High-resolution hadronic atom X-ray spectroscopy with cryogenic detectors

Shinji OKADA (RIKEN)

The HEATES collaboration
- High-resolution Exotic Atom X-ray spectroscopy with TES microcalorimeter -

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RIKEN¹, NIST², INFN-LNF³, Lund Univ.⁴, Univ. of Tokyo⁵, KEK⁶, Tokyo Metropolitan Univ.⁷, Stefan Meyer Institut⁸
New idea

Novel Cryogenic Detector (TES) × DAFNE Kaon Factory

Ultra-high resolution

Unique facility for low-ene K-2

TES
2 ~ 3 eV FWHM

SDD
200 eV FWHM

two orders of magnitude improved resolution
compared with the conventional semiconductor detector
1. Introduction - Missions at the DAFNE K-atom factory

2. Detector - Transition-Edge Sensor (TES)

3. Experiment - K-mass measurement at DAFNE

4. Test experiment - in-beam performance of TES

5. Summary
1. Introduction

Missions at the DAFNE K-atom factory
Kaonic atom

strong-interaction study
the most tightly bound energy levels that are the most perturbed by the strong force

Small $n$

Large $n$

Kaon mass
the higher orbit having almost no influence on the strong interaction
Two major puzzles on K-atom

1. K - nucleus potential puzzle
   - Deep or Shallow? (because of insufficient K-atom data)

2. K- mass puzzle
   - The recent two measurements disagree by more than 5 sigma!
Two major puzzles on K-atom

1. K - nucleus potential puzzle
   - Deep or Shallow? (because of insufficient K-atom data)

2. K- mass puzzle
   - The recent two measurements disagree by more than 5 sigma!
Many measurements so far

shift & width as a function of atomic number $Z$

$\pi^-$ atoms  $K^-$ atoms  $\bar{\rho}$ atoms  $\Sigma^-$ atoms

Shift [eV]  Width [eV]  Atomic number $Z$

Strong Interaction Physics From Hadronic Atoms
Open problem on K-atom

Different scenarios for different exotic atoms

<table>
<thead>
<tr>
<th>particle</th>
<th>real potl.</th>
<th>imaginary potl.</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^-)</td>
<td>repulsive in bulk</td>
<td>moderate</td>
<td>excellent data</td>
</tr>
<tr>
<td></td>
<td>attractive on surface</td>
<td></td>
<td>well understood</td>
</tr>
<tr>
<td>(K^-)</td>
<td>attractive</td>
<td>moderate</td>
<td>good data</td>
</tr>
<tr>
<td></td>
<td>deep or shallow?</td>
<td></td>
<td>open problems</td>
</tr>
<tr>
<td>(\bar{p})</td>
<td>??</td>
<td>very absorptive</td>
<td>excellent data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>understood</td>
</tr>
</tbody>
</table>

E. Friedman : MESON2010 conf.
# K-atom: theoretical approaches

<table>
<thead>
<tr>
<th>model</th>
<th>Density-dep. optical potential</th>
<th>SU(3) chiral unitary</th>
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<td></td>
<td>[ V = -\frac{2\pi}{\mu} \left( 1 + \frac{\mu}{m} \right) \bar{\alpha} \rho(r), ] [ a \rightarrow a_0 + A_0 [\rho(r)/\rho(0)]^\alpha, ]</td>
<td>[ 2\mu V_{opt}(r) = -4\pi \eta\alpha_{eff}(\rho) \rho(r), ]</td>
</tr>
<tr>
<td>exp. data vs calc. results</td>
<td><img src="https://example.com/fig1.png" alt="Image" /></td>
<td><img src="https://example.com/fig2.png" alt="Image" /></td>
</tr>
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Both are well fitted and reproduced! However...
Deep or shallow?

Potential depth

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Open problem

Deep

(-$V_{\text{Real}} = 150 \sim 200$ MeV)

Shallow

(-$V_{\text{Real}} = 40 \sim 60$ MeV)

The number of the kaonic nuclear bound states would be different (depending on the nucleus).

“deeply-bound” K- clusters?
The calculated results agree with the experimental data well. The quality of the agreement is as good as the phenomenological model of Batty et al.

The energy levels for atomic kaonic states in O and Ca are comparable with those of the SU(3) chiral unitary model. This model does not contain any free parameter to reproduce the data.

The real part of this effective scattering length also changes its sign from negative to positive (repulsive to attractive) around the zero density. In addition, the results are similar to Batty’s model. The real part of the density-dependent term as follows:

\[ V_{\text{eff}}(r) = V_{\text{pot}}(r) + V_{\text{Coul}}(r) \]

where

- \( V_{\text{pot}}(r) \) is the parametrized optical potential to be a nonlinear function of the free kaon-nucleon scattering lengths at threshold and
- \( V_{\text{Coul}}(r) \) is the Coulomb transition energy.

