

# Atomic lifetime measurements using electron beam ion traps

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Atomic level lifetime =  $1 / (A_{ki})$

Transition probability  $A_{ki}$

Multipole order E1, M1, E2, M2, E3, M3

Resonance lines, high nuclear charge Z:  
femtosecond lifetimes

E1-forbidden lines, not so high charge states:  
millisecond lifetimes

Ultrahigh vacuum: Collision rates of order 1/s

Level populations (line ratios) depend on excitation and deexcitation: Density diagnostic

Measure radiative decay rates of long-lived levels

Optical depth depends on the A-value

Extreme cases in astrophysics: All lines in absorption, except for those from extremely long lived levels

# Cs<sup>45+</sup> in SuperEBIT at various temperatures

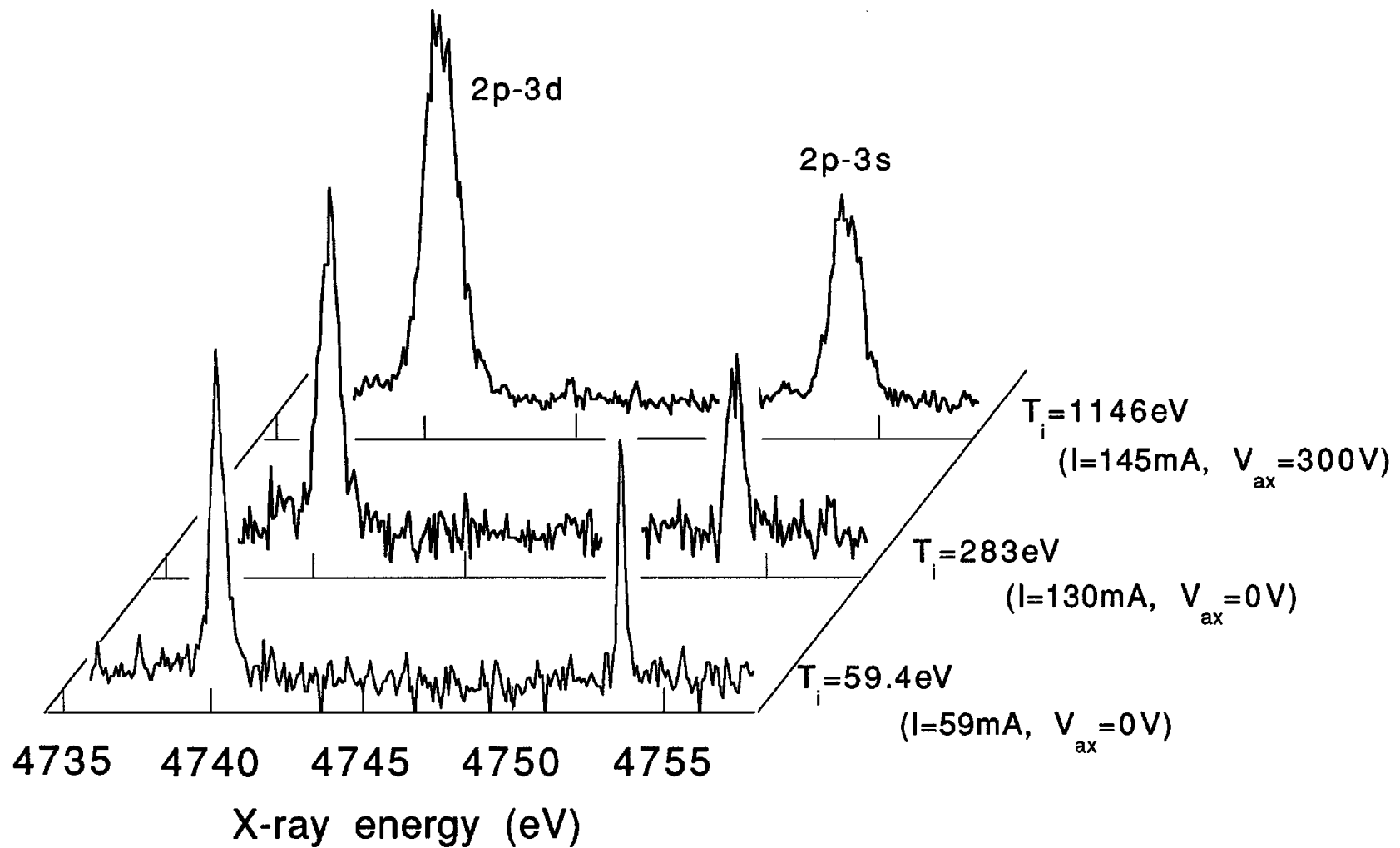


Figure from Beiersdorfer et al., PRL 77, 5353 (1996).

The line width of a "slow" transition shrinks with the temperature, the width of a "fast" transition reveals the natural line width.

The Fourier transform of an exponential is a Lorentzian:  
A lifetime measurement can proceed via  
a line width measurement or via  
exponential decay analysis.

The line width comprises instrumental and intrinsic  
(atomic lifetime, collisionally shortened) contributions.

Elegant approach: Use line pair of decays of short-lived  
and long-lived levels.  
Use long-lived level decay as a template that covers the  
instrumental effects (approximated by a Gaussian);  
use Gaussian width in the analysis of the Voigt profile of  
the short-lived level decay, extract Lorentzian contribution.

With EBIT and cold ion cloud (shallow trap), this is  
doable. Thermal (Doppler) width can be shrunk below  
Lorentzian width.

Lifetime results lie within a factor of two of good theory.

Line 'w' (resonance transition) supposedly is described by a Voigt profile.

The Gaussian part of the profile can be approximated by the (dominantly) Gaussian profiles of 'x' (intercombination line) or 'z' (M1 forbidden line).

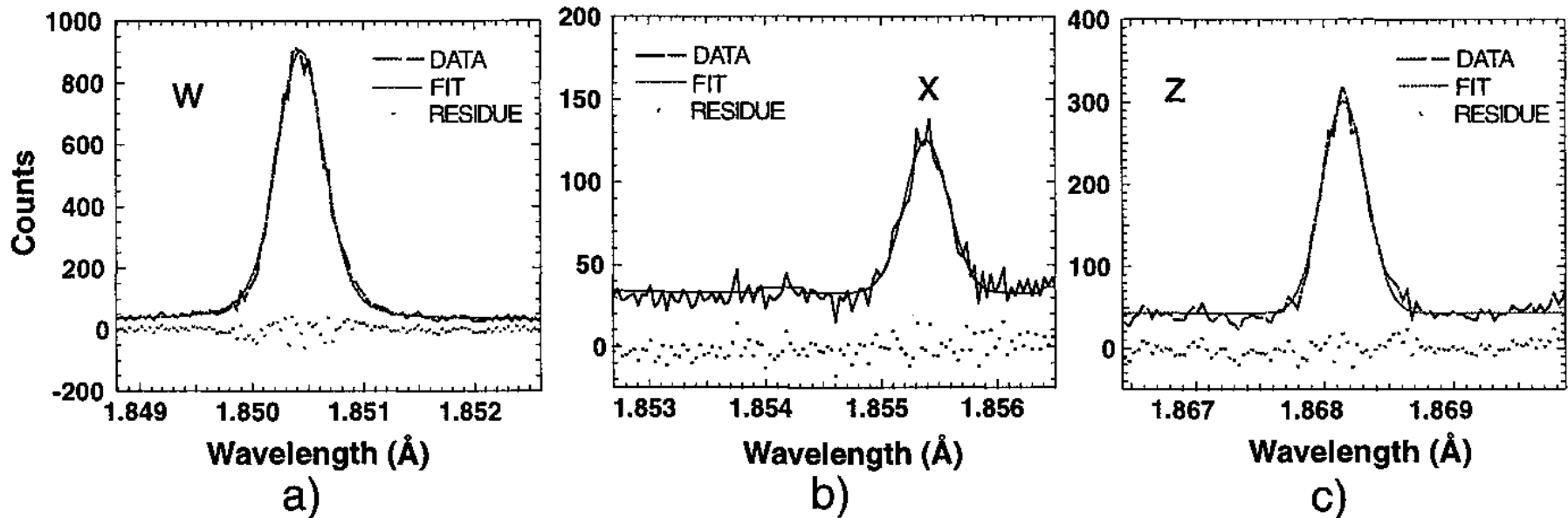
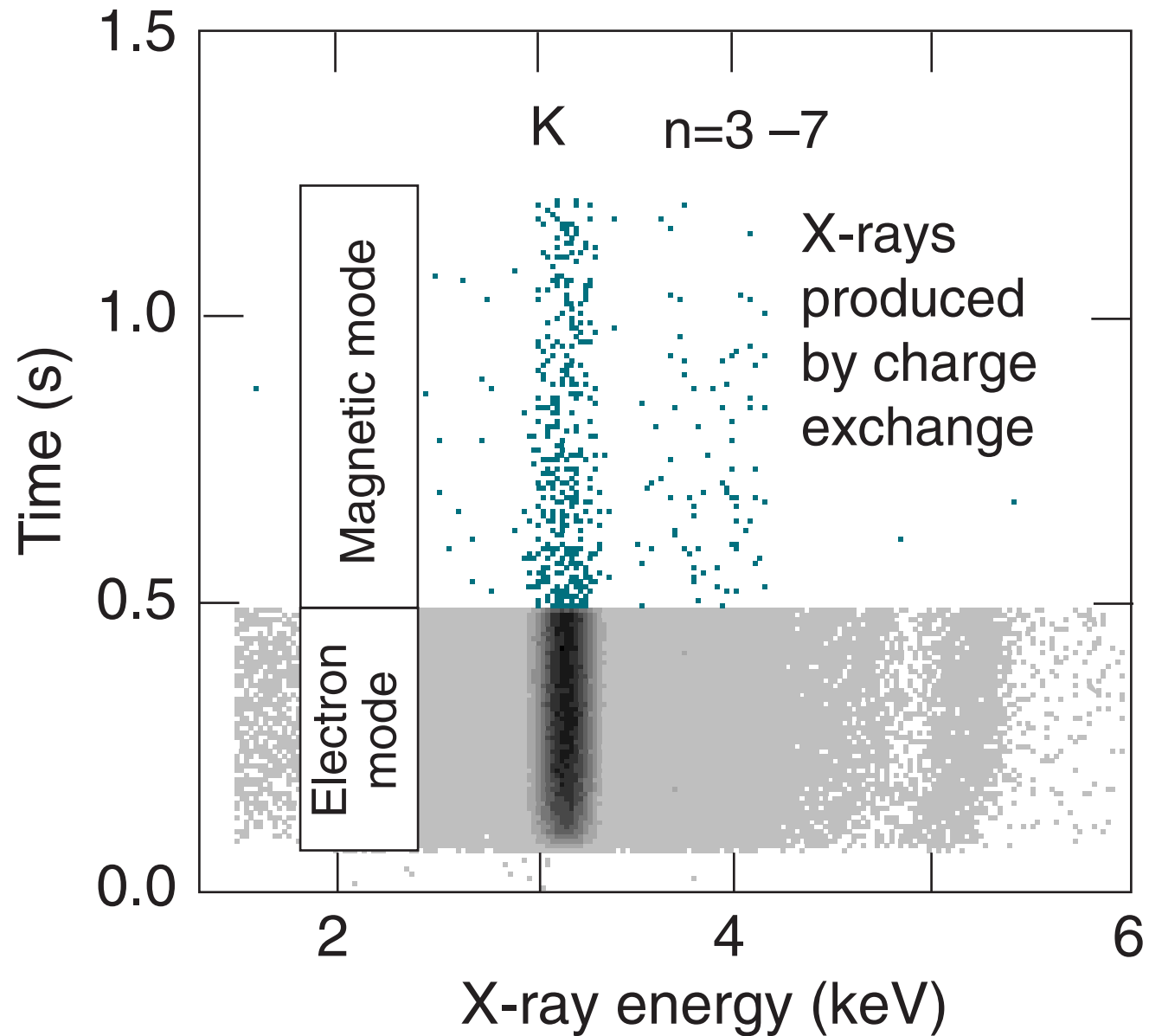


Fig. from Graf et al., 16th ICSSL, AIP Conf. Proc. 645, 74 (2002)

## Major operating modes of electron beam ion traps

	Electron beam	Ion trapping	X-ray production mechanism
Magnetic mode	Off	Magnetic field, drift tube voltage	Ion-neutral collisions
Electron mode	On	Electron space charge, magnetic field, drift tube voltage	Electron-ion collisions

