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First Measurements of the b Lifetime[+]

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Abstract. **This paper reviews the first measurements of the B lifetime, the theoretical and experimental climate in which they were made, and their considerable impact on knowledge of the CKM matrix and B phenomenology.**

Introduction

The first measurements of the b lifetime came just six years after the discovery of the Upsilon, and only three years after the first compelling evidence for the production of hadrons with open b flavor. The average b hadron lifetime was measured to be about 1.5 ps, surprisingly long by the theoretical standards of the day, and remarkably close to today's accepted value. Despite the surprise, the fact that the b is long-lived was accepted almost immediately, and it was confirmed within a year by other experiments. The implications of the long b lifetime were clear even before the first experimental results were in print, and they were far reaching. Significant b meson mixing, a heavy top quark mass, and appreciable CP violation in the b system were among these expectations.

This recollection will review the early theoretical landscape and experimental limits, discuss the first collider lifetime measurements, and examine the impact the first measurements of the b lifetime had on our knowledge of the CKM matrix.

Predictions and Early Limits

The spectator model for heavy quark decays had been sufficiently developed for charm decays that its extrapolation to b decays was straightforward by the time of the Upsilon discovery [1]. Several authors [2] related the b lifetime to the strength of the b → c and b → u couplings, accounting for the phase space differences of the final states:

$$\tau_b = \frac{(M_\mu / M_b)^5 \tau_\mu}{2.75\,|V_{bc}|^2 + 7.7\,|V_{bu}|^2}$$

If the mixing between the third and second generations were like that between the second and the first, the b lifetime would be very short, $\tau_b \sim 3 \times 10^{-14}$s. Predictions of the lifetime used existing constraints on the CKM elements to limit $|V_{bu}|$ and $|V_{bc}|$. The ε parameter in K° decays, expressed in terms of CKM parameters from the box diagram analysis, provided the basis of Harari's estimate. [3]: $10^{-14}\text{s} < \tau_b < 10^{-11}\text{s}$. A more aggressive limit was derived by Barger, Pavasa, and Long [4], which included constraints

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from the K°_L-K°_S mass difference. They concluded $10^{-14}s < \tau_b < 10^{-13}s$, and this became the prevailing theoretical opinion before the first lifetime measurements: the b lifetime is short [5].

Unconventional ideas from Cahn and Fritzsch [6] suggested the b might be nearly stable, and motivated two Fermilab searches [7] for the production of meta-stable b hadrons. Both experiments looked for massive 5 GeV/c^2 particles produced in 400 GeV p-Be collisions. They used existing secondary beamlines to select momentum and long-baseline time-of-flight techniques to measure velocity. Neither saw candidate events, establishing that $\tau_b < 5 \times 10^{-8}s$. The JADE experiment at PETRA established a better limit [8], $\tau_b < 2 \times 10^{-9}s$, by excluding the existence of charged tracks with anomalously high dE/dx in 30 GeV e^+e^- annihilations.

Lifetime Measurement Tools

The 30 GeV e^+e^- storage rings PETRA at DESY and PEP at SLAC became operational soon after the Upsilon discovery. They were ideal laboratories for measuring the b lifetime because the $b\bar{b}$ production cross-section was known, clean b identification was possible, luminosities were adequate, and picosecond lifetimes were boosted into millimeter decay lengths, which were readily measureable.

Semi-leptonic b decays, with their distinctive high transverse momentum leptons, provided a clean b tag. CLEO and CUSB [9] at Cornell first measured the semi-leptonic branching ratio to be about 12% in 1981. Semi-leptonic b decays and the b fragmentations function were measured at PEP by the Mark II and MAC experiments [10] in 1982. Good agreement with the Cornell results established that b tagging was quantitatively understood.

The Mark II Collaboration pioneered lifetime measurements in the collider environment with their 1980 proposal [11] to add a precision drift chamber close to the interaction point. The physics motivations for the device included the measurement of the tau lifetime, measurement of charm particle lifetimes, and the search for a finite b lifetime. A new technique was proposed to measure the tau lifetime by measuring the distance between the interaction point and the $\tau \rightarrow \nu 3\pi X$ decay vertex. This method was soon exploited by Mark II, MAC, and Cello [12] to provide the first indications that the tau lifetime is finite. The first results from the Mark II vertex detector were reported in 1982. [13] The detector's superior impact parameter resolution dramatically reduced the tau lifetime measurement errors and showed exponential tails in distributions that had been broad, slightly offset Gaussians. Techniques for measuring beam positions, optimal decay lengths, resolutions, and systematic errors were developed at this time. The measured value of the tau lifetime [14] was in good agreement with theory, lending credibility to these new techniques.

