New narrow resonance in the $e^+e^- \to \phi\eta$ data by the Belle collaboration

Peter Lichard

Institute of Physics and Research Centre for Computational Physics and Data Processing, Silesian University in Opava, 746 01 Opava, Czech Republic and Institute of Experimental and Applied Physics, Czech Technical University in Prague, 128 00 Prague, Czech Republic

(Received 19 September 2023; accepted 24 October 2023; published 15 November 2023)

Fitting the recent $e^+e^- \to \phi\eta$ data by the Belle Collaboration with a theoretical formula reveals, besides the dominant $\phi(1680)$ resonance, two narrow resonances: expected $\phi(2170)$ resonance and an unexpected resonance with the mass of about 1851 MeV. Close proximity to the $X(1835)$ resonance suggests that the new resonance may be interpreted as the $p\bar{p}$ baryonium in an excited state. Follow-up analysis found the same resonance also in $e^+e^- \to \omega\eta$ data by the CMD-3 experiment.

DOI: 10.1103/PhysRevD.108.092005

Recently, a study of the $e^+e^- \to \eta\phi$ process with the Belle detector at the KEKB asymmetric-energy e^+e^- collider has been published [1]. Experimentalists explored the initial state radiation method and covered the e^+e^- invariant energy range from 1.56 to 3.96 GeV in 120 bins. The published values of the $e^+e^- \to \eta\phi$ cross section are accompanied by statistical and systematic errors.

As the members of the Belle Collaboration stated in the Introduction, one of the experiment's goals was to study the properties of the $\phi(2170)$ resonance. This resonance was discovered in 2006 by the *BABAR* Collaboration at the Stanford Linear Accelerator Center in the $e^+e^- \to \phi f_0(980)$ reaction [2] and later confirmed by several experiments in various processes. Of those, we list two that confirmed the $\phi(2170)$ resonance in the e^+e^- annihilation into the $\eta(547)\phi(1020)$ system: *BABAR* [3] and BESIII experiment [4] at the Beijing Electron Positron Collider.

When analyzing their cross-section data, the Belle Collaboration first fit them by assuming one resonance. They got the parameters of the dominant $\phi(1680)$ resonance correctly, see Table 1 in [1], even if the quality of the fit was not excellent [$\chi^2/\mathrm{NDF} = 85/60$, which translates to confidence level (CL) of 2%]. Then, they used a phenomenological fitting procedure tailored for two resonances to find the signs of the $\phi(2170)$ resonance. Again, the parameters of the dominant $\phi(1680)$ resonance were varied, whereas those of the other resonance were fixed at the values obtained for $\phi(2170)$ by BESIII Collaboration [4]. No significant $\phi(2170)$ signal was found.

To investigate the reason for this conundrum, we decided to perform our own analysis of the Belle [1] cross-section data based on a theoretical formula capable of handling, in principle, any number of resonances.

For the description of the electron-positron annihilation into the vector meson ϕ and pseudoscalar meson η, we use a vector meson dominance (VMD) model based on the Feynman diagram depicted in Fig. 1 and the interaction Lagrangian

$$\mathcal{L}_{V\phi\eta}(x) = \frac{g_{V\phi\eta}}{m_V}\epsilon_{\mu\nu\rho\sigma}\partial^\mu V^\nu(x)\partial^\rho\phi^\sigma(x)\eta(x),$$

where particle symbols denote the corresponding quantum fields. The γV junction is parametrized as eM_V^2/g_V in analogy with the $\gamma\rho^0$ junction $eM_{\rho^0}^2/g_\rho$. Further, we define dimensionless quantity $r = g_{V\phi\eta}/g_V$. When we consider several intermediate vector mesons V_i, the $e^+e^- \to \phi\eta$ cross section comes out as

$$\sigma = \frac{\pi\alpha^2}{6}\frac{\lambda^{3/2}(s)(s+2z)}{s^3\sqrt{s(s-4z)}}\left|\sum_{i=1}^{n}\frac{r_i M_i e^{\mathrm{i}\delta_i}}{s - M_i^2 + \mathrm{i}M_i\Gamma_i}\right|^2, \qquad (1)$$

where $x = m_\phi^2$, $y = m_\eta^2$, $z = m_e^2$, $\lambda(s) = s^2 + x^2 + y^2 - 2sx - 2sy - 2xy$, and $\delta_1 = 0$.

