

Newly observed $\kappa(2600)$ and the highly excited states of the K_0^* family

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We conducted a study using the modified Godfrey-Isgur quark model and quark pair creation model to investigate the spectrum and two-body strong decays of the newly discovered $\kappa(2600)$ resonance by the LHCb collaboration. Our analysis revealed that this resonance can be assigned as the fourth radial excitation within the 0^+ light strange meson family. Furthermore, we predicted additional radial excitations in this meson family and systematically discussed their spectra, decay behaviors, and branching ratios. These results provide critical guidance for future to identify their signatures in experiments.

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I. INTRODUCTION

Recently, the LHCb Collaboration reported the discovery of a new resonance $\kappa(2600)$ [or named $K_0^*(2600)$] in the further states of Particle Data Group (PDG) [1] in the $B^+ \rightarrow (K_S^0 K \pi) K^+$ decay channel, with a statistical significance of 26.6σ , by analyzing the invariant mass spectrum of $K\pi$. The new resonance has a mass of $2662 \pm 59 \pm 201$ MeV (the natural unit system is adopted in this work, where the speed of light $c = 1$, and all mass units in the following text are expressed in MeV) and a width of $480 \pm 47 \pm 72$ MeV, respectively [2]. This discovery intrigued us to investigate whether the $\kappa(2600)$ could belong to the $J^P = 0^+ K$ mesons family.

P -wave K mesons have three J numbers under the coupling of spin and orbital angular momentum, $^{2S+1}L_J = ^1P_1$, 3P_0 , and 3P_2 . Li *et al.* discussed a new structure $X(2085)$ in $J^P = 1^+ K$ meson family, and investigated the other members of this meson family [3]. In our previous work, we studied the K_2^* meson family, especially the $K_2^*(1980)$ [4]. For the low-lying excited states of 0^+ light strange meson family, $K_0^*(1430)$ is the ground state, and $K_0^*(1950)$ can be its first excited state [5,6]. For the lowest scalar $\kappa(700)$, it is widely believed that it may be an

exotic state [7–12]. Wang *et al.* identify that $K_0^*(2130)$ can be assigned as the second excited state of 0^+ light strange meson family [13]. In Ref. [13], the predicted mass and width of the $K_0^*(4P)$ state are 2404 and 180 MeV, respectively, whereas its mass was 2424 MeV in our previous work [6]. It is obvious that $\kappa(2600)$ could not be $K_0^*(4P)$ state. The internal structure of this state, as well as the nature of the highly excited states of the 0^+ light strange meson family, becomes an interesting issue.

Regge trajectories are an efficient method for investigating the spectrum of meson families [14,15]. The following relation holds for the masses and radial quantum numbers of mesons within the same meson family

$$M^2 = M_0^2 + (n-1)\mu^2, \quad (1.1)$$

where M_0 denotes the mass of the ground state, n represents the radial quantum number of the corresponding meson with the mass M , and μ^2 is the trajectory slope. For the K_0^* family, we adopt $\mu^2 = 1.287 \text{ GeV}^2$ as depicted in Fig. 1.

By analyzing the Regge trajectory, the results demonstrate that $K_0^*(1430)$, $K_0^*(1950)$, and $K_0^*(2130)$ are the $1P$, $2P$, and $3P$ states, respectively. The newly observed state, $\kappa(2600)$ can be a good candidate for the fourth radially excited state of $K_0^*(1430)$. The $K_0^*(4P)$ is still misty. The mass of $K_0^*(4P)$ given by the modified Godfrey-Isgur (MGI) model is consistent with the value from the Regge trajectory and the mass of $K_0^*(6P)$ provided by the MGI model is slightly smaller than that given by the Regge trajectory.

Both mass spectral analysis and two-body strong decay calculations provide effective approaches to probe the internal structure of mesons. Via the simple mass analysis,

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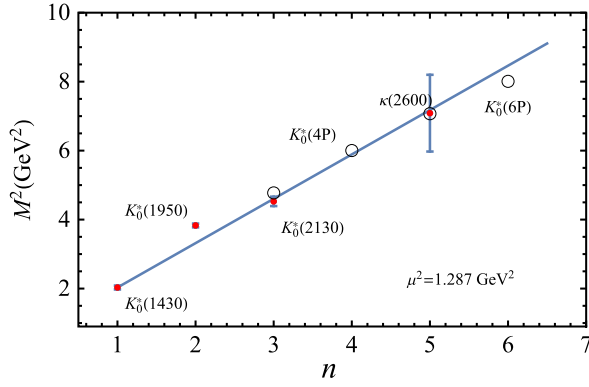


FIG. 1. The Regge trajectories for the K_0^* family. Here, open circles represent theoretical values (obtained with the modified Godfrey-Isgur model), and filled geometries indicate experimental measurements [1]. The radial quantum number, denoted by n , corresponds to the meson in question.

we find that $\kappa(2600)$ can be arranged as the fourth radially excited state of $K_0^*(1430)$. This preliminary conclusion needs to be substantiated with more quantitative analysis. We will study the mass spectra of the 0^+ light strange meson family using the MGI model. In 1985, Godfrey and Isgur proposed the Godfrey-Isgur (GI) quark model for describing relativistic meson spectra with great success, exactly for low-lying mesons [16], and for excited states, the screened potential must be taken into account for coupled-channel effects [17–24]. We also study the two-body strong decays of the 0^+ light strange meson family through the quark pair creation model (QPC model, also known as 3P_0 model) which was initially formulated by Micu [25] and is widely applied to the Okubo-Zweig-Iizuka (OZI)-allowed two-body strong decays of mesons in Refs. [4,6,20–24,26–46].

The paper is organized as follows: In Sec. II, we briefly review the Regge trajectory, the MGI model, and the 3P_0 model. In Sec. III, the obtained masses of the K_0^* family are presented and compared with available experimental data and other results from different models. Then, we systematically study the OZI-allowed two-body strong decay behaviors of the newly observed $\kappa(2600)$ and predicted states $K_0^*(4P)$ and $K_0^*(6P)$. Finally, a conclusion is given in Sec. IV.

II. MODELS EMPLOYED IN THIS WORK

In this work, we employ two models, the MGI model and the QPC model, which will be introduced in this section. Taking the process $K_0^*(2P) \rightarrow K^*\phi$ as an example, the parameter dependence in the QPC model will be analyzed.

A. The modified GI model

In 1985, Godfrey and Isgur proposed the GI quark model for describing relativistic meson spectra with great success, especially for low-lying mesons [16]. To describe the excited states well, the screened potential term has been introduced [17–24]. Then, Song *et al.* proposed the MGI

model [47] based on the GI model. And it has achieved great success in calculating light meson spectroscopy [20–24]. In the MGI model, the Hamiltonian reads

$$\tilde{H} = \sum_i (m_i^2 + \mathbf{p}_i^2)^{1/2} + \tilde{V}^{\text{eff}}, \quad (2.1)$$

where m_i denotes the mass of the quark or antiquark. The masses adopted here are $m_s = 0.377$ GeV and $m_{u(d)} = 0.162$ GeV, which are smaller than those in the GI model [$m_s = 0.419$ GeV, $m_{u(d)} = 0.22$ GeV] [16], and $\tilde{V}^{\text{eff}}$ includes short-range $\gamma^\mu \otimes \gamma_\mu$ one-gluon-exchange interaction and $1 \otimes 1$ linear confinement interaction between q and $\bar{q}$, which is given by

$$\tilde{V}^{\text{eff}} = \tilde{G}_{12} + \tilde{V}^{\text{cont}} + \tilde{V}^{\text{tens}} + \tilde{V}^{\text{so(v)}} + \tilde{S}_{12}(r) + \tilde{V}^{\text{so(s)}}, \quad (2.2)$$

where $\tilde{G}_{12}$, $\tilde{V}^{\text{cont}}$, $\tilde{V}^{\text{tens}}$, $\tilde{V}^{\text{so(v)}}$, $\tilde{S}_{12}(r)$, and $\tilde{V}^{\text{so(s)}}$ are the Coulomb potential term, the contact potential term, the tensor potential term, the vector spin-orbit potential term, the screened confinement potential term and the scalar spin-orbit interaction term, respectively.

The spin-independent potential terms of the nonrelativistic potential read

$$\tilde{G}(r) = -\sum_k \frac{4\alpha_k}{3r} \left[\frac{2}{\sqrt{\pi}} \int_0^{\gamma_k r} e^{-x^2} dx \right], \quad (2.3)$$

where $\alpha_k = (0.25, 0.15, 0.2)$ and $\gamma_k = (1/2 \text{ GeV}, \sqrt{10}/2 \text{ GeV}, \sqrt{1000}/2 \text{ GeV})$ for $k = 1, 2, 3$ [16], and

$$S(r) = \frac{b(1 - e^{-\mu r})}{\mu} + c, \quad (2.4)$$

where $\mu = 0.0779$ GeV is the screening parameter given by our previous work [48] and listed in Table I. This parameter characterizes the strength of the color screening effect, which is absent in the GI model and also represents an improvement of the MGI model over the GI model [16]. The color screening effect leads to a significant suppression of highly excited states' masses compared to the GI model [16]. And b is the confining parameter, while c is the vacuum constant. As shown in Table I, since the quark masses adopted in the MGI model of this work are all smaller than those in the GI model, the energy density b of the interquark string must be increased to fit the mass spectrum, and the vacuum constant is also raised accordingly. Here $b = 0.222$ GeV 2 and $c = -0.228$ GeV, which are taken from Ref. [48].

