DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 77/54
August 1977

Semileptonic Decays of the F-Mesons and the Ensuing Lepton Spectrum

by

Ahmed Ali
II. Institut für Theoretische Physik der Universität Hamburg

T. C. Yang
Deutsches Elektronen-Synchrotron DESY, Hamburg

NOTKESTRASSE 85 · 2 HAMBURG 52

To be sure that your preprints are promptly included in the
HIGH ENERGY PHYSICS INDEX ,
send them to the following address (if possible by air mail) :

DESY
Bibliothek
2 Hamburg 52
Notkestieg 1
Germany

Semileptonic Decays of the F-Mesons and the Ensuing Lepton Spectrum

Ahmed Ali[+]
II. Institut für Theoretische Physik der
Universität Hamburg

and

T.C. Yang[++]
Deutsches Elektronen-Synchrotron DESY, Hamburg

[+] Work supported in part by the Bundesministerium für Forschung und Technologie.

[++] Address after Sept. 1, 1977: Department of Physics and Astronomy, University of Massachusetts, Amherst, Mass./USA

Preliminary evidence for the charmed meson $F^{\pm}$, through its non-leptonic decay mode $\eta\pi^{\pm}$, has recently been reported by the DASP collaboration at DESY[1]. The mass of the $F^{\pm}$ constructed through the $\eta\pi^{\pm}$-mode has a value 2.03 $\pm$0.06 GeV, with the mass of the F^* set at 2.14 $\pm$0.06 GeV. This establishes the $F\bar{F}$ and $F\bar{F}^*$ thresholds near 4.1 and 4.2 GeV, respectively. The same group has also presented inclusive electron spectra between 3.99 GeV and 5.2 GeV c.m. energy[2]. The events, characterized by a single electron plus at least two charged tracks, are divided into three energy regions, namely, (i) $3.99 < E_{cm} < 4.08$ GeV, (ii) $4.08 < E_{cm} < 4.52$ GeV and (iii) $4.52 < E_{cm} < 5.2$ GeV. The division is made with the view of studying the semi-leptonic decay spectrum coming from (i) the D-decays alone, (ii) the possible effects due to the F-production and decay, and (iii) the effects due to possible charmed baryon production and decays. The qualitative features of the electron spectra in the three energy regions are not very different, but a more detailed analysis is probably necessary in order to notice any difference. An immediate theoretical question is: How does the lepton spectrum from the $F^{\pm}$ semi-leptonic decays compare with the one from the D-decays?

We give in this note a quantitative estimate of the semi-leptonic decay modes of the F-meson. The semi-leptonic decays of the D-mesons were previously studied by the present authors[3] and by others[4]. The qualitative features of the electron spectrum in the interval $3.99 < E_{cm} < 4.08$ GeV are well described by the decay modes $D \rightarrow K e \bar{\nu}_e$ and $D \rightarrow K^* e \bar{\nu}_e$. This means presumably that the multi-hadronic decay modes do not contribute significantly to the semi-leptonic decays. We shall adopt a similar attitude toward the semi-leptonic decays of the $F^{\pm}$ meson, namely, it is an equally good approximation to neglect the multi-hadron semi-leptonic decay modes of the F-meson. The semi-leptonic decays of the F-meson are different from that of the D-mesons in the following respect: there are more low lying single-particle modes avaiable to the $F^{\pm}$ meson than to the D-mesons. Thus, a priori, the lepton spectrum from F-decays could be different from that of the D-meson decays (in details).

We assume the standard $\Delta c = \Delta s$ rule. Since in the standard charm model both the charm-changing charged weak current and the F-meson are isosinglets, the semi-leptonic decays of F involve only final states with I = Y = 0. We consider only the following low lying single particle decay modes:

$$
\begin{aligned}
F^{\pm} &\longrightarrow \eta \ell^{\pm} \nu_\ell \\
&\longrightarrow \eta' \ell^{\pm} \nu_\ell \\
&\longrightarrow \varphi \ell^{\pm} \nu_\ell \qquad (1) \\
&\longrightarrow \omega \ell^{\pm} \nu_\ell
\end{aligned}
$$

The last decay mode of (1), namely, $\omega\ell^{\pm}\nu_\ell$, is suppressed by the Zweig rule, since ω has very little strange quark content (ideal mixing). But for the pseudo-scalars, η and η', since they are not ideally mixed, the amount of mixing is quite important. This introduces an additional complication which is not present in the decays of D-mesons. To a good approximation, the η and η' mesons are SU(3) octet and singlet respectively,

$$\eta \sim \eta_8 = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s}) \text{ and } \eta' \sim \eta_0 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

