ηN SCATTERING PARAMETERS AND POSSIBLE $\eta' d$ BOUND STATE FROM η PHOTOPRODUCTION ON THE DEUTERON*

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Two physics programs, determination of low-energy scattering parameters between the eta meson (η) and nucleon (N), and search for a possible bound state between the eta prime meson (η') and deuteron, using η photo-

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production from the deuteron target are conducted at the Research Center for Electron Photon Science (ELPH), Tohoku University. Among the two-body dynamics of the meson–nucleon systems, the ηN interaction is not well-known although it has been found attractive. An experiment is carried out to determine the low-energy ηN scattering parameters using a special kinematics. The energy and momentum of the emitted proton (p) are measured at 0 degrees for η photoproduction on the deuteron (d) at incident energies around 0.94 GeV, which gives the low relative momentum between η and neutron (n) in the final state. Low-energy ηn scattering is likely to take place in this condition, and the scattering parameters can be determined from the differential cross section as a function of the ηn invariant mass. The measurement is currently in progress to determine the real part of the ηn scattering length. A possible $\eta' d$ bound state is theoretically predicted, and a structure corresponding to the state can be observed via the $\gamma d \to \eta d$ reaction at incident energies around 1.2 GeV. In the case of backward η emission, the structure becomes prominent because a background contribution coming from quasi-free single-step η emission is highly suppressed. The $\gamma d \to \eta d$ reaction has been also studied at ELPH below the incident energy of 1.15 GeV. The angular differential cross sections are determined at backward η emission angles. The tail of the corresponding peak is not observed, and the background level is much higher than predicted.

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1. ηN scattering length

The structure of hadrons is one of the most important subjects to be studied in the non-perturbative domain of quantum chromodynamics (QCD). The interaction between the eta meson (η) and the nucleon (N) is not known yet due to the difficulties in realizing scattering experiments because of the neutral and unstable nature of η. Currently, the estimated ηN scattering length ($a_{\eta N}$) values scatter especially in the real part [1]. Detailed information on low-energy ηN scattering would reveal the structure of the nucleon resonance $N(1535)S_{11}$, which is speculated to be the chiral partner of the nucleon.

To determine $a_{\eta N}$, we are performing a $\gamma d \to \eta pn$ experiment [2] at the Research Center for Electron Photon Science (ELPH), Tohoku University, Japan. We use the photon beam with energies around 0.94 GeV [3], detecting two photons from the η decay and protons at 0°. The energies of the photons are measured with a large solid-angle electromagnetic calorimeter (EMC) FOREST [4], and the momenta of the protons are measured with a dipole-magnetic spectrometer BLC. In this kinematic condition, η is likely to be produced almost at rest from the quasi-free (QF) proton and is expected to interact with the spectator neutron (n). In addition, the forward-going proton has a large momentum and little chance to interact with η or n almost at rest. The sensitivity to $a_{\eta N}$ of the proposed reaction has been theoretically investigated [5]. At the low ηn invariant mass $M_{\eta n}$ (corresponding to the small ηn relative momentum), it is confirmed that the ηn scattering effect is dominant, and that the $\pi n \to \eta n$-transition and pn-rescattering effects are small. The differential cross section $\mathrm{d}^3\sigma/\mathrm{d}M_{\eta n}/\mathrm{d}\Omega_p$ of 5% error per MeV bin in the low $M_{\eta n}$ region can determine $\mathrm{Re}\, a_{\eta N}$ at a precision of 0.1 fm.

The measurement of the $\mathrm{d}^3\sigma/\mathrm{d}M_{\eta n}/\mathrm{d}\Omega_p$s is currently in progress. The incident photon energy ranges from 0.82 to 1.26 GeV using the circulating electron energy of 1.32 GeV in an electron synchrotron [6]. Figure 1 shows the $M_{\eta n}$ distribution for the $\gamma d \to \eta p n$ reaction. The $M_{\eta n}$ value is calculated as a $d(\gamma, p)$ missing mass after the $\gamma d \to \eta p n$ reaction is identified. Although acceptance correction is not yet applied, a clear peak is observed at 0 MeV corresponding to QF η production from the proton. The momentum calibration of the BLC spectrometer is not completed, and the current data statistics is too poor to determine $\mathrm{Re}\, a_{\eta N}$, and we continue the measurement to increase the statistics.