The effective potential $\tilde{V}^{\text{eff}}$ considers relativistic effects, particularly in meson systems, which are embedded in two ways. First, a smearing function for a meson $q\bar{q}$ is introduced, which has the form

TABLE I. The value of γ in the QPC model and the parameters of the MGI model, which are all taken from Ref. [48]. The parameter γ characterizes the strength of quark-pair creation in the QPC model. $m_{u(d)}$ and m_s are the masses of the $u(d)$ and s quarks (or antiquarks), μ is the screening parameter, b is the confining parameter, while c is the vacuum constant. σ_0 is a universal parameter in Eq. (2.6), and s is a parameter related to heavy quarkonium masses. ϵ_c , ϵ_t , $\epsilon_{so(v)}$, and $\epsilon_{so(s)}$ represent the relativistic corrections to the potential terms $\tilde{V}^{\text{cont}}$, $\tilde{V}^{\text{tens}}$, $\tilde{V}^{\text{so}(v)}$, and $\tilde{V}^{\text{so}(s)}$, respectively.

Parameter	Value	Parameter	Value
γ	10.16	σ_0 (GeV)	1.791
$m_{u(d)}$ (GeV)	0.162	s	0.711
m_s (GeV)	0.377	μ (GeV)	0.0779
b (GeV ²)	0.222	c (GeV)	-0.228
ϵ_c	-0.137	$\epsilon_{so(v)}$	0.0550
$\epsilon_{so(s)}$	0.366	ϵ_t	0.493

$$\rho_{ij}(\mathbf{r} - \mathbf{r}') = \frac{\sigma_{ij}^3}{\pi^{3/2}} e^{-\sigma_{ij}^2(\mathbf{r}-\mathbf{r}')^2}, \quad (2.5)$$

with

$$\sigma_{ij}^2 = \sigma_0^2 \left[\frac{1}{2} + \frac{1}{2} \left(\frac{4m_i m_j}{(m_i + m_j)^2} \right)^4 \right] + s^2 \left(\frac{2m_i m_j}{m_i + m_j} \right)^2, \quad (2.6)$$

where $\sigma_0 = 1.791$ GeV is a universal parameter in Eq. (2.6), and $s = 0.711$ is a parameter related to heavy quarkonium masses. Both the above two parameter values shown in Table I are taken from Ref. [48]. The Coulomb term $\tilde{G}_{12}(r)$ is defined as

$$\tilde{G}_{ij}(r) = \int d^3\mathbf{r}' \rho_{ij}(\mathbf{r} - \mathbf{r}') G(r') = \sum_k -\frac{4\alpha_k}{3r} \text{erf}(\tau_{kij} r), \quad (2.7)$$

where the values of τ_{kij} read

$$\tau_{kij} = \frac{1}{\sqrt{\frac{1}{\sigma_{ij}^2} + \frac{1}{\gamma_k^2}}}. \quad (2.8)$$

The potential $\tilde{S}_{12}(r)$ can be expressed as

$$\begin{aligned} \tilde{S}_{12}(r) = & \int d^3\mathbf{r}' \rho_{12}(\mathbf{r} - \mathbf{r}') S(r') \\ = & \frac{b}{\mu r} \left[r + e^{\frac{\mu^2}{4\sigma^2} + \mu r} \frac{\mu + 2r\sigma^2}{2\sigma^2} \left(\frac{1}{\sqrt{\pi}} \int_0^{\frac{\mu+2r\sigma^2}{2\sigma}} e^{-x^2} dx - \frac{1}{2} \right) \right. \\ & \left. - e^{\frac{\mu^2}{4\sigma^2} - \mu r} \frac{\mu - 2r\sigma^2}{2\sigma^2} \left(\frac{1}{\sqrt{\pi}} \int_0^{\frac{\mu-2r\sigma^2}{2\sigma}} e^{-x^2} dx - \frac{1}{2} \right) \right] + c. \end{aligned}$$

Second, due to relativistic effects, the general potential should depend on the mass of the interacting quarks. Momentum-dependent factors, which are unity in the nonrelativistic limit, are applied as

$$\tilde{G}_{12}(r) \rightarrow \tilde{G}_{12} = \left(1 + \frac{\mathbf{p}^2}{E_1 E_2} \right)^{1/2} \tilde{G}_{12}(r) \left(1 + \frac{\mathbf{p}^2}{E_1 E_2} \right)^{1/2}. \quad (2.9)$$

The semirelativistic corrections of the spin-dependent terms are written as

$$\tilde{V}_{\alpha\beta}^i(r) \rightarrow \tilde{V}_{\alpha\beta}^i = \left(\frac{m_\alpha m_\beta}{E_\alpha E_\beta} \right)^{1/2 + \epsilon_i} \tilde{V}_{\alpha\beta}^i(r) \left(\frac{m_\alpha m_\beta}{E_\alpha E_\beta} \right)^{1/2 + \epsilon_i}, \quad (2.10)$$

where $\tilde{V}_{\alpha\beta}^i(r)$ denote the contact term, the tensor term, the vector and the scalar spin-orbit terms, and $\epsilon_i = \epsilon_c, \epsilon_t, \epsilon_{so(v)}$, and $\epsilon_{so(s)}$ impacts the potentials $\tilde{V}^{\text{cont}}$, $\tilde{V}^{\text{tens}}$, $\tilde{V}^{\text{so}(v)}$, and $\tilde{V}^{\text{so}(s)}$, respectively [22]. These relativistic correction parameters are larger than their counterparts in the GI model, which may also lead to more significant differences in the wave functions for meson masses involving spin-spin and spin-orbit couplings. They have the following forms

$$\tilde{V}^{\text{cont}} = \frac{2\mathbf{S}_1 \cdot \mathbf{S}_2}{3m_1 m_2} \nabla^2 \tilde{G}_{12}^c, \quad (2.11)$$

$$\tilde{V}^{\text{tens}} = - \left(\frac{3\mathbf{S}_1 \cdot \mathbf{r} \mathbf{S}_2 \cdot \mathbf{r} / r^2 - \mathbf{S}_1 \cdot \mathbf{S}_2}{3m_1 m_2} \right) \left(\frac{\partial^2}{\partial r^2} - \frac{1}{r} \frac{\partial}{\partial r} \right) \tilde{G}_{12}^t, \quad (2.12)$$

$$\begin{aligned} \tilde{V}^{\text{so}(v)} = & \frac{\mathbf{S}_1 \cdot \mathbf{L}}{2m_1^2} \frac{1}{r} \frac{\partial \tilde{G}_{11}^{\text{so}(v)}}{\partial r} + \frac{\mathbf{S}_2 \cdot \mathbf{L}}{2m_2^2} \frac{1}{r} \frac{\partial \tilde{G}_{22}^{\text{so}(v)}}{\partial r} \\ & + \frac{(\mathbf{S}_1 + \mathbf{S}_2) \cdot \mathbf{L}}{m_1 m_2} \frac{1}{r} \frac{\partial \tilde{G}_{12}^{\text{so}(v)}}{\partial r}, \end{aligned} \quad (2.13)$$

$$\tilde{V}^{\text{so}(s)} = - \frac{\mathbf{S}_1 \cdot \mathbf{L}}{2m_1^2} \frac{1}{r} \frac{\partial \tilde{S}_{11}^{\text{so}(s)}}{\partial r} - \frac{\mathbf{S}_2 \cdot \mathbf{L}}{2m_2^2} \frac{1}{r} \frac{\partial \tilde{S}_{22}^{\text{so}(s)}}{\partial r}. \quad (2.14)$$

The Hamiltonian matrix in Eq. (2.1) is diagonalized using the simple harmonic oscillator (SHO) base, whose functional form is given by

$$\psi_{nLM_L}^{\text{SHO}}(\mathbf{p}) = R_{nL}^{\text{SHO}}(p, \beta) Y_{LM_L}(\mathbf{\Omega}_p), \quad (2.15)$$

with

$$\begin{aligned} R_{nL}^{\text{SHO}}(p, \beta) = & \frac{(-1)^{(n-1)} (-i)^L}{\beta^{3/2}} N_{nL} e^{-\frac{p^2}{2\beta^2}} \left(\frac{p}{\beta} \right)^L \\ & \times L_{n-1}^{L+1/2} \left(\frac{p^2}{\beta^2} \right), \end{aligned} \quad (2.16)$$

TABLE II. The mass spectra of n^3P_0 states. The unit of mass is MeV.