# Excitation vs. decay curve Prompt vs. delayed emission



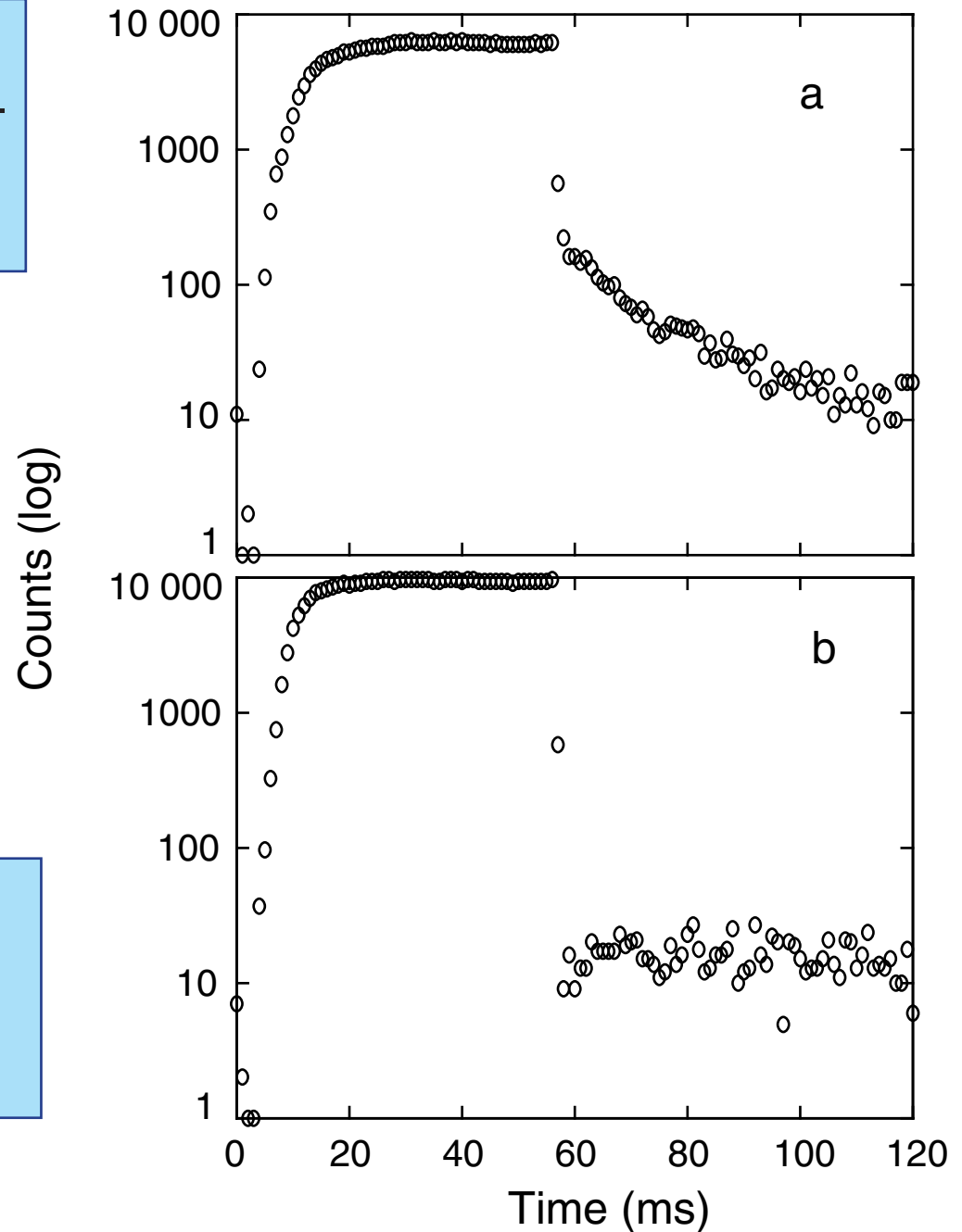
When the electron beam is switched off, delayed photons arise from long-lived excited levels or from charge exchange (CX).

XRS microcalorimeter data of Xe

a) at the position of the M3 decay in Xe XXVII

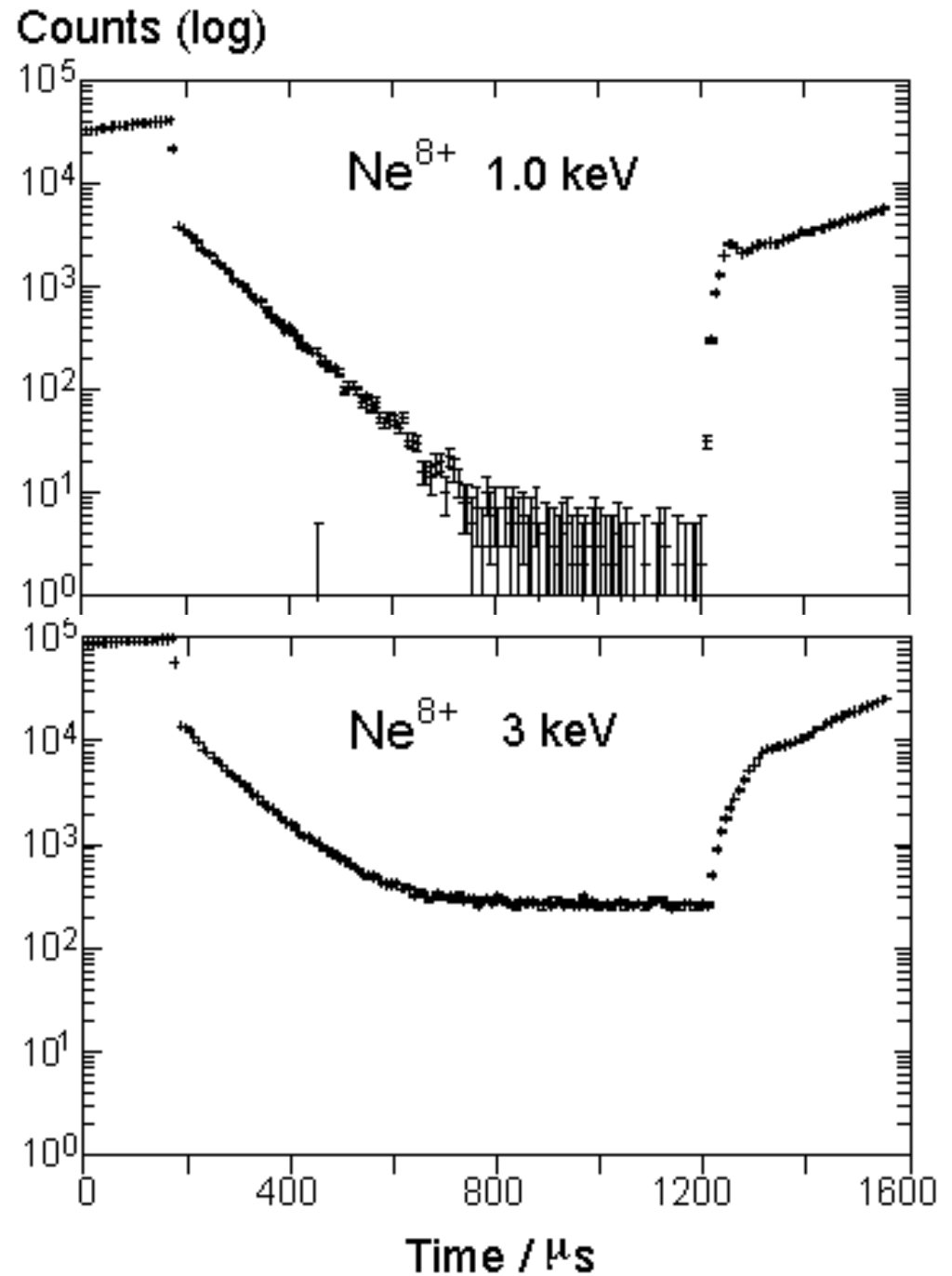
b) at the position of O VIII Lyman alpha

In (near) Ni-like Xe, there is only one level with a long (millisecond range) lifetime.

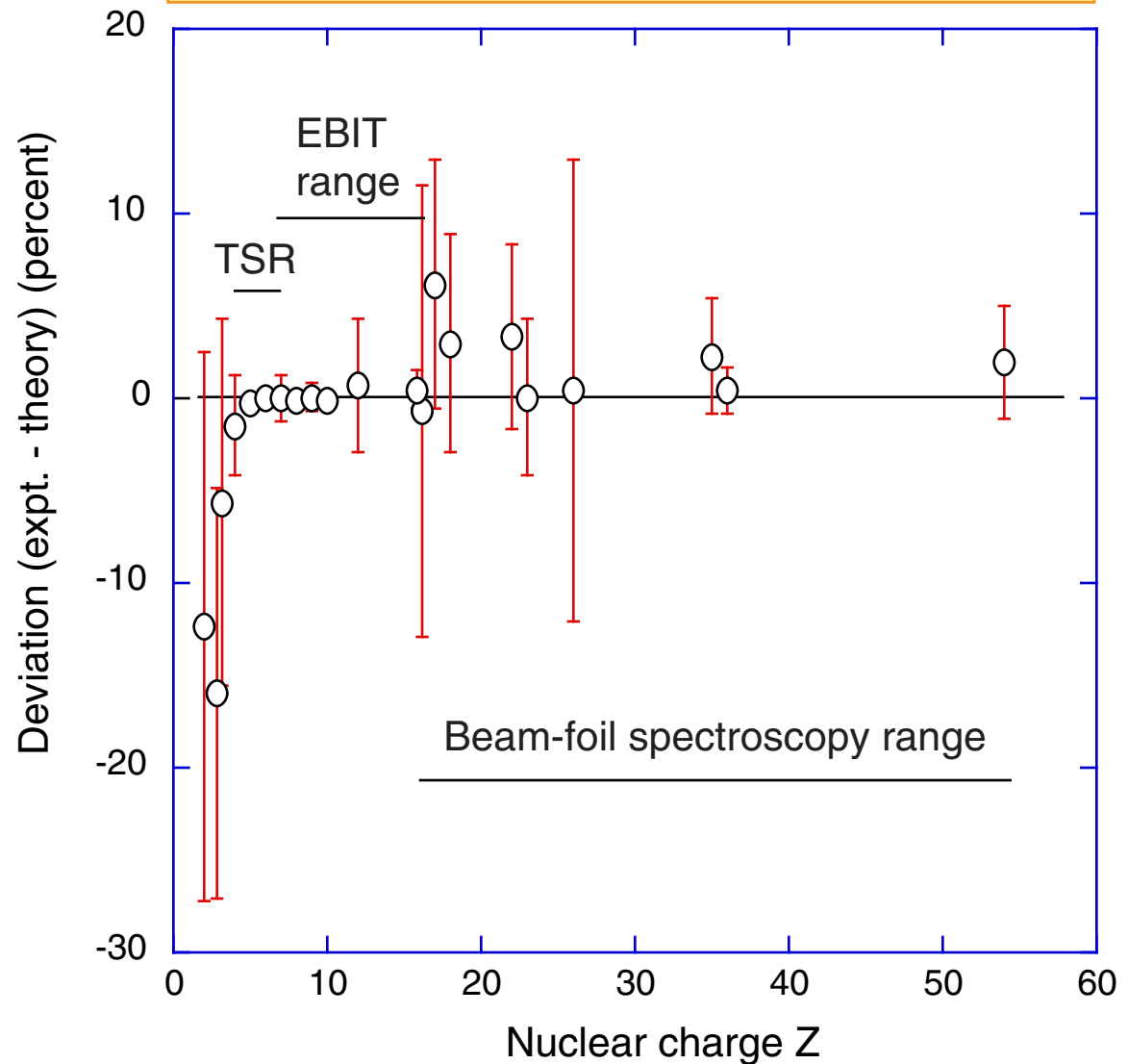




A higher electron beam energy facilitates a higher electron beam current which yields a much higher signal rate. However, the production of higher charge state ions results in CX contributions to the X-ray signal and to systematic errors.

