Physics – Uspekhi **53** (3) 219 – 241 (2010)

REVIEWS OF TOPICAL PROBLEMS

PACS numbers: 12.38.Qk, 13.66.Bc, 14.40.Pq, 14.40.Rt

Exotic charmonium*

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DOI: 10.3367/UFNe.0180.201003a.0225

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Abstract. **The most significant results on the spectroscopy, production, and decay of charmonium and charmonium-like states are reviewed. The surprise-filled physics of charmonium is currently attracting great experimental and theoretical attention. Unexpected properties exhibited by numerous discovered states fail to be explained by the theory, which instead suggests the existence in the spectra of charmonium-like particles of exotic systems different from usual bound states.**

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Received 7 September 2009
Uspekhi Fizicheskikh Nauk **180** (3) 225 – 248 (2010)
DOI: 10.3367/UFNr.0180.201003a.0225
Translated by S V Vladimirov; edited by A M Semikhatov

1. Introduction

The observation of the J/ψ-meson in 1974 [1, 2] was the convincing confirmation of the existence of the c quark, introduced theoretically in 1970 to explain the cancellation of loop diagrams in K^0-meson decays (the so-called Glashow, Iliopoulos, and Maiani (GIM) mechanism [3]). It should not be assumed that this discovery was expected, however. On the contrary, experimentalists from the S Ting and B Richter groups could not believe their good luck for some time, and the guess that the newly found narrow state contained a new quark came only after some contemplation. Consisting of the relatively heavy charmed c quark and $\bar{c}$ antiquark (the c-quark mass is $m_c \sim 1.3\ \mathrm{GeV}/c^2$), the J/ψ particle became a forebear of a whole family of bound states with hidden charm, the charmonium family. The name 'charmonium' appeared not only because of a formal similarity to the positronium — as a bound state of a fermion–antifermion pair — but also because of the similar spectroscopy and decay dynamics. For example, the parapositronium decays into two photons, while its charmonium analogue η_c decays into two gluons, and the ortopositronium decays into three photons, while 'ortocharmonium' J/ψ decays into three gluons.

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* This article is an extended version of the report presented at the Scientific Session of the Division of Physical Sciences, RAS, on December 14th, 2009 (*Editor's note.*)

A similar family of heavier b quarks and $\bar{b}$ antiquarks, which was discovered three years later [4], was called bottomonium. The general name for charmonia and bottomonia, complemented by mixed B_c^+ mesons ($b\bar{c}$), is quarkonium. But the t-quark and $\bar{t}$-antiquark pair does not form a bound state for which a nice name — toponium — was invented in the expectation of its discovery. Because the mass of the t quark, found in 1995 by the CDF and D0 collaborations [5, 6], appeared to be relatively large,[1] the heavy t quark decays before forming a bound hadron state.

Similarly to the positronium, which served as a laboratory to test quantum electrodynamics half a century ago, the charmonium provides a unique possibility to investigate the properties of strong interactions. Quantum electrodynamics, which is built on the gauge group U(1), allows calculating all observable electrodynamic quantities in the perturbation theory. The theory of strong interactions (quantum chromodynamics, QCD) is based on the local color gauge group SU(3) of Yang–Mills fields. The perturbation theory in QCD is applicable only to a narrow range of problems, and the majority of QCD phenomena (confinement and the hadron spectrum) is related to the complex vacuum structure (where gluon field fluctuations are not described by the perturbation theory), as well as to other nonperturbative effects. Even now, there is still no mathematical apparatus for detailed calculations in the fundamental theory of strong interactions. Because of the large masses of both quarks in a quarkonium, a theoretical description of perturbative effects at small distances is more consistent for a quarkonium than for hadrons containing a light quark. Because the properties of quarkonium states are also determined by the interaction at large distances, the theory, after the discovery of quarkonium, has acquired a new interesting object to test nonperturbative models.

After the discovery of J/ψ, ten charmonium states were found within five years, with the first radial excitation, $\psi(2S)$, found only two weeks later. We list all charmonium states discovered before 1980: η_c, J/ψ, χ_{c0}, χ_{c1}, χ_{c2}, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$. More than half of these (having the letter ψ) are produced directly in e^+e^- annihilations, while the others are discovered in radiative decays of J/ψ or $\psi(2S)$. Between 1980 and 2002, not a single new charmonium state was found; however, decays of the ten known states were carefully investigated; the development of theory allowed describing masses, widths, and transitions between known charmonium states, as well as hadron, two-photon, and lepton decays, with sufficiently good accuracy. From the end of the 1970s to the middle of the 1980s, theoretical and experimental reviews devoted to the physics of quarkonia were published in *Physics–Uspekhi* [8–10].

A new era of charmonium physics began in 2002. Within the last seven years, more than ten new states containing the $c\bar{c}$ pair have been observed. These discoveries became possible mostly due to the huge integrated luminosity collected in the BaBar and Belle experiments at B-factories — asymmetric e^+e^--colliders working at energies close to 10 GeV in the center of mass of the beams. These installations, constructed for the investigation of CP violation in the B-meson system, are copious sources of charmonium produced via various mechanisms, and are therefore also *charmonium factories.* Important information on new charmonium states was also obtained in experiments in e^+e^- annihilation at the energy in the open charm threshold region[2] (CLEOc and BES) and in the Tevatron $p\bar{p}$-collider experiments (CDF and D0). But the B-factories played a special role in introducing revolutionary changes into this seemingly well-understood field of physics. Today, when the BaBar collaboration has completed data taking and the Belle collaboration will complete this in the near future, it is possible to summarize the preliminary results of these discoveries.

Only three of the recently found states, h_c, $\eta_c(2S)$, and $\chi_{c2}(2P)$, are identified as probable candidates for charmonium excitations. For the others, with their masses above the open charm threshold, the name 'charmonium-like' state was introduced, addressing the possible presence of $c\bar{c}$ pairs, but stressing that their properties poorly correspond to those expected in the charmonium model. The X(3872), Y(3940), X(4140), $Z^+(4430)$, and $Z_{1,2}^+$ states were found in B-meson decays. In the double charmonium production in e^+e^- annihilation, X(3940) and X(4160) particles were observed. New states with the quantum numbers $J^{PC} = 1^{--}$ produced in e^+e^- annihilation, Y(4260), Y(4360), and Y(4660), decay into a charmonium and a pair of pions. The discovery of the last family caused a reconsideration of the inclusive annihilation cross section of e^+e^- into hadrons close to the open charm production threshold, which had been measured a long time ago and, seemingly, had already been explained. To understand the nature of structures in this cross section (ψ-states) and the nature of the new Y family, exclusive pair production cross sections of charmed hadrons should be investigated. Such measurements appeared very recently, and their interpretation is far from trivial.

There have been various attempts to explain these new states theoretically. The most conservative explanations suggest reconsidering the influence of opening thresholds for various charmed hadron pair production on the parameters of charmonium states predicted by potential models. But the majority of theoreticians recognize that new charmonium-like states can hardly be explained without assuming the existence of exotic systems (different from the usual bound states of heavy $c\bar{c}$ quarks). The molecular, tetra-quark, or hybrid states are among them. Today, none of the suggested traditional or exotic models are able to simultaneously explain the whole variety of properties of the new states.

2. Theoretical models of charmonium

2.1 Charmonia in the quark model

The standard quark model allows a qualitative description of the structure of charmonium states by proceeding from its elementary representation as a bound state of valent quarks (in this case, c and $\bar{c}$). It is customary to use the spectroscopic notation $n^{2s+1}l_J$ for charmonium levels, where n is the radial quantum number, l is the orbital moment between quarks (it is written as S, P, D, etc.), $s = 0, 1$ is the total spin of the quarks, and J is the charmonium spin ($|l - s| \leqslant J \leqslant l + s$). It should be kept in mind, however, that among the above four quantum numbers, only the state spin can be measured; the others are merely assigned based on the measured spatial (P)

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[1] The large t-quark mass was predicted by the Standard Model in 1987 after observation of the unexpectedly large mixing value of $B_d^0 - \bar{B}_d^0$ mesons by the ARGUS collaboration [7].

[2] That is, the production threshold for a pair of charmed mesons containing a c quark and a light antiquark.

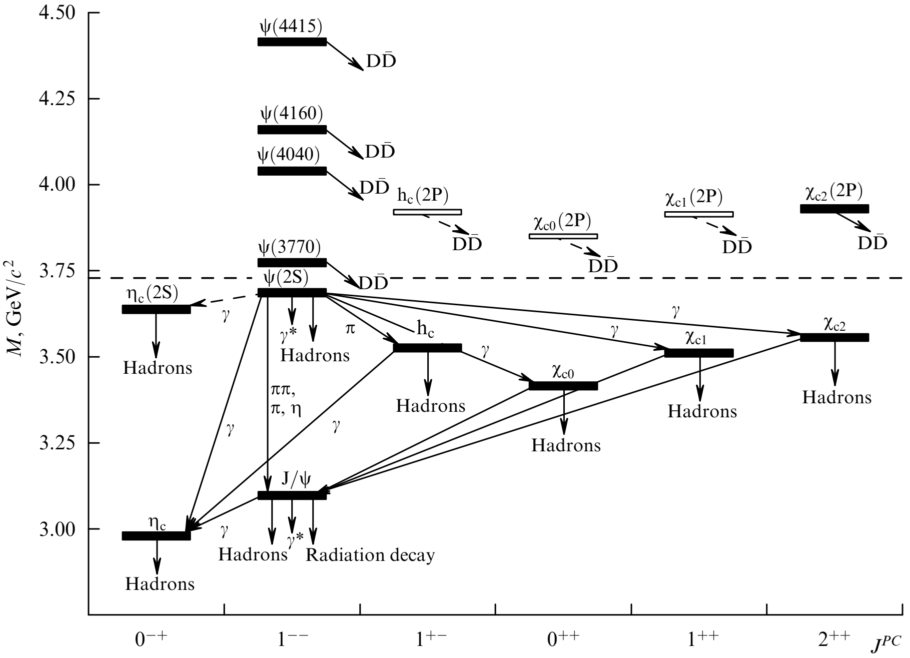

Figure 1. The spectrum of charmonium states, the scheme of transitions between various levels, and decay channels. Black bars correspond to found states, and white bars, to predicted states. Solid lines with arrows show detected transitions and decays, and dashed lines show the expected ones.

and charge (C) parities related to l and s by

$$P = (-1)^{l+1}, \qquad C = (-1)^{l+s}. \tag{1}$$

If the spin or parities cannot be measured, or if they cannot fix l and s uniquely, identification of a charmonium state can be attempted based on the model predictions for mass, width, decay channels, or production mechanisms.

Now, temporarily ignoring valent quark interactions, we discuss the most general properties of the charmonium family. Although the sequence of levels ordered in accordance with the masses of the states (1^1S_0, 1^3S_1, 1^3P_0, 1^3P_1, 1^1P_1, 1^3P_2, 2^1S_0, 2^3S_1, $1^1D_2, \ldots$) somewhat differs from that for positronia, where the Coulomb degeneration of $2S-1P$ levels is observed, the pattern as a whole appears to be similar. Charmonium states with a mass below the open charm threshold are relatively narrow (the experimentally measured widths range from hundreds of keV to tens of MeV). Charmonium decays into light hadrons pass through an annihilation into two or three gluons. Three-gluon annihilation is suppressed so strongly that electromagnetic annihilation is capable of competing with it. Strong transitions between charmonium states with the emission of one π^0 meson are suppressed by the isospin conservation, and those with emission of an η meson or two π mesons, by phase space. However, radiative transitions that give information on wave functions of states useful for theoretical models are observed. The scheme of levels for the known and expected charmonium states and transitions between them is shown in Fig. 1.

2.2 On the capability of theory not only to explain but also to predict

It is interesting to note that even before the development of current charmonium models, theoreticians were able not only to calculate some properties but also to draw bold (and most importantly, correct) conclusions. We recall quite an old story. In 1977, the DASP collaboration reported an observation of candidates for the η_c meson with the mass 2.83 GeV/c^2 and for the $\eta_c(2S)$ meson with the mass 3.45 GeV/c^2 [11]. In 1978, Shifman, Vainshtein, Voloshin, and Zakharov, based on QCD sum rules, showed that the η_c mass should be (3.00 ± 0.02) MeV/c^2 [12]. Thus, they concluded that either the experimental results were wrong or the elementary charmonium model was incorrect. In 1979, the contradiction was resolved. The Crystal Ball collaboration, using significantly larger statistics and with a better energy resolution of photons, did not find any hint of the previously declared η_c-candidates. Not long after, the true η_c with the mass 2.98 GeV/c^2 was nevertheless observed in this experiment (theory triumphs!) [13]. The $\eta_c(2S)$ candidate has experienced the same fate, with the only difference being that its reincarnation was repeated twice: in 1981, Crystal Ball reported on $\eta_c(2S)$ detection with the mass 3.594 GeV/c^2 [14]. Yet, this finding was apparently wrong. Later (and, probably, for the final time), $\eta_c(2S)$ was 'rediscovered' by the Belle collaboration in 2002 in B-meson decays [15] and in the process of charmonium pair production in e^+e^- annihilation [16]. Its mass appeared to be larger by approximately 40 MeV/c^2 than that measured by the Crystal Ball collaboration.

2.3 Potential models

For the quantitative prediction of the masses and the full and partial widths of charmonium states, it is necessary to use phenomenological models because it is not yet possible to calculate these data from first principles. Despite being empirical, such an approach is guided by qualitative QCD properties to describe the dynamics of heavy quark interactions, and concrete parameters are fitted to experimental data. The most popular computational method for charmonium masses and widths is their calculation in potential models. In this approach, quarks are located in a potential $V(r)$ and wave functions are found as solutions of the stationary nonrelativistic Schrödinger equation. The poten-

Table 1. Masses of charmonium states [MeV/c^2] according to potential models. The names of the models are formed according to the first letters of the names of coauthors and the publication year of the results.

State	Experiment [22]	GI85 [23]	F91 [24]	EQ94 [25]	ZVR95 [26]	EFG03 [27]	BGS05 [28]
1^1S_0 η_c	2979.8 ± 1.8	2975	2987	2980	3000	2979	2982
1^3S_1 J/ψ	3096.9	3098	3104	3097	3100	3096	3090
1^1P_1 h_c	3525.9 ± 0.3	3517	3529	3493	3510	3526	3516
1^3P_0 χ_{c0}	3415.0 ± 0.8	3445	3404	3436	3440	3424	3424
1^3P_1 χ_{c1}	3510.51 ± 0.12	3510	3513	3486	3500	3510	3505
1^3P_2 χ_{c2}	3556.18 ± 0.13	3550	3557	3507	3540	3556	3556
2^1S_0 $\eta_c(2S)$	3637 ± 4	3623	3584	3608	3670	3588	3630
2^3S_1 $\psi(2S)$	3686.0	3676	3670	3686	3730	3686	3672
1^1D_2 η_{c2}		3837	3872		3820	3811	3799
1^3D_1 $\psi(1D)$	3769.9 ± 2.5	3819	3840		3800	3798	3785
1^3D_2 ψ_2		3838	3871		3820	3813	3800
1^3D_3 ψ_3		3849	3884		3830	3815	3806
2^1P_1 $h_c(2P)$		3956			3990	3945	3934
2^3P_0 $\chi_{c0}(2P)$		3916			3940	3854	3852
2^3P_1 $\chi_{c1}(2P)$		3953			3990	3929	3925
2^3P_2 $\chi_{c2}(2P)$	3929 ± 5	3979			4020	3972	3972
3^1S_0 $\eta_c(3S)$		4064			4130	3991	4043
3^3S_1 $\psi(3S)$	4039 ± 1	4100			4180	4088	4072
2^3D_1 $\psi(2D)$	4153 ± 3	4194					4142
4^1S_0 $\eta_c(4S)$		4425					4384
4^3S_1 $\psi(4S)$	4421 ± 4	4450					4406

tial tends to the Coulomb potential $V(r) \sim -(4/3)(\alpha_s(r)/r)$ at small distances corresponding to the QCD one-gluon exchange. The weak distance dependence of the strong interaction constant $\alpha_s(r)$ related to gluon self-action leads to a slow decrease in the effective attractive force at small r. At large distances, a linear potential dependence on r is expected, which is qualitatively based on a representation of field lines stretched in a string. There are a variety of means to parameterize the potential, which were discussed on the pages in *Physics–Uspekhi* [10]. In addition, methods to account for spin–spin and spin–orbit interactions and relativistic corrections were described there.

2.4 Threshold effects

If a charmonium state can decay into a pair of charmed mesons ($D\bar{D}$, $D\bar{D}^*$, and so on) and has a mass near the production threshold, then the relative momenta of produced charmed mesons are very small, and there is a possibility for exchange of light mesons (the charmed mesons scatter slowly and there is time for the exchange). This introduces an essentially nonperturbative contribution to the mass of the corresponding charmonium state. The QCD sum rules used in the late 1970s allowed taking some of these effects into account [17, 18]. Within the next decades, more popular was the phenomenological approach relating charmonia with neighboring (by mass) multiparticle states. The coupling between $c\bar{c}$ bound states without light valent quarks and the two-meson sector is described, for example, by the Cornell model of coupled channels [19] or by the model of quark pair production from the vacuum [20].

The recent discovery of charmonium-like states has focused attention on threshold effects, capable of leading to the appearance of structures in charmed meson pair production cross sections, which are not necessarily related to the existence of a resonance [21]. On the other hand, attractive forces during a light meson exchange can be so large that a bound state of charmed mesons appears that is not associated with the charmonium. We discuss this last possibility in Section 2.7.1.

