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The search for exotic hadrons

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Contents

Abstract. The recent experimental data of a search for exotic hadrons — mesons and baryons — are presented in an accessible style. The expected properties of these hadron states and methods of their identification are discussed. Evidence for exotic hidden-strangeness baryons and various hybrid mesons is analyzed and the results of a search for heavy exotic strange-charmed pentabaryons are summarized.

1. Hadrons and quarks

Several decades of research into the physics of elementary particles has significantly altered our ideas of these objects. E Fermi wrote in his *Lectures on Atomic Physics* published in 1950 that "the term 'elementary particle' rather reflects the level of our knowledge" [1]. He even considered the number of elementary particles known at the time (9 – 15) to be too large and inconsistent with the very concept of elementarity.

Nearly fifty years have passed since the publication of E Fermi's lectures, and several hundred 'elementary particles' have been revealed, most of which fall into the category of so-called hadrons — particles undergoing strong interactions (the term derives from the Greek word 'hadros' meaning massive or strong). In the case of hadrons the idea of elementarity has lost all sense.

Hadrons are subdivided into two groups:

(1) baryons — particles of half-integral spin and special 'baryon charge', also termed baryon number $B = 1$ [in the case of antiparticles (antibaryons) $B = -1$];

(2) mesons — particles of integral spin and zero baryon charge ($B = 0$).

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It must be stressed that baryon charge is a quantity that is conserved and plays a fundamental role in elementary particle physics. Baryon charge conservation results in the lightest baryon, the proton, being stable, i.e. not decaying into lighter particles with zero baryon charges (mesons, leptons). From experiments it follows that even if the proton is not an absolutely stable particle, its lifetime $\tau_p > 10^{31}$ years. Such data characterize the high degree of baryon charge conservation. Most hadrons are very short-lived particles ('resonances') decaying via strong interactions into other, lighter hadrons in a time $\tau \sim 10^{-22} - 10^{-23}$ s.

In accordance with quantum-mechanical reasoning the lifetime of a particle, τ, being finite results in the distribution of measured values of the particle's mass having the form of a certain resonance peak (the so-called Breit – Wigner distribution). The maximum of this peak, M, is determined by the particle mass, while the width of the peak at half-height, Γ, is determined by its lifetime: $\Gamma = 1/\tau$ (in the system of units adopted in elementary particle physics we put $\hbar = c = 1$). If width is measured in megaelectronvolts, and the lifetime in seconds, then Γ [MeV] $= 0.7 \times 10^{-21}/\tau$ [s]. Therefore, when it comes to a particular resonance, one gives its mass M and its decay width Γ. Usually, the mass of a particle is reflected in the name of resonance.

The first short-lived hadrons discovered by Fermi and his colleagues long ago were the nucleonic isobars $\Delta(1232)$ with masses $M \simeq 1232$ MeV and a width $\Gamma \simeq 120$ MeV. These isobars were observed like peaks — 'resonances' (hence their name) in the effective mass spectra of the nucleon – pion (Nπ) system, i.e. the energy spectra in the (Nπ) center-of-mass system.

Four such particles ($\Delta^{++}, \Delta^{+}, \Delta^{0}, \Delta^{-}$) were discovered with very close masses (differing by not more than several megaelectronvolts) and electric charges $Q = +2, +1, +0, -1$ (in units of the proton charge). Manifestations of these particles were revealed, respectively, in the effective mass spectra of the pπ^+-, nπ^+- or pπ^0-, pπ^--, or nπ^0-, nπ^--states.

The example of the four $\Delta(1232)$-isobars is characteristic, also, of other particles. All known hadrons have been shown to group into families of particles with very close properties differing, mainly, in their electric charges. Besides the $\Delta(1232)$-isobars, such families are represented by the proton and the neutron, by the three π-mesons, and, also, by many other hadrons. These families are termed isotopic multiplets.

Isotopic multiplets are characterized by a certain quantum number — the isotopic spin I determining the number N of particles composing the isotopic multiplet: $N = 2I + 1$. Components of an isotopic multiplet differing in their charges are characterized by different projections of their isospin I_3. Thus, π-mesons that form an isotopic triplet have isospin $I = 1$, while the individual members of this triplet (π^+, π^0, π^-) correspond to the isospin projections $I_3 = +1, 0, -1$.

The properties of the isotopic multiplet are reminiscent of the properties of a quantum-mechanical system with a proper angular momentum (spin) J, which also forms a $(2J+1)$ multiplet of states with differing spin projections J_z. Precisely this analogy led to the term 'isotopic spin'. Isomultiplets of hadrons, in turn, group into more complex families — supermultiplets [1].

Investigation of the properties of hadrons and of the systematics of their isomultiplets and supermultiplets has confirmed that hadrons are not elementary particles. Like atomic nuclei composed of nucleons, hadrons represent bound systems of truly elementary, or conventionally termed fundamental, particles — quarks, which, most likely, cannot exist in a free state owing to their specific 'color charges' (this will be dealt with in greater detail below). Then the baryons are composed of three quarks qqq (antibaryons — of three antiquarks $\bar{q}\bar{q}\bar{q}$), while mesons consist of a quark and an antiquark $q\bar{q}$.

Hadrons are characterized by a series of special quantum numbers termed 'flavors' (isospin, strangeness, charm, etc.). 'Flavors' are carried by various sorts of quarks that are constituents of hadrons [2].

The quark model provides for a correct description of the properties of hadrons and of their grouping into families of isotopic multiplets and higher supermultiplets. Thus, protons and neutrons that compose the nucleonic isodoublet exhibit baryon charge $B = 1$ and electric charges $Q_p = +1$ and $Q_n = 0$, respectively. Their quark structure is the following: p = (uud) and n = (udd). One can readily see that such a quark structure is consistent with the above indicated nucleonic charges. Antinucleons — antiprotons $\bar{p} = (\bar{u}\bar{u}\bar{d})$ and antineutrons $\bar{n} = (\bar{u}\bar{d}\bar{d})$ — have baryon charge $B = -1$, and electric charges $Q_{\bar{p}} = -1$ and $Q_{\bar{n}} = 0$, respectively.

The nucleonic isobars $\Delta(1232)$ possess quark structures (uuu), (uud), (udd), (ddd), which correspond to their electric charges $Q_\Delta = +2, +1, 0, -1$ (the isospin $I = 3/2$). The π^+- and π^--mesons have the following quark structures: $\pi^+ = (u\bar{d})$ and $\pi^- = (d\bar{u})$, while the π^0-meson represents a superposition of $u\bar{u}$- and $d\bar{d}$-states. Here, the existence of isotopic multiplets of particles exhibiting similar properties is related to the very similar properties of the u- and d-quarks, while differing in their electric charges and related projections of isospin I_3. The approximate symmetry in the properties of u- and d-quarks has been termed isotopic symmetry. The grouping of particles into isomultiplets is a consequence of such symmetry.

There also exist so-called strange hadrons — hyperons and K-mesons, which are not only composed of u- and d-quarks, but also of s-quarks that are carriers of a new quantum number — strangeness S. Thus, the Λ-hyperon quark composition is the following: (uds) with $Q = 0$, $I = 0$, $S = -1$, and Σ-hyperons form an 'isotriplet' (Σ^+, Σ^0, Σ^-) with $S = -1$, charges $Q = +1, 0, -1$, isospin $I = 1$ and projections of isospin $I_3 = +1, 0, -1$. Their quark structure is as follows: $\Sigma^+ = $ (uus), $\Sigma^0 = $ (uds), and $\Sigma^- = $ (dds).

Likewise, it is possible to consider the structure of other hadrons. The formation of supermultiplets of particles with similar properties is due to the so-called SU(3)-symmetry, which is manifested in the relative similarity of the properties of the three light quarks — u, d, s (although this similarity is not so close, as between u- and d-quarks).

Thus, the quark structure of hadrons has been revealed and quarks have been shown to be the actual structural elements of hadron matter that determine the diversity of the hadron world. It has been established that quarks possess special types of 'charges' termed 'color charges' (or, simply 'colors'). Strong interactions between quarks are due to their exchanging with 'colored' massless particles — gluons. The theory describing interactions between quarks and gluons due to their 'color charges' has been called quantum chromodynamics (QCD).

Quarks are characterized by three types of 'color charges' (or, colloquially, three 'colors'). At the same time gluons are sort of 'two-colored' and can occupy eight different 'color states'.

A certain analogy is to be noted between the electromagnetic interactions of electric charges due to the exchange of massless quanta of the electromagnetic field — photons, and strong interactions due to the exchange of massless gluons. There also exist, however, very important differences between these processes.

First of all, photons themselves carry no charges, and their electromagnetic fields are capable of interacting only with the electric charges of particles. Photons do not interact directly with each other. At the same time, gluons are carriers of 'color charges' and can undergo interactions not only with quarks, but with each other also, thus even forming bound gluon systems — glueballs.

Further, particles with electric charges and photons exist in a free state and can travel in space. But, all the same, numerous attempts to find quarks (or gluons) in a free state have never met with success. This has resulted in the development of one of the most fundamental ideas of modern elementary particle theory — the idea of confinement (the 'imprisonment' of quarks). According to the concept of confinement, 'colored' particles (quarks, gluons and their 'color' combinations) cannot exist in a free state. Only quark systems without 'color charges' ('colorless' particles) are observable.

The experimental basis of the concept of confinement comprises unsuccessful searches for free quarks, diquarks and other 'colored' particles, carried out over many years. The theoretical model of confinement is inherent in the interaction theory of 'color' quarks and gluons (quantum chromody-

[1] One must bear in mind that now the term 'supermultiplet' is applied in a totally different sense — for describing families of supersymmetric particles uniting fermions and bosons (see Ref. [2]).

[2] There exist six sorts of quarks: 'up quarks' u, c, t with electric charge $Q = +2/3$ (in terms of the proton charge); 'down quarks' d, s, b with $Q = -1/3$. Quarks are characterized by the baryon charge $B = 1/3$. Each sort of quark has another quantum number — 'flavor' — corresponding to it. Thus, for example, u- and d-quarks are carriers of isospin I and differ in the sign of its projection I_3 (the u-quark has $I_3 = +1/2$, while the d-quark has $I_3 = -1/2$), the s-quark is the carrrier of strangeness $S = -1$, the c-quark of charm $C = +1$, and so on.

Besides quarks, there also exist antiquarks, for which all 'charges' and 'flavors' (Q, B, I_3, S, C, etc.) change sign. In this work, we shall mainly consider hadrons consisting of the light quarks u, d, s and their antiquarks $\bar{u}$, $\bar{d}$, $\bar{s}$.

namics), although its development has not yet been completed. The interaction between quarks is assumed to increase infinitely with the distance between them, so that it is never possible to 'tear apart' a $q\bar{q}$-meson and create free quarks.

Consider possible quantum numbers for mesons consisting of quark–antiquark pairs $q\bar{q}$. Such quantum numbers may include the total quark spin $\mathbf{S}$ of the $q\bar{q}$-system, its orbital angular momentum $\mathbf{L}$ characterizing the relative motion of quarks within the $q\bar{q}$-system, its total angular momentum (or meson spin) $\mathbf{J}$ determined by the vector sum of the spin $\mathbf{S}$ and the orbital momentum $\mathbf{L}$. The addition of angular momenta is performed according to the laws of quantum mechanics asserting, for instance, that the total angular momentum $|\mathbf{J}| = |\mathbf{L}+\mathbf{S}|$ can assume all possible values from $L+S$ to $|L-S|$. Similarly, the total quark spin S of the $q\bar{q}$-system can assume two values: $1/2+1/2=1$ and $1/2-1/2=0$ (each quark has spin $1/2$, the angular momenta are measured in the units of $h/2\pi = \hbar$, where h is the Planck constant).

The next important quantum number is the parity of the space wave function of the $q\bar{q}$-system that shows how the wave function behaves under specular reflection of coordinates: whether it changes sign (negative parity $P=-1$) or does not (positive parity $P=+1$). The parity of the wave function of the $q\bar{q}$-system is determined by its orbital momentum L: $P=-(-1)^L$.

In the case of neutral mesons which transform into themselves under charge conjugation (i.e. under the exchange $q \rightleftarrows \bar{q}$), there exists the concept of charge parity. The charge parity of neutral mesons, C, assumes the values -1 or $+1$, depending on how the wave function behaves under this operation: on whether it does or does not change sign.

We note that although charge parity is defined only for neutral mesons, it is possible for the charged mesons belonging to the same isotopic multiplet as the neutral meson to introduce another quantum number — so-called G-parity which is determined by the C-parity of the respective neutral meson and the isotopic spin characterizing the given isomultiplet. Therefore, we shall further simply mention meson C-parity without indicating each time that C-parity has sense only for neutral particles. The C-parity of the neutral $q\bar{q}$-meson is determined by the expression $C=(-1)^{L+S}$.

From the quark model it follows that $q\bar{q}$-mesons consisting of the light u-, d- and s-quarks group into nonets with definite quantum numbers: spin J, parity P, and charge parity C. In the case of $q\bar{q}$-mesons only certain combinations of the quantum numbers J^{PC} are realized that meet the conditions $C=P=(-1)^J$ or $C=P=(-1)^{J+1}$ (with the exception of $J=0$), or $C=(-1)^J$, $P=(-1)^{J+1}$. No $q\bar{q}$-states can exist with $C=(-1)^{J+1}$, $P=(-1)^J$ or with $J=0$, $C=-1$ (if $J=0$, then $S=L=0$ or 1 and, then, $C=+1$).

