Storage-ring measurements of hyperfine-induced and two-photon transition rates in berylliumlike ions

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Outline

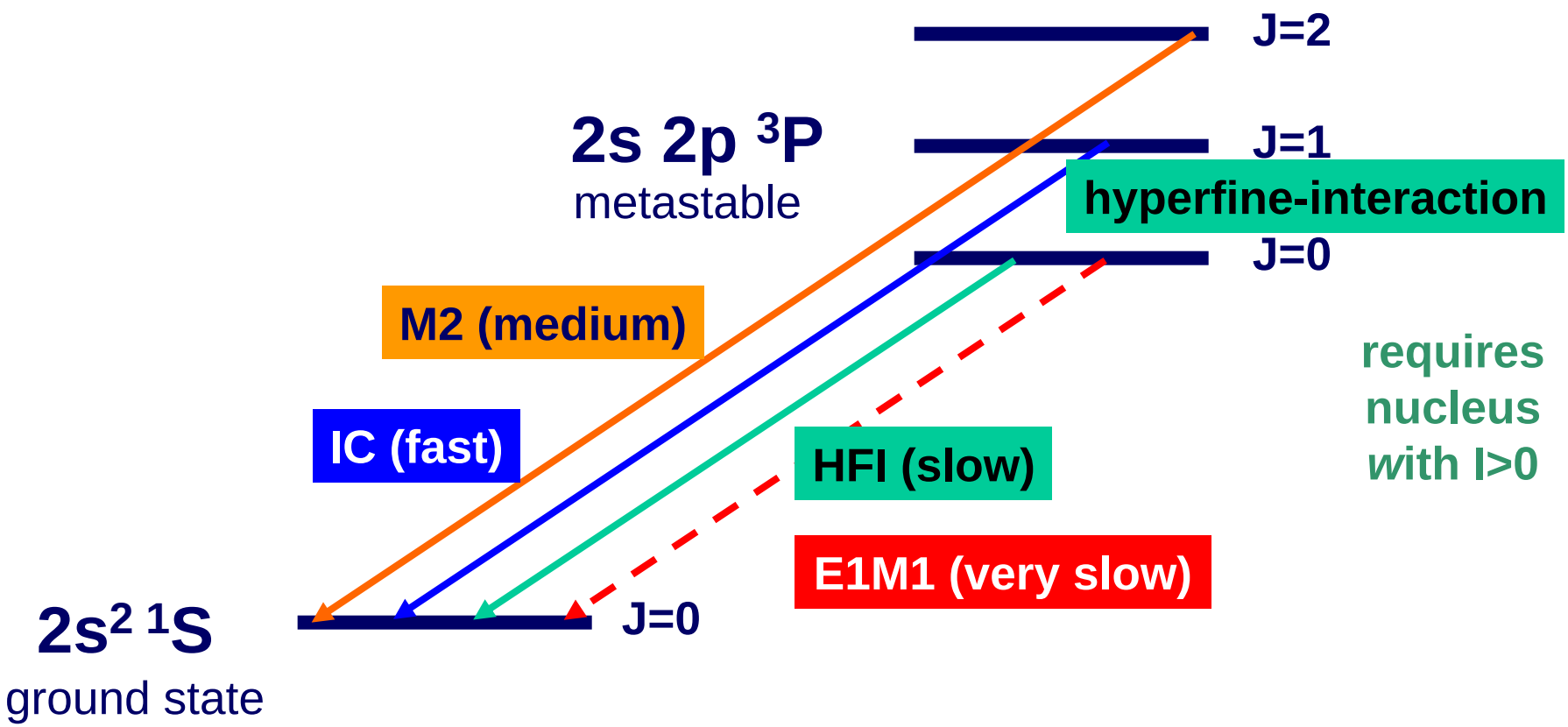
1. **Motivation**
   - hyperfine quenching of ns np $^3P_0$ states in divalent atoms and ions
   - theoretical and experimental results
   - some applications

2. **Experiments at heavy-ion storage rings**
   - lifetime measurements
   - electron-ion recombination

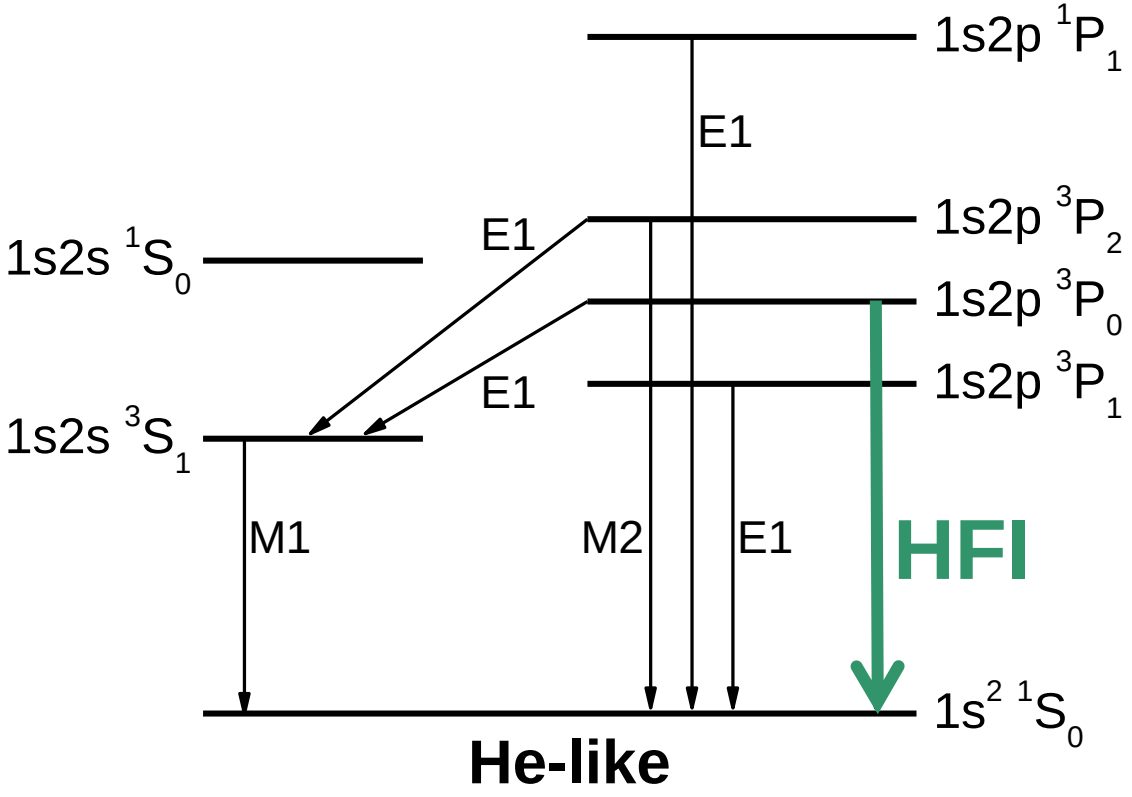
3. **Hyperfine induced $^3P_0 \rightarrow {}^1S_0$ transition rate**
   - results for $^{47}Ti^{18+}$
   - results for $^{33}S^{12+}$

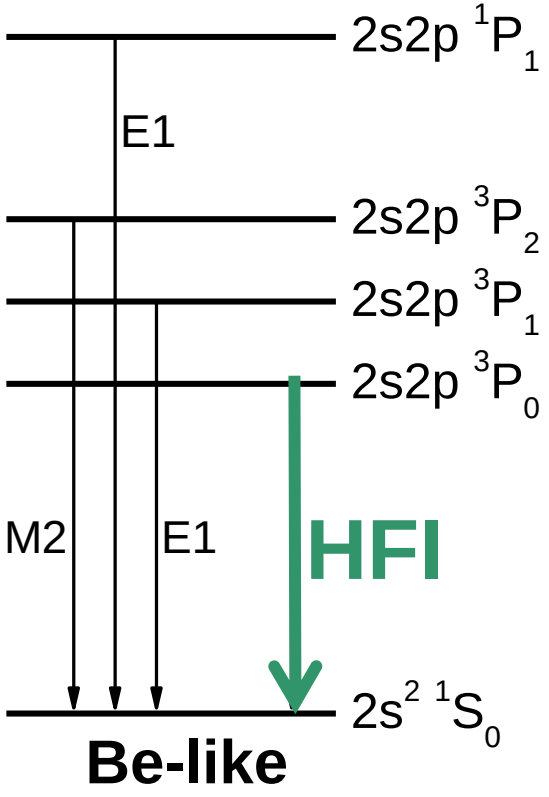
4. **E1M1 two-photon $^3P_0 \rightarrow {}^1S_0$ transition rate**
   - results for $^{136}Xe^{50+}$

