Hinode / EIS is operating - is there anything on Fe in the EUV left to be done in the laboratory?

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Fe in the solar corona; EUV 20 – 35 nm

Fe^{8+} to Fe^{14+} A matter of temperature and density

Properties of laboratory light sources
- Laser-produced plasma
- Tokamak
- Electron beam ion trap (EBIT)
- Foil-excited ion beams (beam-foil spectroscopy)
- Heavy-ion storage ring

Examples of individual techniques or data combinations
Time integrated vs. time resolved data

Tokamak + LPP + BFS
BFS prompt / delayed spectra
Lifetime measurements (BFS, storage ring, EBIT)

Promising approaches for Fe

BFS	Spectra of elemental purity
BFS	Delayed spectra
Storage ring	E1-forbidden decay rates
EBIT	High-resolution survey spectra
	Time characteristics?

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

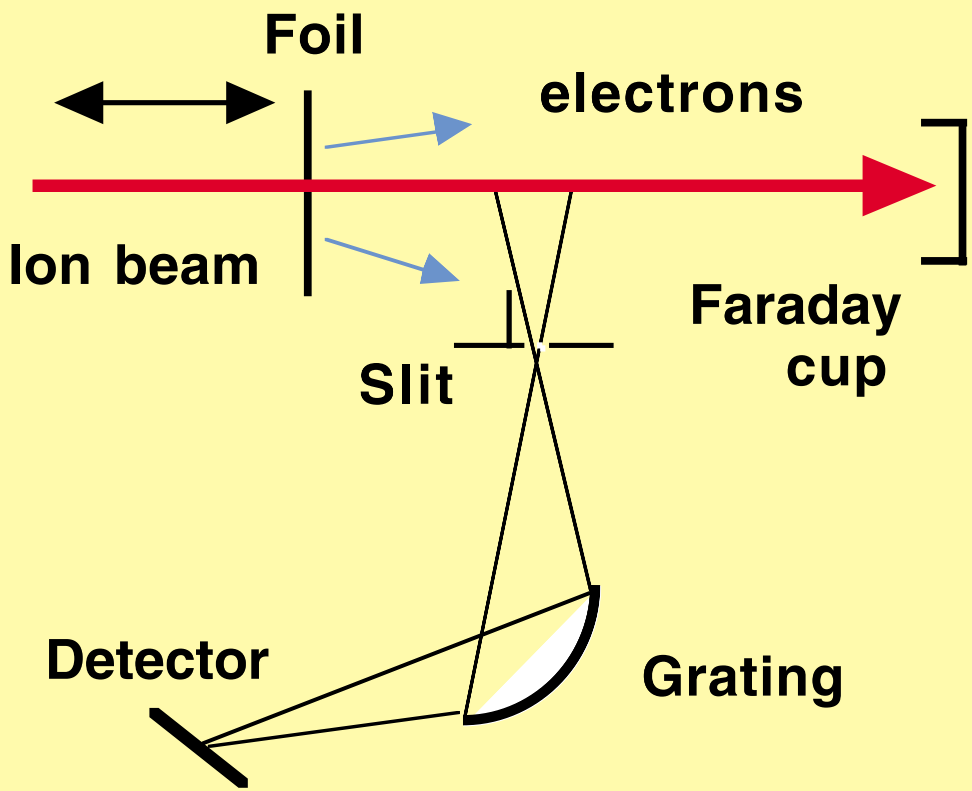
Properties of laboratory light sources: temperature and density

- Laser-produced plasma
- Tokamak
- Electron beam ion trap (EBIT)
- Foil-excited ion beams (beam-foil spectroscopy)
- Heavy-ion storage ring

Density

Solid / Laser-produced plasma	10^{23}	cm^{-3}	atoms
Gas (1 bar)	$3\ 10^{19}$	cm^{-3}	atoms
Tokamak	10^{13}	cm^{-3}	atoms
	10^{12}	cm^{-3}	electrons
EBIT	10^{5}	cm^{-3}	atoms
	10^{11}	cm^{-3}	electrons
Solar corona	10^{8-11}	cm^{-3}	electrons
Planetary nebulae	10^{4-8}	cm^{-3}	electrons

Beam-foil spectroscopy

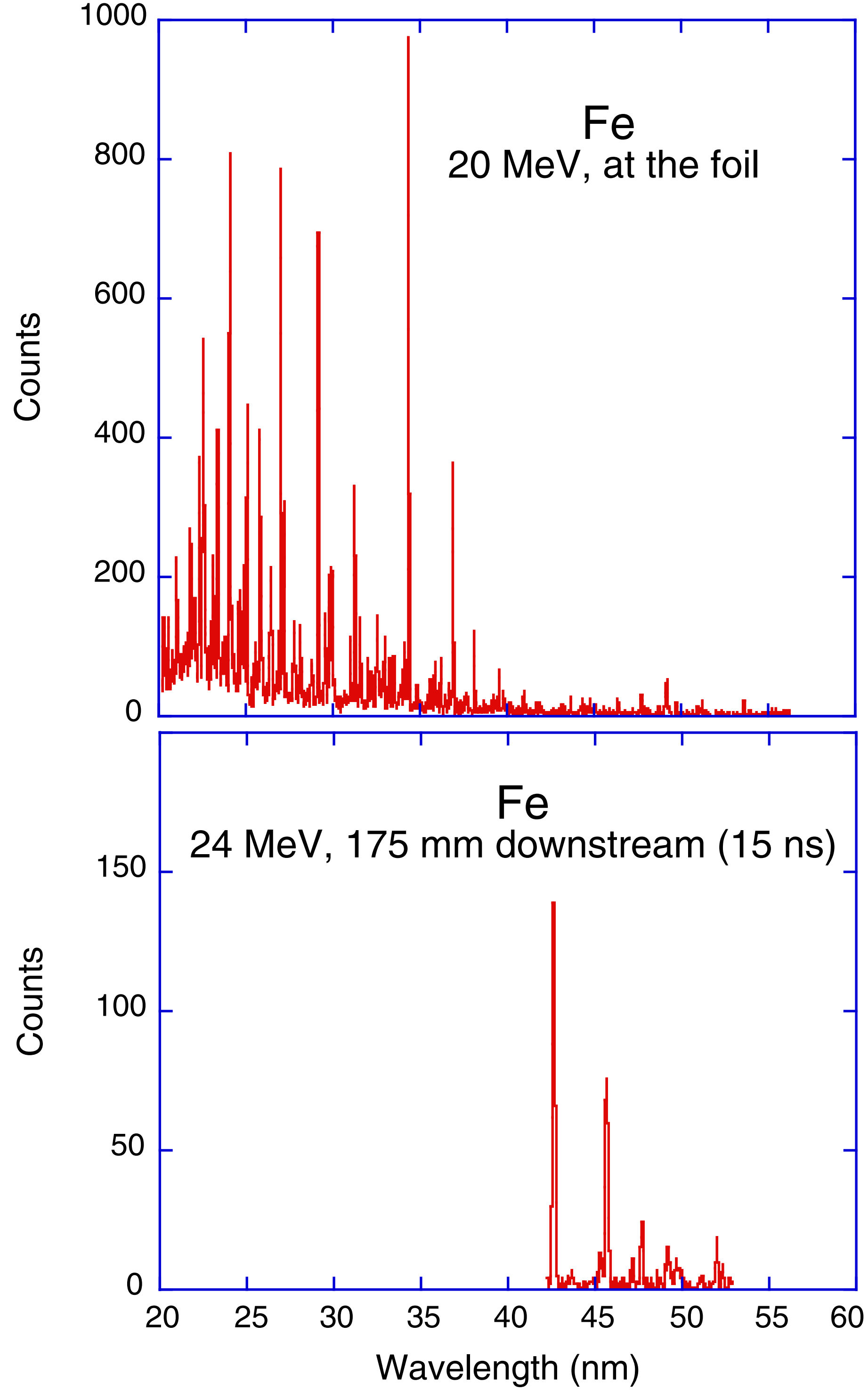


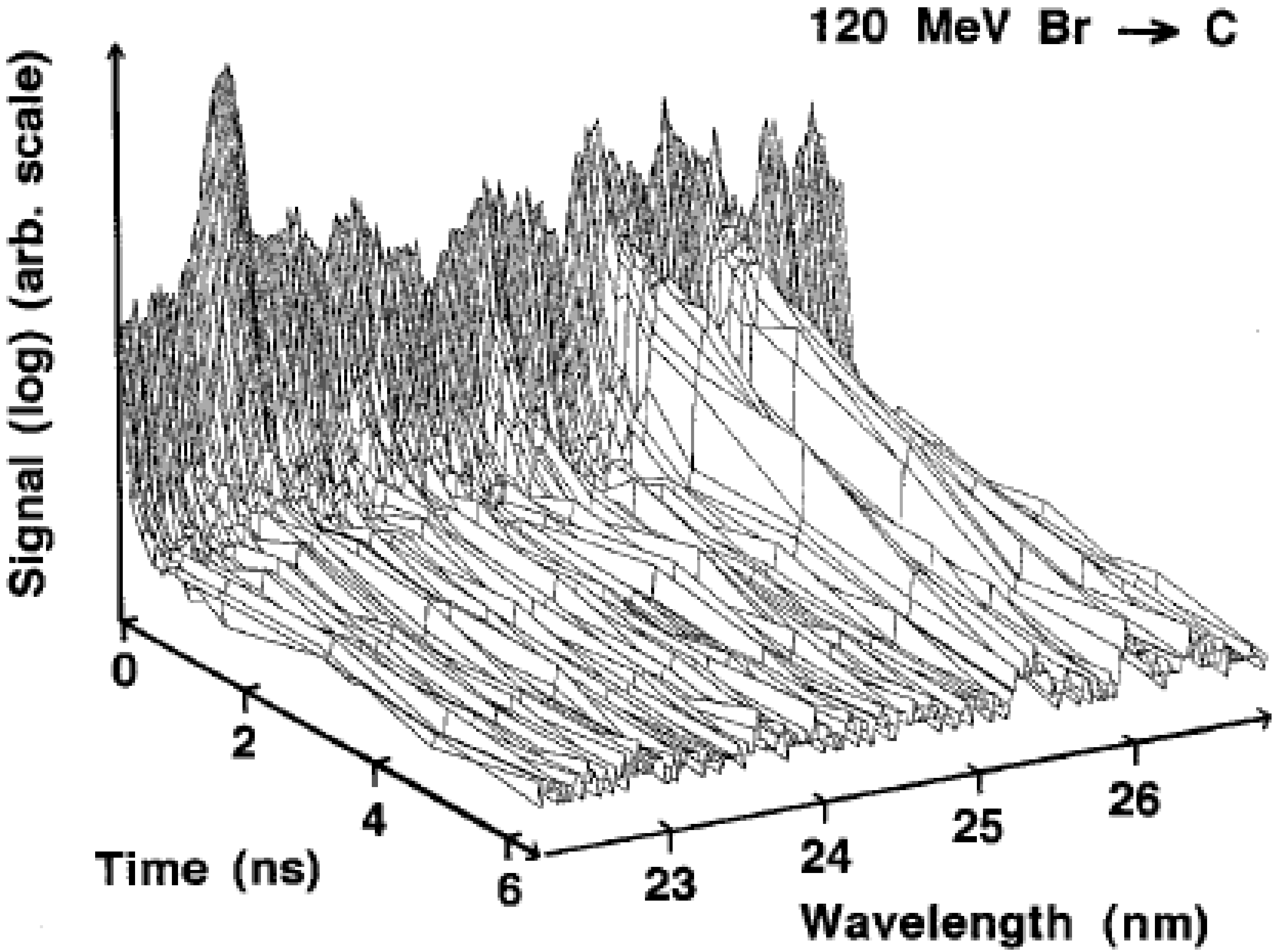
$$v = \frac{x}{t} \Rightarrow t = \frac{x}{v}$$

v Ion velocity
x Distance from the foil
t Time after excitation

Beam-foil spectra
recorded at the foil (prompt spectra)
are very line-rich
(excitation under high density conditions).

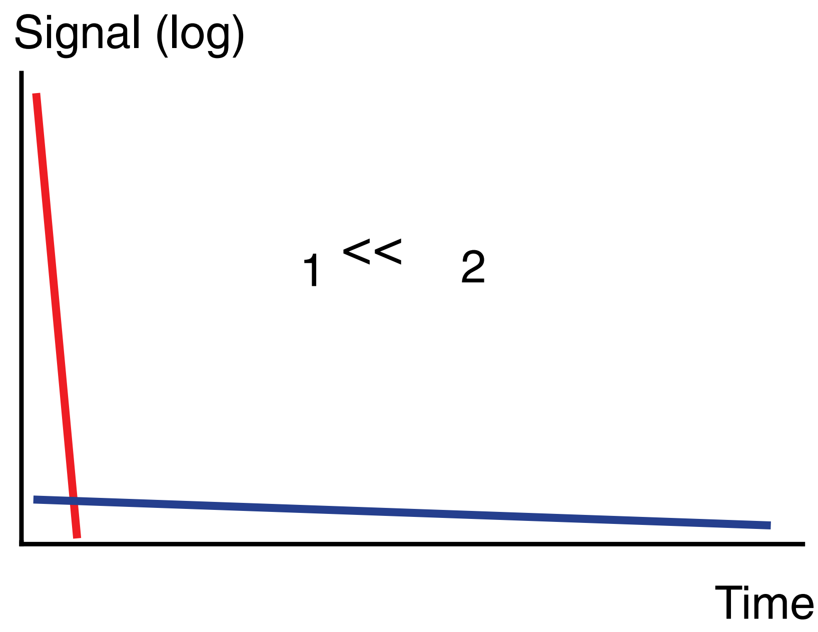
Delayed spectra
much more resemble the spectra obtained
of the solar corona
(low density environment). The lines
represent intercombination transitions.




120 MeV Br → C
Signal (log) (arb. scale)
0
2
4
6
Time (ns)
23
24
25
26
Wavelength (nm)

Beam-foil spectroscopy
Observation at the foil: The spectrum is dominated by decays of short-lived levels
Delayed observation: Much fewer lines, almost no background

Problem: Long-lived levels
==> little signal per time interval



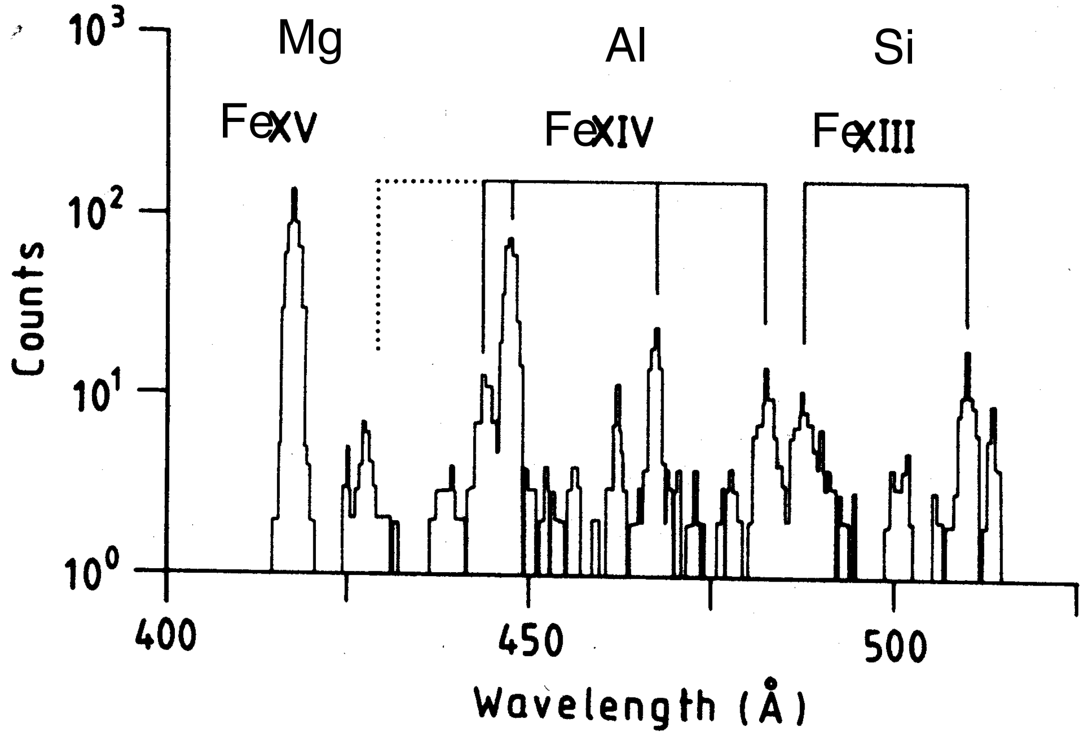


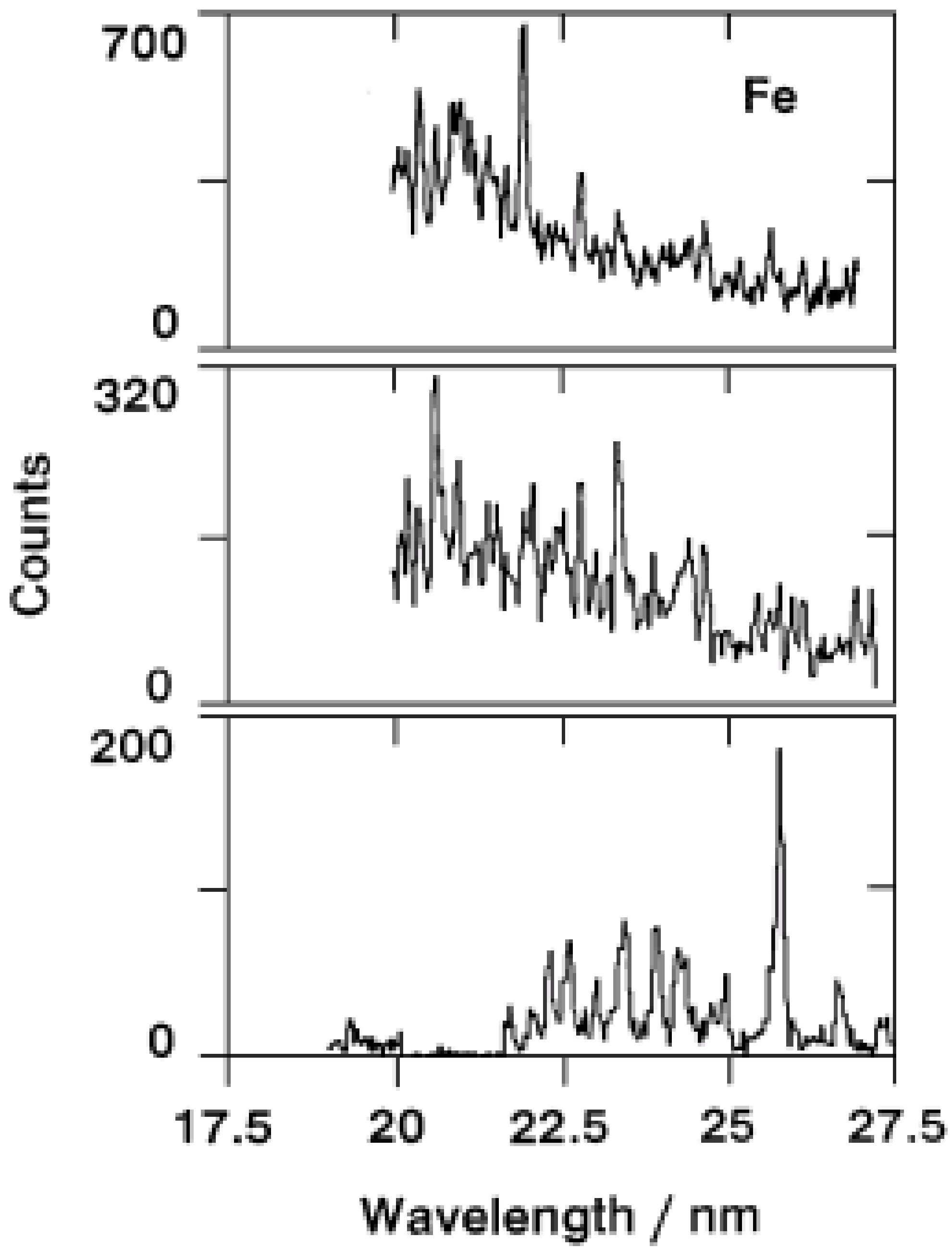
Figure 1. Delayed beam-foil spectrum of Fe. The intercombination lines in Fe XV, Fe XIV and Fe XIII are indicated. A dotted line marks the calculated location of the weak $^2P_{1/2}$–$^4P_{3/2}$ transition in Fe XIV.

