Precision X-ray spectroscopy of kaonic atoms as a probe of kaon-nucleon/nuclei interaction at low energy

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Laboratori Nazionali di Frascati, INFN
on behalf of SIDDHARTA Collaboration
Introduction
Kaon - Nucleus Interaction

K^- - Nucl. potential

Atomic state

Coulomb

Atomic state

Nuclear state

V_0+iW_0

Precision measurement

Peak search
- direct observation -

SIDDHARTA
J-PARC E17
SIDDHARTA2
e tc...

FOPI
J-PARC
E15/E27/E31
AMADEUS
e tc...

From Dr. S. Okada @ ECT* Trento 2011
QCD predictions near $K$-$p$ threshold

$\pi$-$p$ system: successfully described by the chiral perturbation theory

-> but NOT with $K$-$p$ system
due to the presence of $\Lambda(1405)$ resonance only 25 MeV below threshold

Kaon-nucleus deeply-bound state?
-> Kaon condensation in dense matter.

Chiral SU(3) effective theory with a relativistic coupled-channels approach:
Kp$\to$Kp forward scattering amplitude obtained from the NLO calculation extrapolated to the sub-threshold region
Kaonic atom formation

1. Initial capture

\[ n \sim \sqrt{M^*/m_e}, \quad n' \sim 25 \text{ (for K-p)} \]

(M\(^*\) : K-p reduced mass)

highly-excited state

2. Cascade

deexcite

X-ray

3. Strong interaction

stopped in a target medium
Kaonic atoms

Kaonic hydrogen case

$2p$  

$1s$  

$E_{1s}$  

$E_{1s}(e.m.)$  

$\Gamma_{1s}$  

$\varepsilon_{1s}$  

$K\beta$  

$E_{2p}$  

$K\alpha \sim 6\text{ keV}$
Kaonic atoms

Deser-Truman formula

\[ \epsilon_{1s} + \frac{i}{2} \Gamma_{1s} = 2 \alpha^3 \mu_c^2 a_{K-p} \]

Kaonic hydrogen shift and width

s-wave scattering length using isospin I=0 and I=1 components \(a_0, a_1\):

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

Kaonic hydrogen case

\(K\alpha \sim 6 \text{ keV}\)
Kaonic atoms

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SIDDHARTA gaseous target & beam time

<table>
<thead>
<tr>
<th>target gas</th>
<th>transition</th>
<th>I.L. [pbarn(^{-1})]</th>
<th>type of exp.</th>
<th>significance</th>
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<tr>
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<td>2p-1s</td>
<td>350</td>
<td>precision</td>
<td>best precision</td>
</tr>
<tr>
<td>Deuterium</td>
<td>2p-1s</td>
<td>100</td>
<td>exploratory</td>
<td>first time</td>
</tr>
<tr>
<td>Helium-4</td>
<td>3d-2p</td>
<td>55</td>
<td>precision</td>
<td>first gaseous</td>
</tr>
<tr>
<td>Helium-3</td>
<td>3d-2p</td>
<td>9</td>
<td>precision</td>
<td>first time</td>
</tr>
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# of K : ~ 100 k [events / pbarn\(^{-1}\)]
# of KHe La : ~ 50 [events / pbarn\(^{-1}\)]
Kaonic atoms

Deser-Truman formula

\[ \epsilon_{1s} + \frac{i}{2} \Gamma_{1s} = 2\alpha^3 \mu_c^2 a_{K-p} \]

Kaonic hydrogen shift and width

\[ \mu_c : \text{reduced mass of } K-p \]

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

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\# of K : ~ 100 k [events / pbarn\(^{-1}\)]

\# of KHe Lα : ~ 50 [events / pbarn\(^{-1}\)]
Experiment
Difficulty of Kp and Kd X-ray measurement

Density-dependent yield due to **Stark mixing**

- **Kaonic Hydrogen**
- **Mixture between \( l \) and \( l + 1 \)**
- **Dipole field**
- **Proton**

