J-PARC Experimental Proposal

25 December 2023

Study of the peculiar bump structure at 1680 MeV by the $\pi^- p \to \eta n$ reaction with momenta of p_π=0.85-1.2 GeV/c.

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EXECUTIVE SUMMARY

Reaction:	$\pi^- \ p \to \eta \ n$ reaction
Beamline:	K1.8 beamline
Beam:	π^--meson beams with momenta from 850 to 1200 MeV/c
Target:	Liquid hydrogen target with a thickness of 30 mm
Detector:	CsI(Tl) calorimeter
Beam time:	9 days in total

Abstract

Exotic four-quark and five-quark particles have been continuously discovered in recent 20 years. Most of the exotic particles include a $c\bar{c}$ quark pair. The search for new exotic particles including other quark pairs, such as $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, or $b\bar{b}$, is needed in order to establish the multi-quark hadron physics. The mass of the visible matters in the universe is mostly due to nucleons, which are composed of three quarks. The study of the exotic particles with four-quarks and five-quarks is important to understand how the universe is created after the Big Bang.

Photo-production and pion-production of mesons on the nucleon provide important information on the nucleon excitations including exotic five-quark states. The total cross sections for the $\gamma p \to \eta p$ reaction are dominated by the exitation of the nucleon resonance $N^*(1535)$. 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 1535 MeV is also observed in the total cross sections for the $\gamma n \to \eta n$ reaction. However, a bump structure at 1680 MeV is observed only in the case of the neutron target. In addition, the width of the bump was measured to be about 25 MeV that is very narrow compared with usual nucleon widths of a few 100 MeV. This bump structure is inferred to be due to a peculiar state, which is excited only for the neutron target and not excited for the proton target.

The mass of this peculiar state is close to the mass 1710 MeV selected as one of exotic anti-decuplet baryons by Diakonov et al. This peculiar state might be an exotic state with five quarks including $s\bar{s}$. The discoveries of the exotic particles continuously happen and recent discovery of P_c^+ with five quarks strongly inspired our search for the new exotic particles.

One of weak points of the evidence of the bump structure at 1680 MeV is nuclear effects, such as rescattering. In the case of the γn reaction, deuterium target was used, and a proton was a spectator. However, the spectator proton shadowed a neutron, or scattered with a η-meson or a neutron, which might produce strange structures in the excitation spectrum. Another weak point is Fermi motion of the neutron. Although the total energy W can be calculated by detecting the η-meson and neutron, insufficient energy resolutions made the structure wide and the intrinsic width of the narrow bump was difficult to measure precisely.

In order to overcome these difficulties, we would like to propose a new experiment to measure the total and differential cross sections for the $\pi^- p \to \eta n$ reaction which has the same final state as $\gamma n \to \eta n$. The energy dependence and angular distribution of differential cross sections will be measured from W=1600 to 1780 MeV (p_π=0.85 to 1.2 GeV/c). The decay γ-rays from η-mesons will be detected by using a CsI(Tl) calorimeter which was used by the E36 collaboration. 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 state with a mass of 1680 MeV is not observed in the existing data. A narrow peak structure might be undetected because of scarce data points or insufficient calibration of the π^- beam momentum. Since the bump structure at 1680 MeV was clearly observed at four photon beam facilities with the $\gamma n \to \eta n$ reaction, it can be observed with the $\pi^- p \to \eta n$ reaction. New high-statistics data are needed and expected to conclude the existence of the peculiar state at 1680 MeV. We measure the peak position and width precisely.

There is no other experimental facility which provides intense pion beams with momenta of about 1 GeV/c than J-PARC. The beam intensity of the pion beams at HADES/GSI is $\sim 10^5$/s at most. We would like to carry out an experiment at J-PARC and request a beam time of 9 days.

