# Recent results on charm meson decays at FOCUS

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**Abstract.** E831-FOCUS is a photoproduction experiment which collected data during the 1996/1997 fixed target run at Fermilab. More than 1 million charm particles have been reconstructed. Using this sample we measure the lifetimes of all the weakly decaying singly charmed particles, establishing the charm lifetime hierachy. Then we present recent results on semileptonic decays of charm mesons, including the new s-wave inteference phenomena in $D^+ \to K^- \pi^+ \mu^+ \nu$, and high statistics branching ratio and form factor measurements.

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## 1 Introduction

Investigations of the $K$ and $B$ systems have and will continue to play a central role in our quest to understand flavor physics [1], but investigations of the charm-quark sector are fundamental too. Since charm is the only *up-type* quark for which the decay modes can be studied, it has a unique role to investigate flavor physics. Charm allows a complementary probe of Standard Model beyond to that attainable from the *down-type* sector. Here we present recent analyses on lifetimes and semileptonic decays.

The E831-FOCUS spectrometer is an upgraded version of the E687 fixed target spectrometer [2], located in the Fermilab proton beam area, which collected data during the 1996–97 fixed target run. More than 1 million charm particles have been fully reconstructed.

## 2 Charm lifetimes

The determination of lifetimes allows to convert the branching ratios measured by experiments to partial decay rates predicted by theory. FOCUS is the only experiment (with the predecessor experiment E687) to have measured the lifetimes of all the weakly decaying charmed particles. This is particulary important when one forms the ratio of lifetimes because most of the systematic errors cancel out. In Fig 1 we show a comparison between the PDG 2002 [4] values and the FOCUS lifetime measurements (in two cases our results are already included in the weighted averages). FOCUS produced new lifetimes results with precision better than the previous world average. An accurate measurement of the $D^0$ lifetime for the golden decay mode into $K\pi$ is a crucial ingredient to determine the lifetime difference, and consequently the parameter $y$ of the $D^0 - \overline{D^0}$ mixing.

The increasingly precise measurements of the heavy quark lifetimes have stimulated the further development of theoretical models, like the Heavy Quark Theory [5], which are able to predict successfully the rich pattern of charm hadron lifetimes, that span one order of magnitude from the longest lived ($D^+$) to the shortest lived ($\Omega_c^0$).

For the charm mesons a clear lifetime pattern emerges in agreement with the theoretical predictions:

$$\tau(D^0) < \tau(D_s^+) < \tau(D^+) \qquad (1)$$

Even the expectations [6,5] for the charm baryon lifetimes reproduce the data, which is quite remarkable since, in addition to the exchange diagram, there are constructive as well as destructive contributions to the decay rate. The experimental results lead to the following baryon lifetime hierarchy :

$$\tau(\Omega_c^0) \leq \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) \qquad (2)$$

## 3 Semileptonic decays of charm particles

Traditionally, the semileptonic decays of heavy flavored particles are accessible to both collider and fixed target experiments. The decays have clean and distinguishable signatures, and the Cabibbo-allowed decay channels like $D^0 \to K^- l^+ \nu_l$, $D^+ \to \overline{K}^{*0}(K^- \pi^+) l^+ \nu_l$ have large branching ratios.

Their fully explicit decay rates can be calculated from first principles, for example, theoretical tools like Feynman diagrams. Involving a lepton in the final decay stage implies that we do not have to worry about the usual final state interaction between hadrons. The possible complications coming from QCD corrections of the decay process are contained in form factors. The form factors can be