**Energy**

**Angular momentum**

**Stark mixing (target density dependent)**

- Initial capture: \( n \sim \sqrt{m^*/m_e} \sim 25 \)
Difficulty of Kp and Kd X-ray measurement

Density-dependent yield due to Stark mixing

Stark mixing (target density dependent)

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

Energy

Angular momentum

Initial capture

$n \sim \sqrt{m^*/m_e} \sim 25$
Difficult of $K_p$ and $K_d$ X-ray measurement

Density-dependent yield due to Stark mixing

Kaonic Hydrogen

Mixture between \( l \) and \( l + 1 \)

Existential Auger effect

Electromagnetic interaction only

Initial capture

Stark mixing (target density dependent)

\[ n \sim \sqrt{m^*/m_e} \sim 25 \]

Low density gaseous target

Low energy Kaon with small energy spread
SIDHARTA experiment

DAFNE $e^+e^-$ collider in Frascati

- $\phi \rightarrow K^+ K^-$ (49.1%)
- Monochromatic $K^-$
  (~127 MeV/c, 0.1% momentum bite)
- Low hadronic background comparing to secondary-particle beam line
SIDDHARTA experiment

DAFNE e+e- collider in Frascati

- $\phi \rightarrow K^+ K^- (49.1\%)$
- Monochromatic $K^-$ ($\sim 127$ MeV/c, 0.1% momentum bite)
- Low hadronic background comparing to secondary-particle beam line
- Kaon origin X-ray by timing info. of SDD
- 144 SDDs : 10 % solid angle

SDD features
- $\sim 1$ $\mu$s time resolution
- $1$ cm$^2$ x 144 effective surface
- 150 eV FWHM @ 6 keV
Target cooling system
APD - cooler 8 W @ 20 K

SDD cooling system
Pulse tube cooler
18 W @ 150 K

Turbo molecular pump
Varian 150 L/s
Figure 1: A schematic side view of the SIDDHARTA setup installed at the electron–positron interaction point of DAΦNE. 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 µm and 50 µm 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 µm. 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 µsec 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-\(\alpha\) 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.
Kaon detector

Beam pipe

SDD system

e⁻ e⁺ interaction point

+-

10 cm

Target cell

Degrader

Titanium foils

Copper foil

Lead shield

Vacuum chamber

Kaon detector Beam pipe SDD system e⁻ e⁺ interaction point +− 10 cm Target cell Degrader Titanium foils Copper foil Lead shield Vacuum chamber x y 12
Top-bottom coincidence of scintillators \( K^+K^- \)
Top-bottom coincidence of scintillators $K^+ K^-$

detection by SDD

x-ray
Target material: Kapton
C:O:N = 22:5:2
synchronous background from stopped kaons
Analysis & results
Kaon ID and timing information of X-ray events

Kaon event: coincidence of two scintillators

Kaon coincidence timing w.r.t. DAFNE RF (~368.7 MHz) clock
Kaon ID and timing information of X-ray events

Kaon event: coincidence of two scintillators

Figure 2: Kaon identification using timing of the coincidence signals in the kaon detector with respect to the RF signal of ∼368.7 MHz from DAFNE.

The physics results of the strong-interaction 2p-level shifts of kaonic 3He and kaonic 4He 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 ∼340 pb$^{-1}$ for the hydrogen and ∼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 ∼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.

Figure 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]).
Energy to timing correlation of SDD events

- Synchronous BG from kaon stopped in Kapton
- Kaon gate
- BG gate
- Asynchronous BG from beam

Graph showing energy vs. timing with various peaks and gates indicated.
Kaonic hydrogen

Counts / 50 [eV]

Energy [keV]

Counts / 50 [eV]

Hydrogen

Deuterium

$K\alpha$

$K\beta$ higher

$\varepsilon_{1s}$
Kaonic hydrogen

Simultaneously fit

Background estimation

Hydrogen

Deuterium
Residuals of $K$-$p$ spectrum after the subtraction of the fitted background.
Residuals of $K\rho$ spectrum after the subtraction of the fitted background shift and width determined by $K\alpha$, $K\beta$

