Heavy Quarkonium Spectra and its Decays in the Framework of Quark Models*

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Introduction

The main aim of the thesis is to study heavy quarkonium properties in the non-relativistic quark model formalism and to understand the applicability of the model and suggest possible improvements. For heavy quarkonia, we employ instanton potential, Hulthen and one gluon exchange potential. The mass spectrum is obtained by the variational approach and by diagonalizing the Hamiltonian matrix. Three phenomenological models have been proposed by incorporating the suggestions from lattice QCD and other theoretical approaches. The three non relativistic quark models(NRQM) have been developed: i) NRQM with a Coulomb like potential and the linear confining potential along with the instanton potential(PM1), ii) NRQM with Hulthen potential and linear confinement potential(PM2), iii) NRQM with one gluon exchange potential(OGEP) and linear confinement potential(PM3). Using the potential parameters and numerical solution of wave-function, we have studied meson properties. The properties investigated are mass spectrum, decay constants and radiative transitions. For charmonium, we have also calculated leptonic decays, two-photon and two-gluon decays. The obtained results are compared with the experimental data and with the predictions from other approaches.

Theoretical Background

In PM1 we have investigated the mass spectrum and decay rates of charmonium states within the framework of the NRQM by employing a Coulomb like one gluon exchange potential, linear confining potential along with the potential derived from instanton vacuum. We have predicted radiative E1, M1, two-photon, leptonic and two-gluon decay rates of low lying charmonium states. An overall agreement has been obtained with the experimental masses and decay widths. We have estimated the branching ratio of two gluons decaying into light hadrons.

The full $q\bar{q}$ potential used in PM2 has a Hulthen potential and a confining linear potential. The hyperfine interaction is introduced to obtain the splittings of the spin-singlet and triplet states, while the spin-orbit and tensor interactions provide the fine structure splittings. The model parameters and the wave function that reproduce the mass spectra are used to investigate the decay properties of B and B_s mesons.

In PM 3, the quark-antiquark interaction potential has OGEP. The OGEP also provides the spin dependent interactions leading to hyperfine structure splittings. The non-relativistic potential with OGEP has been successful in predicting the D and D_s meson spectra. In PM 3, the meson wave functions are expressed in terms of the oscillator wave functions corresponding to the relative and CM coordinates, restricting the CM wave function to the 0S state. The total energy or mass of the meson is obtained by calculating the energy eigenvalues of the Hamiltonian in the harmonic oscillator basis spanned over a space extending up to the radial quantum number $n = 5$ for the S state and $n = 3$ for the P and D states. The obtained results are fairly in good agreement with the experimental results.

Results and Discussions

In PM1,PM2 and PM3 we have used the harmonic oscillator wave function which has been extensively used in atomic and nuclear physics as the trial wave function for obtaining the $Q\bar{Q}$ mass spectrum. In PM1 and PM2 we have obtained the quarkonium spectrum and several excited states using the variational method with the harmonic oscillator wave function and the same has been

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employed in the calculation of $|\psi(0)|^2$. In PM3 the $q\bar{q}$ wave function for each meson is expressed in terms of oscillator wave functions corresponding to the centre of mass and relative coordinates. The oscillator quantum number for the CM wave functions are restricted to N_{CM}=0.

In PM1, we calculated mass specturm, radiative E1, M1, two-photon, leptonic and two-gluon decay rates of low lying charmonium states. A very good agreement is obtained with the experimental masses and decay widths for all the states. The estimated branching ratio of two gluons decaying into light hadrons are in good agreement with experiment and lattice results. Below the open charm threshold, the theoretically calculated masses are in agreement with lattice calculations and with experimental results.

The mass spectrum was obtained variationally, and the model parameters and the wave function that reproduce the mass spectra were used to investigate the decay properties of B and B_s mesons. The spectra obtained for both B and B_s agree with the experimental results and with the theoretical predictions from other models.

In PM3, the calculated mass spectrum, decay constants and the radiative decay widths for D and D_s mesons are good agreement with experiment and with other theoretical models.

We have compared the three models PM1, PM2 and PM3. All the three models employed have been successful in fairly reproducing the mass spectrum, decay widths and decay constants of heavy quark mesons. The calculations clearly point out the importance of potential derived from instanton vacuum in PM1, Coulombs like Hulthen potential in PM2 and significance of OGEP in PM3. Success of the non-relativistic model is that the effects like screening of short-range Coulombic potential and sting-breaking of long range confining potentials can be taken into account. We find that all the heavy quark mesons like, charmonium, B, B_s, D and D_s mesons may be considered as non-relativistic systems. Though the phenomenological interaction potential employed for the study is not directly derived from the basic QCD interactions, it contains contributions from physical processes involving QCD. From our calculations, we conclude that the inclusion of QCD correction factors is of importance for obtaining accurate results for radiative decay widths.

From our work, we cannot conclude that one of the models considered here is preferable. The PM1 model has both OGEP and instanton potential. The spin dependent terms of instanton potential gives rise to the hyperfine splitting. The PM1 has OGEP which is required as it is consistent with asymptotic freedom. Instantons were introduced in relation to the UA(1) problem and their role was pointed out by t'Hooft by deriving effective interactions by coupling of the instantons and light quarks, whose strength of interaction depends on the instanton density, which was estimated from the gluon condensate of the QCD vacuum. It was argued that the NRQM should include the instanton potential as a short-range non-perturbative gluon effect. Also,lattice QCD suggests that the QCD vacuum contains instantons and its density is consistent with the gluon condensate expected from QCD sum rules. Also, it is well known that chiral symmetry is dynamically broken by the instanton vacuum and massless quarks are transformed into constituent quarks, which acquire mass as a function of momentum. Hence a consistent quark model Hamiltonian should have both OGEP and instanton potential. The PM1 has both OGEP and instanton potential and hence is more rigorous from the theoretical point of view. The PM1 results showed that the instanton-induced potentials improved the mass spectrum of heavy quark mesons.

References

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