Amplitude analysis of D0 → K− + + − postprint

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Abstract

We present an amplitude analysis of the decay D0 → K− + + − based on a data sample of 2.93 fb−1 acquired by the BESIII detector at the (3770) resonance. With a nearly background free sample of about 16000 events, we investigate the substructure of the decay and determine the relative fractions and the phases among the different intermediate processes. Our amplitude model includes the two-body decays D0 → K¯ ∗0 0, D0 → K−a+(1260) and D0 → K−(1270) +, the three-body decays D0 → K¯ ∗0 + − and D0 → K− + 0, as well as the four-body nonresonant decay D0 → K− + + −. The dominant intermediate process is D0 → K−a+(1260), accounting for a fit fraction of 54.6%.

Full Text

Preamble

Amplitude analysis of D → K

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Abstract

We present an amplitude analysis of the decay D → K based on a data sample of 2.93 fb 1 acquired by the BESIII detector at the (3770) resonance. With a nearly background-free sample of about 16,000 events, we investigate the substructure of the decay and determine the relative fractions and phases among the different intermediate processes. Our amplitude model includes the two-body decays D → K̄ , *D → K a (1270) , the three-body decays D → K* and D → K , as well as the four-body nonresonant decay D → K . The dominant intermediate process is D → K a (1260), accounting for a fit fraction of 54.6%.

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INTRODUCTION

The decays D → K and D → K are among the three golden decay modes of the neutral D meson (the other being D → K). Due to their large branching fractions and low backgrounds, they are well suited for use as reference channels for other D meson decays [1]. Accurate knowledge of their resonant substructure and the relative amplitudes and phases is important for reducing systematic uncertainties in analyses that use these channels as references.

In particular, the lack of knowledge of the substructure leads to one of the largest systematic uncertainties in measurements of absolute branching fractions of D hadronic decays [2]. Knowledge of the decay substructure, combined with precise measurements of strong phases, can also help improve the measurement of the CKM angle (the phase of V_cb relative to V_ub) [3]. In measurements of , the parametrization model is important input information for model-dependent methods and can also be used to generate Monte Carlo simulations to check sensitivity in model-independent methods [4]. Furthermore, the branching fractions of intermediate processes can be used to understand D -D̄ mixing theoretically [5, 6].

The decay D → K a (1260) → K was studied by Mark III [7] and E691 [8] more than twenty years ago, but both measurements suffer from low statistics. Using about 1,300 signal events, Mark III obtained branching fractions for D → K a (1260), D → K̄* , D → K a (1270) , as well as for three- and four-body nonresonant decays. Based on 1,745 signal events and 800 background events, E691 obtained similar results but without considering the D → K a (1270) decay mode. The results from both experiments have large uncertainties. Therefore, further experimental study of the D → K decay is crucial for improving the precision of future measurements.

In this paper, we use a data sample of about 2.93 fb ^{1} [9, 10] collected at the (3770) resonance with the BESIII detector in 2010 and 2011. We perform an amplitude analysis of the decay D → K (charge conjugate reactions are implied) to study the resonant substructure. The (3770) decays into a D D̄ pair without additional hadrons. We employ a double-tag method to measure the branching fraction. To suppress backgrounds from other charmed meson decays and continuum (QED and q̄q) processes, we use only the decay mode D̄ → K to tag the D D̄ pair. A detailed discussion of backgrounds can be found in Sec. III. The amplitude model is constructed using the covariant tensor formalism [11].

II. DETECTION AND DATA SETS

The BESIII detector is described in detail in Ref. [12]. Its geometrical acceptance is 93% of the full solid angle. Starting from the interaction point (IP), it consists of a main drift chamber (MDC), a time-of-flight (TOF) system, a CsI(Tl) electromagnetic calorimeter (EMC), and a muon system (MUC) with layers of resistive plate chambers (RPC) in the iron return yoke of a 1.0 T superconducting solenoid. The momentum resolution for charged tracks in the MDC is 0.5% at a transverse momentum of 1 GeV/c.

Monte Carlo simulations are based on GEANT4 [13]. The production of (3770) is simulated with the KKMC [14] package, accounting for beam energy spread and initial-state radiation (ISR). The PHOTOS [15] package simulates final-state radiation (FSR) of charged tracks. The MC samples, which consist of (3770) decays to D̄D, non-D̄D decays, ISR production of low-mass charmonium states, and continuum processes, are referred to as "generic MC" samples. The EvtGen [16] package simulates known decay modes with branching fractions from the Particle Data Group (PDG) [1], while remaining unknown decays are generated with the LundCharm model [17]. The effective luminosities of the generic MC samples correspond to at least five times the data sample luminosity and are used to investigate possible backgrounds.

