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Observation of a New $X(3872)$ Production Process $e^+e^- \to \omega X(3872)$

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Using 4.7 fb^{-1} of e^+e^- collision data at center-of-mass energies from 4.661 to 4.951 GeV collected by the BESIII detector at the BEPCII collider, we observe the $X(3872)$ production process $e^+e^- \to \omega X(3872)$ for the first time. The significance is 7.8σ, including both the statistical and systematic uncertainties. The $e^+e^- \to \omega X(3872)$ Born cross section and the corresponding upper limit at 90% confidence level at each

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energy point are reported. The line shape of the cross section indicates that the $\omega X(3872)$ signals may be from the decays of some nontrivial structures.

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A number of experimentally observed quarkoniumlike states do not fit within the conventional quarkonium spectrum and are thus popular candidates for exotic hadrons. As the first experimentally observed quarkoniumlike state in this category, the $X(3872)$ was found by Belle in the decay $B^\pm \to K^\pm \pi^+\pi^- J/\psi$ in 2003 [1]. It was subsequently confirmed by other experiments [2–4]. After two decades of studies, its resonance parameters and quantum numbers are well measured. The mass and width are determined to be $M = 3871.65 \pm 0.06$ MeV$/c^2$ and $\Gamma = 1.19 \pm 0.21$ MeV, and the spin, parity, and C-parity quantum numbers are $J^{PC} = 1^{++}$ [5–8]. The nature of this particle, however, is still not well understood. Because of the proximity of its mass to the $D^{*0}\bar{D}^0$ + c.c. mass threshold, it is conjectured to have a large $D^{*0}\bar{D}^0$ + c.c. molecular component [9]. The 2^3P_1 conventional charmonium state $\chi_{c1}(2P)$ with $J^{PC} = 1^{++}$ is another possible interpretation.

In addition to exploring the $X(3872)$ via its decays, studying its production mechanisms is another way to investigate its internal structure. Besides its production in B meson decays, the $X(3872)$ was also observed in the process $e^+e^- \to \gamma X(3872)$ at BESIII [10]. According to the analysis of the line shape of the $e^+e^- \to \gamma X(3872)$ cross section, the $X(3872)$ is produced through the radiative transition $Y(4230) \to \gamma X(3872)$. Large production rates are also observed in prompt production in pp and $p\bar{p}$ collisions [4,11–13], with rates comparable to the production rates for conventional charmonium states, which suggests the $X(3872)$ may include a conventional charmonium $\chi_{c1}(2P)$ component. Therefore, searching for new production mechanisms will provide vital information to unravel the mysterious nature of the $X(3872)$. The hadronic transitions to the spin-triplet charmonium states $\chi_{cJ}(1P)$ via $e^+e^- \to \omega\chi_{cJ}(1P)$ $(J = 0, 1, 2)$ have been observed at BESIII [14–16]. If the $X(3872)$ contains a component of the excited spin-triplet charmonium state $\chi_{c1}(2P)$, the process $e^+e^- \to \omega X(3872)$ could exist. As the center-of-mass energy ($\sqrt{s}$) threshold to produce $\omega X(3872)$ is about 4.654 GeV, the e^+e^- annihilation data samples taken at BESIII above this production threshold offer an excellent opportunity to search for this process.

In this Letter, we report the first observation of the new $X(3872)$ production process $e^+e^- \to \omega X(3872)$. The significance is 7.5σ, which includes both the statistical and systematic uncertainties. We use 4.7 fb^{-1} of e^+e^- annihilation data at $\sqrt{s}$ from 4.661 to 4.951 GeV collected by the BESIII detector. We reconstruct the signal process using the decays $X(3872) \to \pi^+\pi^- J/\psi$, $J/\psi \to \ell^+\ell^-$ $(\ell = e, \mu)$, $\omega \to \pi^+\pi^-\pi^0$, and $\pi^0 \to \gamma\gamma$.

