Applications of superconducting transition-edge sensors (TES) for next-generation x-ray spectroscopies

TES principle

Motivation

Application

21st June 2013, Hideyuki Tatsuno, INFN LNF

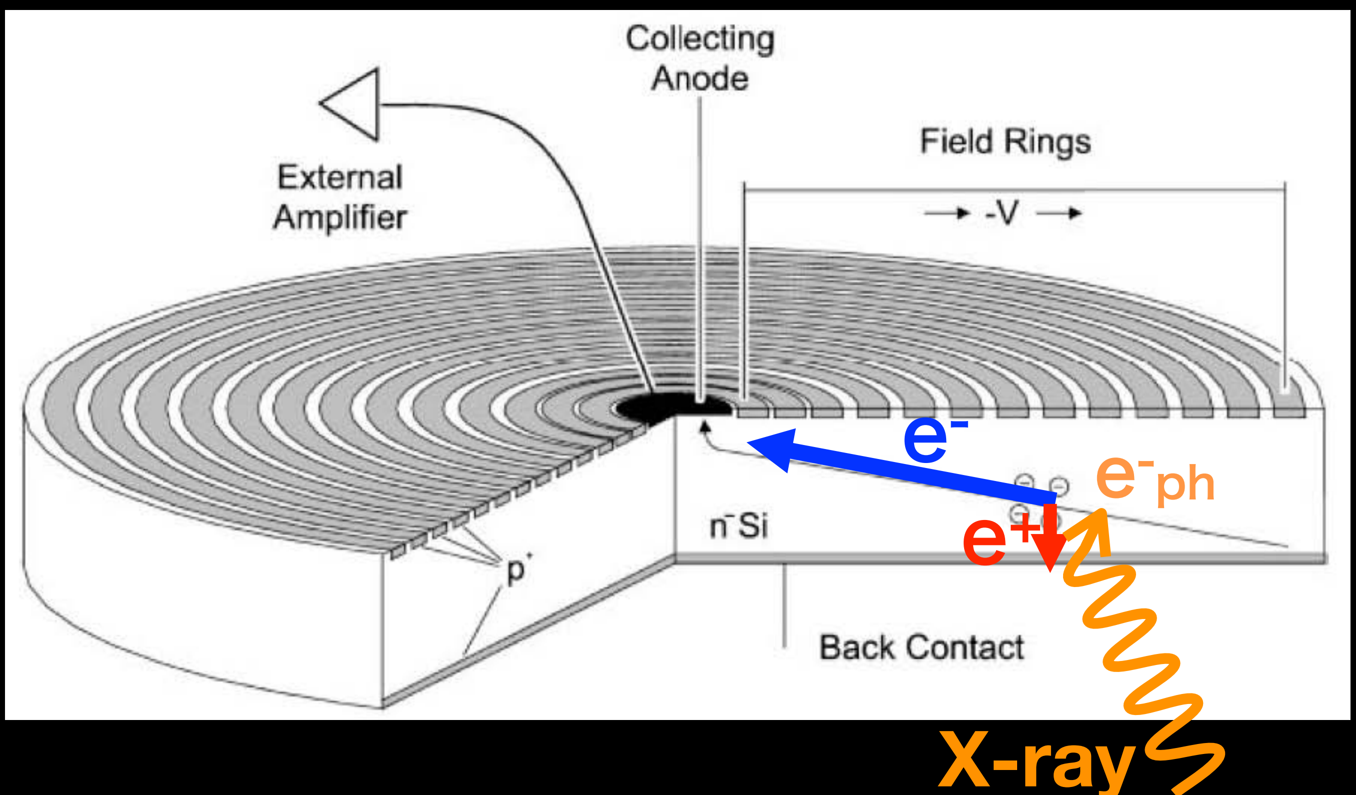
grate thanks to *Shinji Okada, RIKEN*

Single photon detector

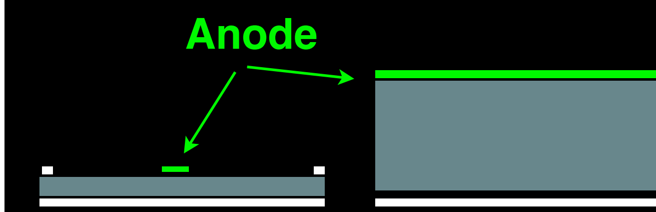
- ✓ large area
- ✓ multi-channel or array
- ✓ mobility
- ✓ high energy resolution
- ✓ timing information

Silicon Drift Detector - SDD

small anode capacitance (<pF) → high resolution



SDD	Si(Li)



resolution (FWHM) at 6keV

150eV	350eV

drift time ~1μs

<u>large active area</u> (1cm²) and <u>very thin</u> (450μm)

↳ *high X-ray yield*

↳ *suppress Compton scattering background*

Next-Generation

Single photon detector

× ~~large area~~ 0.35mm x 0.35mm

✓ multi-channel or array

160 array (or more)

✓ mobility

✓ ultra-high energy resolution

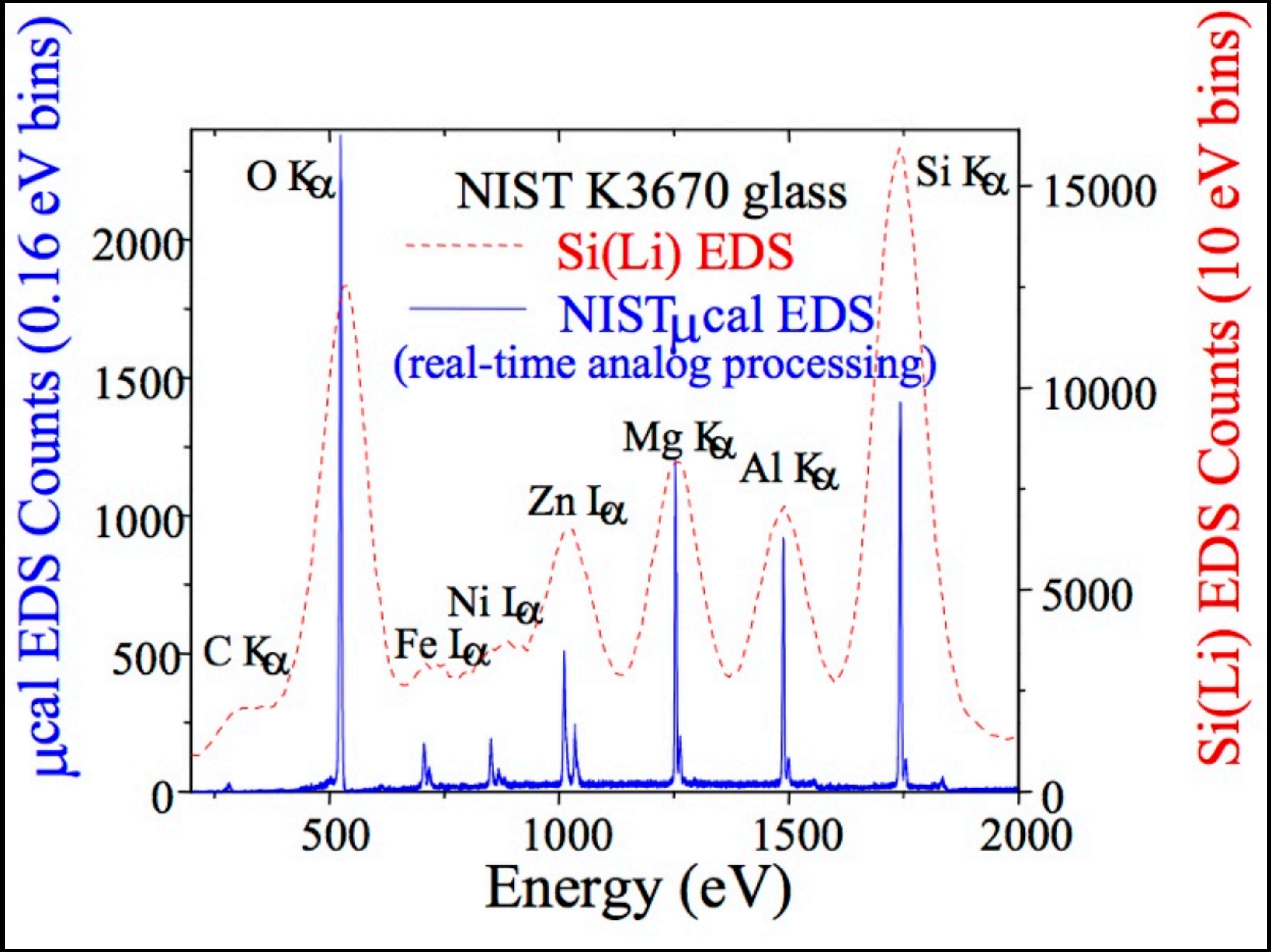
200 eV (FWHM) → 2 eV (FWHM)

