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B MESON RECONSTRUCTION AND LIFETIME STUDIES WITH THE MARK II AT PEP*

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ABSTRACT

We have measured the lifetime of an ensemble of particles containing b quarks, tagged with a high p_T lepton from their semileptonic decay. Using a method which estimates the production point of each particle in the beam ellipse, we measured a lifetime of $0.98 \pm 0.12 \pm 0.13$ psec. We have also studied methods of partially reconstructing B mesons decaying into D^{*-} mesons plus charged leptons or mesons. We have searched the Mark II PEP data samples and find five candidates for B^0 decay. Four of these B^0 candidates form good vertices, and their measured proper lifetimes are presented.

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The measured lifetimes of particles containing b quarks impacts the study of weak interactions, B meson mixing, CP violation, and the dynamics of heavy meson decay. So far there have only been ~ 100 B meson decays reconstructed,[1] mostly by CLEO and ARGUS, and the flight times of only two partially reconstructed B mesons have been published.[2] Most measurements of τ_b come from e^+e^- experiments where B mesons are tagged by their semileptonic decay or by the high sphericity of their decays.[3] If the various B hadrons (B^+, B^0, B_s^0, Λ_b, etc) have significantly different lifetimes (as is the case with D hadrons), then the measured τ_b will be the average of the various B hadron lifetimes weighted by their fractional population in the tagged sample. For example, τ_b measured in the lepton-tagged sample is the average B hadron lifetime weighted by each B hadron's production cross section times semileptonic branching ratio (BR). Each B hadron's semileptonic BR is approximately proportional to its lifetime, so the lepton-tagged τ_b will be weighted towards the lifetimes of the longer-lived B hadrons.

In this paper we will present both a high-statistics, lepton-tagged τ_b, and the measured proper lifetimes of four candidates for B^0 decay. The lepton-tagged τ_b analysis is based on 204 pb^{-1} of e^+e^- hadronic annihilation data at $\sqrt{s} = 29$ GeV taken with the Mark II/PEP5 detector.[4] This data set and an additional 31 pb^{-1} of data at the same $\sqrt{s}$, taken with the Mark II detector upgraded for its eventual use at the SLC,[5,6] were used in the search for $B \to D^{*-}X$ decays.

The PEP5 multihadronic data sample yielded 386 high quality electrons and 231 muons with $p > 2$ and $p_T > 1$ GeV. The lepton-tagged τ_b study reported here[7,8] represents several significant improvements over the previous published Mark II τ_b analysis.[9] Detailed studies of detector resolution and lepton backgrounds were performed.[10] The B semileptonic BR's and the $< z_b >$ used in the determination of τ_b were taken from fits to the data (Table 1). A technique was developed to estimate the production point of the B in the e^+e^- beam interaction region by vertexing all quality tracks in each Thrust hemisphere. This estimated production point significantly reduced the error on the impact parameter for nearly vertical tracks. A maximum likelihood fit (including background functions) to the impact parameter distribution of the high p_T leptons (Fig. 1) gives $\tau_b = 0.98 \pm 0.12 \pm 0.13$ psec.

Table 1. Results from the inclusive lepton analysis.

Quantity	Electron	Muon
$\text{BR}(c \to \ell)$	$9.6 \pm 0.7 \pm 1.5$ (%)	$7.8 \pm 0.9 \pm 1.2$ (%)
$\text{BR}(b \to \ell)$	$11.2 \pm 0.9 \pm 1.1$ (%)	$11.8 \pm 1.2 \pm 1.0$ (%)
$< z_b >$	$0.85 \pm 0.03 \pm 0.05$	$0.82 \pm 0.04 \pm 0.05$

The search for $B \to D^{*-}X$ decays[11] used tracks in the same Thrust hemisphere as the D^{*-} to tag B decays. The $D^{*\pm}$ signal used in this analysis (Fig. 2) was isolated with the standard Δm technique for the daughter D^0 meson decays to $K^-\pi^+$ and $K^-\pi^+\pi^0$. The cuts used to isolate the D^0 candidates are similar to those used in the recent Mark II D^0 lifetime analysis,[6] except that we required the π^0 to be fully reconstructed and we reduced the $D^{*\pm}$ $x_E (= E_{D^{*\pm}}/E_{BEAM})$ cut to 0.3 to pick up more $D^{*\pm}$ mesons from B decay.