1 Physics Motivation

Meson and baryon productions and their decays have played an important role in clarifying the existence of various hadrons. After the report of the evidence for the five-quark 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 four-quark mesons has been reported by KEK, BaBar, BES, and LHCb [2]. Recently, very high-statistics data suggesting the existence of five-quark 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^+. In addition, a new five-quark baryon with a strange quark and a $c\bar{c}$ quark pair was discovered in 2023 [6]. Most of the exotic particles include the $c\bar{c}$ quark pair. The search for new exotic particles including other quark pairs, such as $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, or $b\bar{b}$, is needed in order to establish the multi-quark hadron physics. These results strongly inspired us to search for new exotic states.

We have been carrying out photo-production experiments at SPring-8 and ELPH/Tohoku. 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 [7, 8]. Theorists predicted that the strangeness partner of P_c^+ should exist and have masses around 2080 MeV [9]. These narrow bump structures are inferred to be potent candidates for P_s^+. Another bump structure was observed in the experiment with the $\gamma n \to \eta n$ reaction at ELPH/Tohoku [10]. The cross sections for the $\gamma p \to \eta p$ and $\gamma n \to \eta n$ reactions are dominated by the nucleon resonance $N^*(1535)1/2^-$ 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 width of the bump structure was measured to be about 25 MeV [11] that is very narrow compared with usual nucleon widths of a few 100 MeV. Although theoretically the narrow bump structure is reproduced by introducing a nucleon resonance $N^*(1710)1/2^+$ [12], its strong target dependence cannot be explained. This narrow bump structure at 1680 MeV is a very peculiar state.

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).

The mass of this peculiar state is close to the mass 1710 MeV selected as one of exotic anti-decuplet baryons by Diakonov et al. [16]. The peculiar state at 1680 MeV might be an exotic state with five quarks including $s\bar{s}$.

One of weak points of the evidence of the bump structure at 1680 MeV is nuclear effects, such as rescattering. In the case of the γn reaction, deuterium target was used, and a proton was a spectator. However, the spectator proton shadowed a neutron, or scattered with a η-meson or a neutron, which might produce strange structures in the excitation spectrum. Another weak point is Fermi motion of the neutron. In the case of the γp reaction using hydrogen target, the total energy W is calculated from the photon beam energy easily. This calculation cannot be done correctly in the case of the γn reaction using the deuterium target. Although the W can be calculated by detecting the η-meson and neutron, insufficient energy resolutions made the structure wide and the intrinsic width of the narrow bump was difficult to measure precisely.

