LIFETIME MEASUREMENT OF CHARM MESONS PRODUCED IN $\pi^- p$ AND
pp INTERACTIONS AT 360 GeV/c

LEBC-EHS Collaboration

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ABSTRACT

Results are presented on charm meson lifetimes. The sample of charm particle decays was obtained by exposing the high resolution rapid cycling hydrogen bubble chamber (LEBC) coupled with the European Hybrid Spectrometer to π^- and p beams at 360 GeV/c from the CERN SPS. The analysis of ~ 850 k pictures has yielded 77 events containing a total of 60 charm decays. The measured mean lifetimes for $D^\pm$ and D^0 are (where the symbol D^0 means D^0 and $\bar{D}^0$)

$$\tau(D^\pm) = 8.4 \begin{matrix} + 3.5 \\ - 2.2 \end{matrix} \times 10^{-13} \text{ s}$$

$$\tau(D^0) = 4.1 \begin{matrix} + 1.3 \\ - 0.9 \end{matrix} \times 10^{-13} \text{ s}$$

Three unambiguous examples of $F^\pm$ decay have also been observed and the corresponding lifetime is:

$$\tau(F^\pm) = 2.1 \begin{matrix} + 3.6 \\ - 0.8 \end{matrix} \times 10^{-13} \text{ s}$$

In this letter we present results on the lifetimes of charged and neutral charm particles produced in high energy π^- and p interactions.

The rapid cycling hydrogen bubble chamber (LEBC) equipped with a high resolution two view optical system has been exposed to 360 GeV/c π^- and proton beams from the CERN SPS. LEBC operated at 30 Hz and with a resolved bubble diameter of $\sim 50 \mu\text{m}$. The data taking was controlled by a simple interaction trigger system, giving ~ 0.4 hydrogen interactions per picture. The bubble chamber was coupled to the European Hybrid Spectrometer (EHS) for charged particle momentum analysis and π^0 detection. Limited particle identification was provided by the pictorial drift chamber ISIS1. A detailed description of the experimental set-up can be found elsewhere [1].

A total of 350 k pictures with incident π^- and 500 k pictures with incident p have been taken corresponding to a sensitivity of 7.8 events/ μb for the π^- and 7.3 events/ μb for the proton exposure. Preliminary results on the observation of a $D^0-\bar{D}^0$ pair in the π^- run have been published earlier [2].

All the film has been scanned twice and checked by physicists looking for decays of charged and neutral particles from the primary vertex. Decays hidden in the forward confusion region have been detected by either searching for secondary tracks not pointing to the primary vertex or looking for increases of ionization.

Negligible secondary interaction contamination is expected in this sample due to the use of hydrogen as the sensitive liquid. In order to reduce the strange particle background, only events with a decay having a transverse distance smaller than 0.06 cm with respect to the incoming beam direction have been considered for this analysis. This cut has a negligible effect on charm particles with decay times less than 2×10^{-12} s.

The bubble chamber measurements have been combined with the spectrometer information to obtain charged particle momenta. Photons inside the acceptance of the gamma detectors have been used for π^0 reconstruction.

All the selected decays have been subjected to a kinematic fit. In order to remove from the sample any possible background coming from the much more abundant strange particle decays and photon conversions, an acceptable charm decay has to satisfy all the following criteria.

(a) Neutral two-prong decays

- e^+e^- effective mass $> 30 \text{ MeV}/c^2$
at 3 standard deviations (3σ) level
or (if one of the momenta is not measured)
non zero opening angle (3σ)
  - No kinematic fit to the decay hypothesis:
$K_S^0 \rightarrow \pi^+\pi^-$ ($P(\chi^2) < 10^{-4}$) $\Lambda^0 \rightarrow p\pi^-$ ($P(\chi^2) < 10^{-3}$) $\bar{\Lambda}^0 \rightarrow \bar{p}\pi^+$ ($P(\chi^2) < 10^{-3}$)	}	Ordinary strange particle decay rejection
$\pi^+\pi^-$ effective mass $> 500 \text{ MeV}/c^2$ (3σ) $p\pi^-$ ($\bar{p}\pi^+$) effective mass $> 1120 \text{ MeV}/c^2$ (3σ) or (if only one of the momenta is missing) same limits on $(\pi\pi)$ and $(p\pi)$ using the minimum effective mass ^(*)	}	Rare strange particle decay rejection

