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Observation and Polarization Measurements of $B^{\pm} \rightarrow \phi K_1^{\pm}$ and $B^{\pm} \rightarrow \phi K_2^{*\pm}$

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With the full *BABAR* data sample of 465×10^6 $B\bar{B}$ pairs, we observe the decays $B^{\pm} \to \varphi K_1(1270)^{\pm}$ and $B^{\pm} \to \varphi K_2^*(1430)^{\pm}$. We measure the branching fractions $(6.1 \pm 1.6 \pm 1.1) \times 10^{-6}$ and $(8.4 \pm 1.8 \pm 1.0) \times 10^{-6}$ and the fractions of longitudinal polarization $0.46^{+0.12+0.06}_{-0.13-0.07}$ and $0.80^{+0.09}_{-0.10} \pm 0.03$, respectively. We also report on the $B^{\pm} \to \varphi K_0^*(1430)^{\pm}$ decay branching fraction of $(7.0 \pm 1.3 \pm 0.9) \times 10^{-6}$ and several parameters sensitive to *CP* violation and interference in the above three decays. Upper limits are placed on the $B^{\pm}$ decay rates to final states with φ and $K_1(1400)^{\pm}$, $K^*(1410)^{\pm}$, $K_2(1770)^{\pm}$, or $K_2(1820)^{\pm}$. Understanding the observed polarization pattern requires amplitude contributions from an uncertain source.

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Measurements of polarization in rare vector-vector B meson decay, such as $B \to \varphi K^*$ [1,2], have revealed an unexpectedly large fraction of transverse polarization and suggested contributions to the decay amplitude which were previously neglected. Decays to other excited spin-J kaons $K_J^{(*)}$ can also take place. The differential width for a $B \to \varphi K_J^{(*)}$ decay has three complex amplitudes $A_{J\lambda}$, which describe the three helicity states $\lambda = 0, \pm 1$, except when $J = 0$. The expected hierarchy of the $A_{J\lambda}$ amplitudes $|A_{J0}|^2 \gg |A_{J+}|^2 \gg |A_{J-}|^2$ is sensitive to the (V-A) structure of the weak interactions with the left-handed fermion couplings [3–5], and therefore is sensitive to physics beyond the standard model. For example, tensor or scalar interactions would violate $|A_{J0}|^2 \gg |A_{J+}|^2$ and the right-handed fermion couplings would violate $|A_{J+}|^2 \gg |A_{J-}|^2$ [3]. Strong interaction effects could change these predictions as well, but they were originally expected to be small [3].

However, all previous studies have been limited to the two-body $K_J^* \to K\pi$ decays, thus considering only the spin-parity K_J^* states with $P = (-1)^J$. In this Letter we report the measurement with the three-body final states $K_J^{(*)} \to K\pi\pi$ which include $P = (-1)^{J+1}$ mesons such as K_1 and K_2. We complement these measurements with the two-body K_J^* final states in the $B^{\pm}$ decays and report polarization in the $\varphi K_1(1270)^{\pm}$ and $\varphi K_2^*(1430)^{\pm}$ final states which have not been seen before. We also search for other final states with φ and $K_0^*(1430)^{\pm}$, $K_1(1400)^{\pm}$, $K^*(1410)^{\pm}$, $K_2(1770)^{\pm}$, or $K_2(1820)^{\pm}$.

We use data collected with the *BABAR* detector [6] at the PEP-II e^+e^- collider. A sample of $(465 \pm 5) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ events was recorded at the e^+e^- center-of-mass energy $\sqrt{s} = 10.58$ GeV. Momenta of charged particles are measured in a tracking system consisting of a silicon vertex tracker with five double-sided layers and a 40-layer drift chamber, both within the 1.5 T magnetic field of a solenoid. Identification of charged particles is provided by measurements of the energy loss in the tracking devices and by a ring-imaging Cherenkov detector. Photons are detected by a CsI(Tl) electromagnetic calorimeter.