✓ timing information

~100 usec

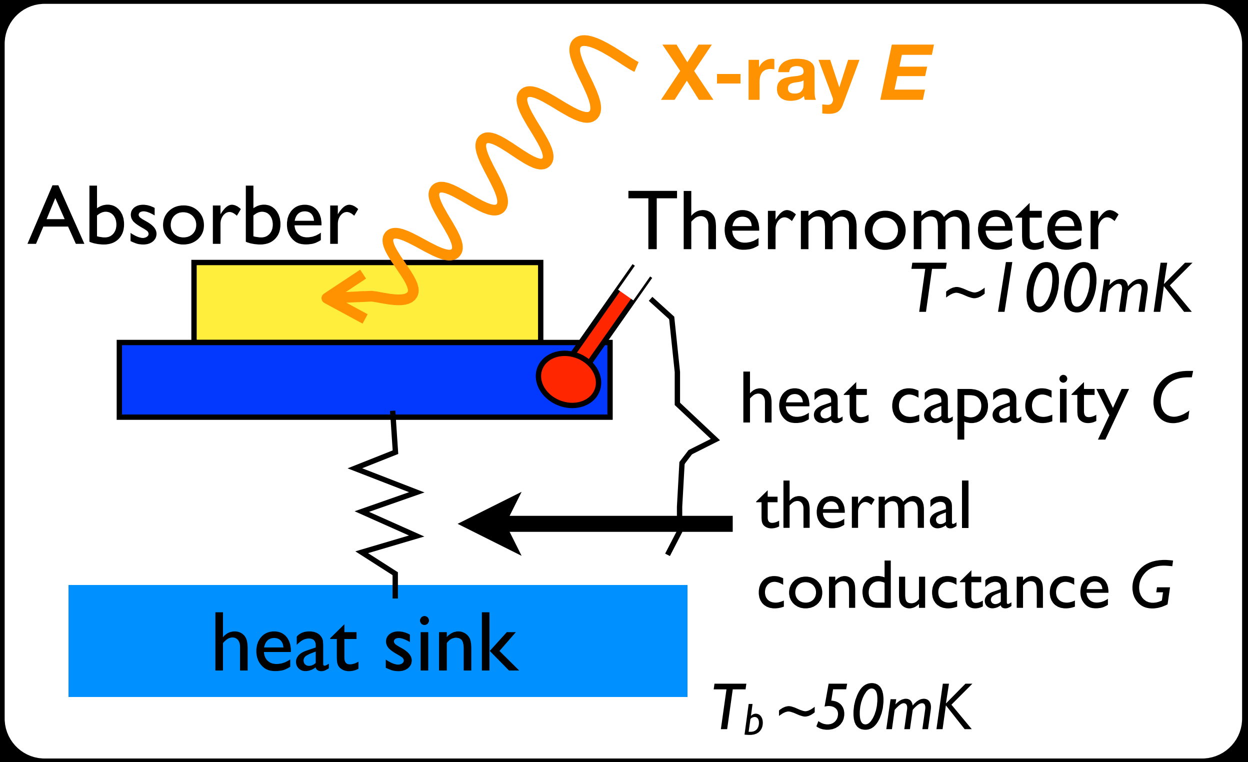
Micro-Calorimeter

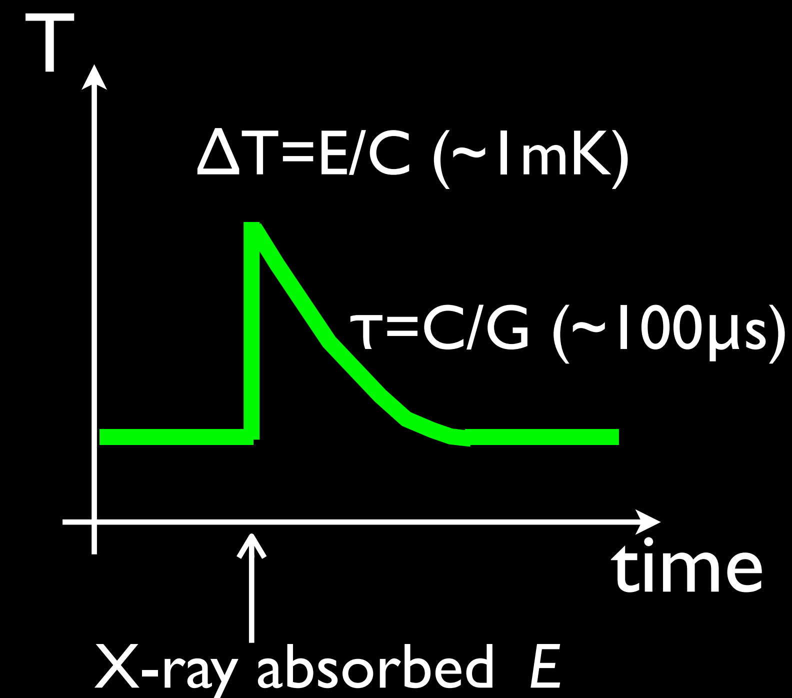
data of μcal and Si(Li) @NIST (from SNIC2006 slide by Joel Ullom)



Micro-Calorimeter

*S. H. Moseley, J. Mather and D. McCammon, J. Appl. Phys., **56**: 1257 (1984)*





Number of phonons in the sensor

$$N \sim CT/k_B T = C/k_B$$

Thermal fluctuation

$$\sqrt{N} k_B T = \sqrt{k_B T^2 C}$$

Energy resolution

$$\Delta E = \xi \sqrt{k_B T^2 C}$$

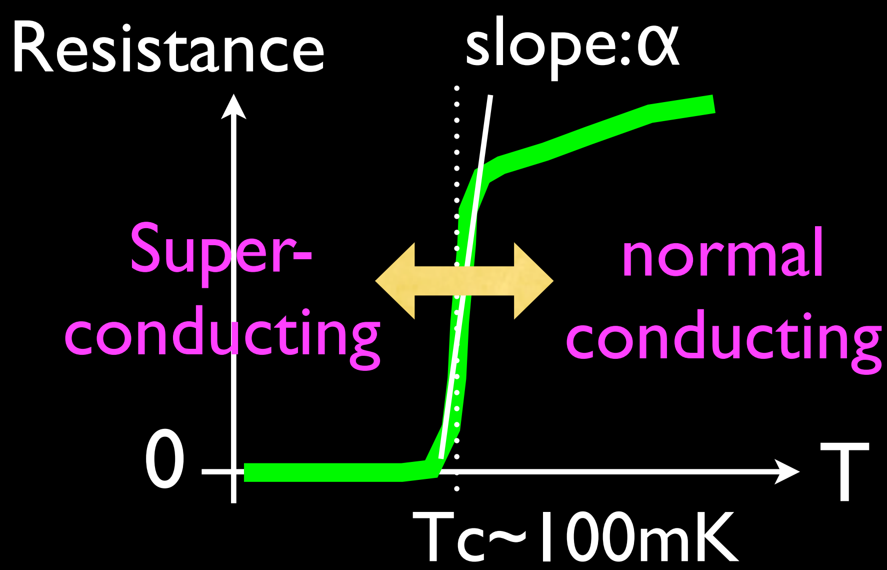
ξ: coefficient for thermometer's intrinsic noise

Superconducting TES

*S. H. Moseley, J. Mather and D. McCammon, J. Appl. Phys., **56**: 1257 (1984)*

TES = thermometer

sensitive to the very small temperature difference ΔT=1mK



slope $\alpha = \frac{d \ln R}{d \ln T}$ ~1000

$$\Delta E_{FWHM} = 2.35\sqrt{\frac{4k_B T^2 C}{|\alpha|}\sqrt{\frac{n}{2}}}$$

T dependent conductance $G \propto nT^{n-1}$

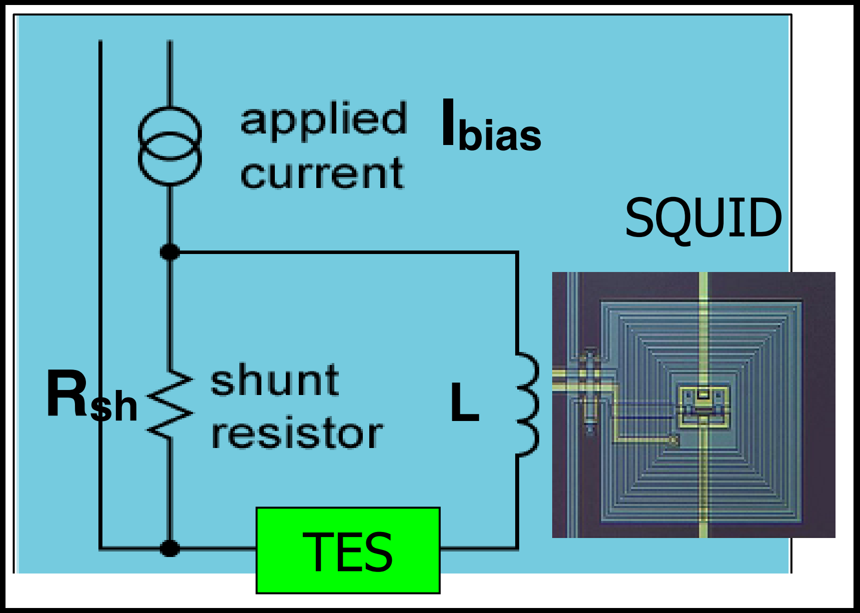
T=0.1K, C=1pJ/K, n=5

k_B = 1.38 x 10^{-23} J/K

1eV = 1.6x10^{-19} J

ΔE~1.4eV (FWHM)

TES Operation



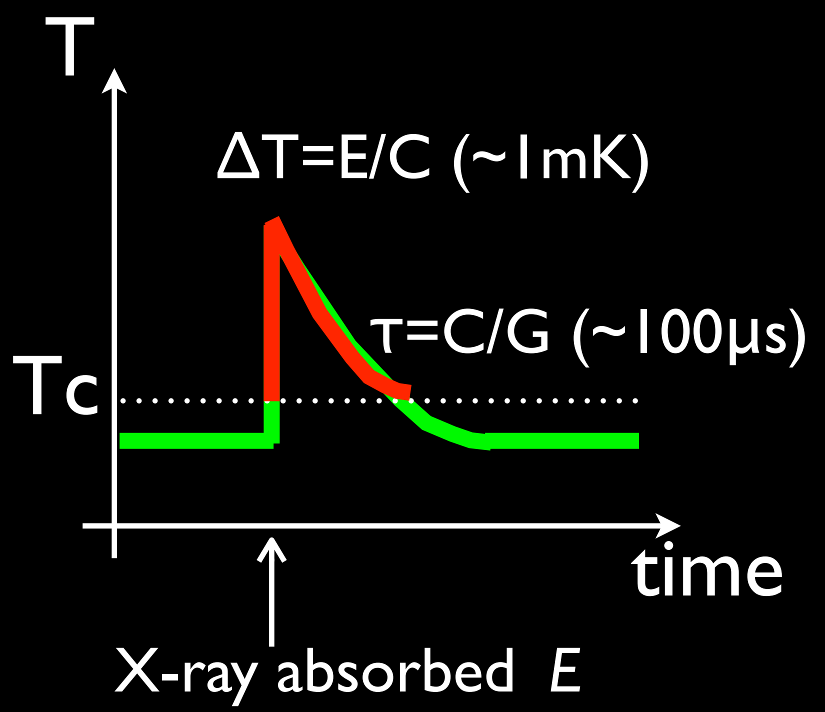
50-100mK cooled down by Adiabatic Demagnetization Refrigerator (ADR)

Voltage biased TES

apply I_{bias} to a shunt resistor

$$V = I_{bias} R_{sh} \qquad P_{bias} = \frac{V^2}{R}$$

negative electrothermal feedback



X-ray absorbed
→ increase T
→ increase R
→ decrease I and P_{bias}
→ back to initial T

TES Optimization

Excess noise proportional to Jonson noise

$$\Delta E = 2.35\sqrt{\frac{4k_B T^2 C}{\alpha}\sqrt{\frac{n(1+M^2)}{2}}}$$

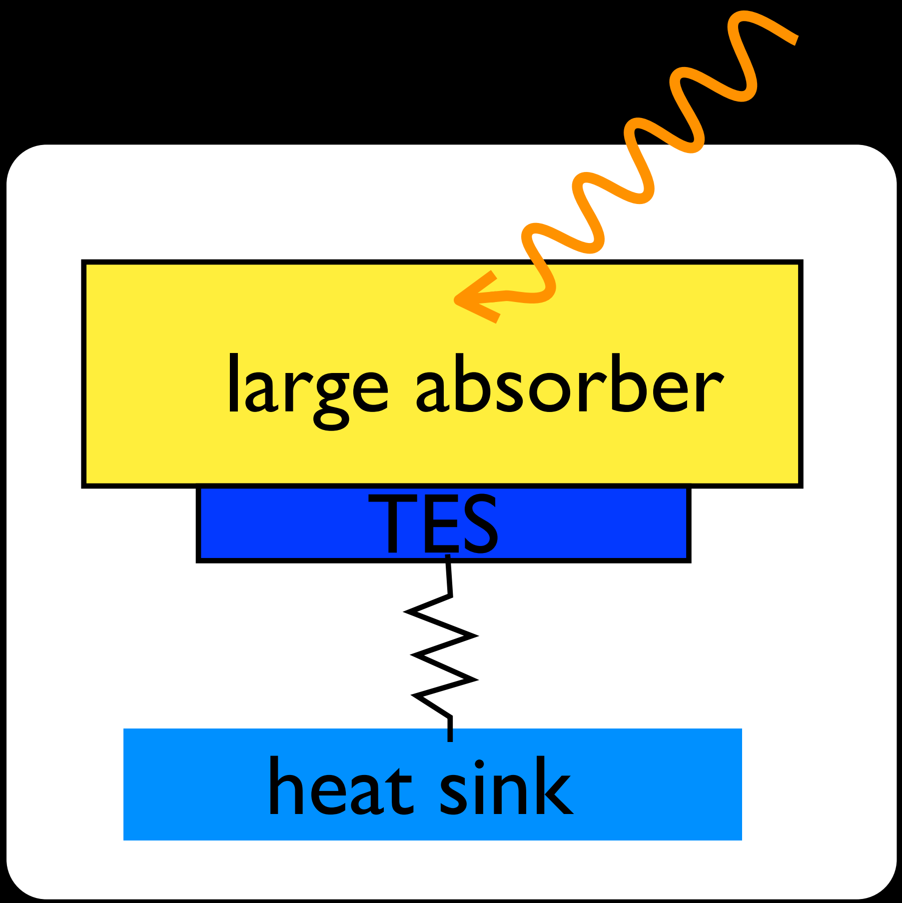
$M \sim 0.2\alpha^{1/2}$ empirically, lower α to lower excess noise

