pi^0\gamma$, $\varphi \to 3\pi$ and $\omega \to 3\pi$] it can be estimated that for ordinary $(1/\sqrt{2})\ (u\bar{u} - d\bar{d})$ vector mesons the ratio R_C must be of order 1/200–1/400. This estimate deviates by two orders of magnitude from the experimental bound $R_C > 0.5$. At the same time, according to QCD sum rules, it is precisely in the vector channel that the OZI suppression must hold particularly well.[31] This is why the large value of R_C led to the exotic interpretation of the $C(1480)$ meson in Refs. 1–4.

As an additional illustration of the expected smallness of R_C for isovector mesons of ordinary $q\bar{q}$ type, let us compare the ratios of the probabilities of the $\varphi\pi^0$ and $\omega\pi^0$ decay channels for the $C(1480)$ and $B(1235)$ mesons: $R_C > 0.5$ and $R_B < 5 \times 10^{-3}$. For the well-known $B(1235)$ meson [$I^G = 1^+$, $J^{PC} = 1^{+-}$, quark structure $(1/\sqrt{2})(u\bar{u} - d\bar{d})$] the decays $B(1235) \to \omega\pi^0$ and $B(1235) \to \varphi\pi^0$ take place mainly in states with $l = 0$. Therefore, the ratio R_B can be represented in the form

$$R_B = [p_\varphi^{(B)}/p_\omega^{(B)}]\,[g^2_{B\varphi\pi^0}/g^2_{B\omega\pi^0}] \leqslant 5 \cdot 10^{-3}$$

or

$$[g^2_{B\varphi\pi^0}/g^2_{B\omega\pi^0}] \leqslant 1{,}2 \cdot 10^{-2}.$$

Here, $P_\varphi^{(B)}$, $p_\omega^{(B)}$ are the momenta of the decay φ and ω mesons in the rest frame of the $B(1235)$ meson; $g_{B\varphi\pi^0}$, etc., are the corresponding coupling constants. Since $\varphi\pi^0$ and $\omega\pi^0$ decays of the vector $C(1480)$ mesons take place in states with $l=1$,

$$R_C=[p_{\varphi}^{(C)}/p_{\omega}^{(C)}]^3\,[g^2_{C\varphi\pi^0}/g^2_{C\omega\pi^0}]=0{,}4\,[g^2_{C\varphi\pi^0}/g^2_{C\omega\pi^0}].$$

If $C(1480)$ were a meson of the ordinary $q\bar{q}$ type, then under the natural assumption

$$[g^2_{B\varphi\pi^0}/g^2_{B\omega\pi^0}]\simeq[g^2_{\text{OZI forb}};\ _{3g}/g^2_{\text{OZI all}}]$$

$$\simeq[g^2_{C\varphi\pi^0}/g^2_{C\omega\pi^0}]\leqslant 10^{-2}$$

(in both cases, the OZI-forbidden decay takes place through the three-gluon vertex) we would again obtain a very low expected bound $R_C<5\times10^{-3}$, in sharp disagreement with experiment.

It is important to emphasize that the model of Refs. 29 and 30 also cannot explain the large value of R_C. The estimate $BR(\rho'\to\varphi\pi^0)\simeq0.005$ in this model is based on the large tabulated value of $BR(\rho'\to\bar{K}^*K+K^*\bar{K})=0.09\pm0.02$ (Ref. 27) (in what follows, we shall denote this decay more briefly by $\rho'\to\bar{K}^*K$). Then in accordance with SU(3) symmetry, the $\rho'\to\omega\pi^0$ decay should have, in the quark model, probability $BR(\rho'\to\omega\pi^0)\simeq4BR(\rho'\to\bar{K}^*K)\sim0.4$ (Ref. 30), i.e., in this mechanism too it is natural to expect a small ratio $R_{\rho'}\sim1/50$–1100. Breaking of $SU(3)$ symmetry (suppression of processes with s quarks) can only increase the expected value of $BR(\rho'\to\omega\pi^0)$, i.e., decrease still further the prediction for $R_{\rho'}$. At the same time, it follows from a number of experimental data that $BR(\rho'\to\omega\pi^0)<0.01$–$0.03$ (see the discussion in Ref. 30). Then if $BR(\rho'\to\varphi\pi^0)\simeq0.005$, we must have $R_{\rho'}>0.2$–0.5, and it is difficult to reconcile this with the properties of a ρ' meson as an ordinary $q\bar{q}$ state. In Ref. 30, the small value of $BR(\rho'\to\omega\pi^0)$ was regarded as a mystery of the ρ' meson.

However, as was shown in Ref. 6, for the model of Refs. 29 and 30, with all its achievements and puzzles, there are now simply no weighty experimental grounds. The touchstone for this model is the large value of the branching ratio $BR(\rho'\to\bar{K}^*K)=0.09\pm0.02$, which is given in the PDG table.[27] Let us therefore consider how well this value is established. It is based on the single experiment with colliding e^+e^- beams,[32,33] in which there is a difficult problem of separating the $e^+e^-\to\rho'\to\bar{K}^*K$ and $e^+e^-\to\varphi'\to\bar{K}^*K$ contributions (the latter process is the dominant one). The complete statistics of $\bar{K}^*K$ events for the two processes does not exceed 150, and the analysis used to estimate the partial cross sections is model-dependent and does not take into account the uncertainties in the parameters of the ρ' state. In addition, even in the framework of this experiment the tabulated value of $BR(\rho'\to\bar{K}^*K)$ is strongly overestimated by a misunderstanding. Indeed, it should be $BR(\rho'\to\bar{K}^*K)=0.045\pm0.010$ and, for a different normalization, even 0.025 ± 0.007.[5)] All this shows that at the present time there exists merely an upper bound for this branching ratio: $BR(\rho'\to\bar{K}^*K)<0.05$. Therefore, there are at present no serious grounds for speaking of a mysterious weakness of the decay $\rho'\to\omega\pi^0$, as is done in Ref. 30; rather, the upper limit for the corresponding probability can be used in the $SU(3)$ scheme to make a more sensitive estimate of the upper bound $BR(\rho'\to\bar{K}^*K)\simeq\frac{1}{4}BR(\rho'\to\omega\pi^0)\lesssim0.025-0.01$. It is obvious that such a small value of $BR(\rho'\to\bar{K}^*K)$ (which, of course, must still be confirmed in direct experiments) completely rules out an explanation of the $\varphi\pi^0$ peak in (1) with the parameters (17) and (18) through a mechanism[29,30] associated with the ρ' meson.

Summarizing this part of the discussion, we must emphasize that at the present time there does not exist an explanation for the large value $R_C>0.5$ for the $C(1480)$ meson if it is assumed that this hadron is an ordinary state with quark structure $(1/\sqrt{2})(u\bar{u}-d\bar{d})$. Therefore, such a conjecture appears improbable.

1.10.2. Could C(1480) be a meson of the type φ'?

Now suppose that $C(1480)$ is an isoscalar meson with hidden strangeness of the type φ', and let us estimate the probability of the decay $|C(1480)\rangle|_{I=0}=|s\bar{s}\rangle\to\varphi\pi^0$ (with nonconservation of isospin).

As a mechanism leading to maximal breaking of isotopic invariance in the decay $C(1480)_{I=0}\to\varphi\pi^0$, we must consider π^0–η mixing. The contribution of such a mechanism can be estimated from the branching ratio $\Gamma(\eta'\to\pi^0\pi\pi)/\Gamma(\eta'\to\eta\pi\pi)$ (i.e., from decays that take place without and with isospin conservation) by means of the method developed in Ref. 34. As follows from the calculations of Ref. 34,

$$r_{+-}=\Gamma(\eta'\to\pi^0\pi^+\pi^-)/\Gamma(\eta'\to\eta\pi^+\pi^-)$$

$$=16{,}8N=16{,}8\left[\frac{3}{16}\left(\frac{m_d-m_u}{m_s}\right)^2\right].$$

Here, the first factor 16.8 is due to the phase spaces, while the second factor $N=\frac{3}{16}[(m_d-m_u)/m_s]^2$ represents the suppression due to π^0–η mixing; m_d, m_u, and m_s are the masses of the current quarks.

Two methods can be used to estimate N.

a) The theoretical estimate of $(m_d-m_u)/m_s$ from the $\omega\to\pi^+\pi^-$ width and from other data (see, for example, Ref. 35): $N_{\text{theor}}\lesssim10^{-4}$.

b) The experimental estimate from data on $\eta'\to3\pi$ decays. Unfortunately, there is as yet no information about the width $\Gamma(\eta'\to\pi^0\pi^+\pi^-)$. However, there has been observation of the decay $\eta'\to3\pi^0$, in which there is also nonconservation of isospin, and there has been a measurement of $r_{00}=\Gamma(\eta'\to3\pi^0)/\Gamma(\eta'\to\eta\pi^0\pi^0)=0.0075\pm0.0018$ (Ref. 36). Since $r_{+-}\sim r_{00}$, it follows that $N_{\text{exp}}=r_{+-}/16.8\sim r_{00}/16.8=5\times10^{-4}$.

Thus, the suppression factor of the decay $C(1480)|_{I=0}\to\varphi\pi^0$ due to breaking of isotopic invariance in the mechanism of $\eta\pi^0$ mixing must be $\sim5\times10^{-4}$. It is therefore to be expected that $BR[C(1480)_{I=0}\to\varphi\pi^0]<5\times10^{-4}$ (or even $\ll5\times10^{-4}$), since this is only one of the possible $C(1480)_{I=0}$ decay channels. The partial width is $\Gamma((C(1480)_{I=0}\to\varphi\pi^0)$ MeV (for $\Gamma_C=130$ MeV). But if the decay $C(1480)_{I=0}\to\varphi\pi^0$ is due to second-order electromagnetic processes, the corresponding width is well below this limit. It should be noted that quite generally the partial widths are very small for all known decays due to breaking of isotopic invariance. For example, $\Gamma(\omega\to\pi^+\pi^-)=0.17$ MeV (in this case, the breaking of the isotopic invariance is anomalously large, owing to the proximity of the masses m_ρ and m_ω), and $\Gamma(\eta'\to3\pi)\simeq0.4$ keV.

For $BR(C(1480)_{I=0} \to \varphi\pi] < 5\times10^{-4}$ and the cross section of the OZI-suppressed reaction $\sigma[\pi^- p \to C(1480)_{I=0} n] < 1\times10^{-31}$ cm^2, we can finally obtain an upper bound for the probability of the considered process: $\sigma[\pi^- p \to (C(1480)_{I=0} \equiv \varphi')n] BR[C(1480)_{I=0} \to \varphi\pi^0] < 5\times10^{-35}$ cm^2. This deviates by three orders of magnitude from the experimental value for the cross section: $\sigma[\pi^- p \to C(1480)n] BR[C(1480) \to \varphi\pi^0] = (40 \pm 15) \times 10^{-33}$ cm^2.

In addition, the reaction $\pi^- p \to [C(1480)_{I=0} \equiv \varphi']n$ is not only OZI-suppressed but also, for pion exchange, suppressed by G parity, since $G(\pi\pi) = +1$, while $G(\varphi') = C_{\varphi'}(-1)^I = -(-1)^0 = -1$. This also disagrees with experiment.

Thus, the interpretation of the experimental data of Refs. 1–4 in the model of an ordinary $s\bar{s}$ hadron of the type φ' with hidden strangeness ($|C(1480)\rangle_{I=0} \simeq |s\bar{s}\rangle$) and subsequent decay $C(1480)_{I=0} \to \varphi\pi^0$ with nonconservation of isospin is completely ruled out.

1.10.3. Is the C(1480) an exotic state?

A consistent explanation of all the properties of the $C(1480)$ meson and, above all, of the large value of R_C [see (29)] can be obtained if it is interpreted as a cryptoexotic four-quark state with the quark structure

$$|C(1480)\rangle = \left|\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})\, s\bar{s}\right\rangle. \tag{37}$$

In this case there is a natural explanation of the isotopic spin $I = 1$ of this state and its strong coupling to the $\varphi\pi^0$ system.[6)] Possibilities of looking for four-quark vector states in the $\varphi\pi$ system were first noted in Ref. 19. The existence of a resonance $\varphi\pi$ state was also predicted on phenomenological grounds.[37]

Another possible explanation of the nature of the $C(1480)$ meson is based on a model of hybrid states (meiktons).[38–40] In this scheme

$$|C(1480)\rangle = \left|\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})\, g\right\rangle. \tag{38}$$

A vector meikton was considered in particular in Ref. 40, and for it a mass 1520 MeV was predicted. The branching ratios of decays of vector meiktons through the $\varphi\pi^0$ and $\omega\pi^0$ channels must be of the same order of magnitude (because the constant of the coupling of a gluon to a $q\bar{q}$ quark pair does not depend on their flavor).

Thus, if no new explanations are found for the large breaking of the OZI rule in the decays of the $C(1480)$ meson ($R_C > 0.5$), this new hadron must have an exotic structure.

Further information about the exotic nature of the $C(1480)$ meson can be obtained from analysis of its various decay channels, and also from searches for other objects with a similar nature. For example, a study was made in Ref. 41 of the possible SU(3) structure of an exotic family of particles to which the $C(1480)$ meson belongs if it is a $(qq\bar{q}\bar{q})$ hadron of the type (37). A coupling of $C(1480)$ to the $\rho\eta$ channel with $BR(C(1480) \to \rho\eta) \sim \frac{1}{4} BR(C(1480) \to \varphi\pi^0)$ was predicted. Also predicted was the existence of an isoscalar partner of the $C(1480)$ meson: a meson $|\tilde{C}\rangle = |(1/\sqrt{2})(u\bar{u} + d\bar{d})s\bar{s}\rangle$ with mass and width similar to that of $C(1480)$. The $|\tilde{C}\rangle$ state may be manifested as a resonance in the mass spectrum of the $\omega\eta$ system. It should be noted that an isoscalar state $|\tilde{C}\rangle = |(1/\sqrt{2})(u\bar{u} + d\bar{d})g\rangle$ with a similar mass could also exist in the hybrid model for the $C(1480)$ meson.

In Ref. 42 the nature of the $C(1480)$ meson and processes of its production and decay are discussed. Possible mechanisms of mixing of the quark combinations in the wave function of the four-quark exotic state are considered. It is suggested that in this case there must exist states with similar properties conjugate with respect to G and C parity. In the framework of this hypothesis, there must exist not only the $C(1480)$ meson with $J^{PC} = 1^{--}$ but also a meson with similar mass and exotic quantum numbers $J^{PC} = 1^{-+}$. Just such a particle, $M(1405)$ with mass $M = 1406 \pm 20$ MeV and width $\Gamma = 180 \pm 30$ MeV, was discovered in an entirely different experiment in an analysis of the mass spectrum of the $\eta\pi^0$ system in the reaction $\pi^- p \to \eta\pi^0 n$ with the GAMS-4000 facility[43] (see the Appendix). The possible coupling between these states is of very great interest and requires further study. In particular, another possibility was discussed in Ref. 44; according to it, the mesons $C(1480)$ and $M(1405)$ and hybrid states conjugate with respect to G and C parity (meiktons).

It was also shown in Ref. 42 that if the $C(1480)$ meson belongs to the 10–10* representation of SU(3), i.e., if it is a superposition of states from the representation 10 and the conjugate representation 10*, which has definite G parity, then there must exist a relation between probabilities of the decay channels $C(1480) \to \varphi\pi^0$ and $C(1480) \to \omega\pi^0$: $BR[C(1480) \to \varphi\pi^0] = 2BR[C(1480) \to \omega\pi^0]$, i.e., $R_C = 2$. This does not contradict the experimental data, according to which $R_C > 0.5$ [see (29)].

Potential models for exotic multiquark mesons and the position of $C(1480)$ in such models were considered in Ref. 45.

1.11. The $C(1480)$ meson in electromagnetic processes

Since the quantum numbers of the $C(1480)$ meson, $J^{PC} = 1^{--}$, are the same as those of the photon, there is considerable interest in a search for production of this particle in electromagnetic processes.

An experiment with the OMEGA spectrometer[46] led to detection of about 25 events of the $\gamma p \to \varphi\pi^0 p$ reaction in the range of energies from 20 to 70 GeV. Although the number of events is small, a certain excess of events is observed in the mass spectrum of the $\varphi\pi^0$ system in the region of ~ 1.4 GeV (Fig. 14). From the data of Ref. 46 it is possible to obtain the cross section for photoproduction of the $C(1480)$ meson: $\sigma(\gamma p \to C(1480)p) BR(C(1480) \to \varphi\pi^0) \simeq (3 \pm 1.5) \times 10^{-33}$ cm^2 or, more precisely, the upper limit

$$\sigma\,[\gamma p \to C\,(1480)p]\; BR\,[C\,(1480) \to \varphi\pi^0] \leqslant 6\cdot10^{-33}\ \text{cm}^2 \tag{39}$$

(95% confidence level).

Theoretical estimates for the cross section of diffraction photoproduction of the $C(1480)$ meson can be made in the vector-dominance model (VDM)[19] (Fig. 15a):

$$\sigma\,[\gamma p \to C\,(1480)\,p] \simeq \sigma\,[\gamma p \to \rho^0 p] \left[\frac{\sigma_{\text{tot}}\,[C(1480)p]}{\sigma_{\text{tot}}\,[\rho^0 p]}\right]^2 \times \left[\frac{M_{\rho^0}}{M_C}\right]\left[\frac{b_{\rho^0}}{b_C}\right]\frac{\Gamma\,[C\,(1480) \to e^+e^-]}{\Gamma\,[\rho^0 \to e^+e^-]}. \tag{40}$$

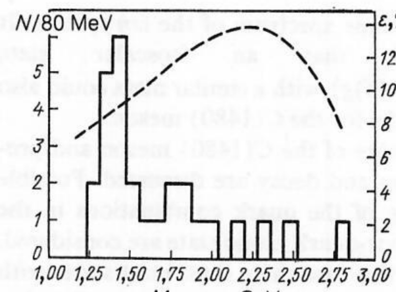


FIG. 14. Effective-mass spectrum of the $K^+K^-\pi^0$ in the photoproduction reaction $\gamma p \to K^+K^-\pi^0 p$ at photon energy $20 < E_\gamma < 70$ GeV (for events from the region of the φ peak $1.01 < M_{K^+K^-} < 1.03$ GeV). The scale on the right gives the acceptance of the facility (broken curve).

