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MEASUREMENT OF THE MASSES AND LIFETIMES OF THE CHARMED MESONS

D^0, D^+ AND D_s^+

(ACCMOR Collaboration)

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ABSTRACT

We present the final results on the measurement of the masses and lifetimes of the mesons D^0 , D^+ and D_s^+ in the NA32 experiment at the CERN SPS, using silicon microstrip detectors and charge-coupled devices for vertex reconstruction.

We measure the following lifetimes : $\tau_{D^0} = 3.88 \pm_{0.21}^{0.23} \cdot 10^{-13} \text{s}$ using a sample of 479 $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ and 162 $D^0 \rightarrow K^- \pi^+$ decays ; $\tau_{D^+} = 10.5 \pm_{0.72}^{0.77} \cdot 10^{-13} \text{s}$ with a sample of 317 $D^+ \rightarrow K^- \pi^+ \pi^+$ decays ; $\tau_{D_s^+} = 4.69 \pm_{0.86}^{1.02} \cdot 10^{-13} \text{s}$ with a sample of 54 $D_s^+ \rightarrow K^+ K^- \pi^+$ decays. We measure the following masses : $m_{D^0} = 1864.6 \pm 0.3 \pm 1.0 \text{ MeV}$, $m_{D^+} = 1870.0 \pm 0.5 \pm 1.0 \text{ MeV}$ and $m_{D_s^+} = 1967.0 \pm 1.0 \pm 1.0 \text{ MeV}$.

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1. INTRODUCTION

Weak decays have always played an important role in testing the $SU(2) \times U(1)$ model of electromagnetic and weak interactions. However, to extract information about the standard model from the study of weak decays of heavy quarks is not straightforward, since the quarks are confined inside hadronic bound states and the underlying dynamics of heavy flavour meson or baryon decays is affected by strong interactions. Precise measurement of the lifetimes of the 3 charmed mesons D^0 , D^+ and D_s^+ provides an interesting test ground for the interplay between weak and strong interactions and for the various models that attempt to describe it [1].

We report here on the final results of the NA32 experiment on the measurement of the D^0 , D^+ and D_s^+ masses and lifetimes using very clean samples of the various mesons detected with the help of a high resolution vertex telescope, composed of silicon microstrip detectors and charge-coupled devices*).

In section 2 of this paper we describe the experiment and in section 3 the analysis of the data. Results are presented in section 4 and we conclude in section 5.

2. THE EXPERIMENT

The NA32 experiment at the CERN SPS has pursued a programme of study of properties of charmed particles produced in hadronic interactions. In the first phase, data have been collected in the collisions of 200 GeV π^- , K^- and p on a Si target, using an interaction trigger. The vertex detector consisted of a segmented silicon active target and silicon microstrip detectors. A sample of 90 D^0 , 59 D^+ and 12 D_s^+ mesons was extracted from a total of 38 million triggers and used for lifetime and cross section measurements [2].

We report here on the second phase of the NA32 experiment which was designed to be a dedicated study of Λ_c^+ and D_s^+ production and decay. It used a two-level trigger [3] selecting preferentially events containing a pair of kaons and/or protons of opposite charge. An increase in sensitivity of a factor 5 for decays of $\Lambda_c^+ \rightarrow pK^-\pi^+$ and $D_s^+ \rightarrow K^+K^-\pi^+$ was obtained [4,5]. The trigger proved to be effective as well for decays to final states containing a single kaon like $D^0 \rightarrow K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$ or $D^+ \rightarrow K^-\pi^+\pi^+$ decays. In this case the requirement of the second kaon is fulfilled by the kaon from the other charmed particle in the event or by a pion misidentified as a kaon at the trigger level or by a kaon or proton from the primary vertex. A total of 17 million triggers have been recorded with a 230 GeV incident π^- beam on a copper target.

Hadronic charm decays into charged particles were fully reconstructed with the large acceptance forward spectrometer and the vertex detector. The spectrometer [6] consisted of 2

*) Throughout this paper particle symbols stand for both particles and antiparticles.

magnets and 48 planes of drift chambers arranged in 4 groups. Three multicellular Cerenkov counters were used to identify π , K, p in the momentum range 4 - 80 GeV.

The vertex detector [4,5] consisted of two parts : a beam telescope of 7 silicon microstrip detectors (MSDs) and a vertex telescope consisting of 2 charge-coupled devices (CCDs) and 8 MSDs. A short 2.5 mm Cu target was used so that decay vertices could be observed in vacuum close to the primary vertex. The CCDs [7], with pixel size of $22 \times 22 \mu\text{m}^2$, measure space points with a precision of $\sim 5 \mu\text{m}$ in two orthogonal coordinates and a two-track resolution of $40 \mu\text{m}$. The CCDs were positioned at 10 and 20 mm behind the target. The 8 MSDs were positioned from 65 to 180 mm downstream of the target.