The BESIII detector [17] has an effective geometrical acceptance of 93% of 4π. A helium-based main drift chamber (MDC) in a 1 T magnetic field measures the momentum and the energy loss (dE/dx) of charged particles. The resolution of the momentum is about 0.5% at 1 GeV$/c$, and the resolution of the dE/dx is better than 6%. An electromagnetic calorimeter (EMC) is used to measure energies and positions with an energy resolution of 2.5% in the barrel and 5.0% in the end caps for 1.0 GeV photons. A time-of-flight system with a time resolution of 80 ps (110 ps) in the barrel (end cap) is used for particle identification together with dE/dx. A muon chamber (MUC) based on resistive plate chambers with 2 cm position resolution provides information for muon identification.

Monte Carlo (MC) samples, simulated using GEANT4-based [18] software, are used to optimize the selection criteria, determine the detection efficiency, and study the potential backgrounds. The inclusive MC samples, which include open-charm hadronic processes, continuum processes, and the effects due to initial state radiation (ISR), are generated with KKMC [19] in conjunction with EVTGEN [20]. The signal MC samples, $e^+e^- \to \omega X(3872)$, $X(3872) \to \rho^0 J/\psi$, $\rho^0 \to \pi^+\pi^-$, $J/\psi \to \ell^+\ell^-$ $(\ell = e, \mu)$, $\omega \to \pi^+\pi^-\pi^0$, and $\pi^0 \to \gamma\gamma$, are generated with the final state radiation (FSR) simulated by PHOTOS [21]. Each track is required to have its point of closest approach to the beamline within 1 cm in the radial direction and within 10 cm from the interaction point along the beam direction, and to lie within the polar-angle coverage of the MDC, $|\cos\theta| < 0.93$, in the laboratory frame. Photons are reconstructed from isolated showers in the EMC, which are at least 10 deg away from any track. The EMC energy is at least 25 MeV in the barrel ($|\cos\theta| < 0.80$) and 50 MeV in the end caps ($0.86 < |\cos\theta| < 0.92$). In order to suppress electronic noise and energy deposits unrelated to the event, the EMC time t of the photon candidate must be in coincidence with collision events in the range $0 \le t \le 700$ ns.

The final state of the signal process includes six charged tracks (a lepton pair and four charged pions) and two photons. In order to improve the detection efficiency, candidate events with five or six reconstructed charged tracks are both retained. Since the leptons from the J/ψ decay have higher momentum than the pions, the momentum information is used to separate the leptons from pions. Two charged particles with momenta greater than 1.0 GeV$/c$ and opposite charges are identified as the lepton pair from the J/ψ decay, and the remaining tracks are each assigned a pion hypothesis. Electrons and muons are discriminated by requiring their deposited energies in the EMC to be greater than 0.8 GeV and less than 0.4 GeV, respectively. In order to suppress the continuum background, at least one muon from $J/\psi \to \mu^+\mu^-$ needs to penetrate more than three layers of the MUC. As the pions are either from the $X(3872)$ or ω and the combinatorial background shows smooth distributions in the signal regions according to a study with signal MC, all possible combinations are retained.

For the candidate events with six charged particles, the net charge is required to be zero and at least one photon is required. Instead of reconstructing the two photons from a π^0 decay directly, a kinematic fit is applied to constrain the recoiling invariant mass of the four pions and the lepton pair against the initial e^+e^- collision system to the known π^0 mass [5]. The four-momentum of the nonreconstructed π^0 is calculated from the kinematic fit. The χ^2 of the one-constraint kinematic fit is required to be less than 15. The selection criteria are optimized by maximizing $S/\sqrt{S+B}$, where the number of signal events (S) is determined with the signal MC sample based on the yield observed with an unoptimized selection in data, and the background (B) is estimated with an inclusive MC sample. After applying these requirements, a clear signal peak is seen in the distribution of the lepton pair invariant mass $M(\ell^+\ell^-)$. The J/ψ mass window is set to be $3.07 < M(\ell^+\ell^-) < 3.13\ \mathrm{GeV}/c^2$, and the sideband regions are defined as $2.96 < M(\ell^+\ell^-) < 3.05\ \mathrm{GeV}/c^2$ and $3.15 < M(\ell^+\ell^-) < 3.24\ \mathrm{GeV}/c^2$ with a width of three times the J/ψ mass window to estimate the non-J/ψ backgrounds. The main backgrounds are processes including an η or $\psi(2S)$ in the final states, e.g., $e^+e^- \to (\gamma_{\mathrm{ISR}})\pi^+\pi^-\psi(2S)$, $\psi(2S) \to \pi^+\pi^-J/\psi$ or $\eta J/\psi$. These backgrounds are reduced by requiring all charged track combinations have $M(\pi^+\pi^-\pi^0)$ and $M(\pi^+\pi^-J/\psi)$ outside the η and $\psi(2S)$ mass windows $[0.52, 0.58]\ \mathrm{GeV}/c^2$ and $[3.680, 3.692]\ \mathrm{GeV}/c^2$, respectively. The efficiency varies from 18.1% to 22.0% at different energy points. To improve the resolution, $M(\pi^+\pi^-J/\psi)$ is defined as $M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) + m(J/\psi)$, where $m(J/\psi)$ is the known J/ψ mass [5].