The intercombination lines in Fe XIII and Fe XIV were recognized in beam-foil spectra on the basis of unidentified solar corona observations. The solar data had been recorded with ten times better resolution and accuracy, but it took BFS to tell the element and note the upper level longevity.

Beam-foil spectra of Fe
top: at the foil (prompt)
middle: delayed by about 1 ns
bottom: delayed by about 10 ns

At the time of measurement, and for years after, even the strongest lines in each of the spectra remained unidentified.

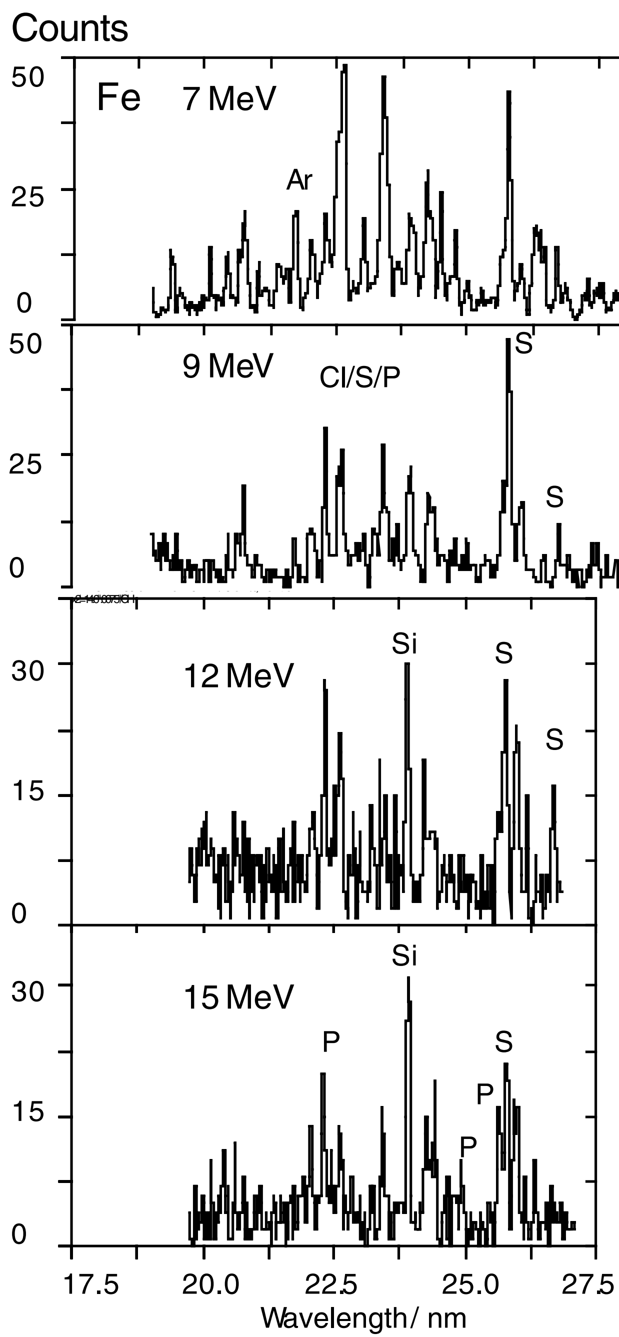
By now we know that in the bottom spectrum, most lines are from Fe X and Fe XI. The strongest lines are from levels with lifetimes in the range 10 - 60 ns. The strongest lines in the solar corona (in this range) have upper levels of lifetimes closer to 600 ns.



Beam-foil spectroscopy

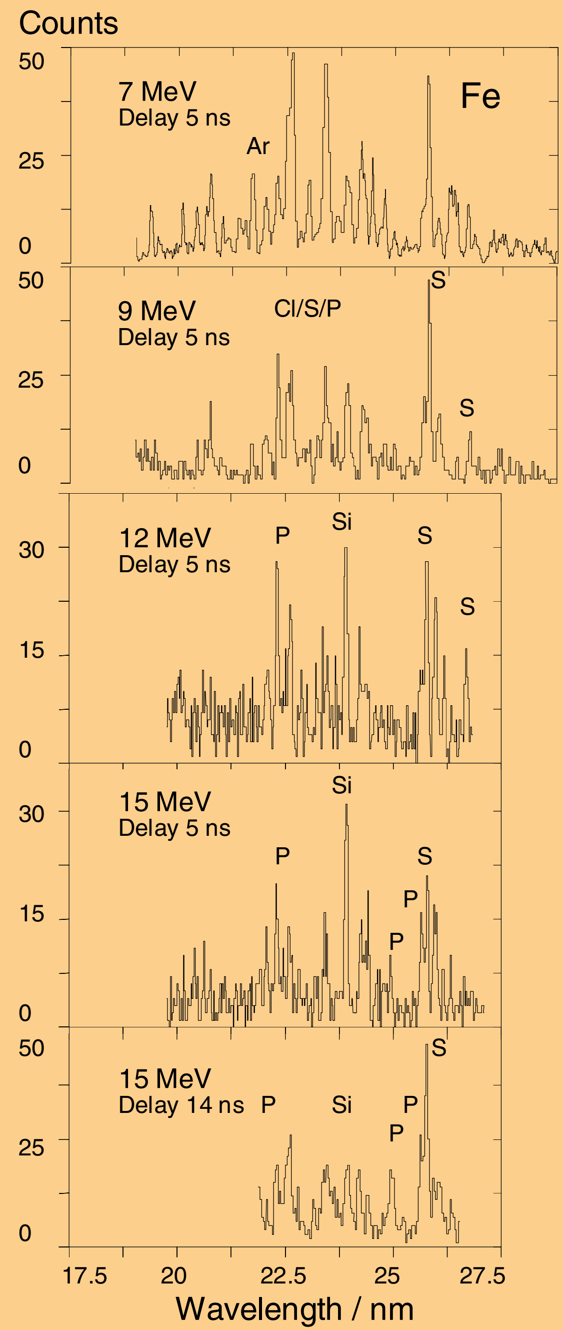
The ion beam energy determines the average charge state reached. Lines from particular charge state ions can thus be enhanced or suppressed.

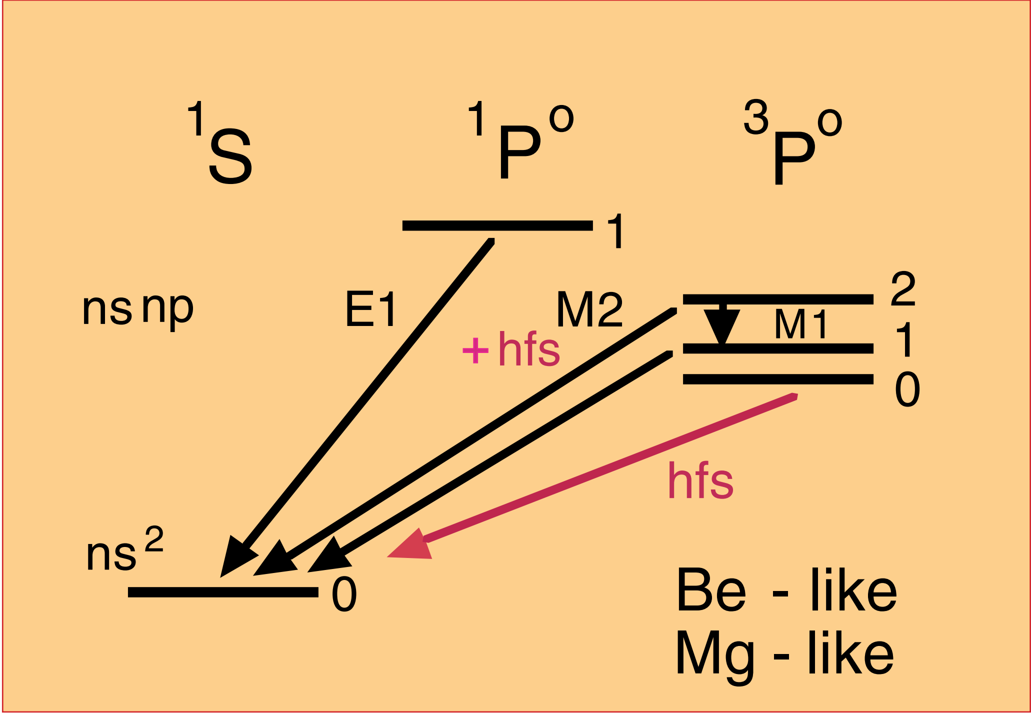
The delayed spectra shown here were recorded during a search for specific Fe IX (Ar-like, not all of them found yet) and Fe XIII (Si-like, successful search) lines.



The ion beam energy defines the charge state distribution after the ion-foil interaction.

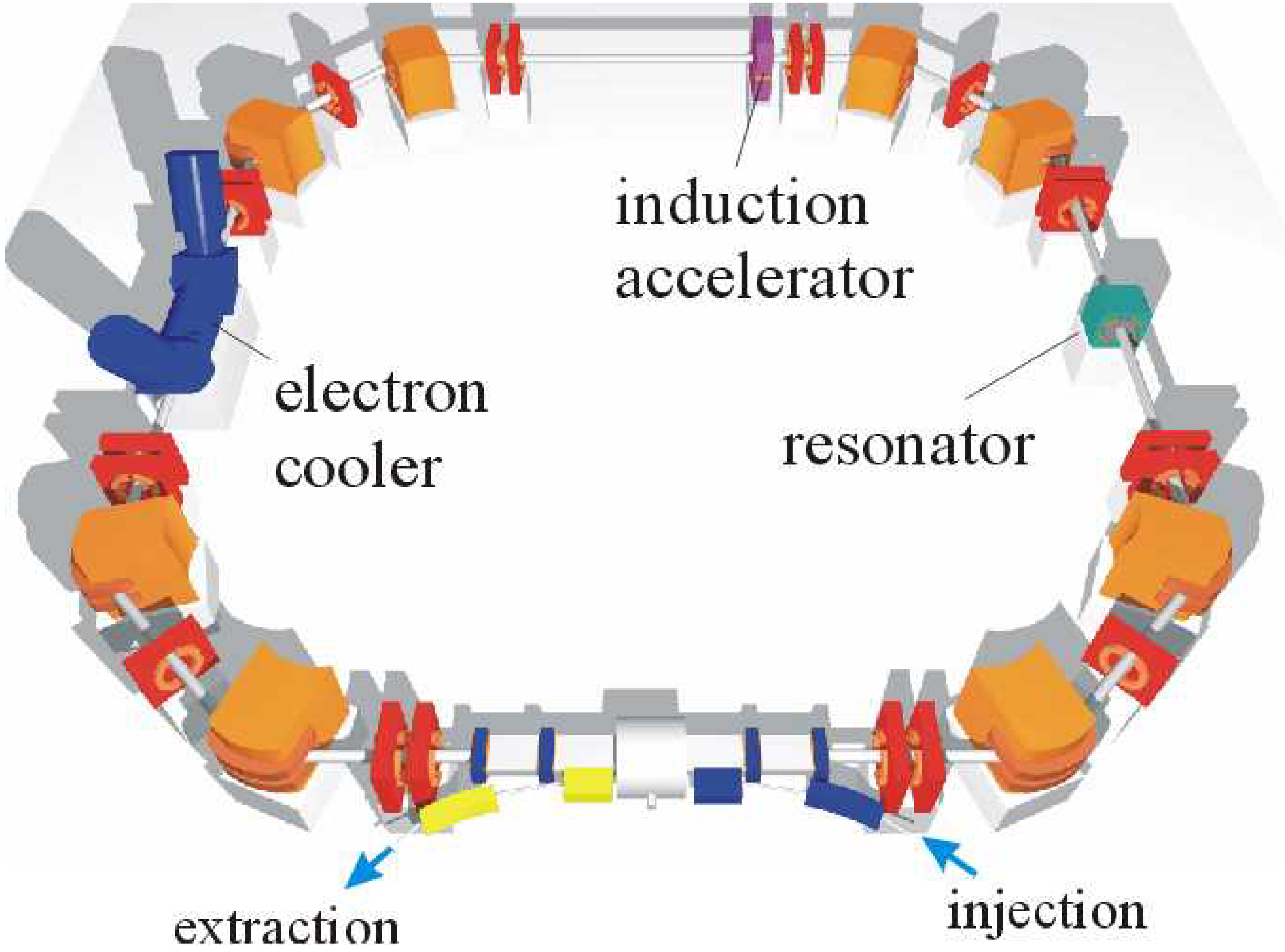
Systematic variation of the ion beam energy can help to maximize individual spectra and to identify the charge state of origin.





1S
1Po
3Po
1
ns np
E1
M2
+hfs
2
M1
1
0
hfs
ns2
0
Be - like
Mg - like

Heavy-ion storage ring TSR at Heidelberg — Circumference 55 m

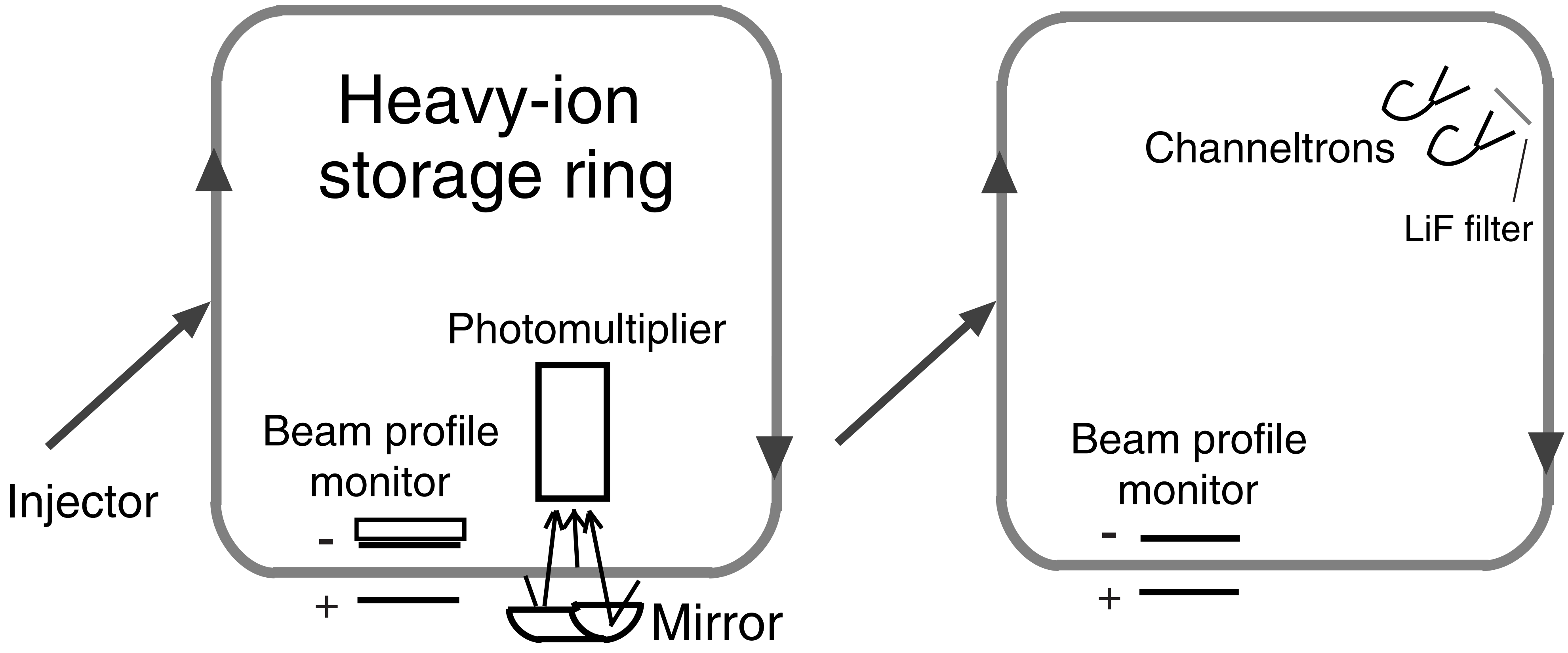


from 12 MV tandem accelerator

The ring is mostly used for atomic physics.

