論　文　内　容　要　旨

(NO.　1)

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学位論文の 題　　　目	Charge symmetry breaking in ΛN interaction studied via the γ-ray spectroscopy of $^{4}_{\Lambda}$He ($^{4}_{\Lambda}$He のγ線分光によるΛN 相互作用の荷電対称性の破れの研究)		

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論文内容要旨

1. Introduction

Charge symmetry is a general property of nuclear and hadronic systems; hadronic states as well as their interactions are invariant under reversal in isospin space. Charge symmetry holds almost exactly in NN interaction. On the other hand, an unexpectedly large charge symmetry breaking (CSB) effect in ΛN interaction was reported from the past experiments; measured Λ binding energies (B_{Λ}) of ground 0^{+} state and 1st excited 1^{+} state of the mirror hypernuclei, ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He, were significantly different.

The excitation energy of ${}^{4}_{\Lambda}$H(1^{+}) has been measured three times [1, 2, 3], and the weighted average is 1.09 ±0.02 MeV, from which B_{Λ}(${}^{4}_{\Lambda}$H(1^{+})) value can be obtained. On the other hand, the excitation energy of ${}^{4}_{\Lambda}$He(1^{+}) was once reported as 1.15 ±0.04 MeV by a γ-ray spectroscopic experiment using NaI detectors [2]. The ${}^{4}_{\Lambda}$He data is criticized to be statistically insufficient to claim the existence of the CSB effect. Therefore, experimental re-examinations by independent and modern techniques with higher sensitivity have been awaited. A break-through has been brought by our γ-ray spectroscopic experiment of $^{4}_{\Lambda}$He; we has measured the transition energy between the Λ-spin doublet states (1^+, 0^+) using germanium (Ge) detectors with a much better energy resolution of 5 keV (FWHM) for 1 MeV γ ray.

2. Experiment

We performed a γ-ray spectroscopic experiment of $^{4}_{\Lambda}$He (J-PARC E13) at the J-PARC K1.8 beam line [4] to examine the existence of the CSB effect in the mirror hypernuclei, $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He. The hypernucleus $^{4}_{\Lambda}$He was produced via the (K^-,π^-) reaction with a beam momentum of p_K = 1.52 GeV/c. The hypernuclear production was tagged by measuring the missing mass of the ^{4}He(K^-,π^-)X reaction, where the beam K and the scattered π were particle identified and momentum analyzed by the beam line spectrometer and the superconducting dipole magnet (SKS) with a modified detector configuration for γ-ray spectroscopy (SksMinus), respectively. In addition, γ rays from the produced hypernucleus were detected by a large solid-angle Ge detector array (Hyperball-J) in coincidence with the (K^-,π^-) reaction. An event-by-event Doppler-shift correction was necessary because the lifetime of the $^{4}_{\Lambda}$He(1^+) state is expected to be much shorter than the stopping time of the recoiling hypernucleus, and thus the measured γ-ray peak was subject to Doppler broadening.

3. Analysis and result

From the analysis of the present data, we clearly identified $^{4}_{\Lambda}$He production events by selecting the missing mass. In the mass-gated spectrum after the Doppler-shift correction, we observed a γ-ray peak at 1.4 MeV with a statistical significance of 7.4σ. It is attributed to the $^{4}_{\Lambda}$He($1^+ \rightarrow 0^+$) transition. The peak energy and yield were found to be 1406 ± 2 (stat.) ± 2 (syst.) keV and 94 ±13 counts, respectively. The result of the present data superseded the claim of the previous experiment (1.15 MeV) and established the level scheme of $^{4}_{\Lambda}$He. The Λ binding energy of the excited state was obtained to be $B_\Lambda(^{4}_{\Lambda}\mathrm{He}(1^+)) = 0.98 \pm 0.03$ MeV by combining with the emulsion data of $B_\Lambda(0^+)$.