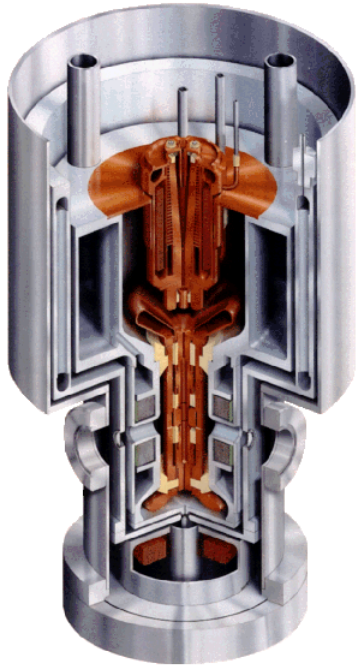


## M1 transition rate in the He sequence

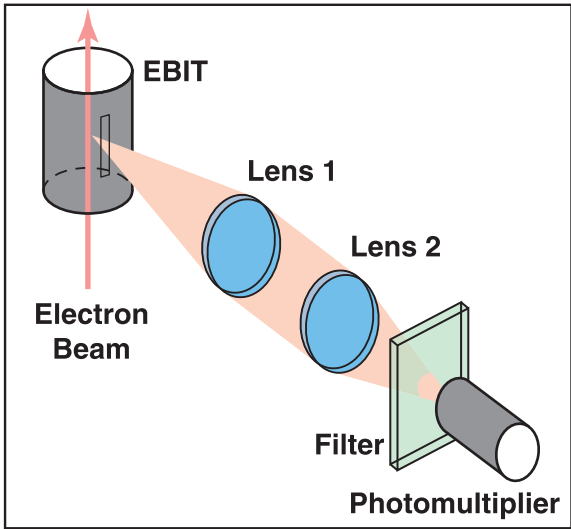


The measurements at the heavy-ion storage ring TSR and at the LLNL EBIT are in excellent agreement with relativistic theory

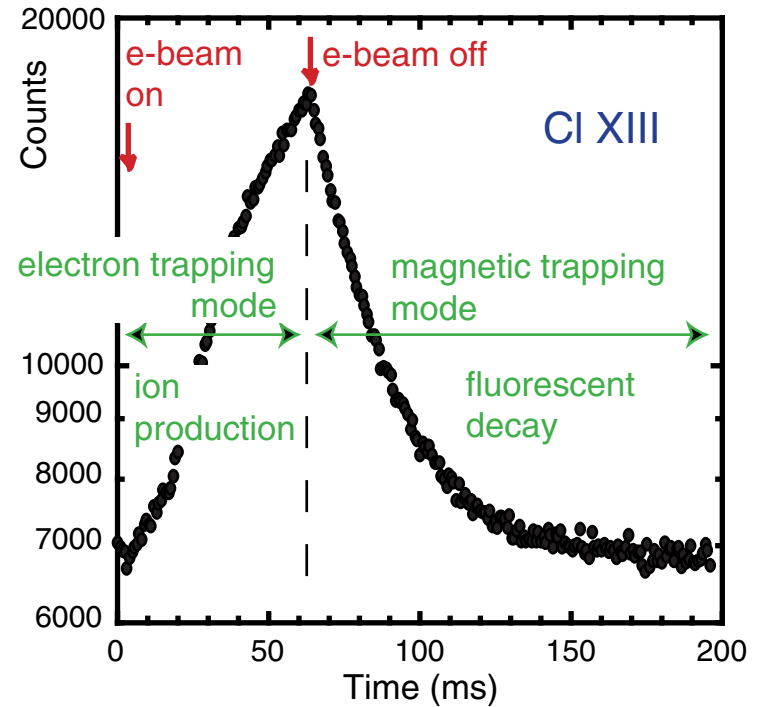
# Atomic lifetime measurement in the visible range of the spectrum



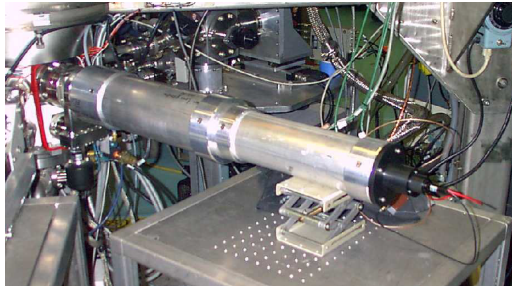
Livermore electron beam ion trap - the archetypical EBIT



Excitation curve in the fast trapping cycle for an atomic lifetime measurement

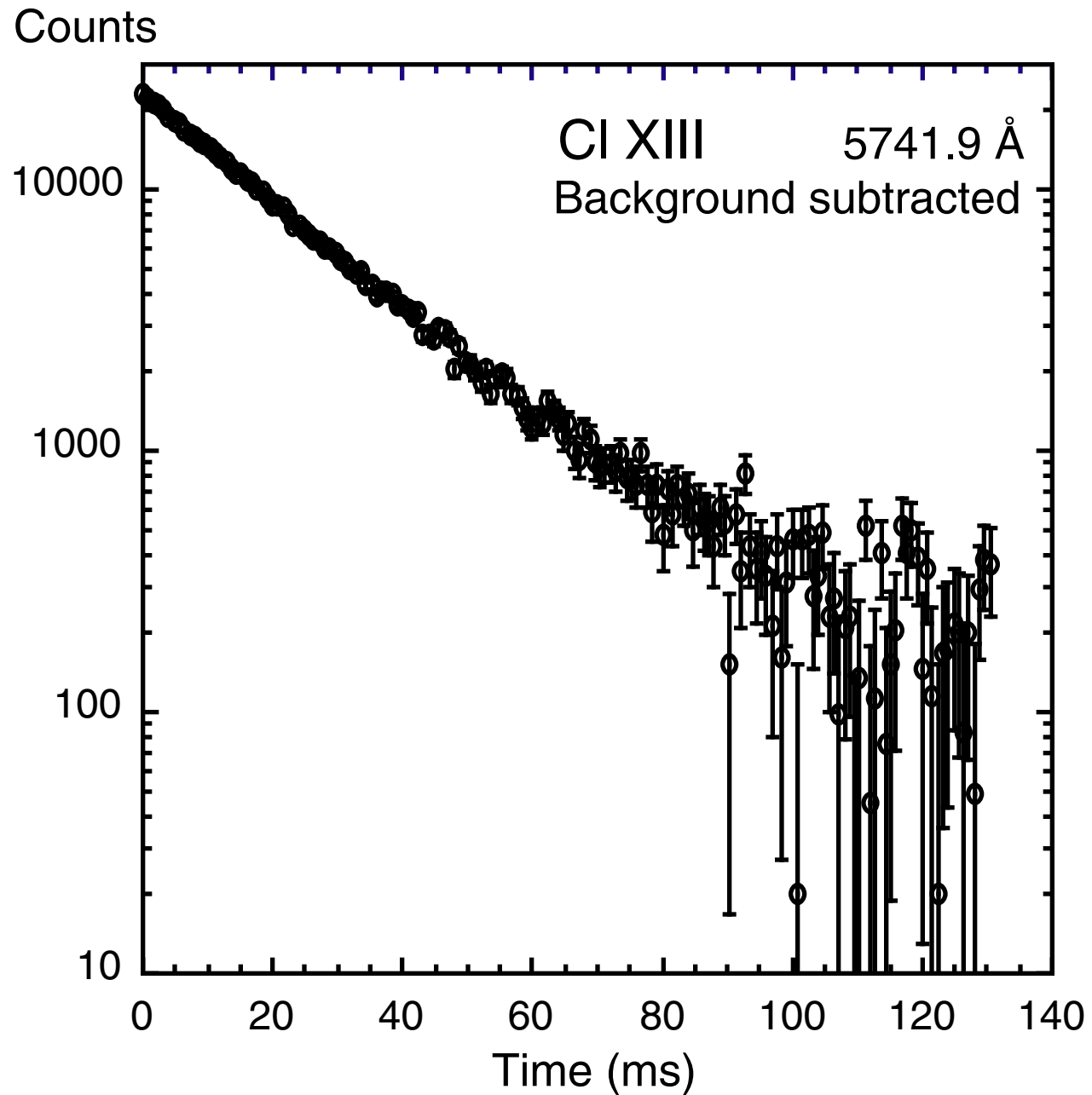


Stovepipe for optical observations



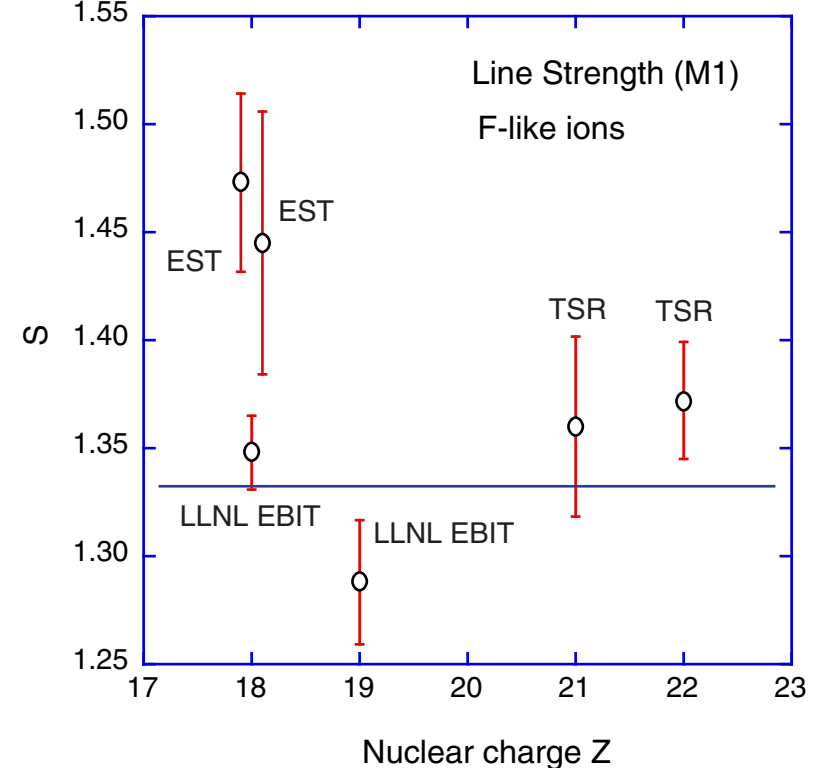
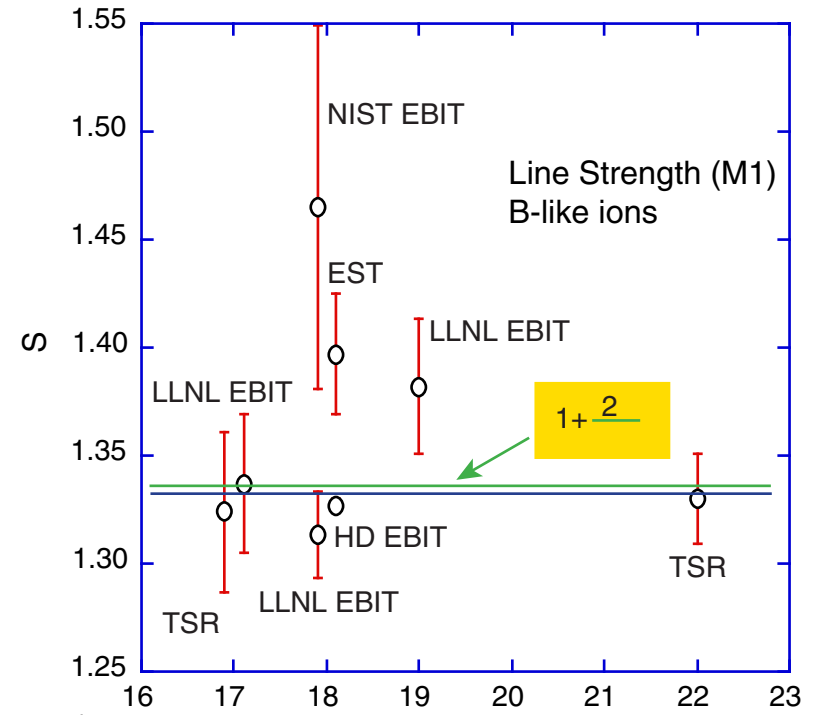
The basic technique is simple and robust.

