Proposal for J-PARC 50 GeV Proton Synchrotron

Precision spectroscopy of Kaonic Helium 3 $3d \rightarrow 2p$ X-rays

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Executive Summary

We propose to measure the strong-interaction shift of $3d \rightarrow 2p$ X-rays of kaonic helium 3 atoms with a precision better than 2 eV at the J-PARC 50-GeV PS. The proposed experiment, analyzed together with that for kaonic helium 4 atoms measured by the KEK-PS E570 collaboration [1], will provide crucial information on the isospin-dependent $\bar{K}$-nucleus strong interaction at the low energy limit, and will provide decisive data to understand the basis of the Akaishi-Yamazaki prediction of deeply-bound kaonic nuclei [2], and to clarify the nature of the strange multibaryon candidates recently reported at KEK [3], DAΦNE [4] and BNL [5]. The major parameters of the proposed experiment are summarized below:

Reaction : stopped $K^- + {}^3\mathrm{He} \rightarrow h\nu(\sim 6.4\mathrm{keV}) + X$
Primary beam : 30 GeV, 9 μA proton
Secondary beam : 0.75 GeV/c K^-
Beamline : K1.8BR or K1.1
Target : Liquid ^{3}He, diameter 6.4 cm, length 15 cm (482.5 cm^3)
Detectors : 8 × 100 mm^2 silicon drift detectors (SDD),
beamline counters and chambers,
vertex trigger counters and tracking chambers.
Beam time : 10 days for commissioning
+3.5 days at K1.8BR (assuming full PS intensity)
+35 days at K1.8BR (with 10% of the design intensity)[4]

The present proposal is closely related to another proposal to the J-PARC 50-GeV PS, "A search for deeply-bound kaonic nuclear states by in-flight $^3\mathrm{He}(K^-, n)$ reaction"[6]. Both of these experiments address the question of deeply-bound kaonic states, and there is a large overlap of the collaboration members. Both experiments will use the same beamline and the same ^{3}He target. In view of the relative simplicity of the X-ray measurement and its modest beam requirement, we believe it is appropriate to execute the present X-ray proposal before the "in-flight" experiment. The proposed experiment will be ready on DAY-1, and can quickly deliver crucial physics results. It is hence most suited as the J-PARC DAY-1 experiment.

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[4] At K1.1, the number of days needed to collect data will be 2 days (full intensity) or 20 days (10% intensity).

1 Physics motivation

The kaonic atom is a K^-−nucleus Coulomb bound system, which can be produced by stopping kaons in a target medium. Upon production, kaonic atoms are in highly excited states, with a typical principal quantum number of $n \sim \sqrt{M_K^*/m_e} \sim 30$, where M_K^* and m_e respectively are reduced masses of the kaon and the electron. The atoms then deexcite by emitting Auger electrons and X-rays, until the kaon-nucleus strong-interaction width $\Gamma_{\rm abs}$ becomes larger than the radiative-transition width Γ_X. Such an orbit is called the "last orbit", since X-rays cannot be observed below this level. In the case of kaonic helium, $2p$ is the last orbit.

From the spectroscopy of X-rays feeding the last orbit, the strong-interaction shift[5] and width of the last orbit can be deduced. This information offers the unique possibility to precisely determine the $\bar{K}$-nucleus strong interaction at vanishing relative energy, and hence many experiments have been done to collect data on various targets, from He to U inclusively [7][6].

It has been known that most of the available kaonic-atom data can be fitted fairly well by optical-potential models [7, 9], except for kaonic helium. The average $2p$ shift of the three kaonic-^{4}He measurements is $\Delta E_{2p}^{exp} = -43 \pm 8$ eV [10, 11, 12], while a majority of theoretical calculations predict $\Delta E_{2p}^{calc} \sim 0$ (*e.g.,* one of the recent calculations indicates $\Delta E_{2p}^{calc} \sim -0.2$ eV [9]). This discrepancy is known as the "kaonic helium puzzle".

