A new measurement of kaonic hydrogen X-rays

SIDDHARTA Collaboration


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1. Introduction

Low energy phenomena in strong interactions are described by effective field theories which contain appropriate degrees of freedom to describe physical phenomena occurring at the nucleon-meson scale. Chiral perturbation theory was extremely successful in describing systems like pionic atoms, however it is not directly applicable for the kaonic systems. This is due to the presence of resonances like the $\Lambda(1405)$, only slightly below the $K^-p$ reaction threshold of 1432 MeV. Instead, non-perturbative coupled-channel techniques are used. These calculations generate the $\Lambda(1405)$ dynamically as a $\bar{K}N$ quasibound state and as a resonance in the $\pi\Sigma$ channel. A general feature of the theory in this field is that it relies heavily on input from experimental data.

The measurement of the strong-interaction induced energy-level shift and width of the kaonic-hydrogen 1$s$ atomic state provides direct information on the $\bar{K}N$ interaction at $K^-p$ threshold. Kaonic-hydrogen X-ray data are therefore important for theories of the $\bar{K}N$ system, together with the experimental data of low-energy $\bar{K}^{-}p$ scattering, $\pi\Sigma$ mass spectra, and $K^-p$ threshold decay ratios. These studies allow the investigation of chiral SU(3) dynamics in low-energy QCD and the role of explicit chiral symmetry-breaking due to the relatively large strange quark mass. These data are also strongly related to recent hot topics – the structure of the $\Lambda(1405)$ resonance (e.g., [1–3]) and the deeply
bound kaonic systems (e.g., [4–7]). Recent progress in this field is summarized in [8].

The shift and width are deduced from the spectroscopy of the K-series kaonic-hydrogen X-rays. The first distinct peaks of the kaonic-hydrogen X-rays were observed by the KEK-PS E228 group [9] following the absorption of a stopped $K^-$ within a gaseous hydrogen target using Si(Li) detectors. The observed repulsive shift was consistent with the analysis of the low energy $\bar{K}N$ scattering data, resolving the long-standing sign discrepancy generated by old experiments [10–12].

The most recent values were reported by the DEAR experiment [13], in which the errors were reduced by a factor of 2 when compared with those of E228 [9].

Using the results obtained by DEAR, theoretical studies have been performed with possible higher order contributions using several models [14–24]. However, the question still remains that most of them had difficulties in explaining all the experimental results in a consistent way. See also [25,26].

Here we report on results based on the X-ray detection technique recently developed by the SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) collaboration, using the microsecond timing and excellent energy resolution of large area silicon drift detectors (SDDs) [27]. This technique reduced the large X-ray background coming from beam losses and improved the signal-to-background ratio by more than a factor of 10 with respect to the corresponding DEAR ratio of about 1/100.

2. Experiment

The SIDDHARTA experiment was performed at the DAFNE electron–positron collider at the Laboratori Nazionali di Frascati of INFN. The $\phi$-resonances produced decay into back-to-back $K^+K^-$ pairs emitted with a branching ratio of about 49%. The monochromatic low-energy kaons ($\sim 16$ MeV of kinetic energy) are stopped efficiently in a gaseous target to produce kaonic hydrogen atoms. It is essential to use a gaseous target for the measurements since the X-ray yields quickly decrease towards higher density due to the Stark mixing effect. Therefore, a cryogenic gaseous hydrogen target was used at typical values of a pressure 0.1 MPa and a temperature 23 K, resulting in a density of $1.3 \times 10^{-3}$ g/cm$^3$ of the isotopically pure hydrogen.

Fig. 1 shows the SIDDHARTA setup. To detect the back-to-back correlated $K^+K^-$ pairs from $\phi$ decay, two plastic scintillation counters (1.5 mm thick), called the kaon detector, were mounted above and below the $e^+e^-$ interaction point where the $\phi$ resonance is produced. A kaon trigger was defined by the coincidence of the two scintillators. Minimum ionizing particles (MIPs) coming from beam losses were highly suppressed by setting a high pulse-height threshold in the kaon detector – the slow kaons deposit much more energy in the scintillators than the faster MIPs.

To obtain a uniform distribution of $K^-$ momenta entering the gaseous target, a shaped degrader made of mylar foils with a thickness ranging from 100 to 800 $\mu$m was placed as shown in Fig. 1, to correct for a slight momentum boost of the $\phi$ resulting from the 55 mrad $e^+e^-$ crossing angle. The cylindrical target cell, 13.7 cm in diameter and 15.5 cm high, was located just above the degrader inside the vacuum chamber. The lateral wall and the bottom window were made of Kapton Polyimide film of 75 $\mu$m and 50 $\mu$m thickness.