(b) Charged 1-prong decays

- Transverse momentum $> 250 \text{ MeV}/c$ (3σ)

(c) Charged 3-prong decays

- e^+e^- effective mass $> 30 \text{ MeV}/c^2$ (3σ)
(all 2 track combinations).
  - No kinematic fit to the hypothesis:
$K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ ($P(\chi^2) < 10^{-2}$) or (if one of the momenta is not measured) $\pi^\pm \pi^+ \pi^-$ minimum effective mass ^(*) $> 500 \text{ MeV}/c^2$ (at 3σ)	}	Σ^+ Dalitz decay rejection Strange particle decay rejection

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(*) Minimum of the mass of the system as a function of the unmeasured momentum.

- Topologies consistent with a neutral 2-prong decay superimposed on a prong from the primary interaction are in addition analyzed as in (a).

Based on these criteria we have estimated via Monte-Carlo that the sample should not contain more than 3% of strange decay background. The background from π^-p and pp secondary interactions with an invisible recoil proton (range less than 0.03 cm) and with effective mass compatible with that of a charm meson or baryon has been estimated to be less than 1%.

With the outlined procedure we have selected a sample of 51 events containing 60 identified charm decays: 55 of them give a good kinematic fit to a charm decay hypothesis with one or more degrees of freedom (1C, 2C and 3C fits). Two of the decays give 0C fits and three have a track identified as an electron in the gamma detectors^(*) and give 0C solutions to charm hypotheses, being therefore good candidates for semileptonic decays. A further sample of 26 events selected by the same procedure are attributed to charm decays with greater than 1 neutral particle escaping detection. These decays are excluded from the following analysis.

Decays very close to the production vertex have almost no information available on the line of flight of the decaying particle. Therefore, fits of short decays with more than one non-reconstructed track or with unseen neutrals (π^0 , K^0) are essentially underconstrained. In the subsequent lifetime analysis only decays having kinematic fits with 3 or 2 degrees of freedom (3C and 2C) have been used. A total of 52 charm decays (23 neutral, 28 charged and 1 charge ambiguous) have been selected in this way.

Charm decays can in principle give spurious fits using a π^0 from the primary vertex or a fake π^0 from the combinatorial background present under the π^0 peak. We have performed a Monte-Carlo study of the effect of such an erroneous π^0 association on the proper time of the decaying particle. The uncertainty introduced in the lifetime determination shows no systematic effect and is anyway less than 10%; therefore we can safely accept decays with neutral pions in our sample.

(*) For two of these events the electron identification is supported by ISIS1.

In case of ambiguity between Cabibbo-favoured and Cabibbo-unfavoured interpretations, Cabibbo-favoured fits have been preferred. Moreover, Cabibbo-favoured $D^\pm$ hypotheses have been selected over any ambiguous Λ_c^+ and $F^\pm$ interpretation. For the sample of Λ_c^+/F^+ fits, a D^+ hypothesis with missing neutral pions not seen in the gamma detectors cannot be ruled out. However, the Monte-Carlo study of the π^0 background indicates a maximum of 1 wrong $F^\pm$ and 0.2 Λ_c^+ .

Finally, an event with confused topology which is also kinematically ambiguous between D^0 and Λ_c^+ has been excluded from the lifetime sample. Table 1 summarizes the subdivision of the decays into the various channels.

In order to estimate lifetimes, we have used the maximum likelihood method, with the likelihood function defined as:

$$L(\tau) = \prod_i \frac{\frac{1}{\tau} e^{-t^i/\tau}}{e^{-t_m^i/\tau} - e^{-t_M^i/\tau}}$$

where t^i is the proper time and $t_{m,M}^i$ are the times corresponding to the minimum and maximum detectable lengths of the i -th decay. The minimum detectable length (l_m^i) has been computed for each event on the basis of the scanning detection criteria, l_m^i being the smallest of:

- (a) The length necessary to detect the decay as a significant ionization jump (with or without overlapping tracks); l_m^i depends on the production vertex configuration and decay topology.
- (b) the length for which one of the decay prongs has a detectable impact parameter (track from the decay not pointing to the primary vertex). Impact parameter detection depends on bubble size and on the event configuration.