Radiative decay curves can be followed  
for several atomic lifetimes

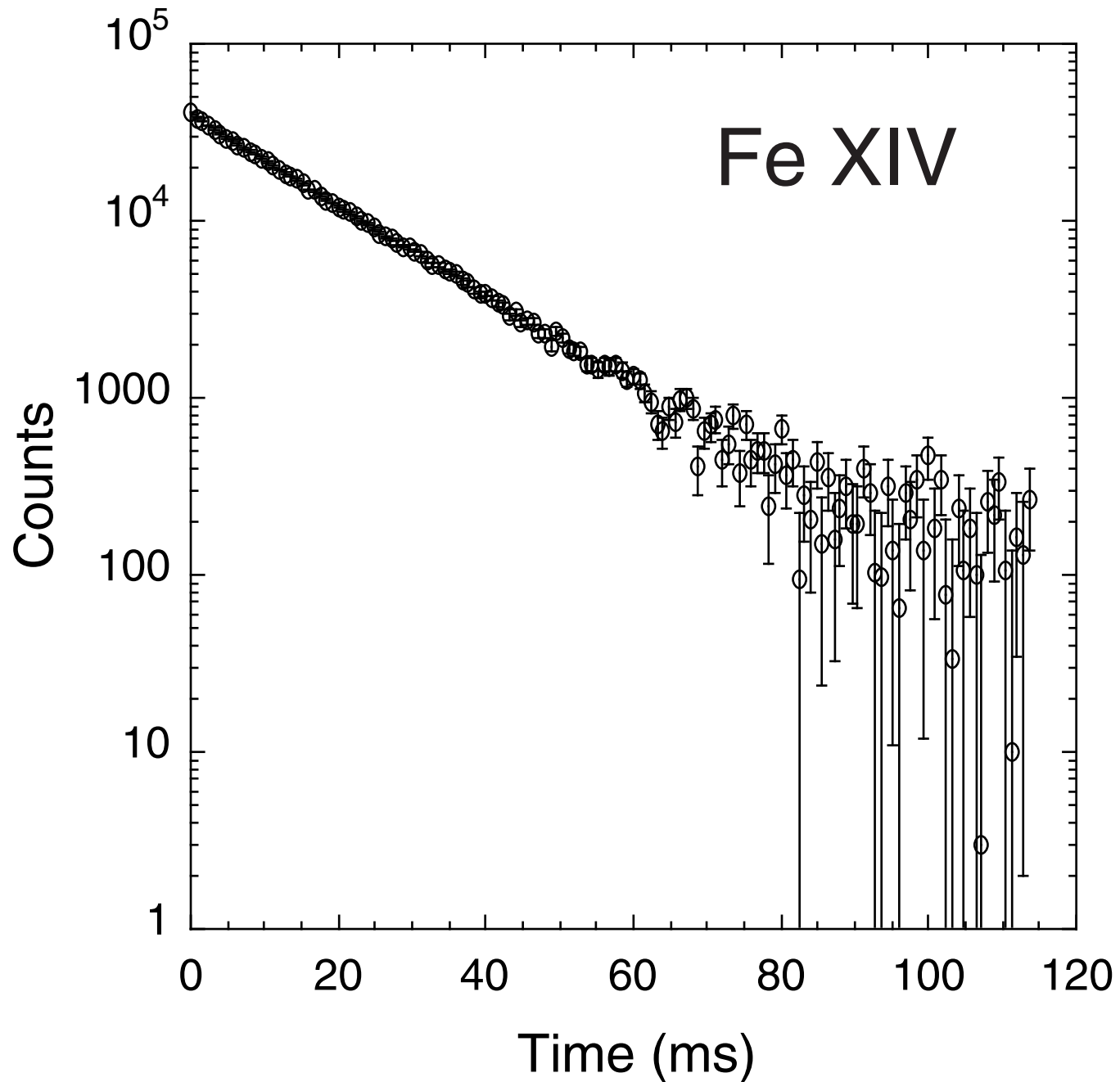


$n=2$  M1 transition between the fine structure levels of the ground state.  
 Predicted line strength  $S = 4/3$ .

EST Electrostatic ion trap  
 (Kingdon trap)  
 TSR Heavy ion storage ring  
 at Heidelberg  
 EBIT Electron beam ion traps  
 at NIST Gaithersburg,  
 Livermore, and Heidelberg

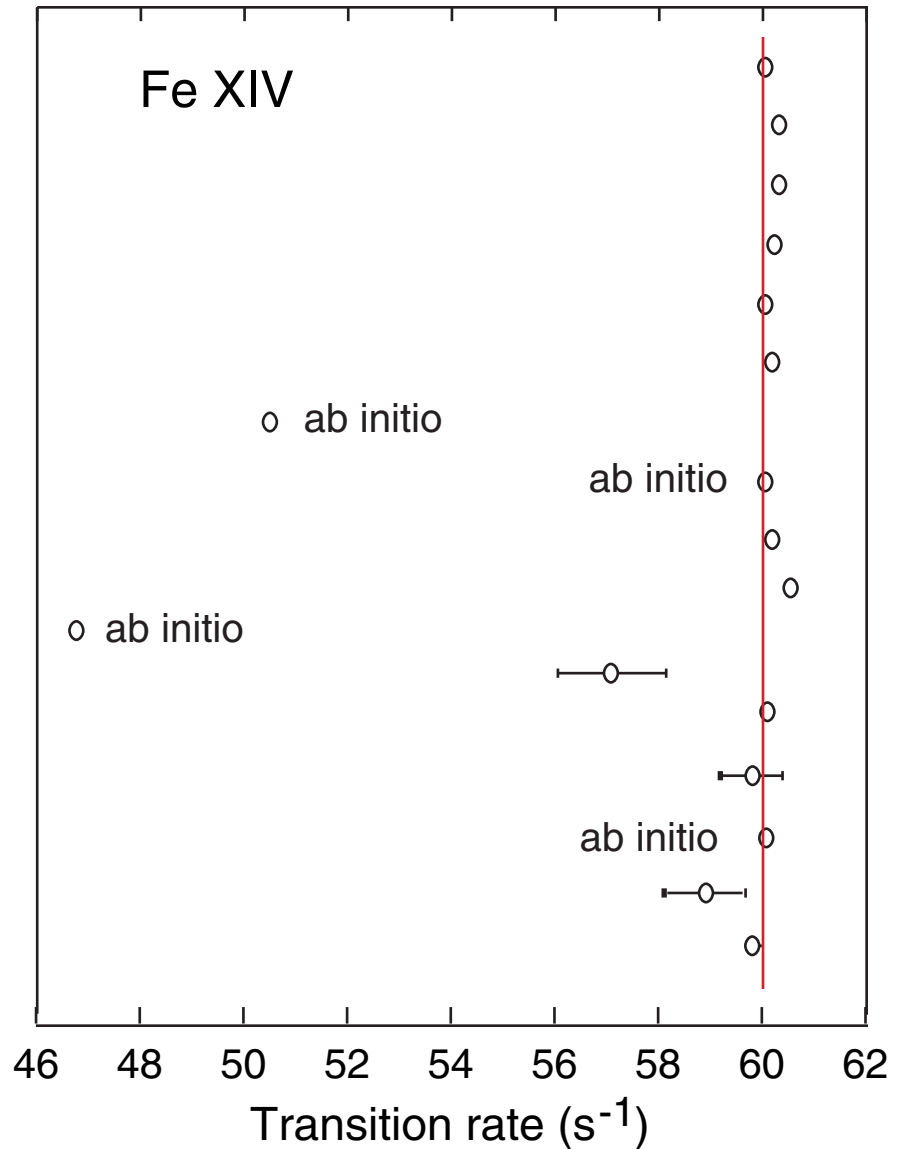


The "green iron line" decay curve  
as seen in the LLNL EBIT

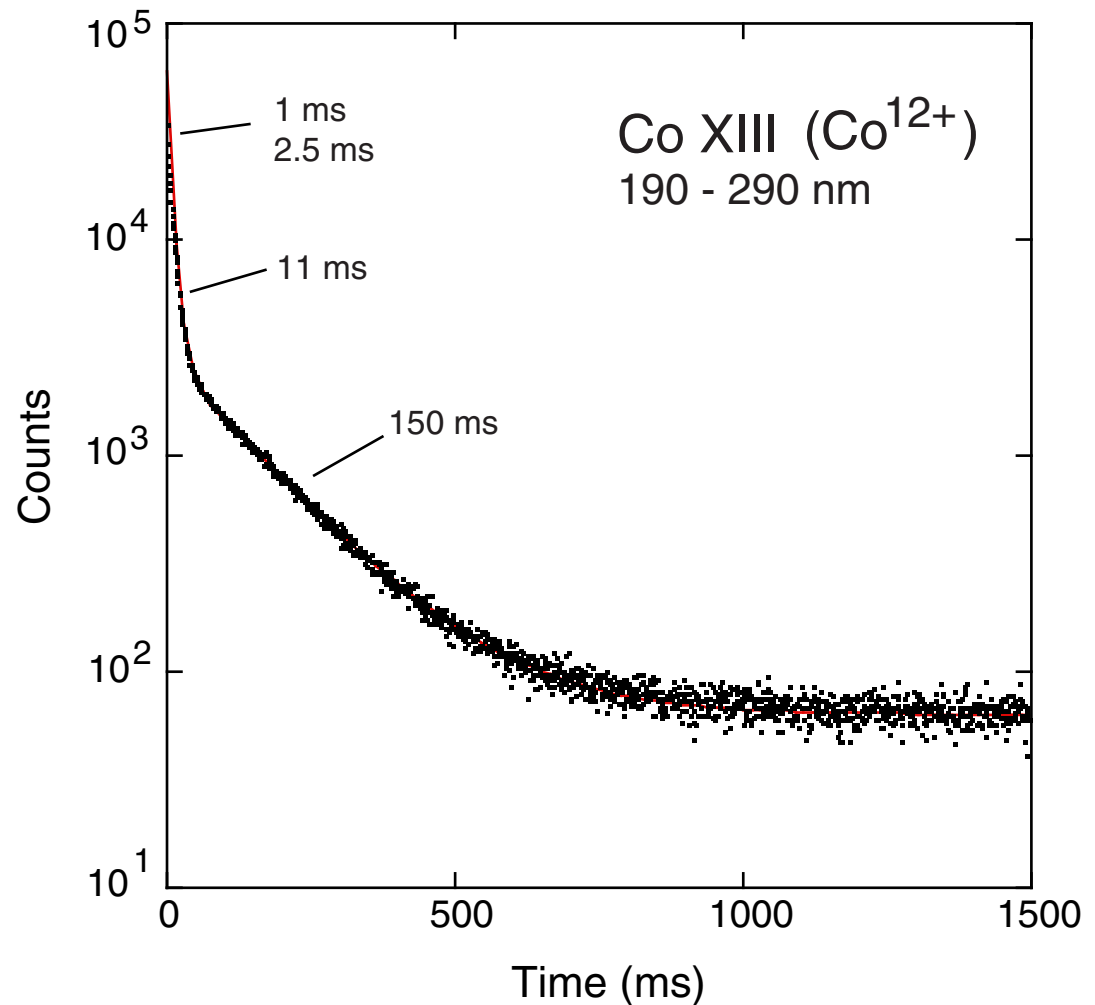
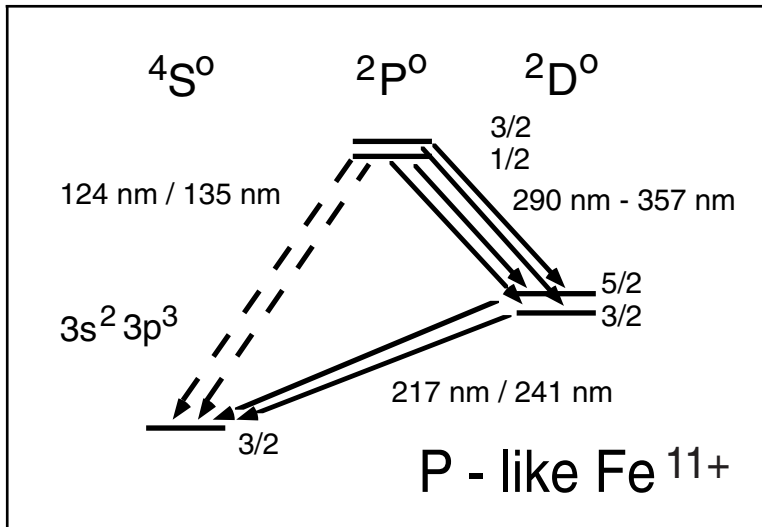


# The "green iron line" in the solar corona has found plenty of interest

Krueger & Czyzak 1966  
 Warner 1968  
 Smith & Wiese 1973  
 Kastner 1976  
 Kafatos & Lynch 1980  
 Eidelsberg et al. 1981  
 Froese Fischer  
 & Liu 1986  
 Huang 1986  
 Kaufman & Sugar 1986  
 Biemont et al. 1988  
 Bhatia & Kastner 1993  
 Moehs & Church 1999  
 Storey et al. 2000  
 Beiersdorfer et al. 2003  
 Vilkas & Ishikawa 2003  
 Smith et al. 2005  
 Crespo Lopez-U. et al.  
 2006



Measurement of M1 and E2 transition probabilities in the ground configuration of ions that are of astrophysical interest