We search for $B^{\pm} \to \varphi K_J^{(*)\pm}$ decays using three final states of the $K_J^{(*)\pm}$ decay: $K_S^0\pi^{\pm}$, $K^{\pm}\pi^0$, and $K^{\pm}\pi^+\pi^-$, where $K_S^0 \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$. We define the two helicity angles θ_i as the angle between the direction of the K or K^+ meson from $K_J^* \to K\pi$ (θ_1) or $\varphi \to K^+K^-$ (θ_2) and the direction opposite to the B in the K^* or φ rest frame. The normal to the three-body decay plane for $K_J^{(*)} \to K\pi\pi$ is chosen as the analyzer of the $K_J^{(*)}$ polarization instead of the direction of K from K_J^* in the two-body decays. We define $\mathcal{H}_i = \cos\theta_i$.

We identify B meson candidates using two kinematic variables: $m_{\rm ES} = (s/4 - \mathbf{p}_B^2)^{1/2}$ and $\Delta E = \sqrt{s}/2 - E_B$, where $(E_B, \mathbf{p}_B)$ is the four-momentum of the B candidate in the e^+e^- center-of-mass frame. We require $m_{\rm ES} > 5.25$ GeV and $|\Delta E| < 0.1$ GeV (or 0.08 GeV for $K_J^{(*)\pm} \to K^{\pm}\pi^+\pi^-$). We also require the invariant masses to satisfy $1.1 < m_{K\pi} < 1.6$ GeV, $1.1 < m_{K\pi\pi} < 2.1$ GeV, and $0.99 < m_{K^+K^-} < 1.05$ GeV. To reject the dominant $e^+e^- \to$ light quark-antiquark background, we use the angle θ_T between the thrust axis of the B-candidate decay products and that of the rest of the event requiring $|\cos\theta_T| < 0.8$, and a Fisher discriminant $\mathcal{F}$ which combines event-shape parameters [7].

To reduce combinatorial background in the mode $K_J^{*\pm} \to K^{\pm}\pi^0$, we require $\mathcal{H}_1 < 0.6$. When more than one candidate is reconstructed (7.6% of events with $K_S^0\pi^{\pm}$, 2.9% with $K^{\pm}\pi^0$, and 14.6% with $K^{\pm}\pi^+\pi^-$), we select the one whose χ^2 of the charged-track vertex fit combined with χ^2 of the invariant mass consistency of the K_S^0 or π^0 candidate is the lowest. We define the b-quark flavor sign Q to be opposite to the charge of the B meson candidate.

We use an unbinned extended maximum-likelihood fit [1] to extract the event yields n_j and the probability density function (PDF) parameters, denoted by $\boldsymbol{\zeta}$ and $\boldsymbol{\xi}$, to be described below. The index j represents the event categories, which include continuum background and several B-decay modes. In the $B^{\pm} \to \varphi K_J^{*\pm} \to (K^+K^-)(K\pi)$ topology, the following event categories are considered: $\varphi K_2^*(1430)^{\pm}$, $\varphi(K\pi)_0^{*\pm}$, and $f_0(K\pi)_0^{*\pm}$, where the $J^P = 0^+$ $(K\pi)_0^{*\pm}$ contribution includes both a nonresonant component and the $K_0^*(1430)^\pm$ resonance [8]. In the $B^\pm \to \varphi K_J^{(*)\pm} \to (K^+K^-)(K\pi\pi)$ topology, we consider $\varphi K_1(1270)^\pm$, $\varphi K_1(1400)^\pm$, $\varphi K_2^*(1430)^\pm$, $\varphi K^*(1410)^\pm$, $\varphi K_2(1820)^\pm$, a nonresonant $\varphi K^\pm\pi^+\pi^-$, and $f_0K_1(1400)^\pm$ contributions. In the latter topology, the mode $\varphi K_2(1770)^\pm$ is also considered in place of $\varphi K_2(1820)^\pm$. In all cases, the modes with a f_0 model can account for a possible broad non-φ (K^+K^-) contribution under the φ.

