Plan for the measurement of Ξ^--atomic X rays at J-PARC

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Abstract. We present our plan to measure X rays from Ξ^- atoms for the first time in the world at J-PARC. The measurement of X rays from Ξ^- atoms is a promising method to study the optical potential between Ξ^- and a nucleus as proved in the cases of other negative hadrons (π^-, K^-, $\bar{p}$, and Σ^-). While we are intending to measure X rays from as many targets as possible over the periodic table, we have chosen Fe (iron) as the first target because the measurement will be the easiest and because large X-ray energy shift and width may be expected. Choice of other targets will be determined based on the result of the first experiment. We can accumulate several thousand counts of X rays and determine its energy shift down to ~ 0.05 keV. This is sensitive enough to observe expected energy shift (~ 1 keV) with reasonable accuracy, while sensitivities for X-ray width is somewhat weaker (measurable down to ~ 1 keV).

PACS. 36.10.Gv Mesonic atoms and molecules, hyperonic atoms and molecules – 21.30.Fe Forces in hadronic systems and effective interactions – 29.30.Kv X- and gamma-ray spectroscopy

1 Physics motivation

Strangeness nuclear physics in the $S = -2$ sector 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, this is a significant step forward from $S = -1$ system towards the multi-strangeness hadronic systems, where interactions between hyperons may play an important role. The interactions between two hyperons with strangeness first appear in $S = -2$ sector, so that investigation of the $S = -2$ systems is essential.

Furthermore, strong coupling between ΞN and $\Lambda\Lambda$ is expected bacause the mass difference is as small as 28 MeV. This is much smaller than the case of $S = -1$ (ΛN-ΣN, $\Delta M \sim 80$ MeV), and $S = 0$ (ΔN-NN, $\Delta M \sim 300$ MeV), and the coupling effect is inversely proportional to the mass difference. Therefore, $S = -2$ nuclei may be the first system where the baryon coupling effect plays a dominant role.

In the $S = -2$ world, Ξ-hypernuclei will play an important role as the entrance channel. Ξ-hypernuclei give valuable information on the $S = -2$ baryon-baryon effective interactions such as ΞN, and $\Xi N \to \Lambda\Lambda$. An interesting feature in standard one-meson-exchange models is that space (Majorana) exchange is forbidden. For example, in Nijmegen Hard-core model D (NHC-D) [1], this feature leads to a strong P-state attraction, which gives a prediction that ΞA interaction has significant mass number dependence. This prediction should be examined experimentally. In addition, knowledge of the depth of the Ξ-nucleus potential is important also 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 [2], which means Σ^- hyperons may no longer appear in neutron stars. Disappearance of Σ^- hyperons does not necessarily leads to crucial changes of neutron stars 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 Ξ 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., [1,3,4]) are proposed, but they give remarkably different ΞN and hence ΞA interactions. This fact demonstrates that the experimental information on U_Ξ, including its mass dependence, is crucially important in order to discriminate reasonable interaction models.

2 The planned experiment

2.1 Principle

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^-, and thus promising.

By measuring Ξ^--atomic X rays, the information on the ΞA interaction can be obtained in the following way. When hadronic interaction is ignored, the level energies of atomic states (denoted by principal quantum number n and orbital angular momentum l), and hence the X-ray energies, can be precisely calculable by solving Dirac equation. Then, the difference of the measured X-ray energy and the calculated value and X-ray width is attributed to the $\Xi^- A$ strong interaction, which is often represented by an optical potential.

If we use first order purturbation theory for simplicity, the energy shift and width are directly related to the optical potential (U_Ξ) via the known (calculable) atomic wave function $\Psi_\Xi(r)$ as

$$\Delta E = \int |\Psi_\Xi(r)|^2 U_\Xi(r) dr. \quad (1)$$

Although this is not always a good approximation in reality, more elaborate calculations are capable of finding optical potentials that reproduces the observed energy shift and width. If we assume a shape (e.g., Woods-Saxon) of the optical potential, even a single X ray measurement can give the potential depth. As we accumulate X-ray data on various states of many atoms, we will be able to test such an assumption and eventually to reconstruct properties of the ΞA optical potential.

While X-ray measurement gives rather direct information on the ΞA optical potential, the obtained information is mostly for the peripheral part of the nucleus because the atomic wave function is far more extended than the nuclear size. Therefore, the X-ray energy measurement proposed here is complimentary to the spectroscopic study of Ξ hypernuclei proposed by Nagae *et al.* [5], which is sensitive to the central part of the ΞA potential, but somewhat suffers from an ambiguity in nuclear structure.

