Observation of Kaonic Hydrogen K_α X Rays

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We have measured the shift and width of the kaonic hydrogen $1s$ state due to the $\overline{K}N$ strong interaction. We have observed, for the first time, distinct K-series kaonic hydrogen x rays with good signal-to-noise ratio in the energy spectrum. The measured energy shift and width were determined to be $\Delta E(1s) = -323 \pm 63(\text{stat}) \pm 11(\text{syst})$ eV (repulsive) and $\Gamma(1s) = 407 \pm 208(\text{stat}) \pm 100(\text{syst})$ eV, respectively. [S0031-9007(97)02992-X]

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The determination of the strong-interaction energy level shift and width of the kaonic hydrogen x rays is one of the most important subjects for the understanding of the $\overline{K}N$ interaction. It is strongly affected by the presence of the $\Lambda(1405)$ subthreshold resonance. The study of the $\overline{K}N$ interaction is also relevant to the important question of K^- condensation in dense matter [1,2].

The observation of the shift and width of the kaonic hydrogen $K_\alpha(2p \rightarrow 1s)$ x rays gives direct information about the $\overline{K}N$ s-wave interaction at the K^-p threshold energy in a fairly model independent way [3]. The status of the study was quite puzzling due to the contradiction between the signs of the scattering lengths obtained by the previous x-ray measurements [4–6] and those extracted from the analyses of the low energy $\overline{K}N$ data, e.g., Refs. [7–9], as shown in Fig. 1. This contradiction is known to be almost impossible to reconcile within the conventional theoretical framework. Moreover, the x-ray signals of the previous experiments are very difficult to identify in their spectra. Therefore, a definitive experiment has been long awaited.

We accumulated data for 760 hours at KEK-PS K3. A detailed description of our experimental setup is given in a separate paper [10]. Here we present a short summary.

Optimization of the target density is quite important for this experiment. As a compromise between kaon stopping yield and kaon loss during the atomic cascade due to the Stark effect, we chose to operate the hydrogen

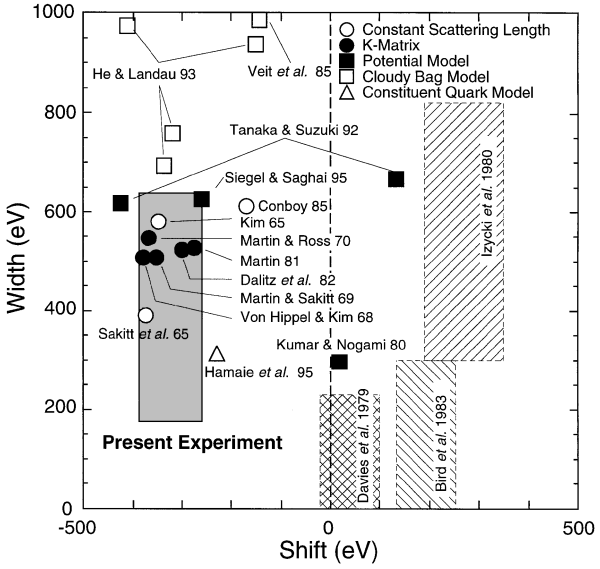

FIG. 1. The energy shift and width of $1s$ state. One-standard-deviation region of shift and width of the previous experiments are plotted together with theoretical calculations. The present result is shown in bold.

target at 4 atm and 100 K ($\sim 0.94 \times 10^{-3}$ g/cm^3) giving an effective thickness of 50 mg/cm^2.

An array of 60 Si(Li) crystals, each with a sensitive area of 200 mm^2, was positioned directly in the hydrogen gas inside the aluminum target vessel to view the stopping volume of the kaons. The inner surface of the vessel was covered by thin titanium (Ti) foils whose fluorescence served as an in-beam energy calibration.

Since the kaon beam is contaminated by pions ($K/\pi \sim 0.01$ just before the target), the timing of the x-ray signal is important for reducing the accidental background. After time walk corrections of the Si(Li) detectors, a resolution of 290 ± 10 nsec (FWHM) was obtained for the summed time spectrum. We defined a "prompt time" gate for kaons with a ±360 nsec width. We recorded the time of beam pions striking the beam counters and rejected signals of the Si(Li) detectors coincident with these pions.

