

First Observation of $D^{0(+)} \rightarrow \bar{K}\omega e^+\nu_e$ and Determination of the Branching Fraction of $\bar{K}_1(1270) \rightarrow \bar{K}\omega$

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Using 20.3 fb⁻¹ of e^+e^- annihilation data collected at a center-of-mass energy of 3.773 GeV with the BESIII detector, we report the first observation of the semileptonic decays $D^0 \rightarrow K^-\omega e^+\nu_e$ and $D^+ \rightarrow K_S^0\omega e^+\nu_e$ with significances of 8.0σ and 5.8σ , respectively. Their decay branching fractions are measured to be $\mathcal{B}(D^0 \rightarrow K^-\omega e^+\nu_e) = (9.4_{-1.8}^{+2.0} \pm 0.6) \times 10^{-5}$ and $\mathcal{B}(D^+ \rightarrow K_S^0\omega e^+\nu_e) = (8.0_{-2.1}^{+2.4} \pm 0.7) \times 10^{-5}$. Combining these with the latest measurements of $D^{0(+)} \rightarrow K^-\pi^+\pi^{-(0)}e^+\nu_e$ and assuming $\bar{K}_1(1270)$ to be the sole mediating resonance in all processes, the branching ratios are determined to be $\{[\Gamma(K_1(1270)^- \rightarrow K^-\pi^+\pi^-)]/[\Gamma(K_1(1270)^- \rightarrow K^-\omega)]\} = 3.4_{-0.7}^{+0.8} \pm 0.3$ and $\{[\Gamma(\bar{K}_1(1270)^0 \rightarrow K^-\pi^+\pi^0)]/[\Gamma(\bar{K}_1(1270)^0 \rightarrow \bar{K}^0\omega)]\} = 7.9_{-2.1}^{+2.4} \pm 0.7$. The combined branching fraction is determined to be $\mathcal{B}(\bar{K}_1(1270) \rightarrow \bar{K}\omega) = (8.4 \pm 1.4 \pm 0.5)\%$, which is the most precise measurement from a collider experiment. Furthermore, for the first time based on a single vector-pseudoscalar decay channel, the $\bar{K}_1(1270)$ mass is measured to be $(1336 \pm 9 \pm 2)$ MeV/ c^2 , providing unique experimental support for the two-pole structure of the $\bar{K}_1(1270)$ resonance. The first uncertainties are statistical, and the second are systematic.

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Semileptonic (SL) decays of $D^{0(+)}$ mesons offer an ideal test bed to understand nonperturbative strong-interaction dynamics in weak decays [1,2]. The SL transitions of $D^{0(+)}$ mesons into the axial-vector meson $\bar{K}_1(1270)$, which provide valuable information on the $\bar{K}_1(1270)$, are especially appealing. Reference [3] notes that the combined measurements of $D^{0(+)} \rightarrow \bar{K}_1(1270)\ell^+\nu_\ell$ and $\bar{B} \rightarrow \bar{K}_1(1270)\gamma$ offer a possible approach for determining the photon polarization in $b \rightarrow s\gamma$ transitions with no theoretical ambiguity. Furthermore, improved knowledge of the $\bar{K}_1(1270)$ will facilitate the search for new physics in $\bar{B} \rightarrow \bar{K}_1(1270)\ell^+\ell^-$, which has recently drawn much interest from both theorists [4–11] and experimentalists [12].

The SL decays $D^{0(+)} \rightarrow \bar{K}_1(1270)e^+\nu_e$ have been observed in the modes of $\bar{K}_1(1270)^0 \rightarrow K^-\pi^+\pi^0$, $K_1(1270)^- \rightarrow K^-\pi^+\pi^-$, and $\bar{K}_1(1270)^{(0)-} \rightarrow K_S^0\pi^-\pi^{+(0)}$ [13–15]. Most recently, the first amplitude and angular analyses of the five-body decays of $D^{0(+)} \rightarrow K^-\pi^+\pi^{-(0)}e^+\nu_e$ have been performed, where the

$\bar{K}_1(1270)$ is found to be the only intermediate state in the $\bar{K}\pi\pi$ system [16]. As the only notable four-body $\bar{K}_1(1270)$ decay, studies of the $\bar{K}_1(1270) \rightarrow \bar{K}\omega$ with $\omega \rightarrow \pi^+\pi^-\pi^0$ decay will aid our understanding of the $\bar{K}_1(1270)$ line shape, and provide important external inputs for establishing a more reliable model of $\bar{K}_1(1270) \rightarrow \bar{K}\pi\pi$. A two-pole interpretation for the $\bar{K}_1(1270)$ meson has been proposed and exploited theoretically [17–20], where the lower (higher) mass pole couples predominantly to the $\bar{K}^*\pi$ ($\rho\bar{K}$) channel. Because of the phase-space limitation and narrow ω width, the lower pole at ~ 1195 MeV/ c^2 can hardly couple to the $\bar{K}\omega$ channel, making the $\bar{K}\omega$ mode an ideal probe to isolate the higher mass pole and test the two-pole hypothesis of the $\bar{K}_1(1270)$ meson. Reference [21] points out that theoretical discussions have often underestimated some difficulties and complications in studying $K_1 \rightarrow K\pi\pi$ decays. These three-body processes involve multiple interfering intermediate channels. Further complications arise from the large widths of the K^* and ρ isobars, as well as from the overlap and mixing of the two close $K_1(1270)$ and $K_1(1400)$ states. The width of the ω meson is relatively narrow compared with ρ and $\bar{K}^*(892)$, substantially suppressing any bias caused by the modeling of intermediate-state width effects. The dominance of the $\bar{K}\omega$ resonance in the $\bar{K}_1(1270) \rightarrow \bar{K}\pi^+\pi^-\pi^0$ channel, which is supported by the result of this analysis, eliminates the multichannel interference effects prevalent in the $\bar{K}_1(1270) \rightarrow \bar{K}\pi\pi$ decays, where significant complexity

