A letter of intent for an experiment at INPS, KEK Proton Synchrotron

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

– A key to understanding the nature of the strange tribaryon $S^0(3115)$ –

Abstract

We propose to measure the strong-interaction shift of $3d \rightarrow 2p$ 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 tribaryon $S^0(3115)$, recently discovered by the E471 collaboration [1].

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1 Physics motivation

The strange tribaryon $\mathrm{S}^0(3115)$, 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^-ppn system with isospin 0, and 2) $\mathrm{S}^0(3115)$ with isospin 1 may correspond to the isobaric analog state of the predicted $T = 1$ K^-ppp, 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 $\overline{K}N$ potential so as to simultaneously reproduce the $\overline{K}N$ 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 $\overline{K}$ nuclear systems in light nuclei, and predicted discrete $\overline{K}$-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 $\overline{K}$-nucleus potentials (not just with the Akaishi potential but with all other theories) in reproducing the measured $2p$ level shift of the kaonic ^{4}He atom. The measured shift and width (see Table 1),

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

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

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

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.*

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

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

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 experiment presented in this LOI.

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 $\bar{K}N$ potential is definitely excluded [10, 12]. The large shift such as $\gtrsim |10|$ 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 $\bar{K}N$ interaction. Therefore, it is very important to achieve the better energy determination as proposed herein.

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 2×10^7 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 ~ 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 $\sim$ 1MHz) 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 μm for our SDD as opposed to some 5 mm in the case of Si(Li) detectors used in the past experiments).

ΔE_{2p} (eV)	Γ_{2p} (eV)	Si(Li) Detector area, thickness	Resolution @ 6.5 keV (eV FWHM)	Reference
-41 ± 33	–	254 mm^2, 4 mm	340	[7]
-35 ± 12	30 ± 30	300 mm^2, 5 mm	250	[8]
-50 ± 12	100 ± 40	300 mm^2, 5 mm	360	[9]
-43 ± 8	55 ± 34			Average

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

Shift	Significance
~ -40eV	Past experiments are correct. $S^0(3115)$ is likely to be a kaon-nucleus bound state, but more theoretical work is necessary.
~ -10 eV	Past experiments are wrong. X-ray data reinforces the picture that $S^0(3115)$ being a kaon-nucleus bound state.
$\lesssim |2|$eV	Past experiments are wrong. Not much physics can be extracted.

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.

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 7.5cm liquid helium (transmission of $\sim$ 82%) and a 75-μm mylar window before reaching the SDD (transmission of $\sim$ 87%).

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

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 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.

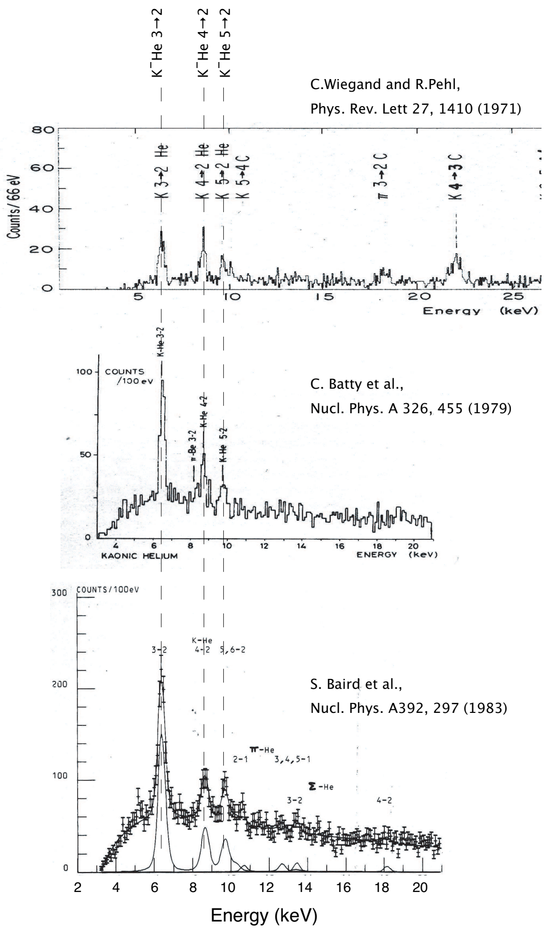

Figure 1: Comparison of the three previous measurements.

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 this experimental program.

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. This makes it possible to operate SDDs even at room temperature or with moderate cooling.

