Charge symmetry breaking of a hypernucleus $^4_{\Lambda}$He

K. Hosomi$^{1,2}$, H. Sako$^1$, K. Ima$^1$, S. Hasegawa$^1$, S. Sato$^1$, K. Tanida$^1$, H. Sugimura$^1$, Y. Ichikawa$^1$, and H. Ekawa$^1$

1) : Hadron Nuclear Physics Gr., JAEA

It has been known for a long time that nuclei of equal mass and with inverted proton and neutron numbers (mirror nuclei) exhibit very similar properties. These similarities are due to a characteristic of the nuclear force called charge symmetry. A question to answer is whether this symmetry holds also for hypernuclei which include a $\Lambda$ particle.

In the past, an experiment to study $^4_{\Lambda}$He gamma rays measured a mass difference between $1^+$ and $0^+$ states of 1.15±0.04 MeV. The mass difference is very similar to that for $^4_H$ of 1.09±0.02 MeV. This measurement indicated that charge symmetry holds for these hypernuclei [1]. However, these experiments had rather poor energy resolution, signal-to-noise ratio, and gamma-ray statistics.

In order to improve the data quality, we proposed a new experiment E13, where we irradiate $K$ beams on a $^4$He target, produce $^4_{\Lambda}$He, and measure the gamma ray from its exited state as shown in Fig. 1 [2]. The reaction is $K^+ + ^4$He$\rightarrow ^4_{\Lambda}$He$^* + \pi^+$, $^4_{\Lambda}$He$^*\rightarrow ^4$He$ + \gamma$. For extremely intense $K$ beams at J-PARC (typically 3 x 10$^3$ / spill), we developed the gamma-ray detector system Hyperball-J, shown in Fig. 1. We included a mechanical cooling system of Ge crystals to reduce radiation damage due to high beam rates, and employed PbWO$_4$ counters with fast response time (~10 ns) to reject background, such as a Compton scattering and high energy photons from $\pi^0$ decay with high particle rates. We also suppressed background reactions by identifying the incident $K$ beam particle and the produced $\pi$ with aerogel Cherenkov counters and time-of-flight detectors shown in Fig. 1.

In April 2015, as the first experiment after recovering from the radiation accident at J-PARC Hadron Experimental Facility, we performed the E13 experiment for 5 days with 2.3x10$^{10}$ $K$ beams at 1.5 GeV/c. We succeeded to measure gamma-ray energy spectra with a very high energy resolution of 5 keV (FWHM), i.e. a factor of 20 improvement compared to the past experiment. The measured gamma-ray energy spectrum after the ($K^-,\pi^+$) event selection is shown in Fig. 2. We observed the peak corresponding to the transition of $^4_{\Lambda}$He from the 1$^+$ excited state to the 0$^+$ ground state. The energy is determined to be 1.406±0.002 (stat.) ±0.002 (syst.) MeV, which excludes the previous experimental data of 1.15±0.04 MeV.

By comparing the resulting energy levels in $^4_{\Lambda}$He and $^4$He, as shown in Fig. 3, a very large charge symmetry breaking of 320 keV is confirmed. This result implies that there is a difference between the $\Delta n$ interaction and $\Delta p$ interaction, depending strongly on their spin states. The present work provides important data to understand the strong interaction between baryons, and has triggered new theoretical studies on this problem.

References


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Fig. 1: The experimental setup of E13 [2]. The $K$ beam is injected to the $^4$He target. The incident $K$ and the produced $\pi$ are identified with the aerogel Cherenkov detectors BAC2 and SAC1. The gamma rays emitted from the target are detected with the Hyperball-J Ge detectors.

Fig. 2: Gamma-ray energy spectra from $^4_{\Lambda}$He requiring $(K^-,\pi^+)$ reactions [1].

Fig. 3: Energy levels of mirror nuclei $^4\Lambda$H and $^4_{\Lambda}$He [2].