## Charm lifetimes
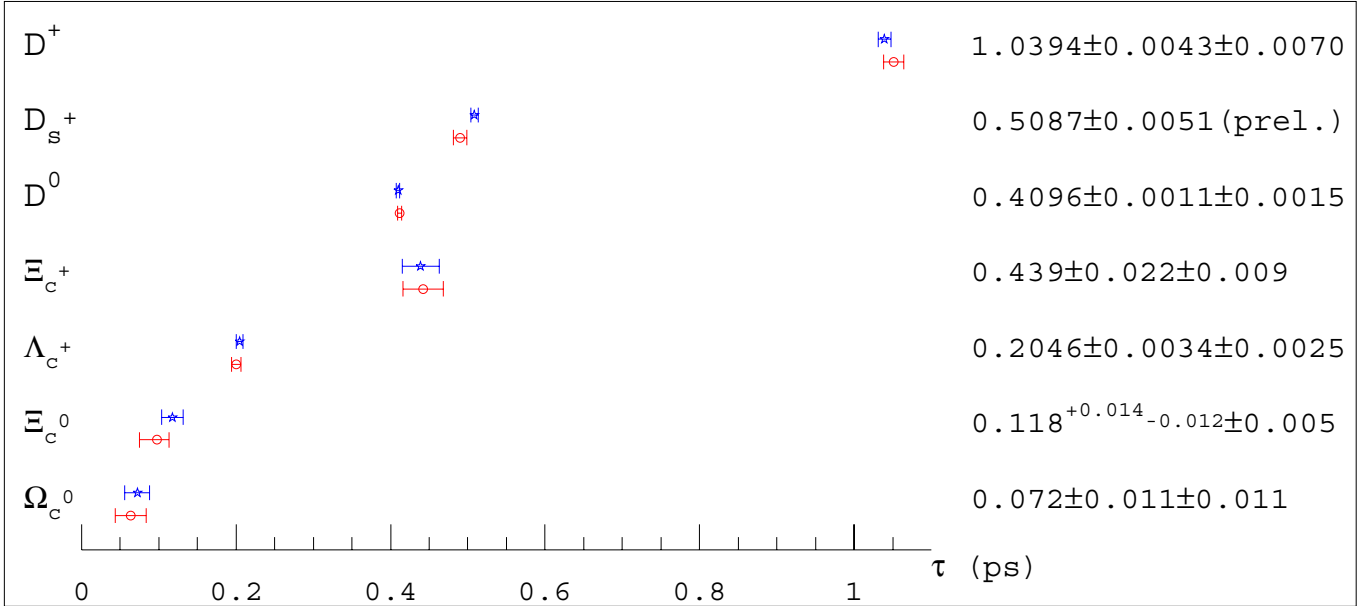


**Fig. 1.** Charm particle lifetimes, comparison between the FOCUS lifetime measurements and the PDG 2002 values. The ⋆ are the FOCUS results reported also on the *right*, while the ∘ correspond to the PDG 2002 values. The PDG 2002 values for $\Xi_c^+$ and $\Lambda_c$ include already our measurements

calculated by various methods, Lattice Gauge Theories (LGT) and quark models. The angular distributions and invariant masses among the decay products would determine the form factor ratios while the branching ratio measurements and information from the CKM matrix would give the absolute scale for the form factors. For the last 20 years, people regarded the $D^+ \to K^- \pi^+ \mu^+ \nu$ decays as 100% $D^+ \to \overline{K}^{*0}(K^-\pi^+)\mu^+\nu$ events. The E687 and E691 groups set an upper limit for the possible scalar contributions in the $D^+ \to K^-\pi^+ l^+ \nu_l$ decays [10,11], but they could not provide clear evidence of decay paths other than the dominant P-wave $D^+ \to \overline{K}^{*0}(K^-\pi^+)l^+\nu_l$ channel. The situation was changed when the next generation data set from the FOCUS spectrometer was analyzed to get form factors of the $D^+ \to K^-\pi^+\mu^+\nu$ decays [7]. After the selection cuts involving vertex confidence levels and particle identification requirements, we obtained 31,254 $D^+ \to K^-\pi^+\mu^+\nu$ and its charge conjugate decays. During the form factor analysis, we checked the angular distribution of Kaon in the $K\pi$ rest frame $(\cos\theta_V)$ and found that it showed a huge forward-backward asymmetry below the $K^*(892)$ pole mass while almost no asymmetry above the pole. Since the $K^*$ is a P-wave, pure $K^* \to K\pi$ decays would have shown only a symmetric forward-backward $\cos\theta_V$ distribution over the entire $K\pi$ invariant mass range. This suggests a possible quantum mechanics interference effect.

A simple approach to emulate the interference effect is adding a spin zero amplitude in the matrix elements of the $D^+ \to K^-\pi^+\mu^+\nu$ decays. We tried a constant amplitude with a phase, $A\exp(i\delta)$, in the place where the $K^*$ couples to the spin zero component of the $W^+$ particle. We

made the simplest assumption that the $q^2$ dependence of this anomaly S-wave coupling would be the same as that of the $K^*$. The $D^+ \to K^-\pi^+\mu^+\nu$ event is a 4-body decay, which is represented by 5 kinematic variables, two invariant masses and three angular variables. For each of these variables, we extracted interference effects by using various weighting schemes and studied if our measured $A = 0.36$ and $\delta = \pi/4$ are working properly in reproducing the effects for Monte Carlo (MC) events [7].

One interesting side effect of the S-wave interference is that it breaks the $\chi \leftrightarrow -\chi$ symmetry of the distribution of the azimuthal angle $(\chi)$ between the $K\pi$ and the $W^+$ decay planes in the $D^+$ rest frame. The proper definition of $\chi$ requires that it should change sign between $D^+ \to K^-\pi^+\mu^+\nu$ and its charge conjugate decays. Without the proper sign convention, we would see a false CP violation between the charge conjugate decays in the $\chi$ distribution.

