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Double neutral pion photoproduction off the proton with FOREST at ELPH

Q. He[1,a], H. Fujimura[2], H. Fukasawa[3], R. Hashimoto[1], Y. Honda[1], T. Ishikawa[1], T. Iwata[2], S. Kaida[1], J. Kasagi[1], A. Kawano[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], S. Ogushi[1], Y. Okada[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. Yoshida[2]

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

Abstract. Total cross section for the double neutral pion photoproduction off the proton is presented in the incident photon energy range of 0.58 to 1.15 GeV. The data were accumulated in the years 2009-2010, recorded by a 4π EM calorimeter at ELPH, named FOREST. The number of recorded events obtained during this period is 1.6×10^9 for a hydrogen target. Two neutral pions are reconstructed via detecting their decay products, four gammas ($2\pi^0 \to 4\gamma$). Compared to the previous results obtained by other groups, our data are in good agreement with theirs within error bars.

1 Introduction

Meson photoproduction off the nucleon is one of the tools to study the structure of hadrons in the non-perturbative domain of QCD. While single pion photoproduction has been applied to studying nucleon resonances especially for the Δ-excitation, double pion channels may offer complementary information, particularly on the resonances that couple weakly to a single pion, which is useful to disentangle the overlapping resonances at higher excitation energies. Double pion photoproduciton on the proton has three possible channels: $\gamma p \to \pi^0\pi^0 p$, $\gamma p \to \pi^+\pi^- p$, and $\gamma p \to \pi^+\pi^0 n$. The $2\pi^0$ channel is a unique one, which provides interesting details because Born terms are strongly suppressed and the ρ^0 meson can not directly couple to $2\pi^0$. Also, Bose-Einstein (BE) correlations in π^0 pairs can provide useful information about the space-time properties of the $2\pi^0$ emitting source.

A 4π EM calorimeter complex, named FOREST [1], was utilized to detect neutral mesons decaying into γ's as well as some charged particles in the final state. FOREST consists of three different EM calorimeters: (1)"SCISSORS III" comprised of 192 pure CsI crystals, (2) "Backward Gamma" made up of 252 lead scintillating fiber modules and (3) "Rafflesia II" composed of 62 lead glass Cerenkov

[a] e-mail: qhhe@lns.tohoku.ac.jp

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counters. The energy resolutions for SCISSORS III, Backward Gamma and Rafflesia II are 3%, 7% and 5% for 1 GeV positrons, respectively [2]. In order to distinguish between neutral and charged incident particles, a plastic scintillator (PS) hodoscope is placed in front of each calorimeter.

The experiment was performed at Research Center for Electron Photon Science (ELPH), Tohoku University. ELPH provides a Bremsstrahlung photon beam which is generated by inserting a carbon fiber into circulating electrons in the 1.2 GeV synchrotron ring. Scattered electrons are detected with the tagging system “STB-Tagger II” to determine the photon energy. The details of the photon tagging counter STB-Tagger II are given in [3]. The Bremsstrahlung photon beam is provided under two operation modes: (1) 920 MeV Mode ($E_\gamma = 580 - 880 MeV$) and (2) 1200 MeV Mode ($E_\gamma = 740 - 1150 MeV$).

2 Identification of particles and reaction channels

Basically, final state particles from photo-induced reactions are identified by "clusters", which is defined as a group of adjacent crystals in the EM calorimeter to which a final state particle induced electromagnetic shower extends. The number of crystals in a "cluster" varies depending on the energy of the incident particle. The incident particle’s energy and position are reconstructed as the sum energy and the geometrical center of gravity of the "cluster", respectively. The plastic scintillator (PS) hodoscopes in front of calorimeters separate neutral hits (photon and neutron candidates) from charged hits (proton, π^+, π^- or other charged particle candidates). They are also capable of determining the positions of the charged hits. In the next step, these clusters are assigned to different particle types with the methods presented below.

