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THE OBSERVATION OF THE MUONIC DECAY $D_s^\pm \to \mu^\pm \nu_\mu$

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Abstract

The muonic decay of charmed strange mesons has been observed in the analysis of a sample of 144 decays of charged charmed particles into a muon and no other charged particle. The branching ratio is estimated to be $\mathrm{BR}(D_s^\pm \to \mu^\pm \nu_\mu) = (4.0^{+1.8+0.8}_{-1.4-0.6} \pm 1.7) \times 10^{-3}$, assuming a ratio r=0.27 between production cross sections of $D_s^\pm$ and neutral charmed particles. The decay constant f_{D_s} is estimated to be $(232 \pm 45 \pm 20 \pm 48)$ MeV/c^2 and does not depend on theoretical assumptions.

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1. Introduction

A measurement of the leptonic decay branching ratios of heavy pseudoscalar mesons provides a direct estimate of their pseudoscalar decay constants $f_{\rm P}$, analogue of that of the pion decay f_π, through the equation (here we consider explicitly the decay $\rm D_s^\pm \rightarrow \mu^\pm\nu_\mu$):

$$\rm BR(D_s^\pm \rightarrow \mu^\pm\nu_\mu) = \frac{G_F^2}{8\pi} f_{D_s}^2 \tau_{D_s} m_{D_s} m_\mu^2 |V_{cs}|^2 (1 - \frac{m_\mu^2}{m_{D_s}^2})^2,$$

where $\rm G_F$ is the Fermi constant, $\tau_{\rm D_s}$ and $m_{\rm D_s}$ are the mean lifetime and the mass of $\rm D_s^\pm$, m_μ is the mass of the muon, and $\rm V_{cs}$ is the Kobayashi-Maskawa matrix element.

The constants $f_{\rm P}$ have been estimated for D and B mesons using various theoretical approaches, e.g. QCD-inspired potential models [1], QCD sum rules [2], numerical simulations of QCD on the lattice [3], and alternative non-perturbative methods [4]. As the $f_{\rm P}$ are related to the probability of annihilation of the heavy and the light quarks inside the meson (thus, in the constituent quark model, to the $\rm Q\bar{q}$ wave function at the origin), they play an important role both in characterizing the properties of confinement and as absolute normalizations of numerous heavy-flavour transitions, including mixing, semi-leptonic and non-leptonic decays. Indeed, in this respect, it is possible to attempt to indirectly extract the values of $f_{\rm P}$ from measured rates of appropriate non-leptonic decays via the factorization assumption. This same procedure has been used also to estimate the $f_{\rm D_s}$ value [5]. Since the role of the factorization assumption is quite important in this method, causing a theoretical uncertainty which is not fully under control, it is still highly desirable to attempt direct, model-independent experimental determinations of $f_{\rm P}$.

Concerning direct measurements, up to now only the upper limits of a few leptonic branching ratios of heavy mesons have been obtained: $\rm BR(D^\pm \rightarrow \mu^\pm\nu_\mu) \leq 7.2 \times 10^{-4}$ [6] and $\rm BR(D_s^\pm \rightarrow \mu^\pm\nu_\mu) \leq 3\%$ [7].

It can easily be seen that the tauonic decays have the highest branching ratios, but their detection is considerably more difficult owing to the small mass differences; on the other hand, electronic decays are suppressed by four to five orders of magnitude with respect to muonic ones (as in the corresponding $\pi^\pm$ and $\rm K^\pm$ decays). Furthermore, the leptonic decays of $\rm D^\pm$ are Cabibbo-suppressed with respect to the corresponding $\rm D_s^\pm$ decays. For these reasons, the decay $\rm D_s^\pm \rightarrow \mu^\pm\nu_\mu$ is likely to have the highest detection probability once a sizeable sample of charmed strange mesons has been produced.