2s2p ^{3}P – 2s^2 ^{1}S transitions in Be-like ions



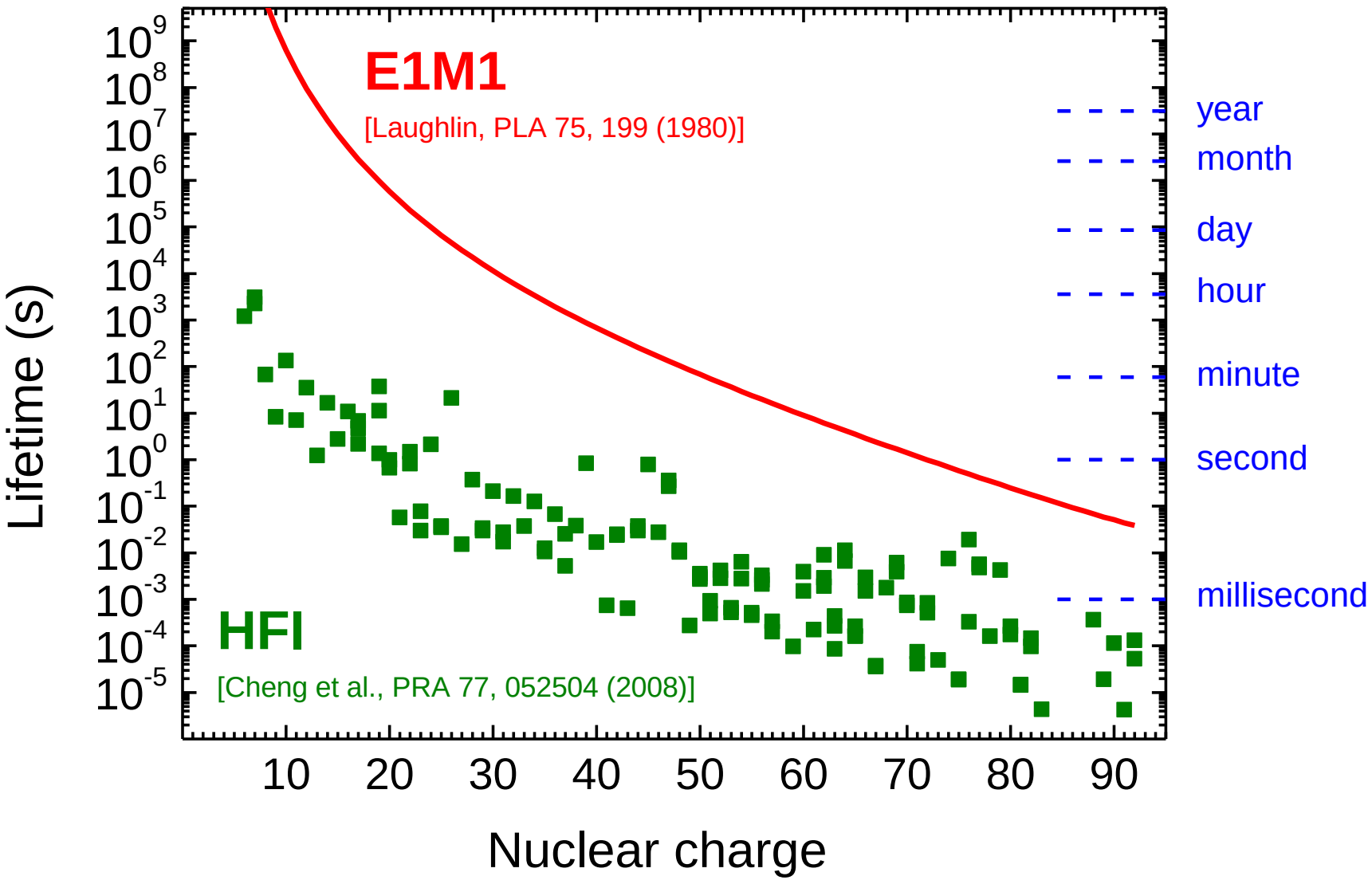
He-like vs. Be-like ions





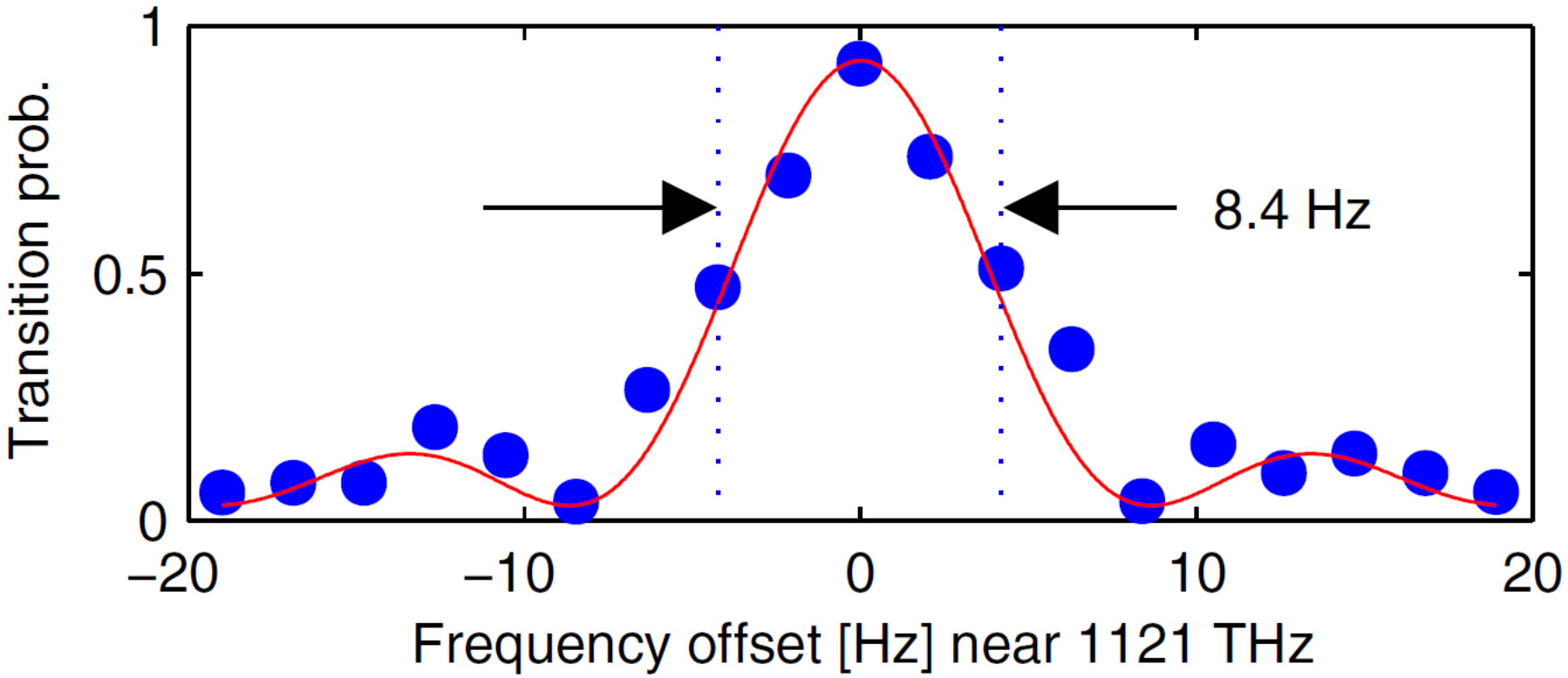
Review: W. Johnson, Can. J. Phys. **89** (2011) 429

Theoretical predictions of 2s2p $^3P_0$ lifetimes



Ultraprecise optical clocks

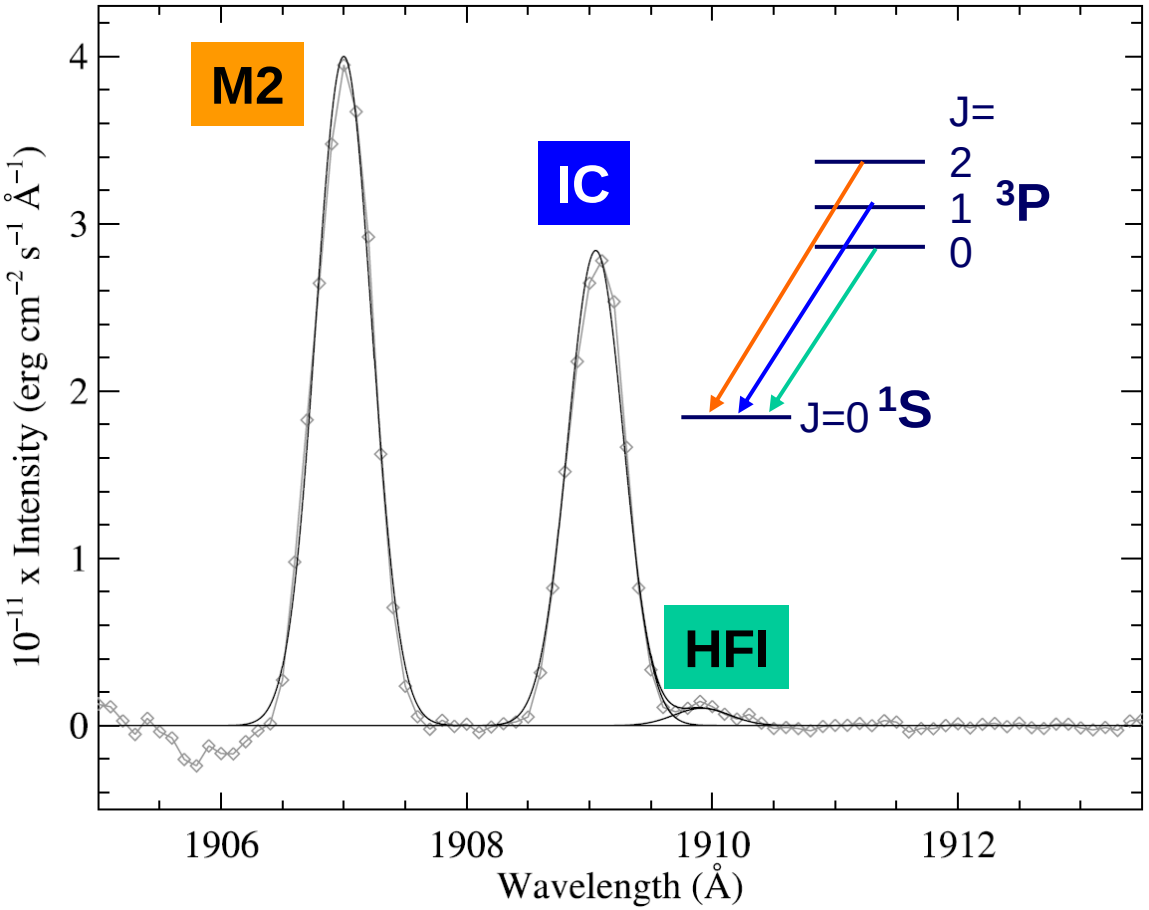
Al^+ clock transition: $3s\,3p\ ^3P_0 \rightarrow 3s^2\ ^1S_0$