The Lepton Impact Parameter Method

The JADE experiment at PETRA reported a technique suitable for measuring the b lifetime in Spring 1982. It involved measuring the signed impact parameter of a lepton track, which presumably originated from the b decay. Signing the impact parameter positive (if the track appeared to come from positively displaced vertex) or negative meant one would see lifetime effects by a slight offset of the mean of the resolution function. Monte Carlo techniques were used to relate the amount of offset to the lifetime. Since the lepton spectrum in b decays was known and the fragmentation function hard, model dependence was manageable. JADE used this method to measure the average impact parameter of 27 high momentum muons coming from a 10 pb^{-1} dataset. The result was consistent with zero, and was used to establish a much improved limit, $\tau\beta < 1.4 \times 10^{-12}$ s [15]. The MAC and Mark II experiments quickly adopted similar strategies. MAC reported [16] $\tau_b = 1.7 \pm 1.0$ ps at the 1982 Paris Conference. The value was insignificantly positive, but tantalizing. Mark II also learned that it was hard to improve on JADE's limit when there are hints of finite lifetime in the data. We chose to keep mum.

First Measurements at PEP

The 1982-83 year at PEP provided record luminosities to the MAC and Mark II experiments. PETRA meantime was trading high luminosity for high energy in its quest for a 20 GeV top quark. By year's end, MAC had accumulated and speedily processed 100 pb^{-1} of data, giving a sample of 270 electrons and muons, measured with 600 μm impact parameter resolution. Mark II had 80 pb^{-1}, only 104 leptons, but 200 μm resolution. Both experiments were relying on the semi-leptonic b tag for their event identification, and lepton impact parameter as a measure of the lifetime. We in Mark II were convinced by early Spring '83 that the mean impact parameter was positive, but struggled to implement a full maximum likelihood fit to exploit our good resolution. MAC saw effects late in the spring when the full data set, electrons and muons, was available. MAC measured the mean of the lepton impact parameter, weighted by the impact parameter error. They beat Mark II to press, and announced early in the summer that $\tau_b = 1.8 \pm 0.6 \pm 0.4$ ps. [17] Mark II reported its results one month later at the SLAC Summer Institute [17]: $\tau_b = 1.20 {+.45} {-.36} \pm .3$ ps. The data are shown in Fig. 1.

Bill Reay reviewed the lifetime results [18] at the Lepton-Photon Symposium that year: "My conclusion is that the three standard deviation effect seen by two experiments for the impact parameter is a strong indication that the b lifetime is of order 10^{-12} seconds." The result was widely accepted. There were after all two independent experiments, seeing effects in electrons and muons, checking that average hadronic impact parameters were very small as expected, and cross-checking that the charm lifetime was as expected. It was a strong case experimentally.

DELCO at PEP and TASSO and JADE at PETRA confirmed the result in 1984 [19]. The early results were quite consistent with values accepted today.

