Proc. 8th Int. Conf. Quarks and Nuclear Physics (QNP2018)
JPS Conf. Proc. **26**, 024004 (2019)
https://doi.org/10.7566/JPSCP.26.024004

Measuring Space-Time Properties of the $\Delta(1232)$ via Bose-Einstein Correlations

Qinghua HE[1,a,*], Hisako FUJIMURA[1,b], Hiroshi FUKASAWA[1], Ryo HASHIMOTO[2,c], Yuki HONDA[1], Takatsugu ISHIKAWA[1], Takahiro IWATA[2], Shun KAIDA[1], Hiroki KANDA[4,h], Jirohta KASAGI[1], Atsushi KAWANO[3], Shuzo KUWASAKI[1], Kazushige MAEDA[4], Shinichi MASUMOTO[5], Manabu MIYABE[1], Fusashi MIYAHARA[1,d], Keiichi MOCHIZUKI[1], Norihito MURAMATSU[1], Akihiko NAKAMURA[1], Kenichi NAWA[1], Shoei OGUSHI[1], Yasuyuki OKADA[1], Yoshihito ONODERA[1], Kyoichiro OZAWA[6], Yasunobu SAKAMOTO[3], Mamoru SATO[1], Hajime SHIMIZU[1], Hiroyuki SUGAI[1,e], Koutaku SUZUKI[1,f], Yasuhisa TAJIMA[2], Shinichiro TAKAHASHI[1], Yusuke TANIGUCHI[1], Yusuke TSUCHIKAWA[1], Hirohito YAMAZAKI[1,g], Ryuji YAMAZAKI[1], and Hiroshi Y. YOSHIDA[1] (the FOREST collaboration)

[1] *Research Center for Electron Photon Science, Tohoku University, Sendai 982-0826, Japan*
[2] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[3] *Department of Physics, Yamagata University, Yamagata 990-8560, 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 (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[a] *Department of Nuclear Science and Engineering, Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing 210016, China*
[b] *Department of Physics, Wakayama Medical University, Wakayama 641-8509, Japan*
[c] *Institute of Materials Structure Science, KEK, Tsukuba 305-0801, Japan*
[d] *Accelerator Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[e] *Department of Quantum Science and Energy Engineering, Tohoku University, Sendai 980-8579, Japan*
[f] *The Wakasa Wan Energy Research Center, Tsuruga 914-0192, Japan*
[g] *Radiation Science Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[h] *Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan*
**E-mail: heqh@nuaa.edu.cn*

(Received January 18, 2019)

We are trying to study the space-time properties of the excited nucleon Δ (1232) 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. There are two main challenges in this study: 1) Developing a viable event mixing method for low-multiplicity BEC analysis; 2) How to extract Δ size information from BEC effects of two π^0s in the sequential decay $\gamma p \to \pi^0 \Delta \to \pi^0 \pi^0 p$. We attempt to address the low-multiplicity BEC mixing method via adding additional mixing constraints to delicately control the mixing process in order to reduce the non-BEC correlations impact. For the second challenge, we are now developing a new BEC observing model taking the Δ decay time into consideration.

KEYWORDS: Bose-Einstein correlations, event mixing, excited baryon radii

1. Introduction

Measuring the radius of $\Delta(1232)$ using Bose-Einstein correlations (BEC) [1,2] between identical bosons (Fig. 1) in exclusive reactions with low multiplicity in the non-perturbative QCD energy region is still challenging, though BEC has already a widespread application in high-energy hadron-hadron collisions [3–7] and relativistic heavy ion collisions [8–10] for measuring space-time properties of hadron reaction volume. The BEC effect was used for the first time in the 1950s in astronomical physics [11] and later introduced in particle/nuclear physics. BEC observation involves the measurement of a two-particle correlation function [3,12]

$$C_{BEC}(p_1,p_2) = \frac{P_{BEC}(p_1,p_2)}{P_0(p_1,p_2)} = N\left(1+\lambda_2 e^{-r_0^2 Q^2}\right) \quad (1)$$

where $P_{BEC}(p_1,p_2)$ represents the joint probability of emitting two bosons of momenta p_1 and p_2, and $P_0(p_1,p_2)$ the probability of the so called "reference sample" free from BEC effects. In general, the correlation function is dependent on the relative momentum Q ($Q^2 = -(p_1-p_2)^2$) in terms of two parameters r_0 and λ_2, where r_0 is the Gaussian radius of the source, and λ_2 (varying in the region from 0 to 1) a measurement of emission chaoticity of the boson emitting volume [3]. This parameterization is based on the assumption that the boson-emission source has a Gaussian density distribution. N is the normalization factor. Generally, the event mixing method [13,14] is used to construct the reference sample via selecting two bosons' momenta from different events.

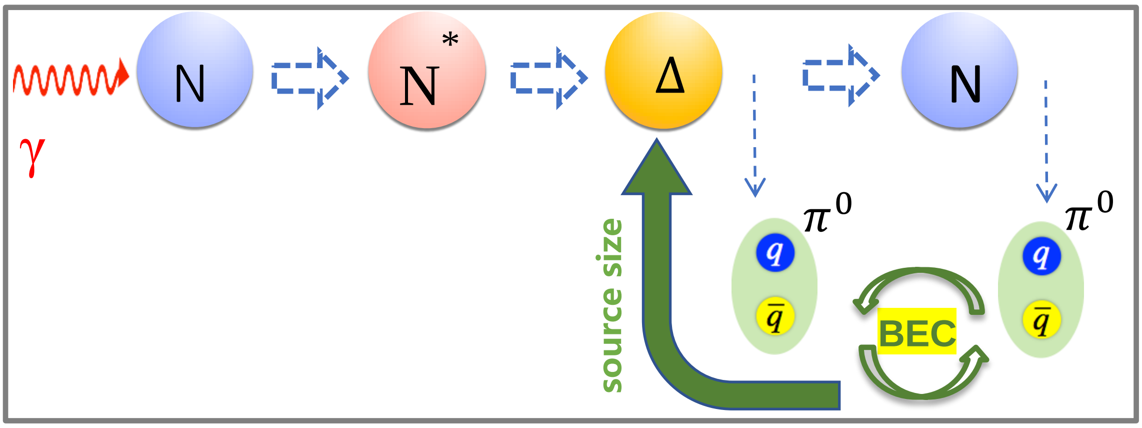

Fig. 1. Schematic view of measuring the $\Delta(1232)$ size via BEC effects between two neutral pions in the double neutral pion photoproduction $\gamma p \to \pi^0\Delta \to \pi^0\pi^0 p$.