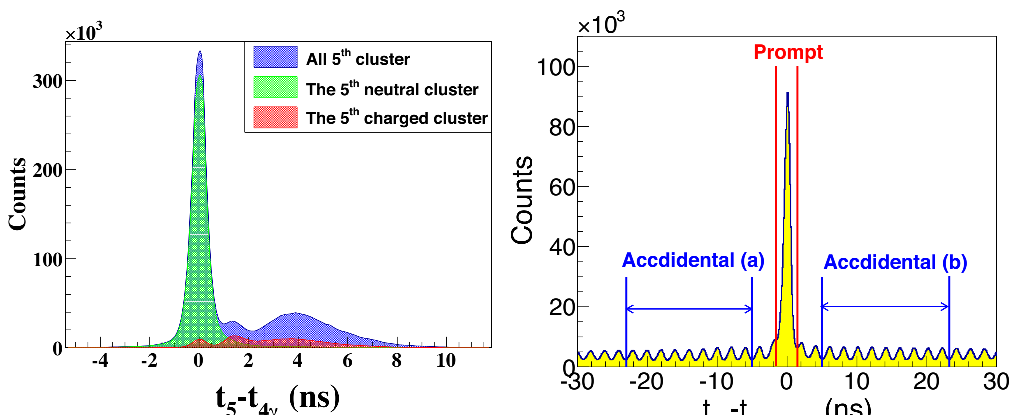

Figure 1. Left: Time difference between the fifth cluster and the average time of four photons. Right: Time difference between tagging time of the incident photon and the average time of four produced photons. Prompt time window is indicated by the region between two red vertical lines. Accidental coincidence regions besides the prompt window are indicated by the blue vertical lines.

The reaction $\gamma p \rightarrow \pi^0\pi^0 p$ is reconstructed by its decay channel $\gamma p \rightarrow \pi^0\pi^0 p \rightarrow 4\gamma p$ which has 5 final particles. Therefore, it is required that four neutral clusters (4 photon candidates) and one charged cluster (proton candidate) should be detected by FOREST. The event which satisfies the following conditions will be accepted as a candidate for the reaction $\gamma p \to \pi^0\pi^0 p$:

- Two pairs of neutral clusters with a time difference within [-1.5,1.5] ns are detected.
- One charged cluster in time window [+1.5,15] ns with respect to the average time of four photons $t_{4\gamma}$ is detected, as shown in Fig. 1 (Left).
- There are no other neutral and charged clusters in [-3,15] ns with respect to $t_{4\gamma}$.

Once a candidate event is picked up, one needs to find the proper combination of two paris of photons in order to reconstruct two pions from the undistinguishable four photons, denoted as γ_1, γ_2, γ_3 and γ_4. There are three possible combinations of two pairs of photons out of four: (1) (γ_1, γ_2), (γ_3, γ_4); (2) (γ_1, γ_3), (γ_2, γ_4); (3) (γ_1, γ_4), (γ_2, γ_3). The best combination is chosen by a kinematic fitting analysis discussed below.

The probability of accidental coincidence between FOREST events and tagging signals is evaluated to eliminate the contribution of accidental coincidence events by means of the scaled distributions of random background events outside the prompt time window, as depicted in Fig. 1 (Right).

2.1 Kinematic fitting

The events that satisfy the conditions mentioned above are subjected to a kinematic fitting analysis[9], which will provide a quantity, named confidence level (CL), that reflects the goodness of fitting for the measured variables to the hypothesis of the $\gamma p \to \pi^0\pi^0 p$ reaction. To improve the fitting, some constraint conditions are applied. In this analysis, we employ the four-momentum conservation law and the invariant masses of pions and proton as constraints.

The confidence level distribution is shown in Fig. 2 (Left), displaying a flat distribution when CL > 20%. This indicates a valid kinematical fitting performance. In order to judge the quality of the error estimation for the measured variables, pull distributions [9] are utilized for six kinematic variables, E_1, θ_1, ϕ_1, θ_p, ϕ_p, E_γ, when CL > 1% (see Fig. 2), where E_1, θ_1 and ϕ_1 are the energy, polar angle and azimuthal angle of the first photon, θ_p and ϕ_p are the polar angle and azimuthal angle of the proton, and E_γ is the incident photon energy, respectively. Because the first photon is selected randomly out of four photons, the pull distributions of E_1, θ_1 and ϕ_1 can reflect the behavior of other three photons. These pull distributions are sufficiently to be a Gaussian distribution with mean (μ) of 0 and sigma (σ) of 1, indicating that our error estimation is reasonable.

