Resonance-like structure near the $\eta d$ threshold in the $\gamma d \rightarrow \pi^0 \eta d$ reaction

T. Ishikawa,1 H. Fujimura,1 H. Fukasawa,1 R. Hashimoto,1 Q. He,1 Y. Honda,1 T. Iwata,2 S. Kaida,1 J. Kasagi,1 A. Kawanoto,3 S. Kuwasaki,1 K. Maeda,4 S. Masumoto,5 M. Miyabe,1 F. Miyahara,1 K. Mochizuki,1 N. Muramatsu,1 A. Nakamura,1 K. Nawa,1 Y. Obara,5 S. Ogushi,1 Y. Okada,1 K. Okamura,1 Y. Onodera,1 K. Ozawa,6 Y. Sakamoto,3 M. Sato,1 H. Shimizu,1 H. Sugai,1 K. Suzuki,1 Y. Tajima,2 S. Takahashi,1 Y. Taniguchi,1 Y. Tsuchikawa,1 H. Yamazaki,1 R. Yamazaki,1 and H.Y. Yoshida2

1Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai 982-0826, Japan
2Department of Physics, Yamagata University, Yamagata 990-8560, Japan
3Department of Information Science, Tohoku Gakuin University, Sendai 981-3193, Japan
4Department of Physics, Tohoku University, Sendai 980-8578, Japan
5Department of Physics, University of Tokyo, Tokyo 113-0033, Japan
6Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan

To investigate the interaction between the nucleon $N$ and nucleon resonance $N(1535)/1^-\pi$, the $\eta d$ threshold structure connected to the isoscalar $S$-wave $N$-$N(1535)/1^-\pi$ system has been experimentally studied in the $\gamma d \rightarrow \pi^0 \eta d$ reaction at incident photon energies ranging from the reaction threshold to 1.15 GeV. A strong enhancement is observed near the $\eta d$ threshold over the three-body phase-space contribution in the $\eta d$ invariant-mass distribution. An analysis incorporating the known isovector resonance $D_{13}$ with a spin-parity of $2^+$ in the $\eta d$ channel reveals the existence of a narrow isoscalar resonance-like structure with $1^-$ in the $\eta d$ system. Using a Flatté parametrization, the mass is found to be $2.427^{+0.004}_{-0.006}$ GeV, close to the $\eta d$ threshold, and the width is $(0.029^{+0.008}_{-0.006}$ GeV) + $(0.007^{+0.041}_{-0.003})$ GeV, where $p_\eta$ denotes the $\eta$ momentum in the rest frame of the $\eta d$ system. The observed structure would be attributed to a predicted isoscalar $1^-\eta NN$ bound state from $\eta NN$ and $\pi NN$ coupled-channel calculation, or an $\eta d$ virtual state owing to strong $\eta d$ attraction.

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The structure and interaction of hadrons provides crucial insight into the non-perturbative mechanisms in quantum chromodynamics. Attraction between an $\eta$ meson and a nucleon $N$ makes it possible to form an $\eta$-mesic nucleus, as predicted by Haider and Liu. This is an exotic state in which $\eta$ is bound to the nucleus by the strong interaction force alone, and allows the study of the behavior of $\eta$ in a dense nuclear environment. The binding energy of $\eta$ in the nuclear medium is sensitive to a singlet component of $\eta$ ($\eta$-$\eta'$ mixing) and $\eta$ width. A level and width of an $\eta$-mesic nucleus can yield the in-medium properties of nucleon resonance $N(1535)/1^-\pi$ ($N^*$), which is speculated to be the chiral partner of $N$. This is because $\eta$ in the nuclear medium is expressed by mixing of the $\eta$-mesonic state, and the $N^*$-particle and $N$-hole excitation state.

Exotic $\eta$-mesic nuclei have been intensively investigated theoretically, and searched for experimentally. Experimental hints of possible $\eta$-mesic nuclei have been obtained in the threshold behavior of $\eta$-production reactions. The existence of an $\eta$-mesic nucleus enhances the cross section near the reaction threshold compared with phase space. The total cross section shows a steep increase from the threshold in $\eta$-$^3$He production from the $pd$ collisions. The possibility of an $\eta$-$^3$He weakly bound state is claimed by analyzing the $\eta$ angular distribution. If an $\eta$-$^3$He bound state exists, it should appear independently of the initial state of reactions. Coherent $\eta$ photoproduction on $^3$He also shows a strong threshold enhancement, and the angular distribution of $\eta$ emission is rather flat near the threshold as compared with the expected distribution based on the nuclear form factor. The WASA-at-COSY collaboration has searched for $\eta$-mesic $^3$He and $^4$He nuclei in the $pd$ and $dd$ reactions, respectively, by detecting daughter particles from $\eta$ or $N^*$ in a nucleus. No convincing evidence for an $\eta$-mesic nucleus has yet been obtained.

