J-PARC Letter of Intent

19 June 2023

Study of the bump structure at 1680 MeV by the $\pi^- p \to \eta n$ reaction at p_π=0.7 to 1.2 GeV/c.

H. Kohri, T. Hashimoto, T. Hotta, T. Ishikawa, H. Katsuragawa, R. Kobayakawa, H. Noumi, K. Shirotori, and S.Y. Ryu
Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan

K. Horie and S. Shimizu
Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

H. Ito
Department of Physics and Astronomy, Tokyo University of Science, Noda, Chiba 278-8510 Japan

H. Ohnishi and A.O. Tokiyasu
Research Center for Electron Photon Science, Tohoku University, Sendai, Miyagi 982-0826, Japan

Y. Igarashi and K. Ozawa
High Energy Accelerator Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

J.K. Ahn
Department of Physics, Korea University, Seoul 02841, Republic of Korea

P.L. Cole
Department of Physics, Lamar University, Beaumont, Texas 77710, USA

H. Fujioka
Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan

K. Joo
Department of Physics, University of Connecticut, Storrs, CT 06269-3046, USA

H. Sako
Japan Atomic Energy Agency, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan

I.I. Strakovsky
Department of Physics, The George Washington University, Washington, D.C. 20052, USA

Abstract

Photo-production and pion-production of mesons on the nucleon provide important information on the nucleon excitation spectrum which is still not sufficiently understood. The total cross sections for the $\gamma p \to \eta p$ reaction are dominated by the exitation of the well-known nucleon resonance $N^*(1535)$ with a spin-parity of $1/2^-$. The $N^*(1535)$ lies 50 MeV above the ηp threshold. As the total energy W increases, the cross sections decrease gradually and become flat around W=1680 MeV. The dominant peak at W=1535 MeV is also observed in the total cross sections for the $\gamma n \to \eta n$ reaction. However, a bump structure at W=1680 MeV is observed only in the case of the neutron target. This bump structure is inferred to be due to a peculiar nucleon resonance, which is excited only for the neutron target and not excited for the proton target. The nucleon resonance at W=1680 MeV is inferred to have very strong isospin dependence.

The mass of this peculiar nucleon resonance is close to the mass 1710 MeV predicted as one of exotic anti-decuplet baryons by Diakonov et al. This peculiar nucleon resonance might be an exotic state with 5 quarks including $s\bar{s}$. The discovery of exotic mesons with 4 quarks continues for a long time and recent discovery of P_c^+ with 5 quarks strongly inspired our further search for new exotic states.

One of weak points of the evidence of the bump structure at 1680 MeV is Fermi motion of the neutron target. In the case of the γn reaction, deuteron targets were used and Fermi motion of the neutron widened and smeared the structure. Although scattered neutrons were tagged and their energies were measured by TOF in recent experiments, insufficient energy resolution made the structure wide. The second weak point is nuclear effects, such as rescattering, which might produce strange structures.

In order to overcome these difficulties, we are interested in a new experiment to measure the total and differential cross sections for the $\pi^- p \to \eta n$ reaction precisely. The energy dependence and angular distribution of differential cross sections will be measured from W=1490 to 1780 MeV (p_π=0.7 to 1.2 GeV/c). The decay γ-rays from η-mesons will be detected by using CsI calorimeters which were used by E36. Thanks to the proton target without Fermi motion, precise cross sections are expected without the nuclear effects. Existing data for the $\pi^- p \to \eta n$ reaction were published about 40-50 years ago and very scarce. A bump structure due to the peculiar nucleon state $N^*(1680)$ is not observed in the existing data. A narrow peak structure might be undetected because of scarce data points. Since the bump structure at 1680 MeV was clearly observed at four photon beam facilities with the $\gamma n \to \eta n$ reaction, it should be observed with the $\pi^- p \to \eta n$ reaction. New data are needed and expected to conclude the existence of the peculiar nucleon resonance at W=1680 MeV and the width of the resonance is precisely measured.

The total cross sections for the $\pi^- p \to \eta n$ reaction are about 1 mb. If we assume the intensity of π^- beams is 10^6/s and the thickness of liquid hydrogen target is 3 cm, the yield of η-mesons is estimated to be about 130/s. Thanks to high intensity pion beams at J-PARC and large cross sections, η-mesons can be produced with a high rate. Precise cross section data are expected for a new experiment within 1 month.

We have two difficulties for the new experiment now. After preparing the answer for these difficulties, we would like to submit a new proposal to J-PARC.