2.5 Numerical predictions and their comparison with experimental results

Because all potential models contain free parameters fitted for a better description of experimental data, it is not surprising that (as can be seen from Table 1) charmonium spectroscopy below the open charm threshold is well described by them. This agreement is illustrated by Fig. 2: the spread of predictions for various models is shown by rectangles and the measured masses, by filled circles appearing inside the rectangles.

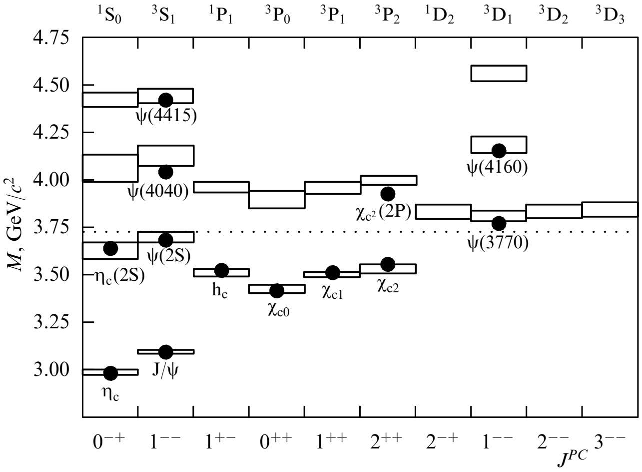

Figure 2. The spectrum of known charmonium states and prediction of masses in potential models.

Table 2. Masses of charmonium states [MeV/c^2] obtained in lattice QCD.

State	Experiment [22]	CP – PACS [29]	Columbia [30, 31]	QCD – TARO [32]
1^1S_0 η_c	2979.8 ± 1.8	3013 ± 1	3014 ± 4	3010 ± 4
1^3S_1 J/ψ	3096,9	3085 ± 1	3084 ± 4	3087 ± 4
1^1P_1 h_c	3525.9 ± 0.3	3474 ± 10	3474 ± 20	3528 ± 25
1^3P_0 χ_{c0}	3415.0 ± 0.8	3408	3413 ± 10	3474 ± 15
1^3P_1 χ_{c1}	3510.51 ± 0.12	3472 ± 9	3462 ± 15	3524 ± 16
1^3P_2 χ_{c2}	3556.18 ± 0.13	3503 ± 24	3488 ± 11	
2^1S_0 $\eta_c(2S)$	3637 ± 4	3739 ± 46	3707 ± 20	
2^3S_1 $\psi(2S)$	3686.0	3777 ± 40	3780 ± 43	
2^1P_1 $h_c(2P)$		4053 ± 95	3886 ± 92	
2^3P_0 $\chi_{c0}(2P)$		4008 ± 122	4080 ± 75	
2^3P_1 $\chi_{c1}(2P)$		4067 ± 105	4010 ± 70	
2^3P_2 $\chi_{c2}(2P)$	3929 ± 5	4030 ± 180		

Above the open charm threshold, the situation becomes more complicated: all four states known before 2002 are discovered in e^+e^- annihilation, and their quantum numbers are 1^{--}. These can be n^3S_1 or m^3D_1 states; however, pure D-states have a negligibly small dielectronic width and cannot therefore appear in e^+e^- annihilation. To arrange the four found ψ-particles, the n^3S_1 and m^3D_1 states are assumed to be mixed. For example, it is supposed that $\psi(3770) = \cos\theta\,|1^3D_1\rangle + \sin\theta\,|2^3S_1\rangle$, where the mixing angle θ can be determined from dielectronic widths of $\psi(2S)$ and $\psi(3770)$. Thus, the problem of calculation of masses for 1^{--} states contains additional uncertainties and the poor observed agreement is excusable.

Recently, three new states were discovered: h_c, $\eta_c(2S)$, and $\chi_{c2}(2P)$, which on the one hand are reliably measured, and on the other hand are unambiguously interpreted. Because their masses were not used to adjust the potential parameters, it is interesting to compare the predicted masses of these states to their measured values. We do this in Section 4.

2.6 Charmonium spectroscopy on a lattice

Ideally, calculations in lattice QCD are based on evaluation of Feynman path integrals and rely directly on the QCD Lagrangian. It is claimed that no additional parameters except the fundamental QCD parameters (quark masses and coupling constants) are used in the calculations. Continuous space–time is replaced by lattice sites (four-dimensional cubes with the characteristic edge $a \approx 0.1$ fm), $(x, t) \to (\mathbf{n}_i a, n_t a)$, and the integral is replaced by the corresponding sum ($\int d^4x \to \sum_n a^4$). Quarks 'live' at the lattice sites and gauge fields are located on the links connecting neighboring sites, because gluons are intended for color transport between the sites. In lattice QCD, the QCD regularization of ultraviolet divergences is naturally guaranteed because momenta exceeding π/a make no sense. The contribution of large momenta is taken into account based on renormalization of the fundamental constants calculated in the perturbation theory.

Proceeding from the first principles of the theory, scientists hope to obtain an exact result. It would seem that this obvious advantage makes a phenomenological approach unnecessary. However, it must be taken into account that results of discrete calculations tend to the correct solution as $a \to 0$, while undesirable corrections exist for finite a. The enormous power of supercomputers does not yet suffice for calculating masses of charmonium states for sufficiently large numbers of lattice sites (giving an acceptable error to compare with experimental results). Attempts to simplify calculations lead either to the sacrifice of accuracy or to the exclusion of some effects,[3] or to the use of additional parameters fixed by experiment, which eventually levels down the accuracy of the theoretical description.

The simplest way to calculate masses of quarkonium states in lattice QCD is to use the Monte Carlo method, i.e., to randomly 'scatter' the field values over lattice sites and links according to the probability of observing such an ensemble of values. Any quantity (in this case, the state mass) is 'measured' as the average over all ensembles of field configurations. The systematic 'measure' error arises because of corrections due to the finite lattice spacing and size. The Monte Carlo method introduces one more source of uncertainty (a statistical error) related to the fact that the total sum is taken only for a finite number of possible paths (field ensembles), although the neglected paths have a minimum weight and weakly influence the result.

Some research groups have calculated masses of charmonium states by using an anisotropic lattice[4] with a different spacing and anisotropy parameter. Results are given in Table 2, from which we see that the accuracy of mass determination ranges from ≈ 1 MeV/c^2 for ground charmonium states to $\approx (10-100)$ MeV/c^2 for orbital and radial excitations. Despite such large errors, agreement with experimental data remains less than brilliant. In the process of increasing computer speeds and, accordingly, of decreasing statistical error, it will be possible to conclude how much today's lattice QCD approaches are suitable for the description of charmonium spectroscopy, and whether the inaccuracies of predictions for masses are the result of approximations made to optimize the computer calculations.

2.7 Models of exotic states

2.7.1 Molecular states. The existence of meson–antimeson molecular states was predicted in 1976 in Ref. [33]. The meson–antimeson pair where each constituent contains one heavy and one light quark can exchange light mesons. The interaction length ($\sim 1/M_m$, where M_m is the mass of a light meson) is then larger than the light meson size. The potential well depth (which determines whether bound levels exist) is determined by the unknown effective interaction constants of light mesons with the heavy meson–antimeson pair. Rough estimates allowed concluding that at least the isosinglet S and

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[3] For example, neglecting the contribution of dynamic quarks.

[4] The lattice spacing a_τ in the time component is chosen to satisfy the condition $a_\tau < m_c^{-1}$, and computer time is saved by setting a larger space step $a_\sigma = \xi a_\tau$ with $\xi > 1$. The calculation time is thus reduced by ξ^3 times.

P levels can exist in the system of charmed meson–antimesons.

Initially, the idea of molecular states was invoked to explain an excessively large $D^*\bar{D}^*$ production cross section compared with the $D\bar{D}$ and $D\bar{D}^*$ production cross sections at the peak of $\psi(4040)$ in e^+e^- annihilation [33, 34]. It was supposed that $\psi(4040)$ can be a P-wave molecular resonance in the $D^*\bar{D}^*$ system. Subsequently, this idea was forgotten for many decades (at least for explaining this state), while the amplification of the $\psi(4040) \to D^*\bar{D}^*$ decay was quite inelegantly explained by a random suppression of other channels because of the zeros of the $\psi(4040)$ wave function. An enthusiastic revival of the molecular state models began in 2003 after the discovery of the X(3872) particle, whose unusual properties are quite successfully explained by the molecular model.

2.7.2 Hadrocharmonium. One more object potentially useful for the description of new states — the hadrocharmonium — was recently (2008) suggested in connection with the discovery of heavy charmonium-like resonances that decay into charmonia and light mesons [35]. It was noted that each of the new states decays into a light meson or a pair of mesons and a certain charmonium state. The absence of decays into other states promoted the idea that a specific charmonium is initially present in these objects, comprising their nuclei immersed in light excited meson matter. Although both the compact charmonium and the 'loose' cloud of a light mesons are colorless, they can interact by means of a color analogue of van der Waals forces,[5] and the interaction forces are too weak to destroy the charmonium nucleus or to convert it to another state during the hadrocharmonium decay.

Calculating the properties of such an object or at least rigorously proving the possibility of its existence is unfortunately impossible given the current development of QCD calculation techniques; it is only possible to conclude on the basis of experimental data how well the hadrocharmonium model is capable of qualitatively describing the properties of new states.

2.7.3 Multiquark states. For many years, the problem was not why multiquark states can exist but why they are not observed. In reality, the quark model merely postulated that all known hadrons consist of either a quark–antiquark pair (mesons) or three quarks (baryons). It is obviously impossible to determine whether, for example, four-quark (tetraquark) states can exist without considering the dynamics of strong interactions. Unfortunately, these dynamics can hardly be calculated in the relevant region of transferred momenta. It is possible to approach the problem differently and to try to determine whether some of the known states are multiquark ones. Already in the late 1970s, the idea of tetraquarks was considered an option for describing the known light scalar mesons whose properties are poorly explained by the usual quark model. By assuming that scalar mesons such as $f_0(600)$, $f_0(980)$, and $a_0(980)$ are tetraquarks, their parameters were estimated in the model of quark bags [37].

Today, advocates of the existence of tetraquark states have received the support of lattice QCD calculation experts. As a result of these calculations, a strong color attraction of two quarks in the antitriplet state was found, leading to a pair of such quarks becoming a compact object, the diquark [38]. The simplest diquark configuration appears when the spins of two quarks are antiparallel and the angular momentum between them is zero. In this case, the diquark is a scalar color object. According to these arguments, tetraquarks should be considered bound states of the color diquark and antidiquark, and they can be calculated in the scalar QCD. A more consistent description of a nonet of light scalar mesons, including σ and κ mesons, was obtained relatively recently in terms of diquark–antidiquark states [39]. Tetraquarks containing a $c\bar{c}$ pair began to be actively studied after a series of experimental discoveries of new charmonium-like particles [40–42].

2.7.4 Charmonium hybrids. Hybrid mesons are states with an excited gluon degree of freedom. Such states appear, for example, in the chromoelectric flux-tube model (the strong interaction field lines stretched into a string at large distances) [43]. If we restrict to the lowest flux-tube excitations, the model is reduced to the elementary quark one and describes usual mesons. The next transverse energy excitations of the chromoelectric flux tube lead to an octet of the lightest hybrids. These excitations introduce an additional degree of freedom related to gluons and add the spin and the angular momentum. As a consequence, some of the octet components have quantum numbers forbidden for usual mesons ($J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$). Among the experimentally detected and studied light mesons, there are some candidates for hybrid states, but no reliable one (with quantum numbers forbidden in the quark model) has been identified.

In the chromoelectric flux-tube model, the octet of the lightest charmonium hybrids was predicted in the range $4.1-4.2$ GeV$/c^2$ [44]. Lattice QCD calculations estimate the average octet mass as (4.19 ± 0.03) GeV$/c^2$ [45]. The splitting within the octet is estimated as ~ 100 MeV$/c^2$. It is not yet possible to describe the production or decays of hybrid states in the lattice QCD in detail. At a qualitative level, it is expected that charmonium hybrids should decay mainly into usual charmonium due to electromagnetic or hadron transitions; however, decays into a pair of charmed mesons are also possible.

3. Charmonium production at B-factories

3.1 Charmonia in B-meson decays

B-mesons are produced with a large cross section, around 1.2 nb, at the peak of the $\Upsilon(4S)$ resonance (for comparison, the total $e^+e^- \to$ *hadrons* cross section at this energy is about 4.2 nb). B-mesons decay with noticeable probability (of the order 10^{-3}) into charmonium and K-mesons (or K^*-mesons) (Fig. 3a). By using the kinematic variables characteristic of the production of B-mesons, it is possible to reconstruct such decays with an extremely low background level.

Because spatial as well as charge parities are broken in weak decays, charmonium with any quantum numbers can be produced in two-body decays of B-mesons. But the production of certain states in $B \to (c\bar{c})K$ decays appears to be dynamically suppressed. For example, among the four P-wave states, only the χ_{c1} state is produced with a high rate in such decays; the probability of χ_{c0} production is five times less, and decays of B-mesons into χ_{c2} or h_c and K are suppressed by an order of magnitude at least. If a new state

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[5] The idea of charmonium bound to nuclear matter via van der Waals forces was already discussed in QCD in 1990 [36].

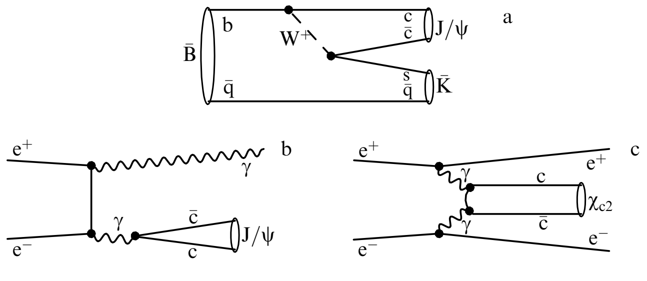

Figure 3. Diagrams of charmonium production in various processes at B-factories: (a) in B-meson decays, (b) in e^+e^- annihilations with initial state radiation, (c) in two-photon interaction.

is detected in two-body B-meson decays, its quantum numbers can be measured using the angular analysis of its decay.

3.2 Charmonium production in e^+e^- annihilation with initial state radiation

The existence of the initial state radiation process, in which a hard photon emitted before the electron or positron annihilation takes away a significant part of the initial energy (Fig. 3b), allows studying charmonium production in e^+e^- annihilations at B-factories that operate at the energy of the order of 10 GeV in the center-of-mass system of the beams. The continuous energy spectrum of this radiation allows investigating the production of charmonium with quantum numbers $J^{PC} = 1^{--}$ over the whole energy range. The electromagnetic suppression of hard photon radiation is compensated by an enormous integrated luminosity collected at the B-factories, and selection criteria specific for the initial state radiation processes provide high efficiency at considerable suppression of the background. Altogether, these factors allow obtaining results competitive with the CLEOc and BES experimental data in which 1^{--}-charmonium is resonantly produced in e^+e^- annihilations without electromagnetic suppression. In these experiments, data are collected in a scan over a broad range of center-of-mass energies $\sqrt{s}$.

3.3 Two-photon charmonium production

Another source of charmonium states at B-factories is the two-photon interaction, in which initial electrons and positrons emit photons, typically at small angles to their momentum directions and with small virtuality ($Q^2 \sim 0$) (Fig. 3c). As a result, a hadron system produced in the two-photon collision has a small total energy and a small transverse momentum, and the electron and the positron scatter in almost the initial directions and are not detected. Charmonium states can be produced in such processes without additional hadrons in the event, which allows considerably suppressing the background and studying the produced charmonium states in pure conditions.

A charmonium state appearing in the two-photon collision has positive charge parity. According to the Landau–Yang theorem [46, 47], interaction of two quasireal photons forbids the production of a spin-1 system. The allowed charmonium quantum numbers are therefore given by $J^{PC} = 0^{-+}$, 0^{++}, 2^{-+}, and 2^{++}. The total cross section of two-photon production of a resonance R with mass m and spin J is proportional to $(2J+1)\Gamma(\mathrm{R} \to \gamma\gamma)\log^3(E_{\mathrm{CM}})/m^3$, where E_{CM} is the energy of e^+e^- beams in the center-of-mass system. Due to high integrated luminosity in experiments at B-factories, a few thousand events of traditional charmonium states (η_c, χ_{c0}, χ_{c2}) formed in two-photon collisions can be detected despite small relative probabilities of decays into reconstructed final states [48].

3.4 Pair charmonium production

The above mechanisms of charmonium production in B-factories are the traditional sources of new information on charmonium properties, while production of a pair of charmonium states is a rather exotic case.

Creation of J/ψ in e^+e^- annihilation at $\sqrt{s} \sim 10.6$ GeV was first detected by the CLEO collaboration in 1992 [49]. The cross section of the $e^+e^- \to J/\psi + X$ process was approximately 2 pb. In later years, attempts were made to estimate this cross section theoretically. Due to the lack of additional experimental information, all possible production mechanisms were considered. Among them were the so-called color-singlet and color-octet diagrams shown in Fig. 4a, b. In the first case, two hard gluons are emitted (two gluons provide a colorless $c\bar{c}$ pair that is projected onto a physical charmonium state, e.g., J/ψ), and in the second case, a single hard gluon is emitted, leading to the formation of an intermediate color state $(c\bar{c})^8$, which becomes colorless with the emission of a soft gluon, $(c\bar{c})^8 \to (c\bar{c})^0 g$, subsequently transformed into a physical charmonium state. The second mechanism was seen as a 'savior' of nonrelativistic QCD in describing J/ψ and $\psi(2S)$ production with large transverse momenta in the proton–antiproton interaction, because the first mechanism estimated the cross section to be 30 times smaller than the measured one.[6] The contribution of these two mechanisms to the J/ψ production cross section in e^+e^- annihilation at $\sqrt{s} \sim 10.6$ GeV was expected in the range $1.1-1.6$ pb, which corresponds well to the value measured by CLEO [50–52].

