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Energy dependence of semileptonic branching ratio averaged over D mesons

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The energy dependence of the semileptonic branching ratio averaged over the D^0 and D^+ mesons is discussed. It is pointed out that the semileptonic branching ratio averaged over D mesons at $\sqrt{s} = 4.0$–4.2 GeV should be considerably smaller than at $\sqrt{s} = 3.77$ GeV and $\sqrt{s} = 4.2$–4.5 GeV in order to be consistent with the experimental data on the ratios of lifetimes and production cross sections for charged versus neutral D mesons.

I. INTRODUCTION

There has been a recent accumulation of experimental results concerning D mesons. In this paper we study how to test the consistency among various D-meson data. We discuss first a couple of experimental results[1,2] reported very recently. One of them[1] is

$$\tau(D^+)/\tau(D^0) \geq 5.6 \pm 1.5\,, \qquad (1)$$

where $\tau(D^i)$ means the lifetime of the D^i meson. This large ratio has already been predicted by several authors,[3-5] and also the possibility of a longer lifetime of a new charged particle than that of a neutral one has been pointed out in the cosmic-ray experiments.[6]

Another experiment[2] is concerned with the energy dependence of the inclusive D-meson production cross sections in e^+e^- annihilation, where the data on cross sections for charged D meson and neutral D meson are given separately. The earlier data[7,8] on these production cross sections are tabulated in Ref. 2. The present discussion is made by using the new data as well as the earlier ones.

The important results of the new data are

$$\sigma_{D^0+\bar{D}^0}(\sqrt{s} = 3.76-3.79\,,\ 4.0-4.2\,,\ \text{and } 4.2-4.4\ \text{GeV}) = 11.5 \pm 2.5\,,\ 16.5 \pm 5.0\,,\ 3.5 \pm 2.1\ \text{nb}\,, \qquad (2)$$

$$\sigma_{D^++D^-}(\sqrt{s} = 3.76-3.79\,,\ 4.0-4.2\,,\ \text{and } 4.2-4.4\ \text{GeV}) = 9.1 \pm 2.0\,,\ 6.2 \pm 2.5\,,\ \text{and } 6.0 \pm 2.9\ \text{nb}\,, \qquad (3)$$

where $\sigma_{D^i+D^j} = \sigma(e^+e^- \to D^i x) + \sigma(e^+e^- \to D^j x)$. Therefore, r defined as

$$r(\sqrt{s}) \equiv \sigma_{D^0+\bar{D}^0}/\sigma_{D^++D^-} \qquad (4)$$

varies considerably with energy, that is

$$r(\sqrt{s} = 3.76-3.79\,,\ 4.0-4.2\,,\ \text{and } 4.2-4.4\ \text{GeV}) = 1.3 \pm 0.4\,,\ 2.7 \pm 1.3\,,\ \text{and } 0.6 \pm 0.4\,, \qquad (5)$$

respectively. This behavior of r with energy is understood naturally below $\sqrt{s} = 4.2$ GeV in the model[9,10] as we will discuss later, however, it seems hard to explain the small value at $\sqrt{s} = 4.2$–4.4 GeV.

It should be noticed that what is observed as the semileptonic branching ratio of the D meson is only the averaged one over the D^0 and D^+ mesons which will be defined in Eq. (6) below. Therefore, the experimental facts[1,2] stated above should lead to the semileptonic branching ratio which depends on energy, and we can estimate the lifetime ratio $\tau(D^+)/\tau(D^0)$ from the data on the semileptonic branching ratio averaged over the D mesons and the production-cross-sections ratio r; however, the present data have too large error bars.

The purpose of this paper is to examine the consistency among the data of Refs. 1 and 2 and the data on the energy dependence of the semileptonic branching ratio averaged over the D^0 and D^+ mesons which are available at present.

