Atomic lifetime measurements using electron beam ion traps

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Physics & Advanced Technologies

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in collaboration with
P. Beiersdorfer, G. V. Brown, H. Chen, J. H. T. Clementson, D. B. Thorn, a. o.

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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

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Cs^{45+} in SuperEBIT at various temperatures

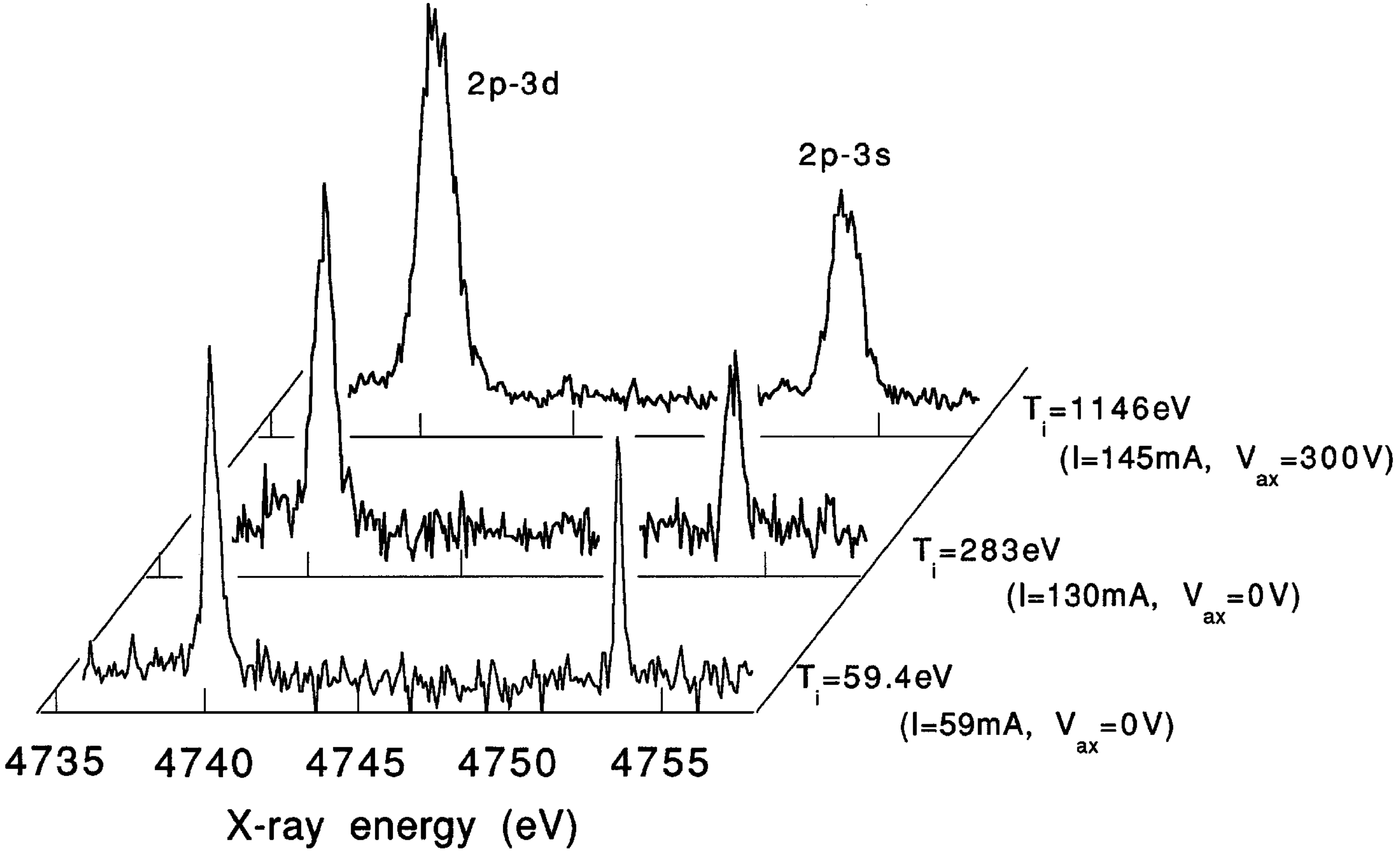


Figure from Beiersdorfer et al., PRL 77, 5353 (1996).

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.

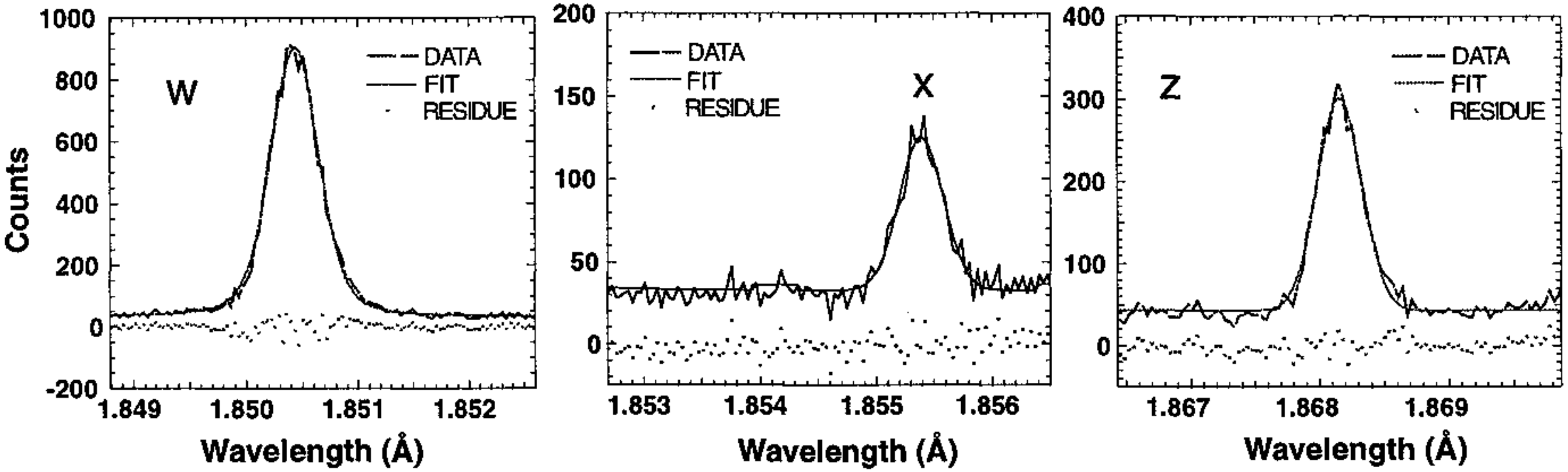
Elegant approach: Use line pair of decays of short-lived and long-lived levels.
Use long-lived level decay as a template that covers the instrumental effects (approximated by a Gaussian);
use Gaussian width in the analysis of the Voigt profile of the short-lived level decay, extract Lorentzian contribution.

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).



a) b) c)

Fig. from Graf et al., 16th ICSLS, 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

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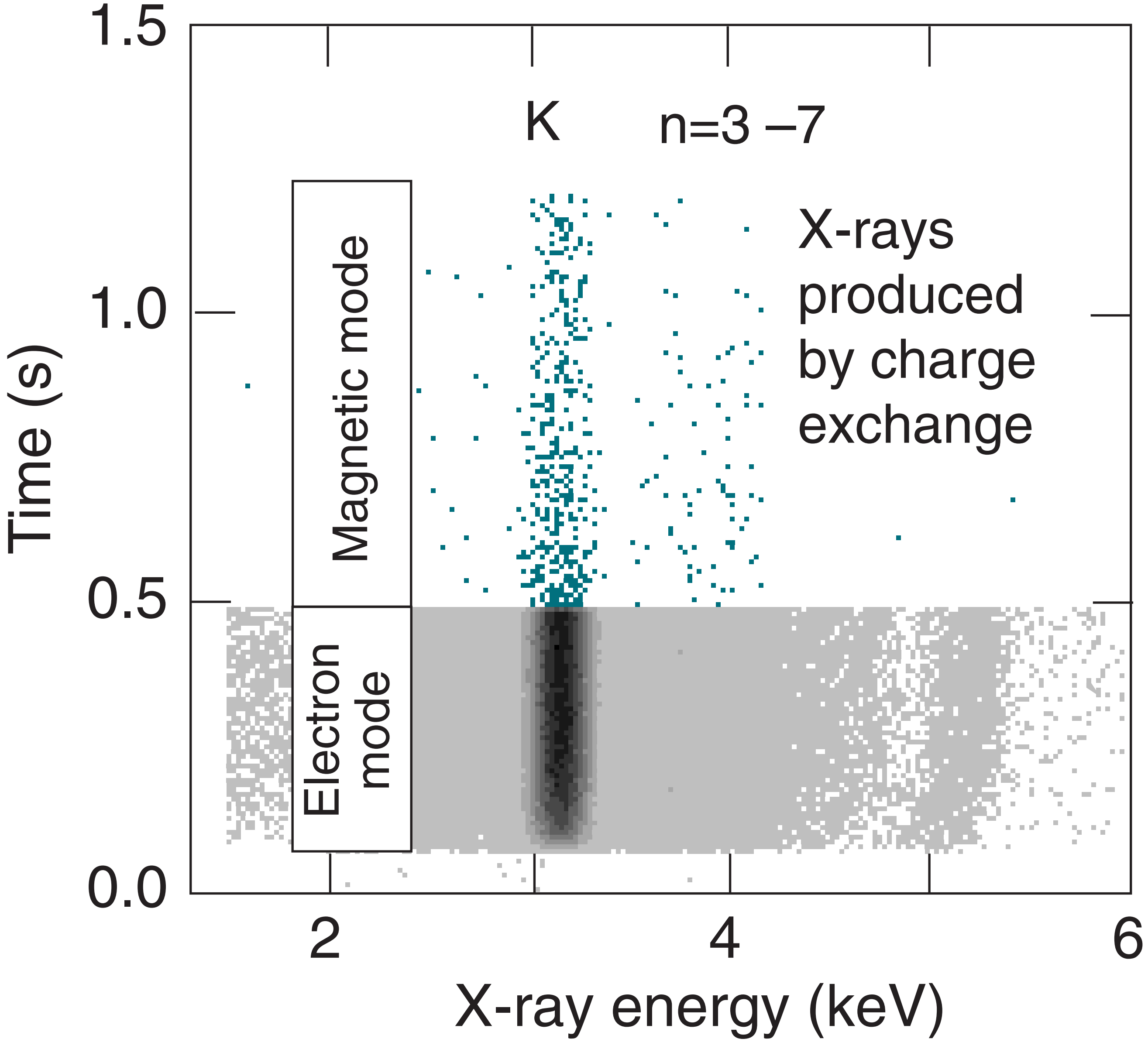
Excitation vs. decay curve
Prompt vs. delayed emission