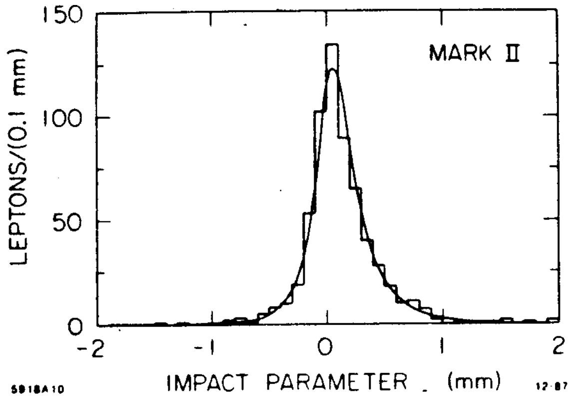

Fig. 1. Impact parameter distribution for high p_T leptons.

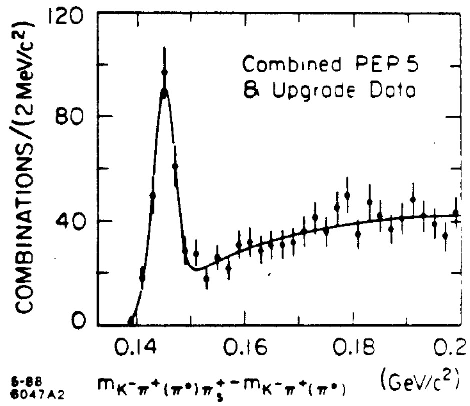

Fig. 2. Δm distribution for $D^{*+} \to \pi_S^+ D^0$, $D^0 \to K^-\pi^+$ and $K^-\pi^+\pi^0$.

We first searched for $D^{*-}\ell^+$ pairs from the decay $B^0 \to D^{*-}\ell^+\nu$. Using the ARGUS measurement[12] of BR$(B^0 \to D^{*-}\ell^+\nu) = 0.070 \pm 0.012 \pm 0.019$, combined with the B total semileptonic BR (Table 1) and some simple assumptions, one can conclude that if one tags both the ℓ^+ and the D^{*-} from a B decay, the probability that one has tagged a B^0 decay rather than a B^+ decay is large ($> 80\%$).

We combined the $D^{*\pm}$ candidates with identified leptons ($p_e > 1$, $p_\mu > 2$ GeV) in the same Thrust hemisphere. For this analysis, we chose to plot the cosine of the helicity angle (θ_H) of the ℓ^+ in the $D^{*-}\ell^+$ rest frame versus the invariant mass of the $D^{*-}\ell^+$ pair. While $D^{*-}\ell^+$ pairs from B decay do not uniformly populate the $\cos\theta_H$ versus $m_{D^{*-}\ell^+}$ plane, many do have both high mass and central values of θ_H. Backgrounds tend to have either low invariant mass ($m_{D^{*-}\ell^+} < 3$ GeV), very forward θ_H (a real direct lepton with combinatorial background under the D^{*-} signal), or very backward θ_H (a hard, real D^{*-} in a $c\bar{c}$ event with a misidentified or non-direct lepton). Requiring central values of θ_H and high mass is essentially equivalent to requiring that both the D^{*-} and the ℓ^+ have high momentum and high p_T with respect to the Thrust axis.

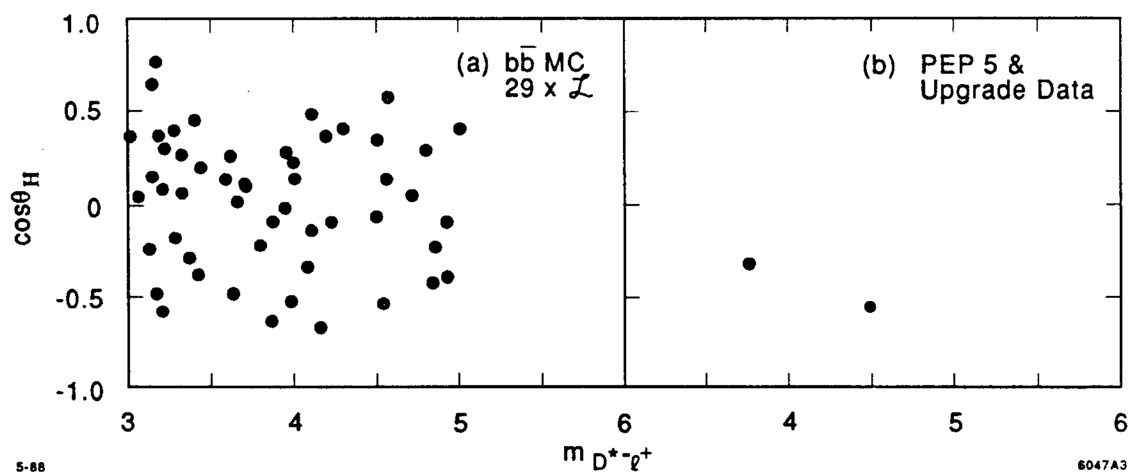

Fig. 3. $\cos\theta_H$ versus m distributions for $D^{*-}\ell^+$ pairs.

