A proposal for an experiment at INPS, KEK Proton Synchrotron

Precision spectroscopy of Kaonic Helium 3d → 2p X-rays
– A key to understanding the nature of the strange tribaryons S^0(3115) –

See the cover page (in Japanese) for the collaboration List

Abstract

We propose to measure the strong-interaction shift of 3d → 2p X-rays of kaonic helium with a precision better than \( \sim 2 \) eV, using silicon drift X-ray detectors mounted inside the E549 helium-target assembly. The measurement will provide a crucial information to understand the nature of the strange tribaryons S^0(3115), recently discovered by the E471 collaboration [1].

1 Physics motivation

The strange tribaryon S^0(3115), recently discovered by the E471 collaboration [1], has the following remarkable features which had not been theoretically expected. Namely, 1) the binding energy (measured from the \( K^- p + n + n \) threshold) is as deep as 194 MeV, nearly twice deeper than was originally predicted by Akaishi and Yamazaki [2] for the \( K^- p p n \) system with isospin 0, and 2) S^0(3115) with isospin 1 may correspond to the isobaric analog state of the predicted \( T = 1 \) \( K^- p p p \), but the observed binding energy is about 100 MeV larger than the theoretical value [3, 4].

To be more specific, Akaishi and Yamazaki [2] constructed a bare \( \bar{K}N \) potential so as to simultaneously reproduce the \( \bar{K}N \) scattering lengths [5], the binding energy and width of kaonic hydrogen atom [6] and those of \( \Lambda(1405) \). They then used the \( g- \)matrix method to study the structure of \( \bar{K} \) nuclear systems in light nuclei, and predicted discrete \( \bar{K} \)-bound states with large binding energies, narrow widths and high nucleon densities. For example, the nuclear ground state of a \( K^- \) in \(^3\)He is predicted to be \( T = 0 \) with a binding energy of 108 MeV and a total width of 32 MeV.
It had been known that there is a problem with the $K$-nucleus potentials (not just with the Akaishi potential but with all other theories) in reproducing the measured 2p level shift of the kaonic $^4\text{He}$ atom. The measured shift and width (see Table 1),

$$\Delta E_{2p}^{\text{exp}} = 43 \pm 8\text{eV} \text{ and } \Gamma_{2p}^{\text{exp}} = 55 \pm 34\text{eV},$$

are both far too large to be reconciled with theoretical predictions. For example, predictions for shift and width with an optical potential are [10]

$$\Delta E_{2p}^{\text{opt}} = -0.9\text{eV} \text{ and } \Gamma_{2p}^{\text{opt}} = 4\text{eV},$$

respectively. More than 10 years ago, a possibility of kaon-nucleus bound state was considered to be a way to explain the large shift: [11]

*no simple modification ... (to the optical potential) ... gives a good fit to the helium data unless a kaon-nucleus bound state ... is involved.*

\[
\begin{array}{cccccc}
\Delta E_{2p} \text{ (eV)} & \Gamma_{2p} \text{ (eV)} & \text{Si(Li) Detector area, thickness} & \text{Resolution @ 6.5 keV} & \text{Reference} \\
-41 \pm 33 & - & 254 \text{mm}^2, 4 \text{ mm} & 340 & [7] \\
-35 \pm 12 & 30 \pm 30 & 300 \text{ mm}^2, 5 \text{ mm} & 250 & [8] \\
-50 \pm 12 & 100 \pm 40 & 300 \text{ mm}^2, 5 \text{ mm} & 360 & [9] \\
-43 \pm 8 & 55 \pm 34 & & & \text{Average} \\
\end{array}
\]

Table 1: Experimental values for the strong interaction shift and width for $K^-4\text{He}$ atoms. The bottom row shows the weighted average of the three experimental results.

A recent study by Akaishi [10] using a set of coupled-channel potentials having a $K$ nuclear bound state indeed predicts larger shift and width of

$$\Delta E_{2p}^{\text{cc}} = -11\text{eV} \text{ and } \Gamma_{2p}^{\text{cc}} = 21\text{eV},$$

but these are still small compared with the experimental result. Whatever the merits of these theoretical explanations, it is [11]

*important that the experimental results should be checked and measurements of improved accuracy obtained.*

This is exactly the purpose of the proposed experiment.

