Experimental study for spectroscopy of Ξ --atomic X rays

著者	Fujita Manami
number	87
学位授与機関	Tohoku University
学位授与番号	理博第3244号
URL	http://hdl.handle.net/10097/00126680

東北大学第６４号

博士学位論文内容の要旨
及び
審査結果の要旨

理　学　第　８７　集
（令和元年１１月２７日授与）

東　北　大　学

令和元年度

（別紙様式５）

論　文　内　容　要　旨

(NO.　1)

氏　　名	藤田　真奈美	提出年	令和元年
学位論文の題　　目	Experimental study for spectroscopy of Ξ^--atomic X rays (Ξ^-原子X線分光の実験的研究)		

論　文　目　次

1. Introduction

This thesis describes a first pioneering study on exotic atoms containing Ξ^-, one of the hyperons with two strange quarks. The Ξ^- atomic X-ray spectroscopy is one of the useful ways to obtain information on the ΞN interaction. The shift of the X-ray energy (ΔE) from the energy by the Coulomb interaction only and the X-ray peak width give information of the real and imaginary parts of the Ξ^--nuclear potential, respectively. Most of produced Ξ^-s decay before stopping and cause a huge background. The key of experiments to measure X rays with good significance is to select Ξ^--stop events cleanly. In this experiment, two methods to select Ξ^--stop events were developed. In Method 1, Ξ^--stop events are identified in the developed nuclear emulsion image. On the other hand, in Method 2, the Ξ^- with a large stop probability at the target is selected using information of the Ξ^- momentum.

2. Experiment

The first Ξ^- atomic X-ray spectroscopy experiment (J-PARC E07) to measure Ξ^-C, Ξ^-Ag, and Ξ^-Br atomic X rays was performed at J-PARC K18 beam line in 2016 and 2017. In the experiment, Ξ^-s were produced in a diamond target via the $p(K^-, K^+)\Xi^-$ reaction. Some of them were stopped in the target, or in the nuclear emulsion placed downstream of the target, and then formed Ξ^- atoms. To identify the $p(K^-, K^+)\Xi^-$ reaction, two magnetic spectrometers, the K1.8 beam line and the KURAMA spectrometers, were used. As a tracking detector which predicts the Ξ^- hit position at the surface of the emulsion placed downstream of the target, the silicon strip detectors (SSDs) were placed to sandwich the emulsion. Their prediction makes the time of emulsion image analysis shorter. This is called the emulsion-counter hybrid method. The X-ray energies of Ag($8J\rightarrow7I$) or Br($7I\rightarrow6H$) transitions without strong interaction are 370 keV and 316 keV, respectively, and theoretically predicted shifts are 0.3 - 5 keV. The statistical and systematic errors should be small enough to measure X rays with accuracy of a few hundreds eV. To measure these X rays, the Ge detector array, called Hyperball-X, was used. Its energy resolution was ~2 keV (FWHM) at 370 keV. Since the peak position is shifted between beam on and off periods due to a huge beam background, in-beam reference γ-ray data were necessary. A new high precision energy calibration system using LSO scintillators and ^{22}Na sources was developed. Three γ rays (202 keV, 307 keV, and 511 keV) from ^{176}Lu in LSO and ^{22}Na were used as reference γ rays. The β-γ and γ-γ coincidence detection using a Ge detector and a LSO counter made it possible to take in-beam calibration data continuously during the data-taking period. It was found that this system achieved energy calibration with a 100-eV accuracy.

3. Analysis and Results

The (K^-,K^+) reaction was reconstructed by analysis of two magnetic spectrometers and Ξ^- production events were identified. This reaction analysis and the X-ray analysis by Hyperball-X were applied in both of the Method 1 and 2.

In the emulsion image analysis (Method 1), the events in which Ξ^-s reached the emulsion and stop red there were selected. In addition to K^- and K^+, the Ξ^- track was analyzed by SSD. From the Ξ^- track, the Ξ^- injected point on the surface of the first layer of the emulsion was given. Then the Ξ^- track was searched for in the image of the developed emulsion. The Ξ^-Ag or Ξ^-Br atom production events were identified as two kinds of image in the emulsion. One is called "σ-stop" event in which one or more tracks of charged particles are observed at the end of the Ξ^- track. The other is "ρ-stop with Auger emission" event in which no track of charged particles are observed except Auger electrons at the end. By selecting the σ- and ρ-stop events, the X-ray spectrum of Ξ^-Ag and Ξ^-Br atoms was obtained. For both of them, no evident peaks were found in the expected X-ray energy regions. The background level was evaluated to be $0.17^{+0.78}_{-0.16}$ per 1 keV around the 370-keV region.

In the kinematical analysis (Method 2), the events in which a Ξ^- was stopped in the target and captured by a ^{12}C atom were selected. Because the Ξ^- missing momentum has uncertainty due to the Fermi motion of a proton in a nucleus, the probability that the Ξ^- stops inside the target was estimated event by event using Monte Carlo (MC) simulation by Geant4, and the Ξ^-s with the stop probability of 9% or more were selected. In addition, in the analysis of the SSD1, Ξ^-s which do not stop in the target and reach the SSD1 were rejected. By applying the Method 2, the spectrum of Ξ^-C atomic X rays was obtained. No evident X-ray peak was found. From the upper limit of the X-ray yield, the upper limit of the branching ratio $BR(E1;\ 3D\rightarrow 2P)$ was obtained as a function of the X-ray peak width.

