Upper Limit on the Absolute Branching Fraction for $D_s^+ \to \phi\pi^+$

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We report a study of the hadronic branching fractions of the D_s^+ meson, which is used to extract an upper limit on the absolute branching fraction for $D_s^+ \to \phi\pi^+$. A search is made for fully reconstructed events from the reaction $e^+e^- \to D_s^{*\pm} D_s^{\mp}$, $D_s^{*\pm} \to \gamma D_s^{\pm}$, using seven exclusive D_s^+ decay modes. The data sample of 6.30 ± 0.46 pb^{-1} was collected at $\sqrt{s} = 4.14$ GeV with the Mark III detector at the SLAC e^+e^- storage ring SPEAR. No candidate events are observed. The measured relative D_s^+ branching fractions and $\sigma B(D_s^+ \to \phi\pi^+)$ are used to establish the limit $B(D_s^+ \to \phi\pi^+) < 4.1\%$ at 90% confidence level.

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Knowledge of the absolute branching fractions of the D_s^+ meson[1] is necessary for studies of D_s^+ production and decay. For example, theoretical predictions for the decay rates of B mesons to the D_s^+ cannot be compared with experimental results unless the absolute D_s^+ branching fractions are known. Measurements of these branching fractions also provide new tests for charm-decay models. To date, there has been no direct measurement of an absolute branching fraction of the D_s^+ meson, in contrast with the D^0 and D^+, for which precise branching-fraction measurements have been obtained.[2]

The D_s^+ has been readily observed in e^+e^- annihilation, photoproduction, and hadronic interactions through the decay $D_s^+ \to \phi\pi^+$. In addition, the decay rates for a number of other hadronic D_s^+ decay modes have been measured relative to that for $D_s^+ \to \phi\pi^+$. However, the experiments have measured only the product of the D_s^+ production cross section and the branching fraction for $D_s^+ \to \phi\pi^+$. Estimates of the D_s^+ production cross section in high-energy e^+e^- annihilation have been made, based on assumptions about the charm production cross section, the probability that a D_s^+ is formed from a charm quark, and the D_s^+ momentum spectrum. Given these assumptions, estimates of $B_{\phi\pi^+} \equiv B(D_s^+ \to \phi\pi^+) = 2\%$-$13\%$ have been obtained.[3-5] It is impossible to assign meaningful systematic errors to these estimates because of the uncertainties in the assumptions. The D_s^+ branching fractions may, however, be determined by studying D_s^+ production near threshold in e^+e^- annihilations in the charm resonance region, where the mesons are produced in pairs. Using a technique based on full reconstruction of $D_s^+D_s^-$ pairs ("double tags"), the absolute branching fractions can be obtained without assumptions about the D_s^+ production cross section.

We report herein the results of a search[6] for fully reconstructed $D_s^+D_s^-$ pairs in e^+e^- collisions at $\sqrt{s} = 4.14$ GeV. At this energy, D_s^+ production is dominated by the reaction $e^+e^- \to D_s^{*\pm} D_s^{\mp} \to \gamma D_s^+ D_s^-$.[7] The search includes the seven D_s^+ decay modes $\phi\pi^+$, $\bar{K}^0K^+$, $f_0(975)\pi^+$, $\bar{K}^*(892)^0K^+$, $\bar{K}^{*0}K^{*+}$, $\phi\pi^+\pi^+\pi^-$, and $\phi\pi^+\pi^0$. The 49 ($=7^2$) possible $\gamma D_s^+ D_s^-$ final states are considered. The expected number of reconstructed double-tag events is

$$\langle N \rangle = [\sigma L B_{\phi\pi^+}] B_{\phi\pi^+} \sum b_i b_j \epsilon_{ij}, \tag{1}$$

where $\sigma \equiv \sigma(e^+e^- \to D_s^{*\pm} D_{s^\mp})$, L is the integrated luminosity, $b_i \equiv B(D_s^+ \to \text{mode } i)/B(D_s^+ \to \phi\pi^+)$, and ϵ_{ij} is the detection efficiency for the double-tag final state i vs j. The absolute branching fraction $B_{\phi\pi^+}$ may therefore be determined from the number of observed double-tag events and the previously measured $\sigma L B_{\phi\pi^+}$ and b_i. We have used this technique to place a model-independent upper limit on $B_{\phi\pi^+}$.

The data sample of 6.30 ± 0.46 pb^{-1} was collected with the Mark III detector[8] at the SLAC e^+e^- storage ring SPEAR. In this analysis, data from the main drift chamber, the time-of-flight system, and the electromagnetic calorimeter are used. For a particular $\gamma D_s^+ D_s^-$ final state, all events which contain the correct number of charged tracks and at least the correct number of photons are selected. All showers in the calorimeter not associated with charged tracks are considered to be photon candidates. No restriction is placed on the number of extra photons because spurious showers may be created by $K^\pm$ decay products, hadronic interactions, and electronic noise. Time-of-flight information is used to identify charged π and K candidates.[9] All combinations of photons and particle-identification hypotheses consistent with the final state under study are formed. For each combination a kinematic fit which imposes total-event-energy and momentum-conservation conditions (four constraints) is performed; combinations with $\chi^2 < 50$ are retained for further consideration. The fitted photon energies are required to be greater than 50 MeV since above that energy the detection efficiency is well modeled.