Because the overlap of kaon wave function and nuclear density is small for the atomic 2p level, it is natural to expect the shift to be very small [10, 11]. If the strong-interaction shift of the 2p state of kaonic helium atom is confirmed to be substantially bigger than 2 eV, the shallow and absorptive $KN$ potential is definitely excluded [10, 12] (see Table 2). The large shift such as $\gtrsim |10|\text{ eV}$ can only occur if the kaonic “nuclear” 2p pole comes close to the atomic one. This happens only in a very narrow window of the $KN$ interaction. Therefore, it is very important to achieve the better energy determination as proposed herein.
Table 2: What we can learn from the $2p$ energy shift. By measuring the $2p$ shift with an accuracy better than 2 eV, we can pin down the nature of $S^0$ and obtain much improved information of the $\bar{K}N$ interaction.

<table>
<thead>
<tr>
<th>Shift</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim -40\text{eV}$</td>
<td>Past experiments are correct. $S^0(3115)$ is likely to be a kaon-nucleus bound state, but more theoretical work is necessary.</td>
</tr>
<tr>
<td>$\sim -10 \text{eV}$</td>
<td>Past experiments are wrong. X-ray data reinforces the picture that $S^0(3115)$ being a kaon-nucleus bound state.</td>
</tr>
<tr>
<td>$\lesssim 2\text{eV}$</td>
<td>Past experiments are wrong. Not much physics can be extracted.</td>
</tr>
</tbody>
</table>

2 Outline of the proposed experiment

The X-ray spectra measured by the three experiments are compared in Fig. 1. The $3d \rightarrow 2p$ peak is at 6.5 keV, and is statistically significant in all three measurements. Other transitions feeding the $2p$ state, $4d \rightarrow 2p$ and $5d \rightarrow 2p$ are also visible. All these experiments were done by stopping kaons in a liquid helium target, and by detecting X-rays using a Si(Li) detector, having a typical FWHM resolution of some 350 eV at 6.5 keV. The number of stopped kaons was about $2 \times 10^7$ in the most recent experiment [9].

In the present experiment, a significant improvement over the past experiments will be achieved by incorporating the following:

1. Instead of a conventional Si(Li) X-ray detector, we will use multiple silicon drift detectors (SDDs), described in detail in the next section. An SDD 1) has a good energy resolution of $\sim 150$ eV FWHM (more than a factor 2 improvement over the previous measurements), 2) has a good (as compared with Si(Li)) time resolution of $\sim 0.5 \mu s$, 3) can be operated at high rate (up to $\sim 1\text{MHz}$) and 4) is resistant against minimum-ionizing charged particles as well as soft Compton induced fake-X-ray signals due to its thin active layer (450 $\mu m$ for our SDD as opposed to some 5 mm in the case of Si(Li) detectors used in the past experiments).

2. Fiducial cut will be applied to the X-ray events. The existing kaon trigger/tracking detectors and vertex chambers of the E549 setup will be used to measure the kaon stopping position.

As shown in Fig. 2, six windowless SDDs will be thermally anchored to the nitrogen cooling rod of the E549 target assembly, and will view the superfluid helium target from down stream. The SDDs will be mounted towards the periphery of the target cell (23.5 cm in diameter), so as to avoid direct hits by the beam particles. X-rays emitted from the kaon stopping position will penetrate an average of 7.5-cm liquid helium (transmission of $\sim 82\%$) and a 75-$\mu m$ mylar window before reaching the SDD (transmission of $\sim 87\%$).
Figure 1: Comparison of the three previous measurements.

Energy calibration will be done by attaching thin titanium and nickel foils to the target frame. Electronic X-rays from these foils (4.5 keV for Ti and 7.5 keV for Ni) will provide accurate in-situ calibration.

3 The SDD X-ray detector

3.1 X-ray spectroscopy using SDDs

Silicon Drift Detectors (SDDs) are based on the principle of sideward depletion introduced by Gatti and Rehak in 1984 [13].

In an advanced SDD design optimized for X-ray spectroscopy (see Fig. 3), the concentric ring-shaped n+ strip system for the generation of the drift field as well as the
Figure 2: Six windowless silicon drift detectors (SDDs) mounted on the E549 superfluid helium target.

The collecting anode in their center are placed on one side of the structure, while the opposite surface is a non-structured p⁺ junction acting as the radiation entrance window.

There is no field-free region in the device. That means the whole volume is sensitive to the absorption of ionizing radiation. Each electron generated in this volume has to fall down to the point of lowest potential energy, which is the anode in the center of the front side. The small value of the anode capacitance (which is almost independent of the detector area) results in a large amplitude and a short rise time of the output signal. Compared to conventional photodiodes the SDDs can be operated at higher counting rates and of course yield a much better energy resolution.

