Measuring space-time properties of baryon resonances around 1 GeV using intensity correlations

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Abstract. We measured the Δ(1232) radius using Bose-Einstein correlations (BEC) between two neutral pions from photo-production off a hydrogen/deuterium target at the incident photon energies around 1 GeV. The experiment was carried out at Research Center for Electron Photon Science (ELPH) in Tohoku University with a 4π electromagnetic calorimeter complex, named FOREST. For low-multiplicity BEC measurements, we developed an event mixing technique by introducing additional mixing constraints to delicately reduce the effect of other non-BEC correlations arising from global conservation law and resonance decays. In addition, a new BEC observing model was established to extract radius information from BEC effects in the presence of resonance decays.

1. Introduction
Space-time structure of baryon resonances, like Δ(1232), may provide fundamental information for theoretical model test. We attempt to employ intensity correlations [1,2] between identical bosons (known as Bose-Einstein correlations) emitted from baryon resonances to measure the space-time properties of them. Although the two-particle intensity interference effect discovered by Hanbury Brown and Twiss [3,4] sixty years ago (two photons emitted from a chaotic source tended to bunch together because of quantum amplitude interference) is an increasingly important method for studying space-time properties of quark-gluon plasma created in high energy elementary-particle collisions and heavy-ion collisions [5,6], it still remains challenging to introduce this method into spatial-time properties measurements of ultra-short lifetime excited nucleons emitting identical bosons in exclusive reactions with low multiplicity in the non-perturbative QCD energy region. This is mainly due to lack of reliable observing method in low multiplicity situation at low energies.

Current efforts on establishing low multiplicity correlation observing method mainly focus on searching appropriate constraints on event mixing method [7,8] which is a key technique for constructing reference sample for correlation function measurement. In 2016, we developed two event mixing constraints, the missing mass consistency (MMC) cut and pion energy (PE) cut, for two-pion BEC measurement in the γp → π0π0p reaction at photon beam energies Eγ = 1-1.15 GeV [9]. Because the PE cut causes reduction of data samples (about 40%), a multi-mixing method was also proposed later to increase the samples of mixed events [10]. In order to maintain the original kinematical correlations of two pions in the sequential decay reactions γp → π0Δ → π0π0p, a mixing cut known as energy hierarchy correspondence (EHC) cut that requires a boson with relatively higher/lower energy...
can only be swapped with a boson from another event with relatively higher/lower energy was proposed [9].

In this work, we try to measure the $\pi^0\pi^0$ intensity correlation in double pion photoproduction $\gamma p \rightarrow p\pi^0\pi^0$ for the purpose of extracting information on spatial extension of the baryon resonance $\Delta(1232)$, taking advantage of the fact that around 1 GeV the double neutral pion photoproduction is dominated by the $\Delta$ resonance process $\gamma p \rightarrow \Delta\pi^0 \rightarrow p\pi^0\pi^0$ [11–13]. In this process the first $\pi^0$ and $\Delta$ are produced at the same time at first and then the $\Delta$ decays into $\pi^0\pi$. This poses a problem that two $\pi^0$s are not produced at the same time and thus an important step towards $\Delta$ radius measurement in this study is how to relate the experimentally measured $\pi^0\pi^0$ correlations to the space-time structure of the $\Delta$ resonance. This is addressed via establishing a new correlation observing frame in the rest $\Delta$ frame, details of which are described in the next section.

2. Method

In order to measure the size of $\Delta$ resonance through $\pi^0\pi^0$ BEC effects in double pion photoproduction $\gamma p \rightarrow p\pi^0\pi^0$, a model was established in the reference frame of $\Delta$ at rest [14], in which hadron spatial extension is equivalent to the three constituent valence quark distribution inside it and the relation between the $\Delta$ size and two pion correlation is established based on the assumption that the emitting pion arises from an energetic quark somewhere inside the $\Delta$ domain (Figure 1) and the wavefunctions of the first pion and $\Delta$ overlap each other in the original $\pi^0\Delta$ system. The originating place of the pion emitted from an energetic quark provides information on the pion emitting source distribution.

