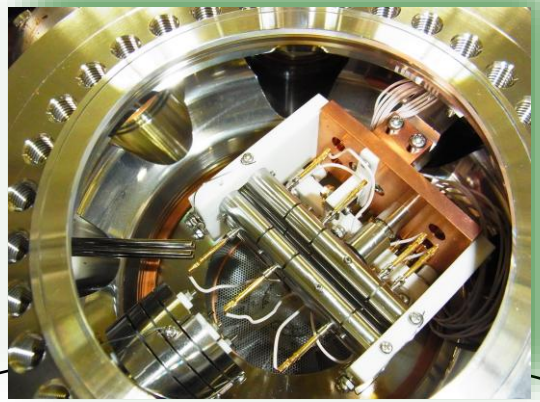
様々なイオントラップ実験で覗く原子分子の個性と可能性

核融合科学研究所 プラズマ量子プロセスユニット
木村 直樹

1. Introduction
2. Property（個性）～Decay dynamicsの研究を例に～
   - Intercombination transition in Be-like Ar^{14+}
   - Fermi resonance in vibrational decay of N_2O^+
3. Prospect （可能性）　～基礎物理への貢献を目指して～
   - Ultracold ion (Coulomb crystal)
   - Future plan toward HCI clocks
4. Summary

Our ion traps

RF trap



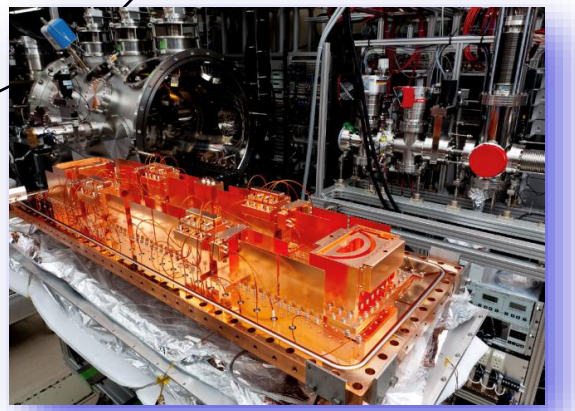
@ Sophia

AMO physics

@ UEC

EBIT

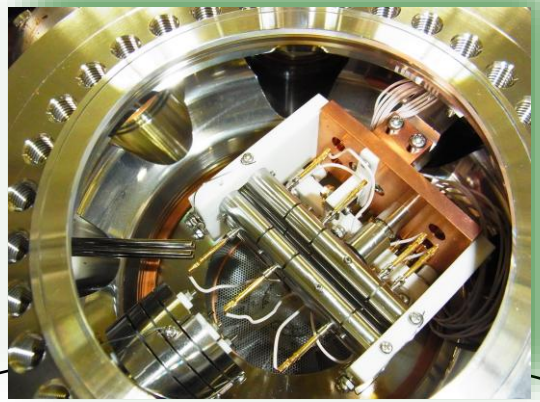
@ RIKEN



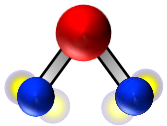
RICE

Our targets

RF trap

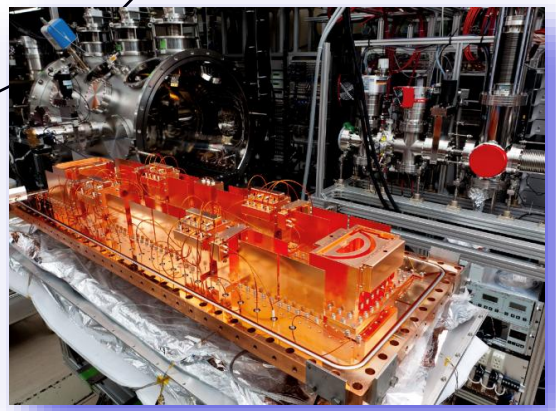


AMO physics



Atomic ion

