A. A. Bykov, I. M. Dremin, and A. V. Leonidov. *Quark atoms and their spectroscopy*. This report concerns the problem of describing the physical characteristics of mesons consisting of a heavy quark and an antiquark within the framework of the potential model.[1–4] Interest in these particles stems primarily from the fact that, on the one hand, very rich experimental information about mesons of this type has been accumulated,[5] while on the other hand these systems have much in common with positronium, the simplest two-particle bound state formed by an electron and a positron. The deep analogies between two-particle bound states—the hydrogen atom or positronium in quantum electrodynamics and quarkonium in the theory of strong intereactions—make theoreticians hopeful that the study of the properties of quarkonia will elucidate the nature of their constituent elements, i.e., that it will lead to an understanding both of the static properties of heavy quarks and the dynamics of their interaction.

The main experimentally measured characteristics of quarkonia are the energy levels (masses and quantum numbers), the leptonic and hadronic decay widths, as well as the width and multipolarity of the electromagnetic transitions between the members of a given family of mesons. The high accuracy of the measurements of the energy levels of quarkonia, which enable one to study the spin-spin and spin-orbital structure of the interaction between a quark and an antiquark, should be noted.

The main assertion of the potential-model description of quarkonia is that the constituent quarks in quarkonia are nonrelativistic objects and can be adequately described in terms of a local static interaction potential within the framework of the Schrödinger equation or the Breit-Fermi equation. Here the main ingredient of the theory—the quark-antiquark interaction potential—can be chosen both purely phenomenologically and also in accordance with the basic assumptions of QCD, which predict a quite definite behavior of the potential at small and large distances. It is interesting that the quark-antiquark interaction potential can be related to the form of the Gell-Mann–Low β function, which controls the dependence of the coupling constant on the value of the four-momentum transferred.[6] This makes it possible to check the interpolation formulas, given in the literature, for the β function by comparing with experimental data the results on the spectroscopy of quarkonia obtained within the framework of this approach.

After the interaction potential has been given, it is possible to calculate, starting from the Schrödinger equation, the mass spectrum, the leptonic decay widths, the values of the widths of the radiative transitions between levels, the rms radii of mesons and other characteristics (see the review in Ref. 4).

From a comparison of the experimental mass spectrum and the mass spectrum computed in potential models, one can draw conclusions concerning the form of the potential in the range of distances corresponding to the rms radii of quarkonia. It turns out that all potentials given in the literature behave similarly in the range of distances $0.2\ \text{fm} \leqslant r \leqslant 1\ \text{fm}$ and lead to practically identical predictions. To distinguish potentials it is necessary to move to smaller distances ($r < 0.2$ fm), and this will become possible when the sixth t quark and its bound states with the $\bar{t}$ antiquark (toponium) are discovered. From a comparison of the experimental data on toponium and the computational results[7] otained by using different potentials it will be possible to determine which potential gives a better description of the interaction dynamics at small distances. For example, the difference between the 2S and 1S levels varies under different assumptions from 0.5 to 4 GeV.

Important information can be obtained from the study of the leptonic decay widths of quarkonia, because these widths are most sensitive to the form of the potential and therefore considerably reduce the arbitrariness in the choice of the quark-antiquark interaction potential.

The radiative transitions between levels of a quarkonium family are the charcteristic most difficult to reproduce, because in the potential model their value is very sensitive to the accuracy with which the relative positions of the nodes and maxima of the wave functions of different states are determined. In addition, the widths of the radiative transitions are very sensitive to relativistic corrections and if the relativistic corrections are ignored, they exceed the experimental values obtained for the J/ψ family of particles by a factor of 2–4.

A very important problem for the physics of heavy quarkonia is the problem of taking into account the corrections associated with the finiteness of the quark velocities in such systems. This problem is not only linked to the more accurate determination of the values of the mass spectrum and of the widths of leptonic decays and of electromagnetic transitions calculated based on the Schrödinger equation, but it also permits drawing a number of conclusions concerning the Lorentz structure of the confining potential. In particular, it is generally believed that the confining part is a superposition of a Lorentz-scalar and a Lorentz-vector potential, which is directly reflected, for example, in the fine structure of the quarkonia levels.

The Lorentz-scalar part of the potential can be interpreted here as the manifestation of the dynamic mass of quarks,[8] which is a function of the relative distance between them and which is associated, in particular, with the difference of the masses of the current and constituent quarks.

A detailed study of the quark-antiquark interaction potentials at small and intermediate distances ($r \lesssim 0.5$ fm) will very likely also help to clarify the nontrivial structure of the QCD vacuum. In particular, the existence of long-wavelength fluctuations in the QCD vacuum cannot be absorbed into the local static interaction potential, while the short-wavelength fluctuations can be accounted for in terms of the local potential.

On the basis of the results obtained (see the review of Ref. 4), it may be asserted that the potential model adequately describes the physics of the interaction of heavy quarks in quarkonia. It has great predictive power, it is mathematically simple, and it gives at the same time information on very subtle properties of the dynamics of the interaction of quarks: the Lorentz structure of the interaction potential, the asymptotic decrease of the coupling constant, the independence of the potentials from the quark flavors, and even the nontrivial structure of the QCD vacuum. At the same time, the potential model is a reliable guide for the experimenter and will undoubtedly be very useful in the study of the bound states of the hypothetical superheavy t quark and $\bar{t}$ antiquark (toponium).

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