Figure 3: Scheme of a Silicon Drift Detector with circular geometry.

SDDs combine a large sensitive area with a small value of output capacitance and are therefore well suited for high resolution, high count rate X-ray spectroscopy as required...
in the proposed experiment.

### 3.2 Prototype SDD test results

The SDDs to be used in this experiment have a hexagonal structure (see Fig. 4) with an active area of 100 mm$^2$ and a thickness of 450 µm. First prototypes, which we have tested, show an excellent energy resolution due to the low leakage current level obtained by the refined processing technology (even at room temperature or with moderate cooling).

![Hexagonal SDD design](image)

**Figure 4:** Hexagonal SDD design with an active area of 100 mm$^2$. Shown here is the anode side (to which an amplifier is connected), and X-rays enter the detector from the other side.

Test measurements were done with SDDs cooled down to a temperature of $-30^\circ$ C. The energy resolution was measured with a $^{55}$Fe source using a shaping time of only 0.5µs, which results in an energy resolution of 183 eV (FWHM) at 6 keV (see Fig. 5). Of course, the energy resolution can be improved by further cooling the SDDs to lower temperature. For the proposed experiment the SDDs will be installed close to the liquid helium target and therefore cooled down to $-120^\circ$ C. At this working temperature an improvement of the energy resolution to about 150 eV (FWHM) is feasible.

Beside the energy resolution the other important feature is the timing resolution of a large area SDD, which depends on one hand on the position where the X-ray hits the active area of the SDD and on the other hand on the applied drift field.

Figure 6 shows the result of measurements with a collimated $^{55}$Fe source (open diameter approx. 1 mm) with the collimator pointing towards the center of the SDD and for a second series of measurements pointing to a position close to the edge of the active SDD area. The signal rise time was measured for each position with different drift fields, by changing the last-ring voltage from 50 V to 130 V.
Figure 5: Energy spectrum of a 100 mm$^2$ SDD, measured at $-30^\circ$ C with a shaping time of 0.5$\mu$s. For calibration a $^{55}$Fe source was used, the $K_\alpha$ and $K_\beta$ lines of manganese are clearly resolved at 5.9 keV and 6.5 keV respectively, with an achieved energy resolution of 183 eV.

3.3 SDD preamplifiers

In order to achieve the best energy resolution, an FET\textsuperscript{1}-input preamplifier has to be placed as close as possible to the detector, and the FET must be cooled. In KEK E228 (KpX), in which sixty Si(Li) detectors were used in a cryogenic hydrogen gas target, only the input FET was mounted on the Si(Li) detector and the signal was sent over a coaxial cable to the main amplifying stage of the preamplifier mounted outside the cryostat.

In the present case, in order not to interfere with the chambers surrounding the helium target, we need to put cryogenic feed-through connectors on the down-stream flange of the target cryostat. In this case, cables of up to 1.5 m are needed to connect the SDDs to the feed-through connectors, which would lead to severe degradation of resolution. We therefore plan to epoxy-mold preamplifiers, and mount them near the SDDs. The fabrication of the molded preamplifier is relatively simple, but it nevertheless requires a few rounds of tests, as will be discussed further in Sec. 6.

3.4 SDD readout

The trigger logic of E471/E549 is, in essence, $K \otimes TC \otimes NC$, where $K$ denotes incoming $K^{-}$ identified by the beam and Lucite Cherenkov counters, TC denotes a hit in vertex trigger counters placed above and below the target, and NC denotes a hit in neutron counters.

For the X-ray measurement, the trigger condition should be $K \otimes TC \otimes SDD$, where

\textsuperscript{1}field-effect transistor
SDD denotes a hit in one of the SDDs. It is essential that the SDD data are taken together with the beamline-chamber and vertex-chamber data, so that we can impose the target-fiducial condition in the offline analysis.

To make the $K \otimes TC \otimes SDD$ trigger, each SDD output, preamplified in the cryostat, will be fed to a timing-filter amplifier (and in parallel to a shaping amplifier). We plan to set up the data acquisition (DAQ) system so that both (neutron and X-ray) triggers can coexist. In this way, as we take the X-ray data, we can also increase the statistics in the neutron spectrum.

