LOW-ENERGY SCATTERING PARAMETERS BETWEEN THE ETA MESON AND NUCLEON FROM ETA PHOTOPRODUCTION ON THE DEUTERON*

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Among the two-body dynamics of the meson–nucleon systems, the attractive interaction between the eta meson and nucleon is not well-known. A new photoproduction experiment is planned for the determination of the low-energy scattering parameters between the eta meson and nucleon at the Research Center for Electron Photon Science, Tohoku University. The emitted proton is measured at 0° for eta photoproduction on the deuteron at the incident energy of 0.94 GeV, which gives small relative momentum between the eta meson and neutron in the final state to increase rescattering probability. The kinematics is found to have a good resolving power of the scattering length and effective range. In this contribution, the current status of the new experiment is presented.

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1. Introduction

The interaction between hadrons is fundamental and important in the non-perturbative domain of quantum chromodynamics. Among the two-body dynamics of meson–nucleon systems, the attractive interaction between the η meson and nucleon (N) is not well-known [1]. This is because neither direct ηN scattering experiments nor X-ray measurements from η-mesic atoms can be performed owing to the neutral and unstable nature of the η meson. The low-energy ηN interaction is described using the scattering length $a_{\eta N}$ and effective range $r_{\eta N}$ in an effective-range expansion of the S-wave phase shift

$$k \cot \delta(k) = \frac{1}{a_{\eta N}} + \frac{1}{2} r_{\eta N} k^2 + O\left(k^4\right) . \tag{1}$$

The $a_{\eta N}$ values have been extracted using many theoretical analyses from the differential and total cross sections for the $\pi N, \gamma N \to \pi N, \eta N$ reactions. Although the imaginary part of $a_{\eta N}$ ($\mathrm{Im}[a_{\eta N}]$) is found to be ~ 0.26 fm for different analyses, its real part ($\mathrm{Re}[a_{\eta N}]$) is scattered in a wide range from 0.2 to 1.1 fm [2, 3]. The $\mathrm{Re}[a_{\eta N}]$ value is important and sensitive to the pole position of the $N(1535)S_{11}$ resonance [4], to the existence of exotic η-mesic nuclei [1], and to the η–η' mixing angle [5]. We propose the $\gamma d \to \eta p n$ reaction to determine $a_{\eta N}$ at a certain kinematics, which enhances the ηN scattering effect.

A possibility of the precise determination of $a_{\eta N}$ from the $\gamma d \to \eta p n$ reaction was first investigated by Sibiritsev *et al.* [6] and followed by Fix and Arenhövel [7]. The opposite conclusions for the resolving power of $a_{\eta N}$ from the experimental data are shown in these works. However, the kinematics in these pioneering works is near the threshold ($E_\gamma < 0.7$ GeV). The contribution from the first-order ηN rescattering is not well-separated from the others. We will show the ideal condition to extract $a_{\eta N}$ from the $\gamma d \to \eta p n$ reaction in the next section.

2. Proposed $\gamma d \to p \eta n$ reaction

To determine $a_{\eta N}$, we plan to measure the $\gamma d \to p \eta n$ reaction [8] at the Research Center for Electron Photon Science (ELPH), Tohoku University, using the photon beam with energies around 0.94 GeV [9, 10] and detecting the protons at 0°. The bremsstrahlung photon beam at ELPH covers the energies from 0.82 to 1.26 GeV. Figure 1 (a) shows the expected diagram of the proposed reaction. The incident photon bombards the proton in the deuteron and produces a virtual η meson with a very low momentum. We will select the events in which the incident energy is approximately 0.94 GeV and the proton (with a momentum around 0.94 GeV/c) is detected at 0°.

This kinematics satisfies the recoilless condition of the produced η mesons. Figure 1 (b) shows the recoil momentum of η mesons for the $\gamma p \to \eta p$ reaction for the free proton target. The incident photon energy of 0.932 GeV can produce η mesons at rest. The ideal low-energy ηn scattering is expected to take place at the incident photon energy around 0.94 GeV taking into account the binding energy of the deuteron. It should be noted that the pn and ηp rescattering effects are suppressed due to their large relative momenta (~ 0.94 GeV/c) in this kinematic condition.