An $\eta d$ bound state, if it exists, is the lightest $\eta$-mesic nucleus. The $S$-wave $\eta d$ system has an isospin of 0 and a spin-parity $J^P$ of $1^-$, and its properties are connected to the $NN^*$ interaction. An $\eta NN$ bound state has been predicted near the $\eta d$ threshold with a width $\Gamma$ of 0.01–0.02 GeV from the three-body $\eta NN$-$\pi NN$ coupled-channel calculation. This state can be located lower than the threshold by 8 MeV. This state is suggested by the significant deviation from phase space near the threshold in $\eta d$ production from the $pn$ collisions. In contrast, the $\gamma d \rightarrow \eta d$ reaction does not show any indication of this state; its angular distribution is explained by the quasi-free (QF) $\gamma N \rightarrow \eta N$ process. The possibility of an $\eta d$ bound state is ruled out in several theoretical three-body calculations for various $\eta N$ scattering parameters. Instead, a narrow $\eta d$ virtual state is inferred to reproduce the experimental data. However, qualitative disagreement is still observed in different theoretical calculations which cannot be ex-
plained by uncertainties in the $\eta N$ scattering parameters alone. It should be noted that the existence of an $\eta d$ bound or resonance state near the threshold is claimed in Ref. \[37\].

The $\gamma d \rightarrow \pi^0 \eta d$ reaction can provide a condition of low $\eta d$ relative momentum, producing a possible $\eta d$ bound state. In a similar $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction, a sequential process $\gamma d \rightarrow D_{IS} \rightarrow \pi^0 D_{IV} \rightarrow \pi^0 \pi^0 d$ \[38\] is dominant, where $D_{IS}$ and $D_{IV}$ denote isoscalar and isovector states with a baryon number of 2, respectively. In $\gamma d \rightarrow \pi^0 \eta d$, the two sequential processes, $\gamma d \rightarrow D_{IV} \rightarrow \pi^0 D_{IS} \rightarrow \pi^0 \eta d$ and $\gamma d \rightarrow D_{IV} \rightarrow \eta D'_{IV} \rightarrow \pi^0 \eta d$, are expected to be observed, and the tail of the possible $\eta d$ bound state appears as $D_{IS}$. In this letter, we study the $\gamma d \rightarrow \pi^0 \eta d$ reaction to clarify the structure that appears in the low-relative-momentum region of the $\eta d$ system generated after $\pi^0$ emission.

A series of experiments \[39\] were carried out using a bremsstrahlung photon beam from 1.20-GeV electrons circulating in a synchrotron \[44\] at the Research Center for Electron Photon Science (ELPH), Tohoku University, Japan \[45\]. The photon energy ranging from 0.75 to 1.15 GeV was determined by detecting a bremsstrahlung photon beam \[40–43\] from 1.20-GeV electrons circulating in a synchrotron \[44\] at the Reaction Facility \[39\] are expected to exhibit $\chi^2$ probability below 0.01 in another KF for the $\gamma d \rightarrow \pi^0 \eta d$ hypothesis where the $x$, $y$, and $z$ momenta of the initial bound proton were assumed to be measured with a centroid of 0 MeV/c and a resolution of 40 MeV/c, and the total energy of the bound proton was given assuming the on-shell spectator neutron. Finally, sideband-background subtraction was performed for accidental-coincidence events detected in STB-Tagger II and FOREST.

The total cross section was obtained by estimating the acceptance of $\gamma \gamma \gamma \gamma d$ detection in a Monte Carlo simulation based on GEANT4 \[40–51\]. Here, event generation was modified from pure phase space to reproduce the following three measured distributions: the $\pi^0 d$ invariant mass $M_{\pi^0 d}$, the $\eta d$ invariant mass $M_{\eta d}$, and the deuteron emission angle $\cos \theta_d$ in the $\gamma d$ center-of-mass (CM) frame. Figure 1 shows the total cross section $\sigma$ as a function of the incident photon energy $E_{\gamma}$ (excitation function). The data obtained in this work were consistent with those ob-