Figure 3(a) shows the $\cos\theta_H$ versus $m_{D^{*-}\ell^+}$ distribution for a Monte Carlo (MC) sample[13,14] of $b\bar{b}$ events which corresponds to 29 times our integrated luminosity for B

hadrons which decay through the $\overline{D}^0 \to K^+\pi^-$ reaction.[15] The forward θ_H region is depopulated by the x cut on the $D^{*\pm}$ and the backwards θ_H region is depopulated by the minimum momentum cut on the lepton. The rest of the plot with $m_{D^{*-}\ell^+} < m_{B^0}(= 5.280$ GeV) is fairly uniformly populated by $B^0 \to D^{*-}\ell^+\nu$. This BR is fairly well measured and represented in our MC, and the expectation for our data samples is ~ 1.8 of these decays with a subsequent $D^{*-} \to \pi_S^-\overline{D}^0$, $\overline{D}^0 \to K^+\pi^-$ decay, and less (~ 1) going through $\overline{D}^0 \to K^+\pi^-\pi^0$. To study our main source of background, we applied our analysis program to a $c\bar{c}$ MC sample corresponding to 7.5 times our integrated luminosity for $D^{*+} \to \pi_S^+ D^0$, $D^0 \to K^-\pi^+$. We found no $D^{*-}\ell^+$ pairs which passed our cuts and appeared in the equivalent of Fig. 3(a).

The results of this analysis program on our PEP data samples are shown in Fig. 3(b). There are two events with same-hemisphere $D^{*-}\ell^+$ pairs, and no events with same-hemisphere $D^{*-}\ell^-$ pairs (one measure of our background). Another background measure, $D^{*-}\ell^\pm$ pairs with $m_{D^{*-}\ell^\pm} > m_B$, is also empty. The lower mass pair ($m_{D^{*-}e^+} = 3.772$ GeV) has a D^{*-} with $x_E = 0.36$ and $p_T = 1.71$ GeV, and an isolated e^+ with $p = 1.85$ and $p_T = 1.16$ GeV. While this is a very good candidate for B^0 decay, there are problems with track overlap and hit association in the vertex chamber which prevents an accurate lifetime determination with this pair, and so we will not discuss it further.