Within each track combination, candidates for the decays $D_s^+ \to \text{mode } i$ and $D_s^- \to \text{mode } j$ are formed from all permutations of identical particles in the combination. The number of permutations is considerably reduced by requirements on the resonant substructure of the D_s^+ decay modes.[10]

Further background rejection is achieved by imposing additional kinematic constraints on the candidate events. Kinematic fits by the hypotheses $e^+e^- \to D_s^{*+} D_s^-$ and $D_s^{*-} D_s^+$ are attempted for each track permutation, requiring $M(\gamma D_s^\pm) = M(D_s^*) = 2.109$ GeV/c^2.[7] The D_s^+ and D_s^- candidates in the event are constrained to have equal but unspecified mass $M(X)$; this quantity is determined in the fit. The fit with the smaller χ^2 is retained, with the confidence-level requirement C.L.$(\chi^2) > 5\%$. Double-tag events would produce a signal at the D_s^+ mass in the resulting $M(X)$ distribution.

For each final state, a signal region in the $M(X)$ distribution is selected which contains 95% of a Monte Carlo–generated signal. The half-widths of the signal regions range from 8 to 30 MeV/c^2. Figure 1 shows the combined $M(X)$ distribution for the 49 double-tag final states. No signal events are observed.

An upper limit on $B_{\phi\pi^+}$ is found by computing the likelihood of observing zero candidate events as a function of $B_{\phi\pi^+}$. The expected number of reconstructed double-tag events is obtained from Eq. (1), using the following measured quantities as input:[11] $\sigma L B_{\phi\pi^+} = 156 \pm 38$,[12] $b_{\bar{K}^0 K^+} = 0.92 \pm 0.38$,[13] $b_{f_0 \pi^+} = 0.28 \pm 0.10$,[14] $b_{\bar{K}^{*0} K^+} = 0.93 \pm 0.12$,[15–18] $b_{\bar{K}^{*0} K^{*+}} = 2.3 \pm 1.4$,[17] $b_{\phi\pi^+\pi^+\pi^-} = 0.41 \pm 0.10$,[4,16,17] and $b_{\phi\pi^+\pi^0} = 2.4 \pm 1.1$.[19] The detection efficiencies are determined with a Monte Carlo simulation. The likelihood function $\mathcal{L}(B_{\phi\pi^+}, \sigma L B_{\phi\pi^+}, b_i)$ is constructed with Poisson statistics for the number of observed events and Gaussian errors for the measured quantities. Correlations between the measurements of $\sigma L B_{\phi\pi^+}$, $b_{\bar{K}^0 K^+}$, and $b_{\bar{K}^{*0} K^+}$ are taken into account. The marginal likelihood[20] $\mathcal{L}(B_{\phi\pi^+})$ (Fig. 2) is computed by integrating $\mathcal{L}(B_{\phi\pi^+}, \sigma L B_{\phi\pi^+}, b_i)$ with respect to the seven measured quantities $\sigma L B_{\phi\pi^+}$ and the b_i.[21] The upper limit of a 90% likelihood interval is $B_{\phi\pi^+} = 3.8\%$.[22] The number of signal events expected for $B_{\phi\pi^+} = 3.8\%$ is 2.8, using the measured central values of $\sigma L B_{\phi\pi^+}$ and b_i. The uncertainty on the number of signal events includes contributions from the charged- and neutral-track reconstruction efficiency (7%), Monte Carlo statistics (2%), and the efficiency of the resonance- and signal-region requirements (2%). These contributions are added in quadrature to give a total of 8%. This uncertainty is included by increasing the limit by $1/(1-0.08)$, which

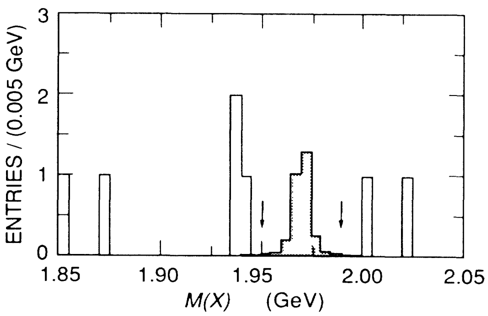

FIG. 1. Combined $M(X)$ distribution (unshaded histogram). The arrows indicate the widest signal region (± 20 MeV/c^2) among the double-tag final states which yield entries between 1.85 and 2.05 GeV/c^2. The shaded histogram shows the expected signal for $B_{\phi\pi^+} = 4.1\%$.