Of course, the experimental difficulties in detecting such rare decays are increased by the short mean lifetimes of charmed mesons that usually prevent an accurate measurement of $p_{\rm T}$, the muon momentum perpendicular to the line-of-flight of the parent particle. These difficulties have been overcome in the WA75 Experiment: here, stacks of nuclear emulsions were used in conjunction with an external apparatus to give a reliable event selection and a very accurate geometrical reconstruction.

In the present paper we report results from 339 events with charmed particle candidates selected from about 4.5×10^8 π^- nucleus interactions. From the subsample of events containing charged charmed particles decaying into a muon unambiguously reconstructed in the external apparatus, a clear signal from the decay $D_s^\pm \to \mu^\pm\nu_\mu$ has been extracted for the first time. The observed signal consists of events with muon p_T above the kinematical limit for Cabibbo-allowed three-body decays of non-strange charmed particles.

2. The experiment

The WA75 emulsion-hybrid experiment was designed to search for heavy quark pair production in 350 GeV/c π^- nucleus interactions. A total of about 80 litres of nuclear emulsion was exposed to a π^- beam from the CERN SPS. The set-up also included a vertex detector, a dump (later replaced by a hadron calorimeter), and a muon spectrometer equipped with a 1.5 T superconducting magnet, whose momentum resolution was $\Delta p/p = 6.0 \times 10^{-4} p$ (GeV/c).

The on-line trigger required the presence of at least one muon in the magnetic spectrometer; the events to be searched for in emulsion were further constrained off-line by requiring that the muon momentum transverse to the beam direction be ≥ 1.0 GeV/c (≥ 0.6 GeV/c for a subsample), or by applying a combined selection on tranverse momentum and missing energy. These requirements selected about 10^{-4} of the interactions, and greatly enhanced the fraction of events containing the decay of heavy particles into a muon. Furthermore, as the observed muon transverse momentum combines contributions from production and decay, there is an increasing acceptance for decays with a high muon momentum transverse to the parent's line-of-flight.

After scanning in emulsion to locate primary interactions and decay candidates, about 500 events showed one or more decay-like topologies (either charged or neutral); among them, 339 events were finally selected by requiring that the tagged muon track to be associated with one of these topologies.

A detailed description of the set-up, of the selection and measurement procedures, as well as results on beauty and charmed particle production have already been given [8]. The same sample of events was analysed to obtain the charmed particle production cross-section [9], and to study their inclusive and correlation properties [10]. In particular, it has been shown that the selection criteria reduced to almost zero any contamination from interactions and from decays of particles lighter than charmed particles.

In view of the present analysis, where the shape of the tail of the muon p_T distribution is crucial, a careful inspection and remeasurement of all decays showing a muon with $p_T \geq 0.85$ GeV/c was carried out. A few events were removed because of errors either in the previous measurements or in data recording:to be more preciese, two events were removed from the sample of charged-particle and three from that of neutral-particle decays; in all the other cases, no discrepancy was observed within the errors. Table 1 shows the main features of the charged decays with muon

$p_{\mathrm{T}} \geq 0.85$ GeV/c. It can be seen that the accuracy achieved in the p_{T} measurement is on the average 3%. On the other hand, the accuracy achieved in the muon p_T measurement from neutral decays decreases to 6% on the average, owing to the larger uncertainty in the determination of the line-of-flight of neutral particles. Finally, any systematic errors in muon momenta were less than 0.7% from an analysis of events where a J/ψ was produced [8].

3. Analysis and results

The fraction of leptonic decays could be extracted from a sample of semi-leptonic decays if the spectrum of lepton momenta in the c.m. system of the charmed particle were available. In fact, for a two-body decay p_{l}^{*} has values of 0.98 GeV/c for $\mathrm{D}_{\mathrm{s}}^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$, and 0.93 GeV/$c$ for $\mathrm{D}^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$, whereas for multi-body decays p_{l}^{*} spreads over phase space up to the kinematical limit. In the laboratory system the same technique can be applied using transverse momenta, taking into account that the p_{T} distribution from a two-body decay appears as a spectrum peaked at the kinematical limit but also extends towards smaller values.

