Atomic lifetimes for highly charged ions

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Abstract

In this talk I give an overview of the present status of our theoretical understanding of Lifetimes. I discuss a few examples and describe the latest measurement of Hyperfine Quenching of gold at GSI. I discuss prospects for new experiments with applications to nuclear physics

Experiment:

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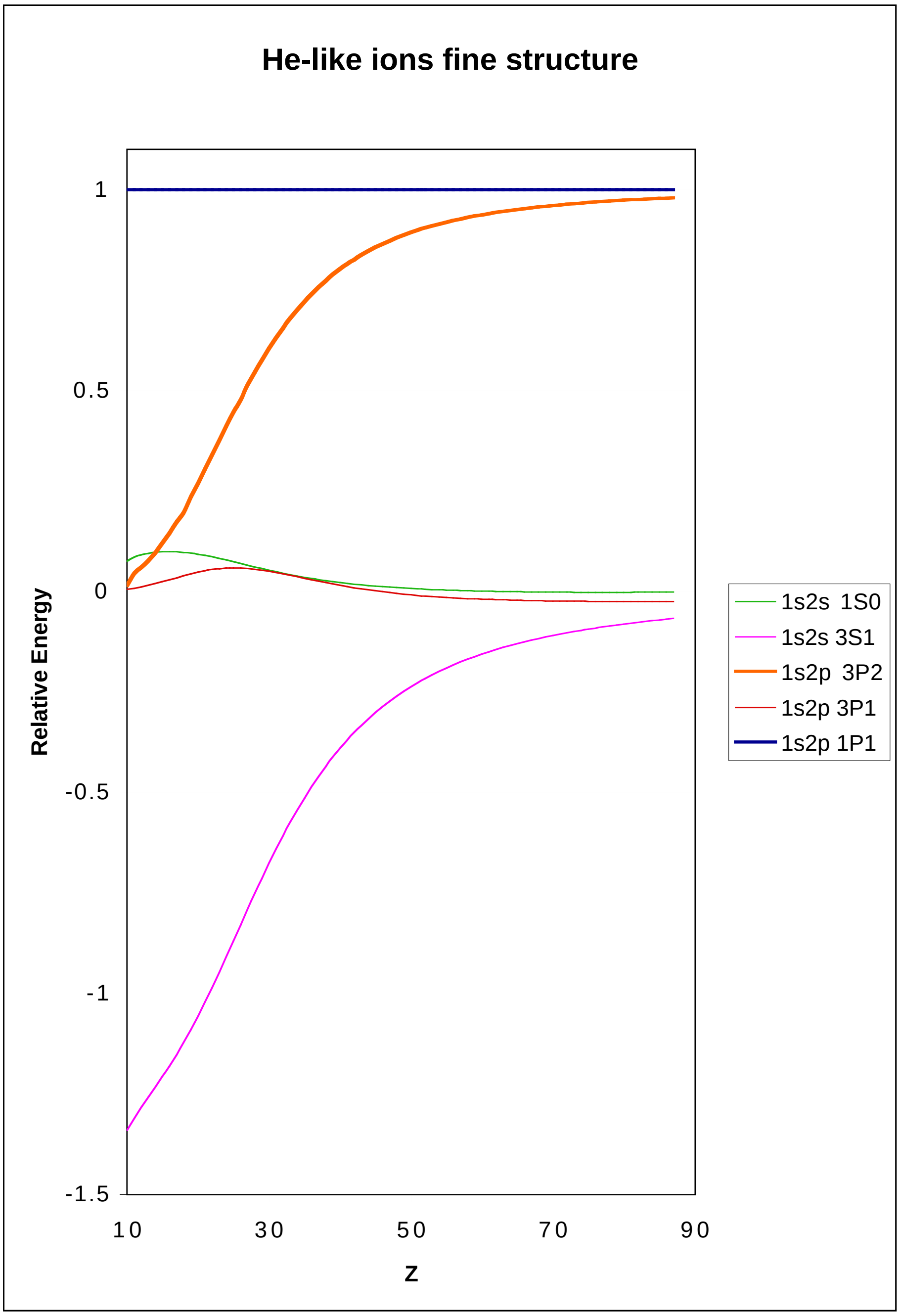
Why studying lifetimes in heavy ions?

1. Not sensitive to the same correlation contribution as energies (e.g., single excitations)
2. Not sensitive to the same part of the wave function (can be adjusted by choosing different multipoles)
3. Metastable levels can be very sensitive to weak perturbations ⇒ good tool to study energy differences that cannot be reached directly, nuclear magnetic moments, parity violation. . .
    - Measurement of 2s Lamb shift in H-like Ar by measurement of the $2s$ lifetime in an electric field (Marrus and Gould, 1974).
    - Measurement of $1s2p\,^3P_0 - 1s2p\,^3P_1$ separation when nuclear magnetic moment is known by Hyperfine Quenching.
    - Measurement nuclear magnetic moment assuming $1s2p\,^3P_0 - 1s2p\,^3P_1$ separation is known.
    - Negative energy continuum and other relativistic/QED effects