$n^{2s+1}L_J$	State	This work	GI [16]	Ebert [49]	Expt. [1]
1^3P_0	$K_0^*(1430)$	1284	1233	1362	1425 ± 50 [1]
2^3P_0	$K_0^*(1950)$	1829	1890	1791	1957 ± 14 [1]
3^3P_0	$K_0^*(2130)$	2185	2356	2160	$2128 \pm 31 \pm 9$ [50]
4^3P_0	$K_0^*(4P)$	2451	2749	...	...
5^3P_0	$K_0^*(5P)$	2659	3092	...	$2662 \pm 59 \pm 201$ [2]
6^3P_0	$K_0^*(6P)$	2832	3404	...	...

$$N_{nL} = \sqrt{\frac{2n!}{\Gamma(n+L+1/2)}}, \quad (2.17)$$

where $Y_{LM_L}(\Omega)$ is a spherical harmonic function, $L_{n-1}^{L+1/2}(x)$ is the associated Laguerre polynomial and $\Gamma(n+L+1/2)$ is the gamma function. Then the mass spectra of 0^+ light strange meson family can be obtained, which are listed in Table II. The spatial wave function of the mesons can be expressed as

$$R_{nL}(p) = \sum_{n=1}^{n_{\max}} C_n R_{nL}^{\text{SHO}}(p, \beta). \quad (2.18)$$

Then the SHO wave function depends only on a single parameter: the harmonic oscillator scale β . If a wave function is expanded in a complete set of SHO basis

functions, then in principle, the solution of the potential model should be independent of the oscillator parameter β . However, in practical calculations, the number of basis functions used in the expansion is limited, which necessitates choosing an appropriate value for the parameter β . An effective method for selecting the parameter β is to choose the value that minimizes the eigenvalue E_{nL} , i.e., $(\frac{\partial E_{nL}}{\partial \beta_i} = 0, \frac{\partial^2 E_{nL}}{\partial \beta_i^2} > 0)$, where i denotes different light mesons.

In this work, we set $n_{\max} = 21$. For the mesons $K_0^*(2P)(K_0^*(1950))$, $K_0^*(4P)$, $K_0^*(5P)(\kappa(2600))$, and $K_0^*(6P)$, the corresponding β values take 0.475, 0.328, 0.301, and 0.258 GeV, respectively. The β values for the other mesons mentioned in this work are listed in Table III and the expansion coefficients C_n of $K_0^*(2P)$, $K_0^*(4P)$, $K_0^*(5P)$, $K_0^*(6P)$, K^* , and ϕ are listed in Table IV.

We give the model dependence of the radial wave functions' shapes of $K_0^*(4P)$, $K_0^*(5P)$, and $K_0^*(6P)$

TABLE III. The β values in Eq. (2.18), the masses of the missing states, as well as some flavor mixing angles or spin mixing angles for each state of the light mesons mentioned in this work. The particles ω , ρ , η' , ϕ , b_1 , h_1 , h'_1 , a_0 , a_1 , a_2 , f_1 , K^* , K_1 , K'_1 , and K_2^* correspond to the mesons $\omega(783)$, $\rho(770)$, $\eta'(958)$, $\phi(1020)$, $b_1(1235)$, $h_1(1170)$, $h_1(1380)$, $a_0(1450)$, $a_1(1260)$, $a_2(1320)$, $f_1(1285)$, $K^*(892)$, $K_1(1270)$, $K_1(1400)$, and $K_2^*(1430)$, respectively. $\eta(4S)$, $K_1(2P)$, $K_1(3P)$, $\pi(4S)$, and so on, represent the states that exist theoretically but have not yet been observed experimentally in Table VI, and their masses are calculated via the MGI model. $\beta(\text{Component})$ represents the β value of the component of the meson. For example, $[646(n\bar{n} * \cos(-39.3^\circ)), 781(s\bar{s} * \sin(-39.3^\circ))]$ represents the flavor wave function of η , which is $(n\bar{n} * \cos(-39.3^\circ)) + (s\bar{s} * \sin(-39.3^\circ))$, the β value of the spatial wave function of $n\bar{n}$ ($(u\bar{u} + d\bar{d})/\sqrt{2}$) component is 646 MeV, and the β value of the spatial wave function of $s\bar{s}$ component is 781 MeV. The units of mass and β are MeV.

State(Mass)	β	State(Mass)	β (Component)	State(Mass)	β	State(Mass)	β (Component)
K^*	373	η [51]	646($n\bar{n} * \cos(-39.3^\circ)$) 781($s\bar{s} * \sin(-39.3^\circ)$)	$K_0^*(1430)$	556	η' [51]	646($-n\bar{n} * \sin(-39.3^\circ)$) 781($s\bar{s} * \cos(-39.3^\circ)$)
$K_0^*(2130)$	407	$\eta'(1475)$ [52]	507($-n\bar{n} * \sin(-39.3^\circ)$) 580($s\bar{s} * \cos(-39.3^\circ)$)	a_0	541	$\eta(4S)(2119)$	420($n\bar{n}$)
$a_0(1740)$	475	$K_2(1770)$ [6]	458($1^1D_2 \cos(-39^\circ)$) 427($1^3D_2 \sin(-39^\circ)$)	$\rho_3(1690)$	279	$K_2'(1820)$ [6]	458($-1^1D_2 \sin(-39^\circ)$) 427($1^3D_2 \cos(-39^\circ)$)
π	646	K_1 [53]	566($1^1P_1 \cos(-34^\circ)$) 537($1^3P_1 \sin(-34^\circ)$)	$\pi(1300)$	507	$K_1(2P)(1916)$	434($2^1P_1 \cos(-42^\circ)$) 447($2^3P_1 \sin(-42^\circ)$)
$\pi(1800)$	484	$K_1(3P)(2260)$	410($3^1P_1 \cos(-42^\circ)$) 382($3^3P_1 \sin(-42^\circ)$)	$\pi(4S)(2119)$	363	$K_1(4P)(2517)$	336($4^1P_1 \cos(-43^\circ)$) 328($4^3P_1 \sin(-43^\circ)$)
K	632	K'_1 [53]	566($-1^1P_1 \sin(-34^\circ)$) 537($1^3P_1 \cos(-34^\circ)$)	$K(1460)$	524	$K'_1(2P)(1760)$	434($-2^1P_1 \sin(-42^\circ)$) 447($2^3P_1 \cos(-42^\circ)$)
$K(3S)(1917)$	476	$K'_1(3P)(2111)$	410($-3^1P_1 \sin(-42^\circ)$) 382($3^3P_1 \cos(-42^\circ)$)	$K(4S)(2261)$	380	$K'_1(4P)(2388)$	336($-4^1P_1 \sin(-43^\circ)$) 328($4^3P_1 \cos(-43^\circ)$)

(Table continued)

TABLE III. (Continued)

$K(5S)(2517)$	343	$K'_1(5P)(2608)$	$306(-5^1 P_1 \sin(-44^\circ))$ $295(5^3 P_1 \cos(-44^\circ))$	$\pi_2(1880)$ [49]	336	$K_2(2D)(2165)$	$365(2^1 D_2 \cos(-44^\circ))$ $373(2^3 D_2 \sin(-44^\circ))$
$\pi_2(3D)(2273)$	317	$K'_2(2D)(2074)$	$365(-2^1 D_2 \sin(-44^\circ))$ $373(2^3 D_2 \cos(-44^\circ))$	$\rho_2(1D)(1644)$	411	$K'_2(3D)(2355)$	$339(-3^1 D_2 \sin(-44^\circ))$ $338(3^3 D_2 \cos(-44^\circ))$
$\rho_2(2D)(2001)$	343	$K_2(4D)(2580)$	$293(4^1 D_2 \cos(-45^\circ))$ $290(4^3 D_2 \sin(-45^\circ))$	ρ	303	$K_3(1F)(2028)$	$368(1^1 F_3 \cos(-44^\circ))$ $410(1^3 F_3 \sin(-44^\circ))$
$K_2^*(1980)$	395	$K_3(3F)(2545)$	$292(1^1 F_3 \cos(-45^\circ))$ $301(1^3 F_3 \sin(-45^\circ))$	$a_3(2030)$ [49]	311	$K'_3(2F)(2312)$	$320(-2^1 F_3 \sin(-44^\circ))$ $316(2^3 F_3 \cos(-44^\circ))$
$\rho(1450)$ [41]	477	$K'_3(3F)(2545)$	$292(-3^1 F_3 \sin(-45^\circ))$ $301(3^3 F_3 \cos(-45^\circ))$	K_2^*	344	$K_4(1G)(2274)$	$315(4^1 D_2 \cos(-45^\circ))$ $337(4^3 D_2 \sin(-45^\circ))$
a_1	475	h_1 [54]	$571(n\bar{n} * \cos(4.4^\circ))$ $631(-s\bar{s} * \sin(4.4^\circ))$	$a_1(1640)$ [55]	416	h'_1 [54]	$571(n\bar{n} * -\sin(4.4^\circ))$ $631(s\bar{s} * \cos(4.4^\circ))$
$a_1(3P)(2065)$	364	$h_1(1595)$ [48]	$404(n\bar{n} * \cos(4.4^\circ))$ $482(-s\bar{s} * \sin(4.4^\circ))$	b_1	571	$h_1(1965)$ [48]	$398(n\bar{n} * \cos(4.4^\circ))$ $445(-s\bar{s} * \sin(4.4^\circ))$
$b_1(2P)(1699)$	404	$h_1(2215)$ [48]	$313(n\bar{n} * \cos(4.4^\circ))$ $368(-s\bar{s} * \sin(4.4^\circ))$	$b_1(1960)$ [55]	398	ω	$303(n\bar{n})$
$b_1(2240)$ [55]	313	$f_3(2050)$ [49]	$311(n\bar{n})$	a_2	293	f_1 [56]	$475(n\bar{n} * \cos(-15.8^\circ))$ $588(s\bar{s} * \sin(-15.8^\circ))$
$a_3(2275)$ [49]	254	f'_1 [56]	$475(-n\bar{n} * \sin(-15^\circ))$ $588(s\bar{s} * \cos(-15^\circ))$	$\rho(1700)$ [41]	484	$f_1(2P)(1717)$	$395(n\bar{n})$
$K^*(1680)$	487	$f'_1(2P)(1739)$	$470(s\bar{s})$	$K^*(3S)$	379	$f_1(3P)(2065)$	$364(n\bar{n})$
$K^*(1410)$	480	$f_2(2P)(1739)$	$373(n\bar{n})$	$a_2(1700)$ [57]	395	ϕ	$488(s\bar{s})$

obtained with the MGI model (MGI wave function) and the GI model (GI wave function) [16] in Fig. 2. The choice of potential model significantly affects the radial spatial wave functions (such as the positions of nodes and the maximum values).