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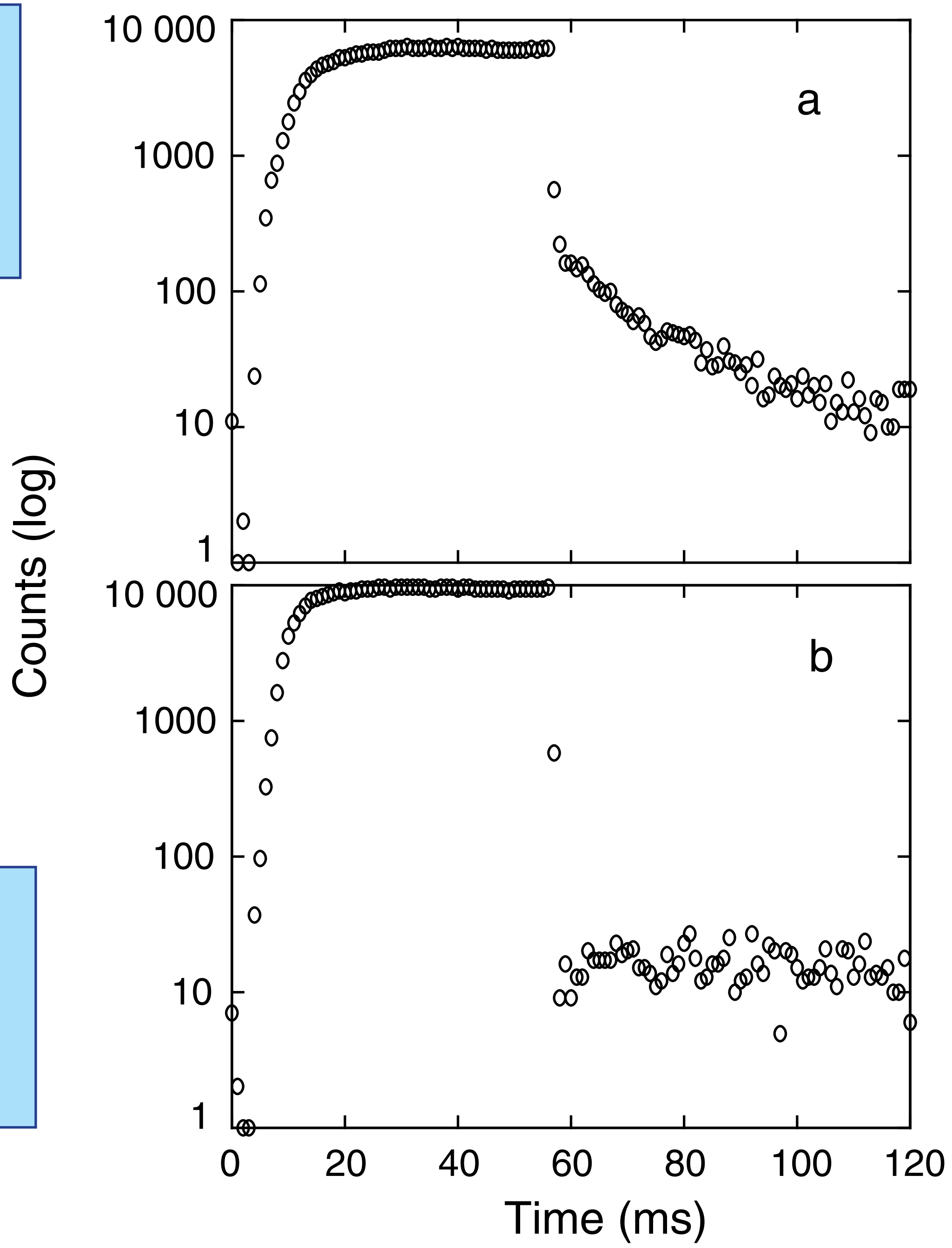
When the electron beam is switched off, delayed photons arise from long-lived excited levels or from charge exchange (CX).

XRS microcalorimeter data of Xe

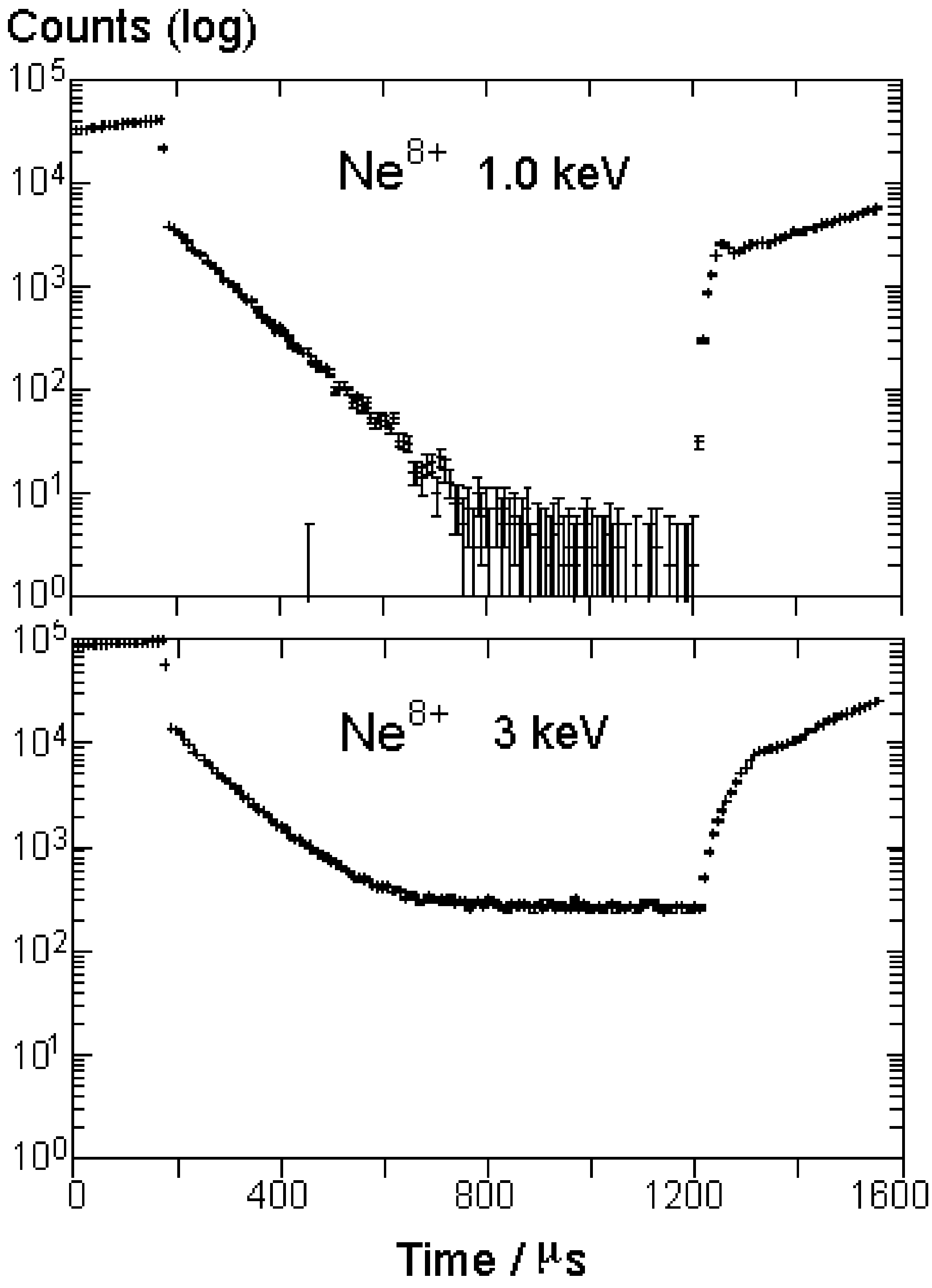
a) at the position of the
M3 decay in Xe XXVII

b) at the position of
O VIII Lyman alpha

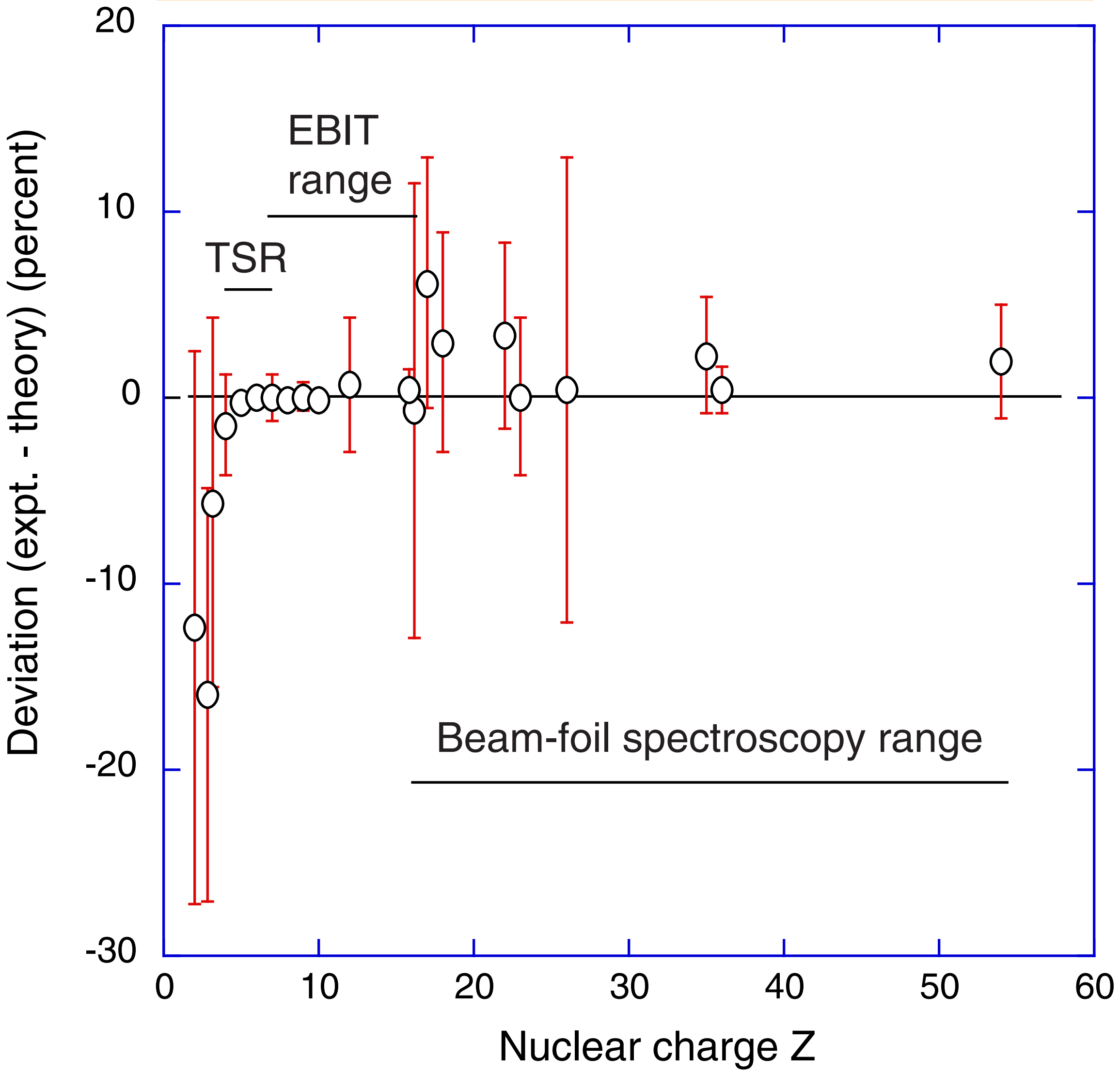
In (near) Ni-like Xe, there is only one level with a long (millisecond range) lifetime.



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.

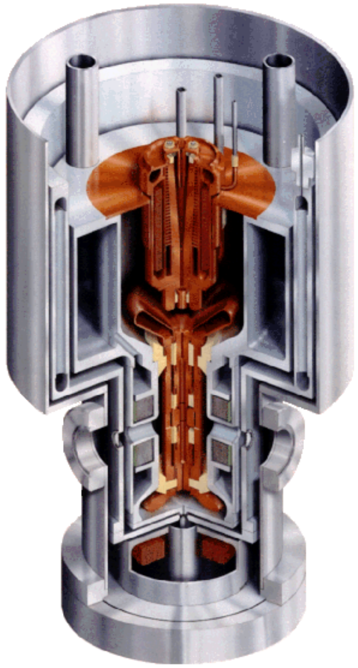


M1 transition rate in the He sequence

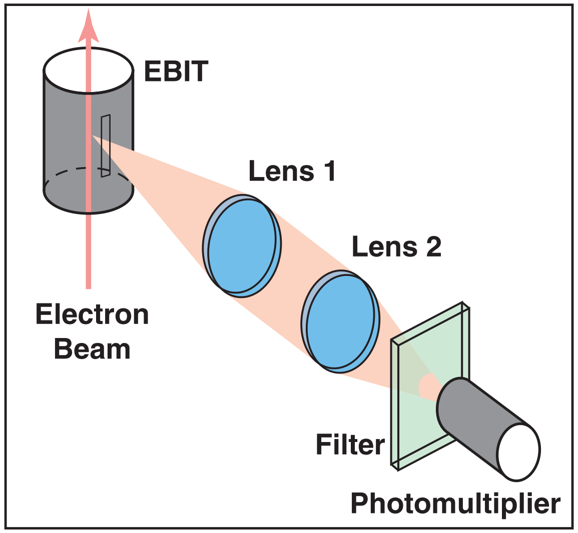


The measurements at the heavy-ion storage ring
TSR and at the LLNL EBIT
are in excellent agreement with relativistic theory