The kaonic helium puzzle has recently attracted a renewed interest in connection with the Akaishi-Yamazaki (AY) prediction of "deeply-bound kaonic nuclei" [2]. Treating $\Lambda(1405)$ as a $\bar{K} - N$ bound state and using coupled channels, the AY model predicts unconventionally deep $\bar{K}$−nucleus potentials, which accommodate the deeply-bound $\bar{K}$−nucleus states. When the AY model is applied to kaonic helium 3 and 4 atoms, their $2p$ level shifts can be $|\Delta E_{2p}| \sim 10$ eV as shown in Fig. 1 [13]. The figure shows those shifts as a function of the real part U_0 of the potential depth between K^- and ^{3}He / ^{4}He. In their predicted U_0 region, $200 \sim 300$ MeV, the shifts of the two helium isotopes are of opposite sign, downward shift for K^--^{3}He and upward shift for K^--^{4}He. On the other hand, almost all theories except for Akaishi-Yamazaki's have predicted ∼0 eV shift for the kaonic helium atom X-rays [9]. If the measured $2p$ energy shifts were $|\Delta E_{2p}^{exp}| <\sim 10$ eV for either atom and of predicted signs, the strongly attractive potential advocated by Akaishi and Yamazaki will be justified. This will therefore help clarify the nature of the strange multibaryon candidates reported by E471 at KEK [3], FINUDA at LNF[4], and by Kishimoto *et al.* at BNL [5].

This situation motivated us to measure the shift of $3d \to 2p$ X-rays of kaonic helium 4 atoms. It may be that all the past experiments reporting large shifts were wrong, or there are serious flaws in the theories. The experiment was recently carried out at KEK-PS (E570), whose details are described in Section 2. Although the E570 data are still being analyzed and hence the final results are not yet available at the time of writing the present proposal, it is clearly important to measure the $2p$ shifts of **both** kaonic helium 4 and kaonic helium 3 in order to test the isospin dependence predicted by Akaishi (Fig.1). The

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[5] The shift ϵ is defined as the difference between the (fictitious) binding energy calculated assuming a pure-Coulomb potential and the strong-interaction-affected (*i.e.,* actual) binding energy.

[6] Measuring the kaonic hydrogen X-rays is much more difficult. The first definitive result was obtained by Iwasaki *et al.* at KEK PS [8], which unambiguously determined the strong-interaction shift to be $\Delta E_{1s}^{exp} = -323 \pm 63(stat.) \pm 11(syst.)$ eV (repulsive).

shifts of the two helium isotopes will give us information on the isoscalar and isovector strengths of the kaon-nucleus interaction at the low energy limit. Unlike the case of kaonic helium 4, no data exist yet on the kaonic helium 3 X-rays.

We therefore propose to measure the $3d \rightarrow 2p$ X-rays of kaonic helium 3 at J-PARC, using a setup similar to the one we used for KEK-PS E570.

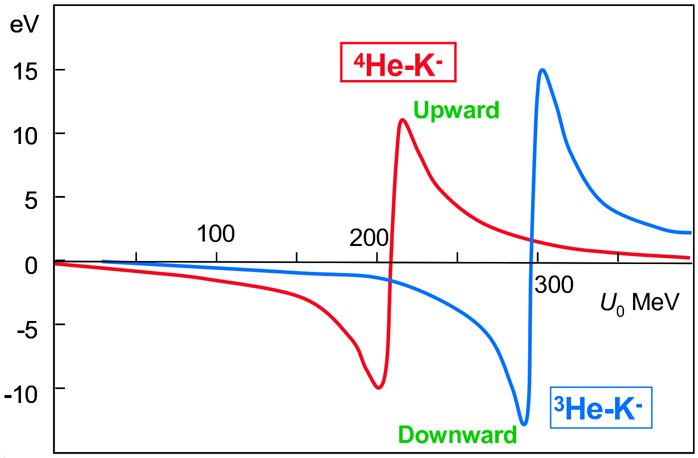

Figure 1: $2p$ level shifts of the K^--^{3}He and K^--^{4}He atoms as a function of the real part of the potential strength U_0 (here, $U_0 > 0$ means attractive) calculated by using coupled-channel calculation [13]. Note that positive (upward) level shift reduces the $3d \rightarrow 2p$ X-ray energy (and hence negative ΔE_{2p}).

2 KEK-PS E570 experiment

E570 at KEK PS, "Precision spectroscopy of kaonic helium 4 $3d \rightarrow 2p$ X-rays"[1], took data from October to December 2005. The goal of E570 is to measure the $2p$ level shift with a precision better than ~ 2 eV, in order to shed light on the kaonic helium puzzle discussed above. Figure 2 shows a schematic view of the experimental setup.