He-like fine structure

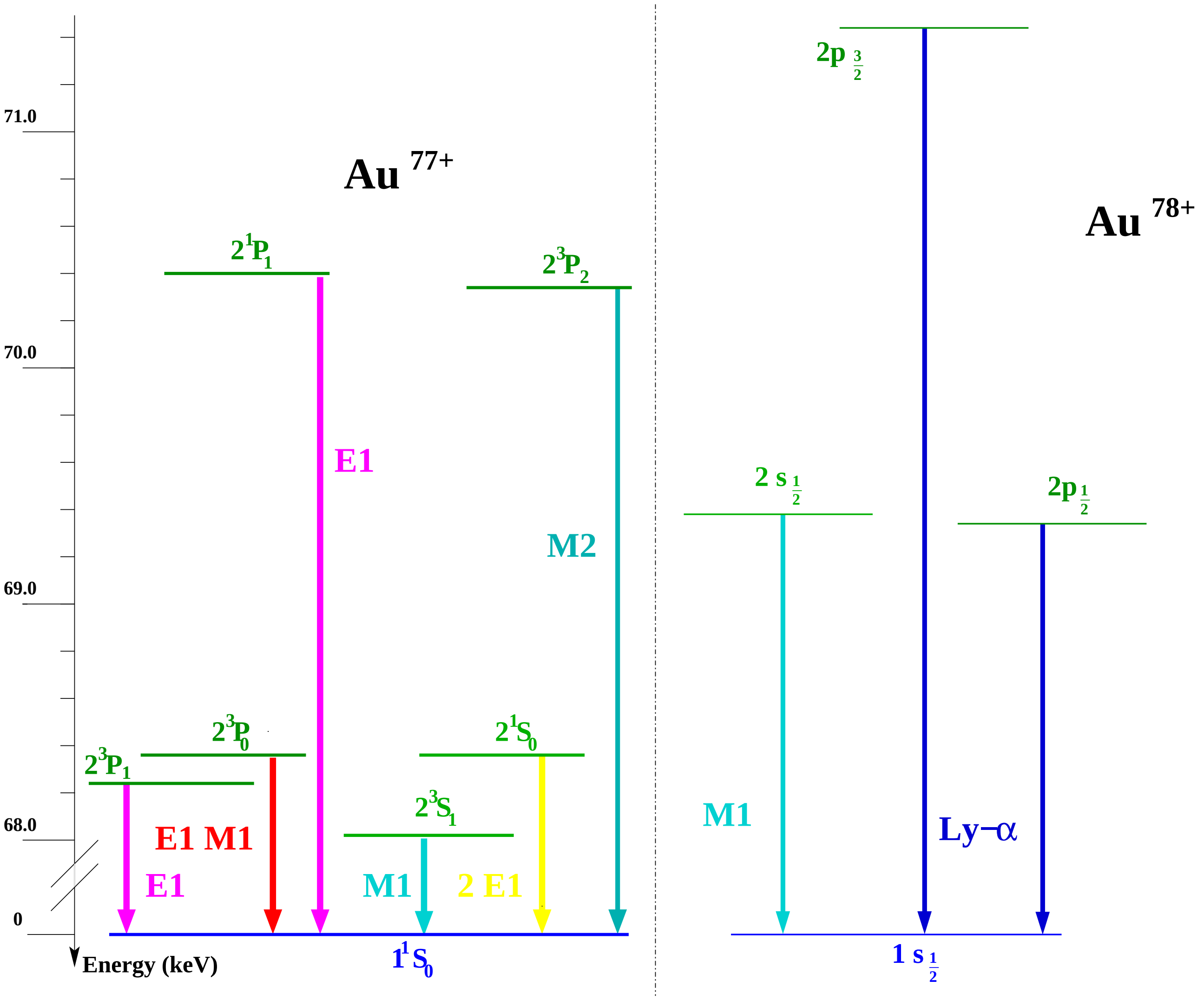
- The $n = 2$ fine structure of He-like ions is rich in accidental level crossing
- $1s2p\,^3P_0$ and $1s2p\,^3P_1$ cross at $Z = 3$ and $46 \le Z \le 47$.
- $1s2p\,^3P_0$ and $1s2s\,^1S_0$ cross at $Z \approx 69$ and $91 \le Z \le 93$



Relative position of $n = 2$ levels, normalized to $1s2p\,^3P_0 - 1s2p\,^1P_1$ separation, $1s2p\,^3P_0$ is at 0.