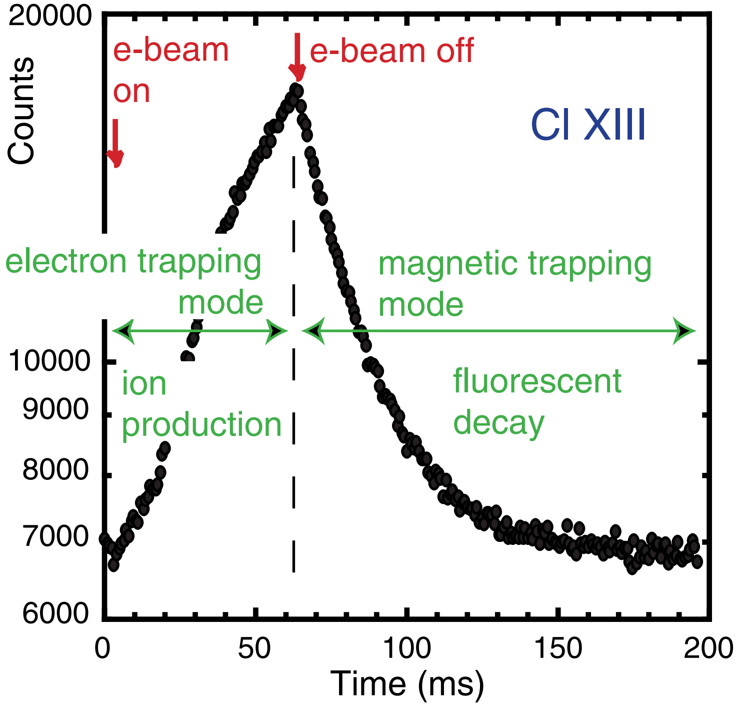
Atomic lifetime measurement in the visible range of the spectrum



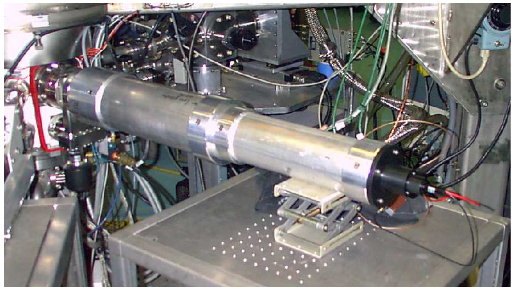
Livermore electron beam ion trap - the archetypical EBIT



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

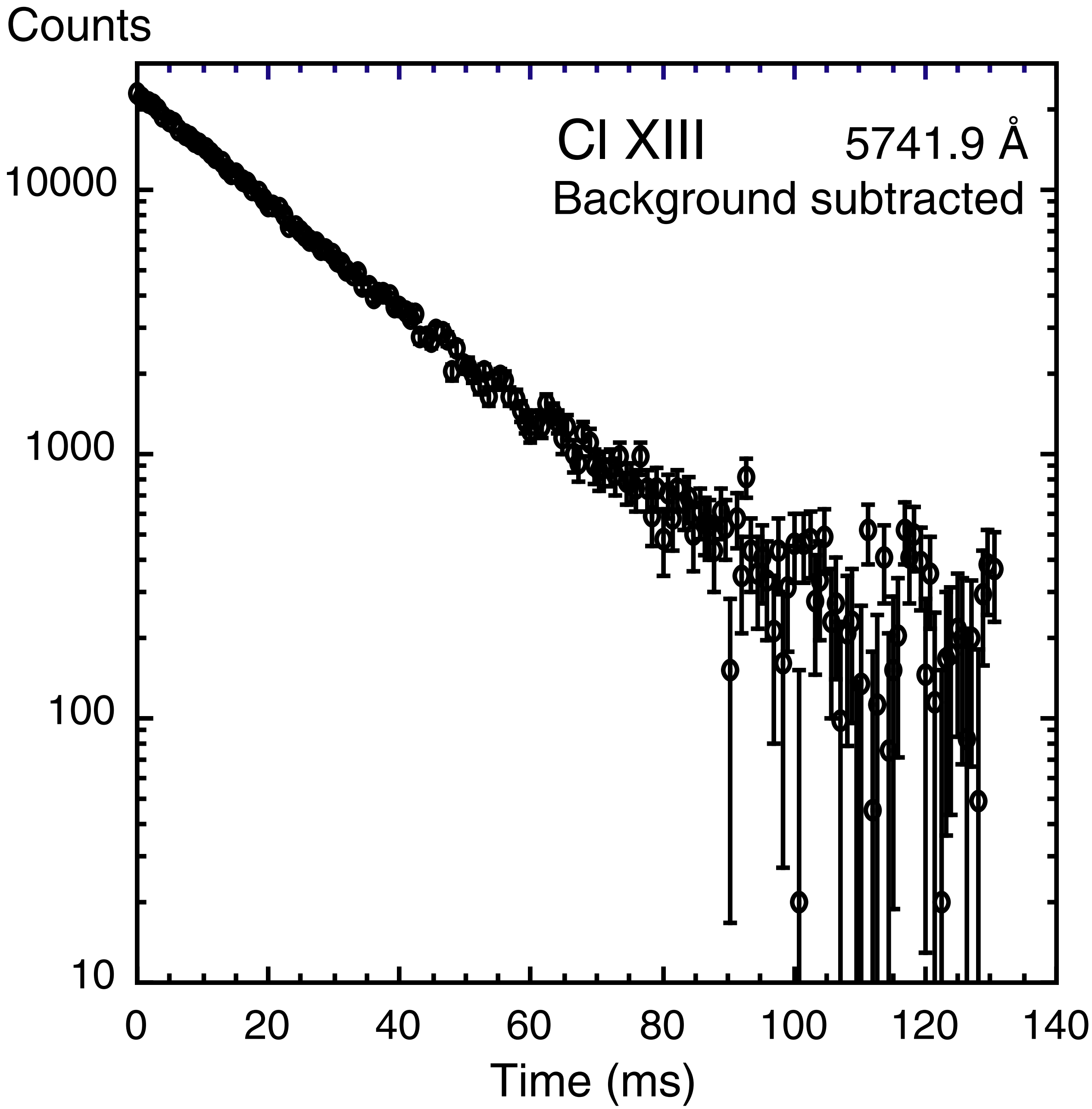


Stovepipe for optical observations



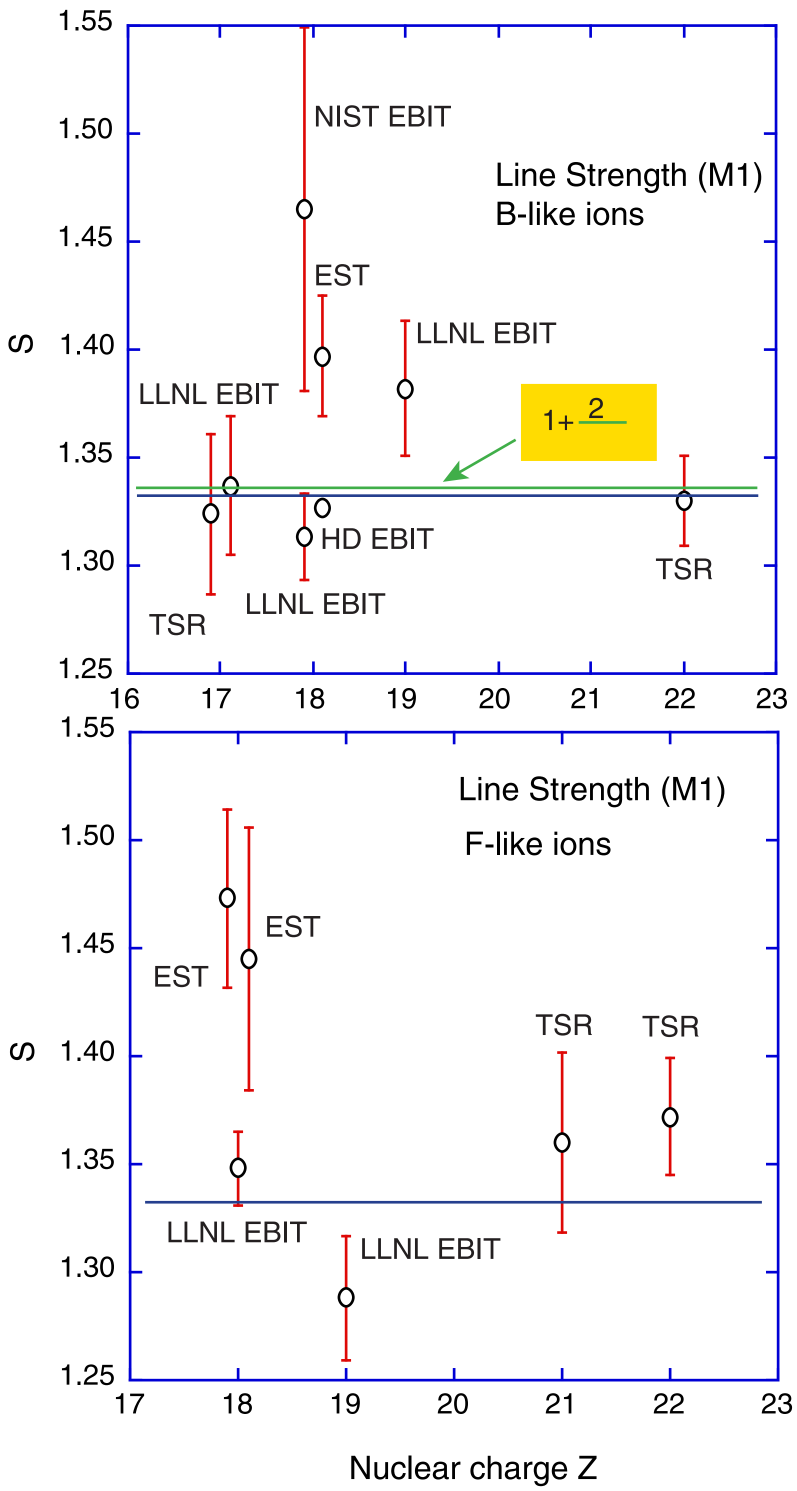
The basic technique is simple and robust.

Radiative decay curves can be followed for several atomic lifetimes

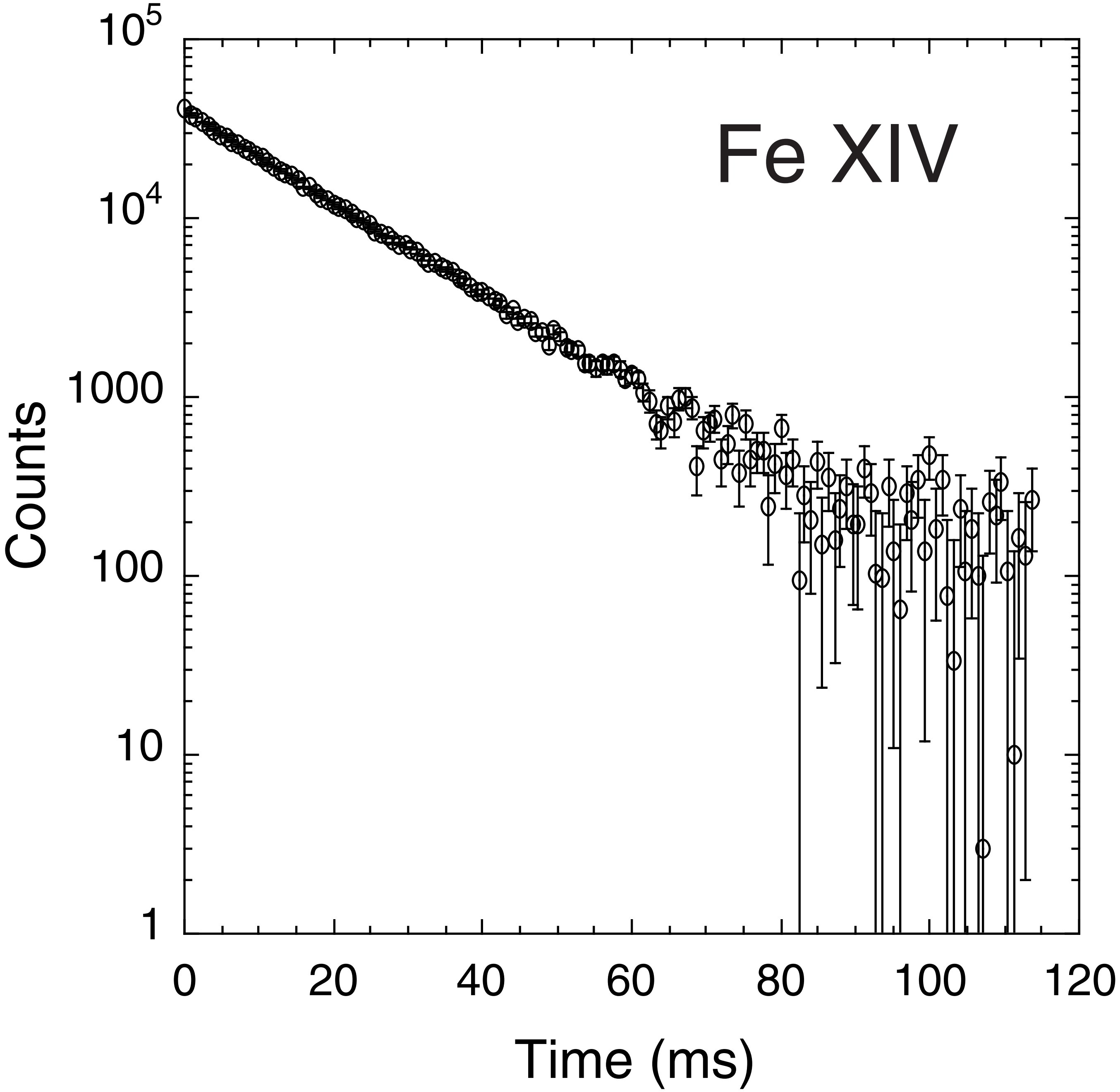


n=2 M1 transition between the fine structure levels of the ground state. Predicted line strength S = 4/3.