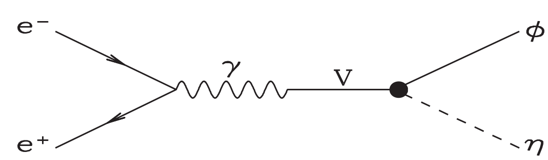

FIG. 1. Feynman diagram defining our VMD model.

Performing the fits with one or two resonances, we got similar results as Belle Collaboration. One-resonance fit yielded a resonance with parameters close to those listed by the Particle Data Group (PDG) [5] for the $\phi(1680)$ [6].

When doing the fit with two resonances, we did not fix the mass and width of one of them to the expected $\phi(2170)$ values, which the Belle Collaboration did. Even thus, we got a clear signal of only one resonance, namely, $\phi(1680)$. The parameters of the second one do not correspond to any conceivable resonance. They reflect the effort of the minimalization program [7] to bring the theoretical curve closer to the data in the vast region around 1920 MeV.

However, when we allowed three resonances, the situation drastically changed. The quality of the fit increased to CL = 90.4%, and two narrow resonances appeared accompanying the dominant $\phi(1680)$ resonance; see Fig. 2 and Table I. The one with the higher mass lies in the region where the $\phi(2170)$ resonance is expected. The mass of it is higher than the PDG average but agrees with the three BESIII measurements [8]. Here, $\phi(2170)$ manifests as a sudden drop of the excitation curve, not as a peak in some experiments. The width we found is smaller than the PDG average. However, it agrees with those obtained in several experiments listed in [5].

The statistical significance of the newly found resonance with a mass of (1850.7 ± 5.3) MeV and width of (25 ± 35) MeV is low. There is a possibility that it is not a true resonance but a mere product of statistical fluctuation in data. To investigate this issue, we use the following

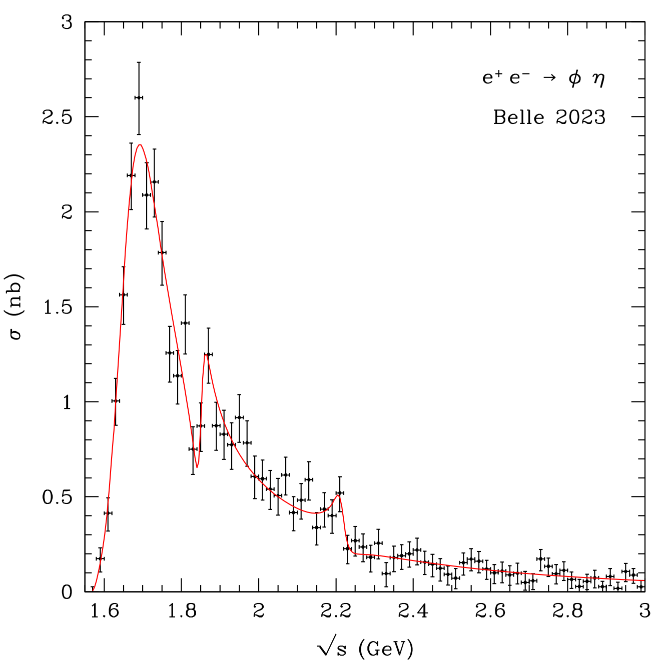

FIG. 2. The excitation curve obtained by the Belle Collaboration [1] and our fit to it using formula (1) with three resonances. Only statistical errors of data are shown and were used in fitting. The parameters of the fit are provided in Table I.

TABLE I. Parameters of the fits to the Belle data [1] up to 3 GeV based on Eq. (1). The statistical significance of the ith resonance is denoted as Σ_i.