1 Physics Motivation

Meson and baryon productions and their dacays have played an important role in clarifying the existence of various hadrons. After the report of the evidence for the pentaquark baryon θ^+ [1], the search for exotic mesons and baryons has been extensively carried out at various experimental facilities in recent 20 years. The evidence for several tetraquark mesons has been reported by KEK, BaBar, BES, and LHCb [2]. Recently, very high statistics data suggesting the existence of pentaquark baryons have been reported by LHCb [3, 4, 5]. They claimed that four peak structures at 4312, 4337, 4440, 4457 MeV were observed in the invariant mass spectrum of $J/\psi p$ [4, 5]. These states are considered to include a $c\bar{c}$ pair and called P_c^+. These results inspired us to search new exotic states to establish multiquark hadron physics.

We have been carrying out photo-production experiments at SPring-8 and ELPH, Tohoku University. We found some peculiar bump structures at both facilities. Narrow bump structures were observed at the same mass of about 2100 MeV in the experiments of the $\gamma p \to \phi p$ and $K^+\Lambda(1520)$ reactions at SPring-8 [6, 7]. Another bump structure was observed in the experiment with the $\gamma n \to \eta n$ reaction at ELPH/Tohoku [8]. The cross sections for the $\gamma p \to \eta p$ and $\gamma n \to \eta n$ reactions are dominated by the nucleon resonance $N^*(1535)$ with $1/2^-$ near the threshold. The ηp cross sections decrease gradually above the $N^*(1535)$ peak and become flat around W=1680 MeV. The ηn cross sections also decrease gradually above the $N^*(1535)$ peak. However, the bump structure is observed at W=1680 MeV only in the ηn cross sections as shown in Fig. 1(a). The bump structure is inferred to be due to a nucleon resonance in the intermediate state of γn, and the nucleon resonance at W=1680 MeV is a very peculiar nucleon resonance which has strong isospin dependence. The bump structure at W=1680 MeV in the $\gamma n \to \eta n$ reaction was also observed at photon beam facilities in Europe as shown in Fig. 1(b,c,d).

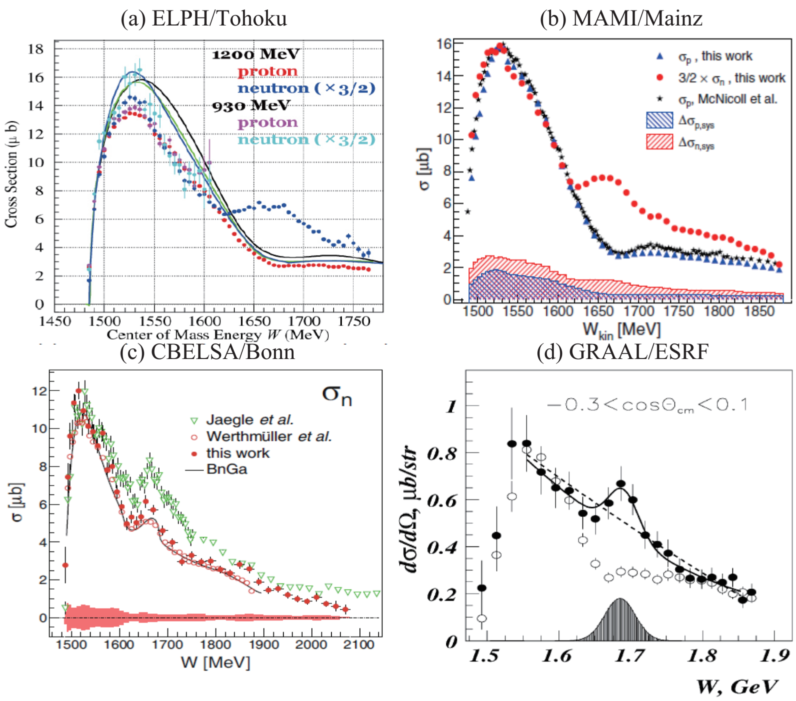

Figure 1: The total cross sections for the $\gamma p \to \eta p$ and $\gamma n \to \eta n$ reactions measured at (a) ELPH, Tohoku University, (b) MAMI/Mainz [9], (c) CBELSA/Bonn [10], and (d) GRAAL/ESRF [11].

The mass of this peculiar nucleon resonance is close to the mass 1710 MeV predicted as one of exotic anti-decuplet baryons by Diakonov et al. [12]. The peculiar nucleon resonance $N^*(1680)$ might be an exotic state with 5 quarks including $s\bar{s}$.