Here, $\sigma_{tot}[C(1480)p]/\alpha/_{tot}[\rho^0 p] \simeq [\sigma_{tot}(\rho^0 p) + \sigma_{tot}(\varphi p)]/\sigma_{tot}[\rho^0 p] \simeq 3/2$ is the ratio of the corresponding total interaction cross sections in the additive quark model, $b_{\rho^0}/b_C \simeq 1$ is the ratio of the slopes of the diffraction peaks, and ρ^0 denotes "ordinary" vector mesons with $I = 1$: $\rho^0(770)$ and $\rho^{0'}$. From the upper bound (39), from data on the cross sections of diffraction photoproduction, $\sigma[\gamma p \to \rho^0(770)p] \simeq 13 \times 10^{-30}$ cm^2 or $\sigma[\gamma p \to \rho^{0'} p] \simeq 1.3 \times 10^{-30}$ cm^2, and from the values of the electron widths $\Gamma[\rho^0(770) \to e^+e^-] \simeq \Gamma[\rho^{0'} \to e^+e^-] \simeq 7$ keV, we can estimate

$$\Gamma[C(1480) \to e^+e^-]\, BR\,[C(1480) \to \varphi\pi^0]$$

$$\leqslant \begin{cases} 4 \text{ эВ eV from data on } \rho^0(770); & (41) \\ 21 \text{ эВ eV from data on } \rho^{0\prime} & (42) \end{cases}$$

(95% confidence level).

The limit (42) based on data for the $\rho^{0'}$ meson, is evidently more reliable because of the proximity of the masses $M[C(1480)]$ and $M(\rho^{0'})$, as well as the corresponding decrease in the uncertainties of the VDM estimates associated with the transition from real to virtual photons with $q^2 = M_V^2$.[7)]

Thus, we see that under the assumption of a large value of $BR(C(1480) \to \varphi\pi^2)$ the electron width for the $C(1480)$ meson differs sharply from the electron widths for "ordinary" vector mesons. This emphasizes once more the exotic nature of the $C(1480)$ meson. The small electron width of the $C(1480)$ meson finds a natural explanation in the four-quark model.[45]

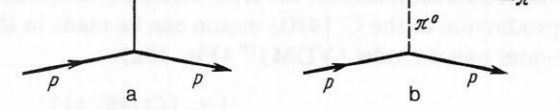


FIG. 15. Diagram of diffraction photoproduction of a vector meson in the vector-dominance model (diagonal approximation) (a) and diagram of photoproduction of the $C(1480)$ meson in the OPE model (b).

Photoproduction of the $C(1480)$ meson can also take place through one-pion exchange (Fig. 15b). In this mechanism, all constants can be estimated from experimental data. N. N. Achasov (private communication) obtained the relation

$$\sigma[\gamma p \to C(1480)\, p]|_{OPE}\, BR\,[C(1480) \to \varphi\pi^0] = \left[\frac{1.3 \cdot 10^{-31}\ \text{cm}^2}{s^2}\right][BR\,(C(1480) \to \varphi\pi^0)]^2 \qquad (43)$$

(here, s is measured in GeV^2). Hence, and from data on photoproduction of $C(1480)$ in experiments with the OMEGA spectrometer, a bound is established for $BR[C(1480)p/\varphi\pi^0]$:$\sigma[\gamma p \to C(1480)]BR[C(1480)\varphi\pi^0] = 35 \times 10^{-33}$ cm^2 $[BR(C(1480) \to \varphi\pi^0)]^2$ + diffraction contribution) $\leqslant 6 \times 10^{-33}$ cm^2 or

$$BR[\,C\,(1480) \to \varphi\pi^0] < 0{,}4 \ (95\%\text{- confidence level}) \qquad (44)$$

Following Ref. 19, we can estimate the cross section for resonance production of the $C(1480)$ meson in colliding e^+e^- beams:

$$\sigma\,[e^+e^- \to C\,(1480)]\ BR\,[C\,(1480) \to \varphi\pi^0] < 0{,}16 \cdot 10^{-33}\ \text{cm}^2 \qquad (45)$$

{for $\Gamma[C(1480) \to e^+e^-]BR[C(1480) \to \varphi\pi^0] < 21$ eV (42)}. Here, the resonance background is estimated from data on the nonresonance reaction $e^+e^- \to \omega\pi^0$ with allowance for OZI suppression:[19]

$$\sigma\,(e^+e^- \to \varphi\pi^0)_{\text{nonres}} = \sigma\,(e^+e^- \to \omega\pi^0)_{\text{nonres}}\ \frac{1}{300} \sim 0{,}03 \cdot 10^{-33}\ \text{cm}^2. \qquad (46)$$

The existing experimental data establish an upper bound for resonance production of the $C(1480)$ meson in e^+e^- collisions; it is several times higher than the levels (42) and (45): $\Gamma[C(1480) \to e^+e^-]BR[C(1480) \to \varphi\pi^0] < 85$ eV.[48]

In connection with the possible existence of an isoscalar partner of the $C(1480)$ meson, $\widetilde{C}(1/\sqrt{2})(u\bar{u} + d\bar{d})s\bar{s}$ or $\widetilde{C} = (1/\sqrt{2})(u\bar{u} + d\bar{d})g$, with parameters close to those of the $C(1480)$ meson and with $\widetilde{C} \to \omega\eta$ as one of the main decay channels[41] (see Sec. 1.10), the results of an experiment on photoproduction of mesons performed with the OMEGA spectrometer at CERN, in which the $\gamma p \to (\omega\eta)p$ reaction in the region of energies $20 < E_\gamma < 50$ GeV was studied,[47] are noteworthy. In the mass spectrum of the $\omega\eta$ system there is found to be a structure $X(1600)$ with mass $M = 1.16 \pm 0.04$ GeV and width $\Gamma = 0.23 \pm 0.08$ GeV. The possible quantum numbers of this state are $J^P = 1^-, 1^+, 2^-$. The cross section is estimated at $\sigma[\gamma p \to X(1600)p]BR \times [X(1600) \to \omega\eta] \sim 40 \times 10^{-33}$ cm^2. The nature of this peak and the possibility of identifying it with the predicted isoscalar $\widetilde{C}$ meson remain open questions.

1.12. Searches for $C(1480)$ mesons in decays of J/ψ particles and in $\bar{p}p$ annihilation

The DM2 facility[49] was used to investigate the decay of J/ψ mesons through the channel $J/\psi \to \varphi\pi^+\pi^-$, and its probability was measured: $BR[J/\psi \to \varphi\pi^+\pi^-] = (7.8 \pm 0.3 \pm 0.3) \times 10^{-4}$. In an analysis of the $\varphi\pi^\pm$ mass spectrum, a search was made for a signal from the

$C(1480)$ meson, i.e., from the decay $J/\psi \to C(1480)^{\pm}\pi^{\mp}$. Decays of the type $J/\psi \to X\pi$ are natural processes for searches for exotic hybrid mesons $X = \bar{q}qg$ with isospin $I = 1$, since the intermediate states for these decays are enriched with gluons. Although in the $\varphi\pi^{\pm}$ mass spectrum in $J/\psi \to \varphi\pi^{+}\pi^{-}$ there is a certain excess of states compatible with a manifestation of the $C(1480)$ meson, the statistical significance of the excess is low and permits only the establishment of an upper bound for the probability: $BR[J/\psi \to C(1480) \pm \pi^{\mp}]BR[C(1480) \pm \to \varphi\pi^{\pm}] < 1.5 \times 10^{-4}$ (95% confidence level).

Searches for the $C(1480)$ meson in $J/\psi \to \varphi\pi^{+}\pi^{-}$ decays are complicated not only by the combinatorial background (two combinations with $\varphi\pi^{\pm}$) but also by the fact that experiments reveal in the $\pi^{+}\pi^{-}$ mass spectrum an appreciable contribution from resonance $\pi\pi$ processes: production of the $a_0(975)$ meson and, perhaps, some state in the region of masses $1.1 < M_{\pi\pi} < 1.5$ GeV $(BR[J/\psi \to \varphi a_0(975)]BR[a_0(975) \to \pi^{+}\pi^{-}] = (2.4 \pm 0.2 \pm 0.4) \times 10^{-4}$ and $BR[J/\psi \to \varphi(\pi^{+}\pi^{-})|1.1 < M_{\pi\pi} < 1.5\text{GeV}] = (2.5 \pm 0.2 \pm 0.4) \times 10^{-4})$.

To confirm production of $C(1480)$ mesons in J/ψ decays, there must be a significant increase in the statistics using the accelerators of the new generation with high luminosity. In particular, with the recently commissioned $e^{+}e^{-}$ accelerator BEPC (Chinese People's Republic), it should be possible to increase the statistics by at least an order of magnitude.

Analysis of the $\bar{p}p \to K^{+}K^{-}\pi^{+}\pi^{-}$ reaction in experiments with ASTERIX revealed a certain maximum in the region of the $C(1480)$ meson in the $K\bar{K}\pi$ mass spectrum. However, it was interpreted as due to kinematic reflections from production of the $K^{*}\bar{K}^{*}$ system.[50] A detailed analysis of processes with production of $\varphi\pi$ states in $\bar{p}p$ annihilation reactions can be made in new-generation experiments with the antiproton source LEAR.

Questions relating to the nature of $C(1480)$ were also discussed in Refs. 51–61 and in some other studies (see also Appendix 2).

2. INVESTIGATIONS OF THE REACTION $\pi^{-}p \to K^{+}K^{-}n$ AT MOMENTUM $p_{\pi} = 32.5$ GeV AND DATA ON THE OZI-SUPPRESSED PROCESS $\pi^{-}p \to \varphi n$

The reaction

$$\pi^{-}p \to K^{+}K^{-}n \tag{47}$$

(6×10^{5} events at momentum 32.5 GeV) was analyzed, and preliminary data were obtained on the cross section of the process

$$\pi^{-}p \to \varphi n, \tag{48}$$

which is suppressed by the OZI rule. Figure 16 shows the mass spectrum for $K^{+}K^{-}$ pairs in (47), in which one can observe a clear peak of the φ meson. The total cross section was found to be

$$\sigma(\pi^{-}p \to \varphi n) = (13 \pm 5) \cdot 10^{-33}\ \text{cm}^2 \tag{49}$$

(the error is due to the systematic errors associated with the normalization of the cross sections). Comparison of (49) with data on the reaction

$$\pi^{-}p \to \omega n, \tag{50}$$

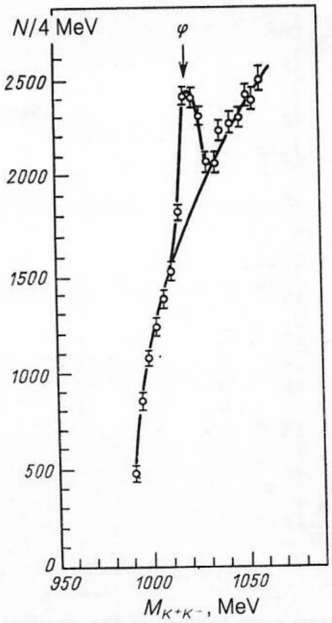


FIG. 16. Effective-mass spectrum of the $K^{+}K^{-}$ system in the reaction $\pi^{-}p \to K^{+}K^{-}n$ (in the region of small masses) for $|t'| > 0.1$ GeV^2. The arrow shows the tabulated value of the mass of the φ meson.

obtained in Ref. 62, yields the branching ratio

$$R(\varphi/\omega)|_{p_{\pi^-}=32,5\,\text{GeV}} = \frac{\sigma(\pi^{-}p \to \varphi n)}{\sigma(\pi^{-}p \to \omega n)}\Big|_{p_{\pi^-}=32,5\,\text{GeV}} = (0{,}42 \pm 0{,}17) \cdot 10^{-2}. \tag{51}$$

This ratio characterizes the extent to which the processes with vector mesons are suppressed by the OZI selection rule. The data on the reactions (48) and (50) at various energies are presented in Fig. 17.

The ratio (51) can be used in a simple quark model to determine the mixing angle ϑ_V for the nonet of vector mesons. The deviation of the mixing angle from the ideal value $\alpha_V = \vartheta_V - \vartheta_0$ ($\vartheta_0 = 35.3°$ is the ideal mixing angle) is related to (51) by the equation $\tan^2 \alpha_V = R(\varphi/\omega)$.[64] Hence $|\alpha_V| = 3.7 \pm 0.7°$, in good agreement with the results obtained from comparison of the radiative widths $\Gamma(\varphi \to \pi^{0}\gamma)$ and $\Gamma(\omega \to \pi^{0}\gamma)$ ($|\alpha_V| = 3.0 \pm 0.2°$, Ref. 65) and from the quadratic mass formula ($|\alpha_V| = 3.7 \pm 0.4°$, Ref. 27).

3. SEARCHES FOR THE RADIATIVE DECAYS $D(1285) \to \varphi\gamma$ AND $E(1420) \to \varphi\gamma$ AND NATURE OF THE E MESON

3.1. The E/iota problem and properties of axial-vector mesons

Searches for exotic hadronic states are intimately intertwined with experiments in which the structure of the families of ordinary mesons and baryons is determined more precisely. Without such work, the interpretation of new resonances frequently cannot be unambiguously carried through. Exotic particles must be "superfluous states" that do not fit into the schemes of ordinary $SU(3)$ families (or their radial excitations). Therefore, searches for exotic hadrons and investigations of "blank spots" in ordinary hadron spectroscopy are indissolubly linked.

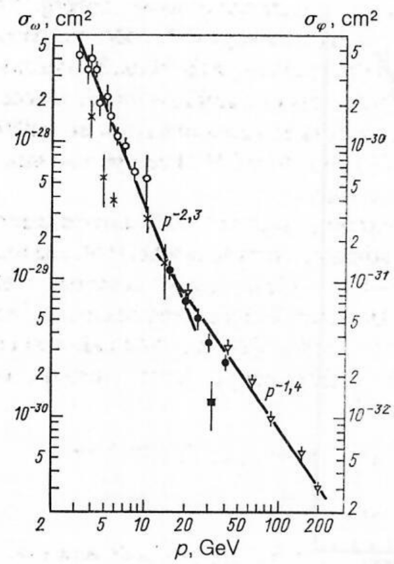


FIG. 17. Experimental data for total cross sections of the reactions $\pi^- p \to \omega n$ and $\pi^- p \to \varphi n$ as functions of the initial momentum: the reaction $\pi^- p \to \omega n$ (scale on the left, Ref. 62): the open circles are the cross sections at low energies, the black circles are the data of Ref. 62, the open triangles are the data of Ref. 63, and the straight lines are the power-law dependences $\sigma \sim p^{-2.3}$ and $p^{-1.4}$; the reaction $\pi^- p \to \varphi n$ (scale on the right): the crosses are the data at low energies, and the black square is the result of the Lepton-F experiment.

As an example, we may mention the well-known E/iota problem, which arises in connection with searches for glueballs.[8)] For its solution, it is important to obtain new and more informative data on the quantum numbers of the state $E(1420)$, on the composition of the axial meson nonet ($J^{PC} = 1^{++}$), and on radially excited pseudoscalar states.

For the axial-vector nonet of two isoscalar states in this family, only one can be regarded as firmly established—the $D(1285)$ meson. The $E(1420)$ meson is usually considered as another isoscalar. However, its quantum numbers, as we have already noted, have not yet been unambiguously determined.

The situation with regard to the structure of the nonet of axial mesons is still more complicated, since for the role of the isotopic singlet ($s\bar{s}$) in this family there is now not only the original pretender—the $E(1420)$ meson—but a further candidate—the so-called $D'(1530)$ meson. Data on possible observation of such a particle in $K^- p$ reactions were obtained in bubble-chamber experiments[66] and in the wide-aperture magnetic spectrometer LASS.[67]

New information about the composition of the axial nonet and its mixing angle can be obtained from radiative decays of axial mesons and, in particular, from the decays $M(J^{PC} = 1^{++}) \to \varphi\gamma$. Since the φ meson is an almost pure $s\bar{s}$ state, the $\varphi\gamma$ decay is a good analyzer, separating the $s\bar{s}$ component in the meson wave function.

3.2. Separation of radiative decays

The experimental study of radiative decays of hadrons involves serious difficulties. As a rule, they are rare processes with a small branching ratio under conditions of a large background from $\pi^0 \to \gamma\gamma$ decays with "lost" photons. To separate the radiative decays, it is necessary to detect all secondary products (charged particles and photons), measure their momenta, and reconstruct the effective mass of the decaying particle. An important part here is played in kinematic overdetermination, since this permits suppression of background processes.[9)]

In experiments with the Lepton facility the source of the investigated particles is exclusive charge-exchange reactions, in which one can realize the best background conditions for rare phenomena. For example, the decays

$$M \to \varphi\gamma, \quad \varphi \to K^+K^- \tag{52}$$

were investigated by means of the reactions $\pi^- p \to Mn$, $M \to \varphi\gamma$, $\varphi \to K^+K^-$ or $K^- N \to MY$, $M \to \varphi\gamma$, $\varphi \to K^+K^-$. To separate these processes and detect the known decays $\eta \to \pi^+\pi^-\gamma$ and $\eta' \to \pi^+\pi^-\gamma$ (which are used to calibrate the facility), $\pi^- p \to (K^+K^-\gamma)n$, $K^- N \to (K^+K^-\gamma)Y$, and $\pi^- p \to (\pi^+\pi^-\gamma)n$ events were analyzed.

To reduce the background from the π^0 mesons with lost photons, Lepton-F was equipped with a special protective system of scintillation counters sandwiched with lead, which suppressed at the trigger level events with γ rays emitted outside the aperture of the multichannel hodoscope γ spectrometer GAMS-200 (see Fig. 1). The spectrometer itself is also part of a protective system, since the data analysis required detection of one and only one γ ray in it.

The protective system reduced the background from "lost" photons by a factor 10–20.

To separate processes of the type (6), (10), and (14)–(16), and to investigate radiative decays, the following set of standard event selection criteria was used:

a) the event is characterized by two (and only two) tracks of charged particles in the spectrometer with opposite signs of the charge and emitted from an interaction point within the target;

b) the event is characterized by a single γ ray with minimal energy $E_\gamma > 5$ GeV (in some reactions $E_\gamma > 6$ GeV);

c) no additional photons with energy $E_\gamma > 0.5$ GeV must be detected in the gamma spectrometer;

d) the total released energy satisfies the condition 30.8 GeV $< (E_{\text{tot}} = E_+ + E_- + E_\gamma) < 34$ GeV (E_+ and E_- are the energies of the charged particles).

In the evaluation of these criteria, which are needed for optimal suppression of the lost photons, the well-known radiative decays $\eta \to \pi^+\pi^-\gamma$ (under conditions of a background from $\eta \to \pi^+\pi^-\pi^0$) and $\eta' \to \pi^+\pi^-\gamma$ were used. To this end, the spectrum of effective masses of $\pi^+\pi^-\gamma$ events in the reaction (14) was analyzed (Fig. 18).