Dropping the additional mixing angle (between η_8 and η_0), one finds that

$$\frac{\Gamma(F^{\pm} \rightarrow \eta \ell^{\pm} \nu_\ell)}{\Gamma(F^{\pm} \rightarrow \eta' \ell^{\pm} \nu_\ell)} \simeq 2 \times \text{phase space} \qquad (2)$$

where the factor 2 comes simply from counting the $s\bar{s}$ quark content of η_8 and η_0. However, the small mixing angle between η_8 and η_0 (around 11 degree) turns out to make significant modification to (2). If we express η and η' as

$$
\begin{aligned}
\eta &= \cos\theta\, \eta_8 + \sin\theta\, \eta_0 = \eta_\sigma \cos\alpha - \eta_s \sin\alpha \\
\eta' &= -\sin\theta\, \eta_8 + \cos\theta\, \eta_0 = \eta_\sigma \sin\alpha + \eta_s \cos\alpha
\end{aligned}
\qquad (3)
$$

(where $\eta_\sigma \equiv \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ and $\eta_s \equiv s\bar{s}$)
we find that $\theta \simeq 11^\circ$ corresponds to $\alpha \simeq 43.7^\circ$, and thus the probability of finding $s\bar{s}$ pair in the η-meson is about the same as in η'. Consequently we find

$$\frac{\Gamma(F^{\pm} \rightarrow \eta \ell^{\pm} \nu_\ell)}{\Gamma(F^{\pm} \rightarrow \eta' \ell^{\pm} \nu_\ell)} \simeq 0.92 \times \text{phase space} \qquad (4)$$

(The number 0.92 becomes 1 if one uses $\alpha = 45^\circ$).
In deriving (4), we have assumed SU(3) symmetry for the ratio of the $f_+(0)$ form factors of the above two processes. Since SU(3) symmetry breaking correction to the difference of the form factors at zero momentum transfer comes in second order[F1], we have reasons to believe that (4) provides a good approximation

(up to the uncertainty of the mixing angle). (4) could be checked experimentally.

What remains to be calculated now is the branching ratio of $F \to \eta \ell \nu$ and $F \to \varphi \ell \nu$. We define as in ref. 3 the following form factors

$$\langle \eta(k) | V_\mu^{\Delta C = \Delta S} | F(p) \rangle = f_+(q^2)\,(p+k)_\mu + f_-(q^2)\,q_\mu \tag{5}$$

where $q = p - k$. Here only the vector current contributes. For $F \to \varphi \ell \nu$ we have the form factors of the vector and axial-vector currents as given by

$$\begin{aligned} \langle \varphi(k) | V_\mu | F(p) \rangle &= i\, F_1^V(q^2)\, \epsilon_{\mu\nu\lambda\sigma}\, \epsilon^\nu k^\lambda q^\sigma \\ \langle \varphi(k) | A_\mu | F(p) \rangle &= F_1^A(q^2)\, \epsilon_\mu + F_2^A(q^2)\,(\epsilon \cdot p)\, k_\mu \\ &\quad + F_3^A(\epsilon \cdot p)\, q_\mu \end{aligned} \tag{6}$$

Where ϵ is the polarization vector of the φ-meson.

As in ref. 3, we employ the Current Algebra Hard meson technique[5] to calculate the various form factors. However, in the case of $F \to \eta \ell \nu$ (or $\eta' \ell \nu$) the method is not useful, since we do not know the mixing among the hitherto poorly understood I = Y = 0 axial-vector mesons. But since the form factors $f_+(0)$ for $F \to \eta \ell \nu$ and $D \to K \ell \nu$ are related by SU(3), and as remarked above[F1] the SU(3) breakings to the difference of them appears in second order, we take the $f_+(0)$ of $F \to \eta \ell \nu$ as given by SU(3) symmetry. We assume for simplicity a monopole form factor[F2]. One finds

$$f_+^\eta(q^2) = f_+^\eta(0)\, \frac{m_{F^*}^2}{m_{F^*}^2 - q^2} = \frac{1}{\sqrt{2}}\, \frac{m_{F^*}^2}{m_{F^*}^2 - q^2} \tag{7}$$

The contribution of the q_μ term in (5), being proportional to m_ℓ in the decay rate, can be neglected.