One of weak points of the observation of the bump structure at 1680 is Fermi motion of the neutron target. In the case of the γn reaction, deuteron targets were used and Fermi motion of the neutron widened and smeared the peak. Although scattered neutrons were tagged and their energies were measured by TOF in recent experiments, insufficient energy resolution made the structure wide. Another weak point is nucleon effects, such as rescattering, which might produce strange structures in the spectrum. The bump structure at W=1680 MeV in the $\gamma n \to \eta n$ reaction is not completely trusted.

In order to overcome these difficulties, we are interested in a new experiment to precisely measure the total and differential cross sections for the $\pi^- p \to \eta n$ reaction. Thanks to the proton target without Fermi motion, precise cross sections are expected without the nuclear effects. Figure 2 shows existing data for the $\pi^- p \to \eta n$ reaction. The data around W=1680 MeV were taken about 40-50 years ago. A bump structure due to the peculiar nucleon resonance $N^*(1680)$ is not observed in the existing scarce data. A narrow peak structure might be undetected because of scarce data points. Since the bump structure at 1680 MeV was clearly observed at four photon beam facilities with the $\gamma n \to \eta n$ reaction, it should be observed with the $\pi^- p \to \eta n$ reaction. New data are needed and expected to conclude the existence of the peculiar nucleon resonance at W=1680 MeV.

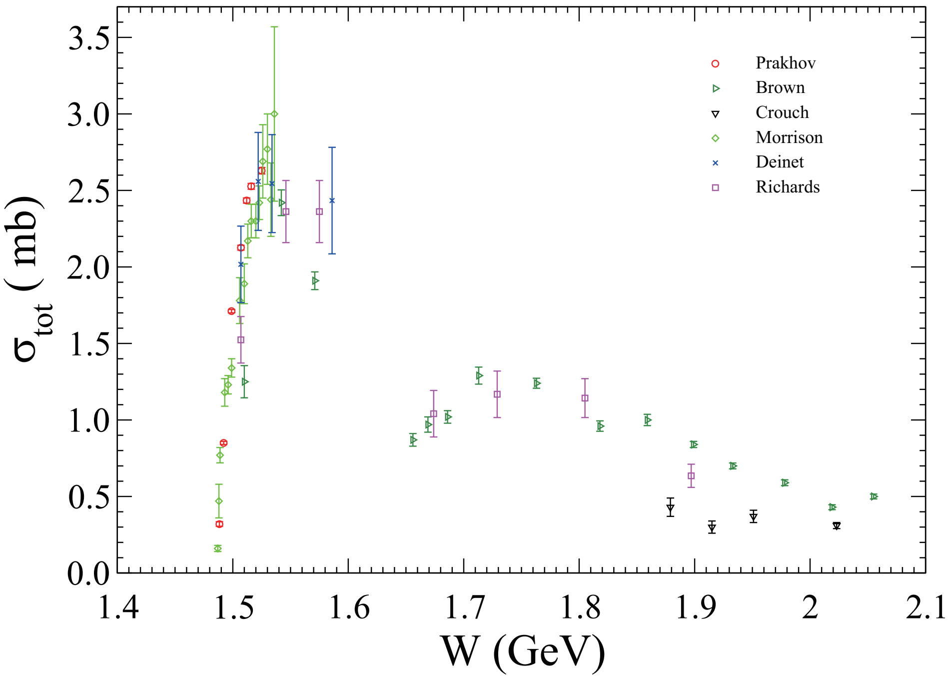

Figure 2: Existing data for the $\pi^- p \to \eta n$ reaction [13].

2 Experimental Apparatus

2.1 Beamline

There are 3 possible beamlines to be used for our experiment. The first possilibity is to use the K1.8BR beamline, and the second possibility is to use the K1.8 beamline. The final possibility is to use the K1.1 beamline which will be constructed by the extension of the hadron hall. Because of the recent limitation of beamtime, both of the K1.8BR and K1.8 beamlines have some apprroved experiments now. We are going to hear the status of these experiments continuously and determine which beamline is suitable for our experiment.