In Fig. 3, we show the β dependence of MGI wave function of $K_0^*(2P)$ and SHO wave function. We can

conclude that the β value (in the range of 0.25–0.6 GeV) has very little influence on the shape of MGI wave function as shown in Fig. 3(a). The wave functions of K^* and ϕ have no node as the ground states. However, it can be seen from Fig. 3(b) that for the SHO wave function of $K_0^*(2P)$, the node positions are sensitive to the value of β .

TABLE IV. The values of C_n ($n = 1 \sim 21$) to reproduce the numerical radial wave functions (obtained with the MGI model) of $K_0^*(2P)$, $K_0^*(4P)$, $K_0^*(5P)$, $K_0^*(6P)$ and the final channel $K^*\phi$ in Figs. 2–4.

C_n	$K_0^*(2P)$	$K_0^*(4P)$	$K_0^*(5P)$	$K_0^*(6P)$	K^*	ϕ
C_1	0.222449	-0.0555655	0.0140115	-0.00276401	0.972251	0.98974
C_2	0.75125	-0.28638	-0.119631	-0.0653887	0.157035	-0.00561464
C_3	-0.353308	0.228128	-0.360601	0.0791252	0.150245	0.135653
C_4	0.388185	0.614452	0.337153	0.502814	0.0582049	0.0117256
C_5	-0.20643	-0.211652	0.402642	-0.156157	0.0492352	0.0379793
C_6	0.193626	0.486748	-0.121086	-0.323823	0.026903	0.00892844
C_7	-0.107969	-0.195027	0.47625	0.107893	0.0216017	0.0144072
C_8	0.0999782	0.303553	-0.205859	-0.476104	0.0142003	0.00574549
C_9	-0.0568647	-0.124537	0.36619	0.172665	0.0110234	0.006496
C_{10}	0.0538771	0.180566	-0.168788	-0.397328	0.0081847	0.00364168
C_{11}	-0.0307483	-0.0719283	0.251402	0.146651	0.0061147	0.00323952
C_{12}	0.0302112	0.107503	-0.117035	-0.286246	0.00503853	0.00235587
C_{13}	-0.0170692	-0.039884	0.166517	0.102934	0.00352374	0.00168728
C_{14}	0.0174768	0.0647301	-0.0759667	-0.194213	0.00329114	0.00158749
C_{15}	-0.00960039	-0.0210649	0.10914	0.0648543	0.0020084	0.000850251
C_{16}	0.0102464	0.0391984	-0.0474513	-0.126728	0.00230035	0.00114293
C_{17}	-0.00529678	-0.00998488	0.0709918	0.0361078	0.00102572	0.000338474
C_{18}	0.00590122	0.0231947	-0.0281582	-0.0782416	0.00175917	0.000906316
C_{19}	-0.00265197	-0.00304648	0.0448996	0.0147282	0.000307947	-0.0000173967
C_{20}	0.00305022	0.0121834	-0.0143011	-0.0413795	0.00147647	0.000784372
C_{21}	-0.000700966	0.00224554	0.0247396	-0.00338177	-0.000177699	-0.00022083

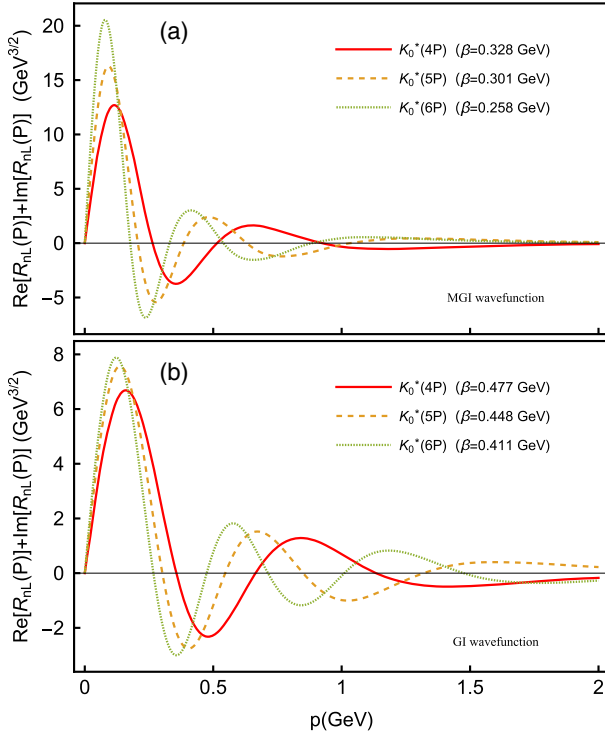


FIG. 2. The model dependence of the radial wave functions' shapes of $K_0^*(4P)$, $K_0^*(5P)$, and $K_0^*(6P)$ derived from (a) the GI potential model (GI wave function); and (b) the MGI potential model (MGI wave function). “Re” and “Im” denote the real part and the imaginary part of the wave functions, respectively.

In the QPC model, the decay width has a strong dependence on the shape of the wave function, because of the node effect [59]. We will discuss this point in the next subsection.

The mass and the spatial wave function of the meson can be obtained by diagonalizing Hamiltonian matrix in Eq. (2.1) and applied to the calculation of the strong decay processes.

B. The QPC model

The QPC model (or 3P_0 model) was initially proposed by Micu [25] and further developed by the Orsay group [60–64]. This model is widely applied to calculate the OZI-allowed two-body strong decays of mesons [4,6,20–24,26–46]. The $\mathcal{T}$ operator describes a quark-antiquark pair (denoted by indices 3 and 4) creation from vacuum, which reads $J^{PC} = 0^{++}$. For the process $A \rightarrow B + C$, $\mathcal{T}$ can be written as

$$\mathcal{T} = -3\gamma \sum_m \langle 1m; 1-m | 00 \rangle \int d\mathbf{p}_3 d\mathbf{p}_4 \delta^3(\mathbf{p}_3 + \mathbf{p}_4) \times \mathcal{Y}_{1m} \left(\frac{\mathbf{p}_3 - \mathbf{p}_4}{2} \right) \chi_{1,-m}^{34} \phi_0^{34}(\omega_0^{34})_{ij} b_{3i}^\dagger(\mathbf{p}_3) d_{4j}^\dagger(\mathbf{p}_4), \quad (2.19)$$

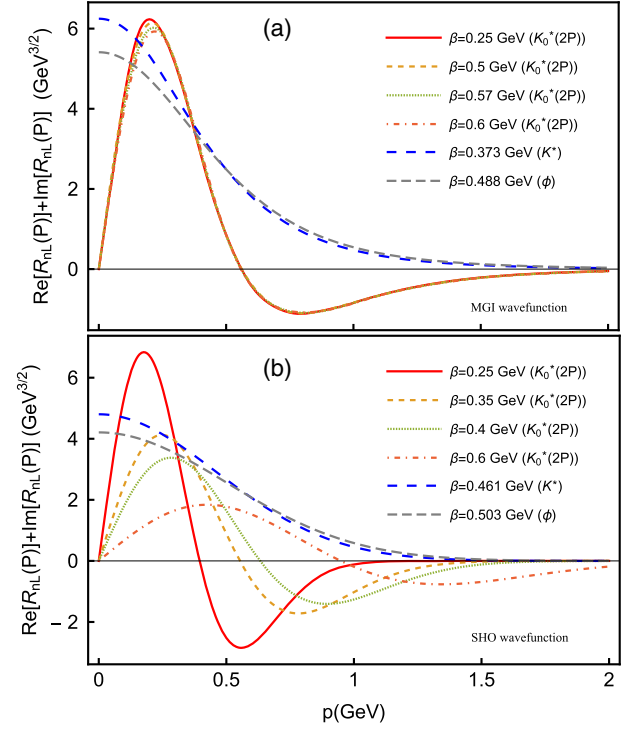


FIG. 3. (a) The β dependence of the radial wave functions' shapes of $K_0^*(2P)$, and the radial wave functions' shapes of K^* and ϕ derived from the MGI model (MGI wave function); (b) The β dependence of the radial wave functions' shapes of $K_0^*(2P)$, and the radial wave functions' shapes of K^* and ϕ from the SHO wave function directly. The β values for the SHO wave functions of K^* and ϕ , referred to as effect β , are calculated based on the MGI wave functions [58]. “Re” and “Im” denote the real part and the imaginary part of the wave functions, respectively.