picture credit: M. Grieser

Passive atomic lifetime measurements at TSR Heidelberg



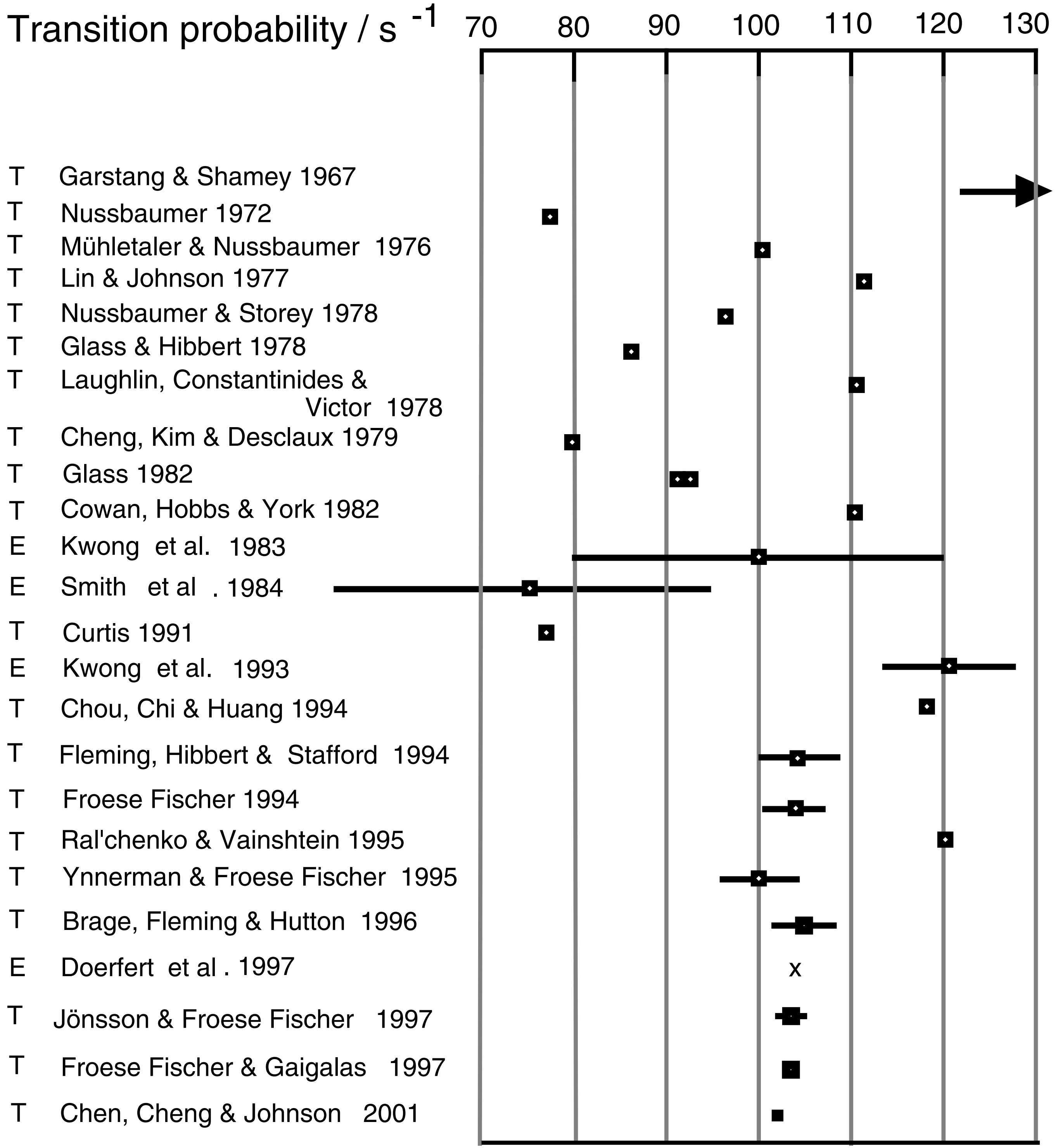
Beam current monitor

Detector of visible / near UV / UV light

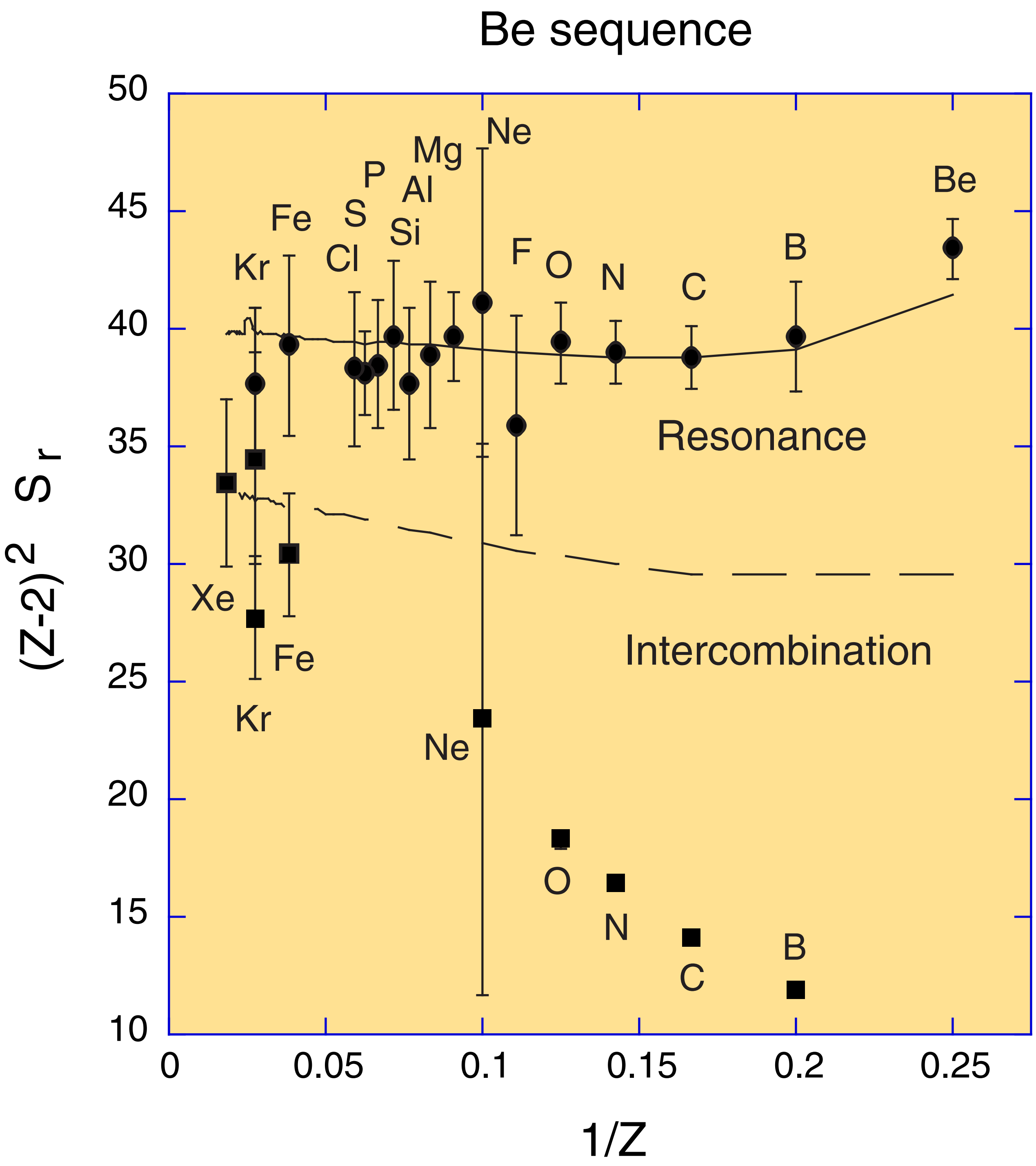
Detection of VUV / EUV light

Atomic lifetime measurements at TSR have reached high accuracy: as little as 0.14% uncertainty.

Intercombination transition in C III (Be-like)

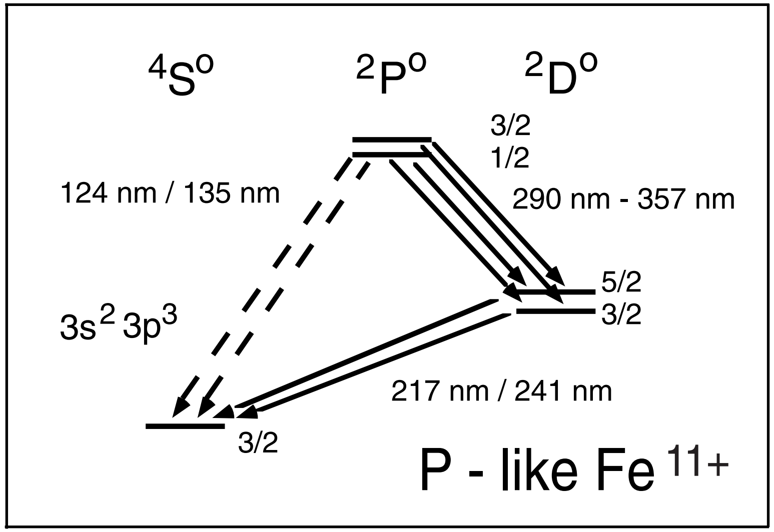


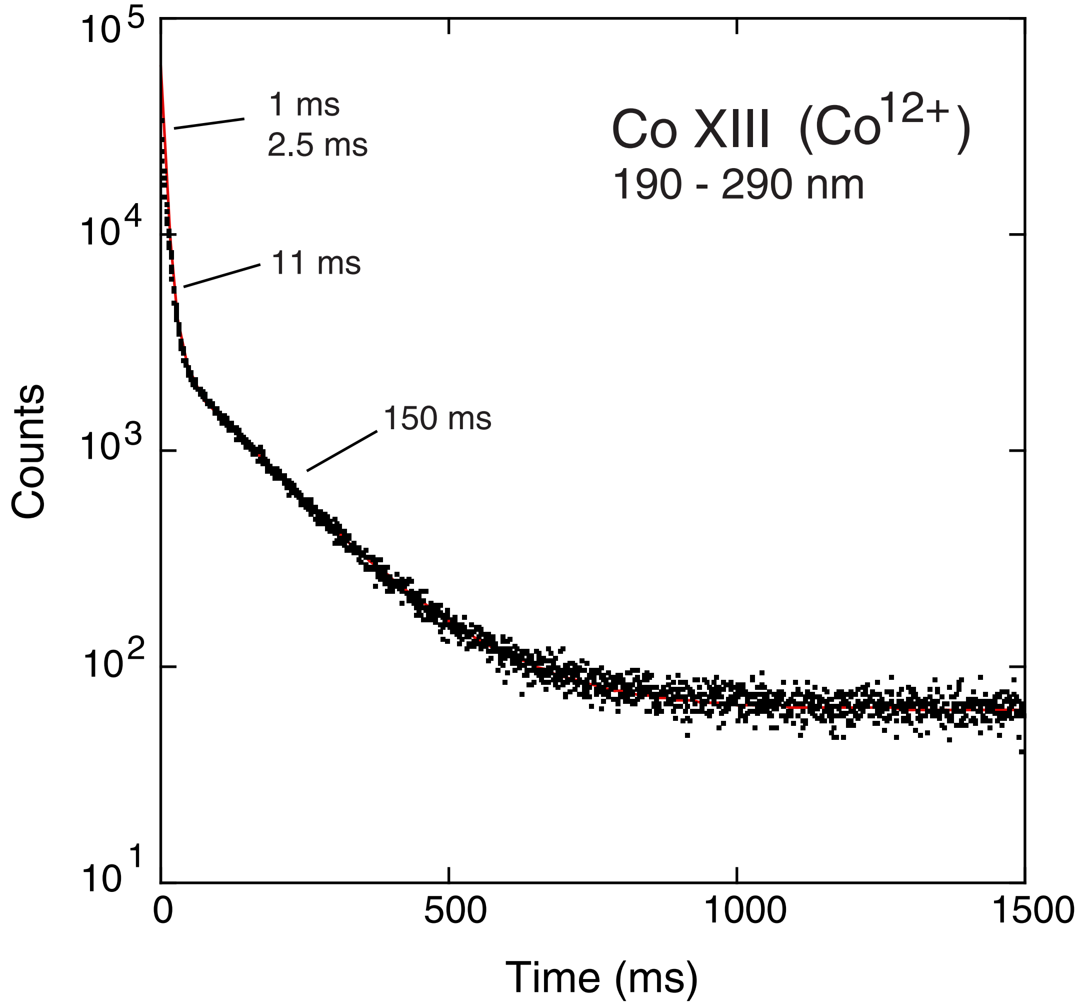
The agreement of experiment and theory, achieved after so many years, is splendid - but not perfect.



L J Curtis has derived a mixing-angle formalism that interconnects resonance and intercombination line strengths on the basis of spectroscopic data.
The heavy-ion storage ring lifetime results on Be-like ions of B through O are internally consistent, but do not agree with the prescribed trend.

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

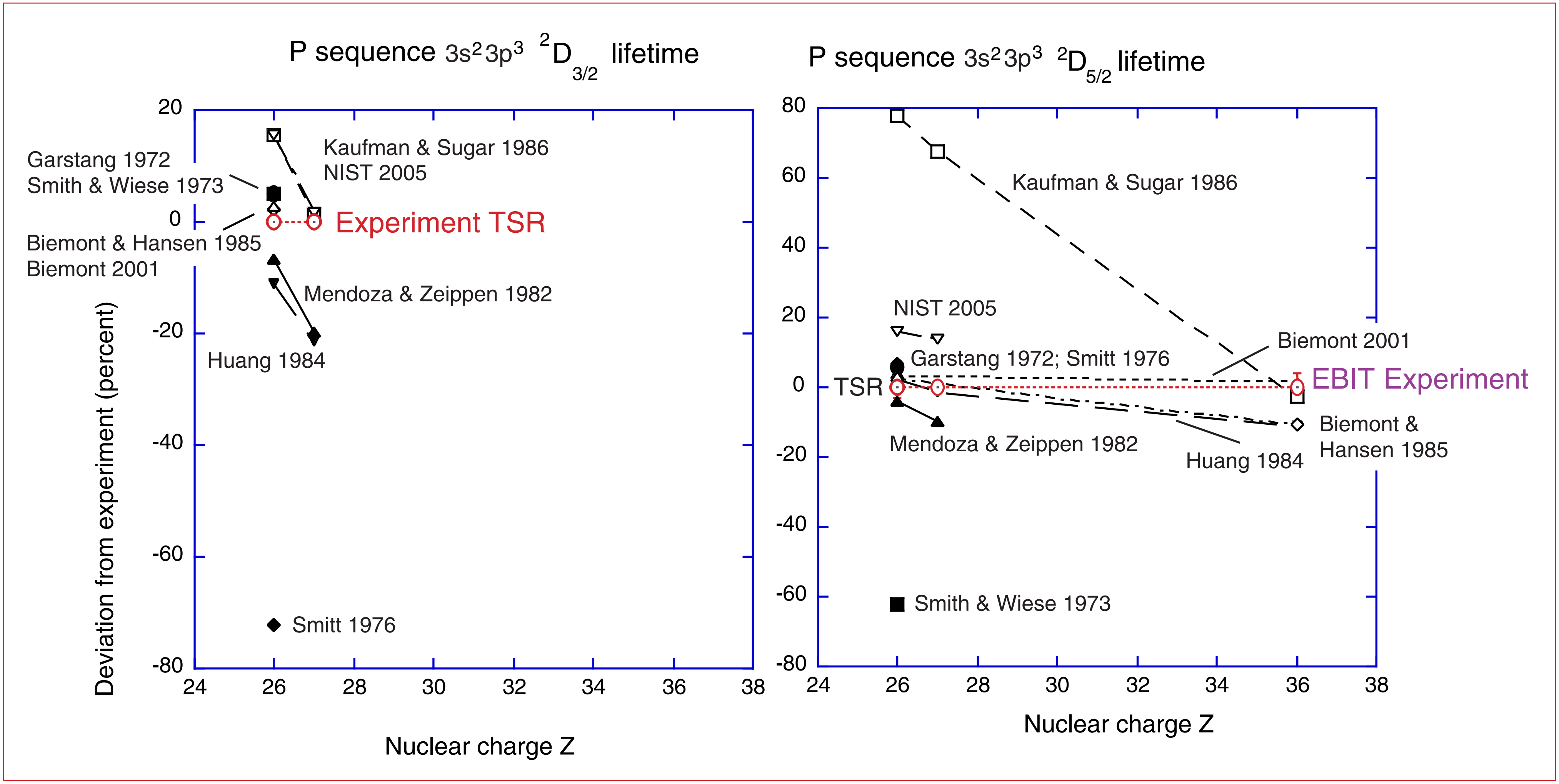




The line intensities in the ground configurations of N- and P-like ions serve as temperature diagnostics in astrophysics.

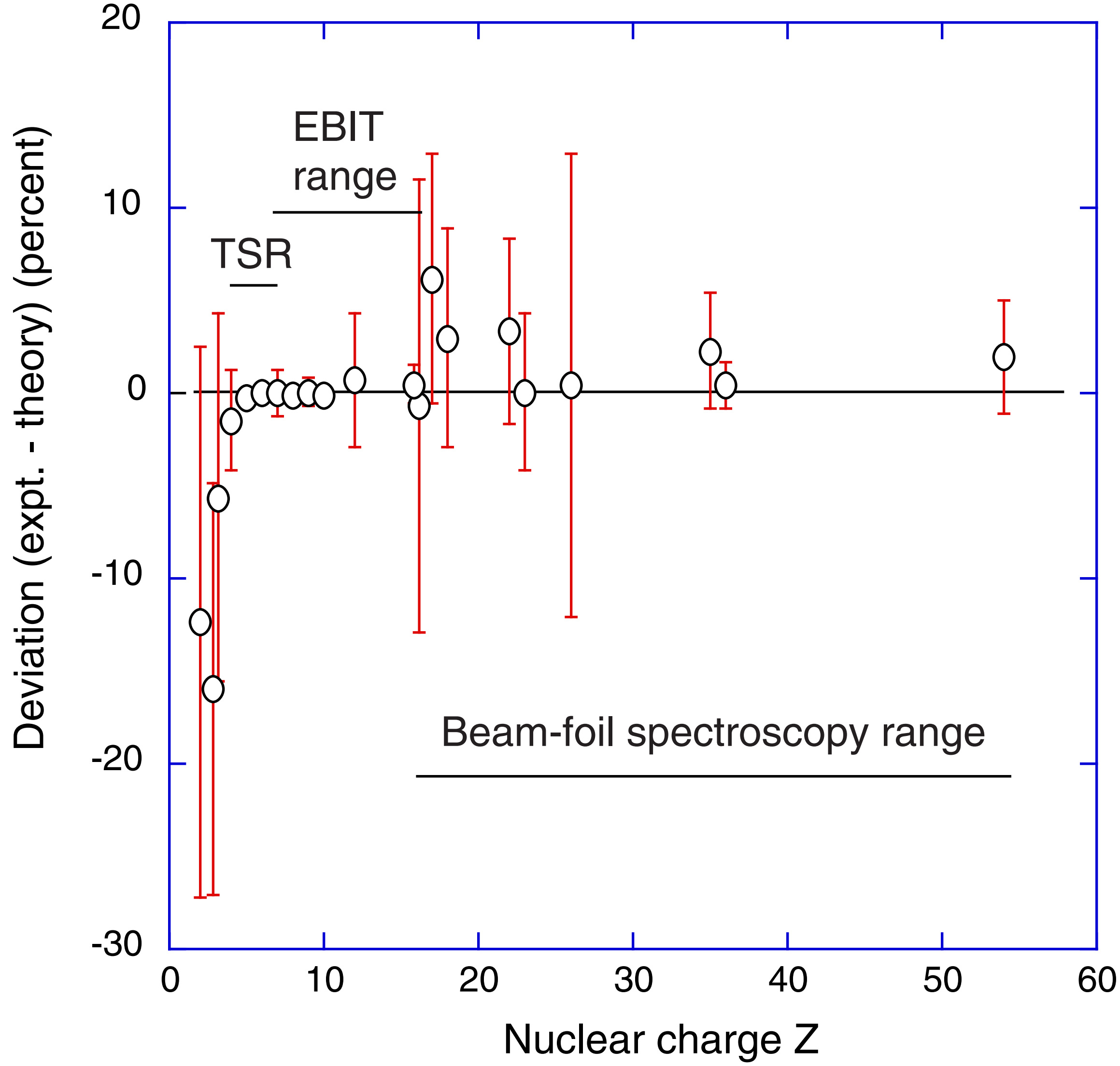
Very few calculations predict all four level lifetimes in P-like ions close to the experimental findings.

