Search for the NΛ resonance in the ?d→ dπ+ π- reaction

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論　文　内　容　要　旨

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学位論文の 題　　目	Search for the $N\Delta$ resonance in the $\gamma d \to d\pi^+\pi^-$ reaction ($\gamma d \to d\pi^+\pi^-$反応における$N\Delta$共鳴の探索)		

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1. Introduction

A dibaryon, which is an object with baryon number 2 (B=2), has been studied for a long time as a candidate of an exotic hadron with a compositeness of six constituent quarks. Dyson and Zuon classified six dibaryon states without strangeness based on SU(6) symmetry in 1960's [PRL13(1964)815]. One of the predicted dibaryon named D_{03} (dibaryon with isospin 0, spin 3) was reported by the CELSIUS/WASA and WASA-at-COSY collaboration, recently [PRL102(2009)052301] [PRL106(2011)242302]. That interesting result triggered lots of experimental studies of other dibaryon states in the world. In 2019, an isovector dibaryon were found in the $d\pi^0$ system of the $\gamma d \to d\pi^0\pi^0$ reaction [PLB789(2019)413]. They separated dibaryon production process from conventional pion production process using angular distribution of deuteron. The mass and width of the reported isovector dibaryon are 2.14 ± 0.01 GeV and 0.09 ± 0.01 GeV, respectively. The isovector dibaryon was regarded as one of predicted NΔ dibaryon D_{12}.

In this thesis, we investigated other charge states of an isovector NΔ dibaryon (D_{12}) in $d\pi^{\pm}$ system via the $\gamma d \to d\pi^+\pi^-$ reaction.

2. Experiment

The experiment was performed at 2nd experimental hall of the Research Center of ELectron and PHoton science (ELPH), Tohoku University, in October 2010. In this experiment, tagged photon (timing and energy of the photon were tagged event by event) in the energy region of $0.78 < E_\gamma < 1.08$ GeV was irradiated to the liquid deuterium target with a thickness of 516 mg/cm^2. The number of irradiated tagged photon was $\sim 3 \times 10^{12}$.

The charged particles in the final state of the $\gamma d \to d\pi^+\pi^-$ reaction were detected and analyzed by a magnetic spectrometer, Neutral Kaon Spectrometer 2 (NKS2). NKS2 covered a solid angle of $\sim 25\%$ in total for a single charged particle and had capabilities of p/π separation and multi-track vertex reconstruction. NKS2 detectors consisted of 2 drift chambers for momentum analysis, 2 layers of plastic scintillator hodoscopes for the Time-of-Flight measurement, and additional plastic scintillator bars to reject e^+e^- background events.

3. Analysis and Results

The $\gamma d \to d\pi^+\pi^-$ reaction events were identified by analysis of NKS2. We reconstructed vertices of multi-track and extracted the $\gamma d \to d\pi^+\pi^-$ reaction events from information of the vertices and tracks. We analyzed data by using two different methods, 2-track analysis and 3-track analysis.

In the 3-track analysis, we extract the events in which all final state particles (d, π^+,

and π^-) were detected by NKS2. From the conservation laws in the four kinematic variables, momentum of each axis (p_x, p_y, p_z) and total energy (E), we defined likelihood as a weighted sum of variable as,

$$LH = \left(\frac{\Delta p_x}{\sigma_{px}}\right)^2 + \left(\frac{\Delta p_y}{\sigma_{py}}\right)^2 + \left(\frac{\Delta p_z}{\sigma_{pz}}\right)^2 + \left(\frac{\Delta E}{\sigma_E}\right),$$

where ΔX and σ_X represent a residual of the initial state and final state and resolution of a kinematic variable X, respectively. The event with a condition of $LH < 20$ was selected as the $\gamma d \to d\pi^+\pi^-$ event.

In the 2-track analysis, we extract the events in which a deuteron and a charged pion $(\pi^\pm)$ were detected by NKS2. The other pion $(\pi^\mp)$ was identified using a missing mass method. In the 2-track analysis, the missing mass of the $\gamma d \to d\pi^\pm X$ reaction was calculated and the region of $0.05 < M_X < 0.20\ \mathrm{GeV}/c^2$ was selected.

After the background estimation and subtraction, the number of the $\gamma d \to d\pi^+\pi^-$ events were ~15000 and ~2000 for 2-track analysis and 3-track analysis, respectively. In both 2-track and 3-track analysis, enhancements of $d\pi^\pm$ invariant mass spectra were consistently observed around 2.13 GeV with a width of ~0.1 GeV.

The differential and total cross section were derived for 2-track analysis which had higher statistics. The acceptance of NKS2 was estimated by a Monte-Carlo simulation based on GEANT4.

The total cross section in the region of $|t| > 0.15\ \mathrm{GeV}^2$ was also derived for 12 energy regions, where t is a Mandelstam variable defined as $t = \left(P_\gamma - P_{\pi\pi}\right)^2$. P_γ and $P_{\pi\pi}$ represent four vectors of an incident photon and 2-pion system, respectively. The obtained cross section was almost flat around 2 μb in the measured energy region.