A few decays had to be excluded from the lifetime computation because they have decay lengths smaller than the computed minimum detectable length; some of these decays have been detected only at the measuring stage and others reflect a reduced, but non-zero detection efficiency for $l^i < l_m^i$.

The finite length of LEB, the depth of focus and the 0.06 cm cut on the transverse distance of the decay point from the direction of the beam contribute to the definition of the maximum detectable length.

In the absence of losses the mean value of t_i gives the best estimate of the particle lifetime. For the D^0 and $D^\pm$ samples discussed here, these values are within 20% of the final maximum likelihood estimates given below, thus showing that the minimum length and potential length corrections are small.

The full sample of 23 neutral D decays shown in table 1 gives

$$\tau(D^0) = 4.1^{+1.3}_{-0.9} \times 10^{-13} \text{ s},$$

where 16 decays were used in the likelihood fit and 7 were excluded by the l_m^i cut. In fig. 1(b) the $t_i - t_m^i$ distribution is compared with the fit result. The stability of the result has been checked as a function of the definition of the l_m^i and of different event samples (two prong or four prong decays only, all or all but one reconstructed tracks, decays with or without neutrals, etc.). All results obtained are compatible with the above value.

In the charged particle lifetime determinations only three-prong decay topologies have been used (20 decays), the one-prong sample selection criterion being strongly dependent on the decay length (high p_T with small errors implying a long decay path).

A sizeable fraction of the charged decay sample is affected by kinematic ambiguity between different charm interpretations. If we compute the lifetime of the full 20 decay $D^\pm$ sample (3C and 2C fits), we obtain (see fig. 1(a)):

$$\tau(D^\pm) = (8.4^{+3.5}_{-2.2}) \times 10^{-13} \text{ s}, \quad (\text{based on 15 decays})$$

where 5 decays are eliminated by the l_m^i cut. Using the 3C sample alone (16 decays), which Monte-Carlo calculations show has at most a 5% contamination from misidentified $F^\pm$ or Λ_c^+ , we obtain:

$$\tau(D^\pm) = (9.9^{+5.7}_{-3.0}) \times 10^{-13} \text{ s}, \quad (\text{based on 12 decays})$$

where 4 decays are eliminated by the 1_m^i cut. These estimates of $\tau(D^\pm)$ are consistent within half a standard deviation and we consider the result based on the full sample to be our best estimate of the $D^\pm$ lifetime.

The corresponding value of the ratio between charged and neutral D meson lifetimes is:

$$R = \frac{\tau(D^\pm)}{\tau(D^0)} = 2.1 \begin{smallmatrix} + 1.4 \\ - 0.6 \end{smallmatrix}$$

We have a total of 6 decays which fit a $F^\pm/\Lambda_c^+$ and not a $D^\pm$ interpretation. Out of these, 3 have a unique $F^\pm$ fit and 3 are ambiguous $F^\pm/\Lambda_c^+$.

The 3 decays with a unique fit to $F^\pm$ give:

$$\tau(F^\pm) = 2.1 \begin{smallmatrix} + 3.6 \\ - 0.8 \end{smallmatrix} \times 10^{-13} \text{ s, (based on 2 decays)}$$

where 1 decay is eliminated by the 1_m^i cut.

The remaining sample of 3 ambiguous decays contains an unknown mixture of $F^\pm$ and Λ_c^+ ; the proper decay times are 0.6, 1.9 and 3.9×10^{-13} s, respectively.

We note that on the basis of the Monte-Carlo study we do not expect differences in τ for a sample of $D^\pm$ misinterpreted as Λ_c^+ or $F^\pm$. The fact that the $F^\pm/\Lambda_c^+$ samples exhibit a lifetime substantially different from the $D^\pm$ sample seems to indicate that indeed the $F^\pm/\Lambda_c^+$ selection is correct.

With our experimental set-up, electrons can be identified by comparing the momentum measured in the spectrometer with the energy released in the gamma detectors. At momenta greater than 10 GeV the background from misidentified hadrons is $< 1\%$. In this way 3 candidates for $D^0/\bar{D}^0$ semileptonic decays have been selected in the sample of neutral charm decays. Moreover this particle identification is supported by ISIS1 in two of the three cases. A $\gamma + e^+e^-$ interpretation for these events is also ruled out on the basis of the effective mass.