One challenge in the context of low-multiplicity BEC observation at low energies is that the event mixing technique is vulnerable to other non-BEC correlations generally caused by resonance decays and global conservation laws [15,16]. To extract correct BEC effects, modern efforts focus on developing appropriate mixing constraints to suppress the impact of those non-BEC correlations. In 2016, we developed two event mixing constraints, namely missing mass consistency (MMC) cut and pion energy (PE) cut, for two-pion BEC measurement in the $\gamma p \to \pi^0\pi^0 p$ reaction at photon beam energies $E_\gamma =$ 1-1.15 GeV [17]. In that work, a mixing 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 in order to maintain the original kinematical correlations of two pions in the sequential decay reactions $\gamma p \rightarrow \pi^0\Delta \rightarrow \pi^0\pi^0 p$. Because the PE cut causes reduction of data samples (about 40%), a multi-mixing method was also proposed later [18] to increase the samples of mixed events.

Another challenge in our study is that in order to obtain the size of Δ through BEC effects in the reaction $\gamma p \rightarrow \pi^0\Delta \rightarrow \pi^0\pi^0 p$, the different generation time of two pions should be considered. The BEC parameter r_0 includes the decay time of Δ. Thus we need to find a way to extract the Δ radius from r_0, or to develop a new BEC observation model to get around this problem.

Double neutral pion BEC measurement is also challenging. There are quite few measurements even at high energies [4,6] since this analysis involves detecting four identical photons, requiring a 4π electromagnetic (EM) calorimeter. In addition, the energy threshold of photon detection may have an impact on event mixing technique. Thus, special care is needed in event mixing for double neutral pion BEC study.

2. Measuring Δ size through $\pi^0\pi^0$ BEC effects

Measuring the size of Δ via BEC effects of two identical neutral pions in the reaction $\gamma p \rightarrow \pi^0\pi^0 p$ takes advantage of the fact that this reaction is dominated by the sequential decay $\gamma p \rightarrow \pi^0\Delta \rightarrow \pi^0\pi^0 p$ around 1 GeV [19–21]. The existence of the intermediate Δ resonance, however, makes the BEC measurement not straightforward. The extraction of the size of Δ is complicated because in the sequential decay a Δ appears when the first π^0 is emitted and then disappears at the same time when the second π^0 comes out and consequently the time difference between the pair of π^0s corresponds to the lifetime of the Δ [17]. Special cares are required to deduce the size of Δ from the space-time interval r_0 of two pions.

We are now developing a new model to measure the BEC effects in the reference frame of Δ at rest [22] in order to get around the impact of Δ decay and to extract the Δ radius from the BEC parameter r_0 directly. In the new model, the relative angular momentum of the decay process $\Delta \rightarrow \pi^0 N$ is also taken into consideration [22].

In addition, the Δ resonance significantly affects the momentum assignment of two pions: the π^0 coming from Δ decay tends to share a relatively small momentum compared to the other one. Special care may be required for event mixing method in order to make a valid reference sample for BEC measurements. We are now developing a new event mixing method with new appropriate cut conditions for this study. The new method will solve the biased momentum sharing problem. In the new mixing approach, constraint conditions related to the boson energy hierarchy, the boson energy sum and sub-regional constraints are considered. The cut condition suggested in Ref. [17] is also included, which requires exchanging two pions both with lower/higher energies from two different events. In searching for appropriate mixing cuts, we follow the perspective that the non-BEC correlations between bosons in the original events may provide useful constraints on event mixing and minimum sample population reduction is required in order to get better statistical accuracy.

For low-multiplicity BEC measurements, the event mixing is sensitive to the energy lower limit of bosons. The $\pi^0\pi^0$ BEC observations also involve detecting four photons decayed from π^0 and the existence of the photon energy detection threshold may affect the event mixing. The investigation of the photon energy lower limit effects on event mixing is necessary and relevant studies are one the way.

3. Summary

We are trying to measure the space-time properties of the Δ (1232) resonance using Bose-Einstein correlations between two identical neutral pions from photoproduction off a hydrogen/deuterium target both in exclusive and inclusive cases in the energy region of 0.5-1.2 GeV, carried out at the Research Center for Electron Photon Science (ELPH) at Tohoku University. In order to extract the Δ(1232) radius from BEC effects of $\pi^0\pi^0$ in the reaction $\gamma p \rightarrow \pi^0\Delta \rightarrow \pi^0\pi^0 p$, we are correspondingly developing a viable event mixing approach with additional mixing constraints reducing impacts of non-BEC correlations and trying to establish a new BEC observing model to get around the impact of the Δ decay and to directly extract the Δ radius from the BEC parameter r_0.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (No. 11805099), the Fundamental Research Funds for the Central Universities (Nos. 1006-XAA18059 and 1006-YAH17063), the Ministry of Education and Science of Japan (No. 19002003) and JSPS KAKENHI (Nos. 24244022, 26400287).

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