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



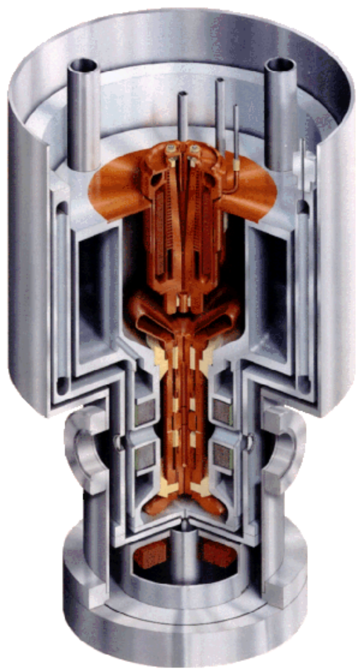
The predicted M1 and E2 transition rates in the literature or on the web (including the NIST data base) are not all as bad as in this case. The problem is how to find out which calculational results are good, and one finds out - by experiment ...

M1 transition rate in the He sequence

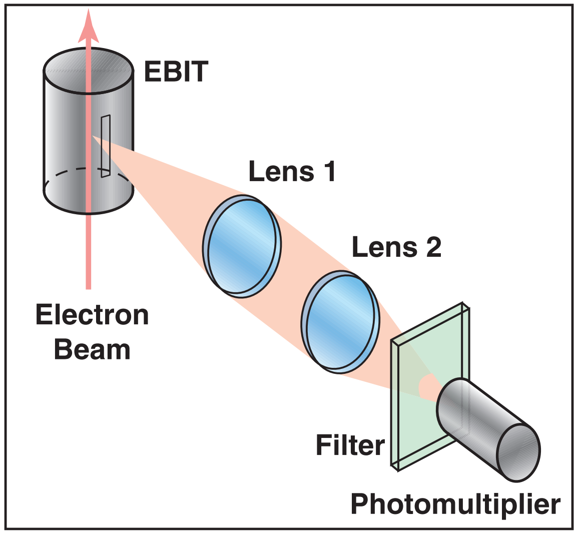


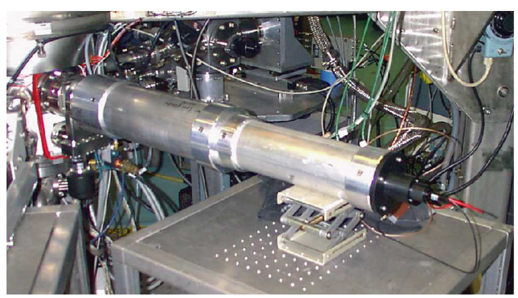
The measurements at the heavy-ion storage ring TSR and at the LLNL EBIT are in excellent agreement with relativistic theory

Atomic lifetime measurement in the visible range of the spectrum



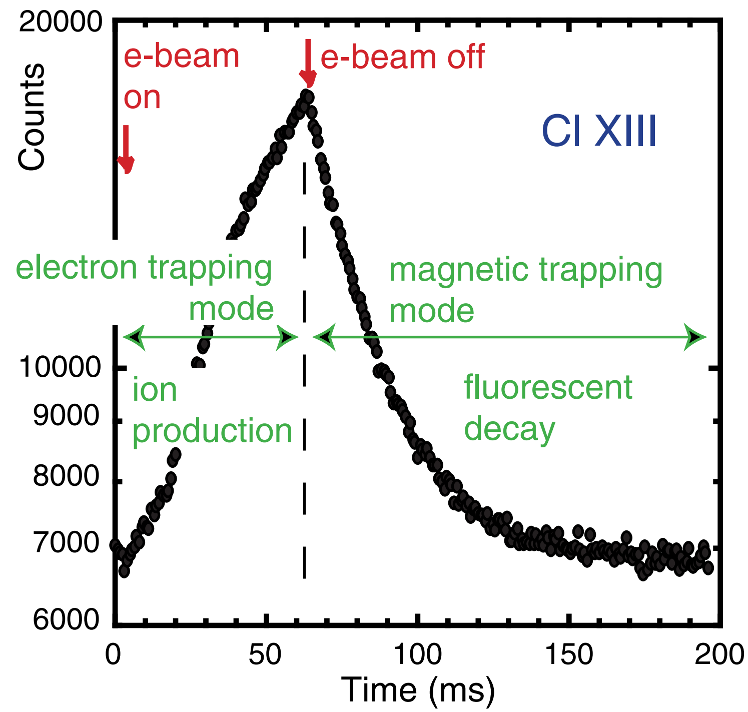
Livermore electron beam ion trap - the archetypical EBIT



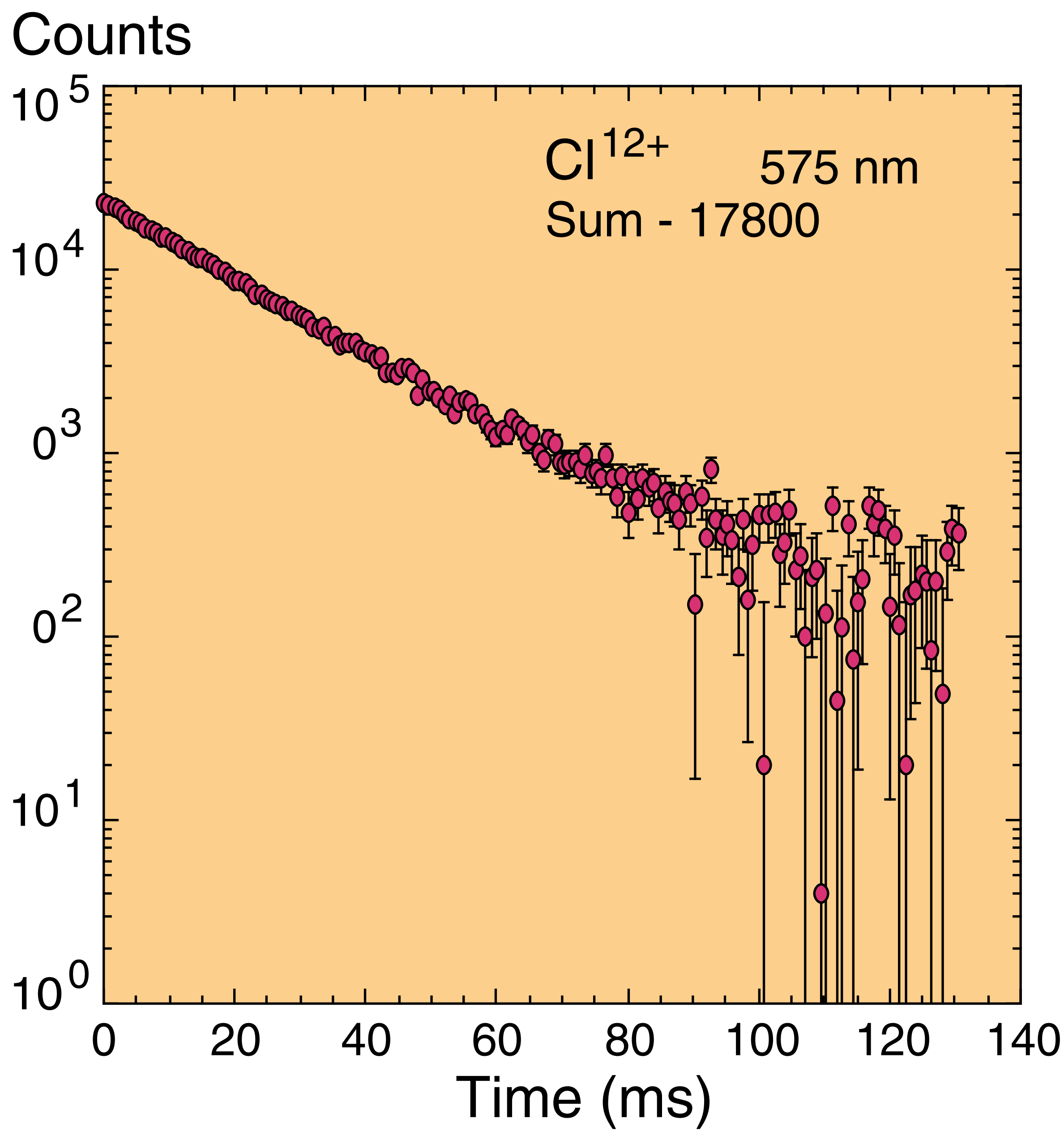


Stovepipe for optical observations

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

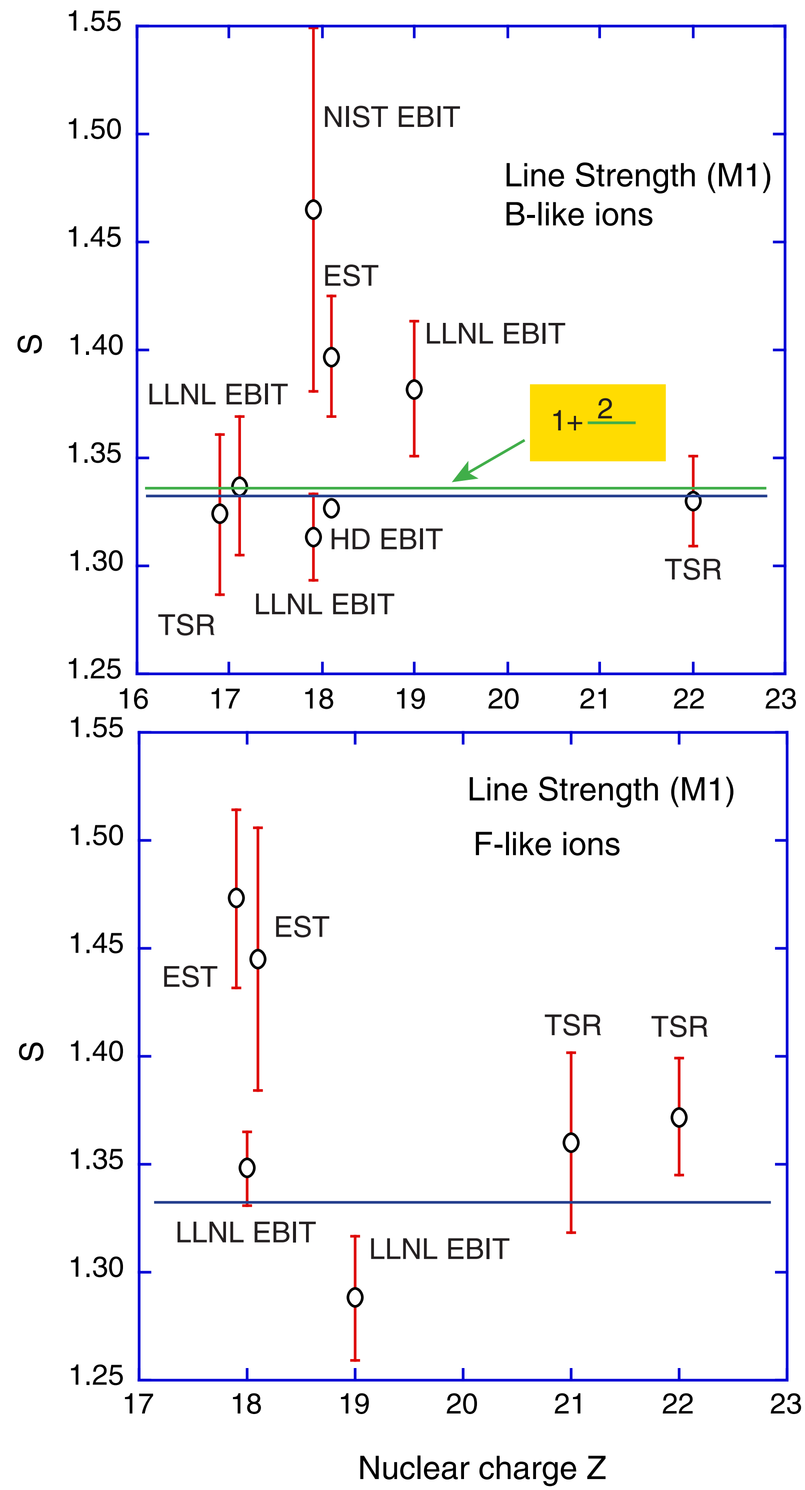


The basic technique is simple and robust.



Counts
Cl^12+
575 nm
Sum - 17800
10^5
10^4
0^3
0^2
10^1
10^0
0
20
40
60
80
100
120
140
Time (ms)

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

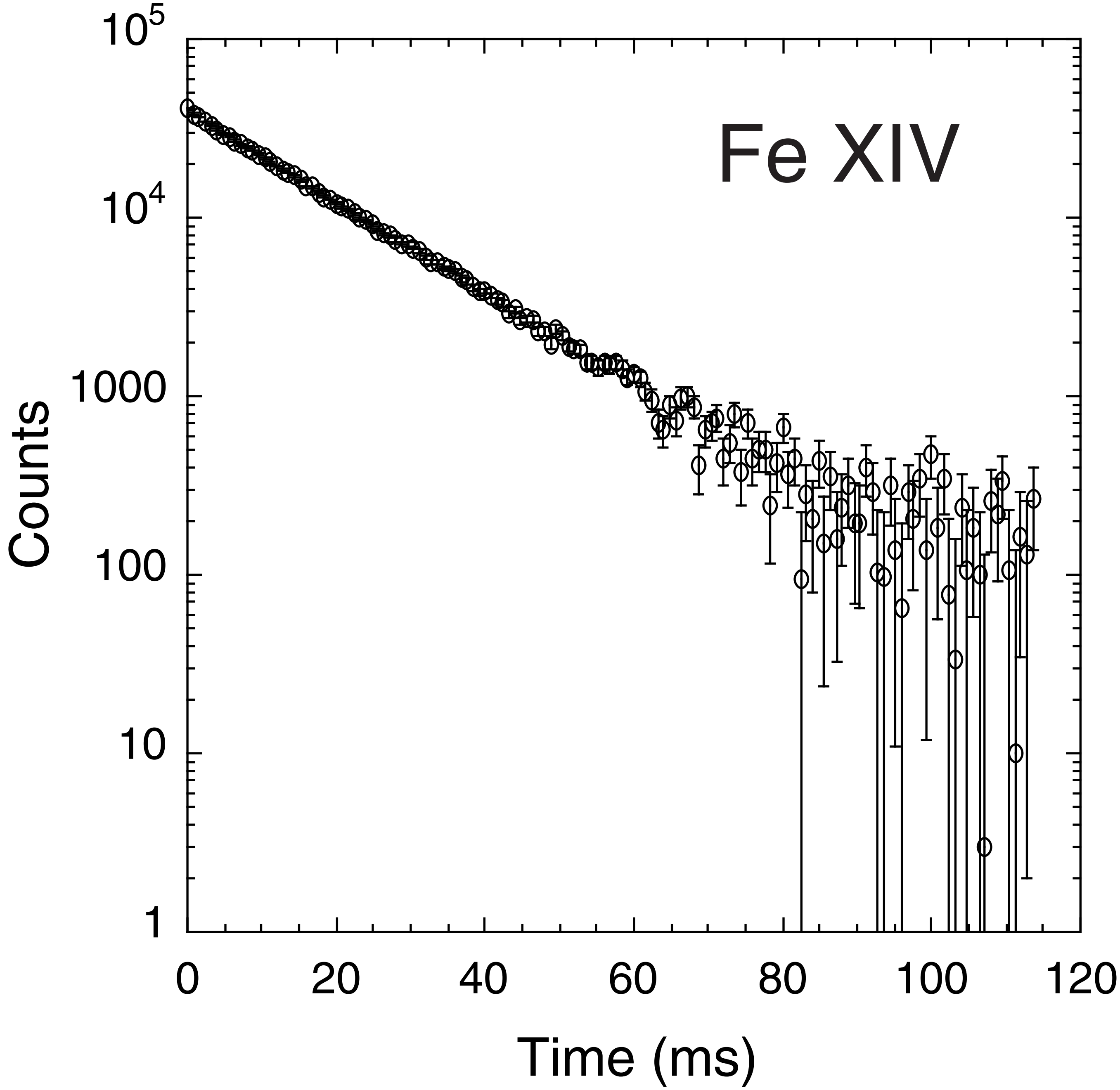


EST Electrostatic ion trap (Kingdon trap)