Thus, the combinations of quantum numbers $J^{PC} = 0^{--}$, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, ... for ordinary $q\bar{q}$-mesons are forbidden (these combinations of quantum numbers are called exotic). Different meson nonets have various appropriate orbital momenta L: $0, 1, 2, \ldots$ (so-called excitation in the orbital momentum or orbital excitation). States with $L=0$ are termed S-wave states (S-mesons), and states with $L=1$ are P-wave (P-mesons).

The quark model predicts that in the case of $q\bar{q}$-meson states, besides orbital excitation, radial excitation can also occur, i.e. meson nonets can exist with the same values of J^{PC}, differing from each other by the values of the quantum number n defining the radial part of the meson wave function. The ground state exhibiting the lowest energy is characterized by the value $n=1$ (which is usually not indicated), while in the case of radially excited meson families $n=2$ (the first radial excitation), $n=3$ (the second radial excitation), etc.

At present a whole series of radially excited states have been discovered. Their existence complicates the meson systematics and renders especially important a thorough definition of their quantum numbers. Searches for and studies of radially excited meson families represent an important line of research in modern hadron spectroscopy.

Baryons in the quark model are systems consisting of three quarks qqq, so the structure of baryon families and the regularities manifested by their quantum numbers turn out to be more complex as compared with meson families. The total quark spin S in baryons, made up of the spins of the three quarks, can assume the values 3/2, 1/2, while the orbital motion of the quarks is already described by two orbital momenta L_1 and L_2 (the first describes the relative motion of a quark pair in the baryon, the second describes the motion of the third quark with respect to the center of mass of the two first quarks). Here, the total orbital momentum $\mathbf{L} = \mathbf{L}_1 + \mathbf{L}_2$ is characterized by the total orbital number L.

Owing to the structure of baryons being more complex and to the complex composition of baryonic families, experimental data are at present available only on some such families: the supermultiplet of baryons with quark orbital momenta $L_1 = 0$, $L_2 = 0$ (this supermultiplet includes 56 of the lightest baryonic states [3]) and certain supermultiplets corresponding to the total orbital momentum $L=1$.

Further development of the systematics of baryons is an important line of research in hadron physics. Here, good prospects seem to be particularly connected with precision experiments in electron and photon beams at the new high-current electron accelerators (CEBAF in the USA, ELSA in the Germany).

A more detailed description of the main ideas underlying the quark model and hadron physics can be found, for example, in the well-known monographs [2–5].

2. Exotic hadrons

During the past one decade and a half significant progress has been achieved in research in hadron spectroscopy, which in a certain sense is undergoing its second birth. This is greatly due to the development of strong interaction theory — quantum chromodynamics, and of the hadron models based on it: the bag and string models, the 'color tube' model, and others. But an extremely important role, also, must be attributed to the development of experimental techniques,which has essentially extended the facilities of novel investigations. Nontraditional scientific research lines have arisen related to experiments with colliding e^+e^--beams, at high-current electron accelerators, in pure antiproton beams produced with special antiproton sources.

[3] The baryonic 56-plet and other similar families include SU(3)-multiplets of particles in various spin states: the (56-plet) = (octet of baryons with spin 1/2) + (decouplet of baryons with spin 3/2) = $(8\times 2)+(10\times 4)$ = 56 states. Two spin states correspond to spin 1/2, while four states with different spin projections onto an arbitrary coordinate axis correspond to spin 3/2.

However, the greatest role in the development of studies in the field of hadron spectroscopy should, probably, be attributed to experiments performed in high-intensity hadron beams at a qualitatively new level, making use of high-luminosity installations permitting recording and identification of both charged and neutral secondary particles and the investigation of rare processes with nanobarn cross sections.

All the above has led to significant development of the systematics of already known hadron families, to the discovery of a series of new particles, to studies of rare electromagnetic decays and of the electromagnetic properties of a number of nonstable hadrons.

Recently, the issue that has given rise to the most significant interest is, apparently, the problem dating from the very threshold of the 'quark era' to which no unambiguous answer has yet been found: do there exist in nature 'colorless' hadrons that have a more complex quark structure — multiquark mesons $qq\bar{q}\bar{q}$, baryons $qqqq\bar{q}$, and dibaryons qqqqqq?

The development of quantum chromodynamics gave rise to the natural assumption that gluons might also play the role of the fundamental structural elements of matter, viz. that there should exist mesons composed entirely of gluons (glueballs) or mixed hadrons made up of quarks and gluons — so-called hybrids ($q\bar{q}g$-mesons or qqqg-baryons). All these new sorts of particles were termed exotic hadrons.

It must be specified more exactly that when we mention, say, ordinary baryons having the structure (qqq) or exotic fivequark baryons ($qqqq\bar{q}$), or hybrids (qqqg), we actually mean only those hadronic components that determine their principal characteristics (quantum numbers). They are called valence quarks and gluons.

Any hadron also contains a quark – gluon 'sea' of virtual gluons and quark – antiquark pairs emitted and absorbed by the valent structural elements. The quark – gluon 'sea' determines many hadron properties (such as, for example, the spatial distributions of electric charges and magnetic moments inside the particles). In the region of large distances compared with the dimensions of hadrons (i.e. in the region of small momentum transfers, in accordance with the uncertainty principle) hadrons may behave like systems composed of valence quarks. When studies of phenomena at relatively small distances are performed (i.e. when the structure of hadrons is investigated) manifestations of the quark – gluon 'sea' also arise. This picture is qualitatively consistent with quantum-chromodynamic ideas.

Therefore, when we speak of the complex quark or quark – gluon structure of exotic hadrons, we actually mean the valence composition of these particles, which determines their quantum numbers and their dynamic properties that are displayed at large distances (decay widths, branching ratios of decay channels, mechanisms of particle production and so on).

The theoretical models related to exotic hadrons are extremely diverse. Arguments have been put forward that exotic particles sort of consist of ready 'colorless' hadrons and decay into 'colorless' components without producing additional $q\bar{q}$-pairs from vacuum. Such decays may have very broad widths (so-called superallowed transitions) provided that there is no kinematic suppression. The respective particles cannot practically be observed, therefore.

However, other arguments were also put forward in accordance with which the possibility for relatively narrow exotic states to exist is based on the complex internal 'color' structure of these objects and in salient features peculiar to the dynamics of 'color'. If an exotic hadron consists of two 'color' parts separated in space (owing, for instance, to a centrifugal barrier), then its decay involving the production of 'colorless' final states will be suppressed. Such exotic particles may be characterized by normal or even anomalously narrow decay widths depending on the degree of suppression of their decays, which is related to the mechanism leaving the produced final states devoid of color.

How can one distinguish between ordinary and exotic hadrons, which were noted above to pass part of their time in states with many quarks and gluons from the 'sea'? The differences between them are determined by their valent structural elements which are sort of the main 'bricks' for 'building up' hadrons and are always present inside them. There may exist two types of exotic hadrons, the properties of which are discussed below.

1. Owing to their more complex valence composition, the quantum numbers of exotic hadrons (their 'charges' and 'flavors') may assume such values that are simply impossible for ordinary hadrons. Making use of the 'charges' and 'flavors' of quarks one can readily verify, for example, that ordinary qqq-baryons cannot exhibit electric charge $Q > 2$, positive strangeness ($S > 0$), etc. At the same time, the exotic baryon $uuuu\bar{d}$ has $Q = 3$, while the baryon $uuud\bar{s}$ exhibits strangeness $S = +1$. Ordinary $q\bar{q}$-mesons cannot have charge $|Q| = 2$ or strangeness $|S| = 2$. The exotic $uu\bar{d}\bar{d}$-meson has $Q = 2$, while the $uu\bar{s}\bar{s}$-meson is characterized by the charge $Q = 2$ and strangeness $S = 2$. Such exotic states possess extremely striking peculiarities, and they are easily distinguished from ordinary hadrons. However, searches for particles exhibiting 'explicit exotics' have hitherto achieved no definite success.

In the case of mesons there can exist clearly exotic combinations of such quantum numbers as spin J, parity P and charge parity C. As mentioned above, ordinary $q\bar{q}$-mesons can only have certain sets of these quantum numbers. The combinations $J^{PC} = 0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, 3^{-+}$, etc. are exotic and cannot be realized in the case of 'normal' $q\bar{q}$-mesons. Although measurement of the spin and parity of a meson is a quite complicated and delicate problem that requires thorough investigation of the angular distributions of the decay products of state at issue, it can actually be resolved in a number of cases. If the meson is shown to be characterized by an exotic set of quantum numbers J^{PC}, then its exotic nature can be established unambiguously. The possibility of observing certain such states has been reported in the scientific literature, but the situation here still remains quite uncertain, however.

2. There may also exist exotic states with 'hidden exotics' — so-called cryptoexotic hadrons that have quantum numbers coinciding with the quantum numbers of ordinary hadrons. The complex valence structure of cryptoexotic hadrons manifests itself in their unusual dynamic properties (for example, in anomalously narrow decay widths, in unusual branching ratios between the probabilities of their different decay channels, in the specific features peculiar to their production mechanism). Examples of the anomalous dynamic properties of such hadrons, apparently due to the cryptoexotic nature of the observed particles, will be dealt with below. It should be mentioned that nearly all the existing candidates for exotic hadrons belong precisely to the second type of particles, i.e. they are cryptoexotic.

The methods for identification of various types of exotic hadrons and the prospects for finding them are presented in Table 1. The possible existence of exotic hadrons represents an issue of principle from the standpoint of the main ideas of the nature of hadron matter, of quantum chromodynamics and the concept of confinement, of all modern models of hadronic structure. Therefore, searches for such hadrons are of utmost interest.

During the past decade significant achievements have been made in meson spectroscopy, where at least several unusual states have been found that are, apparently, cryptoexotic mesons. Thus, for example, such mesons were observed in experiments carried out at $E_{\mathrm{p}} = 70$ GeV at the accelerator of the Institute for High-Energy Physics (IHEP, Protvino) with the installations GAMS, VES, LEPTON and other detectors.

Extremely important results have been obtained in experiments on $\bar{\mathrm{p}}\mathrm{p}$-annihilation at the antiproton sources LEAR (CERN) and Fermilab, and also in experiments with the hadrons beams of the collider AGS (Brookhaven National Laboratory, USA), SPS (CERN) and in other scientific centers. Many of these foreign experiments were performed in collaboration with groups of Russian researchers.

New data relevant to meson spectroscopy and to searches for exotic meson states can be found in the Conference Proceedings on hadron spectroscopy and in other reviews [6 – 14].

The situation with exotic baryons remained uncertain for a long time. However, new data obtained at IHEP with the experimental setup SPHINX have recently made possible significant progress in this direction (the previous state of affairs in baryonic research was discussed in the review [15]). Searches for exotic baryons are also performed in experiments at the Fermilab Tevatron (SELEX E781, E791); relevant experiments are also under preparation in the photon beams of the CEBAF collider [16 – 18]. In the present article certain new results of searches for exotic hadrons are discussed.

3. Searches for exotic baryons in diffractive reactions and the discovery of a new state X(2000)

In experiments recently performed with the setup SPHINX in the proton beam of the IHEP accelerator at $E_{\mathrm{p}} = 70$ GeV, a broad program of experiments was initiated, aimed at investigating hadron production processes and at searching for cryptoexotic baryons with hidden strangeness, possessing the quark valence composition $|\mathrm{qqqs\bar{s}}\rangle$ (here and below q stands for a u- or a d-quark). In experiments [19 – 24] searches for the production of exotic baryons were performed primarily in gluon-enriched diffractive reactions on nucleons and nuclei that are known to occur owing to pomeron exchange (see, for instance, Ref. [25]).

According to modern ideas, the main component of a pomeron is sort of a gluon 'ladder' which can provide for pomeron processes playing a special role in production reactions of exotic hadrons (Fig. 1).

Of significant interest are coherent diffractive processes taking place on the nucleus as a whole. We shall deal with such processes in more detail and discuss methods for identification of them. Consider a diffractive production reaction of a certain set of secondary particles, for example, the reaction $\mathrm{a} + \mathrm{N}(A) \to [\mathrm{b}_1\mathrm{b}_2\mathrm{b}_3] + \mathrm{N}(A)$, which can proceed either on individual nucleons N or coherently on the nucleus A as a whole (A denotes the atomic number of the target nucleus).

For identification of a coherent process we consider the distribution of events for the reaction of interest over the square of a momentum transfer p_T^2, i.e. over the component squared of the total momentum of the $[\mathrm{b}_1\mathrm{b}_2\mathrm{b}_3]$ system,

Table 1. Methods for identification of exotic mesons and baryons and prospects for finding them.

