A new measurement of kaonic hydrogen X-rays

INFN-LNF  Shinji Okada
on behalf of SIDDHARTA collaboration

13 June 2011, Hadron 2011 at Munich
A New Measurement of Kaonic Hydrogen X rays

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Abstract

The $\overline{K}N$ system at threshold is a sensitive testing ground for low energy QCD, especially for the explicit chiral symmetry breaking. Therefore, we have measured the $K$-series x rays of kaonic hydrogen atoms at the DAΦNE electron-positron collider of Laboratori Nazionali di Frascati, and have determined the most precise values of the strong-interaction energy-level shift and width of the $1s$ atomic state. As x-ray detectors, we used large-area silicon drift detectors having excellent energy and timing resolution, which were developed especially for the SIDDHARTA experiment. The shift and width were determined to be $\epsilon_{1s} = -283 \pm 36$(stat) $\pm 6$(syst) eV and $\Gamma_{1s} = 541 \pm 89$(stat) $\pm 22$(syst) eV, respectively. The new values will provide vital constraints on the theoretical description of the low-energy $\overline{K}N$ interaction.

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Preprint submitted to Physics Letters B May 17, 2011
Introduction
X-ray spectroscopy of kaonic atoms

The last orbit

$1s$ (only Coulomb)

$2p - 1s$ X-ray ($\sim 6$ keV)

Width: $\Gamma_{1s}$

Shift: $\varepsilon_{1s}$

Nuclear absorption

Kanoic hydrogen case

due to strong int.
Kaonic atoms for $Z \geq 3$

Batty, Friedman and Gal, Phys. Rep. 287 (1997) 385

Shift [eV]

| Atomic Number | Shift [eV] |
|---------------|------------|
| $Z=3$ (Li)    | $n=2$, $n=3$, $n=4$, $n=5$, $n=6$, $n=7$ |
| $Z=92$ (U)    | $n=2$, $n=3$, $n=4$, $n=5$, $n=6$, $n=7$, $n=8$ |

Width [eV]

| Atomic Number | Width [eV] |
|---------------|------------|
| $Z=3$ (Li)    | $n=2$, $n=3$, $n=4$, $n=5$, $n=6$, $n=7$ |
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Global fit with optical potential for $Z \geq 3$

- Imaginary part: large ($W_0 \sim 70$ MeV)
- Real part (depth): allowed to be both deep and shallow
| Z=1 | Kaonic atoms       | transition | energy | status |
|-----|--------------------|------------|--------|--------|
| K-hydrogen | 2p-1s            | 6.5 keV   |        |        |
| K-deuterium |                 | 7.8 keV   |        |        |

| Z=2 | Kaonic atoms | transition | energy | status |
|-----|--------------|------------|--------|--------|
| K-³He | 3d-2p        | 6.2 keV   |        |        |
| K-⁴He |              | 6.4 keV   |        |        |
## Kaonic atoms for $Z = 1$ & $2$

| $Z$ | Kaonic atoms | transition | energy   | status               |
|-----|--------------|------------|----------|----------------------|
| 1   | K-hydrogen   | 2p-1s      | 6.5 keV  | several data         |
|     | K-deuterium  |            | 7.8 keV  | No data so far       |
| 2   | K-$^3$He     | 3d-2p      | 6.2 keV  | No data so far       |
|     | K-$^4$He     |            | 6.4 keV  | several data         |
Kaonic atoms for $Z = 1$ & $2$

| $Z=1$ | Kaonic atoms |
|-------|--------------|
|       | K-hydrogen   |
|       | K-deuterium  |

| $Z=2$ | Kaonic atoms |
|-------|--------------|
|       | K-$^3$He     |
|       | K-$^4$He     |

ALL measured in SIDDHARTA
| Kaonic atoms | <- this talk |
|--------------|--------------|
| **Z=1**      |              |
| K-hydrogen   |              |
| K-deuterium  |              |
| **Z=2**      |              |
| K-$^3$He     | <- previous talk |
| K-$^4$He     |              |
Deser-Truman Formula

\[ \Delta E_1^s - \frac{i}{2} \Gamma_1 = -2\alpha^3 \mu_c^2 a_{K-p} \]