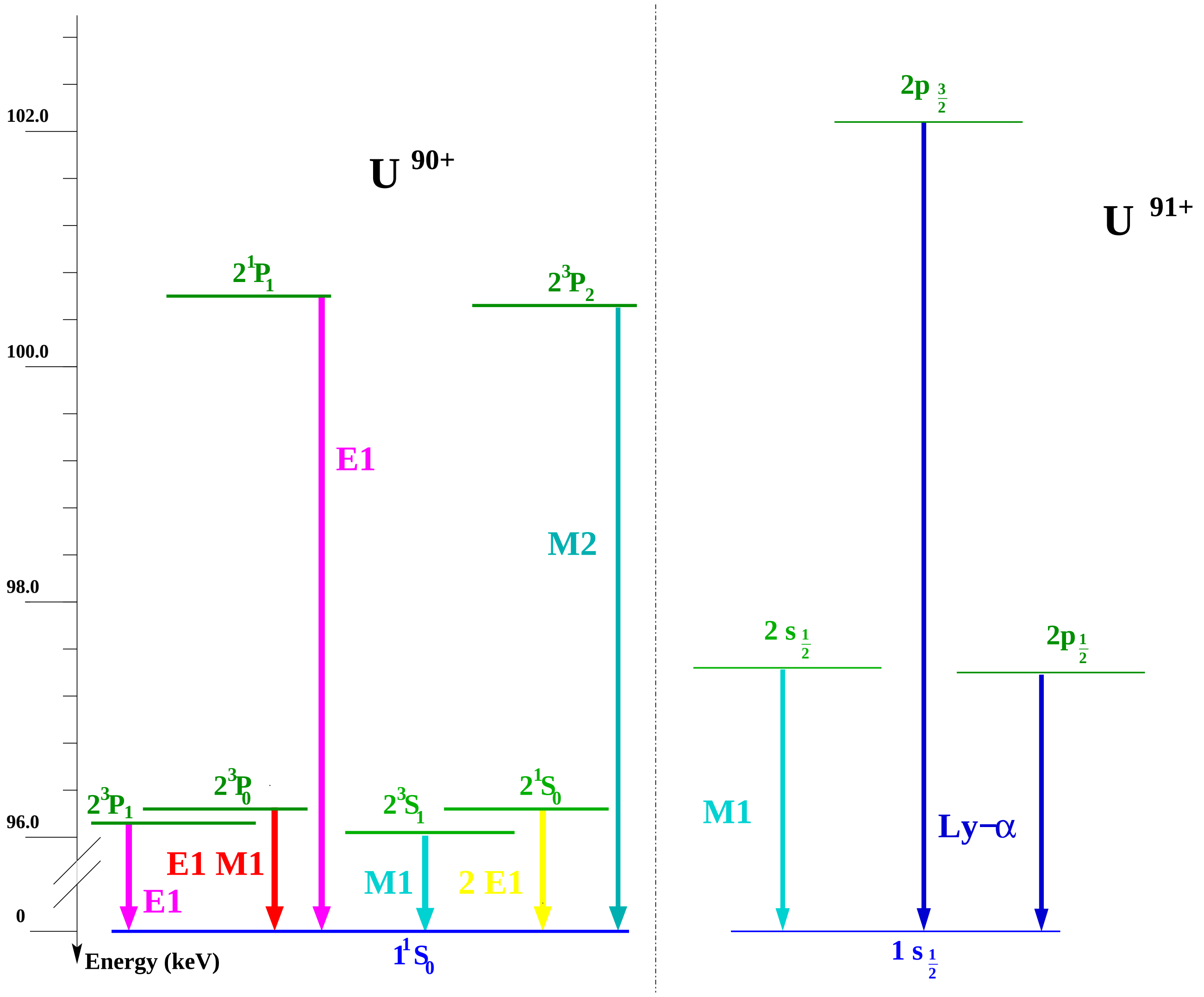
H-like and He-like ion level scheme at high-Z

- At high-Z the Helium-like and Hydrogen-like spectra overlap because fine structure is in $(Z\alpha)^4$ while He-like energy difference with H-like is $a_1 Z + a_2 + a_3/Z \cdots$.
- Coincidences are thus needed to improve signal-to-noise ratio and disentangle H-like and He-like lines



Level scheme for gold

H-like and He-like ion level scheme for Uranium

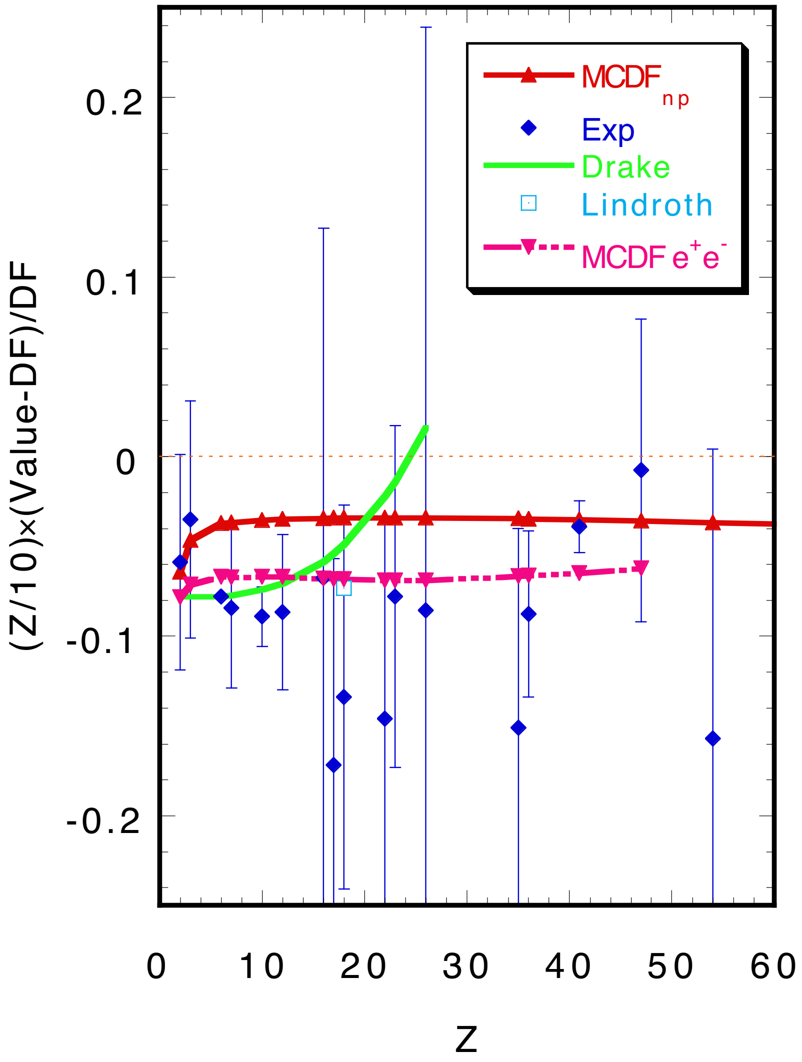


Level scheme for Uranium: note quasi-degeneracy of $1s2p\,^3P_0$ and $1s2s\,^1S_0$

Effect of the Negative energy continuum on the Relativistic M1 transition

The $1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$ transition is called the Relativistic M1 because it is strictly forbidden in a non-relativistic case.

When doing all-order calculations, such as Multi-Configuration Dirac-Fock, it has been found that the negative energy continuum plays a large role (Indelicato, 1996, Derevianko, 1999), including at low Z.



Comparison between theory and experiment for the $1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$ transition

Hyperfine Quenching

How does it work?