The J/ψ production can also be accompanied by the appearance of an additional $c\bar{c}$ pair, leading to the formation of charmed hadrons (Fig. 4c) or a second charmonium state (Fig. 4d). The contribution of the $e^+e^- \to J/\psi\, c\bar{c}$ diagram to the total cross section, which was estimated in the range $0.05-0.1$ pb, was so small that detection of this process was considered hardly possible [53]. Contrary to expectations, it

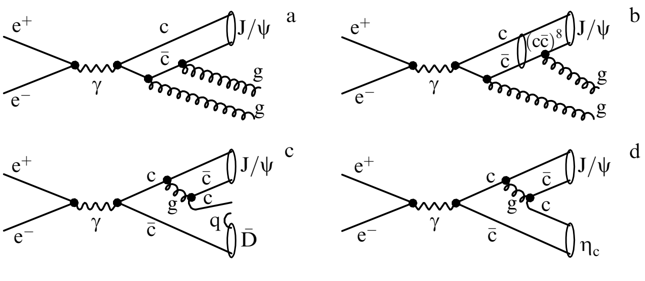

Figure 4. Diagrams of J/ψ creation in e^+e^- annihilations: (a) $e^+e^- \to J/\psi\, gg$, (b) $e^+e^- \to J/\psi\, g$, (c) $e^+e^- \to J/\psi\, c\bar{c}$, and (d) $e^+e^- \to J/\psi\, \eta_c$.

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[6] We note that the color-octet contribution was not calculated theoretically and its value was determined as the difference between experimental data for the $p\bar{p}$ interaction and the color-singlet model contribution in the first order of the perturbation theory. It is now shown that the contributions of higher orders in the color-singlet model are large, and after taking them into account, there is almost no need in the additional $(c\bar{c})^8$-contribution.

was discovered by the Belle collaboration in 2002, and its cross section appeared to be an order of magnitude larger than the theoretically predicted one [16]. In recent Belle work [54], the $e^+e^- \to J/\psi\, c\bar{c}$ cross section measured in a model-independent way was equal to $(0.74 \pm 0.08 \pm 0.09)$ pb.

For us, only that part of the cross section in which an additional $c\bar{c}$ pair is transformed into one more charmonium state is important. For the second charmonium with the mass below the open charm threshold, this fraction is $(16 \pm 3)\%$ [54]. Despite the small value of the cross section, investigation of the pair production process appeared to be very productive, not only in the search for new states but also for the study of their properties. It turned out that it is sufficient to reconstruct only one of two charmonium states in the detector, for example, J/ψ, to observe the process of pair production. The second state can be 'seen' in the spectrum of masses recoiling against the reconstructed ones, $M_{\rm rec}(J/\psi) = [(E_{\rm CM} - E^*_{J/\psi})^2 - p^{*2}_{J/\psi}]^{1/2}$, where $E^*_{J/\psi}$ and $p^*_{J/\psi}$ are the energy and momentum of J/ψ. In this way, the Belle collaboration observes thousands of events of the $e^+e^- \to J/\psi\, \eta_c$ process. In the processes of pair charmonium production in e^+e^- annihilation, the final charmonium states have opposite charge parities. It was experimentally found that either scalar mesons with the quantum numbers $J^{PC} = 0^{++}$ (χ_{c0}) or pseudoscalar mesons with $J^{PC} = 0^{-+}$ [η_c and $\eta_c(2S)$] are produced together with J/ψ, and the production of orbital excitations is not suppressed [55].

4. New traditional charmonium states

4.1 Radial excitation of η_c

The $\eta_c(2S)$ (2^1S_0) state was first reliably detected in 2002 by the Belle collaboration in B-meson decays [15]. In the invariant mass spectrum of the $K^0_S K^\mp \pi^\pm$ combinations from the $B^+ \to K^0_S K^\mp \pi^\pm K^+$ decay (Fig. 5a), two significant peaks were observed: a large one near the mass of η_c and a smaller one near the mass 3.65 GeV/c^2. The latter is interpreted as a signal of the $B^+ \to \eta_c(2S)K^+$ decay. Simultaneously, the Belle collaboration observed the process of pair charmonium production [16]. Peaks corresponding to the $e^+e^- \to J/\psi\, \eta_c$ processes, χ_{c0} and $\eta_c(2S)$, were found in the spectrum of masses recoiling against J/ψ (Fig. 5b).

The $\eta_c(2S)$ mass measured in the first work [15], $(3654 \pm 6 \pm 8)$ MeV/c^2, appeared to significantly exceed the calculated one. It must be remembered, however, that an interference of $\eta_c(2S)$ with the nonresonance contribution of $K^0_S K^\mp \pi^\pm$ shifting the position of the resonance peak can occur in B-meson decays. Subsequent mass measurements in the $e^+e^- \to J/\psi\, \eta_c(2S)$ process [56, 57] and in two-photon production [58, 59] were in better agreement with the predictions. Today, the world average mass value of $\eta_c(2S)$ is (3637 ± 4) MeV/c^2 [22]. The measured difference of the $\psi(2S)$ and $\eta_c(2S)$ masses, (49 ± 4) MeV/c^2, agrees with that predicted in some models, although in others the $\psi(2S) - \eta_c(2S)$ mass difference is expected to be in the range $80 - 100$ MeV/c^2 (see Table 1).

The full width of this state, $\Gamma_{\rm tot} = (14 \pm 7)$ MeV [22], as well as the two-photon width $\Gamma_{\gamma\gamma} = (1.3 \pm 0.6)$ keV [58] (estimated by assuming the equal branching fractions for the decays of η_c and $\eta_c(2S)$ into $K^0_S K^\mp \pi^\pm$), are within the bounds of expected values, considering large errors in their measurement.

4.2 Singlet orbital excitation

The twenty-year-old history of the discovery of the singlet state h_c (1^1P_1) is like a fascinating detective story in which a finishing touch was made in the 'newest era' of the charmonium. The first indications of its detection were obtained in 1986 by the R704 collaboration. In the energy scanning for antiprotons colliding with a hydrogen target, five events were detected with a low significance $(2.3\,\sigma)$, which could be interpreted as the $p\bar{p} \to h_c \to J/\psi\, \pi^+\pi^-$ process [60]. Six years later, the E760 collaboration did not see any hint of this decay of h_c for the specified mass; however, it reported on the observation of the $p\bar{p} \to h_c \to J/\psi\, \pi^0$ process [61]. In 2005, the E835 experiment based on significantly larger data statistics failed to confirm observation of h_c in a decay into $J/\psi\, \pi^0$, instead presenting the first indication of the existence of h_c in a completely different decay channel, $h_c \to \eta_c \gamma$, with the significance about $3\,\sigma$ and the mass $M = (3525.8 \pm 0.2 \pm 0.2)$ MeV/c^2 [62].

The CLEOc experiment confirmed the reliability of the discovery of h_c in the same year [63], and precisely measured the h_c parameters in 2008 by using larger data statistics [64]. The CLEOc collaboration studied the $\psi(2S) \to h_c \pi^0$ process suppressed by the isospin symmetry by identifying h_c as a peak in the spectrum of masses recoiling against the reconstructed π^0 meson. Two measurement methods were used: an inclusive one in which decays of h_c were not detected (Fig. 6a), and an exclusive one in which the $h_c \to \eta_c \gamma$ decay was observed (Fig. 6b). Both methods reached a high signal significance $(10\,\sigma$ and $13\,\sigma$ for inclusive and exclusive decays, respectively). The measured mass averaged over the results of both measurements was $(3525.20 \pm 0.18 \pm 0.12)$ MeV/c^2.

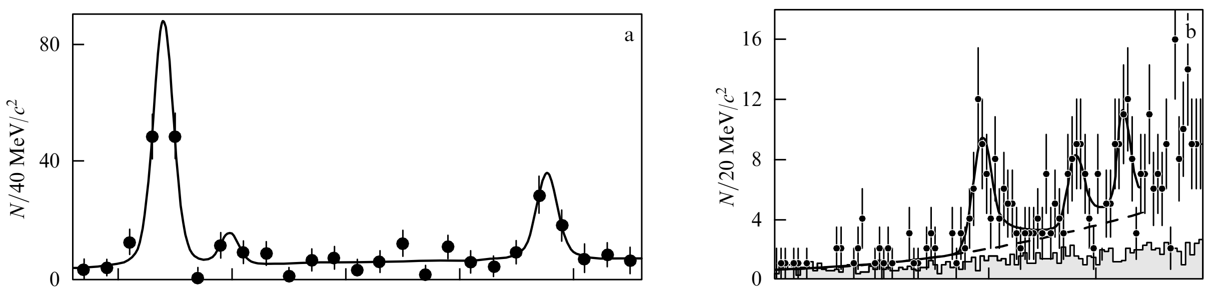

Figure 5. (a) The spectrum of invariant masses of the $K^0_S K^\mp \pi^\pm$ combinations from the $B^+ \to K^0_S K^\mp \pi^\pm K^+$ decay. (b) The spectrum of masses recoiling against J/ψ. N is the number of events.

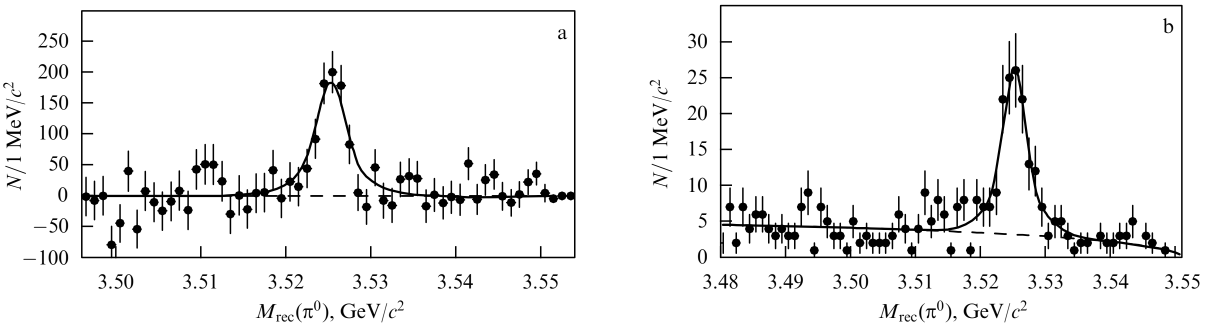

Figure 6. The spectra of masses recoiling against π^0: (a) in inclusive decays $\psi(2S)$ after the background subtraction, (b) in decays $\psi(2S) \rightarrow \pi^0 X$, $X \rightarrow \eta_c \gamma$.

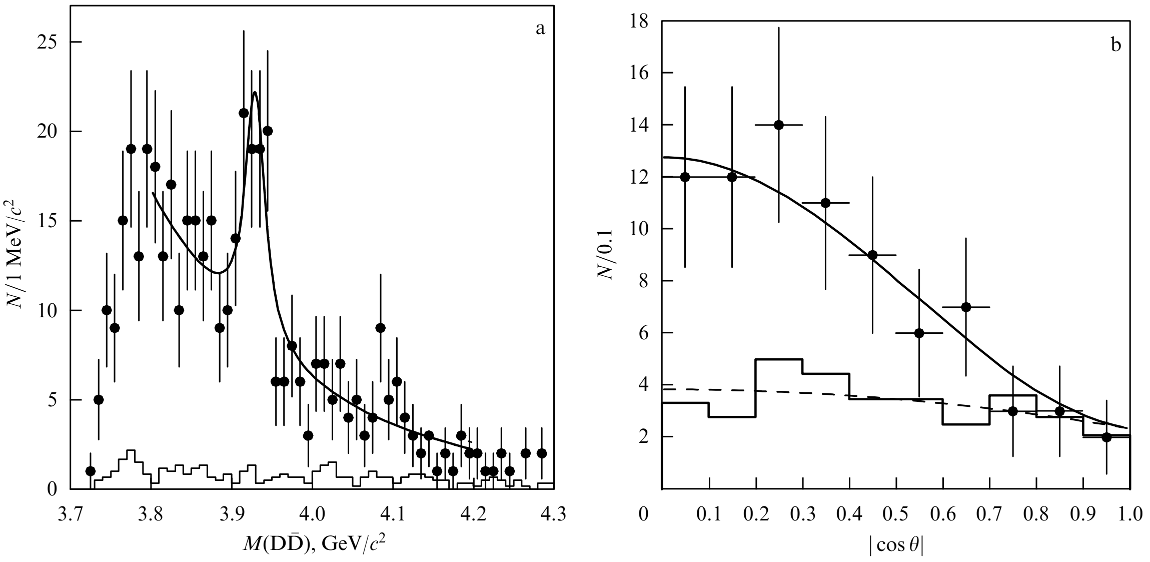

Figure 7. (a) The invariant mass spectrum of the $\mathrm{D\bar{D}}$ combinations. (b) The polarization angle distribution of the $\mathrm{D\bar{D}}$ system in the resonance region and the background.

In the lowest order of the perturbation theory, the mass of the singlet state $1^1\mathrm{P}_1$ is predicted to be equal to the unperturbed mass of the triplet $1^3\mathrm{P}_J$ state. For the latter, the centroid mass can be used:

$$\langle M_{1^3\mathrm{P}_J} \rangle = \frac{\sum_{J=0}^{2} \left[(2J+1)\, M_{\chi_{cJ}} \right]}{\sum_{J=0}^{2} (2J+1)} = (3525.30 \pm 0.04)\ \mathrm{MeV}/c^2\,, \qquad (2)$$

which undeniably agrees well with the $\mathrm{h_c}$ mass measured in the CLEOc and E835 experiments. We stress that because naive assumptions of the equality of the singlet mass to the triplet center-of-gravity mass were initially made in the model, the good agreement of predictions with the experiment in this case should not be considered a serious confirmation of the models. The full width of $\mathrm{h_c}$ is, predictably, very small [$\Gamma_{\mathrm{tot}} < 1.0$ MeV at 90% confidence level (CL)].

4.3 Radial excitation of χ_{c2}

One more charmonium state with the mass above the open charm threshold was observed in 2005 by the Belle collaboration in the $\gamma\gamma \rightarrow \mathrm{D\bar{D}}$ process (where $\mathrm{D\bar{D}} = \mathrm{D^0\bar{D}^0}$ and $\mathrm{D^+D^-}$) [65]. In the invariant mass spectrum of the $\mathrm{D\bar{D}}$ combinations selected with the kinematic conditions characteristic of two-photon production, the concentration of events at the $M(\mathrm{D\bar{D}})$ values about 3.93 GeV$/c^2$ is clearly seen (Fig. 7a). A fit to this spectrum under the assumption that the observed peak is caused by the contribution of a new resonance gives 64 ± 14 signal events with the statistical significance $5.3\,\sigma$. The mass of the new state is $(3929 \pm 5 \pm 2)$ MeV$/c^2$, and its full width is $(29 \pm 10 \pm 2)$ MeV.

From the analysis of the angular distribution of the $\mathrm{D\bar{D}}$ pairs, the spin of this state,[7] equal to 2, was determined (Fig. 7b). Together with the information on the production mechanism and on the observed decay channel, the spin measurement allows fixing the quantum numbers unambiguously: $J^{PC} = 2^{++}$ corresponding to $2^3\mathrm{P}_2 \equiv \chi_{c2}(2\mathrm{P})$.[8] The two-photon width is

$$\Gamma_{\gamma\gamma}\,\mathcal{B}(\chi_{c2}(2\mathrm{P}) \rightarrow \mathrm{D\bar{D}}) = (0.18 \pm 0.05 \pm 0.03)\ \mathrm{keV}\,.$$

The two-photon width as well as the full width of the found particle are in agreement with those estimated for the $\chi_{c2}(2\mathrm{P})$ charmonium state at the measured mass. But the

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[7] For $J = 2$, the distribution should follow the law $\mathrm{d}N/\mathrm{d}\cos\theta \sim \sin^4\theta$; in the case $J = 0$, a uniform distribution is expected.

[8] It is expected that another possible state with the same quantum numbers, $1^3\mathrm{F}_2$, is substantially heavier.

