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Testing the Standard Model using Bottom Quarks

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Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) at the Los Alamos National Laboratory (LANL). The goal of this project was to develop the necessary tools and provide theoretical input needed to interpret the wealth of experimental results, thus enabling us to look for failures of the existing theory and estimating its fundamental parameters. Included was the study of the spectroscopy of hadrons containing up, down, strange, charm and bottom quarks, the determination of the masses of these quarks, and the calculation of the decay constants of B and B_s. We succeeded in this endeavor: Our careful analyses of the light quark masses reduced the previous world estimates for these parameters by a factor of two; and the control of systematic errors in our determination of f_B and f_{B_s} ranks it amongst the best in the field.

Background and Research Objectives

Even though the standard model of elementary particle physics has been immensely successful, its large number of parameters and ad hoc implementation of the flavor structure of fermions points to a deeper underlying theory. Such a theory is expected to manifest itself in small and subtle deviations between the experimental observations and the results predicted by the theory. The extraction of Cabibbo-Kobayashi-Masakawa matrix elements that parameterize the quark mixings and CP violation is however hindered by the absence of reliable theoretical estimates of the decay constants f_B, f_{B_s}, f_D, and f_{D_s}, the bag parameters B_B and B_{B_s}, and the quark masses. Because of strong interaction effects, accurate determinations of these quantities require non-perturbative methods and perhaps the most promising approach is simulations of lattice QCD.

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Unfortunately the large mass of the b quarks makes the usual techniques of lattice QCD expensive beyond today's computational resources. A number of collaborations had tried to obtain the decay constants of B and B_s by extrapolating the results at lighter quarks. The large range over which these extrapolations were performed led to large uncertainties in their value. In recent years, therefore, an attempt was made to pinpoint these quantities by treating the heavy quark as having infinite mass. Tests, however, soon showed that this was inadequate as well: the corrections from this so called 'static limit' were also large, though the limited perturbative analyses available then could only estimate the magnitude of these effects.

Similarly, though the lattice technology dealing with the light quark sector is quite advanced, a compilation of the world results show that the discretization errors are rather large and the systematic errors involved in extrapolations to the continuum were unclear. This LDRD project, therefore, focussed on simultaneously reducing the relativistic, perturbative and discretization errors in both the heavy and light quark sectors. Instead of treating the heavy b quark as either a light relativistic object, or an infinitely heavy static charge, we treated it as a slowly moving non-relativistic particle, putting in both the leading and the first subleading terms in an expansion in the inverse mass. For the light quarks, we used a formulation that eliminated the leading discretization errors, which would therefore improve the final extrapolated results.

This method was tested by reproducing the spectrum of the known mesons and baryons. The same calculation predicted the masses of the unobserved states and estimate the splittings between them. In addition, the matching condition between the predicted and observed spectrum provided us with estimates of the quark masses and the strength of the strong coupling constant; the light quark masses turned out to be much smaller than previously believed from other non-perturbative methods.
After analysing these other calculations, we found that the previous estimates were over optimistic with their errors, and that our results were both reasonable and consistent with known physical constraints.

With all these ingredients in hand, we calculated the decay constants f_B and f_{B_s}, with control over systematic errors not possible in previous calculations.

Importance to LANL's Science and Technology Base and National R&D Needs

A large amount of effort in Experimental High Energy Physics is concentrated on detecting evidence for the incompleteness of the current model of particle physics. Experiments at Cornell University, in Geneva, and the B factories planned at Stanford, in Germany, and in Japan, are but examples of this effort. However, unraveling the underlying theoretical structure from the performed measurements requires the ability to calculate accurately, and with known uncertainty, the predictions of the strongly interacting theory. This project performed some of those calculations.

Equally importantly, large scale computations have always been a testbed for new technological developments in the field of supercomputing.
Our calculations were performed, partly, on the SGI/Origin 2000 cluster of computers at the Advanced Computation Laboratory. The lessons learnt optimizing the code for these machines helped debug and improve the compilers for these machines.

Scientific Approach and Accomplishments

The major improvements of our calculations over previous ones was the use of methods to simultaneously reduce the discretization, relativistic and perturbative errors in our calculations. We used the tadpole improved Sheikholeslami-Wohlert formulation of light fermions and an $O(1/M^2)$ improved NRQCD approach for the heavy quarks.
The perturbative factors relating the lattice results to the continuum ones were calculated to one loop and used to convert our results into the form directly usable by experimentalists. We also reanalyzed results on quark masses from previous lattice studies [1] and from other non-perturbative methods [2].

Our estimates for the light quark masses, $(m_u + m_d)/2 = 2.7 \pm 0.6$ MeV, $m_s = 68 \pm 19$ MeV, are lower by a factor of two than indicated by previous studies. Later reanalysis by other workers have confirmed our estimates. This result, in isolation, would predict a much larger direct CP violation as has recently been observed. We also calculated the matrix elements of 4-fermion operators that arise in the weak decays of kaons [3, 4]. They include both the B parameter that controls the mixing of the neutral kaon with the anti-kaon, and the B parameter of the electromagnetic penguin operators that contributes to the CP violation in Kaon decays.

The major highlight of this project was the calculation of the decay constants [5] of B and B_s mesons with complete control of all the systematic errors other than quenching. Our results,

$$f_B = 147(11)(^{+8}_{-12})(9)(6) \text{ MeV and } f_{B_s}/f_B = 1.20(^{+6}_{-4}) \text{ [5]},$$

represent a significant advance in this field.

In addition, the rich spectrum of mesons and baryons containing b quarks was studied. With our NRQCD approach, we provided the first analysis of the complete spectrum of S and P wave states of mesons containing a b and a light quark, as well as that of baryons containing one or two heavy quarks [6]. Comparing with experiments the states that have already been observed provided us with estimates of the b quark mass. A similar analysis of the mesons containing a heavy quark and anti-quark provided estimates of the strong coupling constant α_s [10].

Gupta organized the LXVIII session of the Les Houches Summer School "Probing the Standard Model of Particle Interactions". Bhattacharya and Gupta organized and ran the 1998 Santa Fe Workshop "Perturbative and Non-perturbative aspects of the Standard Model". The discussions at this workshop led to a better understanding of the different approaches to studying heavy quarks, and the systematic errors inherent in them. Bhattacharya and Gupta gave the plenary talk on the quark masses at LATTICE 97. Gupta also served on the organizing committee of LATTICE 98, the XVI International Symposium on Lattice Field Theories, Boulder, CO.

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