- Two nearby levels 0 and 1 of energy E_0 and E_1. Level 0 is metastable (*e.g.*, $1s2p\,^3P_0$ which cannot decay to the ground state because of the strictly forbidden $J = 0 \rightarrow J = 0$ transition, and can decay only by a weak E1 transition to $1s2s\,^3S_1$ or an even weaker E1M1 two-photon transition to the ground state).
- the two levels must be of the same parity

If the nucleus has a magnetic moment and a quadrupole moment:

- Coupling parameter: $W_{10} =< 0|H_{\mathrm{pert}}|1 >$.
- Using Breit-Wigner formula :

$$\begin{aligned}\Gamma_0 &= \frac{W_{10}^2\Gamma_1}{(\Delta E_{01})^2 + \Gamma_1^2} \\ &\approx \frac{W_{10}^2\Gamma_1}{(\Delta E_{01})^2}\end{aligned}$$

  when $\Gamma_1 \ll \Delta E_{01}$, *i.e.*, when one is far from crossing.
- Exact solution, necessary when $\Gamma_1 > \Delta E_{01}$, and Γ_0 is not negligibly small, is obtained by diagonalizing the effective perturbed Hamiltonian (Indelicato et al. 1989, Johnson et al, 1997).

$$H_{\mathrm{eff}} = \begin{pmatrix} E_0 + \frac{\mathrm{i}\Gamma_0}{2} & W_{10} \\ W_{10} & E_1 + \frac{\mathrm{i}\Gamma_1}{2} \end{pmatrix}$$

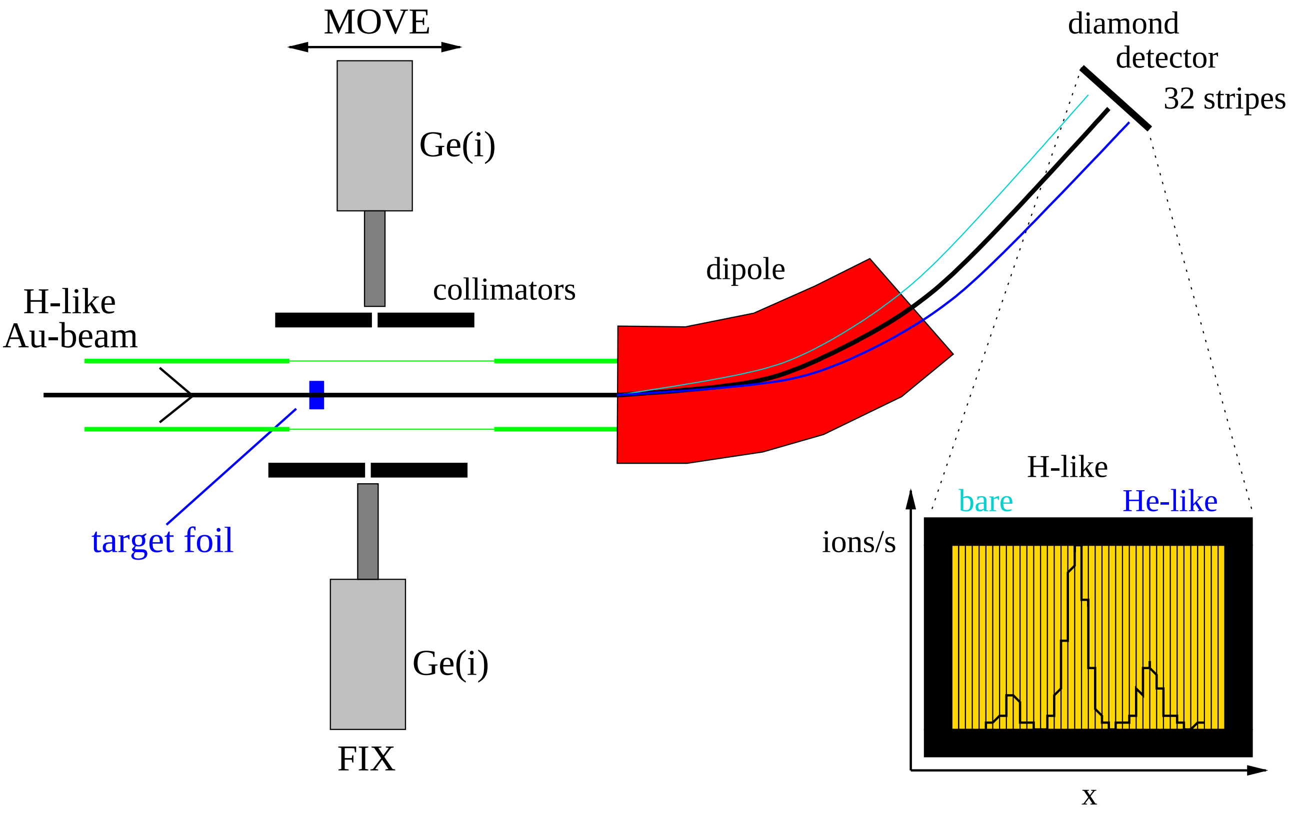
- At low-Z, $1s2p\,^1P_1$ and $1s2p\,^3P_2$ must be taken into account.

Applications of Hyperfine Quenching

- Knowing the nuclear magnetic moment and assuming atomic lifetime calculations are not too sensitive to correlation one can extract ΔE_{01} even when $\Delta E_{01} \leq \Gamma_1$ (Ag^{45+}), *i.e.*, the levels cannot be separated in spectroscopy.
- Assuming all atomic structure calculations are accurate, one can measure nuclear magnetic moments of radioactive nuclei or of long-lived nuclear excited states.
- A case has been found in which one could measure nuclear quadrupole moments
- Uncertainty on either ΔE_{01} or nuclear magnetic moments, because they appear squared, is two times better than on the lifetime measurement, and can reach $\approx 1\%$.