In E570, a significant improvement over the past experiments was achieved by incorporating the following:

- **SDDs** : Instead of a conventional Si(Li) X-ray detector, we used eight silicon drift detectors (SDDs). In the SDD, the electrons produced by an X-ray hit are radially drifted toward the anode at the center and are collected there, so that the anode size (and hence its capacitance) can be kept small, independent of the detector area. This results in a good energy resolution despite a large effective area of some 100 mm^2. In addition, the small anode area makes it possible to reduce the active layer thickness, while still keeping the small capacitance. The thin active layer (260 μm in the case of E570 SDDs, compared with 4 mm for Si(Li) counters used in the past experiments) helps reduce continuum background caused by the soft-Compton process.

  Figure 3 shows a typical SDD spectrum measured with a ^{55}Fe source. The typical energy resolution is ~185 eV (FWHM) at 6.4 keV which corresponds to the energy of $3d \rightarrow 2p$ X-rays of kaonic helium atoms.

- **Fiducial volume cut** : Continuum background events could be drastically reduced by applying a "fiducial volume cut", which requires that the reaction vertex obtained by tracing an incident kaon and a secondary charged particle is within the liquid helium volume (Fig. 4). With the fiducial cut, a good S/N ratio of ∼4 was achieved as shown in Fig. 6, which is about 5 times better than that of the past experiments.

- **In-beam energy calibration** : The energy calibration was done by characteristic X-rays induced by the incident beam (mainly contaminating pions in the kaon beam) on pure titanium and nickel foils, and simultaneously measuring the kaonic helium atom X-rays. Since the energy of the $3d \rightarrow 2p$ kaonic helium atom X-ray, ∼6.4 keV, lies between the characteristic X-ray energies, 4.5 keV(Ti) and 7.5 keV(Ni), this will provide an accurate in-situ calibration. Figure 5 shows a characteristic X-ray spectrum for a typical SDD with calibration self trigger. We have observed 4.0×10^3 titanium K_α X-rays per one shift (8 hours) for each SDD.

Figure 6 shows a preliminary kaonic helium 4 atom X-ray energy spectrum for about 50% of the total E570 statistics. The $3d \rightarrow 2p$ peak at ∼6.4 keV has been clearly observed, together with other transitions feeding the $2p$ state, $4d \rightarrow 2p$ and $5d \rightarrow 2p$. In total, E570 accumulated about 1.5×10^3 counts of nearly background-free $3d \rightarrow 2p$ X-rays, which implies, with a 185 eV (FWHM at 6.4 keV) resolution, we will achieve a statistical error of $\sigma \sim 2$ eV ($=185/2.35/\sqrt{1.5 \times 10^3}$ eV).

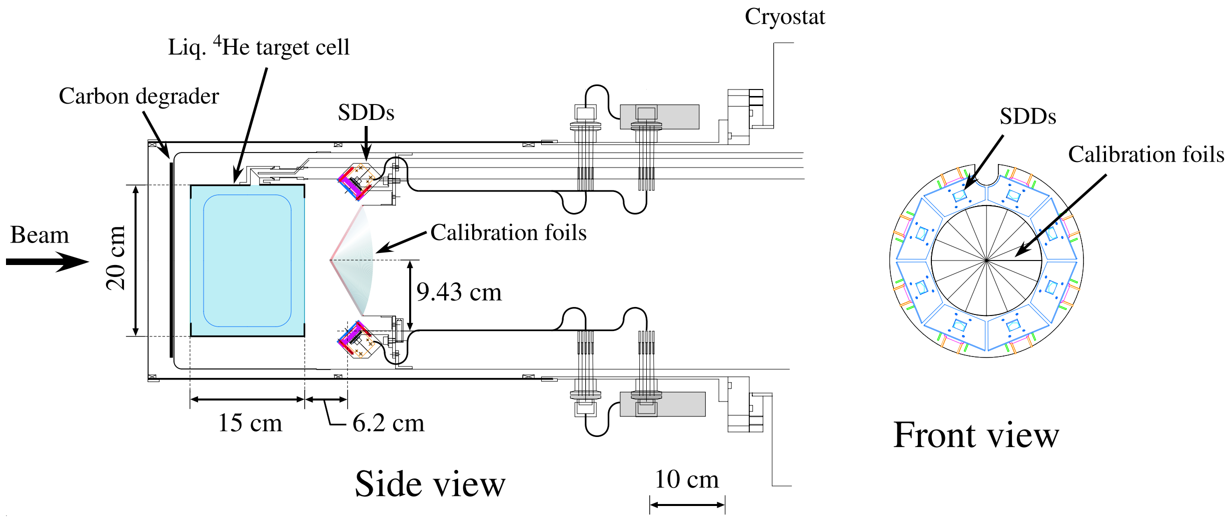

Figure 2: Schematic view of the liquid ^{4}He target assembly with the X-ray detector system of KEK-PS E570.