Type of exotic behavior	Prospects for mesons	Prospects for baryons
Exotic hadrons with anomalous charges or flavors (hadrons with open exotics, exotics of the first kind)	Mesons with charges $\lvert Q\rvert > 1$, $\lvert S\rvert > 1$, $I > 1, \ldots$ The identification of exotic states is unambiguous and simple; however, there exist no reliable candidates for such mesons	Baryons with charges $\lvert Q\rvert > 2$, $S > 0$, $I > 3/2$. The identification is unambiguous and simple; however, no serious candidates of this type have yet been found
Exotic hadrons with anomalous combinations of quantum numbers J^{PC} (exotics of the second kind)	Mesons with $J^{PC} = 0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, \ldots$ Such quantum numbers are impossible for $\mathrm{q\bar{q}}$-mesons. The identification of exotic states is quite complicated (vast statistics are required, as well as partial-wave analysis, etc.); however, in the case of success it will be possible to identify unambiguously exotic mesons. There exist some meson candidates with $J^{PC} = 1^{-+}$, although these data are not final	No such baryonic states exist, and the method cannot be realized
Cryptoexotic hadrons (hadrons with hidden exotics, exotics of the third kind). They are characterized by the same quantum numbers, charges, and flavors as ordinary $\mathrm{q\bar{q}}$- or qqq-type hadrons; however, their complex valence structure results in anomalous dynamic properties (anomalously narrow decay widths, anomalous probability branching ratios for certain channels, etc.)	Difficult but most promising way for revealing and identifying exotic states. Over 10 mesons have been found with properties that cannot be described within the $\mathrm{q\bar{q}}$-model. These are serious candidates for exotic mesons	Difficult but most promising way for revealing and identifying exotic baryons. Several candidates for cryptoexotic baryons with hidden strangeness ($\lvert\mathrm{qqqs\bar{s}}\rangle$) have been found
'Superfluous' cryptoexotic states that do not fall into the existing systematics of ordinary hadrons	Such an identification criterion is feasible, although its application is often troublesome due to the existence of additional families of radially excited states of standard hadrons	This method cannot be practically applied owing to the complex and poorly studied systematics of qqq-baryons

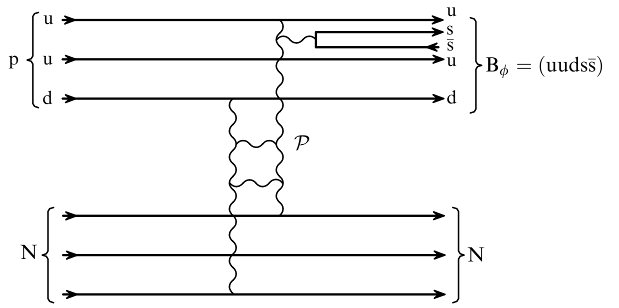

Figure 1. Diagram for the production of an exotic baryon with hidden strangeness in diffraction processes due to pomeron exchange. The main component of the pomeron $\mathcal{P}$ represents a gluon 'ladder'. In such gluon-enriched reactions the production probability of exotic hadrons may be quite high.

orthogonal to the momentum of the incident particle a. In accordance with the uncertainty principle, a coherent process proceeding on a nucleus as a whole is characterized by relatively small transverse momenta p_T inversely proportional to the radius of the target nucleus R: $p_T \sim \hbar/R = \mathrm{const}/A^{1/3}$. A coherent process manifests itself as a narrow diffraction peak in the distribution of events over p_T^2.

Coherent processes proceeding on a nucleus as a whole serve as a certain filter that permits more clear identification of the produced resonances with respect to the nonresonance many-particle background. In the case of many-particle events the probability of secondary interactions in the nucleus exceeds the respective probability for resonances. Secondary interactions violate the condition of coherence. Therefore, in the case of coherent events the nonresonance background can be significantly reduced with respect to the resonance effects. These arguments are qualitatively illustrated by the diagrams depicted in Fig. 2.

The experimental setup SPHINX used for studies of diffractive processes represents a wide-aperture magnetic spectrometer with a large number of track detectors for registration of secondary charged particles produced in proton interactions in the target.

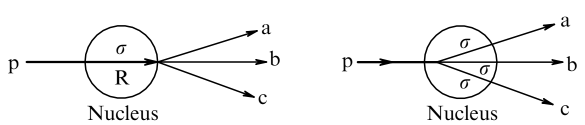

Figure 2. Schematic illustration of suppression of the nonresonance many-particle background with respect to the production of a resonance in the coherent reactions

$\mathrm{p} + (\text{nucleus}) \to \mathrm{R} + (\text{nucleus}), \qquad \mathrm{R} \to \mathrm{a} + \mathrm{b} + \mathrm{c}$

(reaction involving production and cascade decay of resonance R), and

$\mathrm{p} + (\text{nucleus}) \to [\mathrm{a} + \mathrm{b} + \mathrm{c}] + (\text{nucleus})$

(nonresonance many-particle background). Many-particle states interact in the nucleus with a higher probability and violate the condition of coherence more strongly than in the case of a resonance R (σ represent the interactions cross sections of secondary particles inside the nucleus). Therefore, the following relationship holds valid for the cross sections of the processes at issue:

$$\frac{\sigma_{\mathrm{coh}}\,(\text{resonance})}{\sigma_{\mathrm{coh}}\,(\text{nonres. background})} > \frac{\sigma_{\mathrm{noncoh}}\,(\text{resonance})}{\sigma_{\mathrm{noncoh}}\,(\text{nonres. background})}\,.$$

Coherent processes on nuclei act like a filter in making the identification of hadron resonances more unambiguous (the so-called coherence filter).

Charged particles leaving the target were detected in hodoscopic scintillation counters and gas-discharge track devices with wire electrodes (proportional chambers, drift chambers, drift tubes). In these devices, the ionization produced by the charged particles along their trajectories in the gas caused electric discharges. The discharges developed in the electric field of the wires forming the high-voltage electrodes of the track detectors and gave rise to induced electric signals in the respective wires. Therefore, from the ordinal numbers of triggered wires it was possible to determine track coordinates of the particles that passed through the detectors. In the drift detectors, the coordinates of tracks were refined by measuring the drift time of electrons, produced during ionization of the gas, to the respective wire.

The experimental setup included several tens of gas track detectors that allowed the obtaining of full information on the tracks of all the charged particles leaving the target and the determination of the deflection angle of the particles in the magnetic field of the spectrometer, i.e. the measurement of the momenta of these particles.

Registration of γ-quanta was performed in the multichannel γ-spectrometer of the setup, which included over 1000 Cherenkov counters made of lead glass with a cross section of 50×50 mm. The γ-quanta hitting the detector gave rise to electron – photon showers that were totally absorbed in the γ-spectrometer. The energy of γ-quanta was measured with a high accuracy (up to several percent) by the total amplitude of signals of the Cherenkov radiation of the shower electrons in the counters of the spectrometer, while the transverse coordinate of the point at which the γ-quantum was converted in the detector was measured with an accuracy of a few millimeters from the position of the 'center-of-mass' of the shower.

Besides the momenta of charged particles, their velocities were also measured in the SPHINX setup. This made possible the determination of the mass of each particle and the identification of its type (proton, antiproton, $\pi^{\pm}$-meson, or $\mathrm{K}^{\pm}$-meson). Precision measurements of particle velocities were performed with special gas Cherenkov counters of various types, making use of the properties of the Cherenkov radiation caused by the particles. Cherenkov radiation arises when the velocity of a charged particle exceeds the speed of light in the given medium, i.e. $v > c/n$ (where n is the refraction index of light).

Precise measurements of the velocities of particles with high energies, which may differ from the speed of light, c, by one part in a thousand, or ten thousand, or even a hundred thousand, are performed using gaseous Cherenkov counters (the refraction index of a gas, n, is close to unity). In threshold gas counters, the actual origination of Cherenkov radiation detected by a sensitive photomultiplier permits establishing that the velocity of a particle exceeds a certain threshold, i.e. the particle is relatively light (for instance, it is a π-meson, instead of a K-meson or a proton).

However, significantly greater possibilities are presented by Cherenkov detectors registering radiation rings — RICH detectors (Radiative Imagine CHerenkov detector). The optical system of a RICH detector permits focusing the light of Cherenkov radiation onto a ring in the focal plane of the system. The radius of such a ring is determined by the velocity of the particle, and the position of the ring's center by the angle of departure of the particle from the target. By placing a photosensitive matrix in the focal plane of the system, it is

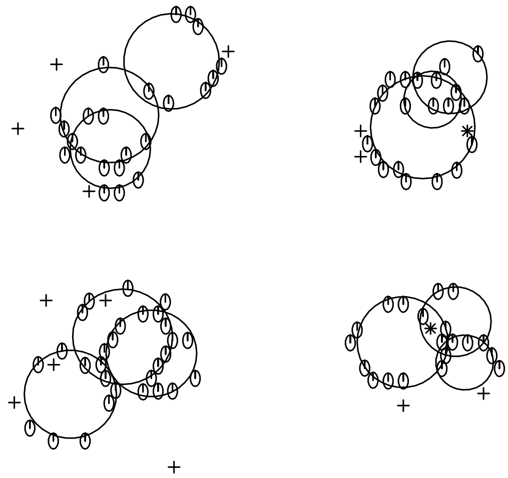

Figure 3. Illustration of the operation of a Cherenkov RICH detector. The Cherenkov radiation of three secondary particles a, b, c produced in diffractive interactions $p + N \rightarrow [a + b + c] + N$ identified by the trigger logic of the SPHINX setup, is focused in the focal plane of the optical system of the detector in the form of three rings. The radius of each ring is determined by the velocity of the respective particle, and the position of the ring's center by the angle of departure of the particle. Registration of the rings takes place in a photomatrix comprising 732 small-size photomultipliers, situated in the focal plane of a spherical mirror (the circles on the rings indicate the triggered PM). The symbols '+' denote additional random triggerings of the PM in the photomatrix; from the pictures this background is seen to be small.

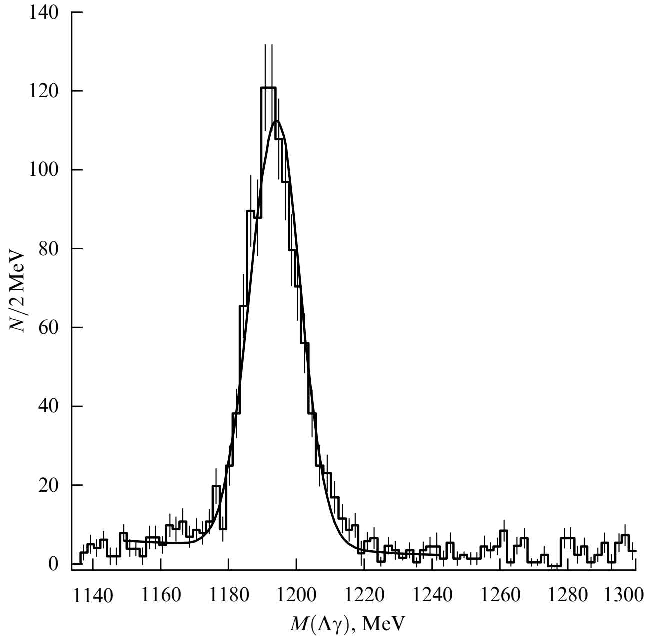

Figure 4. Identification of the reaction $p + N \rightarrow [\Sigma^0 K^+] + N$, $\Sigma^0 \rightarrow \Lambda\gamma$ in a study of processes involving Λ-hyperons, K^+-mesons and single photons. The Σ^0 peak in the mass spectrum of the $\Lambda\gamma$-system corresponds to production of the Σ^0-hyperon and its subsequent decay $\Sigma^0 \rightarrow \Lambda\gamma$.

possible to simultaneously register several rings of Cherenkov radiation (from several secondary particles).

In the Cherenkov RICH detector of the experimental SPHINX setup, a photomatrix consisting of small-size photomultipliers (732 PM-60 photomultipliers with photocathodes 10 mm in diameter) was applied for the first time. For this reason, the Cherenkov detector could operate at high intensity, exhibited high stability and a low background level. The rings of Cherenkov radiation were clearly identified in the photomatrix [an average of 7–8 points determined by the number of photomultipliers triggered by the Cherenkov photons were registered at each ring (Fig. 3)].

Thus, the SPHINX setup permits the obtaining of full information on the events of interest and the reconstruction of their kinematics. In experiments performed with this setup a large number of diverse reactions were studied. We shall illustrate this by the example of a diffractive process with Σ^0-hyperons and K^+-mesons in the final state

$$\begin{aligned} &p + N(A) \rightarrow [\Sigma^0 K^+] + N(A)\,, \\ &\Sigma^0 \rightarrow \Lambda\gamma\,, \qquad \Lambda \rightarrow p\pi^-\,, \end{aligned} \tag{1}$$

for which the most interesting results were obtained. Here and below, $N(A)$ stands for nucleons (or nuclei, if a coherent process is identified, in our case the carbon nuclei); the Σ^0-hyperon is a baryon with strangeness $S = -1$, decaying nearly instantaneously (in a time of the order of 10^{-19} s) into a Λ-hyperon and a photon; the Λ-hyperon is a neutral baryon with strangeness $S = -1$, which owing to its weak interactions decays into a proton and a π^--meson, having time to travel in the process a distance of several tens or even hundreds of centimeters.

The $\Lambda \rightarrow p\pi^-$ decays are registered as 'forks' with vertices separated from the interaction vertices in the target. For separation of reaction (1) one first identifies events with Λ-decays, K^+-mesons and single photons. Then, the effective mass spectrum is analyzed for the $\Lambda\gamma$-system (the effective mass is the total energy of a system of particles in its own center-of-mass system). In the mass spectrum $M(\Lambda\gamma)$, there is a narrow dominant peak, which is due to the decay $\Sigma^0 \rightarrow \Lambda\gamma$ (Fig. 4). Selecting events from this peak, one finally identifies reaction (1), while further investigation of coherent processes on the carbon nucleus requires imposing an additional restriction on the transverse component of the momentum of the $[\Sigma^0 K^+]$-system: $p_T^2 < 0.1$ (GeV/c)^2.