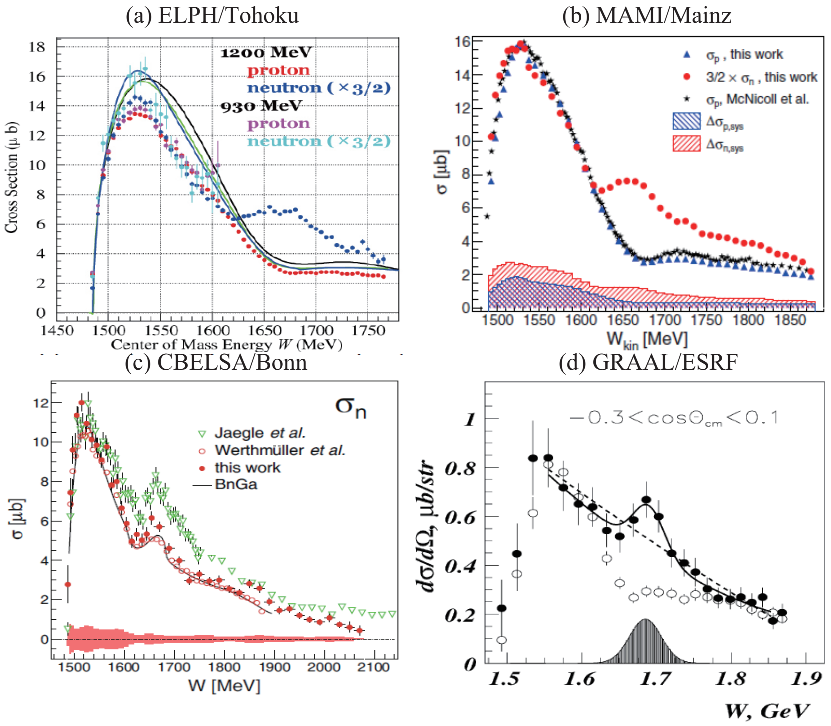

Figure 1: The total cross sections for the $\gamma p \to \eta p$ and $\gamma n \to \eta n$ reactions measured at (a) ELPH/Tohoku [10], (b) MAMI/Mainz [13], (c) CBELSA/Bonn [14], and (d) GRAAL/ESRF [15].

In order to overcome these difficulties, we would like to propose a new experiment to precisely measure the total and differential cross sections for the $\pi^- p \to \eta n$ reaction which has the same final state as $\gamma n \to \eta n$. Thanks to the proton target without Fermi motion, precise cross sections are expected without the nuclear effects. Figure 2(a) shows existing total cross section data for the $\pi^- p \to \eta n$ reaction. The data around W=1680 MeV were taken about 40-50 years ago [17, 18]. A bump structure due to the peculiar sate with a mass of 1680 MeV is not observed in the existing data. A Bewit-Wigner function with a width of 25 MeV (FWHM) with a mass of 1680 MeV with an assumed height of 1 mb is drawn for easy imagination of the narrow bump structure. A narrow peak structure might be undetected because of scarce data points or insufficient calibration of the π^- beam momentum.

Figure 2(b) shows relatively precise differential cross section data below W <1630 MeV. There is no reliable data above 1630 MeV. Since the bump structure at 1680 MeV was clearly observed at four photon beam facilities with the $\gamma n \to \eta n$ reaction, it can be observed with the $\pi^- p \to \eta n$ reaction. New high-statistics data are needed and expected to conclude the existence of the peculiar state with a mass of 1680 MeV.

2 Experimental Apparatus

2.1 Beamline

We would like to carry out an experiment at the K1.8 beamline. There are some experimental plans to use the K1.8 beamline. However, if we install the apparatus in front of the S-2S spectrometer, the possibility of the execution of our experiment becomes higher before the extension of the hadron hall as shown in Fig. 3. If BC4 is moved upstream by 250 mm and an

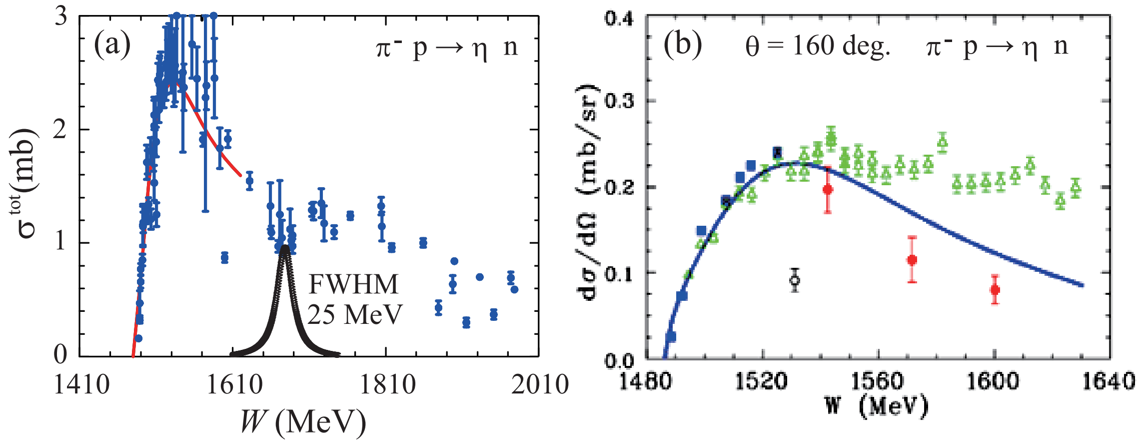

Figure 2: (a) Existing total cross section data for the $\pi^- p \to \eta n$ reaction. A Breit-Wigner function with a width of 25 MeV (FWHM) with a mass of 1680 MeV with an assumed height of 1 mb is drawn for easy imagination. (b) Existing differential cross section data at θ=160 deg. below W <1630 MeV.

empty space with a distance of 1200+250 mm is reserved, we can install a CsI(Tl) calorimeter to be explained below.