2.2 Liquid Hydrogen Target

We plan to detect 2 γ-rays and the vertex position of the reaction $\pi^- p \to \eta n$ is unknown. In order to reconstruct the mass of the η-meson, 4-dimensional momenta of the γ-rays are needed. Thus, the central position of the target is assumed as the emission position of the γ-rays. If a long target is used, the resolution of the invariant mass of 2 γ-rays becomes worse. Judging from our experimental experiences, reasonable thickness of liquid hydrogen target is about 3-5 cm. Detailed simulations and yield estimations will be done in order to fix the target thickness.

2.3 CsI Calorimeters

In the experiment to measure 2 γ-rays from a η-meson, calorimeters surrounding the target are used. One possibility is to use CsI calorimeters (Fig. 3) used for detecting 2 γ-rays from a π^0-meson at E36 [14].

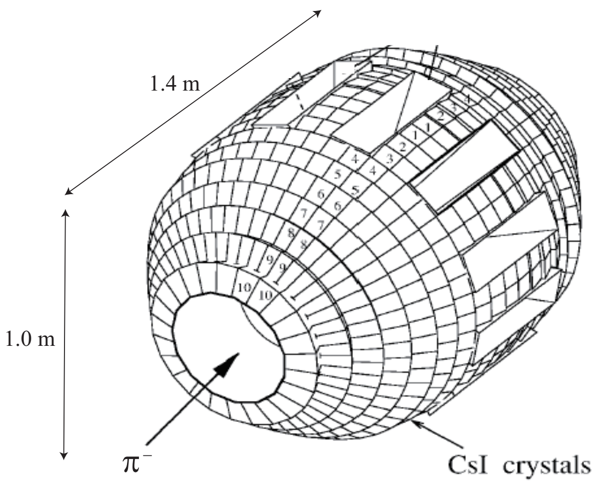

Figure 3: CsI calorimeters to be used for the detection of 2 γ-rays from the η meson [14].

The number of CsI(Tl) crystals is 768 and 75% of solid angle is covered around the target. The total weight of the CsI calorimeters is 1.7 ton. The CsI calorimeters are stored at KEK and not used now. One weak point of the calorimeters is that there are 12 holes for detecting μ^+ at E36. These holes decrease the detection efficiency of the η-meson. Two dominant decay channels of the η-meson are $\gamma\gamma$ (39.36%) and $\pi^0\pi^0\pi^0$ (32.57%) and the latter channel gives

6γ's in the final state. The probability of one of them escaping from the holes or making a cluster near the holes is very high. The decay channel of $\gamma\gamma$ seems to be the best channel to detect the η-meson with these calorimeters.

Figure 4 shows the result of Monte Carlo simulation Geant4. η-mesons are produced by π^- beams with momenta from 0.7 to 1.2 GeV/c and decay 2 γ-rays are energy-analyzed by the CsI calorimeters. The detection efficiency for the $\gamma\gamma$ channel is found to be about 10%. The η-meson peaks are clearly observed for every beam momenta. The centroid of the peaks is shifted to the lower side from the nominal η-meson mass of 548 MeV. A part of showers is lost because of the 12 holes in the calorimeters. It is confirmed that the identification of the η-meson peak is possible with these CsI calorimeters.