Optimization: reduce T, C, α, and M
match C/α

from SNIC2006 slide by Joel Ullom

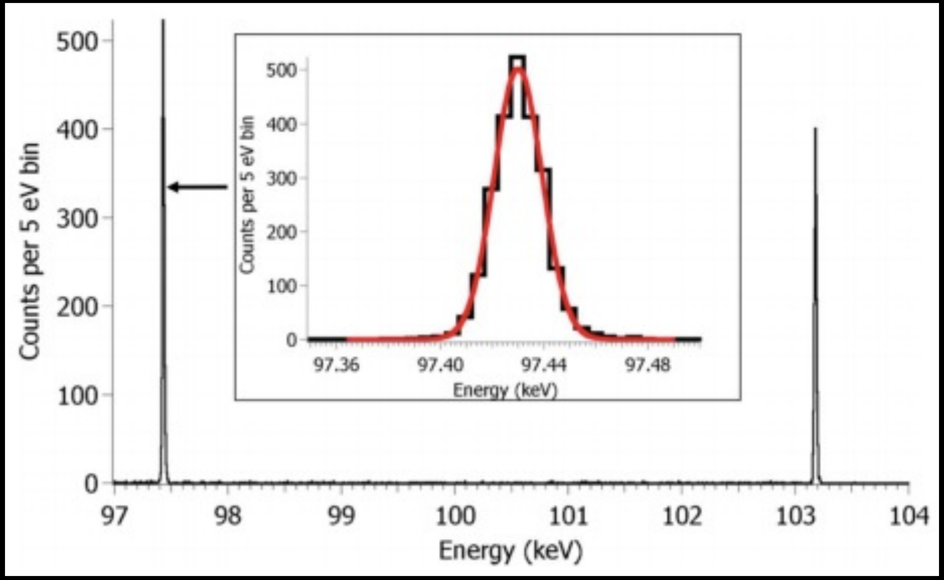
Transition Edge Sensor

for γ-ray



TES at NIST

single pixel 22eV FWHM @ 97keV



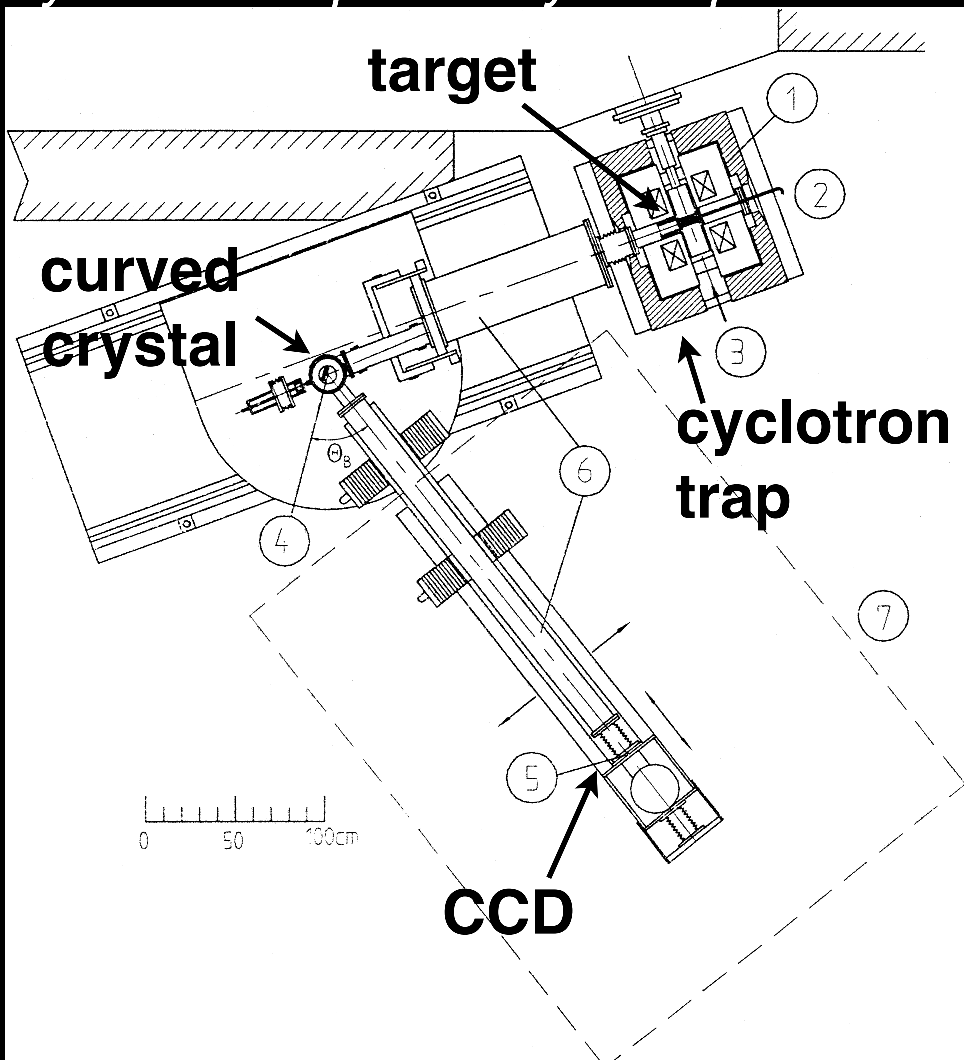
M.K. Bacrania et al., IEEE Trans. Nucl. Sci., 56 (2009) 2299

256 pixels 53 eV FWHM @ 97 keV

D.A. Bennett et al., Rev. Sci. Instrum. 83 (2012) 093113

What difference with crystal diffraction method?

cyclotron trap and crystal spectrometer in πE5 at PSI



- limited solid angle
- limited mobility, inflexible
- limited energy range

  lattice constant and angle

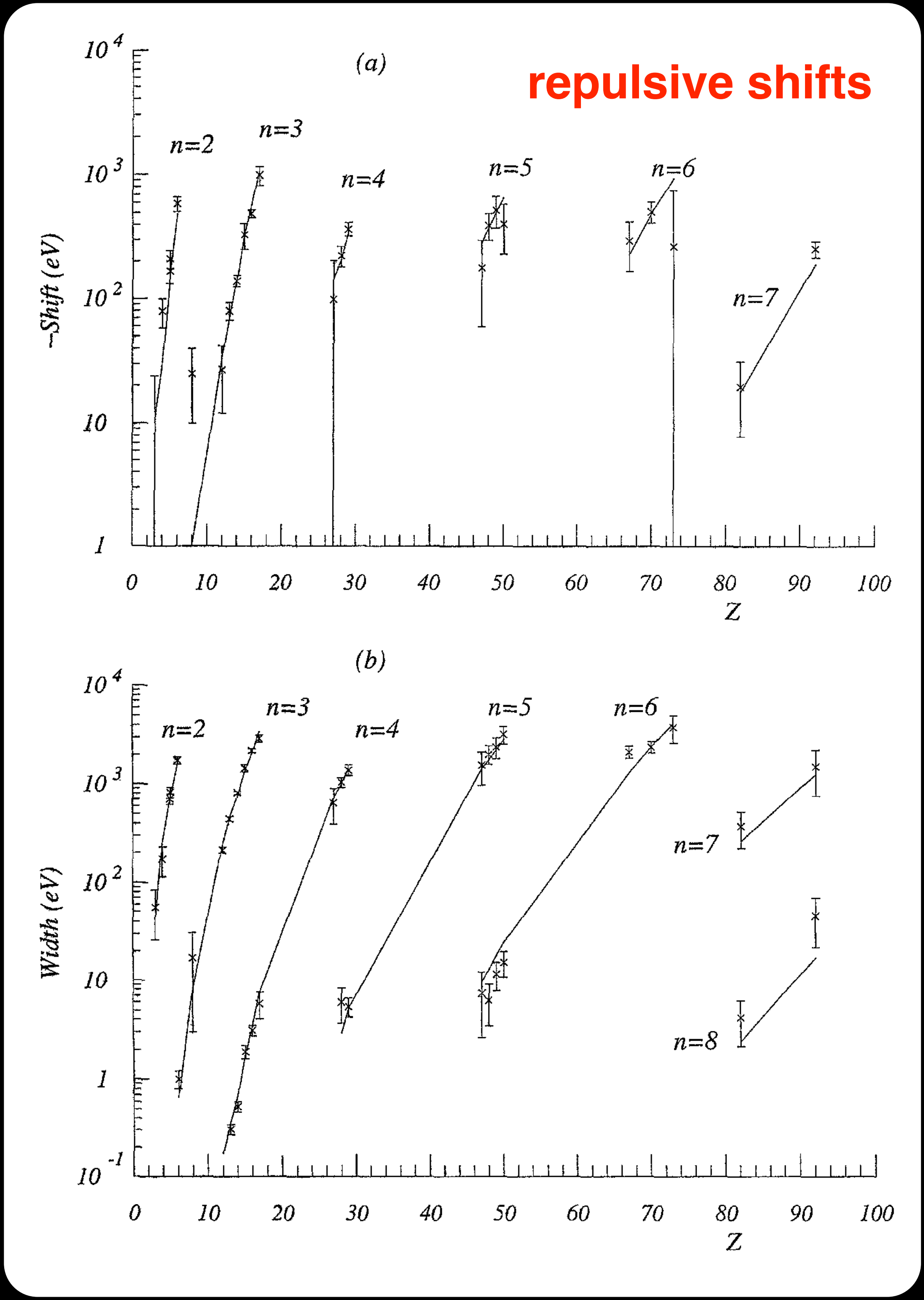
Motivation

1. Strong interaction study

Two theories of kaonic-atom potential

“deep or shallow”

2. Mass of kaon



Various targets data

strong-interaction shift and width

Phenomenological optical potential model (density dependent)

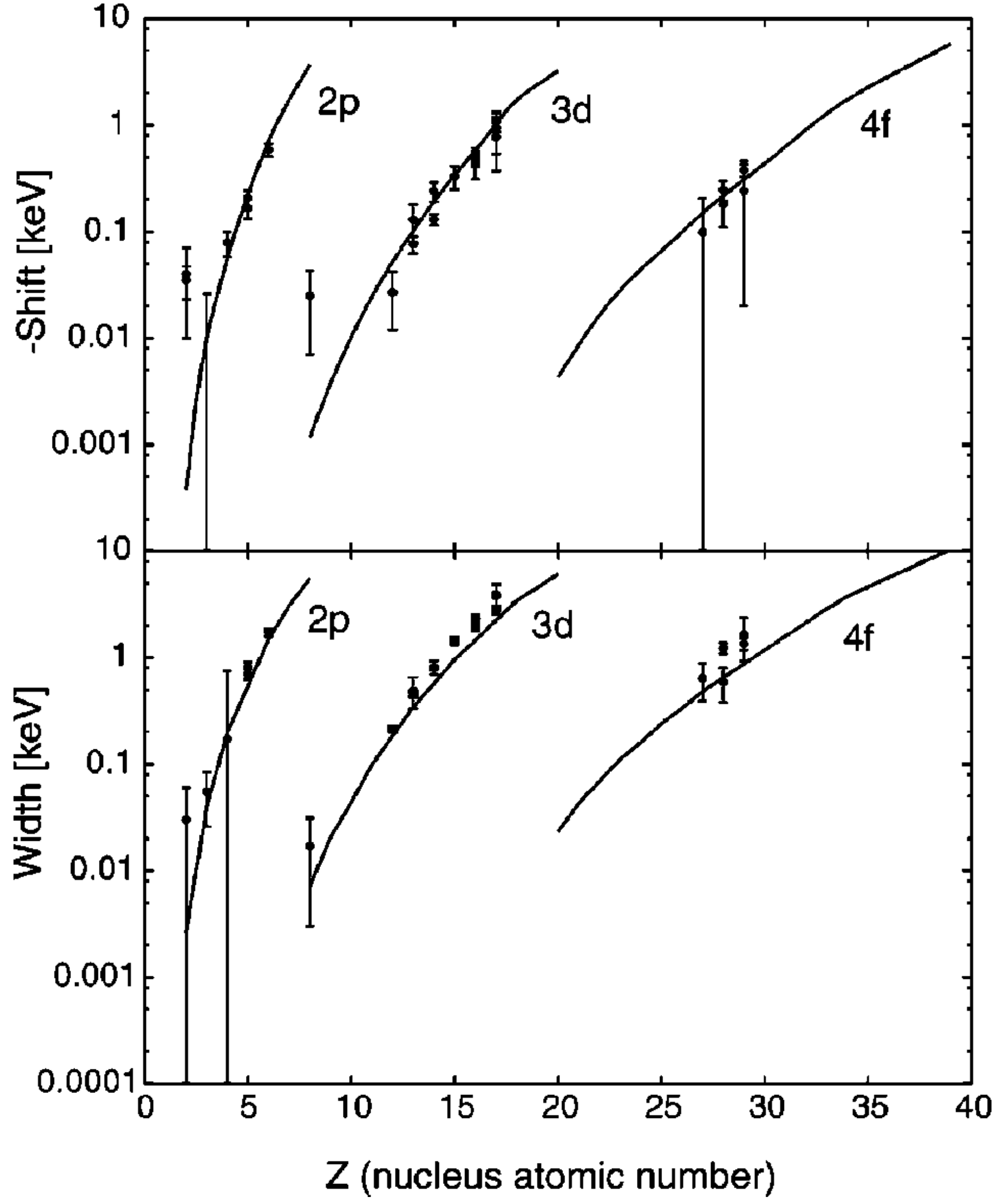
$$V = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m}\right)\bar{a}\rho(r),$$