S-wave scattering length “a_{K-p}” expressed with isospin dependent scattering lengths \(a_0\) \((l=0)\), \(a_1\) \((l=1)\)

\[ a_{K-p} = \frac{1}{2} (a_0 + a_1) \]

\(-\) Together with shift & width of K-d atom, \(a_0\) and \(a_1\) can be disentangled by taking into account higher order contributions associated with the K-d three-body interaction.

\[ \Delta E_n^s - \frac{i}{2} \Gamma_n = -\frac{\alpha^3 \mu_c^3}{2\pi M_{K+n}^3} \]

\[ \times T_{KN} \left\{ 1 - \frac{\alpha \mu_c^2}{4\pi M_{K+}} T_{KN}(s_n(\alpha) + 2\pi i) + \delta_{n}^{\text{vac}} \right\} \]

U.-G. Meißner et al, Eur Phys J C35 (2004) 349
\[ QCD \text{ predictions} \]

\[ \pi\text{-H system} \]: successfully described by the chiral perturbation theory

\[ \rightarrow \text{but NOT with } K\text{-H system} \]

due to the presence of \( \Lambda(1405) \) resonance only 25 MeV below threshold

**Chiral SU(3) effective theory**
in combination with a relativistic coupled-channels approach

**Strong elastic K-p amplitude**

\[
 f^{\text{str}}_{K^-p\rightarrow K^-p} = \frac{1}{(8\pi\sqrt{s})} T^{\text{str}}_{K^-p\rightarrow K^-p}.
\]

**DEAR exp. ('95)**

with correction of isospin braking effect

**Kaon-nucleus deeply-bound state ?**

\[ \rightarrow \text{Kaon condensation in dense matter.} \]

\[ B. \text{ Borasoy, R. Nißler & W. Weise} \]

\[ PRL 94, 213401 (2005) \]
History
70-80’s : Kaonic hydrogen puzzle

J. D. Davies et al., Phys. Lett. 83B, 55 (1979)
M. Izycki et al., Z. Phys. A 297, 11 (1980)
P. M. Bird et al., Nucl. Phys. A404, 482 (1983)

EM value
K-p Kα

Attractive shift

theory shows repulsive ...

Liquid target
The first distinct peak @ KEK
2005: Repulsive shift again @ LNF

G. Beer et al., PRL 94, 212302 (2005)
Kaonic hydrogen: Shift vs. Width

- Repulsive shift
- Attractive shift

KEK (1997)

DEAR (2005)

Davies (1979)

Bird (1983)

Izycki (1980)
Kaonic hydrogen: Shift vs. Width

Recent exp.

The data from KEK and DEAR do not agree perfectly ... (despite their relatively large errors)

Davies, Bird, Izycki
do not agree perfectly ... (despite their relatively large errors)

SIDDHARTA : KH measurement again at LNF (after DEAR)

with x-ray detector having excellent timing and energy resolution

drastically improved S/N ratio
Experiment
## Silicon Drift Detector - SDD

|                          | KpX, 1998 | DEAR, 2005 | SIDDHARTA |
|--------------------------|-----------|------------|-----------|
| Detector                 | Si(Li)    | CCD        | SDD       |
| Energy Resolution        | 360 eV    | 180 eV     | 150 eV    |
| Thickness                | sub 10 mm | sub mm     | sub mm    |
| Effective area           | 120 cm²   | 116 cm²    | 114 cm²   |
| Time resolution          | sub μsec  | ~ 30 sec   | sub μsec  |
| Efficiency @ 6keV        | ~ 100 %   | ~ 60 %     | ~ 100 %   |
Difficulty of KH measurement

Density-dependent yield due to Stark mixing

Kaonic Hydrogen

Dipole field

proton

Mixture between $\ell$ and $\ell + 1$

induces transition between different angular momentum state with the same principal quantum number.

-> When target density is high, the high n-state absorption rate will increase.