Figure 1 shows the muon p_{T} distributions in decays with different topologies, namely C1 (charged particles into a single charged particle), and N2 (neutral particles into two charged particles); 144 decays are observed as C1 (Fig. 1a) and 157 as N2 (Fig. 1b). Obviously, a possible two-body muonic decay signal can only be observed in the C1 sample, but cannot be present in N2 decays.

Indeed, six charged particles are observed to decay with a muon $p_{\mathrm{T}} \geq 0.90$ GeV/c, above the kinematical limit for $\mathrm{D}^{\pm} \rightarrow \mathrm{K}\mu^{\pm}\nu$, the spectral location and shape being those expected from the decay $\mathrm{D}_{\mathrm{s}}^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$; none are observed in the sample of decays of neutral particles. All this shows that rare decays such as $\mathrm{D} \rightarrow \pi\mu\nu$, with similar p_{T} distributions in the charged and neutral mode, do not contribute appreciably in the tail of our histograms. The same conclusion is reached by computing the fraction of phase space for $p_{\mathrm{T}} \geq 0.90$ GeV/c, and taking into account the known branching ratios. The solid line in Fig. 1b repesents the best fit to the data by means of a Monte Carlo simulation (see below) with 5% of the events ascribed to $\mathrm{D}^0 \rightarrow \pi\mu\nu$.

Further evidence that at least the majority of decays reported in Table 1 are correctly ascribed to $\mathrm{D}_{\mathrm{s}}^{\pm}$ mesons, comes from the distribution of proper decay times, computed from the measured decay length and from the momentum, evaluated assuming the muons were emitted at 90 degrees to the line-of-flight in the c.m. system. The mean lifetime of this sample of 7 decays turns out to be $(2.7^{+1.8}_{-1.1}) \times 10^{-13}$ s (the result includes corrections that take into account geometrical and scanning efficiencies, as well as the bias of the method), consistent with the mean lifetime of $\mathrm{D}_{\mathrm{s}}^{\pm}$ mesons ($\tau = 4.50 \times 10^{-13}$ s [11]). On the other hand, the mean lifetime of the remaining 137 decays of the C1 sample, determined by taking into account both the muon momentum and the impact parameter [10], turns out to be $(10.9 \pm 2.5) \times 10^{-13}$ s, consistent with their being in majority $\mathrm{D}^{\pm}$ mesons ($\tau = 10.66 \times 10^{-13}$ s [11]).

In order to estimate the muonic decay branching ratio of $\mathrm{D}_{\mathrm{s}}^{\pm}$ we need to know,

i) the number $N_{D_s}^{obs}$ of observed muonic decays in the sample of Fig. 1a, ii) their selection and detection efficiencies in order to determine the true number of decays, and iii) the total number of $D_s^\pm$ mesons produced.

Assuming there is no background, the number $N_{D_s}^{obs}$ among the 144 C1 semi-muonic decays of charmed particles has been estimated with the Maximum Likelihood method from the function

$$L(N_{D_s}^{obs}) = \prod_i \left\{ N_{D_s}^{obs} \cdot P_1(p_T^i) + (144 - N_{D_s}^{obs}) \cdot P_2(p_T^i) \right\},$$

where P_1 and P_2 are the probability functions of finding a decay with the given muon p_T in the muonic decay of $D_s^\pm$, and in the semi-muonic decay of any charged charmed particle, respectively. These probabilities were computed with a Monte Carlo simulation which included, in addition to the production and decay of charmed particles, the experimental set-up and emulsion-scanning procedures to locate primary interactions and decays. The main features of this Monte Carlo have been described elsewhere [9,10]. The result of the fitting procedure gave $N_{D_s}^{obs} = (9.1^{+3.7}_{-3.0})$ events, and is displayed in Fig. 1a (continuous line) according to the Monte Carlo simulation. It is estimated that the remaining 135 events are the semi-muonic decays of $D^\pm$ (65%), of $D_s^\pm$ (20%) and of Λ_c (15%).