The decay D → K ( )K has the same final state as signal and is investigated using a dedicated MC sample with the decay chain (3770) → D D̄ , D̄ → K , D → K K , referred to as the "K K MC" . The decay model for D → K K is generated according to CLEO' s results [18].

For the amplitude analysis, two sets of signal MC samples using different decay models are generated. One sample is generated with a uniform distribution in phase space for the D → K decay, used to calculate MC integrations and called the "PHSP MC" sample. The other sample is generated according to the results obtained in this analysis for the D → K decay. It is used to check fit performance, calculate goodness-of-fit, and estimate detector efficiency, and is called the "SIGNAL MC" sample.

III. EVENT SELECTION

Good charged tracks are required to have a point of closest approach to the interaction point within 10 cm along the beam axis and within 1 cm in the plane perpendicular to the beam. The polar angle between the track and the e beam direction must satisfy |cos | < 0.93. Charged particle identification (PID) is implemented by combining energy loss (dE/dx) in the MDC and time-of-flight information from the TOF. Probabilities P(K) and P( ) for the kaon and pion hypotheses are calculated. Tracks without PID information are rejected. Charged kaon candidates must satisfy P(K) > P( ), while pion candidates must satisfy P( ) > P(K). The average efficiencies for kaons and pions in D → K are 98% and 99%, respectively.

The D D̄ pair with D̄ → K and D → K is reconstructed with the requirement that the two D mesons have opposite charm and share no tracks. Since the tracks in D → K have distinct momenta from those in D̄ → K , misreconstructed signal events and K/ misidentification are negligible. Furthermore, a vertex fit assuming all tracks originate from the IP is performed, and the ^{2} of the fit must be less than 200.

For the K and K combinations, two variables, M_BC and ΔE, are calculated:

M_BC √(E_beam^2 - |p_D|^2)

ΔE E_D - E_beam

where p_D and E_D are the reconstructed momentum and energy of a D candidate, and E_beam is the calibrated beam energy. Signal events form a peak around zero in the ΔE distribution and around the D mass in the M_BC distribution. We require -0.03 < ΔE < 0.03 GeV for the K final state, -0.033 < ΔE < 0.033 GeV for the K final state, and 1.8575 < M_BC < 1.8775 GeV/c^2 for both. The corresponding ΔE and M_BC distributions of selected candidates are shown in Fig. 1 [Figure 1: see original paper], where the background is negligible.

To ensure the D meson is on-shell and improve resolution, selected candidate events undergo a five-constraint (5C) kinematic fit that constrains the total four-momentum of all final-state particles to the initial four-momentum of the e e system and constrains the invariant mass of the signal-side K to the D mass from the PDG [1]. Events with ^{2} of the 5C kinematic fit larger than 40 are discarded.

To suppress background from D → K K with K → , which has the same final state as our signal decay, we perform a vertex-constrained fit on any pair in the signal side if the invariant mass falls within |m_{ } - m_{K }|

< 0.03 GeV/c² (where m_{K } is the nominal K mass [1]), and reject the event if the corresponding significance of the decay length (distance from decay vertex to IP) exceeds 2 . This K veto eliminates about 80% of D → K K background while retaining about 99% of signal events.

After applying all selection criteria, 15,912 candidate events are obtained with a purity of 99.4%, as estimated by MC simulation. MC studies indicate that the dominant background arises from D → K K decay. The corresponding number of events is estimated according to:

N(K K) = N(K) × [B(D → K K) × (K K)] / [B(D̄ → K) × (K)]

where N(K) is the signal yield with background subtracted but without efficiency correction, and is the corresponding efficiency obtained from the SIGNAL MC sample. The branching fractions B(D → K K) and B(D̄ → K) are quoted from the PDG [1]. According to this equation, the number of peaking background events (N_peaking) is estimated to be 96.8.

All other backgrounds from D̄D, q̄q, and non-D̄D decays are studied with the generic MC sample. Their total contribution is estimated to be less than ten events, of which 5.5 and 2.0 are from D D̄ decays and non-D̄D decays, respectively. These backgrounds are neglected in the following analysis, and their effect is considered as a systematic uncertainty, as discussed in Sec. VI 2.

