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Towards more exoticness – X-ray spectroscopy of Ξ^- atoms at J-PARC

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Abstract Atoms with a doubly-strange hadron, namely Ξ^-, are really exotic and interesting objects. We are planning to measure X rays from Ξ^- atoms for the first time at J-PARC, where a high intensity and high quality kaon beam is available. Our purpose is to obtain the strength of the optical potential, and hence to provide information on the Ξ-N interaction which is currently very poorly known. We can accumulate several thousand counts of X rays and determine the level energy shift down to ~ 0.05 keV. This is sensitive enough to observe the expected level shift (~ 1 keV) with reasonable accuracy, while the sensitivities for the level width is somewhat weaker (measurable down to ~ 1 keV).

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1 Introduction

Exotic atoms with strangeness $S = 0$ (e.g., pionic atoms) or $S = -1$ (e.g., kaonic atoms) have been well studied. This situation is dramatically different in the sector of $S = -2$ where virtually no experimental data exists. Thus, atoms with a doubly-strange hadron, namely Ξ^-, are really exotic and interesting objects to study.

The physics motivation for the study of Ξ atoms is the strong interaction of baryons in the $S = -2$ sector. It has attracted a lot of attention for various reasons, and has been the biggest motivation for the construction of the J-PARC 50 GeV proton synchrotron. Firstly, based on the SU(3) classification, new interactions appear up to $S = -2$. Especially, the isospin 0 channel ($\Lambda\Lambda$-ΞN-$\Sigma\Sigma$) is the unique SU(3) singlet, so that investigation of the $S = -2$ systems is essential.

The possibility of strong mixing of ΞN components into $\Lambda\Lambda$ hypernuclei is another interesting subject, because the mass difference of ΞN and $\Lambda\Lambda$ is as small as 28 MeV. This is much smaller than in the case of $S = -1$ (ΛN-ΣN, $\Delta M \sim 80$ MeV), and

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$S = 0$ (ΔN-NN, $\Delta M \sim 300$ MeV), and the coupling effect is inversely proportional to the mass difference. If the conversion from ΞN to $\Lambda\Lambda$ is found to be strong, then a significant amount of Ξ should mix in $\Lambda\Lambda$ hypernuclei. Therefore, a measurement of the conversion strength is very interesting.

In addition, the knowledge of the depth of the Ξ-nucleus potential is also important for estimating the existence of strange hadronic matter with Ξ's. For a long time, it was believed that Σ^- hyperons would appear in neutron stars earlier (i.e., at lower densities) than even lighter Λ hyperons due to their negative charge. However, recent data strongly suggest that the interaction of Σ^- with neutron-rich nuclear systems is strongly repulsive [1], which means Σ^- hyperons may no longer appear in neutron stars. Disappearance of Σ^- hyperons would not necessarily lead to crucial changes of neutron star features if they were substituted effectively by Ξ^- hyperons. In this point of view, it becomes more important to investigate the Ξ dynamics in the nuclei than it was considered previously.

However, despite the importance of $S = -2$ systems as described above, very little is known experimentally. Reflecting this situation, there is no established interaction model in $S = -2$ channels. Various models (e.g., [2–4]) are proposed, but they give remarkably different ΞN and hence ΞA interactions. This fact demonstrates that the experimental information on the ΞA optical potential (U_Ξ) including its mass dependence, is crucially important in order to discriminate reasonable interaction models.

2 The planned experiment

Here we are planning to measure X rays from Ξ^- atoms to obtain information on the ΞA interaction for the first time in the world. This method has been successfully applied for the study of the interaction of negatively-charged hadrons, such as π^-, K^-, $\bar{p}$, and Σ^- (e.g., [5]), and is thus promising.

Though it is ideal to measure Ξ^--atomic X rays from all the atoms over the periodic table, it is not practical, and so we have to choose target nuclei. There are several things that should be considered in choosing targets both from physics and experimental points of view.

The choice of optimum targets from the physics points of view is discussed by Batty *et al.* [6]. For a given atomic state, the energy shift and width are larger (and hence easier to measure) for heavier atoms. However, for too heavy atoms, the absorption by the target nuclei at the initial state is much faster than the X-ray emission and X-ray detection becomes almost impossible. Practically, the maximum width of a final state which can be reachable by X ray is an order of a few keV, while the energy shift could be larger if the absorption potential is very weak.