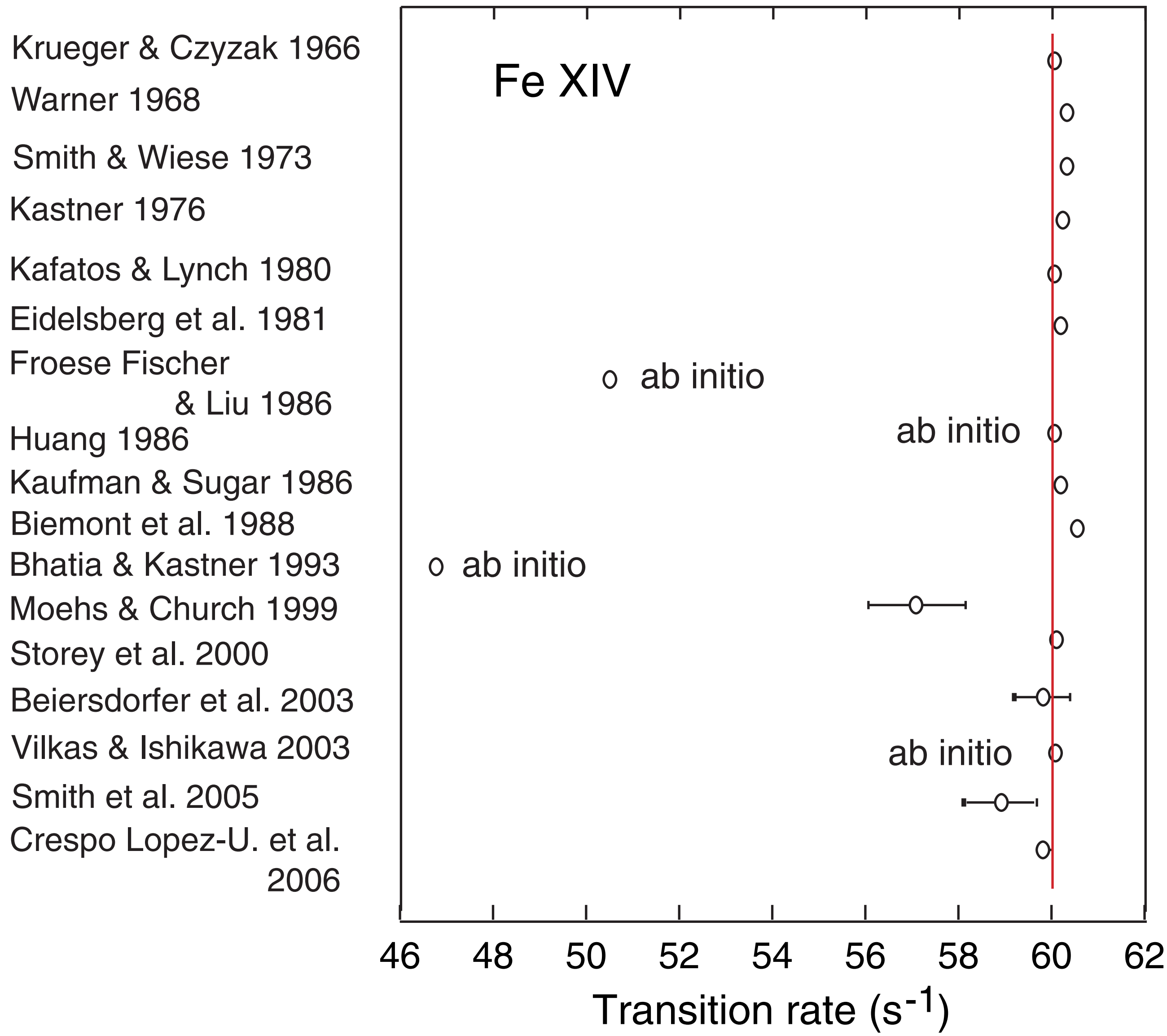
TSR Heavy ion storage ring at Heidelberg

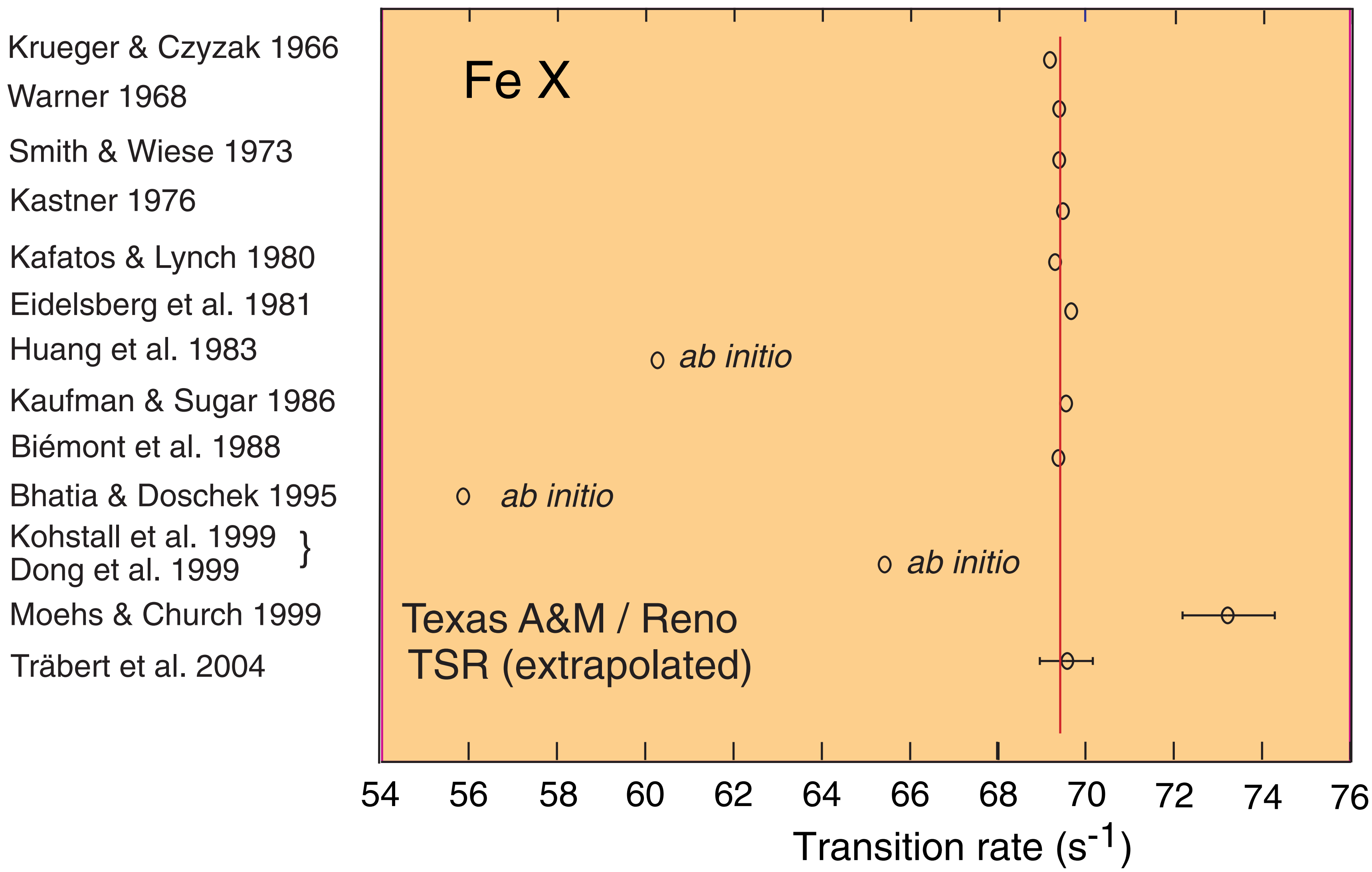
EBIT Electron beam ion traps at NIST Gaithersburg, Livermore, and Heidelberg

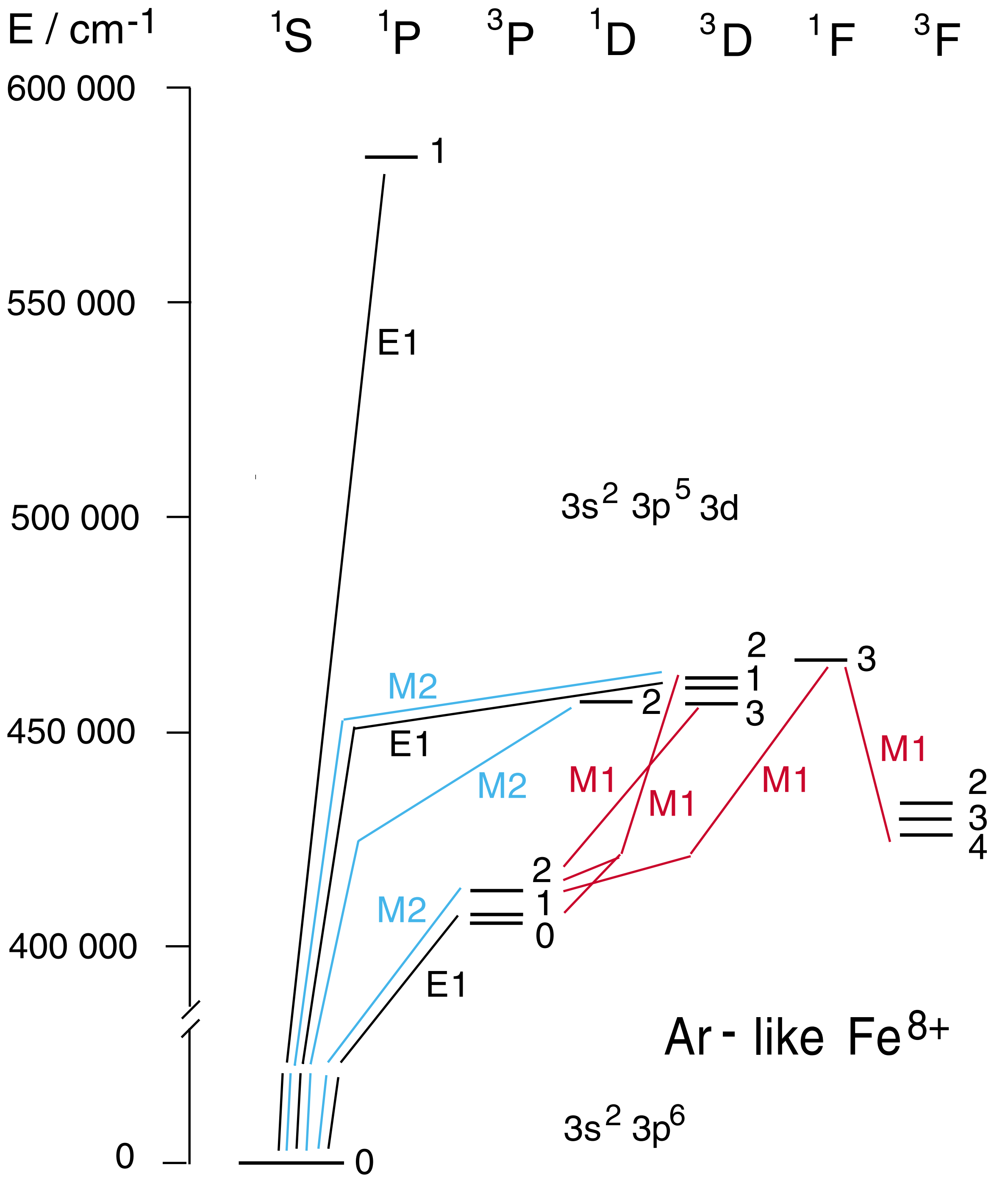
The "green iron line" decay curve as seen in the LLNL EBIT



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



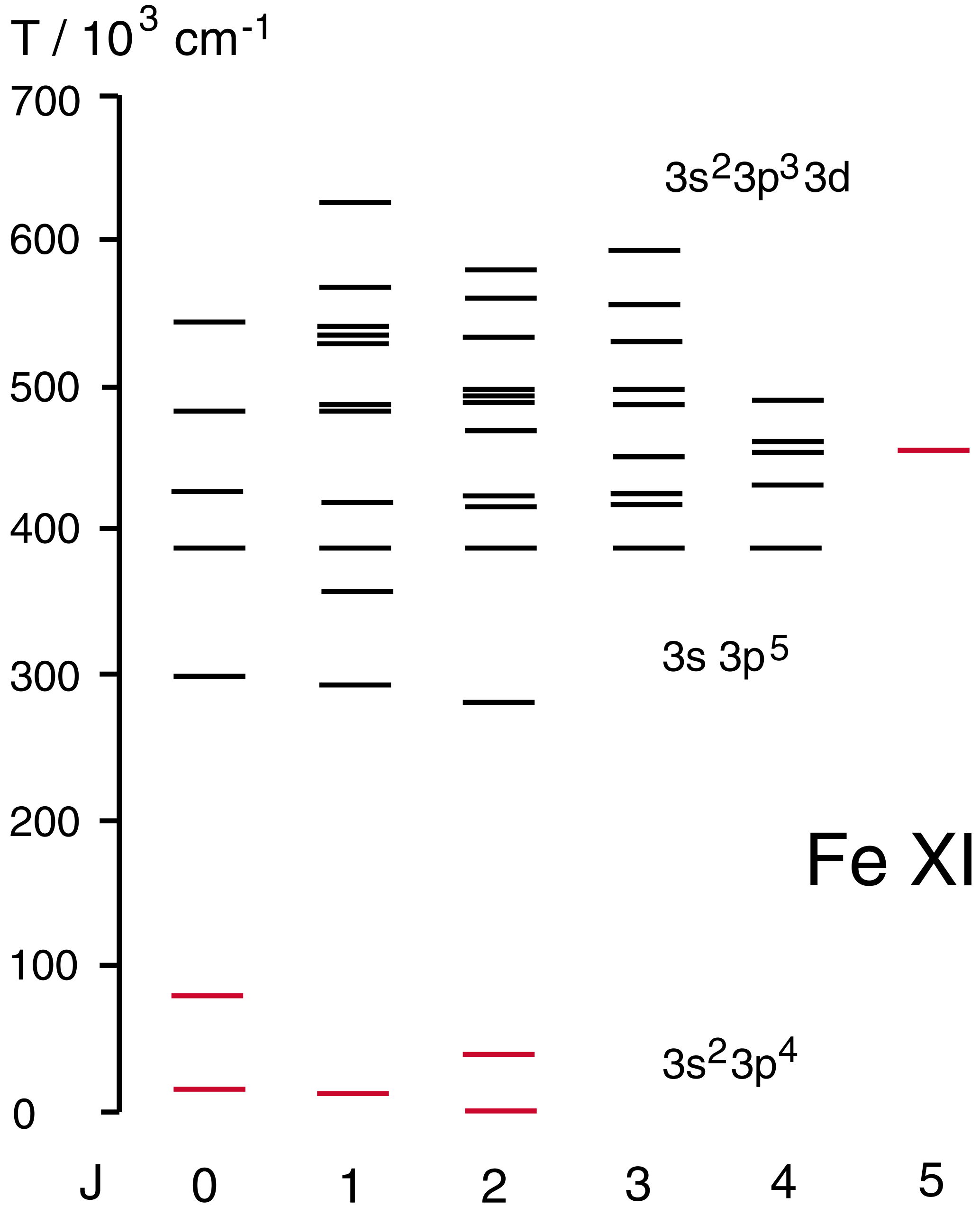

Krueger & Czyzak 1966
Warner 1968
Smith & Wiese 1973
Kastner 1976
Kafatos & Lynch 1980
Eidelsberg et al. 1981
Huang et al. 1983
Kaufman & Sugar 1986
Biémont et al. 1988
Bhatia & Doschek 1995
Kohstall et al. 1999
Dong et al. 1999
Moehs & Church 1999
Träbert et al. 2004
Fe X
ab initio
ab initio
ab initio
Texas A&M / Reno
TSR (extrapolated)
54
56
58
60
62
64
66
68
70
72
74
76
Transition rate (s-1)



In Ar-like Kr ions, two lifetimes have been measured of levels with major M2 decay branches.

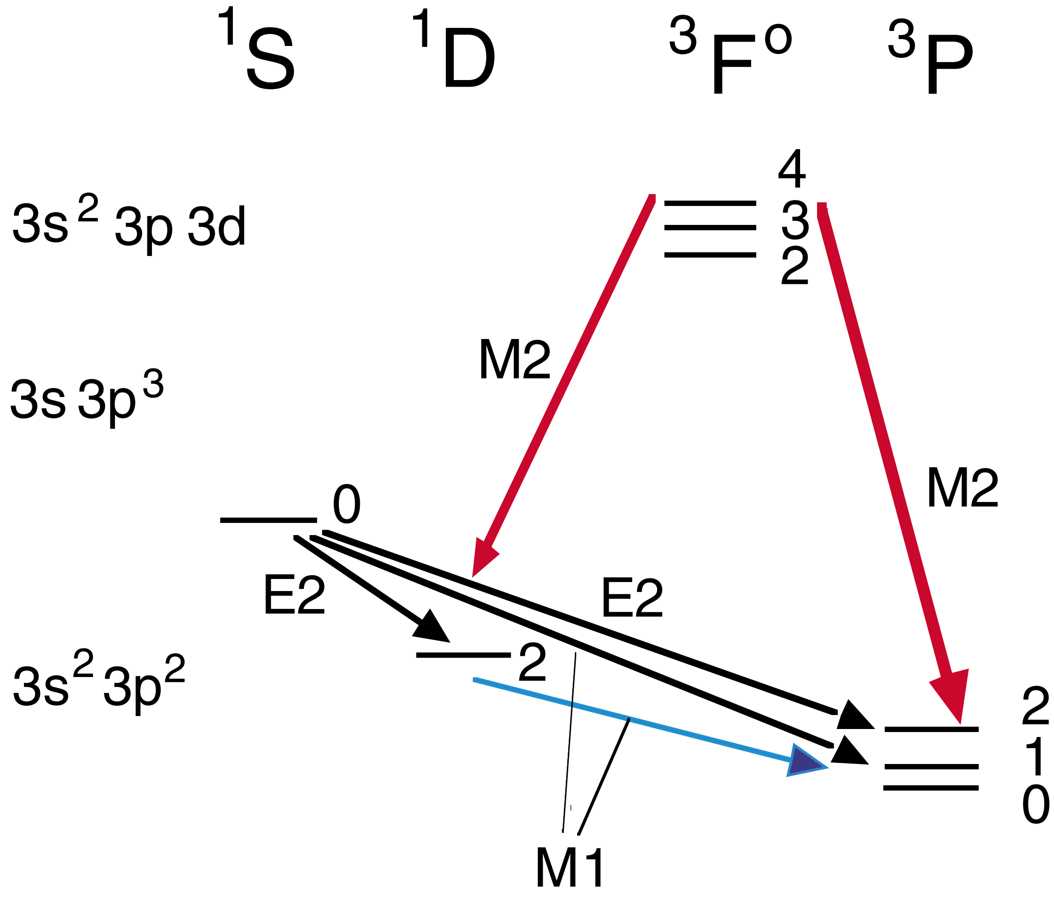
In Ar-like Fe IX, several of the "slow" ground state transitions are still being sought in terrestrial light sources.