An ^{55}Fe source was inserted periodically when beam was off to determine the calibration of each Si(Li) detector. Only Si(Li) detectors whose resolution was better than 400 eV ($\sim$25 detectors on average) were selected and summed.

The Ti fluorescence x rays in the prompt time gate (shown in Fig. 2) were used as an in-beam energy calibration source to monitor the gain stability. By fitting the summed spectrum of Ti K_{α_1}, K_{α_2}, and K_β with the known intensity ratios and energies [11], we obtained an energy resolution of 407 ± 7 eV (FWHM). This resolution is consistent with that obtained using ^{55}Fe. It is predominantly determined by microphonic noise and its energy dependence is negligible in the region of interest.

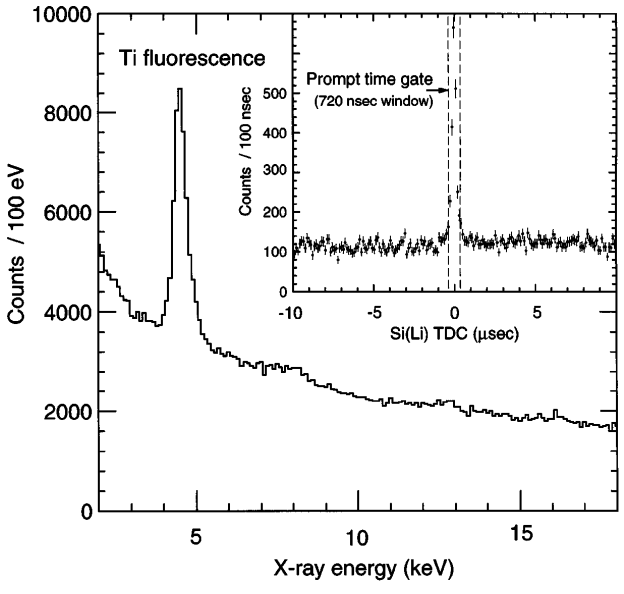

FIG. 2. X-ray spectrum in the prompt time gate. The inset shows the typical x-ray time spectrum for the x rays from 2 to 20 keV. The dashed line is the prompt time gate.

$K^- p$ absorption produces various reaction products including high energy γ rays which were the major background source of the previous experiments. By selecting the branches $K^- p \to \Sigma^\pm \pi^\mp$ followed by $\Sigma^\pm \to n\pi^\pm$, we can exclude all reactions producing high energy γ rays. These branches ($\sim$50%) were identified by tagging on two charged pions.

Furthermore, this two-charged-pion tag enables us to determine the kaon reaction point as a vertex by tracking both pion trajectories. We used two layers of cylindrical wire chambers to reconstruct the vertex point and two layers of plastic scintillation counters to trigger those events. We applied the fiducial selection of the target volume using the vertex point. False triggers caused by high energy electrons, which are mainly produced by γ-ray conversion, were rejected by water Čerenkov counters placed just behind the trigger counters.

In order to identify the formation of kaonic hydrogen atoms and to reject the contaminating in-flight decays/reactions, we utilized the correlation between the kaon range and its time of flight in the hydrogen gas. Because the stopping power of our gaseous target is quite low, the "kaon stop" events have a large delay depending on their range in the gas.

After applying these event selections, we obtained the x-ray energy spectrum shown in Fig. 3. In the spectrum, we clearly observed kaonic hydrogen K-series x rays at about 6 and 8 keV, which are identified to be K_α ($2p$ to $1s$) and K_{complex} ($3p$ or higher to $1s$), respectively. The pure electromagnetic value of the kaonic hydrogen K_α x-ray energy [$E_{\text{EM}}(K_\alpha)$] is 6.480 ± 0.001 keV, which

