Kaonic Helium X-rays

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Abstract. The long-standing “Kaonic-helium puzzle”, i.e., the discrepancy between the measured and calculated 2p-level strong-interaction shift of kaonic helium 4, has been solved by the KEK E570 experiment; the measured 2p-level shift was 2 \pm 2(stat) \pm 2(syst) eV, thus agreeing with a majority of the theoretical calculations in contradiction to the previous average of 3 experiments of \(-43 \pm 8\) eV. The smallness of the kaonic helium-4 2p-level shift has recently been confirmed by the SIDDHARTA collaboration at DAΦNE. Both of these experiments used silicon drift X-ray detectors (SDDs), and have used elaborate in-situ calibration methods. In order to further study the low-energy kaon-nucleus interaction, the J-PARC E17 experiment will soon measure the kaonic helium-3 2p-level shift to high precision. I also briefly discuss the status of kaonic hydrogen x-ray spectroscopy.

1. Introduction
The measurement of the strong-interaction energy-level shift and width of kaonic atom x-rays offers a unique possibility to precisely determine the \(K^-\)-nucleus strong interaction in the low energy limit. Therefore many experiments have been performed to collect data on a variety of targets from hydrogen to uranium.

Of these, the most fundamental is kaonic hydrogen, from which one can deduce the \(K^-p\) scattering length at threshold. Until about 15 years ago, even the sign of the shift was problematic, as experiments reported the 1s-level shift to be “attractive”\(^1\) [1–3], while theories (analyses of low-energy \(KN\) data) preferred “repulsive”. This discrepancy was settled by new experiments, KpX [4, 5] and DEAR [6], both of which found the 1s-level shift to be repulsive.

The second simplest system, kaonic helium, has been also known to be puzzling. While most of the available kaonic-atom data can be fitted fairly well for \(Z \geq 2\) by optical-potential models [7], there was a 5\(\sigma\) theory-vs-experiment discrepancy for the 2p-level shift. This discrepancy has been known as the “kaonic helium puzzle”.

In this talk, I will discuss the following three experiments, E570 at KEK [8], SIDDHARTA [9] at DAΦNE and E17 at J-PARC (Table 1).

2. Kaonic Hydrogen
2.1. KpX
Before the KpX experiment [4, 5], the status of the kaonic-hydrogen study was quite puzzling due to the contradiction between the signs of the scattering lengths obtained by the previous

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\(^1\) Here, “attractive” means that the measured 2p–1s x-ray energy (at around 6.5 keV) is larger than that calculated by taking account of the Coulomb interaction only.
Table 1. The three modern kaonic x-ray experiments.

| Experiment | Accelerator | Targets      | Status      |
|------------|-------------|--------------|-------------|
| E570       | KEK 12-GeV  | liquid $^3$He | Published   |
| SIDDHARTA  | DAΦNE       | gaseous H, D, $^4$He, $^3$He | Data taken |
| E17        | J-PARC      | liquid $^3$He | “Day-1”     |

x-ray measurements [1–3] and those extracted from the analyses of the low energy $\bar{K}N$ data, e.g., Refs. [10–12].

KpX was the first to observe a statistically-significant kaonic hydrogen $2p$–$1s$ peak with low background (Fig. 1 top panel). This was achieved by the use of

(i) a gaseous rather than a liquid hydrogen target (1.3% of liquid hydrogen density),
(ii) sixty Si(Li) X-ray detectors each having an active area of 200 mm$^2$ and a FWHM resolution of some 400 eV, operated inside the hydrogen target chamber,
(iii) an elaborate vertex reconstruction and background suppression scheme (most importantly, a two-charged-pion trigger method to eliminate the $\pi^0$-induced background), and
(iv) an in-situ energy calibration scheme using the fluorescence from titanium (Ti) foils attached to the inner surface of the target vessel.

The obtained shift and width were $\Delta E_{1s} = -323 \pm 63$ (stat) $\pm 11$ (syst) eV (repulsive) and $\Gamma_{1s} = 407 \pm 208$ (stat) $\pm 100$ (syst) eV, respectively.

![Figure 1](image1.png)  
**Figure 1.** Comparison of the KpX (top) and DEAR (bottom) kaonic hydrogen x-ray spectra.

![Figure 2](image2.png)  
**Figure 2.** Comparison of the KpX (top) and SIDDHARTA (bottom: preliminary) kaonic hydrogen x-ray spectra.