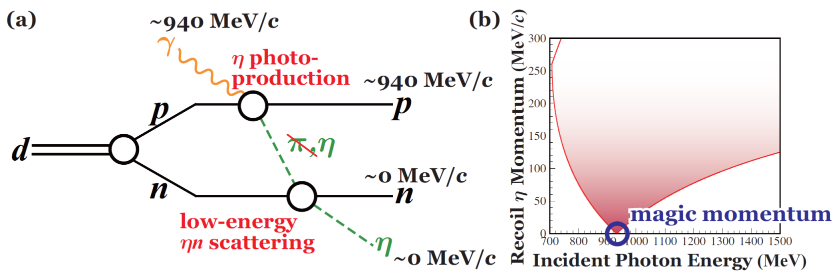

Fig. 1. (a) Expected diagram for the $\gamma d \to p\eta n$ reaction at the incident photon energy of 0.94 GeV and with the proton detection at 0°. The photon bombards the proton in the deuteron and produces a virtual η meson with a very low momentum. The ideal low-energy ηn scattering takes place where the pn and ηp rescattering effects are suppressed due to their large relative momenta. (b) Recoil momentum of η mesons for the $\gamma p \to \eta p$ reaction for the free proton target. The incident photon energy of 0.932 GeV can produce η mesons at rest.

The sensitivity to ηn scattering length of the proposed reaction has been checked [11] using the dynamical coupled-channels (DCC) model [12, 13]. The DCC model solves the coupled-channel Lippmann–Schwinger equation for meson–baryon scattering, where the coupled-channel unitarity, on- and off-shell amplitudes is fully considered. The DCC model itself gives

$$\begin{cases} a_{\eta N} = +0.75 + i0.26 \text{ fm}\,, & \text{and} \\ r_{\eta N} = -1.6 + i0.6 \text{ fm} \end{cases} \tag{2}$$

for the low-energy scattering parameters. Three kinds of diagrams as shown in Fig. 2 are taken into account in the treatment of the $\gamma d \to \eta pn$ reaction. Here, the $\gamma N \to \pi N$, $\gamma N \to \eta N$, and $\pi N \to \eta N$ amplitudes are given by the DCC model, and the amplitudes for the pn final-state interaction (FSI) and deuteron wave function are provided by the CD-Bonn [14], Nijmegen I [15], and Reid93 [15] potentials. The differential cross section $\mathrm{d}\sigma/\mathrm{d}M_{\eta n}/\mathrm{d}\Omega$ are calculated as a function of the ηn invariant mass ($M_{\eta n}$). The contribution of each term shown in Fig. 2 can be obtained turning off the corresponding amplitude. The results of the calculation show:

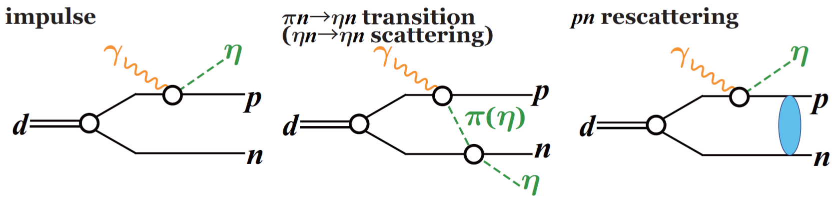

Fig. 2. Three kinds of diagrams considered in the DCC model calculation for the $\gamma d \to \eta p n$ reaction [11]: impulse, $\pi n \to \eta n$ transition ($\eta n \to \eta n$ scattering), and pn rescattering terms.

1. ηn scattering effect is visible at small $M_{\eta n}$ (enhancement factor ~ 1.2),
2. $\pi n \to \eta n$ transition (π exchange) effect is small, and
3. pn rescattering effect is also small.

The $\mathrm{d}\sigma/\mathrm{d}M_{\eta n}/\mathrm{d}\Omega$ values are calculated for different sets of $\mathrm{Re}[a_{\eta n}]$, and sensitivity of $\mathrm{Re}[a_{\eta n}]$ is checked. The $\mathrm{d}\sigma/\mathrm{d}M_{\eta n}/\mathrm{d}\Omega$ cross section with 5% error, binned in 1 MeV width of $M_{\eta n}$, can determine the $\mathrm{Re}[a_{\eta n}]$ value at the precision of approximately ± 0.1 fm. The model dependence of the deuteron wave function is found to be less than 0.5% near $M_{\eta n} \sim M_\eta + M_n$. The details of the results can be found in Ref. [11], where the possibility of the effective-range extraction is also discussed.