Batty *et al.* suggested a set of 4 candidates for optimum targets, namely, ${}_{9}$F, ${}_{17}$Cl, ${}_{53}$I, and ${}_{82}$Pb, for $(n, l) = (3, 2)$, $(4, 3)$, $(7, 6)$, and $(9, 8)$ states, respectively, where (n, l) denotes the principal quantum number and orbital angular momentum of an atomic state. They predicted energy shifts and widths of order 1 keV for these states. Also, by interpolating their discussion, one could guess ${}_{27}$Co, ${}_{39}$Y, and ${}_{67}$Ho might be the best targets for $(n, l) = (5, 4)$, $(6, 5)$, and $(8, 7)$, respectively. However, these discussions are largely dependent on the optical potential itself, so that we cannot know what are the optimum targets before the first experiment.

Therefore, experimental viewpoints are more important for the selection of the first target. Here, we mainly considered the following three points:

1. Production rate of Ξ^-. Since the mass dependence of production cross section is known to be represented by $A^{0.38}$ [7], the production rate will be proportional to $A^{-0.62}$ for the same target thickness.
2. Stopping probability of producded Ξ^-. The produced Ξ^- has a momentum of ~ 500 MeV/c (range: 10-20 g/cm^2), and the target material must be dense enough to stop a significant fraction of the Ξ^- before it decays.
3. X-ray absorption in the target. For heavy targets, most of the emitted Ξ^--atomic X rays would be absorbed within the target.

Considering these points combined, we found transition metals of $24 \leq Z \leq 30$ are the best because they have reasonably high density ($\rho > 7$ g/cm^3) while the X-ray absorption probability and Ξ^- production rate are modest. The first target is thus chosen to be $_{26}$Fe, for which, according to a calculation by Koike *et al.*, a significant energy shift (4.4 keV) and width (3.9 keV) are expected assuming a reasonable optical potential (Woods-Saxon, $U_\Xi = -24 - 3i$ MeV) [8].

The planned experiment will be performed at the K1.8 beamline of J-PARC together with the KURAMA spectrometer and an germanium (Ge) detector array, Hyperball-J [9]. Ξ^-'s are produced by the quasi-free $p(K^-, K^+)\Xi^-$ reaction at 1.8 GeV/c where the cross section of the elementary process is at maximum. An almost pure sample of Ξ^- can be obtained by selecting K^+ momentum between 1.2 to 1.5 GeV/c. The KURAMA spectrometer system has been long used for experiments at the KEK-PS K2 beamline (see, for example, Ref. [10]), and minor modifications are necessary to accomodate the high kaon intensity, which is assumed to be 1.4×10^6 per 4 second cycle (flattop: 1.2 s). It has a large acceptance of 0.2 sr, which allows us to maximize the yield of Ξ^-. The produced Ξ^- is then brought to stop in the same target (iron plate of 6 cm width, 1.5 cm height, and 3 cm thickness).

The X-ray detector system, Hyperball-J, is an upgraded version of Hyperball (constructed in 1998), and Hyperball2 (constructed in 2005), which have been used for hypernuclear γ spectroscopy experiments. It consists of about thirty Ge detectors, each surrounded by fast PWO counters for background suppression instead of the previous BGO counters. The total photo-peak efficiency of Hyperball-J is about 16% for the Ξ^--Fe X ray of interest $[(6,5) \to (5,4)]$ at around 286 keV[1].

The Ge detectors are constantly monitored and calibrated by a system using lutenium oxyorthosilicate (LSO) scintillators, which include ^{176}Lu as a natural radioactive source. This source emits several γ rays (mainly 202 keV and 307 keV) in the region of our interest, and an efficient data taking is possible as it is self-triggerable using β rays. Thanks to this feature, we can simultaneously take calibration data together with X-ray data, although LSO crystals are small (10 mmϕ $\times$ 1 mm) and thus the radioactivity is very weak (~ 23 Bq). The in-beam performance of the LSO calibration system was studied using a positron beam at Tohoku University, and a good result was obtained as shown in Fig. 1. In this test, it was demonstrated 50 eV calibration accuracy can be achieved every 5 hours.

[1] Electromagnetic energies of X-rays are precisely calculated by Friedman [11] to be 285.99 keV and 285.78 keV for $6h_{11/2} \to 5g_{9/2}$ and $6h_{9/2} \to 5g_{7/2}$ transitions, respectively, with leading order vacuum polarization corrections included.

