Proposal for J-PARC 50 GeV Proton Synchrotron

Measurement of X Rays from Ξ^- Atom

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Summary of the Proposed Experiment

Beamline:	K1.8
Beam:	1.8 GeV/c K^-
Intensity:	1.4×10^6 /spill
Flat-top:	1.2 sec (4 sec/spill)
Beam time:	100 shift + 20 shift for setup
Total number of K^- beam:	1.0×10^{12}
Spectrometer etc.:	KURAMA spectrometer, Hyperball-J
Target:	Fe 3 cm (23.6 g/cm^2)
Estimated Yield:	
Number of stopped Ξ^- on Fe	7.5×10^5
Number of detected X rays	2.5×10^3 for $(n, l) = (6, 5) \rightarrow (5, 4)$ transition (~ 284 keV)
Estimated sensitivity:	
X-ray energy shift	~ 0.05 keV
Width	~ 1 keV at $\Gamma = 4$ keV, measurable down to $\Gamma \sim 1$ keV

Abstract

We propose to perform the first measurement of Ξ^--atomic X rays from Fe target at K1.8 beamline.

Physics interest is in the Baryon-Baryon interaction at $S = -2$ sector, for which we have very scarce data so far. In order to approach this goal, measurement of X rays from Ξ^- atoms is a promising method to study the optical potential in nuclei; this method had been successfully used in cases of negative charged hadrons (π^-, K^-, $\bar{p}$, and Σ^-). The X-ray energy shift gives information on the real part of the optical potential, while X-ray width and yield are relevant to the imaginary part.

While we are intending to measure X rays from as many targets as possible over the periodic table, we have chosen Fe as the first target because the measurement will be the easiest and because large X-ray energy shift and width are expected. Choice of other targets will be determined based on the result of the proposed experiment.

For the proposed experiment, we will use a large acceptance spectrometer (KURAMA) and a high-resolution X-ray detector system (Hyperball-J). We will use the same KURAMA spectrometer system as had been used in KEK-PS K2 beamline, with some modifications to accommodate higher beam intensity. Hyperball-J will be commonly used with γ-ray measurement of Λ-hypernuclei and will be newly constructed based on the experience on the existing Hyperball.

The expected X-ray yield is 2500 counts, which give statistical energy shift accuracy of better than 0.04 keV (~ 0.05 keV with systematic errors). 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). Width information can also be obtained from X-ray yields.

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. First, 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. Especially, these knowledges are important to understand the properties of neutron stars of which density is so high that significant amount of hyperons is expected to appear in the core.

Secondly, quark degrees of freedom may appear in the $S = -2$ system. Particularly attractive prediction is the existence of H-dibaryon. Although there was no experimental evidence on the existence of the H-dibaryon so far, there is still the possibility that H-hypernuclei being the ground state of $S = -2$ nuclei.

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.

However, very little is known experimentally on $S = -2$ hypernuclei. As for the Ξ-hypernuclei, there are some hints of emulsion events for the existence. However it is still not conclusive. Some upper limits on the Ξ-nucleus potential have been obtained from the production rate and spectrum shape in the bound region of Ξ-hypernucleus via $^{12}\mathrm{C}(K^-, K^+)$ reaction[1, 2]. In these experiments, Ξ-hypernuclear states were not clearly observed because of the limited statistics and detector resolution. The potential depth, V_Ξ, was suggested to be ~ -14 MeV for $A = 12$ assuming Woods-Saxon type potential shape, but the derivation of the potential was model dependent and was not conclusive. As for double-Λ-hypernuclei, several emulsion events were reported[3, 4, 5, 6, 7]. The production of $^{4}_{\Lambda\Lambda}\mathrm{H}$ was also reported in a counter experiment by detection of pairs of pions in sequential mesonic weak decay[8], but the binding energy of the hypernucleus was not well determined.

In this situation, Ξ-hypernuclei will play an important role as the entrance channel to the $S = -2$ world. Ξ-hypernuclei give valuable information on the $S = -2$ baryon-baryon effective interactions such as ΞN, and $\Xi N \to \Lambda\Lambda$. It is predicted in one-meson-exchange models that the well depth depends considerably on mass number, A. For example, the well depth in $^{207}\mathrm{Tl}$ is estimated to be more than two times deeper than that in $^{11}\mathrm{B}$. This is because the space (Majonara) exchange is impossible within one-meson-exchange picture in the ΞN system, unlike the NN, ΛN, and ΣN systems. Hence, the p-wave attraction is expected to be strong in the ΞN, which leads to the substantial increase of ΞA attraction. This is an interesting prediction to 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 more light 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, which means Σ^- hyperons can no longer appear in neutron stars. It was argued that disappearance of Σ^- hyperons does not necessarily leads to crucial changes of neutron stars features if they were substituted effectively by Ξ^- hyperons. However, better understanding of $\Xi^- N$ interaction is necessary for definite conclusions. With respect to the neutron star structure, it becomes much more important to investigate the Ξ dynamics than it was considered previously, because the Σ^--nuclear repulsion has been established.

Since little is known for $S = -2$ baryon-baryon systems, especially ΞN system, there is no established interaction model in $S = -2$ channels. Various SU(3)-invariant models [9, 10, 11] estimated the depth of the ΞA optical potential. The derived potential, however, are remarkably different among interaction models, which demonstrates that the experimental information on U_Ξ is crucially important in order to discriminate reasonable interaction models.

Here we propose the first measurement of X rays from a Ξ^- atom to obtain information on the ΞA interaction. 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 caused by the $\Xi^- A$ interaction, which is often represented as an optical potential.