Higher

$K_{\gamma}$, $K_{\delta}$ ...
relative yield unknown
Results on $K$-$p\ 1s$ state shift and width

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

Best precision
Results on $K$-$p$ 1s state shift and width

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

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

Best precision

coupled-channels method with for chiral SU(3) dynamics; best fit to together with scattering data

Tomozawa Weinberg (TW)
Deser-Truman formula

\[ \epsilon_{1s} + \frac{i}{2} \Gamma_{1s} = 2 \alpha^3 \mu_c^2 a_{K-p} \]

Kaonic hydrogen shift and width

\[ \mu_c : \text{ reduced mass of } K-p \]

s-wave scattering length using isospin I=0 and I=1 components \( a_0, a_1 \):

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

Kaonic deuterium X-ray measurement:
key to obtain the isospin-dependent antikaon-nucleon scattering lengths at threshold.

➡ breakthrough in the low energy QCD.
SIDDHARTA-2 goal

SIDDHARTA Collaboration / Nuclear Physics A 881 (2012) 88–97

Fig. 6. A global simultaneous fit result of the X-ray energy spectra of hydrogen and deuterium data. (a) Residuals of the measured kaonic-hydrogen X-ray spectrum after subtraction of the fitted background, clearly displaying the kaonic-hydrogen \( K^+p \) transitions. The fit components of the \( K^-p \) transitions are also shown, where the higher transitions, greater than \( K^+\beta \), are summed. (b), (c) Measured energy spectra for each data set. Fit components of the background X-ray lines and a continuous background are also shown. The dot-dashed vertical line indicates the EM value of the kaonic-hydrogen \( K^+_\alpha \) energy. (Note that the characteristic \( K^+_\alpha \) line consists of \( K^+_\alpha 1 \) and \( K^+_\alpha 2 \) lines, both of which are shown.)

The characteristic X rays come from high-purity titanium and copper foils installed for in-situ X-ray energy calibration.

There are three background X-ray lines overlapping with the kaonic-hydrogen signals: kaonic oxygen 7–6 (6.0 keV), kaonic nitrogen 6–5 (7.6 keV) and the characteristic X ray of copper \( K^+_\alpha \) (8.0 keV). In the fitting procedure of the kaonic-hydrogen spectrum, it turned out to be essential to use the kaonic-deuterium spectrum to quantify the kaonic background X-ray lines. Therefore, we performed a simultaneous global fit of the hydrogen and deuterium spectra, where the intensities of the background X-ray lines were determined using both spectra and a normalization factor defined by the intensity ratio of the high-statistics kaonic-carbon 5–4 peak seen in both spectra. In Fig. 6(b) and (c), the resulting fit lines are shown together with components of

\[ Y(K_\alpha) < 0.39\% \text{ (CL 90\%)} \]

NPA 907 (2013) 69

K-d yield upper limit:

\[ Y(K_\alpha) < 0.39\% \text{ (CL 90\%)} \]

NPA 907 (2013) 69

Fit result (all intensities free) sample 1

shift = -556+-86 eV  
width = 1284+-145 eV
## Improvement factors

### MC simulation - summary

<table>
<thead>
<tr>
<th>factor</th>
<th>new geometry &amp; gas density</th>
<th>timing resolution</th>
<th>$K^\pm$ discrimination</th>
<th>del'd anti-coinc.</th>
<th>prompt anti-coinc.</th>
<th>total impr. factor</th>
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<td>kaonic X-rays wall stops</td>
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<td>continuous background / Signal /keV</td>
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<td><strong>2</strong></td>
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<td><strong>15.2</strong></td>
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<td>beam background (asynchron)</td>
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<td><strong>1.5</strong></td>
<td><strong>3</strong></td>
<td></td>
<td></td>
<td><strong>21.6</strong></td>
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From Dr. C. Curceanu, presentation at 45th LNF-INFN Scientific Committee, November 2012
Prototype of the new 4x2 SDD array