4. Discussion and summary

The difference between the excitation energy of $^{4}_{\Lambda}$He(1^+) [1.406 ± 0.004 MeV, the present data] and that of $^{4}_{\Lambda}$H(1^+) [1.09 ±0.02 MeV, the average of the past three experiments [1, 2, 3]] is definitively non zero. Therefore, the existence of CSB in the ΛN interaction has been confirmed via γ-ray data alone. By comparing differences in B_Λ's of the 0^+ and 1^+ states between $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He, namely $\Delta B_\Lambda(0^+) = B_\Lambda(^{4}_{\Lambda}\mathrm{He}(0^+)) - B_\Lambda(^{4}_{\Lambda}\mathrm{H}(0^+)) = +0.35 \pm 0.05$ MeV and $\Delta B_\Lambda(1^+) = +0.03 \pm 0.05$, we have discovered a large spin dependence in the CSB effect; the CSB effect is pronounced in the 0^+ state while vanishingly small in the 1^+ state. This fact suggests that Σ mixing in Λ hypernuclei is responsible for the CSB effect since the 0^+ state in $^{4}_{\Lambda}$H/$^{4}_{\Lambda}$He is expected to receive a one order of magnitude larger energy shift due to Λ-Σ mixing than the 1^+ state [5].

The result presented in this thesis has established the level scheme of ${}^{4}_{\Lambda}$He. It also confirmed a sizable CSB effect in ΛN interaction and its strong spin dependence. Further theoretical studies of ΛN-ΣN interaction will explain the observed CSB effect, giving a relevant contribution to our understanding of baryon-baryon interactions.

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論文審査の結果の要旨

本博士論文は，ハイパー核 ${}^{4}_{\Lambda}$He のγ線を精密に測定し、そのエネルギーからΛ粒子と核子(ΛN) 間の相互作用に極めて大きな荷電対称性の破れがあることを初めて確定させた研究をまとめたものである。荷電対称性（強い相互作用における陽子・中性子間の対称性）は、核力や原子核においてよく成り立つ核物理の基本的対称性である。しかし過去の ${}^{4}_{\Lambda}$H と ${}^{4}_{\Lambda}$He のデータから、Λハイパー核では荷電対称性が大きく破れている可能性が示唆されていた。本研究は、γ線分光という別手法により、ハイパー核の大きな荷電対称性破れの存在を初めて確定させたものである。

実験は、J-PARC の K1.8 ラインにおいて、超伝導磁気スペクトロメータ SKS と東北大で開発したハイパー核専用の大型ゲルマニウム検出器群 Hyperball-J を用いて行われた。山本氏は、磁気スペクトロメータ系の設計と検出器の製作や補修、Hyperball-J の検出器の開発と製作、液体ヘリウム標的の製作等、実験全体にわたるさまざまな開発・準備を行った後、実験装置全体のテストやビーム調整をグループの中心となって行い、データを収集し、その後独力でデータ解析を行った。解析では、^{4}He(K^-, π^-)反応による ${}^{4}_{\Lambda}$He の質量スペクトルを求め ${}^{4}_{\Lambda}$He 生成のピークを観測した。一方 Hyperball-J のデータ解析からγ線スペクトルを得た。${}^{4}_{\Lambda}$He 生成イベントを選択し Doppler 効果の補正を行うと、明確なγ線ピークが現れこれが ${}^{4}_{\Lambda}$He(1^+→0^+)遷移と同定された。こうして得られた ${}^{4}_{\Lambda}$He(1^+, 0^+)の間隔 1.406 MeV は、過去のγ線測定で得られた ${}^{4}_{\Lambda}$H(1^+, 0^+)の間隔 1.09 MeV と大きく異なり、鏡像ハイパー核 ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He の間で荷電対称性が大きく破れていることを示した。さらに過去の ${}^{4}_{\Lambda}$H(0^+)，${}^{4}_{\Lambda}$He(0^+)のΛ束縛エネルギーの測定値と合わせると、励起状態 ${}^{4}_{\Lambda}$H(1^+)，${}^{4}_{\Lambda}$He(1^+)のΛ束縛エネルギーはほとんど差がなく、ΛN 相互作用の荷電対称性の破れにスピン依存性があることが判明した。この結果は従来の理論では説明不可能であるが、最近の理論的研究では、核内で重要な効果をもたらすΛN-ΣN 結合相互作用についての従来の理解を見直すことで説明できる可能性が示唆されている。本論文の成果は、ハイパー核の長年の謎を実験的に決着させただけでなく、ΛN 相互作用の今後の研究に大きな貢献をするものと考えられる。

このように、本論文は著者が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，山本剛史氏提出の博士論文は，博士（理学）の学位論文として合格と認める。