The extended likelihood is $\mathcal{L} = \exp(-\sum n_j)\prod \mathcal{L}_i$. The likelihood $\mathcal{L}_i$ for candidate i is defined as $\mathcal{L}_i = \sum_{j,k} n_j^k \mathcal{P}_j^k(\boldsymbol{x}_i; \boldsymbol{\zeta}, \boldsymbol{\xi})$, where $\mathcal{P}_j^k$ is the PDF for variables $\boldsymbol{x}_i = \{\mathcal{H}_1, \mathcal{H}_2, m_{K\pi(\pi)}, m_{K^+K^-}, \Delta E, m_{\rm ES}, \mathcal{F}, Q\}$. The flavor index k corresponds to the value of Q; that is, $\mathcal{P}_j^k \equiv \mathcal{P}_j \times \delta_{kQ}$. The $\boldsymbol{\zeta}$ are the polarization parameters, relevant only for the signal PDF. The $\boldsymbol{\xi}$ parameters describe the background or the remaining signal PDFs, which are left free to vary in the fit for the combinatorial background and are fixed to the values extracted from Monte Carlo (MC) simulation [9] and calibration $B \to \bar{D}\pi$ decays in other cases.

The signal PDF for a given candidate i is a joint PDF for the helicity angles and resonance mass, and the product of the PDFs for each of the remaining variables. The helicity part of the signal PDF is the ideal angular distribution from Ref. [10], multiplied by an empirical acceptance function $\mathcal{G}(\mathcal{H}_1, \mathcal{H}_2)$. In the $B \to \varphi K_1$ or φK_2 parametrization, the additional kinematic parameters for the decays $K_J^\pm \to K^\pm\pi^+\pi^-$ (such as r_1, r_2, and r_{02} in Ref. [10]) are modeled using the sequential two-body decay chains [4]. A relativistic spin-J Breit-Wigner amplitude parametrization is used for the resonance masses [4,11], and the $J^P = 0^+(K\pi)_0^{*\pm}$ $m_{K\pi}$ amplitude is parametrized with the LASS function [8]. The nonresonant $\varphi K^\pm\pi^+\pi^-$ contribution is modeled through sequential $K^*(892)\pi \to K\pi\pi$ decay, while the decay $K\rho \to K\pi\pi$ is considered in the systematic uncertainty studies. We use a sum of Gaussian functions for the parametrization of ΔE, $m_{\rm ES}$, and $\mathcal{F}$.

The interference between the $J = 2$ and 0 $(K\pi)^\pm$ contributions is modeled with the term $2{\rm Re}(A_{20}A_{00}^*)$, with the three-dimensional angular and $m_{K\pi}$ parametrization. We allow an unconstrained flavor-dependent overall shift $(\delta_0 + \Delta\delta_0 \times Q)$ between the LASS amplitude phase and the tensor resonance amplitude phase. The polarization parameters $\boldsymbol{\zeta}$ include the fractions of longitudinal polarization $f_L = |A_{J0}|^2/\Sigma|A_{J\lambda}|^2$ in several channels, δ_0, and $\Delta\delta_0$. Similar interference between the $K_1(1270)^\pm$ and $K_1(1400)^\pm$ contributions is allowed in the study of systematic uncertainties but is not included in the nominal fit due to observed dominance of only one mode and therefore unconstrained phase of the interference.

Since the $K_2^*(1430)^\pm$ meson contributes to all three $K^0\pi^\pm$, $K^\pm\pi^0$, and $K^\pm\pi^+\pi^-$ final states and $(K\pi)_0^{*\pm}$ contributes to two $K\pi$ final states in this analysis, we consider the total $\mathcal{L}$ as a product of three likelihoods constructed for each of the three channels. The corresponding yields in different channels are related by the relative efficiency. We

TABLE I. Results: the reconstruction efficiency $\varepsilon_{\rm reco}$; the total efficiency ε, including the daughter branching fractions [4]; the number of signal events $n_{\rm sig}$; significance $\mathcal{S}$; fraction of longitudinal polarization f_L; the branching fraction $\mathcal{B}$; and the flavor asymmetry $\mathcal{A}_{CP}$. The branching fraction $\mathcal{B}[B^\pm \to \varphi(K\pi)_0^{*\pm}]$ refers to the coherent sum $|A_{\rm res} + A_{\rm nonres}|^2$ of resonant and nonresonant $J^P = 0^+ K\pi$ components [8] and is quoted for $m_{K\pi} < 1.6$ GeV, while the $\mathcal{B}[B^\pm \to \varphi K_0^*(1430)^\pm]$ is derived from it by integrating separately the Breit-Wigner formula of the resonant $|A_{\rm res}|^2$ $K\pi$ component [8] without $m_{K\pi}$ restriction. When several subchannels contribute, yield and efficiency are quoted for each subchannel. The 90% confidence level upper limit on $\mathcal{B}$ is quoted with the central values and errors in parentheses. The $\varphi K_2(1770)^\pm$ yield is not considered in the nominal fit. The systematic errors are quoted last. Two interference parameters δ_0 and $\Delta\delta_0$ are quote for $\varphi K_2^*(1430)^\pm$ and $\varphi(K\pi)_0^{*\pm}$.