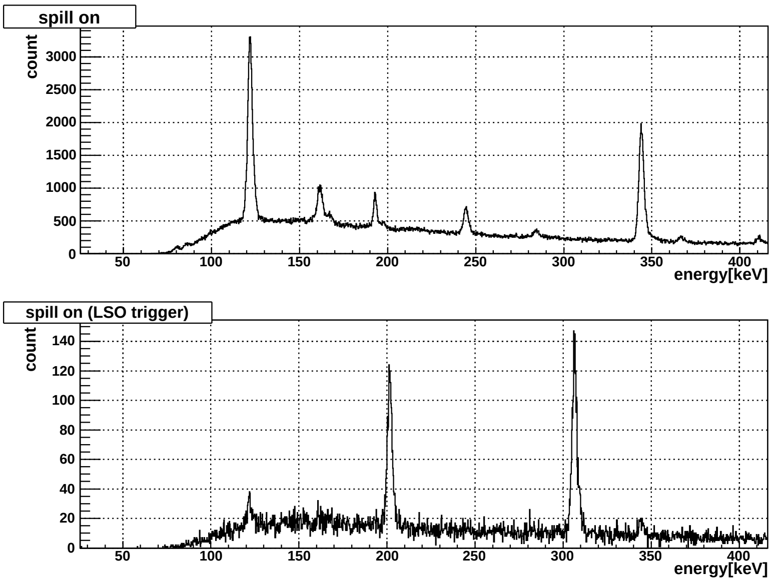

Fig. 1 In-beam spectra of a Ge detector taken simultaneously. Top: with single trigger (prescaled by a factor 30). Bottom: coincident with LSO (not prescaled). Two peaks from ^{176}Lu γ rays are clearly seen in the bottom figure, although they are not seen in the single spectrum. On the other hand, other peaks (mostly from an ^{152}Eu source) and continuum background are strongly suppressed. The S/N ratio is improved by about a factor 1000 over the single spectrum.

3 Expected results

With 800 hours of beam time, a total of 1.0×10^{12} K^- will be irradiated on the target, and 3.7×10^6 Ξ^-'s will be produced by the (K^-, K^+) reaction. According to a GEANT4 simulation, 20% of the produced Ξ^-'s stop in the Fe target (7.5×10^5 events).

The estimation of the number of X ray emitted per stopped Ξ^- has large uncertainty because it is very much dependent on the absorption potential, which we want to know. Another (small) uncertainty is in the calculation of cascade processes in the Ξ^- atom. According to a calculation by Koike [8], the X-ray emission probability for the transition $(6, 5) \rightarrow (5, 4)$ in Ξ^--Fe atoms is 10%, with about 3/4 of the Ξ^-'s at the $(6, 5)$ state absorbed by the nucleus. It is noted that the fact that the X-ray emission probability strongly depends on the absorption potential means that its measurement gives a quite strong constraint on the absorption potential.

The detection efficiency for the X rays is estimated by GEANT4 simulations, taking into account the effect of X-ray self absorption in the target. The obtained value is 6.7% for 286 keV X rays. In addition, the in-beam deadtime of the Ge detectors should be included in the detection efficiency. From our experience, it is estimated to be 50% at worst, which was the value obtained in the experiments at KEK-PS, where very intense ($\sim 3.0 \times 10^6$/s) π^+ beams were used. In this experiment, although the expected beam intensity will be less than half of that, we conservatively take the same value as the

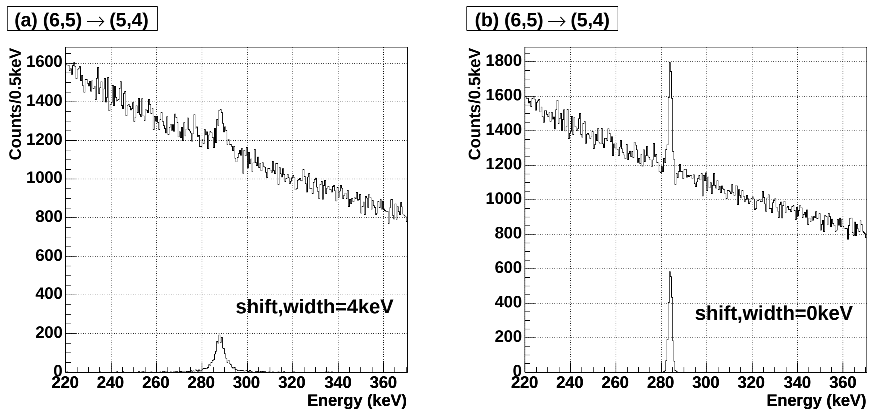

Fig. 2 Expected X-ray energy spectra for (a): $(n, l) = (6, 5) \to (5, 4)$ transition. X-ray width is 4 keV, as predicted by Koike [8]. (b): with no width.

