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Precision Spectroscopy of Kaonic Atoms at DAΦNE

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Abstract. The SIDDHARTA experiment aims at a precise measurement of K-series kaonic hydrogen x-rays and the first-ever measurement of the kaonic deuterium x-rays to determine the strong-interaction energy-level shift and width of the lowest lying atomic states. These measurements offer a unique possibility to precisely determine the isospin-dependent $\bar{K}$-nucleon scattering lengths.

1 Introduction

More than a quarter of a century ago, R.H. Dalitz made the following statement [1] : *The most important experiments to be carried out in low-energy K-meson physics today is the definitive determination of the energy level shift in* K^-p *and* K^-d *atoms, because of their direct connection with the physics of the KN interaction and their complete independence from all other kinds of measurements which bear on this interaction.*

These measurements therefore are eagerly awaited while many studies on the $\bar{K}$-nucleus interaction (*e.g.*, deeply-bound $\bar{K}$-nucleus states) have been intensively performed both experimentally and theoretically over the past several years. The results will set tight constraints on the theories.

The measured strong-interaction 1s-energy-level shift ΔE_{1s} [1] and width Γ_{1s} for kaonic hydrogen can be related to real and imaginary part of complex K^-p S-wave scattering length a_{K^-p} by the Deser-Truemann formula [2] :

$$\Delta E_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K^-p} = 412 \text{ eV fm}^{-1}\, a_{K^-p}$$

where μ is the reduced mass of the K^-p system, α is the fine structure constant. The a_{K^-p} can be expressed by the isoscalar a_0 and isovector a_1 scattering lengths: $a_{K^-p} = (a_0 + a_1)/2$, whereas $a_{K^-n} = a_1$.

The shift and width for kaonic deuterium are also related to a_{K^-d} which could be expressed by a_0 and a_1 by taking into account higher order contributions associated with the K^-d three-body interaction.

For the kaonic hydrogen, the past experimental values of the 1s-state energy-level shift (attraction) [3–5] had disagreed with that of theoretical calculation (repulsion) even for its sign. A repulsive-type shift was observed in the KpX experiment in 1997 [6] and was firmly established by the DEAR experiment in 2005 [7].

Though the “sign” problem has been solved, the two past experiments do not agree perfectly with each other despite their relatively large errors, and still disagree with the theoretical calculations that try to combine the kaonic atom data with scattering results as shown in Fig. 1.

The present experiment aims at a precise measurement of K-series kaonic hydrogen x-rays and the first-ever measurement of the kaonic deuterium x-rays to precisely determine the isospin-dependent $\bar{K}$-nucleon scattering lengths.

2 Experiment

The SIDDHARTA experiment has been performed at the DAΦNE positron-electron collider that produces the ϕ-resonance which decays into K^+K^- with a probability of 49

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[1] ΔE_{1s} is defined as $\Delta E_{1s} \equiv -(E_{1s} - E_{1s}^{EM})$, where E_{1s} is the energy of the 1s level and E_{1s}^{EM} is the energy calculated using only the electromagnetic interaction (EM).

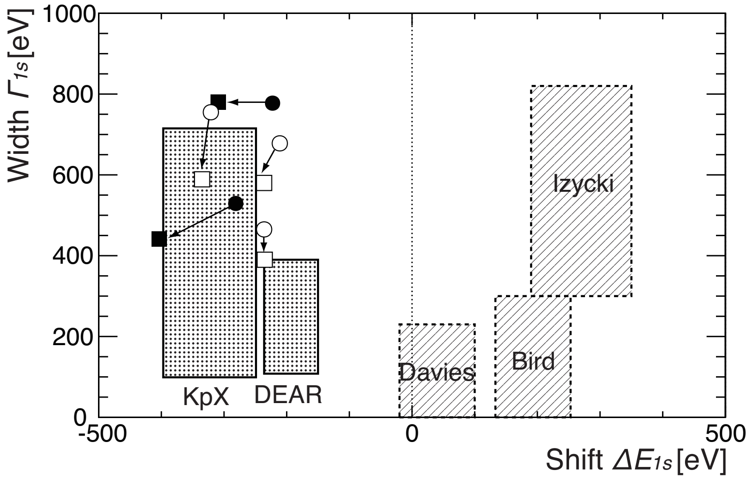

Fig. 1. Comparison of experimental and theoretical results for the strong-interaction 1s-energy-level shift ΔE_{1s} and width Γ_{1s} of kaonic hydrogen. Boxes exhibit experimental results: the recent two experiments KpX [6], DEAR [7], and old three experiments J.D.Davies *et al.* [3], M.Izycki *et al.* [4], P.M.Bird *et al.* [5]. The symbols show the theoretical values of two recent calculations (closed symbols [8], open symbols [9]) that try to combine the results of x-ray measurements with scattering data under various conditions, with (square) and without (circle) isospin braking corrections to the Deser formula.