The beam telescope measured the trajectory of the incoming beam particle with a precision of $7 \mu\text{m}$ horizontally (x) and $3 \mu\text{m}$ vertically (y). The precision on the reconstructed primary vertex was $2 \mu\text{m}$ transversally to the beam direction and $70 \mu\text{m}$ longitudinally. The impact parameter of a track was measured with a precision of $\sigma_{dx} \sim \sigma_{dy} \sim \sqrt{5^2 + (18/p)^2} \mu\text{m}$ (dx,dy are the minimum projected distance of a track from the primary vertex) where the momentum dependent term (p is measured in GeV) is the contribution from the multiple scattering.

3. DATA ANALYSIS

For the measurement of the charmed mesons lifetimes, we have used the following decay modes : $D^0 \rightarrow K^-\pi^+$ or $K^-\pi^+\pi^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$ or $K^+K^-\pi^+$ and $D_s^+ \rightarrow K^+K^-\pi^+$. To ensure a good efficiency for finding charm events, two independent methods of analysis have been developed. The comparison between the two analysis programs during the development stage was found useful to achieve a high efficiency. We describe here the analysis on which the data presented in this paper is based. The other approach has been described in [5].

The analysis proceeds as follows. First, all tracks are reconstructed in the drift chambers. Then these tracks are extrapolated into the MSDs and used to guide the track reconstruction. Finally we search for matching hits in the CCDs. All these tracks are then used together with the beam track to find the primary vertex. The search for charm vertices starts with all combinations of tracks having the correct charges and particle identification for the desired decay modes and having an invariant mass inside a window of about 150 MeV centred at the D mass. For this set of tracks, we look in a first step for secondary vertices without using any CCD hits. Only if the vertex found lies upstream of the CCDs is a search performed for matching CCD hits. In this approach all possible ambiguous track solutions are kept until the final vertex fit, where the best solution is selected according to criteria based on the number of CCD hits and the χ^2 probability for the reconstructed momentum vector sum to originate from the primary vertex.

In order to reduce the background the following cuts were applied :

- 1) To reject fake decay vertices, we require the χ^2 of the fit of the secondary vertex to be smaller than 3 times the number of degrees of freedom. The impact parameters of all decay tracks have to be larger than a certain number of standard deviations, typically 5σ for the track with the largest impact parameter down to 1σ for the track with the smallest impact parameter.
- 2) To reject decays with missing neutral particles, the momentum vector sum of all charm tracks has to point to the primary vertex.
- 3) Finally, to reject secondary interactions, we demand all secondary vertices to be outside the Cu target and to have decay lengths larger than 1 mm.
- 4) Some additional selection criteria specific to a decay mode are applied. For $D^0 \rightarrow K^-\pi^+$, we demand the cosine of the decay angle of the kaon in the D^0 centre of mass system to be $|\cos \theta| < 0.9$. The decay channel $K^+K^-\pi^+$ suffers from background due to reflections of $\Lambda_c^+ \rightarrow pK^-\pi^+$ and $D^+ \rightarrow K^-\pi^+\pi^+$ decays where the particle identification is ambiguous. We remove all combinations with particle identification consistent with a $\Lambda_c^+ \rightarrow pK^-\pi^+$ decay and with a mass in the interval $2.26 \leq m_{pK^-\pi^+} \leq 2.30$ GeV and combinations consistent with a $D^+ \rightarrow K^-\pi^+\pi^+$ decay and with a mass in the interval $1.86 \leq m_{K^-\pi^+\pi^+} \leq 1.88$ GeV.

4. RESULTS

The invariant mass distributions obtained in the analysis of the full sample of 17 million triggers, are presented in part a of Figs. 1-4 for the 4 decay modes. Clean D^0 , D^+ and D_s^+ signals are seen on very small background. Table 1 summarizes the number of events.

In order to extract the lifetime from the data, we have to correct for the acceptance of the selection criteria [8]. For each event we determine the minimum and maximum detectable lifetimes, $t_{\min}$ and $t_{\max}$ respectively. This is done by moving the decay vertex backwards and forwards along the straight line connecting the primary and secondary vertex, keeping all other parameters of the event unchanged. The minimum and maximum distances from the primary vertex, $l_{\min}$ and $l_{\max}$ respectively, where the event just fails the imposed cuts, determine $t_{\min}$ and $t_{\max}$. Here $l_{\max}$ is limited by the end of the decay volume, which is defined by the position of the first MSD plane 65 mm downstream of the target. As discussed in [8], this method requires a constant efficiency between $l_{\min}$ and $l_{\max}$, and we fit the distribution of corrected lifetimes, $t_{\text{cor}}/\tau = (t_{\text{meas}} - t_{\min})/\tau$, where τ is the mean lifetime.