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arises from the interplay of the dominant quasi-two-body pathways such as $\bar{K}_1(1270) \rightarrow \bar{K}^*\pi$ and $\bar{K}_1(1270) \rightarrow \bar{K}\rho$. Finally, the near absence of the $\bar{K}_1(1400)$, $\bar{K}^*(1410)$, $\bar{K}^*(1430)$, which is consistent with the findings of this analysis, suppresses interference from these states, enabling isolation of the $\bar{K}_1(1270)$ dynamics.

The current world average of the branching fraction (BF) of $\bar{K}_1(1270) \rightarrow \bar{K}\omega$ is $(11 \pm 2)\%$ [22]. It comes from only one measurement conducted in a $K^-p \rightarrow K^-\pi^+\pi^+p$ scattering experiment more than 40 years ago [23], determined indirectly under the assumption that the $\bar{K}\omega$ amplitude is proportional to the $\bar{K}\rho$ amplitude. The first measurement in a collider experiment is from the Belle Collaboration, reporting $\mathcal{B}(\bar{K}_1(1270) \rightarrow \bar{K}\omega) = (22.5 \pm 5.2)\%$ via an amplitude analysis of $B^+ \rightarrow J/\psi K^+\pi^+\pi^-$ [24]. Recently, the LHCb Collaboration has reported $\mathcal{B}(\bar{K}_1(1270) \rightarrow \bar{K}\omega) = (6.3 \pm 3.1)\%$ via an amplitude analysis of $B^+ \rightarrow \psi(3686)K^+\pi^+\pi^-$ [25]. All these measurements are based on the $K_1(1270)^- \rightarrow K^-\pi^+\pi^-$ transition, while no experimental result for $\bar{K}_1(1270)^0 \rightarrow K_S^0\omega$ is available to date. The $D^{0(+)} \rightarrow \bar{K}_1(1270)(\rightarrow \bar{K}\omega)e^+\nu_e$ decay with $\omega \rightarrow \pi^+\pi^-\pi^0$ provides an independent and clean opportunity to measure $\mathcal{B}(\bar{K}_1(1270) \rightarrow \bar{K}\omega)$ in both neutral and charged channels. This Letter presents the first measurement of the SL decays $D^0 \rightarrow K^-\omega e^+\nu_e$ and $D^+ \rightarrow K_S^0\omega e^+\nu_e$ using 20.3 fb^{-1} of e^+e^- annihilation data collected at a center-of-mass energy of 3.773 GeV with the BESIII detector. Throughout this Letter, the charged-conjugated modes are always implied.

A description of the design and performance of the BESIII detector can be found in Refs. [26,27]. The inclusive Monte Carlo (MC) sample, described in Refs. [28–32], has been validated to model the background. The exclusive signal samples are generated by simulating the $D^{0(+)} \rightarrow \bar{K}_1(1270)e^+\nu_e$ decays with the ISGW2 model, an update of the ISGW quark model for semi-leptonic meson decays [2], and the $\bar{K}_1(1270)$ resonance shape is parametrized by a relativistic Breit-Wigner function with a mass of 1272 MeV/ c^2 and a width of 90 MeV. The optimization of selection criteria is performed using these initial signal MC samples. The final signal efficiencies and signal shape are determined using updated signal MC samples with a mass of 1336 MeV/ c^2 measured in this Letter and a width of 168 MeV [16]. The subsequent decay of $\bar{K}_1(1270) \rightarrow \bar{K}\omega$ is described by the VVS_PWAVE model, which parametrizes the decay of a vector particle to a vector and a scalar particle [30]. The subsequent decay of $\omega \rightarrow \pi^+\pi^-\pi^0$ is modeled using the OMEGA_DALITZ model that describes the Dalitz amplitude for the decay [33].

At $\sqrt{s} = 3.773 \text{ GeV}$, the D and $\bar{D}$ mesons are produced in pairs without accompanying particles in the final state, which enables the study SL D decays with the double-tag (DT) method [34]. In this method, single-tag (ST) events

are those in which $\bar{D}$ mesons are fully reconstructed via the hadronic decay modes $\bar{D}^0 \rightarrow K^+\pi^-$, $K^+\pi^-\pi^0$, and $K^+\pi^+\pi^-\pi^-$; $D^- \rightarrow K^+\pi^-\pi^-$, $K_S^0\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S^0\pi^-\pi^0$, $K_S^0\pi^+\pi^-\pi^-$, and $K^+K^-\pi^-$. In the presence of the ST $\bar{D}$ mesons, candidates for $D^{0(+)} \rightarrow K_{(S)}^{-(0)}\omega e^+\nu_e$, $\omega \rightarrow \pi^+\pi^-\pi^0$ are selected to form DT events. The BF of the signal decay is determined by