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



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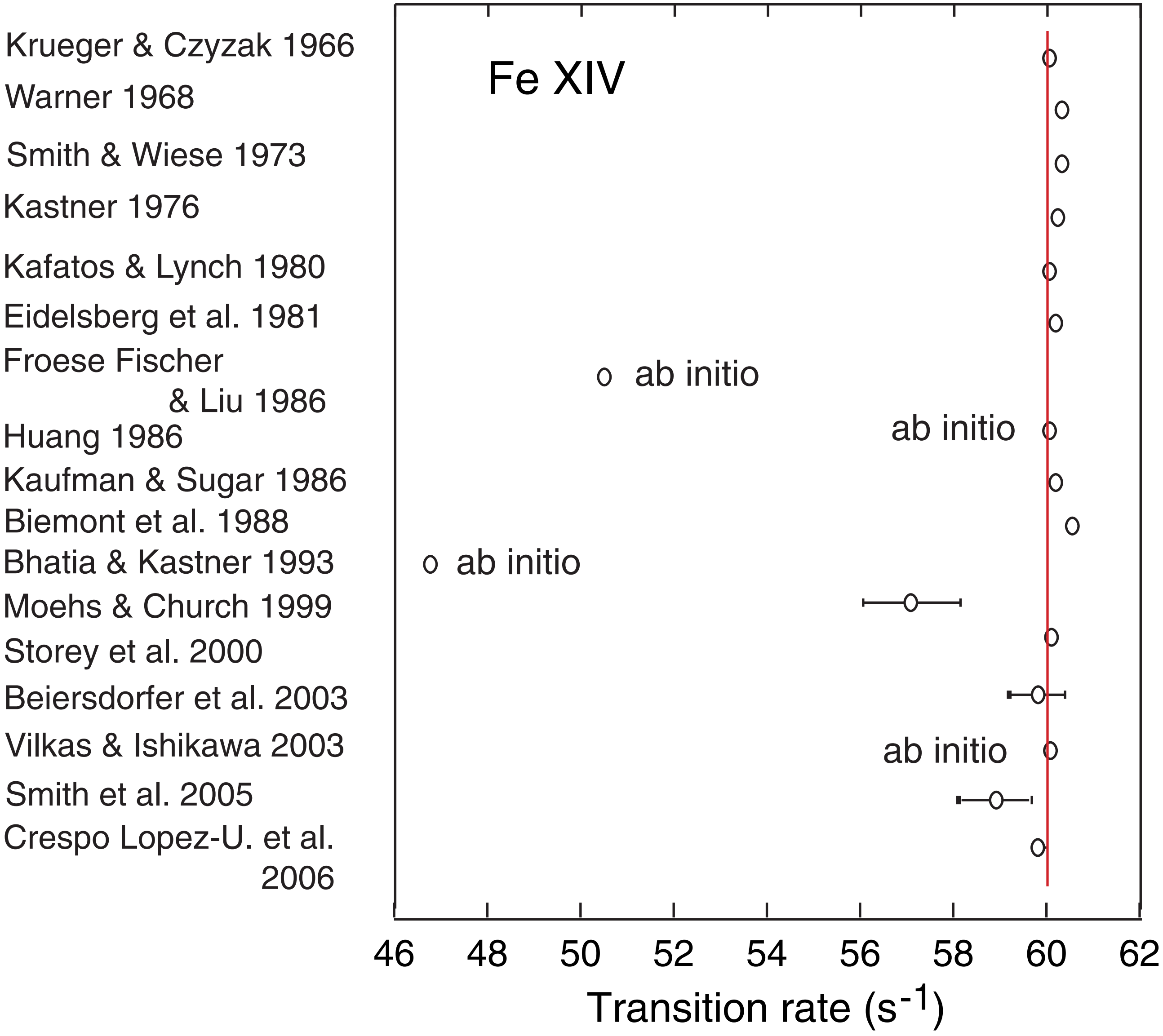
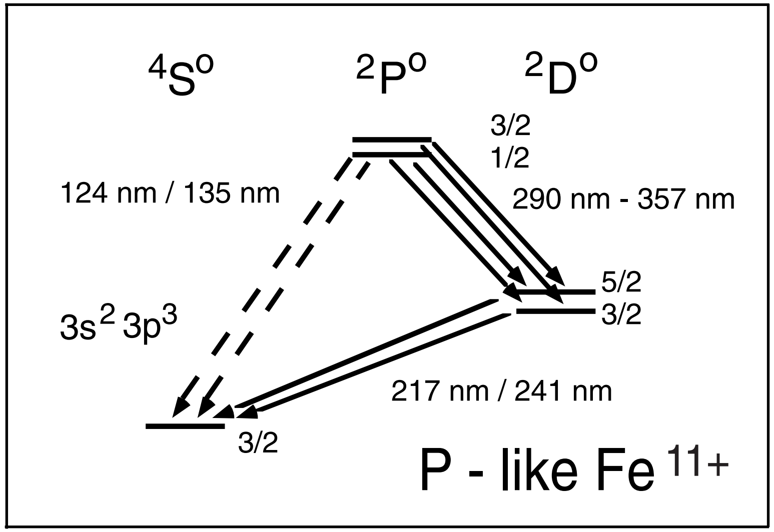
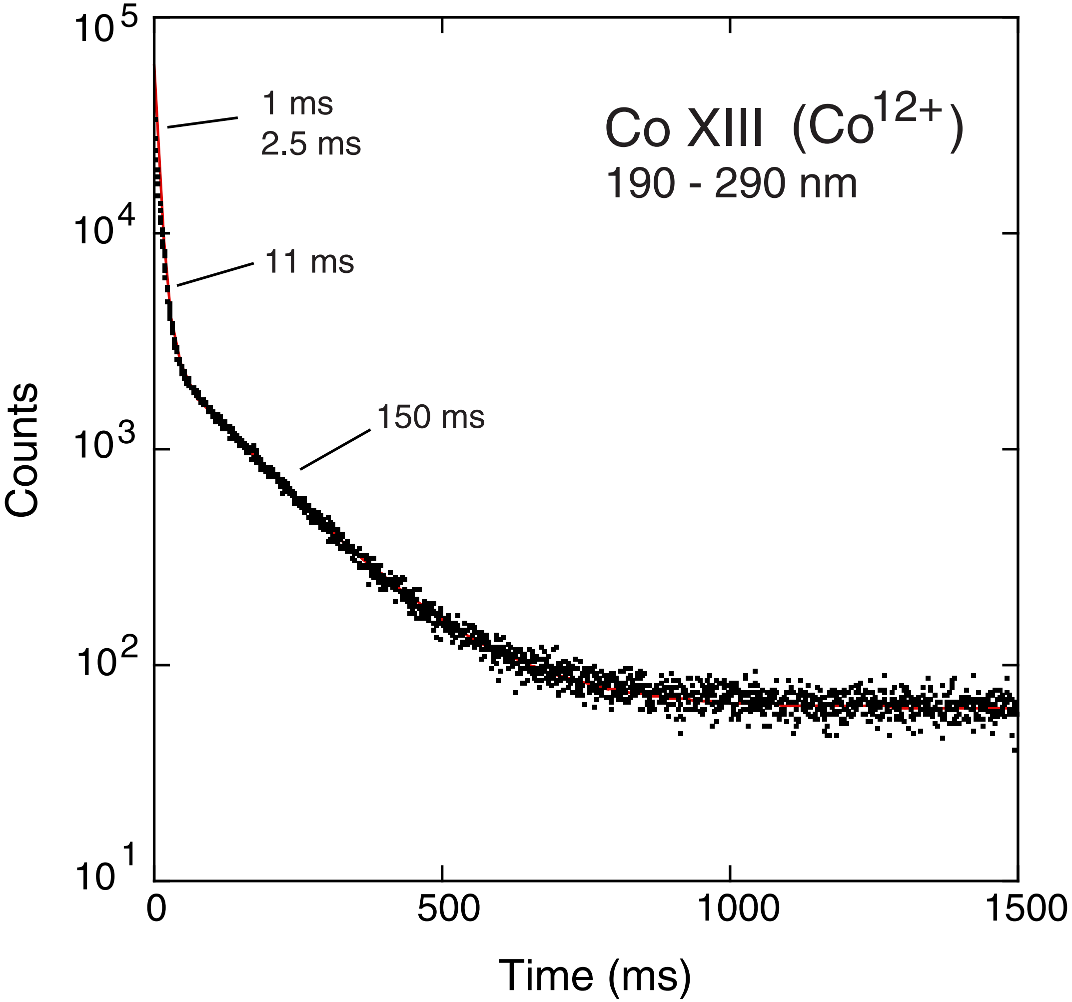
The "green iron line" in the solar corona has found plenty of interest