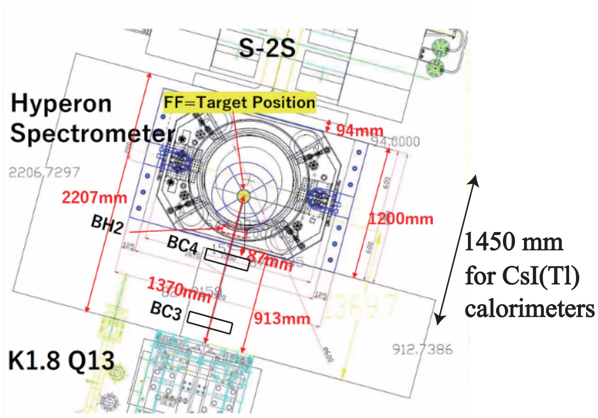

Figure 3: Upstream of the S-2S spectrometer at the K1.8 beamline.

2.1.1 Calibration of beam momentum

In order to measure the bump energy precisely, the calibration of π^- beam momentum is important. The π^- momentum threshold for producing the final state of ηn is 0.684 GeV/c. We would like to observe the increase of the η-meson yields around the threshold, and calibrate the π^- beam momentum.

2.1.2 Momentum resolution

We need a W resolution of about 10 MeV(σ) for measuring the bump width precisely. The total energy W is calculated as,

$$W = \sqrt{m_\pi^2 + m_p^2 + 2m_p\sqrt{m_\pi^2 + p_\pi^2}}, \tag{1}$$

where m_π and m_p are the π and proton masses, respectively, and p_π is the π^- beam momentum. Figure 4(a) shows the relation between W and p_π.

The W resolution (δW) is calculated as,

$$\delta W = \frac{m_p p_\pi}{\sqrt{(m_\pi^2 + p_\pi^2)(m_\pi^2 + m_p^2 + 2m_p\sqrt{m_\pi^2 + p_\pi^2})}}\delta p_\pi, \tag{2}$$

where δp_π is the resolution of the π^- beam momentum. Figure 4(b) shows the resolution (δW) of the total energy as a function of W for $\delta p_\pi/p_\pi = 0.001$, 0.005, 0.01, 0.015, and 0.02. We need a beam resolution better than $\delta p_\pi/p_\pi = 0.015$.