where the parameter γ in QPC model depicts the strength of $q\bar{q}$ creation from the vacuum. In this work, we adopt the value $\gamma = 10.16$ [48]. The decay width is proportional to γ^2 , whereas the branching ratio typically shows no dependence on this parameter. $\mathcal{Y}_l^m(\mathbf{p}) \equiv p^l Y_l^m(\theta_p, \phi_p)$ is the solid harmonics. χ , ϕ , and ω denote the spin, flavor, and color wave functions respectively. $\mathbf{p}_3$ and $\mathbf{p}_4$ denote the three-momenta of the quark pair created in vacuum. Subindices i and j are the color index of the $q\bar{q}$ pair. The amplitude $\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}$ has the form

$$\langle BC | \mathcal{T} | A \rangle = \delta^3(\mathbf{P}_B + \mathbf{P}_C) \mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}, \quad (2.20)$$

where $\mathbf{P}_B$ and $\mathbf{P}_C$ are the three-momenta of the meson B and the meson C in the rest frame of the meson A, M_{J_X} (with $X = A, B, C$) denotes the magnetic quantum number of the corresponding meson. Finally, the general form of the decay width can be expressed as

$$\Gamma = \frac{\pi |\mathbf{P}|}{4 m_A^2} \sum_{J,L} |\mathcal{M}^{JL}(\mathbf{P})|^2, \quad (2.21)$$

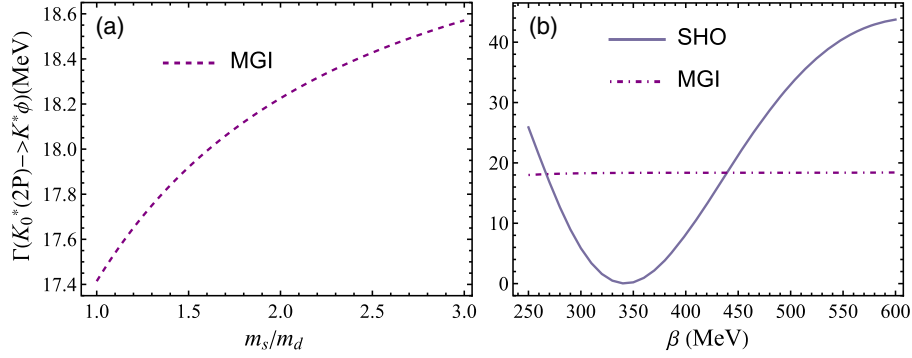


FIG. 4. (a) The m_s/m_d ratio dependence of the decay width of $K_0^*(2P) \rightarrow K^*\phi$ obtained with the MGI wave function. (b) Decay width of $K_0^*(2P) \rightarrow K^*\phi$ as a function of the harmonic oscillator scale β . The solid line and the dashed line represent the widths depending on the β values when we take the SHO wave function and the MGI wave function, respectively, as taken from Fig. 3.

where m_A is the mass of the initial state A , $\mathbf{J} = \mathbf{J}_B + \mathbf{J}_C$, L is the relative orbital angular momentum between the meson B and the meson C , and $\mathbf{P} = \mathbf{P}_B$. The two decay amplitudes can be related by the Jacob-Wick formula [65]

$$\mathcal{M}^{JL}(\mathbf{P}) = \frac{\sqrt{4\pi(2L+1)}}{2J_A+1} \sum_{M_{J_B}M_{J_C}} \langle L0; JM_{J_A} | J_A M_{J_A} \rangle \times \langle J_B M_{J_B}; J_C M_{J_C} | J_A M_{J_A} \rangle \mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}, \quad (2.22)$$

in which

$$\begin{aligned} \mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}} &= \gamma \sum_{\substack{M_{L_A}M_{S_A}M_{L_B} \\ M_{S_B}M_{L_C}M_{S_C}}} m \langle L_A M_{L_A} S_A M_{S_A} | J_A M_{J_A} \rangle \\ &\times \langle L_B M_{L_B} S_B M_{S_B} | J_B M_{J_B} \rangle \langle L_C M_{L_C} S_C M_{S_C} | J_C M_{J_C} \rangle \\ &\times \langle 1m1-m | 00 \rangle \langle \chi_{S_B M_{S_B}}^{14} \chi_{S_C M_{S_C}}^{32} | \chi_{S_A M_{S_A}}^{12} \chi_{1-m}^{34} \rangle \\ &\times [\langle \phi_B^{14} \phi_C^{32} | \phi_A^{12} \phi_0^{34} \rangle I(\mathbf{P}, m_1, m_2, m_3) \\ &+ (-1)^{1+S_A+S_B+S_C+L_C} \langle \phi_B^{32} \phi_C^{14} | \phi_A^{12} \phi_0^{34} \rangle I(-\mathbf{P}, m_2, m_1, m_3)], \end{aligned} \quad (2.23)$$

with

$$\begin{aligned} I(\mathbf{P}, m_1, m_2, m_3) &= \int d^3\mathbf{k} \psi_B^*(\mathbf{k} + U\mathbf{P}) \psi_C^*(\mathbf{k} + V\mathbf{P}) \psi_A(\mathbf{k} - \mathbf{P}) \mathcal{Y}_1^m(\mathbf{k}), \end{aligned} \quad (2.24)$$

here

$$U = \frac{m_3}{m_1 + m_3}, \quad V = \frac{m_3}{m_2 + m_3},$$

m_1 and m_2 are the masses of the quark and the antiquark in meson A , respectively. For the K meson, we take

$m_1 = 0.377$ GeV, $m_2 = 0.162$ GeV. m_3 denotes the mass of the quark (or the antiquark) created from the vacuum, and is set to 0.162 GeV for $u\bar{u}$ or $d\bar{d}$, and 0.377 GeV for $s\bar{s}$. To investigate the quark mass effect on decays, we calculate the decay width of $K_0^*(2P) \rightarrow K^*\phi$ as a function of the ratio m_s/m_d as shown in Fig. 4(a) and find that the decay width is not sensitive to this mass ratio in the range of 1–3.

When we calculate the strong decays of the K_0^* family using QPC model in this work, the spatial wave functions of mesons are obtained using the MGI model (MGI wave function), as introduced in the previous subsection.

As previously discussed, the SHO wave function is characterized by a single scale parameter, β . According to Ref. [59], the node structure of the radial wave function can influence the strong decay width of the process $A \rightarrow BC$, known as the node effect. Specifically, the spatial wave function $R_{nL}(p)$ for the n -th radial excitation contains $(n-1)$ nodes. In Fig. 4(b), we give the line shape of the decay width of $K_0^*(2P) \rightarrow K^*\phi$ depending on the β values. When the SHO wave function is adopted, the decay width exhibits strong β dependence, which is consistent with the conclusions in Ref. [59], as shown in Fig. 4(b). In contrast, when the MGI wave function is used, the width shows virtually no β sensitivity. When employing different potential models (such as the GI model) to derive wave functions, decay widths will also vary even with identical values for other parameters (such as quark masses and γ).

Among the final states, the mixing scheme for natural states ($L = J$) of strange mesons can be expressed as

$$\begin{pmatrix} |K(nL)\rangle \\ |K'(nL)\rangle \end{pmatrix} = \begin{pmatrix} \cos \theta_{nL} & \sin \theta_{nL} \\ -\sin \theta_{nL} & \cos \theta_{nL} \end{pmatrix} \begin{pmatrix} |K(n^1L_L)\rangle \\ |K(n^3L_L)\rangle \end{pmatrix}, \quad (2.25)$$

where θ_{nL} is known as the mixing angle between the $K(n^1L_L)$ and $K(n^3L_L)$ states. In this work, the masses of $K(nL)$ and $K'(nL)$, the mixing angle θ_{nL} for the missing states are also calculated via the MGI model [23] and listed in Table III.

The flavor wave functions of the isoscalar mesons may have the mixing form

$$\begin{pmatrix} X \\ X' \end{pmatrix} = \begin{pmatrix} \cos \phi_x & \sin \phi_x \\ -\sin \phi_x & \cos \phi_x \end{pmatrix} \begin{pmatrix} |n\bar{n}\rangle \\ |s\bar{s}\rangle \end{pmatrix}, \quad (2.26)$$

where X and X' are two isoscalar mesons (such as η and η'), ϕ_x is the mixing angle in the quark flavor scheme, and the flavor $n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}$. We also list the flavor mixing information of the isoscalar mesons appearing in this paper in Table III.

III. MASS SPECTRA AND TWO-BODY STRONG DECAY OF THE HIGHLY EXCITED STATES OF K_0^* FAMILY

In this section, we discuss the mass spectra and two-body strong decay information of the highly excited states of 0^+ strange meson family. We start with the mass spectra.

A. Mass spectra analysis

We employ the MGI model to calculate the mass spectra of 0^+ light strange meson family. The parameters of the MGI model listed in Table I are obtained by fitting the experimental masses of light mesons in our previous work [48]. These parameters are universal and can also be used in the study of masses of other light mesons. Reference [49] calculated the mass spectra of the light mesons within the framework of the relativistic quark model based on the quasipotential approach. This quasipotential model has a similar string tension to the GI model. Experimental values and theoretical results from the GI model, the MGI model (this work) and Ref. [49] are shown in Table II.