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

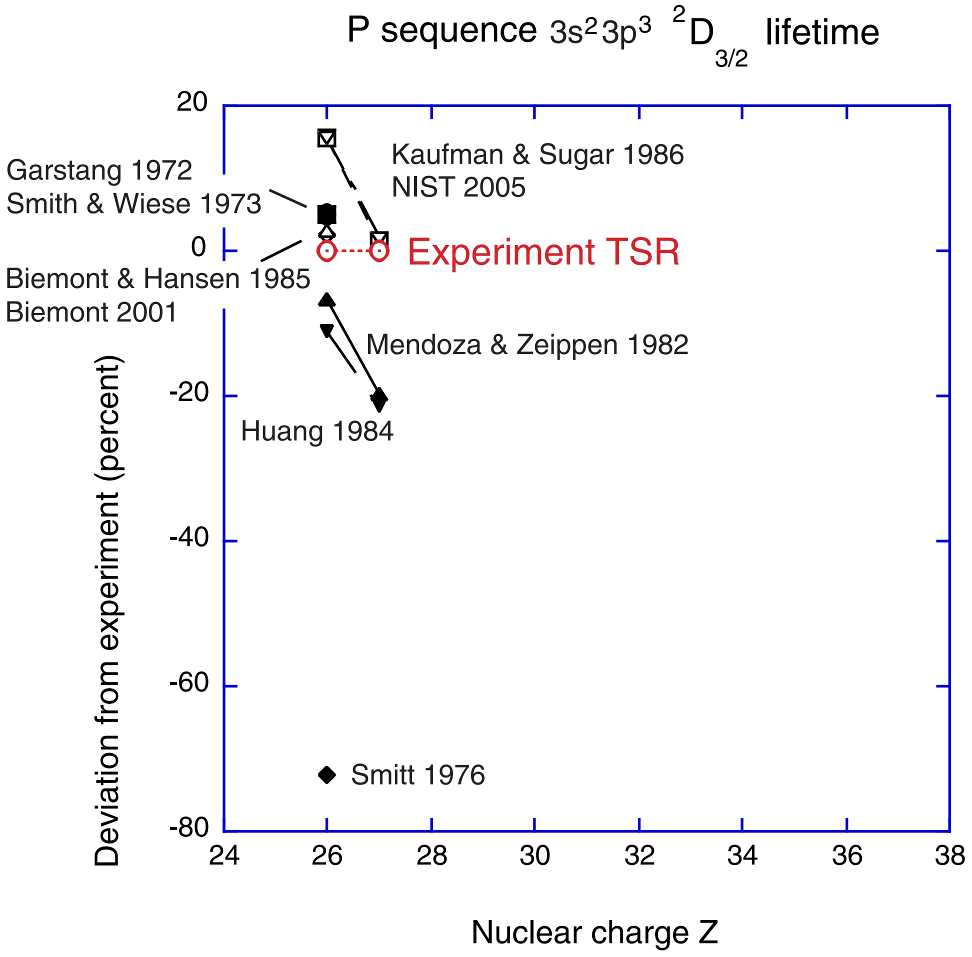


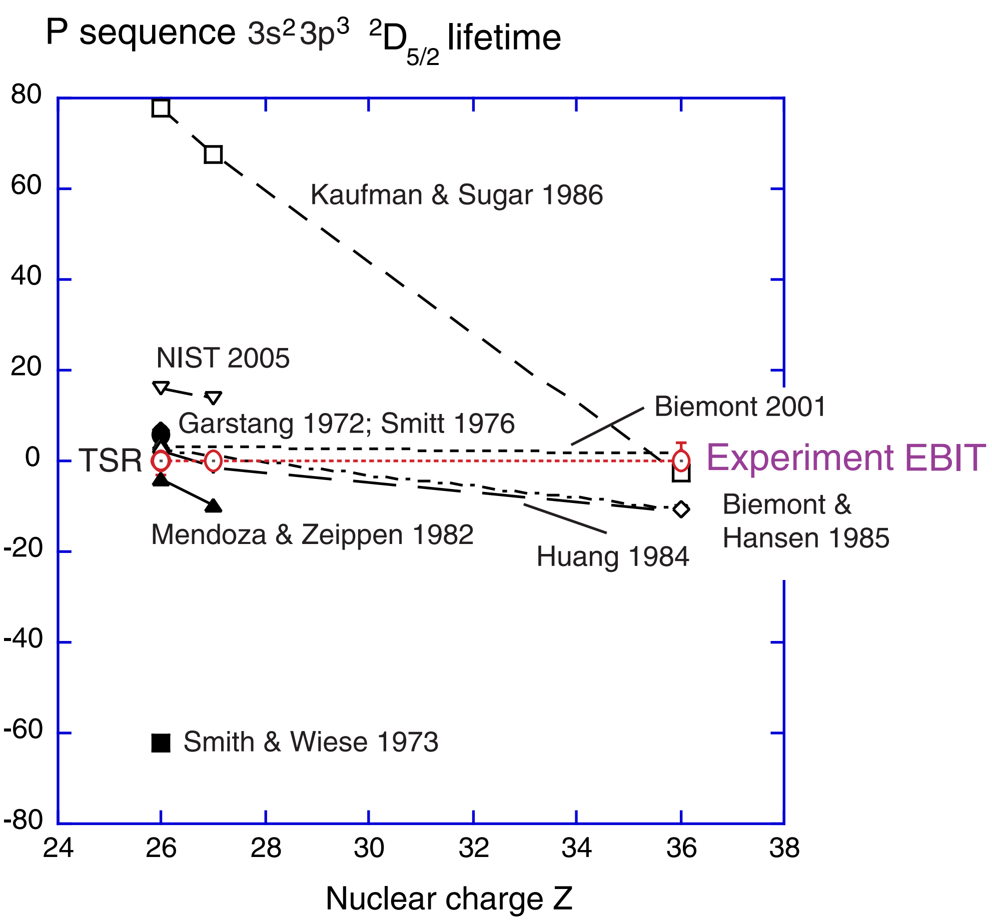


The line intensities in the ground configurations of N- and P-like ions serve as temperature diagnostics in astrophysics.

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.


P sequence $3s^2 3p^3$ $^2D_{3/2}$ lifetime


P sequence $3s^2 3p^3$ $^2D_{5/2}$ lifetime

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 ...

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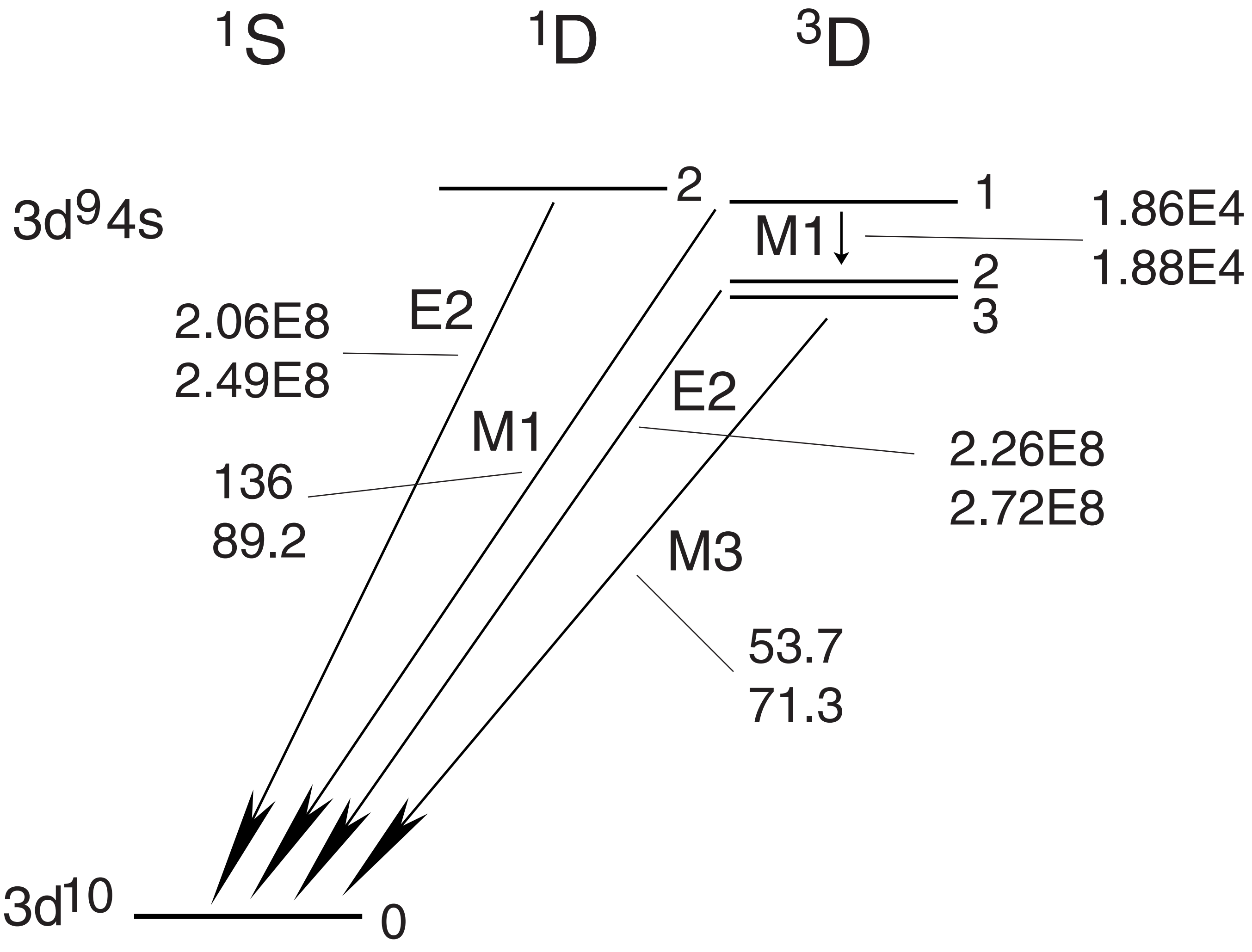
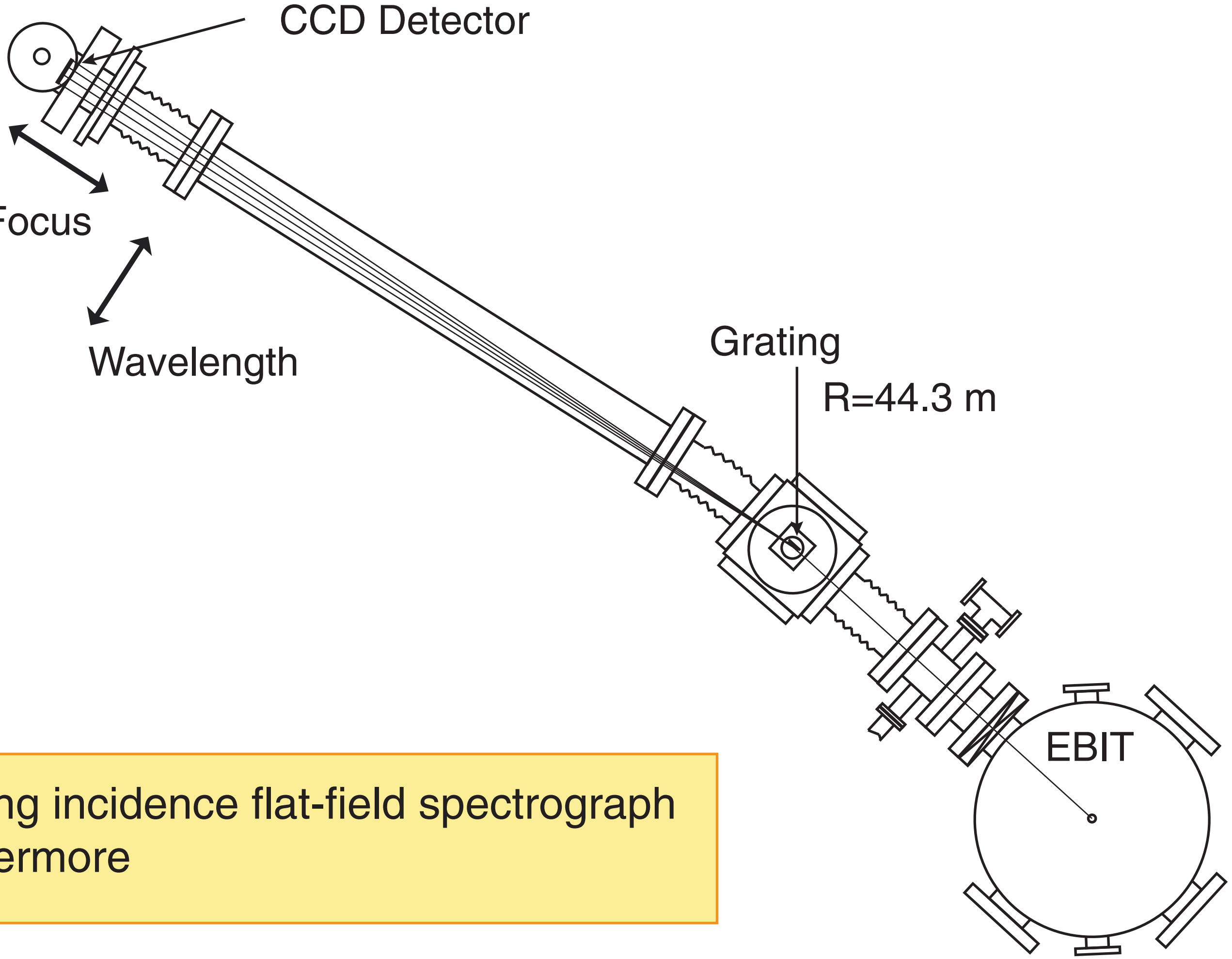
Ni-like Xe XXVII; the transition probabilities shown do not take hyperfine mixing effects into account.



Multichannel detection is a key element for precision spectroscopy.