Indeed, the selection criterion (Section 2) strongly favoured decays with high p_T muons and therefore, also owing to the good accuracy on p_T measurements, most of the observed muonic decays of $D_s^\pm$ mesons included in the sample must be those quoted in Table 1. This means that the estimate of $N_{D_s}^{obs}$ is not affected very much either by the exact composition of charmed particles in the remaining decays or by the exact value of the respective semi-muonic branching ratios.

Possible source of background to the signal can only come from some decay mode of $D_s^\pm$ and from the muonic decay of $D^\pm$; in fact, it has already been shown that other semi-muonic decays of $D^\pm$ contribute to a negligible extent. It is easily seen that semi-muonic decays of $D_s^\pm$ also contribute by a negligible amount: in fact, $D_s^\pm$ preferentially decays into heavy mesons, and taking into account the hadronic modes with maximum $p_T \geq 0.90\text{GeV}/c$, and assuming they have the same proportion in the semi-muonic mode, a contribution of less than 0.1 events is expected in our sample. A decay $D_s \rightarrow \tau\nu$(see Section 4) followed by $\tau \rightarrow \mu\nu\nu$ (this decay has a muon with $p_T \leq 0.89\text{GeV}/c$) would be included in our sample, provided the first decay is not detected (it should appear, in our conditions, as a kink of a few milliradians) and the second has the maximum possible p_T. We estimate that our sample with $pT \geq 0.90\text{GeV}/c$ contains less than 0.1 such events.

Finally, we estimate the contamination from muonic decay of $D^\pm$. If we assume the relative cross-section measured by ACCMOR Collaboration[12] $[\sigma(D_s)/\sigma(D^\pm) \approx 0.6]$, the relative probabilities of the respective decay modes (≈ 10) and of detection due to the different mean lifetime (≈ 2), we find that 0.6 ± 0.2 muonic decays of $D^\pm$ should be included in our sample. Hence, $N_{D_s}^{obs} = 8.5^{+3.7}_{-3.0}$ events.

The sample of decays shown in Fig. 1a contains different kinds of charmed particles, with different detection efficiencies and lifetime. In addition, the semi-muonic branching ratios for $D_s^\pm$ and Λ_c are poorly known[11]. All this provides a very rough estimate (of the order of 10%) for ratio of produced $D_s^\pm$ mesons to all charmed particles.

On the other hand, the sample of neutral particles decaying into a muon consists only of D^0 mesons, which are much easier to handle, and the muonic decay branching ratio of $D_s^\pm$ can be expressed as

$$\mathrm{BR}(D_s^\pm \to \mu^\pm\nu_\mu) = \mathrm{BR}(D^0 \to \mu\nu_\mu X)\cdot\frac{1}{r}\cdot\frac{\epsilon_{D^0}}{\epsilon_{D_s}}\cdot\frac{N^{obs}_{D_s}}{N^{obs}_{D^0}} \quad ,$$

where r is the ratio between production cross-sections of $D_s^\pm$ and D^0, $N^{obs}_{D^0}$ is the number of observed neutral D mesons, and ϵ_{D^0} and ϵ_{D_s} are the probabilities of finding in our experiment D^0 semi-muonic and $D_s^\pm$ muonic decays, respectively. We note that by determining the ratio between efficiencies, rather than the efficiencies themselves, the effect of systematic errors is considerably reduced.

Finally, we find

$$r\cdot\frac{\mathrm{BR}(D_s^\pm \to \mu^\pm\nu_\mu)}{\mathrm{BR}(D^0 \to \mu\nu_\mu X)} = (1.25^{+0.55+0.24}_{-0.44-0.20})\times 10^{-2},$$

where the first error is statistical, and the second is systematic; the systematic error arises mostly from the uncertainty in the parameters defining the production [9,10], assumed to be the same for all charmed mesons.

