Study of Lambda quasi-free production in the 3H(e,e'K+)X reaction

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論　文　内　容　要　旨

(NO.　1)

氏　　名	板橋　浩介	提出年	令和３　年
学位論文の 題　　　目	Study of Lambda quasi-free production in the $^{3}\mathrm{H}(e,e'K^{+})X$ reaction ($^{3}\mathrm{H}(e,e'K^{+})X$反応におけるラムダ粒子準自由生成の研究)		

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Chapter6 Summary

Introduction

A nucleus is a system of baryons which are composed of three quarks, and bound by the strong interaction. We can understand the nuclear system and the origin of matter by studying the strong interaction between baryons. The nucleon-nucleon (NN) interaction has been studied with NN scattering data. However, the Λ-nucleon (ΛN) interaction has large uncertainties due to difficulties of measure the ΛN scattering data. Therefore, the ΛN interaction has been studied by spectroscopy of Λ hypernuclei. A recoil Λ which is produced within a nucleus is known to interact with a nucleon in the nucleus (FSI), and the ΛN interaction can be studied by treating it as a ΛN scattering problem.

An $nn\Lambda$ is a neutral nucleus with a Λ, and the study of this structure provides the information of the Λn interaction. However, the existence of the $nn\Lambda$ is not clear. In 2013, HypHI collaboration at GSI reported a possible bound state of the $nn\Lambda$ by measuring a final state of $\pi^- + t$. However, the peak significance of the invariant mass of $\pi^- + t$ was not enough to establish the bound state of $nn\Lambda$. A theoretical calculation that reproduces the Λ binding energies of light hypernuclei does not support the existence of the bound $nn\Lambda$ state. On the other hand, a resonance state of $nn\Lambda$ may exist as is suggested by the Faddeev calculation in which the Λn interaction is strengthened by about 5% in order to produce the resonance state. Therefore, search for the $nn\Lambda$ state experiment (E12-17-003) was performed in 2018 at JLab Hall A by using the $(e, e'K^+)$ reaction which enables for a high resolution spectroscopy of Λ hypernuclei.

Experimental setup

In the $(e, e'K^+)$ reaction, a target is irradiated with an electron beam, and momenta of e' and K^+ are measured. A mass of a Λ hypernucleus can be calculated with the momenta of e' and K^+ as follows:

$$\mathrm{M_{HYP}} = \sqrt{(E_e + M_{Tar} - E_{e'} - E_K)^2 - (\vec{p}_e - \vec{p}'_e - \vec{p}_K)^2}\,,$$

where $\mathrm{M_{HYP}}$, $\mathrm{M_{Tar}}$ are masses of the Λ hypernucleus and target, respectively. In this experiment, the electron beam with an energy of 4.3 GeV and with a current of 22.5 μA was incident on the ^{3}H gas target with 84.8 mg/cm^2. The momenta of e' with a central momentum of 2.2 GeV/c and $\mathrm{K^+}$ with a central momentum of 1.8 GeV/c were measured by using two spectrometers (HRSs) in this experiment. The HRS is comprised of superconducting magnets (QQDQ) with the momentum resolution of ($\Delta p/p \sim 10^{-4}$).

Analysis and Results

$nn\Lambda$ peak search

In the missing mass spectrum on the $^3\mathrm{H}(e, e'K^+)X$ reaction, any clear peak was not observed. However, since there were some events near the $nn\Lambda$ mass threshold ($-\mathrm{B}_\Lambda \sim 0$ MeV), the differential cross section of this structure was evaluated by using the $nn\Lambda$ peak function. It was represented by the convolution integral of a response function obtained by the SIMC and Breit-

Wigner function assuming $(-\mathrm{B}_\Lambda, \Gamma)$ = (0.55, 4.7) MeV. The differential cross section of the $nn\Lambda$ was obtained as 21.7 ± 6.7(stat.) ± 5.2(syst.) nb/sr by fitting the experimental data with this function, and the upper limit of the $nn\Lambda$ (CL90%) was estimated as 36.5 nb/sr.