For the decay of $F \to \varphi \ell \nu$, the axial vector form factors are given by Current Algebra Hard meson technique as previously applied to $D \to K^* \ell \nu$ decay, we find similarly

$$\begin{aligned} F_1^A(q^2) &= \sqrt{2}\, m_\varphi \left[1 + \frac{1}{2(q^2 - m_{F_A}^2)} \left\{ (m_\varphi^2 - q^2) + \frac{\delta}{2}(m_F^2 + m_\varphi^2 - q^2) \right\} \right] \\ F_2^A(q^2) &= - \frac{\delta\, m_\varphi}{\sqrt{2}\,(q^2 - m_{F_A}^2)} \end{aligned} \tag{8}$$

where δ is a parameter as in ref. 3. The above result (8) already takes into account the SU(3) symmetry between $D \to K^* \ell \nu$ and $F \to \varphi \ell \nu$. As in ref. 3, we have assumed $F_D = F_F = F_K = F_\pi$, where the F's are the (axial-vector current) decay constants of the pseudo-scalar mesons. The vector form factor of $F \to \varphi \ell \nu$ is not determined by the Current Algebra, but is related to $D \to K^* \ell \nu$ by SU(3). We have in the case of $D \to K^* \ell \nu$ considered two approaches: (1) exact SU(4) relation for the three-point vertices, (2) broken SU(4) corrections via the Gell-Mann-Okubo ansatz[6]. This gives for $F \to \varphi \ell \nu$, in pole dominated form

$$\begin{aligned} F_1^V(q^2) &= \frac{\sqrt{2}\, g_{F^*}\, g_{F^*\varphi F}}{(q^2 - m_{F^*}^2)} = \frac{\sqrt{2}\left(\frac{m_{F^*}}{m_\rho}\, g_\rho \right)\left(\frac{g_{\omega\rho\pi}}{\sqrt{2}} \right)}{(q^2 - m_{F^*}^2)} \\ &= \frac{m_{F^*} m_\rho}{\sqrt{2}} \left[\frac{3\, \Gamma(\omega \to \pi\gamma)}{\alpha\, k^3} \right]^{1/2} \end{aligned} \tag{9}$$

where we assumed exact SU(4) symmetry for $g_{F^*\varphi F}$ and $g_{\omega\rho\pi}$. g_{F^*} is defined by $\langle 0 | V_\mu | F^* \rangle = g_{F^*} \epsilon_\mu$. If we take into consideration SU(4) symmetry breaking à la Gell-Mann-Okubo, $g_{F^*\varphi F}$ decreases by about 30 % compared with (8)[3]. Since the vector form factor does not give the dominant contribution, the SU(4) symmetry breaking corrections will not appreciably affect the decay rates.

Taking the F and F^* masses from ref. 1, i. e. m_F = 2.03 GeV, m_{F^*} = 2.14 GeV, our numerical results using eqs.(3 - 8) are given in table I for F_1^V given by (9) and table II for F_1^V including the SU(4) symmetry breaking. We take δ to vary from 0 to -1. The electron spectrum for each individual decay modes are shown in fig. 1. Up to the q^2-dependence, the peaking of the electron energy distribution reflects essentially the kinematics of phase space. In fig. 2 we plot the inclusive electron spectrum after summing over the decay modes, with normalization as determined in table I.

Comparing the electron spectrum from F-decay with that of the D-decays, we note that the decay modes $F \to \eta e \bar{\nu}_e$ and $F \to \phi e \bar{\nu}_e$ are very similar to $D \to K e \bar{\nu}_e$ and $D \to K^* e \bar{\nu}_e$ respectively. The semi-leptonic decays of F have an additional decay mode $F \to \eta' e \bar{\nu}_e$, which tends to make the electron spectrum softer (by phase space). If $\eta' e \bar{\nu}_e$ is an important mode of the semi-leptonic decays, the difference between the electron spectrum from F- and D-decays will be noticable. Our calculation indicates that only 15 % of the semi-leptonic F-decays goes into $\eta' e \bar{\nu}_e$ and thus we do not anticipate any major change in the electron spectrum when the F-meson is produced in e^+e^- annihilation. The data[2] does not indicate any major change in the electron spectrum as E_{cm} moves from 4 to 5 GeV.