**FIG. 1.** Total cross section $\sigma$ as a function of the incident photon energy $E_{\gamma}$. The circles (blue) show $\sigma$ obtained in this work, and the triangles (magenta) show that obtained at the Mainz MAMI facility \[52\]. The horizontal error of each data point corresponds to the $E_{\gamma}$ coverage, and the vertical error corresponds to the statistical error of $\sigma$. The solid (red) and dashed (black) curves show theoretical calculations with $\eta d$ and other FSIs in Ref. \[53\] and Ref. \[54\], respectively. The squares (cyan) show $\sigma$ obtained for the events with $M_{\eta d} < 2.47$ GeV, and the dotted curve (green) shows the corresponding phase space contribution. The lower hatched histograms show the systematic errors of $\sigma$ with right-up straight lines for all the events (blue) and with left-up lines for $M_{\eta d} < 2.47$ GeV (cyan).
The experimental data are presented by the circles with statistical errors, and the systematic uncertainties by the hatched histograms. An enhancement is observed in \( \frac{d\sigma}{dM_{\eta d}} \) over the phase-space contribution (green dotted) in the low-mass region. This enhancement is much broader at \( \gamma = 1.01-1.15 \) GeV than at \( \gamma = 0.95-1.01 \) GeV, suggesting the appearance of another contribution from a resonance in the \( \eta d \) channel. We also obtained the differential cross section \( \frac{d\sigma}{dM_{\eta d}} \) similarly to \( \frac{d\sigma}{dM_{\eta d}} \) as shown in Fig. 2(right). In \( \frac{d\sigma}{dM_{\eta d}} \), we observe a significant enhancement at high masses, corresponding to the known isovector \( D_{12} \) resonance with \( J^P = 2^+ \), \( M \sim 2.14 \) GeV, and \( \Gamma \sim 0.09 \) GeV.  

Only the \( S \)-wave \( \eta d \) system \( (D_{\eta d}) \) forms a peak close to the threshold in \( \frac{d\sigma}{dM_{\eta d}} \). The \( D_{\eta d} \) system with \( J^P = 1^- \) decays into \( \eta d \) dominantly in the \( S \) wave, and possibly in the \( D \) wave. The \( S \) - and \( D \) -wave contributions to the \( \frac{d\sigma}{dM_{\eta d}} \) distribution differ in shape. A fraction of the \( D \)-wave contribution to the \( S \)-wave at a fixed \( M_{\eta d} \) is proportional to \( p_\eta^4 \), where \( p_\eta \) denotes the \( \eta \) momentum in the rest frame of the \( \eta d \) system. The \( D_{\eta d} \) and \( D_{12} \) contributions are separated by fitting a set of functions, expressed as the sum of \( S \) - and \( D \) -wave decay contributions of a Breit-Wigner (BW) resonance in the \( \eta d \) channel and \( D_{12} \) contribution in the \( \pi^0 d \) channel, to the \( M_{\eta d} \) and \( M_{\eta d} \) data at \( \gamma = 1.01-1.15 \) and \( 0.95-1.01 \) GeV simultaneously. The function for \( \frac{d\sigma}{dM_{\eta d}} \) is given by

\[
\frac{d\sigma}{dM_{\eta d}} (M_{\eta d}) = \alpha_0 \int A(M_{\eta d}, M_{\pi d}) V_{PS}(M_{\eta d}, M_{\pi d}) dM_{\pi d}
\]

(1)

where \( V_{PS}(M_{\eta d}, M_{\pi d}) \) expresses the phase-space contribution and \( A(M_{\eta d}, M_{\pi d}) \) gives the enhancement owing to the two resonances:

\[
A(M_{\eta d}, M_{\pi d}) = (1 + \alpha_2 p_\eta^4) L_{M,1}^{\eta d}(M_{\eta d}) + \alpha_1 L_{M,2}^{\eta d}(M_{\eta d}).
\]

(2)

Here, \( L_{M,1}^{\eta d}(M_{\eta d}) \) and \( L_{M,2}^{\eta d}(M_{\eta d}) \) represent BW contributions with \( M \) and \( \Gamma \) for \( D_{\eta d} \) and \( D_{12} \), respectively. To incorporate the opening of the \( \eta d \) channel, the \( \eta d \) partial width is parametrized by the effective coupling \( \Gamma \) (known as the Flatté parametrization \( 60, 61 \)):

\[
\Gamma = \Gamma_0 + gp_\eta c
\]

