M.B. Voloshin. *Heavy quarkonium outside the potential model.* The potential model, widely used to describe heavy quarkonium, despite all its good points is not well-founded within the framework of quantum chromodynamics (QCD). Alternative methods for describing the dynamics of heavy quarks, based on the starting equations of QCD, are therefore of interest. The range of problems which can be solved by such mehtods is obviously narrower than for the potential model, but the results are more reliable and permit drawing conclusions concerning the properties of the starting theory itself—QCD. Three classes of problems referring to the dynamics of heavy quarkonium are examined in this report: 1) spectroscopy of energy levels, 2) annihilation decays, and 3) hadronic transitions between the levels of quarkonium.

Three approaches, differing only technically, are used to describe the levels of the quark-antiquark system (quarkonium) for three different ranges of quark masses. For superheavy quarks, the properties of the deep-lying levels are determined primarily by the Coulomb gluon-exchange potential. The corrections to the Coulomb behavior of the levels appear as a result of the interaction of quarkonium with the gluon field of large-scale vacuum fluctuations (gluon condensate), which are not described by the perturbation theory of QCD and are characterized by the average value of the squared field intensity $\langle G^a_{\mu\nu} G^a_{\mu\nu} \rangle$. Here the calculation of the corrections to the energy of the levels is analogous to finding the shift in the levels in a random electric-type field.

For comparatively light quarkonium—charmonium, the sum rules based on a QCD calculation of the polarization of the vacuum $P(q^2)$ by local operators of the form $j = \bar c(x)\Gamma c(x)$ with unphysical (below the threshold of $4m_c^2$) values of q^2 turn out to be very fruitful. The computed value of $P(q^2)$ is equated to the expression for the same quantity obtained from the dispersion relations in the form of an integral of the spectral density of the operator j, to which the physical states with hidden charm contribute. The sum rules so obtained, taking into account the effects of the gluon condensate, made it possible to explain the mass of the ^3P_J levels of charmonium (χ_J resonances) and the prediction of the mass of the η_c meson before its experimental discovery.

The levels of $b\bar b$ quarkonium, which has an intermediate mass, are far from being Coulomb-like, but the gluon exchange potential plays a large role in their dynamics. For this reason, in deriving the sum rules for the $b\bar b$ system this potential must be taken into account exactly. This can be done in the leading, nonrelativistic approximation by studying the evolution operator with imaginary time: $\exp(-H\tau)$. For sufficiently large τ the projection of the evolution operator on the sector with definite quantum numbers is determined by the ground state (with given quantum numbers). Based on this purely nonrelativistic analysis it is possible to estimate the magnitude of the mass difference of the ground P state (χ_b) and the S state (Υ): $M_P - M_S = 370 \pm 30$ MeV. Experimentally this mass difference turned out to be equal to 440 MeV. The 10–17% difference from the theoretical prediction is probably attributable to relativistic corrections, which are not presently amenable to quantitative analysis. One can only say that the Breit interaction (tens of MeV) makes the main contribution, while the relativistic effects in the interaction with the gluon condensate are small (several MeV). This is confirmed, in particular, by the calculation of the hyperfine splitting $M(\Upsilon) - M(\eta_b)$, which can be carried out completely. The Breit-Fermi interaction makes a contribution of approximately 33 MeV to this splitting, while the spin-dependent interaction with the condensate contributes only approximately 2.5 MeV.

An analysis of the widths of the decays of the $^3S_1$ states of quarkonium into an e^+e^- pair reproduces, within the framework of the indicated methods, the corresponding widths of the J/ψ and Υ resonances, while for the ground $^3S_1$ state of $t\bar t$ quarkonium the following width is predicted:

$$\Gamma_{ee}(t\bar t) \approx 4\ \text{keV} \cdot |1 + (A_Z/A_\gamma)|^2 \quad \text{for} \quad 2m_t \leqslant 50\ \text{GeV}$$

(A_Z and A_γ are the amplitudes of annihilation via a Z boson and a photon, respectively). For $2m_t > 50$ GeV, this width is determined by a purely Coulomb formula.

Likewise, based on the duality of the physical and quark cross sections for e^+e^- annihilation expressed by the sum rules, wide resonances, decaying into pairs of B mesons, should be expected in the e^+e^- annihilation with a mass of about 11 GeV.

The widths of the annihilation of heavy quarkonium into hadrons are of great interest in connection with the discussion of nonperturbative effects. These effects in hadronic annihilation are associated with the transformation of a colorless $q\bar q$ pair into a colored pair as a result of the interaction with the gluon condensate and subsequent gluonic annihilation of the colored $q\bar q$ state (this process is analogous to the two-photon annihilation of orthopositronium in an external magnetic field). The effect has been quantitatively calculated only in the limit of very heavy quarkonium. Extrapolation of the result obtained to Υ and J/ψ resonances indicates that the correction to the perturbation-theory formula for the ratio $R_h = \Gamma_{\text{had}}/\Gamma_{ee}$ is negative and can attain tens of percent for J/ψ and several percent for Υ. The possibility that the indicated effect explains the difference in the values of R_h for ψ' and J/ψ resonances ($R_h(\psi')/R_h(J/\psi) = 2.3 \pm 0.5$) as well as the discrepancy between the values of $R_h(\Upsilon)$ and $R_h(J/\psi)$ and the asymptotic-freedom formula for the evolution of α_s has not been excluded. The same analysis of nonperturbative corrections gives for the relative probability of the decay of the Υ meson into a direct photon and hadrons a very small (not more than a percent) correction compared with the perturbation-theory formula. The last decay is therefore the best object for studying the value of the constant α_s.

Hadronic transitions between the levels of heavy quarkonium with the emission of two pions or an η meson are studied within the framework of the multipole expansion for the interaction of quarkonium with soft gluons, which convert into light mesons.

The spectrum of the invariant masses of the $\pi\pi$ system in the decays $\psi' \to J/\psi\pi\pi$ and $\Upsilon' \to \Upsilon\pi\pi$ agrees with the theoretically expected amplitude of the form $c(m^2_{\pi\pi} - \lambda m^2_\pi)$, where c and λ are constants. The value $\lambda = 2.5 \pm 0.5$ measured by the ARGUS group in the last decay also agrees with the theoretical prediction. The $m_{\pi\pi}$ spectrum in the decay

$\Upsilon'' = \Upsilon\pi\pi$, which does not agree with the indicated form of the amplitude, presents a problem. A possible solution of this problem could be the existence of an isovector four-quark resonance $X = (b\bar{b}u\bar{d})$ with a mass $M(\Upsilon'' - m_\pi < M(X) < M(\Upsilon'')$. It is possible that this resonance can be observed in the decays $\Upsilon''' \to X\pi$.

A precision measurement of the mass difference of the Υ' and Υ resonances permits making a definite prediction concerning the relative probability of the transition between them with the emission of an η meson: $(B(\Upsilon' \to \Upsilon\eta) \sim 0.1\%$, which is only somewhat smaller than the experimental upper limit $(B(\Upsilon' \to \Upsilon\eta) < 0.2\%)$.