The SDDs, used to detect the kaonic-atom X-rays, were developed within a European research project devoted to this experiment [27]. Each of the 144 SDDs used in the apparatus has an area of 1 cm$^2$ and a thickness of 450 $\mu$m. The SDDs, operated at a temperature of $\sim 170$ K, had an energy resolution of 183 eV (FWHM) at 8 keV (a factor of 2 better than Si(Li) detectors used in E228 [9]) and timing resolution below 1 $\mu$s in contrast to the CCD detectors used in DEAR [28] which had no timing capability. Using the coincidence between $K^+K^-$ pairs and X-rays measured by SDDs, the main source of background coming from beam losses was highly suppressed.

To test our experimental technique and optimize the degrader thickness, we repeatedly changed the target filling to helium gas and measured the $L$-transitions of kaonic $^4$He. Due to the high yield of this kaonic atom X-ray transition, one day of measurement was sufficient for each check.

The physics results of the strong-interaction 2p-level shifts of kaonic $^3$He and kaonic $^4$He atoms are available in our recent publications [29,30].

In addition, we have performed the first-ever exploratory measurement of kaonic-deuterium K-series X-rays with the same experimental setup. In the kaonic-hydrogen analysis, it turned out to be essential to use the kaonic-deuterium spectrum to quantify the kaonic background X-ray lines – originating from kaons captured in heavier elements such as carbon, nitrogen and oxygen contained in organic construction materials – which overlap the kaonic-hydrogen signal.

Data were accumulated over six months in 2009 with integrated luminosities of $\sim 340$ pb$^{-1}$ for the hydrogen and $\sim 100$ pb$^{-1}$ for the deuterium measurement.

3. Data analysis

The data acquisition system records the signal amplitudes seen by the 144 detectors along with the global time information. Whenever a kaon trigger occurred, the time difference between the X-ray and kaon was recorded as well as the time correlations between the signals on each of the scintillators and the DAFNE bunch frequency. From these data, the time-of-flight information of the kaon detector, the position of the hit detector and rates of the SDDs, rate of kaon production, etc., could be extracted in the off-line analysis.

The timing distribution of the coincidence signals in the kaon detector with respect to the RF signal from DAFNE shows clearly that kaon events can be separated from MIPs by setting a time gate as indicated by arrows in Fig. 2.
The time difference between kaon arrival and X-ray detection for hydrogen data is shown in Fig. 3. The peak represents correlation between X-rays and kaons, while the flat underlying structure is from uncorrelated accidental background. A typical width of the time-correlation, after a time-walk correction, was about 800 ns (FWHM) which reflected the drift-time distribution of the electrons in the SDD.

In order to sum up the individual SDDs, the energy calibration of each single SDD was performed by periodic measurements of fluorescence X-ray lines from titanium and copper foils, excited by an X-ray tube, with the $e^+e^-$ beams in kaon production mode. A remote-controlled system moved the kaon detector out and the X-ray tube in for these calibration measurements, once every $\sim 4$ hours.

The refined in-situ calibration in gain (energy) and resolution (response shape) of the summed spectrum of all SDDs was obtained using titanium, copper, and gold fluorescence lines excited by the uncorrelated background without trigger (see [29,30] for more details), and also using the kaonic carbon lines from wall stops in the triggered mode.

Fig. 4 shows the final kaonic hydrogen and deuterium X-ray energy spectra. K-series X-rays of kaonic hydrogen were clearly observed while those for kaonic deuterium were not visible. This appears to be consistent with the theoretical expectation of lower X-ray yield and greater transition width for deuterium (e.g., [31]).

The vertical dot-dashed line in Fig. 4 indicates the X-ray energy of kaonic-hydrogen $K\alpha$ calculated using only the electro-magnetic interaction (EM). Comparing the kaonic-hydrogen $K\alpha$ peak and the EM value, a repulsive shift (negative $\epsilon_{1s}$) of the kaonic-hydrogen 1s-energy level is easily seen.

Many other lines from kaonic-atom X-rays and characteristic X-rays were detected in both spectra as indicated with arrows in the figure. These kaonic-atom lines result from high-n X-ray transitions of kaons stopped in the target-cell wall made of Kapton ($C_{22}H_{10}O_5N_2$) and its support frames made of aluminium. There are also characteristic X-rays from titanium and copper foils installed for X-ray energy calibration.

We performed a global simultaneous fit of the hydrogen and deuterium spectra. The intensities of the three background X-ray lines overlapping with the kaonic-hydrogen signals (kaonic oxygen 7–6, kaonic nitrogen 6–5, and copper $K\alpha$) were determined using both spectra and a normalization factor defined by the ratio of the high-statistics kaonic-carbon 5–4 peak in the $K^-p$ and $K^-d$ spectra. Fig. 4 (b) and (c) show the fit result with the components of the background X-ray lines and a continuous background; (a) shows the residuals of the measured kaonic-hydrogen X-ray spectrum after subtraction of the fitted background, clearly displaying the kaonic-hydrogen $K$-series transitions.
The response function of the SDD detectors was found to contain a slight deviation from a pure Gaussian shape, which could influence the determination of the strong-interaction width of the kaonic-hydrogen X-ray lines. The deviation from the pure Gaussian response was treated in two different ways to test systematic effects.