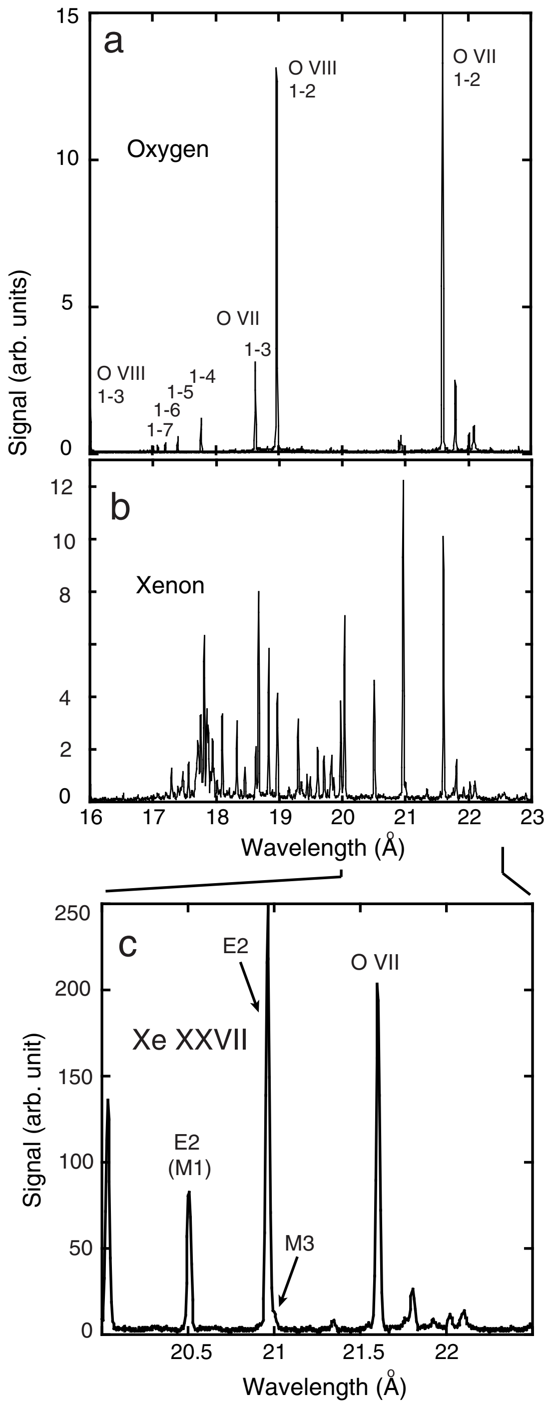


Grazing incidence flat-field spectrograph
at Livermore

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.

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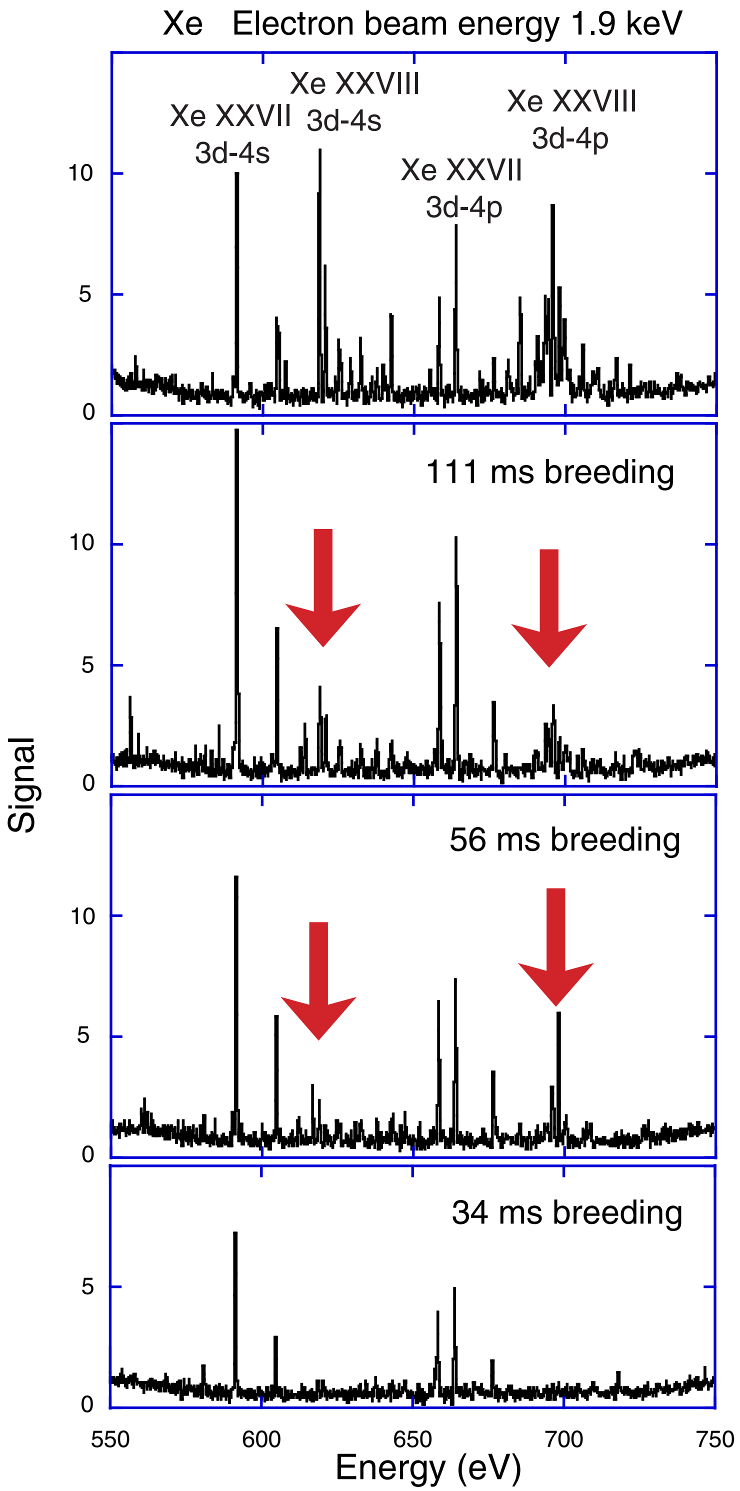
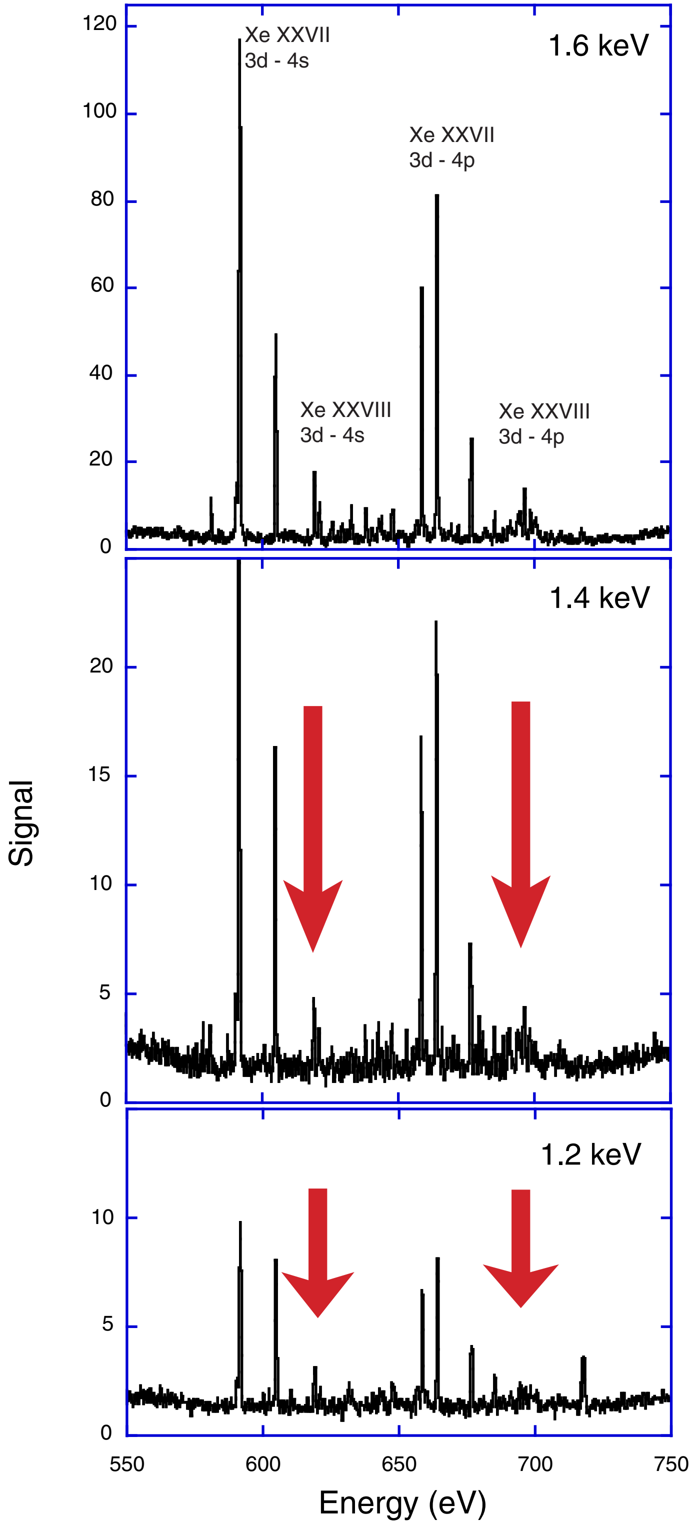


The Co-like ion (Xe XXVIII) needs much more time to breed than the Ni-like ion (Xe XXVII).

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.

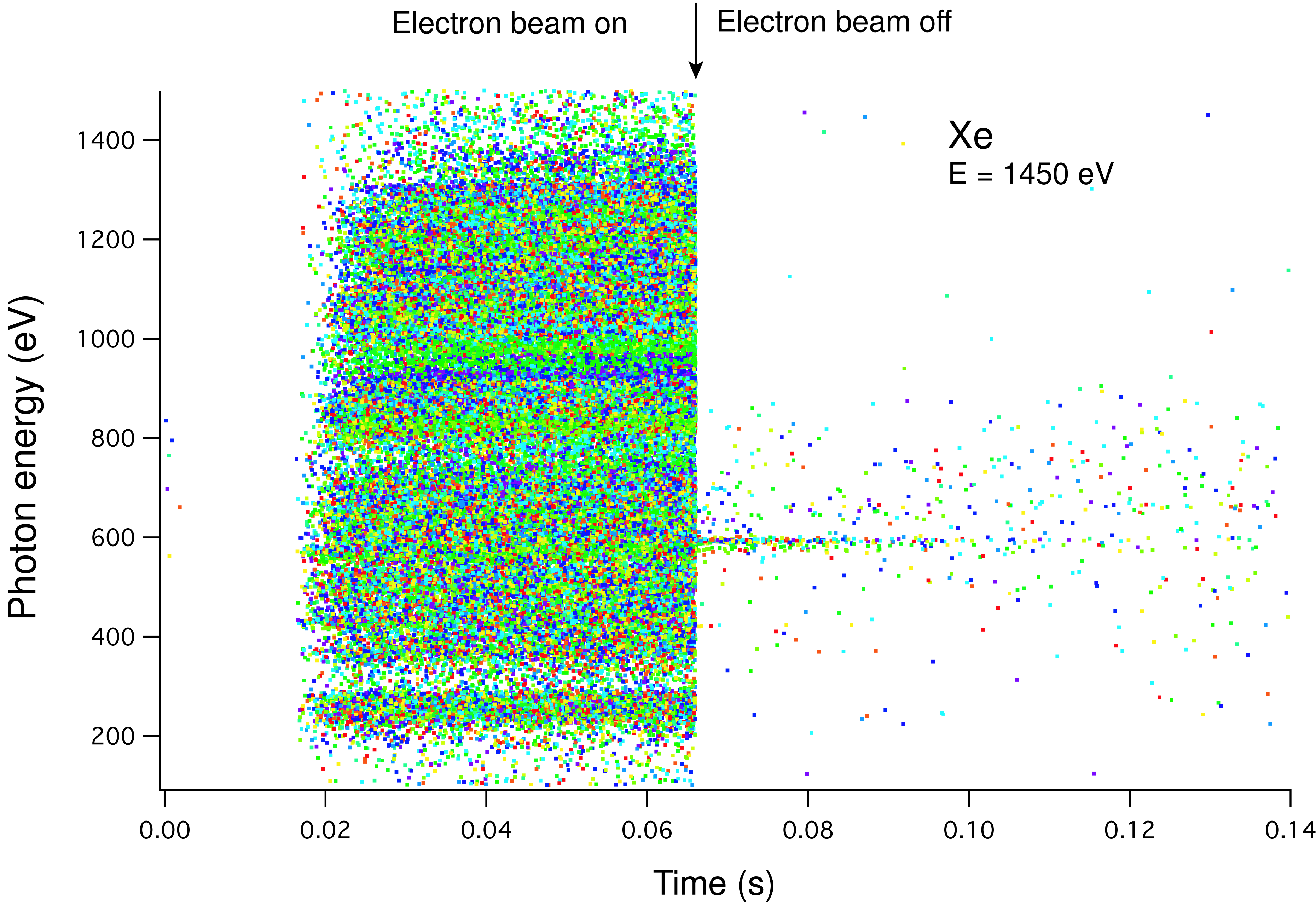


X-ray crystal spectrometers offer high spectral resolution, but suffer from low efficiency

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.