Many ions have a few levels of particularly high J that cannot easily decay (at least not by E1 transitions).
These levels act as population traps and are important for charge state distributions.



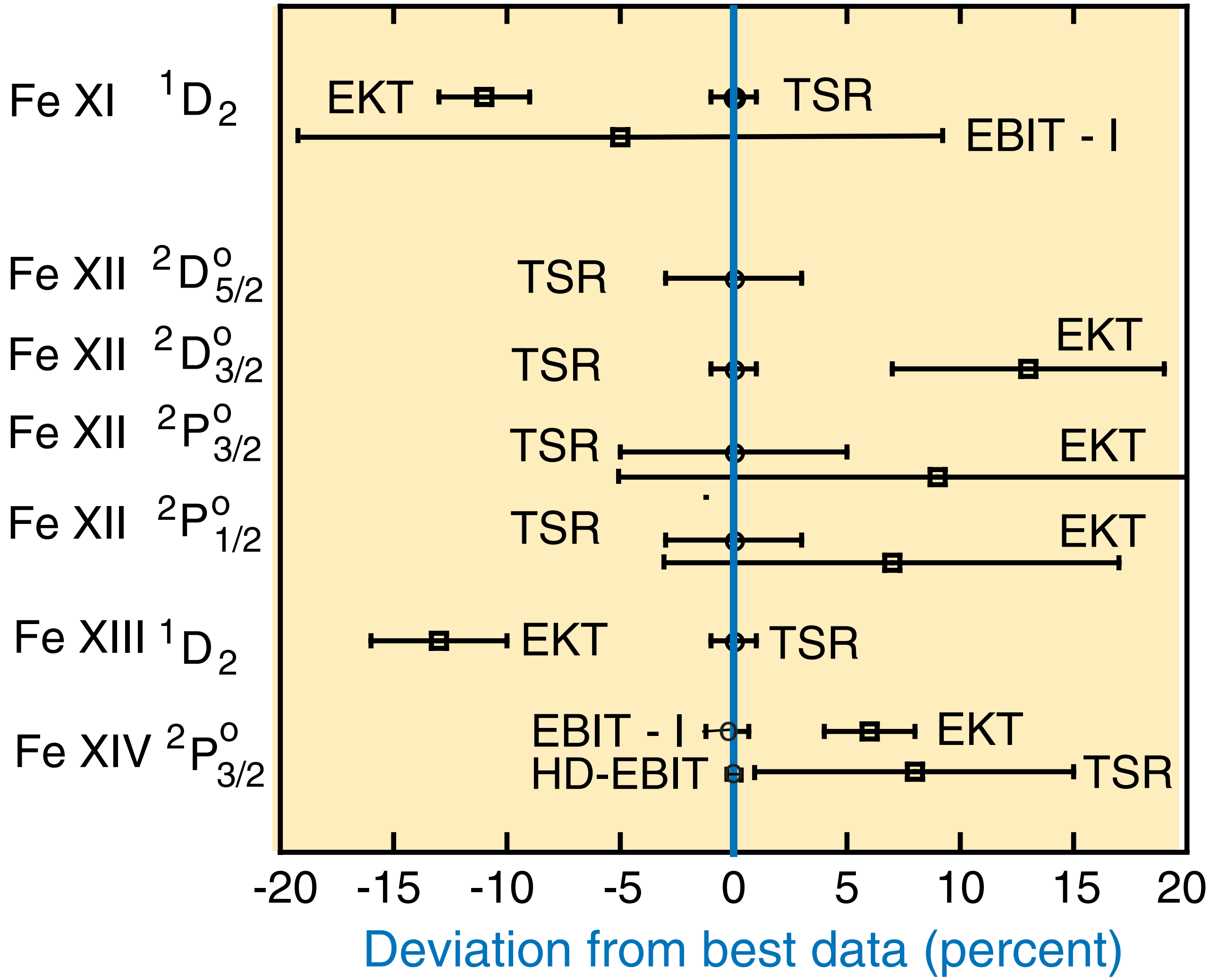
In delayed BFS observations, the $3s^2\ 3p\ 3d\ ^3F^o_3$ level decay has been seen.

The decay of the $3s^2\ 3p\ 3d\ ^3F^o_4$ level has been detected via its influence on an M1 decay curve in the ground configuration.



Si - like Fe^{12+}

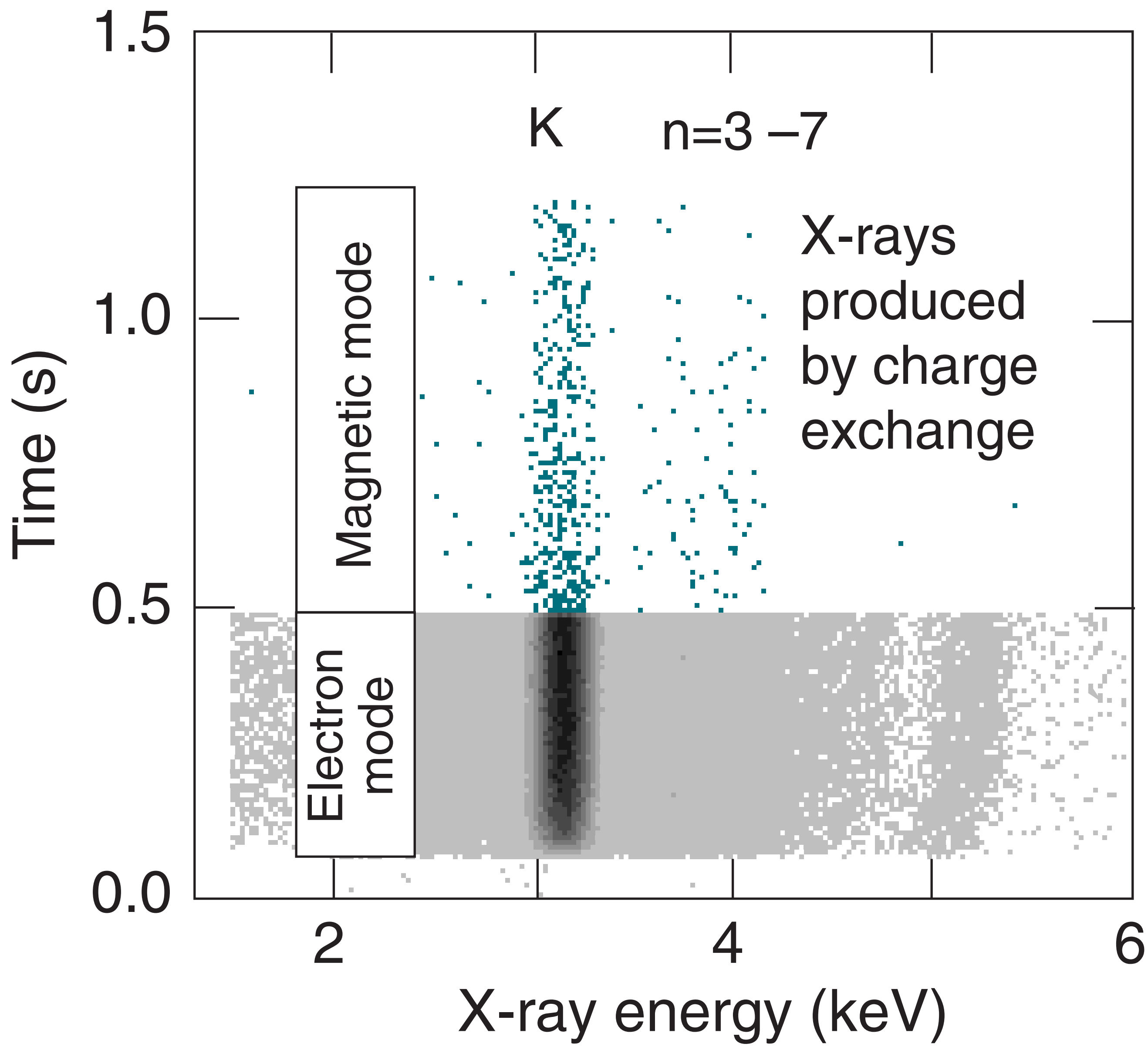
Fe ion lifetimes

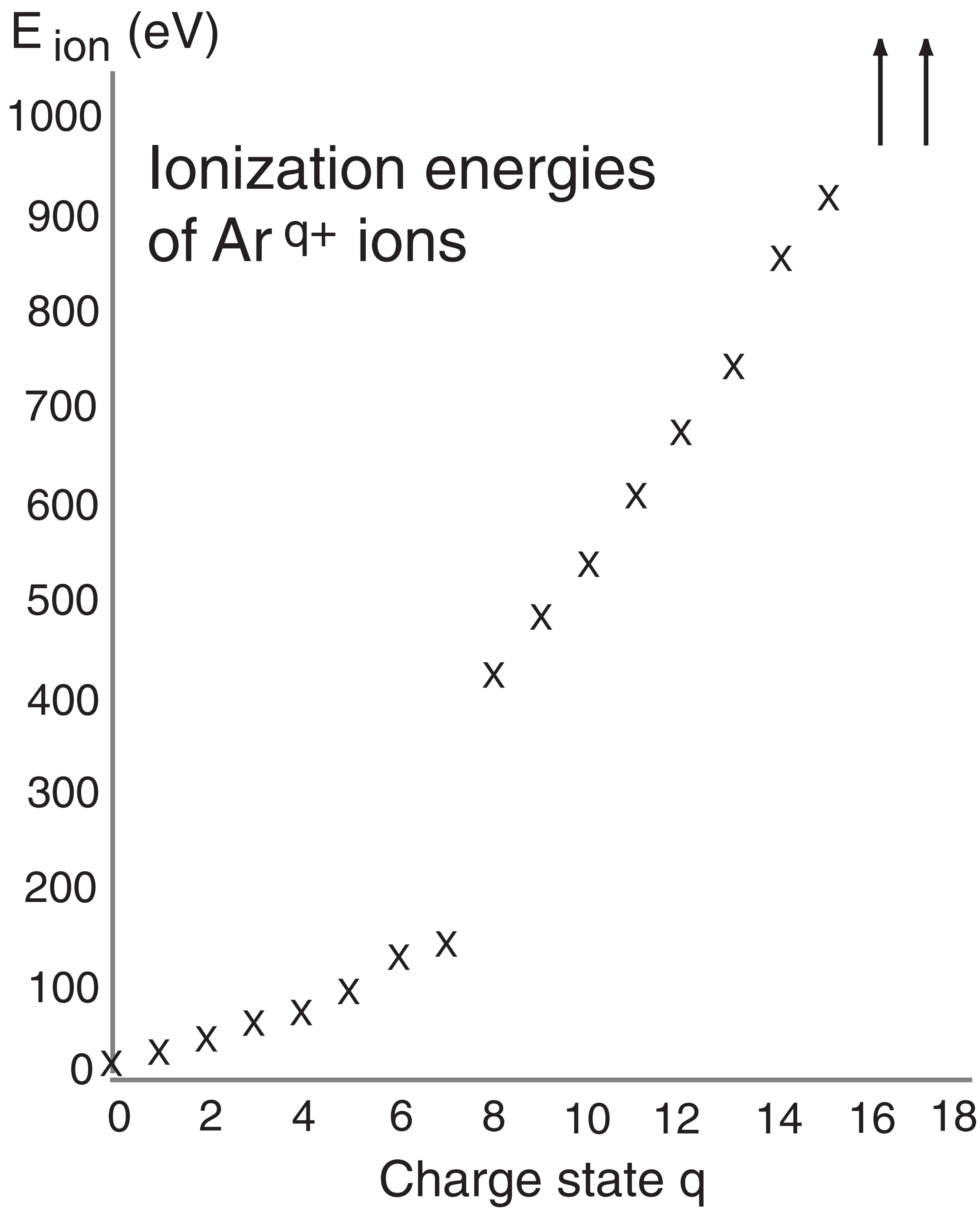


Major operating modes of electron beam ion traps

	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



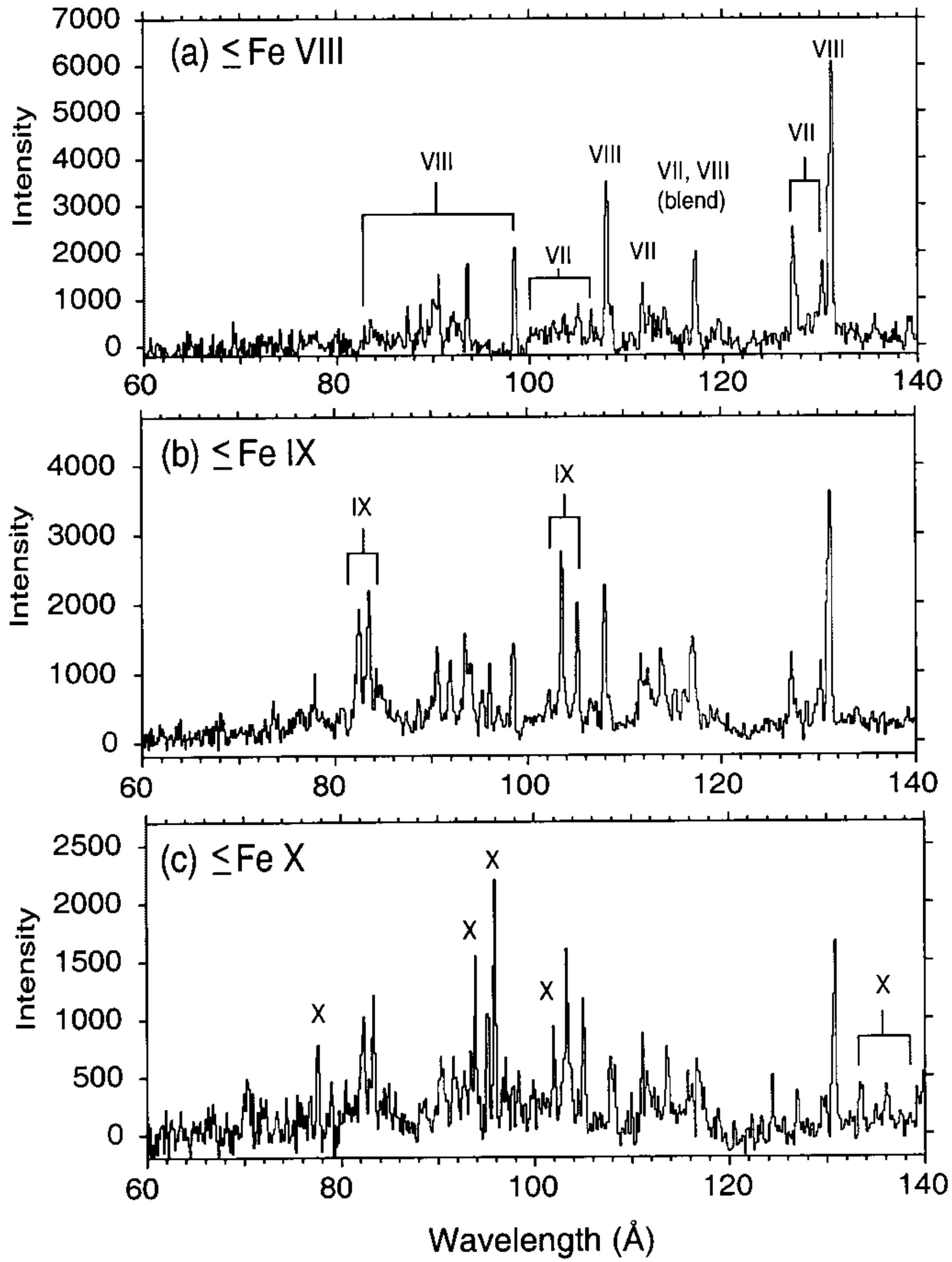


It is easy to reach any charge state of ions in an electron beam ion trap, by adjusting the electron beam energy.

In fact, it is too easy to reach any low charge state - there is little selectivity.
EBIT does better with higher charge states.

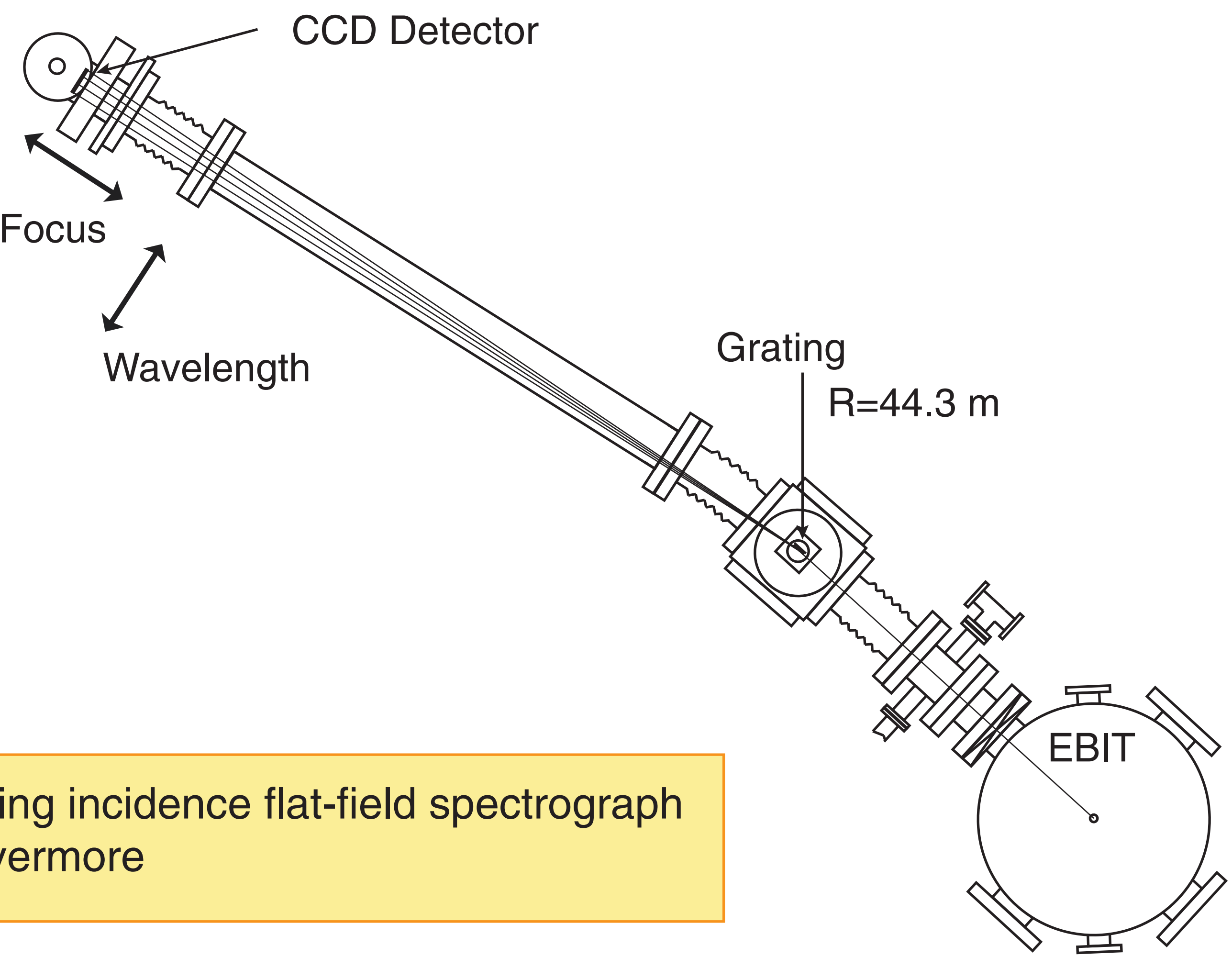
In the electron beam ion trap (EBIT), the electron beam energy determines the highest charge state that can be reached.