$$\mathcal{B}_{\text{sig}} = \frac{N_{\text{DT}}}{N_{\text{ST}}^{\text{tot}} \bar{\epsilon}_{\text{sig}}}, \quad (1)$$

where $N_{\text{ST}}^{\text{tot}} = \sum_i N_{\text{ST}}^i$ and N_{DT} are the total ST and DT yields after summing over all ST modes; $\bar{\epsilon}_{\text{sig}} = \sum_i [(N_{\text{ST}}^i)/(N_{\text{ST}}^{\text{tot}})] [(\epsilon_{\text{DT}}^i)/(\epsilon_{\text{ST}}^i)]$ is the averaged signal efficiency of selecting $D^{0(+)} \rightarrow K_{(S)}^{-(0)}\omega e^+\nu_e$ in the presence of the ST $\bar{D}$ meson, where ϵ_{ST}^i and ϵ_{DT}^i are the ST and DT efficiencies for the i th ST mode, respectively.

To reconstruct ST $\bar{D}$ mesons, the selection criteria of $\pi^\pm$, $K^\pm$, K_S^0 , γ , and π^0 candidates are the same as in Ref. [15]. Two kinematic variables, the energy difference $\Delta E \equiv E_{\bar{D}} - E_{\text{beam}}$ and the beam-constrained mass $M_{\text{BC}} \equiv \sqrt{E_{\text{beam}}^2 - |\vec{p}_{\bar{D}}|^2}$, are used to distinguish the ST $\bar{D}$ mesons from combinatorial backgrounds, where E_{beam} is the beam energy and $(E_{\bar{D}}, \vec{p}_{\bar{D}})$ is the four-momentum of the ST $\bar{D}$ meson in the e^+e^- rest frame. The combination with the smallest $|\Delta E|$ is chosen if there are multiple combinations in an event.

The ST candidates are required to satisfy mode-dependent requirements of ΔE , corresponding to about $\pm 3.5\sigma$ around the fitted peaks. The ST yields in data for each ST mode are extracted by fitting individual M_{BC} distributions. Candidates with $M_{\text{BC}} \in [1.863, 1.877] \text{ GeV}/c^2$ are retained for further analysis. The ΔE requirements, the ST yields in data, and the ST efficiencies for different ST modes are provided in Ref. [35]. Summing over all ST modes yields $N_{\text{ST}}^{\text{tot}} = (16135.4 \pm 4.6) \times 10^3$ for $\bar{D}^0$ and $(10646.9 \pm 3.8) \times 10^3$ for D^- .

In the presence of the ST $\bar{D}$ mesons, candidates for $D^{0(+)} \rightarrow K_{(S)}^{-(0)}\omega e^+\nu_e$ are selected from the remaining tracks and showers. The selection criteria of K^- , $\pi^\pm$, and π^0 are the same as those used in the ST selection. We require that there are no extra tracks. For the case of multiple π^0 candidates, the one with the invariant mass closest to the known π^0 mass is selected [22]. The ω meson is reconstructed in the $\pi^+\pi^-\pi^0$ decay mode, and its invariant mass $M_{\pi^+\pi^-\pi^0}$ is required to be in the range of $[0.60, 0.95] \text{ GeV}/c^2$. The selection criteria of K_S^0 are the same as those used in the ST selection except for the removal of the $L/\sigma_L > 2$ requirement, where L is the distance between the common vertex of the $\pi^+\pi^-$ pair and the interaction point, and σ_L is its uncertainty. For the case of multiple K_S^0 candidates, the one with the largest L/σ_L is

chosen. The e^+ candidates are selected by performing particle identification (PID) based on the specific ionization energy loss (dE/dx), time of flight, and electromagnetic calorimeter information. Confidence levels for the positron, pion, and kaon hypotheses are calculated, denoted as $CL_{e,\pi,K}$. Charged tracks are assigned as e^+ candidates if $CL_e > 0.001$ and $CL_e/(CL_e + CL_\pi + CL_K) > 0.8$. The efficiency of this basic PID requirement for e^+ candidates is about 95%. To further distinguish the positron candidates from hadrons, the e^+ candidates are required to satisfy $E_e/p_e > 0.67$, $\chi^2_{dE/dx} < 4.9$ for the D^0 channel, and $E_e/p_e > 0.66$, $\chi^2_{dE/dx} < 6.0$ for the D^+ channel. Here, E_e is the deposited positron energy in the electromagnetic calorimeter, p_e is the positron momentum measured by the drift chamber, and $\chi^2_{dE/dx}$ is the χ^2 for the positron hypothesis based on the dE/dx information. The efficiencies of the requirements on E_e/p_e and $\chi^2_{dE/dx}$ are about 75% and 79% for the D^0 and D^+ channels, respectively.