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3 Experimental apparatus

The principle of the proposed experiment is the same as that of KEK E570. We stop negative kaons in a liquid helium target, and observe X-rays with silicon drift detectors. Incoming kaons and charged particles emitted from the K^--reaction vertices are tracked

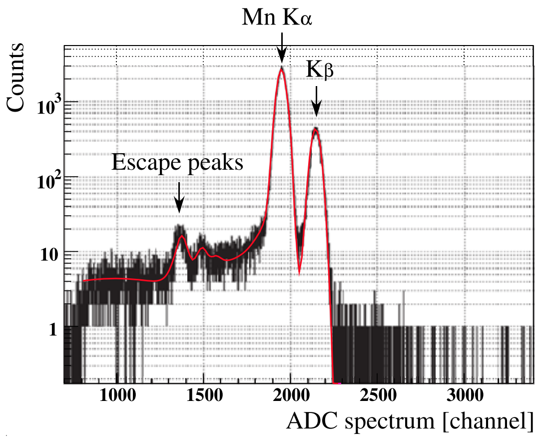

Figure 3: A typical SDD energy spectrum for ^{55}Fe source calibration. The resolution is ~185 eV (FWHM) at 6.4 keV.

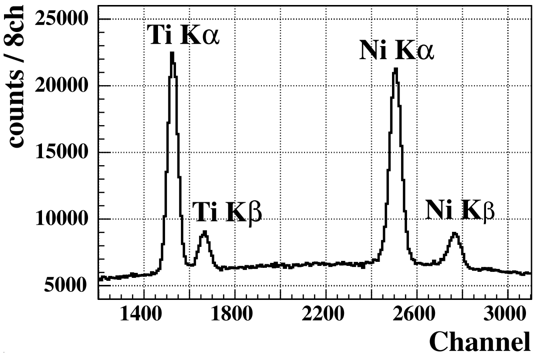

Figure 5: A typical characteristic X-ray spectrum with calibration self trigger.

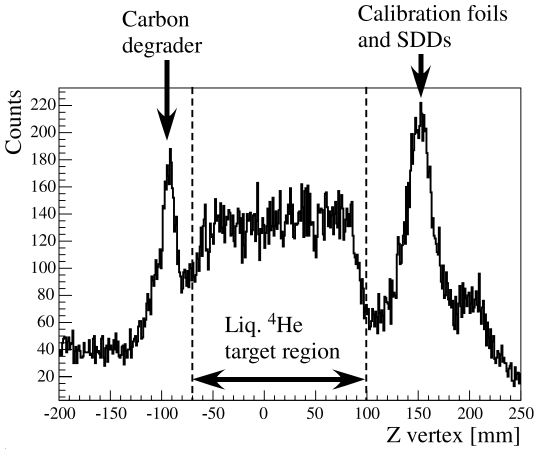

Figure 4: The projection of reaction vertices along the beam axis around the liquid ^{4}He target assembly (E570 preliminary).

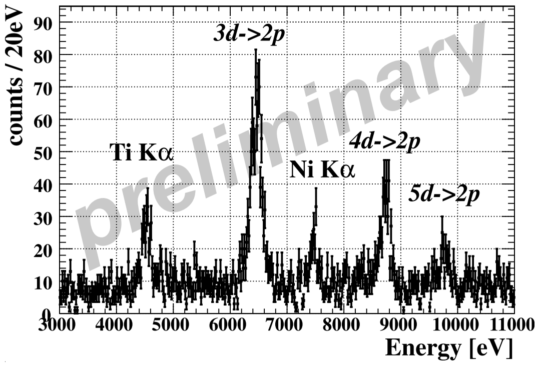

Figure 6: Preliminary kaonic helium atom X-ray energy spectrum for half of all E570 statistics.

by counters and drift chambers. In this section, we describe the target and detectors, highlighting the planned improvements over the E570 setup.

3.1 Tracking detectors

The beamline tracking counters and chambers, and the "vertex" counters and chambers used in E570 will also be used in the present experiment.