II. SEMILEPTONIC BRANCHING RATIO AVERAGED OVER D^0 AND D^+

The semileptonic branching ratio averaged over the D^0 and D^+ is expressed as

$$B = \frac{1}{\sigma(D^+) + \sigma(D^0)} \left[\sigma(D^+)\frac{\Gamma(D^+ \to l^+X)}{\Gamma(D^+ \to \text{all})} + \sigma(D^0)\frac{\Gamma(D^0 \to l^+X)}{\Gamma(D^0 \to \text{all})}\right]$$
$$= \frac{\Gamma(D^+ \to l^+X)}{\Gamma(D^+ \to \text{all})}\left[\frac{1}{1+r} + \frac{\tau(D^0)}{\tau(D^+)}\frac{r}{1+r}\right], \qquad (6)$$

where $\sigma(D^i) = \sigma(e^+e^- \to D^i X)$. Here we set from the beginning

$$\Gamma(D^+ \to l^+X) = \Gamma(D^0 \to l^+X)\,, \qquad (7)$$

because the dominant semileptonic interaction in the charm decays satisfies the isospin selection rule $\Delta I = 0$. From Eq. (6), we can see simply that the new data allow us to discuss the energy dependence of the semileptonic branching ratio B.

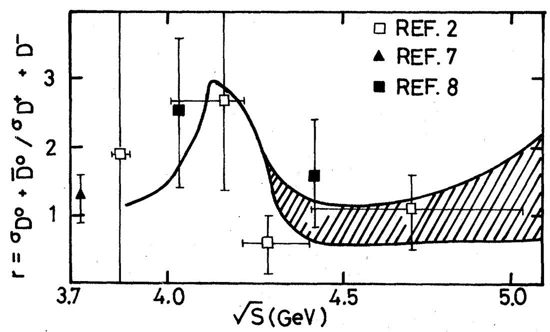

FIG. 1. $r \equiv \sigma_{D^0+\bar{D}^0}/\sigma_{D^++D^-}$. The curve for $3.7 \leq \sqrt{s} \leq 4.2$ GeV is calculated on the basis of the model (Ref. 9) and the shaded band for $\sqrt{s} \geq 4.2$ GeV is assumed to be the allowable region of r which is drawn on the basis of the data (Refs. 2 and 8) (see text).

A. Discussion of *r*

We will discuss first the ratio r defined in Eq. (4) for $3.7 \leq \sqrt{s} \leq 5.0$ GeV, the data for which are shown in Fig. 1. Lane and Eichten[9] and De Rújula *et al.*[10] have discussed the production mechanism of D mesons at thresholds, which can explain very nicely the recoil mass spectrum for quasi-two-body reactions of D mesons and the threshold structure of R where $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$. Therefore, it is reasonable to estimate r on the basis of the proposed model in Ref. 9. By using the same parametrization as in Ref. 9, we have calculated r for $3.7 \leq \sqrt{s} \leq 4.2$ GeV. The results are shown to be quite consistent with the data for $\sqrt{s} \leq 4.2$ GeV (Fig. 1). Here, we have used the experimental branching ratios, $B(D^{*0} \to D^0 X) = 1.0$, $B(D^{*+} \to D^+ X) = 0.4$, and $B(D^{*+} \to D^0 X) = 0.6$.[11]

We may estimate r at the asymptotic region, for example, $r = 2.6$, which comes from the prediction $\sigma(D^*)/\sigma(D) = 3$,[10] where we have used the experimental branching ratios.[11] Note that the fragmentation model[12] predicts $\sigma(D^0)/\sigma(D^+) = \sigma(D^{*0})/\sigma(D^{*+}) = 1.1$, therefore, we can imagine $\sigma(D^0)/\sigma(D^+) > 1.1$ at the asymptotic region. However, it seems to be very difficult at the present stage to have theoretically reasonable estimates of r for $5.0 \geq \sqrt{s} \geq 4.2$ GeV. This is because the inclusive production cross section should dominate over the exclusive ones, $e^+e^- \to D\bar{D}, D\bar{D}^* + D^*\bar{D}, D^*\bar{D}^*$, due to the rapidly falling form factors for the exclusive production with increasing energy. In fact, the small value $r = 0.6 \pm 0.4$ at $\sqrt{s} = 4.2$–4.4 GeV cannot be understood so easily. (The data require that r should fall down very sharply to 0.6 ± 0.4 at $\sqrt{s} = 4.2$–4.4 GeV from 2.7 ± 1.3 at $\sqrt{s} = 4.0$–4.2 GeV.)