In 1980, a theoretical explanation of this feature was understood by a density dependent interpretation. There have been two controversial analyses in the 1970’s, one of which is a relatively “deep” density-dependent term as follows:

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In the framework of multiple scattering theory as formulated by C.J. Batty, E. Friedman, A. Gal, and A. Okumura, the phenomenological potential is expressed by replacing the proton and neutron density distributions with those of the nuclear mass number. In coordinate space this potential depth can be expressed as:

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   - The recent two measurements disagree by more than 5 sigma!
K- mass puzzle

WEIGHTED AVERAGE
493.677 ± 0.013 (Error scaled by 2.4)
± 0.016 (Error scaled by 2.8)

13 keV

Difference
60 keV

Most recent
two experiments

Pb, W

C

Error:
7 [keV]
11 [keV]

K-mass : fundamental quantity

awaited for new measurement!

Requirements:

1. high-resolution detector

2. K-atom with low-Z gas target
to reduce the electron screening effects which could cause an uncertainty of K-mass value
DAFNE e+ e- collider:

- $\Phi \rightarrow K^- K^+ (49.1\%)$
- Monochromatic low-energy $K^- (\sim 127\text{MeV/c})$
- Less hadronic background due to the beam

We can efficiently stop Kaons at gas target
Missions at DAFNE K-atom factory

**complete K-atom data acquisition**

- large width
- low intensity
  - \( \Rightarrow \) SDD etc.

- small width
- high intensity
  - \( \Rightarrow \) TES

- \( ^1 \)s level of K-p, \textbf{K-d} (K-He)
- other K atoms

- \( ^2 \)p level of K-He, K-Li etc...
- other higher level of K-atom

**K-mass** measurement

- SIDDHARTA-2
2. Detector
High-resolution detectors

1. Crystal spectrometer

- Spherically bent Bragg crystal
- Position-sensitive detector
- Charge-Coupled Device (CCD)
- Cyclotron trap gas cell

pionic atom exp.: D. Gotta (Trento’06)

→ small acceptance

2. Cryogenic detector

- TES microcalorimeter
- For now: use TESs designed for 5–10 keV X-rays
- 1 pixel ~ 350 x 350 μm²

W.B. Dorisese, TES Workshop @ ASC (Portland), Oct 8, 2012
Why TES? (1)

The solid angle of a crystal spectrometer (PLB 416 (1998) 50) was converted to the equivalent effective area.

Effective area [mm$^2$]

Silicon detectors
going more...
(toward mega pixel)

TES multiplexing technology
1 pixel
240 pixel

Crystal spectrometer
(Wavelength-dispersive x-ray spectrometer)
Why TES? (2)

✓ Compact and portable

TES system

Crystal spectrometer

G. Beer et al., PLB 535 (2002) 52
X-ray microcalorimeter

a thermal detector measuring the energy of an incident x-ray photon as a temperature rise (= E/C ~ 1 mK)

Decay time constant = C / G (~ 500 μs)

Absorber with larger “Z” (to stop the high energy x-rays)

- Absorber: Bi (320 um × 300 um wide, 4 um thick)
- Thermometer: thin bilayer film of Mo (~65nm) and Cu (~175nm)
TES = Transition Edge Sensor

using the sharp transition between normal and superconducting state to sense the temperature

\[ \alpha \equiv \frac{d \ln R}{d \ln T} \sim 10^{2\sim3} \]

Energy resolution (\(\sigma\))

\[ \Delta E = \sqrt{\frac{k_B T^2 C}{\alpha}} \]

(Johnson noise and phonon noise are the most fundamental)

Dynamic range

\[ E_{\text{max}} \sim C T C / \alpha \]

Trade-off between dynamic range and energy resolution: \(\Delta E \sim \sqrt{E_{\text{max}}}\)

Thermometer sensitivity

\[ \alpha \equiv \frac{d \ln R}{d \ln T} \sim 10^{2\sim3} \]

Width of transition edge \(\Delta E \sim \text{a few mK}\)

\[ E_{\text{max}} \sim C T C / \alpha \]

--> developed by Stanford / NIST at the beginning

applications: astrophysics (space satellite) etc.
NIST’s TES array system for x-rays

e.g., soft-X-ray spectroscopy @ BNL

NIST’s standard TES

- 1 pixel : 300 x 320 μm²
- 240 array : total ~ 23 mm²
- 2~3 eV (FWHM) @ 6 keV

well established system!