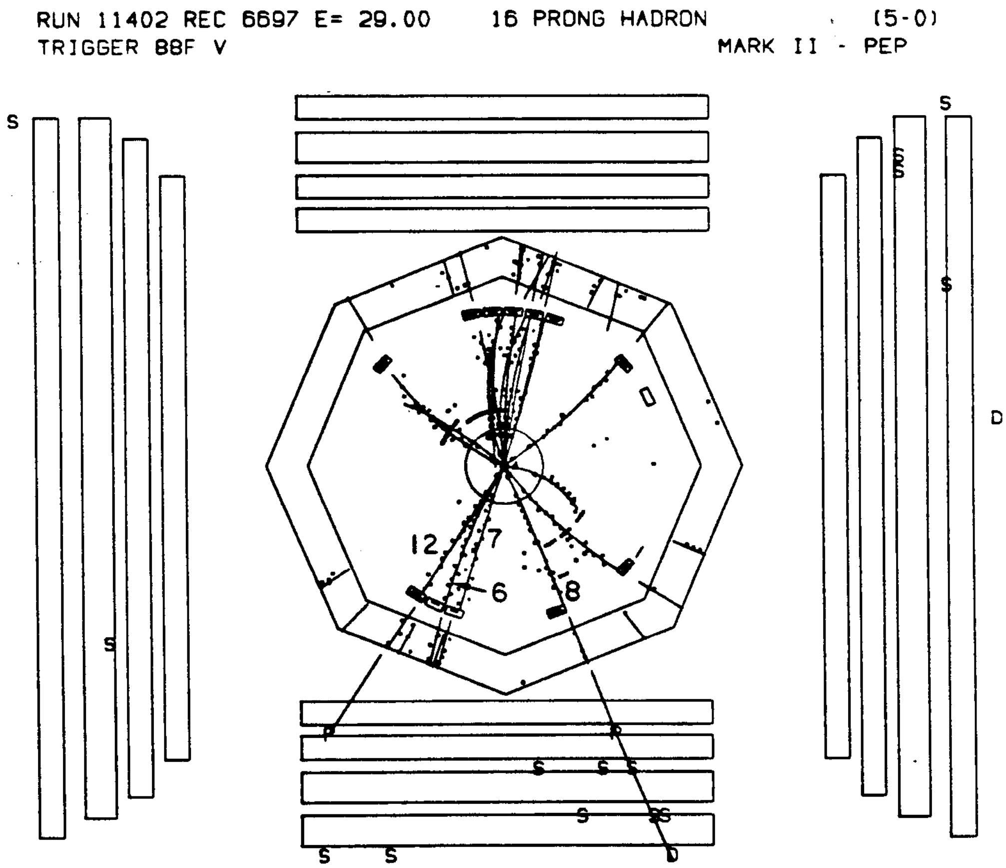

Fig. 4. $D^{*-}\mu^+$ event in the Mark II/PEP5 detector, in the plane transverse to the beam axis.

The event with the higher mass pair ($m_{D^{*-}\mu^+} = 4.504$ GeV) is shown in Fig. 4. There is a good quality isolated μ^+ (Track 8) with $p = 2.37$ and $p_T = 1.34$ GeV, and a $D^{*-} \to \pi_S^-\overline{D}^0$, $\overline{D}^0 \to K^+\pi^-\pi^0$ decay (Tracks 6, 7, and 12, and two nearby photons in the barrel Liquid Argon (LA) calorimeter) with $x_E = 0.61$ and $p_T = 1.98$ GeV.

The technique of tagging *partially* reconstructed B decays by their distribution in mass and θ_H can be adapted to hadronic B decays. After tagging, there is some possibility of fully reconstructing the decay without the problem of the lost ν in semileptonic decays. Again, not all hadronic B decays will have a D^{*-} and a $\pi^{\pm}$ with high mass and central θ_H, but some fraction of low multiplicity decays will, and these we can tag. Since there are few sources of direct leptons in $c\bar{c}$ events other than D semileptonic decays, but there are plenty of pions, background is more of a problem. We have also lost one background measure, as $D^{*-}\pi^{-}$ pairs, while not as common in B decays as $D^{*-}\pi^{+}$ pairs, are still perfectly allowed.

One can imagine that $c\bar{c}g$ events in which low x, high p_T $D^{*\pm}$ mesons are paired with pions from the gluon jets could be a significant source of high mass, central θ_H pairs. To reduce this background, we have tightened two cuts, based on MC studies of $c\bar{c}$ events. We have raised the mass cut on the $D^{*-}\pi^{\pm}$ pair to 4 GeV, and required that the pair have $x_p > 0.8$, where $x_p = p/p_{BEAM}$. The last cut is especially restrictive, both to background and to $D^{*-}\pi^{\pm}$ pairs from B decay, but given the $< z_b >$ in Table 1, a reasonable fraction of partially reconstructed B decays will pass this cut.

All $D^{*-}\pi^{\pm}$ pairs in our $b\bar{b}$ MC sample with $x_p > 0.8$ and $4 < m_{D^{*-}\pi^{\pm}} < 6$ GeV are shown in Fig 5(a). The forward θ_H region is still depopulated due to the $D^{*\pm}$ x cut, but the backwards θ_H region is now populated, as the pions have only nominal minimum momentum requirements. While we know that the $B^0 \to D^{*-}\pi^{+}$ BR is overrepresented (by a factor of ~ 10) in the MC [hence the band at $m_{D^{*-}\pi^{\pm}} \simeq m_B$ in Fig. 5(a)], the multiplicity and the $D^{*\pm}$ x distributions for B decays have been tuned to match data taken on the Υ_{4S}.[16] A correct table of B BR's is not possible, since many large B BR's are either not measured or imprecisely measured.