By the fitting of the three invariant mass spectra ($d\pi^+, d\pi^-,$ and $\pi^+\pi^-$), we derived mass and width as,

$$M_{RIV} = 2.1329 \pm 0.0008(stat.) \pm 0.0085(syst.)\ \mathrm{GeV},$$
$$\Gamma_{RIV} = 0.1033 \pm 0.0021(stat.) \pm 0.0092(syst.)\ \mathrm{GeV}.$$

The obtained mass was lower than the $N\Delta$ threshold (~2.17 GeV) and width was narrower than that of a single Δ particle (~0.12 GeV). The results were consistent with the mass and width of D_{12} obtained by the $\gamma d \to d\pi^0\pi^0$ reaction [PLB789(2019)413].

4. Discussions

The production mechanism was discussed based on the angular distribution of deuteron in the center of mass system of an incident photon and deuteron because the peak structures in the $d\pi$ invariant mass spectra do not always mean resonance. However, the obtained differential cross section in the forward deuteron emission region was too large to explain by the conventional quasi-free 2π production process. That indicates there are some unconventional processes like dibaryon production.

5. Summary and Conclusion

In this thesis, the $\gamma d \to d\pi^+\pi^-$ reaction was measured by using NKS2, a magnetic

spectrometer with a large acceptance. We have shown the total cross section, the differential cross sections of the $\gamma d \to d\pi^+\pi^-$ reaction in the region of $|t|$>0.15 GeV^2.

The total cross section showed flat distribution around 2 μb within the measured energy range.

Peak structures interpreted as isovector dibaryons were observed below the $N\Delta$ threshold in the invariant mass spectra of $d\pi^{\pm}$.

The mass and width obtained as fitted parameters of BW function were

$$M_{RIV} = 2.1329 \pm 0.0008(stat.) \pm 0.0085(syst.)\ \text{GeV},$$

$$\Gamma_{RIV} = 0.1033 \pm 0.0021(stat.) \pm 0.0092(syst.)\ \text{GeV}.$$

They were consistent of D_{12} measured via the $\gamma d \to d\pi^0\pi^0$ reaction in [PLB789(2019)413]. The angular distribution also indicated unconventional processes like dibaryon production process.

Finally, we noted that this measurement provided the world's first cross section of this reaction in this kinematic region.

別　紙

論文審査の結果の要旨

東北大学電子光理学研究センター(ELPH)において行われた$\gamma d \to d\,\pi^+\pi^-$反応を用いたダイバリオン探索実験に関する成果をまとめた博士論文である。

重陽子を筆頭とするバリオン数 2 のシステムであるダイバリオンは半世紀以上に渡り研究されてきた興味深い研究対象であるが、重陽子以外のダイバリオンに関しては明確な実験成果が得られていなかったため長らく忘れ去られていた。

このような状況は、2000 年代初期の CELSIUS/WASA, WASA-at-COSY 実験によりD_{03}と呼ばれる ΔΔ 共鳴状態が発見されることにより一変した。さらに 2019 年に$\gamma d \to d\,\pi^0\pi^0$反応を用いて ELPH FOREST 実験によりNΔ 共鳴状態に相当するD_{12}ダイバリオンが測定されたことにより近年、大きな注目を集めるようになった。

外山氏は ELPH において、0.78-1.08 GeV の標識化光子を重陽子標的に照射し、反応後生じた荷電粒子を大立体角(π sr)の NKS2 磁気分光器を用いることにより測定し$\gamma d \to d\,\pi^+\pi^-$反応を研究した。これにより、FOREST 実験とは異なる荷電チャンネルにおけるD_{12}ダイバリオンを探索し、$d\,\pi^{\pm}$の不変質量分布のNΔ閾値以下に質量$2.1329 \pm 0.0008\,(stat.) \pm 0.0085(syst.)$ GeV、幅$0.1033 \pm 0.0021\,(stat.) \pm 0.0092(syst.)$ GeV の共鳴状態を発見した。この結果は FOREST 実験が$\gamma d \to d\,\pi^0\pi^0$反応で求めた$D_{12}$状態と無矛盾である。さらに、$|t| > 0.15$ GeV^2 領域において$\gamma d \to d\,\pi^+\pi^-$反応の微分反応断面積を求め、そのエネルギー依存性が小さいこと、重陽子放出角分布が僅かに後方分布であること、観測された状態の幅が自由なΔ粒子よりおおよそ20 MeV 細いことを見いだした。このような状態は通常の準自由π中間子光生成反応では説明がつかない。つまり、本研究において外山氏は荷電状態 0 と 2 のD_{12}ダイバリオンの初めての観測に成功し、ダイバリオン研究に対して顕著な貢献をした。

$\gamma d \to d\,\pi^+\pi^-$反応におけるNΔ共鳴の探索研究を遂行し、$D_{12}$ダイバリオンを荷電チャンネルで測定することに成功した外山氏は自立した研究者に要求される高度な研究能力と学識を有している。よって外山裕一氏提出の博士論文を、博士（理学）の学位論文として合格と認める。