Searches for new short-lived baryon states (resonances) produced in diffractive processes are performed by analyzing the effective mass spectra of particles produced in these reactions. New resonance states can be revealed as peaks in the mass spectra.

Thus, for example, investigation of the spectrum of effective masses of the $[\Sigma^0 K^+]$-system in reaction (1) was carried out. Data for reaction (1) were obtained during two different runs: with the first version of the setup and after its significant modernization (with a new γ-spectrometer, a new system for identification of Λ-decays, and additional track detectors), which made possible essential reduction of the background in the processes studied.

It should be stressed that although the first and the new measurements were carried out in various experimental conditions, with significantly differing versions of the setup, the results of both runs are in extremely good agreement with each other, which inspires confidence that they are reliable.

Figure 5 presents the effective mass spectrum $M(\Sigma K^+)$ in reaction (1) for the entire range of transverse momenta p_T^2. A clear peak with parameters

$$M = 1986 \pm 6 \text{ MeV}\,, \qquad \Gamma = 98 \pm 21 \text{ MeV} \tag{2}$$

is seen in the spectrum. We shall denote this new baryon state by X(2000). More detailed investigations revealed that the

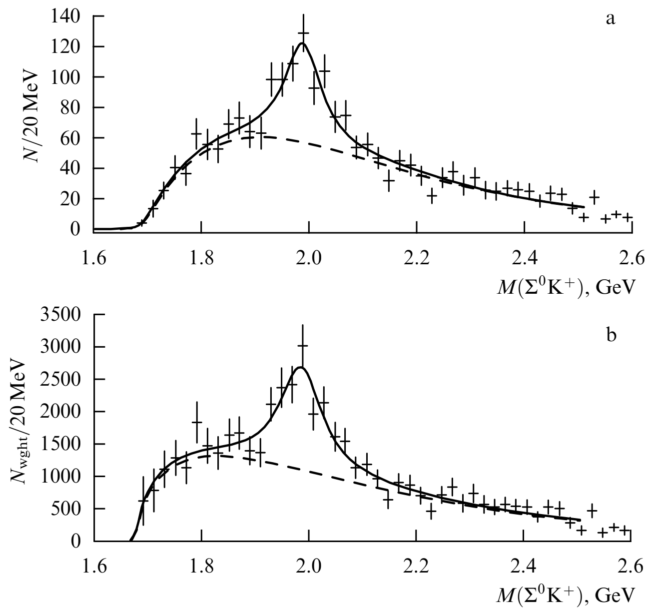

Figure 5. Effective mass spectrum $M(\Sigma^0 K^+)$ in the diffractive reaction $p + N \to [\Sigma^0 K^+] + N$ for the entire range of transverse momenta p_T^2 (run with the modified setup): (a) raw data; (b) spectrum weighted with the efficiency of the setup. A clear peak with parameters $M = 1986 \pm 6$ MeV, $\Gamma = 98 \pm 21$ MeV is seen in the spectrum owing to production of the X(2000) baryon.

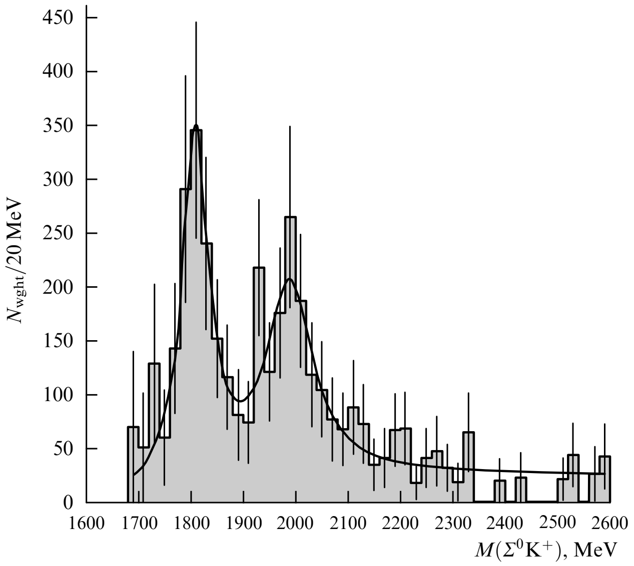

Figure 7. Effective mass spectrum $M(\Sigma^0 K^+)$ in the coherent reaction $p + C \to [\Sigma^0 K^+] + C$ for small transverse momenta $p_T^2 < 0.01$ (GeV/c)^2. The state X(1810) is produced only in the region of very small p_T^2, where it is displayed very clearly and has the parameters $M = 1807 \pm 7$ MeV, $\Gamma = 62 \pm 19$ MeV. The spectrum presented is weighted taking into account the efficiency of the setup; the run is the one with the modified setup.

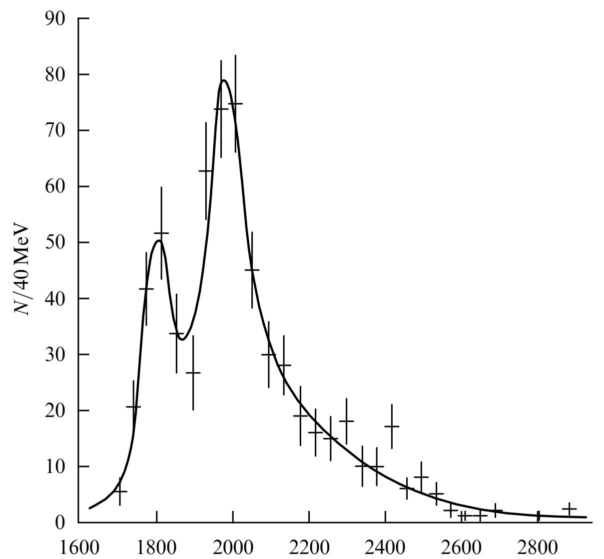

Figure 6. Effective mass spectrum $M(\Sigma^0 K^+)$ in the coherent diffractive reaction $p + C \to [\Sigma^0 K^+] + C$ for transverse momenta $p_T^2 < 0.1$ (GeV/c)^2 (coherence condition). Besides the near-the-threshold structure of X(1810) with mass $M \simeq 1810$ MeV, the spectrum has a dominant clearly defined peak of the X(2000) state. The total spectrum is presented for all runs.

state X(2000) is observed both in the coherent diffractive reaction on carbon nuclei and in diffractive proton – nucleon interactions.

In studies of processes with small transverse momenta p_T, maximum suppression of background processes and careful identification of coherent reaction (1) on carbon nuclei have turned out to be essential. Figure 6 presents the total effective mass spectrum $M(\Sigma^0 K^+)$ in the coherence region [$p_T^2 < 0.1$ (GeV/c)^2], obtained during the two aforementioned runs. From Fig. 6 it is seen that besides the dominant peak of the X(2000)-baryon there is also observed in the coherent reaction (1) a near-the-threshold singularity with a mass of approximately 1810 MeV that we shall denote by the state X(1810). This narrow state has turned out to be produced only in the region of very small transverse momenta (see Fig. 7): $p_T^2 < 0.01$ (GeV/c)^2.

The reason for the unusual dynamic behavior of the X(1810) state is not quite clear yet and requires further investigation. Most likely production of this state is due to the interaction of the incident proton with virtual photons of the Coulomb field of the carbon nucleus [26]. Such Coulomb particle production processes, first dealt with independently in the works of Primakoff [27] and Pomeranchuk and Shmushkevich [28], are known to be characterized by a very narrow distribution over p_T^2. The expected cross section of Coulomb production of the X(1810) state on the carbon nucleus does not contradict available experimental data for X(1810). For further investigation of the hypothesis about Coulomb production of the X(1810) state it is essential to perform new measurements on heavy nuclei (the cross section of Coulomb production is proportional to Z^2, where Z is the charge of the nucleus).

It must be noted that production of the X(2000)-baryon is especially well observed in the 'limited' coherence region $0.02 < p_T^2 < 0.1$ (GeV/c)^2, where the influence of the X(1810) is no longer felt (Fig. 8).

Additional data confirming the existence of the X(2000)-baryon have been obtained in new experiments performed with the SPHINX setup, when analysis of the mass spectrum $M(\Sigma^+ K^0)$ resulted in observation of this state in the reaction $p + C \to [\Sigma^+ K^0] + C$, i.e. in another isotopic channel of the X(2000) decay: $X(2000) \to \Sigma^+ K^0$ [29, 30]. Moreover, the X(2000) state seems to be manifested in a totally different

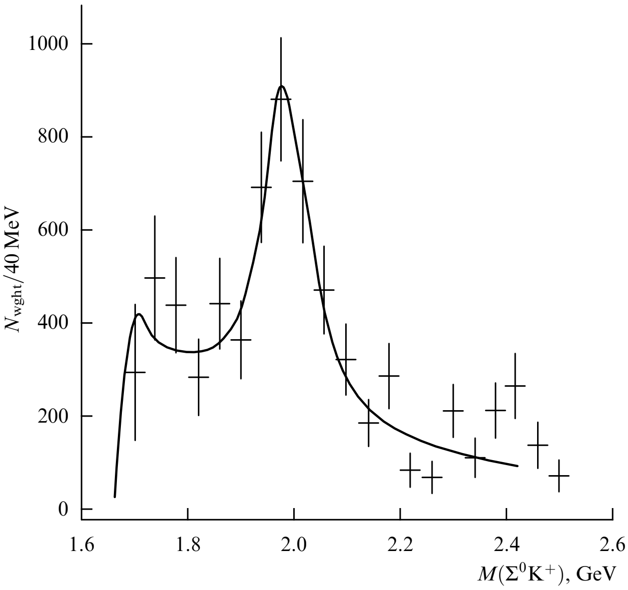

Figure 8. Effective mass spectrum $M(\Sigma^0\text{K}^+)$ of reaction (1) in the 'limited' coherence region for transverse momenta $0.02 < p_T^2 < 0.1$ (GeV/c)^2. In this region the state X(2000) is best manifested, since the influence of the state X(1810) here is nearly negligible. The spectrum presented is weighted taking into account the efficiency of the setup; the run is the one with the modified setup.

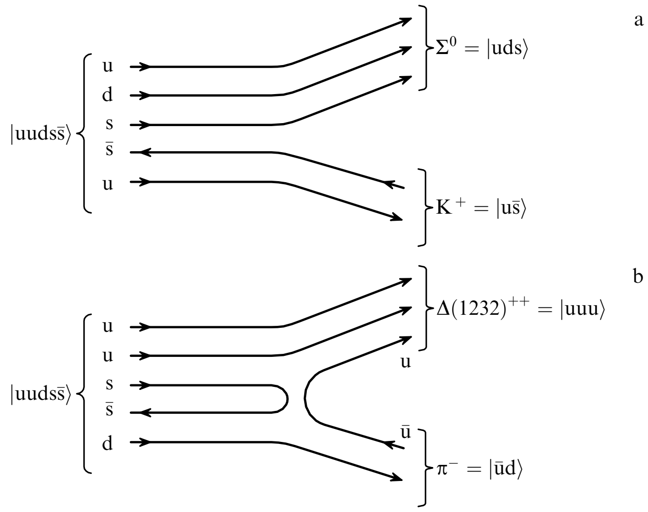

Figure 9. Diagrams for decays of exotic baryons with hidden strangeness, allowed (a) and forbidden (b) by the selection rule relative to continuous quark lines. Processes such as type (b), where the quark lines are seemingly 'disconnected' ($\text{s}\bar{\text{s}}$-quarks annihilate inside the exotic baryon), turn out to be strongly suppressed.

process and in another experiment. Such data were obtained from the analysis of the mass spectrum $M(\Sigma^-\text{K}^+)$ in the reaction $\Sigma^- + \text{N} \to [\Sigma^-\text{K}^+]\text{K}^- + \text{N}$ (see below).

The new baryonic state X(2000) exhibits unusual properties that cannot be explained if it is interpreted as an ordinary baryonic resonance $\text{N}^* = (\text{qqq})$ consisting of three valence u- and d-quarks (a so-called isobar). Actually, all reliably established massive baryonic isobars (with $M \geqslant 2$ GeV) are characterized by large decay widths $\Gamma \geqslant 300$ MeV. The respective decays mainly proceed via channels involving the emission of nucleons and pions: $\text{N}^* \to \text{p}\pi\pi$, $\text{N}^* \to \Delta(1232)\pi \to \text{p}\pi\pi$ and so forth. Decays involving the emission of strange particles such as $\text{N}^* \to \Sigma\text{K}$ have relatively small probabilities that do not exceed several percent. On the contrary, the X(2000) state has been experimentally shown to decay mainly via channels involving emission of strange particles, while the decays $\text{X}(2000) \to \text{p}\pi\pi$, $\Delta(1232)\pi$ turn out to be strongly suppressed (by more than two orders of magnitude). Moreover, the massive X(2000) state has a relatively narrow decay width $\Gamma \leqslant 100$ MeV.