IV. AMPLITUDE ANALYSIS

The decay modes that may contribute to D → K are listed in Table I, where S, P, V, A, and T denote scalar, pseudoscalar, vector, axial-vector, and tensor states, respectively. The letters S, P, and D in square brackets refer to the relative angular momentum between daughter particles. The amplitudes and relative phases between different decay modes are determined with a maximum likelihood fit.

A. Likelihood Function Construction

The likelihood function is the product of probability density functions (PDFs) of observed events. The signal PDF f_S(p_j) is given by:

f_S(p_j) = (|M(p_j)|² R (p_j) (p_j)) / |M(p_j)|² R (p_j) (p_j) dp_j

where (p_j) is the detection efficiency parametrized in terms of final four-momenta p_j, and R (p_j)dp_j is the standard element of four-body phase space [11]:

R (p_j)dp_j = (P_D - Σp_j) Π (d³p_j / (2)³2E_j)

M(p_j) is the total decay amplitude modeled as a coherent sum over all contributing amplitudes:

$$M(p_j) = \Sigma c_n A_n(p_j)$$

where complex coefficients $c_n = \_n e^{i \_n}$ (with $\_n$ and $\_n$ being magnitude and phase for the nth amplitude) describe relative contributions, and $A_n(p_j)$ describes the dynamics of the nth amplitude.

In four-body decays, the intermediate amplitude can be a quasi-two-body decay or cascade decay amplitude, and $A_n(p_j)$ is given by:

$$A_n(p_j) = P^1_n(m\ )\ P^2_n(m\ )\ S_n(p_j)\ F^1_n(p_j)\ F^2_n(p_j)\ F^D_n(p_j)$$

where indices 1 and 2 correspond to the two intermediate resonances. $P^{\ }_n(p_j)$ ($= 1,2$) are propagators, $F^{\ }_n$ are Blatt-Weisskopf barrier factors [19], and $F^D_n(p_j)$ is the Blatt-Weisskopf barrier factor of the D decay. Parameters m and m in propagators are invariant masses of corresponding systems. For nonresonant states with orbital angular momentum between daughters, we set the propagator to unity, which can be regarded as a very broad resonance. The spin factor $S_n(p_j)$ is constructed with covariant tensor formalism [11]. The presence of two mesons imposes Bose symmetry in the K final state, which is explicitly accounted for in the amplitude by exchanging the two same-charge pions.

Background contribution is subtracted in the likelihood calculation by assigning negative weights to background events:

$$\ln L = N_{data} \ln f_S(p_k) - N_{bkg} \ln f_S(p_{k'})$$

where N_{data} is the number of candidate events in data, and w_{bkg} and N_{bkg} are the weight and number of events from the background MC sample, respectively.

In the nominal fit, only the peaking background $D \rightarrow K\ K$ is considered, with weight fixed to $N_{peaking}/N_{bkg}$. p_k^j and $p_{k'}^j$ are four-momenta of the jth final particle in the kth event of the data sample and k' th event of the background MC sample, respectively.

The normalization integral is determined by MC technique accounting for differences in PID and tracking efficiencies between data and MC simulation. The weight for a given MC event is defined as:

$$\_ (p_j) = \_{j,data}(p_j) / \_{j,MC}(p_j)$$

where $\_{j,data}(p_j)$ and $\_{j,MC}(p_j)$ are PID or tracking efficiencies for charged tracks as functions of p_j for data and MC, respectively. These efficiencies are determined by studying the $D \rightarrow K$ sample for data and MC. The MC integration is then:

$$|M(p_j)|^2 R\ (p_j)\ \ (p_j)\ dp_j = (1/N_{MC})\ \Sigma\ |M(p_k^{MC})|^2\ (R\ (p_k^{MC)/M\_gen(p\_k}MC))\ 2\ \_\ (p_k^{MC})$$

where k_{MC} indexes the kth MC event, N_{MC} is the number of selected MC events, and $M_{gen}(p_j)$ is the PDF used to generate MC samples. In the numerator of the signal PDF, (p_j) is independent of fitted variables and is treated as constant.