According to Table II, for the 1^3P_0 state, our theoretical value of the mass (1284 MeV) remains ~ 140 MeV below experimental value (1425 ± 50) MeV. The GI model [16] predicts 1233 MeV (~ 192 MeV deficit), Ebert's result of 1362 MeV is still ~ 60 MeV lower [49]. We will now focus on discussing the spectra of the highly excited states. Our predictions of 3^3P_0 (2185 MeV) overlap with experimental error bars of $K_0^*(2130)$ (2128 ± 40 MeV), the GI model shows ~ 230 MeV deviation, and Ebert's result of 2160 MeV is also consistent with the experimental value. This result shows that introducing the color screening effect into the GI model can significantly improve the predictive power for the high-excited-state meson spectrum.

For the $K_0^*(4P)$ state, our theoretical mass of 2451 MeV is 300 MeV lower than the value given by the GI model. We predict that $K_0^*(5P)$ has a mass of 2658 MeV, which is in excellent agreement with the experimental central value.

We also calculate the mass of $K_0^*(6P)$ to be 2832 MeV, approaching the mass range of charmed mesons.

Through the analysis of the mass spectrum, we conclude that the newly observed $\kappa(2600)$ meson in experiments is a good candidate for the $K_0^*(5P)$ state. Subsequently, we will

TABLE V. The decay information of $K_0^*(1430)$. The unit of the width is MeV.

Channel	Width	BR	Expt. [1]
$K\pi$	252	0.955	0.93 ± 0.1
ηK	11.1	0.042	$0.086^{+0.037}_{-0.034}$
Total width	264		270 ± 80

further validate this conclusion by investigating its decay width and predicting the two-body strong decay properties of $K_0^*(4P)$ and $K_0^*(6P)$.

B. Strong decay analysis

In this section, we discuss the two-body strong decay of the highly excited states in the K_0^* family. At first, we test our model with the ground state K_0^* . We obtain two decay channels of $K_0^*(1430)$, $K\pi$ and ηK as shown in Table V, in which the decay channels with branching ratios (BR) less than 0.2% are omitted.

The $K\pi$ channel accounts for 95.5% of total width ($\Gamma_{K\pi} = 252$ MeV), consistent with experimental branching ratio 0.93 ± 0.1 . The predicted branching ratio of $\frac{\Gamma_{\eta K}}{\Gamma_{\text{Total}}} = 4.2\%$ is roughly consistent with the experimental value $0.086^{+0.037}_{-0.034}$. The calculated total width $\Gamma_{\text{total}} = 264$ MeV shows excellent agreement with the experimental data 270 ± 80 MeV. These results show that the QPC model can work well for $K_0^*(1430)$, and we expect it to also be suitable for the highly excited states of the K_0^* family.

Table VI provides the two-body strong decay information for the excited kaonic states: $K_0^*(4P)$, $\kappa(2600)(5P)$, and $K_0^*(6P)$. These decays are crucial to understanding the resonance structures.

Reference [13] also calculated the two-body strong decays of K_0^* meson family using the QPC model. In their approach, the wave functions were derived from the GI potential model, with the parameter γ fixed at 0.52. In contrast, the value of γ used in our work differs by a factor of $\sqrt{96\pi}$ [66], which leads to different results for the two-body strong decays of $K_0^*(4P)$. And the different γ value would cause our overall results to be 1.3 times larger than those in Ref. [13].

The primary decay channel of $K_0^*(4P)$ is $K_1\pi$, with a width of about 49 MeV, contributing 10.4% to the total width, which is much larger than the one obtained by Ref. [13]. Other significant decay modes include $\pi K(4S)$ and $K\pi$, which contribute 8.15% and 6.11%, respectively. $K\pi$ will be an ideal final channel to search for the $K_0^*(4P)$ state. $K^*(1410)\rho$ and $\pi K_1(2P)$ also have larger contributions to the total width about 5.7%. $K^*(1410)\rho$ has a width of about 33 MeV in Ref. [13]. Other decay channels with branching ratios less than 5% can be found in Table VI. In the QPC model, the processes $K_0^*(4P) \rightarrow K^*(1410)\omega$ and $K_0^*(4P) \rightarrow K^*(1410)\rho$ share the same initial state $K_0^*(4P)$

TABLE VI. The two-body strong decay information of $K_0^*(4P)$ state, $\kappa(2600)(5P)$ state, and $K_0^*(6P)$ state. The unit of the width is MeV. Channels with branching ratios less than 0.2% are omitted.

$K_0^*(4P)$		
Channel	Width	BR
$K_1\pi$	49.4	0.104
$\pi K(4S)$	38.7	0.0815
$K\pi$	29.1	0.0611
$K^*(1410)\rho$	27.3	0.0575
$\pi K_1(2P)$	27.1	0.057
$K\pi(1300)$	20.8	0.0438
$\pi K(3S)$	19.3	0.0406
$Ka_1(1640)$	19.1	0.0402
$\pi K(1460)$	17.4	0.0367
$K^*\rho$	16	0.0338
Ka_1	14.5	0.0304
$\pi K_2(2D)$	13.6	0.0286
$\pi K_1(3P)$	13.3	0.0281
$K\pi_2(1880)$	13.2	0.0277
$\pi K'_1(3P)$	11.4	0.0239
$Kb_1(2P)$	10.3	0.0217
$h_1(1595)K$	10.3	0.0216
$K^*\rho(1450)$	9.55	0.0201
K^*a_1	9.18	0.0193
$K\pi(1800)$	8.77	0.0185
Kb_1	8.37	0.0176
$\omega K^*(1410)$	8.24	0.0173
$\pi K_3(1F)$	6.02	0.0127
$K'_1\rho$	5.41	0.0114
ωK^*	5.05	0.0106
K^*f_1	4.91	0.0103
h_1K	4.32	0.0091
$\pi K'_2(2D)$	4.11	0.00864
$Kf_1(2P)$	3.35	0.00704
$\eta K(1460)$	3.33	0.00701
$K\rho_2(1D)$	3.26	0.00686
$\pi K'_1(2P)$	3.04	0.00639
$\omega(1420)K^*$	3.01	0.00634
$\eta(1475)K$	2.95	0.00621
$f_1(1420)K$	2.79	0.00587
$K^*f_0(1500)$	2.32	0.00488
ηK_1	2.26	0.00476
$\rho K_0^*(1430)$	2.16	0.00454
ηK	1.94	0.00408
$\omega K'_1$	1.82	0.00383
f_1K	1.77	0.00373
K^*a_2	1.74	0.00367
ρK_2^*	1.3	0.00274
$\eta'K$	1.21	0.00256
$K\omega_2(1D)$	1.09	0.00229
$K^*\phi$	1.06	0.00224
$\eta'K(1460)$	1.02	0.00215
...		
Total width	475	1

(Table continued)

TABLE VI. (Continued)

$\kappa(2600)(5P)$		
Channel	Width	BR
$K_1\pi$	32.4	0.0751
$K^*(1410)\rho$	27.6	0.0639
$\pi K_1(2P)$	20.1	0.0466
$Kb_1(1960)$	18.5	0.0428
$K\pi$	17.1	0.0395
$\pi K_1(3P)$	14.7	0.0341
$\pi K(5S)$	14.5	0.0335
$\pi K_2(2D)$	14.1	0.0327
$Ka_1(1640)$	13.7	0.0318
$K\pi(1300)$	13.1	0.0304
$\pi K(4S)$	13.1	0.0302
$\pi K(1460)$	11.5	0.0265
$\pi K'_1(4P)$	11	0.0254
$K^*a_1(1640)$	10.9	0.0254
$\pi K(3S)$	9.85	0.0228
$K\pi_2(1880)$	9.84	0.0228
$\omega K^*(1410)$	8.66	0.0201
$K\pi(1800)$	8.46	0.0196
Ka_1	7.74	0.0179
$\pi K_3(1F)$	7.24	0.0168
$Kb_1(2P)$	6.89	0.016
$Ka_3(2030)$	6.77	0.0157
$h_1(1595)K$	6.31	0.0146
$K^*\rho$	6.1	0.0141
K_1b_1	6.08	0.0141
K^*a_1	5.25	0.0122
$\pi K'_3(2F)$	4.89	0.0113
$K^*\rho(1450)$	4.44	0.0103
$\pi K'_1(3P)$	4.35	0.0101
$h_1(1965)K$	4.33	0.01
$\pi K'_2(3D)$	4.29	0.00993
$\rho K'_1(2P)$	3.91	0.00905
$K^*(1680)\rho$	3.65	0.00844
K_1h_1	3.56	0.00824
Kb_1	3.49	0.00808
$K'_1\rho$	2.92	0.00676
K^*f_1	2.91	0.00674
$\eta K(1460)$	2.82	0.00652
$Kf_1(2P)$	2.76	0.00638
K_1a_1	2.52	0.00584
$K\rho_2(1D)$	2.1	0.00487
h_1K	2.08	0.00482
$K_1\pi(1300)$	2.06	0.00476
ωK^*	1.91	0.00442
$\eta K(3S)$	1.88	0.00435
$\pi K'_2(2D)$	1.73	0.00401
$Kf_3(2050)$	1.73	0.00401
K^*a_2	1.6	0.0037
$Ka_1(3P)$	1.55	0.00358
K^*a_0	1.54	0.00357
$f_1(1420)K$	1.54	0.00356
$K^*(1410)\phi$	1.44	0.00333
ηK_1	1.42	0.00329