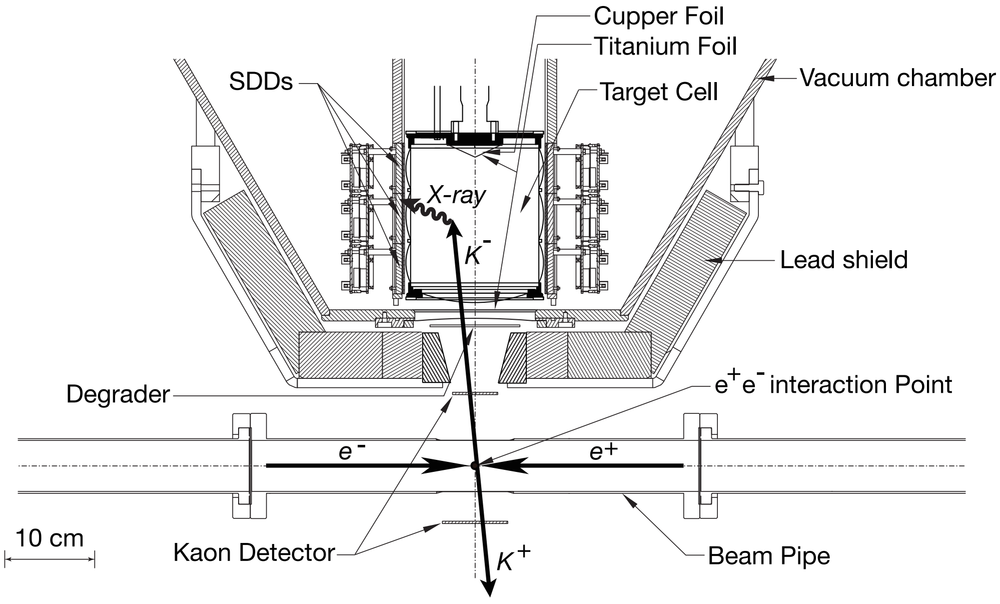

Fig. 2. A schematic side view of the SIDDHARTA setup installed at the interaction point of DAΦNE.

%. Resulting low energy K^-'s (~ 16 MeV of kinetic energy) with small energy spread are well-suited to be stopped at a low density gaseous target efficiently for producing K^-p and K^-d atoms. This is a major advantage to perform the K^-p and K^-d x-ray measurements at DAΦNE. It is essential to employ a low density gaseous target for the measurements, since the yields strongly depend on the target density due to their Stark effects.

Figure 2 illustrates a schematic view of the SIDDHARTA setup. A coincidence of a back-to-back K^+K^- pair signal detected by two plastic scintillation counters installed above and below the positron-electron collision point was employed as a kaon trigger. The incident K^-'s were degraded in an optimized (with respect to the ϕ boost) mylar degrader, and were stopped inside the target. X-rays emitted from the kaonic atoms were detected by x-ray detectors which viewed the target through the 125 μm-thick Kapton window of the target cell.

As x-ray detectors, we employed 144 silicon drift detectors (SDDs) developed especially for this experiment, each having an effective area of 1 cm^2. The energy resolution of the SDD is about twice as good as the Si(Li) detectors used in the past experiment (KpX) [6], and the time resolution of sub-micro seconds whereas CCD detectors employed by the previous experiment (DEAR) [7] were not appropriate for triggered setup due to the long readout time.

The energy calibration was done by using characteristic x-rays induced by an x-ray tube mounted below the beam pipe on high-purity titanium and copper foils placed in front of the target entrance window and topside of the target cell. The energy of the kaonic-hydrogen K_α x-ray, ~6.2 keV, lies between the characteristic x-ray energies, 4.5 keV(Ti) and 8.0 keV(Cu). Calibration data with the x-ray tube have been collected under the beam condition in regular intervals of the production runs.

The SIDDHARTA data taking was completed in November 2009. We have taken data not only with hydrogen and deuterium target but with helium target to measure the L-series x-rays of kaonic helium atoms as well.