If we use first order purturbation, the energy shift and width are directly related to the optical potential (U_Ξ) via the known (calculable) atomic wave function $\Psi_\Xi(r)$ (see also Fig. 1) as

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

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 (see Fig. 1). Therefore, the X-ray energy measurement proposed here is complimentary to the spectroscopic study of Ξ hypernuclei proposed by Nagae *et al.* [12], which is sensitive to the central part of the ΞA potential, but gives rather indirect information.

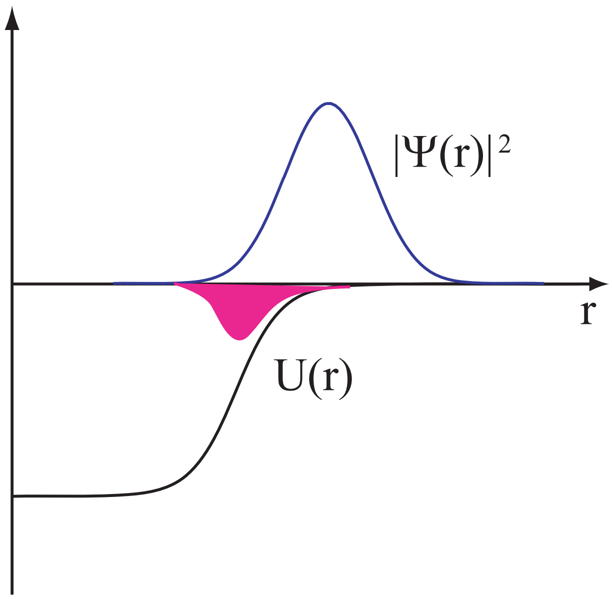

Figure 1: A schematic drawing of the optical potential and wave function of a Ξ^- atom. The overlap is shown as the pink area.

2 Purpose of the proposed experiment

There are two purposes in the proposed experiment, namely,

1. To observe Ξ-atomic X ray for the first time and to establish the experimental method.
2. To extract the depth of the $\Xi^- A$ optical potential.

We think purpose 1 is more important than 2, because we cannot make sure to select a good target to observe significant energy shift (and width) in the first experiment as discussed in Sect. 3.1. Even if significant energy shift is not observed in the first experiment, the result will help us to select optimum targets and such observation will certainly be possible in the future experiments.

3 Experimental Method

The proposed experiment will be performed at the K1.8 beamline together with the KURAMA spectrometer and an germanium detector array, Hyperball-J. Ξ^- is produced by the (K^-, K^+) reaction at 1.8 GeV/c where the cross section of the elementary process, $p(K^-, K^+)\Xi^-$, is at maximum. Details on the beamline and K^+ detection system is explained in Sect. 3.2. As for the target, we will use Fe (iron) in the first experiment; this choice is not trivial, and discussed in detail in Sect. 3.1. The produced Ξ^- is then brought to stop in the same iron target. Once a Ξ^- is stopped, it forms a Ξ^- atom with the target nucleus and emits X rays, which will be detected by Hyperball-J, which is described in Sect. 3.3.

3.1 Choice of Experimental Target

Though it is ideal to measure Ξ^--atomic X rays from all the atoms over the periodic table, it is not realistic 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.* [13]. For a given atomic state, the energy shift and width are larger (and hence easier to be measured) 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 10 keV, while the energy shift could be larger if the absorption potential is weaker than the real potential.

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 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. These discussions, however, are largely dependent on the optical potential we want to know, and we cannot know what are the optimum targets before the first experiment.

On the other hand, from the viewpoint of experimental feasibility, the following three are the most important points to be considered:

1. Production rate of Ξ^-. Since the mass dependence of production cross section is known to be represented by $A^{0.38}$ [14], 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.

Here we note qualitatively that lighter element are better from 1 and 3, while heavier elements are favored from 2. Quantitative discussion on the X-ray yield is performed in Sect. 4.1. Considering these 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.

Both of the physics and experimental viewpoints tell that the elements around $_{27}$Co are the best targets. It is impossible to say for sure which of them is really the best now – again, it depends on the physics we want to know. Then, we have chosen $_{26}$Fe as the first target because significant energy shift (4.4 keV) and width (3.9 keV) is expected from a calculation by Koike [15].

After the result of the proposed experiment is obtained, we can discuss more clearly the choice of the best target. If we find the energy shift and width are small and there are enough statistics, 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 energy shifts (and widths) of the states other than $(n, l) = (5, 4)$ using targets in other mass regions. As Friedman indicated in Ref. [16], it is expected the main features of the ΞA interaction will be reconstructed from a limited data set using targets carefully chosen in this way.

3.2 K1.8 Beamline and KURAMA Spectrometer

The setup for the (K^+, K^-) reaction is mostly common to the one for the Hybrid Emulsion experiment proposed by Nakazawa *et al.* [17]. A schematic drawing of the experimental setup is shown in Fig. 2 and Fig. 3. K^- provided by the K1.8 beamline is identified by The time-of-flight counters (T1 - T2) and an aerogel Cherenkov counter (BAC; $n = 1.03$). Additionally, the direction of K^- is measured by a set of drift chambers with 3 mm pitch (BDC3-4[1]). The intensity of the K^- beam is assumed to be 1.4×10^6 per 4 second cycle (flattop: 1.2 s), with an excellent K/π^- ratio of better than 3.

The size of the Fe target is 6×1.5 cm^2 and 3 cm in length (thickness: 23.61 g/cm^2), assuming the rms beam size is 20 mm (horizontal) $\times$ 3.2 mm (vertical). The actual target size will be adjusted after the beam size is measured in order to minimize the X-ray absorption effect while keeping the size large enough to accomodate the K^- beam. According to a GEANT4 simulation, 20-26% of the produced Ξ^-s will stop in this target setup.