The anomalous properties of the X(2000)-baryon can be readily explained if this state is assumed to be a cryptoexotic fivequark baryon with hidden strangeness ($\text{qqqs}\bar{\text{s}}$). From Fig. 9 it is seen that decays with emission of strange particles $(\text{qqqs}\bar{\text{s}}) \to \Sigma\text{K}$ turn out to be allowed by the selection rule relative to the continuous quark lines — the so-called OZI rule (see below), while the decays $(\text{qqqs}\bar{\text{s}}) \to \Delta\pi$ and so on are strongly suppressed by the OZI rule. This makes it possible to explain, why in the case of exotic baryons with hidden strangeness, the decays via channels with strange particles prove to be dominant.

Moreover, in the case of allowed decays $(\text{qqqs}\bar{\text{s}}) \to \Sigma\text{K}$, owing to the relatively large mass of the particles, the kinetic energy released in the decay turns out to be significantly lower than the energy released in the decays $(\text{qqqs}\bar{\text{s}}) \to \Delta\pi$. This kinematic factor, as well as the more complex internal structure of the exotic baryon, may significantly reduce its total decay width. Thus, the anomalous properties of the X(2000) state make it a strong candidate for cryptoexotic fivequark baryons.

We shall now consider the selection rule relative to continuous quark lines, termed the 'OZI rule' (after its authors S Okubo, G Zweig, J Iizuka [31–33]) in greater detail, for which we again turn to Fig. 9 that illustrates the action of this rule. According to the OZI rule, there may occur processes in which the quark lines of the respective quark diagrams depicting one or another process are continuous (Fig. 9a). Processes in which such continuity seems to be severed (Fig. 9b) turn out to be strongly suppressed — more than by two orders of magnitude as compared with allowed processes. This is due to the suppression dynamics of annihilation (or creation) of the quark–antiquark pairs present in the composition of one hadron (in Fig. 9b this is annihilation of the $\text{s}\bar{\text{s}}$-pair in the exotic baryon).

The production of ϕ- and ω-mesons in π-mesonic reactions is quite consistent with the OZI rule. Thus, for example, in experiments carried out with the LEPTON setup the yields of ϕ-mesons in such reactions were shown to be reduced, as compared with yields of ω-mesons, by factors of 200–500 [34]. This is in excellent agreement with predictions based on the OZI rule and available data on the quark structure of ϕ- and ω-mesons. The wave function of ϕ-mesons has the form $\simeq \text{s}\bar{\text{s}}$ with a very small admixture of $\text{u}\bar{\text{u}}$- and $\text{d}\bar{\text{d}}$-pairs. At the same time no $\text{s}\bar{\text{s}}$-pairs are present in the valence quark composition of the primary π-meson. Therefore, ϕ-meson production turns out to be strongly suppressed by the rule of continuous quark lines (Fig. 10).

It is, however, noteworthy that in recent years significant violations of the OZI rule have been revealed in reactions with protons and antiprotons. Thus, in experiments with the SPHINX setup the yields of ϕ-mesons as compared to ω-mesons have been shown to be suppressed in diffractive proton reactions only by factors of 20–30, i.e. by an order of magnitude weaker than in pion reactions [35]. Strong violations of the OZI rule have also been observed in

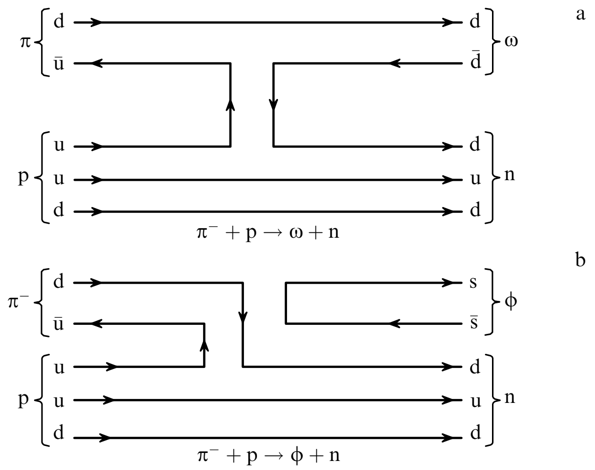

Figure 10. Rule of continuous quark lines (the OZI rule) in charge exchange reactions: (a) $\pi^- + p \to \omega + n$ (this process is allowed by the OZI rule); (b) $\pi^- + p \to \phi + n$ (this process is suppressed by the OZI rule, since the quark lines are disconnected). The ratio of the cross sections for these reactions at high energies amounts to 4×10^{-3} and is in good agreement with OZI predictions (it is determined by a small admixture of $u\bar{u}$- and $d\bar{d}$-quarks in the wave function of the ϕ-meson which, in the main, represents a $s\bar{s}$-state). One must bear in mind that contributions to the production process of ω-mesons (or ρ-mesons in the case of the reaction $\pi^- + p \to \rho^0 + n$) may come from other diagrams with continuous quark lines, allowed by the OZI rule.

antiproton annihilation processes in experiments at the antiproton source LEAR of CERN [36–38].

It is conceivable that the increased yields of ϕ-mesons in proton interactions point to the existence of an enhanced $s\bar{s}$-component in the quark 'sea' of nucleons or even of a small direct $s\bar{s}$-component in their valence composition (i.e. the nucleon contains a small exotic fivequark component — so-called direct strangeness). The action of the OZI rule in proton reactions and the possible existence of direct strangeness in the nucleon is illustrated by the diagrams depicted in Fig. 11.

Although diffractive coherent reactions hold quite promise in searches for certain types of exotic hadrons, there may also exist other exotic particles that are characterized by small sizes, are produced in nucleon – nucleon interactions at small distances, and are more clearly manifested at quite large transverse momenta, where the background from peripheral processes is rather insignificant. This is a consequence of the uncertainty principle: the region of small distances in space corresponds to large transverse momenta. Thus, in experiments with the GAMS setup in IHEP, studies of nonperipheral processes in negative pion (π^-) beams revealed that massive mesonic states X(1740) and X(1910) with small widths and unusual decay channels are possible candidates for exotic mesons [39–40].

By way of example let us consider the properties of the X(1910) state with mass $M = 1911 \pm 10$ MeV and width $\Gamma = 90 \pm 35$ MeV, revealed in a study of the charge exchange reaction

$$\pi^- + p \to X(1910) + n \hookrightarrow \eta\eta' \qquad (3)$$

in the region of relatively high transverse momenta $p_T^2 > 0.2-0.3$ (GeV/c)^2 [40]. In these experiments, the decays

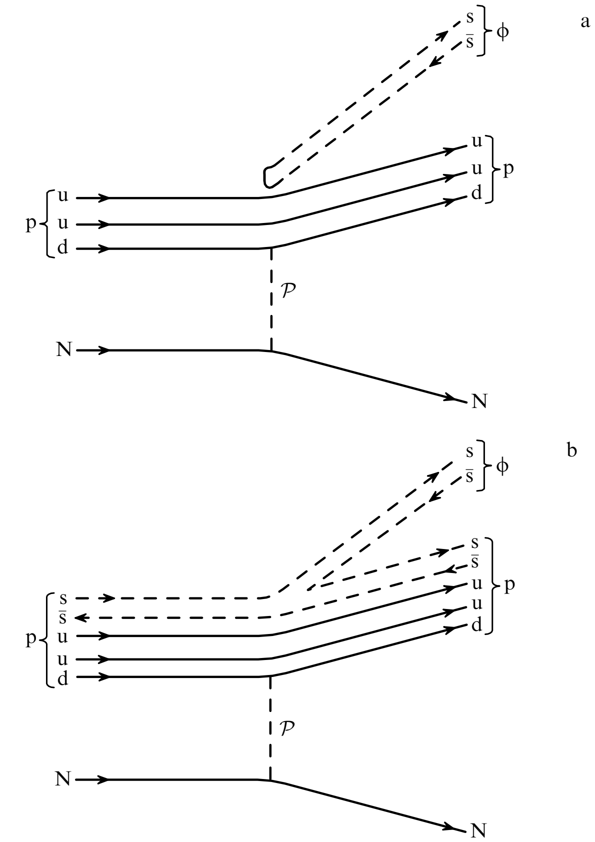

Figure 11. ϕ-meson production in proton – nucleon or proton – nucleus diffractive reactions due to pomeron exchange: (a) disconnected quark diagram (forbidden by the OZI rule); (b) diagram for ϕ-meson production in the model with a small exotic $s\bar{s}$-component in the nucleon wave function (allowed by the OZI rule). In model (b) with so-called direct strangeness in nucleons, the apparent violation of the OZI rule in proton reactions (see text) is explained by the presence of this small exotic admixture in nucleons.

$X(1910) \to \eta\eta'$ were also shown to be at least 15–20 times more probable than decays via the channels $X(1910) \to \pi^0\pi^0$, $\eta\eta$, $K_S^0K_S^0$. Such a dominance of the decays via $\eta\eta'$ channel is difficult to explain applying the model in which X(1910) is an ordinary $q\bar{q}$-meson. At the same time, the strong coupling of the η'-meson with the gluon fields could explain the dominance of the $\eta\eta'$-decay channel, if X(1910) was a hybrid meson.

Thus, investigations in the region of large transverse momenta p_T have made it possible to reveal new meson states which may be candidates for exotic hadrons. Therefore, searches for new baryons in diffraction-like processes with high transverse momenta p_T are of utmost importance. Indeed, the first data on proton nonperipheral production reactions of Σ^0K^+-, $p\eta$-, $p\eta'$-states turned out to be quite interesting. Thus, for example, in the $M(\Sigma^0K^+)$ and $M(p\eta)$ effective mass spectra for $p_T^2 > 0.3$ (GeV/c)^2 a new narrow massive baryon state may be revealed with parameters $M \simeq 2350$ MeV, $\Gamma \leqslant 60$ MeV [22–24].

Besides the aforementioned data, experiments with the SPHINX setup have yielded many other scientific results. Thus, searches have been performed for new baryon states in production processes of a series of baryon systems, where evidences also exist concerning the possible existence of new hadrons with unusual properties [19, 20, 24]. Studies have been carried out of proton – nucleon reactions involving deep fragmentation, in which practically all the primary proton energy is transferred to the secondary meson [41, 42]. The mechanism of deep fragmentation, due to virtual baryon exchange, may turn out to be essential in searches for new meson resonances.

4. On further studies of baryon states

At present, the SPHINX setup has been significantly modified: its sensitivity and rate of data registration have been enhanced. In the near future this will make possible the significant enhancement of the statistics of registered events, implementation of a thorough analysis of the baryon systems produced, determination of the quantum numbers of newly observed states, and investigation of their production mechanisms.

Such research is also under way in experiments with other beams and at higher energies, for example, in experiments with the SELEX setup in hyperon and proton beams of the Tevatron collider of the E Fermi National Laboratory (Fermilab, USA) with energies amounting to several hundreds of gigaelectronvolts [43, 44]. These experiments may yield data on strange and strange-charmed exotic baryons.

The SELEX experiment is being carried out by a large international collaboration with substantial participation of Russian scientists. A feature of this experiment consists in that the main measurements are performed in the so-called hyperon beam with a momentum of 600 GeV/c, enriched with Σ^--hyperons. Such a beam exhibits unique characteristics: over 50% of the beam particles are Σ^--hyperons, and most of the remaining beam particles are π^--mesons.

Creation of the hyperon beam was possible owing to the relativistic enhancement of hyperon lifetimes at high energies. Indeed, the lifetime of Σ^--hyperons in their center-of-mass system $\tau_0(\Sigma^-) = 1.5 \times 10^{-10}$ s, therefore at low energies (of the order of 1 GeV) they can cover distances of several centimeters before decaying. At high energies, however, the effect of relativistic alteration of lifetimes is fully manifested.

The lifetime of particles with a relativistic factor $\gamma = E/m$ (E is the particle energy, m is its mass) equals $\tau = \tau_0\gamma$. In a beam of energy $E = 600$ GeV, the relativistic factor of Σ^--hyperons is $\gamma = E/m = 600\ \mathrm{GeV}/1.2\ \mathrm{GeV} = 5 \times 10^2$. Such hyperons travelling with the speed of light can cover a distance of several tens of meters. Therefore, it becomes possible to prepare real hyperon beams, like the hyperon beam of the Fermilab Tevatron.

For identifying primary particles in the beam and distinguishing between processes due to Σ^--hyperons and those due to π^--mesons in the SELEX setup, a transition radiation detector is applied, in which particle identification is based on the properties of the electromagnetic radiation arising when relativistic particles cross the boundary surface between two dielectric media.

The detector includes a system comprising 200 polypropylene foils. At the foil – air boundary, transition radiation arises with an intensity determined by the relativistic factor of the particles. The intensity of transition radiation in the case of π^--mesons (the γ-factor of which is 8.5 times larger than that of Σ^--hyperons) is significantly higher than for Σ^--hyperons. Therefore, Σ^--hyperons and π^--mesons can be reliably separated in a beam with the aid of a transition radiation detector.

The SELEX setup also includes a set of three magnetic spectrometers with proportional and drift chambers, three γ-spectrometers with detectors of lead glass, a Cherenkov RICH spectrometer and a transient radiation detector for identification of secondary particles. The general operation principles of the detectors were dealt with in Section 3.

It is noteworthy that the Cherenkov RICH detector of the SPHINX setup served as the prototype of the new unique RICH detector for the SELEX setup and has, thus, played an important part in the creation of such a device exhibiting an extremely high resolution in the particle velocity. Registration of the rings of Cherenkov radiation in this detector was performed with the aid of a photomatrix consisting of 3000 small-size photomultipliers [43].