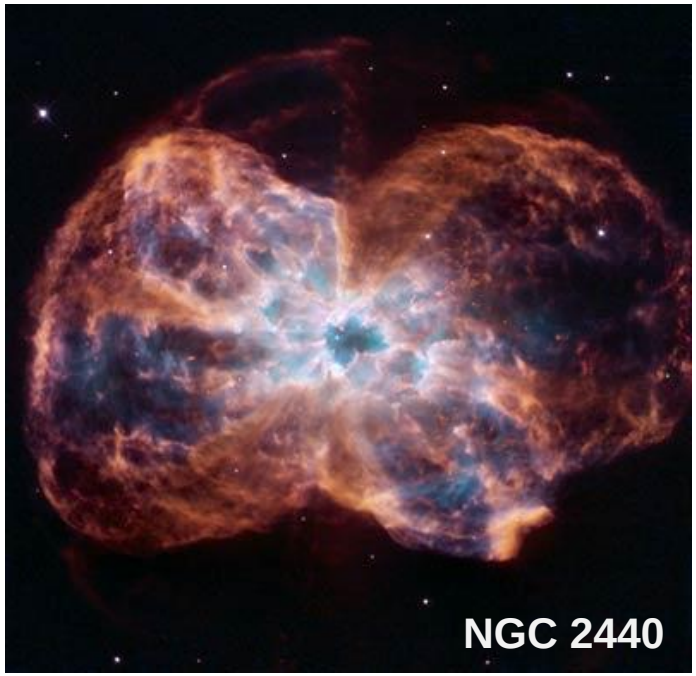


T. Rosenband et al., PRL 98 (2007) 220801

$^{13}C/^{12}C$ abundance ratio in planetary nebulae

shedding light on stellar nucleosynthesis

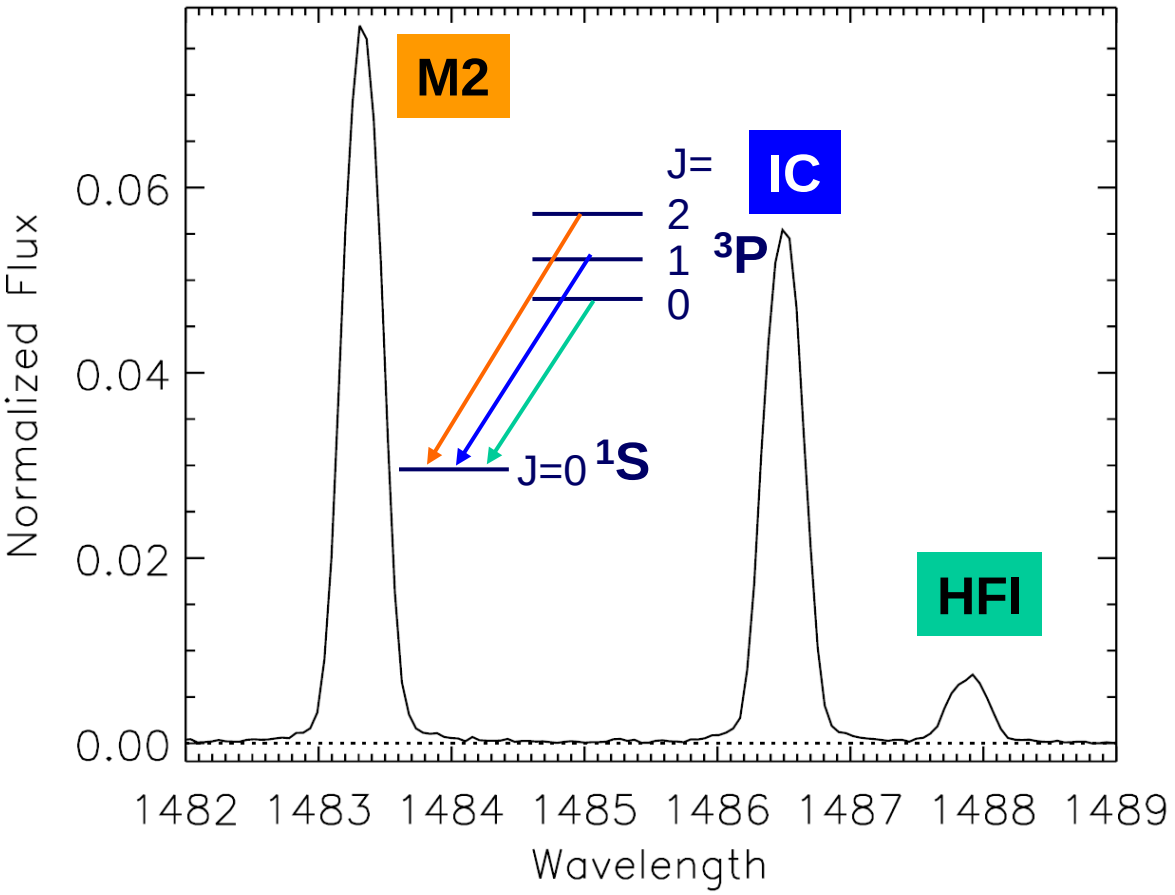




R. H. Rubin et al., ApJ 605 (2004) 784

„Experimental“ HFI lifetime from a planetary nebula

beryllium-like nitrogen
in the planetary nebula NGC 3918



istope A=14
rel. abundance 99.63%
nuclear spin I=1

2s2p $^3P_0$ lifetime:

from astrophysical observation and modeling:
2500±800 s

theory:
Brage et al. 2033 s
Marques et al. 7806 s

T. Brage et al., PRL 89 (2002) 281101

The challenge

measurement of an extremely long lifetime

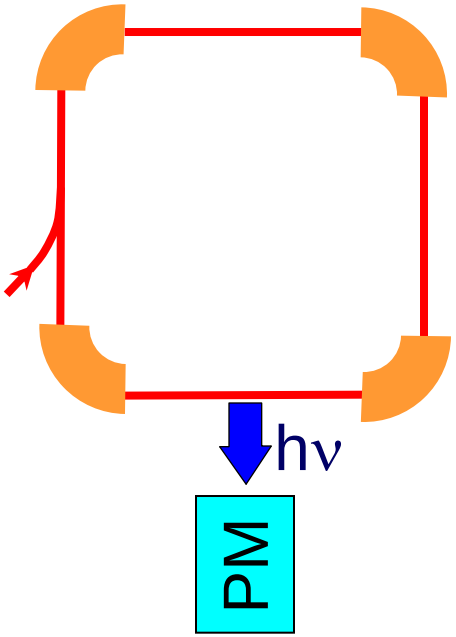
prediction for the $^{47}Ti^{18+}(2s2p\ ^3P_0)$ state: τ = 2.8 s

theory by Marques et al., PRA 47 (1993) 929

needs well defined environment without significant disturbance of the long-lived state

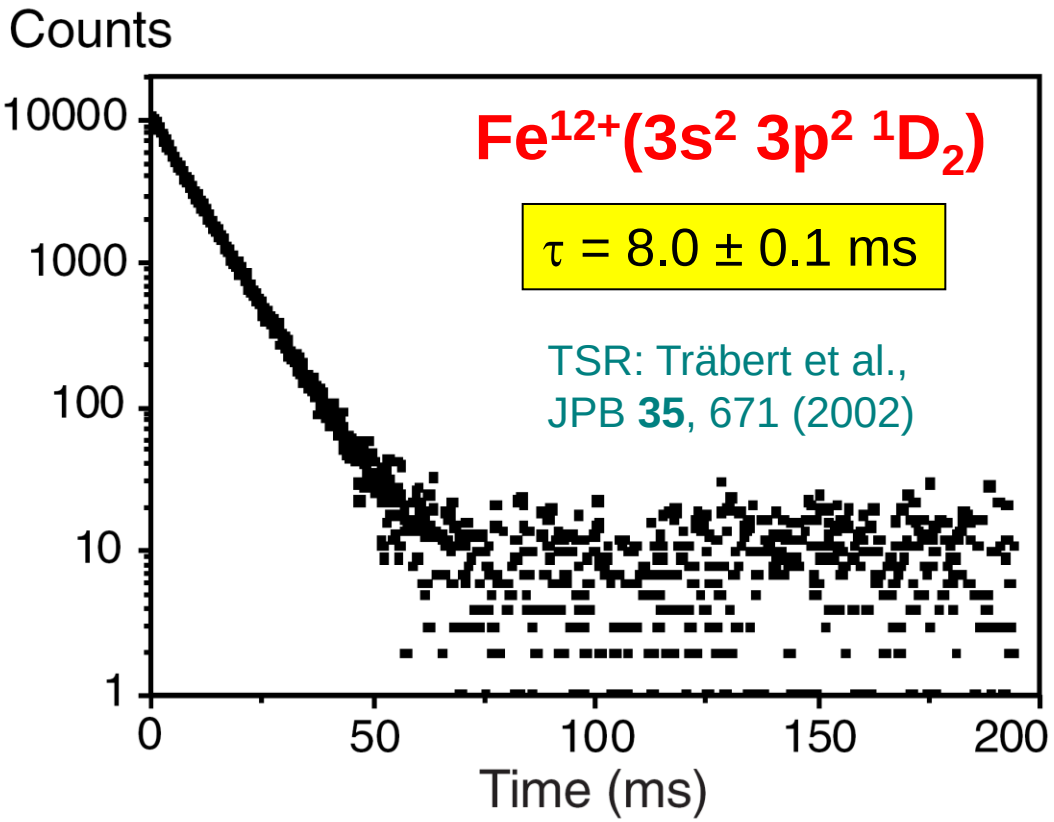
The Heidelberg TSR storage ring at MPIK

Decay of excited states



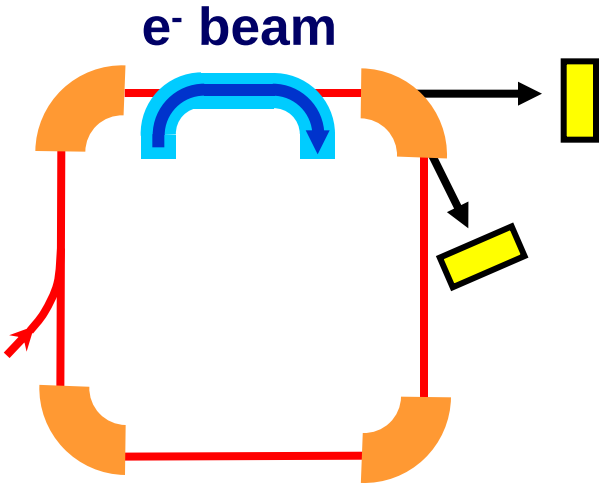
Most photons miss the detector!