Since the neutrino cannot be detected by the BESIII detector, its inferred four-momentum ($E_{\text{miss}}, \vec{p}_{\text{miss}}$) is obtained by calculating the missing energy and momentum via $E_{\text{miss}} = E_{\text{beam}} - \sum_j E_j$ and $\vec{p}_{\text{miss}} = \vec{p}_D - \sum_j \vec{p}_j$. Here, the index j sums over the $K_{(S)}^{(0)}, \pi^+, \pi^-, \pi^0$, and e^+ of the signal candidates and $(E_j, \vec{p}_j)$ is the four-momentum of the j th particle. A kinematic variable $U_{\text{miss}} \equiv E_{\text{miss}} - |\vec{p}_{\text{miss}}|$ is employed to extract the signal yield. To further improve the resolutions of the mentioned variables, the momentum of the D meson is constrained as $\vec{p}_D = -\hat{p}_D \sqrt{E_{\text{beam}}^2 - m_D^2}$, where $\hat{p}_D$ is the unit vector in the direction of the ST $\bar{D}$ meson and m_D is the known $\bar{D}$ mass [22].

Further requirements are applied to suppress background. The maximum shower energy for extra photons not used in event reconstruction, $E_{\text{extra-}\gamma}^{\text{max}}$, is required to be less than 0.3 GeV. The opening angle between e^+ and π^- from ω is required to satisfy $\cos\theta_{e^+\pi^-} < 0.87$ and $\cos\theta_{e^+\pi^-} < 0.92$ for the D^0 and D^+ channels, respectively, to suppress the background of $D^{0(+)} \rightarrow K_{(S)}^{(0)} \pi^+ \pi^- \pi^0$, with $\pi^0 \rightarrow e^+ e^- \gamma$ for one of the two π^0 's. The invariant mass of $K_{(S)}^{(0)} \pi^+ \pi^- \pi^0 \pi_{e \rightarrow \pi}^+$, $M_{K_{(S)}^{(0)} \pi^+ \pi^- \pi^0 \pi_{e \rightarrow \pi}^+}$ is required to be less than 1.77 GeV/ c^2 and 1.80 GeV/ c^2 for the D^0 and D^+ channels to reject the hadronic decays $D^{0(+)} \rightarrow K_{(S)}^{(0)} \pi^+ \pi^- \pi^+ \pi^0$, where $\pi_{e \rightarrow \pi}^+$ denotes using pion mass hypothesis for the e^+ track. For the D^+ channel, the energy of the π^0 candidate must be greater than 0.17 GeV to suppress the background from misidentified π^0 candidates. The opening angle between the missing momentum and the most energetic unused shower is required to satisfy $\cos(\theta_{\text{miss},\gamma}) < 0.9$, to suppress background from D hadronic decays with multiple π^0 's and missing a π^0 . Different requirements for the D^0 and D^+ channels are obtained by

optimizing a figure of merit defined as $S/\sqrt{S+B}$, where S and B are the signal and background yields according to MC simulation, respectively.

To extract the signal yields of $D^{0(+)} \rightarrow K_{(S)}^{(0)} \omega e^+ \nu_e$, two-dimensional (2D) unbinned maximum likelihood fits are performed on the U_{miss} versus $M_{\pi^+ \pi^- \pi^0}$ distributions of the accepted candidates with $|U_{\text{miss}}| < 0.30$ GeV and $0.60 < M_{\pi^+ \pi^- \pi^0} < 0.95$ GeV, as shown in Fig. 1. $M_{\pi^+ \pi^- \pi^0}$ is chosen instead of $M_{K_{(S)}^{(0)} \pi^+ \pi^- \pi^0}$ because of the significantly larger width of $\bar{K}_1(1270)$ compared with ω . In each fit, the signal is described by the MC-simulated shape, while both the peaking and nonpeaking background shapes are derived from the inclusive MC sample. The smooth 2D probability-density functions of signal and background are modeled using RooNDKeysPdf [36,37]. The sizes of the $D^{0(+)} \rightarrow K_{(S)}^{(0)} \pi^+ \pi^- \pi^+ \pi^0$ peaking background contributions are also extracted from the inclusive MC sample. For the D^0 channel, the number of $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+ \pi^0$ peaking background events is estimated from MC simulation, modified by a correction factor of 1.08 ± 0.10 , based on the data-MC inconsistency in the vetoed region of $M_{K^- \pi^+ \pi^- \pi^0 \pi_{e \rightarrow \pi}^+} > 1.77$ GeV/ c^2 . For the D^+ channel, the number of $D^+ \rightarrow K_S^0 \pi^+ \pi^- \pi^+ \pi^0$ peaking background events is fixed according to MC simulation. In this case, no correction is applied due to a much lower peaking contribution. The yields of the signal and nonpeaking background components are allowed to float. The signals of $D^0 \rightarrow K^- \omega e^+ \nu_e$ and $D^+ \rightarrow K_S^0 \omega e^+ \nu_e$ are observed with significances of 8.0σ and 5.8σ , respectively. The