3.2 Target

For KEK-PS E471, E549 and E570, we have developed a liquid ^{4}He target with a thin and low-Z vessel, and established a technique to reliably and stably operate the target. We will extend this technique to the liquid ^{3}He target.

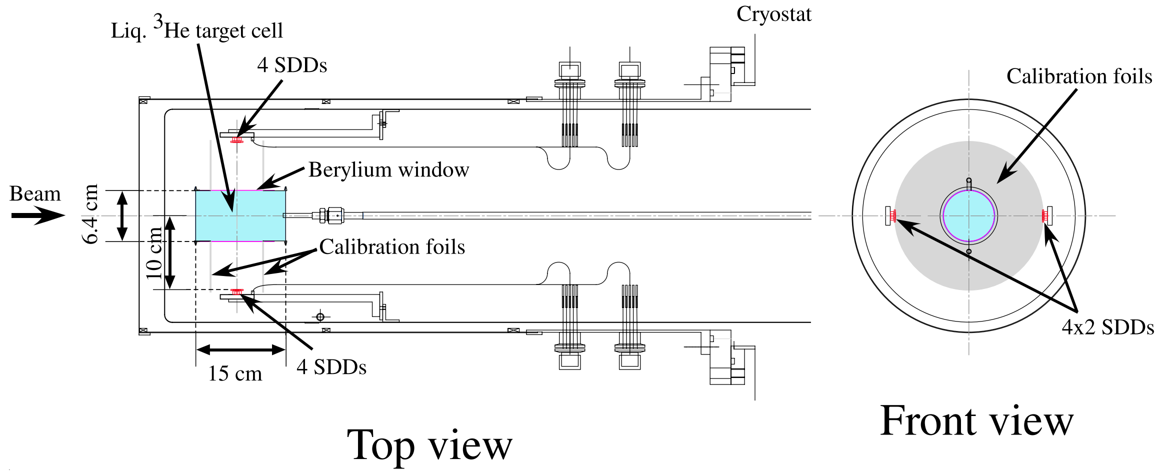

Figure 7: A schematic view of the liquid ^{3}He target assembly.

In E570, we used a cylinder-shaped helium 4 target cell with a diameter of 20 cm and a length of 15 cm (4712 cm^3), but filling such a target with liquid helium 3 will be financially prohibitive. Our present plan is to reduce the diameter of the target cell to 6.4 cm while keeping the 15-cm length. The volume is thus 482.5 cm^3, about 10 times less than the E570 helium-4 target.

In order to accumulate sufficient X-ray counts despite the smaller target volume, we will use a 200-μm-thick beryllium window instead of the 75-μm-thick Mylar window used in E570. This will increase the transmission of the 6.4 keV X-rays from 87% (Mylar) to 93% (beryllium). Figure 7 shows a schematic view of the liquid ^{3}He target assembly under study for the proposed experiment.

3.3 Silicon drift detector (SDD)

In E570, we have successfully measured the X-ray spectrum with good energy resolution and S/N ratio by using prototypes of KETEK 100 mm^2 SDDs (Fig. 8). Recently, KETEK has developed the unique slim-line component of the 100 mm^2 SDD for applications with special space constraints (Fig. 9). Making use of the hexagonal detector shape, this slim-line setup allows the configuration of multi element detector arrays to achieve detection areas never realized before (Fig. 10). In the proposed experiment, we will use two sets of custom-ordered four element detector arrays of KETEK 100 mm^2 SDDs (8 SDDs in total).

As shown in Fig. 2, there was no space to install the SDDs other than behind the target cell when we reuse the existing target assembly in E570. To increase the acceptance of the SDDs in the proposed experiment, SDDs will be installed to view from the side (left and right) of the target as pictured in Fig. 7. With this configuration, the acceptance was calculated to be 3 times higher than that of E570.

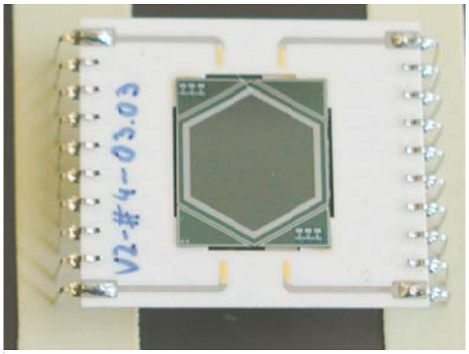

Figure 8: The KETEK SDD prototype (100 mm^2) used in E570.