Injection of ions in metastable states



Electron-ion recombination experiments

$$A^{q+} + e^- \rightarrow A^{(q-1)+} + \text{photons}$$



Reaction products

- beams of high directionality
- high particle energies in lab frame

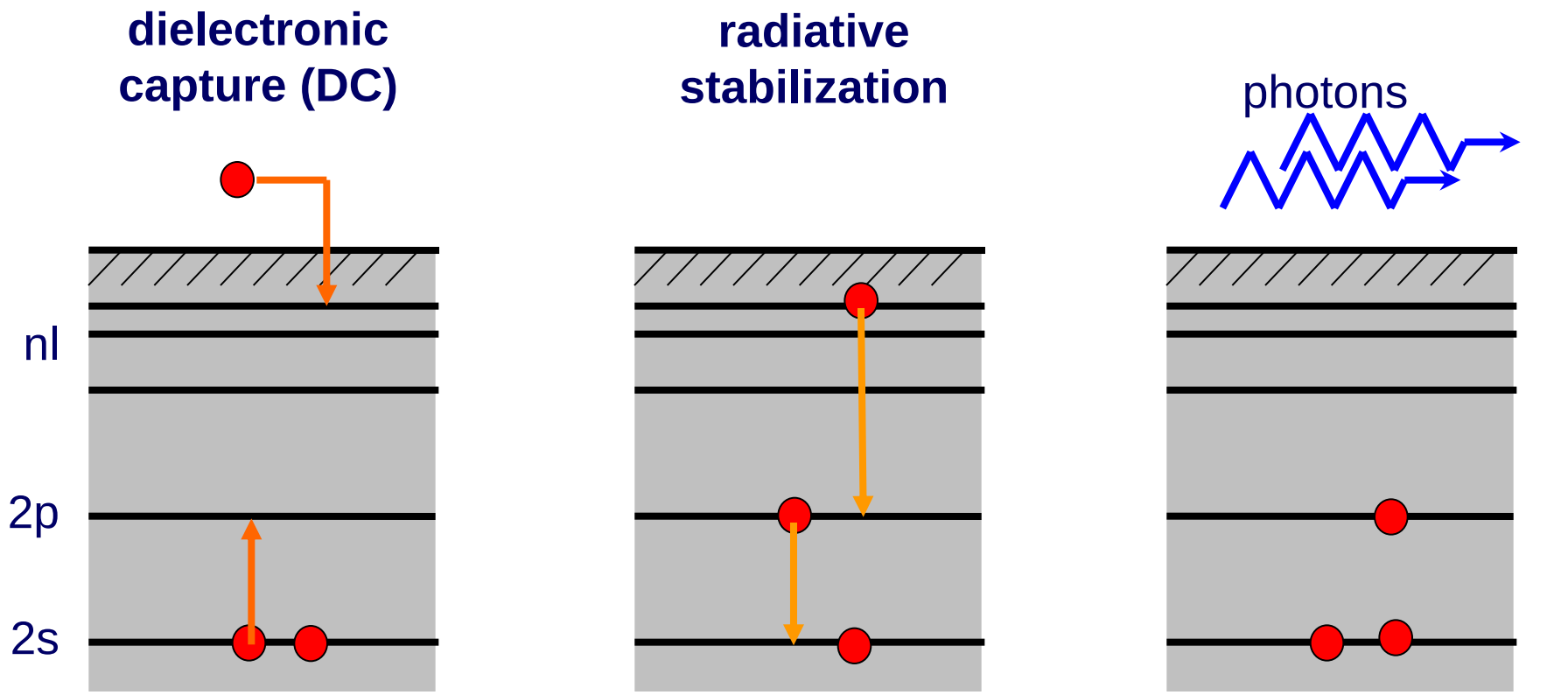
100% detection efficiency

collision experiments with dilute ensembles of particles

tunable relative energy: sub **meV** to sub **MeV**

Dielectronic recombination (DR)

- viewed as a two-step process -



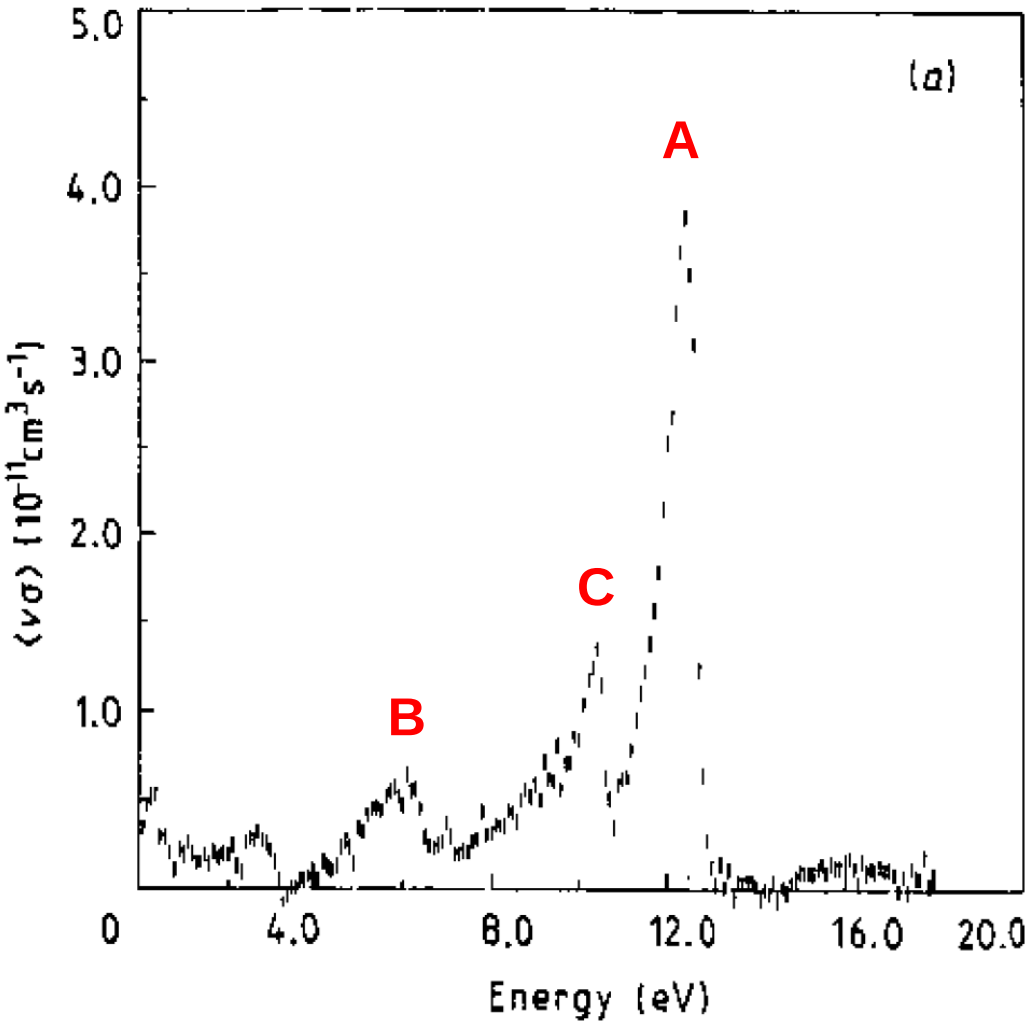
$$Ti^{18+}(2s^2) + e^- \longrightarrow Ti^{17+}(2s\ 2p\ nl) \longrightarrow Ti^{17+}(2s^2\ 2p) + h\nu$$

Measuring the $^3P_0$ lifetime using DR as a tool

Idea:

- **stored Be-like ion beam contains a $^3P_0$ fraction, if $^3P_0$ lifetime is sufficiently long (> 1ms)**
- **2s 2p $^3P_0$ excitation produces distinct DR (e.g. $2p^2$ nl) resonances**
- **measure the „apparent“ DR resonance strength as a function of storage time**
- **deduce $^3P_0$ lifetime**