Λn final state interaction

The differential cross section of Λ-QF productions was obtained at $880 \pm 20\ (\mathrm{stat.}) \pm 140\ (\mathrm{syst.})$ nb/sr. The differential cross section including FSI can be obtained as the product of the differential cross section without FSI and the influence factor $(I(k_{rel}))$ which depends on Λn relative momentum (k_{rel}). With the effective range approximation (ERA), the influence factor can be written by using two Λn potential parameters, scattering length (a) and effective range (r). Multiplying each event generated in SIMC by the weight of the influence factor, the distribution of the differential cross section including the Λn FSI effect was obtained. As a result of fitting the experimental data with the SIMC spectrum including the $nn\Lambda$ peak and the Λn FSI effect the reduce chi-square within the range of $0 \leq -\mathrm{B}_\Lambda < 60$ MeV took minimum value of 0.98 when the Λn potential parameters of the scattering length (a) and the effective range (r) were (a, r)= (−2.6, 5.0) fm, respectively. Moreover, the effective range at given a scattering length could be constrained in this experiment. When the scattering length is assumed as -2.6 fm, the effective range was obtained as $5.0^{+1.3}_{-1.2}$ fm.

Summary

E12-17-003 experiment was performed to investigate the $nn\Lambda$ state at JLab Hall A with two HRSs. Any clear $nn\Lambda$ peaks could not be observed, but the enhancement exists near the $nn\Lambda$ mass threshold. The 90%CL of upper limit for the $nn\Lambda$ differential cross section was obtained to be 36.5 nb/sr with the assumption of $(-\mathrm{B}_\Lambda, \Gamma)$ = (0.55, 4.7) MeV. The chi-square of Λ-QF production events within the range of $0 \leq -\mathrm{B}_\Lambda \leq 60$ MeV had the minimum value of 59 (ndf= 60) at (a, r) = (−2.6, 5.0) fm when the differential cross section of $nn\Lambda$ was 15 nb/sr. Moreover, the effective range at given a scattering length could be constrained in this experiment. When the scattering length is assumed as -2.6 fm, the effective range was obtained as $5.0^{+1.3}_{-1.2}$ fm.

別　紙

論文審査の結果の要旨

米国ジェファーソン国立研究所(JLab)において行われた $^{3}\mathrm{H}(e,e'K^{+})$反応を用いた$nn\Lambda$探索および準自由Λ粒子電子生成反応を用いた$\Lambda n$終状態相互作用の研究の成果をまとめた博士論文である。

$nn\Lambda$はもし存在すれば原子番号ゼロの極めて特異的なハイパー核である。10年近く前にドイツ GSI 研究所における実験によりその発見が報告されたものの、確立したというほどの精度がなく、さらに、これまでに培われたΛ粒子-核子間相互作用の知見に基づけば束縛するとは考えられず大きな問題となっていた。従来、Λ粒子-核子間相互作用は、わずかに存在するΛp 散乱実験データから議論されていたがΛn 散乱に関してはデータが存在しない。もし、Λn 間相互作用がΛp に比べ5 % 程度強ければ、$nn\Lambda$は共鳴状態としてなら存在する可能性が理論的に指摘された。

このため、板橋氏は JLab において東北大学が中心となり開発してきた$(e,e'K^{+})$反応によるハイパー核分光実験技術を三重水素標的に適用し欠損質量分布を得ることで、$nn\Lambda$の存否を調べ、同時に準自由生成されたΛ粒子と中性子間の終相互作用からΛn 間相互作用の情報を引き出すことを試みた。

板橋氏は米国において実験準備、データ収集を中心的に推進し、帰国後は日本の解析グループの中核として解析を進めた。この結果、 $^{3}\mathrm{H}(e,e'K^{+})$反応の欠損質量分布の$nn\Lambda$閾値付近に一定のイベントが存在するものの明確な$nn\Lambda$のピークは見つからなかった。理論モデルの予想する$nn\Lambda$共鳴状態のピーク位置と幅を仮定したフィットの結果、これらのイベントは微分散乱断面積に換算して$21.7 \pm 6.7\ (stat.) \pm 5.2\ (syst.)$nb/srに相当し、$nn\Lambda$共鳴状態微分断面積の上限値として36.5 nb/srを得た。

さらに、板橋氏は、様々なΛn 間相互作用ポテンシャルを仮定して求めた散乱長(a)、有効距離(r)を用いてΛn終状態相互作用の効果を計算し詳細なシミュレーションを遂行した。本実験により観測されたΛ粒子準自由生成断面積とシミュレーションの結果より、散乱長(a)が最小二乗法で得られる推定値とした場合に有効距離(r)に制限を付けることに成功した。

$^{3}\mathrm{H}(e,e'K^{+})X$反応におけるラムダ粒子準自由生成実験を国際共同研究のもと中心的に推進し、データ解析を主導した板橋氏は自立した研究者に要求される高度な研究能力と学識を有している。よって板橋浩介氏提出の博士論文を、博士（理学）の学位論文として合格と認める。