4. Discussion and conclusions

In order to give the $D_s^\pm$ muonic branching ratio we need to know r, and this can hardly be determined in our experiment. However, the ACCMOR Collaboration recently determined [12] the production properties of D and D_s mesons in 230 GeV/c π^--Cu interactions. In particular, for $x_F > 0$ and assuming an A^1 dependence, they obtain

$$\sigma(D^0) = (6.3 \pm 0.3 \pm 1.2)\mu\text{b per nucleon}$$

$$\sigma(D_s^+) \cdot BR(D_s^+ \to K^+K^-\pi^+) = (0.067 \pm 0.011 \pm 0.010)\mu\text{b per nucleon.}$$

Using the presently known D_s branching ratio $BR(D_s^+ \to K^+K^-\pi^+) = (3.9 \pm 0.4)\%$ [11] and combining statistical and systematic errors, we obtain $\sigma(D_s) = (1.7 \pm 0.4)\mu$b per nucleon. Hence, assuming that the ratio is the same under our conditions, we argue that $r = 0.27 \pm 0.08$.

Finally, using the value $BR(D^0 \to \mu\nu_\mu X) = (8.8 \pm 2.5)\%$ [11], it turns out that

$$BR(D_s^\pm \to \mu^\pm\nu_\mu) = (4.0^{+1.8+0.8}_{-1.4-0.6} \pm 1.7) \times 10^{-3},$$

where the third error combines those from r and from $BR(D^0)$. We note that from this we can estimate the muonic branching ratio of $D^\pm$ to be $\approx 4 \times 10^{-4}$, consistent with the present upper limit [6].

Other leptonic branching ratios can be estimated as well: for instance, for the tauonic decay mode of D_s, likely to be a source of ν_τ beams in future accelerators,

$$\frac{BR(D_s^\pm \to \tau^\pm\nu_\tau)}{BR(D_s^\pm \to \mu^\pm\nu_\mu)} = (\frac{m_\tau}{m_\mu})^2 \times (\frac{1-(\frac{m_\tau}{m_{D_s}})^2}{1-(\frac{m_\mu}{m_{D_s}})^2})^2 \approx 9.2,$$

hence $BR(D_s^\pm \to \tau^\pm\nu_\tau) = (3.7 \pm 2.3)\%$.

The value of the pseudoscalar decay constant turns out to be

$$f_{D_s} = (232 \pm 45 \pm 20 \pm 48)\ \text{MeV}/c^2,$$

using $\tau_{D_s} = 4.50 \times 10^{-13}$s, $|V_{cs}| = 0.974$, and our result on $BR(D_s^\pm \to \mu^\pm\nu_\mu)$. This value, which does not depend on theoretical assumptions, is in the range foreseen by most models (see Section 1), but the large error does not allow much selection. Such a selection could be possible, however, as soon as a better estimate of r and of $BR(D^0)$ are available.

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Table 1. Summary of $D_s^\pm \to \mu^\pm\nu_\mu$ candidates: decay p_T(GeV/c), flight length (μm), estimated lifetime [$\times 10^{-13}$s] and the presence of a detected partner [C1,C3 and N2 indicate their charge status and number of charged prongs].

Event no.	Decay p_T	Flight length	Life-time	Partner
1	0.99 ± 0.03	938	2.25	C1
2	0.97 ± 0.03	1204	2.20	N2
3	0.91 ± 0.04	5317	3.75	N2
4	0.87 ± 0.03	415	1.52	C3
5	0.92 ± 0.02	3577	4.54	–
6	0.96 ± 0.04	2317	2.25	C3
7	0.93 ± 0.03	197	0.33	–

Figure caption

Fig. 1. Decay p_T distributions of muons from 144 C1 decays (a) and from 157 N2 decays (b). The solid lines represent Monte Carlo results; the contribution from $D_s^\pm \to \mu^\pm\nu_\mu$ in (a) is evaluated to be $(9.1^{+3.7}_{-3.0})$ events in the absence of background.