DR of Be-like C^{2+}
- single-pass merged-beams experiment -



mixture
of 75% $2s\,2p\ ^3P$
and 25% $2s^2\ ^1S$
in the ion beam

Resonances of the types

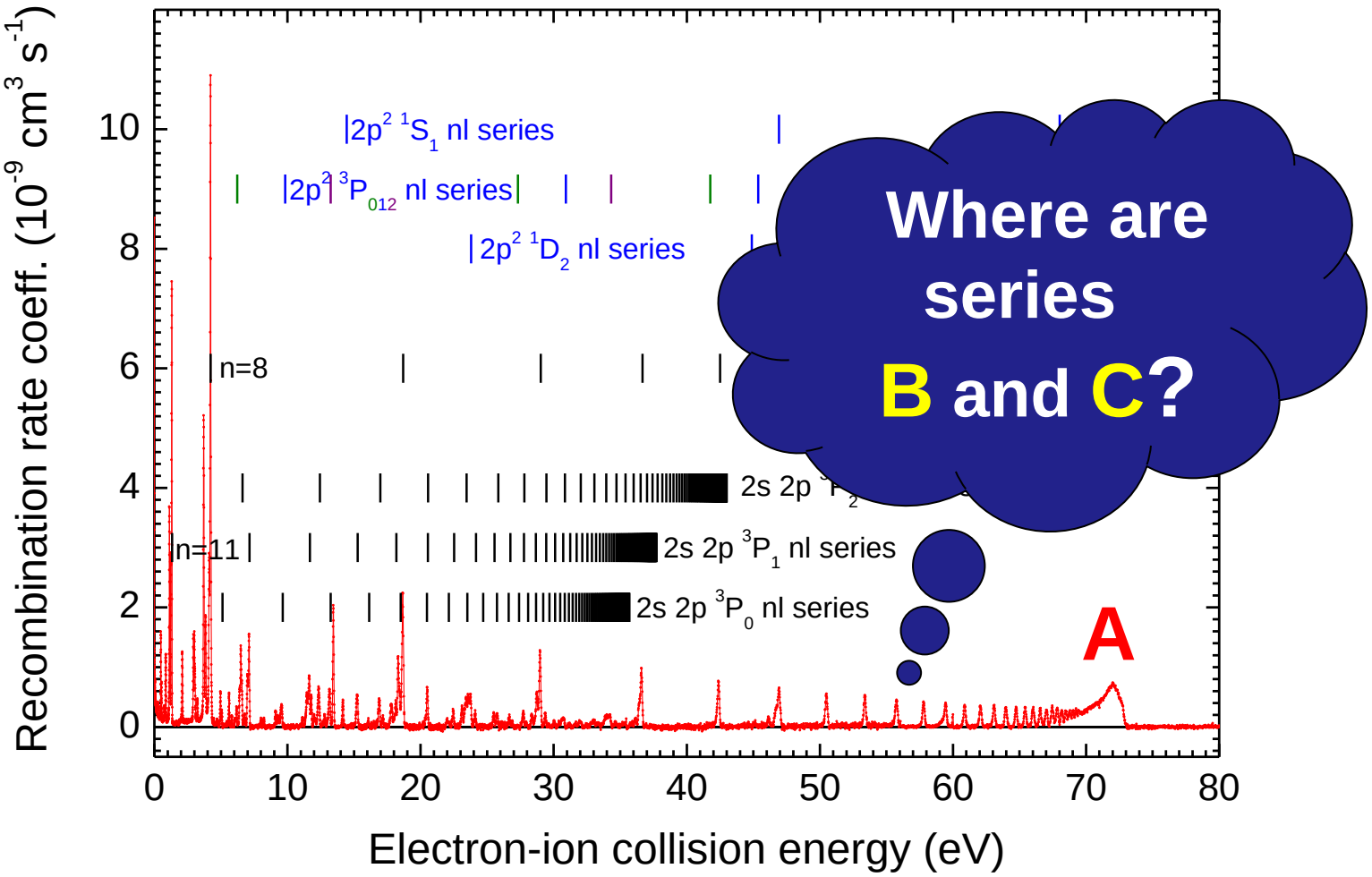
A: $2s^2\ ^1S \rightarrow 2s\,2p\ ^1P\ nl$

B: $2s\,2p\ ^3P \rightarrow 2s\,2p\ ^1P\ nl$

C: $2s\,2p\ ^3P \rightarrow 2p^2\ ^3P\ nl$

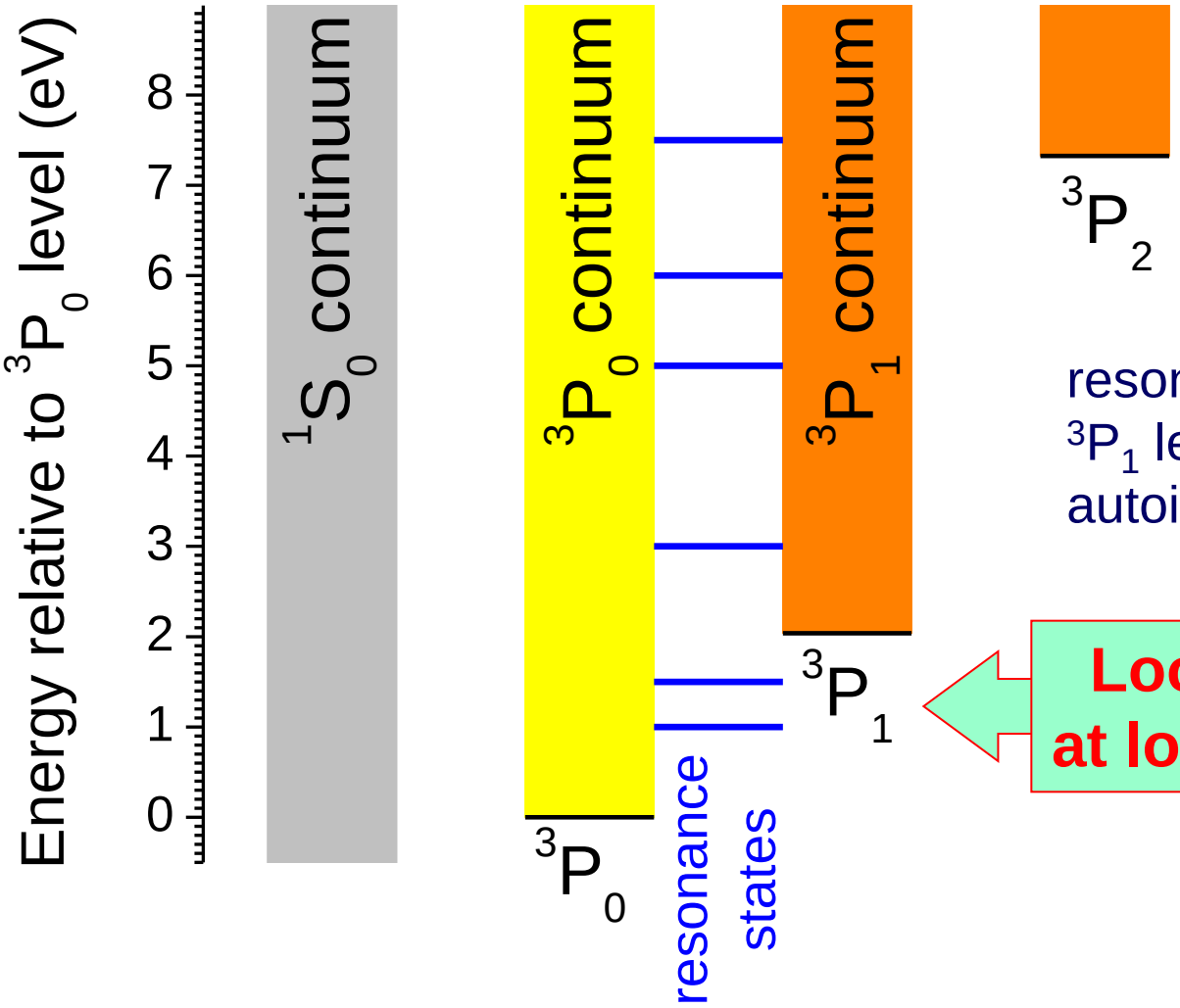
N. R. Badnell et al., J. Phys. B 24 (1991) 4441

DR spectrum of Be-like $^{48}Ti^{18+}$



S. Schippers et al., JPCS 58 (2007) 137

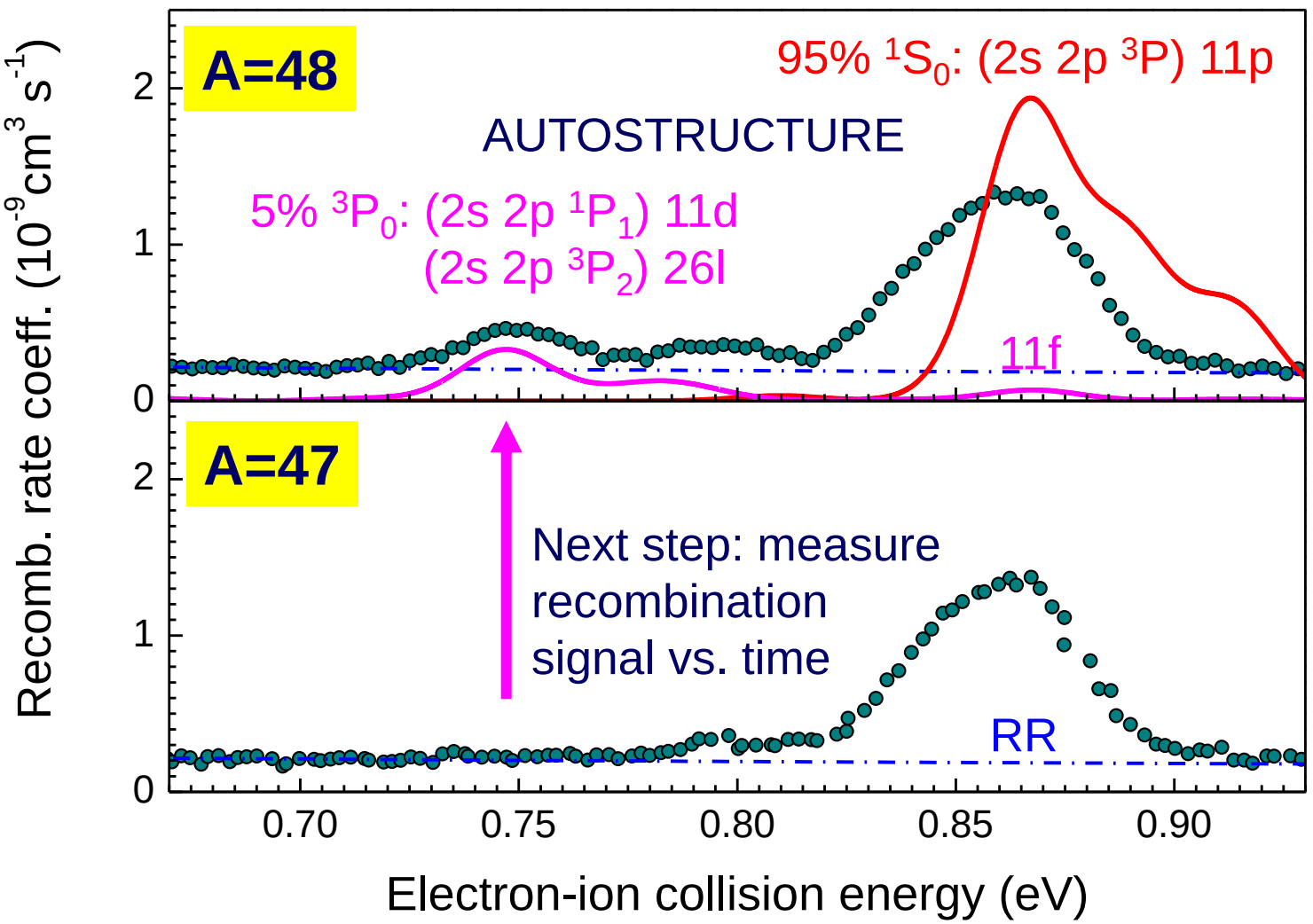
Why are $^3P_0$ resonances missing?



