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Scrutinizing the evidence for $N(1685)$

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The helicity-dependent observable E for the reaction $\gamma d \to \eta n(p)$ with a spectator proton was recently measured by the A2 Collaboration at MAMI in Mainz. The data were interpreted as further evidence for a narrow resonance with spin and parity $J^P = 1/2^+$ (P_{11} wave). However, a full partial-wave analysis without any narrow resonance leads to an excellent description of the data. Imposing a narrow resonance with the properties suggested by the A2 Collaboration leads to a significant deterioration of the fit quality: there is no need for a narrow resonance.

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A narrow structure was observed at a mass of about 1685 MeV in the $\gamma d \to \eta n(p)$ excitation function [1–7]. The structure was interpreted [8,9] as the nonstrange member of the antidecuplet of pentaquarks with spin-parity $J^P = 1/2^+$ predicted by Diakonov, Petrov, and Polyakov [10]. In 2012, the observations reported in Refs. [1,3,6] were introduced into the *Review of Particle Properties* (RPP) under the heading of a new one-star nucleon resonance, $N(1685)$ [11], but was removed from the listings in the most recent issue of the RPP [12]. The interpretation of the structure as narrow resonance was supported by further studies [13–16]; the results reported in Ref. [17] were ambiguous. In a study of the helicity asymmetry of the reaction $\gamma p \to \eta p$, no evidence for $N(1685)$ was found [18].

However, also coupled-channel and interference effects of known nucleon resonances have been discussed in the literature to explain the narrow structure. The Gießen group interpreted the narrow dip in the $\gamma d \to \eta n(p)$ excitation function as the $N(1650)1/2^-$ and $N(1710)1/2^+$ coupled-channel effect [19]. Shyam and Scholten [20] assign the dip to interference effects between the $N(1650)1/2^-$, $N(1710)1/2^+$, and $N(1720)3/2^+$ resonances; alternatively, the dip could be produced due to effects from strangeness threshold openings [21].

The narrow dip can, however, also be explained naturally by interference effects in the $J^P = 1/2^-$ wave [17,22–24]. In Ref. [24], the precise data reported by the A2 Collaboration at the Mainz Microtron accelerator (MAMI) [4,5] were used to study the structure. It was found that it can be explained quantitatively by interference of the two nucleon resonances $N(1535)1/2^-$ and $N(1650)1/2^-$ within the $J^P = 1/2^-$ partial wave. Fits which included a narrow $J^P = 1/2^+$ resonance returned a zero production strength. If the properties of the narrow $J^P = 1/2^+$ resonance as reported in Refs. [4,5] were imposed, the fit deteriorated significantly.

Recently, the A2 Collaboration at MAMI reported a measurement of the helicity-dependent double polarization variable E of the $\gamma d \to \eta n(p)$ reaction [25], where $E = (\sigma_{1/2} - \sigma_{3/2})/(\sigma_{1/2} + \sigma_{3/2})$, with σ_h being the cross section for $\gamma d \to \eta n(p)$ with neutron and photon spins aligned (helicity $h = 3/2$) or opposite ($h = 1/2$). Exploiting the data on the differential cross sections from Refs. [4,5], the two helicity components were determined. The data show clearly that the structure originates from the $h = 1/2$ contribution. The authors fitted the angular distributions (five data points per energy interval) with third-order Legendre polynomial functions and found a narrow dip at 1650 MeV in the first-order Legendre coefficient. They concluded the following: *The extracted Legendre coefficients of the angular distributions for* $\sigma_{1/2}$ *are in good agreement with recent reaction model predictions assuming a narrow resonance in the* P_{11} *wave as the origin of this structure.* In this paper we show that their conclusions are incompatible with the data.

As a first step, we repeated the fit with Legendre polynomials. Figure 1 shows the first-order Legendre coefficients $A_1^{\sigma_{1/2}}$, $A_1^{\sigma_{3/2}}$, and $A_1^{\sigma_{\rm tot}}$ as functions of the invariant mass W for fits to the angular distributions of $\sigma_{1/2}$, $\sigma_{3/2}$, and $\sigma_{\rm tot} = (\sigma_{1/2} + \sigma_{3/2})/2$. The coefficients $A_0^{\sigma_{1/2}}$, $A_0^{\sigma_{3/2}}$, and $A_0^{\sigma_{\rm tot}}$ are similar to the corresponding total cross sections; the coefficients A_2 and A_3 for the cross sections $\sigma_{1/2}$ and $\sigma_{3/2}$ are shown in Ref. [25]. In the coefficient $A_1^{\sigma_{1/2}}$ there is indeed a narrow dip at about 1650 MeV. Since the $J^P = 1/2^-$ partial wave dominates the reaction, significant contributions to $A_1^{\sigma_{1/2}}$ have to come from the interference between the $J^P = 1/2^-$ partial wave and P-wave contributions. Indeed, a comparison of $A_1^{\sigma_{1/2}}$ with results from BnGa fits to the data of Refs. [4,5]