(3)

for \( D_{\eta d} \), and \( \Gamma_0 \) is the width for the other open channels \( (NN, \pi NN, \pi \pi NN) \). It should be noted that the phase space of the \( \eta d \) decay is taken into account in \( V_{PS}(M_{\eta d}, M_{\pi d}) \). The other \( M \) and \( \Gamma \) parameters are assumed to be constant. Equation (1) is evaluated by the convolution of a Gaussian with an experimental mass resolution of \( \sigma_{M_{\eta d}} = 6.0 \) (4.8) MeV at \( \gamma = 1.01-1.15 \) (0.95–1.01) GeV. The function for \( \frac{d\sigma}{dM_{\eta d}} \) is given by

\[
\frac{d\sigma}{dM_{\eta d}}(M_{\eta d}) = \alpha_0 \int A(M_{\eta d}, M_{\pi d}) V_{PS}(M_{\eta d}, M_{\pi d}) dM_{\pi d}
\]

(4)

with \( \sigma_{M_{\eta d}} = 6.1 \) (4.8) MeV at \( \gamma = 1.01-1.15 \) (0.95–1.01) GeV. In Fig. 2 the mass spectrum is an incoherent sum of two resonances for the following reason. As discussed later, we consider that \( D_{\eta d} \) and \( D_{12} \) are produced in paths (5) and (9), respectively. The mass spectrum is a plot of the integrated yield for the angular distributions of \( \pi^0 \) and \( \eta \). The interference term of the two paths is zero unless \( L_1 (\pi^0) = L_2 (\pi^0) \) and \( L_2 (\eta) = L_1 (\eta) \), owing to the orthogonality of the spherical harmonics which appear in the angular component of the wave function. In the analysis, the \( L_1 (\eta) = 1 \) component is deduced to be \( \sim 100\% \); therefore, almost no effect of the interference effect is expected in the mass spectra.

The obtained parameters in the fit are \( (M, \Gamma, g) = (2.427_{+0.006}^{+0.006} \text{ GeV}, 0.029_{+0.006}^{+0.006} \text{ GeV}, 0.000_{+0.006}^{+0.006} \text{ GeV}) \) for \( D_{\eta d} \), and \( (M, \Gamma) = (2.158_{-0.003}^{+0.003}, 0.116_{-0.011}^{+0.005}) \) GeV for \( D_{12} \), where \( \chi^2 = 131.4 \) and the number of data points is 76. Also plotted in Fig. 2 are the \( S \)- (blue solid) and \( D \)-wave (cyan double-dotted) decay contributions as well as the \( D_{12} \) contribution (red dot-dashed). Each of \( \frac{d\sigma}{dM_{\eta d}} \)
and \( \frac{d\sigma}{dM_{\eta d}} \) consists of two peaks. The centroid of the low-mass peak in \( \frac{d\sigma}{dM_{\eta d}} \) is close to the \( \eta d \) threshold independently of \( E_\gamma \). The high-mass peak reflects the appearance of the 2.14-GeV peak in \( \frac{d\sigma}{dM_{\eta d}} \). The centroid of the high-mass peak decreases with a decrease of \( E_\gamma \). Because the \( M_{\eta d} \) coverage is limited at \( E_\gamma \approx 0.95-1.01 \) GeV, the two peaks merge into a bump in \( \frac{d\sigma}{dM_{\eta d}} \) with substantial distortion of the 2.14-GeV peak. It is thus revealed that a narrow resonance-like structure exists in the vicinity of the \( \eta d \) threshold (2.423 GeV). This is not observed due to its isoscalar nature in \( \gamma d \rightarrow \eta d \) where the QF process is dominant.

The S-wave \( \eta d \) resonance states with widths broader than 0.05 GeV are ruled out for the threshold enhancement in \( \frac{d\sigma}{dM_{\eta d}} \). It could be attributed to the predicted \( \eta d \) bound state \([22, 23, 57]\), being a Feshbach resonance in the \( \eta d \) and isoscalar \( \pi NN \) coupled channels. If so, the corresponding enhancement can be observed in the isoscalar \( \pi NN \) and \( \pi^0 \pi^0 d \) channels (corresponding to the \( \Gamma_0 \neq 0 \) case). Possibly related to this is a bump observed \( \sim 2.31 \) GeV in the isoscalar \( \eta d \rightarrow \pi NN \) reaction \([53]\). The spin-parity of this bump is not clear (\( 1^+ \) and \( 0^+ \) are discussed in Ref. \([50, 51]\)), and the bump may include a \( 1^- \) state \([58]\) corresponding to the \( \eta d \) bound state.