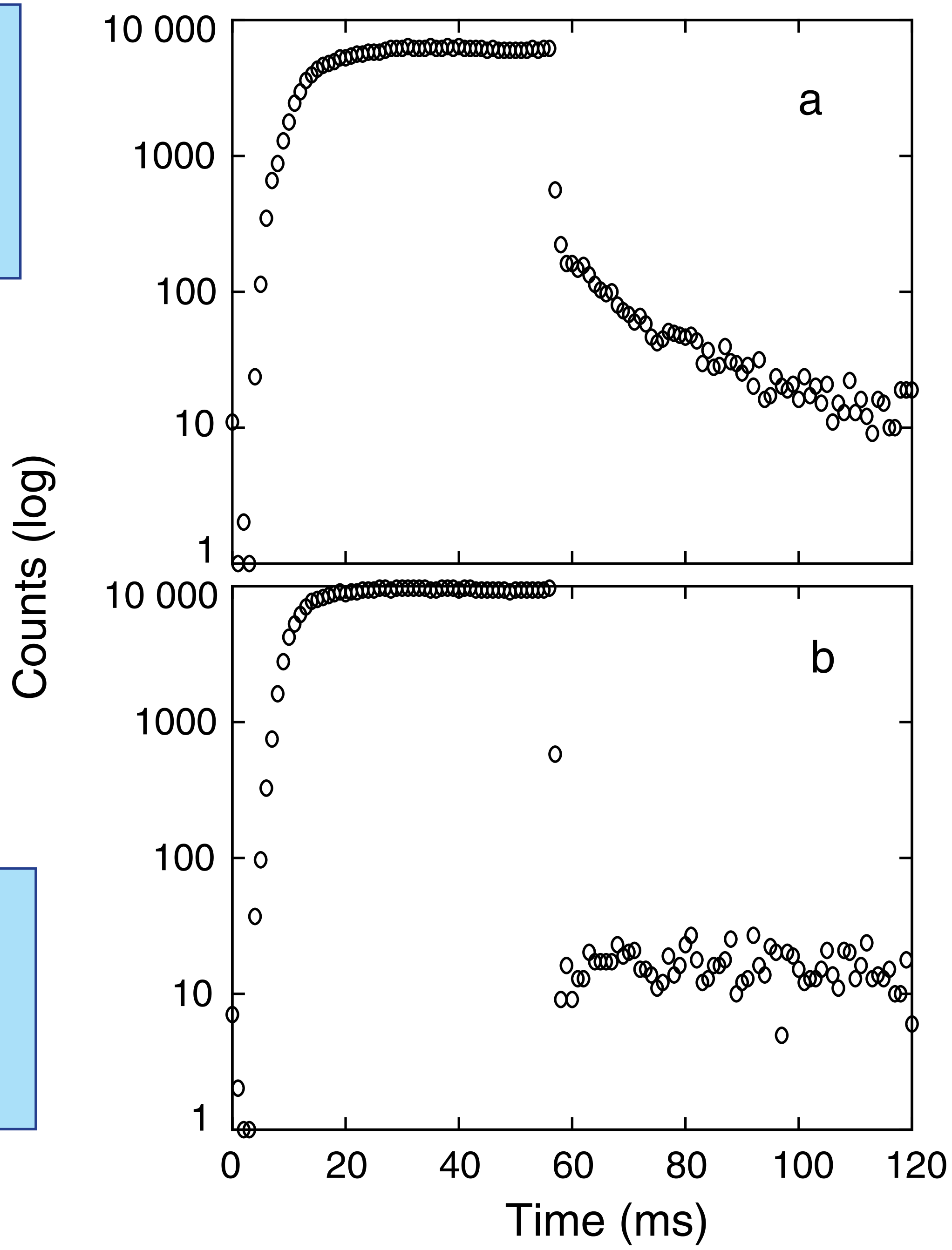
When the electron beam is switched off, delayed photons arise from long-lived excited levels or from charge exchange (CX).

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.



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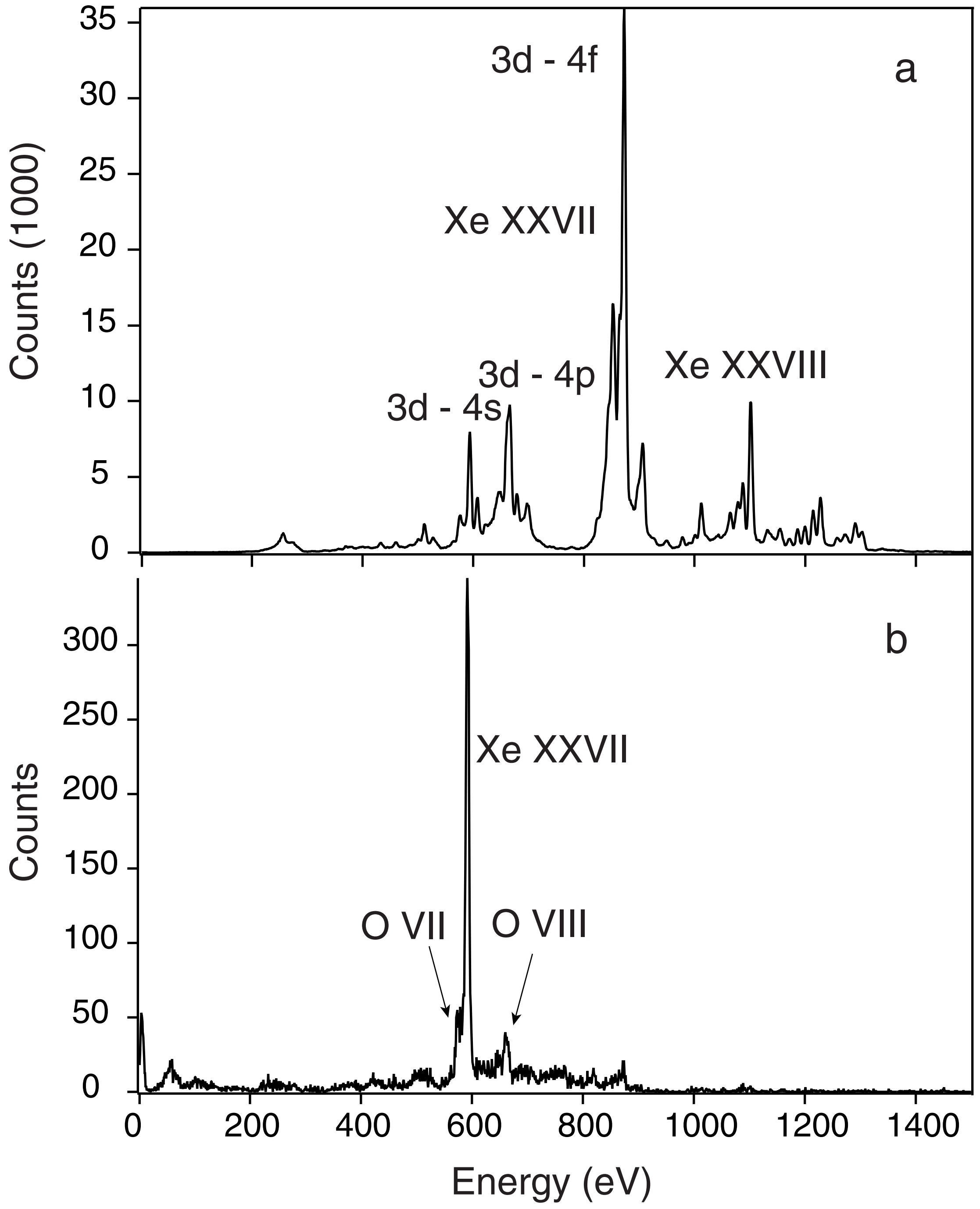
Each signal pulse is time-stamped; the data can be sorted by X-ray energy or time within the trap cycle.

XRS microcalorimeter spectra of Xe
(E = 1450 eV)

a) electron beam on

b) electron beam off

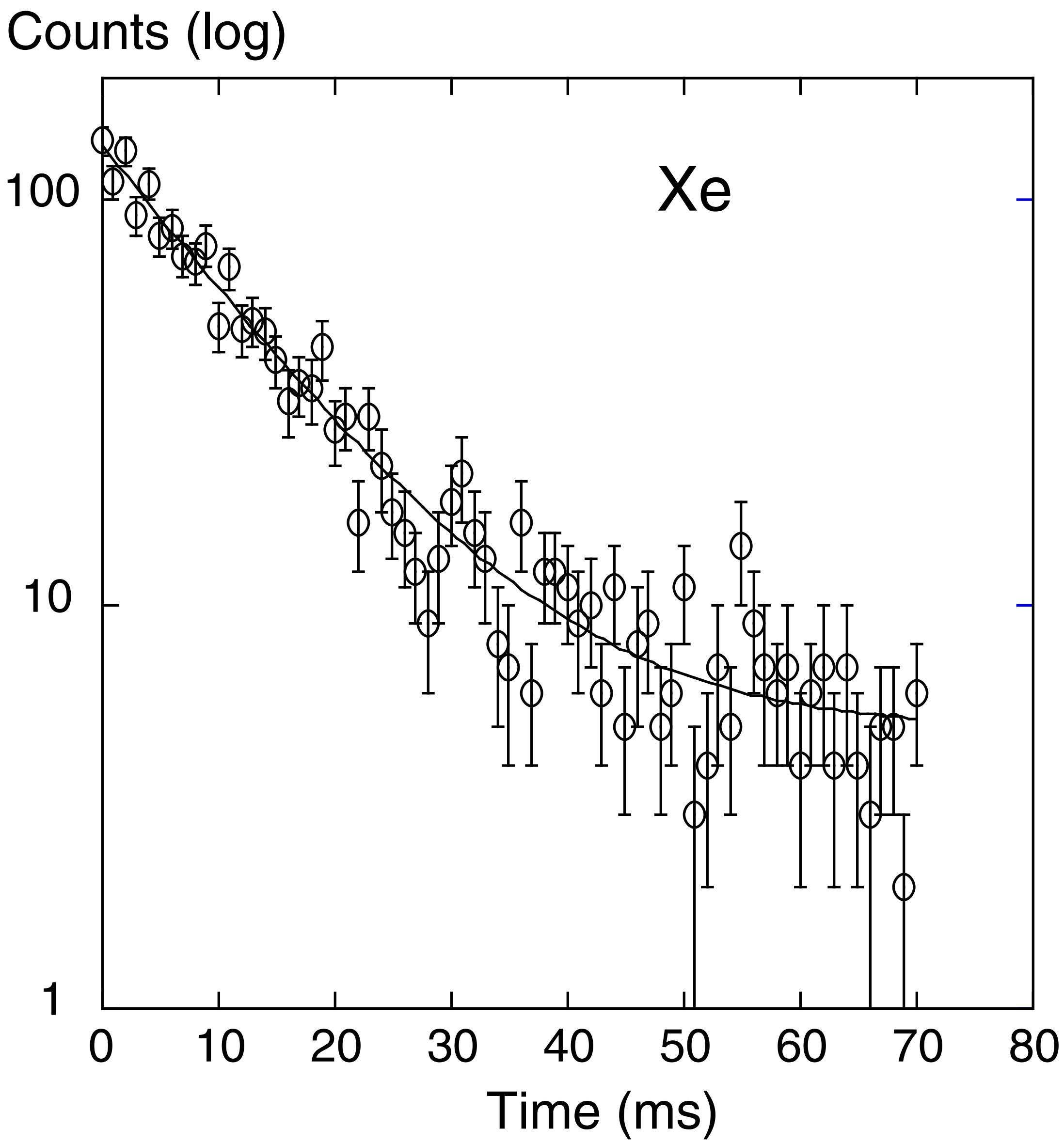
Time resolved spectra reflect level population dynamics.