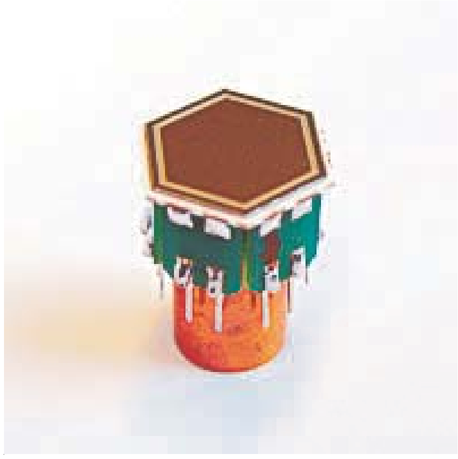

Figure 9: 100 mm^2 VITUS SDD slim-line component (courtesy, KETEK).

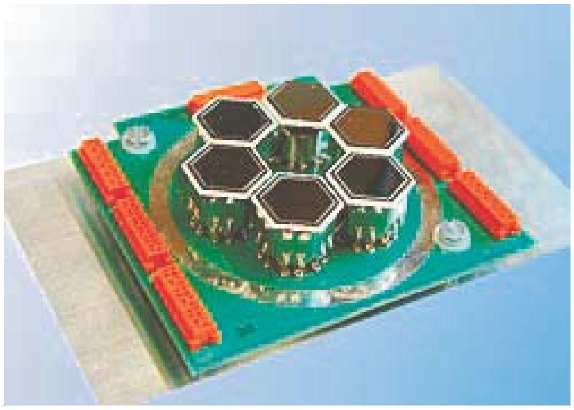

Figure 10: Large-area customized VITUS SDD array (courtesy, KETEK).

4 Yield estimation

On DAY-1, there will be no kaon beam lines optimized for stopped kaons at J-PARC. K1.8BR (and K1.1) are both nearly 30-m long, and we need to carefully optimize the beam momentum and the amount of degrader to stop a sufficient number of kaons in the small ^{3}He target.

Our studies show that K1.1, if constructed, is the best beamline to carry out the proposed experiment. As will be shown below, with an optimized setup and with a primary-beam intensity of 9μA (at 30 GeV), the event rate will be nearly an order of magnitude higher than in E570 performed at the KEK-PS K5 beamline. At K1.8BR the event rate will be some 40% lower than at K1.1, but this is still higher than the E570 rate.

In the following, we present the result of our study both for K1.1 and K1.8BR (see Fig. 11). Table 1 lists the expected performance of the two beamlines. For each beamline, incident K^- beam intensities at final focus point were calculated using Sanford-Wang formula [14] and beamline simulation code, TURTLE. Figure 12 shows stopped K^- yields

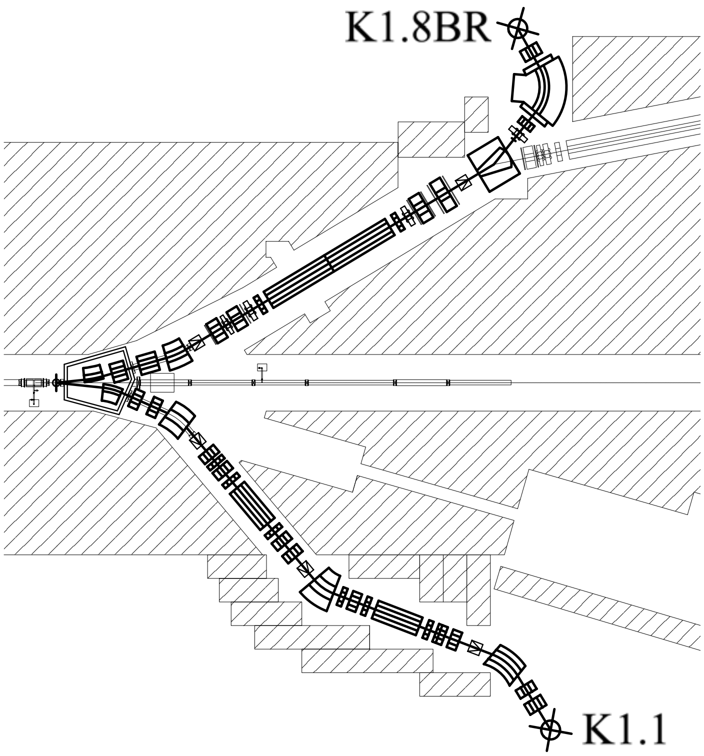

Figure 11: The layout of K1.8BR and K1.1 beamlines.