By variation of the selection criteria (minimal photon energy $E_{\gamma\text{min}}$ and range of variation of the total energy E_{tot}) the ratio

$$R_\eta = \frac{N(\eta_{\text{spur}})}{N(\eta \to \pi^+\pi^-\gamma)} = \frac{\text{no. of spurious events,} \eta \to \pi^+\pi^-\gamma\text{''}}{\text{no. of true events } \eta \to \pi^+\pi^-\gamma} \quad \frac{{}^+\pi^-\gamma\text{''}}{\pi^+\pi^-\gamma}$$

(spurious events from $\eta \to \pi^+\pi^-\pi^0$).

was monitored. The choice of the selection criteria was regarded as optimal when R_η was minimal for insignificant loss of $\lambda \to \pi^+\pi^-\gamma$ detection efficiency (for more details, see Ref. 9).

The possibilities of studying rare radiative decays of mesons in Lepton-F experiments can be well illustrated by the results of searches for the decay

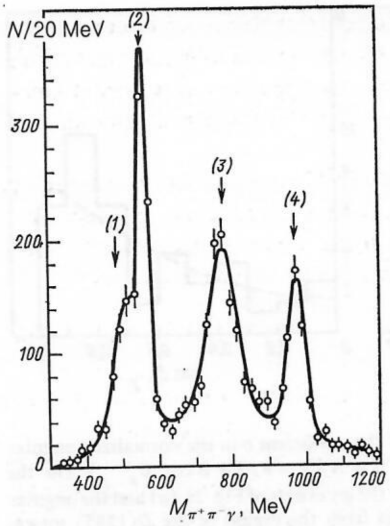


FIG. 18. Investigations of the effective-mass spectrum of the $\pi^+\pi^-\gamma$ system in the reaction $\pi^- p\to(\pi^+\pi^-\gamma)n$ (20% of the statistics). Four structures are observed in the spectrum: 1) a "spurious peak" due to the process $\pi^- p\to\eta n$, $\eta\to\pi^+\pi^-\pi^0$, $\pi^0\to 2\gamma$ with one lost photon; 2) a peak from the radiative decay $\eta\to\pi^+\pi^-\gamma$ in the reaction $\pi^- p\to\eta n$; 3) a spurious peak due to the process $\pi^- p\to\omega n$, $\omega\to\pi^+\pi^-\pi^0$, $\pi^0\to 2\gamma$ with one lost photon; 4) a peak from the radiative decay $\eta'\to\pi^+\pi^-\gamma$ in the reaction $\pi^- p\to\eta' n$.

$$\omega\to\pi^+\pi^-\gamma \tag{53}$$

under difficult background conditions due to the main decay $\omega\to\pi^+\pi^-\pi^0$ (with one lost photon) of this meson.

Figure 19 gives the spectrum of effective masses of the $\pi^+\pi^-\gamma$ system in (14) in the region of the ω meson. The events included in this spectrum satisfied, in addition to the selection criteria (a)–(d), an additional criterion:

e) for the selected events, the momentum transfer must satisfy $|t'|>0.1$ GeV^2. This requirement, which suppresses the contribution of pion-exchange processes to the reaction (14), served to reduce the background from ρ mesons (radiative decay $\rho\to\pi^+\pi^-\gamma$, background of random coincidences of the decay $\rho\to\pi^+\pi^-$ and a shower in the gamma spectrometer).

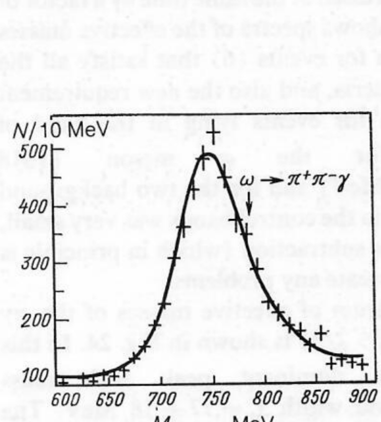


FIG. 19. Total effective-mass spectrum of $\pi^+\pi^-\gamma$ events from the region of the "spurious ω peak" (see Fig. 18), i.e., for events basically due to the process $\pi^- p\to\omega n$, $\omega\to\pi^+\pi^-\pi^0$, $\pi^0\to\gamma\gamma$ with one lost photon. The arrow shows the expected position of the peak for the radiative decay $\omega\to\pi^+\pi^-\gamma$.

The spectrum of $\pi^+\pi^-\gamma$ effective masses in Fig. 19 was used to look for the radiative decay (53). Monte Carlo simulation showed that the spurious peak from the decay $\omega\to\pi^+\pi^-\pi^0$, $\pi^0\to 2\gamma$ with loss of one photon is displaced relative to the true position of the ω-meson mass by about 30 MeV and has a width of about 65 MeV. The experimental data agree well with this result.

Analysis of the spectrum of $\pi^+\pi^-\gamma$ effective masses (Fig. 19) yielded an estimate for the number of events: $N(\omega\to\pi^+\pi^-\gamma)=30\pm 52$. The total number of $\omega\to\pi^+\pi^-\pi^0$ decays detected during measurements on Lepton-F was $N(\omega\to\pi^+\pi^-\pi^0)=26\,400$. With allowance for the efficiency of the facility, upper limits were determined for the cross section

$$\sigma\,[\pi^- p\to\omega n]\;BR\;[\omega\to\pi^+\pi^-\gamma)]<17\cdot 10^{-33}\ \text{cm}^2,$$

and for the branching ratio,

$$BR\;(\omega\to\pi^+\pi^-\gamma)=\Gamma\;(\omega\to\pi^+\pi^-\gamma)/\Gamma\;[\omega\to(\text{ all channels })]$$

$$<4\cdot 10^{-3} \tag{54}$$

(95% confidence level).

This bound strengthens by more than an order of magnitude the previously existing limit: $BR(\omega\to\pi^+\pi^-\gamma)<5\%$.[27] These results show that in the Lepton-F experiments it is possible to study rare radiative decays of hadrons that have branching ratios of the order of one or a few percent of the main channels for decay of these particles with π^0 mesons, which determine the background level.

3.3. Searches for radiative decays $M\to\varphi\gamma$ and detection of the decay $D(1287)\to\varphi\gamma$

During the Lepton-F experiments 4.5×10^3 events of the $\pi^- p\to(K^+K^-\gamma)n$ reaction [see (6)] satisfying the standard selection criteria (see Sec. 3.2) were detected. However, most of these were background events, corresponding to the reaction $\pi^- p\to(K^+K^-\pi^0)n$, $\pi^0\to\gamma+\gamma$ with one lost γ ray. The data on (6) were used to separate the reactions $\pi^- p\to(\varphi\gamma)n$ and $\pi^- p\to Mn$, $M\to\varphi\gamma$, $\varphi\to K^+K^-$. This is needed above all to suppress the background due to the events $\pi^- p\to(\varphi\pi^0)n$, $\varphi\to K^+K^-$, $\pi^0\to\gamma+\gamma$ with a lost photon. Since the reaction (1) is characterized by a narrow t distribution, due to the OPE (see Fig. 8), to suppress this background the requirement $|t'|>0.1$ GeV^2 was introduced, decreasing it by about five times. Simultaneously, this requirement reduced relatively little the probability for production of axial mesons in charge-exchange reactions, since for such processes pion exchange is forbidden, and the corresponding t distribution is broader. Thus, the yields of $D(1285)$ mesons (see Fig. 4) for $|t'|>0.1$ GeV^2 are reduced by not more than 25%.

In the spectrum of masses of the K^+K^- system a clear peak is observed in the reaction (6), corresponding to production of the φ meson (Fig. 20).

The events (7) were selected from the region of the φ peak ($1018<M_{K^+K^-}<1026$ MeV). The contribution of the background was taken into account by subtracting the half-sum of the number of events in the neighboring mass intervals ($1006<M_{K^+K^-}<1014$ MeV and

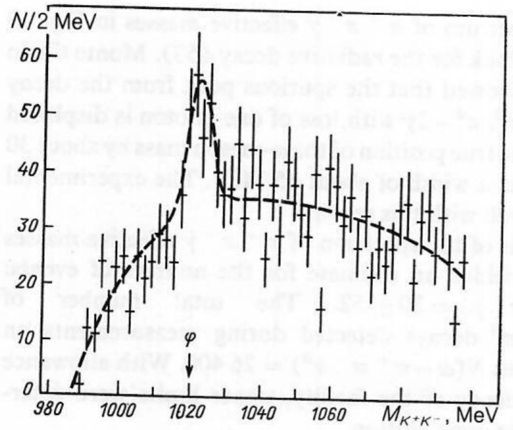


FIG. 20. Effective-mass spectrum of the K^+K^- system in the reaction $\pi^- p \to (K^+K^-\gamma)n$ for events with $|t'| > 0.1$ GeV^2. The arrow shows the tabulated value of the mass of the φ meson. The position of the peak $[M_{K^+K^-} = 1022 \pm 2$ MeV$]$ agrees with the tabulated value, while its width $[7.3 \pm 1.2$ MeV$]$ is determined by the instrumental resolution.

$1030 < M_{K^+K^-} < 1038$ MeV). The total number of events (7) was 87 ± 14. The effective mass spectrum of the events (7) is shown in Fig. 21.

For further analysis of the $\varphi\gamma$ system and searches for radiative decays of axial mesons, the corresponding angular distributions in the reaction (7) were studied. By the well-known Landau–Yang theorem, a particle with spin 1 cannot decay into two massless photons. This prohibition is due to the fact that photons do not have a component with zero helicity. Since the φ meson is a massive vector particle, the decay

$$M\ (J^{PC} = 1^{++}) \to \varphi\gamma \tag{55}$$

is not forbidden by this theorem, but in it the φ component with zero helicity, $\lambda_\varphi = 0$, is dominant.[70] To separate the processes of production of φ mesons with $\lambda_\varphi = 0$, a study

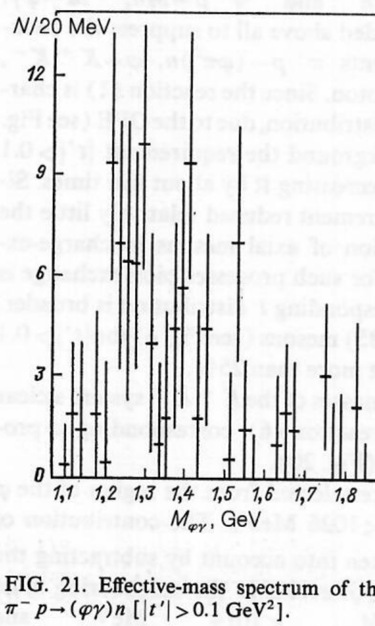


FIG. 21. Effective-mass spectrum of the $\varphi\gamma$ system in the reaction $\pi^- p \to (\varphi\gamma)n$ $[|t'| > 0.1$ GeV$^2]$.

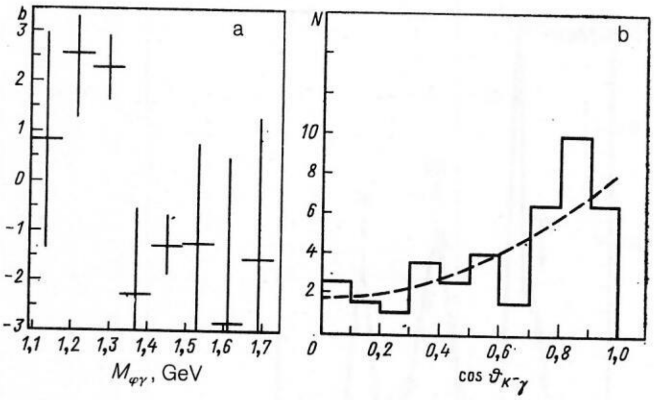


FIG. 22. Mass dependence of the coefficient b in the normalized angular distribution $dN/d|\cos\vartheta_{K^-\gamma}| = N[1 - b/3 + b\cos^2\vartheta_{K^-\gamma}]$ (in the rest frame of the φ meson) for the $\varphi\gamma$ events of Fig. 21 (a) and the angular distribution for the $\varphi\gamma$ events from the region of the $D(1285)$ meson $[1230 < M(\varphi\gamma) < 1330$ MeV$]$; the broken curve corresponds to $b = 1.7 \pm 0.7$ (b).

was made of the distribution with respect to the angle $\vartheta_{K^-\gamma}$ (in the rest frame of the φ meson) for various intervals of the spectrum of effective masses of the $\varphi\gamma$ system in (7). The angular distribution was represented in the normalized form $dN/d|\cos\vartheta_{K^-\gamma}| = \text{const}\,[1 - (b/3) + b\cos^2\vartheta_{K^-\gamma}]$. For $\lambda_\varphi = 0$ [i.e., for the decay (55)], this distribution must have the form $dN/d|\cos\vartheta_{K^-\gamma}| \sim \cos^2\vartheta_{K^-\gamma}$ (i.e., $b = 3$). For decay of the pseudoscalar mesons $M(J^{PC} = 0^{-+}) \to \varphi\gamma$ the φ mesons are formed only in states with $\lambda_\varphi = \pm 1$, and the corresponding angular distribution has the form $dN/d|\cos\vartheta_{K^-\gamma}| \sim \sin^2\vartheta_{K^-\gamma}$ (i.e., $b = -1.5$). Figure 22a shows the coefficient b in the angular distribution as a function of the effective mass $M(\varphi\gamma)$ in (7). It can be seen that in the region of $D(1285)$ masses the angular distribution is very different from the other parts of the mass spectrum (see also Fig. 22b).

Thus, for the separation of decays of the type (55) the requirement $|\cos\vartheta_{K^-\gamma}| > 2/3$ may play an important part, since for radiative decays of axial mesons it reduces the number of events by just 30%, whereas the decays of the pseudoscalar particles are suppressed at the same time by a factor of more than 6. Figure 23 shows spectra of the effective masses of the $K^+K^-\gamma$ system for events (6) that satisfy all the introduced selection criteria, and also the new requirement $|\cos\vartheta_{K^-\gamma}| > 2/3$, both for events lying in the band of K^+K^- masses for the φ meson $[1018 < M(K^+K^-) < 1026$ MeV$]$ and for the two background bands. The background in the control bands was very small, and the procedure for its subtraction (which in principle is not necessary) did not create any problems.

The resulting spectrum of effective masses of the $\varphi\gamma$ events (with $|\cos\vartheta_{K^-\gamma}| > 2/3$) is shown in Fig. 24. In this spectrum there is a dominant peak with mass $M = 1278 \pm 10$ MeV and width $\Gamma = 77 \pm 18$ MeV. The peak contains 19 ± 5 events. The position of the peak agrees well with the tabulated value of the $D(1285)$ mass, while its width is determined by the instrumental resolution. The statistical significance of the observed peak exceeds seven standard deviations.

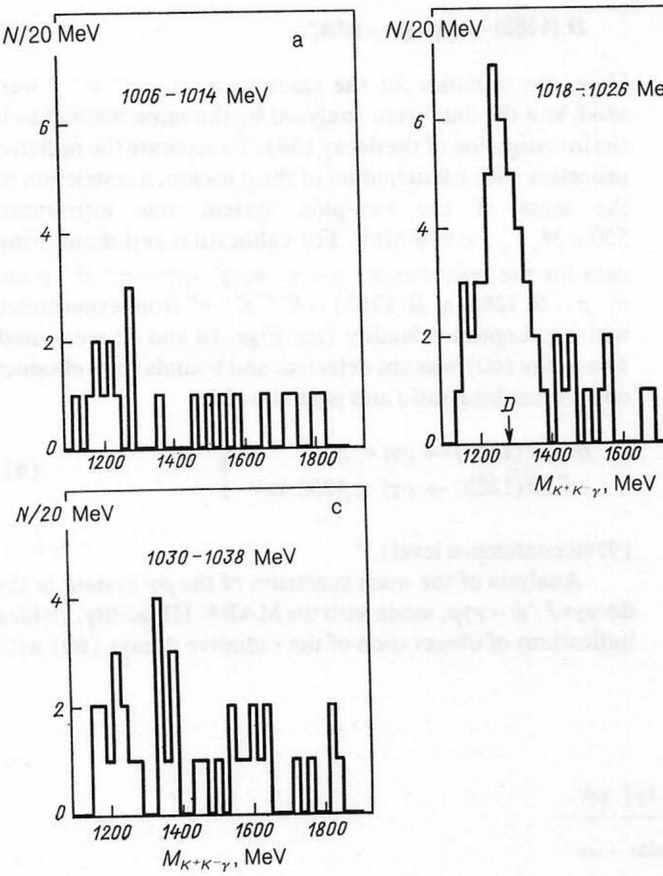


FIG. 23. Effective-mass spectrum of the $K^+K^-\gamma$ system for events of the reaction $\pi^- p \to (K^+K^-\gamma)n(|t'| > 0.1\ \text{GeV}^2$ and $|\cos\vartheta_{K^-\gamma}| > 2/3)$ for mass interval of the K^+K^- system corresponding to the φ meson ($1018 < M_{K^+K^-} < 1026$ MeV) (b) and for two background intervals: $1006 < M_{K^+K^-} < 1014$ MeV (a) and $1030 < M_{K^+K^-} < 1038$ MeV (c).

An attempt to explain the observed peak by $\varphi\gamma$ decays of certain other known mesons[27] showed that all such allowed decays are incompatible with the peak observed in Fig. 24 as regards the masses and (or) widths by not less than six standard deviations.

Thus, the data on the mass, width, and angular distribution for the peak found in the mass spectrum of the $\varphi\gamma$ system (Fig. 24) shows that this experiment has detected the radiative decay

$$D\ (1285) \to \varphi\gamma. \tag{56}$$

The cross section of the process is found to be

$$\sigma\ [\pi^- p \to D\ (1285)\ n]\ BR\ [D\ (1285) \to \varphi\gamma] = (1{,}5 \pm 0{,}4) \cdot 10^{-33}\ \text{cm}^2. \tag{57}$$

The corresponding normalization was based on the reaction (15) with separation of the radiative decay of the η meson: $\eta \to \pi^+\pi^-\gamma$.