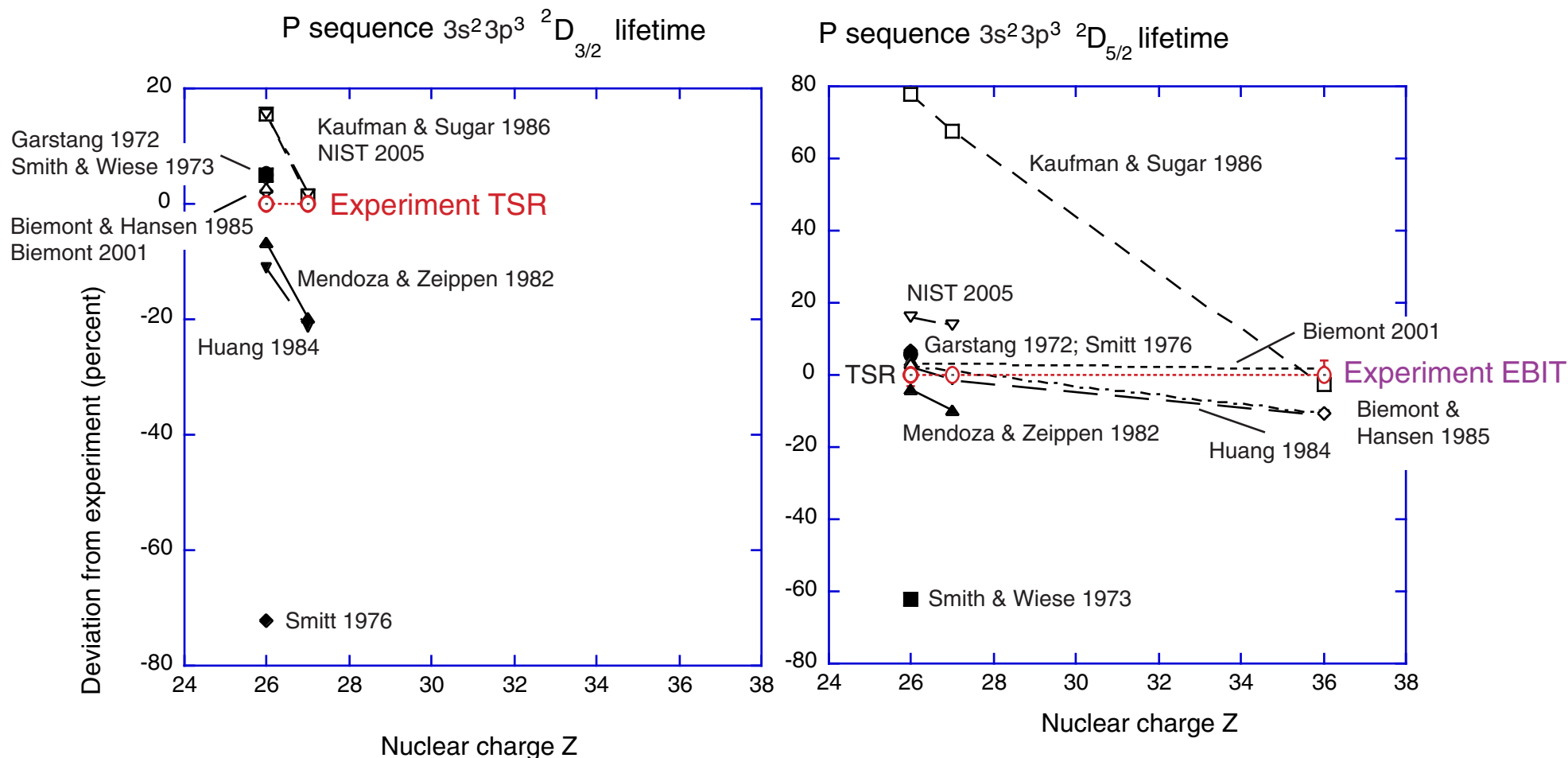


The line intensities in the ground configurations of N- and P-like ions serve as temperature diagnostics in astrophysics.

Very few calculations predict all four level lifetimes in P-like ions close to the experimental findings.

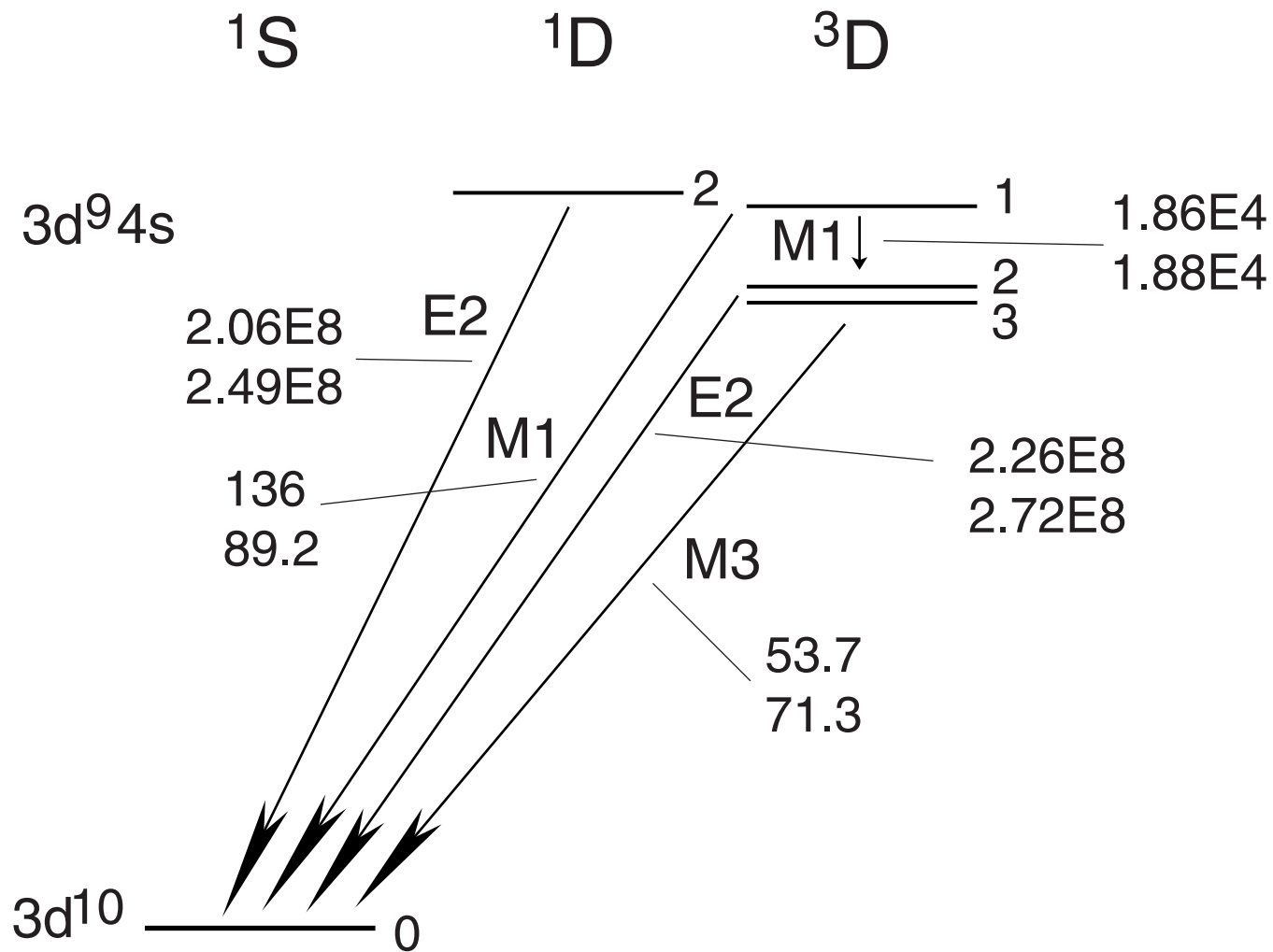


# Isoelectronic trends can be used to ascertain the consistency of data sets.

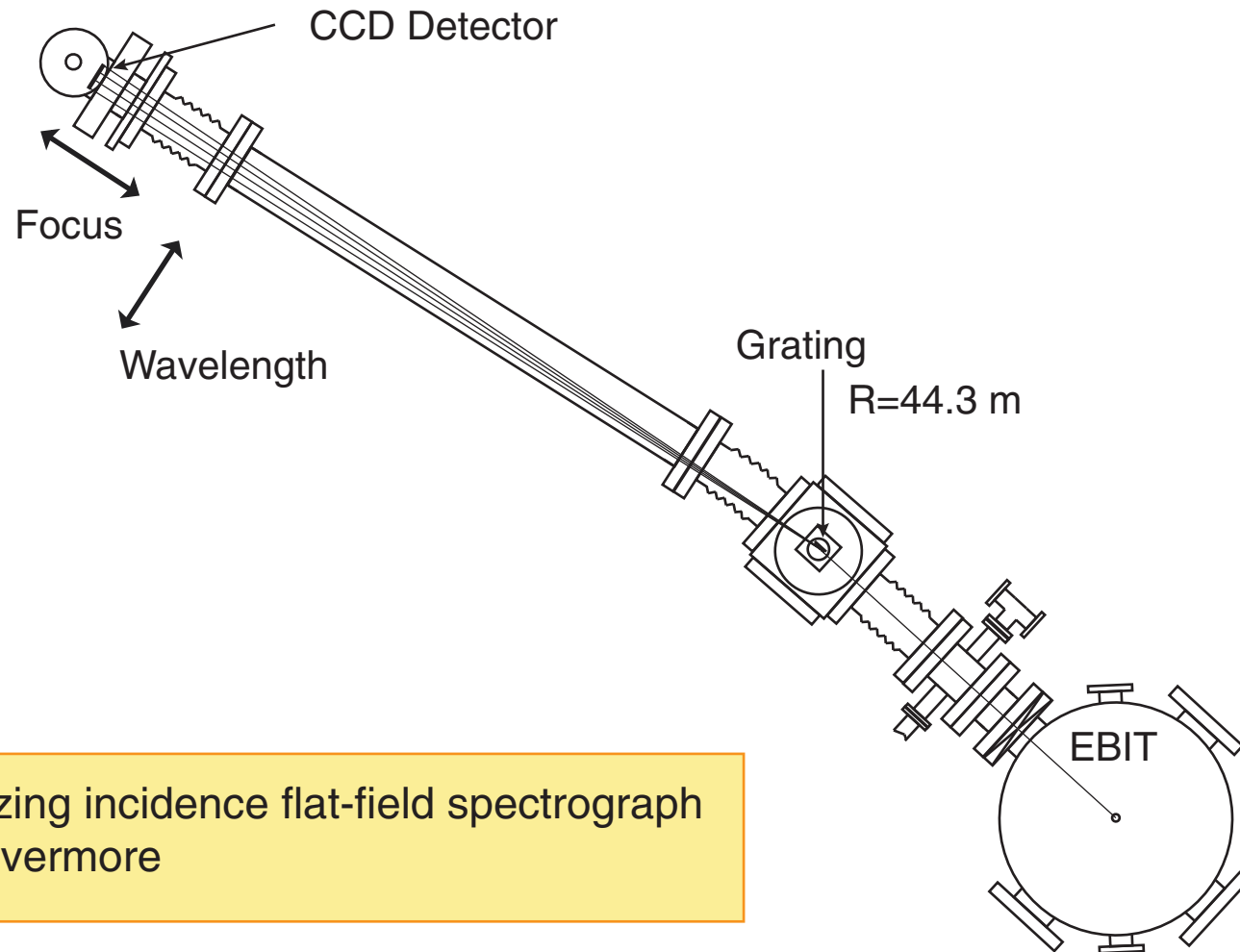


The predicted M1 and E2 transition rates in the literature or on the web (including the NIST data base) are not all as bad as in this case. The problem is how to find out which calculational results are good, and one finds out - by experiment ...

Ni-like Xe XXVII; the transition probabilities shown do not take hyperfine mixing effects into account.



Multichannel detection is a key element for precision spectroscopy.



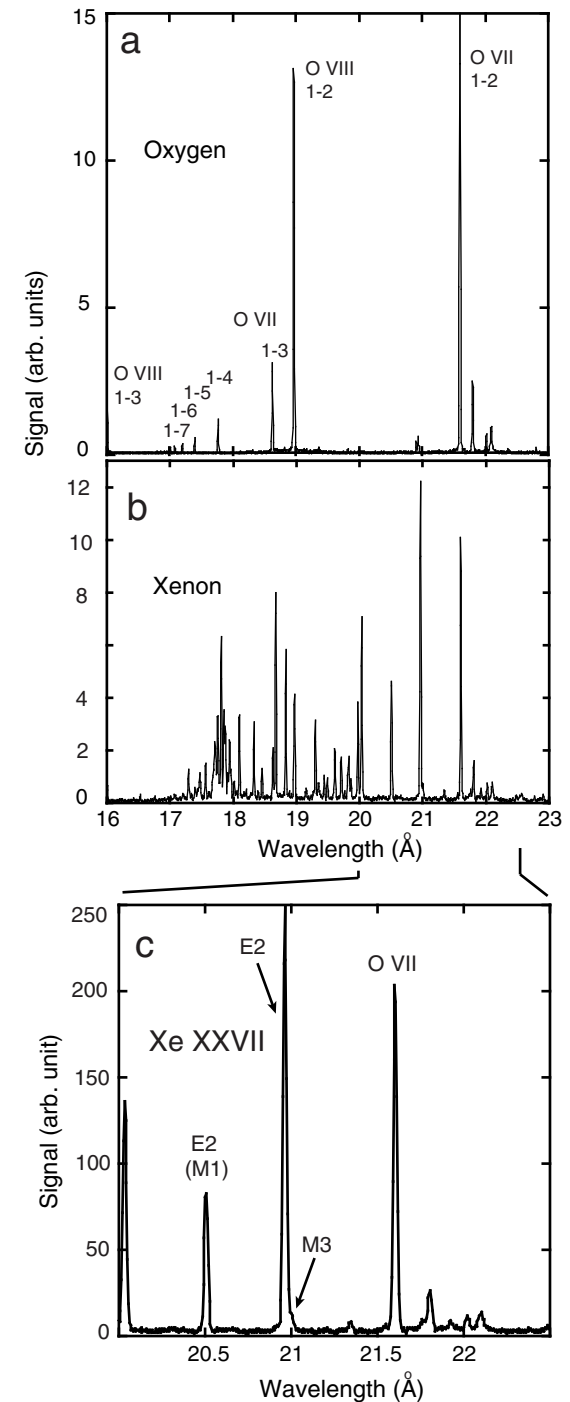
Grazing incidence flat-field spectrograph  
at Livermore

This instrument provides the highest spectral resolution  
of any EUV equipment at any electron beam ion trap.

