Measurement of Ξ?atomic X rays using iron target

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論　文　内　容　要　旨

（NO.　1）

氏　　名	石川　勇二	提出年	令和　　4年
学位論文の 題　　　目	Measurement of Ξ⁻ atomic X rays using iron target （鉄標的を用いたΞ原子X線測定の研究）		

論　文　目　次

1 Introduction

The hyperon-nucleon and hyperon-hyperon interactions in the S (strangeness) = −2 sector are important to understand the baryon-baryon interaction under the flavor SU(3) symmetry. X-ray spectroscopy of Ξ^- atoms is a useful method to study the Ξ^-- nuclear interaction, since the shift of the X-ray energy from that considering only the Coulomb interaction and the width of the X-ray peak give information on the real and the imaginary parts of the Ξ-nucleus optical potential.

In the present work, Ξ^- Fe atomic X ray was studied. The 5G orbit of the Ξ^- Fe atom is expected to be the last orbit before Ξ^- absorption. An energy shift (4.4 keV) and an energy width (3.9 keV) of the 5G orbit are predicted from a theoretical calculation assuming a Woods-Saxon shape optical potential of −24−3i MeV [1]. Focusing on the imaginary term, predictions based on a one-boson-exchange model [2] and a lattice QCD calculation [3] differ by more than one order of magnitude. Ξ^- atomic X-ray data may give constraint to the strength of the absorption interaction. The X ray of the (6H→5G) transition (~286 keV) can be observed if the peak width is less than 1 keV, which was suggested by the lattice QCD calculation. In addition, the X ray of the (7I→6H) transition (172 keV) can be also observed without significant energy shift and peak broadening. Furthermore, even if the absorption strength is too weak to obtain finite width from the peak structure, the yield ratio of these X rays can provide information on the imaginary part.

2 Experiment

An X-ray spectroscopy experiment of Ξ^- Fe atom (J-PARC E03 experiment) was performed at the J-PARC K1.8 beam line. The purpose of this experiment was the world-first measurement of Ξ^- atomic X rays to obtain information on the Ξ^-- nucleus potential. In this experiment, Ξ^- hyperons were produced via the p(K^-, K^+)Ξ^- reaction in the quasi-free process on an iron target using K^- beam at 1.8 GeV/c. Some of produced Ξ^- hyperons were slowed down and stopped in the target. An advantage of using the iron target is its high density leading to a large probability of Ξ^- being stopped in the target. The stopped Ξ-hyperon was captured by a Fe atom then a Ξ^- atom was formed. The captured Ξ^- hyperon transits to lower atomic orbits with X-ray emission, and is eventually absorbed by the nucleus via the $\Xi^- p \rightarrow \Lambda\Lambda$ conversion. For tagging the Ξ^- production, the missing mass of the p(K^-, K^+)X reactions was reconstructed using beam K^- and scattered K^+ momenta. Two magnetic spectrometers, the beam line spectrometer and the KURAMA spectrometer, were used for the momentum analysis of the beam K^-s and the scattered K^+s, respectively. In addition, a Ge detector array, Hyperball-X', installed surrounding the target, was used for detection of the X rays from Ξ^- Fe atoms in coincidence with the (K^-, K^+) reaction. For energy calibration of the Ge detectors, the calibration method using LSO(Lu_2SiO_5) scintillator [4] was employed and two γ-ray peaks from ^{176}Lu, at 202.843 and 306.791 keV, were used.

3 Analysis

The missing mass spectrum for the p(K^-, K^+)X kinematics was obtained from the analysis of magnetic spectrometers and the missing mass gate (less than 1.44 GeV/c^2) was applied to select Ξ^- production events considering background from misidentification of scattered particles and reaction processes except for the p(K^-, K^+) Ξ^- reaction. To obtain a good signal-to-noise ratio, an additional analysis for selecting Ξ^- with a large stopping probability in the target was performed using a Monte-Calro simulation based on measured missing momenta.