We have to ensure that each individual event of our selected sample would have been found everywhere in the decay volume from $l_{\min}$ to $l_{\max}$. Our decay volume extends over 3 regions (target-CCD1, CCD1-CCD2, CCD2-MSD1). As we move the decay point across different regions, we have to change the errors assigned to the decay tracks according to the number of CCD hits associated to each track. The CCDs being only about 90% efficient, we do not know whether a particular track would have had an associated CCD-hit. Therefore for events decaying in front of CCD2 we assign systematically to all tracks the error corresponding to one hit in CCD2 giving an error of dx and $dy \sim \sqrt{7.5^2 + (25/p)^2} \mu\text{m}$. For events decaying behind CCD2 we assign the same error as soon as the vertex moves into the region before CCD2 in the procedure for the determination of $l_{\min}$. In the latter case, we checked that all events would have been seen all the way to CCD2. The events which fail to pass the original selection criteria with the new error assignments are rejected.

We perform a combined maximum likelihood fit to the mass and corrected lifetime distributions for signal and background. The lifetime of the background is fitted by an exponential distribution which provides an adequate parametrization, the background being mostly of charm origin. For the mass spectrum we assume a Gaussian signal above a linear background. The width is obtained from the calculated mass resolution of each event. Part b of Figs. 1-4 and Fig. 4c show the corrected lifetime distributions for the D mesons and part c of Figs. 1-3 and Fig. 4d show the same distribution for the background. The results of the fits for the mass and lifetime are summarized in Tables 1 and 2.

We have studied our procedure with a Monte Carlo program simulating all features of the vertex detector. This study has shown as expected that keeping the original track errors rather than the error quoted above would result in a slightly shorter D^+ lifetime, while the D^0 and D_s^+ are not affected since most of them decay before CCD2. Experimentally we indeed measure in that case $\tau_{D^+} = 9.87 \pm_{0.61}^{0.67} \cdot 10^{-13}\text{s}$ instead of our quoted value of $\tau_{D^+} = 10.5 \pm_{0.72}^{0.77} \cdot 10^{-13}\text{s}$ while τ_{D^0} and $\tau_{D_s^+}$ are unchanged.

We have investigated possible sources of systematic errors :

- 1) There is a small sample of decays in the region in front of CCD2 where one of the tracks has no associated CCD hit. The Monte Carlo study, which fully simulates those effects, has shown that it has a negligible effect on the fitted lifetimes.
- 2) In order to rule out a possible dependence on a particular choice of the selection criteria, we varied the values of the impact parameter cuts and/or the cut on the minimum decay length. The changes in the lifetime were in all cases compatible with the statistical fluctuations expected from the fraction of events excluded.

- 3) Finally, as already discussed in [5], we compared the results of the two independent analysis programs. A study on a total of 700 charm decays ($\Lambda_c^+ \rightarrow pK^-\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$) has shown a relative efficiency for fully reconstructed charm decays of about 85% for each program. This corresponds to an absolute track reconstruction efficiency of about 95%. No dependence of the relative efficiency on the decay length is observed. All values are in very good agreement with the results of the analysis presented here. The agreement on the Λ_c^+ lifetime [5] was also very good.

We conclude that all sources of systematic errors on the mean D lifetime are small with respect to the statistical error. We have estimated the systematic error on the masses to be about 1 MeV, the main contribution coming from the calibration of the magnetic field.

5. CONCLUSIONS

We have used very clean samples of D^0 , D^+ and D_s^+ mesons for mass and lifetime measurement. The results are summarized in Tables 1 and 2. They are in agreement with the world averages [9] dominated by the results of the experiment E691 [10]. The simple spectator quark model predicts the correct order of magnitude for the charmed mesons lifetimes [11] but does not explain the large difference observed between the D^+ and D^0 lifetimes. For a comparison with models we have computed the ratios :

$$\tau_{D_s^+}/\tau_{D^0} = 1.21 \pm_{0.23}^{0.27}$$

$$\tau_{D^+}/\tau_{D^0} = 2.71 \pm 0.25$$

Various effects contribute to this pattern of lifetimes [12]. Destructive quark interference in the final state lengthens the D^+ lifetime with respect to the D^0 and D_s^+ lifetimes. However this cannot be the only mechanism behind the τ_{D^+}/τ_{D^0} ratio, since the semileptonic decay width of D^0 would come out too high compared to the measured value [9]. General hadronic decay enhancement has been invoked to solve that problem. W exchange or annihilation diagrams that contribute to D^0 and D_s^+ decay have also been considered, although they should be helicity suppressed. Soft gluon emission could relax the suppression, and if they played an important role they would result in a shorter D_s^+ lifetime than D^0 lifetime which is not really supported by the data.