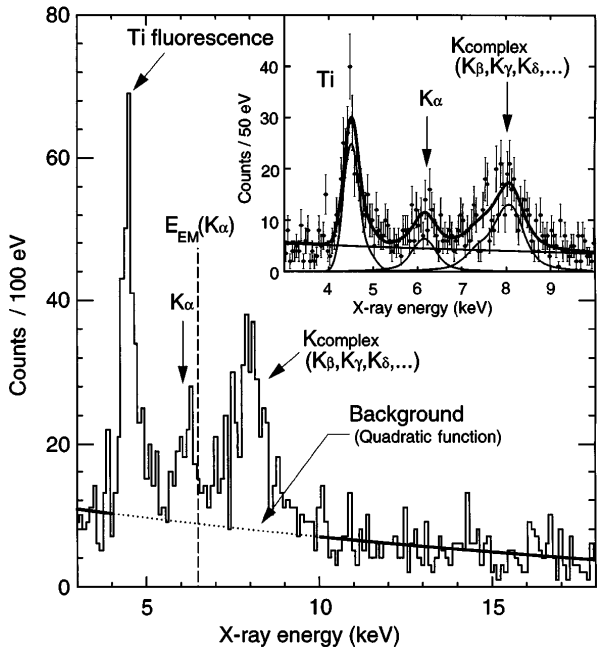

FIG. 3. Kaonic hydrogen x-ray spectrum. The inset shows the result of peak fitting and the components.

includes finite size effect and vacuum polarization. In Fig. 3, $E_{\rm EM}(K_\alpha)$ is plotted as a dotted line. Clearly, the energy of the K_α peak is located on the lower energy side (a repulsive shift) and is broadened.

We utilized a Lorentz function convoluted with a Gaussian function for the detector resolution to represent each x-ray component. We fitted the background of Fig. 3 in the energy region from 3 to 4 and from 10 to 18 keV, where no structure is expected, with a quadratic function.

In order to avoid the uncertainties due to the unknown intensity ratios of the individual K lines, we adopted a fitting strategy that determines the energy and width primarily from the K_α. First we fitted a region around K_α (R_{K_α}, defined below) to determine the peak position and width with fixed background. Then, using these shift and width values to give the position and width of each complex component, we fitted the 3–10 keV region to determine the shape of $K_{\rm complex}$ and Ti fluorescence. We iterated this procedure, treating the tails of $K_{\rm complex}$ and Ti given by the second step as part of the background in the first step, until the energy and width converge. The convergence was quite fast and the contribution of the tail to the K_α fit was small.

R_{K_α} was varied in steps between 0.8 and 2.3 keV centered at 6.1 keV to estimate the systematic uncertainty associated with the procedure. We also evaluated the systematic error originating from the uncertainty of the background spectrum. These are the dominant components of our systematic error and are also normally distributed. Additional systematic errors were estimated for the Si(Li) energy resolution and the absolute energy calibration.

We obtained an energy shift and width of K_α;

$$\Delta E(1s) = E(K_\alpha) - E_{\rm EM}(K_\alpha) = -323 \pm 63 \pm 11 \text{ eV}$$

$$\text{and} \quad \Gamma(1s) = 407 \pm 208 \pm 100 \text{ eV},$$

respectively, where the first error is statistical and the second is systematic. We estimated the K_α yield per stopped kaon to be $1.1 \pm 0.3\%$.

We also examined the same iterative fitting procedure with the relative intensities of the K lines except K_α given by a cascade calculation [12]. The result was consistent with the present one with resonable cascade parameters: [$\Gamma(2p) \sim 0.3$ meV, Stark parameter $k_{\rm STK} = 1.8$ and the kinetic energy of the atom $T_{\rm kin} = 1$ eV]. The relative intensity of K_α obtained by this procedure was in agreement with the cascade calculation within 10%.

Simply applying Deser's formula [3], we obtained the complex scattering length: $A(K^- p) = (-0.78 \pm 0.15 \pm 0.03) + (0.49 \pm 0.25 \pm 0.12)i$ fm.

In Fig. 1, we plot the one-standard-deviation region of the shift and width in comparison with that of the previous experiments and theoretical calculations. As shown in Fig. 1, the shift given in the present experiment is opposite in sign to the previous three experiments and consistent with the analysis of the low energy $\bar{K}N$ data. This resolves the long-standing kaonic hydrogen puzzle.

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