3. Experiment

The $\gamma d \to p \eta n$ reaction will be measured at ELPH using the FOREST electromagnetic calorimeter system [16, 17] together with an additional forward charged-particle spectrometer [18]. Figure 3 shows the experimental setup for the precise determination of $a_{\eta n}$. The incident photon energy ranges from 0.82 to 1.26 GeV [9] for the circulating electron energy of 1.32 GeV in the electron synchrotron [19]. The details of the FOREST detector including the liquid deuterium target is described elsewhere [16]. The forward scattered proton is momentum-analyzed with a bending magnet (transported from the low-energy ring of KEKB) behind FOREST. The trajectory of a charged particle is measured with two planar drift chambers (DCs), and the time of flight is measured with plastic scintillator (PS) hodoscopes. Additional e/π and π/K separations are made using SF5 lead-glass and aerogel Cherenkov counters, respectively.

The expected proton missing-mass resolution, which corresponds to the ηN invariant-mass resolution, is approximately 5 MeV. The value of the mass resolution is given by the photon-tagging resolution (0.5–2.5 MeV) [9], the time resolution for the PS hodoscopes (40 ps), and the flight length of approximately 4.5 m. Commissioning of the new detectors at downstream of the forward spectrometer has been finished.

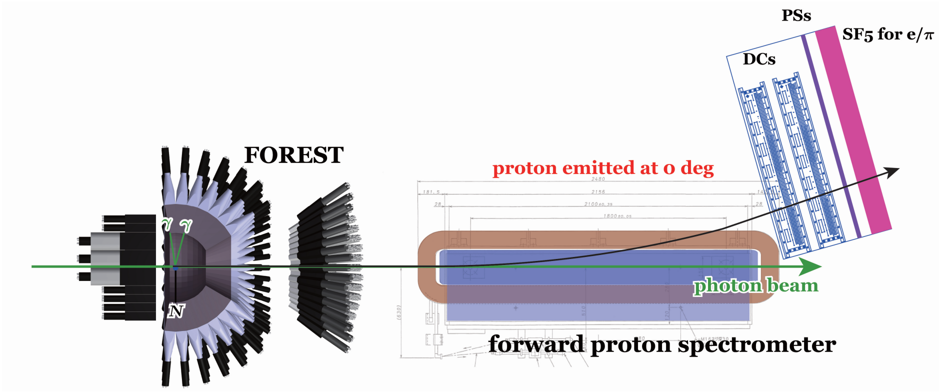

Fig. 3. Experimental setup at ELPH for the precise determination of $a_{\eta n}$. The forward emitted proton is momentum-analyzed with a bending magnet behind FOREST. The trajectory of a charged particle emitted at 0° is measured with two planar drift chambers, and the time of flight is measured with plastic-scintillator hodoscopes. Additional e/π separation is made using SF5 lead-glass Cherenkov counters.

We plan to determine $\mathrm{Re}[a_{\eta n}]$ using the ratio of measured cross sections for $\gamma d \to \eta pn$ divided by those for $\gamma p \to \eta p$ convoluted with the proton momentum distribution in the deuteron. This can reduce the systematic uncertainty from the coverage of the forward spectrometer. The ratio also cancels the uncertainty of the elementary $\gamma p \to \eta p$ amplitudes [11]. Thus, we take both the data with the liquid-hydrogen and deuterium targets. The first series of the experiments will start in the end of October 2017 to determine $\mathrm{Re}[a_{\eta n}]$ with a precision of 0.2–0.3 fm. Our final goal is to provide $\mathrm{Re}[a_{\eta n}]$ ($\mathrm{Re}[r_{\eta n}]$) with a precision of 0.1 fm (0.5 fm) using more high-intensity photon beams.

4. Summary

An experiment is planed at ELPH using the FOREST detector to determine the ηn scattering length $a_{\eta n}$ using the $\gamma d \to p\eta n$ reaction. Proton detection at 0° using 0.94 GeV photon beam gives the recoilless condition of η mesons. The ηn final-state interaction can be studied thanks to the small relative momentum between ηn. We will provide an accurate $\mathrm{Re}[a_{\eta n}]$ value in the near future.

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