(Table continued)

TABLE VI. (Continued)

$\eta(1295)K_1$	1.42	0.00328
ηK	1.38	0.00319
$\eta(1475)K$	1.37	0.00317
ρK_2^*	1.33	0.00307
$\omega K_1'(2P)$	1.26	0.00291
$K\rho_2(2D)$	1.17	0.00271
$\pi K_1'(2P)$	1.14	0.00263
$\rho K_0^*(1430)$	1.13	0.00261
$\omega K^*(1680)$	1.11	0.00257
$K_1\rho$	1.02	0.00235
$f_1 K$	1.01	0.00234
$\omega K_1'$	0.996	0.00231
$\omega(1420)K^*$	0.982	0.00228
$K^*\rho_2(1D)$	0.956	0.00221
$\rho K_2(1770)$	0.93	0.00215
...		
Total width	432	1

$K_0^*(6P)$		
Channel	Width	BR
$K^*(1410)\rho$	21.6	0.0568
$K_1\pi$	20.8	0.0548
$\pi K_1(2P)$	14.6	0.0384
$Kb_1(1960)$	13.7	0.036
$\pi K_1(3P)$	11.8	0.0312
$\pi K_2(2D)$	11.6	0.0305
$K\pi$	10.8	0.0283
$\pi K(5S)$	9.69	0.0255
$Ka_3(2030)$	9.68	0.0255
$\pi K_1'(5P)$	8.95	0.0236
$K\pi(1300)$	8.87	0.0233
$\pi K_2(4D)$	8.63	0.0227
$\pi K(1460)$	8.16	0.0215
$Ka_1(1640)$	8.13	0.0214
$\pi K_1(4P)$	7.63	0.0201
$\pi K(4S)$	7.39	0.0194
$K\pi(1800)$	7.31	0.0193
$K^*a_1(1640)$	7.29	0.0192
$\pi K_3'(2F)$	7.25	0.0191
$\omega K^*(1410)$	6.87	0.0181
$\pi K_3(1F)$	6.4	0.0169
$K\pi_2(1880)$	6.2	0.0163
$\pi K(3S)$	5.89	0.0155
K_1b_1	5.64	0.0148
$\pi K_1'(4P)$	5.3	0.0139
$K^*(1410)a_1$	4.76	0.0125
$Kb_1(2P)$	4.67	0.0123
$h_1(1595)K$	4.32	0.0114
Ka_1	4.18	0.011
$\pi K_1'(3P)$	2.19	0.00577
K_1h_1	2.17	0.00572
$\eta K(3S)$	2.16	0.00569
$K^*f_1(2P)$	2.09	0.00549
$K^*\rho(1450)$	2.08	0.00548
$\eta K(1460)$	2	0.00526
$K^*\rho_2(1D)$	1.89	0.00498

(Table continued)

TABLE VI. (Continued)

$\rho K^*(3S)$	1.87	0.00493
$h_1(2215)K$	1.76	0.00464
$Kf_1(2P)$	1.68	0.00441
Kb_1	1.66	0.00436
K^*f_1	1.65	0.00434
$K^*a_0(1740)$	1.62	0.00427
$Kb_1(2240)$	1.62	0.00427
$b_1K(1460)$	1.61	0.00423
$K_1'\rho$	1.58	0.00416
$\pi(1300)K(1460)$	1.52	0.004
K^*a_2	1.46	0.00384
$K_1'a_1$	1.44	0.00379
$\rho K_1'(2P)$	1.42	0.00375
$K\rho_2(2D)$	1.42	0.00374
$\pi K_4(1G)$	1.27	0.00334
$\rho K_1(2P)$	1.22	0.00322
$K\pi_2(3D)$	1.2	0.00317
$\rho K_2(1770)$	1.15	0.00303
$\omega K^*(1680)$	1.12	0.00296
ηK_1	1.08	0.00285
K^*a_0	1.08	0.00285
h_1K	1.08	0.00285
$K\eta(4S)$	1.04	0.00274
$K^*(1410)f_1$	1.02	0.0027
$K\rho_2(1D)$	1.02	0.00269
$Kf_1(3P)$	0.939	0.00247
$K^*f_2(2P)$	0.938	0.00247
$f_1(1420)K$	0.934	0.00246
$K_1\rho$	0.927	0.00244
$K^*\rho(1700)$	0.894	0.00235
ρK_2^*	0.887	0.00233
ωK^*	0.885	0.00233
$\pi K_2'(2D)$	0.87	0.00229
ηK	0.832	0.00219
$\eta(1475)K$	0.799	0.0021
$K^*\rho_3(1690)$	0.797	0.0021
$\rho K_2^*(1980)$	0.788	0.00207
...		
Total width	380	1

and the $K^*(1410)$ final-state component. The wave functions of ω and ρ are the same except for the flavor wave functions. Combining the relationship $m_\omega \simeq m_\rho$, their decay outcomes depend on the overlap of the flavor matrix elements. Finally, we can roughly obtain $\frac{\Gamma_{K^*(1410)\rho}}{\Gamma_{K^*(1410)\omega}} \simeq 3$. In our calculation, $\frac{\Gamma_{K^*(1410)\rho}}{\Gamma_{K^*(1410)\omega}} \simeq 3.31$. Another relation, $\frac{\Gamma_{K^*\rho}}{\Gamma_{K^*\omega}} \simeq 3.17$, is also consistent with 3. Other decay channels can be found in Table VI. Due to differences in both the model parameter γ and the choice of wave functions, our calculated total width of 475 MeV for the $K_0^*(4P)$ state is about 2 times larger than that reported in Ref. [13] when they take $M_{K_0^*(4P)} = 2450$ MeV. In addition to the different choices of γ and wave functions, we have also considered the higher excited final states which have not yet been found in experiment (such as $\pi K(3S)$ and $\pi K(4S)$).

For $\kappa(2600)(5P)$, the largest decay channel is also $K_1\pi$, accounting for 7.5% of the total width. $K^*(1410)\rho$ is comparably significant (6.39%). This state also exhibits considerable decay fractions into higher excitations, such as $\pi K_1(2P)$ and $Kb_1(1960)$, each contributing larger than 4%. The $K\pi$ channel constitutes a major decay mode of the $\kappa(2600)(5P)$ state, consistent with its experimental observation in the same channel. $\pi K_1(3P)$, $\pi K(5S)$, $\pi K_2(2D)$, $Ka_1(1640)$, and $\pi K(4S)$, all have a significant contribution to the total width of $\kappa(2600)(5P)$, with branching ratios being all about 3%. Other decay channels of $\kappa(2600)(5P)$ with branching ratios less than 3% can be found in Table VI. The important thing is the total decay width of $\kappa(2600)(5P)$ overlaps with the experimental value $480 \pm 47 \pm 72$ MeV. This result supports our classification of $\kappa(2600)$ as the $K_0^*(5P)$ resonance.

$K_0^*(6P)$ configuration demonstrates remarkable parallels to $K_0^*(5P)$, with the primary eight decay channels showing negligible divergence. The most important decay modes include $K^*(1410)\rho$ (5.7%) and $K_1\pi$ (5.5%). $\pi K_1(2P)$, $Kb_1(1960)$, $\pi K_1(3P)$, and $\pi K_2(2D)$ are its larger decay channels with branching ratios of 3.1% to 3.8%. As in $K_0^*(5P)$, the $K\pi$ channel constitutes a major decay mode of this $K_0^*(6P)$ state. Experiments can search for this state through the $K\pi$ final channel. This state exhibits a more evenly distributed decay pattern, with multiple channels contributing between 2% and 4%. Other decay channels of $K_0^*(6P)$ with more details are listed in Table VI. We find that the total width of $K_0^*(6P)$ is 380 MeV.

IV. CONCLUSION

In this work, we have systematically studied the mass spectra and the OZI-allowed two-body strong decay behaviors of the newly observed $\kappa(2600)$, along with the higher excited kaonic states, $K_0^*(4P)$ and $K_0^*(6P)$.

The newly observed state $\kappa(2600)$ is a good candidate for the $K_0^*(5P)$ state. The findings are supported not only by the Regge trajectory and the MGI model results, but also through an analysis of the QPC model. The total and branching decay widths allow for the identification of $\kappa(2600)$ as the $K_0^*(5P)$ state. Its two most important decay channels are $K_1\pi$ and $K^*(1410)\rho$.

The masses of $K_0^*(4P)$ and $K_0^*(6P)$ states are predicted to be about 2450 and 2830 MeV, respectively. The total widths for the $K_0^*(4P)$ state and $K_0^*(6P)$ state are about 475 and 380 MeV, respectively. The $K\pi$ channel is an ideal final channel for searching these two K_0^* states. $K_1\pi$ and $\pi K(4S)$ are two of the most important decay channels of the $K_0^*(4P)$ state, with branching ratios of 10.4% and 8.2% respectively. The branching ratio of $K\pi$ channel is about 6% for the $K_0^*(4P)$ state. The $K^*(1410)\rho$ and $K_1\pi$ channels are two main final states of the $K_0^*(6P)$ state, and they have branching ratios larger than 5%.