Using data on the reaction $\pi^- p \to D(1285)n$, $D(1285) \to K^+K^-\pi^0$ obtained in the same experiment (see Fig. 4), we can determine the ratios

$$\left.\begin{aligned} &BR\,[D\,(1285) \to \varphi\gamma]/BR\,[D\,(1285) \to K^+K^-\pi^0] \\ &\qquad = (4{,}9 \pm 1{,}3 \pm 1{,}2) \cdot 10^{-2}; \\ &BR\,[D\,(1285) \to \varphi\gamma]/BR\,[D\,(1285) \to K\overline{K}\pi] \\ &\qquad = (0{,}82 \pm 0{,}21 \pm 0{,}20) \cdot 10^{-2}. \end{aligned}\right\} \tag{58}$$

Hence, and from the tabulated values for $BR[D(1285) \to K\overline{K}\pi]$ and Γ_D (Ref. 27), we obtain

$$\left.\begin{aligned} &BR\,[D\,(1285) \to \varphi\gamma] = (0{,}9 \pm 0{,}2 \pm 0{,}4) \cdot 10^{-3}; \\ &\Gamma\,[D\,(1285) \to \varphi\gamma] = (23 \pm 5 \pm 10)\ \text{keV}. \end{aligned}\right\} \tag{59}$$

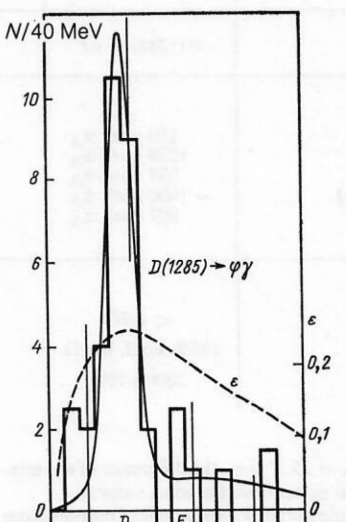


FIG. 24. Effective-mass spectrum of the $\varphi\gamma$ system in the reaction $\pi^- p \to (\varphi\gamma)n$ for events with $|t'| > 0.1\ \text{GeV}^2$ and $|\cos\vartheta_{K^-\gamma}| > 2/3$. The arrows show the tabulated masses of the $D(1285)$ and $E(1420)$ mesons.a The broken curve and the scale on the right show the acceptance of the facility.

The systematic errors include the uncertainties associated with the normalization and the errors in the tabulated parameters.

The value $\Gamma[D(1285)\to\varphi\gamma]$ (59) was compared with the predictions of various theoretical models[69,71-73] (Table I). The comparison shows that the deviation of the mixing angle ϑ_A for the axial nonet from the ideal value ($\vartheta_0 = 35.3°$) must be large: $|\alpha_A| = |\vartheta_A - \vartheta_0| \gtrsim 20$–$30°$, i.e., the wave function of the $D(1285)$ meson must contain a significant $s\bar{s}$ component.

Independent information about the angle α_A can be obtained from the results of experiments on the facilities DM2 and MARK III, in which searches were made for the decays $J/\psi\to\varphi D(1285)$; $\omega D(1285)$. The branching ratio for these decays, $BR[J/\psi\to\varphi$ "$D(1285)$"$]/BR[J/\psi\to\omega$ "$D(1285)$"$] = 0.37\pm0.22$ (Ref. 74) is determined by the value of $\tan^2\alpha_A$.[10)] Hence $|\alpha_A|\simeq 22$–$37°$, in agreement with the data on the probability of the radiative decay (56).

Searches were also made for another radiative decay of the $D(1285)$ meson:

$$D(1285)\to\rho\gamma;\ \rho\to\pi^+\pi^-. \tag{60}$$

Here, the statistics for the reaction $\pi^- p\to\pi^+\pi^-\gamma$ were used, and the data were analyzed by the same method as in the investigation of the decay (56). To separate the radiative processes with participation of the ρ meson, a restriction on the mass of the two-pion system was introduced: $550 < M_{\pi^+\pi^-} < 850$ MeV. For calibration and monitoring, data for the reactions $\pi^- p\to\eta^- n$, $\eta'\to\rho\gamma\to\pi^+\pi^-\gamma$ and $\pi^- p\to D(1285)n$, $D(1285)\to K^+K^-\pi^0$ from experiments with the Lepton-F facility (see Figs. 18 and 4) were used. The decay (60) was not detected, and bounds were obtained on its branching ratio and partial width:

$$\left.\begin{array}{l} BR[D(1285)\to\rho\gamma] < 5\%; \\ \Gamma[D(1285)\to\rho\gamma] < 1250\ \text{keV} \end{array}\right\} \tag{61}$$

(95% confidence level).[78]

Analysis of the mass spectrum of the $\rho\gamma$ system in the decays $J/\psi\to\gamma\gamma\rho$, made with the MARK III facility, yielded indications of observation of the radiative decays (60) with

TABLE I. Theoretical and experimental values of the widths $\Gamma[D(1285)\to V\gamma]$, keV.

Reference	$D(1285)\to\varphi\gamma$	$D(1285)\to\omega\gamma$
Theory:		
J. Babcock *et al.* [70]	—	$\sim 16\cos^2\alpha_A$
M. K. Volkov [71]	$22\sin^2\alpha_A$	$138\cos^2\alpha_A$
M. Dineĭkhan *et al.* [72]	$46\sin^2\alpha_A$	$0{,}08\cos^2\alpha_A$
B. V. Geshkenbeĭn *et al.* [73]	$54\sin^2\alpha_A$	$111\cos^2\alpha_A$
S. Ishida *et al.* [69]	$136\sin^2\alpha_A$	$64{,}5\cos^2\alpha_A$
Experiment:		
Lepton-F [7–9]	$23\pm5\pm10$	—
Reference	$D(1285)\to\rho\gamma$	$\lvert\alpha_A\rvert$, deg
Theory:		
J. Babcock *et al.* [70]	$150\cos^2\alpha_A$	
M. K. Volkov [71]	$1258\cos^2\alpha_A$	47—90
M. Dineĭkhan *et al.* [72]	$938\cos^2\alpha_A$	31—59
B. V. Geshkenbeĭn *et al.* [73]	$\sim 1000\cos^2\alpha_A$	28—52
S. Ishida *et al.* [69]	$607\cos^2\alpha_A$	17—30
Experiment:		
Lepton-F [78]	<1250 (95% conf. level)	—
MARK III [79]	2600 ± 700	

Notes: 1) $\alpha_A = \vartheta_A - \vartheta_0$, where $\vartheta_0 = 35.3°$ (i.e., the difference of the mixing angle in the axial-vector meson nonet from the ideal value).
2) The difference of the mixing angle for the vector nonet of mesons from the ideal value is ignored.
3) The values of $|\alpha_A|$ given in the table are obtained from a comparison of $\Gamma[D(1285)\to\varphi\gamma]_{\rm exp}$ with theoretical calculations in various models.
4) In most theoretical models $\Gamma[D(1285)\to\rho\gamma]/\Gamma[D(1285)\to\omega\gamma]\sim 9$, a value that finds a natural explanation in a simple quark model:

$$\frac{\Gamma[D(1285)\to\rho\gamma]}{\Gamma[D(1285)\to\omega\gamma]} \simeq \frac{\Gamma\{|(u\bar{u}+d\bar{d})/\sqrt{2}\rangle\to|(u\bar{u}-d\bar{d})/\sqrt{2}\rangle+\gamma\}}{\Gamma\{|(u\bar{u}+d\bar{d})/\sqrt{2}\rangle\to|(u\bar{u}+d\bar{d})/\sqrt{2}\rangle+\gamma\}} \sim \left(\frac{q_u-q_d}{q_u+q_d}\right)^2 = 9$$

(if $|\alpha_A|$ is not large).

width $\Gamma[D(1285)\to\rho\gamma] = 2600 \pm 700$ keV.[79] This result appreciably exceeds the upper limit (61), and also theoretical estimates (see Table I).

3.4. Nature of the $E(1420)$ meson

As was noted above, the question of the nature of the $E(1420)$ meson is intimately related to the E/iota problem and the structure of the axial meson nonet. The results of investigations in the region of masses of the E/iota in hadron reactions are contradictory. In some experiments mesons with the quantum numbers $J^{PC} = 0^{-+}$ are observed, and in others, mesons with $J^{PC} = 1^{++}$. In particular, in charge-exchange reactions of the type $\pi^- p \to (K\bar{K}\pi)n$ the spectrum of effective masses of the $K\bar{K}\pi$ system is found to include a pseudoscalar state, but in central-production reactions an axial-vector state (see Ref. 61, and also the Appendix). It is possible that here different mesons are manifested in different processes. It is also possible that the procedures of phase-shift analysis used to determine the quantum numbers of the meson are not perfect and in some cases lead to incorrect results. One way or the other, new investigations are needed.

A new approach could be realized by analyzing data on the radiative decays of mesons. In the $K^+K^-\pi^0$ mass spectrum in the charge-exchange reaction (5) there is found to be a narrow peak corresponding to production of the $D(1285)$ meson, and also some structure in the region of E/iota masses (see Fig. 4). We make the assumption that in these experiments $D(1285)$ and $E(1420)$ mesons, belonging to a single axial meson nonet, are produced. Then in the framework of a simple quark model one can show that the ratio of the charge-exchange cross sections is $\sigma[\pi^- p\to D(1285)n]/\sigma[\pi^- p\to E(1420)n] = \tan^{-2}\alpha_A$ (Ref. 64) and that the branching ratio of the radiative decays is $BR[D(1285)\to\varphi\gamma]/BR[E(1420)\to\varphi\gamma] = (\Gamma_E/\Gamma_D)(K_D/K_E)^3 \tan^2\alpha_A$ (here, K_D and K_E are the momenta of the photons for the corresponding decays, and Γ_D and Γ_E are the total widths of the mesons). From this we obtain the expected ratio for the number of events of the radiative decays (55)

$$R = \frac{N[E(1420)\to\varphi\gamma]}{N[D(1285)\to\varphi\gamma]} = \frac{\sigma[\pi^-p\to E(1420)\,n]\,BR[E(1420)\to\varphi\gamma]}{\sigma[\pi^-p\to D(1285)\,n]\,BR[D(1285)\to\varphi\gamma]}$$

$$= (K_E/K_D)^3(\Gamma_D/\Gamma_E) \simeq 1{,}4. \quad (62)$$

The experiment (Fig. 24) gives for this ratio the upper limit

$$R_{\exp} < 0{,}6 \quad (95\%\ \text{confidence level}) \quad (63)$$

(when the background is subtracted, this limit is <0.4).

Thus, the result of the experiment, with observation of radiative decay of the $D(1285)$ meson and nonobservation of the decay of the axial meson of mass 1420 MeV and width 55 MeV, indicates that the $E(1420)$ does not belong to the axial nonet [under the assumption that the simple quark relation (62) holds]. We note that the validity of such an approach has been tested in charge-exchange experiments for pseudoscalar (η, η') and vector (ω,φ) mesons (see Ref. 75 and Sec. 2).

If instead of $E(1420)$ the axial nonet contains a meson with $M \gtrsim 1.5$–1.6 GeV and $\Gamma > 150$nd200 MeV, then the expected number of events for its $\varphi\gamma$ decay does not contradict the data of this experiment. For the $D'(1530)$ meson with $M = 1530$ MeV and $\Gamma = 107$ MeV (Refs. 66 and 67), $R_{D'\,\exp} < 1.1$ (95% confidence level), and $R_{D'\,\text{expected}} \simeq 1.4$ [i.e., here there is no great contradiction, and the D' meson can occur with the D meson in a single axial SU(3) nonet].

In the relativistic model of the radiative decays of mesons,[69] the ratio of the partial radiative widths is predicted to have a more complicated dependence on the photon momentum than the one used in the derivation of (62). This model yields the predictions $R_{E(1420)\,\text{theor}} = 0.63$ and $R_{D'(1530)\,\text{theor}} = 0.45$ [under the assumption that the axial nonet of mesons contains, together with $D(1285)$, either $E(1420)$ or $D'(1530)$]. Comparison with the experimental bounds also shows that the $E(1420)$ meson probably does not occur in the axial nonet, although this conclusion becomes less significant than the one drawn earlier on the basis of (62).

The question of the nature of the $E(1420)$ meson remains open. For its analysis, one must also bear in mind the data on radiative $\varphi\gamma$ decays and the contradictory results of experiments to determine the quantum numbers of the $E(1420)$ meson in hadron beams and the discovery of an $E(1420)$ peak in $\gamma\gamma^* = (Q^2)$ collisions in e^+e^- colliders, and the observation of decays $J/\psi\to\omega E(1420)$ [in the absence of $J/\psi\to\varphi E(1420)$]. Some models for the 1^{++} family are shown in Table II. It appears that all data on the $E(1420)$ meson can be explained by assuming that this particle, if it does have the quantum numbers $J^{PC} = 1^{++}$, does not belong to an axial SU(3) nonet and, thus, is probably a "superfluous" exotic hadron.

4. SEARCHES FOR THE RADIATIVE $M(0^{-+})\to\varphi\gamma$ AND $f_2'(1525)\to\varphi\gamma$

Investigations were made of the mass spectrum of the $\varphi\gamma$ system for events (7) corresponding to the requirement $|\cos\vartheta_{K^-\gamma}| < 2/3$, i.e., under the conditions when events enriched with states in which the φ mesons have helicities $\lambda_\varphi = \pm 1$ are selected. Then the contribution from the decays $M(J^{PC} = 1^{++})\to\varphi\gamma$ is suppressed by more than a factor of 3, and the decays $M(J^{PC} = 0^{-+})$ are separated very efficiently. However, as the results of investigation of the $\varphi\gamma$, mass spectrum obtained by such a selection showed, it is possible to determine under these conditions only upper limits for the product of the production cross sections and the probabilities of radiative decays of the mesons $\eta(1440)$ and $\eta(1275)$ with the quantum numbers $J^{PC} = 0^{-+}$:

$$\sigma[\pi^-p\to\eta(1440)\,n]\,BR[\eta(1440)\to\varphi\gamma] < 2{,}4\cdot10^{-33}\ \text{cm}^2; \quad (64)$$

$$\sigma[\pi^-p\to\eta(1275)\,n]\,BR(\eta(1275)\to\varphi\gamma] < 1{,}3\cdot10^{-33}\ \text{cm}^2. \quad (65)$$

It follows from (57) and (63) that for the $E(1420)$ meson with $J^{PC} = 1^{++}$

TABLE II. Models for the 1^{++} nonet and the $E(1420)$ meson.

Model for neutral mesons $I=0$

1. A very old model: $D(1285)$ and $E(1420)$ mesons as members of a 1^{++} nonet:

$$|D(1285)\rangle=\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})\cos\alpha_A-s\bar{s}\sin\alpha_A\,,\qquad |E(1420)\rangle=-\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})\sin\alpha_A-s\bar{s}\cos\alpha_A$$

Ideal mixing: $\alpha_A=0$ ($\vartheta_A=\vartheta_0$)

$(\alpha_A=\vartheta_A-\vartheta_0;\ \vartheta_0=35,3°)$

2. The axial nonet contains $D(1285)$ and $|1^{++}\rangle$ with $M\gtrsim 1.5$–1.6 GeV, $\Gamma\gtrsim 150$ MeV. It is possible that this particle is the $D'(1530)$ meson. The $E(1420)$ meson does not belong to the axial nonet ("superfluous" exotic meson?[53,61]).

3. New model (J. Iizuka *et al.*[80]): the $D(1285)$ meson is an $s\bar{s}$ meson in a 1^{++} nonet. The $(1/\sqrt{2})(u\bar{u}+d\bar{d})$ term of this nonet has mass $\simeq 1075\pm 25$ MeV (almost degenerate with the A_1 meson). Decays of this meson (through the channels 4π, $\rho 2\pi$) have not been observed because of the large background.

4. Sh. S. Eremyan and A. É. Nazaryan.[81] Model $J^{PC}=1^{++}$ of the family as 10 mesons (mixing with glueball)

$$|\psi\rangle=x\,\left|\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})\right\rangle+y\,|s\bar{s}\rangle+z\,|G\rangle\quad(x^2+y^2+z^2=1)$$

	$D(1285)$	$E(1420)$	$D'(1530)$
x	0.74 ± 0.04	-0.31 ± 0.03	0.60 ± 0.05
y	-0.67 ± 0.04	-0.43 ± 0.07	0.61 ± 0.03
z	0.07 ± 0.01	-0.85 ± 0.05	-0.53 ± 0.07

Problems and conclusions

1. a) $R_{\rm exp}=N[E\to\varphi\gamma]/N[D\to\varphi\gamma]<0.6$ (95% confidence level) but should be $R=1.4$ [see (62), (63)].
b) Large $s\bar{s}$ component in $D(1285)$, incompatible with ideal mixing ($|\alpha_A|>30°$).
c) The data on the production of the $D(1285)$ and $E(1420)$ mesons in $\gamma\gamma^*$ ($Q^2\neq 0$) collisions are incompatible with ideal mixing ($10<\alpha_A\lesssim 30°$).
d) The decays $J/\psi\to\omega E(1420)$ are observed, but not $J/\psi\to\varphi E(1420)$.
Summary: $E(1420)$ evidently does not belong to an axial nonet. In the axial nonet ideal mixing is strongly violated.

2. In this case there are no particular difficulties with the ratio $R(63)$ [even for the $D'(1530)$ meson]. There is a strong violation of ideal mixing in the axial nonet.

3. In this model there are no difficulties with the $D(1285)\to\varphi\gamma$ decay. In it, the $E(1420)$ meson does not belong to the axial nonet. however, it is necessary to make a very careful investigation of all the experimental data on the $D(1285)$ meson in order to show that there are no contradictions with such a revolutionary model.

4. In this model:
a) large $s\bar{s}$ component in $D(1285)$ ($|\sigma_A|\sim 40°$);
b) No difficulties with the ratio $R_E=N[E(1420)\to\varphi\gamma]/N[D(1285)\to\varphi\gamma]<0.6$, since in this model there is not a single mixing angle but two parameters. Theoretical prediction: $R_E=0.09\pm0.05$, i.e., <0.6. } No difficulties with the $D(1285)\to\varphi\gamma$ decay.

Problem: Glueball with 1^{++} strongly mixed with other 1^{++} mesons? The (gg) state is doubtful because of the Landau–Yang theorem. The state (ggg) must evidently have a large mass.

$$\sigma\,[\pi^-p\to E\,(1420)n]\,BR\,[E\,(1420)\to\varphi\gamma]<0{,}9\cdot10^{-33}\ \text{cm}^2\qquad(66)$$

[all the bounds (64)–(66) are given at the 95% confidence level].

Analysis of the events $K^-N\to(\varphi\gamma)Y$ and $K^-N\to K^+K^-Y$ established the following bound for the probability of radiative decay of the tensor $f_2'(1525)$ meson:

$$BR\,[f_2\,(1525)\to\varphi\gamma]=\Gamma\,[f_2'\,(1525)\to\varphi\gamma]/\Gamma\,[f_2'\,(1525)\to K^+K^-]<4\cdot10^{-3}\qquad(67)$$

(95% confidence level).