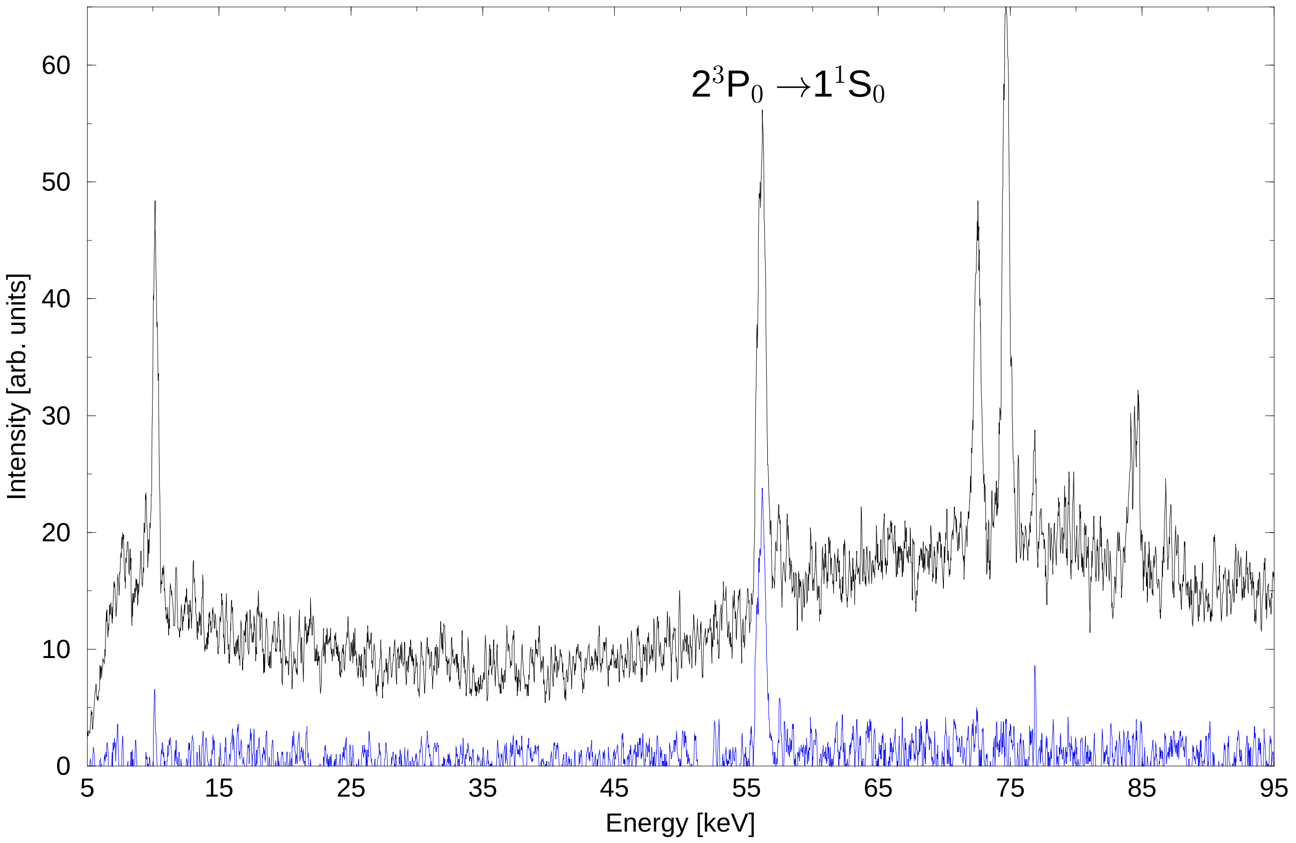
The experimental Set-Up

- At high-Z the Helium-like and Hydrogen-like spectra overlap.
- Coincidence are needed to improve signal-to-noise ratio and disentangle H-like and He-like lines, when close to the foil