2.2 Selection of target nuclei

Though it is ideal to measure Ξ^--atomic X rays from all the atoms over the periodic table, it is not practical and 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 1-10 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 $(9,8)$, respectively. They predicted energy shifts and widths of order 1 keV for these states. Also, by interpolating this 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], 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 significant fraction of the Ξ^- before it decays.
3. X-ray absorption in the target. For heavy target, most of the emitted Ξ^--atomic X ray would be absorbed within the target.

Considering these combined, we found transition metals of $24 \le Z \le 30$ 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.*, significant energy shift (4.4 keV) and width (3.9 keV) are expected assuming a reasonable optical potential (Woods-Saxon, $-24 - 3i$ MeV) [8].

2.3 Setup

The planned experiment will be performed at the K1.8 beamline together with the KURAMA spectrometer and an germanium (Ge) detector array, Hyperball-J [9]. Ξ^- is 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^- production can be obtained by selecting K^+ momentum between 1.2 to 1.5 GeV/c. The KURAMA spectrometer system was long used for experiments at KEK-PS K2 beamline (see,

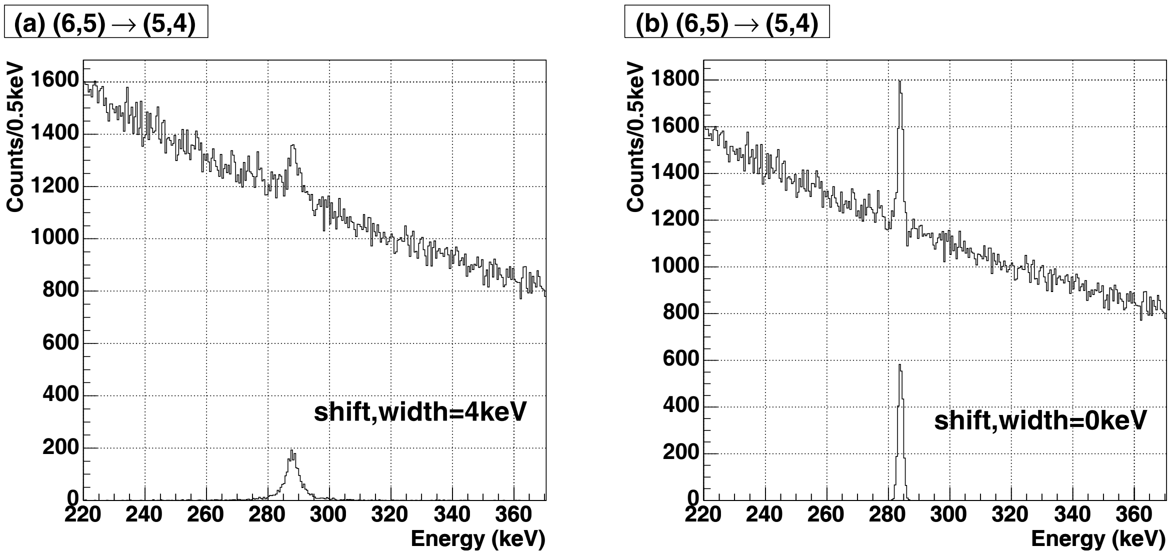

Fig. 1. Expected X-ray energy spectra for (a): $(n, l) = (6, 5) \to (5, 4)$ transition. Energy shift and width are both 4 keV, as predicted by Koike [8]. (b): Same as (a), but with no energy shift and width.

for example, Ref. [10]), and minor modifications are necessary to accomodate 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 wide, 1.5 cm high, and 3 cm thick).

Once a Ξ^- is stopped, it forms a Ξ^- atom with the target nucleus and emits X rays. The X-ray detector system, Hyperball-J, is an upgraded version of Hyperball (constructed in 1998, photo-peak efficiency $\epsilon = 2.5\%$ at 1 MeV), and Hyperball2 (constructed in 2005, $\epsilon = 5\%$), which have been used for hypernuclear γ spectroscopy experiments. It consists of about forty 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 284 keV.

The in-beam performance of Ge detectors will be constantly monitored by triggerable ^{22}Na β-γ sources embedded in plastic scintillation counters. Since the beam rate in the planned experiment ($< 1.5 \times 10^6$ particles/s) is less than half of that in the previous experiments at KEK-PS, we expect the Ge detectors will work fine. Absolute energy calibration will be better than 0.05 keV in the range of 100-400 keV with frequent (more than once a day) calibration measurements under both in-beam and off-beam conditions. The X-ray energy resolution is expected to be better than 2 keV FWHM including the in-beam peak broadening effect.