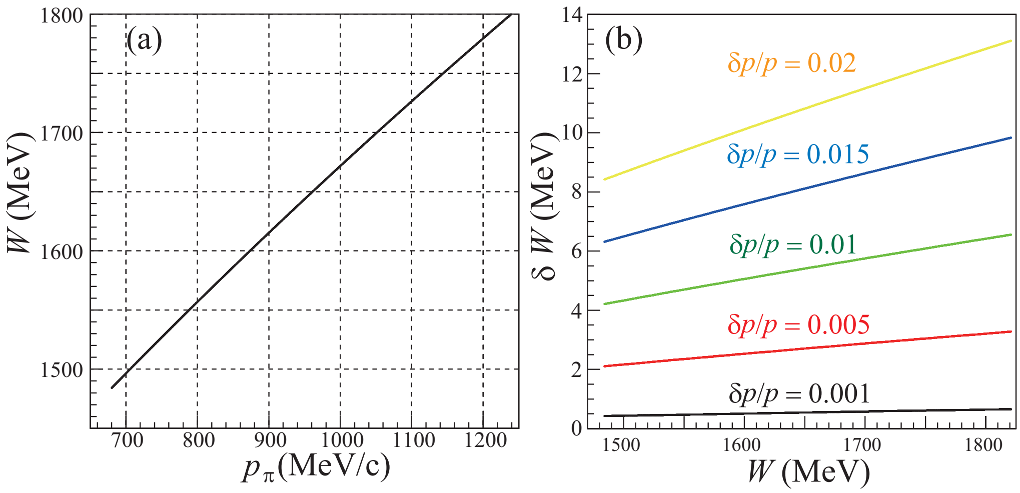

Figure 4: (a) The relation between W and p_π. (b) The resolution (δW) of the total energy as a function of W.

2.2 Calorimeter

2.2.1 CsI(Tl) calorimeter used in the E36 experiment

In the experiment to measure 2 γ-rays from a η-meson, a calorimeter surrounding the target is used. We are going to use a CsI(Tl) calorimeter (Fig. 5) which was used for detecting 2 γ-rays from a π^0-meson by the E36 collaboration [19].

The number of CsI(Tl) crystals is 768 and 75% of solid angle is covered around the target. The total weight of the CsI(Tl) calorimeter is 1.7 ton. The CsI(Tl) calorimeter is stored at the North Counter hall in KEK. One weak point of the calorimeter 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 the calorimeter.

2.2.2 Geant4 simulation

Figure 6 shows the results of Monte Carlo simulation Geant4. η-mesons are produced by π^- beams with momenta from 0.85 to 1.2 GeV/c and decay 2 γ-rays are energy-analyzed by the CsI(Tl) calorimeter. Figure 6(a) shows the invariant mass of $\gamma\gamma$. The η-meson peak is clearly observed although the peak has a lower-energy tail because of the leakage of showers from the

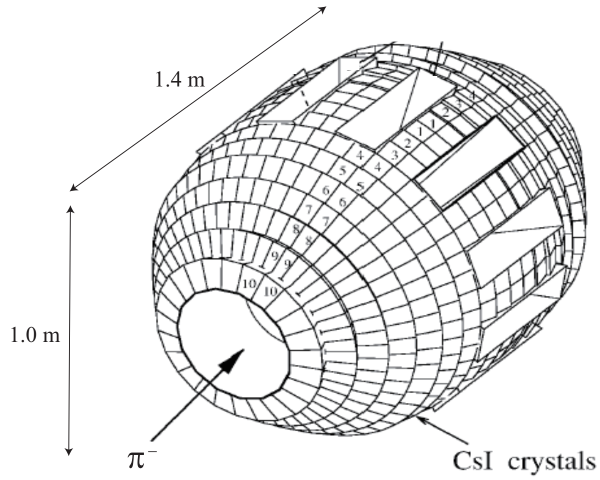

Figure 5: CsI(Tl) calorimeter used for the detection of 2 γ-rays from the η-meson [19].

holes. Figure 6(b) shows the detection efficiencies for the $\gamma\gamma$ channel. The efficiencies are low at around θ_η=110° because of the holes, and relatively high at small and large η-meson angles. The detection efficiencies are inferred to be greater than 10% even in the worst case.