	1 resonance	2 resonances	3 resonances
r_1	0.3761(94)	0.291(29)	0.360(14)
M_1 (MeV)	1650.5 ± 4.1	1661.8 ± 6.0	1656.8 ± 4.9
Γ_1 (MeV)	158.7 ± 5.3	125 ± 12	150.8 ± 7.0
Σ_1	40σ	10σ	25σ
r_2		0.050(32)	0.0077(43)
M_2 (MeV)		1921 ± 86	1850.7 ± 5.3
Γ_2 (MeV)		290 ± 230	25 ± 35
δ_2		0.8 ± 1.2	5.59(44)
Σ_2		1.5σ	1.7σ
r_3			0.0044(22)
M_3 (MeV)			2215.7 ± 8.3
Γ_3 (MeV)			35 ± 23
δ_3			2.59(39)
Σ_3			2.0σ
χ^2/NDF	83.6/69	58.5/65	47.1/61
CL (%)	11.1	70.2	90.4

"look everywhere" method: The minimalization of the χ^2 procedure is repeated many times with starting values of resonances 1 and 3 kept at values from Table I. The starting value of M_2 is randomly generated in the interval (1600, 2900) MeV, that of Γ_2 in the interval (10, 40) MeV. The other starting values are chosen at $r_2 = 0$ and $\delta_2 = \pi$. After the minimalization procedure, the observed new "resonances" were grouped into clusters with the masses within a narrow interval (we chose a width of 12 MeV). After repeating the procedure a thousand times, we identify 20 clusters (some with only a few entries), of which the most populated are shown in Table II. Judging from the number of entries in clusters and the mean values of χ^2, the behavior of the excitation curve around 1851 MeV satisfies the resonance requirement better than other parts of the spectrum outside the two established resonances. Also, the extremely narrow widths of the other "resonances" shown in Table II indicate that they are products of statistical fluctuations. All this makes resonance 2 in the rightmost column of Table I the only plausible candidate for the true resonance accompanying $\phi(1680)$ and $\phi(2170)$ in the

TABLE II. Mean mass, width, and χ^2 together with number of resonances in the most populated clusters after a thousand randomly generated searches.

$\bar{M}$ (MeV)	$\bar{\Gamma}$ (MeV)	$\overline{\chi^2}$	n
1850.8	21.7	47.2	247
2734.5	0.9	54.3	117
2529.4	1.9	55.2	106
2396.2	5.7	58.4	77

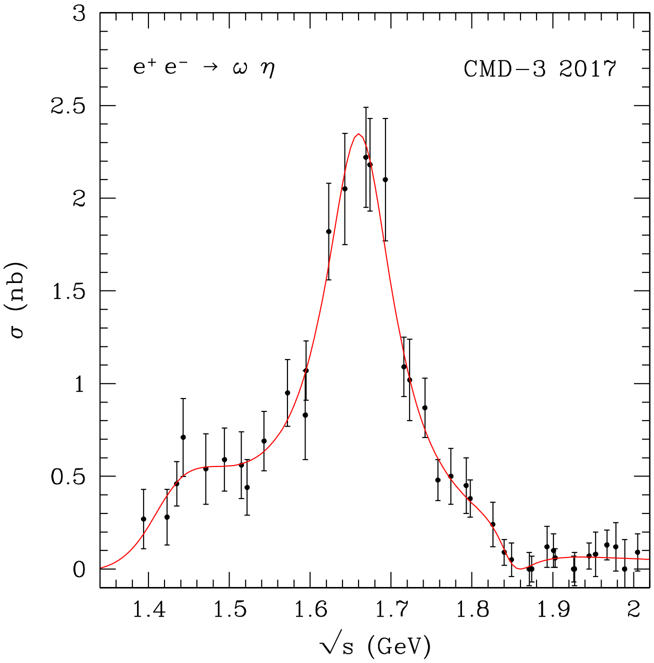

FIG. 3. 3-resonance fit to the cross-section data measured in the CMD-3 experiment [14] using formula (1). The parameters of the fit are given in Table III.

TABLE III. Parameters of the 3-resonance fit to the CMD-3 data [14] based on Eq. (1). The statistical significance of the ith resonance is denoted as Σ_i.

i	1	2	3
r_i	0.102(97)	0.092(38)	0.013(18)
M_i (MeV)	1420 ± 60	1660.0 ± 8.4	1847 ± 16
Γ_i (MeV)	136 ± 115	106 ± 15	52 ± 31
δ_i	0	1.79(59)	5.3 ± 1.0
Σ_i	1.0σ	2.4σ	0.7σ
$\chi^2/\mathrm{NDF} = 11.8/29$		Confidence level = 99.8%	

Belle data. Of course, the statistical fluctuation origin of a resonance there cannot be completely ruled out.

