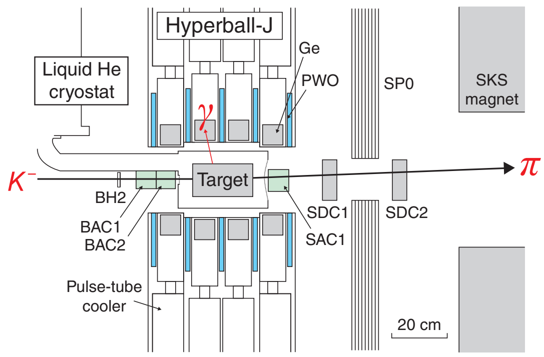
3–4 A “Strange Particle” Breaks the Charge Symmetry of a Nucleus

— Successful Measurement of the Energy Levels of a Helium Hypernucleus —

(a) Experimental setup of J-PARC-E13



(b) Reaction of the hypernuclear production

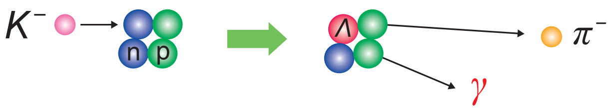


Fig.3-9 (a) Experimental setup of J-PARC-E13 and (b) reaction of the hypernuclear production
(a) The E13 setup comprises a γ-ray detector (Hyperball-J) and a ^{4}He target as well as K^- and π^- identification detectors (BAC1, BAC2, and SAC1).
(b) A schematic view of the $K^- + {}^4\mathrm{He} \rightarrow {}^4_\Lambda\mathrm{He} + \pi^- + \gamma$ reaction.

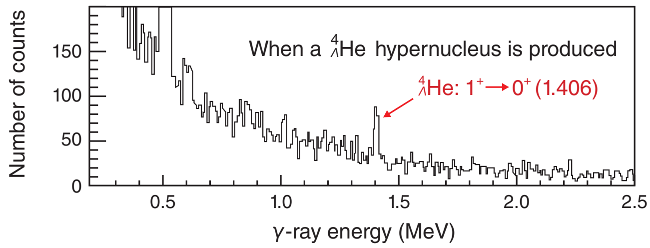


Fig.3-10 Measured γ-ray-energy spectrum
A γ-ray energy spectrum measured by the γ-ray detector. In this spectrum, only ${}^4_\Lambda$He-production-candidate events are selected.

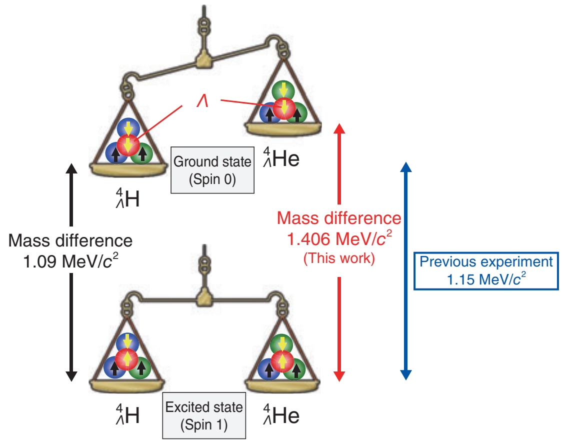


Fig.3-11 Comparison of mass between ${}^4_\Lambda$H and ${}^4_\Lambda$He
The mass difference between the excited states of ${}^4_\Lambda$He measured in this experiment is 1.406 MeV/c^2, whereas that of ${}^4_\Lambda$H is 1.09 MeV/c^2. There is a large mass difference of 0.32 MeV/c^2 between ${}^4_\Lambda$H and ${}^4_\Lambda$He, which shows a large charge-symmetry breaking.

Two normal nuclei for which the protons and neutrons are exchanged (known as mirror nuclei) have almost the same mass. This is known as the charge symmetry. Is this also the case for hypernuclei, which include a Λ particle known as a “strange particle?” Λ is a similar type of heavy particle (baryon) to a proton or a neutron but includes a rather heavy strange quark; this contrasts with protons and neutrons, which consist only of light up and down quarks.

A past experiment that involved measuring γ rays emitted from ${}^4_\Lambda$He hypernucleus showed there was almost no mass difference from its mirror nucleus ${}^4_\Lambda$H in either the ground or excited states. Therefore, it was claimed that the charge symmetry held. However, since this experiment had poor energy resolution and signal-to-noise ratio, confirmation by an improved experiment has been required.

Therefore, we have proposed an experiment at the J-PARC Hadron Experimental Facility to measure γ rays at high-energy resolution from ${}^4_\Lambda$He hypernuclei that are produced by injecting the world’s highest-intensity K^- beam (the total number of K^- is 2.3×10^{10}) onto a ^{4}He target. This reaction is $K^- + {}^4\mathrm{He} \rightarrow {}^4_\Lambda\mathrm{He} + \pi^- + \gamma$, as shown in Fig.3-9(b). For this experiment, we developed a γ-ray detector which can be operated at 10^6 Hz K^- beams as shown in Fig.3-9(a), and developed a fast-rejection technique for background γ rays with mechanical refrigerators for Ge crystals and PWO (lead tungstate) crystal-scintillation counters. Consequently, we obtained the γ-ray spectrum shown in Fig.3-10 and succeeded in improving γ-ray energy resolution 20 fold.

In this experiment, we measured a mass difference of 1.406 MeV/c^2 between the excited and ground states, as shown in Fig.3-11. The precise experimental data excluded the previous experimental result of 1.15 MeV/c^2. Consequently, we discovered that the mass difference from the mirror nucleus ${}^4_\Lambda$H is significant, namely 0.32 MeV/c^2, in contrast to the small mass difference of 0.06 MeV/c^2 for normal nuclei. From this large mass difference, i.e., the charge-symmetry breaking, we learned that the forces between a Λ and a neutron and between a Λ and a proton differ largely depending upon the spin state (namely the excited state). This work provided important data concerning the nuclear force between baryons such as protons, neutrons, and Λs.

Reference

Yamamoto, T.O., Sako, H. et al., Observation of Spin-Dependent Charge Symmetry Breaking in ΛN Interaction: Gamma-Ray Spectroscopy of ${}^4_\Lambda$He, Physical Review Letters, vol.115, issue 22, 2015, p.222501-1-222501-5.