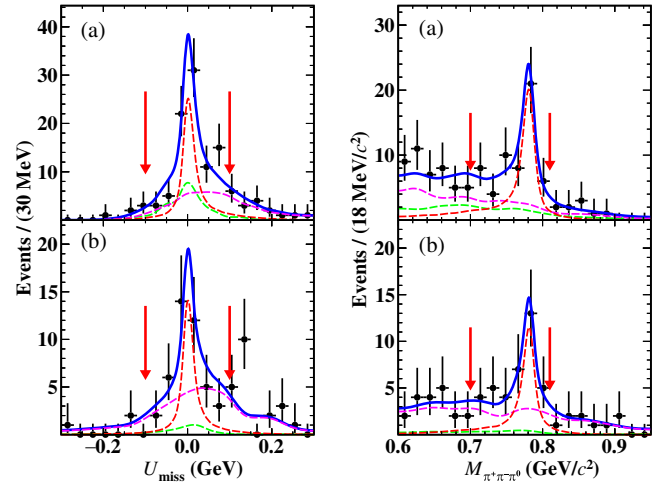


FIG. 1. Projections of the fits to the U_{miss} versus $M_{\pi^+ \pi^- \pi^0}$ distributions of the (a) D^0 and (b) D^+ channels. The points with error bars are data. The solid blue lines denote the total fits. The dashed red, green, and magenta lines show the signal, $D^{0(+)} \rightarrow K_{(S)}^{(0)} \pi^+ \pi^- \pi^+ \pi^0$ peaking background, and nonpeaking background contributions, respectively. The red arrows indicate the requirements $|U_{\text{miss}}| < 0.1$ GeV and $M_{\pi^+ \pi^- \pi^0} \in [0.70, 0.81]$ GeV/ c^2 .

TABLE I. Fitted signal yields in data (N_{DT}), averaged signal efficiencies ($\bar{\epsilon}_{\text{sig}}$), and the obtained BFs ($\mathcal{B}_{\text{sig}}$), where the first uncertainties are statistical and the second systematic.

Channel	N_{DT}	$\bar{\epsilon}_{\text{sig}}$ (%)	$\mathcal{B}_{\text{sig}} (\times 10^{-5})$
D^0	$42.2^{+9.2}_{-8.3}$	3.08 ± 0.03	$9.4^{+2.0}_{-1.8} \pm 0.6$
D^+	$21.4^{+6.5}_{-5.7}$	4.08 ± 0.04	$8.0^{+2.4}_{-2.1} \pm 0.7$

significance is calculated as $\sqrt{-2\Delta \ln L}$, where $\Delta \ln L$ is the difference of the log-likelihoods with and without the signal component in the fit, taking into account systematic uncertainties of the 2D fits. The signal efficiencies are estimated based on the signal MC samples. The fitted signal yields from the data, the average signal efficiencies, and the obtained BFs are summarized in Table I.

Table II summarizes the systematic uncertainties in the BF measurement from different sources. The total uncertainties are calculated by combining all individual contributions in quadrature. Details of the systematic uncertainties in the BF measurement are discussed below. The uncertainty associated with the ST yield $N_{\text{ST}}^{\text{tot}}$ is estimated to be 0.3% by varying the signal and background shapes [38]. The systematic uncertainty due to MC statistics is calculated by $\sqrt{(1-\epsilon)/(N\epsilon)}$ to be 0.3% for both decays, where N is the number of events generated in the signal MC sample and ϵ is the signal efficiency. The uncertainties from the quoted BF of $K_S^0 \rightarrow \pi^+\pi^-$ and $\pi^0 \rightarrow \gamma\gamma$ are negligible, and that from $\omega \rightarrow \pi^+\pi^-\pi^0$ is 0.8% [22].

The efficiencies of tracking and PID of $\pi^\pm$ and K^- , π^0 , and K_S^0 reconstructions are studied with hadronic $D\bar{D}$ decays. The tracking and PID efficiencies of $\pi^\pm$ or K^- are reweighted with the data-MC difference, depending on the $\pi^\pm$ or K^- momentum. The uncertainties of π^0 and K_S^0 reconstruction efficiencies are assigned to be 1.0% for each π^0 and K_S^0 , according to the momentum dependent data-

MC difference. The efficiencies of tracking and PID for the e^+ are investigated with $e^+e^- \rightarrow \gamma e^+e^-$. The tracking and PID efficiencies of e^+ are weighted with the data-MC difference, depending on both momentum and $\cos \theta$ of e^+ .

The uncertainties associated with various kinematic cuts are studied with the control samples of $D^0 \rightarrow K_S^0 \pi^- e^+ \nu_e$ and $D^+ \rightarrow K_S^0 \pi^0 e^+ \nu_e$. The cut efficiency differences between data and MC simulation are found to be $(-2.6 \pm 1.5)\%$ for D^0 and $(-1.3 \pm 1.3)\%$ for D^+ . After correcting the BF of $D^0 \rightarrow K^- \omega e^+ \nu_e$ by -2.6% and $D^+ \rightarrow K_S^0 \omega e^+ \nu_e$ by -1.3% , the uncertainties from variable requirements are assigned as 1.5% and 1.3% for the D^0 and D^+ channels, respectively.