2.2. DEAR

The DEAR experiment [6] took advantage of the low-energy (16 MeV), nearly mono-energetic ($\Delta p/p = 0.1\%$) kaons from the decay of $\phi$ mesons produced by $e^+e^-$ collisions at DAΦNE. The kaons were stopped in a gaseous hydrogen target (3% of liquid hydrogen density), and the x-rays were detected by sixteen CCD (charged-coupled device) x-ray detectors, each having a good FWHM resolution of 150 eV at 6 keV. However, due to the lack of timing information (the DEAR CCDs were read out every 90 s), the observed spectrum was dominated by a continuum background. After subtracting the background (about $10^5$ events per channel), the...
spectrum shown in the bottom panel of Fig. 1 was obtained. The deduced shift and width were 
\[ \Delta E_{1s} = -193 \pm 37 \text{(stat)} \pm 6 \text{(syst)} \text{ eV (i.e., repulsive)} \] 
and \[ \Gamma_{1s} = 249 \pm 111 \text{(stat)} \pm 30 \text{(syst)} \text{ eV, respectively.} \]

**Figure 3.** Comparison of experimental and theoretical results for the strong-interaction shift and width of the kaonic hydrogen 1s level. The squares with error bars exhibit experimental results: the two recent experiments KpX [4, 5], DEAR [6] (bullet), and three old experiments [1–3] (circles). The circles are the result of a recent calculation [13] that combined the KpX and DEAR results with the low-energy KN scattering data, with (•) and without (◦) isospin-breaking corrections to the Deser-Trueman formula [14–16]. The fit restricted to the DEAR data is represented by the triangles.

### 2.3. SIDDHARTA

While both KpX and DEAR agreed on the sign of the shift (repulsive), the shift values did not overlap with each other (Fig. 3). A new measurement is clearly needed.

The SIDDHARATA experiment at DAΦNE [17] therefore aims at determining the kaonic hydrogen 1s shift and width with a precision higher than in DEAR. To achieve this goal, 144 silicon drift detectors (SDDs, each having an area of 100 mm²), which have both good energy resolution (≈150 eV) and time resolution (≈1 µs), were used. Two sets of thin plastic “kaon” counters were placed above and below the \( e^+e^- \) collision point to detect kaons, and data were collected with triple-coincidence triggers (a \( K^- \) in the top kaon counter, a \( K^+ \) in the bottom kaon counter, and an x-ray hit in one of the SDDs constituted the trigger). This, together with shield optimization, significantly reduced the background level.

A preliminary kaonic hydrogen spectrum is shown in Fig. 2. Although the data still need to be carefully analyzed as there are background contributions from \( K^-C, K^-O, \) etc., produced by kaons stopped in the target vessel made of Kapton. For more details, see Ref. [9].

### 3. Kaonic Helium 4

#### 3.1. The kaonic helium puzzle

Fig. 4 shows the kaonic-atom strong-interaction shift values for light elements, together with lines drawn by connecting those calculated using the best-fit optical potential [7]. As shown, there is a 5σ theory-vs-experiment difference in the case of kaonic \( ^4 \text{He} \). The kaonic \( ^4 \text{He} \) 2p-level shift shown therein, \( \Delta E_{2p} = -43 \pm 8 \text{ eV} \) is based on three past x-ray experiments [18–20], while theoretical calculations give \( \Delta E_{2p} \sim 0 \text{ eV} \) [21, 22]. This discrepancy has been known as the kaonic helium puzzle. Note that there is another deviation in kaonic \( ^{16} \text{O} \) which still remains unsolved.
3.2. E570

In 2005, Akaishi [23] predicted that a large (∼ ±10 eV) shift may appear near the resonance between atomic and nuclear poles. This calculation was made in conjunction with the Yamazaki-Akaishi prediction of deeply-bound kaonic nuclear states [24]. As a search for such deeply-bound states in the $^4\text{He}$stopped $K^-$, $n/p$X reaction was already in progress at the KEK 12-GeV proton synchrotron (E471/E549), the E570 experiment, motivated by Akaishi’s prediction, was proposed to measure the kaonic $^4\text{He}$ 3$d$–2$p$ x-rays (for the fourth time) parasitically to the E549, by mounting x-ray detectors in the E549 liquid helium target cryostat (Fig. 5), and by mixing the x-ray triggers to the E549 ($K^-$; $p=n$) triggers.

The aim of the E570 experiment at the KEK 12-GeV PS (proton synchrotron) therefore was to measure the transition energy of the kaonic $^4\text{He}$ 3$d$–2$p$ x-rays to a precision of ∼ 2 eV, so as to confirm or refute the large 2$p$-level shift. For this, the E570 employed the following [8]:

(i) Eight SDDs each having an area of 100 mm$^2$ and a resolution of ∼ 180 eV FWHM at 6 keV were used. This improved the energy resolution by a factor 2 as compared with Ref. [20] (which used a conventional Si(Li) detector). In addition, the statistics was higher by about a factor 3.