The first analysis used satellite peaks on the left and right flanks. The left flank is generally found in silicon detectors and is defined as a function having a feature decreasing exponentially in intensity towards lower energy [32]. The right flank could be interpreted as an effect of pile-up events and was defined as a Gaussian [33].

In the second analysis, the correction of the “ideal” response was done by convoluting the Gauss function with a Lorentzian (producing symmetric tails) and additionally with an exponential low energy tail.

In both analyses, the kaonic-hydrogen lines were represented by Lorentz functions convoluted with the detector response function, where the Lorentz width corresponds to the strong-interaction broadening of the 1s state. The continuous background was represented by a quadratic polynomial function.

The region of interest of $K^+ d$ X-rays is illustrated in Fig. 4 (c). With the realistic assumption of one order of magnitude lower intensities than that of kaonic hydrogen [31] and predicted values of shift (−0.3)−(−1.0) keV and width (∼1 keV) [34–36], the influence of a possible kaonic-deuteron component on the kaonic-hydrogen shift and width values was found to be negligible.

In the kaonic-hydrogen spectrum, the higher transitions to the 1s level, $K\gamma$ and above, produce an important contribution to the total intensity. The relative intensities of these lines, however, are only poorly known from cascade calculations and the free fit cannot accurately distinguish between them, since their relative energy differences are smaller than their width, as seen in Fig. 4. As a result, fitting all the transitions at once, leads to large errors on the shift and width of the 1s level. To minimize the influence of the higher transitions, we adopted the following iterative fitting procedure. In a first step, we performed a free fit of all the transitions, with the energy differences between the kaonic-hydrogen lines fixed by their EM differences, since the shifts and the widths of the levels higher than 1s are negligible. In a second step, we fixed the energies and the widths of the higher transitions to the values found in the first step, and fitted leaving free all intensities and the common shift and width for $K\alpha$ and $K\beta$, which are well resolved transitions. With the new values for shift and width we repeated the described procedure until the values for the shift and width converged, meaning that all K-lines had the same values for their shift and width, as it should be.

We performed two independent analyses, where the event selection, the calibration method, the fit range and the detector response function (as described above) were chosen differently. The comparison of the shift and width values gives a direct measurement of the systematic error from the use of differing procedures. The resulting shift values were consistent with each other within 1 eV, however the width differed by ∼40 eV which comes mainly from the use of different detector-response functions. For shift and width we quote here the mean value of the two analyses and take into account the difference as one of the sources of the systematic error.

As a result, the 1s-level shift $\epsilon_{1s}$ and width $\Gamma_{1s}$ of kaonic-hydrogen were determined to be

$$\epsilon_{1s} = -283 \pm 36(\text{stat}) \pm 6(\text{syst}) \text{ eV}$$

and

$$\Gamma_{1s} = 541 \pm 89(\text{stat}) \pm 22(\text{syst}) \text{ eV},$$

respectively, where the first error is statistical and the second is systematic. The quoted systematic error is a quadratic summation of the contributions from the ambiguities due to the SDD gain shift, the SDD response function, the ADC linearity, the low-energy tail of the kaonic-hydrogen higher transitions, the energy resolution, and the procedural dependence shown by independent analysis.

If we could fix the intensity pattern of all transitions, which would be possible if more accurate cascade calculations existed, the statistical error would be better than ±25 eV for shift and ±55 eV for width.

4. Conclusion

In conclusion, we have performed the most precise measurement of the K-series X-rays of kaonic hydrogen atoms. This was made possible by the use of new triggerable X-ray detectors, SDDs, developed in the framework of the SIDDHARTA project, which lead to a much improved energy and time resolution over the past experiments [9,13] and much lower background in comparison with the DEAR experiment.

The strong-interaction 1s-energy level shift and width of kaonic hydrogen are plotted in Fig. 5 along with the results of the previous two measurements, E228 [9] and DEAR [13]. The error bars correspond to quadratically added statistical and systematic errors.

**Fig. 5.** Comparison of experimental results for the strong-interaction 1s-energy-level shift and width of kaonic hydrogen, KEK-PS E228 [9] and DEAR [13]. The error bars correspond to quadratically added statistical and systematic errors.

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Our determination of the shift and width does provide new constraints on theories, having reached a quality which will demand refined calculations of the low-energy $K\bar{N}$ interaction.

For further study of the $K\bar{N}$ interaction, it is essential to measure the kaonic-deuteron K-series X-rays to disentangle the isoscalar and isovector scattering lengths. The present result combined with deuteron data to be collected in the SIDDHARTA-2 experiment [37] will provide invaluable knowledge about the behavior of low-energy QCD in the strangeness sector.

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