$$a \to a_0 + A_0[\rho(r)/\rho(0)]^{\alpha},$$

Re(V)~ -150~200 MeV

“deep” potential

C.J.Batty, E.Friedman, A.Gal, Physics Reports 287 (1997) 385-445



Chiral unitary model

a kind of fundamental approach

$$2\mu V_{opt}(r) = -4\pi\eta a_{eff}(\rho)\rho(r),$$

Re(V)~ -40~60 MeV

“shallow” potential

S.Hirenzaki, Y.Okumura, H.Toki, E.Oset, and A.Ramos, Phys. Rev. C 61 (2000) 055205

- No precise data to distinguish the "deep" or "shallow" potentials

Can distinguish the potentials depth with the data of strong-interaction shift and width?

- Probably... Yes!
  (discussions with many theorists: Friedman, Akaishi, Hirenzaki, Yamagata, Hiyama, Koike) *(Honorifics omitted)*

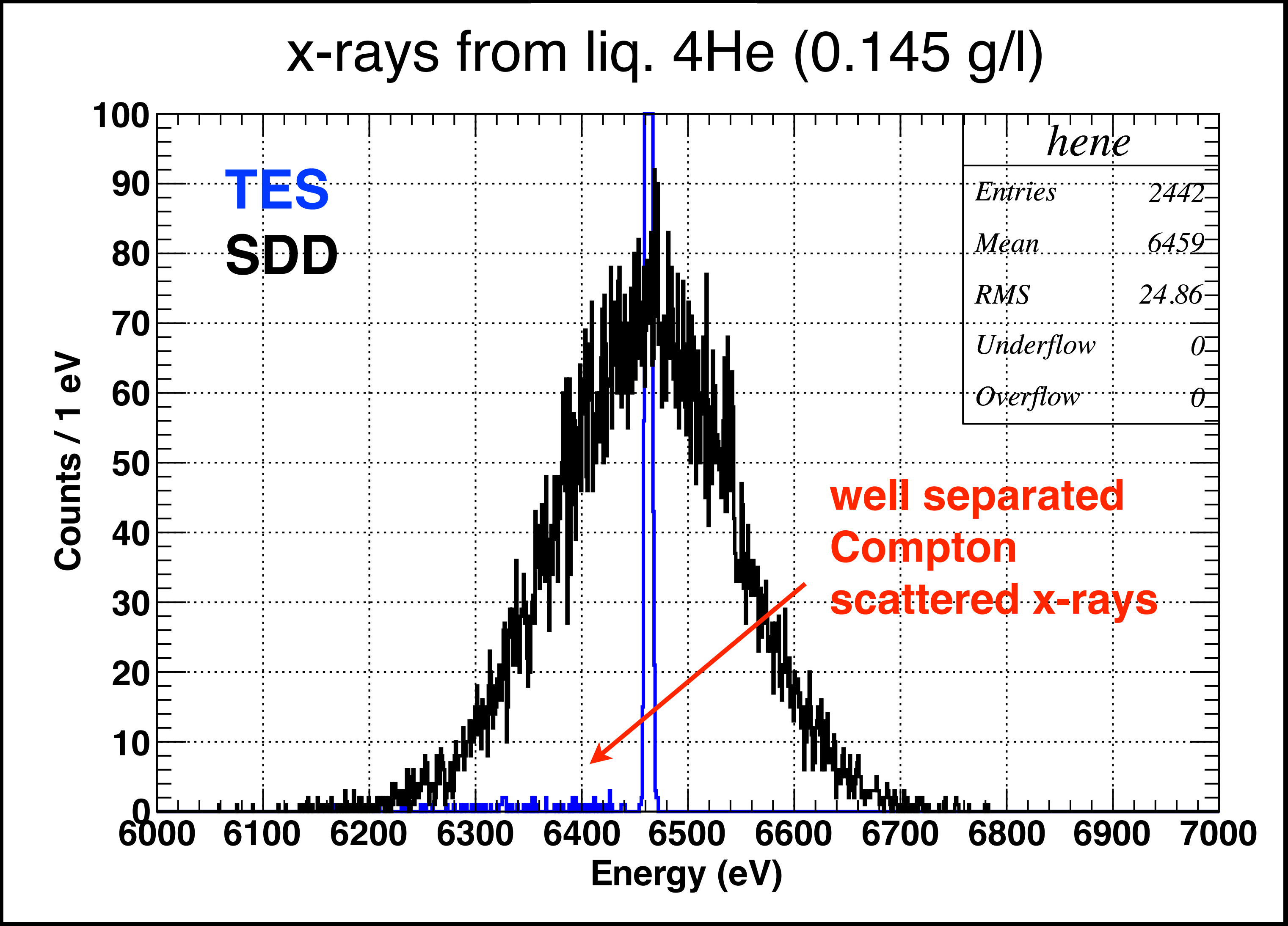
- Need precision of
  ~0.1-eV shift and a-few-eV width
- Measure a series of targets
  (^{3,4}He, ^{6,7}Li, ... and heavy atoms)

How much is the precision?

Very simple simulation

Simple comparison

- TES: Bi, 20mm², 5um thickness 5eV FWHM
- SDD: Si, 100mm², 400um thickness 190eV FWHM



Simple comparison

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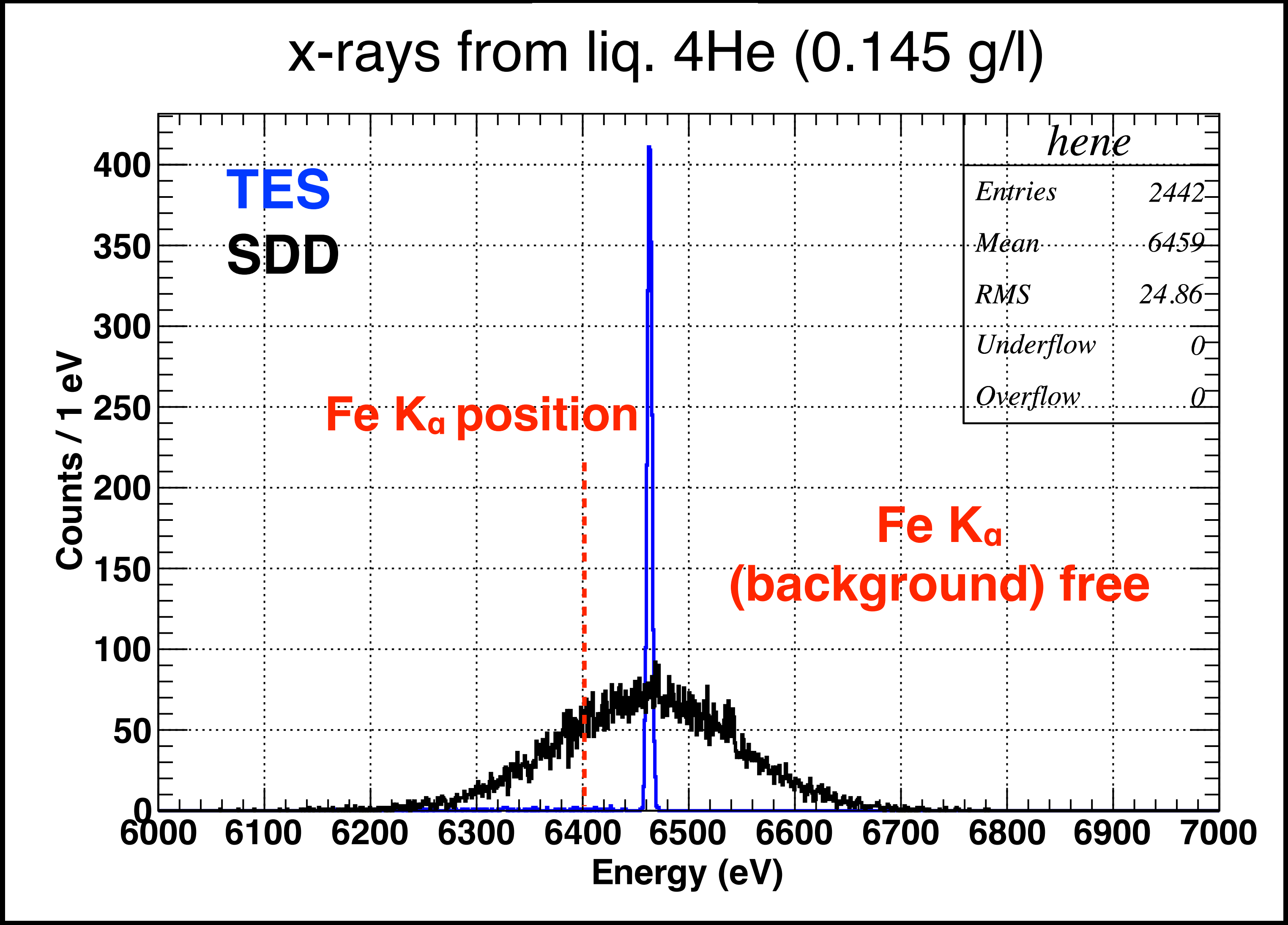