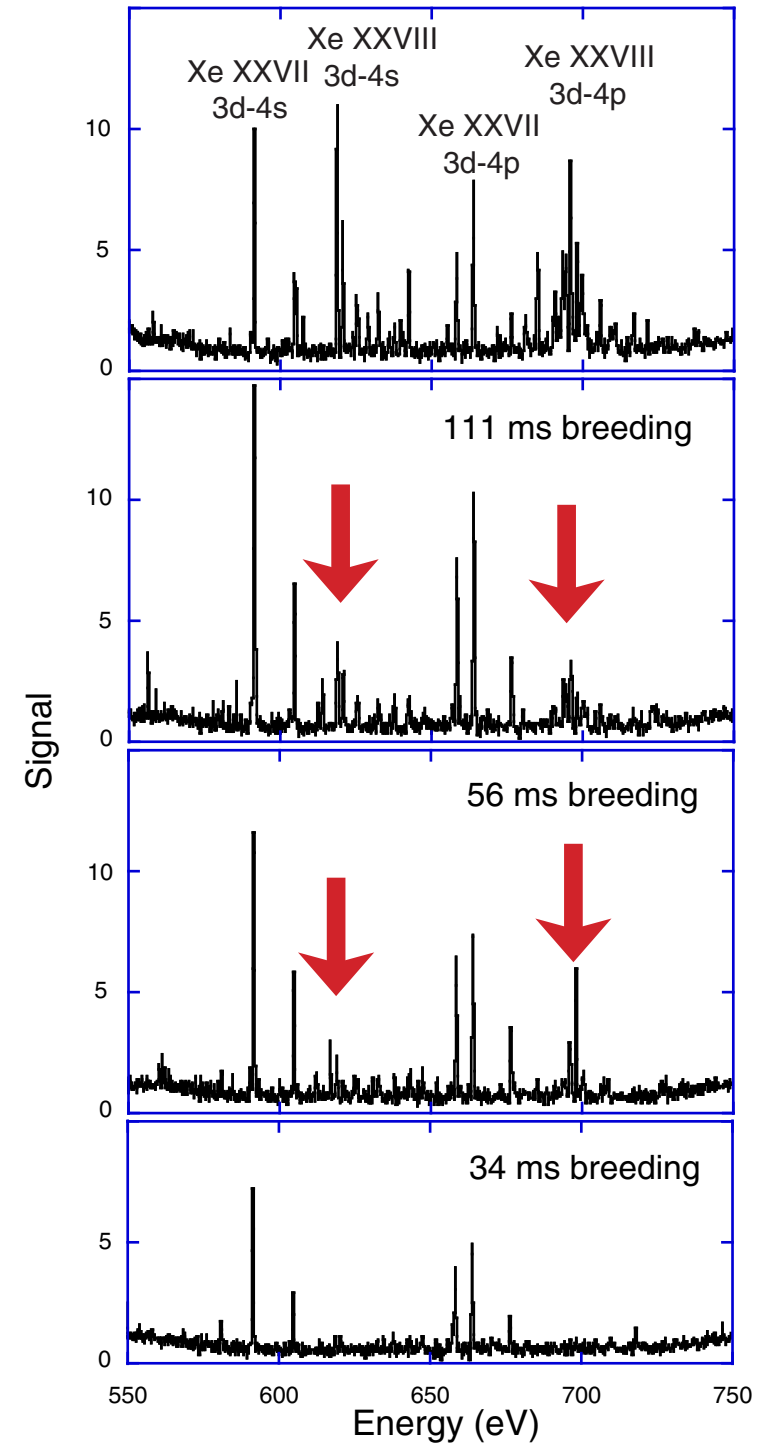
Many EUV spectra can be calibrated with the well known spectral line series of H- and He-like ions.

EUV spectra of oxygen and xenon recorded with a flat-field spectrograph at the LLNL EBIT

The decays of the lowest excited levels in Ni-like Xe ions have been identified and the wavelengths measured.

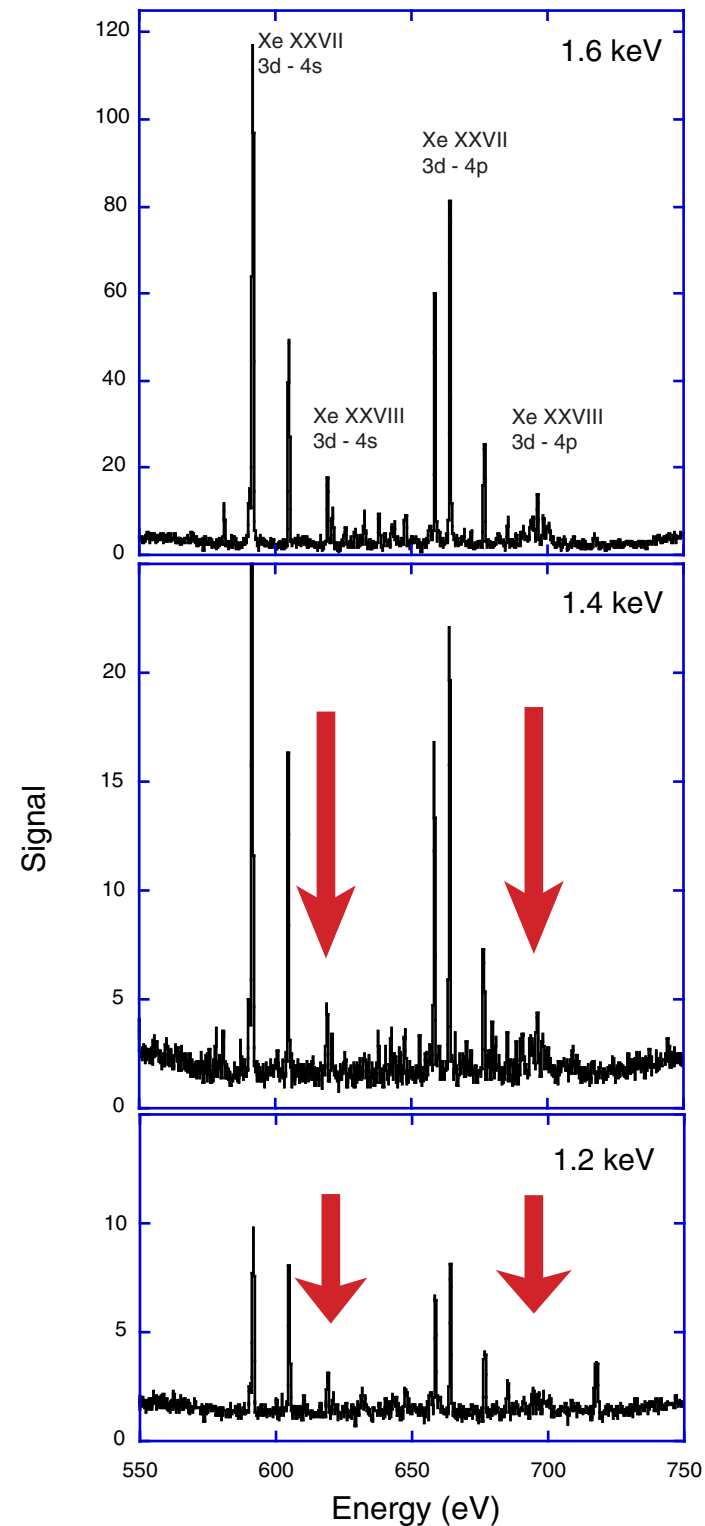


Xe Electron beam energy 1.9 keV



The Co-like ion (Xe XXVIII) needs much more time to breed than the Ni-like ion (Xe XXVII).

The ionization potential of Xe XXVII is 1.5 keV. Xe XXVIII is produced below this threshold via the metastable level of Xe XXVII at 590 eV.

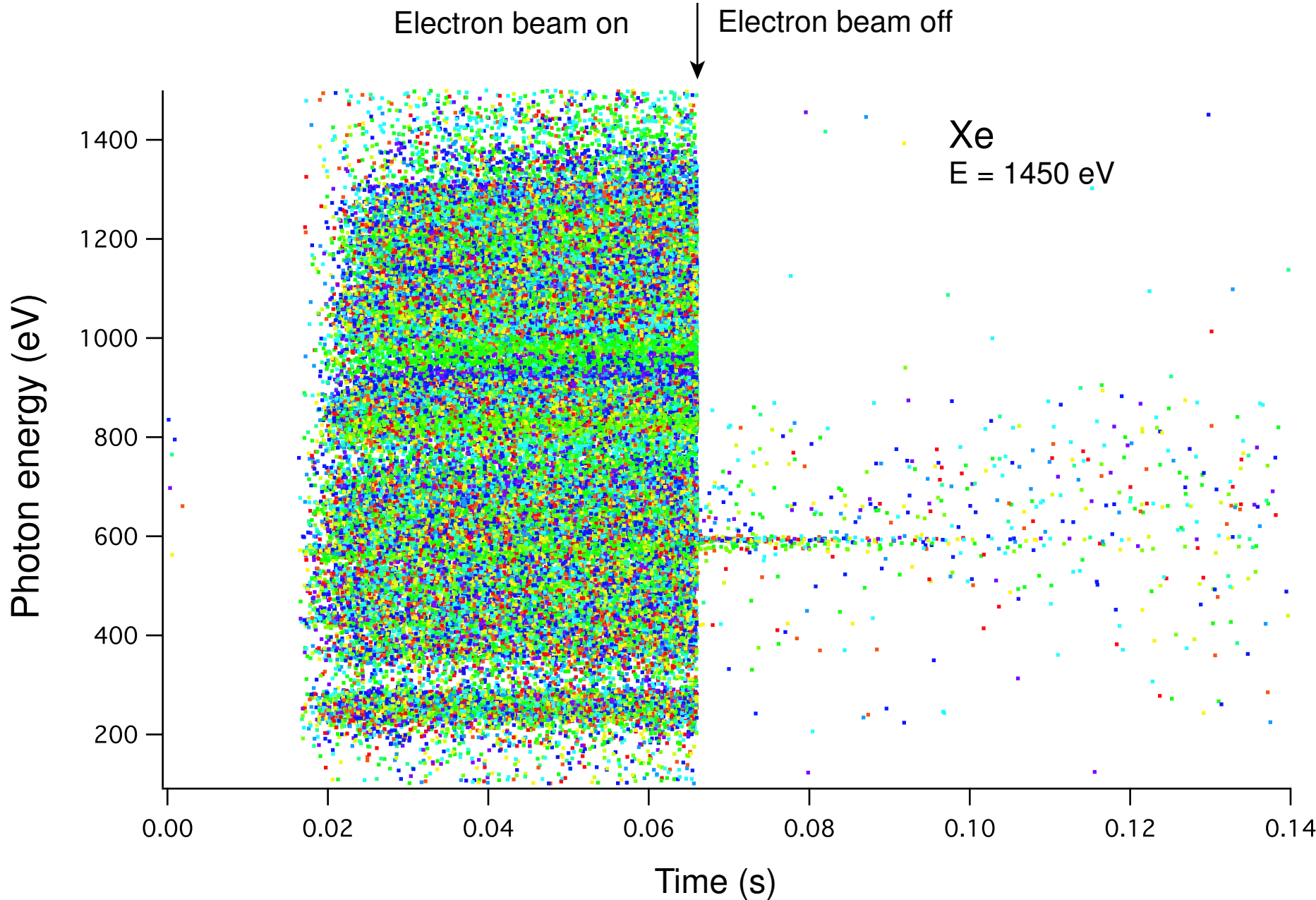


X-ray crystal spectrometers offer high spectral resolution,  
but suffer from low efficiency

XRS Microcalorimeter built at  
Goddard Space Flight Center  
for Astro-E / Astro-E2 spacecrafts

Covers X-ray energy range  
300 eV to 20 keV  
with 6 eV line width at low E  
32 pixels of 0.6 mm x 0.6 mm each  
Working temperature about 60 mK

Microcalorimeters feature a poorer resolution than  
crystal spectrometers, but are much superior to solid  
state diodes in low-energy access and in resolution.