The scattered K^+ particles are detected with the KURAMA spectrometer system which was used for KEK-PS E373 experiment. It consists of a magnet, time-of-flight counters (FTOF-T2), aerogel Cherenkov counters (BVAC, FAC1), drift chambers (DC1-3). It has a large acceptance of 0.2 sr, which allows us to maximize the yield of Ξ^-. The identification of K^+ is done by time-of-flight counters and aerogel Cherenkov counters. Almost perfect identification of K^+ is possible as shown in the mass spectrum of scattered particles obtained in E373. The momentum of the K^+ particle is measured with the KURAMA magnet and drift chambers. The momentum resolution obtained in E373 is good enough to identify quasi-free Ξ^- production from the carbon target.

3.3 X-ray Detection System

For the X-ray detection, we will use Hyperball-J, which will be constructed newly for J-PARC. It 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.

[1]BDC1-2, which will be installed in the upstream of K1.8 beamline to measure the K^- momentum, will not be used in this experiment.

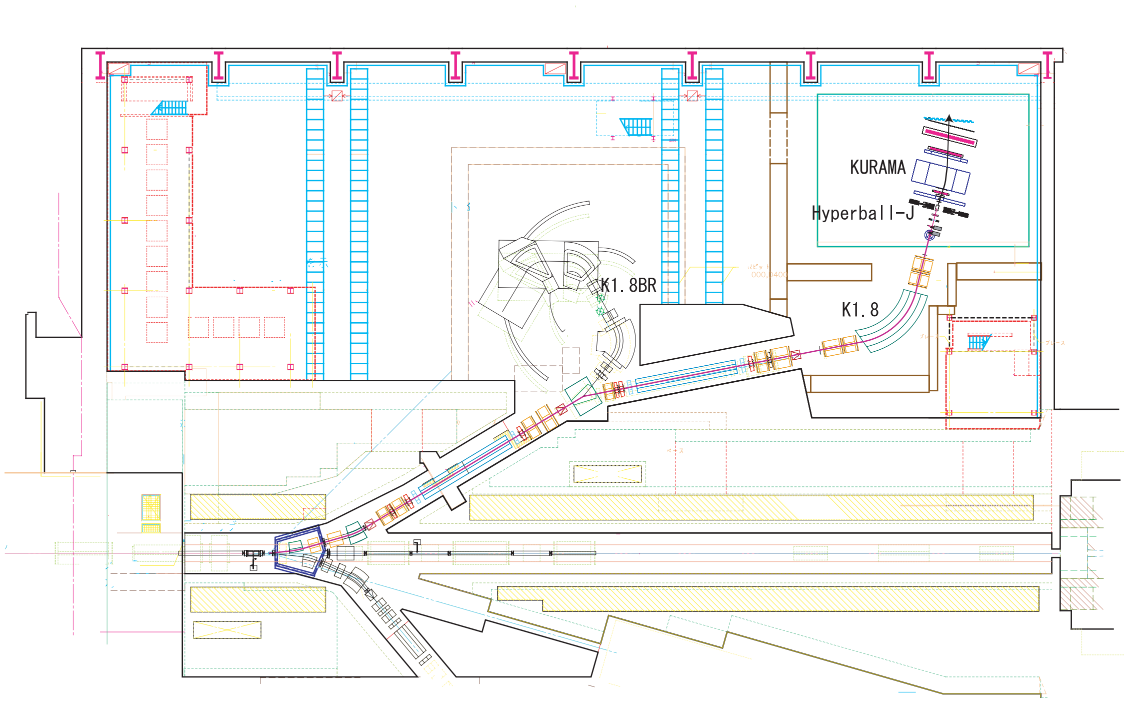

Figure 2: A schematic overview of the K1.8 beamline.

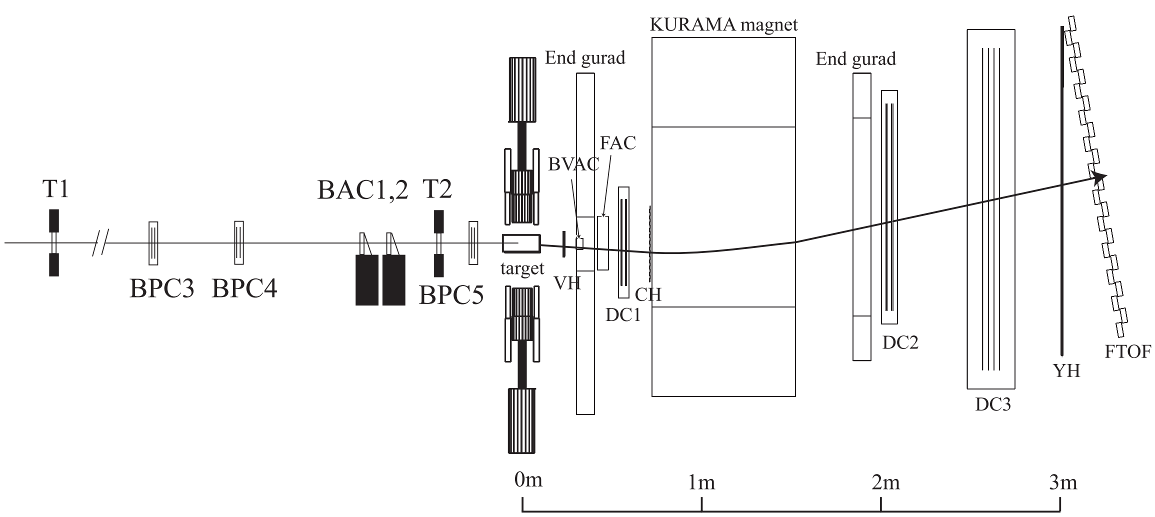

Figure 3: A schematic overview of the KURAMA spectrometer.