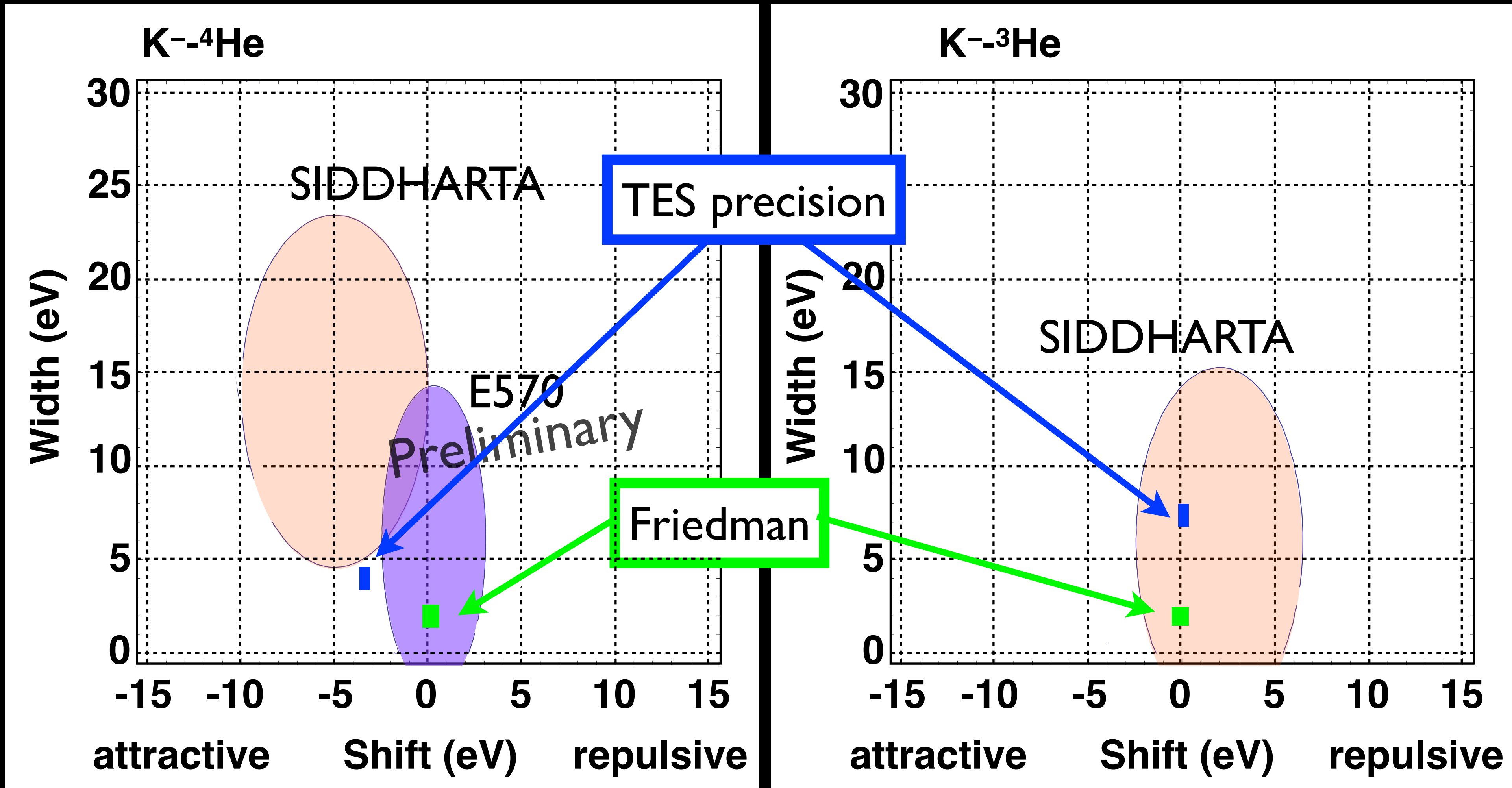
contaminated materials can be energy calibration sources!

Expected precision

	K-4He L_α counts	Energy resolution (FWHM)	Statistical accuracy of x-ray energy
SDD KEK-PS E570 1st and 2nd cycles	1500 (total 1.5 month)	190 eV	**2 eV** =190/2.35/sqrt(1500)
TES J-PARC	100 (4 days?)	2 eV	**0.09 eV** =2/2.35/sqrt(100)
		3 eV	0.13 eV
		4 eV	0.17 eV

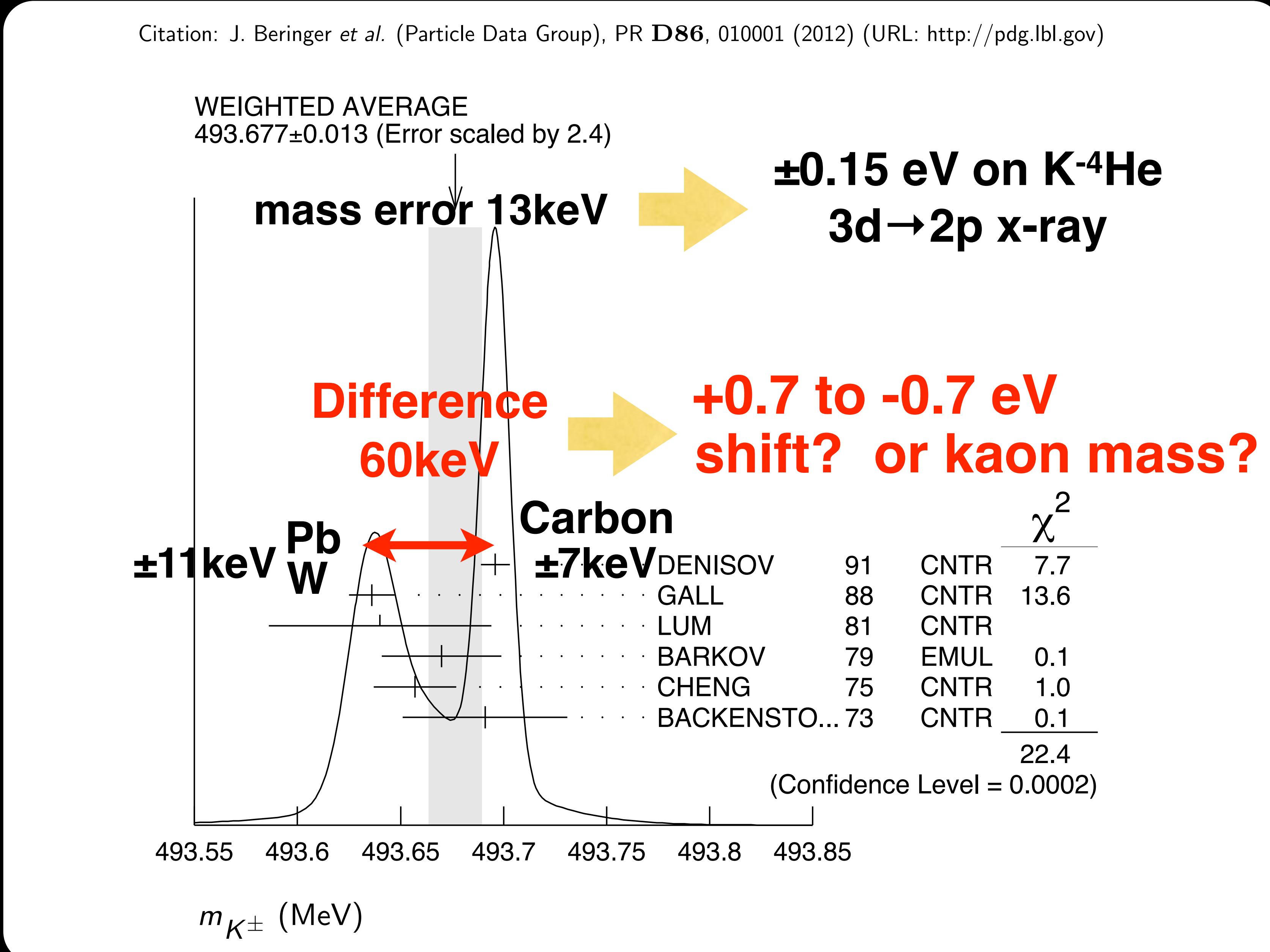
from S.Okada

Direct comparison with theories



but there is a problem on systematics error...

Charged kaon mass



Charged kaon mass

The latest measurement
K-C 4f→3d x-rays with crystal spectroscopy

Crystal diffraction method

K-^{12}C (4f→3d) 22105.61**±0.26** eV

Mass error: 7 keV

correspond to ±0.08 eV for K-He

TES (expect)

K-^{12}C(5→4) 10.2 keV

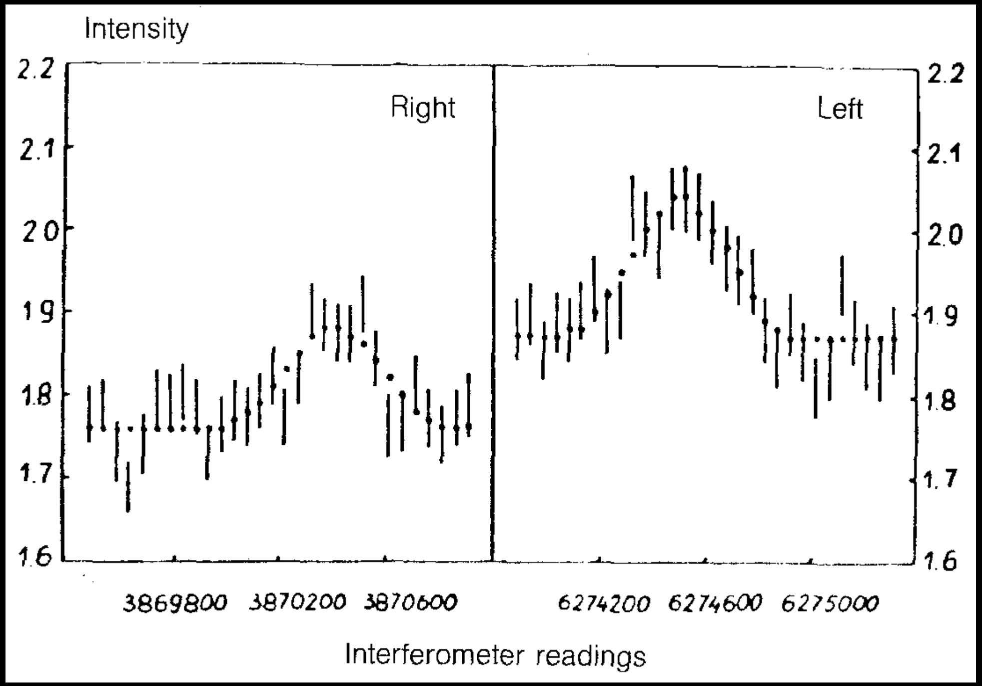
2000 events, ΔE=5eV(FWHM)

Stat. and syst. error ±0.05 eV

Mass error = 3.5 keV

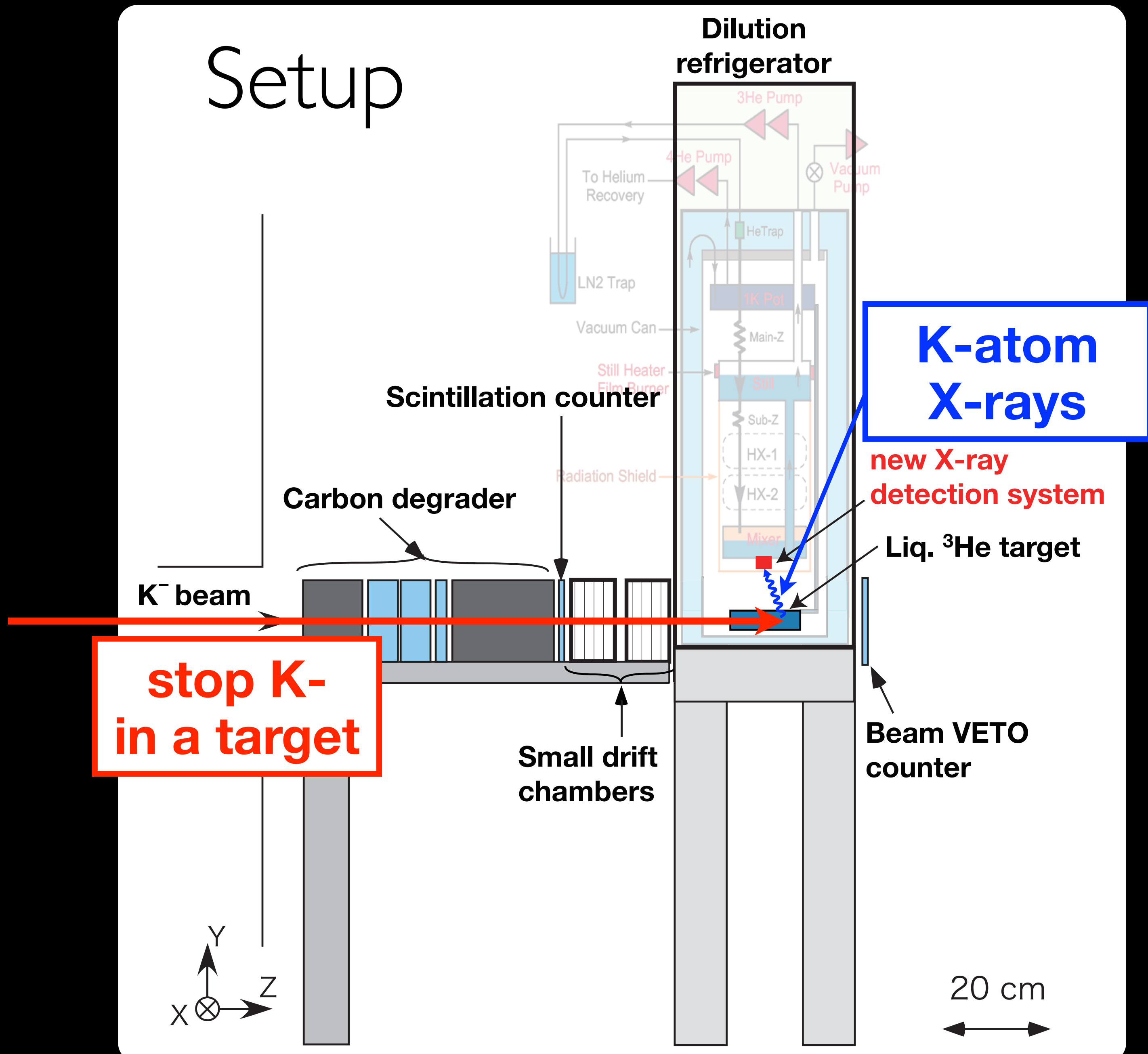
correspond to ±0.04 eV for K-He

A.S. Denisov et al. JETP Lett. 54 (1991) 558



Kaon mass is essential to determine the strong-interaction shift with 0.1-eV order of magnitude