for each beamline, derived from the K^- beam intensities and the stopping rate, as a function of the K^- beam momentum. The calculated K^- beam intensities for 0.75 and 1.0 GeV/c are listed in Table 1. Meanwhile the K^- stopping rate at the helium 3 target cell (15-cm long, 6.4-cm in diameter) was calculated by a Monte Carlo simulation with the incident K^- beam distributions and the momentum bites estimated using TURTLE. As a result, the maximum values of the stopped K^- yield for the K1.1 and K1.8 beamlines were respectively estimated to be 1400 and 900 events per pulse[7] at 0.75 GeV/c K^- beam momentum. We will thus obtain $\sim$3.5/$\sim$2 times higher stopped K^- yield at J-PARC K1.1/K1.8BR beamline than that of E570 since the stopped K^- yield in E570 was about 400 events per pulse. In addition, the acceptance for the SDDs was calculated to be 3 times higher than that of E570 as stated in previous section.

The intensity of K^--^{3}He $3d \rightarrow 2p$ X-rays per stopped kaon is expected to be similar to that of K^--^{4}He because of almost the same range of the strong interaction between the K^- and ^{3}He / ^{4}He and the small difference (a few %) of the principal quantum number in the initial capture, which is attributed to the difference between those reduced masses. As described in Section 2, we have achieved a statistical error of $\sigma \sim 2$ eV with $\sim$20 days in E570. Due to the increase of the stopped K^- yield ($\times$3.5 or $\times$2) and the SDD acceptance ($\times$3), the proposed experiment can be performed with only $\sim$2 or $\sim$3.5 days at K1.1 or K1.8BR beamline respectively. Here, it should be noted that the calculated value of the K^- beam intensity is on the full intensity beam at Phase-I (with 30GeV-9μA primary beam).

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[7] Spill duration : 3.53 [sec], Flat top : 0.7 [sec]

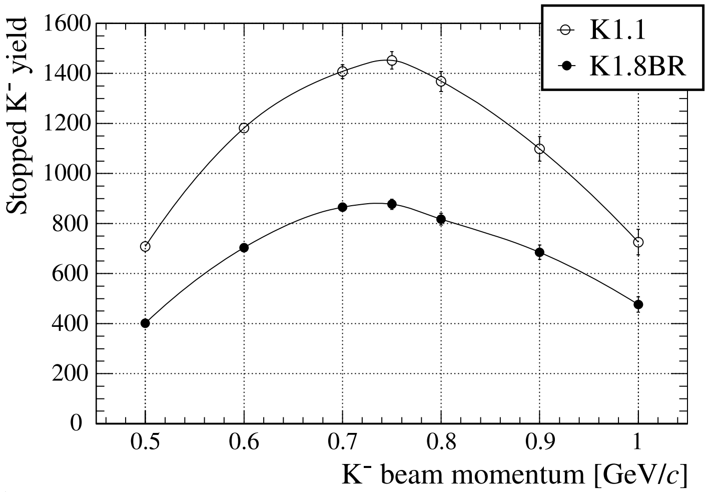

Figure 12: Calculated stopped-K^- yield for K1.1 and K1.1BR beamlines.

		Phase-I (30GeV-9μA)	
		K1.1 beamline	K1.8BR beamline
Maximum Momentum	[GeV/c]	1.1	1.1
Length	[m]	27.085	27.573
Acceptance	[msr·%]	3.9	2.5
Momentum bite	[%]	±3.0	± 2.5
K^- intensity [/pulse]	for 0.75 GeV/c @ FF	0.33×10^6	0.19×10^6
	for 1.00 GeV/c @ FF	1.4×10^6	0.8×10^6
K/π ratio	for 0.75 GeV/c @ FF	7.8	12.6
	for 1.00 GeV/c @ FF	3.6	5.9

Table 1: The design specifications of K1.1 and K1.8BR beamlines. These values are still preliminary. The K/π ratio does not yet include the effect due to the so-called "cloud π". (FF : final focus point)

5 Trigger

In E570, the trigger logic was, in essence, (K⊗TC)⊕(K⊗PA⊗PB), where K denotes incoming K^- identified by scintillation counters and Lucite Čherenkov counters located in the beam line, TC denotes a hit in vertex trigger counters installed above and below the target, and PA / PB denotes a hit in scintillator wall placed left and right of the target (30 cm / 200 cm from the target center respectively). A hit in the SDD was not added to this trigger since the timing of the SDD signal from shaping preamplifier was too late for the trigger timing with existing E471/E549 trigger logic. In addition, self triggers of the SDDs were mixed for the energy calibration. In this trigger logic, the number of triggers was ∼800 per spill while the total number of stopped kaons is estimated to be ∼400.