The uncertainties of the 2D fits are estimated by changing the signal and background shapes. Two issues of uncertainty from the signal shape are investigated. First, two independent fits are performed with the original signal shape convolved with a Gaussian function for the U_{miss} or $M_{\pi^+\pi^-\pi^0}$ distribution. The change in the signal yields are negligible. Second, alternative fits are performed with the RooKeysPDF smooth parameters of the signal shapes increased by 50% from the default values of 1.0. The changes in signal yields, 0.2% and 0.4%, are assigned as the systematic uncertainties for the D^0 and D^+ channels, respectively. The uncertainty from final state radiation of e^+ is estimated by an alternative fit with the signal altered by final state radiation recovery, meaning that neutral showers within 5° of the initial positron direction are merged with the four-momentum of the positron measured by the drift chamber. The changes of signal yields, 0.2% and 2.0% for the D^0 and D^+ channels, are assigned as the uncertainties. The uncertainties associated with the non-peaking background shape are estimated by varying the relative fractions of the major background processes by the uncertainties of their BF. The maximum changes of signal yields, 0.2% and 0.4% for the D^0 and D^+ channels, are assigned as the uncertainties. The uncertainty associated with the peaking background shape for the D^0 channel is estimated by varying the correction factor of the number of $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+ \pi^0$ events by $\pm 1\sigma$. For the D^+ channel, the uncertainty is estimated by modifying the number of $D^+ \rightarrow K_S^0 \pi^+ \pi^- \pi^+ \pi^0$ events from MC simulation with a correction factor, 0.72 ± 0.23 , acquired using the same method as in the D^0 channel. The maximum changes of signal yields, 0.9% and 1.2% for the D^0 and D^+ channels, are assigned as the related uncertainties. The uncertainties due to contribution from the nonresonant $D^{0(+)} \rightarrow K_{(S)}^{-(0)} \pi^+ \pi^- \pi^0 e^+ \nu_e$ decays are investigated by adding a nonresonant decay component based on MC simulation in the fit with the related yield floating. The fitted yields are consistent with zero, and the changes in signal yields are negligible. Contributions from nonresonant $\bar{K}\omega$ are also estimated to be negligible. Contributions from other strange

TABLE II. Relative systematic uncertainties, in %, for the BF measurements.

Source	D^0	D^+
$N_{\text{ST}}^{\text{tot}}$	0.3	0.3
MC statistics	0.3	0.3
$\omega \rightarrow \pi^+\pi^-\pi^0$ BF	0.8	0.8
Tracking	1.0	1.8
PID	2.1	1.7
π^0 reconstruction	1.0	1.0
K_S^0 reconstruction	-	1.0
Kinematic requirements	1.5	1.3
2D fit	1.0	2.4
$\bar{K}_1(1270)$ line shape	2.9	5.1
Signal decay model	4.9	5.4
Total	6.5	8.5

resonances, such as $\bar{K}_1(1400)$ and $\bar{K}_2^*(1430)$, are estimated to yield fewer than one event in each channel based on the known BFs or upper limits on the BF of $D \rightarrow \bar{K}_1(1400)/\bar{K}_2^*(1430)e^+\nu_e$ [16,39], and are thus neglected. The listed uncertainties are then combined in quadrature.

The uncertainties from the $\bar{K}_1(1270)$ line shape are estimated by varying the mass of $\bar{K}_1(1270)$ by $\pm 1\sigma$, and changing the width into 146 or 200 MeV and remeasure the signal efficiency. The maximum changes of the signal efficiencies, 2.9% and 5.1% for the D^0 and D^+ channels, are assigned as the uncertainties.

The uncertainties due to the signal decay model are estimated by generating $D^{0(+)} \rightarrow K^-\pi^+\pi^{-(0)}e^+\nu_e$ MC events using the amplitude model from Ref. [16], and applying a gradient-boosted reweighting technique [40] to $D^{0(+)} \rightarrow \bar{K}\omega e^+\nu_e$ MC events at the generator and reconstructed levels, using q^2 , p_{K_1} , and p_e as input variables. The resulting changes in signal efficiencies, 4.9% and 5.4% for the D^0 and D^+ channels, are assigned as the uncertainties.

To determine the $\bar{K}_1(1270)$ mass pole, $m_{\bar{K}_1(1270)}^{\bar{K}\omega}$, we perform a simultaneous unbinned maximum-likelihood fit to the $M_{\bar{K}\pi^+\pi^-\pi^0}$ spectra of the D^0 and D^+ channels in the signal-enhanced region defined by $|U_{\text{miss}}| < 0.1$ GeV and $M_{\pi^+\pi^-\pi^0} \in [0.70, 0.81]$ GeV/ c^2 . The modeling of the backgrounds are the same as in the 2D fits. The numbers of both peaking and other background events are fixed to the integrals of the corresponding probability-density functions in the signal region from the 2D fits, and the signal yields are free to vary. In the $D^{0(+)}$ channel, the signal shape is described by the shape from simulated signal events, and convolved with a Gaussian function $\mathcal{G}(M_{\bar{K}\pi^+\pi^-\pi^0}; m_0, \sigma_{D^{0(+)}})$. Here, m_0 is shared between the D^0 and D^+ channels to measure the pole position, $m_{\bar{K}_1(1270)}^{\bar{K}\omega} = m_{\text{input}} + m_0$, with m_{input} being the input $\bar{K}_1(1270)$ mass for the signal MC samples, while the widths $\sigma_{D^{0(+)}}$ are allowed to vary independently. The signal MC samples for both channels are iteratively updated with m_{input} shifted by the fitted m_0 central value from the prior iteration until $|m_0|$ becomes negligible (within 10% of its uncertainty). We measure $m_{\bar{K}_1(1270)}^{\bar{K}\omega} = (1336 \pm 9 \pm 2)$ MeV/ c^2 , where the first uncertainty is statistical and the second systematic. The systematic uncertainty from signal modeling is estimated by reproducing the signal MC samples based on different input widths of $\bar{K}_1(1270)$, 146 or 200 MeV, and rerunning the simultaneous fit with updated signal line shapes. The maximum change of the fitted Gaussian mean, 0.5 MeV/ c^2 , is taken as the uncertainty. The systematic uncertainty from background modeling, 1.5 MeV/ c^2 , is estimated by changing background shapes and varying the background yields. To study the uncertainty from possible detector effects, the same strategy is applied to measure the mass pole of $K^*(892)^-$ with a