Application at J-PARC



from S.Okada

Rough yield estimation

		Acceptance (including x-ray attenuation)	Number of stopped kaon	Absolute x-ray yield / stopped K	Time	X-ray counts
KEK-PS E570 2nd cycle with SDDs		0.126% / 7SDDs	~300/spill (2sec)	~8%	272 hours	1700 w/o cuts (including trigger condition ~40%)
TES J-PARC (30kW)	He	0.024%	~300?/spill (2sec) duty ~45%	~8%	**4 days**	**130**
	C	~0.01% self attenuation	~2000?/ spill (2sec) duty ~45%	~17%	**1 weeks**	**2500**

must be checked!

Starting successful collaboration with NIST!

NIST

D.A. Bennett
W.B. Doriese
J.W. Fowler
K.D. Irwin
D.S. Swetz
D.R. Schmidt
J.N. Ullom

Working persons in Japan

S. Ishimoto (KEK)
S. Okada (RIKEN)
H. Shi (U-Tokyo)
S. Yamada (RIKEN)

Planning a test experiment with beam... in 2013-2014

Preparing a proposal ... experiment in 2014-2015

Summary

Ultra-high resolution photon detector

Micro-calorimeter : superconducting TES

2eV FWHM @ 6keV

possibly solve the “deep” or “shallow” problem of the kaonic-atom optical potential depth

0.1-eV shift and a-few eV width

Kaon mass is essential to determine the shift

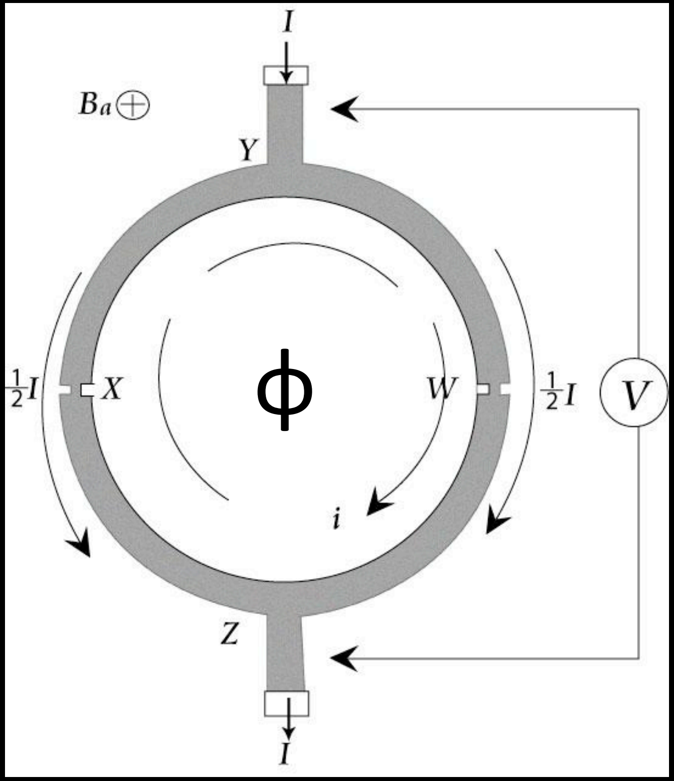
Plans for near-future test and experiment