Microcalorimeter data of about one week total run time

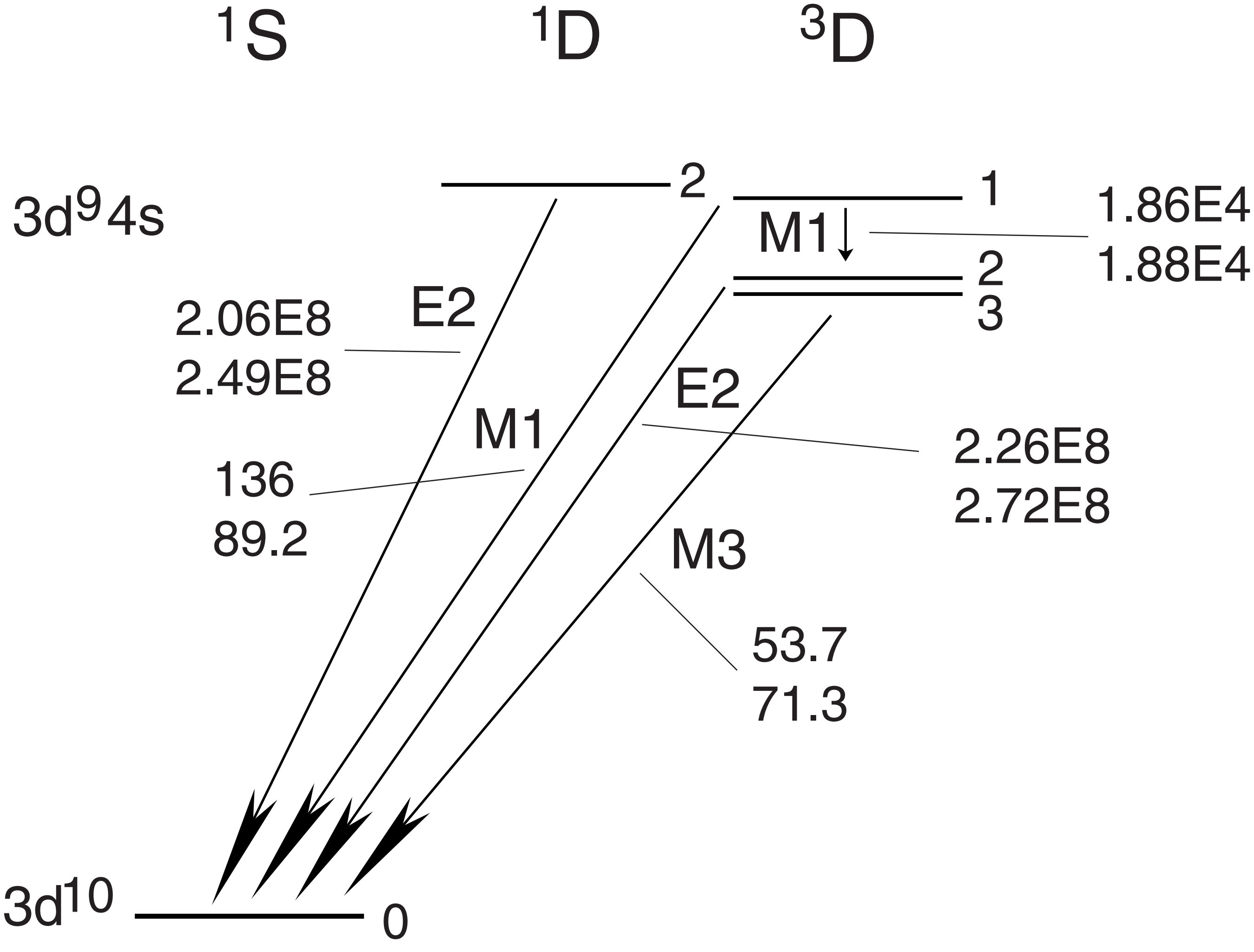
Decay curve
extracted from the
XRS microcalorimeter data
at the position of the
Xe XXVII M3 decay

Apparent lifetime
11.0±0.5 ms

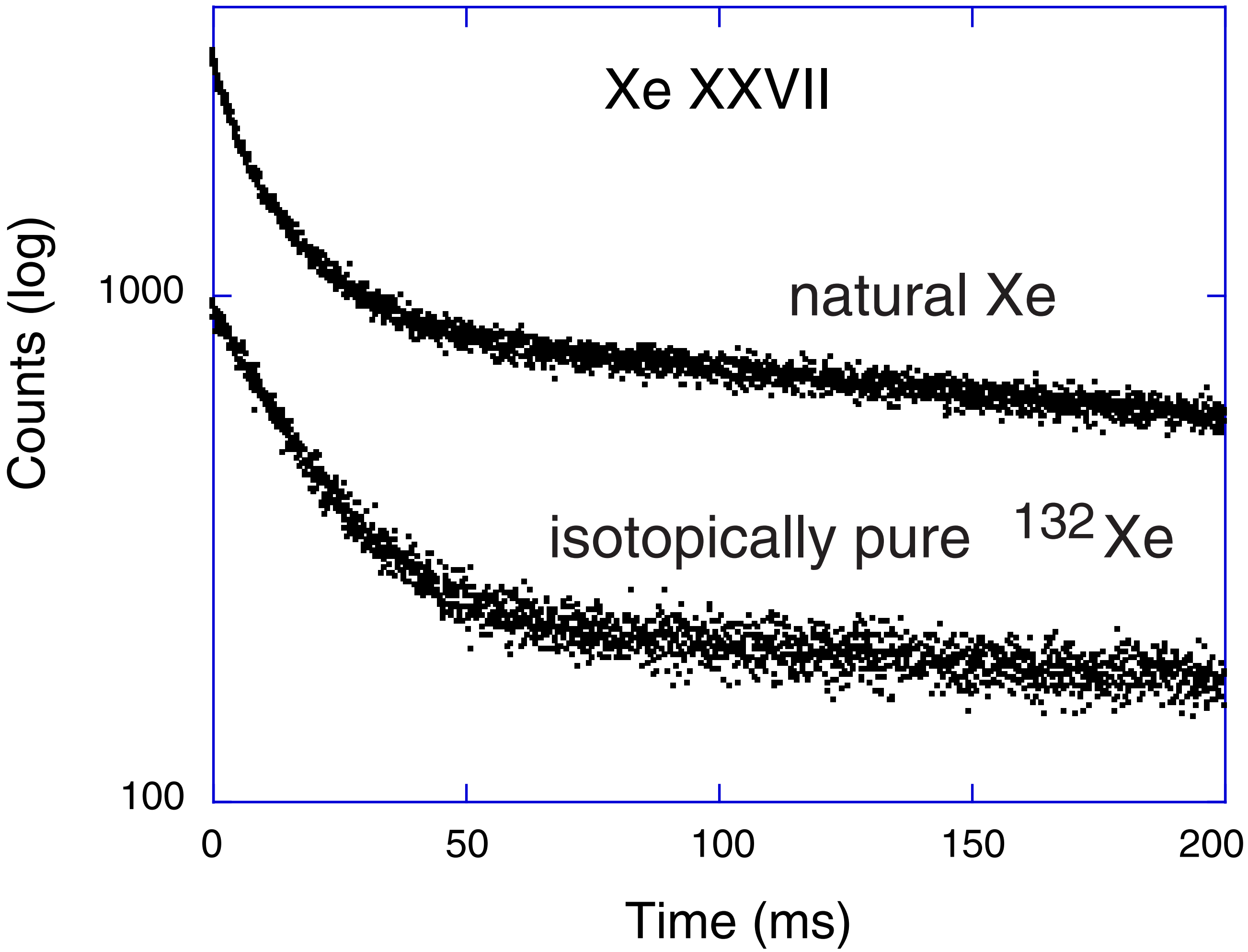


This is the first atomic lifetime measurement using a microcalorimeter at an electron beam ion trap.

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



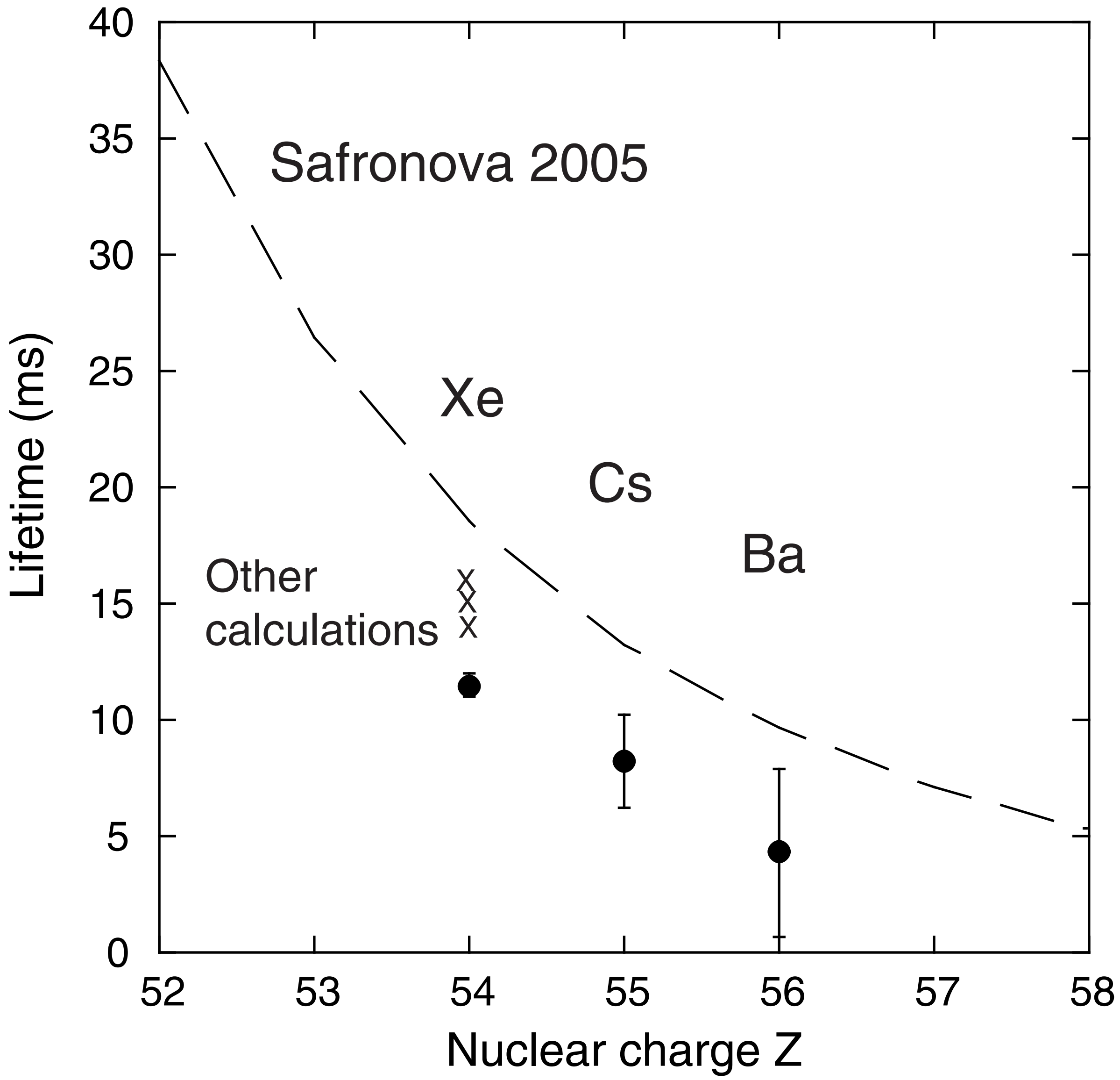
Soft-X-ray signal of Xe at SuperEBIT
The even isotope Xe132 has no hyperfine structure.
It features a single-component M3 radiative decay
(and a tail from charge exchange (CX) processes).
Natural Xe has about equal parts of odd and even
isotopes and a more complex decay curve.



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