resonance states above the $^3P_1$ level have an additional autoionization decay channel

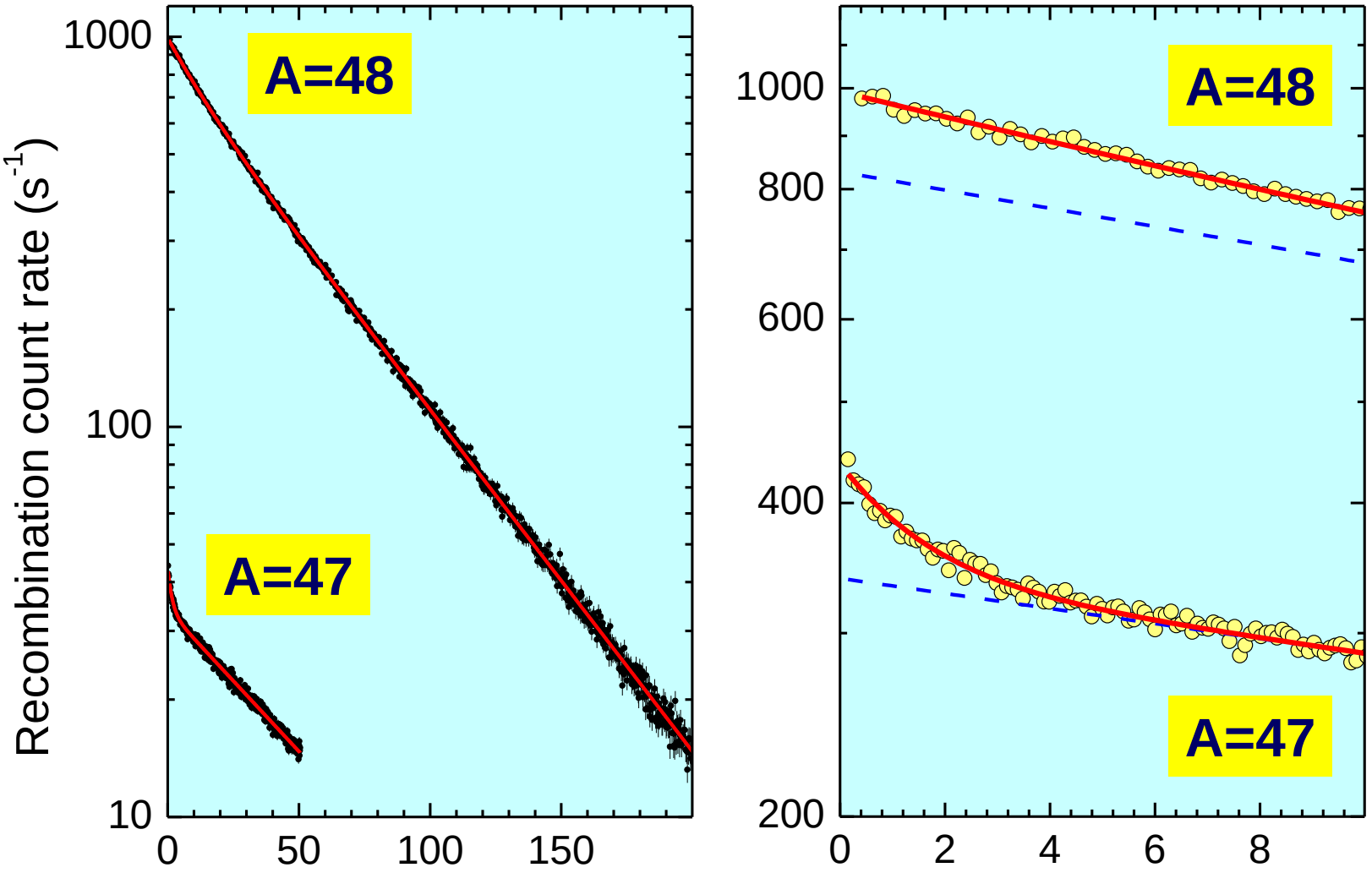
Look for resonances at low relative energies!

Ti^{18+} DR spectrum at low energies



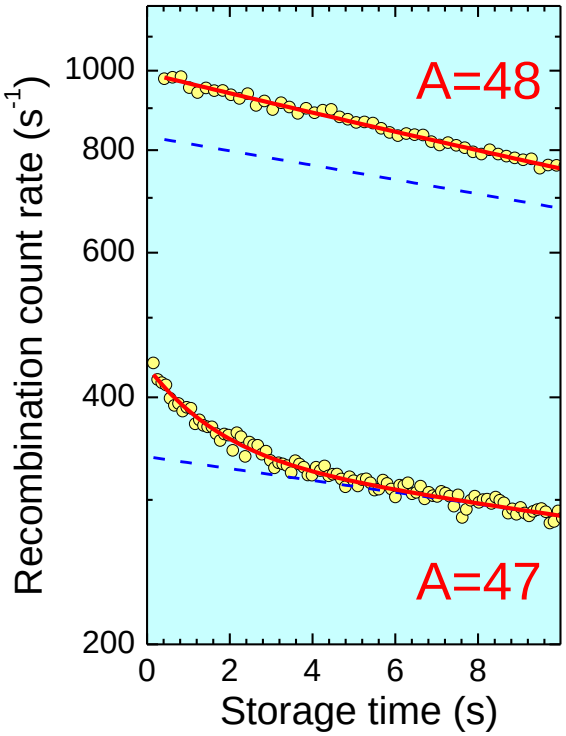
S. Schippers et al., JPCS 58 (2007) 137

Recombination signal at 0.75 eV vs. time



S. Schippers et al.,
PRL 98 (2007) 033001

Data analysis



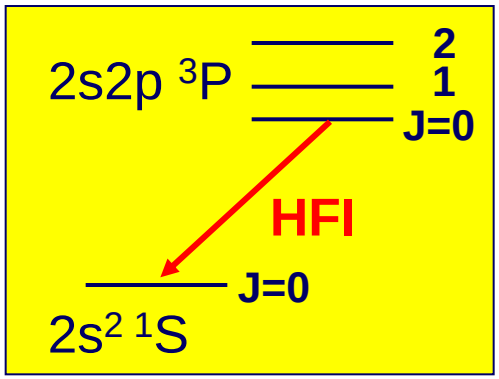
essential feature of the method
usage of two isotopes

Fit: $F^{(\mathrm{A})}(t) = c_m^{(\mathrm{A})} e^{-\lambda_m^{(\mathrm{A})} t} + c_g^{(\mathrm{A})} e^{-\lambda_g^{(\mathrm{A})} t}$

m = $^3P_0$
g = $^1S_0$

isotope	$\lambda_m^{(\mathrm{A})}$ (s^{-1})	$\lambda_g^{(\mathrm{A})}$ (s^{-1})	$c_m^{(\mathrm{A})}$ (s^{-1})	$c_g^{(\mathrm{A})}$ (s^{-1})
$A = 48$	0.070(2)	0.0202(5)	161(35)	831(48)
$A = 47$	0.62(3)	0.01665(6)	9.8(3)	33.86(6)