B. Blatt-Weisskopf Barrier Factors

The Blatt-Weisskopf barrier factor [19] $F_L(p_j)$ is a function of angular momentum L and four-momenta p_j of daughter particles. For a process $a \to bc$, the magnitude of momentum q of daughter b or c in the rest system of a is:

$q = (1/2m_a) \sqrt{[(m_a^2 - (m_b + m_c)^2)(m_a^2 - (m_b - m_c)^2)]}$

The Blatt-Weisskopf barrier factor is then:

$F_L(q) = z_L X_L(q)$

where $z = qR$, with R being the effective radius of the barrier, fixed to 3.0 GeV ¹ for intermediate resonances and 5.0 GeV ¹ for the D meson. $X_L(q)$ is given by:

$X_{L=0}(q) = 1$
$X_{L=1}(q) = \sqrt{(z^2/(z^2 + 1))}$
$X_{L=2}(q) = \sqrt{(z /(z\ + 3z^2 + 9))}$

C. Propagator

Due to limited phase space, we only consider states with angular momenta up to 2. As discussed in Ref. [11], we define the spin projection operator $P^{(S)}_{bc}$ as:

$P^{(0)}_{\ } = g_{\ }$
$P^{(1)}_{\ } = -g_{\ } + p_a\ p_a\ / p_a^2$
$P^{(2)}_{\ } = ½[P^{(1)}_{\ }\ P^{(1)}_{\ } + P^{(1)}_{\ }\ P^{(1)}_{\ }] - (1/3)P^{(1)}_{\ }$
$P^{(1)}_{\ }$

for spins 0, 1, and 2, respectively. The covariant tensors $\tilde{t}^{(L)}_{\ \cdots}$ for final states of pure orbital angular momentum L are constructed from relevant momenta p_a, p_b, p_c [11]:

$\tilde{t}^{(L)}_{\ \cdots} = (L!)^{(-1)}\ P^{(L)}_{\ \cdots\ \cdots}\ r^{\cdots r}$

where $r = p_b - (p_a \cdot p_b/p_a^2)p_a$.

Ten decay modes used in the analysis are listed in Table I. We use $\tilde{T}^{(L)}_{\ \cdots}$ to represent decay from the D meson and $\tilde{t}^{(L)}_{\ \cdots}$ to represent decay from intermediate states.

The resonances K* and a (1260) are parametrized as relativistic Breit-Wigner functions with mass-dependent width:

$P(m) = 1/(m\ ^2 - m^2 - im\ \Gamma(m))$

where m is the resonance mass to be determined, and $\Gamma(m)$ is:

Γ(m) = Γ (q/q)^(2L+1) (m /m) (X_L(q)/X_L(q))²

with q denoting q at m = m .

The K (1270) is parametrized as a relativistic Breit-Wigner with constant width Γ(m) = Γ , while   uses the Gounaris-Sakurai line shape [20]:

P_GS(m) = (1 + dΓ /m) / [m ² - m² + f(m) - im Γ(m)]

where:

f(m) = Γ (m ²/m²) (q²(h(m) - h(m)) + (m ² - m²)q ² h' (m))

h(m) = (2/)(q/m) ln[(m + 2q)/(2m_)]

and h' (m) = dh/dm²|_{m²=m ²}. The normalization condition P_GS(0) fixes parameter d = f(0)/(Γ m), found to be:

d = h(m)[(8q ²) ¹ + (2 m ²) ¹] - (1/2)(q /m)

where m_ is the charged pion mass.

D. Parametrization of the K S-wave

For the K S-wave [denoted (K)_S-wave], we use the same parametrization as BABAR [21], extracted from scattering data [22]. The model combines a Breit-Wigner shape for K* (1430) with an effective-range parametrization for the nonresonant component:

A(m_K) = F sin _F e^{i _F} + R sin _R e^{i _R} e^{i2 _F}

where:

_F = _F + cot ¹[(1/(aq)) + (r/2)q]
_R = _R + tan ¹[MΓ(m_K)/(M² - m_K ²)]

with a and r being scattering length and effective interaction length. F (_F) and R (_R) are relative magnitudes (phases) for nonresonant and resonant terms. In the fit, parameters M, Γ, F, _F, R, _R, a, and r are fixed to values from the D → K   Dalitz plot fit [21], summarized in Table II. These fixed parameters are varied within their uncertainties to estimate corresponding systematic uncertainties, discussed in Sec. VI 1.