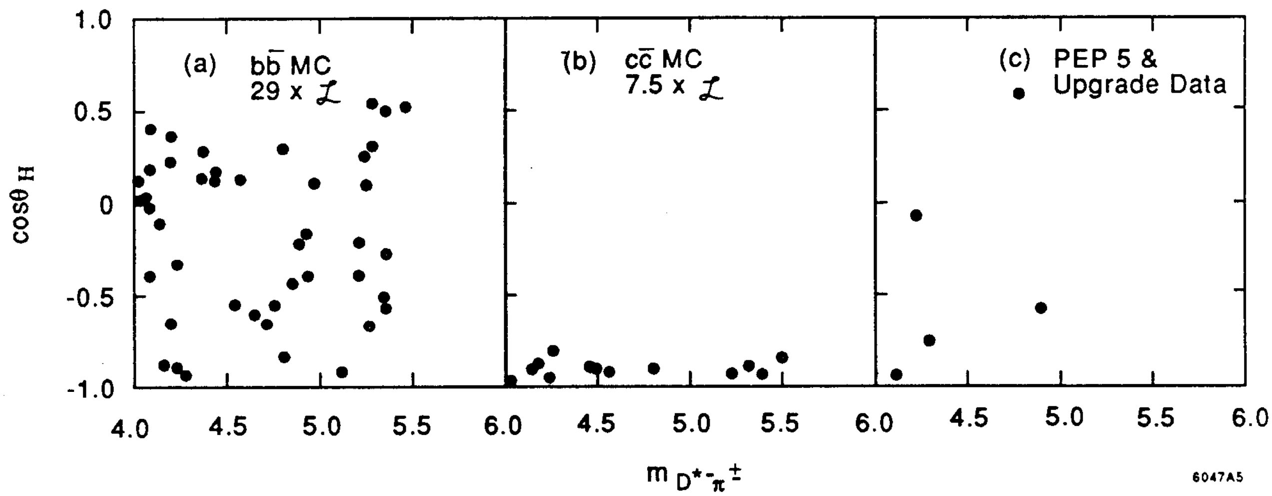

Fig. 5. $\cos\theta_H$ versus m distributions for $D^{*-}\pi^{\pm}$ pairs.

Our MC is well-tuned for gluon radiation[14], and the $\cos\theta_H$ versus $m_{D^{*-}\pi^{\pm}}$ distribution for our $c\bar{c}$ MC sample is shown in Fig. 5(b). The $D^{*-}\pi^{\pm}$ pairs from $c\bar{c}$ events are all clustered at backwards values of θ_H, corresponding to hard, real $D^{*\pm}$ mesons paired with soft, low p_T fragmentation pions. To remove this background, we now require $\cos\theta_H > -0.7$. Note that, without this cut, there are several entries with $m_{D^{*-}\pi^{\pm}} \simeq m_B$ in Fig. 5(b). From Fig. 5(a), we expect ~ 1.5 tagged B decays, where the B decay includes $\overline{D}^0 \to K^+\pi^-$, in our data samples (slightly less with the $\cos\theta_H$ cut), though this number is particularly sensitive to the B BR's used in the MC. We expect ~ 1.7 pairs from $D^{*+} \to \pi_S^+ D^0$, $D^0 \to K^-\pi^+$, production in $c\bar{c}$ events, all with $\cos\theta_H < -0.7$. We expect fewer events (~ 1 each) in both categories for reactions which go through $D^0 \to K^-\pi^+\pi^0$.

Figure 5(c) shows the $\cos\theta_H$ versus $m_{D^{*-}\pi^\pm}$ distribution for our PEP data samples. There are five $D^{*-}\pi^\pm$ pairs, all with $m < m_B$, and three of these have central values of θ_H. The three events passing the $\cos\theta_H$ cut are labeled A, B, and C, in order of decreasing mass.