In most theoretical models[70,76,77] the value of $BR\,[f_2'(1525)\to\varphi\gamma]$ is in the range from 2.5×10^{-3} to 2.5×10^{-2}. From the branching ratio $BR[f_2'(1525)\to\gamma\gamma]=(1.6\pm0.7)\times10^{-6}$ (Ref. 27) and from the vector-dominance model the expected value of $BR\,[f_2'(1525)\to\varphi\gamma]$ is 6×10^{-4}–1.6×10^{-3} (obtained from Ref. 70).

5. ELECTROMAGNETIC TRANSITION FORM FACTORS IN THE DECAYS $\eta\to\mu^+\mu^-, \eta\to\mu^+\mu^-\gamma, \eta'\to\mu^+\mu^-\gamma$, AND $\omega\to\pi^0\mu^+\mu^-$

5.1. Experiments with Lepton-G and searches for electromagnetic leptonic decays of the η, η', and ω mesons

The facility Lepton-G (a previous form of the spectrometer Lepton) was used during 1978–1980 to carry out large series of experiments to detect and investigate conversion electromagnetic decays (Refs. 10–12):[11)]

$$\eta \to \mu^+\mu^-\gamma; \tag{68}$$

$$\eta' \to \mu^+\mu^-\gamma; \tag{69}$$

$$\omega \to \pi^0\mu^+\mu^-. \tag{70}$$

Also investigated was the decay[13]

$$\eta \to \mu^+\mu^-, \tag{71}$$

which had been discovered earlier in experiments at CERN.[82]

Searches were made for the processes

$$\eta \to \pi^0\mu^+\mu^-; \tag{72}$$

$$\eta \to \pi^0\mu^+\mu^-\gamma; \tag{73}$$

$$\eta' \to \pi^0\mu^+\mu^-; \tag{74}$$

$$\eta' \to \eta\mu^+\mu^- \tag{75}$$

and upper bounds for their branching ratios were established.[14]

The facility Lepton-G (Refs. 10 and 83) used in these investigations (Fig. 25) was a combined spectrometer that permitted effective detection of processes with simultaneous emission of muon pairs and photons.

The facility included detectors of the primary beam, a target with protective counters, and wire proportional chambers for measuring the coordinates of charged particles directly behind the target. For measurement of the coordinates and energies of the photons, a 64-channel hodoscope spectrometer with lead-glass counters was used. The muon pairs were detected, and their momenta were measured, in the wide-aperture magnetic spectrometer with wire spark chambers and in a multichannel muon detector.

The experiments were carried out with beams of secondary negative particles of energy 70 GeV from the IHEP accelerator with momenta p_{π^-} equal to 25 and 33 GeV and intensity up to 4×10^6 particles/cycle.

The source of the mesons was quasi-two-particle exclusive reactions of the type

$$\pi^-p \to Mn\ (M = \eta;\ \eta';\ \omega), \tag{76}$$

which were investigated in detail in the working range of energies and ensure favorable background conditions for searches for and studies of rare electromagnetic decay processes.

One of the features of the facility Lepton-G was the position of the gamma spectrometer and the copper filter standing behind it near the target of the facility, in front of the wide-aperture magnetic spectrometer. This configuration of the experimental apparatus appreciably reduced the background from decays of secondary π and K mesons in flight with emission of muons, and also reduced the size of the gamma detector. In addition, the load of the spark chambers of the magnetic spectrometer was reduced by several times, and this made it possible to increase the intensity of the primary beam.

During the time of the measurements, about 5×10^{11} π^- mesons were passed through the facility, and this corresponded to production in the target of $\sim2\times10^7$ η mesons and $\sim10^7$ of each η' and ω mesons in the binary reactions (76).

In the first stage of analysis of the experimental data, events with two energetic muons ($E_\mu > 4.5$ GeV) detected in the magnetic spectrometer were selected.

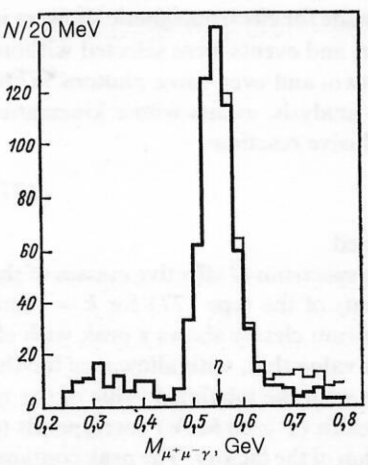


FIG. 26. Mass spectrum of the $\mu^+\mu^-\gamma$ system in the reaction $\pi^-p\to(\mu^+\mu^-\gamma)n$ at $E_\gamma > 1.5$ GeV. The peak corresponds to the decay $\eta\to\mu^+\mu^-\gamma$. The arrow indicates the tabulated mass of the η meson; the thin histogram represents all events, and the heavy histogram represents the events with $M_{\mu^+\mu^-} < 0.24$ GeV^2 used to determine the transition form factor of the η meson.

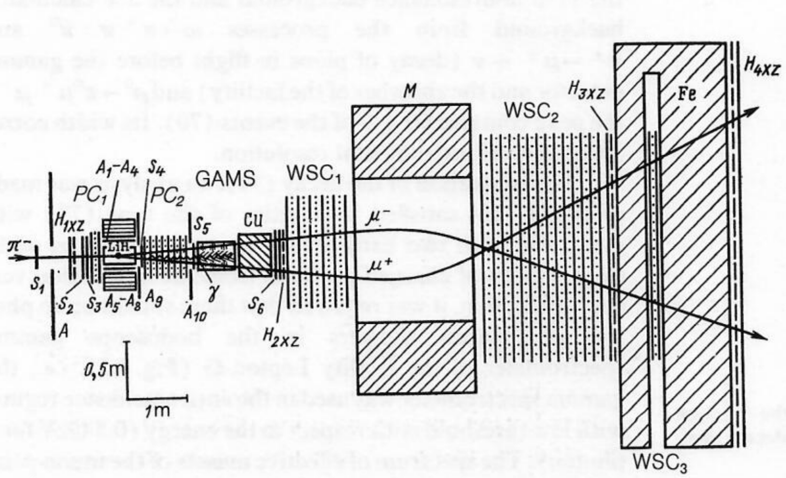


FIG. 25. Schematic arrangement of the experimental facility Lepton-G: S_1–S_6 are scintillation counters; A_1–A_{10} are protective scintillation counters; PC_{1-2} are proportional chambers; H_{1xz}–H_{4xz} are scintillation hodoscopes; WSC_1–WSC_3 are wire spark chambers; LiH is the target; Cu is a copper filter; GAMS is the hodosocope gamma spectrometer; M is a magnet.

A search was then made for electromagnetic showers in the gamma spectrometer, and events were selected without photons, and with one, two, and even three photons in the final state. For the final analysis, events whose kinematics corresponded to the exclusive reactions

$$\pi^- p \to \mu^+\mu^- (k\gamma)\, n \tag{77}$$

($k = 0,1,2,3$) were selected.

Figure 26 shows the spectrum of effective masses of the $\mu^+\mu^-\gamma$ system for events of the type (77) for $k=1$ and $E_\gamma > 1.5$ GeV. This spectrum clearly shows a peak with effective mass 563 MeV, a value that, with allowance for the systematic errors, agrees with the tabulated value of the η-meson mass. The peak width ($\Gamma < 60$ MeV) corresponds to the instrumental resolution of the facility. The peak contains about 600 events (at a background level not exceeding 8%). Thus, the existence of decay of the η meson into a muon pair and a photon, $\eta \to \mu^+\mu^-\gamma$, was established experimentally.

Searches for the decays $\eta' \to \mu^+\mu^-\gamma$, the expected number of which must be at a much lower level than for (68), were made by investigating the spectrum of effective masses of the $\mu^+\mu^-\gamma$ states in the region above the η-meson mass. For maximal suppression of the background, more stringent cutoffs on the energies of the photons detected in the gamma spectrometer were introduced: $5 < E_\gamma < 16$ GeV. A Monte Carlo analysis showed that these cutoffs reduced the efficiency for detection of the decay (69) by not more than 25%. At the same time, the increase in the threshold for the photon energy made possible an additional suppression of the background from the detection of hadronic showers, while the cutoff with respect to the maximal energy ($E_\gamma < 16$ GeV) reduced the background from fast π^0 mesons, for which showers from two photons were not resolved in the detector. The final spectrum of effective masses of the $\mu^+\mu^-\gamma$ system from (77) for $k=1$ and $M_{\mu^+\mu^-\gamma} > M_\eta$ is shown in Fig. 27.

In this spectrum there is a clear peak at mass $M = 0.95 \pm 0.01$ GeV, corresponding to the tabulated mass

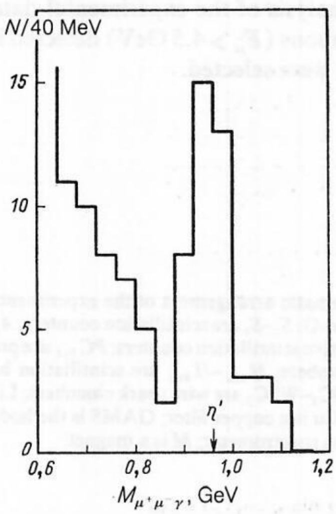


FIG. 27. Mass spectrum of the $\mu^+\mu^-\gamma$ system in the reaction $\pi^- p \to (\mu^+\mu^-\gamma) n$ in the region above m_η. The arrow indicates the tabulated mass of the η' meson.

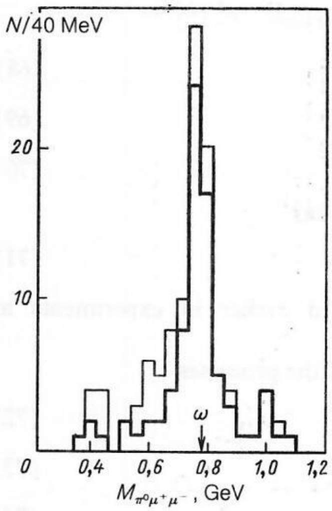


FIG. 28. Mass spectrum of the $\mu^+\mu^-\pi^0$ system in the reaction $\pi^- p \to (\pi^0\mu^+\mu^-) n$ for events with $M^2_{\mu^+\mu^-} < 0.4$ GeV^2 (used then to measure the transition form factor). The peak corresponds to the decay $\omega \to \pi^0\mu^+\mu^-$. The arrow shows the tabulated mass of the ω meson. The outer and inner histograms correspond to energy thresholds of the photons equal to 1 and 1.4 GeV, respectively [with increasing $(E_\gamma)_{\rm thr}$ the background conditions of the experiment improved].

of the η' meson. The width of the peak is due to the experimental resolution. The peak, after subtraction of the 20% background, contains 33 ± 7 events of $\eta' \to \mu^+\mu^-\gamma$ decay.

The decay $\omega \to \pi^0\mu^+\mu^-$ was discovered by analysis of the exclusive events (77) with two muons and two photons ($E_\gamma > 1$ GeV) in the final state. Special calibration measurements showed that the efficiency of simultaneous detection of two photon showers in the γ detector was close to 100% for distances between the shower axes greater than 30 mm. Monte Carlo modeling showed that this is precisely the region that contains practically all events from the decay $\omega \to \pi^0\mu^+\mu^-$, so that for them the correction for loss in the detection of two showers did not exceed 1%.

Figure 28 gives the distribution with respect to the effective mass $M_{\pi^0\mu^+\mu^-}$ for events with $M_{\gamma\gamma} \simeq m_{\pi^0}$. To reduce the background, events were selected if $M^2_{\mu^+\mu^-} < 0.4$ GeV^2, i.e., in the kinematic region in which the transition form factor of the $\omega\pi^0$ vertex was subsequently investigated. The mass spectrum contains a clear peak corresponding to the tabulated value of the ω-meson mass. After subtraction of the 11% nonresonance background and the 3% calculated background from the processes $\omega \to \pi^+\pi^-\pi^0$ and $\pi^\pm \to \mu^\pm + \nu$ (decay of pions in flight before the gamma detector and the absorber of the facility) and $\rho^0 \to \pi^0\mu^+\mu^-$, the peak contains 60 ± 9 of the events (70). Its width corresponds to the instrumental resolution.

For separation of the decay (71), an analysis was made of events that satisfied kinematics of the type (77) with $k=0$ and with two hard muons unaccompanied by additional tracks of charged particles from the interaction vertex. In addition, it was required that there should be no photon or hadron showers in the hodoscope gamma spectrometer of the facility Lepton-G (Fig. 25), i.e., the gamma spectrometer was used in the anticoincidence regime with low threshold with respect to the energy (0.5 GeV for a photon). The spectrum of effective masses of the muon pairs

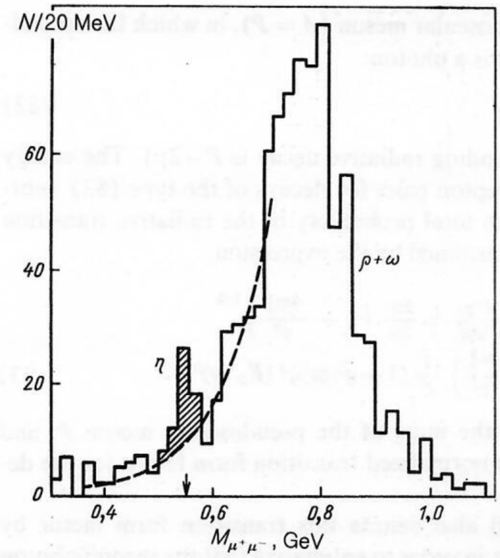


FIG. 29. Mass spectrum of $\mu^+\mu^-$ pairs in the reaction $\pi^- p \to (\mu^+\mu^-)n$. The arrow indicates the tabulated mass of the η meson. The broken curve is the result of fitting the background. The hatched peak corresponds to the $\eta \to \mu^+\mu^-$ decay.

for the selected events was investigated (Fig. 29).

The dominant process in this spectrum is $\pi^- p \to \rho(\omega)n$, $\rho(\omega) \to \mu^+\mu^-$. In the region of η-meson masses there is a peak corresponding to the decay $\eta \to \mu^+\mu^-$. The width of the peak is determined by the instrumental resolution, while the mass, equal to 551 ± 4 MeV, agrees with the tabulated value for the η meson. The peak contains 27 ± 8 events of the decay (71), rising above the background by more than five standard deviations. The background below the peak has a physical nature and can be described in the vector-dominance model as a direct process of production of muon pairs. The contribution of the decay $\eta \to \mu^+\mu^-\gamma$ with a "lost" photon (and also of decays of pions in flight with meson production) is negligibly small.

The results of measurements of the branching ratios of the decays (68)–(71), made with Lepton-G, are given in Table III together with the upper limits established in these experiments for the probabilities of (72)–(75). The method of analysis of the data used in the searches for (72)–(75) was similar to the one used to select the events $\omega \to \pi^0\mu^+\mu^-$.

The probability of the decay (71), $BR(\eta \to \mu^+\mu^-) = (6.5 \pm 2.1) \times 10^{-6}$, was found to be half the value obtained earlier in Ref. 82: $(2.2 \pm 0.8) \times 10^{-5}$. When comparing the results of these experiments on the $\eta \to \mu^+\mu^-$ decay, it should be borne in mind that the data obtained at Serpukhov are more reliable, since they were normalized by means of the well-determined probability of the conversion decay $\eta \to \mu^+\mu^-\gamma$, which was observed in the same experiment. In addition, a measurement of the probability of the decay $\rho \to \mu^+\mu^-$ (Ref. 84), made at CERN with the same facility and simultaneously with the study of the decay (71), led to $BR(\rho \to \mu^+\mu^-) = (0.97 \pm 0.31) \times 10^{-4}$, which greatly exceeds the average world value $BR(\rho \to e^+e^-) = (0.45 \pm 0.02) \times 10^{-4}$ (Ref. 27). It may therefore be supposed that in the experiments of Refs. 82 and 84 there is a common systematic error in the normalization, which leads to an overestimation of $M \to \mu^+\mu^-$ decay probability.

The comparatively large value of $BR(\eta \to \mu^+\mu^-)$ from Ref. 82 was in contradiction with most theoretical estimates for this probability. This contradiction was eliminated

TABLE III. Results of experimental investigations of rare electromagnetic decays of light mesons with the Lepton-G facility.

Reference	Decay	No. of events	Branching ratio			Fit for form factor $F(q^2)$	Slope of form factor b **	
			Experiment	VDM	QED		b_{exp}, GeV^{-2}	b_{VDM}, GeV^{-2}
[10]	$\eta \to \mu^+\mu^-\gamma$	600	$(3{,}1 \pm 0{,}4) \cdot 10^{-4}$	$(3{,}08–3{,}13) \cdot 10^{-4}$	$2{,}1 \cdot 10^{-4}$	$(1 - q^2/\Lambda_\eta^2)^{-1}$ $\Lambda_\eta = (0{,}72 \pm 0{,}09)$ GeV	$1{,}9 \pm 0{,}4$	1,8
[11]	$\eta' \to \mu^+\mu^-\gamma$	33	$(8{,}9 \pm 2{,}4) \cdot 10^{-5}$	$(7{,}0–8{,}7) \cdot 10^{-5}$	$3{,}4 \cdot 10^{-5}$	Qualitative agreement with ρ-pole fit	$1{,}7 \pm 0{,}4$	1,5
[12]	$\omega \to \pi^0\mu^+\mu^-$	60	$(9{,}6 \pm 2{,}3) \cdot 10^{-5}$	$8 \cdot 10^{-5}$	$5{,}0 \cdot 10^{-5}$	$(1 - q^2/\Lambda_\omega^2)^{-1}$ $\Lambda_\omega = (0{,}65 \pm 0{,}03)$ GeV	$2{,}4 \pm 0{,}2$	1,7
[13]	$\eta \to \mu^+\mu^-$	27	$(6{,}5 \pm 2{,}1) \cdot 10^{-6}$	$(4–5) \cdot 10^{-6}$	—	—	—	—
[14]	$\eta \to \pi^0\mu^+\mu^-$	—	$\leqslant 5 \cdot 10^{-6}$	90% confidence level				
	$\eta' \to \pi^0\mu^+\mu^-$	—	$\leqslant 6 \cdot 10^{-5}$					
	$\eta' \to \eta\mu^+\mu^-$	—	$\leqslant 1{,}5 \cdot 10^{-5}$					
	$\eta \to \pi^0\mu^+\mu^-\gamma$	—	$\leqslant 3 \cdot 10^{-6}$					

*The experimental values for the decay branching ratios $BR(\mathrm{exp})$ are given together with the expected probabilities in the vector-dominance model [$BR(\mathrm{VDM})$] and for structureless mesons [$BR(\mathrm{QED})$].
**The slope of the form factor is $b = dF/dq^2|_{q^2=0}$. If the form factor is parametrized in the form $F_{AB} = (1 - q^2/\Lambda^2)^{-1}$, then $b = 1/\Lambda^2$. The values of b_{exp} are given together with the predictions for these slopes in the VDM.

by the result of the experiment of $\eta \to \mu^+\mu^-$ decay carried out with Lepton-G (for a more detailed discussion of this problem, see Refs. 13 and 15).