For signal candidates with one undetected charged pion, only five charged tracks are reconstructed. In this case, the net charge must be ±1, and at least two photons must be found. A two-constraint kinematic fit is applied to these events. The invariant mass of the two photons $M(\gamma\gamma)$ is constrained to the known π^0 mass [5], and the recoiling mass of the five tracks and the π^0 against the e^+e^- initial collision momentum is constrained to the known π^+ mass [5]. If there are more than two photons in an event, the combination with the minimum χ^2 from the kinematic fit is chosen. The χ^2 is required to be less than 25. The main backgrounds, after placing these requirements, are similar to the six-track case, and are suppressed using the same criteria. The inclusive MC sample, which is five times larger than the data sample, is used to study the backgrounds for the five- and six-track cases [22]. The remaining backgrounds are mainly from continuum processes, and no peaking background is observed. The efficiency varies from 5.7% to 7.1% at different energy points for the five-track case.

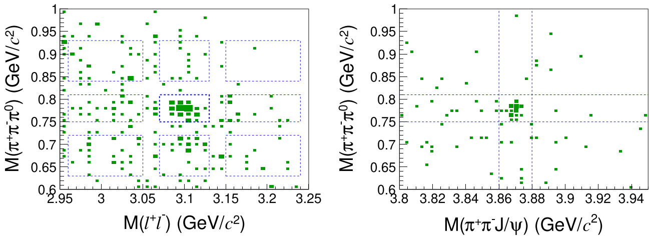

FIG. 1. Distributions of $M(\pi^+\pi^-\pi^0)$ versus $M(\ell^+\ell^-)$ (left) and $M(\pi^+\pi^-\pi^0)$ versus $M(\pi^+\pi^-J/\psi)$ (right) from the data samples at $\sqrt{s} = 4.661$–4.951 GeV. The central dashed box in the left plot indicates the ω and J/ψ signal regions, and the other boxes show the two-dimensional ω and J/ψ sideband regions. The dashed lines in the right plot denote the ω and $X(3872)$ signal regions after imposing the J/ψ selection.

After applying all the selection requirements, Fig. 1 shows the distribution of $M(\pi^+\pi^-\pi^0)$ versus $M(\ell^+\ell^-)$ and $M(\pi^+\pi^-\pi^0)$ versus $M(\pi^+\pi^-J/\psi)$ with the combinations of the five- and six-track candidates from the data samples taken at $\sqrt{s} = 4.661$–4.951 GeV. The presence of the $e^+e^- \to \omega X(3872)$ signals can be seen around the intersection of the ω and $X(3872)$ signal regions. The ω candidates are required to have $M(\pi^+\pi^-\pi^0)$ within the ω mass window $[0.75, 0.81]\ \mathrm{GeV}/c^2$, and the ω sideband regions are defined as $[0.63, 0.72]\ \mathrm{GeV}/c^2$ and $[0.84, 0.93]\ \mathrm{GeV}/c^2$, which are three times the signal region size. The sidebands are used to estimate the non-ω backgrounds. Figure 2 shows the $M(\pi^+\pi^-J/\psi)$ distribution after imposing the ω signal selection. A clear peak is seen around the $X(3872)$ signal region. The two-dimensional ω and J/ψ sidebands are used to check the backgrounds in the $X(3872)$ region as shown in Fig. 2, which illustrates a flat distribution.