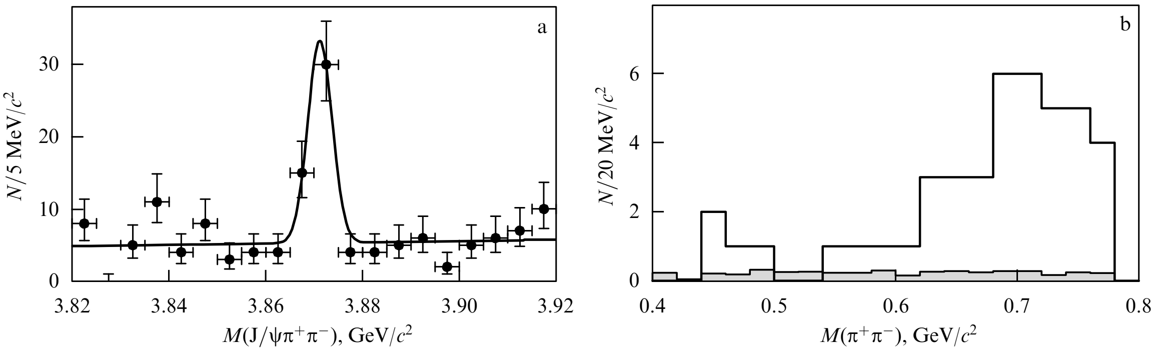

Figure 8. (a) The mass spectrum of the $J/\psi\,\pi^+\pi^-$ combinations; the results of the fit are shown by a solid line. (b) The mass spectrum of the $\pi^+\pi^-$ combinations from the signal region of X(3872) (the open histogram) and the renormalized spectrum of a control sample representing the background contribution (the shaded histogram).

observed mass is 50 – 100 MeV$/c^2$ less than the expected one. This disagreement is serious enough if we recall that all states below the open charm threshold agree with predictions within $\sim$ (10 – 20) MeV$/c^2$.

Concluding the results in Sections 4.1–4.3, we can state that, as a whole, all three states found recently and identified in the framework of the charmonium quark model are in a good enough agreement with the predictions of potential models. The production mechanisms as well as the decays detected and the parameters measured do not cause serious concern from the theoretical standpoint. The disagreement between the predicted and measured masses of $\chi_{c2}(2P)$ apparently indicates that the account of the coupling between the charmonium states and the two-meson sector should be corrected.

5. Charmonium-like state X(3872)

5.1 The discovery of X(3872)

A narrow state named X(3872) was discovered in 2003 by the Belle collaboration in $B^+ \to K^+ J/\psi\,\pi^+\pi^-$ decays [66]. In addition to the known $\psi(2S)$ resonance in the invariant mass spectrum of the $J/\psi\,\pi^+\pi^-$ combinations, a second peak near 3.87 GeV$/c^2$ was found (Fig. 8a). The statistical significance of the signal was 10.3 σ, and the number of signal events at the X(3872) peak was (35.7 ± 6.8), from which the ratio

$$\frac{\mathcal{B}\big(B^+ \to K^+X(3872)\big)\,\mathcal{B}\big(X(3872) \to J/\psi\,\pi\pi\big)}{\mathcal{B}\big(B^+ \to K^+\psi(2S)\big)\,\mathcal{B}\big(\psi(2S) \to J/\psi\,\pi\pi\big)} = 0.063 \pm 0.012 \pm 0.007 \qquad (3)$$

was calculated.

It might seem that the mass of the found state and the observed decay channel (with a particle containing a $c\bar{c}$ pair among the decay products) indicated that X(3872) is one of the charmonium states. But the measured parameter values of X(3872) gave rise to doubts about this explanation. The mass determined in the Belle work, $M_X = (3872.0 \pm 0.6 \pm 0.5)$ MeV$/c^2$, was equal (within error) to the sum of D^0- and D^{*0}-meson masses, thus causing a natural suspicion that this is not an accidental coincidence. Today, after scrupulous examinations, we are inclined to believe that the proximity of the X(3872) mass to the $D^0\bar{D}^{*0}$ threshold is related to the nature of the discovered particle.

The width of the X(3872) signal is consistent with zero: $\Gamma_{\rm tot} < 2.3$ MeV at 90% CL. Such a small value for a state with a mass ≈ 138 MeV$/c^2$ above the $D\bar{D}$ production threshold means that the $X(3872) \to D\bar{D}$ decay is either forbidden, e.g., by parity conservation (if X(3872) has unnatural spin parities, $J^P = 0^-, 1^+, 2^-$, and so on), or is strongly suppressed for some reason, e.g., by a large orbital moment (if $J^P = 3^-, 4^+$, and so on). The suppression can also be dynamic if X(3872) is not a charmonium state and, in addition to a $c\bar{c}$ pair, contains a gluon or a pair of light quarks. The decay of X(3872) into $D\bar{D}$ is not observed experimentally, and the established upper limit of the ratio $\Gamma(X(3872) \to D\bar{D})/\Gamma(X(3872) \to J/\psi\,\pi^+\pi^-) < 7$ at 90% CL [67], although being insufficiently strict, allows assessing the possible degree of suppression. For comparison, this ratio exceeds 440 for the traditional charmonium state $\psi(3770)$, whose mass is significantly closer to the $D\bar{D}$ threshold [22].

In the first study [66], another unusual property of the new particle was discovered: for signal events, the $\pi^+\pi^-$ system mass is concentrated near the kinematic limit $M_{X(3872)} - M_{J/\psi} = 0.78$ GeV$/c^2$ (Fig. 8b) as if the decay proceeded via ρ^0-mesons.[9] Because the decay into $J/\psi\,\rho^0$ is suppressed for a charmonium by isotopic symmetry, the confirmation that the observed dynamics is caused by the ρ^0-meson contribution would evidence against the traditional charmonium hypothesis [for comparison, the probability of $\psi(2S) \to J/\psi\,\pi^0$, suppressed by isospin decay, is only $(1.26 \pm 0.13) \times 10^{-3}$]. To verify that the $\pi^+\pi^-$ system is indeed a ρ^0 meson, it is necessary to measure quantum numbers of X(3872).

5.2 X(3872) in other experiments

The discovery of X(3872) was soon confirmed by the CDF [68] and D0 [69] collaborations in inclusive production in $p\bar{p}$ interactions. The invariant mass spectra of the $J/\psi\,\pi^+\pi^-$ combinations, where a distinct second peak corresponding to the X(3872) production is observed in addition to the large $\psi(2S)$ peak, are given in Fig. 9. Both collaborations confirmed that the $\pi^+\pi^-$ system is created preferentially with large masses. Investigation of the X(3872) production vertex allowed concluding that X(3872) is produced predominantly in $p\bar{p}$ interactions directly and only $(16.1 \pm 4.9 \pm 2.0)\%$ of

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[9] In the $\psi(2S) \to J/\psi\,\pi^+\pi^-$ decay, the $\pi^+\pi^-$ system is also concentrated near the upper kinematic decay threshold, but this is caused by the dynamics of a particular decay for 2S → 1S transitions (by the so-called Adler zeros, suppressing transitions with small $\pi^+\pi^-$ masses).

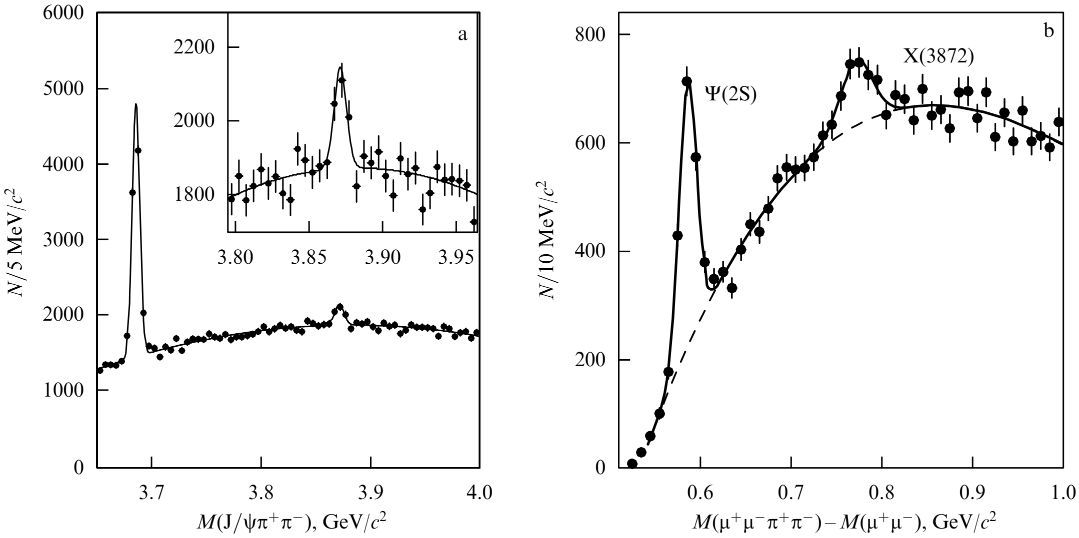

Figure 9. (a) Invariant mass spectrum of the $J/\psi\,\pi^+\pi^-$ combinations in the CDF experiment. (b) The spectrum of the mass differences for the $\mu^+\mu^-\pi^+\pi^-$ and $\mu^+\mu^-$ combinations under the condition $M(\pi^+\pi^-) > 0.5$ GeV/c^2 in the D0 experiment.

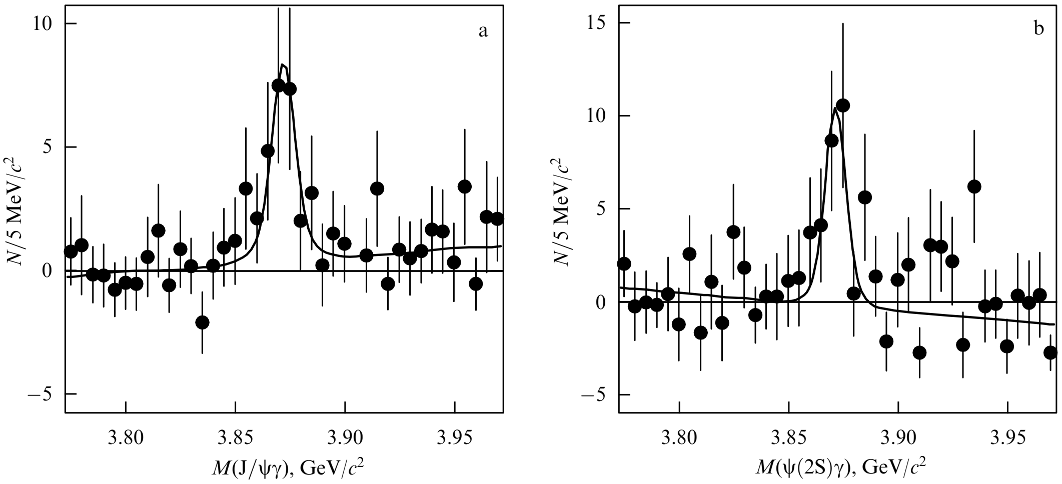

Figure 10. The invariant mass spectrum of: (a) $J/\psi\,\gamma$ and (b) $\psi(2S)\,\gamma$ in the BaBar experiment after subtraction of the background.

all the reconstructed X(3872) are products of the decay of hadrons containing a b quark.

Production of X(3872) in the $B^+ \to K^+ X(3872)$ decay was also confirmed by the BaBar collaboration [70]. Moreover, the BaBar collaboration cleverly attempted to measure the $B^+ \to K^+ X(3872)$ and $X(3872) \to J/\psi\,\pi^+\pi^-$ branching fractions separately [71]. For this purpose, only a charged kaon (from a B^+-meson decay) and a second B^- meson were reconstructed in the event. Thus, all particles except X(3872) were detected and their momenta measured. Due to the energy–momentum conservation, the mass of the nonreconstructed particle is $M_X = [(E_{CM} - E_{B^-} - E_{K^+})^2 - (\mathbf{p}_{B^-} + \mathbf{p}_{K^+})^2]^{1/2}$. Although an X(3872) signal was not detected in this work (while the expected charmonium states were observed), an important conclusion was made: the $B^+ \to K^+ X(3872)$ decay has a relatively small branching fraction and therefore the $X(3872) \to J/\psi\,\pi^+\pi^-$ decay branching fraction is large: $\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) > 4.2$ at 90% CL! Such impressively large value seems surprising when taking into account that (as shown in Section 5.3) this decay is suppressed for charmonium by isotopic symmetry.

5.3 Measuring quantum numbers

A year after the discovery of X(3872), the Belle collaboration found an indication of the existence of a $X(3872) \to J/\psi\,\gamma$ decay [72]. This observation was confirmed by the BaBar collaboration [73], and in 2008 BaBar presented new results of more precise measurements of the $X(3872) \to J/\psi\,\gamma$ branching fractions [74]. The invariant mass spectrum of $J/\psi\,\gamma$ from $B^+ \to K^+ J/\psi\,\gamma$ decays measured in this last study is given in Fig. 10a. The product of decay branching fractions

$$\mathcal{B}\big(B^+ \to K^+ X(3872)\big)\,\mathcal{B}\big(X(3872) \to J/\psi\,\gamma\big) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$$

agrees with the values obtained earlier by the Belle and BaBar collaborations.

The BaBar collaboration also reported on the observation of a new mode of the $X(3872) \to \psi(2S)\,\gamma$ decay [74] (Fig. 10b), with the product of decay branching fractions

$$\mathcal{B}\big(B^+ \to K^+ X(3872)\big)\,\mathcal{B}\big(X(3872) \to \psi(2S)\,\gamma\big) = (9.5 \pm 2.7 \pm 0.6) \times 10^{-6}\,.$$

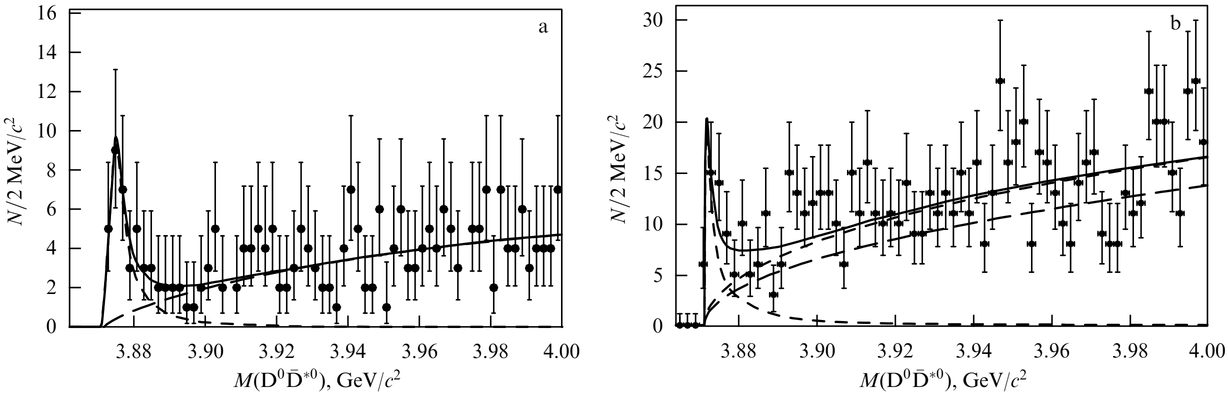

Figure 11. Invariant mass spectrum of the $D^0\bar{D}^{*0}$ combinations in the Belle (a) and BaBar (b) experiments.

Despite the significantly smaller phase space in this decay, its branching fraction was three times greater than the $J/\psi\,\gamma$ decay probabilities. This unexpected effect should be accepted with care because the errors of both measurements are quite large.

From observations of radiative transitions to J/ψ and $\psi(2S)$, which fix the positive charge parity of X(3872) ($C_{X(3872)} = C_{J/\psi}\,C_\gamma = +1$), it follows that the $\pi^+\pi^-$ system has a negative charge parity, i.e., an odd angular momentum and a negative spatial parity. These quantum numbers indicate that the $X(3872) \to J/\psi\,\pi^+\pi^-$ decay actually proceed via the ρ^0 meson.[10] In the Belle collaboration work [72], an indication was obtained on the existence of a $X(3872) \to J/\psi\,\pi^+\pi^-\pi^0$ decay. In the system of three π mesons, the contribution of the under-threshold ω resonance dominated, and the branching fraction of this decay was comparable to that of $X(3872) \to J/\psi\,\pi^+\pi^-$. The existence of the transition of X(3872) into J/ψ, with emission of both even and odd number of π mesons, also indicates the significant breaking of isotopic invariance in X(3872) decays.

Direct measurement of the X(3872) quantum numbers is possible if an angular analysis of decays of this state is conducted. Conservation of the angular momentum, parity, and charge parity in strong decays allows predicting (sometimes ambiguously) the distributions of a set of angular variables for a certain set of J^{PC}. The $X(3872) \to J/\psi\,\rho^0 \to (l^+l^-)\,(\pi^+\pi^-)$ decay is characterized by three angles that can be chosen, for example, as follows:

- the angle between the momenta of π^+ and X(3872) in the rest frame of the $\pi^+\pi^-$ system (defines the $\pi^+\pi^-$-system polarization);
- the angle between the momenta of l^+ and X(3872) in the rest frame of J/ψ (defines the J/ψ polarization);
- the angle between the $(\pi^+\pi^-)$ and (l^+l^-) planes in the rest frame of X(3872).

If X(3872) is produced in two-particle B-meson decays, there is a possibility of using additional angle variables for the analysis. It must only be remembered that B-meson decay proceeds via weak interaction in which the angular momentum is conserved, but spatial parity is not.

The Belle collaboration compared the expected angular distributions for a particle with the quantum numbers $J^{PC} = 0^{++}$ or 0^{-+} with experimental results and excluded these possibilities [75]. At the same time, the data agree well with the hypothesis that $J^{PC} = 1^{++}$. Later, the CDF collaboration performed a more comprehensive consistent analysis, in which all possible sets of J^{PC} quantum numbers with $J \leqslant 3$, and even those impossible for charmonium states, were checked [76]. A fit of the angular distributions shows that the quantum numbers $J^{PC} = 1^{++}$ and 2^{-+} are possible with approximately equal probabilities. Other quantum numbers are completely excluded.