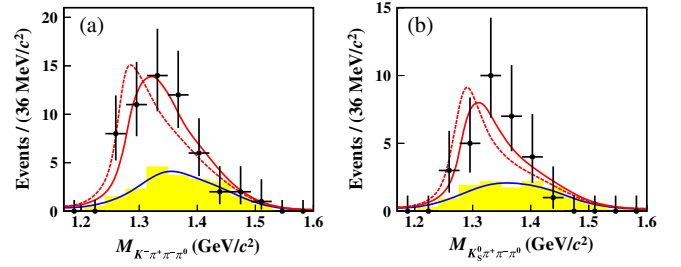


FIG. 2. The $M_{\bar{K}\pi^+\pi^-\pi^0}$ distributions of the accepted candidates for the (a) D^0 and (b) D^+ channels. The points with error bars are data. The yellow histograms and the blue curves denote the estimated contributions and kernel-estimation functions based on the inclusive MC samples, respectively. The red dashed and solid curves denote the total distributions with signal components modeled from signal MC samples with m_{input} set at 1272 and 1336 MeV/ c^2 , respectively.

high-statistics control sample of $D^0 \rightarrow K^-\pi^0 e^+\nu_e$. The difference of our measurement with the known $K^*(892)^-$ mass [22], 0.3 MeV/ c^2 , is taken as the uncertainty. The total systematic uncertainty is obtained by summing the individual contributions in quadrature. Requiring $|U_{\text{miss}}| < 0.1$ GeV and $M_{\pi^+\pi^-\pi^0} \in [0.70, 0.81]$ GeV/ c^2 , the $M_{\bar{K}\pi^+\pi^-\pi^0}$ distributions of the accepted candidates for $D^{0(+)} \rightarrow K_{(S)}^{-(0)}\omega e^+\nu_e$ are shown in Fig. 2. The data distributions are consistent with MC predictions that include only signals from $D^{0(+)} \rightarrow \bar{K}_1(1270)e^+\nu_e$. The final signal MC samples with the input $\bar{K}_1(1270)$ mass determined by this analysis offer significantly improved description of the data $\bar{K}_1(1270)$ line shapes than those from signal MC samples generated with the $\bar{K}_1(1270)$ mass set at 1272 MeV/ c^2 .

Assuming the $\bar{K}_1(1270)$ to be the sole mediating resonance in the $D^{0(+)} \rightarrow \bar{K}\pi\pi e^+\nu_e$ and $D^{0(+)} \rightarrow \bar{K}\omega e^+\nu_e$ decays, the branching ratios are determined to be $\gamma_{D^0} \equiv \{\Gamma(K_1(1270)^- \rightarrow K^-\pi^+\pi^-)/[\Gamma(K_1(1270)^- \rightarrow K^-\omega)]\} = \{[\mathcal{B}(D^0 \rightarrow K^-\pi^+\pi^-e^+\nu_e)]/[\mathcal{B}(D^0 \rightarrow K^-\omega e^+\nu_e)]\} = 3.4^{+0.8}_{-0.7} \pm 0.3$ and $\gamma_{D^+} \equiv \{\Gamma(\bar{K}_1(1270)^0 \rightarrow K^-\pi^+\pi^0)/[\Gamma(\bar{K}_1(1270)^0 \rightarrow \bar{K}^0\omega)]\} = \{[\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^0 e^+\nu_e)]/[\mathcal{B}(D^+ \rightarrow K_S^0\omega e^+\nu_e)]\} = 7.9^{+2.4}_{-2.1} \pm 0.7$, where the BF of $D^{0(+)} \rightarrow K^-\pi^+\pi^{-(0)}e^+\nu_e$ are taken from Ref. [16]. Following the formalism in Ref. [16], by applying isospin relations and neglecting the insignificant contributions from decays other than $\bar{K}_1(1270) \rightarrow K^*(892)\pi$, $K\rho$, and $K\omega$, the BF of $K_1(1270)^- \rightarrow K^-\pi^+\pi^-$ and $\bar{K}_1(1270)^0 \rightarrow K^-\pi^+\pi^0$ are written as $\mathcal{B}[K_1(1270)^- \rightarrow K^-\pi^+\pi^-] = \{(3+4\alpha)/[9(1+\alpha)]\}\mathcal{B}[\bar{K}_1(1270) \rightarrow \bar{K}\pi\pi]$ and $\mathcal{B}[\bar{K}_1(1270)^0 \rightarrow K^-\pi^+\pi^0] = \{(6+4\alpha)/[9(1+\alpha)]\}\mathcal{B}[\bar{K}_1(1270) \rightarrow \bar{K}\pi\pi]$. Here, $\mathcal{B}[\bar{K}_1(1270) \rightarrow \bar{K}\pi\pi] = 1 - \mathcal{B}[\bar{K}_1(1270) \rightarrow \bar{K}\omega]$ is the BF of $\bar{K}_1(1270)$ decay into $\bar{K}\pi\pi$ final states and $\alpha = \{(\mathcal{B}[\bar{K}_1(1270) \rightarrow \bar{K}^*(892)\pi])/(\mathcal{B}[\bar{K}_1(1270) \rightarrow \bar{K}\rho])\} = (20.3 \pm 2.1 \pm 8.7)\%$ [16]. Finally, we have $\mathcal{B}[K_1(1270)^- \rightarrow K^-\omega] = ((\gamma_{D^0})\{[9(1+\alpha)]/(3+4\alpha)\} +$