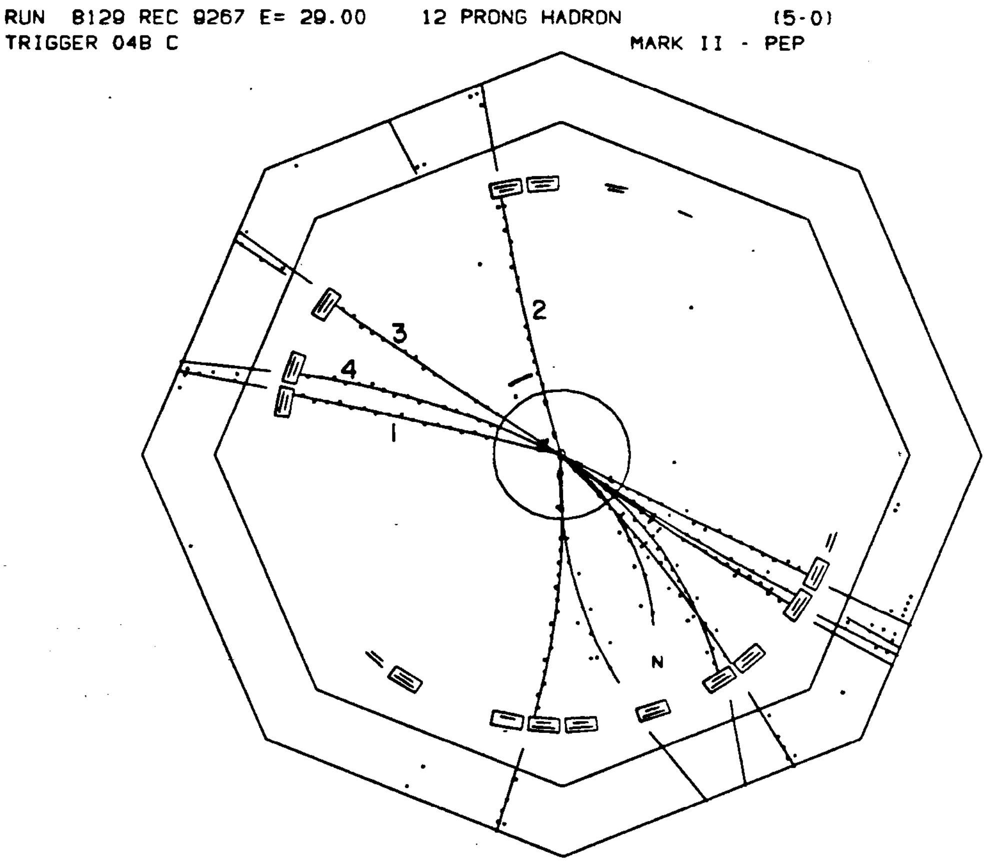

Fig. 6. Event A in the Mark II/PEP5 detector.

Event A (shown in Fig. 6) has $m_{D^{*-}\pi^+} = 4.908$ GeV and $x_p = 0.84$. Tracks 1, 3, and 4 form the $D^{*-} \to \pi_S^-\overline{D}^0$, $\overline{D}^0 \to K^+\pi^-$, candidate with $x_E = 0.73$ and $p_T = 1.86$ GeV, and Track 2, the π_B^+ paired with the D^{*-}, has $p = 2.57$ and $p_T = 1.63$ GeV. These are the only charged tracks in the entire hemisphere. There are two photons which make a good π^0 candidate, which when combined with the $D^{*-}\pi^+$ pair yields $m_{D^{*-}\pi^+\pi^0} = 5.123$ GeV (consistent with what we expect our $B^0 \to D^{*-}\pi^+\pi^0$ mass resolution to be) and $x_p = 0.88$. This is the best candidate for B^0 decay in our combined PEP data samples.

Event B (not shown) is very similar to Event A. There are only four charged tracks in the hemisphere; three from the $D^{*-} \to \pi_S^-\overline{D}^0$, $\overline{D}^0 \to K^+\pi^-$, decay ($x_E = 0.36$, $p_T = 1.47$ GeV) and the π_B^+ ($p = 9.31$, $p_T = 2.01$ GeV) which, with the D^{*-}, tags this as a partially reconstructed B decay. There are two photons in the barrel LA which form an acceptable π^0, and some neutral energy in the endcap calorimeter. The π^0 along with the $D^{*-}\pi_B^+$ forms another candidate ($m_{D^{*-}\pi^+\pi^0} = 5.203$ GeV, $x_p = 1.00$) for $B^0 \to D^{*-}\pi^+\pi^0$ decay. However, this event is our least reliable reconstructed B^0 decay. The π_B^+ track has a small angle with respect to the beam axis, only a few hits in the central drift chamber, and therefore a large uncertainty in its 9.31 GeV momentum assignment, though total event momentum balance gives us additional confidence in this momentum measurement. This track does have a sufficient number of hits in the vertex chamber and endcap calorimeter PWCs to make it worth vertexing, though this B^0 will have the largest error on its lifetime measurement.