largest contribution to the experimental uncertainty



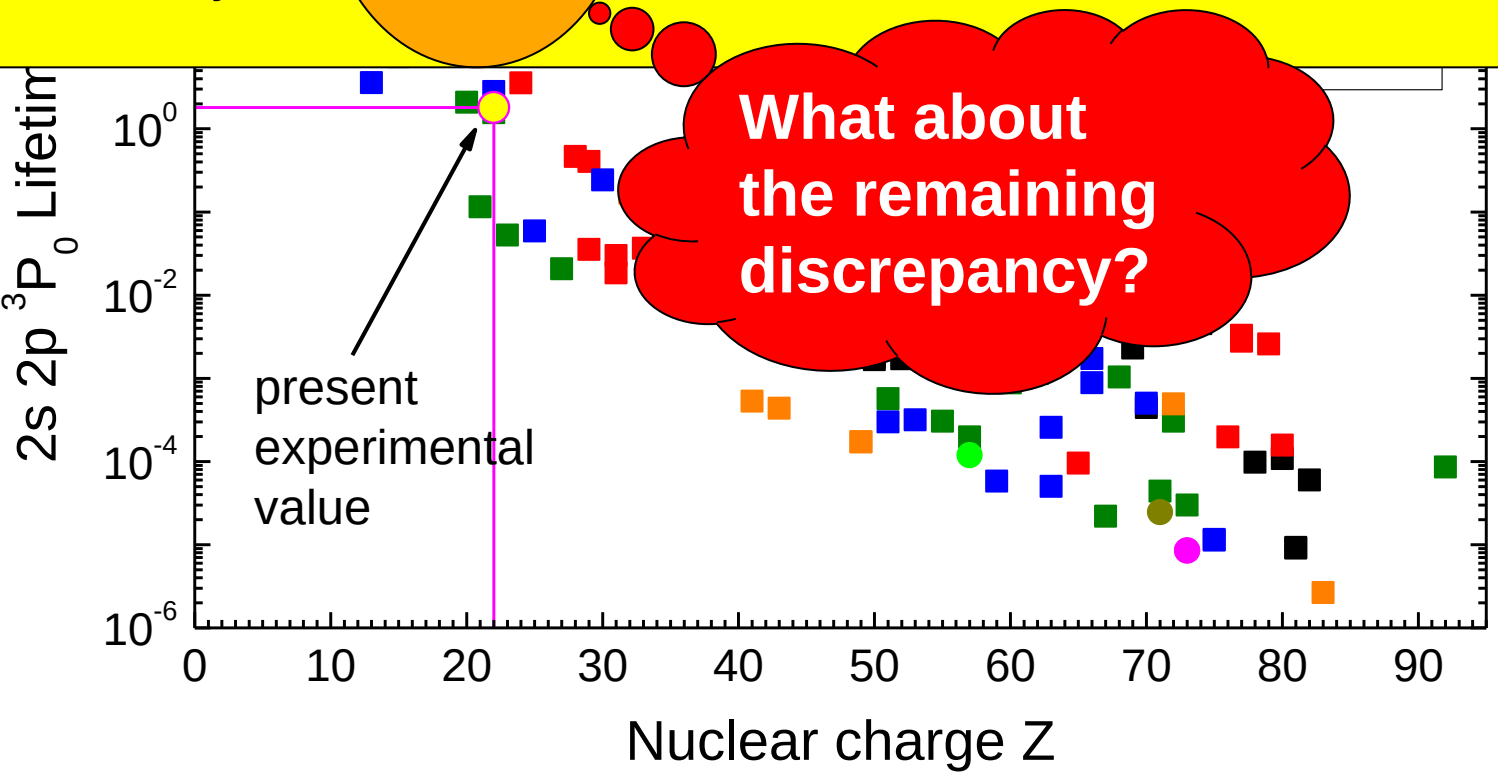
$$A_{\mathrm{HFI}} = \gamma^{(47)}[\lambda_m^{(47)} - \lambda_g^{(47)} - \lambda_m^{(48)} + \lambda_g^{(48)}]$$

^{47}Ti^{18+}: A_{HFI} = 0.56(3) s^{-1}

Theoretical and experimental 2s2p $^3P_0$ HFI lifetimes

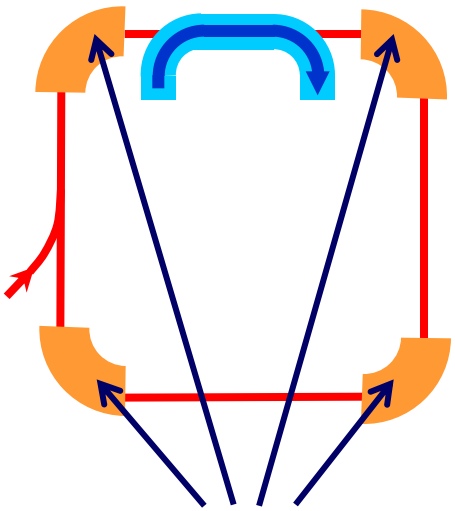
Ti^{18+} values

1993 theory:	**2.812 s**	Marques et al. PRA 47 (1993) 929
2007 experiment:	**1.8(1) s**	Schippers et al., PRL 98 (2007) 033001
2008 theory:	**1.487 s**	Cheng et al., PRA 77 (2008) 052504
2009 theory:	**1.476 s**	Andersson et al., PRA 79 (2009) 032501
2010 theory:	**1.51 s**	Li & Dong, Plas. Sci. Technol. 79 (2010) 032501



J. P. Marques, F. Parente & P. Indelicato, PRA **47** (1993) 929

Influence of external fields



dipole magnets with B up to 1.3 T

B-field

Zeeman effect: τ_{HFI} becomes m_F dependent

effect too weak to explain discrepancies

Li et al., Phys. Lett. A 375 (2011) 914

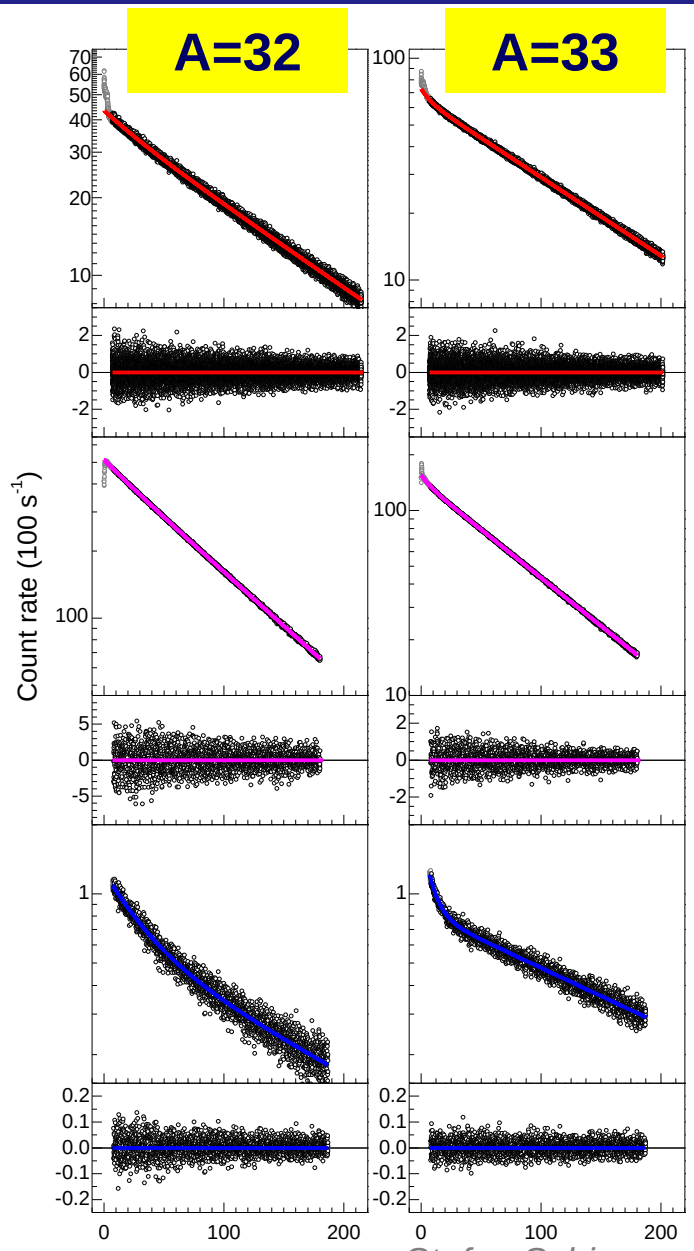
E-field (via v x B)

Stark mixing of $^3P_0$ and $^3P_1$ levels:

effect much too weak to explain discrepancies

Maul et al., J. Phys. B 31 (1998) 2725

New measurements with Be-like $^{A}S^{12+}$ ions



B = 0.44 T

τ_{HFI} = 10.5(7) s

S^{12+} values

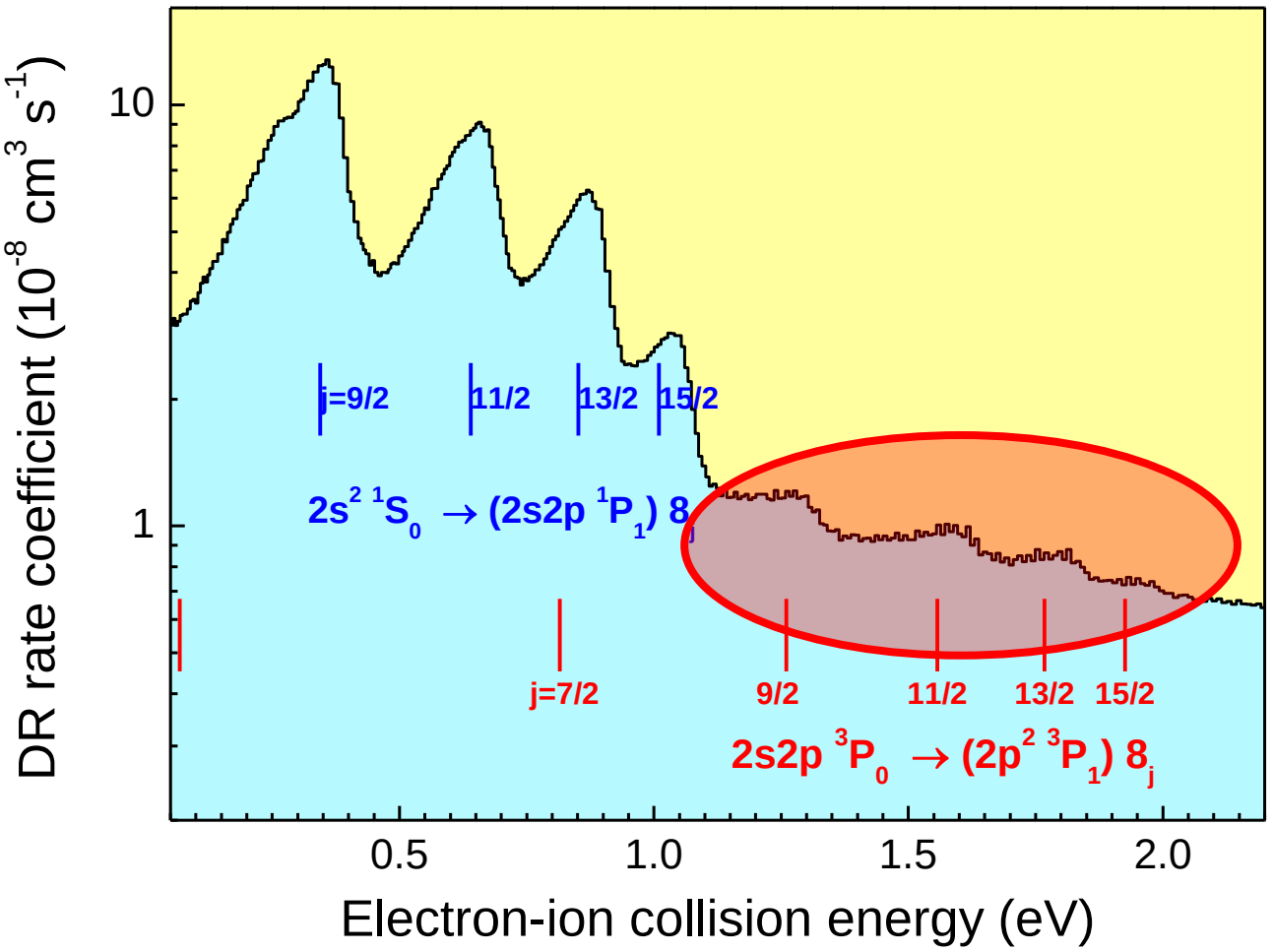
theory:	**27.69 s**	Marques et al. (1993)
theory:	**10.73 s**	Cheng et al. (2008)
theory:	**10.69 s**	Andersson et al. (2009)
experiment:	**10.4(5) s**	TSR (2011)