5.4 Decays in charmed mesons

In 2005, the Belle collaboration reported the observation of an excess of events in the invariant mass spectrum of the $D^0\bar{D}^0\pi^0$ combinations from the $B \to KD^0\bar{D}^0\pi^0$ decay. The significance of the near-threshold peak was $6.4\,\sigma$ and the mass measured under the assumption of a resonant state decaying into $D^0\bar{D}^0\pi^0$ was $(3875.2 \pm 0.7^{+0.9}_{-1.8})$ MeV$/c^2$ [77]. However, it was not possible to reliably determine whether that was a three-body decay or it proceeded via an intermediate $D^0\bar{D}^{*0}$ state. A year later, the BaBar collaboration presented the results of an investigation of $B \to KD^0\bar{D}^{*0}$ decays and confirmed the presence of a peak with the mass $(3875.1^{+0.7}_{-0.5} \pm 0.5)$ MeV$/c^2$ [78] (Fig. 11a). The mass values obtained in the Belle and BaBar studies agree well with each other and their average differs by 3 MeV$/c^2$ ($4.5\,\sigma$) from the mass measured in the $J/\psi\,\pi^+\pi^-$-decay mode. These results only complicated the X(3872)-related puzzle: does the peak found in the invariant mass spectrum of the $D^0\bar{D}^0\pi^0$ combinations correspond to another new particle different from X(3872), or was the $X(3872) \to D^0\bar{D}^0\pi^0$ decay observed in the experiment? In the latter case, the mass difference can be explained by a statistical or systematic error, although it is not excluded that a physical explanation exists for the observed shift. For example, it was suggested in Refs [79–82] that X(3872) is a virtual state with the mass slightly below the $D^0\bar{D}^{*0}$ threshold. In the $J/\psi\,\pi^+\pi^-$ decay channel, the signal must then be narrow, and in the $D^0\bar{D}^{*0}$ channel, a mass shift and a noticeable signal width must be observed.

In 2008, the Belle collaboration presented new results of the investigation of $B \to KD^0\bar{D}^{*0}$ decays for a larger data set (Fig. 11b) [83]. The branching fraction and the decay width are comparable with the values published earlier by Belle [77] for nonresonant $D^0\bar{D}^0\pi^0$ decays, and the mass, $1\,\sigma$ lower [$M = (3872.6^{+0.5}_{-0.4} \pm 0.4)$ MeV$/c^2$], is now in agreement with the world average value for X(3872) in the $J/\psi\,\pi^+\pi^-$ mode [22].

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[10] Or, at least, that the $\pi^+\pi^-$ system has the ρ^0-meson quantum numbers, which does not change the statement on the significant breaking of isotopic symmetry in X(3872) decays.

5.5 Interpretations and their verification

Two yet undiscovered charmonium states, $\chi_{c1}(2P)$ (2^3P_1) and η_{c2} (1^1D_2), correspond to the measured quantum numbers of X(3872). The first one, $\chi_{c1}(2P)$, can be narrow if its mass is close to the $D^0\bar{D}^{*0}$ threshold. Although such a mass for $\chi_{c1}(2P)$ contradicts the potential models that predict the mass in the range $3.93 - 3.99$ GeV/c^2, it is not necessary to consider this argument against $\chi_{c1}(2P)$ as a serious one. As was already discussed, the mass measurement of $\chi_{c2}(2P)$ does not confirm the reliability of mass predictions. More critical for the hypothesis that X(3872) can be identified as $\chi_{c1}(2P)$ is the small probability of X(3872) decay into $J/\psi\gamma$. Estimates of the partial width for the $\chi_{c1}(2P) \to J/\psi\gamma$ decay give a value ~ 10 keV, while a typical decay width with isospin violation does not exceed ~ 0.5 keV for charmonium. At the same time, the measured ratio is $\mathcal{B}(X(3872) \to J/\psi\gamma)/\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.4$ at 90% CL, i.e., two orders of magnitude below the expected one.

The predicted mass of the second candidate, η_{c2}, is too small [84, 85]; it is more important, however, that this state is not expected to be narrow independently of its mass. Although decay into $D\bar{D}$ is also forbidden for it, a decay of η_{c2} via two-gluon annihilation should have the partial width of a few MeV or even a few dozen MeV. The isospin-suppressed decays just cannot compete with decays into light hadrons and their branching fraction should be negligibly small.

Today, the most popular explanation of the X(3872) nature is the assumption of a weakly bound state of D^0 and $\bar{D}^{*0}$ mesons (a $D^0\bar{D}^{*0}$ molecule) [86–89] that is based on the extraordinarily close proximity of the X(3872) mass to the position of the $D^0\bar{D}^{*0}$ threshold.[11] This hypothesis agrees with the measured quantum numbers $J^{PC} = 1^{++}$ expected for an S-wave $D^0\bar{D}^{*0}$ molecule. Furthermore, the molecular model predicts a comparable branching fractions for the decay to $J/\psi\rho^0$ and $J\psi\omega$, and a small branching fraction for the decay to $J/\psi\gamma$, which agrees well with experimental data. A problem for the molecular model is the absence of a reasonable explanation for the production mechanism of such weakly bound states in B-meson decays and especially in $p\bar{p}$ interactions. To resolve this, it is necessary to assume that X(3872) is a mixture of a $D^0\bar{D}^{*0}$ molecule with the usual charmonium having the same quantum numbers. It can then be produced as a usual charmonium and decay as a molecular state. The recently measured, too high strength of the $X(3872) \to \psi(2S)\gamma$ transition also contradicts the purely molecular interpretation of X(3872) and supports the model predicting a mixture of the $D^0\bar{D}^{*0}$ molecule with $\chi_{c1}(2P)$ [90].

Another tentative explanation of the nature of the X(3872) is given by tetraquark states [40–42]. The X(3872) in this case is a member of the family of $c\bar{q}\bar{c}q'$ tetraquarks, also including two charged states. A naive tetraquark model predicts equal branching fractions for the decays $B \to KX(3872)$ $(\to J/\psi\pi^+\pi^-)$ and $B \to KX^-(3872)$ $(\to J/\psi\pi^-\pi^0)$. To verify this hypothesis, the BaBar collaboration unsuccessfully searched for a charged partner of X(3872) in the last chain of decays [91]. The established upper limits for the probability of its production [approximately an order of magnitude smaller than the X(3872) production probability] excluded the isovector hypothesis for X(3872). After this measurement, the tetraquark model was modified such that the charged partner is produced weakly and the neutral 'colleague' of X(3872), whose mass according to this model is ~ 10 MeV/c^2 higher, prefers to be produced in decays of charged B-mesons (the diquark–antidiquark model [40–42]). To verify the new hypothesis, both the BaBar [92] and Belle [93] collaborations studied X(3872) in $B^+ \to K^+X(3872)$ and $B^0 \to K^0_S X(3872)$ decays. They obtained the ratio of branching fractions $\mathcal{B}(B^0 \to K^0X(3872))/\mathcal{B}(B^+ \to K^+X(3872))$ to be equal to $0.41 \pm 0.24 \pm 0.05$ (BaBar) and $0.82 \pm 0.22 \pm 0.05$ (Belle), which is consistent with unity. The difference of the measured mass values for X(3872) states created by charged and neutral B-mesons, given by $\Delta M \equiv M_{XK^+} - M_{XK^0} = (2.7 \pm 1.6 \pm 0.4)$ MeV/c^2 (obtained by the BaBar collaboration) and $(0.18 \pm 0.89 \pm 0.26)$ MeV/c^2 (obtained by Belle), is consistent with zero and contradicts the diquark–antidiquark model.

Among other possibilities, hybrids [94] or threshold effects [21] are considered; we do not discuss them here, however, because of the weak predicting power of these models. They are more difficult to exclude; according to K Popper, this just demonstrates the weakness of these approaches [95].

This year, we celebrate the seventh anniversary of the discovery of the X(3872)! Despite the considerable amount of experimental data obtained over these years and a variety of theoretical interpretations, the nature of this state remains mysterious.

6. The Y(3940) state

In investigating $B^+ \to J/\psi\omega K^+$ decays, the Belle collaboration found a near-threshold excess of events in the invariant mass spectrum of $J/\psi\omega$ combinations [96]. This was interpreted as a resonance with positive charge parity (it is fixed by the observed decay channel) and was called Y(3940). From the fit to the mass spectrum of $J/\psi\omega$ (Fig. 12a), the resonance parameters were determined as $M = (3943 \pm 11 \pm 13)$ MeV/c^2 and $\Gamma_{\text{tot}} = (87 \pm 22 \pm 26)$ MeV. The probability of Y(3940) production calculated from the observed number of events in the near-threshold peak (58 ± 11) was

$$\mathcal{B}\big(B^+ \to Y(3940)K^+\big)\,\mathcal{B}\big(Y(3940) \to J/\psi\omega\big) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}\,. \tag{4}$$

If we assume that the $B \to Y(3940)\,K$ decay branching fraction does not exceed 10^{-3}, which is a typical value for $B \to (c\bar{c})\,K$ decay modes, where $(c\bar{c}) = \eta_c$, J/ψ, χ_{c0}, χ_{c1}, $\psi(2S)$, then the partial width $\Gamma(Y(3940) \to J/\psi\omega)$ can be estimated from the measured production probability. Such an estimate gives the decay width of a few MeV, which is an order of magnitude higher than the values of partial widths of hadron transitions for known charmonium states, which are typically near 100 keV. Equally mysterious is that the Y(3940) decays to charmed mesons is not observed: decays of this state into either $D\bar{D}$ [67] or $D\bar{D}^*$ [83] were not found. If a decay into the first final state can be forbidden by parity conservation (unnatural quantum numbers $J^P = 0^-, 1^+, 2^-$, etc.), the second decay should dominate for charmonium having a mass much above the $D\bar{D}^*$ threshold.

The width estimate and the lack of decay channels natural for charmonium led to the idea of the exotic nature of

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[11] According to recent data, $M_X = (3872.2 \pm 0.8)$ MeV/$c^2 \sim M_{D^0} + M_{D^{*0}} = (3871.81 \pm 0.25)$ MeV/c^2 [22].

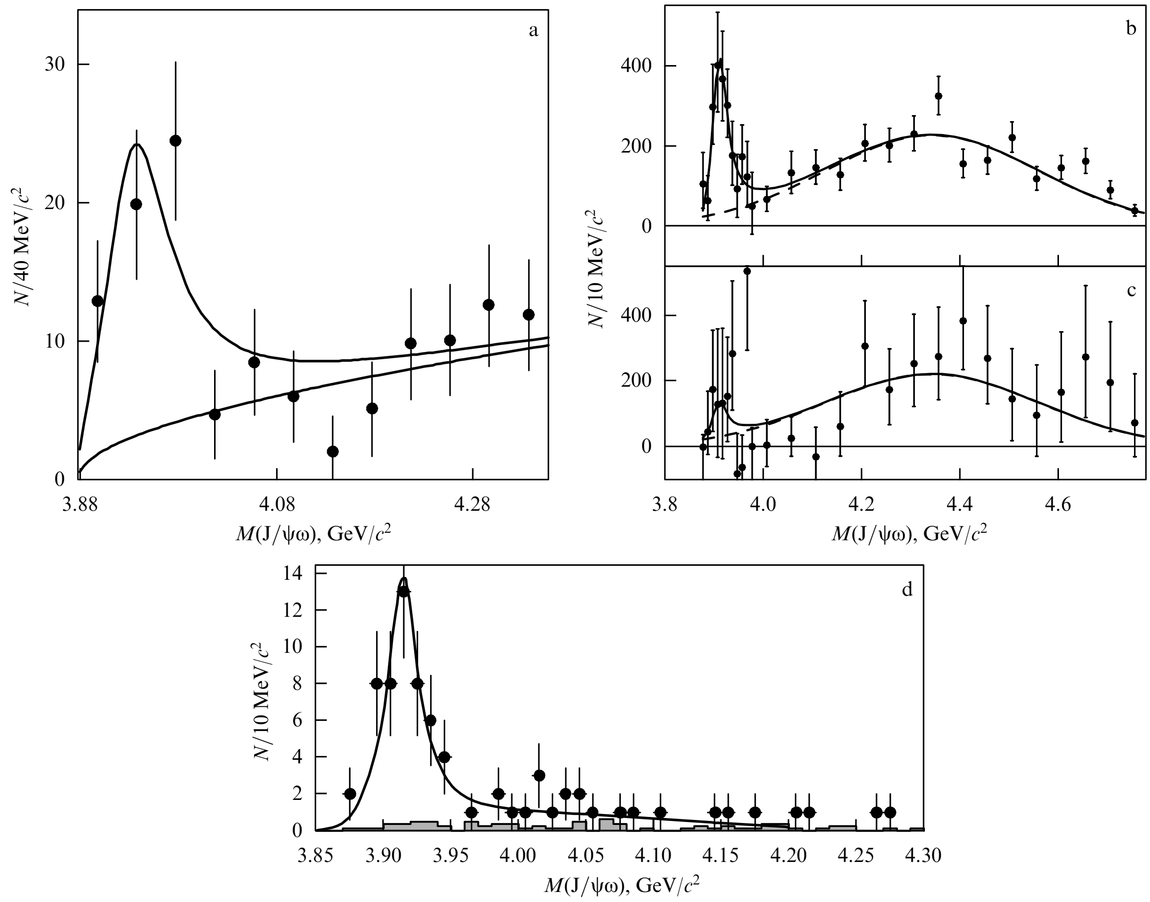

Figure 12. The mass spectra of J/ψ ω in B → J/ψ ω K decays obtained by Belle (a) and BaBar (b, c). BaBar studied Y(3940) production separately for charged (b) and neutral (c) B-mesons under the assumption of the existence of a resonance at the threshold. (d) The mass spectrum of J/ψ ω in γγ interactions in the Belle experiment. Results of fitting are shown by solid curves.

Y(3940). An assumption was made that Y(3940) can be a hybrid $c\bar{c}-g$ state, for which a decay into J/ψ or ψ(2S), accompanied by light hadrons, would be preferable [97, 98].

In 2007, the BaBar collaboration presented the results of a similar investigation for a larger data set [99]. In the invariant mass spectrum of J/ψ ω (Fig. 12b, c), a near-threshold peak was observed that qualitatively agrees with that found by the Belle collaboration. Although the branching fraction $(4.9 \pm 1.0 \pm 0.5) \times 10^{-5}$ measured by BaBar does not contradict the data measured by Belle, the mass and width values of Y(3940) differ substantially. In the BaBar investigation, they were $M = (3914.6^{+3.8}_{-3.4} \pm 1.9)$ MeV/c^2 and $\Gamma_{\text{tot}} = (33^{+12}_{-8} \pm 5)$ MeV. Assuming that the newly measured Y(3940) parameters are correct partially facilitates the interpretation of Y(3940) as one of charmonium states. Indeed, according to our arguments, $\Gamma(\text{Y}(3940) \to \text{J}/\psi\,\omega)$ becomes approximately four times smaller with the new data and the discrepancy with rough estimates is no longer very significant. On the other hand, the Y(3940) mass measured by the BaBar collaboration is much closer to the $\text{D}\bar{\text{D}}^*$ threshold, and this decay can be suppressed due to the small phase space.

In 2009, the Belle collaboration found a state in the mass spectrum of J/ψ ω (Fig. 12d) in γγ interactions, whose parameters coincide with Y(3940) [100]. The significance of the peak observation was 7.5 σ and the mass and full width, $M = (3915 \pm 3 \pm 2)$ MeV/c^2 and $\Gamma_{\text{tot}} = (17 \pm 10 \pm 3)$ MeV, in perfect agreement with the BaBar results. Apparently, there should be no doubt that Y(3940) was found, and only the inherent caution of the authors of this discovery prevents that conclusion. The ability of Y(3940) to be produced in γγ-interactions means that its spin is not equal to one.

We note that conclusions about the possible exotic nature of Y(3940) are still quite shaky. New experimental data are necessary for interpreting this state. In particular, an angular analysis would allow fixing the remaining unknown spin and spatial parity of this state.

7. Charmonium-like states produced together with J/ψ

In 2006, the Belle collaboration found another peak in the spectrum of masses recoiling against J/ψ in e^+e^- annihilation, a peak in addition to the known η_c, χ_{c0}, and $\eta_c(2S)$, with the mass close to 3.94 GeV/c^2 and the statistical significance 5.0 σ (Fig. 13) [56]. From fitting the spectrum (by assuming the contribution of one new resonance), the parameters of the state called X(3940) were found: $M = (3943 \pm 6 \pm 6)$ MeV/c^2 and $\Gamma_{\text{tot}} < 52$ MeV at 90% CL.

To search for decays of X(3940) into charmed hadrons, a partial reconstruction of the final state was used:[12] in addition to J/ψ, one $\text{D}^{(*)}$ meson was reconstructed in the event, and the existence and mass of the second charmed meson could be

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[12] It was impossible to reconstruct both charmed mesons from X(3940) decay because of the low reconstruction efficiency for each of them.