Systematic observations of this kind have been done at Livermore in support of Chandra and XMM/Newton data evaluation.



Sample spectra taken from Lepson et al., Ap. J. 578, 648 (2002).

Multichannel detection is a key element for precision spectroscopy.



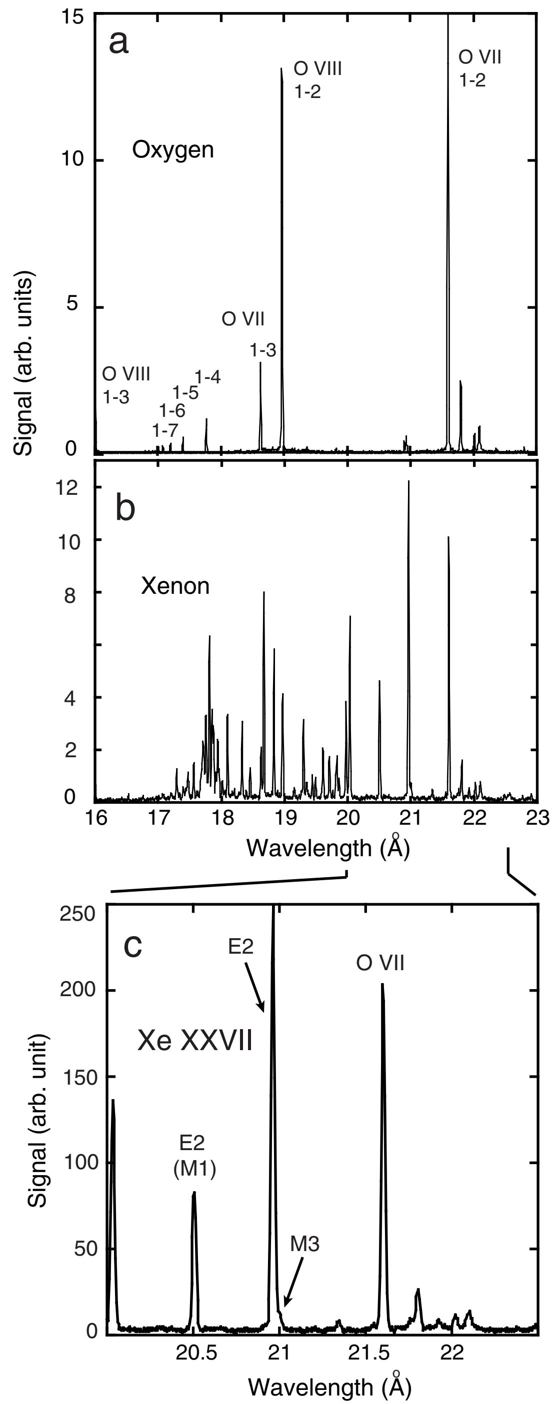
Grazing incidence flat-field spectrograph at Livermore

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

20 Years of Spectroscopy EBIT LA LIVERMORE since 1986

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.

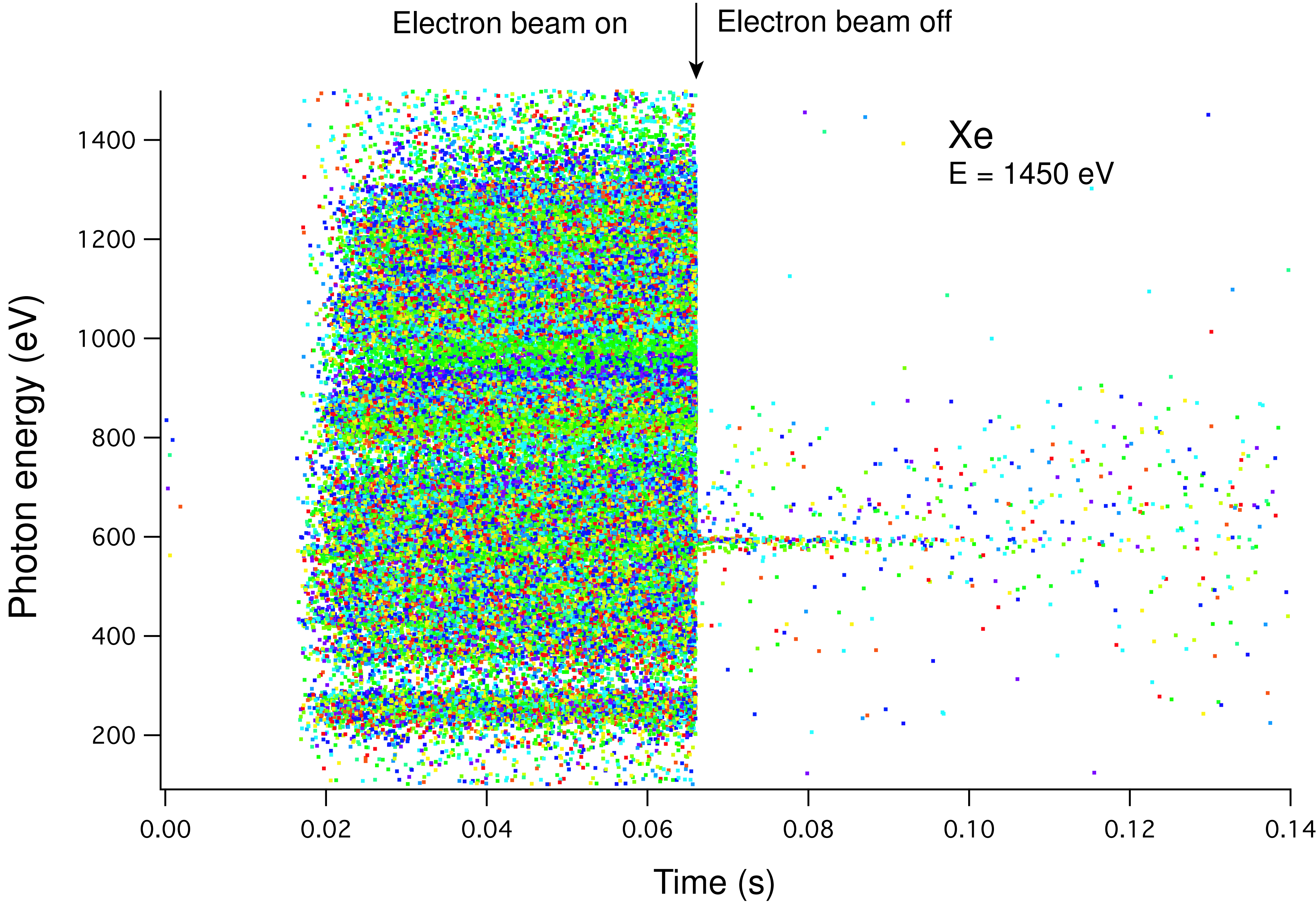
X-ray crystal spectrometers offer high spectral resolution, but suffer from low efficiency

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.

20 Years of Spectroscopy EBIT LAB since 1986 LIVERMORE



20 Years of Spectroscopy EBIT LA LIVERMORE

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

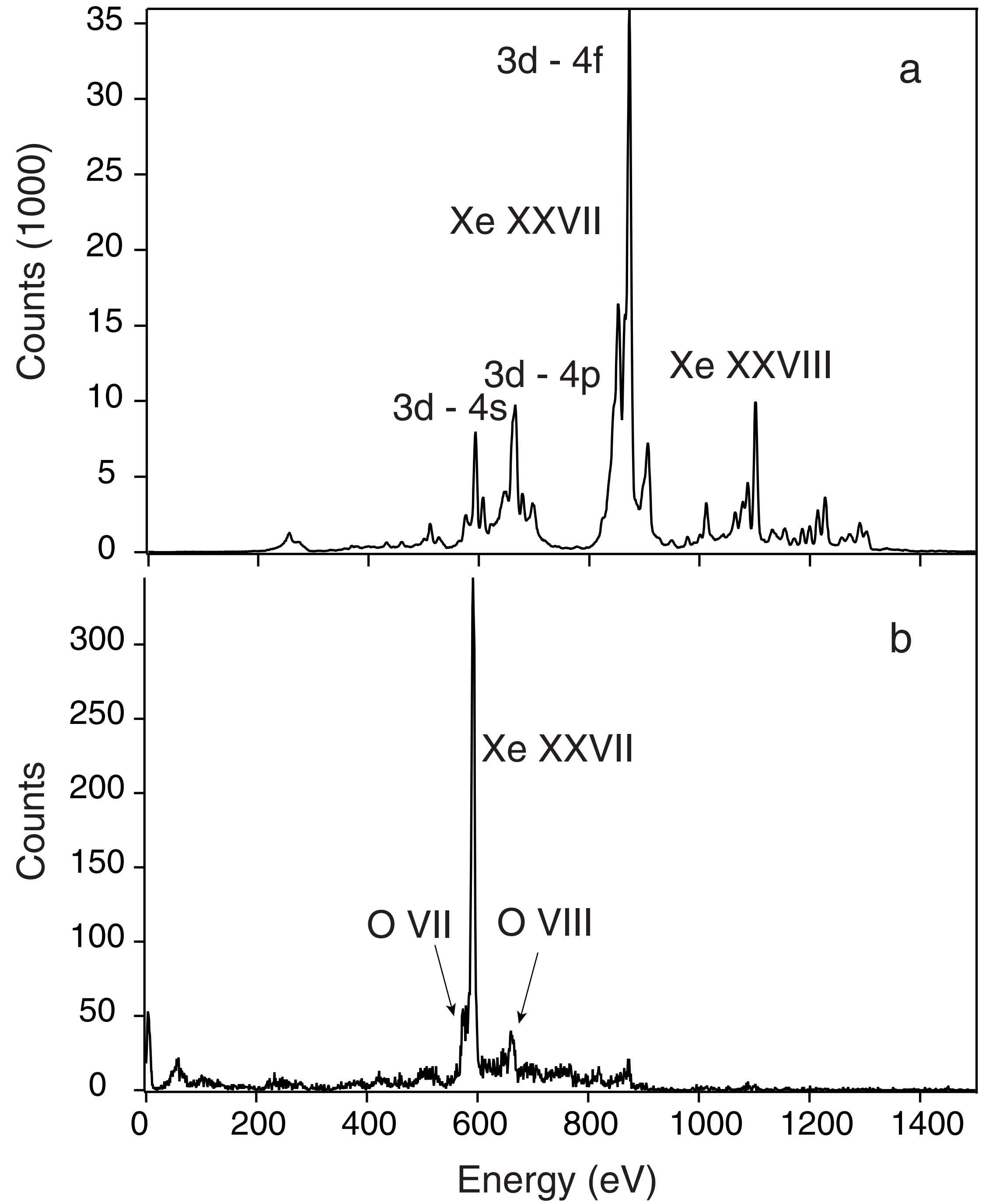
Each signal pulse is time-stamped; the data can be sorted by X-ray energy or time within the trap cycle.

XRS microcalorimeter spectra of Xe
(E = 1450 eV)

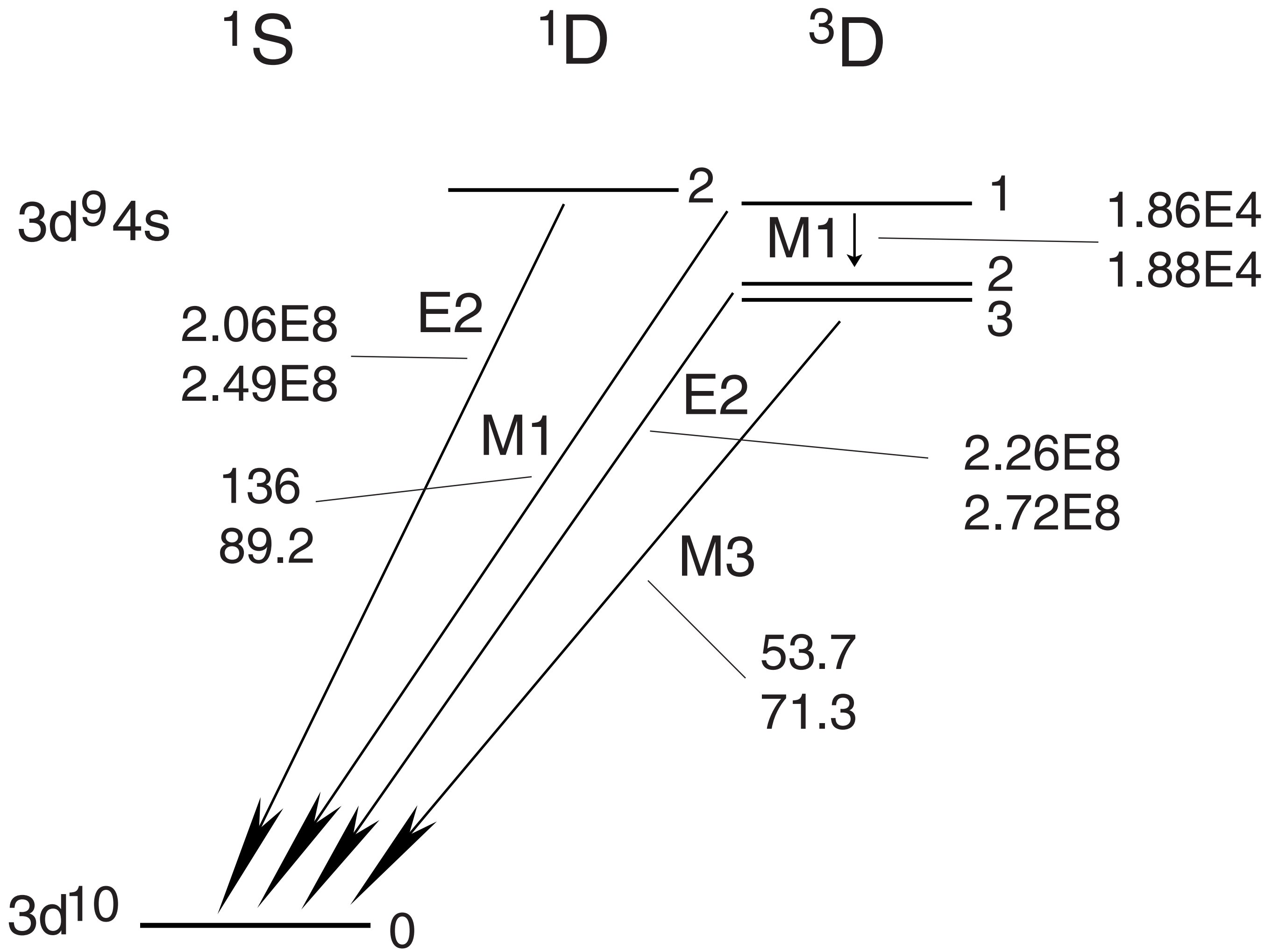
a) electron beam on

b) electron beam off

Time resolved spectra reflect level population dynamics.



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



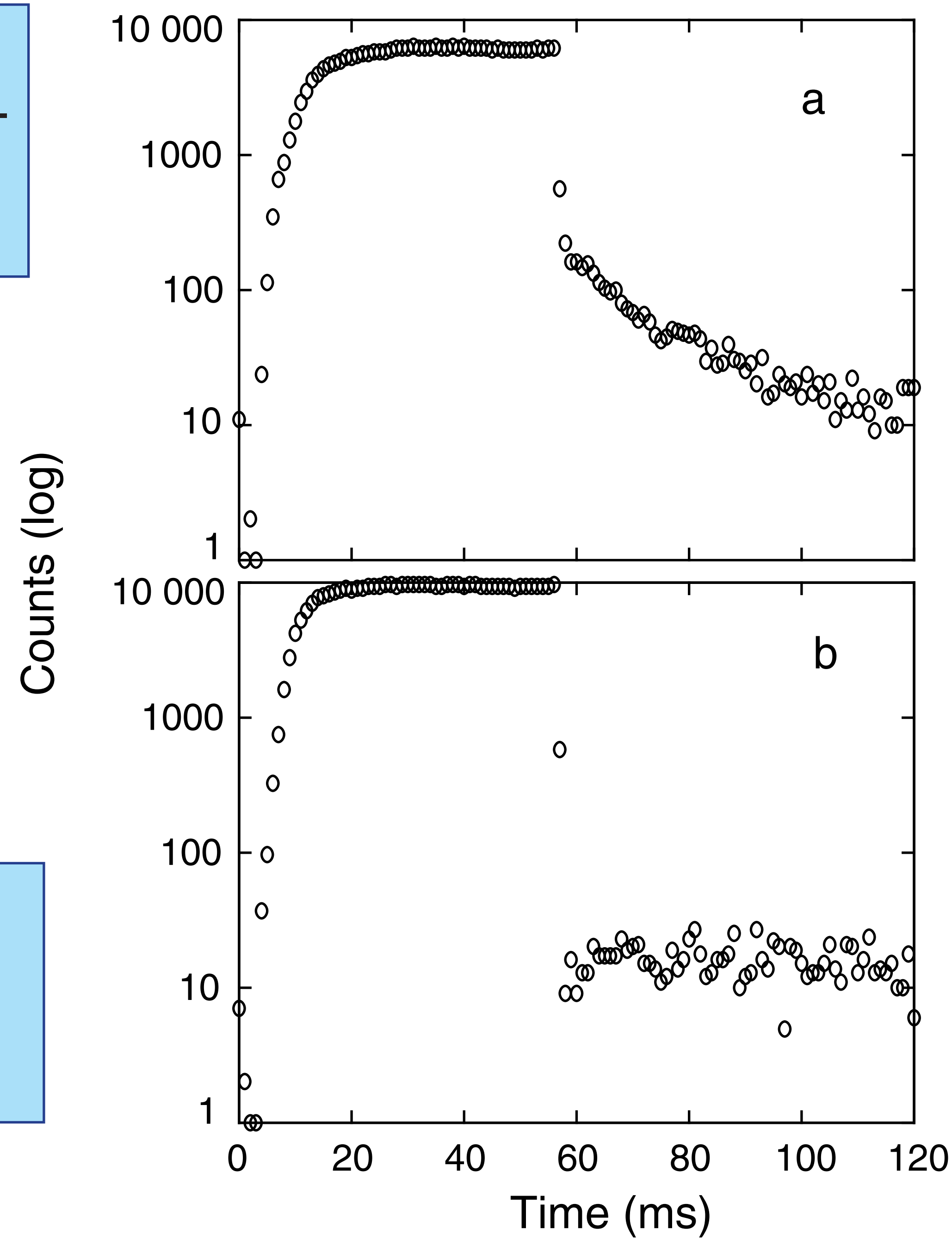
When the electron beam is switched off, delayed photons arise from long-lived excited levels or from charge exchange (CX).