We measured the relative branching ratio between $D^+ \to \overline{K}^{*0}\mu^+\nu$ and $D^+ \to K^-\pi^+\pi^+$ decays. With a tighter selection than the one used in the interference analysis, we selected 11,698 $D^+ \to K^-\pi^+\mu^+\nu$ and its charge conjugate decays. With a selection cut set designed to be similar to the one applied upon the $D^+ \to K^-\pi^+\mu^+\nu$ decays, we obtained 65,421 $D^+ \to K^-\pi^+\pi^+$ and its charge conjugate decays. From a MC study, we determined that the pure $D^+ \to \overline{K}^{*0}\mu^+\nu$ events are 94.5% of the selected events. When this correction factor is applied, we obtained [8],

$$\frac{\Gamma(D^+ \to \overline{K}^{*0}\mu^+\nu)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = 0.602 \pm 0.010 \pm 0.021 \quad (3)$$

When comparing this muon decay channel result with electron decay channel results from other experiments, a correction factor 1.05 should be applied. Our number, the only one considered an S-wave interference explicitly, is 1.6 $\sigma$ lower than the recent CLEO II result from the electronic decay channel [12] and 2.1 $\sigma$ higher than the E691 measurement [13]. Including our result, the new world average of $\Gamma(K^*l\nu)/\Gamma(K\pi\pi)$ is $0.62 \pm 0.02$ each experiment's statistical and systematic errors were added in quadrature prior to making the weighted average.

We also measured the relative branching ratio between $D_s^+ \to \phi(K^-K^+)\mu^+\nu$ and $D_s^+ \to \phi(K^-K^+)\pi^+$ decays. Our selection yields 793 $D_s^+ \to \phi(K^-K^+)\mu^+\nu$ and its charge conjugate decays, and 2,192 $D_s^+ \to \phi(K^-K^+)\pi^+$ and its charge conjugate decays. The result is [8]

$$\frac{\Gamma(D_s^+ \to \phi(K^-K^+)\mu^+\nu)}{\Gamma(D_s^+ \to \phi(K^-K^+)\pi^+)} = 0.540 \pm 0.033 \pm 0.048 \quad (4)$$

Our number is comparable with all the other measurements in this channel, and the new world average of $\Gamma(\phi\mu\nu)/\Gamma(\phi\pi)$ is $0.540 \pm 0.040$.

We measured the form factor ratios of $D^+ \to \overline{K}^{*0}\mu^+\nu$ and it charge conjugate decays with consideration on the S-wave contribution. Our study shows that the effect of S-wave on the measurement is minimal while the effect of charm background is significant. The new FOCUS results are as follows [9],

$$R_V = 1.504 \pm 0.057 \pm 0.039 \quad (5)$$
$$R_2 = 0.875 \pm 0.049 \pm 0.064 \quad (6)$$

The new world averages are $1.66 \pm 0.060$ and $0.827 \pm 0.055$ for $R_V$ and $R_2$, respectively.

## 4 Note on the hadronic decays of charm particles

The proper interpretation of the hadronic decays is more complicated than expected. We observed that Final State Interactions (FSI) play a central role in the hadronic decays. For example our recent analysis on the branching ratio $\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to \pi^-\pi^+)$ [14], confirm that FSI are fundamental. Actually an isospin analysis of the channels $D \to KK$ and $D \to \pi\pi$ reveals that the elastic FSI cannot account for all the large deviation from unity (we measure $2.81 \pm 0.10 \pm 0.06$) of this ratio. The most reasonable explanation seems to be inelastic FSI that also allow for the transition $KK \to \pi\pi$.

For the multibody modes, where resonances are present, we think that the amplitude analysis (Dalitz plot analysis) is the correct way to determine the resonant substructure of the decays. An extensive program of Dalitz plot analyses is going on for the 3-body final states. Actually FOCUS is conducting a pioneer work using, for the first time in the analyses of charm decays, the formalism of K-matrix.

As an example consider the $CP$-odd state $K_s^0\phi$ from the decay mode $D^0 \to K_s^0K^-K^+$; one cannot get a *pure*

$CP$-odd eigenstate near the $\phi(= K^-K^+)$ region because of the presence of the $CP$-even $K_s^0 f_0$ decaying into the same final state. Instead a Dalitz plot analysis is necessary to determine properly the relative fractions. And this is valid also for the beauty decay mode $B^0 \to K_s^0 K^- K^+$.

## 5 Conclusions

The FOCUS experiment has measured the lifetime of all the weakly decaying singly charmed particles, establishing the charm lifetime hierachy.

We found new S-wave interference phenomena in $D^+ \to K^-\pi^+\mu^+\nu$ decays. Considering this effect in further analyses, we measured the branching ratio $\Gamma(D^+ \to K^*\mu\nu)/\Gamma(D^+ \to K\pi\pi)$ and the form factor ratios of $D^+ \to K^-\pi^+\mu^+\nu$ decays with improved statistical errors. We also measured the branching ratio $\Gamma(D_s \to \phi\mu\nu)/\Gamma(D_s \to \phi\pi)$.

This lead us to the following question: will there be similar effects (interference) in other charm semileptonic or beauty semileptonic channels? We will see, in the meanwhile the analyses in other semileptonic charm decay modes are actively going on and we expect new results soon.

At 30 years from the discovery of the $c$ quark the physics analyses of the first heavy quark have reached a complete maturity. With the large statistics now available in the charm sector we start to see unexpected effects which complicate the interpretation of the decay processes, both in semileptonic and hadronic decays.

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