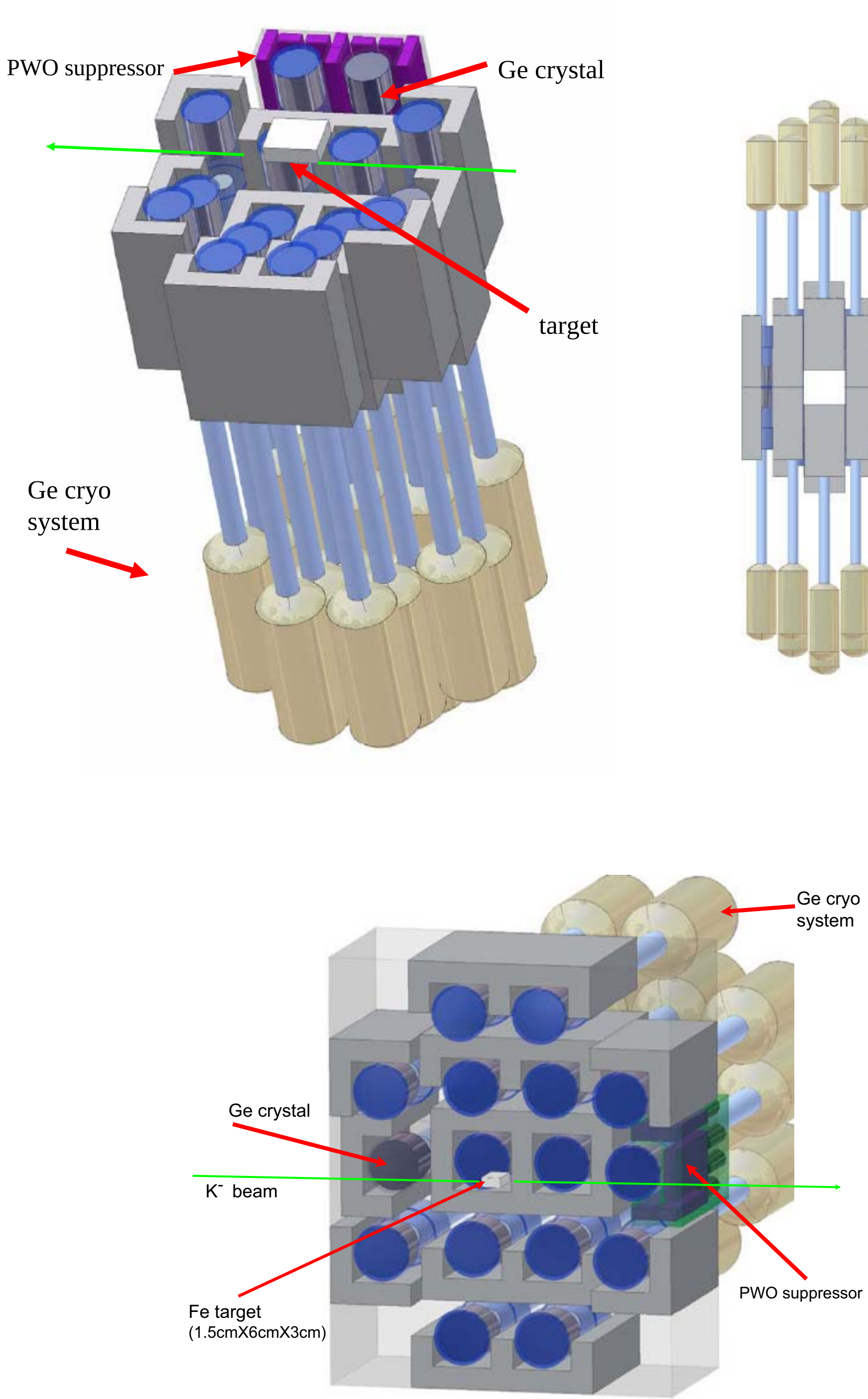

Figure 4: Schematic view of Hyperball-J, a newly-constructed Ge detector array. Top-Left: View of the half-array from side. Top-right: View from upstream. Bottom: View from top.

As shown in Fig. 4, Hyperball-J consists of about forty Ge detectors and holds a total photo-peak efficiency more than 6% at 1 MeV. Each Ge detector is surrounded by fast PWO counters for background suppression instead of the previous BGO counters. The expected counting rate and energy deposit rate to the Ge detectors will be much lower than those in the previous experiments at KEK-PS using (π^+, K^+) reaction with 3×10^6/s pion beam. Therefore, the fast readout electronics used in the present Hyperball2 will work fine under the beam intensity for the proposed experiment ($< 1.5 \times 10^6$ particles/s), as we found in our BNL E930 experiment with (K^-, π^-) reaction that the counting and energy deposit rates of Ge detectors are roughly proportional to the total beam (kaon+pion) rate regardless of the particle species. The X-ray energy resolution is expected to be better than 2 keV FWHM including the in-beam peak broadening effect.

As shown in Fig.4, the Ge detectors are arranged at top and bottom and the distance of each detector from the target can be adjusted according to the requirement of the experiment and beam conditions. In the proposed experiment, the detectors are installed about 18-20 cm from the target center. Figure 5 shows the simulated photo-peak efficiency. It is about 16% for the Ξ^--Fe X ray of interest $[(6,5) \rightarrow (5,4)]$ at around 284 keV.