B = 0.88 T

τ_{HFI} = 10.2(7) s

S. Schippers et al., PRA 85 (2012) 012513

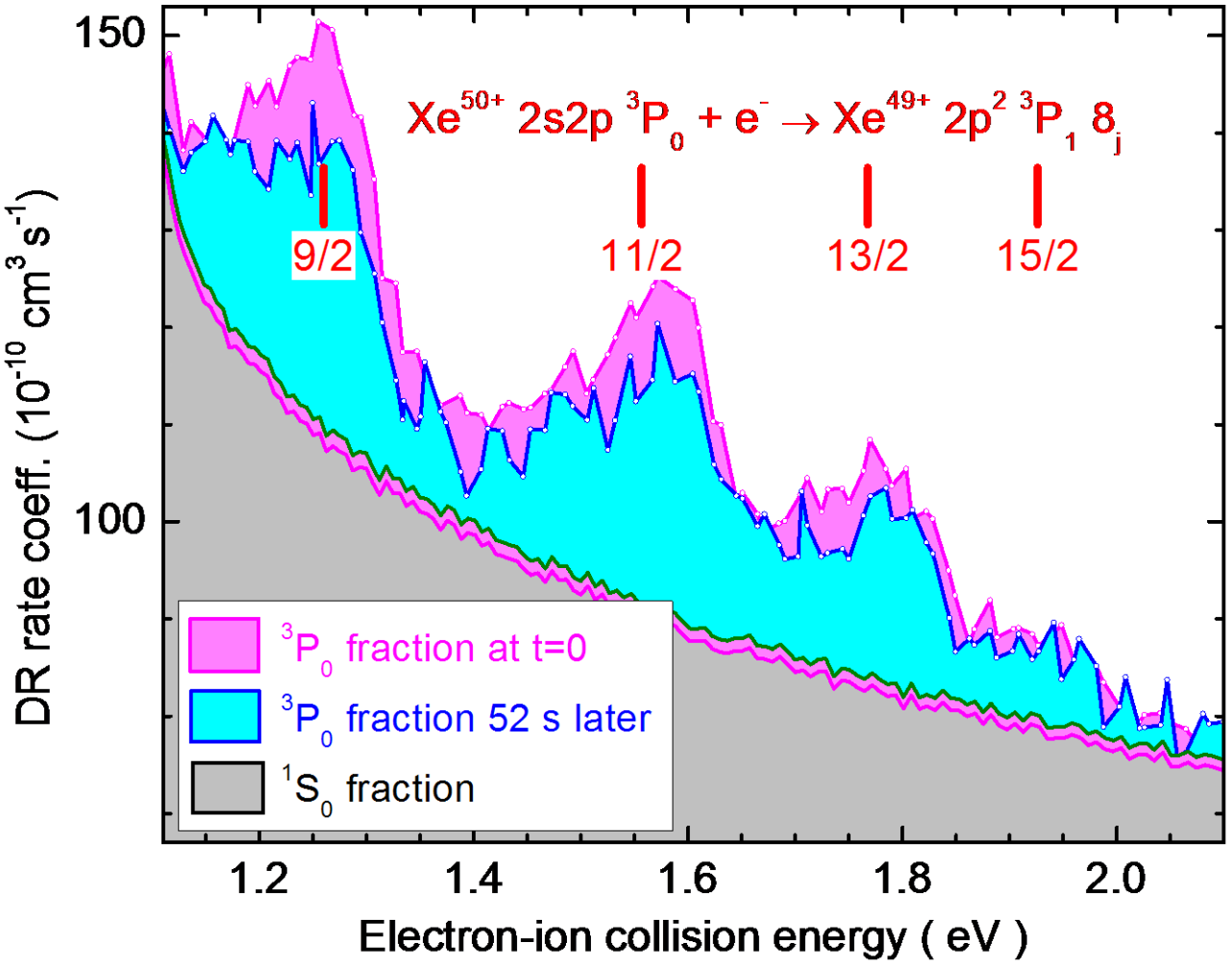
DR of Be-like $^{132}Xe^{50+}$



D. Bernhardt et al., in preparation

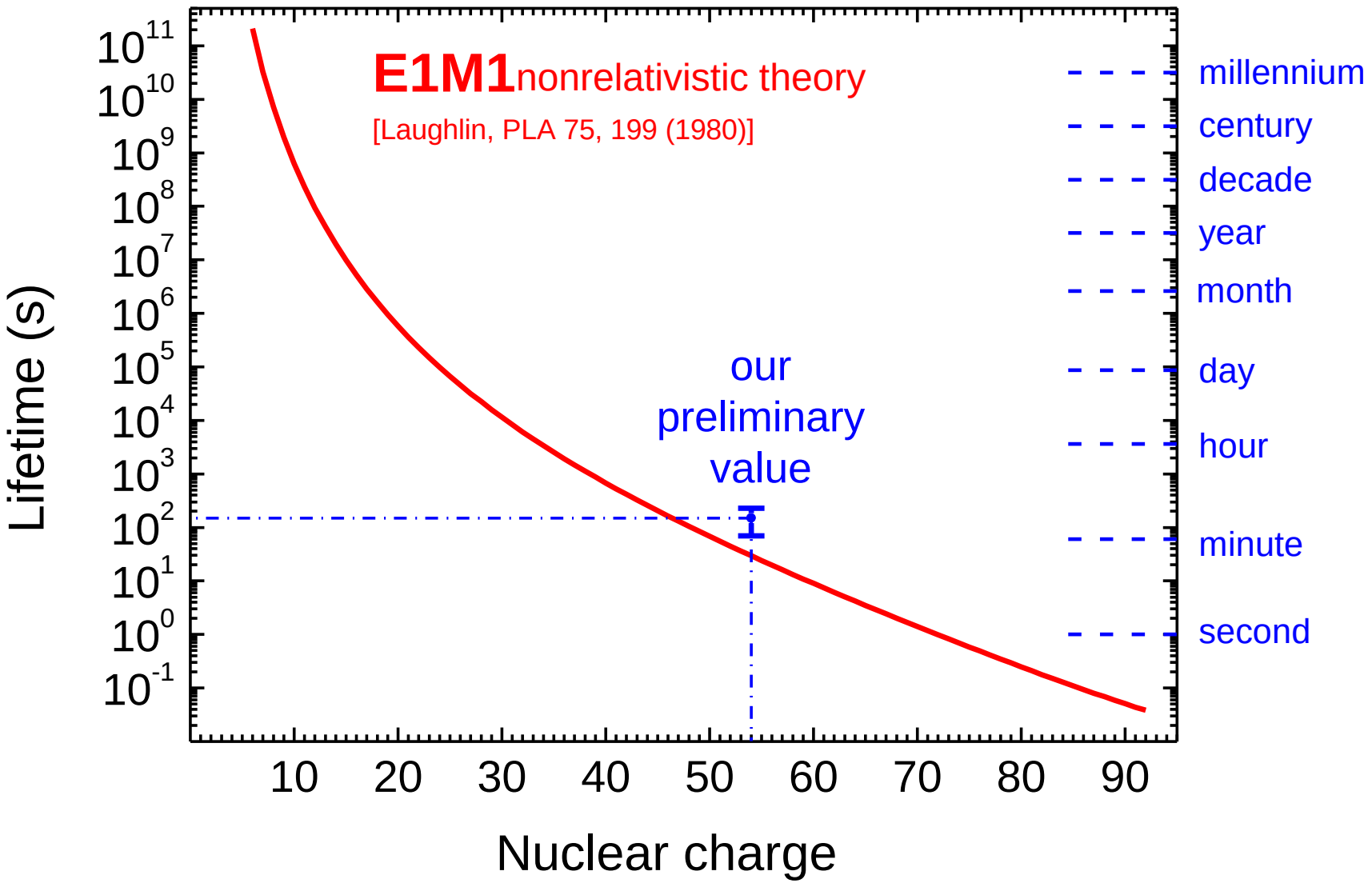
Time dependence of $^3P_0$ DR resonance strength

Measurement of the E1M1 two-photon transition rate should be feasible



D. Bernhardt et al., JPCS (in print)

Comparison with theory



Summary

- **Hyperfine-induced (HFI) transitions have specific applications**
  - accurate atomic clocks
  - astrophysics: isotope specific abundances

- **HFI $2s2p\ ^3P_0 \rightarrow 2s^2\ ^1S_0$ transition in Be-like ions**
  - does not compete with any other one-photon transition

- **First laboratory experiments with Be-like ions in a storage ring**
  - comparision of measurements with two istopes
  - lifetimes determined with 5% accuracy
  - $^{47}Ti^{18+}$: 20% discrepancy with recent theoretical results
  - $^{33}S^{12+}$: Agreement with recent theoretical results
  - in the future determination of nuclear magnetic moments?

- **E1M1 two-photon transition rate**
  - measurements will be pursued for heavy Be-like ions at the ESR

Collaborators & Funding

TSR - HFI transitions

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ESR – E1M1 transitions

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