5.2. Conversion decays of mesons and their transition electromagnetic form factors

For conversion decays of mesons

$$A \to B + \gamma_V \to Bl^+l^- \tag{78}$$

examples of which are the processes (68)–(70), the probability of production of a lepton pair with a definite value of the effective mass $M_{l^+l^-}$ is proportional to the probability of emission of a virtual photon with timelike 4-momentum $q^2 = M^2_{l^+l^-}$. The probability of emission of such a photon is due to the dynamical electromagnetic structure which arises in the vertex of the transition $A \to B$. This electromagnetic structure, which is due to a cloud of virtual states in the region of the transition, is characterized by a specific form factor, which has become known as the transition form factor.

Data on the electromagnetic structure in the region of the transition $A \to B$ can be obtained by studying the probability of the decay $A \to B + (l^+l^-)$ as a function of the square of the effective mass of the lepton pair, $q^2 = M^2_{l^+l^-}$, i.e., by analyzing the mass spectrum of the lepton pairs.[12)]

If the particles A and B were structureless objects, then one could calculate with a high accuracy the mass spectrum of the lepton pairs, $[d\Gamma/dq^2]_{\rm QED}$, by means of the methods of quantum electrodynamics. The complicated internal structure of the particles changes this spectrum:

$$[d\Gamma/dq^2]_{\rm exp} = [d\Gamma/dq^2]_{\rm QED} \mid f_{AB}(q^2)\mid^2. \tag{79}$$

Comparing the measured spectrum of lepton pairs in the decays (78) with the QED calculations for point particles, it is possible to determine experimentally the square of the transition form factor $|f_{AB}(q^2)|^2$, in the timelike region of momentum transfers.

Quantitatively, the effective-mass spectrum of the lepton pairs for the conversion decays (78), normalized to the width of the corresponding radiative decay $A \to B\gamma$, has the form

$$\frac{d\Gamma[A \to Bl^+l^-]}{dq^2\Gamma(A \to B\gamma)} = \left\{\frac{\alpha}{3\pi}\left(1-\frac{4m_l^2}{q^2}\right)^{1/2}\left(1+2\frac{m_l^2}{q^2}\right)\right.$$
$$\left.\times\frac{1}{q^2}\left[\left(1+\frac{q^2}{m_A^2-m_B^2}\right)^2-\frac{4m_A^2q^2}{(m_A^2-m_B^2)^2}\right]^{3/2}\right\}$$
$$\times\ |f_{AB}(q^2)/f_{AB}(0)|^2 \tag{80}$$

(for vector and pseudoscalar mesons, i.e., for decays $V \to Pl^+l^-$ or $P \to Vl^+l^-$). Here, m_l, m_A, and m_B are the masses of the lepton and of the mesons A and B; $q^2 = M^2_{l^+l^-}$; $\{...\} = [d\Gamma/dq^2]_{\rm QED}/\Gamma(A \to B\gamma)$ (i.e., for point particles).

We shall denote the normalized form factor of the $A \to B$ transition by

$$f_{AB}(q^2)/f_{AB}(0) = F_{AB}(q^2) \tag{81}$$

[the normalization has the form $F_{AB}(0) = 1$].

Somewhat different is the special case of conversion decay of a pseudoscalar meson ($A = P$), in which the secondary particle B is a photon:

$$P \to l^+l^-\gamma \tag{82}$$

(the corresponding radiative decay is $P \to 2\gamma$). The energy spectrum of lepton pairs for decays of the type (82) (normalized to the total probability of the radiative transition $P \to 2\gamma$) is determined by the expression

$$\frac{d\Gamma(P \to l^+l^-\gamma)}{dq^2\Gamma(P \to 2\gamma)} = \frac{2\alpha}{3\pi}\left(1-\frac{4m_l^2}{q^2}\right)^{1/2}$$
$$\times\left(1+2\frac{m_l^2}{q^2}\right)\frac{1}{q^2}(1-q^2/m_P^2)^3\,|F_P(q)^2|^2. \tag{83}$$

Here, m_P is the mass of the pseudoscalar meson P, and $F_P(q^2)$ is the normalized transition form factor for the decay (82).

We shall also denote this transition form factor by $F_P(q^2; 0; m_p^2)$ in order to emphasize that the second photon is on the mass shell.

The good background conditions under which the decays (68)–(70) were identified made it possible to study the electromagnetic transition form factors for the η–γ, η'–γ, and ω–π^0 vertices in these decays. The relations (80) and (83) were used to analyze the spectrum of muon pairs. The results of the measurements of the transition form factors are shown in Figs. 30–32 and in Table III.

The general behavior of the transition form factors agrees basically with the vector-dominance model (VDM), although there are certain deviations from the predictions of this model for the ω–π^0 transitions. Such agreement with the VDM for processes of the type (82) was established for the first time in the Lepton-G experiments (Fig. 33). A subsequent theoretical analysis based on QCD showed that in these decays the deviations from the VDM must be small (not exceeding $\sim 10\%$).[87] The transition form factors in the decays (82) were also analyzed by means of "Q^2 duality," which establishes the equivalence of two different descrip-

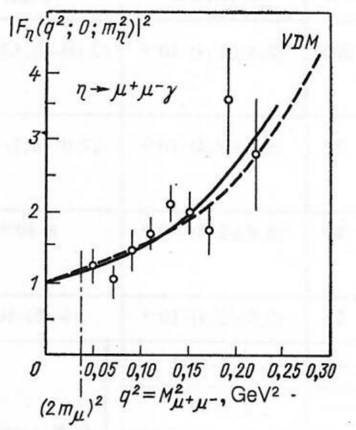


FIG. 30. Measurement of the electromagnetic transition form factor $F_\eta(q^2) = F_\eta(q^2; 0; m_\eta^2)$ of the η meson in the decay $n \to \mu^+\mu^-\gamma$. The points are the experimental values for $|F_\eta(q^2; 0; m_\eta^2)|^1$. The continuous curve is the result of fitting the experimental data by the pole dependence $K(1-q^2/\Lambda_\eta^2)^{-2}$, where $\Lambda_\eta = 0.72 \pm 0.09$ GeV, and the coefficient K takes into account the error in the absolute normalization of the results of measurements of $|F_\eta|^2$. The broken curve is the prediction based on the vector-dominance model.

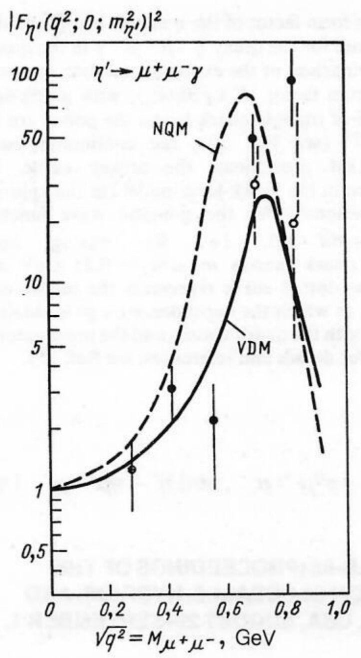


FIG. 31. Measurement of the electromagnetic transition form factor of the η' meson (in the decay $\eta' \to \mu^+\mu^-\gamma$). The black circles are the experimental values of the square of the form factor; $|F_\eta(q^2;0;m^2_{\eta'})|^2$; the open circles are the same but with maximal correction for a 20% background below the $\eta' \to \mu^+\mu^-\gamma$ peak in Fig. 27 (under the assumption that the entire background lies in the region of masses of the ρ meson); the continuous curve gives the predictions of the VDM, and broken curve gives the predictions based on the nonlocal quark model (NQM) of Ref. 85.

tions of low-energy phenomena—the purely phenomenological one based on vector dominance, and the dynamical one based on the model of triangle quark loops (with masses of the constituent quarks) (see, for example, Ref. 88 and Fig. 34).

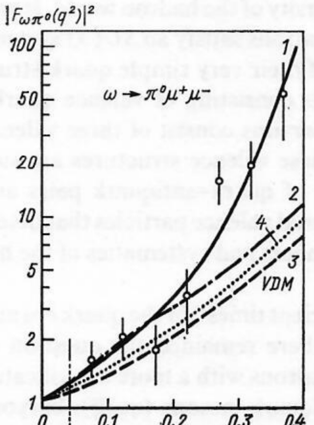


FIG. 32. Transition form factor for the ω–π^0 vertex (in the decay $\omega \to \pi^0\mu^+\mu^-$). The points are the experimental values of $|F_{\omega\pi^0}(q^2)|^2$; curve 1 is the result of fitting the experimental data by the pole dependence $K(1-q^2/\Lambda^2_\omega)^{-2}$ (the coefficient K takes into account the uncertainty in the absolute normalization of the experimental data), $\Lambda_\omega = 0.65 \pm 0.03$ GeV; curve 2 is the prediction of the model of Ref. 86 with a modified ρ propagator; curve 3 is the calculation in accordance with the vector-dominance model; curve 4 is the prediction of the nonlocal quark model.[85]

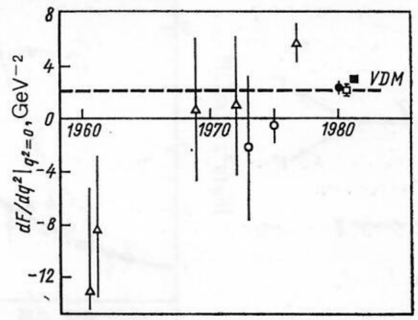


FIG. 33. Experimental data (year by year) on the slopes of the electromagnetic transition form factors of neutral mesons: $[dF/dq^2]|_{q^2 \simeq 0}$. The open triangles are for the decay $\pi^0 \to e^+e^-\gamma$, the open circles for the decay $\eta \to e^+e^-\gamma$, the black circle for the decay $\eta \to \mu^+\mu^-\gamma$ (Ref. 10), the open square for the decay $\eta' \to \mu^+\mu^-\gamma$ (Ref. 11), and the black square for the decay $\omega \to \pi^0\mu^+\mu^-$ (Ref. 12). For references to the investigations of $\pi^0 \to e^+e^-\gamma$ and $\eta \to e^+e^-\gamma$, see Ref. 15; the broken line is the VDM prediction for the slope of the η-meson form factor $[dF_\eta/dq^2]|_{q^2 \simeq 0} = 1.8$ GeV² (the VDM predictions for the remaining slopes are similar; see Table III).

For a detailed analysis of data on the transition form factors in electromagnetic decays, see Ref. 15.

CONCLUSIONS

We summarize here the main results of the hadron-spectroscopy experiments carried out with the Lepton facility.

1. The facility Lepton-F was used to investigate the charge-exchange reaction $\pi^- p \to (\varphi\pi^0)n$ at momentum 32.5 MeV. The mass spectrum of the $\varphi\pi^0$ system is dominated by a peak with mass $M = 1480 \pm 40$ MeV and width $\Gamma = 130 \pm 60$ MeV.

2. It has been shown that the observed state cannot be explained by threshold effects such as the Deck effect and is a new resonance—the $C(1480)$ meson.

3. The cross section for exclusive production of the $C(1480)$ meson has been found to be $\sigma[\pi^- p \to C(1480)n]BR[C(1480) \to \varphi\pi^0] = (40 \pm 15 \times 10^{-33}$ cm².

4. The t' distribution has been studied for the process $\pi^- p \to C(1480)n$, and it has been shown that this reaction is due to pion exchange. The OPE model also agrees with the angular distributions for the cascade decays $C(1480) \to \varphi\pi^0$ and $\varphi \to K^+K^-$.

5. It follows (in a model-independent way) from the data on the decay $C(1480) \to \varphi\pi^0$, $\varphi \to K^+K^-$ that the $C(1480)$ meson has isotopic spin $I = 1$, negative charge parity, and spin $J > 0$. Analysis of the angular distribution in the OPE model led to determination of its quantum numbers: $J^{PC} = 1^{--}$.

6. Some bounds for the decay channels of the $C(1480)$ meson have been obtained:

$$BR\,[C\,(1480) \to \pi^+\pi^-]\,BR\,[C\,(1480) \to \varphi\pi^0] \simeq (1-2)\cdot 10^{-3};$$

$$BR\,[C\,(1480) \to \overline{K^*}K + K^*\overline{K}]/BR\,[C\,(1480) \to \varphi\pi^0] < 4{,}8;$$

$$BR\,[C\,(1480) \to K^+K^-\pi^0]/BR\,[C\,(1480) \to \varphi\pi^0] < 1{,}5.$$

All bounds are at the 95% confidence level.

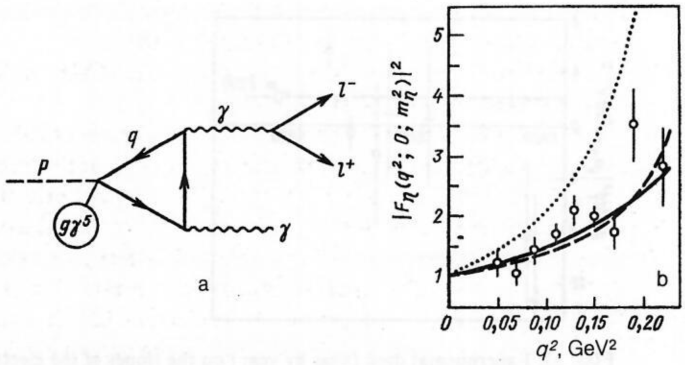


FIG. 34. Transition form factor of the η meson and Q^2 duality (Ref. 88): a) diagram for the decay $\eta\to\mu^+\mu^-\gamma$ in the quark-loop model; b) comparison of the experimental data on the η-meson transition from factor $|F_\eta(q^2;0;m_\eta^2)|$ with predictions based on the model of triangle quark loops: the points are the experimental data[10] (see Fig. 30); the continuous curve represents the VDM predictions; the broken curve, the results of calculation in the quark-loop model (in the approximation of "soft mesons") for the η-meson wave function $|\eta\rangle=(1/\sqrt{3})(u\bar{u}+d\bar{d}-\bar{s}s)$, i.e., for mixing angle $\vartheta_P=-19°$) and quark masses $m_u\simeq m_d=0.25$ GeV and $m_s=0.35$ GeV; the dotted curve represents the model with "double counting," in which the dependence on q^2 is obtained with allowance for both the quark masses and the propagator of the vector meson (for details and references, see Ref. 15).

7. The bound $BR[C(1480)\to\varphi\pi^0]/BR[C(1480)\to\omega\pi^0]>1/2$ (95% confidence level) has been obtained. For ordinary $q\bar{q}$ mesons, this ratio must be $\sim 1/200$–$1/400$ (from the OZI rule). From this it is concluded that the $C(1480)$ meson is a strong candidate for an exotic state. The properties of the C meson can be explained in the framework of an interpretation of it as a four-quark state or a hybrid quark–gluon meson:

$$|C\,(1480)\rangle=\left|\frac{1}{\sqrt{2}}\,(u\bar{u}-d\bar{d})\;s\bar{s}\right\rangle\quad\text{or}\quad|C\,(1480)\rangle=\left|\frac{1}{\sqrt{2}}\,(u\bar{u}-d\bar{d})\;g\right\rangle.$$

8. A bound has been obtained on the probability of the OZI-suppressed decay of the $B(1235)^0$ meson:

$$BR\,[B\,(1235)^0\to\varphi\pi^0]<5\cdot10^{-3}\ \text{(95\% confidence level)}.$$

9. The OZI-forbidden reaction $\pi^-p\to\varphi n$ has been studied at momentum 32.5 GeV. This process was found to have cross section $\sigma(\pi^-p\to\varphi n)=(13\pm5)\times10^{-33}$ cm^2 and ratio $R(\varphi/\omega)|_{p_{\pi^-}}=32.5\text{GeV}=\sigma(\pi^-p\to\varphi n)/\sigma(\pi^-p\to\omega n)|_{p_{\pi^-}}=32.5\text{GeV}=(0.42\pm0.17)\times10^{-2}$.

10. The radiative decay $D(1285)\to\varphi\gamma$ has been discovered. It was found to have $BR[D(1285)\to\varphi\gamma]/BR[D(1285)\to K\bar{K}\pi]=(0.82\pm0.21\pm0.2)\times10^{-2}$. Tabulated data have been used to determine the branching ratio $BR[D(1285)\to\varphi\gamma]=(0.9\pm0.2\pm0.4)\times10^{-3}$ and partial width $\Gamma[D(1285)\to\varphi\gamma]=(23\pm5\pm10)$ keV.

It has been concluded that there is a strong violation of ideal mixing in the nonet of axial mesons.

11. The decay $E(1420)\to\varphi\gamma$ has not been found; the experimental bounds show that the $E(1420)$ meson does not apparently belong to the axial nonet.

12. Bounds have been obtained for the probabilities of radiative decays: $BR\,[f_2'(1525)\to\varphi\gamma]=\Gamma[f_2'(1525)\to\varphi\gamma]/\Gamma[f_2'(1525)\to K^+K^-]<4\times10^{-3}$; $BR[\omega\to\pi^+\pi^-\gamma]<4\times10^{-3}$; $BR[D(1285)\to\rho\gamma]<5\times10^{-2}$ (95% confidence level).

13. Earlier experiments with the facility Lepton-G led to the discovery of the rare electromagnetic decays $\eta\to\mu^+\mu^-\gamma$, $\eta'\to\mu^+\mu^-\gamma$, $\omega\to\pi^0\mu^+\mu^-$ and a more accurate probability of the process $\eta\to\mu^+\mu^-$. The transition form factors for the η–γ, η'–γ, and ω–π^0 vertices were investigated. New upper bounds were obtained for the probabilities of $\eta\to\pi^0\mu^+\mu^-$, $\eta'\to\pi^0\mu^+\mu^-$, and $\eta'\to\eta\mu^+\mu^-$ (see Table III).