E. Fit Fraction and Statistical Uncertainty

The fit model is divided into components according to intermediate resonances (see Sec. V). Fit fractions of individual components (amplitudes) are calculated from fit results and compared to other measurements. In calculations, a large phase-space (PHSP) MC sample without detector acceptance or resolution is used. The fit fraction for an amplitude or component is:

FF(n) = (|c_n A_n(p_j)|² dΦ) / (|Σ_k c_k A_k(p_j)|² dΦ)

where dΦ = R (p_j)dp_j.

To estimate statistical uncertainties of fit fractions, we repeat calculations by randomly varying fitted parameters according to the error matrix. For each amplitude or component, the resulting distribution is fitted with a Gaussian function, whose width gives the statistical uncertainty.

F. Goodness of Fit

To examine fit performance, goodness-of-fit is defined as follows. Since D and all four final-state particles have spin zero, the phase space of D → K can be completely described by five linearly independent Lorentz-invariant variables. Denoting as the pion giving the higher invariant mass and as the other, we choose five invariant masses: m_{ }, m_{ }, m_{K }, m_{K }, and m_{ }.

To calculate goodness-of-fit, the five-dimensional phase space is first divided into cells of equal size. Adjacent cells are combined until each contains >20 events. The deviation in each cell is:

_p = (N_p - N_p^exp)/√N_p

and the overall goodness-of-fit is:

² = Σ_{p=1}^n _p²

where N_p and N_p^exp are observed and expected events in the pth cell, and n is the total number of cells. Degrees of freedom are = n - n_par, where n_par is the number of free parameters.

V. RESULTS

To determine the optimal set of amplitudes contributing to D → K , we start with components having significant contributions and add amplitudes one by one. Statistical significance for new amplitudes is calculated from the change in log-likelihood value ΔlnL, accounting for the change in degrees of freedom Δ .

In the K and invariant mass spectra, clear structures appear for K̄ *and . The intermediate resonance K* or K appears in the invariant mass spectrum as a broad bump. This bump can be fitted as a (1260), also observed by Mark III [7]. If fitted with a nonresonant ( )_A amplitude instead, the significance for a (1260) relative to ( )_A exceeds 10 .

Three-body nonresonant states come from K and K̄ *contributions. The K* /K can be in pseudoscalar, vector, or axial-vector states, while K / can be in scalar states. Four-body nonresonant states are more complex, such as D → VS, D → VP, or D → AP with A → SP, all potentially contributing. Since D → K a (1260) has the largest fit fraction, we fix its magnitude and phase to 1.0 and 0.0, allowing other processes to vary.

We retain processes with significance >5 for the next iteration. The fit including both K a (1260) and nonresonant K ( )_A does not significantly improve the fit, and the fit fractions of the two amplitudes are nearly 100% correlated. We avoid this ambiguity and consider only the resonant term, consistent with Mark III [7]. For K̄* , the significance is only 4.3 , but we include it since the corresponding D-wave process exceeds 9 significance, and better invariant mass projections and improved ^{2} are observed with this S-wave process included.

Finally, we retain 23 processes categorized into seven components. Other tested but unused processes are listed in Appendix A. The masses and widths of K̄* and are determined by the fit. The K (1270) has a small fit fraction, so its mass and width are fixed to PDG values [1]. The a (1260) mass is near the upper boundary of the invariant mass spectrum, so we determine its mass and width via likelihood scans (Fig. 2 [Figure 2: see original paper]), obtaining:

m_{a (1260)} = 1362 ± 29 MeV/c²
Γ_{a (1260)} = 542 ± 29 MeV/c²

(statistical uncertainties only). These values are fixed in the nominal fit.

Our nominal fit yields ^{2}/ = 843.445/748 = 1.128. To calculate statistical significance of a process, we repeat the fit without it and consider changes in log-likelihood and degrees of freedom. Projections for eight invariant masses and the distribution are shown in Fig. 3 [Figure 3: see original paper]. All components, amplitudes, and their significances are listed in Table IV. Fit fractions of all components are given in Table V. Phases and fit fractions of all amplitudes are in Table VI.

VI. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties are divided into four categories: (I) amplitude model, (II) background estimation, (III) experimental effects, and (IV) fitter performance. Uncertainties of free parameters and fit fractions from different contributions are given in units of statistical standard deviations _stat in Tables VII–IX. These uncorrelated uncertainties are added in quadrature for total systematic uncertainties.