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.

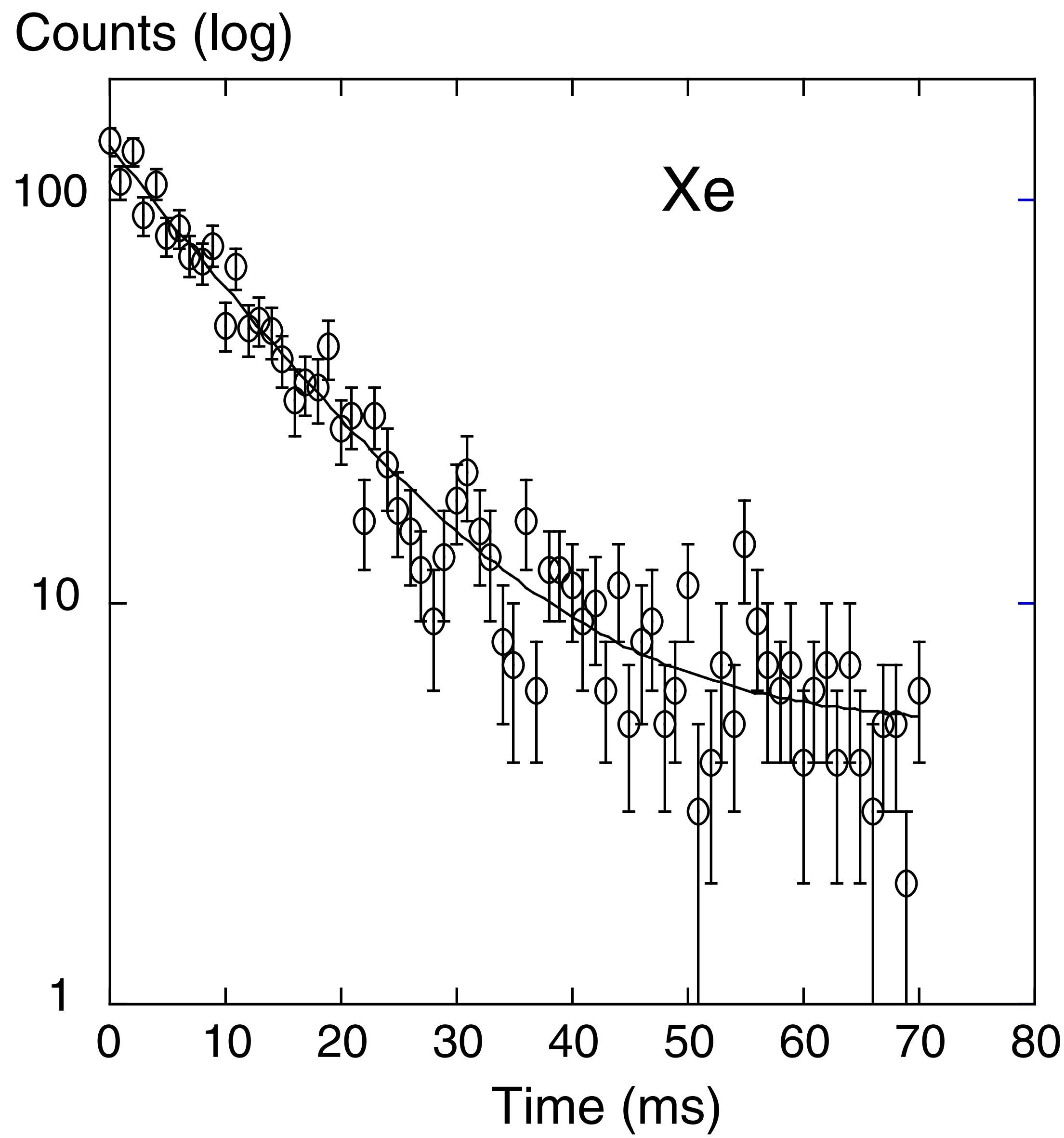


20 Years of Spectroscopy EBIT LLNL LIVERMORE since 1986

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

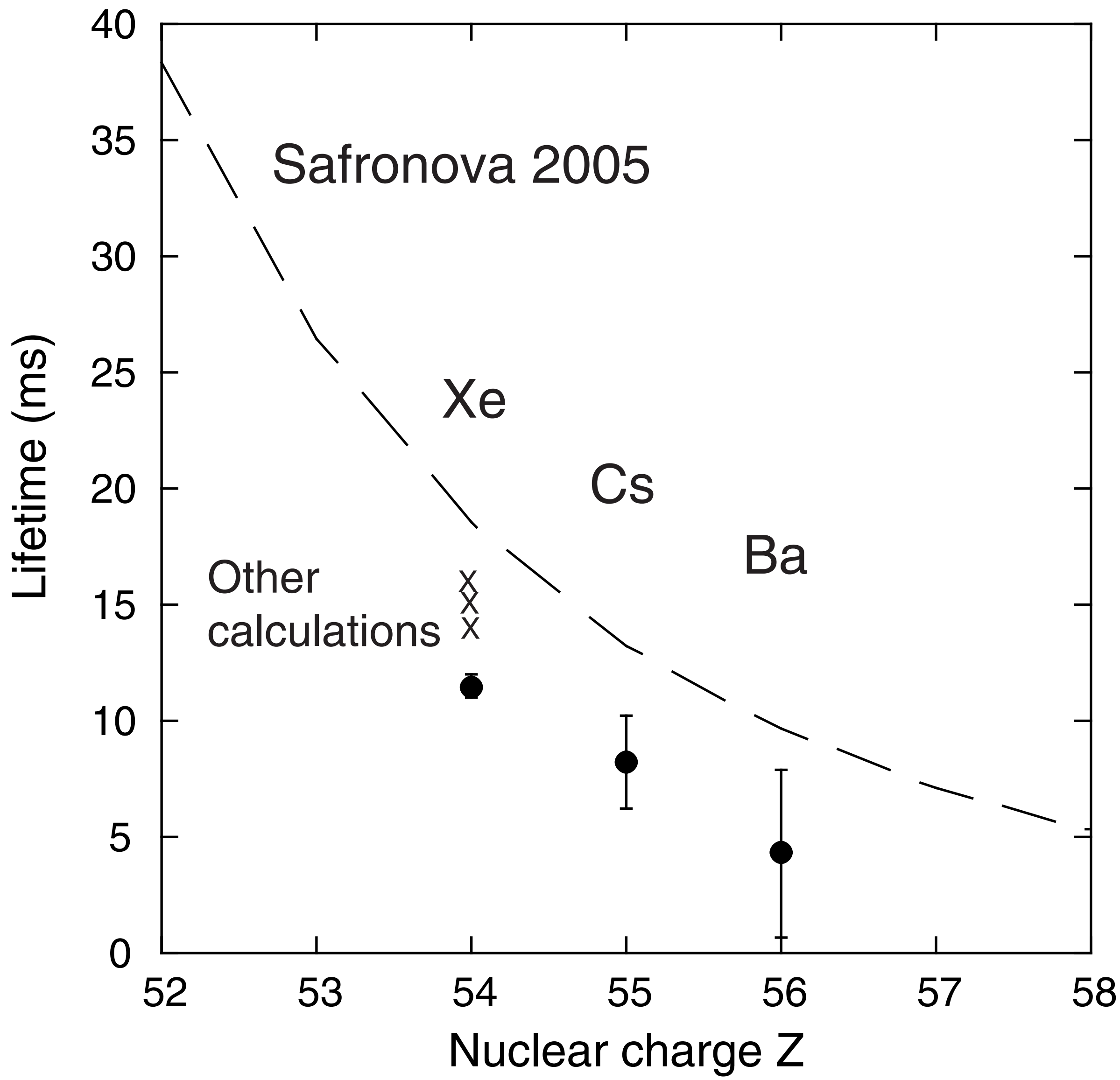


This is the first atomic lifetime measurement using a microcalorimeter at an electron beam ion trap.

20 Years of Spectroscopy EBIT LAB since 1986 LIVERMORE

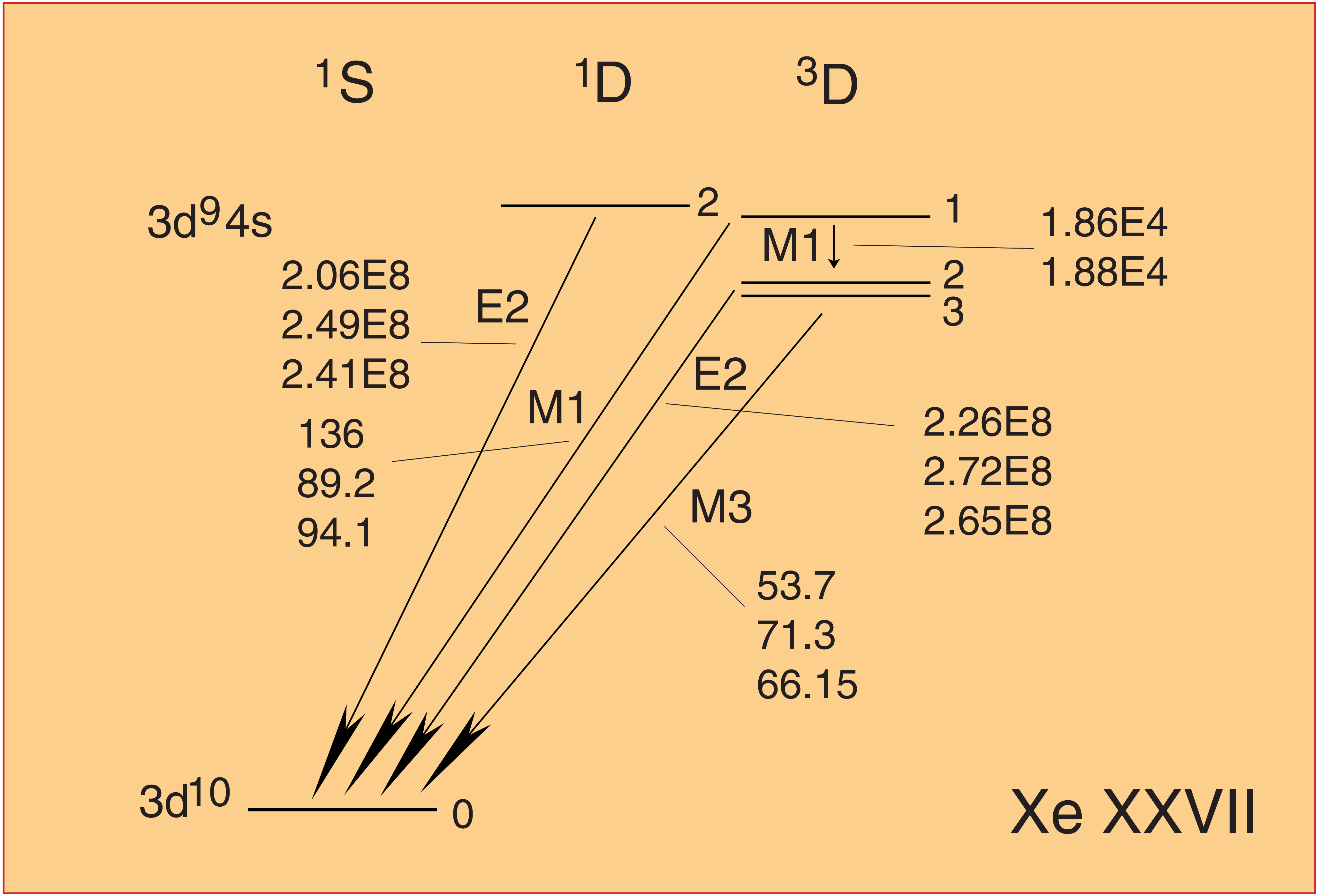
Very few calculations cover the magnetic octupole (M3) decays.

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)



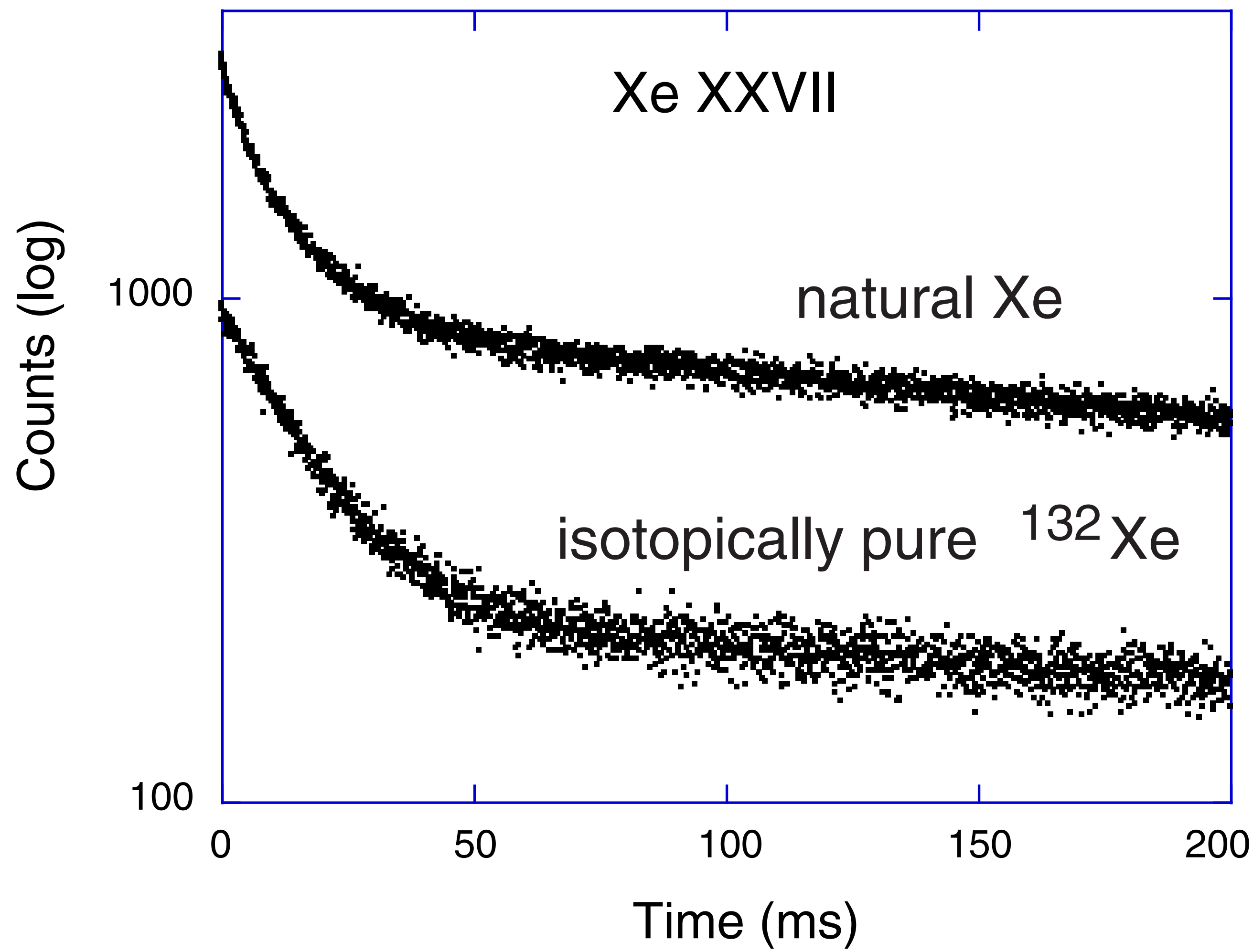
A shorter lifetime than predicted makes the ion less sensitive to density effects.

20 Years of Spectroscopy EBIT LLNL LIVERMORE since 1986



^1S
^1D
^3D
$3d^9 4s$
2
1
M1
1.86E4
1.88E4
2
3
2.06E8
2.49E8
2.41E8
E2
E2
M1
136
89.2
94.1
2.26E8
2.72E8
2.65E8
M3
53.7
71.3
66.15
$3d^{10}$
0
Xe XXVII

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.



Now that Hinode / EIS is orbiting,
is there anything left to be done in the laboratory?

a) The spectroscopy of Fe (and whatever) will be superb from the corona,
but the problem of elemental identification has to be taken care of on the ground.

There is a historic backlog of spectroscopic misidentifications, because not enough good laboratory data were available 40 years ago.

b) Most terrestrial light sources work well with short-lived levels,
but those long-lived ones in the corona have to be confirmed.
This takes a low density apparatus like EBIT.

c) The identification of long-lived levels in the lab takes some time resolution.
Time-resolved spectra can harbour surprises. Consider the example of the metastable level in Ni-like Xe, that only recently has been explicitly left out of an extensive calculation.
Microcalorimeter data on Xe demonstrate how the spectrum dynamics depend on a long lived level.
In the soft part of the EUV, a different device will be needed, for example a microchannel plate-based detector (MCP).

Laboratory work on the EUV spectrum of Fe:
Needs elemental purity, add time resolution

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

Atomic lifetimes (E1-forbidden decays) are of interest in
- astrophysics (solar corona, planetary nebulae, AGN, etc.)
- plasma physics (tokamak, spheromak, divertor)

EBIT experiments offer high spectroscopic accuracy
Beam-foil data guarantee isotopic purity,
reasonable charge state discrimination
200 - 350 Å range: Beam-foil data on Fe are available,
EBIT data may become available in a few years
Heavy-ion storage ring lifetime experiments are in progress