![Figure 1](image.png)

**Figure 1.** A schematic illustration of the space-time coordinate system.

In this model the momenta of two pions are measured in such a space-time coordinate defined so that the center of $\Delta$ is the origin of the coordinates $O$, when the first $\pi^0$ and $\Delta$ appear simultaneously at $\tau = 0$, where $\tau$ denotes the proper time at the rest frame of $\Delta$. In this frame, the first and second $\pi^0$s take place at $A(0,x)$ and $B(\tau, y)$, respectively and the decay time $\tau$ does not give any effect in the measurement as far as strong decay is concerned. Because of the intrinsic spin of $\Delta$, the relative angular momentum between $\Delta$ decayed pion and nucleon should be taken into account. Employing cylindrical coordinates $y=(r,\theta,z)$ with the $z$ axis to be along the momentum vector $p_2$ of the $\pi^0$ decaying from $\Delta$ and assuming a Gaussian density profile of the $\Delta$, the correlation function in the rest $\Delta$ reference frame is given by
\[ C(q, p_2) = 1 + \lambda \exp\left(-\frac{\alpha^2 q^2}{2}\right) \exp\left(-\frac{\alpha^2 q_z^2}{2}\right) J_0(\beta q_r) \]

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(1)

where \( q \) is the 3-d relative momentum of two pions, \( p_2 \) the 3-d momentum of \( \Delta \) decayed pion \( \beta = 1/(2p_2) \), \( q_z \) the \( q \) projection on \( z \) axis which is along the \( p_2 \), \( q_r \) the \( q \) projection on the \( r \) axis which is perpendicular with \( p_2 \) ( \( q^2 = q_z^2 + q_r^2 \) ), and \( \alpha \) the \( \Delta \) Gaussian radius.

Considering current FOREST data statistics, we fix the \( p_2 \) variable in fitting experimental correlation functions. Figure 2 shows the correlation functions plotted in the \((q_r, q_z)\) plane at different \( p_2 \) values.

\[ p_2 = 0.05 \text{ GeV} \]

\[ p_2 = 0.15 \text{ GeV} \]

\[ p_2 = 0.25 \text{ GeV} \]

\[ p_2 = 0.35 \text{ GeV} \]

Figure 2. Two dimensional plots of correlation functions plotted in the \((q_r, q_z)\) plane at different \( p_2 \) values.

3. Experimental results

3.1. FOREST experimental data analysis

The datasets of the \( \gamma p \rightarrow p\pi^0\pi^0 \) reaction used in this study are from FOREST experiment, carried out with a bremsstrahlung photon beam generated by inserting a carbon fiber into circulating electrons in the 1.2 GeV synchrotron ring at Research Center for Electron Photon Science (ELPH) in Tohoku University. A 4\( \pi \) EM calorimeter named FOREST was utilized to detect neutral mesons decaying into \( \gamma \)'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 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 reaction $\gamma p \rightarrow p\pi\pi$ is reconstructed by its decay channel $\gamma p \rightarrow p\pi\pi\pi\pi$ which has 5 final state particles. $\pi^0$ is identified by scanning invariant masses of all possible combinations of two photons, while the proton is identified by the missing mass $m_f$ of $\gamma p \rightarrow X\pi\pi$ and its relative detecting time with respect to the average time of four photons. A kinematic fitting [15] employing constraints of four-momentum conservation law and the invariant masses of pions and proton is performed to increase the observable uncertainties. It also provides a way for event selection to judge the confidence level of the goodness of fitting for the measured variables to the hypothesis of the $\gamma p \rightarrow p\pi\pi$ reaction.

A preliminary result of the different cross section of $m(\pi^0, p)$ shows the double neutral pion photoproduction is dominated by the $(1232)$ resonance process $\gamma p \rightarrow \Delta\pi^+ \rightarrow p\pi\pi$ (Figure 3) [16].

![Figure 3](image_url)

**Figure 3.** $\pi^0$ invariant mass distributions for the $\gamma p \rightarrow p\pi^0\pi^0$ reaction for 16 different energy ranges of incident photons. The experimental data are represented with filled circles. Simulation results are also shown, for comparison, for the pure phase space process (solid lines) and for the pure $\Delta$ sequential decay process $\gamma p \rightarrow \Delta\pi^0 \rightarrow p\pi^0\pi^0$ (dotted lines).