4 Result and discussion

Two X-ray spectra in the energy region of 0-400 keV were obtained by analysis of the magnetic spectrometers and Hyperball-X'. One is the spectrum with the missing mass selection applied to the Ξ^- production region. The other is the spectrum by selecting Ξ^- particles with a stopping probability of more than 10% in addition to the missing mass cut. In both X-ray spectra, no clear peaks with a significance of more than 3σ were observed around 172 and 286 keV corresponding to the expected energies of the Ξ^- Fe atomic X rays. Then, the upper limit of the X-ray intensity per stopped Ξ^- (R_X) was evaluated. The upper limit of R_X (7I→6H) in the range of 172±10 keV was obtained to be 0.19 (90% C.L.). When the emission probability of Ξ^- from the nucleus is assumed to be 70%, the upper limit becomes 0.27.

The distribution of the initial angular momentum l in atomic capture process is usually represented as P~(2l+1)exp(α+1). For μ^-, π^-, and K^- atoms, reasonable results have been found for values of the α parameter between −0.1 and 0.1. In the theoretical calculation [1], P_{Ξ^-}(7I) is expected to be 0.3. with α = −0.056. This α value was based on experimental data of Σ^- atomic X ray and a cascade calculation [5] while the value may have ambiguity due to differences in hyperon mass and target nuclei. R_X (7I→6H) is thus estimated to be 0.3 with $BR^{(7I\rightarrow 6H)}{}_{E1}$∼1 because a negligibly small effect of strong interaction is expected for the 7I state. The obtained upper limit from the preset result is lower than the predicted Rx value. We hope that the present upper limit will be followed by theoretical studies (cascade calculation) to constrain α value for Ξ^- Fe atom.

[1] T. Koike, private communication.
[2] M. M. Nagels et al., Phys. Rev. C 99 (2019) 044003.
[3] K. Sasaki et al., Nucl. Phys. A 998 (2020) 121737.
[4] M. Fujita et al., Nucl. Inst. and Meth. A 1042 (2022) 167439.
[5] C. J. Batty, E. Friedman, and A. Gal, Phys. Rev. C 59, 295 (1999).

別　紙

論文審査の結果の要旨

核子間にはたらく核力を、その近距離部分も含めてクォーク描像に基づいて理解することは、原子核物理学の最重要課題の一つである。核子をハイペロン（ストレンジクォークを含むバリオン）に置き換えて、核力を一般化した「バリオン間力」を調べることで、この問題の解決につなげることができると期待されている。しかし、ストレンジクォークを2個含むΞ粒子と核子との相互作用についてはほとんどデータがなく、研究の進展が待たれていた。

石川勇二氏は、Ξ粒子と核子との相互作用を調べるため、Ξ^-粒子が鉄原子核の原子軌道に束縛したΞ原子を生成し、そのX線エネルギーを高精度で測定することで、Ξ^-と鉄原子核の間の相互作用の情報を得ることを目指して実験研究を行った。Ξ原子X線測定は極めて難しく、これまでに観測例はないが、観測されればΞ原子核間ポテンシャルの大きさが定量的に決定できる。石川氏は、J-PARCハドロン施設のK1.8ビームラインにおいて、K^-中間子ビームを用いてΞ^-を生成して鉄標的中に静止させ、同時に発生するX線を測定した。ビームのK^-と、Ξ^-生成反応後に放出されるK^+の運動量をそれぞれ測定する磁気スペクトロメータ系の検出器の整備・調整を行い、X線測定用のゲルマニウム検出器群の設置・調整や、X線エネルギーを0.1 keVの精度で較正するシステムの開発、高速データ収集システムの開発なども行い、共同実験グループの中心となって実験を遂行した。データ取得後は全てのデータ解析をほぼ独力で遂行した。解析では、X線スペクトル中の大量のバックグランドを軽減するため、標的に静止しやすい事象を選別する独自の解析法を導入した。結果として、得られたX線スペクトルには目的とするX線ピークは観測されず、静止Ξあたりのξ鉄原子X線(7I→6H)の強度の上限値を導出した。この結果から、Ξ鉄原子のX線強度は理論的予想値より低いことが判明し、Ξ原子X線放出の理解と、今後行うさらなる実験のための貴重な指針を与えることとなった。

検出器やデータ収集系の開発などの実験準備、実験遂行、データ解析の全体をグループの中心となって遂行してその結果を論文にまとめたことは，石川氏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，石川勇二提出の博士論文は，博士（理学）の学位論文として合格と認める。