Since the SDD trigger signal comes much later than the $K \otimes TC$ trigger (despite the relatively fast risetime of the SDD – see Fig. 6), we need to modify the E549 data-acquisition system in one of the following two ways:

1. Make an independent data acquisition system for the SDDs, and take data using the $K \otimes SDD + (\pi \otimes SDD)_{\text{prescaled}}$ trigger. Split the signal of the SDDs and feed them to the E471/E549 DAQ and to the SDD’s DAQ. The calibration data are mainly taken by the SDD’s DAQ and the gain fluctuation of the SDDs will be corrected. An event-sequence-number register is to be read out by the two DAQs, so that vertex information can be associated with the SDD events in offline analyses.

2. Construct the DAQ system by two branches and readout NCs and SDDs. The first branch is the same system as the E471/E549 DAQ and the second branch is dedicated to the SDDs. The deadtime for the second branch (for the SDDs) is much shorter compared with the first. The main trigger is $K \otimes TC$ and the rate will increase by a factor of 10 as compared to the E471/E549 scheme leading to a near saturation of the first branch of the DAQ system. While the first branch is in a dead time, the second branch accumulates calibration X-ray data. This system is rather simple, eliminating the need for the event-association process.

Our plan is to test the latter scheme during the coming E549 run and evaluate its consequences. If difficulties are identified, we will adopt the former scheme (the two-DAQ scheme was successfully used in the hypernuclear gamma-ray experiment at SKS).

4 Statistics of neutron spectrum

As discussed in the previous section, as we take the X-ray data in the proposed experiment, we can also increase the statistics in the neutron spectrum. Here, we discuss its significance.

In the proton spectrum, we have discovered a strange tribaryon, $S^0(3115)$, with the peak significance of $8-13 \sigma$ in E471 experiment, depending on the assumption of background shapes. Since the observed state has isospin $T = 1$, one can naturally consider that an isospin partner of the discovered state can be populated in the $^4\text{He} (\text{stopped } K^-, n)$
spectrum. In the $^4\text{He}$ (stopped $K^-,n$) reaction, both isospin $T=0$ and 1 states can be populated, thus we can also search for the $T=0$ state.

Concerning the $^4\text{He}$ (stopped $K^-,n$) spectrum of E471, recently we re-submitted a paper to Physics Letter B (nucl-ex/0310018; attached to this proposal). We observed enhancement in the neutron spectrum, which indicates the formation of strange tribaryon $-S^+(3140)$ with charge +1 with mass of $M_{S^+} = 3141 \pm 3$ (stat.) $^{+4}_{-1}$ (sys.) MeV/$c^2$. The significance of this peak is 3.7σ at this moment. In the neutron spectrum, we also found some enhancement at around 3115MeV, the position same as the $S^0(3115)$ observed in the proton spectrum. However, the statistical significance of this enhancement is poor to conclude that this correspond to the existence of the isospin partner $S^+(3115)$. We need much more data to obtain conclusive results concerning the existence of these peak(s) and to precisely determine the peak parameters (position /width).

There were two reasons why the peak significance was poor only in neutron spectrum: (1) Typical neutron detection efficiency of neutron is about 20%; which gives 5 times less statistics compare to the proton. (2) Simple charge independence relation of the formation reaction tells that the formation rate of the strange trybaryon in $^4\text{He}$ (stopped $K^-,n$) $S^+$ must be 1/2 of the formation rate of $S^0$ in $^4\text{He}$ (stopped $K^-,p$) $S^0$ reaction.

Due to these reasons, the statistics of the signal must be reduced to 1/10 when we apply the same cut condition as we did for proton, where as the background statistics is reduced only by a factor of 1/5. To obtain the same statistical significance, we need to accumulate 20 times more stopped $K^-$. For example, we established a peak in proton spectrum with $8-13\sigma$ significance in E471. The estimated peak significance of the isospin partner becomes $8-13\sigma/\sqrt{20} = 2-3\sigma$, which is quite consistent with the present status.

In the proton spectrum, we are planning to take inclusive $^4\text{He}$ (stopped $K^-,p$) reaction data in E549 with newly constructed proton tracking chambers and with dedicated high resolution TOF counters. With about one month running scheduled at E549, we can rather easily increase the peak statistics by a factor of 30–50 and can determine the peak position/width/formation rate with much improved accuracy. This correspond to the peak significance of 40–90σ, so we have no need to take additional data for proton spectrum in the proposed experiment.