Also in the SELEX installation a multichannel vertex detector with semiconducting microstrip elements is used, which records charged particle tracks like gas track detectors (proportional and drift chambers), but with an essentially higher resolution achieving several micrometers and exceeding the resolution of gas detectors by two orders of magnitude. This detector permits making very precise space measurements, which play an important role in the registration of decays of charmed particles that travel only several millimeters before decaying.

The scientific program under way with the SELEX setup is quite broad and diverse. It includes studies of charmed particle production and decay processes, their spectroscopy, investigation of the electromagnetic properties of hyperons and mesons, of particle production reactions in the Coulomb field of nuclei, searches for exotic hadrons in diffractive and electromagnetic processes. During runs, over 10^9 events were recorded, which at present are undergoing intense processing.

One of the first results of research with the SELEX setup was obtained from the analysis of the diffractive reaction $\Sigma^- + \mathrm{N}(A) \to [\Sigma^-\mathrm{K}^+]\mathrm{K}^- + \mathrm{N}(A)$ [29]. Comparison was made of the effective mass spectra $M(\Sigma^-\mathrm{K}^+)$ and $M(\Sigma^-\mathrm{K}^-)$ in the reaction, and the data on $M(\Sigma^-\mathrm{K}^-)$ were used for estimation of the nonresonance background. These spectra were shown to be very close to each other throughout the entire mass range, with the exception of a narrow region near $M \approx 2$ GeV.

A more thorough analysis revealed a clear peak in the $\Sigma^-\mathrm{K}^+$-system with the parameters $M = 1962 \pm 12$ MeV, $\Gamma = 96 \pm 32$ MeV (see Fig. 12) very close to the parameters (2) for the X(2000) baryon state found earlier in experiments with the SPHINX setup and serving, as discussed above, as a serious candidate for an exotic fivequark baryon. The independent confirmation of the existence of the baryon state X(2000) in another process and in a totally different experiment is distinctly of prime importance.

Interesting results were also obtained in studies of the diffractive reactions

$$\Sigma^- + \mathrm{N} \to [\Sigma^{\mp}\pi^{\pm}\pi^-] + \mathrm{N}\,,$$

where in the region of large transverse momenta [$p_T^2 > 0.3$ (GeV/c)^2 and even $p_T^2 > 0.6$ (GeV/c)^2] a narrow peak is clearly revealed with a mass $M = 1666 \pm 13$ MeV and width $\Gamma = 29 \pm 3$ MeV, which is an excited hyperon state (see Fig. 13) [29]. At present, its properties are being studied.

5. Some new results in meson spectroscopy

In recent years, practically all the most important world scientific centers active in the field of high-energy physics are

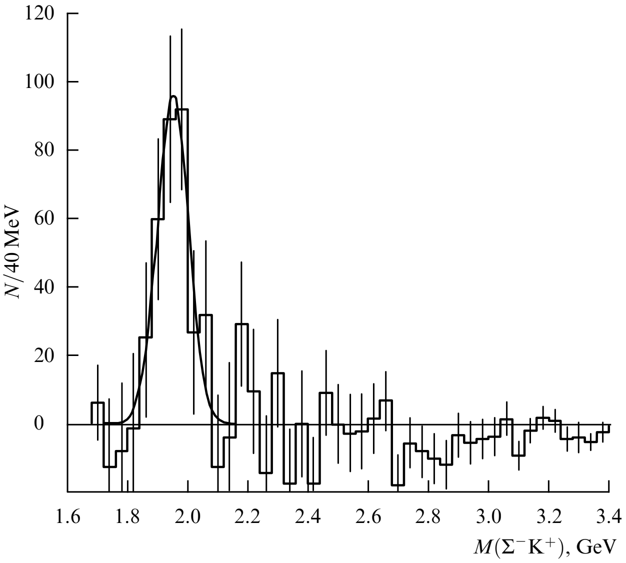

Figure 12. Mass spectrum of the Σ^-K^+-system in the reaction $\Sigma^- + N \to [\Sigma^-K^+]K^- + N$ studied at the SELEX setup. The difference is presented between the Σ^-K^+ and Σ^-K^- mass spectra (the latter is used for describing the nonresonance background). The difference spectrum clearly shows a peak with the parameters $M = 1962 \pm 12$ MeV, $\Gamma = 96 \pm 32$ MeV very close to the parameters for the X(2000) baryon state observed earlier in experiments performed with the SPHINX setup.

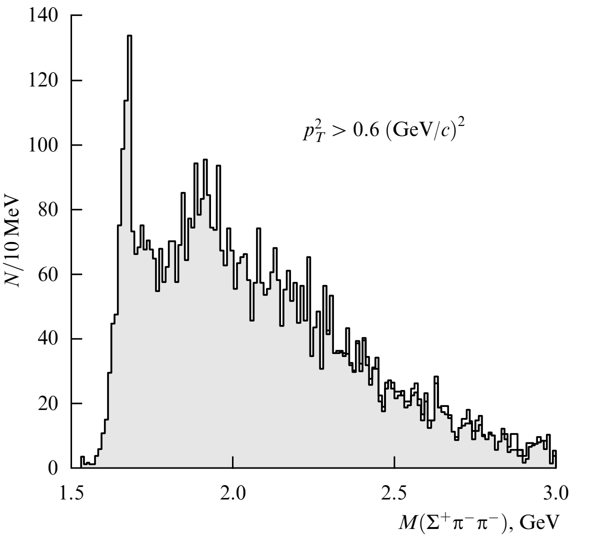

Figure 13. Investigation of the reaction $\Sigma^- + N \to [\Sigma^+\pi^-\pi^-] + N$ studied with the SELEX setup. The effective mass spectrum $M(\Sigma^+\pi^-\pi^-)$ in the region of large transverse momenta [$p_T^2 > 0.6\ (\mathrm{GeV}/c)^2$] shows a narrow peak with the parameters $M = 1666 \pm 13$ MeV, $\Gamma = 29 \pm 3$ MeV, resulting from the excited hyperon.

pursuing studies of meson states. Particularly significant results were obtained in experiments performed at IHEP (Protvino), at CERN, in the Brookhaven National Laboratory and in the E Fermi National Laboratory (USA). Several very serious candidates were found for diverse exotic meson states — multiquark mesons, hybrids, and glueballs.

Studies pursued the following main research lines:

(1) detailed investigation of the production of mesonic states in exclusive reactions such as charge exchange or diffractive processes caused by primary mesons at intermediate energies within the 15 – 40 GeV/c range;

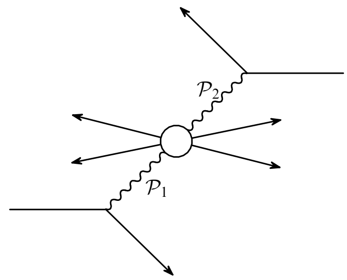

Figure 14. Glueball production in central creation reactions (gluon-enriched reactions involving double pomeron exchange).

(2) investigation of meson production in gluon-enriched reactions of antiproton annihilation, carried out at specialized antiproton sources at CERN (LEAR) and Fermilab;

(3) the production of novel meson states in central interactions at high energies, at which meson creation occurs in pomeron – pomeron collisions (see Fig. 14), i.e. in gluon processes;

(4) the creation of new mesons in e^+e^--reactions including radiative decays of J/ϕ-particles, where strong coupling occurs with the gluon systems:

$$e^+e^- \to J/\psi \to \gamma + \underbrace{(gg)}_{\hookrightarrow\ \text{mesons}} . \qquad (4)$$

In processing the experimental data, a detailed analysis was performed of the angular distributions of the particles produced in the reactions at hand. This made possible the separation of production processes of meson systems in states with definite quantum numbers: with total angular momentum J, space parity P, and charge parity C.

Decomposition of the recorded events into the contributions of states with given quantum numbers has been termed partial-wave analysis. In such an analysis, the contribution of one of the waves with certain quantum numbers to the wave function describing the final state is identified, and resonance states in this wave are sought.

An analysis of the numerous results obtained in the field of meson spectroscopy goes beyond the scope of the present article. Discussions of these data can be found, for example, in reviews [9 – 14]. We shall only deal with one result obtained with the VES setup at IHEP and related to the investigation of the meson state $\pi(1800)$. This meson is characterized by anomalous dynamic properties that permit interpreting it as a possible candidate for a hybrid state.

In experiments with the VES setup (a vertex spectrometer) operating with beams of negative particles, mainly π^--mesons of momentum $p_{\pi^-} = 37$ GeV/c, a program is under way of extensive studies on the spectroscopy of meson states produced, in the main, in reactions of diffractive dissociation of primary π-mesons on nucleons or on beryllium nuclei [46 – 49].

The VES setup includes a wide-aperture magnetic spectrometer with proportional chambers, a γ-spectrometer with Cherenkov counters of lead glass, and a threshold gas Cherenkov counter for identifying secondary charged particles. The general operation principles of such a combined spectrometer for charged particles and photons were considered in Section 3. In measurements with the VES setup, a complete kinematic reconstruction of the events studied was also performed. The VES setup was distinguished for its large acceptance and luminosity, which made possible the registration of over 10^9 pion interactions in the course of measurements.

In experiments with the VES setup, data have been obtained for a number of exclusive diffractive processes caused by the primary π^--mesons. The advantages related to the use of diffractive coherent reactions for revealing new resonance states have been discussed before.

An important result was obtained in studies on several reactions involving the production and cascade decays of a number of meson resonances, for example:

$$\pi^- \mathrm{N} \to [\mathrm{f}_0(980)^0 \pi^-] + \mathrm{N}\,, \qquad (5a)$$
$$\hookrightarrow \pi^+\pi^-,\ \mathrm{K}^+\mathrm{K}^-$$
$$\to [\mathrm{a}_0(980)^0 \eta] + \mathrm{N}\,, \qquad (5b)$$
$$\hookrightarrow \eta\pi^-$$
$$\to [\epsilon(1300)^0 \pi^-] + \mathrm{N}\,, \qquad (5c)$$
$$\hookrightarrow \pi^+\pi^-$$
$$\to [\mathrm{K}^*(1420)^0 \mathrm{K}^-] + \mathrm{N}\,. \qquad (5d)$$
$$\hookrightarrow \mathrm{K}^+\pi^-$$

Here, like previously, $\mathrm{N}(A)$ denotes a nucleon or nucleus (if a coherent process is identified), and $\mathrm{f}_0(980)$, $\mathrm{a}_0(980)$, $\epsilon(1300)$, $\mathrm{K}^*(1420)$ are known mesons characterized by definite masses, decay widths, and other quantum numbers. We note that all these mesons correspond to orbital-excited $\mathrm{q}\bar{\mathrm{q}}$-states with the orbital angular momentum $L = 1$ (they are called P-wave mesons, or P-mesons).

Partial-wave analysis of reactions (5) has shown that in these reactions production occurs of the meson state $\pi(1800)$ (see Fig. 15) characterized by a mass $M \simeq 1800$ MeV, a decay width $\Gamma \simeq 200$ MeV and quantum numbers of a pseudoscalar, $J^{PC} = 0^{-+}$ (like those of the π-meson). This state could represent the second radial excitation of the π-meson. Its first radial excitation, $\pi(1300)$, was revealed in 1981–1982 in several experiments, one of which was carried out by a Dubna (JINR)–Milan–Bologna collaboration at the IHEP collider [50]. It is noteworthy that the first indication of the possible existence of the $\pi(1800)$-meson was also obtained in this work. Another possible explanation of this 'superfluous' meson state that does not fit in the systematics of ordinary $\mathrm{q}\bar{\mathrm{q}}$-meson nonets, is related to its interpretation as an exotic meson — the hybrid $\mathrm{q}\bar{\mathrm{q}}\mathrm{g}$.

To clarify the nature of the $\pi(1800)$-meson it was necessary to investigate the various decay channels for this state. If the $\pi(1800)$-meson represented a radial excitation of the pion, then the decay $\pi(1800)^- \to \rho(770)^0\pi^-$ could be expected as one of its most intense decay channels, while the channel $\pi(1800)^- \to \mathrm{K}^*(890)^0\mathrm{K}^-$ would dominate among its K-meson decays. Here, $\rho(770)$ and $\mathrm{K}^*(890)$ are the well-known mesons representing $\mathrm{q}\bar{\mathrm{q}}$-states with orbital momentum $L = 0$ (i.e. S-wave mesons, or S-mesons). These mesons, in turn, decay via the channels $\rho(770)^0 \to \pi^+\pi^-$ and $\mathrm{K}^*(890)^0 \to \mathrm{K}^+\pi^-$, so that the cascade processes of the $\pi(1800)$-decay involving participation of these resonances could be observed. However, in experiments performed with the VES setup they were not revealed (see Fig. 15). The π-meson is also an S-wave $\mathrm{q}\bar{\mathrm{q}}$-meson with $L = 0$.

Thus, from the experimental findings obtained with the VES setup it follows that the $\pi(1800)$-meson possesses extremely unusual decay properties. It mainly decays via channels such as $\pi(1800) \to \text{P-meson}\ [\mathrm{f}_0(980), \mathrm{a}_0(980), \epsilon(1300), \mathrm{K}^*(1420)] + \text{S-meson}\ [\pi]$, and does not decay via channels $\pi(1800) \to \text{S-meson}\ [\rho(770), \mathrm{K}^*(890)] + \text{S-meson}\ [\pi]$, with the probabilities of the latter decays being suppressed at least several times as compared with the theoretical expectations for ordinary $\mathrm{q}\bar{\mathrm{q}}$-mesons.