1. Amplitude Model

Three sources are considered: masses and widths of K (1270) and a (1260), barrier effective radius R, and fixed parameters in the K S-wave model. Uncertainties from K (1270) mass and width are estimated by varying them within 1 of PDG errors [1]. The R uncertainty is estimated by varying R within 1.5–7.0 GeV ^{1} for intermediate resonances and 3.0–5.0 GeV ^{1} for D . K S-wave parameter uncertainties are evaluated by varying input values within their uncertainties. All result changes relative to nominal are taken as systematic uncertainties.

2. Background Estimation

Sources include amplitude and shape of D → K K background and other potential backgrounds. The D → K K uncertainty is estimated by varying background event numbers within 1 and changing shapes according to PDF parameter uncertainties from CLEO [18]. Other potential background uncertainty is estimated by including corresponding backgrounds (from generic MC) in the fit.

3. Experimental Effects

This includes acceptance differences between MC and data from tracking/PID efficiencies and detector resolution. Tracking/PID efficiency uncertainty is determined by shifting _ (p) in Eq. (9) within its uncertainty. Resolution uncertainty is the difference between pull distributions from simulated data using generated vs. fitted four-momenta, as described in Sec. VI 4.

4. Fitter Performance

Fit process uncertainty is evaluated using toy MC samples. An ensemble of 250 SIGNAL MC samples, each equal in size to data, is generated according to nominal results. These undergo event selection and amplitude analysis. Pull variables (V_input - V_fit)/ _fit are defined to evaluate bias. The pull distribution for 250 samples should be Gaussian; shifts in mean and width indicate bias. Small biases are observed: largest pull mean bias is ~19% of statistical uncertainty (3.0 from zero), and largest pull width shift is 0.87 ± 0.04 (3.0 from 1.0). We add mean and mean error in quadrature, multiply by statistical error to obtain systematic error. Fit results are in Tables X–XII, where uncertainties are statistical uncertainties of fits to pull distributions.

VII. CONCLUSION

An amplitude analysis of D → K decay has been performed using 2.93 fb ¹ of e e collision data at the (3770) resonance collected by BESIII. The dominant components—D → K a (1260), K̄* , four-body nonresonant decay, and K —improve upon earlier Mark III results and are consistent with them. The K (1270) resonance observed by Mark III is confirmed. Detailed results are in Table V.

About 40% of components come from nonresonant four-body (D → K) and three-body (D → K̄*) decays. A detailed study of different orbital angular momenta is performed, which was absent in Mark III and E691 analyses. An especially interesting K S-wave process is described by effective-range parametrization.

Using the inclusive branching fraction B(D → K) = (8.07 ± 0.23)% from

PDG [1] and fit fractions FF(n) from this analysis, we calculate exclusive absolute branching fractions for individual components as B(n) = B(D → K) × FF(n). Results are summarized in Table XIII and compared with PDG values. Our results have significantly improved precision and may inform theoretical calculations. Knowledge of D → K̄* and D → K a (1260) increases understanding of D → AP and D → VV decays, which lack experimental measurements despite large contributions. Furthermore, knowledge of D → K submodes will improve reconstruction efficiency determination when this mode tags D in other measurements, such as branching fractions, strong phases, or angle .

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VIII. APPENDIX A: AMPLITUDES TESTED

The amplitudes listed below were tested when determining the nominal fit model but are not used in final results.

Cascade amplitudes:
K *(1410)(K̄)* , K *(1430)(K̄)* , K *(1680)(K̄)* , K *(1680)(K̄)* , *K* (1770)(K̄ *)* , *K* (1770)(K̄) , K a (1320)( ), K (1300)( ), K a (1260)(f (500))

Quasi-two-body amplitudes:
K̄ *f (500), K̄* f (980)

Three-body amplitudes:
K̄* ( )_V S-, P-, and D-waves, (K)_V S-, P-, and D-waves, K̄ *K* (1430) , K̄* f (1270), (K)_Sf (1270), K ( )_V, K ( )_P, K ( )_A, K ( )_T, (K̄*)_T , (K)_T , (K̄*)_A , K̄ *S- and D-waves, K (1400)(K̄)* , K (1270)(K) , K D-wave

Four-body nonresonance amplitudes:
(K)_T( )_V P- and D-waves, (K)_V( )_T P- and D-waves, (K)_V( )_V P- and D-waves, (K ( )_S)_A

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Note: Figure translations are in progress. See original paper for figures.