APPENDIX 1. GLUEBALLS-88 (PROCEEDINGS OF THE WORKING SYMPOSIUM ON GLUEBALLS, HYBRIDS, AND EXOTIC HADRONS, BNL, USA, AUGUST 29–SEPTEMBER 1, 1988)[13)]

Investigations in the physics of resonances, which have already been going on for more than a quarter of a century, have significantly changed our ideas about the nature of hadrons, i.e., the particles that participate in the strong interactions. After the classical studies of Alvarez, Maglić, and others, which led to the discovery of the ω mesons, this approach began to develop very rapidly. In a comparatively short period several hundred new particles—baryons and mesons—were discovered; a brief reference description of these now occupies a weighty tome.[89]

It became obvious that none of these hadrons were elementary particles, contrary to earlier assumptions, and that a truly elementary level must lie much deeper. The existence of colored quarks and gluons was discovered, and quantum chromodynamics, which describes the interactions between these fundamental objects, was created. It was found that it is the quarks that are the structural elements of hadronic matter, determining the diversity of the hadron world. It was established that all known hadrons satisfy an $SU(3)$ systematics, which is a reflection of their very simple quark structure: Mesons are $q\bar{q}$ systems consisting of valence quark–antiquark pairs, while the baryons consist of three valence quarks (qqq). Of course, these valence structures are surrounded by a virtual "sea" of quark–antiquark pairs and gluons, but it is the fundamental valence particles that determine the main quantum numbers and systematics of the hadrons.

However, from the "ancient times" of the quark era and almost to the present day there remained the question of whether or not there exist hadrons with a more complicated valence composition—multiquark mesons ($qq\bar{q}\bar{q}$), baryons ($qqqq\bar{q}$), or dibaryons ($qqqqqq$). With the development of QCD, it was natural to suppose that gluons too could play the part of fundamental valence structural elements, i.e., that there must exist mesons consisting solely of gluons (they became known as glueballs)[90] or mixed hadrons formed from valence quarks and gluons—so-called hybrids or meiktons ($q\bar{q}g$ or $qqqg$).[38–40] All these new particle species are usually called exotic hadrons.

For a long time, the searches for exotic states were unsuccessful. However, in recent years, in connection with the development of experimental techniques, the situation has changed considerably. There have appeared new directions of scientific research involving experiments with colliding e^+e^- beams (study of hadronic states produced in decays of J/ψ particles and in $\gamma\gamma$ interactions). But the most important part has surely been played by experiments with hadron beams; these have been carried to a new qualitative level by the use of high-luminosity facilities that permit the detection and identification of both the charged and neutral secondary particles and the study of processes with nanobarn cross sections.

This has all led to significant development of the systematics of the already known hadron families and to the discovery of several new particles, the properties of which are hard to explain in the framework of a simple quark model of hadron structure. These particles became very serious candidates for exotic hadrons.

This new stage of the searches for exotic states was recently reviewed for the first time at the Working Symposium at BNL: Glueballs, Hybrids, and Exotic Hadrons. In this Appendix, we briefly summarize the main results discussed at the Symposium and attempt to sketch a general picture of the present status of the physics of exotic hadrons. In accordance with the themes of the Symposium, we shall here consider questions almost exclusively associated with meson spectroscopy, since the investigations into exotic baryons are only at an early stage of their development, and the situation with regard to them is as yet very uncertain.

A.1. Types of exotic hadrons

All the exotic hadron states can be divided into three groups:

Exotics of the first kind. These are states with manifestly exotic values of basic quantum numbers such as the electric charge, strangeness, and isotopic spin (mesons with $|Q|\geqslant 2$, or $|S|\geqslant 2$, or $I>1$, and baryons with $|Q|>2$, or $I>3/2$, or $S>0$). Such particles simply cannot have an ordinary quark structure of the type $q\bar{q}$ or qqq and must be exotic multiquark states.

Exotics of the second kind. These are particles possessing exotic combinations of quantum numbers such as the spin J, parity P, and charge parity C that hadrons with ordinary quark structure cannot possess. For example, for mesons exotic sets of these quantum numbers are $J^{PC}=0^{+-}$, 0^{--}, 1^{-+}, 2^{+-}, 3^{-+}, etc. All forms of exotic mesons—multiquark states as well as hybrids and glueballs—can possess such J^{PC} values.

Exotics of the third kind. These are hadronic states with hidden exotics (cryptoexotic hadrons). For such particles, there are no external exotic indicators, and their complicated internal structure can be established only indirectly—from specific features in their properties (anomalously small widths, anomalous decay channels, special production mechanisms, etc.). Exotic hadrons of all forms can also belong to the exotics of the third kind.

A. 2. Searches for exotics of the first kind

Searches for exotics of the first kind have long been made but have not been crowned with particular successes. The reports from time to time of the observation of such manifestly exotic objects were subsequently refuted by the results of later and more accurate experiments.

At the present time, there exist only two possible candidates for this category of exotic mesons:

The U mesons, which form an isotopic quartet of particles with isospin $I=3/2$, strangeness $S=-1$, and masses around 3.1 GeV ($U\equiv U^+$, U^0, U^-, U^{--} and the corresponding antiparticles $\overline{U}=\overline{U}^-$, $\overline{U}^0$, $\overline{U}^+$, $\overline{U}^{++}$). Data on the possible observation of $\overline{U}$ mesons, which decay through the channels $U\to\Lambda\bar{p}$ + charged pions, were obtained in the WA62 experiment[91] with the hyperon beam at CERN and in the JINR spectrometer BIS-2 (Ref. 92) in a neutron beam of the Serpukhov accelerator. In these experiments, the cross section for production of the U mesons, multiplied by the decay probability for a definite channel, was several microbarns. However, the general view is that these data should be regarded only as indications of the possible existence of exotic U mesons. They require further confirmation. At the Symposium results were presented on searches for U mesons in $\bar{p}p$ annihilation at p_p equal to 6.6 and 8 GeV (experiment E771, MPS BNL). No U mesons were found. Upper limits for their production cross sections were established: $\sigma(\bar{p}p\to\overline{U}^{++}+X^{--})BR(\overline{U}^{++}\to\bar{\Lambda}p\pi^+)<98\times10^{-33}$ cm^2 and $\sigma(\bar{p}p\to\overline{U}^0+X^0)BR(\overline{U}^0\to\Lambda p\pi^-)<364\times10^{-33}$ cm^2 (90% confidence level).

Mesons with isospin $I=2$, manifested indirectly in the production of pairs of vector mesons in $\gamma\gamma$ collisions, $\gamma\gamma\to VV$. According to the models of Refs. 93 and 94, the experimental data on the reactions $\gamma\gamma\to\rho^0\rho^0$ and $\gamma\gamma\to\rho^+\rho^-$ can be explained by interference of isoscalar and isotensor exotic mesons in the intermediate state for the reaction $\gamma\gamma\to(X)\to\rho\rho$ (in the region of masses 1.3–1.8 GeV).

However, it is not yet definitely clear whether these models are unambiguous and whether all data on the $\gamma\gamma\to(X)\to VV$ reactions can be consistently described on their basis. It is therefore very important to carry out direct searches for manifestations of such exotic resonances in other reactions, for example, in the production of the $\rho^\pm\rho^\pm$ system in central $pp\to n_f(\rho^+\rho^+)n_s$ collisions or in antiproton annihilation $\bar{p}n\to(p^-\rho^-)\pi^+$, etc.[14)]

A. 3. Searches for exotics of the second kind

At the BNL Symposium there were detailed discussions of data on the existence of the exotic meson of the second kind $M(1405)$ with the quantum numbers $J^{PC}=1^{-+}$, obtained by the GAMS (IHEP–CERN) collaboration in the study of the process

$$\pi^-p\to X^0n;\quad X^0\to\pi^0\eta \tag{A.1}$$

(momentum 100 GeV; 3×10^4 events).[43] The dominant contribution to the reaction (A.1) is made by production of the tensor meson $A_2(1320)\to\eta\pi^0$. However, a partial-wave analysis of the data of (A.1) also identifies the reaction

$$\pi^-p\to M\ (1405)\ n;\quad M\ (1405)\to\pi^0\eta \tag{A.2}$$

with cross section $\sigma[\pi^-p\to M(1405)n]BR[M(1405)\to\pi^0\eta]=(9.1\pm2.0)\times10^{-33}$ cm^2. The basic properties of the exotic $M(1405)$ meson are $M=1406\pm20$ MeV, $\Gamma=180\pm30$ MeV, $J^{PC}=1^{-+}$, $I^G=1^-$. It has a possible interpretation as a hybrid $(q\bar{q}g)$ state or a multiquark meson. Experiments of the same collaboration at the Serpukhov accelerator at momentum 38 GeV detected 3×10^5 of the (A.1) events, which are now being analyzed.

Searches for exotic states with $J^{PC}=1^{-+}$ were also made in the Coulomb-production reactions

$$\pi^+ + (Z, A) \to [\rho\pi^+;\ \eta\pi^+;\ D\,(1285)\,\pi^+] + (Z, A), \quad (A.3)$$

at a high initial energy ($E_{\pi^+}=200$ GeV; E272 experiments at FNAL).[95] This method is very promising for searches for exotic mesons of the second kind, which have a fairly strong coupling to the $\rho\pi$ channel (needed for effective Coulomb production of such particles). Searches for states with the exotic quantum numbers $J^{PC}=1^{-+}$ were made by means of a partial-wave analysis, which becomes more reliable for the clearly defined Coulomb mechanism in the reaction (A.3).[15)]

However, the results of a new analysis of measurements already made at the FNAL accelerator showed that the existing data are not sufficiently sensitive for detection of exotic states. All that has been obtained are certain restrictions on the possible properties of such hadrons. In particular, it has been shown that there are no exotic mesons with $J^{PC}=1^{-+}$, mass $M<1.5$ GeV, and decay width $\Gamma<200$ MeV having $BR[|1^{-+}\rangle\to\rho\pi]>3\%$. Some possible manifestations of exotic structures with masses in the region 1.6–1.9 GeV and decaying through the channel $D(1285)\pi$ have been found. But these indications are not unambiguous; they need to be confirmed in more sensitive experiments.

Possibilities of new experiments on Coulomb production of exotic mesons at the FNAL accelerator and, later, at the UNK (the large accelerator and storage facility to be operated at Serpukhov) are under discussion.

A. 4. Searches for exotics of the third kind

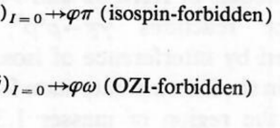
Searches for exotic states of the third kind (cryptoexotic hadrons) occupy a special place in investigations in the nanobarn hadron spectroscopy of recent years. Since the complicated internal structure of cryptoexotic particles can be deduced only from indirect dynamical indicators, the corresponding experiments are rather difficult. Their success is largely associated with the felicitous choice of exclusive pro-

TABLE IV. Some decay channels for exotic mesons $M\to\varphi\pi$, $\varphi\rho$, $M'\to\varphi\omega$.

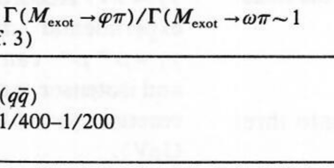
$(q\bar q)_{I=1}\not\to\varphi\pi$ (OZI-forbidden) $(s\bar s)_{I=0}\not\to\varphi\pi$ (isospin-forbidden)	For $M_{\rm exot}\equiv(q\bar q s\bar s)$, $(q\bar q g)$ $R=\Gamma(M_{\rm exot}\to\varphi\pi)/\Gamma(M_{\rm exot}\to\omega\pi\sim1$ (Ref. 3)
$(q\bar q)_{I=0}\not\to\varphi\omega$ (OZI-forbidden)	For $(q\bar q)$ $R\sim1/400$–$1/200$

$G\to\eta\eta$, $\eta\eta'$, $\eta'\eta'$ are characteristic decays for glueballs[98]

Diagrams for glueball decays:



a) quark diagram (the same for $q\bar q$ mesons)



b) Gluon color-rearrangement diagram (characteristic of a glueball)

The gluon color-rearrangement mechanism is due to strong coupling between the gg system and the η and η' mesons. From data on the decay $J/\psi\to\gamma gg\to\gamma\eta$, $\gamma\eta'$ for glueballs with $J^{PC}=0^{++}$ large probabilities of the decays $G\to\eta\eta$, $\eta\eta'$, $\eta'\eta'$ are predicted.

Ratio of the squares of the matrix elements for the decays $G\to P_1P_2$ (P is a pseudoscalar meson)

$G\to P_1P_2$	$\pi\pi$	$\eta\eta$	$\eta\eta'$	$\eta'\eta'$
$\lvert A\rvert^2$	$\ll 1$	1	10	30

$M\to4\pi^0$

The decay $(q\bar q)\to4\pi^\pm$ is enhanced by production of ρ mesons: $(q\bar q)\to\rho^0\rho^0\to\pi^+\pi^-\pi^+\pi^-$, etc. Therefore

$BR\,[(q\bar q)\to4\pi^0]/BR\,[(q\bar q)\to4\pi]\sim1/50$ ($\rho\to\pi^0\pi^0$ is forbidden).

For glueballs, $G\to4\pi^\pm$ is enhanced by ρ production (quark diagrams): $G\to4\pi^0$ is enhanced by the gluon color-rearrangement mechanism.

Result

$$\left.\begin{aligned}&BR\,[G\to4\pi^0]\sim10^{-1}\\&BR\,[(q\bar q)\to4\pi^0]\sim10^{-2}-10^{-3}\end{aligned}\right\}$$ Large probability of the decay $G\to4\pi^0$ is a characteristic glueball property.[101]

cesses with hadronic systems in which, on qualitative grounds, one can expect a clearer manifestation of the exotic states. Some examples of this approach are given in Tables IV and V. Despite the complexity of the searches for the cryptoexotic particles, as discussed above, it is precisely here that, in recent years, important progress has been achieved and several very serious candidates for the role of exotic hadrons have been identified.

Searches for cryptoexotic states are intimately intertwined with experiments in which the structure of the families of ordinary mesons and baryons is more accurately determined. Without such work, the problem of interpreting new resonances often cannot be solved unambiguously; for the exotic particles must be "superfluous" states that do not fit into the schemes of the ordinary meson nonets.

Very interesting results on the structure of some $SU(3)$ nonets of ordinary mesons have been obtained with the facility LASS. In particular, the LASS data for the reaction $K^- p \to K^+ K^- \Lambda$ indicate that the $\xi(2210)$ meson, which is observed in the decays $J/\psi \to \gamma\xi(2210)$, $\xi(2210) \to K^+K^-$, $K_S^0 K_S^0$ (MARK III) and in the hadronic reactions $\pi^- p \to \xi(2210)n$, $\xi(2210) \to \eta\eta'$ (GAMS), $\pi^- p \to \xi(2210)n$, $\xi(2210) \to K_S^0 K_S^0$ (MIS at IHEP), is apparently a meson of the type $(s\bar{s})$ with spin $J=4$ and belongs to the same $SU(3)$ nonet as the $h(2030)$ meson.

Most candidates for exotic states discussed at the Symposium have cryptoexotic quantum numbers, i.e., are exotics of the third kind. The most interest and most extensive discussions were associated with the cryptoexotic mesons listed in Table VI.

The $C(1480)$ *meson.*[1-4] The vector $C(1480)$ meson was discovered in the reaction

$$\pi^- p \to C\ (1480)\ n; \quad C\ (1480) \to \varphi\pi^0 \tag{A.4}$$

at momentum 32.5 GeV (Lepton-F, IHEP). In an investigation of the possible decays of $C(1480)$ through the $\varphi\pi^0$ and $\omega\pi^0$ channels it was found that $R = BR\,[C(1480) \to \varphi\pi^0]/BR\,[C(1480) \to \omega\pi^0] > 0.5$ (95% confidence level) is anomalously large for meson states of the ordinary $q\bar{q}$ type, for which decay through the $\varphi\pi^0$ channel is suppressed by the OZI rule. The expected value of R for such particles must be $\sim 1/200$–$1/400$. For example, for the well-known $B(1235)$ meson this ratio is $< 5\times10^{-3}$. The anomalous violation of the OZI rule in the decays of $C(1480)$ cannot be explained if this state belongs to the ordinary $q\bar{q}$ mesons, and it is a weighty argument for the interpretation of $C(1480)$ as an exotic hadron with the structure

$$|\,C\ (1480)\,\rangle = |\,\frac{1}{\sqrt{2}}\,(u\bar{u} - d\bar{d})\ s\bar{s}\rangle \quad \text{(multiquark meson) or}$$

$$|\,C\ (1480)\rangle\rangle = |\,\frac{1}{\sqrt{2}}\,(u\bar{u} - d\bar{d})\ g\rangle \quad \text{(hybrid meson).}$$

The G(1590) meson and other GAMS results. The scalar $G(1590)$ meson found by the GAMS collaboration in the charge-exchange reaction

$$\pi^- p \to G\ (1590)\ n; \quad G\ (1590) \to \eta\eta;\ \eta\eta';\quad 4\pi^0 \tag{A.5}$$

at momenta 38 and 100 geV is a strong candidate for a glueball.[96,97] The grounds for this interpretation are the following:

a) The probabilities of the decays $G(1590) \to \eta\eta$, $\eta\eta'$, $4\pi^0$ and the upper bounds for the decay of this particle through the $K\bar{K}$ and $\pi\pi$ channels agree well with predictions based on the mechanism of gluon color rearrangement[98] characteristic of glueball decay and cannot be explained for particles of the ordinary $q\bar{q}$ type.

b) The $G(1590)$ is very clearly observed in the central-production reaction[99]

$$\pi^- p \to \pi_f^-\ [G\ (1590) \to \eta\eta]\ p_s \tag{A.6}$$

at initial momentum 300 GeV, where processes due to gg interactions of sea gluons must be well manifested.

It should be noted that the GAMS collaboration found some others mesons. Some of them are also candidates for exotic states [$X(1750) \to \eta\eta$ (Ref. 100), $X(1810) \to 4\pi^0$ (Ref. 101), $X(1920) \to \eta\eta'$ (Ref. 102)]. Data were also given at the Symposium on observation of two new mesons: $X(1640) \to \omega\omega$ and $X(1960) \to \omega\omega$ in the reaction $\pi^- p \to \omega\omega n \to (\pi^0\gamma)(\pi^0\gamma)n$. They have quantum numbers $I^G J^{PC} = 0^+ 2^{++}$, masses $M_1 = 1643 \pm 7$ MeV and

TABLE V. Production of exotic mesons $J/\psi \to \gamma(gg) \to \gamma G$.

$$J/\psi \to \gamma\,(gg) \to \gamma G$$

This decay channel, enriched with gluons, is promising for glueball and, perhaps, hybrid searches.