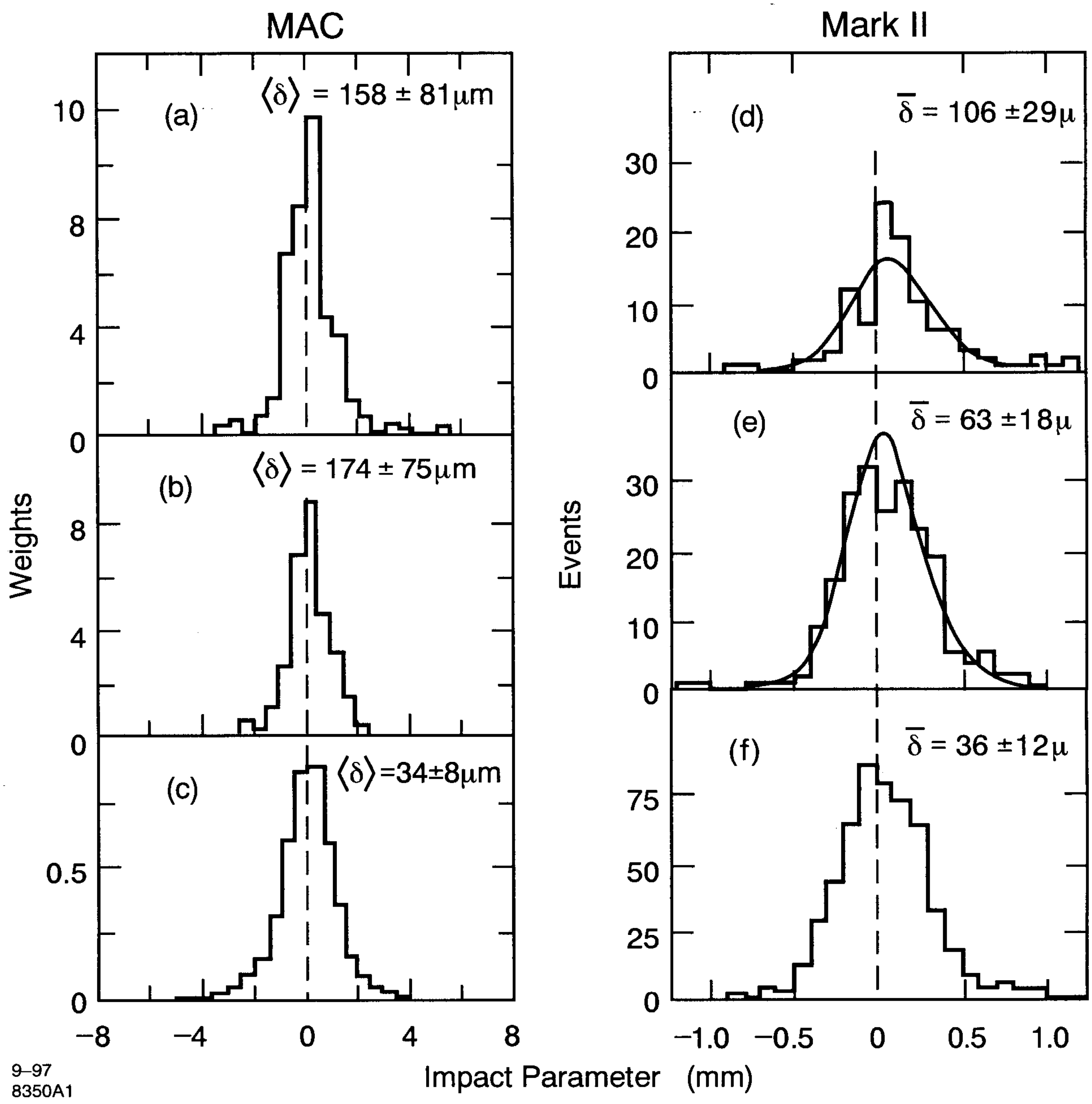

Figure 1. Impact parameter distributions from the two PEP experiments. MAC's results are shown for (a) muons, (b) electrons, and (c) hadrons. Mark II's results are shown for (d) "b leptons," with Pt > 1 GeV/c; (e) "c leptons," with Pt < 1 GeV/c; and (f) hadrons.

Theoretical Impact

The first b lifetime measurements provided the necessary final ingredient to fix the magnitudes of the CKM matrix elements. CLEO and CUSB had established in early 1983 that $|V_{bu}|^2/|V_{bc}|^2 < .04$. [20] Consequently, the b lifetime is essentially a direct measure of $|V_{bc}|$, the b → u term being inconsequential. The first lifetime measurements established that $|V_{bc}| \sim .05$. With this input and the assumption of unitarity, the CKM matrix element magnitudes were established. Table I shows how our knowledge of the CKM matrix advanced after the lifetime measurements [21].

Table I. The CKM Matrix Before and After B Lifetime Measurements

$$\begin{array}{c}\textbf{1982}\\ \begin{array}{cccc} & d & s & b \\ u & .973\pm.024 & .224\pm.006 & .05\pm.05 \\ c & .22\pm.02 & .89\pm.09 & .31\pm.26 \\ t & .06\pm.06 & .28\pm.28 & .90\pm.09 \end{array}\end{array} \qquad \begin{array}{c}\textbf{1983}\\ \begin{array}{cccc} & d & s & b \\ u & .973\pm.024 & .224\pm.006 & .007\pm.007 \\ c & .22\pm.02 & .972\pm.002 & .053\pm.017 \\ t & .007\pm.007 & .053\pm.017 & .998\pm.001 \end{array}\end{array}$$

This improved knowledge of the CKM matrix had interesting phenomenological implications. As Paschos, Stech, and Turke [22] observed, appreciable mixing and CP violation effects were expected in the b meson system. This is a consequence of first order b decays being so strongly suppressed that the second order (box) diagrams were relatively significant. Ginsparg, Glashow, and Wise [23] used the new information on $|V_{bc}|$ and the ε parameter to infer that top must be heavy, which at the time meant $m_t > 45$ GeV. The failure of the prediction for a short b lifetime indicated that short distance effects did not dominate the description of the K°_L - K°_S mass difference. Lastly, the smallness of $|V_{bc}|$ could not be understood in terms of the simple ansatz relating masses and mixing angles that was popular before the measurements.

Experimental Impact

The long b lifetime has made it possible to identify b hadrons by virtue of their decay topology. Early attempts to do so at PEP and PETRA had tagging efficiencies around five-percent and purities in the 60-70% range. [24] The art has developed rapidly since the introduction of high-precision silicon vertex detectors. The CCD vertex detector in SLD [25] tags b jets at the Z with 50% efficiency and nearly 99% purity. Efficient lifetime tags have made it possible to identify the top quark, measure heavy quark electroweak parameters to high precision, and extend searches for the Higgs. This physics has underscored the importance and spurred the development of high precision vertex detectors. These detectors, in turn, are sharpening our view of the underlying vertex structure of high energy interactions, and the wealth of physics implicit in these structures.

Acknowledgements

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