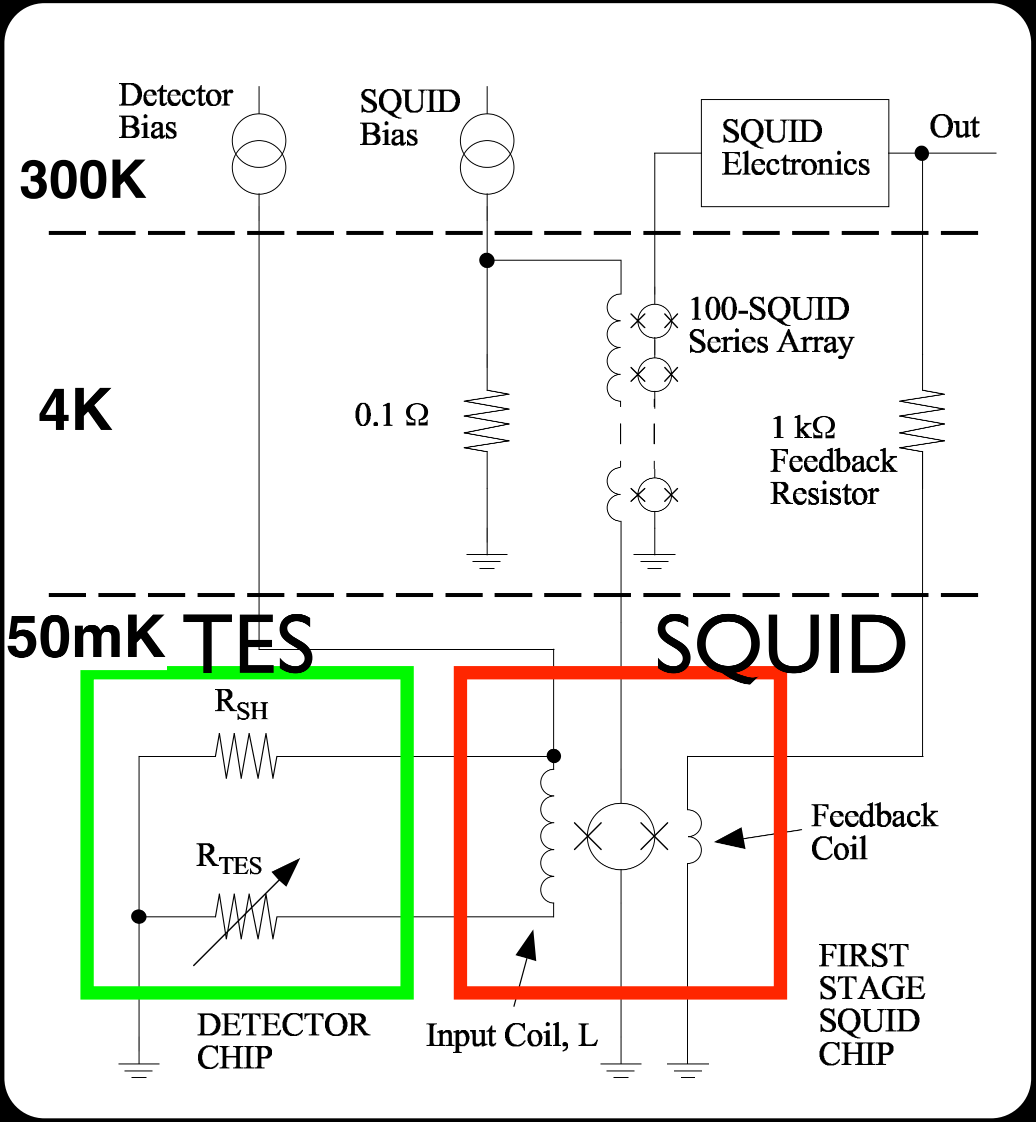
Backup

TES Operation with SQUID

Very sensitive magnetometer

DC SQUID





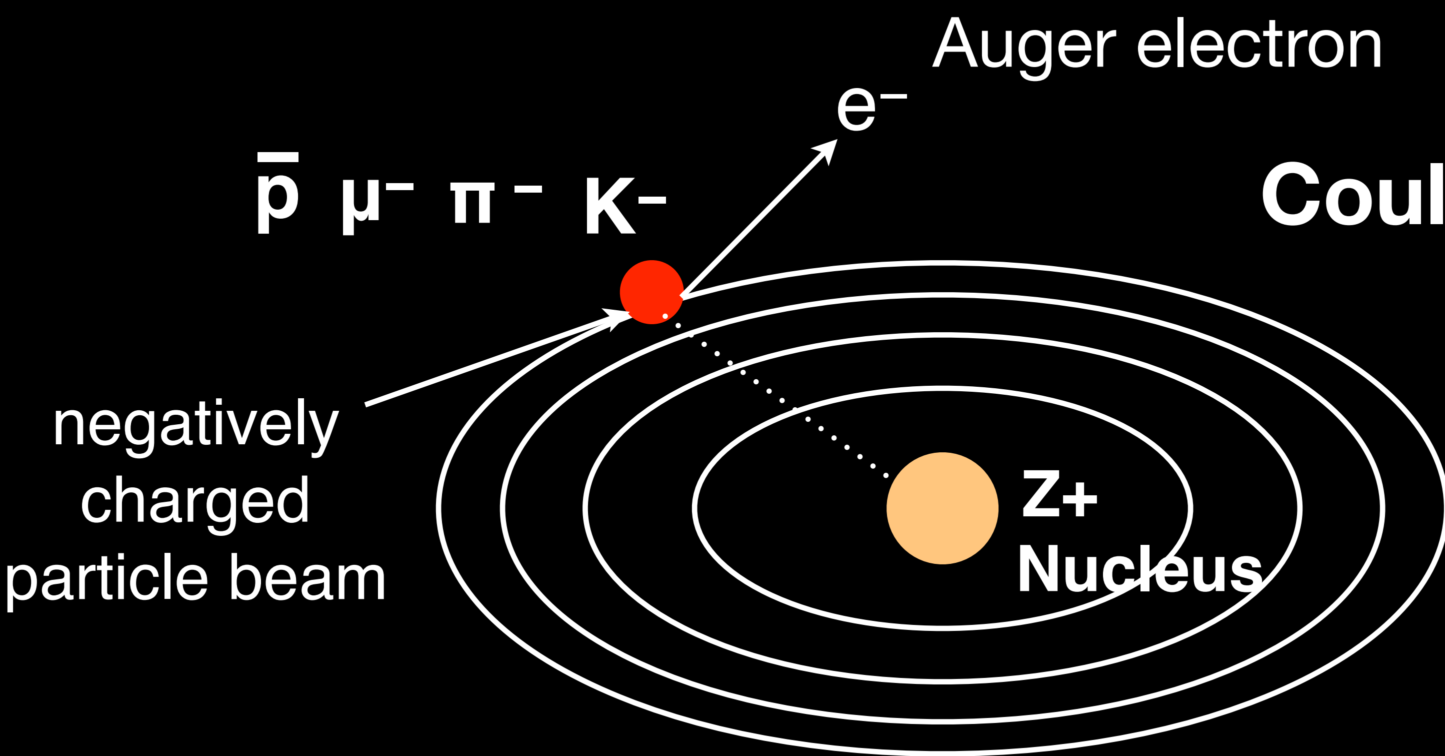
superconductor loop

Josephson junctions

cooper-pairs tunneling

K.D.Irwin and G.C.Hilton (NIST) Appl. Phys. 99 (2005) 63-149

Exotic atoms



Coulomb capture

$$n^* \sim n_e \sqrt{\frac{m_K^*}{m_e}}$$

m_K^* reduced kaon mass

$n^* \sim 30$ for ^4He

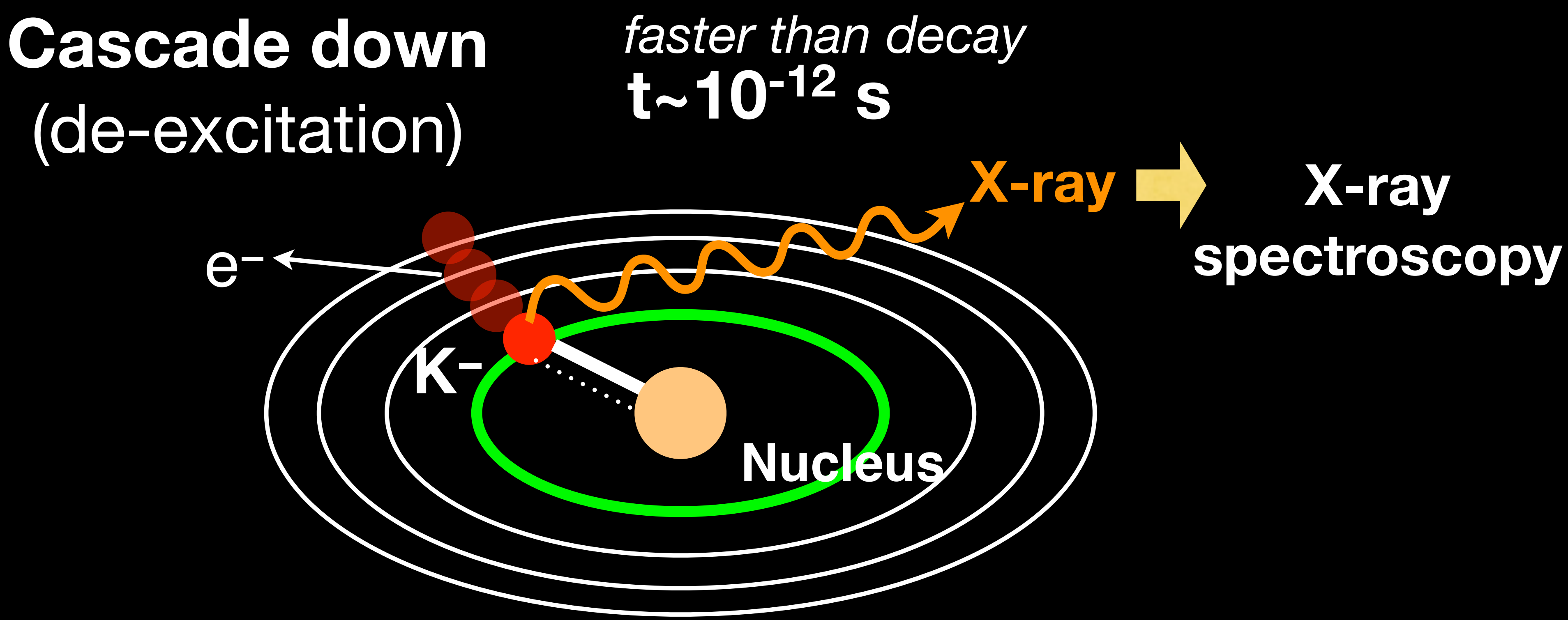
highly excited states

Energy levels (Coulomb interaction)

Dirac eq.

Klein-Gordon eq.

Exotic atoms



Coulomb + **Strong interaction**

Strong-interaction **Shift** and **Width** on the last atomic orbit

Investigations

strong interaction at threshold

$\bar{p}$ π^- K^- Σ^-

mass and magnetic moments

$\bar{p}$ π^- K^- Σ^-

test of QED

μ^-

nuclear charge radius

μ^-

neutron density distribution

$\bar{p}$ π^-

Investigations

✓ strong interaction at threshold

$\bar{p}$ π^- K^- Σ^-

✓ mass and magnetic moments

$\bar{p}$ π^- K^- Σ^-

test of QED

μ^-

nuclear charge radius

μ^-

neutron density distribution

$\bar{p}$ π^-

The beginning of exotic-atom x-ray spectroscopy

X-Rays from Mesic Atoms*

M. CAMAC, A. D. MCGUIRE, J. B. PLATT, AND H. J. SCHULTE
University of Rochester, Rochester, New York
(Received August 18, 1952)

Studies of X-Rays from Mu-Mesonic Atoms*

VAL L. FITCH AND JAMES RAINWATER
Department of Physics, Columbia University, New York, New York
(Received July 23, 1953)

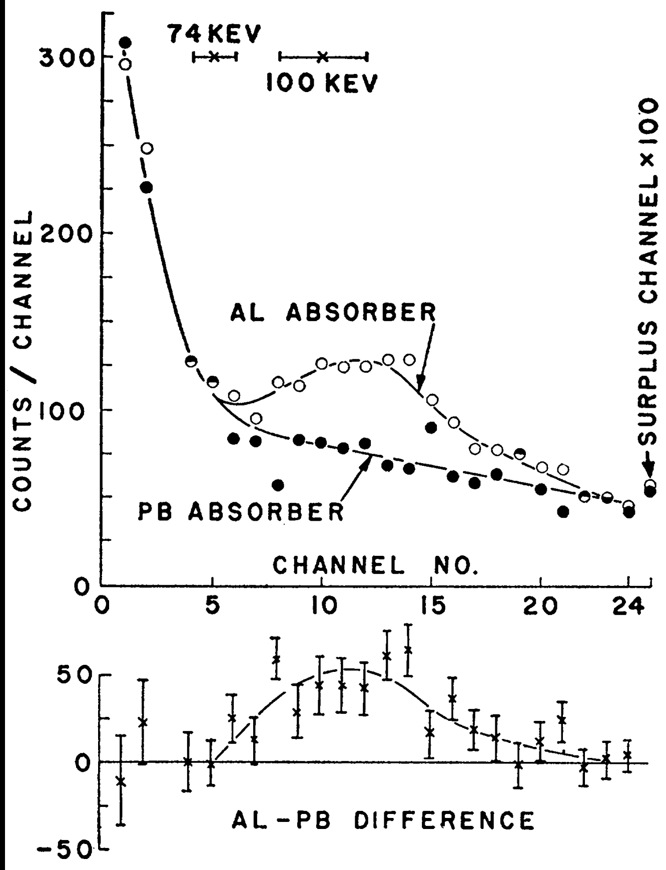


FIG. 1. Pulse-height spectrum from carbon.

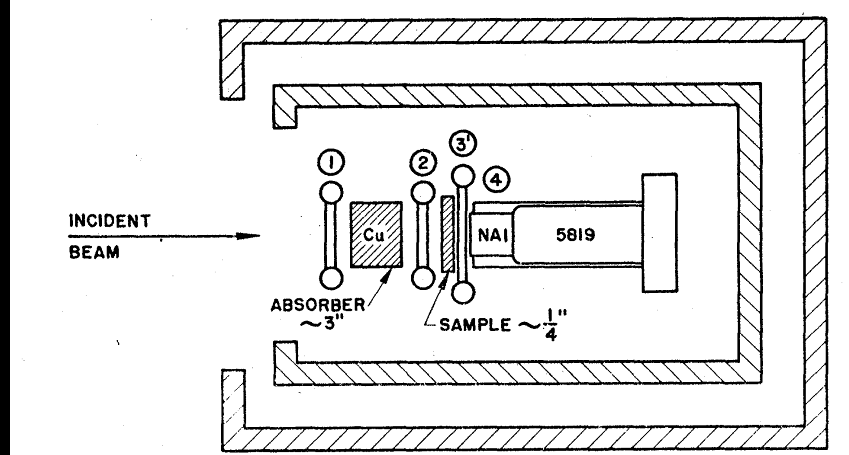


FIG. 4. Diagram of detection system. Stilbene scintillation counters 1, 2, and 3′ select particles stopping in the sample material. NaI scintillation counter 4 serves as the photon detector. The copper absorber between counters 1 and 2 removes the π mesons from the beam. Magnetic shielding is provided by a double walled box of $\frac{1}{2}$-in. iron plate.

Kaonic atom x-ray

OBSERVATION OF K-MESONIC X RAYS IN HELIUM*

G. R. Burleson,† D. Cohen, R. C. Lamb, D. N. Michael,‡ and R. A. Schluter†

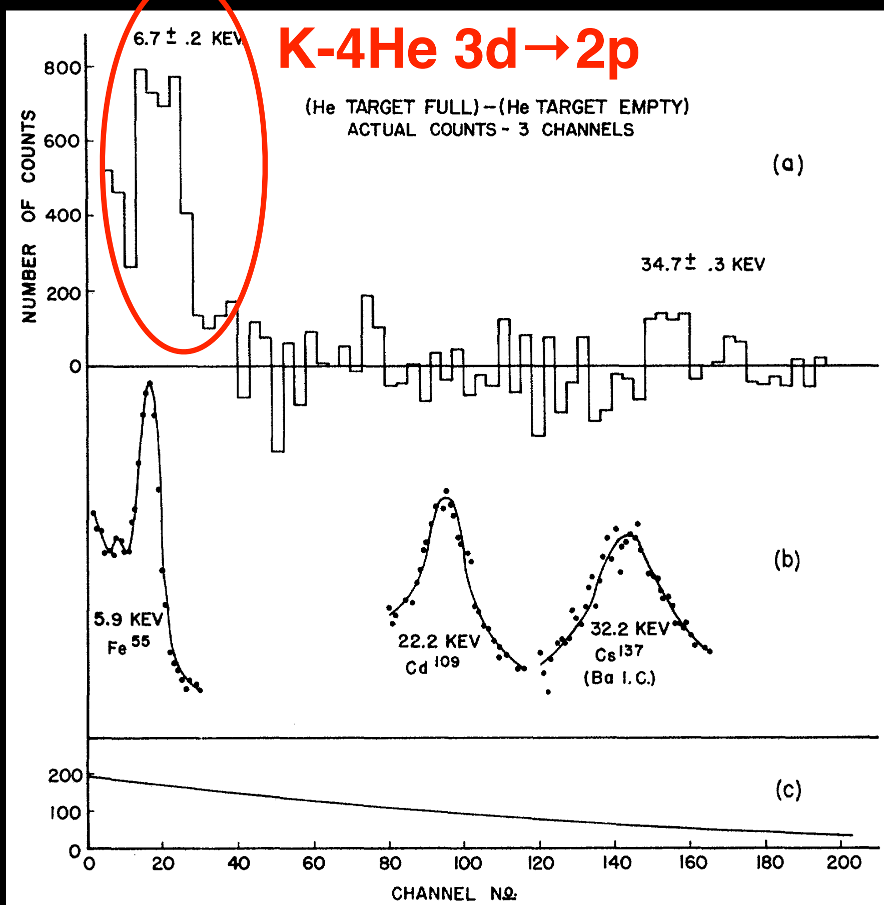
Argonne National Laboratory, Argonne, Illinois

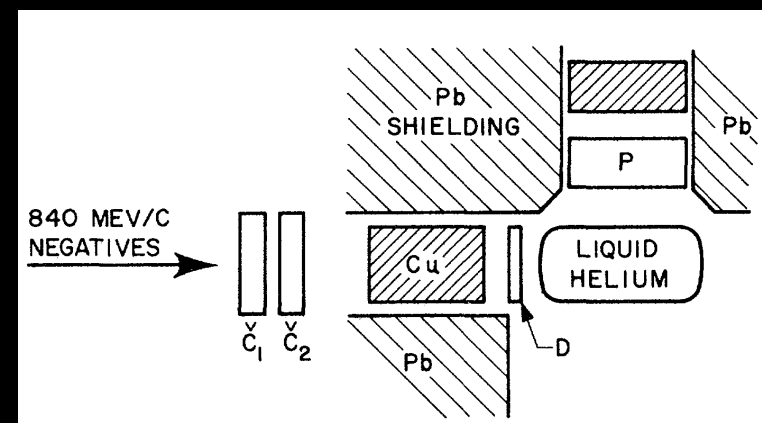
and

T. O. White, Jr.§

Northwestern University, Evanston, Illinois

(Received 9 June 1965)





Argonne ZGS (Zero Gradient Synchrotron), U.S.