In this paper, I will venture to go further by assuming the allowable region for r on the basis of the data[2,8] for $4.2 \leq \sqrt{s} \leq 5.0$ GeV as shown by the shaded band in Fig. 1. The two curves which define the shaded region are smooth extrapolations of the curve below 4.2 GeV which are consistent within one standard deviation with the data above 4.2 GeV.

The estimated r in Fig. 1 is not too unreliable to extract a conclusion, because it is conservative, and our conclusion becomes more confirmed if we estimate r more faithfully with the data. In addition to this fact, the extrapolation only to 4.5 GeV from 4.2 GeV is enough to our present discussions because we do not have reliable data to be compared with our prediction for $\sqrt{s} \geq 4.5$ GeV, as will be discussed in Sec. III.

B. Bounds on *B*

If we assume the ratio $\tau(D^+)/\tau(D^0)$, it enables us to predict B which depends on the energy, since r depends also on the energy. Although some authors[3,5] have predicted a large ratio, $\tau(D^+)/\tau(D^0) = 5$–20, which is consistent with the present data,[1] it seems to be more useful to discuss the bounds on B by using the estimated r of Fig. 1 and the following firm data[1,13]:

$$\tau(D^+)/\tau(D^0) \geq 4.1\,, \tag{8}$$

$$B(D \to l^+X) = 8.0 \pm 1.5\% \text{ at } \psi(3772)\,, \tag{9}$$

$$\frac{\Gamma(\psi(3772) \to D^0\bar{D}^0)}{\Gamma(\psi(3772) \to D^+D^-)} = \frac{0.56}{0.44}\,. \tag{10}$$

The bounds are derived as follows:

$$\frac{11.3}{1+r} \leq B \leq 5.27 \times \left(1 + \frac{3.1}{1+r}\right), \tag{11}$$

which are shown in Fig. 2.

C. Estimate of *B*

If we apply the soft-pion theorem to $D^+ \to \pi^+\pi^+K^-$ amplitude which is assumed to be constant by taking account of the Dalitz plot experiment, we can derive the simple relation[14]

$$\frac{\tau(D^+)}{\tau(D^0)} = \frac{B(D^+ \to \pi^+\pi^+K^-)}{B(D^0 \to \pi^0\bar{K}^0)} \times \frac{1}{0.39} = 6.7 \pm 3.3 \tag{12}$$

which is consistent with the data.[1]

By estimating $\tau(D^+)/\tau(D^0) = 7.0$ as an example, we predict the averaged semileptonic branching ratio of D mesons, B in Fig. 2. Here we set

$$B(D \to l^+x) = 8.0\% \text{ at } \psi(3772) \tag{13}$$

as a normalization, which is the central value of the data given by SLAC-DELCO.[13] [The SLAC-LBL result[15] is $B(D \to l^+X) = 7.2 \pm 2.8\%$ at the same energy.] This normalization with our estimate $\tau(D^+)/\tau(D^0) = 7$ implies

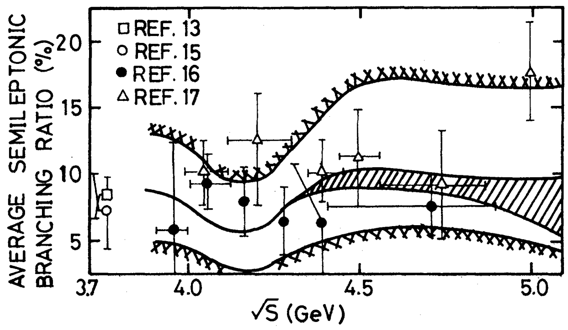

FIG. 2. Prediction and bounds on B. The semileptonic branching ratio averaged over the D^0 and D^+ is predicted in the case of $\tau(D^+)/\tau(D^0)=7$. Here we employ the curve drawn in Fig. 1 for r and we set $B=8\%$ at $\sqrt{s}=3.77$ GeV as an input, which is the center value of the data given by SLAC-DELCO (open square) of Ref. 13. Shown also are $\tilde{B}$ which is the semileptonic branching ratio averaged over the charmed hadrons (closed circle) of Ref. 16 and (open triangle) of Ref. 17. The shaded band corresponds to the shaded band of r in Fig. 1, and the crossed region represents the forbidden region by our bounds on B, see Eq. (11).