→ Low density gaseous hydrogen target

→ Low energy Kaon with small energy spread
Φ → K^- K^+ (49.1\%)

Monochromatic low-energy K^- (∼127MeV/c)

Less hadronic background due to the beam
( compare to hadron beam line : e.g. KEK )

Suitable for Kaonic atom exp.
Detect @ Kaon detector
Detect @ SDD

Detect @ Kaon detector
Kapton: $C_{22}H_{10}O_{5}N_{2}$ (polyimide film)

stopped Kaons in Kapton wall

$\rightarrow$ K-C, K-O and K-N are produced (background)
Analysis
Kaon identification

Timing of coincidence signals with respect to the RF signal from DAFNE (~ 368.7 MHz)

two scintillators
Timing on SDDs

Time difference spectrum between kaon arrival and x-ray detection

two scintillators
Energy vs. Timing on SDDs

After slewing correction

KH dataset

Counts $\times 10^2$

Counts $\times 10^3$

Energy vs. Timing on SDDs

Kaon

BG

Kaon gate

Background gate (asynchronous background)
Kaonic Kapton X-rays

K-p and K-d spectra

Hydrogen

Counts / 50 [eV]

Energy [keV]

Deuterium

Counts / 50 [eV]

Energy [keV]

Clearly observed!

Not visible

small signal wide width

Fluorescence X-ray

Kaonic Kapton X-rays

Kapton

C_{22}H_{10}O_{5}N_{2}
Kaonic hydrogen

$K\alpha$  $K\beta$ higher

EM value $K-\rho K\alpha$

Background estimation

Hydrogen

Deuterium

simultaneous fit
Residuals of K-p x-ray spectrum after subtraction of fitted background
The higher transitions contribute dominantly to the total intensity of KH x-rays. However, the intensity pattern of those transitions is only poorly known from cascade calculation (\( \geq K\gamma \)).
determining the shift and width primarily from the $K\alpha$ and $K\beta$ lines

- iterative fit -

|                   | 2p-1s | 3p-1s | 4p-1s | 5p-1s | 6p-1s | 7p-1s | 8p-1s |
|-------------------|-------|-------|-------|-------|-------|-------|-------|
|                   | K$\alpha$ | K$\beta$ | K$\gamma$ | K$\delta$ | K$\epsilon$ | K$\zeta$ | K$\eta$ |
| intensity         | free   | free   | free   | free   | free   | free   | free   |

Shift & Width

| Shift & Width | 1st fit | 2nd fit | 3rd fit | ... | final fit |
|---------------|---------|---------|---------|-----|----------|
| 1st fit       | free    |         |         |     |          |
| 2nd fit       | free    | fixed with previous values |         |     |          |
| 3rd fit       | free    | fixed with previous values |         |     |          |
| ...           |         |         |         |     |          |
| final fit     | free    | fixed with previous values |         |     |          |

until the shifts and widths converged

The statistical errors of the shift and width come predominantly from the statistics of the $K\alpha$ and $K\beta$ lines.
Result
Result

\[ \epsilon_{1s} = -283 \pm 36 \text{(stat)} \pm 6 \text{(syst)} \text{ eV} \]
\[ \Gamma_{1s} = 541 \pm 89 \text{(stat)} \pm 22 \text{(syst)} \text{ eV} \]

SIDDHARTA

KEK-PS E228

DEAR
With a recent theoretical value

B. Borasoy et al., PRC 74, 055201 (2006)

solely from K-p scattering data!!

Chiral SU(3) unitary approaches

B. Borasoy et al., PRC 74, 055201 (2006)

solely from K-p scattering data!!
Conclusion

reached a quality which will demand refined calculations of the low-energy KN interaction

new constraints on theories
Summary
measured Kaonic x-ray spectra with several gaseous targets (Z = 1 and 2):

- K-p: provided the most precise values (submitted) arXiv:1105.3090
  \[ \varepsilon_{1s} = -283 \pm 36 \text{(stat)} \pm 6 \text{(syst)} \text{ eV} \]
  \[ \Gamma_{1s} = 541 \pm 89 \text{(stat)} \pm 22 \text{(syst)} \text{ eV} \]

- K-d: first-time “exploratory” measurement -> small signal (large width)

- K-³He (L-series): first-time measurement (published) PLB 697(2011)199

- K-⁴He (L-series): measured in gaseous target for the first time (published) PLB 681(2009)310

planing the extension “SI DDHARTA2” with improved technique for re-measurement of K-d and other Kaonic atoms
SIDDHARTA Collaboration

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