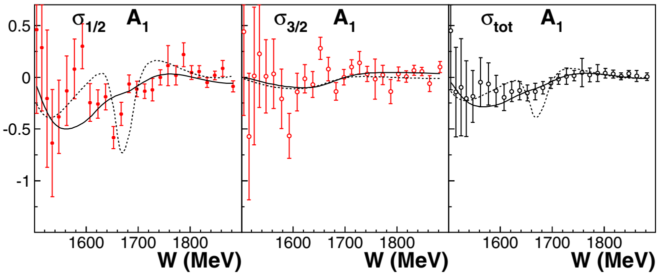

FIG. 1. Legendre coefficients A_1 of the angular distributions of $\sigma_{1/2}$, $\sigma_{3/2}$ [25], and $\sigma_{\rm tot}$ for the reaction $\gamma d \to \eta n(p)$, where $\sigma_{\rm tot}$ is calculated as $(\sigma_{1/2} + \sigma_{3/2})/2$ as functions of the invariant mass W. The experimental results (red circles) are compared to a BnGa fit to the data of Refs. [4,5] without a narrow resonance (solid curve) or a fit imposing a narrow resonance (dotted curve).

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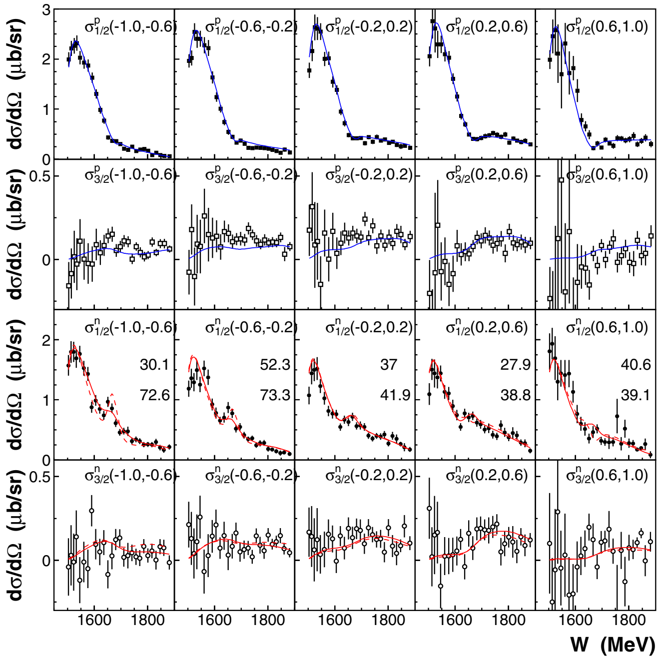

FIG. 2. Excitation functions $\sigma_{1/2}$ and $\sigma_{3/2}$ for five bins in $\cos\theta_\eta^*$ for the reactions $\gamma d \to \eta p(n)$ (top 2 rows) and $\gamma d \to \eta n(p)$ (bottom 2 rows). Statistical and systematic errors are added quadratically. The solid curves represent the new BnGa fit (which include the data from Ref. [25]) without an additional narrow resonance; the dashed lines represent a fit in which a narrow resonance is imposed with the properties given in Ref. [4]. The two numbers give the χ^2 contribution of the bin, the upper number without and the lower number including the narrow resonance.

shows that a model assuming no $N(1685)$ (Fig. 1, solid curve) does not reproduce the narrow dip while a model which includes a narrow $N(1685)$ (Fig. 1, dotted curve) gives qualitative agreement between data and prediction. These observations are the basis for the conjecture in Ref. [25] that a narrow resonance has been observed. There are, however, a few arguments that disagree with this conjecture.

The dip in $A_1^{\sigma_{1/2}}$ is—with a few standard deviations—statistically significant. Relative to the solid line [representing the fit with no $N(1685)$], the dip in $A_1^{\sigma_{1/2}}$ has a mean deviation of -0.24 ± 0.04 and contributes $\chi^2 = 15.9$ for two data points. There are, however, arguments that imply that the dip cannot be a real effect. The dip could be caused by a small systematic deviation of the observable E from its true value. In this case, the dip in $A_1^{\sigma_{1/2}}$ would be accompanied by a peak in $A_1^{\sigma_{3/2}}$.