Mode	$\varepsilon_{\rm reco}$ (%)	ε (%)	$n_{\rm sig}$ (events)	$\mathcal{S}$ (σ)	f_L	$\mathcal{B}$ (10^{-6})	$\mathcal{A}_{CP}$
$\varphi K_1(1270)^\pm$	25.4 ± 1.4	4.07 ± 0.51	$116 \pm 26^{+15}_{-14}$	5.0	$0.46^{+0.12+0.06}_{-0.13-0.07}$	$6.1 \pm 1.6 \pm 1.1$	$+0.15 \pm 0.19 \pm 0.05$
$\varphi K_1(1400)^\pm$	24.6 ± 1.3	5.19 ± 0.44	$7 \pm 39 \pm 18$	0.2		<3.2 $(0.3 \pm 1.6 \pm 0.7)$	
$\varphi K_2^*(1430)^\pm$		3.34 ± 0.14	$130 \pm 27 \pm 14$	5.5	$0.80^{+0.09}_{-0.10} \pm 0.03$	$8.4 \pm 1.8 \pm 1.0$	$-0.23 \pm 0.19 \pm 0.06$
$\to K_S^0\pi^\pm$	11.9 ± 0.6	0.64 ± 0.04	$27 \pm 6 \pm 3$				
$\to K^\pm\pi^0$	12.2 ± 0.7	1.00 ± 0.06	$39 \pm 8 \pm 4$	$\delta_0 = 3.59 \pm 0.19 \pm 0.12$[a]		$\Delta\delta_0 = -0.05 \pm 0.19 \pm 0.06$[a]	
$\to K^\pm\pi^+\pi^-$	24.7 ± 1.3	1.68 ± 0.12	$64 \pm 14 \pm 7$				
$\varphi(K\pi)_0^{*\pm}$		3.33 ± 0.13	$128 \pm 21 \pm 12$	8.2		$8.3 \pm 1.4 \pm 0.8$	$+0.04 \pm 0.15 \pm 0.04$
$\to K_S^0\pi^\pm$	10.9 ± 0.6	1.24 ± 0.07	$48 \pm 8 \pm 4$				
$\to K^\pm\pi^0$	12.8 ± 0.7	2.09 ± 0.12	$80 \pm 13 \pm 8$				
$\varphi K_0^*(1430)^\pm$						$7.0 \pm 1.3 \pm 0.9$	
$\varphi K^*(1410)^\pm$	28.0 ± 2.2	5.71 ± 0.44	$64 \pm 31^{+20}_{-31}$	<2		<4.3 $(2.4 \pm 1.2^{+0.8}_{-1.2})$	
$\varphi K_2(1770)^\pm$	20.8 ± 1.4	2.27 ± 0.16	$(90 \pm 32^{+39}_{-46})$[b]	<2		<15.0	
$\varphi K_2(1820)^\pm$	21.6 ± 1.5	2.35 ± 0.18	$122 \pm 40^{+26}_{-83}$	<2		<16.3	

[a] Two interference parameters δ_0 and $\Delta\delta_0$ for $\varphi K_2^*(1430)^\pm$ and $\varphi(K\pi)_0^{*\pm}$.

[b] The value is obtained with the $\varphi K_2(1820)^\pm$ yield constrained to zero.