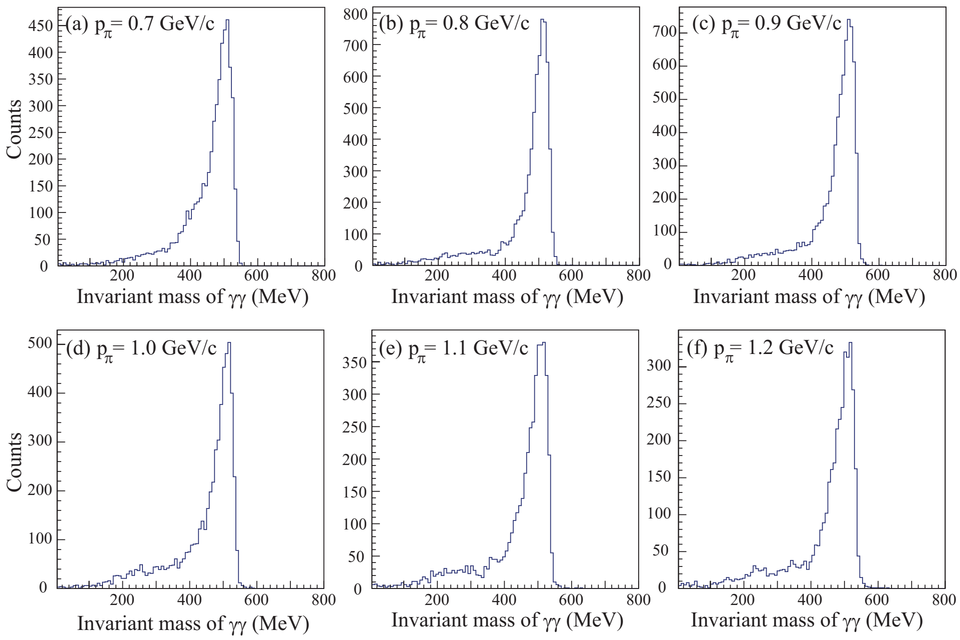

Figure 4: Invariant mass of $\gamma\gamma$ by Monte Carlo simulation Geant4. The momenta of π^- beams are changed from (a) 0.7 GeV/c to (f) 1.2 GeV/c. The missing neutron is loosely selected.

3 Yield Estimation

We assume the π^- beam intensity is about $N_B = 10^6$/s. In the case of detecting γ-rays, the vertex of the reaction is unknown, therefore long liquid hydrogen target makes energy resolution worse. If the thickness of $L = 3$ cm is assumed, the number of target protons N_T is calculated as

$$N_T = \rho L N_A = 1.3 \times 10^{23}, \tag{1}$$

where $\rho = 0.07$ g/cm^3 is the density of the liquid hydrogen target and N_A is Avogadro's number 6.02×10^{23}. The total cross sections are about $\sigma = 1$ mb which equals to 10^{-27} cm^2. The yield (Y) of η-mesons produced is calculated as

$$Y = \sigma N_T N_B = 130/s. \tag{2}$$

Thanks to high intensity pion beams at J-PARC and large cross sections, η-mesons can be produced with a high rate. Since the detection efficiency of 2 γ-rays (39.36%) from η-meson is about 10% depending on the kinematics, the numbers of detected η-mesons are estimated to be about 4×10^5 in a day. Precise cross section data are expected for a new experiment within 1 month.

4 Summary

Recent observation of P_c^+ pentaquark states including $c\bar{c}$ inspired us to search other pentaquark states including $s\bar{s}$. The peculiar nucleon resonance observed at 1680 MeV in the $\gamma n \to \eta n$ reaction may be an exotic state with 5 quarks. Since a deuteron target was used as a neutron target in the case of photon beams, Fermi motion of nucleons and final state interactions deteriorate the reliability of the existing data.

We are interested in a new experiment to measure the total and differential cross sections for the $\pi^- p \to \eta n$ reaction. The use of a hydrogen target and π^- beams is expected to overcome the difficulty and a give a conclusive result for the existence of the peculiar nucleon state $N^*(1680)$.

At present, two difficulties with the new experiment remain. One is the selection of beamlines at J-PARC. We would like to take data using π^- beams with momenta from 0.68 GeV/c to 1.2 GeV/c. There are three possibilities of (1) K1.8BR, (2) K1.8, and (3) K1.1 after the extension of the hadron hall. The other is CsI calorimeters used at E36. The CsI calorimeters will move from KEK to Korea in the future. After the experiment at RAON, they will return to KEK. If the experiment is carried out during the absent period, we need to use other calorimeters. After preparing the answer for these difficulties, we would like to submit a new proposal to J-PARC.

References

[1] T. Nakano et al., Phys. Rev. Lett. **91**, (2003) 012002.

[2] H.X. Chen et al., Phys. Rep. **639**, (2016) 1.

[3] R. Aaij et al., Phys. Rev. Lett. **122**, (2019) 222001.

[4] R. Aaij et al., Phys. Rev. Lett. **115**, (2015) 072001.

[5] R. Aaij et al., Phys. Rev. Lett. **128**, (2022) 062001.

[6] T. Mibe et al., Phys. Rev. Lett. **95**, (2005) 182001.

[7] H. Kohri et al., Phys. Rev. Lett. **104**, (2010) 172001.

[8] T. Ishikawa et al., Private communication.

[9] D. Werthmuller et al., Phys. Rev. C **90** (2014) 015205.

[10] L. Witthauer et al., Eur. Phys. A **53** (2017) 58.

[11] V. Kuznetsov et al., Phys. Lett. B **647** (2007) 23.

[12] D. Diakonov et al., Z Phys. A **359**, (1997) 305.

[13] J. Durand et al., Phys. Rev. C **78**, (2008) 025204.

[14] D.V. Dementyev et al., Nucl. Instr. Meth. A **440**, (2000) 151 .