To determine the $X(3872)$ signal yield and mass, an unbinned maximum likelihood fit is performed. The signal shape is determined by the signal MC sample with an input mass (m_{input}) of $3871.7\ \mathrm{MeV}/c^2$ [5]. The process $e^+e^- \to \gamma_{\mathrm{ISR}}\pi^+\pi^-\psi(2S)$, $\psi(2S) \to \pi^+\pi^-J/\psi$ is used to calibrate the discrepancies in mass (Δm) and resolution ($\Delta\sigma$) between data and the MC simulation which are found to be $-0.5 \pm 0.2\ \mathrm{MeV}/c^2$ and 0.8 ± 0.3 MeV, respectively. The signal MC shape is convolved with a Gaussian function $G(m_g, \sigma_g)$ where m_g is free and σ_g is fixed to $\Delta\sigma$ in the fit. The background is described with a linear function with free parameters. The fit result is shown in Fig. 2. The signal yield is 24.6 ± 5.3, and $m_g = -2.0 \pm 0.7\ \mathrm{MeV}/c^2$. Then, the $X(3872)$ mass is measured

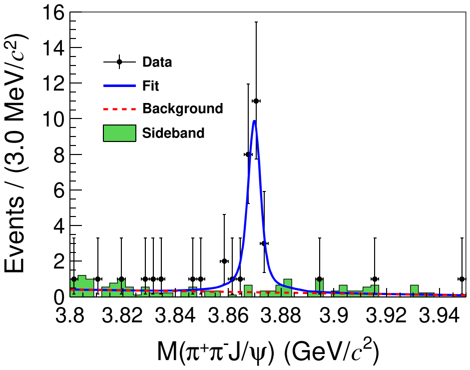

FIG. 2. Fit to the $M(\pi^+\pi^-J/\psi)$ distribution. The points with error bars are data, the solid curve is the fit result, the dashed line is the background component, and the filled histogram represents events from the ω and J/ψ two-dimensional sidebands.

to be $m_x = m_{\rm input} + m_g - \Delta m = 3870.2 \pm 0.7$ MeV/c^2, where the error is statistical only. Two additional background models are checked in the fit. One is to firstly fit the lower mass region [3.8, 3.85] GeV/c^2 with a linear function and the upper mass region [3.89, 3.95] GeV/c^2 with a flat distribution, respectively, and then extract the distribution of the background in the signal region with a linear interpolation between the two fitting functions, and another is a third-order polynomial function. A point-to-point dissimilarity method is applied to test the goodness of fit [23]. The yielded p values corresponding to the three background models are 0.93, 0.94, and 0.82, respectively, which indicate good agreement between the data and the fit results.

The significance is estimated by comparing the difference of log-likelihood values $\Delta(-2\ln\mathcal{L})$ with and without the $X(3872)$ signal in the fit, and taking the change in the number of degrees of freedom Δndf into account. Various fit schemes, e.g., different fitting ranges and background models, are applied to extract the significance. We take the obtained smallest value 7.8σ as the significance in consideration of the systematic uncertainties. The systematic uncertainty of the mass measurement is mainly caused by the Δm error (0.2 MeV/c^2). The uncertainty due to the mass shift in simulation is assigned to be 0.1 MeV/c^2 according to study the signal MC sample. The uncertainties from the fit are estimated by changing different fit schemes, and obtained to be 0.1 MeV/c^2 in total. The total uncertainty of the $X(3872)$ mass measurement is 0.3 MeV/c^2 by summing all these uncertainties assuming they are independent.

The $e^+e^- \to \omega X(3872)$ Born cross section is calculated by

$$\sigma^B = \frac{N_{\rm sig}}{\mathcal{L}_{\rm int}\mathcal{B}_1(\epsilon_{ee}\mathcal{B}_{ee} + \epsilon_{\mu\mu}\mathcal{B}_{\mu\mu})(1+\delta)\frac{1}{|1-\Pi|^2}}, \qquad (1)$$

where $N_{\rm sig}$ is the number of signal events; $\mathcal{L}_{\rm int}$ is the integrated luminosity; ϵ_{ee} and $\epsilon_{\mu\mu}$ are the detection efficiencies of the electron and muon modes, respectively; $\mathcal{B}_{ee}$ and $\mathcal{B}_{\mu\mu}$ are the branching fractions of $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$, respectively; $\mathcal{B}_1$ is the product of the branching fractions of $\omega \to \pi^+\pi^-\pi^0$ and $X(3872) \to \pi^+\pi^-J/\psi$; $(1+\delta)$ is the ISR correction factor obtained by using a QED calculation [24] iteratively by taking the measured cross section in this analysis as an input; and $(1/|1-\Pi|^2) = 1.055$ is the vacuum polarization factor taken from QED with an accuracy of 0.05% [25]. All branching fractions are taken from Ref. [5].