When we accept the possibility that the new resonance is a real effect, we should think about its origin. The mass of (1850.7 ± 5.3) MeV and width of (25 ± 35) MeV points toward the $X(1835)$ resonance. However, the quantum numbers $J^{PC} = 0^{-+}$ of the latter prevent it from being produced in the direct channel of the e^+e^- annihilation, which requires $J^{PC} = 1^{--}$. In the listing dealing with $X(1835)$, the PDG [5] mentions the possibility that this object is a superposition of two states differing in widths. More specifically, the results of BESIII experiment [9] "suggest the existence of either a broad state around 1.85 GeV$/c^2$ with strong coupling to the $p\bar{p}$ final states or a narrow state just below the $p\bar{p}$ mass threshold." The latter's existence was proposed long ago [10] as a $p\bar{p}$ state bound by strong interactions (hereafter, we call it protonium). The idea was later elaborated in several papers.

The quantum numbers of the $X(1835)$ suggest that its protonium component is in the $L = S = J = 0$ state. Because of the large bounding energy (BE) [11], we may expect protonium's excited states to exist below the $2m_p$ threshold. Those of them with quantum numbers $L = 0, S = J = 1$, or $L = 2, S = J = 1$ provide protonium with $J^{PC} = 1^{--}$, which can appear in the intermediate state of e^+e^- annihilation. Guided by this, we suggest that the new narrow resonance in the Belle data [1] is an excited state of the protonium.

The situation is similar to strongly bound kaoniums (K^+K^-) and $(K^0\bar{K}^0)$, the ground states of which cannot be produced in the direct channel of e^+e^- annihilation. Their excited states with $L = 1$ were detected as subthreshold poles in the $e^+e^- \to K^+K^-$ and $e^+e^- \to K_S^0K_L^0$ processes, respectively [12].

The BE of the excited protonium calculated from its mass from Table I comes out as 26 MeV. For comparison, let us recall that the BE of excited kaoniums was estimated at 10 MeV [12]. Salnikov and Milstein [13] have recently predicted a bound state of Λ_c and its antiparticle with BE of 38 MeV.

We have started scanning other sets of the e^+e^- annihilation data. Up to now, we have found indication of excited protonium in the $e^+e^- \to \omega\eta$ data of the CMD-3 experiment [14] at Budker Institute of Nuclear Physics in Novosibirsk, see Fig. 3 and Table III. The excited protonium mass and width (1847 ± 16 MeV, 52 ± 31 MeV) agree with those from Belle data [1] (1850.7 ± 5.3 MeV, 25 ± 35 MeV). Unfortunately, its statistical significance is only 0.7σ.

In conclusion, in this work, we indicated the possible existence of a resonance with the mass and width resembling that of the X(1835) resonance but with different quantum numbers $J^{PC} = 1^{--}$. It may be interpreted as an excited state of the protonium, a strongly bound $p\bar{p}$ system, widely considered one of two components of the X(1835) resonance. Unfortunately, low statistical significance does not allow claiming the new resonance's evidence (3σ). Additional confirmation is needed by analyzing existing data or by a new measurement.

I thank Filip Blaschke, Josef Juráň, and Santu Mondal for the useful discussions.

[1] W. J. Zhu *et al.* (Belle Collaboration), Phys. Rev. D **107**, 012006 (2023).
[2] M. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **74**, 091103 (2006).
[3] B. Aubert *et al.*, Phys. Rev. D **77**, 092002 (2008).
[4] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **104**, 032007 (2021).
[5] R. L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).
[6] Our results also allow the interpretation as $\omega(1650)$, especially considering the width measured in some experiments listed in [5].
[7] We use the program MINUIT by F. James and M. Roos, Comput. Phys. Commun. **10**, 343 (1975).
[8] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **91**, 052017 (2015); **99**, 032001 (2019); **104**, 092014 (2021).
[9] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **117**, 042002 (2016).
[10] B. Loiseau and S. Wycech, Phys. Rev. C **72**, 011001(R) (2005); G. J. Ding and M. L. Yan, Phys. Rev. C **72**, 015208 (2005).
[11] PDG's average mass of $X(1835)$ implies BE ≈ 50 MeV.
[12] P. Lichard, Phys. Rev. D **101**, 111501(R) (2020).
[13] S. G. Salnikov and A. I. Milstein, Phys. Rev. D **108**, L071505 (2023).
[14] R. R. Akhmetshin *et al.*, Phys. Lett. B **773**, 150 (2017).