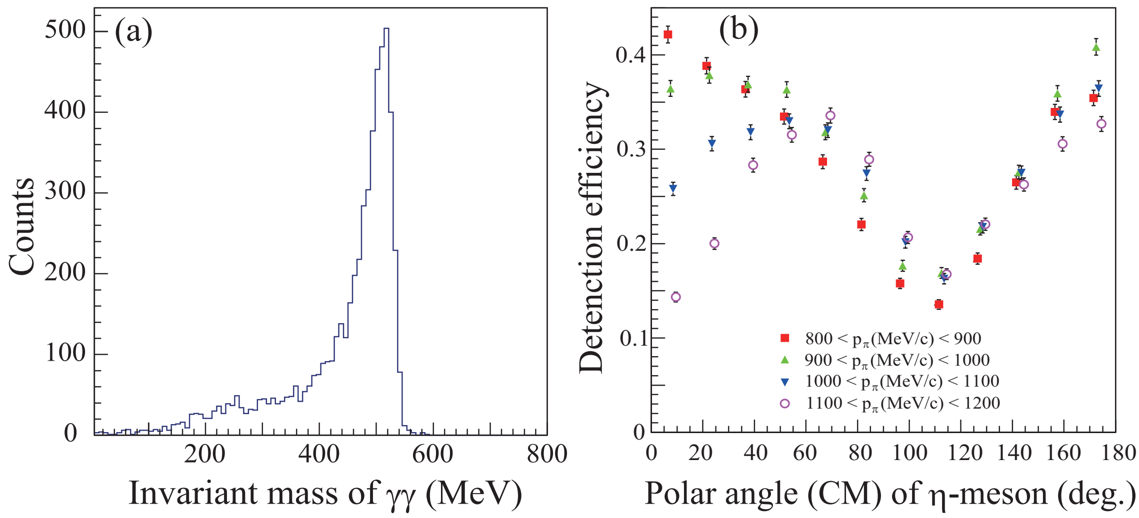

Figure 6: (a) The invariant mass of $\gamma\gamma$ simulated by using Geant4. (b) The detection efficiency for η-mesons with the decay mode of $\gamma\gamma$.

2.2.3 Recovery works

Three experimental groups including our group have plans to use the CsI(Tl) calorimeter in the near future. One group is to carry out an experiment to measure π^--mesons at RAON in Korea. Another group is interested in heavy photon search by using the calorimeter at J-PARC. The three groups are collaborating and try to recover the calorimeter at the North Counter hall in KEK now. Signals through PIN diodes from the calorimeter have been checked by using cosmic-rays and most of them were found to have no serious problem. We will prepare a DAQ system and read FADC data soon.

2.3 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.

Figure 7(a) shows the peak width of η-mesons as a function of the target thickness studied by using the Monte Carlo simulation Geant4. The peak width monotonically increases as the target thickness increases. When η-mesons produced at forward angles are selected, the width becomes much worse than that for all events.

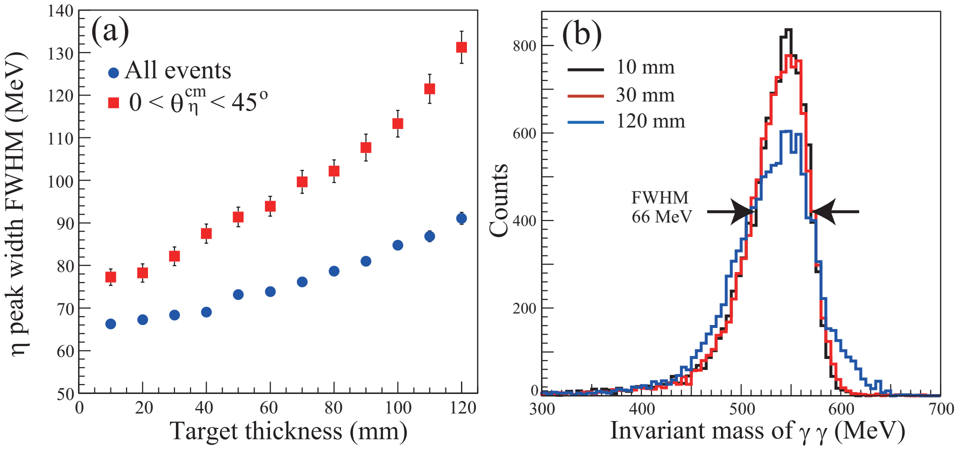

Figure 7: (a) The peak width of η-mesons as a function of target thickness. (b) The invariant mass of $\gamma\gamma$ for the target thickness of 10, 30, and 120 mm.