Test measurements were done with SDDs cooled down to a temperature of $-30°$ 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

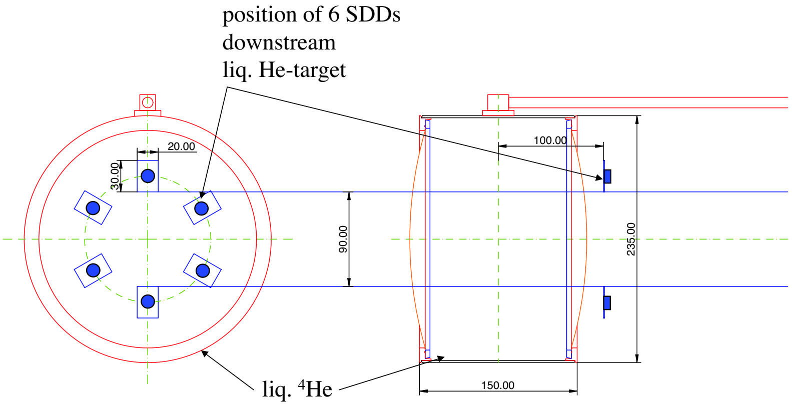

Figure 2: Six windowless silicon drift detectors (SDDs) mounted on the E549 superfluid helium target.

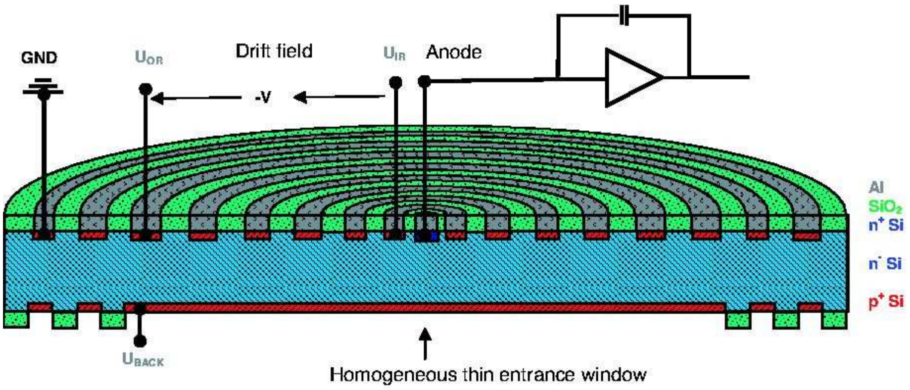

Figure 3: Scheme of a Silicon Drift Detector with circular geometry.

temperature. For the proposed experiment the SDDs will be installed close to the liquid helium target and therefore cooled down to $-120°$ 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

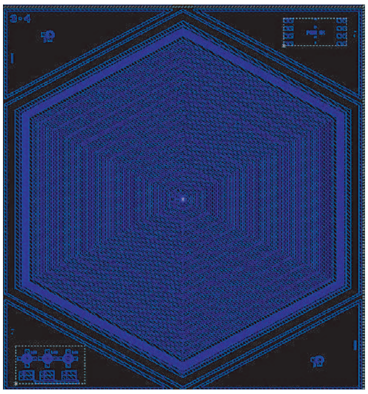

Figure 4: Hexagonal SDD design with an active area of 100 mm^2. Shown here is the anode side (to which an amplifier is connected), and X-rays enter the detector from the other side.

changing the last-ring voltage from 50 V to 130 V.

4 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 cm^2 (1cm^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_α yield per stopped K^- will be taken into account later). The X-ray attenuation in the 75 μm 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 μm 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 μm).

We expect 1.4×10^5 events for 6 SDDs with 6×10^8 stopped kaons (as planned in E549), assuming a K^-He-L_α 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

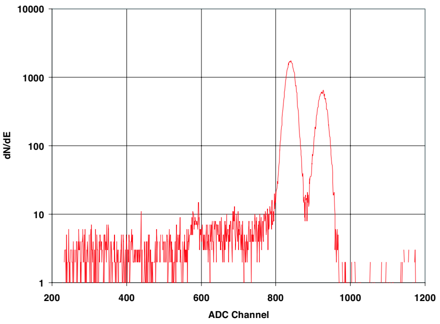

Figure 5: Energy spectrum of a 100 mm^2 SDD, measured at $-30°$ C with a shaping time of 0.5μs. For calibration a ^{55}Fe source was used, the K_α and K_β lines of manganese are clearly resolved at 5.9 keV and 6.5 keV respectively, with an achieved energy resolution of 183 eV.

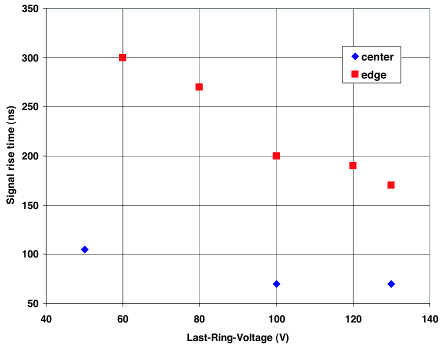

Figure 6: Signal rise time of a 100 mm^2 SDD for different drift fields and two positions of the collimated ^{55}Fe source in the center and at the edge of the active SDD area.

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.

5 Summary

The strong-interaction shift of $3d \rightarrow 2p$ 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 6×10^8 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).

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