The threshold enhancement can also be interpreted as an \( \eta d \) virtual state \([33, 30]\) (corresponding to the \( \Gamma_0 = 0 \) case). The square of the amplitude would be proportional to \( \left| a_{\eta d}^{-1} - i p_n \right|^2 \) for production of an \( \eta d \) system at low relative momentum \( p_n \), where \( a_{\eta d} \) denotes the \( \eta d \) scattering length. Using \( a_{\eta d} = 2.16 + i1.25 \) fm \([59]\) extracted from \( pn \rightarrow \eta d \) \([27, 28]\), the \( M_{\eta d} \) distributions are expected as shown by the long-dashed curves (black) in Fig. 2(left), and similar to the decomposed \( D_{\eta d} \) contributions close to the threshold. They are observed in a wider range as compared with the 10-MeV range of \( pn \rightarrow \eta d \). High \( \eta d \) angular momenta would be suppressed in \( \gamma d \rightarrow \pi^0 \eta d \) because sequential processes are dominant. Additionally, the \( pn \rightarrow \eta d \) data may be affected by FSI between \( \eta \) and the spectator proton.

The \( \pi^0 D_{\eta d} \) and \( \eta D_{12} \)-produced processes are investigated using angular distributions of \( \eta d \) and \( \eta \) obtained for the events with \( M_{\eta d} < 2.47 \) GeV as shown in Fig. 4. Figure 3(left) shows the deduced \( \pi^0 \) angular distributions in the \( \gamma d \)-CM frame with respect to the incident photon direction; the experimental distributions are almost flat. The \( \eta \) angular distributions in the \( \eta d \) rest frame with respect to the opposite direction to \( \pi^0 \) emission are shown in Fig. 3(right). They take a convex-upward shape, and show almost 90° symmetry. Thus, contamination of a state with \( J^\pi \) other than \( 1^- \) (\( 2^+ \)) is assumed to be negligibly small in \( D_{\eta d} \) (\( D_{12} \)).

We calculated the \( \pi^0 \) and \( \eta \) angular distributions for the reaction sequences of interest using the density matrix (statistical tensor) formalism \([62]\):

\[
J_0 (d) = 1 \frac{L_{\alpha}(\gamma)}{J_1(\pi^0 D_{\eta d})} \frac{L_{1}(\pi^0)}{J_2(D_{\eta d})} = 1 \frac{L_{2}(\eta) = 0.2}{J_3(d) = 1}
\]

and

\[
J_0 (d) = 1 \frac{L_{\alpha}(\gamma)}{J_1(\eta D_{12})} \frac{L_{\gamma}(\eta)}{J_2(D_{12})} = 2 \frac{L_{2}(\pi^0) = 1}{J_3(d) = 1},
\]

where \( J_1 \) and \( J_2 \) denote the spins of first and second intermediate states, respectively, and \( J_0 = J_3 = 1 \) are those of the initial and final deuteron. The \( L_0 \) denotes the angular momentum of the incident photons. The \( L_1 \) and \( L_2 \) denote the angular momenta of meson emission from the first and second intermediate states, respectively. A set of the amplitudes \( A_{\alpha \alpha' \lambda \lambda'} \) was determined for all the \( \Lambda = (L_0, J_1, L_1, J_2, L_2) \) combinations with \( L_0, J_1, L_1 \leq 2 \) to reproduce the measured angular distributions at \( E_\gamma = 1.01-1.15 \) and 0.95–1.01 GeV simultaneously (40 data points). The amplitude for a mixed state is given by \( A_{\alpha \alpha' \lambda \lambda'} = (A_{\alpha \alpha' \lambda \lambda'} A_{\alpha' \alpha \lambda' \lambda})^{1/2} \) for the \( L_2 = 2 \) amplitudes are given by \( A_{\alpha \alpha' \lambda \lambda'} = A_{\alpha \alpha' \lambda \lambda'} \tan \phi \), where \( L_2 = 0 \) in \( \Lambda_0 \) is replaced by \( L_2 = 2 \) in \( \Lambda_2 \). The \( L_2 = 1 \) amplitudes are multiplied by an \( E_\gamma \)-dependent factor. The fractions of the \( L_2 = 0, 1, \) and 2 contributions are limited to 38.6–49.3% (49.1%–57.5%), 50.0–61.4% (41.3%–50.9%), and 0.0–2.0% (0.0%–2.3%) for \( E_\gamma = 1.01-1.15 \) (0.95–1.01) GeV, respectively, to match the results from the mass distribution analysis, giving a minimum \( \chi^2 \) of 43.3. The solid curves (magenta) in Fig. 4 show the angular distributions calculated for the best-fit solution. The dashed (blue), dot-dashed (red), and two-dot-dashed (cyan) curves show the \( L_2 = 0, 1, \) and 2 contributions, respectively. The long-dashed curves (black) represent the interference effects; those between even and odd \( L_2s \) (between \( L_2 = 0 \) and 2) are observed in the \( \pi^0 (\eta) \) angular distributions. The \( L_2 = 1 \) amplitudes and the \( L_2 = 0 \) and 2 interference make the \( \eta \) angular distribution convex upward. Regarding \( \pi^0 D_{\eta d} \), the major component is \( 0^- \) (~47%), and the amplitudes are distributed widely to other \( 1^+, \) \( 2^\pm \) components. For \( \eta D_{12} \), the major
component is $2^+$ ($\sim 100\%$).