upper limit. Thus, the X-ray detection efficiency is estimated to be 3.4%, and the yield for the $(6, 5) \to (5, 4)$ X ray will be 2500 counts. In the same way, the yield of the transition $(7, 6) \to (6, 5)$ ($\sim$ 172 keV) can be calculated to be 7200 counts; this yield is used as a reference to estimate the imaginary part of the $\Xi^- A$ optical potential.

Expected X-ray energy spectra are shown in Fig. 2. The background level is estimated by using data from previous Hyperball experiments, corrected for the difference of X(γ)-ray detection efficiency. We can clearly observe the $(6, 5) \to (5, 4)$ X ray, even if the width of the $(5, 4)$ state is as large as $\Gamma = 4$ keV.

The statistical accuracy of the level shift will be 0.04 keV, even when the width of the $(6, 5) \to (5, 4)$ X ray is 4 keV. Then, the actual accuracy is determined by systematic effects, such as energy calibration and background subtraction, and is expected to be about 0.05 keV (or better). Indeed, this level of accuracy was achieved in the past experiments to measure Σ^--atomic X rays [5]. For the expected energy shift of an order of 1 keV, this accuracy is good enough to determine the strength of the real part of the optical potential.

The sensitivity for the level width is not so high, but enough if it is as large as $\Gamma = 3.9$ keV as predicted by Koike [8]. In this case, our accuracy would be $\delta\Gamma \sim 1$ keV. On the other hand, for smaller widths, we will have sensitivities down to $\Gamma \sim 1$ keV.

In addition to the direct measurement of level width, there is another method to obtain information on the imaginary part of the $\Xi^- A$ optical potential. The comparison of the yields for $(n, l) = (6, 5) \to (5, 4)$ and $(n, l) = (7, 6) \to (6, 5)$ gives an estimation of the branching ratio of the nuclear absorption at the $(n, l) = (6, 5)$ state, after correcting for the other small contributions feeding the $(n, l) = (6, 5)$ state, such as from $(n, l) = (8, 6)$. Though such a correction is slightly model-dependent, we can estimate the strength of the imaginary potential using the X-ray transition rate which is precisely calculable. This is especially important when the absorption is so strong that the X-ray peak for $(n, l) = (6, 5) \to (5, 4)$ is not observed. Even in such an extreme case, we will be able to give quite useful information on the strength of the $\Xi N \to \Lambda\Lambda$ coupling.

4 Status and prospects

The proposal for the first experiment was submitted in April 2006 as J-PARC P03 [12]. The proposal was discussed in the meetings of J-PARC Program Advisory Committee (PAC) [13], and stage-1 (scientific) and stage-2 (full) approval was granted in August 2006 and March 2008, respectively. No essential difficulty is anticipated in the experimental setup itself, and the first run is expected in 2010. We would like to establish the experimental method in the first experiment.

After the first experiment, we will design the next experiment as soon as the result is obtained. If we find the energy shift and width are small, we will use heavier targets, such as $_{27}$Co and $_{30}$Cu. In the opposite case, we would choose even lighter targets, such as $_{25}$Mn. We also will measure more X rays using targets in other mass regions. Eventually, our goal is to measure X rays from ~ 10 targets, namely, from 1 or 2 "optimal" targets for each $4 \leq n \leq 9$ and to reconstruct the ΞA optical potential. Also, measurements of γ rays from double-Λ hypernuclei may be possible as a byproduct. Presently, this is the only practical way to perform double-Λ hypernuclear γ-ray spectroscopy, and we will plan a dedicated experiment if such a measurement is found to be really possible in J-PARC E03.

5 Summary

We can accurately measure the energy shift and width of Ξ^--atomic X rays in order to determine the ΞA optical potential. Our plan is to establish the experimental method in the first experiment using an iron target, and then to run a series of experiments over wide mass range. The proposal for the first experiment is approved and is expected to run in 2010.

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