XRS microcalorimeter data recorded at the LLNL EBIT with a 140 ms trap cycle.



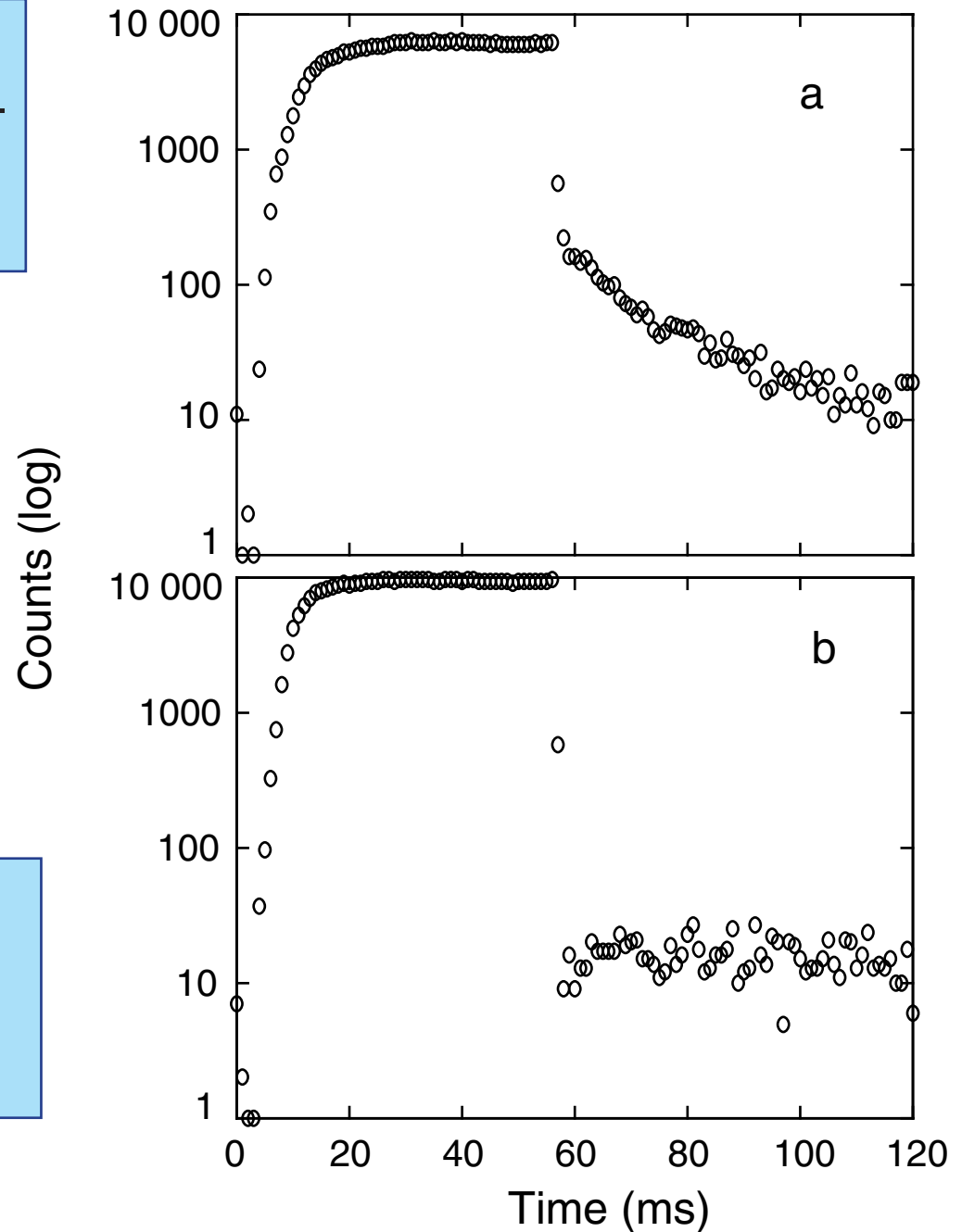
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a) at the position of the M3 decay in Xe XXVII

b) at the position of O VIII Lyman alpha

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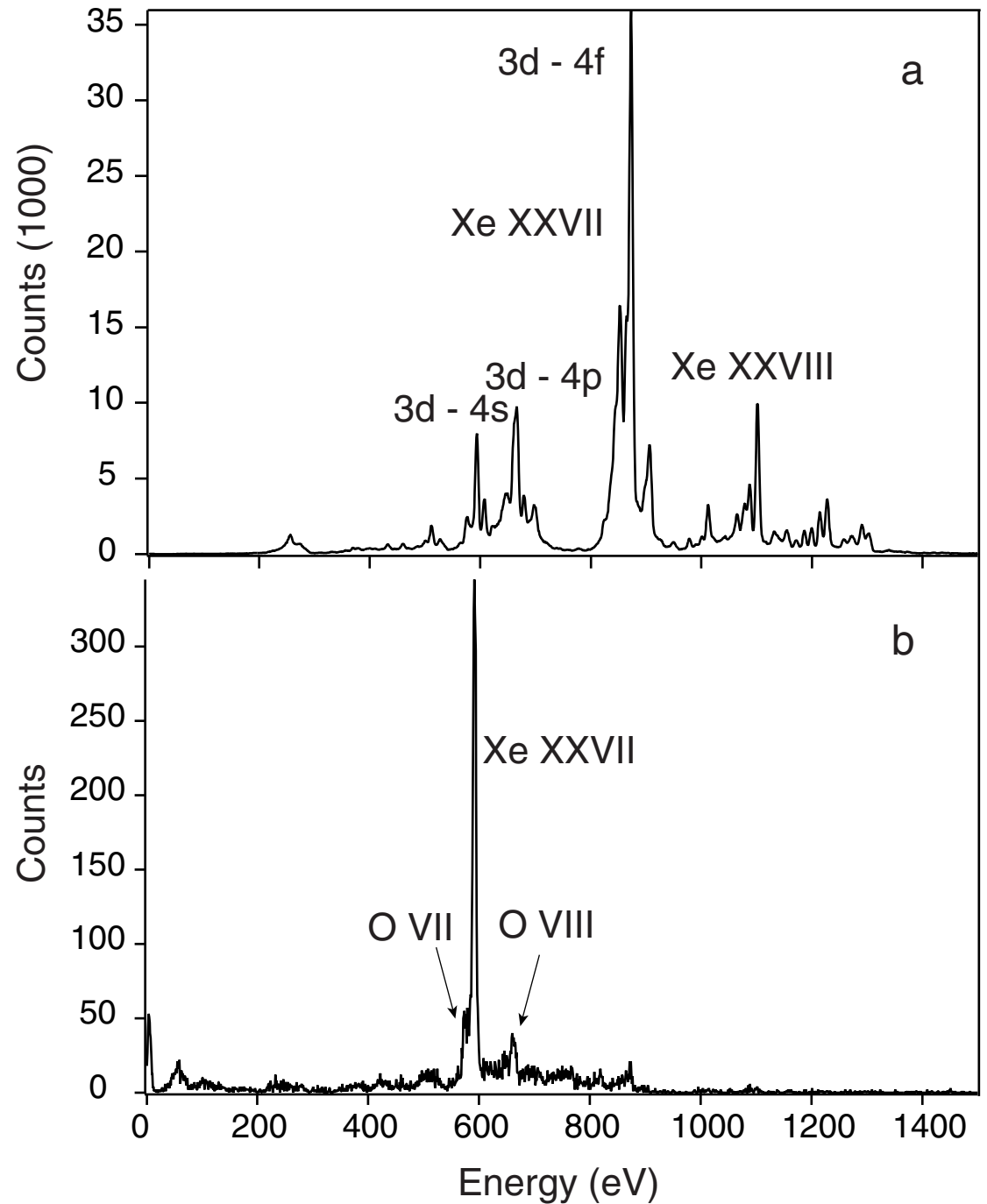
Each signal pulse is time-stamped; the data can be sorted by X-ray energy or time within the trap cycle.

XRS microcalorimeter spectra of Xe  
( $E = 1450$  eV)

a) electron beam on

b) electron beam off

Time resolved spectra reflect level population dynamics.