Figure 7(b) shows the invariant mass of $\gamma\gamma$ produced by the Geant4 simulation for the target thickness of 10, 30, and 120 mm. The peak for η-mesons has a lower-energy tail because of the leakage of part of showers from the holes of the CsI(Tl) calorimeter. There is no big difference between the peak widths for the target thickness of 10 and 30 mm. However, the peak for 120 mm has lower-energy and higher-energy tails. Since the lower-energy tail is inevitable with the use of the CsI(Tl) calorimeter, the higher-energy tail should be removed. In order to separate the signal events from background events due to other reactions, sharp η peaks are wanted. We would like to use a target with a thickness of about 30 mm for the experiment.

3 Background events

We have experiences of measuring γ-rays from η-mesons at ELPH, Tohoku University [10] and LEPS2, SPring-8 [20]. The main background γ-rays are inferred to be produced by the reactions of $\pi^- p \to \pi^0 \eta n$ and $\pi^0 \pi^0 n$. In the case of photoproduction, the $\pi^0\eta$ cross sections are comparable with the ηn cross sections [21]. The $\pi^0\pi^0$ cross sections are about 2 times larger than the ηn cross sections [22].

Figure 8 (a-c) show the correlation between the missing mass $p(\pi^-,\gamma\gamma)X$ and the invariant mass of $\gamma\gamma$ for the ηn, $\eta\pi^0 n$, and $\pi^0\pi^0 n$ reactions studied by the Geant4 simulation where 50000 events were generated for each reaction. Thanks to the kinematics differences, most of the background events are removed by selecting the missing mass region of 900-1100 MeV as shown in Fig. 8(d-f). Although the $\pi^0\pi^0 n$ cross sections are lager than the ηn cross sections, the η peak is inferred to be much higher than the $\pi^0\pi^0 n$ events around the peak.

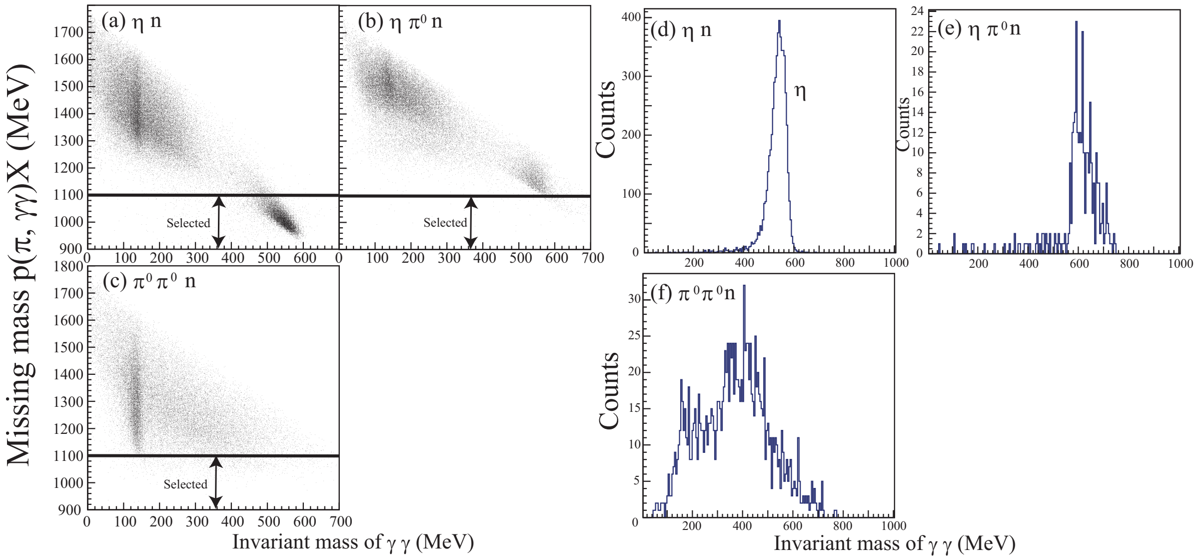

Figure 8: 2-dimensional plot of the missing mass $p(\pi^-,\gamma\gamma)X$ and invariant mass of $\gamma\gamma$ for (a) ηn, (b) $\eta\pi^0 n$, and (c) $\pi^0\pi^0 n$ reactions. The invariant mass for (d) ηn, (e) $\eta\pi^0 n$, and (f) $\pi^0\pi^0 n$ reactions after applying the missing mass cut.