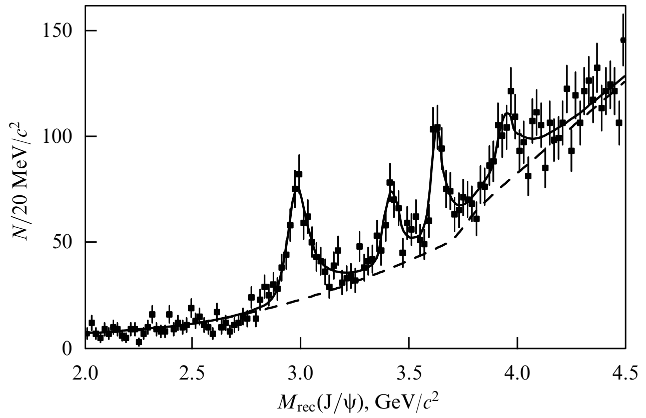

Figure 13. The recoil mass spectrum $M_{\rm rec}(J/\psi)$ according to the Belle experimental data. The fitting results are shown by the solid line, and the dashed line corresponds to the expected background distribution.

inferred from the recoil mass of a combination of the reconstructed $J/\psi\, D^{(*)}$. A good recoil mass resolution allows discriminating among the $e^+e^- \to J/\psi\, D\bar{D}$, $D\bar{D}^*$, and $D^*\bar{D}^*$ processes and studying the invariant mass of a pair of charmed mesons in each of them separately.

Two years after the discovery of X(3940), the Belle collaboration repeated the investigation of these processes by using tripled data statistics [101]. In the $e^+e^- \to J/\psi\, D\bar{D}$ process, the $D\bar{D}$-pair invariant mass is concentrated near the threshold as a broad bump; however, it was not possible to identify that as a resonance. In the $e^+e^- \to J/\psi\, D\bar{D}^*$ process, a peak with significance $5.7\,\sigma$ corresponding to the production of X(3940) (Fig. 14a) is clearly visible in the invariant mass spectrum of $D\bar{D}^*$. The measured mass and width are $M = (3942^{+7}_{-6} \pm 6)$ MeV/c^2 and $\Gamma_{\rm tot} = (37^{+26}_{-18} \pm 8)$ MeV, which agrees well with the results of the first investigation. Another state called X(4160) was found in the $e^+e^- \to J/\psi D^*\bar{D}^*$ process. As can be seen from Fig. 14b, events in the $D^*\bar{D}^*$ mass spectrum concentrate near the threshold, and the background is almost completely absent. The mass and width of X(4160) were $M = (4156^{+25}_{-20} \pm 15)$ MeV/c^2 and $\Gamma_{\rm tot} = (139^{+111}_{-61} \pm 21)$ MeV, and the significance of observation was $5.1\,\sigma$. Although the mass and width of the new X(4160) state agree within errors with the parameters of the known charmonium $\psi(4160)$ state, the latter should be excluded from interpretation because it has the opposite charge parity.

Because scalar and pseudoscalar charmonium states are preferably produced together with J/ψ (see Section 3.4), it is natural to assume that new particles are radial excitations of either $^1S_0$ or $^3P_0$. The latter assignment is unlikely because the decay into $D\bar{D}$ is allowed for a 2^3P_0 state. Due to the large phase space, this decay channel dominates and the 2^3P_0 state is expected to be very broad. This state can probably explain the above-mentioned broad bump of events in the $D\bar{D}$ mass spectrum, but this state is not suitable as an explanation for X(3940) and X(4160).

The most probable remaining candidate for X(3940) is the third radial excitation of the η_c meson, $\eta_c(3S)$; however, such an explanation also leads to certain difficulties. Because the 3^3S_1 state is $\psi(4040)$ with the mass (4039 ± 1) MeV/c^2 [22], interpreting X(3940) as $\eta_c(3S)$ leads to a larger mass split for the radial quantum number $n = 3$ ($\simeq 100$ MeV/c^2) than that for $n = 2$ ($\simeq 50$ MeV/c^2). The possibility of such anomalous splitting is discussed in Ref. [85], where the presence of a large $D\bar{D}^*$ and $D^*\bar{D}^*$ admixture in the wave functions of vector and scalar mesons is assumed. The width of $\eta_c(3S)$, with its mass being close to 3940 MeV/c^2, is expected to be about 50 MeV, which agrees well with the measured value. It would seem that it is possible to accept this interpretation and to recognize the qualitative agreement of theory and experiment; however, the nature of the X(4160) state must also be explained. Assuming that this state is the fourth radial excitation of the η_c meson, we obtain an even larger splitting for $n = 4$ ($\simeq 300$ MeV/c^2) if we accept the established opinion that the 4^3S_1 state is $\psi(4415)$. Such a mass shift for 4^3S_1 or 4^0S_1, or both of them, can hardly be explained by an admixture of charmed meson pairs. It is interesting that the X(4160) state does not decay into $D\bar{D}^*$.

Although the masses, widths, and decay channels of particles discussed in this section are themselves not exotic, there has not yet been found a self-consistent interpretation for them within the charmonium model. For this purpose, help from experimentalists capable of measuring quantum numbers of these particles and investigating their new production and decay channels is also necessary.

8. Charmonium-like states in e^+e^- annihilation

A family of charmonium-like states with masses above the open charm threshold was discovered in $e^+e^- \to J/\psi\, \pi^+\pi^-\, \gamma_{\rm ISR}$ and $e^+e^- \to \psi(2S)\, \pi^+\pi^-\, \gamma_{\rm ISR}$ pro-

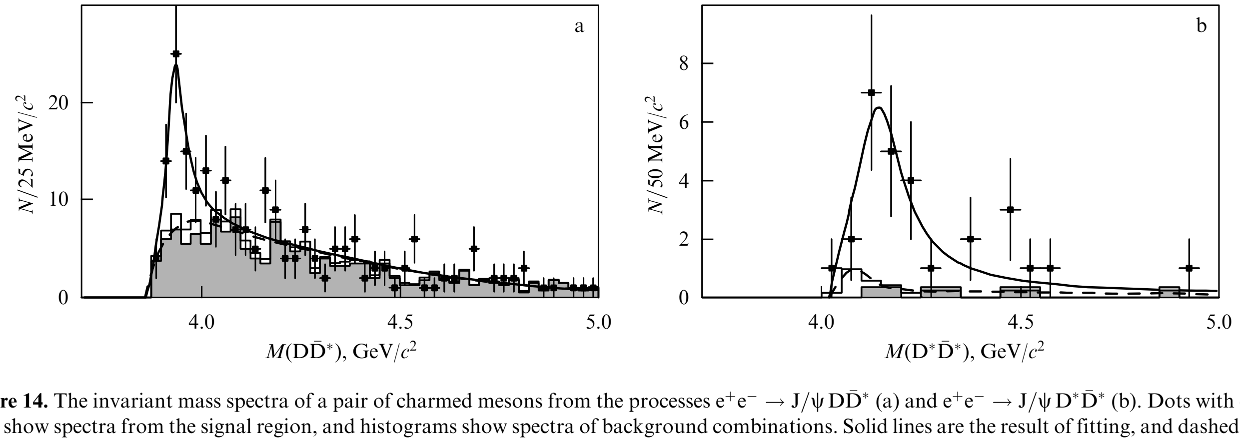

Figure 14. The invariant mass spectra of a pair of charmed mesons from the processes $e^+e^- \to J/\psi\, D\bar{D}^*$ (a) and $e^+e^- \to J/\psi\, D^*\bar{D}^*$ (b). Dots with error bars show spectra from the signal region, and histograms show spectra of background combinations. Solid lines are the result of fitting, and dashed lines correspond to the background contribution.

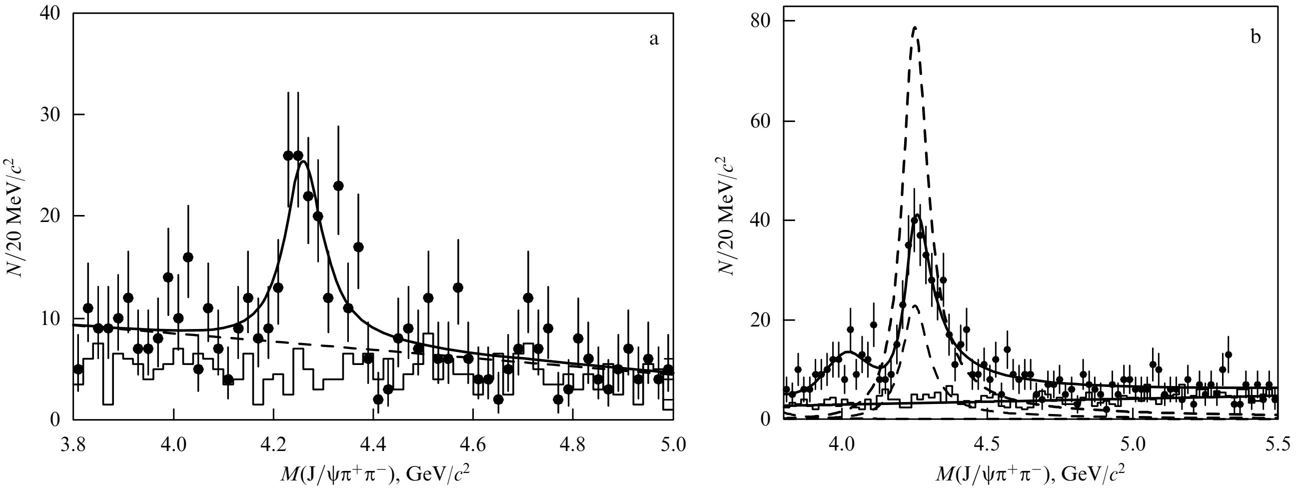

Figure 15. Invariant mass spectra of the $J/\psi\,\pi^+\pi^-$ combinations in the BaBar (a) and Belle (b) experiments. The fit results are shown by the solid lines. In the fit to the Belle data, an interference leading to ambiguous solutions (two possible solutions are shown by the dashed lines) was taken into account.

Table 3. The measured parameters of Y states from the $J^{PC} = 1^{--}$ family.

State	M, MeV/c^2	$\Gamma_{\rm tot}$, MeV	Decay mode	Collaboration	Year
Y(4008)	$4008 \pm 40^{+114}_{-28}$	$226 \pm 44 \pm 87$	$J/\psi\,\pi^+\pi^-$	Belle [108]	2007
Y(4260)	$4259 \pm 8^{+2}_{-6}$	$88 \pm 23^{+6}_{-4}$	$J/\psi\,\pi^+\pi^-$	BaBar [102]	2005
	$4252 \pm 6^{+2}_{-3}$	$105 \pm 18^{+4}_{-6}$	$J/\psi\,\pi^+\pi^-$	BaBar [106]	2008
	$4247 \pm 12^{+17}_{-32}$	$108 \pm 19 \pm 10$	$J/\psi\,\pi^+\pi^-$	Belle [105]	2007
Y(4325)	4324 ± 24	172 ± 33	$\psi(2S)\,\pi^+\pi^-$	BaBar [107]	2007
	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$	$\psi(2S)\,\pi^+\pi^-$	Belle [108]	2007
Y(4660)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$	$\psi(2S)\,\pi^+\pi^-$	Belle [108]	2007

cesses with radiation of a hard photon ($\gamma_{\rm ISR}$) in the initial state. The quantum numbers of resonances are explicitly fixed by their production process: $J^{PC} = 1^{--}$. The first state, called Y(4260), was found in 2005 by the BaBar collaboration, which, exploring the $e^+e^- \to J/\psi\,\pi^+\pi^-\gamma_{\rm ISR}$ process, discovered an excess of events in the invariant mass spectrum of $J\psi\,\pi^+\pi^-$ combinations near 4.26 GeV/c^2 (Fig. 15a) [102]. The peak, containing 125 ± 23 events, was well described by the one-resonance structure. The parameters of Y(4260) and its 'relatives' from the $J^{PC} = 1^{--}$ family, measured in various experiments, are given in Table 3.

The existence of Y(4260) was soon confirmed by the CLEOc collaboration in two independent measurements. In the first of them, the BaBar's analysis was repeated using the data sample collected at the $\Upsilon(4S)$ resonance [103]. The mass and width of Y(4260) were in good agreement with those measured by BaBar (see Table 3). In the second measurement, the data were collected at the center-of-mass energy, $\sqrt{s}$, directly in the region of Y(4260) production [104]. By scanning $\sqrt{s}$ in the range 3.97–4.26 GeV, an increase in the cross section for e^+e^- annihilation into $J/\psi\,\pi^+\pi^-$ was observed at $\sqrt{s} = 4.26$ GeV, thus indicating the existence of a resonance. In 2007, the Belle collaboration also confirmed the existence of Y(4260) in e^+e^- annihilation with initial state radiation [105]. It appeared that the invariant mass spectrum of $J/\psi\,\pi^+\pi^-$ combinations, shown in Fig. 15b, is described by the contribution of two interfering resonances much better than by a single contribution of Y(4260). The interference allows explaining the signal asymmetry also visible in the BaBar collaboration data: a sharp increase in the number of events to the left of the Y(4260) mass and a smooth decrease to the right. The obtained parameters of Y(4260) agree with the BaBar measurements (see Table 3). A second wide and less clear feature near 4.00 GeV/c^2, called Y(4008), cannot be explained by the contribution of $\psi(4040)$, whose width is significantly smaller than that measured for Y(4008). This Belle work could not prove that this lower mass excess is due to the contribution of a new resonance instead of nonresonant production of $J/\psi\,\pi^+\pi^-$; however, the possibility of nonresonant production of $J/\psi\,\pi^+\pi^-$ is quite unexpected. In 2008, the BaBar collaboration did not confirm the presence of the Y(4008) resonance, but the contribution of nonresonant production of $J/\psi\,\pi^+\pi^-$ [106] was not excluded. The nature of the peak near 4.00 GeV/c^2 still remains unclear.

In 2006, the BaBar collaboration found another wide structure close to the mass 4.32 GeV/c^2, this time in the process $e^+e^- \to \psi(2S)\,\pi^+\pi^-\gamma_{\rm ISR}$ [107]. The observed peak (Fig. 16a), called Y(4325), could not be identified as the state Y(4260) because their masses are significantly different (see Table 3). Investigating the same process using a larger set of data statistics, the Belle collaboration not only confirmed the existence of Y(4325) [108] but also found another peak called Y(4660) (Fig. 16b).

Neither Y(4325) nor Y(4660) decay to $J/\psi\,\pi^+\pi^-$, and Y(4260) and Y(4008) were not found in decays to $\psi(2S)\,\pi^+\pi^-$. The Y-states are not seen as peaks in the total cross section of e^+e^- annihilation into hadrons [109], nor in

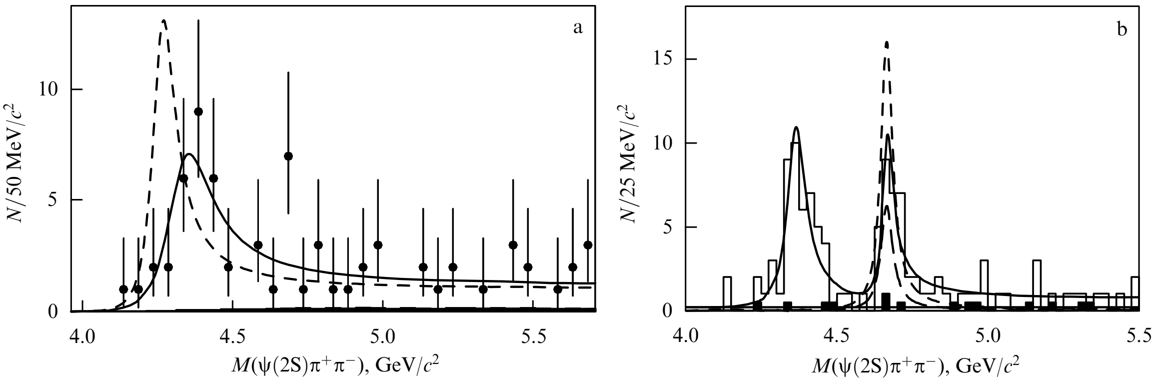

Figure 16. Invariant mass spectra of the $\psi(2S)\,\pi^+\pi^-$ combinations in the BaBar (a) and Belle (b) experiments. The fit results are shown by the solid lines. The two dashed lines show two possible solutions taking interference on the basis of the Belle data into account.

exclusive $e^+e^- \to D\bar{D}$ cross sections [110, 111], $D\bar{D}^*$, $D^*\bar{D}^*$ [112, 113], or $D\bar{D}\pi$ [114]. However, it is probable that Y(4260) appears as a local minimum in the total cross section as well as in the exclusive cross section of $e^+e^- \to D^*\bar{D}^*$ at $\sqrt{s} \sim 4.26$ GeV, with a width comparable to $\Gamma_{\rm tot}(Y(4260))$.

As a result of the detailed analysis of the total e^+e^--annihilation cross section, the lower limit for the branching fraction of the $Y(4260) \to J/\psi\,\pi^+\pi^-$ decay was 0.6% at 90% CL [115]. This value, together with the measured width of Y(4260), allows estimating the partial width of the $Y(4260) \to J/\psi\,\pi^+\pi^-$ decay to be at least an order of magnitude larger than the value expected for a usual charmonium with such a mass. Recently the BaBar collaboration, using their measurements of the exclusive cross sections of e^+e^- annihilation into charmed mesons, set upper limits on the ratio of the branching fractions of the decays $Y(4260) \to D\bar{D}, D\bar{D}^*, D^*\bar{D}^*$ to those of $Y(4260) \to J/\psi\,\pi^+\pi^-$ to be 7.6, 34, and 40 at 90% CL, respectively [111, 113]. For comparison, the ratio $\mathcal{B}(\psi(3770) \to D\bar{D})/\mathcal{B}(\psi(3770) \to J/\psi\,\pi^+\pi^-)$ exceeds 440 (!) [22].