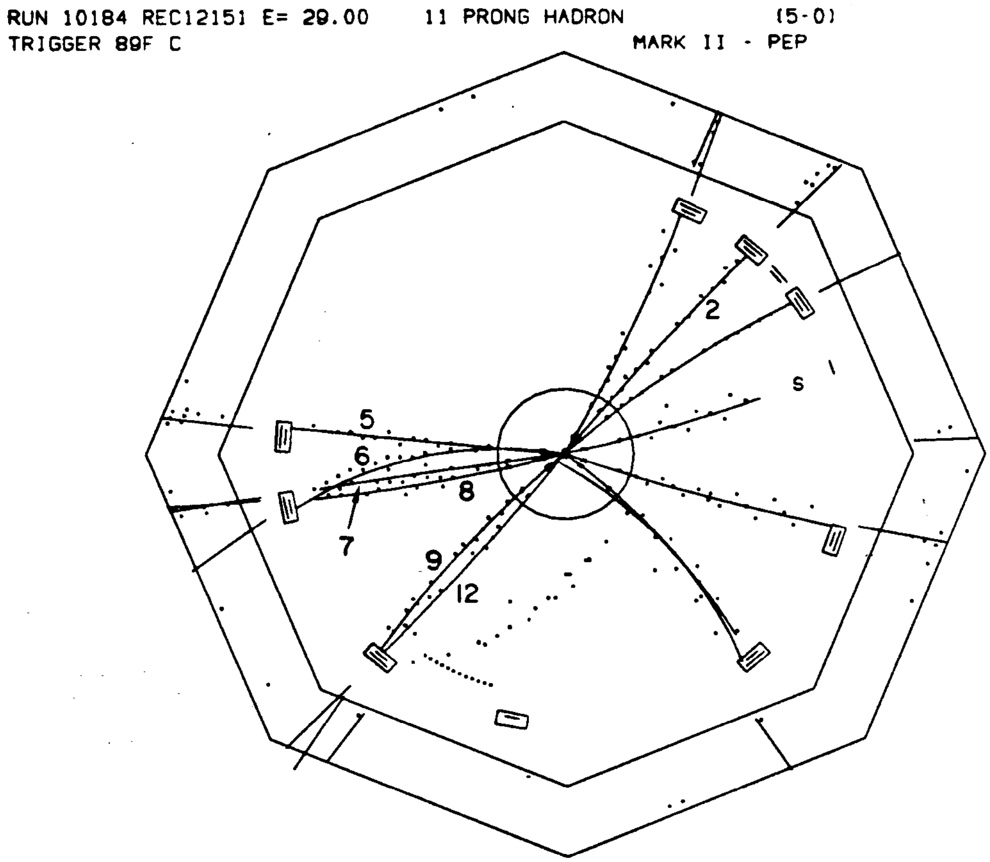

Fig. 7. Event C in the Mark II/PEP5 detector.

Event C (shown in Fig. 7) is the only pair tagged with a same-charge $D^{*+}\pi_B^+$ combination ($m_{D^{*+}\pi^+} = 4.232$ GeV, $x_p = 0.98$). Tracks 7, 8, and 12 form the $D^{*+} \to \pi_S^+ D^0$, $D^0 \to K^-\pi^+$, decay ($x_E = 0.65$, $p_T = 1.33$ GeV) and Track 5 is the π_B^+ ($p = 5.42$, $p_T = 1.92$ GeV). Since this is a doubly charged pair, it cannot form a B decay candidate by itself or with the addition of only neutral particles (there is, once again, a π^0 candidate in this hemisphere). The only other particles in the hemisphere are two negative tracks (6 and 9) which, when added to the tagging $D^{*+}\pi_B^+$ and the π^0, gives a combined $m_{D^{*+}\pi^+\pi^-\pi^-\pi^0} = 5.450$ GeV and $x_p = 1.02$. This is consistent with what we expect our mass resolution for $\overline{B}^0 \to D^{*+}\pi^+\pi^-\pi^-\pi^0$ to be, and all other possible B candidates in this hemisphere are inconsistent with m_B (the highest mass B^- candidate in this hemisphere has $m_{D^{*+}\pi^-\pi^-\pi^0} = 3.255$ GeV).

We now have four candidates for B^0 decay which we can vertex. Our analysis programs have isolated regions where it is kinematically unlikely for anything other than B decays to exist. All the background measures we have studied (same-hemisphere $D^{*-}\ell^-$ pairs, pairs with $m > m_B$, $c\bar{c}$ MC samples) are empty. We have relaxed many of the cuts used in these analyses and find no large sources of background just excluded by one cut. The number of events we see is *consistent* with the number we expect from our MC studies, but this depends on our assumed B BR's. For example, the decay $\overline{B}^0 \rightarrow D^{*+}\pi^+\pi^-\pi^-\pi^0$ should have a large ($\sim 5\%$) BR, but it has never before been observed.