Finally, we note that the non-leptonic decays of the F-meson are very different from the D-mesons. If we could use the signatures of the non-leptonic and semi-leptonic decays of the F to separate the electron spectrum of the F-mesons from that of the D-mesons (e.g. the electron spectrum from inclusive $e\eta + \cdots$ versus $eK + \cdots$ ...), we could test the semi-leptonic decays of the F- and D-mesons in a more quantitative way.

Footnotes

F1 This is a corollary of the Ademollo-Gatto theorem. Let $\lambda H'$ be the SU(4) symmetry breaking term. Under SU(3) transformation, $\lambda H' = \lambda_3 u_3 + \lambda_8 u_8 + \lambda_{15} u_{15}$ with obvious notations. By Ademollo-Gatto theorem, the SU(4) corrections to $f_+(0)$ come in second order of λ. But the difference of the two $f_+(0)$ does not depend on λ_{15}, therefore the SU(3) correction to the difference of the two $f_+(0)$ comes in second order of λ_3, λ_8.

F2 This corresponds to $\delta = -1$ for the $D \to K e \bar{\nu}_e$ form factor as given in ref. 3.

Acknowledgement We would like to thank our experimental and theoretical colleagues at DESY and the University of Hamburg for useful discussions, G. Kramer for reading the manuscript.

References

1. DASP collaboration, R. Brandelik et al., DESY 77/44 (1977).

2. W. Braunschweig et al., Phys. Lett. 63B (1976) 417 and R. Brandelik et al., DESY Report (July 1977).

3. A. Ali and T.C. Yang, Phys. Lett. 65B (1976) 275.

4. A. Ali and Z.Z. Aydin, DESY Report (in press); I. Hineliffe and C.H. Llewellyn-Smith, Nucl. Phys. B114 (1976) 45; F. Bletzacker, H.T. Nieh and A. Soni, Stony Brook Preprint ITP-SB-76-62; K. Kajantie, Phys. Lett. 65B (1976) 69; B. Barger, T. Gottschalk and R.J. N. Phillips, Wisc. Preprint Coo-569; M. Gronau, C.H. Llewellyn-Smith, T.F. Walsh, S. Wolfram and T.C. Yang, Nucl. Phys. B12 (1977) 47.

5. H.J. Schnitzer and S. Weinberg, Phys. Rev. 164 (1967) 1828.

6. A. Kazi, G. Kramer and D.H. Schiller, DESY 76/18 (1976).

Table Captions

Table 1 Decay rates and the relative rates for the semi-leptonic decays of the $F^{\pm}$ mesons with $m_F = 2.03$ GeV and SU(4) symmetry assumed for F_1^V (see text).

Table 2 The same as for table 1, with the SU(4) symmetry breaking for F_1^V calculated à la Gell-Mann-Okubo.

Figure Captions

Fig. 1 Electron spectra from the decays $F^{\pm} \to \eta e^{\pm} \nu_e$, $F^{\pm} \to \eta' e^{\pm} \nu_e$ and $F^{\pm} \to \phi e^{\pm} \nu_e$, all normalised to unit area. The effect of the various values of δ on $F \to \phi e \bar{\nu}_e$ is negligible.

Fig. 2 Inclusve Electron spectrum for the semi-leptonic decays of the $F^{\pm}$ mesons, normalised with $\Gamma(F\to\eta' e\bar{\nu}_e)/\Gamma(F\to\eta e\bar{\nu}_e) = .3$, $\Gamma(F\to\phi e\bar{\nu}_e)/\Gamma(F\to\eta e\bar{\nu}_e) = .55$.

Mode \ Decay Widths	Units (sec^{-1})		
$F \to \eta e \bar{\nu}_e$	1.2×10^{11}		
$F \to \eta' e \bar{\nu}_e$	0.35×10^{11}		
$F \to \phi e \bar{\nu}_e$	$\delta = 0$	$\delta = -0.5$	$\delta = -1.0$
	0.49×10^{11}	0.57×10^{11}	0.66×10^{11}
$\Gamma(F\to\eta' e\bar{\nu}_e)/\Gamma(\eta e\bar{\nu}_e) =$	0.29		
$\frac{\Gamma(F\to\phi e\bar{\nu}_e)}{\Gamma(F\to\eta e\bar{\nu}_e)} =$	$\delta = 0$	$\delta = -0.5$	$\delta = -1$
	0.4	0.48	0.55