In the proposed experiment, careful calibration of X-ray energy and its resolution is essential. We will use various γ-ray standard sources to obtain absolute energy calibration of better than 0.05 keV in the range of 100-400 keV. Especially, the use of ^{133}Ba, ^{57}Co, and ^{152}Eu gives us many good calibration points in this region. Calibration measurements will be performed frequently (more than once a day) under both in-beam and off-beam conditions. These measurements need about 10% of the total beam time. Also, in-beam performance of Ge detectors are constantly monitored by triggerable ^{22}Na $\beta - \gamma$ sources embedded in plastic scintillation counters. The absolute photo-peak efficiency will also be obtained by calibration with the standard sources and the in-beam dead time measurement with the triggerable ^{22}Na sources, after a correction for the target absorption with a simulation. The absolute efficiency will be determined within $\pm 5\%$ accuracy.

The PWO scintillator has a high density and a large effective atomic number similar to BGO but emits a light much faster (decay time ~ 10 ns) than BGO (~ 300 ns). It is suitable for a high counting rate condition as the J-PARC experiments. Although the light output is much smaller than BGO, we can expect nearly 100% efficiency for 100 keV photons when PWO crystals are cooled down to $-20°$. We have made a set of prototype PWO counters and already confirmed their performance; the prototype PWO counters were good enough for high energy γ-ray suppression, and as for the Compton suppression, the PWO counters also have a similar performance to the previous BGO counters as shown in Fig.6.

3.4 Trigger

One problem of the proposed experiment is the trigger. In principle, we use the similar trigger scheme as E373. However, because the beam rate of the proposed experiment is ~ 100 times larger than KEK-PS E373, where the 1st level trigger rate for the (K^-, K^+) event was 75 for 1.1×10^{-4} K^-'s, our trigger rate would be as high as 10^4 per spill, which we

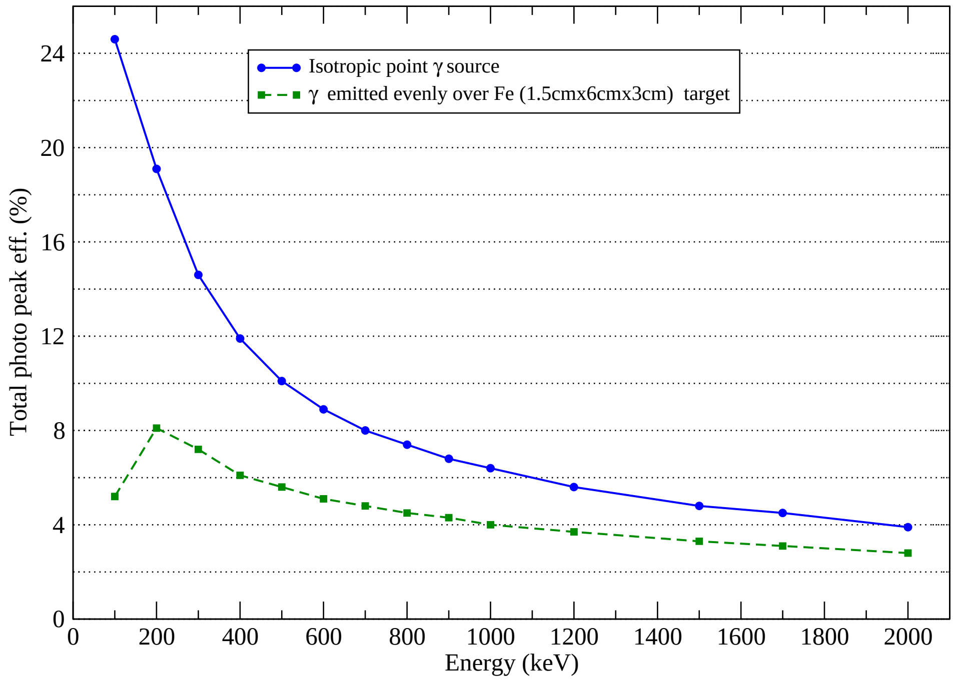

Figure 5: Efficiency curve of Hyperball-J.

cannot handle. Though we can reduce the main trigger rate by a factor of ~ 5 by requiring hits in Ge detectors[2] and there are other 2nd level triggers, we still need a new (K^-, K^+) trigger.

In E373, most of the (K^-, K^+) triggers were actually caused by a misidentification of proton to K^+, because there was no couter to reject protons at the 1st level trigger. These fake triggers can be reduced by factor > 10 by using a Cerenkov counter of $n \sim 1.1$. Recently, high-density aerogel (up to $n = 1.25$) was successfully developed in Russia and by Chiba University. This is a promising technique, and we are starting a test of a sample counter borrowed from Russia. If the test is successful, we will make a new Cerenkov counter, FAC2, to be used in the proposed experiment.

[2]Ge hit is a 2nd level trigger because signals from Ge are very slow.