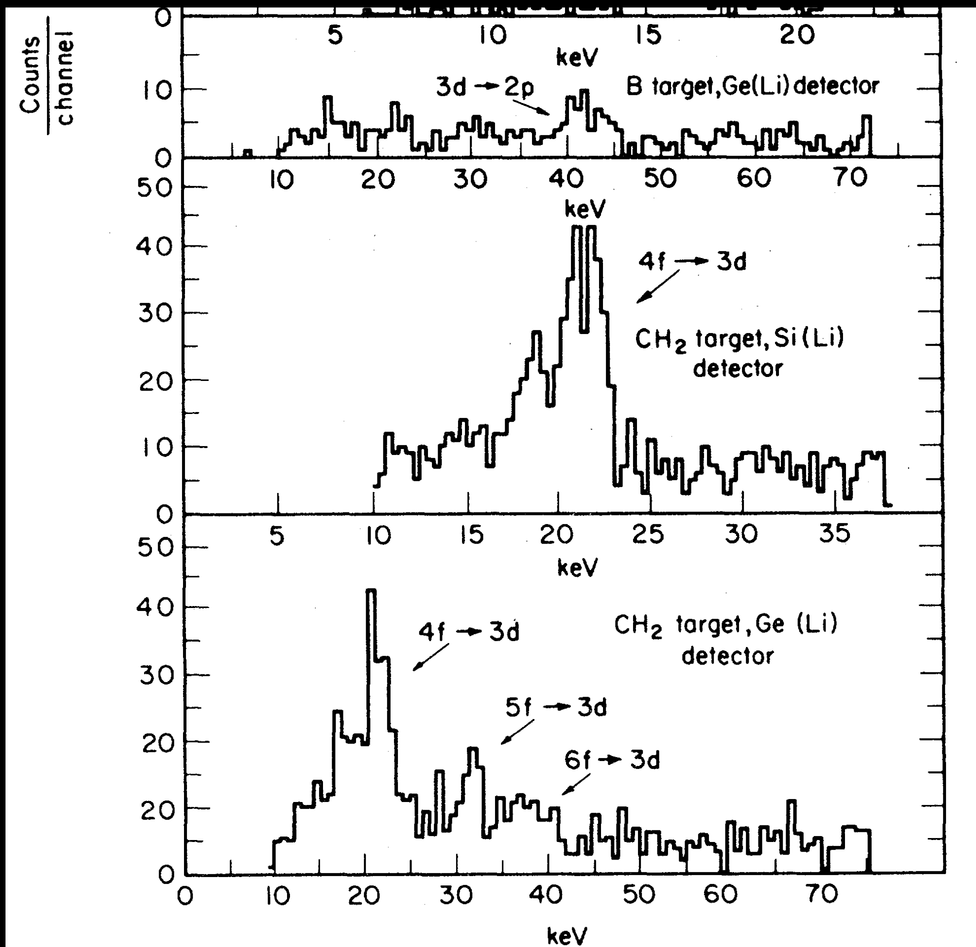
gas-proportional counter

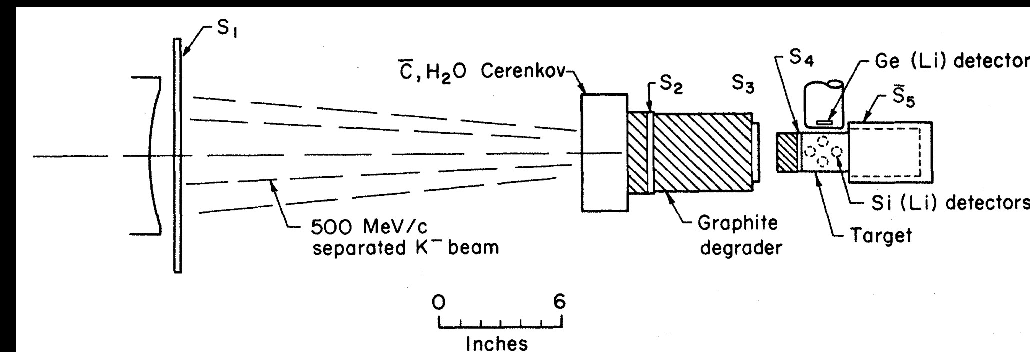
$\Delta E/E$ = 12.5% at 22 keV

Kaonic atom x-ray

MEASUREMENT OF K^--MESONIC X RAYS FROM Li, Be, B, AND C†

Clyde E. Wiegand and Dick A. Mack
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received 6 March 1967)





Bevatron

Si(Li) and Ge(Li) detectors

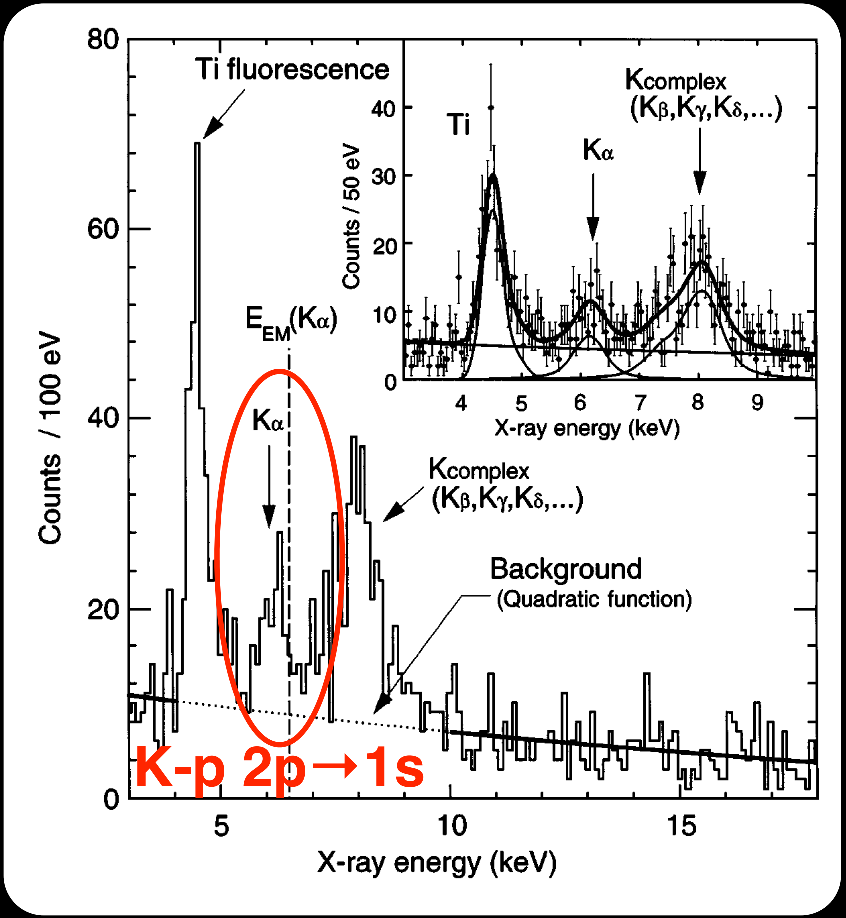
340 eV FWHM at 6 keV

the Bevatron crew for their cooperation. Our appreciation is expressed to Professor E. Segrè for his suggestion that we search for the K^--mesonic x rays and his continued interest.

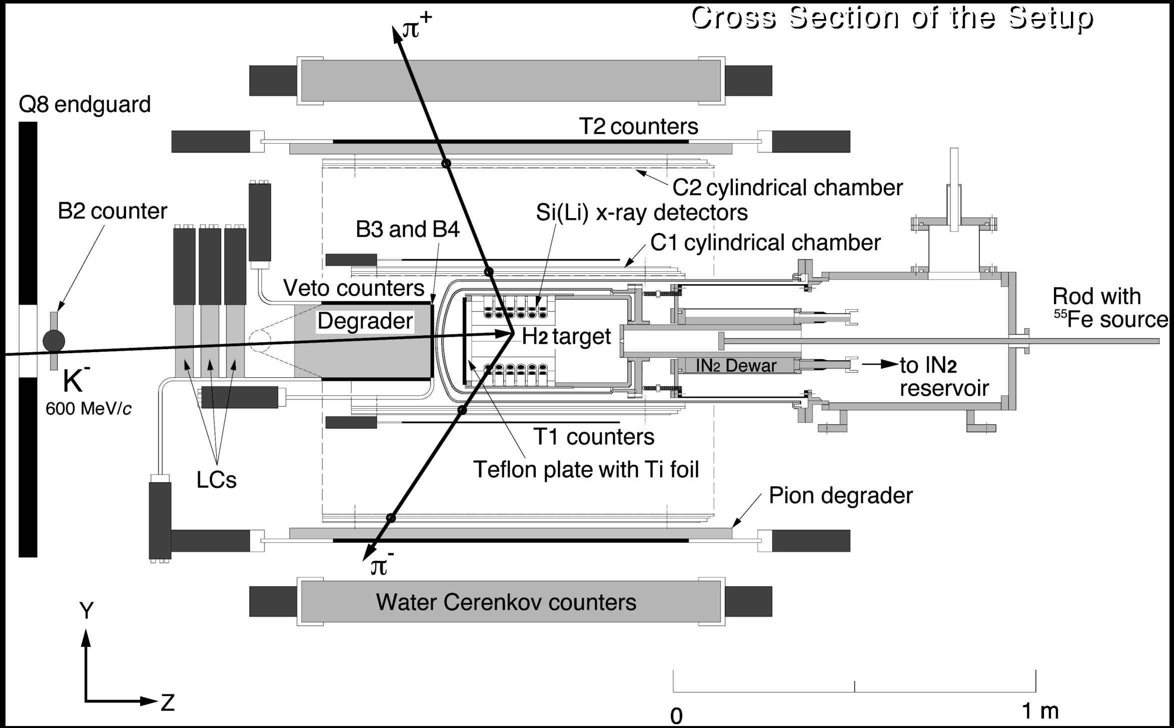
Kaonic atom x-ray

Observation of kaonic hydrogen K_α x rays

M.Iwasaki et al., PRL78(1997)3067



K-p: attractive interaction



KEK-PS

Si(Li) detectors

400 eV FWHM at 6 keV

The latest measurement
K-C 4f→3d x-rays with crystal spectroscopy

A.S. Denisov et al. JETP Lett. 54 (1991) 558

TABLE I. Calculated energies of the transitions with $M_K = 493.6960$ and $M_\pi = 139.5688$ MeV.

Component of transition energy	Value of component, Ev $4f$–$3d$ K^-–^{12}C	 $4d$–$2p$ π^-–^{12}C
Coulomb interaction	22033.941	24782.721
Vacuum polarization, $\alpha(Z\alpha)$	71.110	42.790
$\alpha^2(Z\alpha)$	0.496	0.314
$\alpha(Z\alpha)^3$	− 0.012	− 0.009
Strong interaction	0.009	2.850
Relativistic correction	0.085	0.047
Electron screening*	− 0.016	− 0.373
Polarization of nucleus	0.018	0.009
Finite dimensions of meson	− 0.004	− 0.002
Lamb shift	0.000	− 0.001
Nuclear recoil	− 0.022	− 0.028
Sum	22105.605	24828.318

*The correction was calculated for one $1s$ electron.