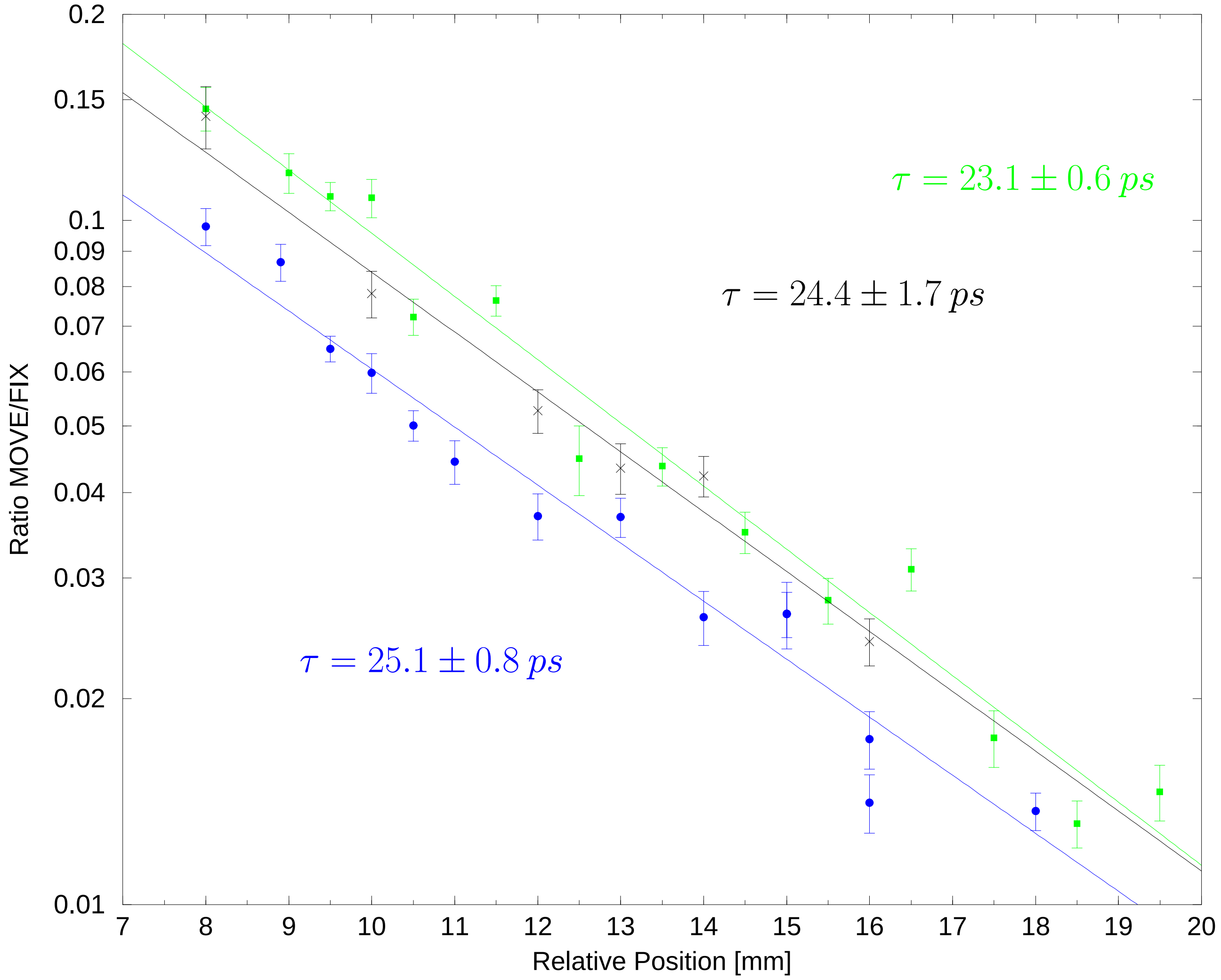
Time-of-flight measurement of a Lifetime in coincidence with outgoing-ion charge state

Experimental spectrum



Effect of the coincidence

Results



Experimental Decay Curves (Preliminary)

- Single spectra decay curves
- Movable detector (Normalization) at 6.5 mm from target
- Movable detector (Normalization) at 8.5 mm from target

Comparison with experiment

Johnson et al (1999) Bohr-Weisskopf	23.04
Indelicato (2001) no Bohr-Weisskopf	22.61
Indelicato (2001) Bohr-Weisskopf	23.35
Experiment (prelim), averaged	$23.82(50)$

Theoretical results (ps)

Z	Exp.	Err.	Err. (%)	Th. (Johnson)	Th. (Indelicato)
28	2.40	0.17	7.1	2.32	2.34
47	-0.82	0.04	4.9	-0.80	-0.74
64	-18.44	0.19	1.0	-18.57	-18.42
79	-54.27	0.65	1.2	-53.89	-53.54

Comparison of ΔE_{01}

Measuring magnetic moment of excited or radioactive nuclei with H-like ion ground state hyperfine splitting

Labzowsky, Nefiodov, Plunien, Soff and Liesen, PRL **84** 851 (2000)

- Direct measurements of the ground state hyperfine splitting is difficult (strong signal (10^5 to 1) from the ions with nuclei in the ground state) and requires high-resolution spectrometers)
- Observation of the $2p - 1s$ transition energy at 97 keV to a fraction of 1 eV is needed (present best is 13 eV).
- To get a 10% measurement of the magnetic moment requires a 0.07 eV measurement of the ground state HFS
- Laser measurement? uncertainty in the calculation and magnetic moment is so large it would be difficult to find the line

Unpert.	0.8968
Self-energy (Persson et al.)	-0.0123
Vac. Pol. corr	0.0054
Bohr-Weisskopf	-0.0267
Total	0.8632
Labzowsky et al.	0.72

Ground state HFS splitting of H-like U assuming $g = \frac{Z}{A}$ for 2^+ level (eV)

Measuring properties of excited or radioactive nuclei with hyperfine quenching

Labzowsky, Nefiodov, Plunien, Soff and Liesen, PRL **84** 851 (2000)
Marrus, Indelicato et al. Letter of intent at SPIRAL (Ganil) 1997

- Hyperfine quenching changes dramatically the lifetime of the $1s2p\,^3P_0$ of the excited nuclei ion.
- If in a reasonable range does not require *a priori* knowledge of the magnetic moment.
- Valid for any radioactive beam

Method	Lifetime (ps)	decay length (mm)
Labzowsky et al. (2000) no Bohr-Weisskopf H-like orbitals, Γ_0 neglected	0.67	0.18
Indelicato (2001) Unperturbed	57.58	15.47
Indelicato (2001) no Bohr-Weisskopf	2.22	0.60
Indelicato (2001) Bohr-Weisskopf	2.36	0.67

Theoretical results assuming $g = \frac{Z}{A}$ for 2^+ level of ^{238}U and a beam velocity $0.67c$