Table 1

Mode \ Decay Widths	Units (sec^{-1})		
$F \to \eta e \bar{\nu}_e$	1.2×10^{11}		
$F \to \eta' e \bar{\nu}_e$	0.35×10^{11}		
$F \to \phi e \bar{\nu}_e$	$\delta = 0$	$\delta = -0.5$	$\delta = -1.0$
	0.45×10^{11}	0.54×10^{11}	0.63×10^{11}
$\Gamma(F\to\eta' e\bar{\nu}_e)/\Gamma(F\to\eta e\bar{\nu}_e) =$	0.29		
$\frac{\Gamma(F\to\phi e\bar{\nu}_e)}{\Gamma(F\to\eta e\bar{\nu}_e)} =$	$\delta = 0$	$\delta = -0.5$	$\delta = -1.0$
	0.38	0.45	0.53

Table 2

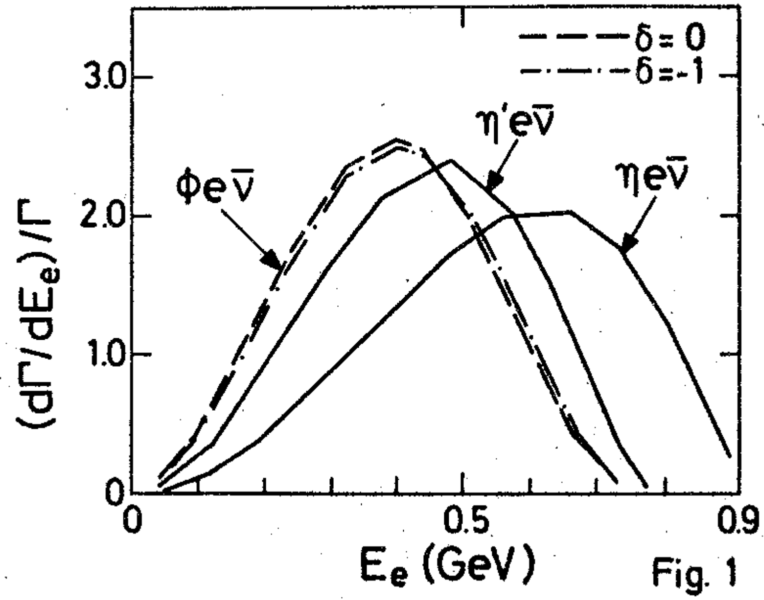

Fig. 1

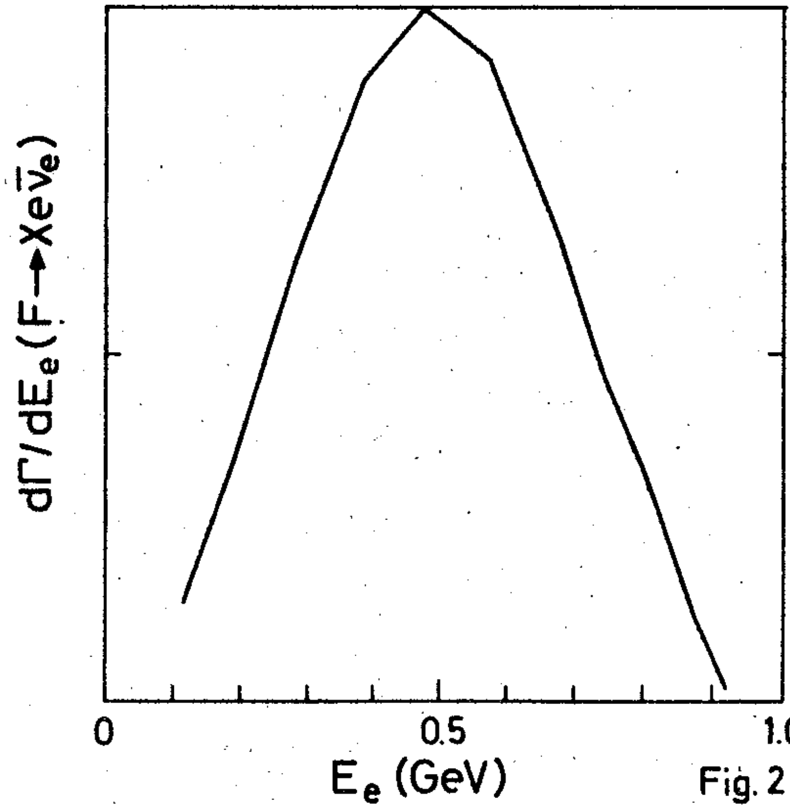

Fig. 2