4 Yield estimation and beam time request

We expect the π^- beam intensity is about $N_B = 0.5\times10^6$/s. If the thickness of $L = 3$ cm is assumed, the number of target protons N_T is calculated as

$$N_T = \rho L N_A = 0.63 \times 10^{23}, \tag{3}$$

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 $\sigma = 0.8$ mb which equals to 0.8×10^{-27} cm^2. The yield (Y) of η-mesons produced is calculated as

$$Y = \sigma N_T N_B = 50/s. \tag{4}$$

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 1.7×10^5/day.

The momenta of the π^- beams are changed from 850 to 1200 MeV/c with the number of steps of 20. The differential cross sections are measured with the η polar angular bins of 18. We want at least 1000 events for a bin on average because at least 100 events are needed even in a bin where the cross section is the smallest among all angular bins. The total number of ηn events needed is about 3.6×10^5.

Before the physics run, we need to calibrate the energy of the CsI(Tl) calorimeter by using π^0 ($\rightarrow \gamma\gamma$) productions. The calibration run and data analysis need at least 2 days. The momentum calibration of the π^- beams and data analysis can be done in 2 days. The physics data can be taken in about 2 days, however the momenta of π^- beams need to be changed. Since the momentum range for one beam momentum setting is about $\pm3\%$, we would like to take data with about 10 momentum settings. At least additional 1 day should be reserved for stable data taking. We will use a liquid hydrogen target which has two thin mylar sheets ($\sim$100 μm in total) for the entrance and exit of particles. For the study of the effect of the sheets, we would like to take data without the liquid hydrogen for 2 days. In total, we would like to request 9 days for the beam time. The summary of the beam time request is shown in Table 1.

Works to do	Time (day)
Energy calibration of CsI(Tl)	2
Momentum calibration of π^- beams	2
Physics run	3
Empty target run	2
Total	9

Table 1: Summary of the requested beam time

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] R. Aaij et al., Phys. Rev. Lett. **131**, (2023) 031901.
[7] T. Mibe et al., Phys. Rev. Lett. **95**, (2005) 182001.
[8] H. Kohri et al., Phys. Rev. Lett. **104**, (2010) 172001.
[9] Y.H. Lin, C.W. Shen, and B.S. Zou, Nucl. Phys. **980**, (2018) 21.
[10] T. Ishikawa et al., JPS Conf. Proc. **10**, (2016) 031001.
[11] I. Jaegle et al., Eur. Phys. J. A **47**, (2011) 89.
[12] L. Tiator et al., Eur. Phys. J. A **54**, (2018) 210.
[13] D. Werthmuller et al., Phys. Rev. C **90** (2014) 015205.
[14] L. Witthauer et al., Eur. Phys. A **53** (2017) 58.
[15] V. Kuznetsov et al., Phys. Lett. B **647** (2007) 23.
[16] D. Diakonov et al., Z Phys. A **359**, (1997) 305.
[17] R.M. Brown et al., Nucl. Phys. B **153**, (1979) 89.
[18] W.B. Richards et al., Phys. Rev. D **153**, 1 (1970) 10.
[19] D.V. Dementyev et al., Nucl. Instr. Meth. A **440**, (2000) 151.
[20] T. Hashimoto et al., Phys. Rev. C **106**, (2022) 035201.
[21] V.L. Kashevarov et al., Eur. Phys. J. A **42**, (2009) 141.
[22] M. Dieterle et al., Eur. Phys. J. A **51**, (2015) 142.