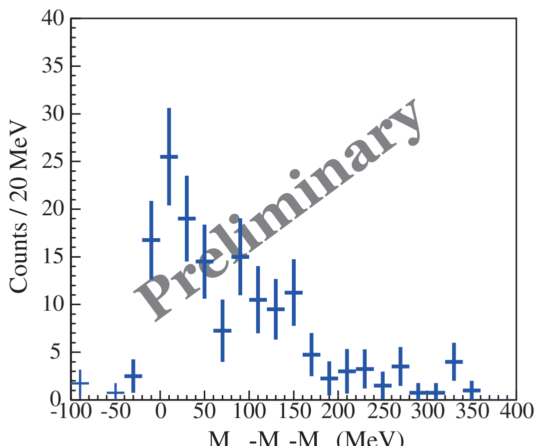

Fig. 1. $M_{\eta n}$ distribution for the $\gamma d \to \eta p n$ reaction. The $M_{\eta n}$ value is calculated as a $d(\gamma, p)$ missing mass.

2. $\eta' d$ bound state

Dynamical quark-mass generation is another subject of interest where chiral symmetry plays a key role. The $\eta'(958)$ meson has an exceptionally large mass although it would be a Nambu–Goldstone boson originating from the spontaneous breakdown of $\mathrm{U}(3)_\mathrm{R} \times \mathrm{U}(3)_\mathrm{L}$ chiral symmetry. Its mass generation is considered to be a result of the interplay of quark symmetry and gluon dynamics in connection with the axial anomaly problem [7]. A possibility of the formation of η'-nucleus bound states (η'-mesic nuclei) has been investigated theoretically [8]. The η'-mesic nuclei are good probes for discovering the properties of the η' meson at finite density. Experimental searches for η'-mesic nuclei are conducted intensively [9, 10] at GSI/FAIR [11] and SPring-8/LEPS2 [12], and any structure corresponding to an η'-mesic nucleus is not found yet.

An $\eta' d$ bound state (the lightest η'-mesic nucleus) is predicted owing to attraction between η and N [13]. The possible state can be formed via the $\gamma d \to \eta d$ reaction. In this case, the angular distribution in the γd center-of-mass (CM) frame shows rather flat. Coherent single meson photoproduction is often discussed using a mechanism with QF meson production followed by deuteron coalescence (QFC). This makes a strongly forward-peaking angular distribution of meson emission. In other words, the background QFC mechanism can be highly suppressed at backward angles of meson emission.

The energy of a primary electron beam has increased from 1.20 to 1.32 GeV after the 2011 earthquake. The current photon-energy coverage corresponds to the CM energy $W_{\gamma d}$ from 2.56 to 2.87 GeV, which is suitable to study the possible $\eta' d$ bound state. Although the acquired data before the earthquake do not include $W_{\gamma d} \geq 2.80$ GeV, enhancement in the lower-side tail may be observed. Thus, we have determined the differential cross sections $\mathrm{d}\sigma/\mathrm{d}\Omega$ at backward η angles for the $\gamma d \to \eta d$ reaction from the acquired data before the earthquake.