SDD-chip back side with bonding pads
SDD-chip glued to ceramic board, bonded to CUBE preamplifier
Summary

❖ kaonic atom X-rays successfully measured with gaseous targets of Z = 1 & 2

• K-p : 1s shift and width determined to the best precision
• K-d : first exploratory measurement
• K-\(^3\)He : strong-shift of 2p state determined for the first time
• K-\(^4\)He : measured for the first-time with a gaseous target

• K-Kapton : yield of X-rays for KO and KN

❖ SIDDHARTA-2 is planning the first precision measurement of the K-d X-ray
SIDDHARTA Collaboration


Appendix
Past experiments-1

P. M. Bird et al. 1983

Shift [eV]  
0  500

Width [eV]  
0  1000

Repulsive shift

Attractive shift

KEK
(1980)

HVD
(1983)

Davies
(1979)

Bird
(1983)

Izycki
(1980)

(1980)

(2005)

(1979)

(1997)

(2005)

P. M. Bird et al. 1983

liquid target
Past experiments-2

KEK-PS E228 (KpX) 1997

DEAR DAFNE 2005
FIG. 5. Density dependence of $K^-p$ atom x-ray yields with varying $(\delta E_{1s})_{\text{strong}}$ and $\Gamma_{\text{abs}}^{1s}$. The solid lines and the dashed lines are the cases which suffer the strongest (Conboy et al. [10]) and the weakest (Tanaka and Suzuki [11]) Stark effects among the parameters given in Table I, respectively. The other cases in Table I lie between these lines. The width $\Gamma_{\text{abs}}^{2p}$ is taken to be 1 meV. The free parameter $k_{\text{stk}}$ is fixed to 2.0.

FIG. 10. Density dependence of $K^-d$ atom x-ray yields with varying the strong-interaction parameters. The solid lines are the case of Martin’s $K$ matrix + Fermi average + binding effect. The dashed lines are for Batty’s optical potential.

~ 1/10 yields
kaonic helium \(2p\) shift results

<table>
<thead>
<tr>
<th></th>
<th>(2p) shift [eV]</th>
<th>Reference</th>
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<tbody>
<tr>
<td>KEK E570</td>
<td>(+2 \pm 2 \pm 2)</td>
<td>PLB653(2007)387</td>
</tr>
<tr>
<td>SIDDHARTA (He4)</td>
<td>(0 \pm 6 \pm 2)</td>
<td>PLB681(2009)310</td>
</tr>
<tr>
<td>SIDDHARTA (He3)</td>
<td>(-2 \pm 2 \pm 4)</td>
<td>PLB697(2011)199</td>
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</table>

**Fig. 5.** Energy spectrum of the kaonic \(^3\)He X-rays in coincidence with the \(K^+K^-\) events. The kaonic \(^3\)He \(3d \rightarrow 2p\) transition is seen at 6.2 keV. Together with this peak, small peaks are seen, which are the kaonic atom X-ray lines produced by kaons stopping in the target window made of Kapton (polyimide), and the Ti K\(\alpha\) line at 4.5 keV.

**Fig. 5.** Energy spectrum of the kaonic \(^4\)He X-rays in coincidence with the \(K^+K^-\) events. Together with the accidental coincidence events of the Ti and Mn X-rays, the kaonic \(^4\)He L\(\alpha\) line is seen at 6.4 keV.
preliminary kaonic hydrogen yield

Kp $K\alpha$ yield with comparison to cascade calculation

$K_{all}$

\[0.012 + 0.003 - 0.004\]

$K_{\alpha}$

\[0.043 + 0.011 - 0.012\]

$K_{complex}$

\[0.012 + 0.003 - 0.004\]

However, experimentally, instead of $K_{all}$, systematic error for $K_{complex}$ is easier to assign, and the result is:

\[K_{complex} \quad 0.029 + 0.008 - 0.009\]