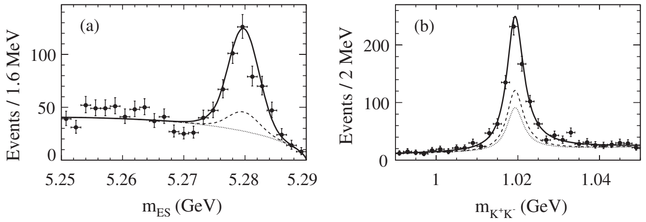

FIG. 1. Projections onto the variables m_{ES} (a) and $m_{K\bar{K}}$ (b) for the signal $B^+ \to \varphi(K\pi)$ and $B^+ \to \varphi(K\pi\pi)$ candidates. Data distributions are shown with a requirement on the signal-to-background probability ratio calculated with the plotted variable excluded. The solid (dotted) lines show the signal-plus-background (combinatorial background) PDF projections, while the dashed lines show the full PDF projections excluding the signal.

fit the yields in each charge category k independently and report them in the form of the total yield $n_j = n_j^+ + n_j^-$ and direct-CP asymmetry $\mathcal{A}_{CP} = (n_j^+ - n_j^-)/n_j$.

The combinatorial background PDF is the product of the PDFs for independent variables and is found to describe well both the dominant quark-antiquark background and the background from random combinations of B tracks. We use polynomials for the PDFs, except for m_{ES} and $\mathcal{F}$ distributions which are parametrized by an empirical phase-space function and by Gaussian functions, respectively. Resonance production occurs in the background and is taken into account in the PDF.

We observe nonzero $B^\pm \to \varphi K_1(1270)^\pm$ and $B^\pm \to \varphi K_2^*(1430)^\pm$ yields with significance (excluding systematic uncertainties in parentheses) of $5.0(5.3)\sigma$ and $5.5(6.0)\sigma$, respectively. The combined $\varphi K_1(1270)^\pm$ and $\varphi K_1(1400)^\pm$ significance is $5.7(6.4)\sigma$. The significance is defined as the square root of the change in $2\ln\mathcal{L}$ when the yield is constrained to zero in the likelihood $\mathcal{L}$. We have tested this procedure with the generated MC samples and account for a small observed deviation from the one-dimensional χ^2 statistical treatment.

In Table I, results of the fit are presented, where the combined results are obtained from the simultaneous fit to the three decay subchannels. In the branching fraction calculations we assume $K_2 \to K_2^*(1430)\pi$ and $\mathcal{B}[K^*(1410) \to K^*\pi] = 0.934 \pm 0.013$ [4]. The signal is illustrated in the projection plots in Figs. 1 and 2, where in the latter we enhance either the $\varphi K_1(1270)^\pm$ signal (left) or the $\varphi K_2^*(1430)^\pm$ signal (right). The nonresonant K^+K^- contribution under the φ is accounted for with the $B^0 \to f_0 K_1$ category, and its yield 7 ± 16 is consistent with zero. Similarly, the nonresonant category $\varphi K\pi\pi$ yield is 148 ± 54 with statistical errors only.

We vary those parameters in $\boldsymbol{\xi}$ not used to model combinatorial background within their uncertainties and derive the associated systematic errors. Interference between the $K_1(1270)^\pm$ and $K_1(1400)^\pm$ is one of the dominant systematic uncertainties on both yields and is modeled with simulated samples. We take the flavor-dependent reconstruction efficiency into account in the study of asymmetries. The biases from the finite resolution of the angle measurement, the dilution due to the presence of false combinations, and other imperfections in the signal PDF model are estimated with MC simulation. Additional systematic uncertainty originates from possible B background, where we estimate from MC simulation that only a few events can fall in the signal region.