In this paper, we focus on the analysis result of the kaonic-^{4}He data to present the performance of this experiment since the kaonic-^{4}He $3d \to 2p$ x-ray has a similar energy (~6.4 keV) to that for K^-p and K^-d atoms, and can be yielded one order of magnitude faster than the K^-p x-ray (higher yield).

3 Analysis of kaonic helium data

Figure 3 shows a typical x-ray spectrum taken with x-ray tube used for the energy calibration. Characteristic x-ray peaks of titanium and copper were obtained with high statistics for all SDDs. The energy scale was calibrated by K_α lines of titanium and copper with the well-known energies and intensity ratios of $K_{\alpha 1}$ and $K_{\alpha 2}$. The typical energy resolution of our SDD was about 150 eV (FWHM) at 6 keV.

The top panel of Fig. 4 shows the correlation plot of the SDD timing (time difference between kaon arrival and x-ray detection) and the x-ray energy measured by SDDs. The vertical band is due to the kaon-induced x-rays, and the most dense spot on this band is due to the kaonic-^{4}He $3d \to 2p$ x-rays. The bottom panel exhibits a projective histogram of this correlation. A typical time resolution after a time-walk correction was ~ 700 ns (FWHM) at a SDD temperature of ~170 K, which reflected the drift-time distribution of the electrons in the SDD. The gate region of the kaon events was selected as indicated with arrows on the figure.

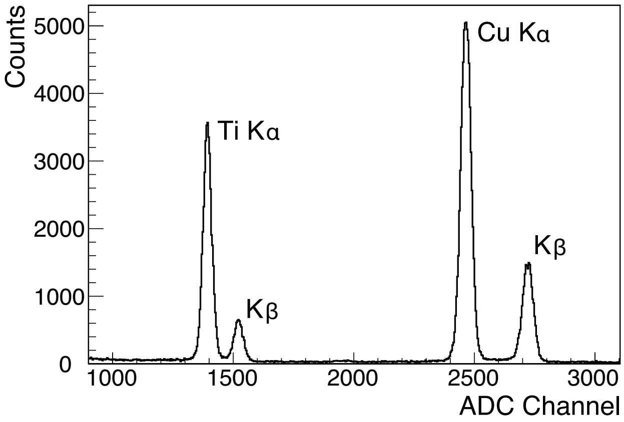

Fig. 3. A typical x-ray spectrum taken with x-ray tube which provides high-statistics energy-calibration information.

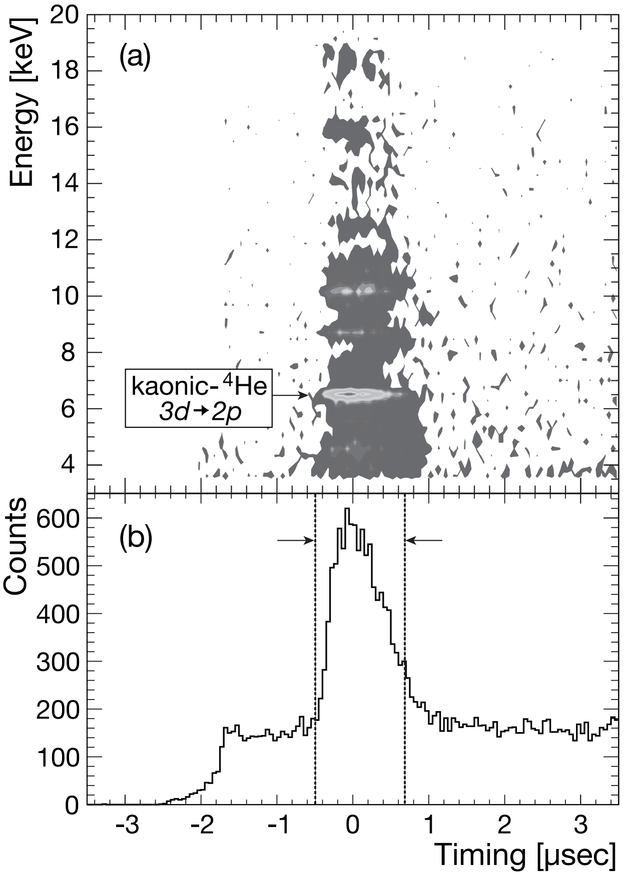

Fig. 4. (a) A correlation plot of the kaon-SDD time difference vs the x-ray energy measured by SDDs. (b) A projective plot of the above correlation. A time-walk correction was applied to those plots.