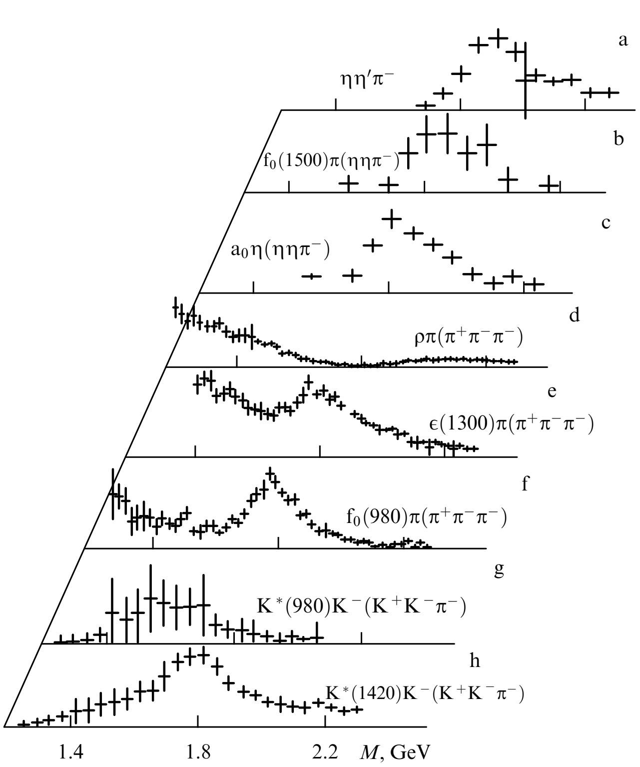

Figure 15. Intensities of states with quantum numbers $J^{PC} = 0^{-+}$ versus the masses of the system for differing channels of reaction (5) in experiments with the VES setup. From the figure, the $\pi(1800)$-state is clearly revealed in decays via the channels $\mathrm{f}_0(1500)\pi$ (b), $\epsilon(1300)\pi$ (e), $\mathrm{f}_0(980)\pi$ (f), and $\mathrm{K}^*(1420)^0\mathrm{K}^-$ (h). It is also possible that the $\pi(1800)$ decay is observed in channels $\eta\eta'\pi^-$ (a), and $\mathrm{a}_0(980)\eta$ (c). The $\pi(1800)$-state is not revealed in the decay channels $\rho\pi$ (d), and $\mathrm{K}^*(980)^0\mathrm{K}^-$ (g).

Moreover, decays via channels with strange particles in the final state also turn out to be anomalously enhanced (having probabilities comparable to those of decays without strange particles). The decay width of the $\pi(1800)$-meson $\Gamma \approx 200$ MeV seems too narrow for a $\mathrm{q}\bar{\mathrm{q}}$-meson with such a large mass. For comparison, one can consider the decay width of the significantly less heavy $\mathrm{q}\bar{\mathrm{q}}$-meson $\pi(1300)$ with the same quantum numbers: it lies somewhere in between the limits of 200 and 600 MeV. Thus, the decay properties of the $\pi(1800)$-meson apparently contradict its interpretation as a radial excitation of the $\mathrm{q}\bar{\mathrm{q}}$-meson.

At the same time, all these properties are in good agreement with the predictions for hybrid mesons, based on the model of 'color tubes' [51, 52]. According to this model, the gluon fields providing for the coupling between quarks represent, in the case of ordinary $\mathrm{q}\bar{\mathrm{q}}$-mesons, sort of a 'color tube' that connects quarks and antiquarks between themselves and is not manifested in the properties of these mesons. At the same time, this model predicts the existence of mesons produced during excitation of a 'color tube'. These are precisely the hybrid mesons with valence structure $\mathrm{q}\bar{\mathrm{q}}\mathrm{g}$.

The prediction attributing a dominant role to the decays $(q\bar{q}g) \to$ P-meson + S-meson is characteristic of the model of 'color tubes' and is in good agreement with the properties of the $\pi(1800)$-meson. Enhancement of the relative probability of decays involving strange particles and the comparatively small total decay width of this state is also in qualitative agreement with its interpretation as a hybrid.

And, finally, there is one more circumstance: indications have been obtained of the possible existence of the decay $\pi(1800)^- \to \pi^- + f_0(\simeq 1500)^0 \to \pi^- + (\eta\eta)$. The scalar meson $f_0(\simeq 1500)$ with quantum numbers $J^{PC} = 0^{++}$ has been observed previously in experiments of the GAMS collaboration (both in π-meson charge exchange reactions and, which is especially important, in gluon-enriched processes of central collisions; see, for example, Ref. [14]) and, also, in experiments at the antiproton source LEAR in $\bar{p}p$-annihilation reactions [7, 13]. It is considered as a serious candidate for a glueball (an exotic meson representing a bound state of gluons). Decays of hybrid mesons emitting glueballs also serve as one of their characteristic properties (see Fig. 16).

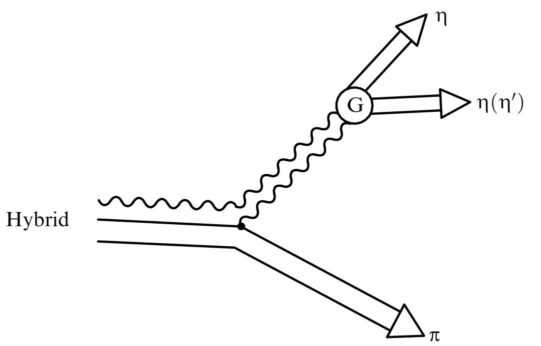

Figure 16. Decay diagram of a hybrid meson involving glueball production: $(q\bar{q}g)^+ \to (gg) + \pi^+$, $(gg) \to \eta'\eta, \eta\eta$.

Thus, in experiments with the VES setup, the existence of the $\pi(1800)$-meson with the quantum numbers of a pseudoscalar, $J^{PC} = 0^{-+}$, has been reliably established. Certain decay characteristics of the $\pi(1800)$-meson have been shown to make it quite a probable candidate for a hybrid-type exotic state. Truly, such an interpretation is based on model arguments and is not indisputable and final. Here, further experimental and theoretical research is required.

Among other results obtained with the VES setup, one should point to searches for meson states exhibiting the exotic set of quantum numbers $J^{PC} = 1^{-+}$. Ordinary $q\bar{q}$-mesons simply cannot have such characteristics (the following are possible sets of quantum numbers for these mesons: $J^{PC} = 1^{++}, 1^{--}, 1^{+-}$).

The states with $J^{PC} = 1^{-+}$ were identified as a result of the partial-wave analysis of a series of reactions, of which the most interesting was the process

$$\pi^- + N(A) \to [\eta'\pi^-] + N(A)\,, \tag{6}$$

since the $[\eta'\pi^-]$-system may be strongly coupled to hybrid mesons, and particularly favorable conditions for appropriate searches are realized within it. The data obtained, however, do not permit concluding that hybrid mesons have been observed in the reactions at issue, since no sufficiently clear resonance peaks are observed in them.

At the same time, close data obtained in the E852 experiment of the Brookhaven National Laboratory (USA) are interpreted by their authors as a manifestation of very broad resonances with the quantum numbers $J^{PC} = 1^{-+}$ [53]. Thus, the issue of possible observations of mesons with the exotic quantum numbers $J^{PC} = 1^{-+}$ remains open and requires further research.

In experiments with the VES setup, studies were also carried out on a series of other hadronic states and data were obtained on rare hadron and electromagnetic decays of some mesons. The processing of the very spacious statistics accumulated using this setup is far from complete, and here many new results are to be expected.

6. Searches for exotic hadrons with heavy quarks

We have hitherto mainly dealt with studies in the spectroscopy of hadrons composed only of the 'light' u-, d-, and s-quarks. Since quarks cannot exist in a free state, the values of their masses are of a somewhat arbitrary nature. The masses of u- and d-quarks are estimated to be 350 MeV, while of s-quarks — 500 MeV (the so-called constituent masses are intended, which play a determinant role in nonrelativistic quark hadron models). In this section, we shall consider certain issues of the physics of hadrons, the composition of which also includes 'heavy quarks' — charmed c-quarks with mass 1.4 GeV or beauty b-quarks with mass about 4.7 GeV.

The investigation of hadron states involving heavy quarks is still at a relatively early stage of development, whereas searches for exotic hadrons with heavy quarks are, as yet, only at the very initial stage. Let us consider merely one aspect of this problem, related to the possible existence of quasi-stable exotic hadrons with heavy quarks, which can solely undergo decays due to weak interactions. They are characterized by the 'ordinary' lifetimes of charmed or beauty particles (of the order of 10^{-13} s), which are governed by weak decays of c- or b-quarks. Such particles are capable of covering distances of the order of several millimeters, and their decays can be registered in precision vertex detectors.

The new properties of hadrons comprising quarks with four different flavors (for instance, c, s, u, d) follow from the general principle of 'maximum flavor antisymmetry' formulated by Lipkin [54]. In accordance with this principle (or, rather, hypothesis), those quark systems exhibit the strongest coupling that are characterized by the maximum possible antisymmetry of quark flavors (both for quarks and for antiquarks), other conditions being equal.

Thus, as an example, the $u\bar{u}d\bar{s}$-system, in which there are no identical quarks, will exhibit stronger coupling than $uu\bar{d}\bar{s}$, and so on. This also signifies that in the case of sixquark configurations of light quarks the strongest coupling is demonstrated by the system H = (udsuds), in which not more than two quarks are in states with identical flavors.

Let us consider now the example of the fourquark mesons $qq\bar{q}\bar{q}$. If their composition includes only u-, d-, s-quarks, then in the case of bound systems with the strongest coupling one quark – antiquark pair (for instance, $u\bar{u}$ for the $u\bar{u}d\bar{s}$-system considered above) will be characterized by opposite values of one and the same flavor, i.e. they will exhibit zero total flavor. Then the quantum numbers of hadrons will be determined by the remaining $q\bar{q}$-pair (in our case $d\bar{s}$), i.e. this exotic hadron has the same quantum numbers as ordinary $q\bar{q}$-mesons (viz. it is cryptoexotic).

So, from flavor antisymmetry it follows that the lightest and most strongly coupled (narrow) $qq\bar{q}\bar{q}$-hadrons comprising u-, d-, s-quarks are cryptoexotic. Weakly bound systems exhibiting explicit exotics (such as $uud\bar{s}$) may have very large decay widths and, then, turn out to be practically unobservable.

If $qq\bar{q}\bar{q}$-mesons contain quarks with four different flavors, then the situation changes. The principle of flavor antisymmetry now permits having, among the lightest charmed mesons of this type, states with explicitly exotic quantum numbers, for instance, mesons $\tilde{F}_s = [cs\bar{u}\bar{d}]$ with an 'erroneous' combination of charm and strangeness. The properties of such mesons are discussed in Refs [54–56].

The existence of fivequark explicitly exotic baryons ('pentabaryons') such as $P^0 = (\bar{c}suud)$ or of similar antibeauty baryons [57, 58] is also possible. In Refs [54–58] arguments are presented in favor of the quasi-stable nature of $\tilde{F}_s$, P^0. This is due to the properties of weak interaction between quarks described in quantum chromodynamics. Owing to this interaction, multiquark systems comprising heavy c- or b-quarks may turn out to exhibit such strong coupling that they cannot decay because of their strong interactions.

Let us consider two examples of exotic quasi-stable hadrons with heavy quarks.

(1) The fourquark meson $\tilde{F}_s = |cs(\bar{u}\bar{d})_{I=0}\rangle$ possessing positive charm $C = 1$, negative strangeness $S = -1$ and zero isospin $I = 0$ is an exotic system, since the 'ordinary' strange-charmed D_s-meson with the quark composition $|c\bar{s}\rangle$ has the quantum numbers $C = 1$, $S = 1$, $I = 0$. The electric charge of the meson is related to its spin projection I_3, strangeness S and charm C by the relationship: $Q = I_3 + (C + S)/2$. Therefore the $\tilde{F}_s$-meson has $Q = 0$, while the D_s-meson has $Q = +1$. This naturally follows from the $\tilde{F}_s$ quark composition as well. If the $\tilde{F}_s$-meson mass is sufficiently large: $M(\tilde{F}_s) > M(D) + M(K) = 2363$ MeV, then the strong decay $\tilde{F}_s \to D^+ + K^-$ takes place.

However, as shown in Ref. [54], it is possible that $M(\tilde{F}_s) < M(D) + M(K) = 2363$ MeV. If so, the strong decay of $\tilde{F}_s$ will be forbidden, and the $\tilde{F}_s$-meson will be quasi-stable: then, it would be only capable of decaying by weak interactions, owing to which the heavy charmed c-quark can undergo transition into lighter quarks ($c \to suu$). One of the characteristic weak decays of such a quasi-stable $\tilde{F}_s$-meson should be of the form $\tilde{F}_s \to K^-K^-\pi^+\pi^+$, and its identification could be relatively easy.