Indeed, there is an unexpected peak in $A_1^{\sigma_{3/2}}$ as well, at the same mass and of similar size and shape as the dip in $A_1^{\sigma_{1/2}}$. The peak deviates from the solid line by $+0.25 \pm 0.04$, contributes $\chi^2 = 12.7$, and is thus of similar importance as the dip. This peak cannot originate from the same narrow resonance as the dip: the interference of any partial wave with the dominant $J^P = 1/2^-$ wave produces effects in $h = 1/2$ only. If the dip in $A_1^{\sigma_{1/2}}$ had a physical significance, there would be no peak in $A_1^{\sigma_{3/2}}$, and the dip should be seen in $A_1^{\sigma_{\rm tot}}$ with a strength as given by the dotted line in Fig. 1, but it is not. The coefficient $A_1^{\sigma_{\rm tot}}$ follows precisely the fit with no $N(1685)$, the data are compatible with the fit with $\chi^2 = 2.1$ for the two data points.

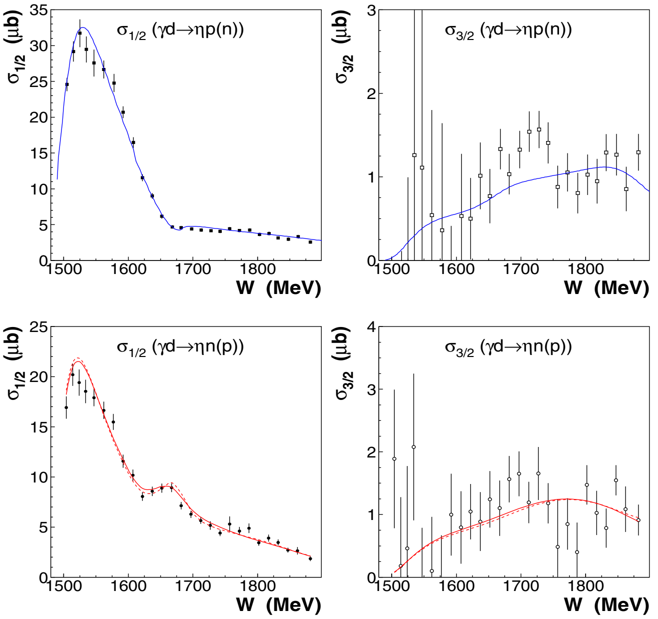

FIG. 3. The total cross sections $\sigma_{1/2}$ and $\sigma_{3/2}$ for the reactions $\gamma d \to \eta p(n)$ (top panels) and $\gamma d \to \eta n(p)$ (bottom panels) and new BnGa fits. The solid lines represent a fit without a narrow resonance, and the dashed lines in the bottom figure represent a fit in which a narrow resonance is imposed with the properties given in Ref. [4].

There is hence the strong suspicion that the dip is false and does not represent real physics.

To scrutinize the possibility further that there could be a narrow resonance with $J^P = 1/2^+$ we performed new fits. In these fits most particle properties were frozen to the values derived from fits to pion and photo-induced reactions off protons. For γn reactions we used the data listed in Ref. [24] and, in addition, the new MAMI data [25]. The latter data are shown in Figs. 2 and 3; the solid line is our fit without introduction of a narrow resonance. For the differential cross sections from Refs. [4,5,25], the fit returns $\chi^2_{\rm MAMI} = 1205$ for 1150 data points. Obviously, there is no need to

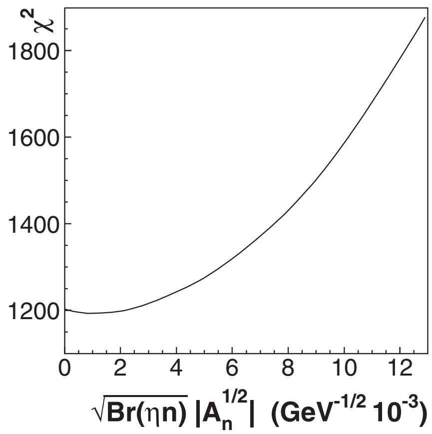

FIG. 4. Increase of χ^2 when a narrow resonance with mass $M = 1670$ MeV, width $\Gamma = 30$ MeV, and $J^P = 1/2^+$ is imposed as a function of the signal strength $\tilde{a} = \sqrt{Br(\eta n)}A_n^{1/2}$. The number of data points is 1150.

TABLE I. Helicity amplitudes determined from a fit without a narrow $N(1685)$ resonance. The T-matrix couplings are the quantities that are listed in the RPP; K-matrix couplings are given in addition. The new results are compared to those obtained in Ref. [24], which are listed in small numbers. The comparison shows the impact of the new data from Refs. [25] and [26].