After applying the kaon-SDD timing selection and calibrating the energy scale, we obtained x-ray energy spectra for K^- triggered events shown in Fig. 5. Kaonic-helium $3d \to 2p$ and $4d \to 2p$ transitions are clearly observed with good signal-to-noise ratio.

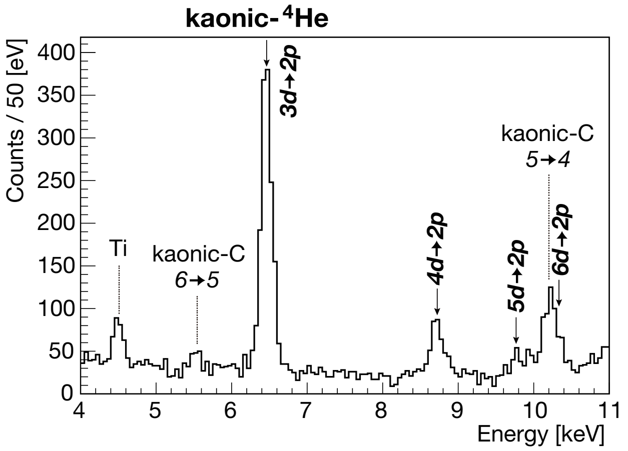

Fig. 5. Measured x-ray spectrum for K^- triggered events.

Very recently, the kaonic-^{4}He x-rays have been measured with liquid-^{4}He target at KEK [10] which resolved a long-standing discrepancy between theory and experiment [11–13] on the strong-interaction shift of $2p$ level for kaonic-^{4}He. In comparison to the previous KEK experiment, we achieved almost comparable energy resolution, signal-to-noise ratio and statistics.

In the present experiment, we measured the kaonic x-rays in a gaseous-^{4}He target for the first time, resulting in negligible Compton scattering in helium which led to a systematic-error source in all past experiments used liquid target [10–13]. The result of the strong-interaction $2p$-level shift was recently published as $\Delta E_{2p} = 0 \pm 6$ (stat) ± 2 (syst) eV using another dataset of our ^{4}He data with ^{55}Fe source used for in-situ energy calibration [14]. As a result, a resolution of this long-standing puzzle provided by the previous experiment was firmly established in this experiment.

4 Conclusion

We have measured kaonic x-rays with hydrogen, deuterium and helium gaseous targets with a large number of SDDs developed especially for this experiment, and demonstrated a good performance of this experiment with an analyses of kaonic-helium data in this paper and a separated paper [14] in which the $2p$-level shift was precisely determined.

Analyses for kaonic hydrogen and deuterium data are currently underway. Those results will yield invaluable constraints for the theories and will provide new information regarding the discrepancy between scattering and x-ray data and the isospin-dependent $\bar{K}$-nucleon interaction.

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References

1. R. H. Dalitz *et al.*, Proceedings of the Conference on Hypernuclear and Kaon Physics, ed. by B. Povh, Max-Plank Institute Report MPI H-1982-V20 (1982) 201
2. S. Deser et al., Phys. Rev. **96** (1954) 774;
   T. L. Truemann, Nucl. Phys. **26** (1961) 57;
   A. Deloff, Phys. Rev. **C13** (1976) 730
3. J. D. Davies *et al.*, Phys. Lett. **B83** (1979) 55
4. M. Izycki *et al.*, Z. Phys. **A297** (1980) 11
5. P. M. Bird *et al.*, Nucl. Phys. **A404** (1983) 482
6. M. Iwasaki *et al.*, Phys. Rev. Lett. **78** (1997) 3067;
   T. Ito *et al.*, Phys. Rev. **C58** (1998) 2366
7. G. Beer *et al.*, Phys. Rev. Lett. **94** (2005) 212302
8. U.-G. Meißner, U. Raha and A. Rusetsky, Eur. Phys. J. **C35** (2004) 349
9. B. Borasoy, R. Nißler and W. Weise, Eur. Phys. J. **A25** (2005) 79
10. S. Okada *et al.*, Phys. Lett. **B653** (2007) 387
11. C. E. Wiegand and R. Pehl, Phys. Rev. Lett. **27** (1971) 1410
12. C. J. Batty *et al.*, Nucl. Phys. **A326** (1979) 455
13. S. Baird *et al.*, Nucl. Phys. **A392** (1983) 297
14. M. Bazzi *et al.*, Phys. Lett. **B681** (2009) 310