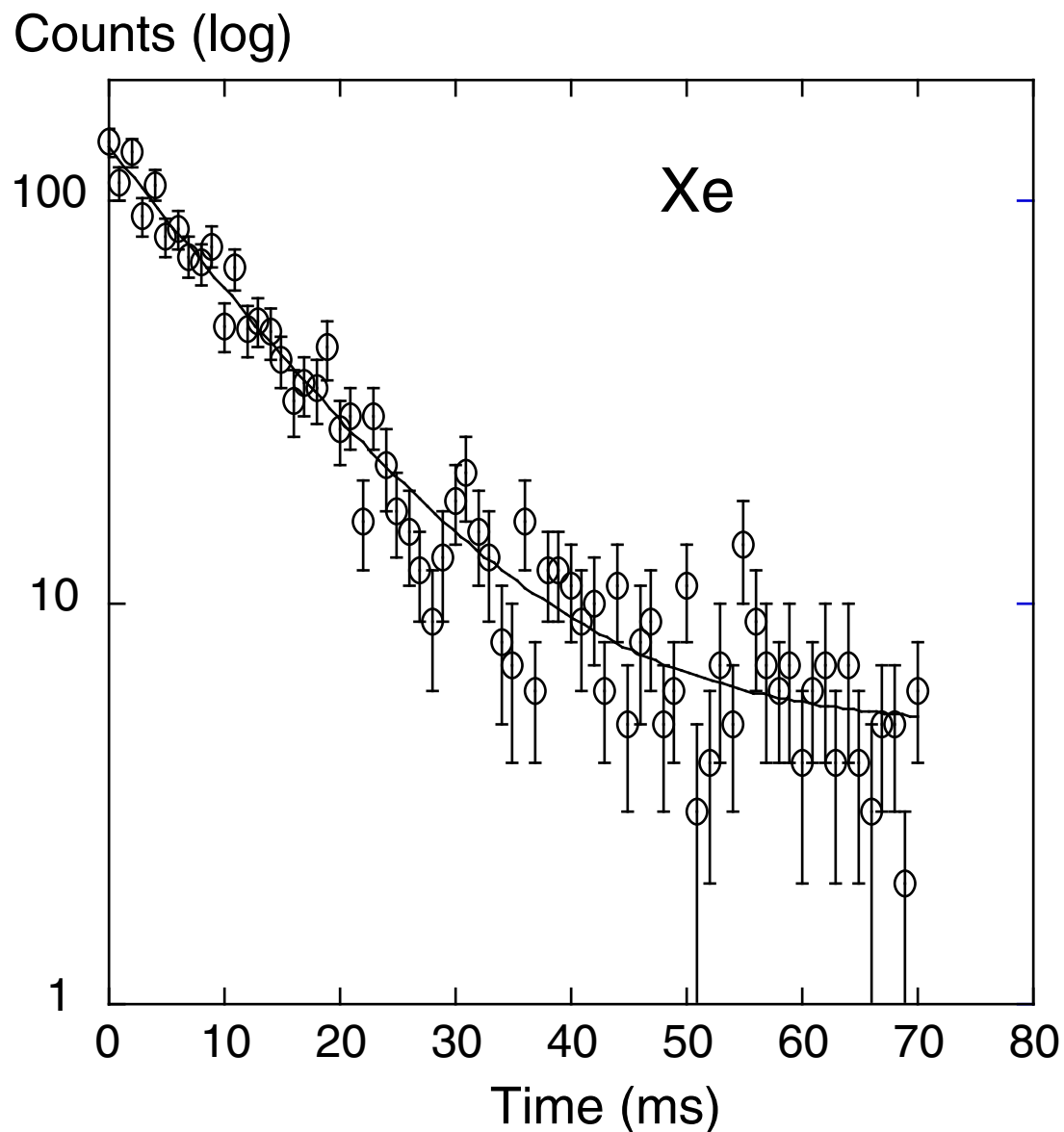


Microcalorimeter data of  
about one week total run time

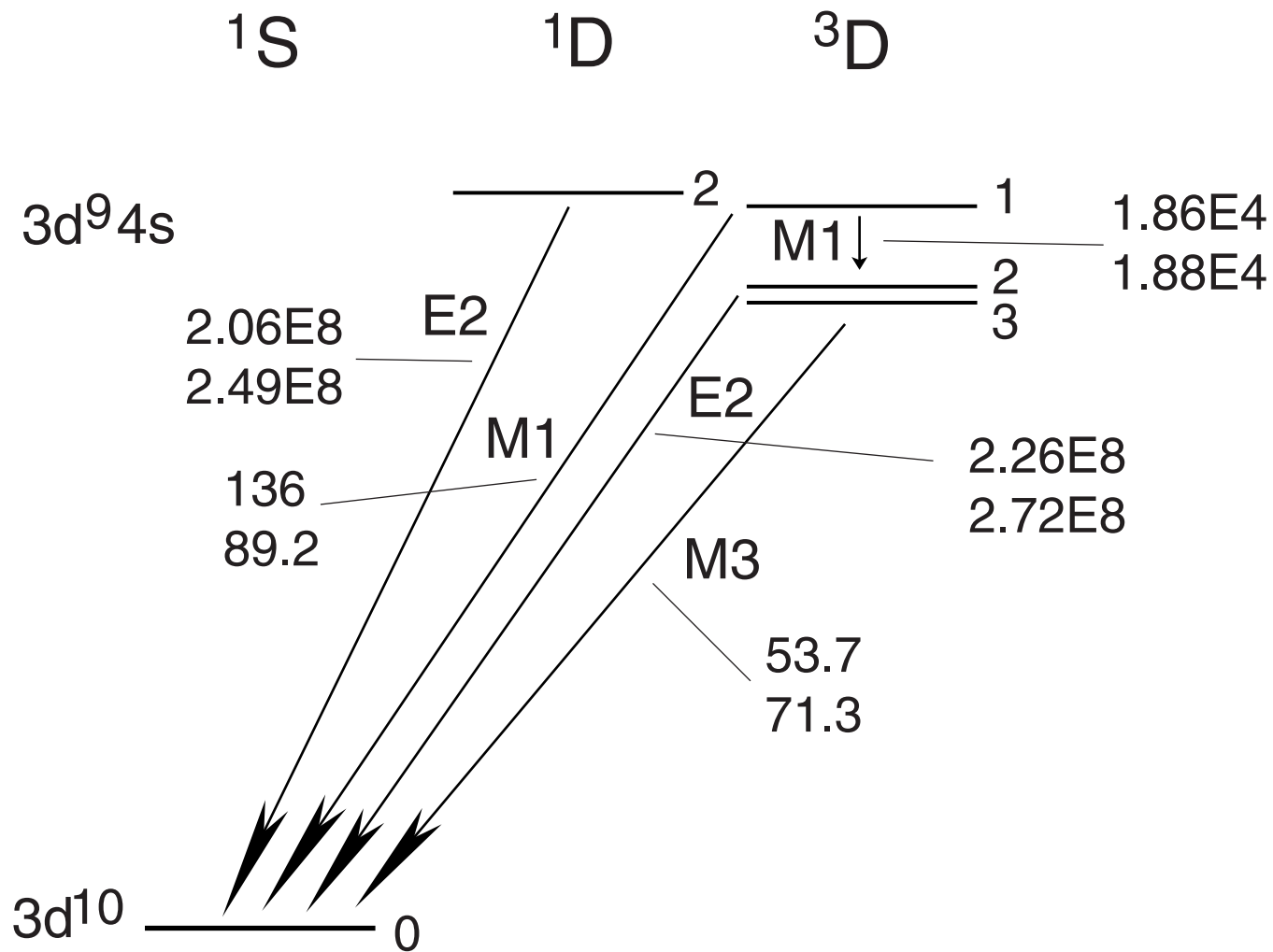
Decay curve  
extracted from the  
XRS microcalorimeter data  
at the position of the  
Xe XXVII M3 decay

Apparent lifetime  
 $11.0 \pm 0.5$  ms

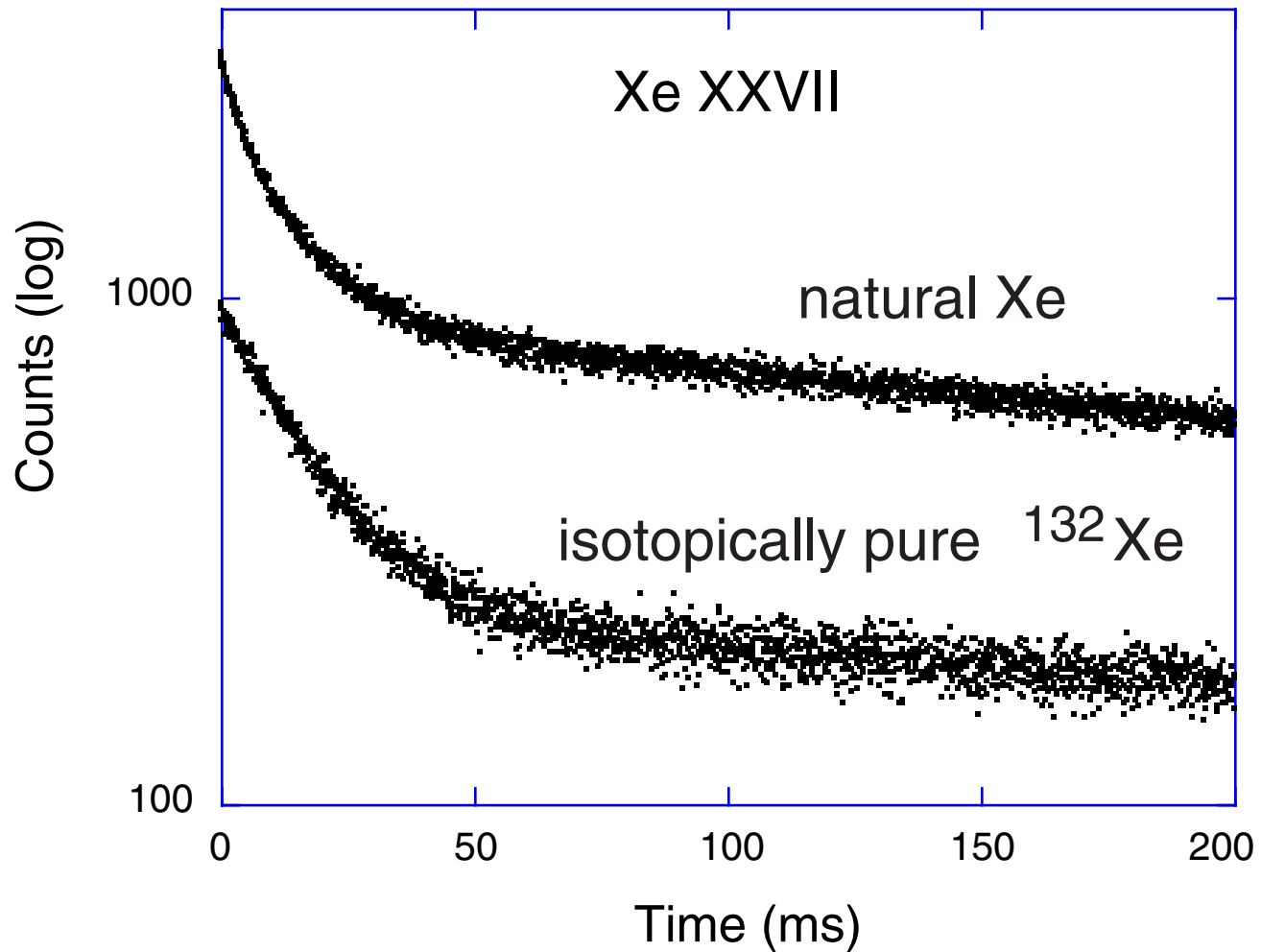
This is the first atomic lifetime  
measurement using a  
microcalorimeter at an  
electron beam ion trap.



Ni-like Xe XXVII; the transition probabilities shown do not take hyperfine mixing effects into account.



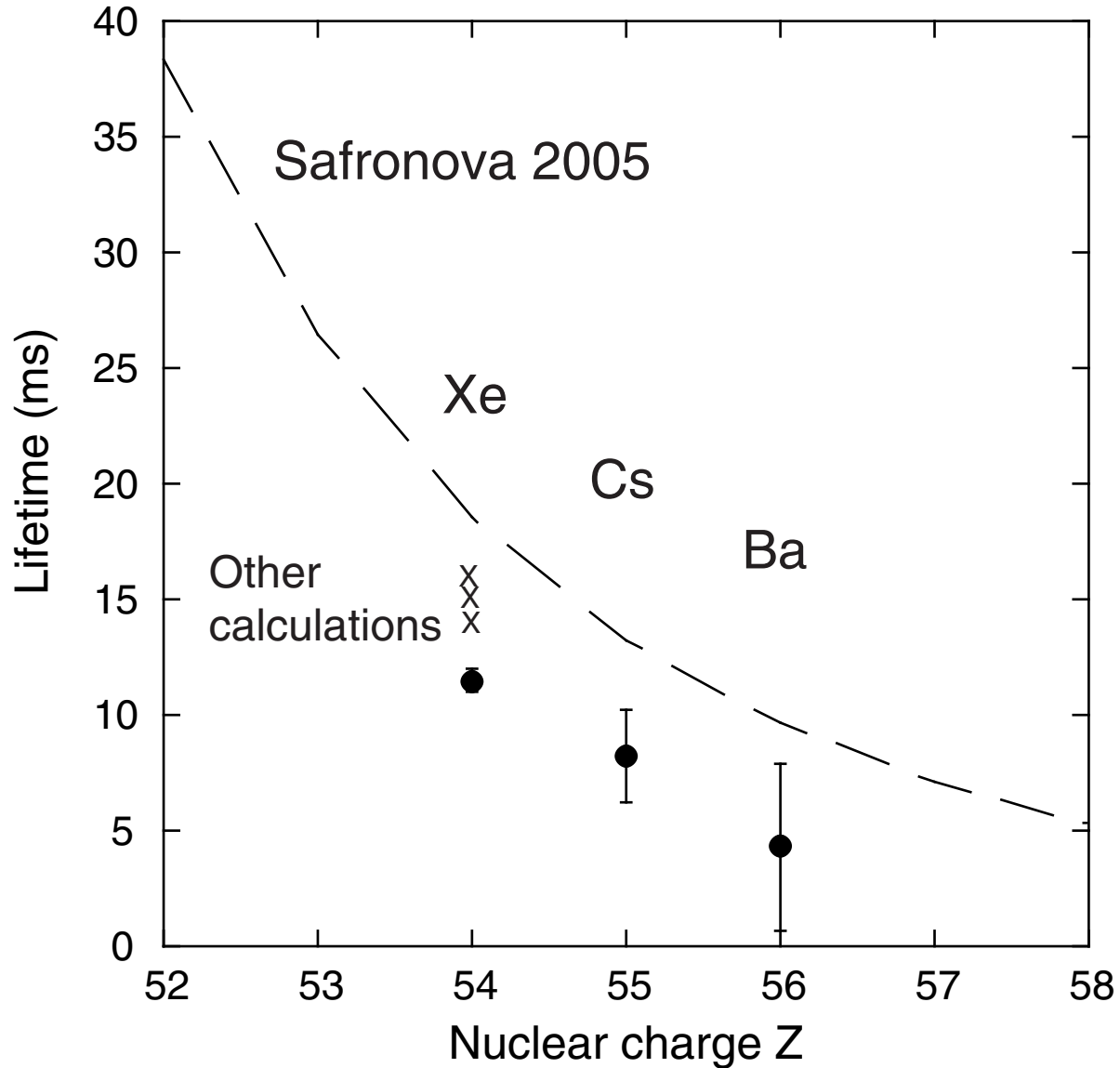
Soft-X-ray signal of Xe at SuperEBIT  
The even isotope Xe132 has no hyperfine structure.  
It features a single-component M3 radiative decay  
(and a tail from charge exchange (CX) processes).  
Natural Xe has about equal parts of odd and even  
isotopes and a more complex decay curve.



Very few calculations cover the magnetic octupole (M3) decays.

Results of LLNL EBIT lifetime measurements on M3 decays in Ni-like ions in comparison to theory (all neglecting any mixing due to hyperfine structure)

A shorter lifetime than predicted makes the ion less sensitive to density effects.



# Atomic lifetime determination

## Working ranges

Beam-foil spectroscopy : picosecond to hundred nanoseconds

Electron beam ion trap : femtosecond and  
microsecond to hundred milliseconds

Heavy-ion storage ring : millisecond to dozens of seconds

## EBIT atomic lifetimes of interest in

- astrophysics (solar corona, planetary nebulae, AGN, etc.)
- plasma physics (tokamak, spheromak, divertor)

## High measurement accuracy of EBIT experiments

- compares well with heavy-ion storage ring work
- outpaces electrostatic ion traps
- provides benchmarks for atomic structure codes and collisional-radiative models
- challenges theory