Another problem is the lack of place for three resonances in the spectrum of charmonium states with 1^{--} quantum numbers. Three levels in this mass interval are already occupied by ψ-resonances: it is assumed that up to the S$-$D mixing, $3^3S_1 = \psi(4040)$, $2^3D_1 = \psi(4160)$, and $4^3S_1 = \psi(4415)$. Their properties, including the branching fractions of their decays to hadrons, agree quite well with the predictions of the charmonium model [23, 84], and there are no obvious reasons to change anything. According to the same model, it is expected that the masses of states not yet found [$3^3D_1(4560)$, $5^3S_1(4760)$, and $4^3D_1(4810)$] are higher than the measured masses of Y-resonances by 300 MeV/c^2. This problem can still be resolved somehow by suggesting mechanisms that allow to shift the expected masses of some states [116, 117]; however, it would hardly explain the existence of exotic decay channels of the new family and the lack of traditional channels. Another possible solution is to include the effects of coupled channels and rescattering between pairs of charmed mesons [118].

One of the popular suggestions is to interpret Y-states as hybrids [97, 98, 119, 120]. As we have already noted, according to QCD models and lattice calculations, the lightest hybrid has a mass near 4.2 GeV/c^2. It is expected that its decays into $D^{(*)}\bar{D}^{(*)}$ are suppressed and decays into $D^{(*)}\bar{D}^{**}$ dominate. The decay threshold into $D\bar{D}_1^{**}$, 4.287 GeV/c^2, is slightly above the Y(4260) mass; hence, the $Y(4260) \to D\bar{D}_1^{**}$ decay should proceed via a virtual $\bar{D}_1^{**}$. This can probably explain why decays of Y(4260) into charmed mesons are suppressed and Y(4260) is not visible in the total cross section of e^+e^- annihilations into hadrons. However, the absence of any sign of Y(4360) and Y(4660) states whose masses exceed the $D\bar{D}_1^{**}$ production threshold is a weak point of the hybrid interpretation. Among other hypotheses are the hadrocharmonium (a compact charmonium state surrounded by an excited light meson) [35], multiquark states, including tetraquark [121, 122], $D\bar{D}_1$ or $D_0\bar{D}^*$ molecules [123, 124], and the $f_0(980)\psi(2S)$ molecule for Y(4660) [125].

The variety of suggested hypotheses and the lack of an obvious leader among them indicate that the new family is still poorly explained.

9. Cross sections of e^+e^- annihilation into charmed hadrons

The discovery of the mysterious family of states with quantum numbers $J^{PC} = 1^{--}$ discussed in Section 8 focused attention on the often measured inclusive cross sections of $e^+e^- \to$ *hadrons*. Until recently, parameters of ψ-states were determined from this cross section by ignoring their possible interference [126], and only in 2008 a first attempt was performed to account for an interference of ten final states from decays of ψ-resonances [127]. But the description of these decays was based on predictions of theoretical models, and therefore the obtained result remained model dependent and consequently unreliable. It is obvious that an attempt to include also a description of the Y-state in the cross section, which would lead to the appearance of a set of free parameters, is doomed to fail. The only way that gives a chance to reliably determine the parameters of ψ, to study their decays, and to establish upper probability limits for decays of Y into two-meson final states is measuring the cross sections of exclusive processes.

Exclusive pair production cross sections of charmed hadrons in e^+e^- annihilations near the open charm threshold were first measured by the Belle [110, 112, 114, 128, 129] and BaBar [111, 113] collaborations, which used initial state radiation. Just a little later, the CLEOc collaboration presented the observation data for $e^+e^- \to D^{(*)}\bar{D}^{(*)}$ and $D_s^{(*)}\bar{D}_s^{(*)}$ cross sections in a narrow range, from $\sqrt{s} = 3.77$ GeV to $\sqrt{s} = 4.26$ GeV, for 13 points obtained upon scanning the beam energy [130].

The Belle collaboration started the investigations in 2007 from the $e^+e^- \to D^{*+}D^{*-}$ and $e^+e^- \to D^+D^{*-}$ processes

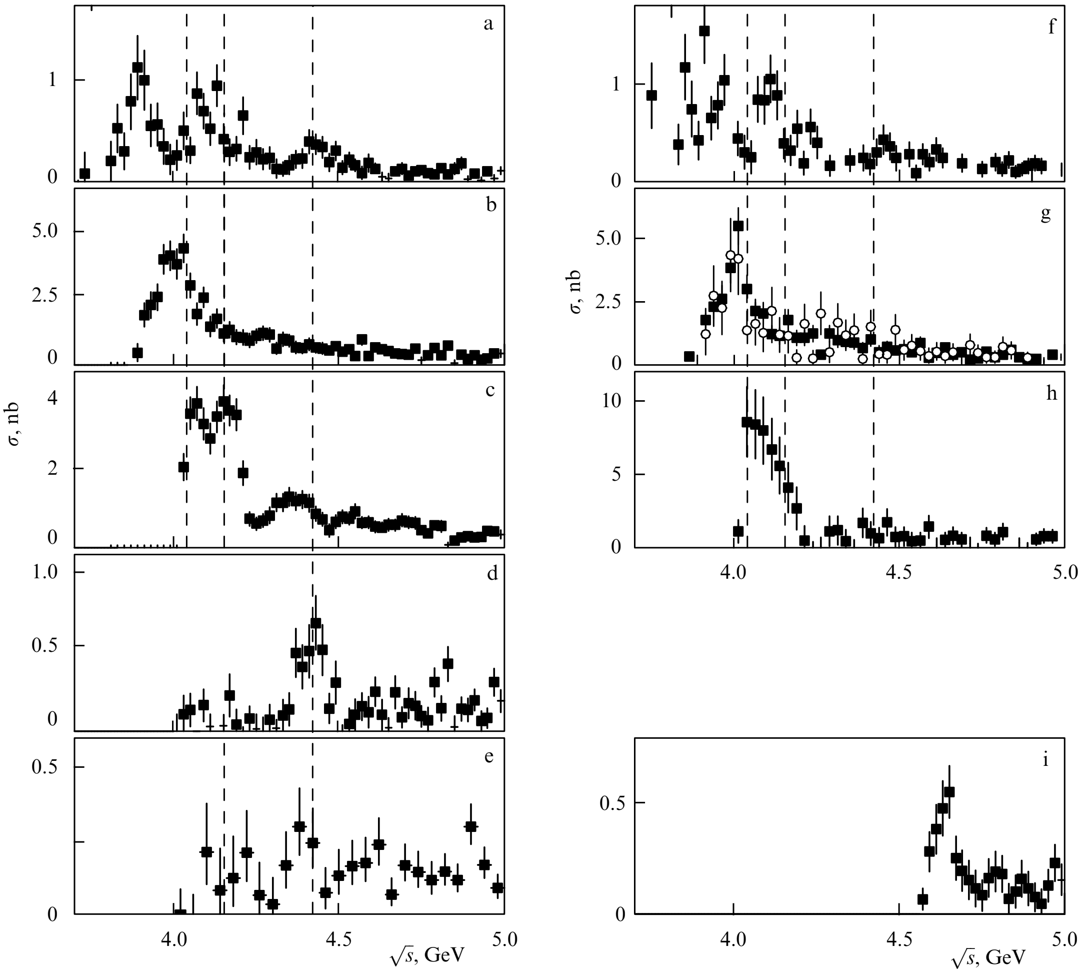

Figure 17. Exclusive cross sections measured in the Belle experiment: (a) $e^+e^- \to D\bar{D}$ (the sum of $D^0\bar{D}^0$ and D^+D^-), (b) $e^+e^- \to D^+D^{*-}$, (c) $e^+e^- \to D^{*+}D^{*-}$, (d) $e^+e^- \to D^0D^-\pi^+$, (e) $e^+e^- \to D^0D^{*-}\pi^+$, (i) $e^+e^- \to \Lambda_c^+\Lambda_c^-$. Exclusive cross sections measured in the BaBar experiment: (f) $e^+e^- \to D\bar{D}$ (the sum of $D^0\bar{D}^0$ and D^+D^-), (g) $e^+e^- \to D^+D^{*-}$ (circles), $e^+e^- \to D^0\bar{D}^{*0}$ (squares), (h) $e^+e^- \to D^*\bar{D}^*$ (the sum of $D^{*0}\bar{D}^{*0}$ and $D^{*+}D^{*-}$). Dashed straight lines show the mass values of ψ-states.

[112] by using a partial reconstruction of the final state[13] to increase the efficiency. Two years later, the BaBar collaboration also measured the $e^+e^- \to D\bar{D}^*$ and $e^+e^- \to D^*\bar{D}^*$ cross sections by using the full reconstruction of the final state (which approximately reduced the statistics by an order of magnitude) and including both the charged and the neutral final states (which doubled the statistics). The results obtained in the Belle (Fig. 17c) and BaBar (Fig. 17f) experiments are in good agreement. The cross section of the $e^+e^- \to D^*\bar{D}^*$ process has a rich structure, whose details are yet to be fully understood. The first two maxima are close to the position of the known ψ(4040) and ψ(4160) states. The distinct minimum close to 4.25 GeV/c^2 probably indicates a destructive interference of Y(4260) with ψ(nS) states or an influence of $D_s^*\bar{D}_s^*$, and $D\bar{D}^{**}$ opening thresholds.

In the cross section of the $e^+e^- \to D\bar{D}^*$ process (the Belle results are shown in Fig. 17b and the BaBar results in Fig. 17g), besides a wide peak near the ψ(4040) mass, no other significant structures are seen. We note that the ψ(4415) signal is not seen explicitly in the $e^+e^- \to D^*\bar{D}^*$ or $e^+e^- \to D\bar{D}^*$ cross section.

In 2007, the $e^+e^- \to D\bar{D}$ cross section was measured by the Belle [110] (Fig. 17a) and BaBar [111, 113] (Fig. 17f) collaborations. In these studies, both D mesons were fully reconstructed. These results, within measurement errors, agree with each other and do not qualitatively contradict the model of coupled channels [131], predicting a peak-like increase in the cross section close to 3.9 GeV/c^2 and its decrease above the $D\bar{D}^*$ threshold, unrelated to a resonance. Because of large measurement errors, it is still difficult to conclude about the nature of a structure observed in the range 4.0–4.2 GeV, which is probably related to ψ(4040) and ψ(4160). In the $e^+e^- \to D\bar{D}$ cross section, there were the first indications of a ψ(4415) signal.

The exclusive production of the heaviest known $J^{PC} = 1^{--}$ charmonium excitations, ψ(4415), was first clearly observed in the $e^+e^- \to D^0D^-\pi^+$ process (Fig. 17d) [114]. The significance of the ψ(4415) signal was approximately $10\,\sigma$ and its measured mass and full width [$M = (4.411 \pm 0.007)$ GeV/c^2 and $\Gamma_{\text{tot}} = (77 \pm 20)$ MeV] are in good agreement with world average values [22] and the last data of the BES collaboration [127]. It was revealed that the ψ(4415) signal arises only if one of the $D^0\pi^+$ or $D^-\pi^+$ combinations is in the $\bar{D}_2^*(2460)$ region, and the ψ(4415) peak disappears outside the $\bar{D}_2^*(2460)$ signal region. The

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[13] In addition to a hard photon, only one $D^{(*)+}$ meson and a soft pion from the second D^{*-} decay were detected.

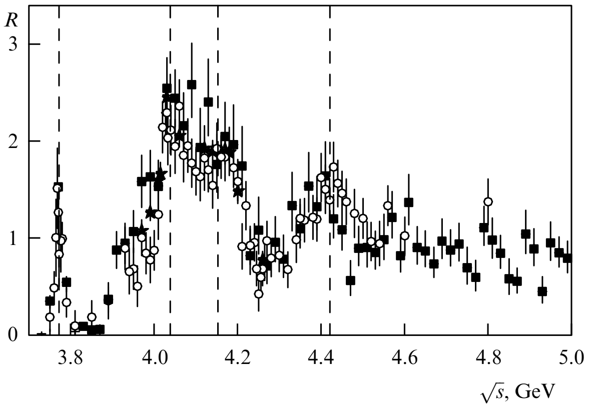

Figure 18. The ratio of cross sections of e^+e^- annihilation into charmed hadrons and into muons measured by the CLEOc (triangles), BES (circles), and Belle (squares) collaborations. Dashed straight lines show the respective mass values of ψ- and Y-states.

obtained upper limit for the ratio of the nonresonant decay to the decay into $D\bar{D}_2^*(2460)$ was 0.22 at 90% CL.

In 2008, the Belle collaboration reported on an observation of a significant peak called X(4630) at the threshold in an $e^+e^- \to \Lambda_c^+\Lambda_c^-$ exclusive cross section (Fig. 17i) [128]. It is still unclear whether the observed peak is a resonance. In particular, in many processes, including three-body baryon decays of B-mesons, peaks at the baryon–antibaryon pair production threshold are observed [132–134]. It is interesting that the mass and the full width of X(4630) measured under the assumption that X(4630) is a resonance, $M = (4634\,^{+8}_{-7}\,^{+5}_{-8})$ MeV/c^2 and $\Gamma = (92\,^{+40}_{-24}\,^{+10}_{-21})$ MeV, agree within errors with the mass and the full width of Y(4660). Such a coincidence (including quantum numbers) seems not to be accidental, although it does not rule out that X(4630) and Y(4660) are different particles. Among possible interpretations, there are suggestions that X(4630) are charmonium ψ(5S) [116, 117, 135, 136] or ψ(6S) [137] states, or a threshold effect caused by the presence of ψ(3D) slightly below the $\Lambda_c^+\Lambda_c^-$ threshold [138].

In 2009, the Belle collaboration measured the $e^+e^- \to D^0D^{*-}\pi^+$ exclusive cross section [129] (Fig. 17e). Contrary to the expectations of some hybrid models predicting $Y(4260) \to D^{(*)}\bar{D}^{(*)}\pi$ decays, no obvious features except a low significant ($\simeq 3.1\,\sigma$) indication of the ψ(4415) state were observed in this cross section.

The ratio of the sum of the $e^+e^- \to D\bar{D}, D\bar{D}^*, D^*\bar{D}^*$, $D\bar{D}\pi$, $D\bar{D}^*\pi$, and $\Lambda_c^+\Lambda_c^-$ exclusive cross sections measured by the Belle collaboration to the $e^+e^- \to \mu^+\mu^-$ cross section and the ratios of the total e^+e^- annihilation cross section into charmed hadrons to the $e^+e^- \to \mu^+\mu^-$ cross section measured by the BES [127] and CLEOc [130] collaborations are shown in Fig. 18. It is seen from comparison of these distributions that the sum of the measured exclusive cross sections almost completely saturates the total e^+e^- annihilation cross section into hadrons. The fraction of charmed strange mesons in the total cross section, according to the CLEOc measurements [130], is expected to be an order of magnitude smaller than the fraction of charmed mesons. In the range of energies above the charmed baryon pair production threshold (more than 4.5 GeV/c^2), measurements of inclusive cross sections are almost absent.

10. The new regarding the old: ψ(3770)

As we have already noted, ψ(3770), the lightest of charmonium states above the pair production threshold of $D\bar{D}$ mesons, is predominantly a 1^3D_1 state with a small 2^3S_1 admixture [139]. Until recently, ψ(3770) was believed to decay exclusively into a pair of $D\bar{D}$ mesons. Indeed, according to the CLEOc collaboration measurements, the difference in cross sections for the $e^+e^- \to \psi(3770)$ and $e^+e^- \to \psi(3770) \to D\bar{D}$ processes, i.e., the cross section of a $e^+e^- \to \psi(3770) \to$ 'non-$D\bar{D}$' process, is equal to $(-0.01 \pm 0.08^{+0.41}_{-0.30})$ nb and is compatible with zero [140]. However, the BES collaboration studies demonstrated that $(14.7 \pm 3.2)\%$ of all ψ(3770) decays are 'non-$D\bar{D}$' decays [141–144]. This serious contradiction motivated an intensive search of non-$D\bar{D}$ decays by both collaborations.

The first non-$D\bar{D}$ decay was discovered by the BES collaboration in observing the $J/\psi\,\pi^+\pi^-$ final state with the branching fraction of $(0.34 \pm 0.14 \pm 0.09)\%$ [145]. The CLEOc collaboration confirmed and refined this observation by showing that ψ(3770) decays into final states with J/ψ ($J/\psi\,\pi^+\pi^-$, $J/\psi\,\pi^0\pi^0$, $J/\psi\,\eta$) with the total probability 0.36% [146]. Moreover, $\psi(3770) \to \chi_{c0(1)}\gamma$ decays were found in the CLEOc experiment: their branching fractions were also small, about 1% [147]. As a result of the search for ψ(3770) decays into final states without charmed particles, only one $\psi(3770) \to \phi\eta$ channel with the branching fraction $(3.1 \pm 0.6 \pm 0.3) \times 10^{-4}$ was found [148]. Thus, the sum of branching fractions of the found ψ(3770) decays appeared to be discouragingly small (less than 2%) and in disagreement with the value of the order of 15% obtained by the BES collaboration.