Taking into account the acceptance for our selection criteria and the total number of D^0 and $\bar{D}^0$ produced [3] we obtain

$$\frac{D^0 \rightarrow e^\pm \bar{\nu}}{D^0 \rightarrow \text{all}} = (5.1^{+4.8}_{-1.4})\%$$

Using the D^0 lifetime measurement given above and this determination of the semileptonic branching ratio, we obtain a semileptonic rate of $(1.2^{+1.2}_{-0.4}) \times 10^{11} \text{ s}^{-1}$.

Our present charged D selection criteria are expected to reject a large fraction of the charged semileptonic decays, preventing any reliable estimate of the $D^\pm$ semileptonic branching ratio.

In conclusion, we have observed a sample of 77 events containing 60 identified charm decays. We have used 52 decays giving good kinematic fits (2C and 3C) to obtain the following mean lifetimes. The D^0 sample gives a lifetime of:

$$\tau(D^0) = (4.1^{+1.3}_{-0.9}) \times 10^{-13} \text{ s}$$

and the $D^\pm$ sample a lifetime of

$$\tau(D^\pm) = (8.4^{+3.5}_{-2.2}) \times 10^{-13} \text{ s}.$$

The corresponding value of the lifetime ratio is

$$R = \frac{\tau(D^\pm)}{\tau(D^0)} = 2.1^{+1.4}_{-0.6}$$

Our values for the D^0 and $D^\pm$ lifetimes can be compared with the present world average values [4] of $(4.0^{+1.2}_{-0.9}) \times 10^{-13} \text{ s}$ and $(9.3^{+2.7}_{-1.8}) \times 10^{-13} \text{ s}$, respectively^(*). It is worth noting that each of the D^0 and $D^\pm$ samples are consistent with a single slope exponential behaviour.

The neutral semileptonic branching ratio is found to be : $BR_e(D^0) = (5.1^{+4.8}_{-1.4})\%$, giving a semileptonic rate $\Gamma = (1.2^{+1.2}_{-0.4})10^{11} \text{ s}^{-1}$. This $BR_e(D^0)$ is to be compared with $BR_e(D^0) < 4\%$ (95% CL) from DELCO [7] and $BR_e(D^0) = (5.5 \pm 3.7)\%$ from MARKII [8] in e^+e^- experiments.

(*) Preliminary results were presented on D^0 and $D^\pm$ lifetimes from the present experiment at the Lisbon Conference [5] and at the Moriond Workshop [6]. The results presented here are in excellent agreement with the earlier results and should be considered as replacing all preliminary results.

Three unambiguous $F^\pm$ have been observed with a mean lifetime of $(2.1^{+3.6}_{-0.8}) \times 10^{-13}$ s.

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TABLE 1

The division by decay mode of the 52 charm decays having 2C or 3C kinematic fit

		n = 0	n = 1	n = 2
$D^0, \bar{D}^0$	$K^\pm \pi^+ n\pi^0$	5	4	3
	$K^\pm \pi^\mp \pi^+ \pi^- n\pi^0$	8	2	0
	$\pi^+ \pi^+ \pi^- \pi^- n\pi^0$	1	0	0
D^+, D^-	$\pi^\pm K^0 n\pi^0$	0	2	0
	$K^\mp \pi^\pm \pi^\pm n\pi^0$	13	4	1
	$\pi^\pm \pi^+ \pi^- n\pi^0$	1	0	0
	$K^0 \pi^\pm \pi^+ \pi^- n\pi^0$	1	0	0
D^0/Λ_c^+ ambiguous		1	0	0
F^+/Λ_c^+ ambiguous		2	0	1
$F^\pm$	$K^+ K^- \pi^\pm n\pi^0$	0	3	0

FIGURE CAPTIONS

Fig. 1   Distribution in $t - t_{\min}$.

(a) $D^{\pm}$ sample.

(b) $D^0/\bar{D}^0$ sample.

The curves represent the maximum likelihood estimates of the mean lifetimes.

Fig.I