3 Total cross section

The events with CL > 20% are accepted for physical analysis. The proper combination of two pairs of photons decaying from two pions is selected with the best CL. Figure 3 shows invariant masses of the selected pairs of photons and the missing mass (m_X) for $\gamma p \to \pi^0\pi^0 X$. The clear signals for two pions and a proton are shown in the plots.

The cross section is given by

$$\frac{d\sigma}{dE_\gamma dm_{\pi\pi}^2 dm_{\pi p}^2} = \left(\frac{A_{target}}{F(E_\gamma)\rho_{target} l_{target} N_A}\right)\frac{y(E_\gamma, m_{\pi\pi}^2, m_{\pi p}^2)}{\eta(E_\gamma, m_{\pi\pi}^2, m_{\pi p}^2)\Gamma_{\pi^0\pi^0\to 4\gamma}}, \tag{1}$$

with the total number of events $y(E_\gamma, m_{\pi\pi}^2, m_{\pi p}^2)$, an acceptance factor $\eta(E_\gamma, m_{\pi\pi}^2, m_{\pi p}^2)$ and the branch ratio $\Gamma_{\pi^0\pi^0\to 4\gamma} = 0.976$ of the decay channel $\pi^0\pi^0 \to 4\gamma$, where A_{target}, ρ_{target}, and l_{target} are the target atomic weight, density, and length, respectively, N_A is the Avogadro number, and $F(E_\gamma)$ is the

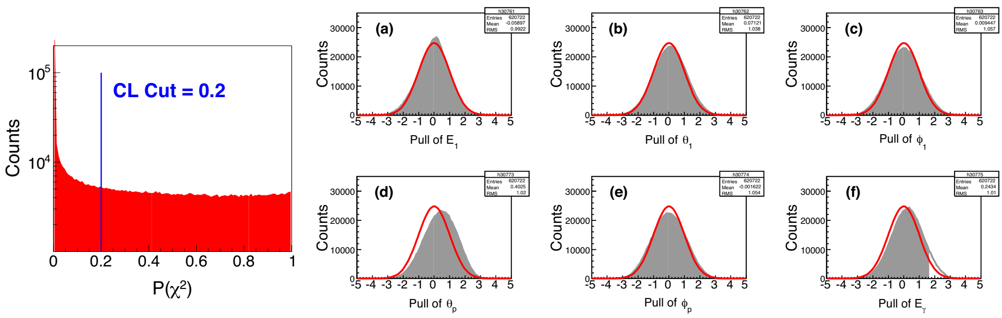

Figure 2. Left: χ^2 probability(CL) distribution. Right: Pull distributions with CL > 1% (indicated by filled areas) for (a) E_1, (b) θ_1, (c) ϕ_1, (d) θ_p, (e) ϕ_p and (f) E_γ. The red lines in all pads indicate a Gaussian distribution with mean of 0 and sigma of 1 for comparison.