(ii) By using the chambers and counters constructed for the E549 experiment (Fig. 5), the reaction vertices were reconstructed from an incoming $K^-$ track and an outgoing charged particle (pions from the ($K^-$, $\pi^-$) reaction on the target, or from hyperon decays), and the target fiducial cut was imposed (Fig. 6). This was in addition to the SDD x-ray coincidence requirement. With these, the signal to noise ratio was improved by a factor 6 as compared with Ref [20].

(iii) The energy calibration was done by using characteristic x-rays induced by charged particles (mostly $\pi^-$ in the beam) on high-purity titanium and nickel foils placed just behind the target cell. The energy of the kaonic-helium 3$d$–2$p$ x-ray, ∼ 6.4 keV, lies between the characteristic x-ray energies, 4.5 keV(Ti) and 7.5 keV(Ni). To obtain high-statistics energy calibration spectra, SDD self-triggered events (Fig. 7 top) were accumulated in addition to...
Figure 6. Front (top) and side (bottom) view of the vertex distributions for E570.

Figure 7. The SDD spectra without (top) and with (bottom) the fiducial and timing cuts in E570.

The stopped-K-triggered events (Fig. 7 bottom, which also includes the fiducial cut discussed above) were accumulated.

The vast improvement achieved by the E570 experiment over the past experiments can be seen in Fig. 8. The measured 2p-level shift was $2 \pm 2\text{(stat)} \pm 2\text{(syst)}$ eV [8], thus agreeing with a majority of the theoretical calculations. This has solved the long-standing kaonic-helium puzzle.

Figure 8. Same-scale comparison of the kaonic helium x-ray spectra. From left to right, Wiegand et al. (1971) [18], Batty et al. (1979) [19] Baird et al. (1983) [20] and E570 [8].

Figure 9. Kaonic helium-4 x-rays spectrum measured using the SIDDHARATA setup. [25].
3.3. SIDDHARTA

The SIDDHARTA experiment used the kaonic helium-4 $3d-2p$ x-rays to optimize the setup for the kaonic hydrogen run, since the energy (6.4 keV) is close to the $K^-p$ $2p-1s$ energy (6.5 keV) and the yield per stopped $K^-$ is higher in the former case. The data were taken in a gaseous helium-4 target (at a temperature of 27 K and a pressure of 0.95 bar) with a strong $^{55}$Fe source for detector calibration. As shown in Fig. 9, the $^{55}$Mn Kβ x-ray peak overlapped with the kaonic $^{4}$He $3d-2p$ line. The spectrum was fitted by fixing the relative ratio of the Mn Kα and Mn Kβ lines from the calibration (no-beam) data. The obtained $2p$-level shift was $\Delta E_{2p} = 0 \pm 6$ (stat) $\pm 2$ (syst) eV, in good agreement with the E570 result [25, 26].

4. Kaonic Helium 3

Using the method established in the E570 experiment, the E17 group at J-PARC [27, 28] is now preparing for an experiment to measure the kaonic helium-3 x-rays. The experiment will be carried out at the K1.8BR beamline in the J-PARC hadron hall [29]. The essential technical differences between the E570 and E17 experiments are:

(i) The volume of the E570 liquid helium-4 target was close to 5000 cm$^3$, but it is only about 500 cm$^3$ for the E17 liquid helium-3 target. This calls for a higher-intensity, better-quality kaon beam [29].

(ii) In order to minimize the cable length between the SDDs and the preamplifiers and also because of the space constraints, the preamplifiers are mounted inside the target cryostat. A careful energy and timing resolution optimization as a function of the SDD and amplifier operating temperatures has been done [30].

The E17 experiment was chosen as one of the “Day-1” experiments, and is waiting for the J-PARC main ring slow-extraction beam intensity to reach $\gtrsim 5$ kW, which is needed to carry out the measurement.

5. Summary

The precision spectroscopy of kaonic atom x-rays offers a unique possibility to determine precisely the $K^-$-nucleus strong interaction in the low energy limit. The existing (slight) discrepancy between the KpX and DEAR results for the $1s$-level shift and width of kaonic hydrogen will soon be settled by higher precision data collected by the SIDDHARATA collaboration. For kaonic helium-4, the E570 experiment has established that the $2p$-level shift is small, $\sim 0$ eV, thereby solving the “puzzle”. This has recently been confirmed by the SIDDHARATA collaboration. For these measurements, the use of silicon drift detectors (SDDs), having good energy and time resolution, has played an essential role. At the newly inaugurated J-PARC, the E17 experiment will soon measure the kaonic helium-3 x-rays, also using SDDs.

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