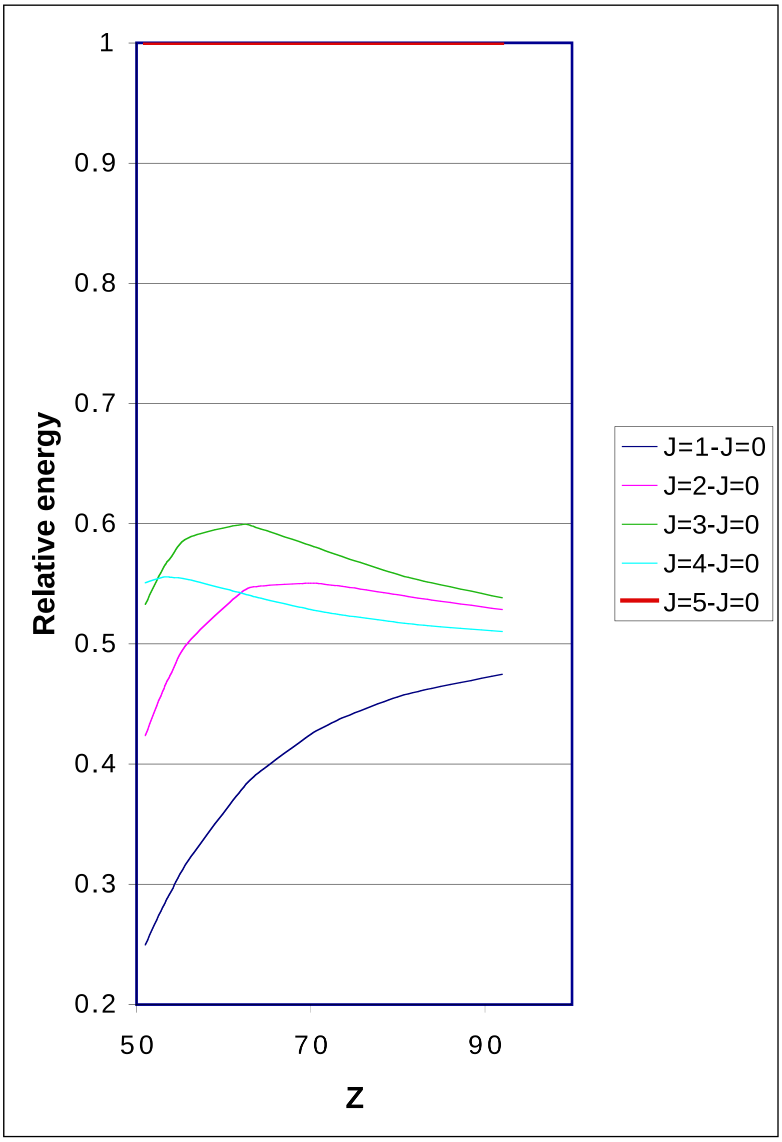
New calculation:

Full Breit self-consistent treatment, Vacuum polarization correction to lifetimes and HFS matrix elements, Fully correlated energies, uncorrelated matrix elements.

An unusual case of Hyperfine Quenching

The titanium-like $3d^4\ J = 3 \rightarrow 3d^4\ J = 2$ transition has an energy in the optical domain up to U^{70+}

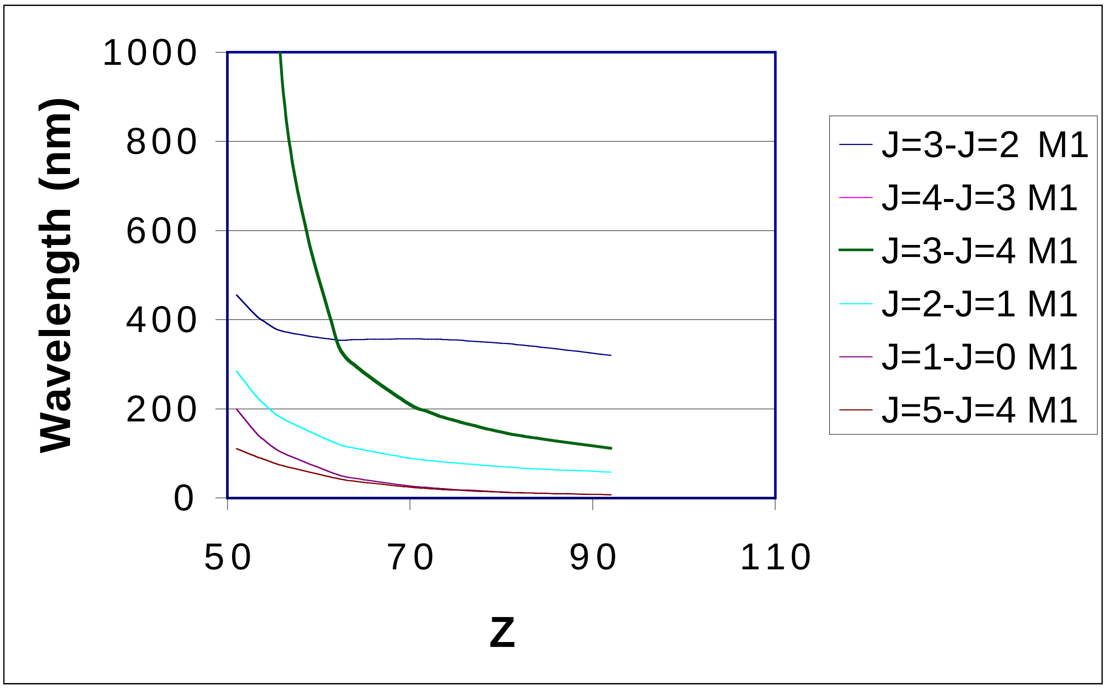
(Feldman, Sugar, Indelicato, 1990)