4. Conclusion and Outlook

In the Method 1, based on the present analysis, the Ξ^-Ag and Ξ^-Br atomic X-ray spectrum was obtained with 20% statistics of the estimated total σ-stop yield. When the emulsion image analysis is completed, an expected X-ray yield of the Ag($8J\rightarrow 7I$) transition will be 7.75 counts for σ-stop events and S/√N would be 4.56 in the ±2σ peak region. The statistical error will be 290 eV and the systematic error is 100 eV. Thus, the energy shift is expected to be measured with 300 eV accuracy.

In the Method 2, the upper limit of the branching ratio $BR(E1;3D\rightarrow 2P)$ of the Ξ^-C atom was experimentally evaluated. This limit was compared to the theoretical calculation using the Woods-Saxon-type Ξ^--nuclear potential optical potential. It was found that the experimental sensitivity was not sufficient to constrain the imaginary part of the Ξ^--nuclear potential. More improvements, for example optimization of the target thickness and detector developments to reject contamination of the background process, are required in the future experiment.

5. Summary

For a general understanding of the baryon-baryon interaction, investigating of ΞN interaction is necessary while experimental data are limited. The first experiment for Ξ atomic X-ray spectroscopy, one of the powerful ways to investigate the strong Ξ^--nuclear potential, was performed at J-PARC. Ξ^-s produced by the (K^-, K^+) reaction were stopped in the diamond target or in the nuclear emulsion located downstream. Ξ^- atomic X rays were measured using the Ge detectors array called Hyperball-X. A new in-beam energy calibration method for the Ge detectors using LSO scintillators and ^{22}Na sources was developed and achieved a 100-eV accuracy. In order to measure Ξ^- atomic X rays with good S/√N, two methods to select Ξ^--stop events were developed. In Method 1, Ξ^--stop events were selected by the nuclear emulsion image analysis. In Method 2, the Ξ^- with a large stop probability at the target was selected using information of the Ξ^- momentum. In this thesis, the sensitivity of the present experiment with both of two methods was evaluated and improvements necessary for future experiments were discussed.

別　紙

論文審査の結果の要旨

本博士論文は,世界で初めて行ったΞ原子 X 線分光実験についてまとめたのである。Ξ粒子はストレンジクォークを 2 つ含む不安定なバリオンで，Ξと核子の間の強い相互作用は不明である。それが明らかになると，核子間相互作用（核力）の深い理解や，中性子星内部の高密度核物質の解明につながる。Ξ・核子間相互作用の明確な情報を得る方法として，Ξ^-が原子核にクーロン力で束縛された「Ξ原子」を作りそのX線エネルギーを精密に測定する方法があるが，実験的困難のためそのような実験はこれまで行われたことがなかった。

J-PARC において，Ξ粒子を生成して原子核乾板によってストレンジクォークを 2 つ含む原子核・原子を研究する国際共同実験 E07 が行われた。この実験は，Ξ原子核・ΛΛ原子核の研究と，Ξ原子の研究とからなるが，藤田氏は後者のテーマの中心人物として，主に X 線測定用の Ge 検出器システムの改良・設置・調整を主導した。特に，強いビームバックグランド下で Ge 検出器を精密にエネルギー較正するため，LSO シンチレータと ^{22}Na 線源を用いた新手法を開発し，ビーム中でも 100eV の精度で較正できることを実証したことは高く評価される。

データ収集後は，X 線のバックグランド低減のため，Ξが崩壊せずに静止した事象を選び出す手法を 2 種類開発し，データを解析した。一方は，原子核乾板中にΞが静止し Ag や Br の核にΞが吸収された事象を原子核乾板の画像解析から 1 つずつ選び出す方法である。乾板解析の専門家の協力のもと，取得データの 20%を解析し，X 線スペクトルのバックグランドレベルを確定した。その結果，今後 100%の解析を完遂すれば，Ξ原子 X 線が有意なピークとして見えることを示した。他方は，Ξ生成用の炭素標的中でΞが静止する可能性の高い事象を運動学解析により選び出す方法で，これによりΞ炭素原子 X 線を探索した。セットアップがΞを炭素中でなく乾板中に止めるよう設計されていたため，Ξ炭素原子 X 線も観測できなかったが，最終遷移 X 線の分岐比の上限値を求め，Ξ原子準位エネルギーの理論計算を行って分岐比を比較することで，Ξ原子核ポテンシャルの虚部に制限を与えるための議論を展開した。この方法の感度と今後の改良点も議論した。こうして、世界初のΞ原子 X 線分光実験を行い、様々な独創的な測定・解析手法を開発したことは、今後のΞ原子 X 線分光研究に指針を与える大きな成果である。

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，藤田真奈美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。