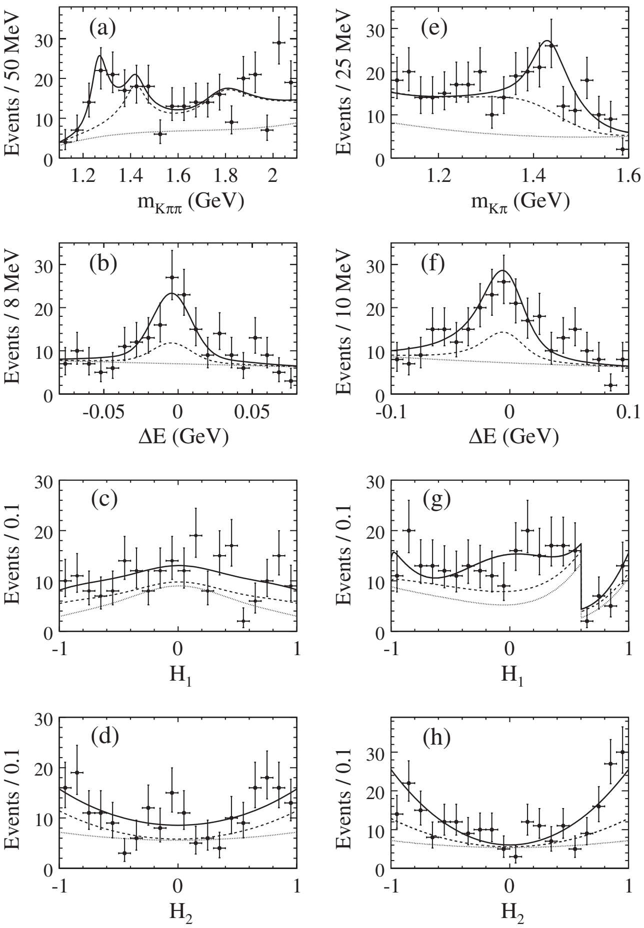

FIG. 2. Left column: Projections onto the variables $m_{K\pi\pi}$ (a), ΔE (b), $\mathcal{H}_1$ (c), and $\mathcal{H}_2$ (d) for the signal $\varphi K_1(1270)^\pm$ candidate. Right column: Projections onto the variables $m_{K\pi}$ (e), ΔE (f), $\mathcal{H}_1$ (g), and $\mathcal{H}_2$ (h) for the signal $\varphi K_2^*(1430)^\pm$ and $\varphi(K\pi)_0^{*\pm}$ candidates combined. The step in (g) is due to selection requirement $\mathcal{H}_1 < 0.6$ in the channel with π^0. Data distributions are shown with a requirement on the signal-to-background probability ratio calculated with the plotted variable excluded. The solid (dotted) lines show the signal-plus-background (combinatorial background) PDF projections, while the dashed lines show the full PDF projections excluding $\varphi K_1^\pm$ (left) or $\varphi K_2^*(1430)^\pm$ (right).

The $\varphi K_2(1770)^\pm$ yield is not considered in the nominal fit due to large correlation with $\varphi K_2(1820)^\pm$. But we substitute the $K_2(1820)$ resonance for the $K_2(1770)$ resonance and find consistent results. The difference is accounted as a systematics uncertainty, while the yield of decay $B^{\pm} \to \varphi K_2(1770)^{\pm}$ is used to obtain its branching fraction. We quote only upper limits on the two branching fractions as their correlation is not accounted for in the central values. For the φK_2 and $\varphi K^*(1410)$ decays, we vary the longitudinal polarization fraction between 0.5 and 0.93, and constrain it to 0.8 in the nominal fit. Polarization variations are included in the branching fraction calculations. We vary the kinematic parameter describing $K_J^{\pm} \to K^{\pm}\pi^+\pi^-$ decay (r_{02} in Ref. [10]) for various partial waves of the quasi-two-body K_2 decay channels and take the largest variations as the systematic uncertainties. The systematic uncertainties in efficiencies are dominated by those in particle identification, track finding, and K_S^0 and π^0 selection. Other systematic effects arise from event-selection criteria, φ and $K_J^{(*)}$ branching fractions, and the number of B mesons.

In summary, we have performed an amplitude analysis and searched for CP violation with the $B^{\pm} \to \varphi K_J^{(*)\pm}$ decays which include significant $K_1(1270)$ and $K_2^*(1430)$ contributions. Our results are summarized in Table I. The polarization measurement in the vector-tensor $B^{\pm}$ decay is consistent with our earlier measurement in the $B^0 \to \varphi K_2^*(1430)^0$ decay [1] and with the naive expectation of the longitudinal polarization dominance. However, our first measurement of polarization in a vector–axial-vector B meson decay indicates a large fraction of transverse amplitude, similar to polarization observed in the vector-vector final state $B \to \varphi K^*(892)$ [1,2]. Both measurements indicate substantial A_{1+1} (or still possible A_{1-1} for vector--axial-vector decay) amplitude from an uncertain source. Among potential sources are penguin annihilation, electroweak penguin contributions, QCD scattering, or physics beyond the standard model [3].

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