$$B(D^+\to l^+X)=15.4\%, \tag{14}$$

$$B(D^0\to l^+X)=2.2\%. \tag{15}$$

Note that the predicted B depends less (more) on energy if we estimate smaller (larger) value for $\tau(D^+)/\tau(D^0)$.

III. COMPARISON WITH DATA

The data to be compared with the prediction have already been published by SLAC-LBL (Ref. 16) ($3.9\le\sqrt{s}\le 7.4$ GeV) and DESY-DASP (Ref. 17) ($4.08\le\sqrt{s}\le 5.20$ GeV). They reported the energy dependence of the average semileptonic branching ratio for charmed hadrons defined by

$$\tilde{B}\equiv\frac{\sigma(e^+e^-\to e^\pm x)}{2\sigma(\text{charm})}. \tag{16}$$

To compare our prediction with the data, we divide the data into three ranges of energy: 3.77–4.08 GeV (below $F\overline{F}$ threshold), 4.08–4.50 GeV (above $F\overline{F}$ threshold and below $\Lambda_c^+\overline{\Lambda}_c^+$ threshold), and >4.50 GeV (above $\Lambda_c^+\overline{\Lambda}_c^+$ threshold). Strictly speaking, the comparison between Eq. (6) and the data can not be made above the $F\overline{F}$ threshold. We feel, however, that $F\overline{F}$ contribution is negligibly small below 4.50 GeV.[18] This is supported by the fact that the electron momentum spectrum[16] observed for $3.90\le\sqrt{s}\le 4.44$ GeV is similar to that from the semileptonic decay of D mesons produced in the decay of the $\psi(3772)$. On the other hand, the comparison between the data and our prediction is not justified above 4.50 GeV, since the $F\overline{F}$, $\Lambda_c^+\overline{\Lambda}_c^+$, $\Sigma_c\overline{\Sigma}_c,\ldots$, may not be negligible.

We could say safely that the data are consistent with our bounds; however, the present data[16,17] have too large error bars to discuss further by comparing them with our prediction.

IV. SUMMARY

We have derived bounds on B by using the firm data which are available at present and by using a reasonable model of the production cross section for D mesons. The data are found to be within these bounds quite consistently.

By assuming $\tau(D^+)/\tau(D^0)=7$, we have predicted the energy dependence of B. The existing data seem to be consistent with our prediction. But this does not necessarily mean that our estimates for r and $\tau(D^+)/\tau(D^0)$ are reasonable. This is only because the present data have too large error bars to be compared with our prediction. We can say, however, that this analysis will become useful for examining the consistency among the experimental data[1,2,13,15-17] if the experiments concerned are improved.

We can assert that B at $\sqrt{s}=4.0$–4.2 GeV should be considerably smaller than B at $\sqrt{s}=3.77$ and 4.2–4.5 GeV, in order to be consistent with the experimental data on the ratios of lifetimes and production cross sections for charged versus neutral D mesons, although the present data[16,17] do not establish such a tendency.

Finally we would like to comment on the data, $r\le 1.0$ at $\sqrt{s}=4.2$–4.4 GeV. We have pointed out that this is hard to understand unless an exotic mechanism is assumed, because the quark-parton model predicts $r\ge 1.0$. (The equality holds when the resonance D^* is assumed not to be produced.) Therefore, if the present data $r\le 1.0$ at $\sqrt{s}=4.2$–4.4 GeV are confirmed, some exotic mechanisms have to be introduced in the e^+e^- annihilation process. From this viewpoint, it would be useful to remeasure r in this region.

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