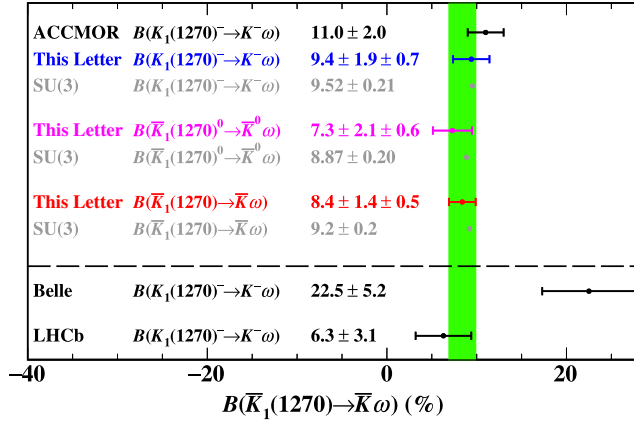


FIG. 3. Comparison of the BF of $\bar{K}_1(1270) \rightarrow \bar{K}\omega$ obtained in this Letter with the previous measurements from ACCMOR [23], Belle [24], and LHCb [25], as well as the prediction from SU(3) flavor analysis [41]. The green band shows our combined $B[\bar{K}_1(1270) \rightarrow \bar{K}\omega]$. The uncertainties of the Belle and LHCb measurements are statistical only.

$1)^{-1} = (9.4 \pm 1.9 \pm 0.7)\%$ and $B[\bar{K}_1(1270)^0 \rightarrow \bar{K}^0 \omega] = ((\gamma_{D^+})\{[9(1+\alpha)]/(6+4\alpha)\} + 1)^{-1} = (7.3 \pm 2.1 \pm 0.6)\%$.

In summary, using 20.3 fb^{-1} of e^+e^- collision data taken at $\sqrt{s} = 3.773 \text{ GeV}$ with the BESIII detector, we report the first observation of $D^0 \rightarrow K^- \omega e^+ \nu_e$ and $D^+ \rightarrow K_S^0 \omega e^+ \nu_e$ with significances of 8.0σ and 5.8σ , respectively, after accounting for systematic uncertainties. Their decay BFs are measured to be $B(D^0 \rightarrow K^- \omega e^+ \nu_e) = (9.4^{+2.0}_{-1.8} \pm 0.6) \times 10^{-5}$ and $B(D^+ \rightarrow K_S^0 \omega e^+ \nu_e) = (8.0^{+2.4}_{-2.1} \pm 0.7) \times 10^{-5}$. These decays are consistent with being mediated through a sole $\bar{K}_1(1270)$ resonance. We determine $B[K_1(1270)^- \rightarrow K^- \omega] = (9.4 \pm 1.9 \pm 0.7)\%$ and $B[\bar{K}_1(1270)^0 \rightarrow \bar{K}^0 \omega] = (7.3 \pm 2.1 \pm 0.6)\%$. The $\bar{K}_1(1270)^0 \rightarrow \bar{K}^0 \omega$ decay is observed for the first time. Under the assumption of isospin symmetry, the combined BF of $\bar{K}_1(1270) \rightarrow \bar{K}\omega$ is determined to be $(8.4 \pm 1.4 \pm 0.5)\%$. Correlations among the systematic uncertainties are neglected as the total uncertainties are dominated by the statistical components. Our combined $B[\bar{K}_1(1270) \rightarrow \bar{K}\omega]$ is consistent with the only measurement [23] quoted by the particle data group with comparable precision, and consistent with the prediction from SU(3) flavor analysis [41]. The comparison of our result with the previous measurements and the theoretical prediction is shown in Fig. 3. Furthermore, we determine $m_{\bar{K}_1(1270)}^{\bar{K}\omega} = (1336 \pm 9 \pm 2) \text{ MeV}/c^2$, which is significantly higher than $m_{\bar{K}_1(1270)}^{\bar{K}\pi\pi} = (1271 \pm 3 \pm 7) \text{ MeV}/c^2$ from $\bar{K}_1(1270) \rightarrow \bar{K}\pi\pi$ decays [16]. This difference is naturally expected in the two-pole scenario: the $\bar{K}\pi\pi$ system receives contributions from both mass poles, while the $\bar{K}\omega$ channel predominantly isolates the higher pole. The measured value is also larger than the theoretical higher pole of $\sim 1284 \text{ MeV}/c^2$ [20], indicating that the $\bar{K}\omega$ channel may probe the higher pole

with additional dynamical effects not fully captured in current models. Our result thus provides unique experimental support for the two-pole structure of the $\bar{K}_1(1270)$ resonance and offers valuable input for refining its theoretical description. This Letter is expected to inspire future $\bar{K}_1(1270)$ -related studies in decays such as $\bar{B} \rightarrow \bar{K}\omega\gamma$ and $\bar{B} \rightarrow \bar{K}\omega\ell^+\ell^-$.

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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