With the same setup and the stopped K^- intensities at K1.1 / K1.8BR, the number of triggers could be estimated to be ∼1800 / ∼ 2800 per spill respectively. In reality, the trigger rate depends on different beamline characteristic and conditions (K/π ratio, incident K^- momentum, radioactive background and so on). Although the trigger rate estimation indicates that the trigger rate will be too high with our existing DAQ system, 1/2∼1/3 lower intensity will be advantageous in terms of the trigger rate with exactly the same setup as that of E570. Meanwhile we are going to rearrange the existing setup to reduce the trigger rate (*e.g.* by installing charged-particle veto counters closer to the target).

6 Beam time request

The requested beam times are summarized below for each beamline, K1.1 and K1.8BR. Since the proposed experiment is estimated to be feasible within 2∼3.5 days on the full intensity beam at Phase-I, even one-order lower K^- beam intensity is acceptable with reasonable beam time, 20∼35 days. However, we requested that we operate under stable conditions.

	K1.1 beamline	K1.8BR beamline
Production run (with full intensity, 30GeV-9μA)	2 days	3.5 days
Commissioning	10 days	10 days

7 Cost estimation

Most of the experimental apparatus used in E570 will be reused except for the target system which will be constructed with another experiment [6]. In Table 2. the items and their costs are summarized.

Item	Cost[kJY]	Comments
X-ray detection system		
X-ray detector (SDD) + preamp	9,000	new
Shaping amp.	—	existing
ADC, TDC modules	—	existing
Calibration foil (Ti and Ni, purity:99.999%)	1,000	new
Target system		
Target cell window (beryllium)	1,000	new
CFRP	—	existing
Liquid Helium 3	—	Grant-In-Aid
Cryostat system	—	Grant-In-Aid
Tracking detector system		
Trigger counters (LC,T0,VTCs)	—	existing
Beamline drift chamber (BLC)	—	existing
Secondary particle drift chamber (small) (PDC)	—	existing
Secondary particle drift chamber (large) (VDC)	—	existing
Readout amp. & discri.	—	existing
TDC module (Dr.T-II)	—	electronics pool
Gas mixer system	—	existing
Cables	—	existing
Electronics		
NIM, TKO, VME modules	—	electronics pool
Rack, Bin, Crate etc.	—	existing
DAQ system	—	existing
Analysis computer system	—	existing
Data storage	—	existing

Table 2: Cost estimation

References

[1] R. S. Hayano *et al.*, Proposal of KEK-PS E570 (2005).

[2] Y. Akaishi and T. Yamazaki, Phys Rev. **C65**, 044005 (2002) .

[3] T. Suzuki *et al.*, Phys. Lett. **B597**, 263-269 (2004).

[4] M. Agnello *et al.*, Phys. Rev. Lett. **94**, 212303 (2005).

[5] T. Kishimoto *et al.*, Nucl. Phys. A **754**, 383c (2005).

[6] M. Iwasaki *et al.*, Proposal of J-PARC 50-GeV PS "A search for deeply-bound kaonic nuclear states by in-flight $^{3}\mathrm{He}(K^{-}, n)$ reaction" (2006).

[7] C.J. Batty, E. Friedman and A. Gal, Phys. Reports **287**, 385 (1997).

[8] M. Iwasaki *et al.*, Phys. Rev. Lett. bf 78, 3067 (1997).

[9] S. Hirenzaki, Y. Okumura, H. Toki, E. Oset, and A. Ramos, Phys. Rev. **C61**, 055205 (2000).

[10] C. E. Wiegand and R. Pehl, Phys. Rev. Lett. **27**, 1410 (1971).

[11] C. J. Batty *et al.*, Nucl. Phys. **A326**, 455 (1979).

[12] S. Baird *et al.*, Nucl. Phys. **A392**, 297 (1983).

[13] Y. Akaishi, Proc. International Conference on Exotic Atoms (EXA05), Austrian Academy of Sciences Press, (Vienna, 2005) p. 45.

[14] J. R. Sanford and C. L. Wang, BNL 11279 (1967); BNL 11479 (1967).