Because of the limited statistics, the signal yield ($N_{\rm sig}$) at each energy point is determined by counting the number of events in the $X(3872)$ signal region [3.86, 3.88] GeV/c^2. The background has been subtracted, which is estimated by using the $X(3872)$ sidebands [3.81, 3.84] GeV/c^2 and [3.91, 3.94] GeV/c^2. Only the [3.81, 3.84] GeV/c^2 sideband region is used at $\sqrt{s} = 4.661$ GeV since $M(\pi^+\pi^-J/\psi)$ has a maximum allowed value of 3.914 GeV/c^2 at that energy. The measured $N_{\rm sig}$ and σ^B at each energy point are listed in Table I. The statistical significance and the upper limits of σ^B ($\sigma^B_{\rm up}$) at the 90% confidence level at various energy points are calculated using a frequentist method with an unbounded profile likelihood treatment by assuming the numbers of observed events in the $X(3872)$ signal and sideband regions follow a Poisson distribution [26].

The systematic uncertainties of the Born cross section measurement mainly originate from the detection efficiency, the ISR correction factor, the method of signal extraction, the integrated luminosity, and the branching fraction of $X(3872) \to \pi^+\pi^-J/\psi$. The sources of the uncertainty from the detection efficiency include the tracking, the photon reconstruction, the kinematic fit, the J/ψ mass window, the muon selection, and the signal generation model. The systematic uncertainty due to tracking is estimated with the process $e^+e^- \to \pi^+\pi^-J/\psi$ to be 1.0% per track [27]. The uncertainty of the photon reconstruction efficiency is assigned to be 1.0% per photon from the study of the process $J/\psi \to \rho^0\pi^0$ [28]. The uncertainties caused by the kinematic fit, the J/ψ mass selection, and the muon selection with the MUC are studied with the control sample of $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$, $\psi(2S) \to \pi^+\pi^-J/\psi$. The corresponding uncertainties are 2.8%, 4.2%, and 1.3%, respectively. The efficiencies are calculated with the signal MC samples generated with a phase space model which is flat in the distributions of ω and ρ^0 helicity angles. The uncertainty caused by the generation model and the $\eta/\psi(2S)$ veto is estimated by varying the distributions of the ω and ρ^0 helicity angles θ to be $1 \pm \cos^2\theta$. The uncertainties are found to be (0.1–1.7)%. The signal yield at each energy point is obtained with the counting method; a 1.6% uncertainty is assigned

TABLE I. Summary of the integrated luminosities ($\mathcal{L}_{\text{int}}$), the signal yields (N_{sig}), the product of average efficiency [$\epsilon = (\epsilon_{ee} + \epsilon_{\mu\mu})/2$] and the ISR correction factor $(1+\delta)$, the obtained $e^+e^- \to \omega X(3872)$ Born cross section or its upper limit (σ^B_{up}), and statistical significances at various energy points. The first uncertainties of the Born cross sections are statistical, the second are systematic, and the third are the uncertainties caused by the branching fraction of $X(3872) \to \pi^+\pi^- J/\psi$.