We look forward to future experimental studies, which will play a crucial role in searching for the higher excited states of kaons.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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- [1] S. Navas *et al.* (Particle Data Group), *Phys. Rev. D* **110**, 030001 (2024).
 - [2] R. Aaij *et al.* (LHCb Collaboration), *Phys. Rev. D* **108**, 032010 (2023).
 - [3] T.-G. Li, S.-C. Zhang, G.-Y. Wang, and Q.-F. Lü, *Phys. Rev. D* **110**, 114020 (2024).
 - [4] T.-Y. Li, Y.-R. Wang, and C.-Q. Pang, *Phys. Rev. D* **107**, 074008 (2023).
 - [5] T. Barnes, N. Black, and P.R. Page, *Phys. Rev. D* **68**, 054014 (2003).
 - [6] C.-Q. Pang, J.-Z. Wang, X. Liu, and T. Matsuki, *Eur. Phys. J. C* **77**, 861 (2017).
 - [7] R. L. Jaffe, *Phys. Rep.* **409**, 1 (2005).
 - [8] G. 't Hooft, G. Isidori, L. Maiani, A. D. Polosa, and V. Riquer, *Phys. Lett. B* **662**, 424 (2008).
 - [9] F.E. Close and N.A. Tornqvist, *J. Phys. G* **28**, R249 (2002).
 - [10] D. Parganlija, P. Kovacs, G. Wolf, F. Giacosa, and D.H. Rischke, *AIP Conf. Proc.* **1520**, 226 (2013).
 - [11] J.R. Pelaez, *Phys. Rev. Lett.* **92**, 102001 (2004).
 - [12] G. Eichmann, C.S. Fischer, and W. Heupel, *Phys. Lett. B* **753**, 282 (2016).
 - [13] T.-G. Li, Z. Gao, G.-Y. Wang, D.-M. Li, E. Wang, and J. Zhu, *Phys. Rev. D* **106**, 034012 (2022).
 - [14] G.F. Chew and S.C. Frautschi, *Phys. Rev. Lett.* **8**, 41 (1962).
 - [15] A. Anisovich, V. Anisovich, and A. Sarantsev, *Phys. Rev. D* **62**, 051502 (2000).
 - [16] S. Godfrey and N. Isgur, *Phys. Rev. D* **32**, 189 (1985).

- [17] E. van Beveren and G. Rupp, *Phys. Rev. Lett.* **91**, 012003 (2003).
- [18] Y.-R. Liu, X. Liu, and S.-L. Zhu, *Phys. Rev. D* **79**, 094026 (2009).
- [19] Y. B. Dai, X. Q. Li, S. L. Zhu, and Y. B. Zuo, *Eur. Phys. J. C* **55**, 249 (2008).
- [20] C.-Q. Pang, Y.-R. Wang, and C.-H. Wang, *Phys. Rev. D* **99**, 014022 (2019).
- [21] Y.-R. Wang, T.-Y. Li, Z.-Y. Fang, H. Chen, and C.-Q. Pang, *Phys. Rev. D* **106**, 114024 (2022).
- [22] L.-M. Wang, S.-Q. Luo, and X. Liu, *Phys. Rev. D* **105**, 034011 (2022).
- [23] L.-M. Wang, W.-X. Tian, and X. Liu, *Phys. Rev. D* **110**, 114049 (2024).
- [24] X.-C. Feng, Z.-Y. Li, D.-M. Li, Q.-T. Song, E. Wang, and W.-C. Yan, *Phys. Rev. D* **106**, 076012 (2022).
- [25] L. Micu, *Nucl. Phys.* **B10**, 521 (1969).
- [26] E. van Beveren, G. Rupp, T. Rijken, and C. Dullemond, *Phys. Rev. D* **27**, 1527 (1983).
- [27] A. I. Titov, T. I. Gulamov, and B. Kampfer, *Phys. Rev. D* **53**, 3770 (1996).
- [28] E. Ackleh, T. Barnes, and E. Swanson, *Phys. Rev. D* **54**, 6811 (1996).
- [29] H. G. Blundell, *arXiv:hep-ph/9608473*.
- [30] R. Bonnaz, B. Silvestre-Brac, and C. Gignoux, *Eur. Phys. J. A* **13**, 363 (2002).
- [31] H. Q. Zhou, R. G. Ping, and B. S. Zou, *Phys. Lett. B* **611**, 123 (2005).
- [32] J. Lu, X.-L. Chen, W.-Z. Deng, and S.-L. Zhu, *Phys. Rev. D* **73**, 054012 (2006).
- [33] B. Zhang, X. Liu, W.-Z. Deng, and S.-L. Zhu, *Eur. Phys. J. C* **50**, 617 (2007).
- [34] Z.-G. Luo, X.-L. Chen, and X. Liu, *Phys. Rev. D* **79**, 074020 (2009).
- [35] Z.-F. Sun and X. Liu, *Phys. Rev. D* **80**, 074037 (2009).
- [36] X. Liu, Z.-G. Luo, and Z.-F. Sun, *Phys. Rev. Lett.* **104**, 122001 (2010).
- [37] Z.-F. Sun, J.-S. Yu, X. Liu, and T. Matsuki, *Phys. Rev. D* **82**, 111501 (2010).
- [38] T. Rijken, M. Nagels, and Y. Yamamoto, *Nucl. Phys.* **A835**, 160 (2010).
- [39] Z.-C. Ye, X. Wang, X. Liu, and Q. Zhao, *Phys. Rev. D* **86**, 054025 (2012).
- [40] X. Wang, Z.-F. Sun, D.-Y. Chen, X. Liu, and T. Matsuki, *Phys. Rev. D* **85**, 074024 (2012).
- [41] L.-P. He, X. Wang, and X. Liu, *Phys. Rev. D* **88**, 034008 (2013).
- [42] Y. Sun, X. Liu, and T. Matsuki, *Phys. Rev. D* **88**, 094020 (2013).
- [43] Y.-R. Wang, Y. Ma, and C.-Q. Pang, *Int. J. Mod. Phys. A* **38**, 2350118 (2023).
- [44] T.-Y. Li, L. Tang, Z.-Y. Fang, C.-H. Wang, C.-Q. Pang, and X. Liu, *Phys. Rev. D* **108**, 034019 (2023).
- [45] L.-M. Wang, Q.-S. Zhou, C.-Q. Pang, and X. Liu, *Phys. Rev. D* **102**, 114034 (2020).
- [46] J.-C. Feng, X.-W. Kang, Q.-F. Lü, and F.-S. Zhang, *Phys. Rev. D* **104**, 054027 (2021).
- [47] Q.-T. Song, D.-Y. Chen, X. Liu, and T. Matsuki, *Phys. Rev. D* **91**, 054031 (2015).
- [48] Y.-R. Wang, X.-H. Liu, C.-Q. Pang, and H. Chen, *Phys. Rev. D* **111**, 054005 (2025).
- [49] D. Ebert, R. Faustov, and V. Galkin, *Phys. Rev. D* **79**, 114029 (2009).
- [50] J. P. Lees *et al.* (BABAR Collaboration), *Phys. Rev. D* **104**, 072002 (2021).
- [51] T. Feldmann, *Int. J. Mod. Phys. A* **15**, 159 (2000).
- [52] J.-S. Yu, Z.-F. Sun, X. Liu, and Q. Zhao, *Phys. Rev. D* **83**, 114007 (2011).
- [53] H.-Y. Cheng, *Proc. Sci. Hadron2013* (2013) 090 [arXiv:1311.2370].
- [54] D.-M. Li, B. Ma, and H. Yu, *Eur. Phys. J. A* **26**, 141 (2005).
- [55] K. Chen, C.-Q. Pang, X. Liu, and T. Matsuki, *Phys. Rev. D* **91**, 074025 (2015).
- [56] K.-C. Yang, *Phys. Rev. D* **84**, 034035 (2011).
- [57] C.-Q. Pang, L.-P. He, X. Liu, and T. Matsuki, *Phys. Rev. D* **90**, 014001 (2014).
- [58] C.-H. Wang, L. Tang, T.-Y. Li, G.-P. Zheng, J.-F. Hu, and C.-Q. Pang, *Nucl. Phys. Rev.* **39**, 160 (2022).
- [59] M.-X. Duan, S.-Q. Luo, X. Liu, and T. Matsuki, *Phys. Rev. D* **101**, 054029 (2020).
- [60] A. Le Yaouanc, L. Oliver, O. Pene, and J. Raynal, *Phys. Rev. D* **8**, 2223 (1973).
- [61] A. Le Yaouanc, L. Oliver, O. Pene, and J.-C. Raynal, *Phys. Rev. D* **9**, 1415 (1974).
- [62] A. Le Yaouanc, L. Oliver, O. Pene, and J. Raynal, *Phys. Rev. D* **11**, 1272 (1975).
- [63] A. Le Yaouanc, L. Oliver, O. Pene, and J. Raynal, *Phys. Lett.* **72B**, 57 (1977).
- [64] A. Le Yaouanc, L. Oliver, O. Pene, and J.-C. Raynal, *Phys. Lett.* **71B**, 397 (1977).
- [65] M. Jacob and G. Wick, *Ann. Phys. (N.Y.)* **7**, 404 (1959).
- [66] Q.-T. Song, D.-Y. Chen, X. Liu, and T. Matsuki, *Eur. Phys. J. C* **75**, 30 (2015).