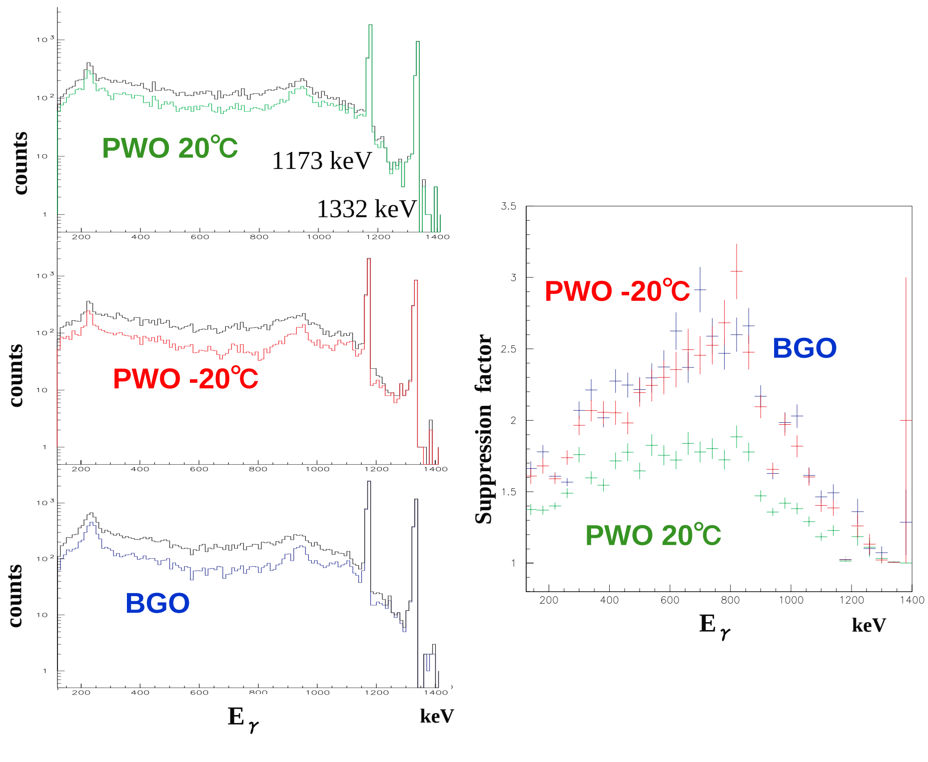

Figure 6: Compton suppression performance of prototype PWO countes (at room temperature and at $-20°$) compared with BGO counters used in previous Hyperball. Left: $^{6}0$ Co γ-ray spectra before and after the suppression. Right: Suppression factor.

3.5 Requested Beamtime

We request 100 shifts (800 hours) for the physics beam time. With this beamtime, we will irradiate 1.0×10^{12} K^-'s in total on the Fe target. Additionally, we need some beam time for setup, which include beam tuning, beam profile measurement, detector setup, performance test, and calibration. If the experiment is performed sequentially with the Hybrid Emulsion experiment [17], we can minimize the setup time, because the most detectors are common to this experiment. We need 20 shifts in this case, namely, 5 shifts for beam tuning and profile measurement, 5 shifts to test detector performances, and 10 shifts for calibration of Ge detectors. Also, we need a few weeks of off-beam time to change the setup. If the proposed experiment will be truly the Day-1 experiment, we additionally need more than 10 shifts for beam tuning and 20 shifts for detector setup.

4 Expected Results

4.1 Expected X-ray Yields

The X-ray yield N_X for the $(n, l) = (6, 5) \rightarrow (5, 4)$ transition is estimated to be 2500 counts in the following way.

N_X can be written as

$$N_X = N_{\text{stopped }\Xi^-} \times R_X \times \eta_X \times \epsilon_X,$$

where

$N_{\text{stopped }\Xi^-}$: Number of stopped Ξ^- in the Fe target.

R_X: Intensity of the X ray of interest per stopped Ξ^-.

η_X: Probability that the X ray passes through the target uninteracted.

ϵ_X: X ray detection efficiency of the Hyperball-J.

and $N_{\text{stopped }\Xi^-}$ can be represented by

$$N_{\text{stopped }\Xi^-} = N_{K^-} \times t \times \sigma_{\Xi^-} \times \Omega_{K^+} \times \epsilon_{K^+} \times \epsilon_0 \times R_{\Xi^-}$$

with

N_{K^-}: Number of total K^- beam (1.0×10^{12}).

t: Target thickness in (number of atoms)/cm^2 (2.6×10^{23} atoms/cm^2).

σ_{Ξ^-}: Differential cross section of the (K^-, K^+) reaction.

Ω_{K^+}: Acceptance of the KURAMA spectrometer (0.2 sr).

ϵ_{K^+}: Overall efficiency of K^+ detection system.

ϵ_0: Overall efficiency due to DAQ deadtime and trigger efficiency.

R_{Ξ^-}: Stopping probability of produced Ξ^-.

Estimation of the parameters are explained in the following.

σ_{Ξ^-} can be taken from Ref. [14] as $38 \times A^{0.38}$ μb/sr and is about 180 μb/sr for Fe. Estimation of ϵ_{K^+} is based on the past experience on the KURAMA spectrometer, and we take $\epsilon_{K^+} = 0.51$ including the effect of K^+ decay loss. ϵ_0 is assumed to be 0.8. Thus, the number of produced Ξ^- is 3.7×10^6.

R_{Ξ^-} is estimated to be 0.2-0.26 by a GEANT4 simulation as mentioned in the previous section. The uncertainty comes from the momentum distribution of the produced Ξ^-. The stopping Ξ^-'s are mostly produced below 500 MeV/c, and fraction of such low momentum components largely affects the stopping probability. To be conservative, we take $R_{\Xi^-} = 0.2$, and hence $N_{\text{stopped }\Xi^-}$ is estimated to be 7.5×10^5.

There are very large uncertainties in estimating R_X because it is very much dependent on the absorption potential we want to know. Another uncertainty is in the calculation of cascade process in the Ξ^- atom. According to a calculation by Koike [15], R_X for the transition $(6,5) \to (5,4)$ in Ξ^--Fe atom is 10%. In this calculation, the branching ratio of X ray emission from the $(6,5)$ state is about 25%. It is noted that the fact that R_X strongly depends on the absorption potential means that measurement of R_X gives quite strong constraint on the absorption potential. This possibility is discussed in Sect. 4.3.