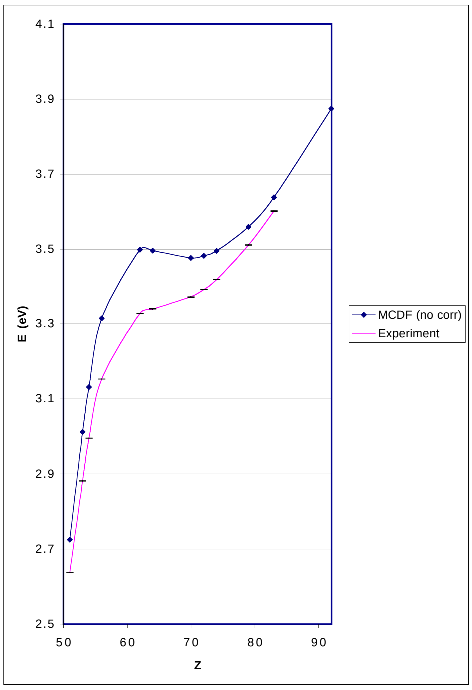
Level crossing in high-Z Ti-like ions. Normal ordering should be $J = 0$, 1, 2, 3, 4, 5

Level crossing leads to a strong hyperfine quenching where the coupling with the stronger transition occurs through the electric-quadrupole term (Parente, Marques, Indelicato, 1994)

An unusual case of Hyperfine Quenching II

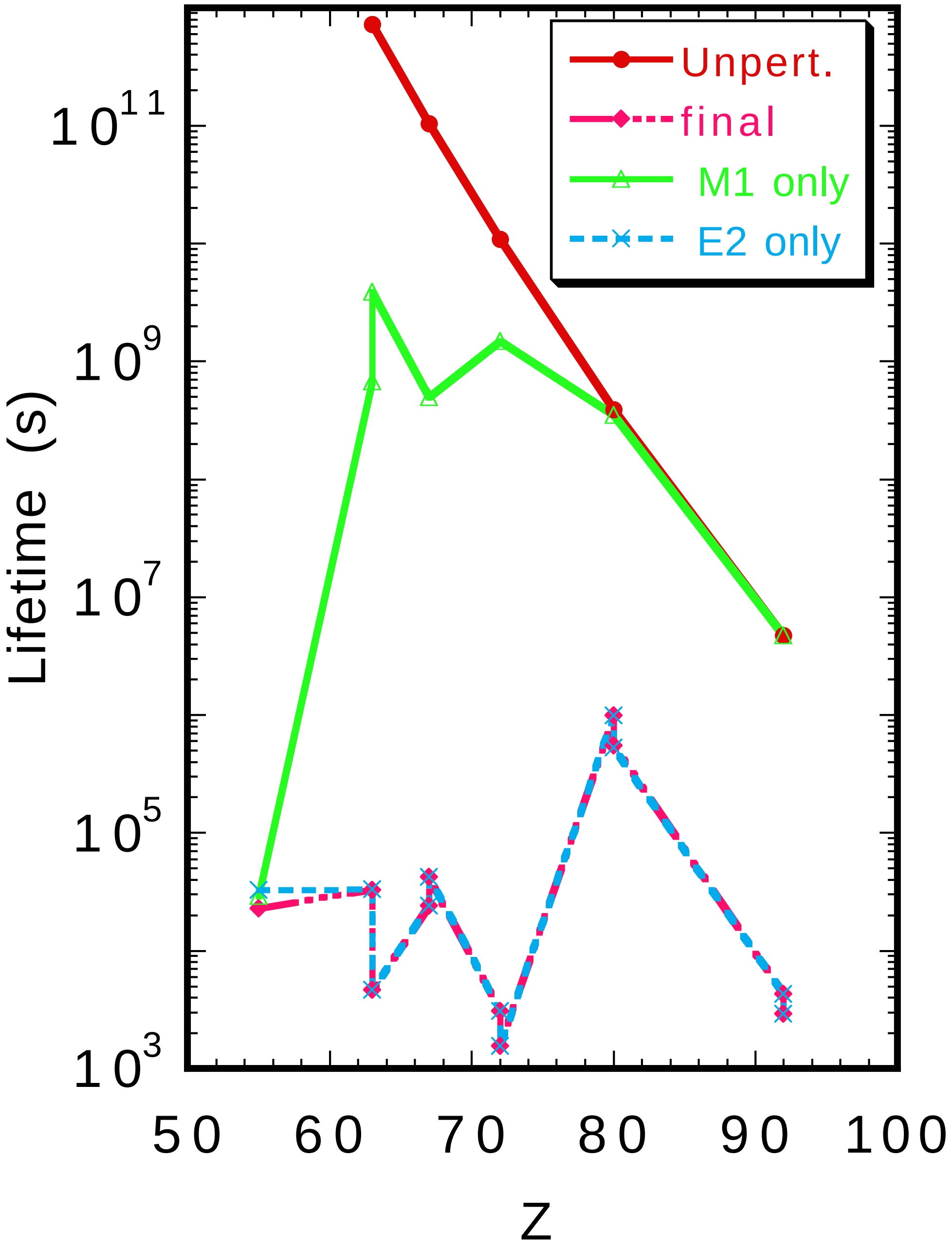


The M1 transitions wavelength in Ti-like ions



Comparison with MCDF calculation no correlation and experiments

An unusual case of Hyperfine Quenching III



Comparison of the effect of magnetic dipole and electric quadrupole hyperfine quenching on the $3d^4\ J = 4$ lifetime

Conclusion

- Lifetimes provide good tests of QED and relativistic effects
- Lifetimes provide good tests of correlation
- Hyperfine quenching offers good opportunities to study hard to reach atomic level separations
- Hyperfine quenching offers good opportunities to measure nuclear parameters including for radio-active ions
- He-like Gold has been studied and provides an accurate measurement of the $1s2p\,^3P_0 - 1s2p\,^3P_1$ energy splitting
- Highly charged ions can have transition in the visible and/or almost infinite lifetimes
- Longer lifetimes may require the use of traps