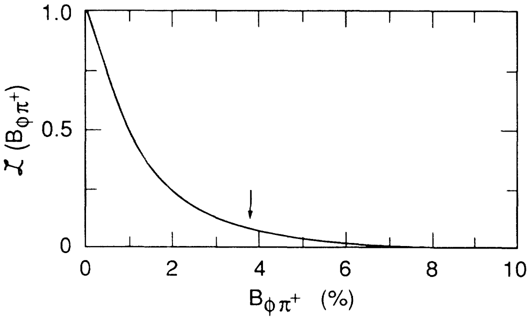

FIG. 2. Marginal likelihood $\mathcal{L}(B_{\phi\pi^+})$. The value $B_{\phi\pi^+} = 3.8\%$ is indicated by the arrow. The vertical scale is arbitrary.

yields

$$B(D_s^+ \rightarrow \phi\pi^+) < 4.1\%$$

at 90% C.L.

In summary, we have obtained the first model-independent limit on the absolute branching fraction for $D_s^+ \rightarrow \phi\pi^+$. Theoretical predictions for $B_{\phi\pi^+}$ from factorization,[23,24] QCD sum rules,[25] and an SU(3)-symmetry model[26] are approximately 3% and are consistent with the upper limit presented. Previous estimates from high-energy e^+e^- annihilations are also consistent with our limit. The experimental results imply that a large fraction of D_s^+ decays have not yet been observed. Future studies of D_s^+ production and decay would benefit from a precise, model-independent determination of $B_{\phi\pi^+}$ which could be made by applying the double-tag technique to a larger data sample.

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[1] Throughout this paper, reference to a charge state also implies reference to its charge conjugate.

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[7] J. Adler *et al.*, Phys. Rev. Lett. **58**, 2171 (1987). We assume $B(D_s^{*+} \rightarrow \gamma D_s^+) = 100\%$.

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[9] A charged track is used as a π or K unless the measured time of flight is more than 5σ from the predicted time for that hypothesis. In order to reduce combinatoric background, a more stringent requirement is imposed on the kaons in the final state $\phi\pi^+\pi^0$ vs $\phi\pi^-\pi^0$.

[10] The half-widths of the accepted mass intervals are $\phi \rightarrow K^+K^-$, 20 MeV/c^2; $K_S^0 \rightarrow \pi^+\pi^-$, 25 MeV/$c^2$; $f_0(975) \rightarrow \pi^+\pi^-$, 40 MeV/$c^2$ (centered at 965 MeV/c^2); $\bar{K}^{*0} \rightarrow K^-\pi^+$, 80 MeV/$c^2$ (for $\bar{K}^{*0}K^+$) or 100 MeV/c^2 (for $\bar{K}^{*0}K^{*+}$); $K^{*+} \rightarrow K_S^0\pi^+$, 100 MeV/$c^2$; $\pi^0 \rightarrow \gamma\gamma$, 30 MeV/$c^2$ (for $\phi\pi^+\pi^0$ vs $\{K^{*0}K^{*-}$ or $\phi\pi^-\pi^-\pi^+\}$) or 35 MeV/c^2 (for $\phi\pi^+\pi^0$ vs all others).

[11] Weighted averages of the measurements are computed after adding the statistical and systematic uncertainties in quadrature.

[12] The Mark III measurement of $\sigma B(D_s^+ \rightarrow \bar{K}^{*0}K^+)$ and the world-average value of $b_{\bar{K}^{*0}K^+}$ are used to obtain $\sigma L B_{\phi\pi^+} = 146 \pm 57$. Combining this with the direct Mark III measurement of 162 ± 51 [J. Adler *et al.*, Phys. Rev. Lett. **63**, 1211 (1989)] and accounting for common systematic errors yields $\sigma L B_{\phi\pi^+} = 156 \pm 38$. The uncertainty on the integrated luminosity cancels entirely in this analysis.

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[21] For each value of $B_{\phi\pi^+}$, the seven-dimensional integral is evaluated numerically using Gaussian quadrature with fourteen nodes in each dimension.

[22] This quantity is the value of $B_{\phi\pi^+}$ below which 90% of the integral of $\mathcal{L}(B_{\phi\pi^+})$ is found.

[23] The D_s^+ lifetime, $(4.36^{+0.38}_{-0.32}) \times 10^{-13}$ s, is taken from Ref. 5.

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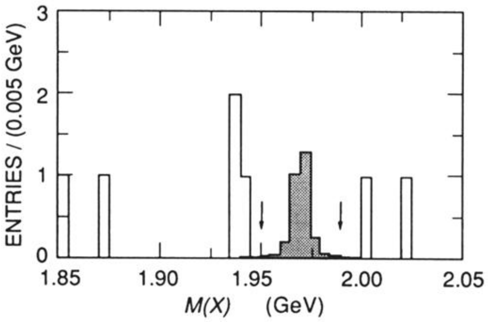

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