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\text{int}}(\text{pb}^{-1})$	N_{sig}	$\epsilon(1+\delta)$ (%)	$\sigma^B(pb)$	$\sigma^B_{\text{up}}(pb)$	Significance
4.661	529.63	$0.33^{+1.36}_{-0.33}$	28.3	$0.5^{+2.1}_{-0.5} \pm 0.1 \pm 0.2$	5.6	⋯
4.682	1669.31	$8.00^{+3.34}_{-2.68}$	24.6	$4.6^{+1.9}_{-1.5} \pm 0.4 \pm 1.5$	11.5	3.4σ
4.699	536.45	$0.00^{+0.95}_{-0.00}$	27.0	$0.0^{+1.6}_{-0.0} \pm 0.0 \pm 0.0$	3.3	⋯
4.740	164.27	$1.67^{+1.77}_{-1.10}$	21.8	$10.9^{+11.6}_{-7.2} \pm 1.0 \pm 3.5$	40.6	1.0σ
4.750	367.21	$5.00^{+2.58}_{-1.92}$	22.4	$14.2^{+7.4}_{-5.5} \pm 1.4 \pm 4.5$	38.2	3.1σ
4.781	512.78	$1.00^{+1.36}_{-0.70}$	31.6	$1.5^{+2.0}_{-1.0} \pm 0.2 \pm 0.5$	6.5	0.7σ
4.843	527.29	$4.67^{+2.58}_{-1.92}$	26.7	$7.8^{+4.3}_{-3.2} \pm 0.7 \pm 2.5$	21.1	2.6σ
4.918	208.11	$1.00^{+1.36}_{-0.70}$	22.6	$5.0^{+6.8}_{-3.5} \pm 0.4 \pm 1.6$	21.7	0.7σ
4.951	160.37	$0.00^{+0.95}_{-0.00}$	20.4	$0.0^{+6.8}_{-0.0} \pm 0.0 \pm 0.0$	14.7	⋯

comparing to that obtained with an alternative fit method at $\sqrt{s} = 4.684$ GeV. The uncertainty due to the ISR correction factor is estimated by scaling the initial input observed line shape within one statistical uncertainty, and the relative difference of the efficiency compared to the nominal scheme is taken as the uncertainty, which varies from 1.4% to 12.0% at different energy points. The integrated luminosity is measured with the Bhabha scattering process with an uncertainty of 1.0% [29]. The total systematic uncertainty at each energy point is obtained by adding all these systematic uncertainties in quadrature. The systematic uncertainties discussed above are summarized in Table II. The uncertainty caused by the branching fraction of $X(3872) \to \pi^+\pi^- J/\psi$ is 31.6% [5], which is listed as a separate uncertainty in the Born cross section.

In summary, based on data samples at $\sqrt{s} = 4.661$–4.951 GeV with a total integrated luminosity of 4.7 fb^{-1} collected by the BESIII detector, a new $X(3872)$ production process $e^+e^- \to \omega X(3872)$ is observed for the first time. The significance is 7.8σ, including the statistical and systematic uncertainties. The measured $X(3872)$ mass is $3870.2 \pm 0.7 \pm 0.3\ \text{MeV}/c^2$. The $e^+e^- \to \omega X(3872)$ Born cross section and the corresponding upper limit at the 90% confidence level at each energy point are reported. The line shape of the cross section indicates that the observed $\omega X(3872)$ signals may be from decays of some nontrivial structures. The production mechanisms of the $X(3872)$ provide crucial information about its properties. The observation of a new production process $e^+e^- \to \omega X(3872)$, combined with the observation of the $X(3872)$ in other production mechanisms, offers an additional window into the composition of the $X(3872)$.

TABLE II. Relative systematic uncertainties (in %) in the Born cross section measurements at various energy points. The uncertainties caused by the integrated luminosity ($\sigma_{\mathcal{L}}$), the detection efficiency (σ_ϵ), the ISR correction factor (σ_{ISR}), the method of signal extraction (σ_{sig}), and their sum in quadrature (σ_{sum}) are listed.

$\sqrt{s}$ (GeV)	$\sigma_{\mathcal{L}}$	σ_ϵ	σ_{ISR}	σ_{sig}	σ_{sum}
4.661	1.0	8.1	5.0	1.6	9.7
4.682	1.0	8.1	2.3	1.6	8.6
4.699	1.0	8.1	12.0	1.6	14.6
4.740	1.0	8.1	4.3	1.6	9.4
4.750	1.0	8.2	5.4	1.6	10.0
4.781	1.0	8.3	12.2	1.6	14.9
4.843	1.0	8.3	1.4	1.6	8.6
4.918	1.0	8.4	1.2	1.6	8.7
4.951	1.0	8.5	0.5	1.6	8.7

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