η_X and ϵ_X are estimated by GEANT4 simulation. The obtained values are 0.42 and 0.16, respectively, for 284 keV X rays. In addition, in-beam deadtime of the Ge detectors should be included in the ϵ_X. From our experience, it is estimated to be 50% at worst, which was the value when the π^+ intensity was as large as 3.0×10^6/s in the experiments at KEK. In the proposed experiment, although the expected beam intensity will be about half, we take the same value as the upper limit. Therefore, ϵ_X is estimated to be $0.16 \times 0.5 = 0.08$.

In the same way, the yields of the transition $(7,6) \to (6,5)$ ($\sim$ 171 keV) can be calculated to be 7200 counts using $R_X = 0.3$, $\eta_X = 0.32$, and $\epsilon_X = 0.1$. The yield of this X ray is used as a reference in the discussion in Sect. 4.3.

4.2 Background Estimation

The background in the X-ray spectrum is estimated in the following way. The background level per (π^+, K^+) event in KEK-PS E419 experiment was 8×10^{-5} counts/keV and 1.4×10^{-4} counts/keV around 284 keV and 171 keV, respectively. Since Hyperball-J has 4 times larger acceptance than Hyperball, this should be multiplied by 4. Also, since both the reaction and target is different from E419, the background could be larger, perhaps by an extra factor 2. Then, for 3.7×10^6 events of (K^-, K^+), we expect background levels of 2400 counts/keV at 284 keV and 4100 counts/keV at 171 keV. This background level is small enough to allow clear observation of the $(6,5) \to (5,4)$ and $(7,6) \to (6,5)$ transitions, even if the width of the $(5,4)$ state is as large as $\Gamma = 3.9$ keV, as predicted by Koike [15] (See Fig. 7 for simulated spectra.).

4.3 Sensitivity and Physics Impacts

If the width of the $(6,5) \to (5,4)$ X ray is 3.9 keV, the statistical accuracy of the X-ray energy would be 0.04 keV. And 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 [18]. 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.

We would like to note that the present accuracy is comparable to the uncertainties in the calculation of X-ray energy without hadronic interaction. The main uncertainty in the calculation is from that of Ξ^- mass ($\sim 10^{-4}$ or 0.03 keV), and also there are contributions