NSLS U7A:
soft-X-ray (200–800 eV) spectroscopy beamline.

installed: late 2011

two-order improved resolution

~ 200 eV (FWHM) @ 6 keV
... a typical Silicon detector used in the previous K-atom exp.

W.B. Dorise, TES Workshop @ ASC (Portland), Oct 8, 2012
NIST’s TES for gamma-rays for 100 - 400 keV

e.g., hard-X-ray spectroscopy

absorbers: Sn

1.45 mm

0.38 mm

NIST’s standard TES

• 1 pixel: 1.45 x 1.45 mm²
• 256 array: total ~ 5 cm²
• 53 eV (FWHM) @ 97 keV

State-of-art high-purity germanium detectors

an order improved resolution

3. Experiment

K-mass measurement at DAFNE
Possible simple experimental setup

- Lead shield
- Nitrogen gas target
- TES array
- TES Cryostat (ADR)

*might possible to install them at bottom side (during K-d measurement)*
Possible simple experimental setup

Lead shield

Nitrogen gas target

TES Cryostat (ADR)

TES array

\[ e^+ \Phi e^- \]

might possible to install them at bottom side (during K-d measurement)
Possible simple experimental setup

Back-to-back Kaon detection

Lead shield

Nitrogen gas target

TES Cryostat (ADR)

might possible to install them at bottom side (during K-d measurement)
Possible simple experimental setup

- Lead shield
- Nitrogen gas target
- X-ray detection by TES
- TES Cryostat (ADR)

Back-to-back Kaon detection

X-ray detection by TES

might possible to install them at bottom side (during K-\(d\) measurement)
Rough yield estimation: K-N 6-5 x-ray (7.6 keV)

Estimated based on DEAR / SIDDHARTA data (just scaled):

- **TES array**: 240 pixel ~ 23 mm$^2$ effective area
- TES located the same position as SDD’s at SIDDHARTA
- Target cell located the same position as that of SIDDHARTA
- Nitrogen gas density: 3.4 $\rho_{\text{STP}}$
  - KN 6-5 x-ray ~ 3 events / day (4.5 pb$^{-1}$)

Assumed improvements:

- ✔️ Bring TES close to target (x ~3)
- ✔️ Bring target close to interaction point (x ~3)
- ✔️ Higher nitrogen gas density (x ~2)

~ 50 events / day (4.5 pb$^{-1}$)
Estimated stat. accuracy of K-mass

assuming:

- K-N 6-5 x-ray $\sim$ \textbf{1500 events / month} (135 pb$^{-1}$)
- Energy resolution $\sim$ 6.5 eV (FWHM)
- No background

Stat. accuracy: $\Delta E$ (x-ray energy) $\sim$ ± 0.07 eV
$\Delta m$ (K-mass) = $\Delta E / E \times m$ $\sim$ ± 4.6 keV

possible improvements for more yield:

 ✓ weak magnetic lens to collect K- at small target
 ✓ polycapillary X-ray lens …
4. Test experiment

in-beam performance of TES
Feasibility test towards K-atom expt.

- **aim**: studying in-beam performance of TES
  - the first measurement of hadronic-atom x-rays with TES
- **when?**: 27 Oct - 5 Nov, 2014 (just finished last week!)
- **where?**: Paul Scherrer Institute (PSI), PiM1 beamline

### schematic view

- **π beam**
  - (~1 MHz/mA, 170 MeV/c)
- **moderator**
- **π-atom x-ray**
- **TES**
- **x-ray tube**
- **target**

- **Pionic carbon**
  - 4f-3d x-rays ~ 6.5 keV
  - no strong-interaction shift & width
  - higher yield (~1200 events / hour)
Experimental setup at PSI PiM1 beamline

- π beam
- Refrigerator (ADR)
- TES arrays
- Carbon moderators
- X-ray tube
- Silicon detector system

For energy calibration: $\pi$ for $\pi$-atom x-rays

With conventional technique: 10 cm
Photos

π beam

TES system
Exotic-atom x-rays with TES for the first time!

Timing difference between the beam and X-rays

- Time resolution \( \approx 0.95 \mu s \) (FWHM)

Energy-timing correlation

**\( \pi C \ 4-3 \)**

- **blue**: without timing cut
- **red**: with timing cut (scaled x10)

\( 6.5 < t < 8.5 \) [\( \mu s \)]

X-ray spectrum with/without timing cut

- FeKa1
- FeKa2
- \( \pi C \ 4-3 \)

Very preliminary
5. Summary
take-home messages

Ultra-high-resolution x-ray spectrometer

1. “TES microcalorimeter” is now available as a powerful tool for exotic-atom research

2. “TES x DAFNE” could provide valuable physics outputs related Kaonic atoms