		$N(1535)1/2^-$	$N(1650)1/2^-$				$N(1535)1/2^-$	$N(1650)1/2^-$	
p	T matrix	0.093 ± 0.009	0.032 ± 0.006	$\mathrm{GeV}^{-1/2}$	n	T matrix	-0.088 ± 0.004	0.016 ± 0.004	$\mathrm{GeV}^{-1/2}$
	[24]	0.114 ± 0.008	0.032 ± 0.007	$\mathrm{GeV}^{-1/2}$		[24]	-0.095 ± 0.006	0.019 ± 0.006	$\mathrm{GeV}^{-1/2}$
	Phase	$8^\circ \pm 4^\circ$	$7^\circ \pm 7^\circ$			Phase	$5^\circ \pm 4^\circ$	$-28^\circ \pm 10^\circ$	
	[24]	$10^\circ \pm 5^\circ$	$-2^\circ \pm 11^\circ$			[24]	$8^\circ \pm 5^\circ$	$0^\circ \pm 15^\circ$	
	K matrix	0.112 ± 0.008	0.075 ± 0.006			K matrix	-0.160 ± 0.030	-0.052 ± 0.005	
	[24]	0.096 ± 0.007	0.075 ± 0.007			[24]	-0.120 ± 0.006	-0.052 ± 0.006	

introduce $N(1685)$. When $N(1685)$ was enforced in the fit with properties as given in Ref. [4], i.e., with $M = 1670$ MeV, width $\Gamma = 30$ MeV, and $\sqrt{Br(\eta n)}A_n^{1/2} = \tilde{a} = 12.3\,\mathrm{GeV}^{-\frac{1}{2}}\,10^{-3}$, the fit returned $\chi^2_{\mathrm{MAMI}} = 1834$. The χ^2 values for the new data from Ref. [25] are shown in Fig. 2 for each angular bin of $\sigma_{1/2}$ for $\gamma d \to \eta n(p)$; the sum is $\chi^2 = 187.9$ for the fit without narrow resonance and 265.8 when it is imposed.

If the production strength was fitted freely, it reduced to $1.2\,[\mathrm{GeV}^{-\frac{1}{2}}\,10^{-3}]$ and the total χ^2 improved by 12 units to 1193. This production strength corresponds to a contribution which is about 100 times smaller than the contribution claimed in Refs. [4,5]. Figure 4 shows how the χ^2 increases with the strength of an imposed narrow $N(1670)$.

The new data on E for the reaction $\gamma d \to \eta p(n)$ in Ref. [25]—with a spectator neutron—differ significantly from the first BnGa fits which were performed before the data on double-polarization observables on $\gamma p \to \eta p$ on protons became available [18,26]. To explore this discrepancy, we included the new MAMI data for η production off protons (bound in deuterons) [25] in the fits. The data are very similar to data for η production off free protons showing that effects due to final-state interactions with the spectator nucleon are small. Figures 2 and 3 show that the new data can be included in the fit without any problems, after a slight tuning of the parameters. In Table I, we show the helicity amplitudes obtained in the new fit in comparison to the fit presented in Ref. [24]. The changes in the photocouplings of $N(1535)1/2^-$ and $N(1650)1/2^-$ for protons are likely due to the inclusion of the new data on $\gamma p \to \eta p$ [26].

In Ref. [27] it is argued that the T-matrix photocouplings of $N(1650)1/2^-$ for protons and neutrons imply that $N(1650)1/2^-$ must have a very large ϕN coupling. The photocouplings of $N(1650)1/2^-$ are strongly influenced by the ΛK and ΣK thresholds; it may hence be more appropriate to use the "undressed" K-matrix photocoupling. Using the formulas given in Ref. [27], we find from the K-matrix couplings that the branching ratio for $N(1650)1/2^- \to \phi N$ vanishes when the $N\omega$ coupling has about half the strength of the $N\rho$ coupling.

Summarizing, we have studied the new data on the helicity dependence of the reaction $\gamma d \to \eta n(p)$ with a spectator proton measured by the A2 Collaboration at MAMI in Mainz [25]. We cannot confirm the conclusions of the authors that the dip in the first-order Legendre coefficient in an expansion of the angular distributions of $\sigma_{1/2}$ is due to a narrow $J^P = 1/2^+$ resonance. First, the dip is accompanied by a peak in the first-order Legendre coefficient of $\sigma_{3/2}$ of the same shape, suggesting that the dip is due to a statistical fluctuation in the measurement of E. Second, a partial wave analysis without a narrow $J^P = 1/2^+$ resonance is excellent; the inclusion of it with the reported properties leads to a significantly worse description of the data.

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