3 Expected results

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

Estimation of the number of X ray emitted per stopped Ξ^- has large uncertainty because it is very much dependent on the absorption potential we want to know. Another (small) uncertainty is in the calculation of cascade process in the Ξ^- atom. According to a calculation by Koike [8], the X-ray emission probability for the transition $(6, 5) \to (5, 4)$ in Ξ^--Fe atom is 10%. In this calculation, about 3/4 of the Ξ^-s at the $(6, 5)$ state is 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 quite strong constraint on the absorption potential.

The detection efficiency for the X ray 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 284 keV X rays. In addition, 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 when the π^+ intensity was as high as 3.0×10^6/s in the experiments at KEK-PS. In this experiment, although the expected beam intensity will be less than half, we conservatively take the same value as the 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 $(7, 6) \to (6, 5)$ (~ 171 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. 1. The background[1] level is estimated by using data from

[1] Background X rays from other negative particles, such as π^- produced by the decay of Ξ^-, are negligible since their

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 X-ray energy will be 0.04 keV, if the width of the $(6,5) \to (5,4)$ X ray is 4 keV. For smaller widths, the statistical accuracy would be better. 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 [11]. 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.

Sensitivities for the X-ray width is not so high, but enough if it is as large as $\Gamma = 3.9$ keV 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 X-ray 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 nucleic 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 correction is slightly model-dependent, we can estimate the imaginary part of the integral (1) for the $(n,l) = (6,5)$ state using the X-ray transition rate, which is precisely calculable. This is especially important when the absorption is so strong that X-ray peak for $(n,l) = (6,5) \to (5,4)$ is not observed. Even in such an extreme case, we will have a strong physics message. Therefore, we can give quite useful information on the strength of the $\Xi N \to \Lambda\Lambda$ coupling.

4 Status and prospects

Proposal for the first experiment was submitted in April 2006 [12]. The proposal was discussed in the meeting of J-PARC Program Advisory Committee (PAC) [13] held in June-July 2006, and stage-1 approval was granted. By this, the PAC recognized that "the scientific merit of the proposal is high and the experimental methods are sound". We are now trying to obtain stage-2 (full) approval as soon as possible. We will be ready by the end of 2008, and the first experiment will run in 2010. No essential difficulty is anticipated in the experimental setup itself. We would like to establish the experimental method in the first experiment.

X-ray energies are not overlapping with the energy region of interest. (Hyper-)nuclear γ rays could be a severe background if their energies are accidentally very near to that of the Ξ^--atomic X ray, though such chance is quite small considering the resolution of Ge detectors (2 keV) and expected X-ray energy shift of less than a few keV.

We are considering to further improve the experimental design from the original one described in Ref. [12] and in this manuscript. Namely, a semi-active target, in which iron plate is segmented into ~ 6 pieces of ~ 5 mm thick each with thin silicon detectors being sandwiched in between, is considered. The semi-active target allows us to select slow Ξ^- which stops in the next target segment by ΔE measurement and hence dramatically improves the signal-to-noise ratio. New collaborators who are interested in constructing the target are very welcome.

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. If vice versa, 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 $4 \le n \le 9$ and to reconstruct the ΞA optical potential. Also, measurements of γ rays from double-Λ hypernuclei may be possible.

5 Summary

We can accurately measure the energy shift and width of Ξ^--atomic X rays in order to determine 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 now at stage-1 approval and is expected to run in 2010.

References

1. M. M. Nagels, Th. A. Rijken and J. J.de Swart, Phys. Rev. D **15**, (1977) 2547.
2. H. Noumi *et al.,* Phys. Rev. Lett. **89**, (2002) 072301.
3. M. Yamaguchi, K. Tominaga, Y. Yamamoto and T. Ueda, Prog. Thoer. Phys. **105**, (2001) 627.
4. Th. A. Rijken and Y. Yamamoto, Phys. Rev. C **73**, (2006) 044008.
5. T. Nagae *et al.*, Proposal P05 submitted to the J-PARC 50 GeV Proton Synchrotron (2006); T. Nagae, in these proceedings.
6. C. J. Batty, E. Friedman, and A. Gal, Phys. Rev. C **59**, (1999) 295.
7. T. Iijima *et al.*, Nucl. Phys. **A546**, (1992) 588.
8. T. Koike, private communication (2006).
9. T. Koike *et al.*, in these proceedings.
10. H. Takahashi, *et al.*, Phys. Rev. Lett. **87**, (2001) 212502.
11. R. J. Powers *et al.*, Phys. Rev. C **47**, (1993) 1263.
12. K. Tanida *et al.*, Proposal P03 submitted to the J-PARC 50 GeV Proton Synchrotron (2006);
13. `http://j-parc.jp/NuclPart/PAC_for_NuclPart.html`