Event selection is made for the $\gamma d \to \eta d \to \gamma\gamma d$ reaction. Events containing two neutral particles and a charged particle are selected. The time difference between the two neutral EMC clusters is required to be less than thrice that of the time resolution for the difference. The two neutral EMC clusters giving the $\gamma\gamma$ invariant mass higher than 300 MeV are selected. The charged particles are detected with the forward plastic-scintillator hodoscope (PSH) in front of the forward EMC, and deuterons are selected by using ΔE–E correlation between PSH and EMC. Further selection is made by applying a kinematic fit with five constraints: energy and three-momentum conservation, and $\gamma\gamma$ invariant mass being the η mass. The momentum of the charged particle was obtained from the time delay assuming that the charged particle had deuteron mass. Events for which the χ^2 probability was higher than 0.4 were selected. Figure 2 shows the differential cross section $\mathrm{d}\sigma/\mathrm{d}\Omega$ as a function of $W_{\gamma d}$ at backward η angles. Owing to deuteron identification using ΔE–E correlation, only events at backward η angles remain.

The excitation function of the differential cross section is similar to that of the total cross section of QF η photopdoruction on the nucleon. A broad bump ranging from 2.5 to 2.7 GeV in each emission angle would be attributed to QF $N(1535)S_{11}$ production. Although the contribution from the QFC mechanism seems 0 at backward η angles in the theoretical calculation, much higher cross sections are observed in the experiment. Further checks are needed for the analysis of the experimental data and the theoretical investigation.

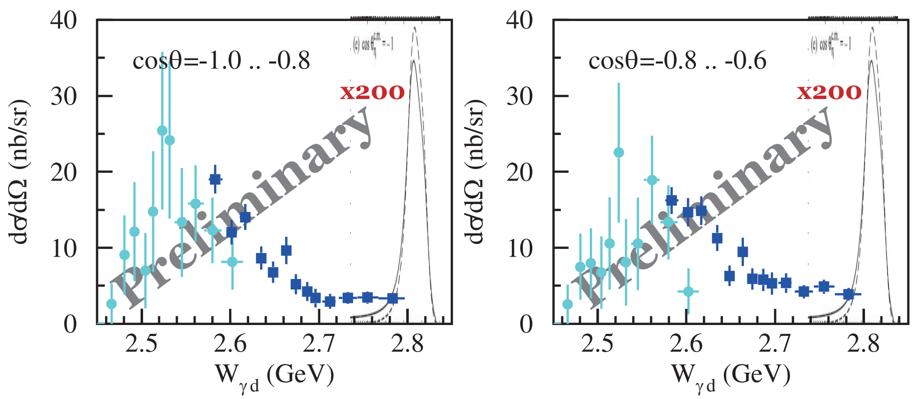

Fig. 2. Differential cross section $\mathrm{d}\sigma/\mathrm{d}\Omega$ as a function of $W_{\gamma d}$. The horizontal error of each data point corresponds to the coverage of the incident photon energy, and the vertical error shows the statistical error of $\mathrm{d}\sigma/\mathrm{d}\Omega$. The data are compared with 200 times those for the theoretical calculation given in Ref. [14].

3. Summary

An experiment is conducted at ELPH with the FOREST detector and BLC spectrometer to determine $a_{\eta N}$ using a special kinematics in the $\gamma d \to \eta pn$ reaction. Protons with large momenta are detected at 0°, and η production is confirmed using the $\gamma\gamma$ invariant mass. At low $M_{\eta n}$s, it is found that ηn scattering effect is dominant in the final-state interaction, and that $\pi n \to \eta n$-transition and pn-rescattering effects are small. The measurement of $\mathrm{d}^3\sigma/\mathrm{d}M_{\eta n}/\mathrm{d}\Omega_p$s is currently in progress to determine $\mathrm{Re}\, a_{\eta N}$.

A possible $\eta' d$ bound state is investigated in the $\gamma d \to \eta d$ reaction. Using the acquired data before the 2011 earthquake, $\mathrm{d}\sigma/\mathrm{d}\Omega$s as a function of $W_{\gamma d}$ has been determined at $W_{\gamma d} \leq 2.80$ GeV for the backward emitted η mesons where the background contribution is suppressed from the QFC mechanism. The corresponding structure is not observed yet, and large discrepancy of $\mathrm{d}\sigma/\mathrm{d}\Omega$ is found at lower incident energies between the experimental data and theoretical predictions.

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