A variety of arguments lead us to believe these events are B^0 and not B^+ decays. For the $D^{*-}\mu^+$ event, we rely on the ARGUS $B^0 \rightarrow D^{*-}\ell^+\nu$ BR and/or theoretical calculations[17] which say that $B \rightarrow D^{*-}\ell^+X$ decays are dominated by $B^0 \rightarrow D^{*-}\ell^+\nu$. However, there are two positively charged tracks in the same hemisphere as the $D^{*-}\mu^+$ pair, and each of these tracks gives $m_{D^{*-}\mu^+\pi^+} \simeq m_B$. If this is a B^+ decay, then $p_\nu \simeq 0$ in the lab frame. While this is not kinematically forbidden, it is improbable (the entries in Fig. 3a stop at $m \simeq 5$ GeV, less than either of the $D^{*-}\mu^+\pi^+$ masses).

For the three hadronic B^0 candidates, the only viable fully reconstructed B decay in each tagged hemisphere is a B^0 consisting of all the particles in that hemisphere (except for the endcap photons in Event B). The absence of fragmentation pions in these hemispheres is probably due to the high x of the B^0 candidates. All the events have zero total charge, and there is no sign of additional tracks which were missed by the tracking algorithms. In no case is it possible to combine tracks from the other hemisphere with the tagged $D^{*-}\pi^\pm$ pair and get a mass consistent with m_B. Events A and B have no charged tracks in the B^0 hemisphere other than the ones which tag the event, and these and the reconstructed neutral pions make good B^0 candidates. In Event C, the tagged $D^{*+}\pi_B^+$ pair is doubly charged, and several particles must be associated with this pair to make the $\overline{B}^0$ candidate. Since the $D^{*+}\pi_B^+$ pair has $\cos\theta_H = -0.07$, the probability that this pair comes from a $\overline{B}$ decay is high. There is another occurrence in Event C which significantly increases the probability that this is a $b\bar{b}$ event, and therefore that the assignment as a $\overline{B}^0$ decay is correct. There is a high p_T isolated e^+ (Track 2, with $p = 1.21$, $p_T = 0.71$ GeV) in the other hemisphere, and same-charge, opposite-hemisphere $D^{*-}\ell^-$ pairs are excellent tags of *unmixed* $b\bar{b}$ events. The other major sources of opposite-hemisphere $D^{*-}\ell$ events (other than combinatorial or direct lepton backgrounds) are mixed $B^0\overline{B}^0$ events, $b\bar{b}$ events with a cascade $B \rightarrow DX$, $D \rightarrow \ell^+\nu X$ decay in one hemisphere and a $\overline{B} \rightarrow D^{*+}X$ decay in the other, and $c\bar{c}$ events. These all produce opposite-hemisphere *opposite*-charged $D^{*-}\ell^+$ pairs.

Table 2. Measured proper lifetimes for B^0 candidates.

Event	Lifetime (psec)
A	0.68 ± 0.32
B	4.70 ± 3.33
C	1.35 ± 0.83
$D^{*-}\mu^+$	1.86 ± 0.31

To measure the decay length[10] of the B^0 candidates, we formed vertices with the charged tracks from the $\overline{D}^0$ decay to determine the $\overline{D}^0$ decay position and the rest of the charged tracks from the B^0 candidate decay to determine the B^0 decay position. The most probable B^0 decay length and its error was then calculated from the measured beam interaction position and extent and the B^0 and $\overline{D}^0$ vertex positions and error matrices. The additional constraints that the B^0 and $\overline{D}^0$ flight paths be parallel to the reconstructed ones were imposed. The B^0 decay lengths were then converted to proper lifetimes using the measured $\gamma\beta c \sin\theta$ (all vertices were found in the transverse plane only). The proper lifetimes for the four B^0 candidates are shown in Table 2. For the $B^0 \to D^{*-}\mu^+\nu$ candidate, we estimated the B^0 four-momentum by that of the $D^{*-}\mu^+$ pair. Use of the Thrust axis in place of the $D^{*-}\mu^+$ momentum vector for the B^0 direction changed the measured lifetime by a negligible amount.

A maximum likelihood fit to an exponential lifetime distribution convoluted with a Gaussian resolution function, assuming all candidates are unambiguous B^0 decays, gave $\tau_{B^0} = 1.3^{+1.2}_{-0.6}$ psec, where the error is statistical only. From previous Mark II measurements of the D^0 and D^+ lifetimes,[6,18] we expect detector associated systematic error to be ≤ 0.5 psec, though this has not been studied in detail for the B^0 case. If any of the B^0 candidates are really B^+ decays or are background not associated with B decay (which should have $\tau \simeq 0$ psec with our decay length method), there will be additional systematic error.

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