However for the neutron spectrum, we have no way to drastically improve the statistics. The statistics can be only linearly increase with the beam time. This is the reason why we want to accumulate the $^4\text{He}$ (stopped $K^-,n$) reaction data also in this proposed experiment.

If we can take neutron data continuously during E549 and the present experiment, then we can stop $10 \times 10^8 K^-$s on the target in whole running time (160 shifts). This stopped $K^-$ number is about 5 times higher than that of the E471 experiment. In E549 experiment, we are now increasing the thickness of the neutron counter from 20cm to 35cm. We are also planning to improve the tracking efficiency of drift chamber used in the E471 experiment by replacing all the preamplifiers. We are considering that these
improvement in E549 will improve the neutron peak statistics by a factor of more than 1.5. Thus we can obtain about 8 times higher statistics when we continuously take neutron data during the present X-ray measurement. Now the statistics becomes close to that of proton spectrum in E471, so we can obtain conclusive answer also for the tribarions with charge +1.

We are also planning to improve the TOF resolution of the neutron detection from $\sigma=300\text{ps}$ (E471) to $\sigma=200\text{ps}$ (goal of E549). The widths of trybaryons observed so far – $S^0(3115)$ and $S^+(3140)$ – are consistent with the experimental resolution. If the peak is much narrower than 25 MeV (FWHM), we have chance to discriminate $S^+(3115)(T=1\text{ state})$ from $S^+(3140)(T=0\text{ state})$ by the improvement of the resolution.

5 Expected precision and beam time estimate

A Monte Carlo simulation was performed using as input the target dimension and the SDD position as it is pictured in Fig. 2. The total active SDD area is $6\text{ cm}^2$ ($1\text{ cm}^2$ per SDD). The simulation starts with 600 MeV/$c$ kaons, which are degraded, enter the liquid helium target and produce a realistic stopping distribution. Each stopped kaon emits a 6.4 keV X-ray (actual $L_\alpha$ yield per stopped $K^-$ will be taken into account later). The X-ray attenuation in the 75 $\mu$m thick Mylar exit window as well as the attenuation inside the liquid helium target is calculated at tracking. The number of X-rays absorbed in the detector divided by the number of stopped kaons gives the total detection efficiency:

$$\epsilon = 2.4 \times 10^{-3}$$

For 6.4 keV X-rays the transmission through a 75 $\mu$m Mylar target window is 0.87 and for liquid helium 0.82, which is included in the above quoted number (intrinsic efficiency for 6.4 keV X-rays is nearly 100 % for a detector thickness of 450 $\mu$m).

We expect $1.4 \times 10^5$ events for 6 SDDs with $6 \times 10^8$ stopped kaons (as planned in E549), assuming a $K^-\text{He}-L_\alpha$ yield of 0.1 as reported in the previous experiments. If a vertex-counter coincidence is applied (solid angle coverage of $\sim 40\%$) still more than 10000 events could be measured using 6 SDDs with a total active area of 6 cm$^2$. To measure an X-ray line with an accuracy of 1.5 eV, having a SDD resolution of 150 eV, ($150/1.5)^2 \gtrsim 10000$ events are required if there is no background. The signal to noise ratio of the past experiment was about 1:1, which will be improved to about 10:1 in the proposed experiment due to the thin (1/10) active layer of the X-ray detector. Therefore, using 6 SDDs the measurement of the $3d \rightarrow 2p$ kaonic helium X-ray transition with an accuracy of 2 eV should be feasible.

6 Timeline and Milestones

If the proposal is approved, we plan to proceed as follows:
Feb/end 2005 Six SDDs delivered. Start of detector tests in a cryogenic environment (including epoxy-molded preamplifiers).

March 2005 Start of the target cryostat modification (SSD mount, feed-through connectors)

June/end 2005 SDD tests completed.

xxx 2005 End of E549 run, start of SDD installation.

xxx+2 months SDD installation and SDD source test completed. Ready to run.

As shown, we will be ready to run about 2 months after the termination of E549. Note that we will NOT be ready to run before summer even if E549 is scheduled earlier, due to the needs for cryogenic tests of SDDs and preamplifiers.

7 Summary

The strong-interaction shift of $3d \to 2p$ X-rays of kaonic helium using six silicon drift X-ray detectors mounted inside the E549 helium-target assembly. A precision better than 2 eV can be achieved by using $6 \times 10^8$ stopped negative kaons (corresponding to 90 shifts of beam time). The measurement will provide a crucial information to understand the nature of the strange tribaryon $S^0(3115)$.

References