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Table 1

Channel	fitted No. of signal events	fitted No. of background events/ 2.5 MeV bin at D peak	Mass (MeV)
$D^0 \rightarrow K^- \pi^+$	162	0.90 ± 0.20	$1863.0 \pm 0.8 \pm 1.0$
$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$	479	3.11 ± 0.34	$1865.0 \pm 0.4 \pm 1.0$
$D^0 \rightarrow K^- \pi^+ + K^- \pi^+ \pi^- \pi^+$	637.5	4.04 ± 0.41	$1864.6 \pm 0.3 \pm 1.0$
$D^+ \rightarrow K^- \pi^+ \pi^+$	316.5	2.39 ± 0.35	$1870.0 \pm 0.5 \pm 1.0$
$D^+ \rightarrow K^+ K^- \pi^+$	57	0.94 ± 0.13	$1868.0 \pm 0.8 \pm 1.0$
$D_S^+ \rightarrow K^+ K^- \pi^+$	54	0.82 ± 0.12	$1967.0 \pm 1.0 \pm 1.0$

Table 2

Channel	τ_D [10^{-13} s]	$\tau_{\text{background}}$ [10^{-13} s]
$D^0 \rightarrow K^- \pi^+$	$3.85 \pm_{0.38}^{0.43}$	$10.4 \pm_{1.62}^{2.06}$
$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$	$3.89 \pm_{0.25}^{0.27}$	$5.5 \pm_{0.60}^{0.66}$
$D^0 \rightarrow K^- \pi^+ + K^- \pi^+ \pi^- \pi^+$	$3.88 \pm_{0.21}^{0.23}$	$6.8 \pm_{0.54}^{0.58}$
$D^+ \rightarrow K^- \pi^+ \pi^+$	$10.5 \pm_{0.72}^{0.77}$	$8.83 \pm_{0.89}^{1.07}$
$D^+ \rightarrow K^+ K^- \pi^+$	$10.39 \pm_{1.78}^{2.34}$	$6.5 \pm_{0.65}^{0.75}$
$D_S^+ \rightarrow K^+ K^- \pi^+$	$4.69 \pm_{0.86}^{1.02}$	$6.5 \pm_{0.65}^{0.75}$

Figure Captions

Fig. 1 $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$.

- a) Mass spectrum and fitted curve;
- b) Corrected lifetime and fitted curve for the signal $1.85 \leq m_{K3\pi} \leq 1.89$ GeV;
- c) Corrected lifetime and fitted curve for the background $1.80 \leq m_{K3\pi} \leq 1.84$ GeV and $1.90 \leq m_{K3\pi} \leq 1.95$ GeV.

Fig.2 $D^0 \rightarrow K^- \pi^+$.

- a) Mass spectrum and fitted curve;
- b) Corrected lifetime and fitted curve for the signal $1.85 \leq m_{K\pi} \leq 1.89$ GeV;
- c) Corrected lifetime and fitted curve for the background $1.80 \leq m_{K\pi} \leq 1.84$ GeV and $1.90 \leq m_{K\pi} \leq 1.95$ GeV.

Fig.3 $D^+ \rightarrow K^- \pi^+ \pi^+$.

- a) Mass spectrum and fitted curve;
- b) Corrected lifetime and fitted curve for the signal $1.85 \leq m_{K2\pi} \leq 1.89$ GeV;
- c) Corrected lifetime and fitted curve for the background $1.80 \leq m_{K2\pi} \leq 1.84$ GeV and $1.90 \leq m_{K2\pi} \leq 1.95$ GeV.

Fig.4 $D^+/D_s^+ \rightarrow K^+ K \pi^+$.

- a) Mass spectrum and fitted curve;
- b) Corrected lifetime and fitted curve for the $D^\pm$ signal $1.85 \leq m_{KK\pi} \leq 1.89$ GeV;
- c) Corrected lifetime and fitted curve for the D_s signal $1.95 \leq m_{KK\pi} \leq 1.99$ GeV;
- d) Corrected lifetime and fitted curve for the background $1.70 \leq m_{KK\pi} \leq 1.85$ GeV and $1.89 \leq m_{KK\pi} \leq 1.95$ GeV and $1.99 \leq m_{KK\pi} \leq 2.2$ GeV.

Fig . 1

Fig . 2

Fig . 3

Fig . 4