(2) Pentaquark strange-anticharmed baryons $P^0 = |\bar{c}suud\rangle$ or $P^- = |\bar{c}sudd\rangle$ [57] are characterized by exotic combinations of quantum numbers $C = -1$, $S = -1$, $I = 1/2$. Ordinary strange-charmed baryons $\Xi_c^+ = |csu\rangle$ and $\Xi_c^0 = |csd\rangle$ have the quantum numbers $C = 1$, $S = -1$, $I = 1/2$. If $M(P) > M(D_s) + M(P) = 2907$ MeV, then pentaquark baryons will decay via the channel $P^0 \to p + \bar{D}_s^-$, owing to strong interactions. However, as shown in Refs [57, 58], there are significant reasons to expect that $M(P) < M(P) + M(D_s) = 2907$ MeV. In this case, pentabaryons will be quasi-stable and their decays will be due to weak interactions. Some characteristic weak decays of pentabaryons should be of the form $P^0 \to pK^-K^+\pi^-$, $p\phi\pi^-$, $pK^{*+}K^-$.

One must bear in mind that the notation used in this section for heavy strange-charmed exotic hadrons was introduced in Refs [54, 57] and reflects the quark structure of these particles ($\tilde{F}$ — 'fourquark meson', and P — 'pentaquark baryon'). The notation P for pentabaryons must not be confused with the notations for P-wave mesons and baryons or the quantum number of parity, dealt with above. Regretfully, such 'overlaps' of notation in elementary particle physics are encountered quite often.

Searches for pentaquark P^0-baryons have been carried out in the experiment E791 (Fermilab) in the π^--meson beam with a momentum of 500 GeV/c [59]. The E791 setup included a precision vertex detector with microstrip registrators, magnetic spectrometers, and two gas threshold Cherenkov multichannel counters for identifying charged particles.

In experiments with the E791 setup, searches were carried out for quasi-stable pentaquark baryons in the decay channels $P^0 \to p\phi\pi^-$, $K^*\bar{K}p$. The decays of short-lived particles were registered in the vertex detector. Identification of secondary particles was performed using Cherenkov counters. Although the mass spectrum of $p\phi\pi^-$ did exhibit a certain concentration of events in the vicinity of 2.86 GeV, these data only permitted obtaining the upper limit for the possible production cross section of P-baryons, $\sigma(P)$.

In the same experiment 293 ± 18 events were detected with decays of ordinary strange-charmed mesons $D_s^{\pm} \to \phi\pi^{\pm}$. Normalization to the D_s-meson production cross section resulted in the following restriction:

$$\frac{\sigma(P) \cdot BR(P \to \phi\pi p)}{\sigma(D_s) \cdot BR(D_s \to \phi\pi)} < 0.02-0.05$$

(confidence level 90%) in the region of pentabaryon masses $M(P) = 2.75-2.9$ GeV and under the condition that the lifetime of pentabaryons $\tau(P) > 0.4 \times 10^{-13}$ s.

Close results were also obtained for the ratio

$$\frac{\sigma(P) \cdot BR(P \to K^*\bar{K}p)}{\sigma(D_s) \cdot BR(K^*\bar{K})} < 0.02-0.04\,.$$

As follows from the quark structure of the $\tilde{F}_s$-meson and P-baryon states, the most favorable conditions for the production of these particles may be realized in hyperon beams (i.e. in beams of particles with strange quarks) [60]. At present, such searches are under way with the SELEX setup operating with a hyperon beam at the momentum of 600 GeV/c.

7. Conclusions

Searches for exotic hadrons, as noted above, are presently under way in several experiments at the IHEP collider. Experiments with the SPHINX setup have yielded data on the possible existence of a new type of hadrons — of exotic pentaquark baryons with hidden strangeness. Of particular interest are the data on the X(2000) baryon already observed in various processes and even in different experiments.

A variety of results related to the possible existence of glueballs and other exotic mesons were established in experiments performed by the GAMS collaboration simultaneously with two installations at IHEP and at CERN, and also in experiments with the VES setup. Interesting data concerning the possible existence of an exotic meson with hidden strangeness were obtained in experiments with the LEPTON setup. Many important results that also testify in favor of the existence of exotic hadrons were obtained in experiments at the antiproton sources of CERN and of the E Fermi National Laboratory, in the Brookhaven National Laboratory (USA), and at other colliders.

At the same time, the majority of the most interesting and serious candidates for exotic states are cryptoexotic, i.e. they have no explicit signs of exotics and are identified indirectly (by their anomalous dynamic properties), therefore the issue of the observation of exotic hadrons cannot be considered completely resolved. As the saying goes, in such cases, Nature pronounces 'no' loudly and whispers 'yes'. Only further searches for already observed and new candidates for exotic hadrons in various processes and in diverse conditions will ultimately permit the establishment of their existence. The development of theoretical models and concepts, which will permit more reliable interpretation of experimental data, is also very important.

Numerous searches for exotic hadrons of various types are presently under way at the most important accelerator scientific centers of the world. In the near future new fundamental results can be expected to be achieved.

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References

1. Fermi E *Conferenze di Fisica Atomica* (Roma: Accademia Nazionale dei Lincei, 1950) [Translated into Russian (Moscow: IL, 1952)]
2. Okun' L B *Fizika Elementarnykh Chastits* (Physics of Elementary Particles) (Moscow: Nauka, 1990)
3. Okun' L B *Leptony i Kvarki* 3rd ed. (Leptons and Quarks) (Moscow: Nauka, 1990) [Translated into English (Amsterdam: North-Holland, 1984)]
4. Close F E *An Introduction to Quarks and Partons* (New York: Academic Press, 1979) [Translated into Russian (Moscow: Mir, 1982)]
5. Cheng D C, O'Neill G K *Elementary Particle Physics* (Reading, Mass.: Addison-Wesley, Advanced Book Program, 1979)
6. Landsberg L G *Yad. Fiz.* **57** 47 (1994) [*Phys. At. Nuclei* **57** 42 (1994)]
7. Amsler C, Close F E *Phys. Lett. B* **353** 385 (1995)
8. *Hadron Spectroscopy* (Hadron-97, Seventh Int. Conf., Upton, N.Y., August 1997) (AIP Conf. Proc., Vol. 432, Eds S-U Chung, H J Willutzki) (New York: AIP, 1998)
9. Barnes T, in *Hadron Spectroscopy* (Hadron-97, Seventh Int. Conf., Upton, N.Y., August 1997) (AIP Conf. Proc., Vol. 432, Eds S-U Chung, H J Willutzki) (New York: AIP, 1998) p. 3
10. Klempt E, in *Hadron Spectroscopy* (Hadron-97, Seventh Int. Conf., Upton, N.Y., August 1997) (AIP Conf. Proc., Vol. 432, Eds S-U Chung, H J Willutzki) (New York: AIP, 1998) p. 867
11. Close F E, in *Hadron Spectroscopy* (Hadron-97, Seventh Int. Conf., Upton, N.Y., August 1997) (AIP Conf. Proc., Vol. 432, Eds S-U Chung, H J Willutzki) (New York: AIP, 1998) p. 897
12. Blum P *Int. J. Mod. Phys. A* **11** 3003 (1996)
13. Spanier S *Yad. Fiz.* **59** 1352 (1996) [*Phys. At. Nuclei* **59** 1291 (1996)]
14. Prokoshkin Yu D, Preprint IHEP 98–13 (Protvino: IHEP, 1998); *Yad. Fiz.* **62** 396 (1999) [*Phys. At. Nuclei* **62** 356 (1999)]
15. Landsberg L G *Usp. Fiz. Nauk* **164** 1129 (1994) [*Phys. Usp.* **37** 1043 (1994)]
16. Burkert V D, Invited talk on Baryon-92 (1 – 5 June 1992); Preprint CEBAF-PR-92-021 (New Haven, 1992)
17. Daytman S A, in *Hadron Spectroscopy* (Hadron-91, Proc. Forth Int. Conf., College Park, 12 – 16 August 1991) (Eds S Oneda, D C Peaslee) (Singapore: World Scientific, 1992) p. 155
18. Schumacher R A, Preprint CMUMEG-96-007 (Pittsburg, 1996)
19. Vavilov D V et al. *Yad. Fiz.* **57** 241, 253, 1449 (1994)
20. Balatz M Ya et al. *Z. Phys. C* **61** 223, 399 (1994)
21. Golovkin S V et al. *Z. Phys. C* **68** 585 (1995)
22. Golovkin S V et al. *Yad. Fiz.* **59** 1395 (1996)
23. Bezzubov V A et al. *Yad. Fiz.* **59** 2199 (1996)
24. Landsberg L G *Yad. Fiz.* **60** 1541 (1997) [*Phys. At. Nuclei* **60** 1397 (1997)]; in *Hadron Spectroscopy* (Hadron-97, Seventh Int. Conf., Upton, N.Y., August 1997) (AIP Conf. Proc., Vol. 432, Eds S-U Chung, H J Willutzki) (New York: AIP, 1998) p. 725
25. Ogawa S, Sawada S, Nakagawa M *Composite Models of Elementary Particles* (Tokyo: Iwanami Shoten, 1980) [Translated into Russian (Moscow: Mir, 1983)]
26. Vavilov D V et al. *Yad. Fiz.* **62** 501 (1999) [*Phys. At. Nuclei* **62** 459 (1999)]
27. Primakoff H *Phys. Rev.* **81** 899 (1951)
28. Pomeranchuk I Ya, Shmushkevitch I M *Nucl. Phys. B* **23** 452 (1961)
29. Landsberg L G, in *Proc. Forth Workshop on Small-X and Diffractive Physics* (Fermilab, Batavia, 17 – 20 September 1998) p. 189
30. Lomkatsi G S, Doklad na Simpoziume "Sovremennye Problemy Fiziki Elementarnykh Chastits", Posvyashchennom 70-letiyu so Dnya Rozhdeniya G E Chikovani (Talk at Symposium "Contemporary Problems of Elementary Particle Physics" Dedicated to the 70th Birthday of G E Chikovani) (Tbilisi, Georgia, September 1999)
31. Okubo S *Phys. Lett.* **5** 165 (1963); *Phys. Rev. D* **16** 2336 (1977)
32. Zweig G, CERN Report TH-401, TH-402 (Geneva: CERN, 1964)
33. Iizuka J *Prog. Theor. Phys. Suppl.* **37 – 38** 21 (1996); *Prog. Theor. Phys.* **35** 1061 (1996)
34. Viktorov V A et al. *Yad. Fiz.* **59** 1229 (1996) [*Phys. At. Nuclei* **59** 1184 (1996)]
35. Golovkin S V et al. *Z. Phys. A* **359** 435 (1997)
36. Faessler M A, in *Proc. NAN-93* (IHEP, Protvino, September 1993); *Yad. Fiz.* **57** 1764 (1994) [*Phys. At. Nuclei* **57** 1693 (1994)]
37. Ellis J et al. *Phys. Lett. B* **353** 319 (1995)
38. Sapozhnikov M G, in *Proc. Hadron-93* (Como, June 1993); *Nuovo Cimento A* **107** 2315 (1994)
39. Alde D et al. *Phys. Lett. B* **182** 105 (1986); *B* **284** 457 (1992)
40. Alde D et al. *Phys. Lett. B* **216** 447 (1989); *B* **276** 375 (1992)
41. Landsberg L G *Nucl. Phys. Proc. Suppl. B* **211** 179 (1991); *Yad. Fiz.* **52** 192 (1990) [*Sov. J. Nucl. Phys.* **52** 121 (1990)]
42. Golovkin S V et al. *Z. Phys. A* **359** 327 (1997)
43. Edelstein R et al. Fermilab Proposal P781 (1987) (revised in 1993); Russ J S *Nucl. Phys. A* **585** 39 (1995)
44. Smith V J "E781 Collaboration", in *Hadron Spectroscopy* (Hadron-97, Seventh Int. Conf., Upton, N.Y., August 1997) (AIP Conf. Proc., Vol. 432, Eds S-U Chung, H J Willutzki) (New York: AIP, 1998) p. 627
45. Engelfried J et al. *Nucl. Instrum. Methods* (in press)
46. Zaĭtsev A M *Yad. Fiz.* **59** 1674 (1996) [*Phys. At. Nuclei* **59** 1617 (1996)]
47. Amelin D V et al. *Yad. Fiz.* **59** 1021 (1996) [*Phys. At. Nuclei* **59** 976 (1996)]
48. Bitukov S I et al. *Phys. Lett. B* **268** 137 (1991)
49. Amelin D V et al. *Phys. Lett. B* **356** 595 (1995)
50. Bellini G et al. *Phys. Rev. Lett.* **40** 1697 (1982)
51. Isgur N, Patton J *Phys. Rev. D* **31** 2916 (1985)
52. Close F E, Page P R *Nucl. Phys. B* **443** 233 (1995)
53. Ostrovidov A, in *Hadron Spectroscopy* (Hadron-97, Seventh Int. Conf., Upton, N.Y., August 1997) (AIP Conf. Proc., Vol. 432, Eds S-U Chung, H J Willutzki) (New York: AIP, 1998) p. 263
54. Lipkin H J *Phys. Lett. B* **70** 113 (1977)
55. Isgur N, Lipkin H J *Phys. Lett. B* **99** 151 (1981)
56. Richard J et al. *Nucl. Phys.* (*Proc. Suppl.*) *B* **211** 254 (1991)
57. Lipkin H J *Phys. Lett. B* **195** 484 (1987)
58. Gignoux C et al. *Phys. Lett. B* **193** 323 (1987)
59. Aitala E M et al. *Phys. Rev. Lett.* **81** 44 (1998)
60. Moinester M A et al. *Z. Phys. A* **356** 207 (1996)