However, an exotic explanation for the deficit of non-$D\bar{D}$ decays related to the presence of other structures or physical effects close to ψ(3770) is possible. The BES collaboration measured the production cross section in the energy range from 3.73 to 3.80 GeV [149]. The slope of the cross section to the right of the ψ(3770) position was noticeably steeper than that to the left, which contradicts the peak shape expected for a single resonance. Indeed, initial state radiation and the threshold effect of $D\bar{D}$ production should lead to an inverse effect. The behavior of the $e^+e^- \to D\bar{D}$ cross section is similar to the anomalous energy dependence of the $e^+e^- \to$ *hadrons*

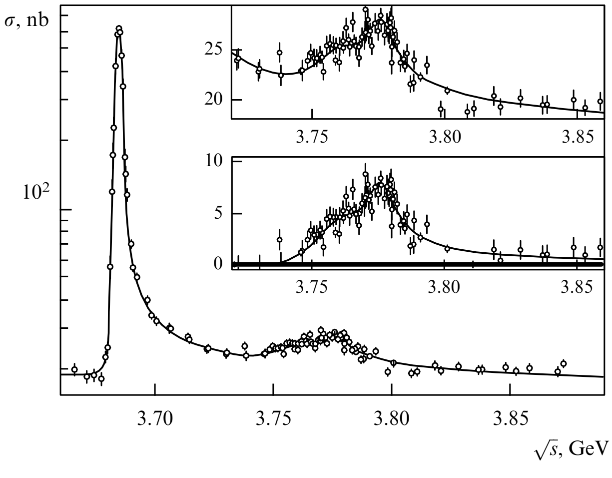

Figure 19. The $\sqrt{s}$ dependence of the cross section of e^+e^- annihilation into hadrons. The result of the fit with a contribution of two resonances in the region of ψ(3770) is shown by the solid line.

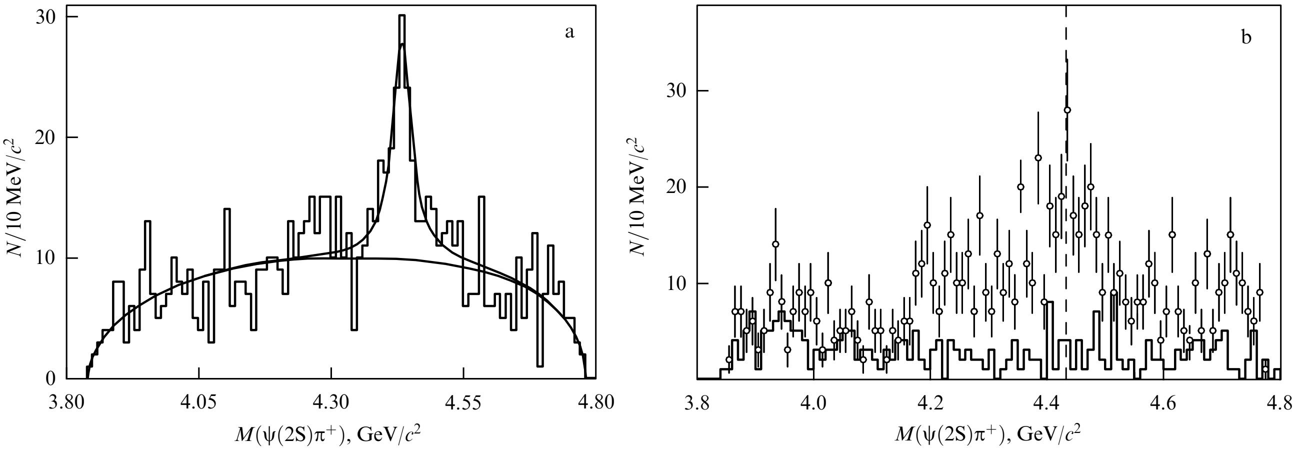

Figure 20. Invariant mass spectrum of the $\psi(2S)\,\pi^+$ combinations in the Belle (a) and BaBar (b) experiments.

cross section observed in the energy range 3.70–3.87 GeV (Fig. 19) [150]. The cross-section shape is well described by the contribution of two resonances that are similar in mass. Presently, the statistics of the CLEOc and BES experiments do not allow reaching unambiguous conclusions on the existence of new structures in this energy range. A new promising BESIII experiment [151] with huge luminosity will certainly help resolve many puzzles.

11. Charged and strange charmonium-like states

The numerous X- and Y-states discussed up to now are electrically neutral and do not contain strange quarks. They still can somehow be 'squeezed' into the quark model: at least, they do not contradict it qualitatively. The states discussed in Sections 11.1–11.3 cannot be reconciled with the quark model anymore. However, we should warn a reader that the reliability of their observation still requires the most accurate verification.

11.1 Charged $Z^+(4430)$ state

In 2007, in studying $B \to \psi(2S)\,\pi^+ K$ decays, the Belle collaboration found a charmonium-like structure with a nonzero electric charge [152]. If the events of the $B \to \psi(2S)\,K^*$ decay that make the dominant contribution to the investigated final state[14] are vetoed, a narrow peak close to 4.43 GeV/c^2 appears in the mass spectrum of the $\psi(2S)\,\pi^+$ combinations (Fig. 20a). Fitting this spectrum by the sum of Breit–Wigner functions and a smooth function describing the phase space gave the statistical significance of $6.5\,\sigma$ for the observation of a resonance called $Z^+(4430)$. Also, the resonance parameters $M = (4433 \pm 4 \pm 2)$ MeV/c^2 and $\Gamma_{\rm tot} = (45\,^{+18}_{-13}\,^{+30}_{-13})$ MeV were determined.

However, it is not necessary to make a hasty conclusion about the observation of a resonance. First, we check whether the peak appearance can be explained by other reasons. In the three-body decay $B \to \psi(2S)\,\pi^+ K$, interference between various partial waves in the $K^-\pi^+$ system [the presence of the S-, P-, and D-wave resonances κ, K^*, and $K_2^*(1430)$ can be expected in this system] leads to structures (probably peaked) appearing in the distribution of $\cos\theta_\pi$, where θ_π is the polarization angle of the $K\pi^+$ system.[15] The value of $M(\psi(2S)\,\pi^+)$ strongly correlates with $\cos\theta_\pi$. Therefore, the interference can also produce a structure in the spectrum of $M(\psi(2S)\,\pi^+)$. Can that explain the observed peak? The Belle collaboration qualitatively demonstrated that the peak presence at the discovered mass, due to the interference of resonances in the $K\pi^+$ system, is possible only with a simultaneous appearance of more evident structures with other mass values in the spectrum of $M(\psi(2S)\,\pi^+)$. Because such structures are absent in the $M(\psi(2S)\,\pi^+)$ spectrum, a conclusion was made that the peak found is not a result of the interference of different partial $K\pi^+$ waves.

A year later, the BaBar collaboration in a similar investigation did not find a significant $Z^+(4430)$ signal [153]. Fitting the invariant mass spectrum of the $\psi(2S)\,\pi^+$ combinations (Fig. 20b) by the Breit–Wigner function with the mass and width equal to the values obtained by Belle determined the statistical significance of the signal, which does not exceed $1.9\,\sigma$. The upper limit on the branching fraction, $\mathcal{B}(B \to Z^+(4430)\,K)\,\mathcal{B}(Z^+(4430) \to \psi(2S)\,\pi^+) < 3.1 \times 10^{-5}$ at 95% CL, is less than the value $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$ measured by Belle. In addition, the BaBar collaboration has not found narrow charged charmonium-like states in the $B \to J/\psi\,\pi^+ K$ decay either.

In 2009, a new study by Belle appeared [154], with more rigorous proofs of the existence of a charged resonance in the $B \to \psi(2S)\,\pi^+ K$ decay. The three-body decay dynamics are characterized by two variables up to rotations of the B-meson decay plane and the axes of subsequent decays (for example, $\psi(2S) \to l^+l^-$). The squared masses of two of the three pairs of final particles are convenient variables; in our case, it is convenient to choose $M^2(K^-\pi^+)$ and $M^2(\psi(2S)\,\pi^+)$. The two-dimensional distribution of $M^2(K^-\pi^+)$ versus $M^2(\psi(2S)\,\pi^+)$ is uniformly populated in the phase space decay, and the resonance looks like a horizontal (in the $K^-\pi^+$ system) or vertical [in the $\psi(2S)\,\pi^+$ system] band, while the density of concentrations along the band is determined by the resonance polarization. A fit to this distributions with the interference of all contributions taken into account is called the Dalitz (plot) analysis. In a new Belle work, the Dalitz analysis was done for the $B \to \psi(2S)\,\pi^+ K$ decay. As a result, the interference

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[14] The mass of the $K\pi^+$ combination must be separated by an interval ± 50 MeV/c^2 from the nominal mass of K^*.

[15] The angle between the π^+-meson momentum and the flight direction of the $\psi(2S)\,\pi^+$ combination in the $K\pi^+$ rest frame.

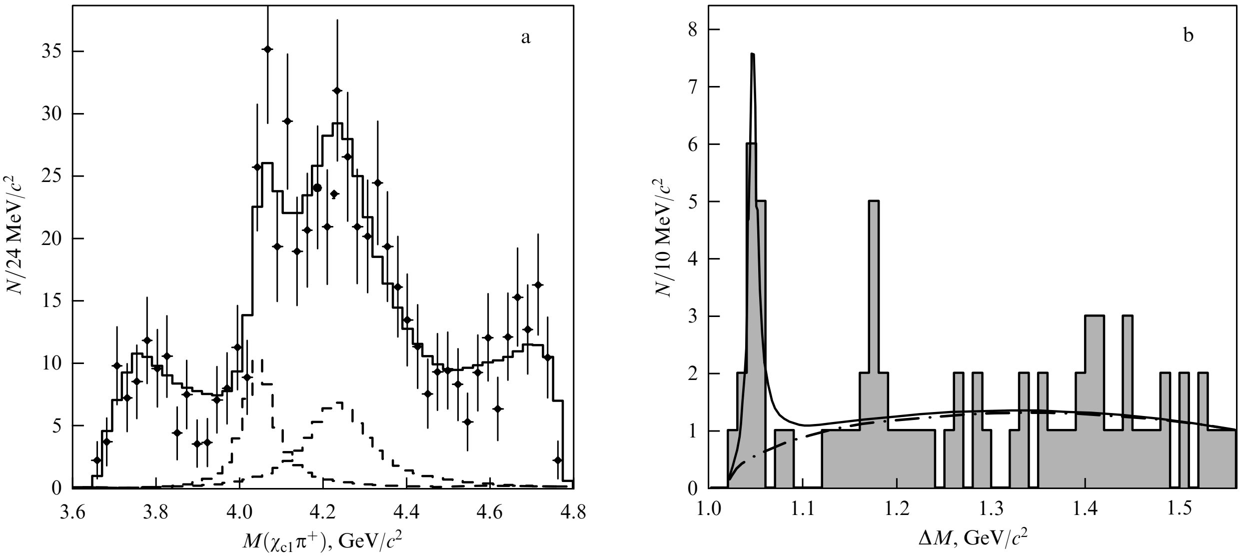

Figure 21. (a) Invariant mass spectrum of the $\chi_{c1}\,\pi^+$ combinations in the Belle experiment. (b) The mass difference spectrum of the $J/\psi\,\phi$ combination and a J/ψ candidate in the CDF experiment.

explanation of the observed peak was rigorously excluded, and the existence of $Z^+(4430)$ was confirmed. The width of $Z^+(4430)$ obtained in [154] by fitting the Dalitz distribution, $\Gamma_{\text{tot}} = (107\,^{+86}_{-43}\,^{+74}_{-56})$ MeV, appeared to be slightly larger than the initially measured one, and its mass agrees well with the results of the first study.

Despite the confidence of the Belle collaboration in the accuracy of their results, the disagreement with the BaBar results compels us to refer to the conclusion about the existence of $Z^+(4430)$ with care.

11.2 Z_1^+ and Z_2^+ states

The discovery of $Z^+(4430)$ motivated the investigation of the $\bar{B}^0 \to \chi_{c1}\,K^-\pi^+$ process. In 2008, the Belle collaboration found a wide feature in the invariant mass spectrum of $\chi_{c1}\,\pi^+$ [155]. As already discussed, this feature can be explained by the interference of partial waves of the $K^-\pi^+$ system. To understand the dynamics of the $\bar{B}^0 \to \chi_{c1}\,K^-\pi^+$ decay, a Dalitz analysis of the final state was made. The fit to the two-dimensional distribution of $M^2(K^-\pi^+)$ vs $M^2(\chi_{c1}\,\pi^+)$ demonstrated that it is not possible to describe the broad structure by the contributions of all known resonances in the $K^-\pi^+$ system and by the nonresonant three-body contribution. If two new resonances in the $\chi_{c1}\,\pi^+$ system, called Z_1^+ and Z_2^+, are added to the fit, the description becomes satisfactory. From the fit of the Dalitz distribution, the following parameters of $Z_{1,2}^+$ resonances were obtained:

$$M_1 = (4051 \pm 14\,^{+20}_{-41})\ \text{MeV}/c^2\,, \quad \Gamma_1 = (82\,^{+21}_{-17}\,^{+47}_{-22})\ \text{MeV}\,,$$

$$M_2 = (4248\,^{+44}_{-29}\,^{+180}_{-35})\ \text{MeV}/c^2\,, \quad \Gamma_2 = (177\,^{+54}_{-39}\,^{+316}_{-61})\ \text{MeV}\,.$$

The mass spectrum of the $\chi_{c1}\,\pi^+$ combinations after the exclusion of two dominant contributions from the resonances in the $K^-\pi^+$ system, K^* and $K_2^*(1430)$, is given in Fig. 21a. The result of the fit is shown by the solid line, and the two dashed lines show the contributions of Z_1^+ and Z_2^+.

11.3 Y(4140) state with hidden strangeness

In 2008, the CDF collaboration reported results of the investigation of the $J/\psi\,\phi$ system produced in exclusive $B^+ \to J/\psi\,\phi K^+$ decays [156]. It was shown that the contribution of $J/\psi\,\phi K^+$ dominates in the $B^+ \to J/\psi\,K^-K^+K^+$ decay, while the contributions of $J/\psi\,f_0(980)K^+$ or $J/\psi\,K^+K^-K^+$ with the phase space distribution are negligibly small. Figure 21b shows the distribution of the mass difference spectrum of the $J/\psi\,\phi$ combination and J/ψ candidate for events from the B-meson signal region. Here, a concentration of events slightly above the threshold is observed. The fit under the assumption of a contribution of the new resonance called Y(4140) gives 14 ± 5 signal events with a statistical significance of $4.3\,\sigma$. The mass and width of the new resonance are $(4143.0 \pm 2.9 \pm 1.2)$ MeV/c^2 and $(11.7^{+8.3}_{-5.0} \pm 3.7)$ MeV.

In 2009, the Belle collaboration, having comparable statistics of reconstructed $B^+ \to J/\psi\,\phi K^+$ decays, did not confirm the peak presence in the mass spectrum of $J/\psi\,\phi$ combinations [157]. In view of the low statistical significance in the CDF experiment, the Belle results strongly question the existence of Y(4140).

Assuming that the states mentioned above in this section and in Sections 11.1 and 11.2 nevertheless exist, we discuss their possible interpretations. Immediately, we can exclude the charmonium or charmonium hybrid hypotheses because they are electrically neutral and do not explicitly contain the $s\bar{s}$ pair. The remaining possibility is to assume that the considered states are multiquark states. The discovery of charged charmonium-like states generated the idea of a hadrocharmonium [35], a bound charmonium state into which they decay [$\psi(2S)$ in the case of $Z^+(4430)$ and χ_{c1} for $Z_{1,2}^+$], and a light (charged) meson. However, many researchers believe that these particles can be explained by molecular states that have already become more common. This hypothesis provides large freedom to invent charged states or states containing an $s\bar{s}$ pair, and to select charmed mesons with suitable mass and forming a molecule. For example, $Z^+(4430) = D^*\bar{D}_1^{**}$ [158], $Z_{1,(2)}^+ = D^*\bar{D}^*$ $(D_1\bar{D})$ [159], and $Y(4140) = D_s^{*+}D_s^{*-}$ [160]. Other authors support a diquark–antidiquark interpretation [161].

It is interesting that $Z^+(4430)$ has some similarity to Y(4360) and Y(4660) states. Indeed, all of them are in the same mass range, have close widths, and prefer to decay into

$\psi(2S)$ instead of J/ψ. If they were 'relatives,' this could cause problems not only for the hybrid interpretation of Y(4360) and Y(4660) but also for the molecular $D^*\bar{D}_1^{**}$ hypothesis for $Z^{\pm}(4430)$. On the other hand, Y(4140) appeared to be very similar to Y(3940) (both decay into J/ψ and a vector light meson at the threshold).

12. Conclusion

Today, scientists working in high-energy physics impatiently await the Large Hadron Collider (LHC) results, opening new energy frontiers accessible to investigation. It is quite interesting that because of numerous surprises, the physics of charmonium, related to the energy range that is far below not only the projected energies but also energies already reached, remains attractive for both experimentalists and theoreticians.

We keep hoping that an avalanche-like increase of unexplained facts will put the theory at a new qualitative level of understanding QCD and we will obtain a more complete and clear picture of events in the charmonium world. Here, experiment should play an important role. Careful and more precise measurements of decays, production, and parameters of states already found, as well as the search for possible new particles, are necessary. For the next few years, there are two projects for the construction of new-generation B-factories, super-B-factories [162] that will allow collecting experimental data samples that are two orders of magnitude larger.

The authors express their deep gratitude to L B Okun for the idea to write this review. We are very thankful to A E Bondar, M B Voloshin, and V L Chernyak for the valuable comments. We are grateful to the Belle collaboration colleagues for many years of fruitful cooperation.

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