### 3.2. Double neutral pion intensity interference results

The correlation function of $\pi^0\pi^0$ is calculated as the ratio of the event density distribution of $\pi^0\pi^0$ events to that of a reference sample constructed via the event mixing method with the MMC and EHC constraints. As current mixing method cannot eliminate all of the non-BEC effects, double ratio (D.R.) method is used to correct the correlation function:

$$C_{D.R.}(q,p_2) = \left(\frac{\rho_{\text{sig}}^{\exp}(q,p_2)}{\rho_{\text{mix}}^{\exp}(q,p_2)}\right) \left(\frac{\rho_{\text{MC}}^{\text{sig}}(q,p_2)}{\rho_{\text{MC}}^{\text{mix}}(q,p_2)}\right).$$

where $\rho_{\text{sig}}(q,p_2)$ is the two-particle density of the original data (signal sample), while $\rho_{\text{mix}}(q,p_2)$ the two-particle density constructed from pairs of pions coming from different event. The upper index “exp”
and “MC” indicate the way of obtaining the two-particle density from experimental data and Monte Carlo simulation, respectively.

With this double ratio method, the corrected correlation function with fixed $p_z = 0.2 - 0.3$ GeV is given in Figure 4. Eq. (2) is used to fit the data. In the fitting, the fitting range of the correlation strength parameter $\lambda_z$ is limited in the region [0,1]. The fitting region of $q_z$ and $q_r$ is [0, 0.7] GeV. And the $p_z$ is fixed to be the middle value between the lower and upper limits of it in the experimental procedure.

**Figure 4.** Two-pion correlation functions plotted in the $(q_z, q_r)$ plane at $p_z = 0.2 - 0.3$ GeV from the FOREST experimental data $\gamma p \rightarrow n \pi^0 \pi^0$ in the incident photo energy ranging from 1.0 to 1.15 GeV.

**Table 1** fit results of two pion emitting source: Gaussian radius $\alpha$ and correlation strength $\lambda$. The root mean square value of the radius $x = \langle x^2 \rangle = 3\alpha^2$ is also given.

| $E\gamma$ (GeV) | N    | $\lambda$ | $\alpha$ (fm) | $\chi^2$/ndf |
|-----------------|------|-----------|---------------|--------------|
| 1.13-1.15       | 0.71±0.07 | 1.00±0.84 | 0.44±0.10   | 84.7/44      |
| 1.11-1.13       | 0.81±0.03 | 1.00±0.08 | 0.59±0.06   | 60.2/44      |
| 1.09-1.11       | 0.79±0.03 | 1.00±0.05 | 0.58±0.05   | 76.9/44      |
| 1.07-1.09       | 0.82±0.03 | 1.00±0.03 | 0.61±0.04   | 63.3/44      |
| 1.05-1.07       | 0.82±0.02 | 1.00±0.02 | 0.65±0.04   | 81.5/44      |
| 1.03-1.05       | 0.85±0.02 | 1.00±0.05 | 0.70±0.05   | 42.5/43      |
| 1.01-1.03       | 0.84±0.03 | 1.00±0.04 | 0.68±0.05   | 38.2/42      |
| 0.99-1.01       | 0.84±0.03 | 0.94±0.15 | 0.69±0.07   | 52.3/42      |

| Ave.            | 0.83±0.01 | 1.00±0.01 | 0.63±0.02 |

| Root mean square radius $x$ (fm) | $\langle (x^2) \rangle = 3\alpha^2$ | $x = 1.09±0.03$ |

Based on these results, the root mean square radius of the pion emitting source is given to be 1.09±0.03 fm. Although the $\Delta(1232)$ resonance process $\gamma p \rightarrow \Delta n^0 \rightarrow p n^0 \pi^0$ is dominant, extracting $\Delta$
radius from $\pi^0\pi^0$ intensity correlation results is not so straightforward. In future work, we will try to select pure $\Delta$ events and estimate the systematic bias considering data purity, event mixing, fitting, etc.

4. Summary

The space-time structure of the excited baryon $\Delta$ (1232) was measured using Bose-Einstein correlations between two identical neutral pions from photoproduction off a hydrogen/deuterium target in the energy region of 0.5-1.2 GeV of incident photons. A model was established in the reference frame of $\Delta$ at rest in order to relate the $\Delta$ size and two pion correlation. A very preliminary result of the two pion correlation is obtained, yielding the root mean square radius of intermediate resonance state ($\Delta$ (1232) dominant) to be about 1 fm. For the future, we plan to improve Delta reconstruction and mixing method.

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