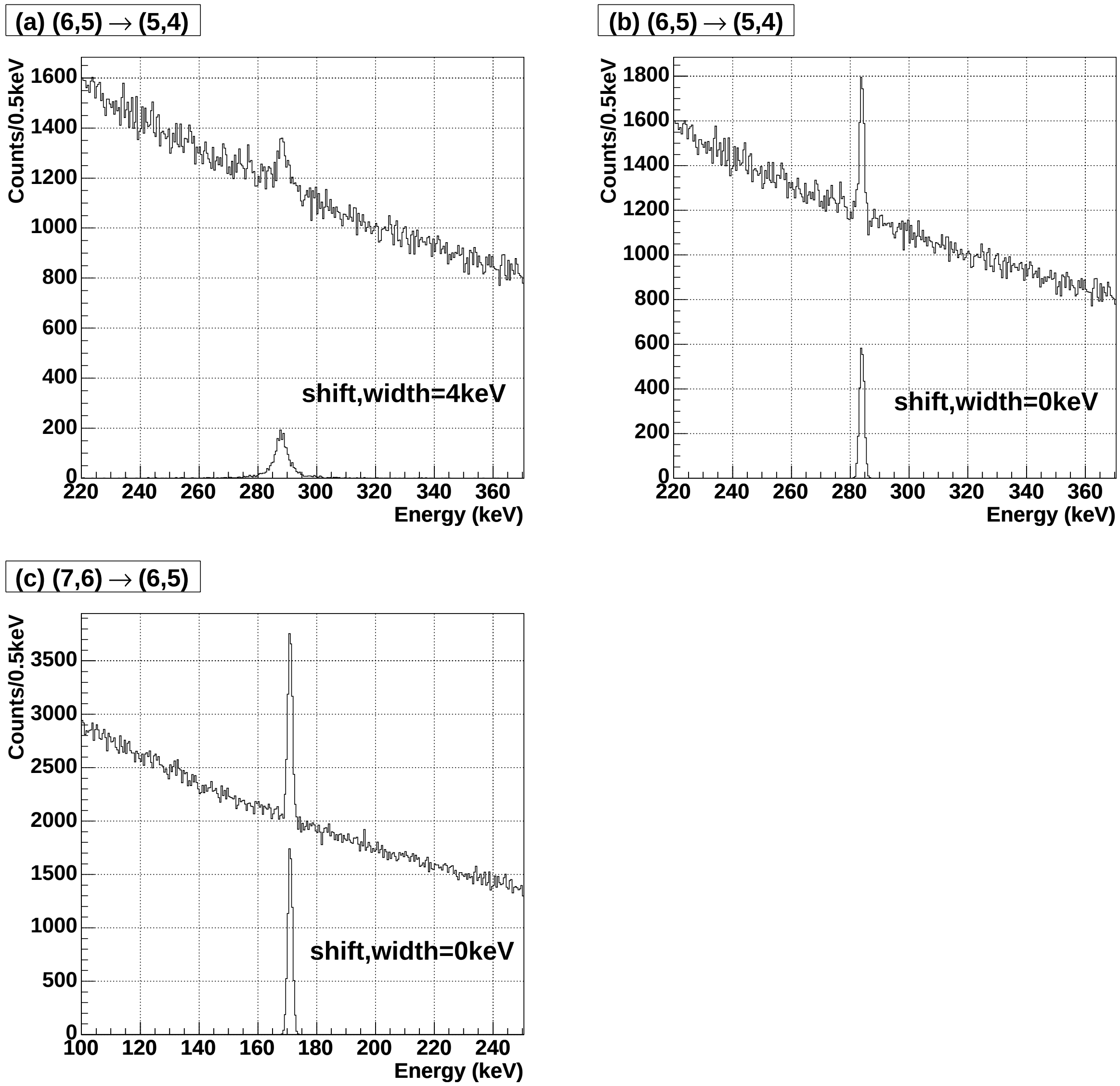

Figure 7: Expected X-ray energy spectra for (a): $(n, l) = (6, 5) \rightarrow (5, 4)$ transition. Energy shift and width are both 4 keV, as predicted by Koike [15]. (b): Same as (a), but with no energy shift and width. (c): $(n, l) = (7, 6) \rightarrow (6, 5)$ transition. No energy shift and width are expected for this X ray.

from nuclear polarization significant at the level of 0.01 keV.

Sensitivities for the X-ray width is not so high, but enough for $\Gamma = 3.9$ keV predicted by Koike [15]. In this case, our accuracy would be $\delta\Gamma \sim 1$ keV. On the other hand, for small 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 N_X 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.

5 Estimation on Construction Cost and Schedule

Most of the detectors for the KURAMA spectrometer including the readout and front-end electronics will be recycled or reused. FAC2, which is used to distinguish K^+ from proton is needed particularly for this experiment. It will be constructed by the collaboration with a help from Chiba University and Matsushita-Denko Company. The cost of the aerogel will be 2 Myen.

Beam line detectors including their readout will be constructed with the budget (Kakenhi) of the Grant-In-Aid for Priority Areas, "Quark many-body systems with strangeness" (2005 – 2009), and will be used commonly with other experiments (for example, [12, 17]). The total cost for the beamline detectors (including readout electronics) will be approximately 100 Myen.

Hyperball-J is under construction in Tohoku University since 2005 with the Grant-in-Aid (spokesperson: H. Tamura, 2005 – 2009) of about 300 Myen. Together with new Ge detectors purchased by this budget, Hyperball-J also includes the old Ge detectors and the readout electronics used in our previous devices, Hyperball and Hyperball2 (property of Tohoku University, 200 Myen in total). The construction and installation of Hyperball-J will be finished by the end of 2008.

Figure 8 shows the time schedule of the preparation for the proposed experiment. All the detectors will be ready by the end of 2008, when the first beam is expected to be delivered.

6 Future prospects

We will design the next experiment as soon as the result of the proposed experiment is obtained. Not only we can choose better targets, but the yield estimation will be more

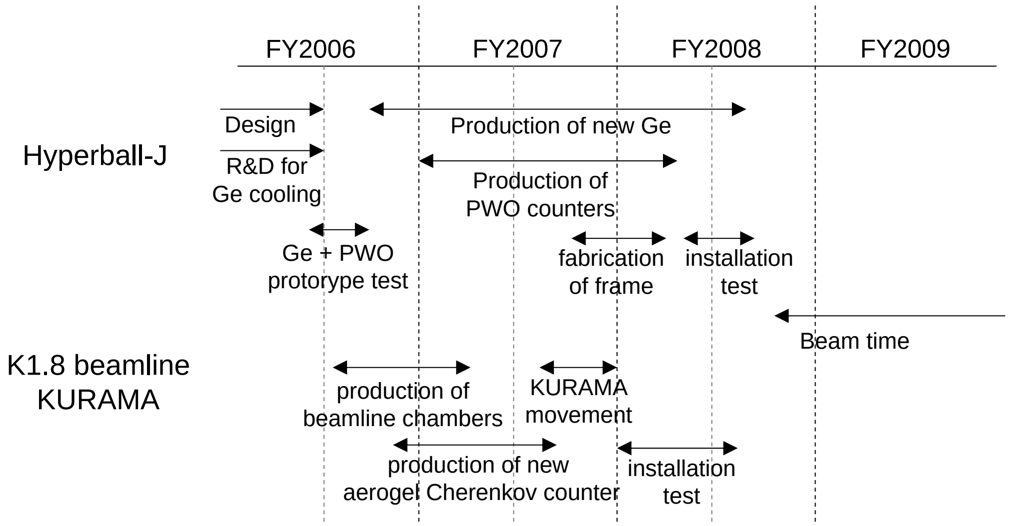

Figure 8: Schedule of the preparation for the proposed experiment.

accurate. As discussed in Sect. 1, our physics goal is to reconstruct ΞA potential utilizing as many X-ray data as possible. In order to achieve this goal, we will measure X rays from ~ 10 targets, namely, from 1 or 2 "optimal" targets for each $4 \leq n \leq 9$.

While the proposed setup may not be applicable to low density targets, there is an alternative setup. Namely, we can use two targets in tandem for Ξ^- production (diamond) and stopping (main target). Between the two targets, there are silicon-strip detectors to measure dE/dx to select slow Ξ^- so that better S/N ratio will be obtained for stopping Ξ^-. This setup is actually very similar to the one in Ref. [17], and can be tested in that experiment. In this setup, target dependence of X ray yield is much smaller, and we expect about 1000 counts in 100 shifts. We found this alternative setup is not better than the proposed setup in case of Fe target, but is certainly better for low density, high-Z targets, such as Iodine. By properly using those two setups, we believe we can achieve our goal.

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