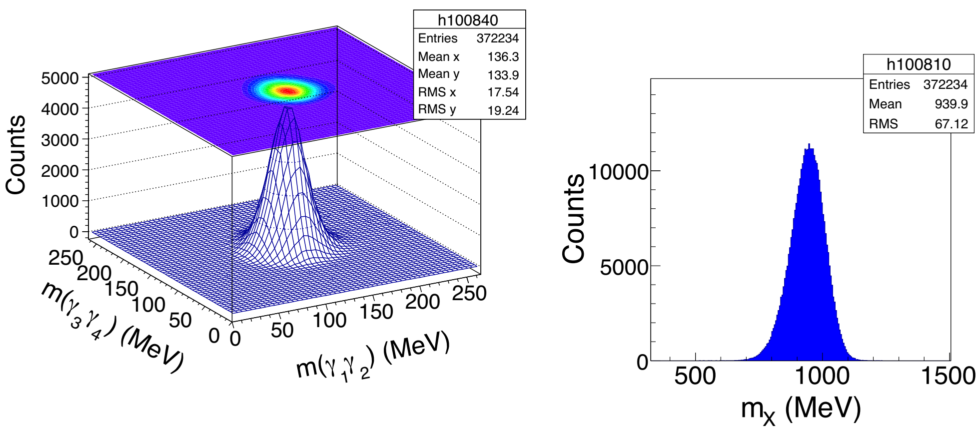

Figure 3. Left: Invariant masses for the best combination for two pairs of photons. Right: Missing mass (m_X) for $\gamma p \to \pi^0\pi^0 X$.

corrected number of incident photons. Here $m_{\pi\pi}$ and $m_{\pi p}$ are the invariant mass of two pions and that of the pion-proton system, respectively.

We estimate the acceptance in each volume of $(E_\gamma, m^2_{\pi\pi}, m^2_{\pi p})$ as,

$$\eta(E_\gamma, m^2_{\pi\pi}, m^2_{\pi p}) = \frac{N_{acc}(E_\gamma, m^2_{\pi\pi}, m^2_{\pi p})}{N_{gen}(E_\gamma, m^2_{\pi\pi}, m^2_{\pi p})}, \tag{2}$$

where N_{acc} and N_{gen} are the number of accepted and generated Monte Carlo events, respectively. We use a GEANT4-based simulator, named RFS, to generate events and simulate the detector response.

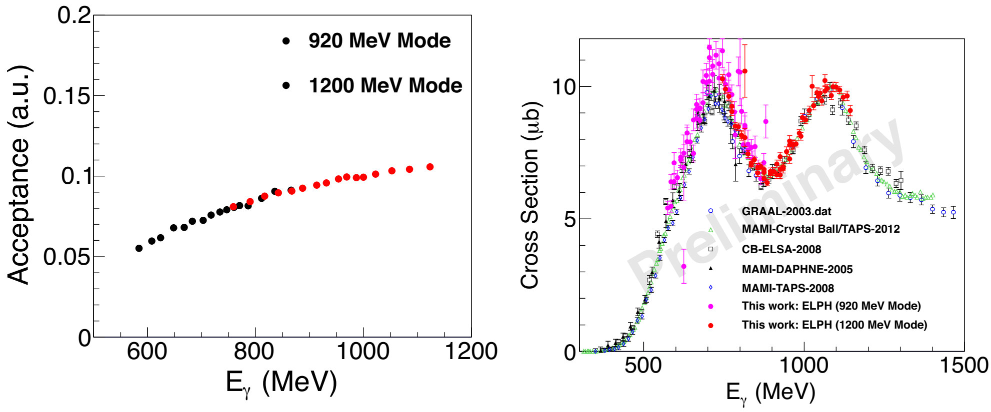

Figure 4. Left: Acceptance as a function of the incident photon energy. The results for 920 MeV Mode and 1200 MeV Mode are consistent with each other in the overlapping region. Right: Total cross section for the reaction $\gamma p \rightarrow \pi^0\pi^0 p$ as a function of the incident photon energy (only statistical errors are shown). Our results are compared to the previous data from GRAAL[4], CB-ELSA[5, 6], DAPHNE[7], TAPS[6], and Crystal Ball/TAPS[8].

The same event selection procedure used for the real data is applied for the generated events to get the number of accepted events N_{acc}. A very preliminary result of the total cross section was obtained. The acceptance and total cross section are shown as a function of the incident photon energy in Fig. 4. Our data are consistent with the results of other groups within the error bars.

4 Summary

Double neutral pion photoproduction off the proton has been studied in a incident photon energy region ranging from 0.58 to 1.15 GeV, utilizing the 4π EM calorimeter FOREST at ELPH. A very preliminary result of the total cross section is reported. Our data are consistent with previously published data from other groups within error bars. We are now refining the event selection and the acceptance estimation to finalize the analysis.

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