We also estimate the excitation function for the events with $M_{\eta d} < 2.47$ GeV, as represented by the squares (cyan) in Fig. 1. It forms a bump at $\sim 1$ GeV corresponding to the $\gamma d$-CM energy of $\sim 2.69$ GeV. The observed broad bump corresponds to some resonances because the expected excitation function monotonically increases for the three-body phase-space contribution with $M_{\eta d} < 2.47$ GeV as plotted by the dotted curve (green) in Fig. 1. Loosely-coupled isovector S-wave molecules $N(1620)1/2^-$ and $N^\ast (1650)1/2^-$ would play the role of a doorway to the $\pi^0 \eta d$ system with $0^-$. It should be noted that neither $\Delta(1620)1/2^-$ nor $N(1650)1/2^-$ is considered a contributor to the elementary $\gamma N \rightarrow \pi^0 \eta N$ reaction (the main contributor is $\Delta(1700)3/2^-$). In contrast, $N^\ast N(1720)3/2^+$ is a candidate doorway to $\eta D_{12}$ with $2^+$ although the branching ratio of $N(1720)3/2^+ \rightarrow \eta N$ is only a few percent.

In summary, the $\eta d$ threshold structure has been experimentally studied in the $\gamma d \rightarrow \pi^0 \eta d$ reaction at $E_\gamma < 1.15$ GeV. It is found that the $M_{\eta d}$ dependence of $d\sigma/dM_{\eta d}$ is quite different from the behavior of the three-body phase space but shows a strong enhancement near the threshold, which changes in shape depending on the incident energy. An analysis incorporating the known resonance $D_{12}$ in the $\pi^0 d$ channel has revealed the existence of a narrow resonance-like structure in the $S$-wave $\eta d$ system, $D_{\eta d}$. Applying a Flatté parameterization to $D_{\eta d}$, we have obtained the mass of $2.427_{-0.013}^{+0.013}$ GeV and the width $\Gamma = \Gamma_0 + g\eta c$ with $\Gamma_0 = 0.029_{-0.029}^{+0.006}$ GeV and $g = 0.06_{-0.00}^{+0.41}$, where $p_\eta$ denotes the $\eta$ momentum in the $\eta d$-CM frame, and $g$ denotes the effective coupling to the $\eta d$ channel. The $S$-wave resonance states with widths broader than 0.05 GeV are ruled out. The $D_{\eta d}$ system would be the predicted $\eta d$ bound state, or an $\eta d$ virtual state originating from strong $\eta d$ attraction. The major component of the $\pi^0 D_{\eta d}$ system is found to be $0^-$ from the $\eta d$ angular distributions for the events with $M_{\eta d} < 2.47$ GeV.

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\( a \) Corresponding author: ishikawa@dns.tohoku.ac.jp
\( b \) Present address: Department of Physics, Wakayama Medical University, Wakayama 641-8509, Japan
\( c \) Present address: Institute of Materials Structure Science (IMSS), KEK, Tsukuba 305-0801, Japan
\( d \) Present address: Department of Nuclear Science and Engineering, Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing 210016, China
\( e \) Present address: Accelerator Laboratory, KEK, Tsukuba 305-0801, Japan
\( f \) Present address: Gunma University Initiative for Advanced Research (GIAR), Maebashi 371-8511, Japan
\( g \) Present address: The Wakasa Wan Energy Research Center, Tsuruga 914-0192, Japan
\( h \) Present address: J-PARC Center, Japan Atomic Energy Agency (JAEA), Tokai 319-1195, Japan
\( i \) Present address: Radiation Science Center, KEK, Tokai 319-1195, Japan

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