$\Gamma(J/\psi \to \gamma G)$, large width for glueballs;
$\Gamma(G \to \gamma\gamma)$, small width for glueballs
} «Stickiness» $S_X = [\Gamma\,(J/\psi \to \gamma X)/\mathrm{LIPS}_1]/[\Gamma\,(X \to \gamma\gamma)/\mathrm{LIPS}_2]$
In a rough approximation, this quantity is determined by the ratio of the color and electric charges of the parton constituents X.

Glueballs: $S_G \gg 1$ and $S_G \gg S_{(q\bar{q})}$ (see the review of Ref. 105)

Glueballs are produced in gg collisions in central-production processes $h + N \to h_f[G \to P_1P_2]N_s$. With increasing $\sqrt{s}$, the importance of gg collisions in the central region increases, and glueball production may be more clearly manifested.[99]

Reactions suppressed by the OZI rule for standard $(q\bar{q})$ mesons [for example, $\pi^- p \to (\varphi\varphi)n$, $\pi^- p \to (\varphi\pi^0)n$] can be successfully used to look for exotic mesons [i.e., cascade processes $\pi^- p \to g_T n$, $g_T \to \varphi\varphi$ or $\pi^- p \to C(1480)n$, $C(1480) \to \varphi\pi^0$]. Because of the complicated color structure of the exotic mesons the OZI rule may be strongly violated when they are produced.[3,4,104]

Note. LIPS: Lorentz-invariant phase space.

TABLE VI. Main candidates for cryptoexotic states discussed at the BNL Symposium.

Types of cryptoexotic. mesons	Collaboration	State and its quantum numbers	Mass, MeV	Width, MeV	Decay channels
Multiquark mesons ($qq\bar{q}\bar{q}$) or hybrids ($q\bar{q}g$)	Lepton-F (IHEP)	$C(1480)$ $I^G J^{PC} = 1^+1^{--}$	1480 ± 40	130 ± 60	$C(1480) \to \varphi\pi^0$
Glueballs	GAMS-2000 GAMS-4000 } GAMS (IHEP–CERN)	$G(1590)$ $I^G J^{PC} = 0^+0^{++}$	1590 ± 30	280 ± 40	$G(1590) \to 4\pi$ $\to \eta\eta'$ $\to \eta\eta$
	MARK II CB MAPK III DM2	$\iota(1440)$ $I^G J^{PC} = 0^+0^{-+}$	1449 ± 4	66 ± 7	$\iota(1440) \to K\bar{K}^*$ $\to \delta\pi$ ($\delta \to K\bar{K}$) $\to \rho\gamma$?
	MARK II MARK III DM2 MIS IHEP OMEGA spectrometer	$\theta(1720)$ $I^G J^{PC} = 0^+2^{++}$	$1709 \pm 2 \pm 20$	$183 \pm 10 \pm 30$	$\theta(1720) \to K\bar{K}$ $\to \eta\eta$ $\to \pi\pi$
	MPS BNL	$g_T(2010)$ $g_{T'}(2300)$ $g_{T''}(2340)$ $I^G J^{PC} = 0^+2^{++}$	2011^{+62}_{-76} 2297 ± 28 2339 ± 55	202^{+67}_{-62} 149 ± 41 319^{+81}_{-69}	$g_{T;\,T';\,T''} \to \varphi\varphi$

$M_2 = 1956 \pm 20$ MeV, and widths $\Gamma_1 < 70$ MeV and $\Gamma_2 = 200 \pm 60$ MeV.[103] Their possible interpretation is as exotic states or radial excitations of the $f(1270)$ meson.

The g_T mesons.[104] Investigation of the reaction

$$\pi^- p \to \varphi\varphi n \qquad (A.7)$$

with the MPS facility at BNL at momentum 22 GeV ($\sim 6.7 \times 10^3$ events) led as a result of a phase-shift analysis to identification of three resonance states: $g_T(2010)$, $g_{T''}(2300)$, and $g_{T'}(2340)$, which have the quantum numbers $J^{PC} = 2^{++}$. It was shown that in the reaction (A.7) there is strong violation of the OZI rule in the intermediate two-gluon channel. This violation is a strong argument for interpreting the g_T mesons as glueballs (although there are other models that permit description of the properties of these particles as multiquark $s\bar{s}s\bar{s}$ mesons or hybrids).

A.5. Radiative decays of J/ψ particles and searches for glueballs

The radiative decays

$$J/\psi \to \gamma\,(gg) \to \gamma G \qquad (A.8)$$

of J/ψ mesons have long been regarded as very promising processes for searches for glueballs, in which one can expect a high probability for the production of these exotic states.[16] On the other hand, it is expected that for glueballs which do not contain charged valence quarks the radiative decay widths $\Gamma(G \to \gamma\gamma)$ must be very small. On the basis of these qualitative arguments, Chanowitz formulated a criterion for glueball identification:[53]

$$S = [\Gamma\,(J/\psi \to \gamma G)/\mathrm{LIPS}_1]/[\Gamma\,(G \to \gamma\gamma)/\mathrm{LIPS}_2] \gg 1. \qquad (A.9)$$

Here, LIPS_1 and LIPS_2 are the corresponding relativistically invariant phase spaces of the J/ψ and G decays. In the reaction (A.8) two states were already observed several years ago that were regarded as very serious candidates for glueballs. These are the $\theta(1720)$ meson with the quantum numbers $J^{PC} = 2^{++}$ and, especially, the $\iota(1440)$ meson with $J^{PC} = 0^{-+}$:

$$J/\psi \to \gamma\iota\,(1440); \quad (1440) \to K\bar{K}\pi \ (J^{PC} = 0^{-+}); \qquad (A.10)$$

$$\to \gamma\theta\,(1720); \ \theta\,(1720) \to K\bar{K}; \ \eta\eta; \ \pi\pi \ (J^{PC} = 2^{++}). \qquad (A.11)$$

For these mesons, the experimental parameter values $S[\iota(1440)] > 60$–80 and $S[\theta(1720)] > 28$ distinguish them among other mesons and are strong arguments for their interpretation as glueballs. Some new data on these states were presented at the Working Symposium at BNL.

$\iota(1440)$. A phase-shift analysis was made for the data on the (A.10) decays obtained with the facilities MARK III and DM2. These data are consistent with the $\iota(1440)$ meson having the quantum numbers $J^{PC} = 0^{-+}$, mass $M = 1449 \pm 4$ MeV, and width $\Gamma = 66 \pm 7$ MeV (DM2 result). The main decay channels of the ι meson are $\iota(1440) \to K\bar{K}^*$, $\delta\pi(\delta \to K\bar{K})$ (50%/50%). The decay $\iota(1440) \to \rho\gamma$ may exist. The large probability at the decay (A.10) and the low bound for the radiative width $\Gamma[\iota(1440) \to \gamma\gamma]$ ($S_\iota > 60$–80) support the interpretation of the iota meson as a glueball.

$\theta(1720)$. The $\theta(1720)$ meson, which was first discovered in the decays (A.11), was apparently also observed in the reaction $\pi^- p \to K_S^0 K_S^0 n$ in the MIS spectrometer at IHEP (at momentum $p_{\pi^-} = 40$ GeV, Ref. 106) and, even more clearly, in central collisions in the OMEGA spectrometer in the reaction $pp \to p_f[\theta(1720) \to K\bar{K}]p_S$ at initial mo-

mentum 300 GeV.[107]

Among the decays of the $\theta(1720)$ mesons, the $\theta \to K\bar{K}$ channels are predominant. On the other hand, the $\theta(1720)$ meson is not observed in the reaction $K^- p \to K\bar{K}\Lambda$ (LASS, MIS at IHEP), and this is evidence against its interpretation as a meson with the quark structure $s\bar{s}$. Thus, the data on the production and decay of the $\theta(1720)$ meson suggest that this state could be a glueball. Note that although for the $\theta(1720)$ meson the quantum numbers $J^{PC} = 2^{++}$ are the most probable, the values $J^{PC} = 0^{++}$ cannot yet be completely excluded.

A. 6. The *E*/iota problem

After the first detection of the $\iota(1440)$ meson and its decay through the channel $\iota(1440) \to K\bar{K}\pi$ in the radiative process (A.10), the questions arose of the connection between this pseudoscalar meson ($J^{PC} = 0^{-+}$) and a state with nearly the same mass (and decay): $E(1420) \to K\bar{K}\pi$, which was observed in hadronic processes but at that time appeared to belong to the axial meson nonet ($J^{PC} = 1^{++}$). However, the quantum numbers of the $E(1420)$ meson were not determined very reliably. The question of whether there exist one, two, or an even larger number of states became known as the E/iota problem. It is intimately related to experiments to clarify the structure of the axial nonet of mesons, and also of pseudoscalar radially excited states. In what follows, to emphasize the difference between the quantum numbers of E and of the iota particle, we shall speak of pseudoscalar $\iota(1440)/\eta(1440)$ and axial-vector $E(1420)/f_1(1420)$ mesons (here, the old notation emphasizes the already long established designations of these particles and of the E/iota problem itself, while the new designations emphasize their quantum numbers—see Ref. 89).

Searches for the $E(1420)/f_1(1420)$ and $\iota(1440)/\eta(1440)$ mesons were made in a number of experiments in many hadronic processes. The earlier results and a corresponding bibliography can be found in the reviews of Ref. 61. Many new data were presented at the BNL Symposium. We briefly summarize the main conclusions of the investigation of the E/iota problem:

a) The $E(1420)/f_1(1420)$ meson with $J^{PC} = 1^{++}$ is produced in central-production processes $\pi^-(p)p \to \pi^-(p)_f[K\bar{K}\pi]_{PS}$ and, possibly, in collisions $\gamma\gamma^*(Q^2 \neq 0) \to K\bar{K}\pi$ (with tagged virtual photons—see Refs. 109 and 110; b) in $\pi^- p$ charge-exchange reactions and in $p\bar{p}$ annihilation one observes only states with $J^{PC} = 0^{-+}$ [$\iota(1440)$, $\eta(1400)$ and, perhaps, something else]; c) in the reaction $K^- p \to (K\bar{K}\pi)Y$ in the LASS facility $D'(1530)$ with $J^{PC} = 1^{++}$ was detected, but the $E(1420)$ was not observed; d) in the Lepton-F facility the radiative decay $D(1285) \to \varphi\gamma$ was found, but not the decay $E(1420) \to \varphi\gamma$. On the basis of all these data, it can be concluded that an $E(1420)/f_1(1420)$ meson with $J^{PC} = 1^{++}$ does apparently exist but probably does not belong to the same axial nonet as the $D(1285)$ meson and is some new and, possible, exotic state. The $D'(1530)$ does belong to the axial meson nonet. Overall, the E/iota problem and the question of the nature of the $E(1420)$ meson have not yet been finally settled despite studies that have been going on since 1980. Here new and very serious efforts are needed.

CONCLUSIONS

Thus, as the discussions at the Working Symposium at BNL (Glueballs-88) showed, at the present time there are very serious candidates for the role of exotic mesons (multiquark states, hybrids, glueballs). However, the discussions emphasized the importance of further independent experimental investigations to confirm the already existing data and to obtain the new information needed to finally establish the existence of exotic hadrons. Some new experiments in this direction under preparation at IHEP, BNL, KEK, and CERN.

A more detailed exposition of the questions discussed in this Appendix can be found in the review of Ref. 111.

APPENDIX 2. POSSIBLE EXPERIMENTS TO INVESTIGATE THE NATURE OF THE *C*(1480) MESON

Study of Coulomb production of the $C(1480)^-$ meson [the charged isotopic partner of the $C(1480)^0$ discovered in experiments with the Lepton-F facility]

$$\pi^- + (Z, A) \to C(1480)^- + (Z, A);\quad C(1480)^- \to \varphi\pi^- \tag{A.12}$$

could be a decisive experiment for elucidating the nature of this state. The prospects of using coherent processes of particle production in the Coulomb field of nuclei at very high energies in searches for exotic states strongly coupled to the $V\pi^-$ channel (V is a vector meson) were discussed in Ref. 95 (see Appendix 1).

The cross section of the reaction (A.12) is proportional to the radiative width $\Gamma[C(1480)^- \to \pi^-\gamma]$, which in the vector-dominance model (VDM) is related to $\Gamma[C(1480)^- \to \varphi\pi^-]$:

$$\begin{aligned}\Gamma[C(1480)^- \to \pi^-\gamma] &\simeq [\alpha/(g_\varphi^2/\pi)]\,(k_\gamma/k_\varphi)^3\,\Gamma[C(1480)^- \to \varphi\pi^-]\\ &= [\alpha/(g_\varphi^2/\pi)]\,(k_\gamma/k_\varphi)^3\,\Gamma_C BR[C(1480)^- \to \varphi\pi^-]\\ &= [7{,}4\cdot 10^2\ \text{keV}]\,BR[C(1480)^- \to \varphi\pi^-].\end{aligned} \tag{A.13}$$

Here, k_γ, k_φ are the momenta of the photon and φ meson for the corresponding decay channels of the $C(1480)$ meson, $\Gamma_C = 130 \pm 60$ MeV is its total width [see (17)], and $g_\varphi^2/\pi \simeq 9$ is the coupling constant of the $\varphi\gamma$ transition in the VDM.

The cross section of the Coulomb process (A.12) has the form

$$\begin{aligned}\sigma[C(1480)^- \to \varphi\pi^-]_{\text{Coul}} &= \sigma[\pi^- + (Z, A) \to C(1480)^- + (Z, A)]\,BR[C(1480)^- \to \varphi\pi^-]\\ &\approx 8\pi\alpha Z^2(2J_C+1)\,[M_C/(M_C^2 - m_\pi^2)]^3\\ &\times BR[C(1480)^- \to \varphi\pi^-]\,\Gamma[C(1480)^- \to \varphi\gamma]\\ &\times \int_{|t_{\min}|}^{\Delta} [|t - t_{\min}|/t^2]\,F_Z(t)|^2\,|dt|.\end{aligned} \tag{A.14}$$

Here, $|t_{\min}| = [M_C^2 - m_\pi^2]^2/4E_\pi^2$ is the minimal square of the momentum transfer, $\Delta \simeq 1\times 10^{-3}$ GeV^2 (for the coherent process on lead nuclei), M_C and J_C are the mass and spin of the $C(1480)$, E_π is the initial energy of the pion, m_π is its mass, and $F_Z(t)$ is the form factor of the target nucleus.

Experiments on Coulomb production of $C(1480)^-$ mesons can be made on lead nuclei at $E_\pi \gtrsim 150$ GeV. The cross section (A.14) increases logarithmically with increasing E_π. At $E_\pi = 500$ GeV,

$$\sigma[C(1480)^- \to \varphi\pi^-]_{\text{Coul}}$$
$$\simeq 1{,}5\cdot 10^3\ (\mu\text{b/Pb nucleus})\ \{BR\,[C\,(1480)^- \to \varphi\pi^-]\}^2. \quad (A.15)$$

Corresponding estimates showed that in experiments of this type it is possible to observe production of $C(1480)^-$ mesons and measure $BR[C(1480)^- \to \varphi\pi]$ if this branching ratio exceeds ~ 0.004. If $BR[C(1480)^- \to \varphi\pi^-] \gtrsim 0.1$–$0.05$, this would be a weighty argument in support of an exotic interpretation of the $C(1480)$ meson.

1) The Lepton-F collaboration: S. I. Bityukov, G.V. Borisov, V. A. Viktorov, N. K. Vishnevskiĭ, S. V. Golovkin, R. I. Dzhelyadin, V. A. Dorofeev, A. M. Zaĭtsev, A. S. Konstantinov, V. P. Kubarovskiĭ, A. I. Kulyavtsev, V. F. Kurshetsov, L. G. Landsberg, V. V. Lapin, V. A. Mukhin, Yu. B. Novozhilov, V. F. Obraztsov, Yu. D. Prokoshkin, V. I. Solyanik (IHEP), and M. V. Gritsuk (Institute of Theoretical and Experimental Physics).

2) The OZI rule is the Okubo–Zweig–Iizuka rule of continuous quark lines, in accordance with which processes described by diagrams of quark-annihilation type must be strongly suppressed.

3) The Letpon-G collaboration: V. A. Viktorov, S. V. Golovkin, R. I. Dzhelyadin, A. M. Zaĭtsev, V. A. Kachanov, A. S. Konstantinov, V. F. Konstantinov, V. P. Kubarovskiĭ, A. V. Kulik, L. G. Landsberg, V. M. Leont'ev, V. A. Mukhin, V. F. Obraztsov, T. I. Petrunina, Yu. D. Prokoshkin (IHEP), and M. V. Gritsuk (Institute of Theoretical and Experimental Physics).

4) The question of the possible breaking of isotopic invariance in the $C(1480) \to \varphi\pi^0$ decay will be considered below (see Sec. 1.10).

5) It should be noted that the value of $BR(\rho' \to \bar{K}^*K)$ is not given in the original papers. It was obtained in the table of Ref. 27 for a certain normalization but was based for some reason on the preliminary result of Ref. 32. The original numbers in the last study[33] on $e^+e^- \to \rho' \to \bar{K}^*K$ are two times lower than these preliminary results.

6) On the question of mixing in the wave function of the $C(1480)$ meson, see Ref. 42.

7) If $\rho^{0\prime}$ is two states ρ_1' and ρ_2' (Ref. 28), the estimate (42) may be somewhat changed.

8) For a discussion of the E/iota problem, see, for example, the reviews of Ref. 61, and also the Appendix.

9) General questions relating to investigations of radiative decays of mesons are discussed in the reviews of Refs. 15, 16, and 68.

10) The designation "$D(1285)$" means that this state with the mass and width of the $D(1285)$ meson is observed in the spectrum of effective masses, but its quantum numbers have not been reliably determined. Therefore, the corresponding data on $|\alpha_A|$ are preliminary.

11) The physics of conversion decays is discussed in Sec. 5.2.

12) For the neutral mesons A and B, the single-photon transitions (78) are possible if the charge parities of A and B have opposite signs.

13) *Glueballs, Hybrids and Exotic Hadrons* (Upton, New York, (1988); *Particles and Fields*, edited by Suh-Urk Chung) (New York, 1989), Ser. 36.

14) Here, n_f and n_S denote the fast and slow particles in the laboratory system [for central production of the investigated systems—in the given case, $(\rho^+\rho^+)$].

15) In the reaction (A.3), charged meson resonances with $J^P = 1^-$ and $I^G = 1^-$ were sought. The quantum numbers $J^{PC} = 1^{-+}$ characterize neutral mesons belonging to the same isotopic triplets.

16) See the review of Ref. 105, which gives a corresponding bibliography.

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