Molecular ion



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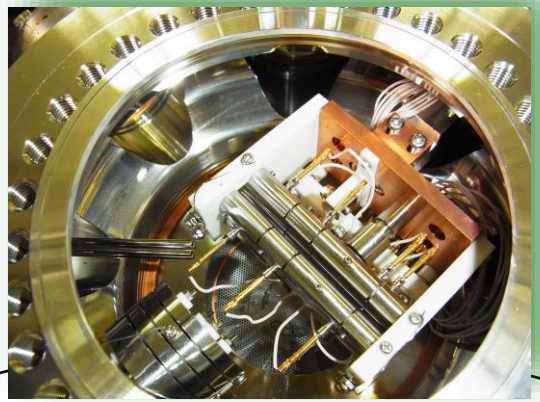
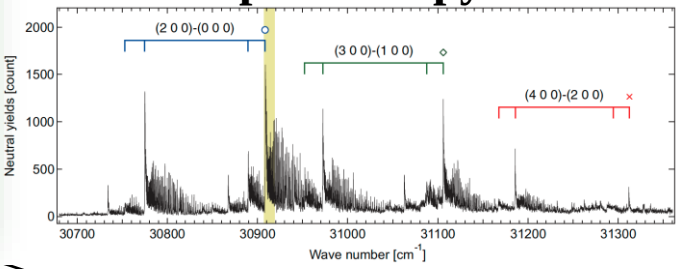
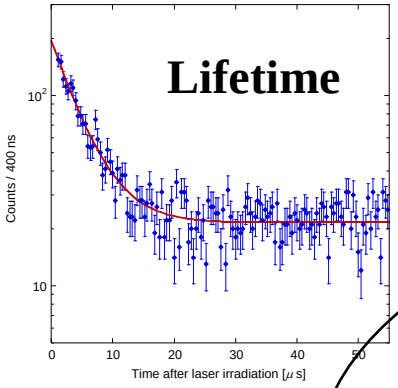
For studying their structures

RF trap



Spectroscopy





AMO physics

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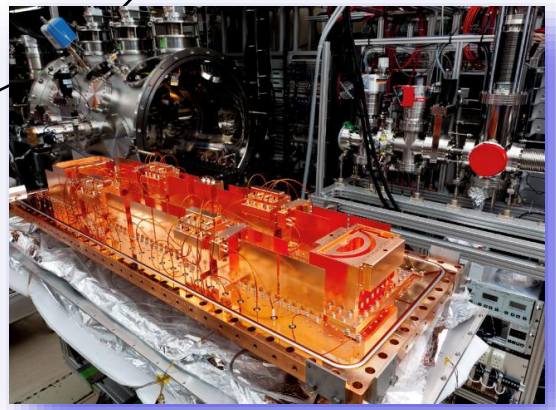

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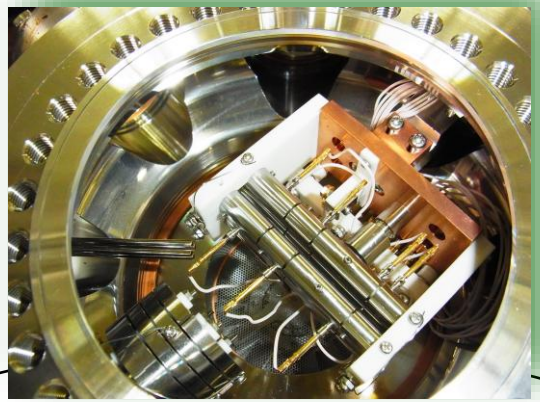
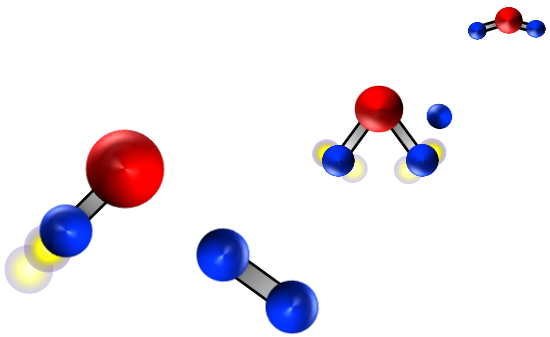
Study on their dynamics

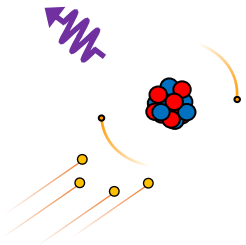
RF trap



Reaction dynamics

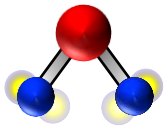


Plasma dynamics



Gas phase

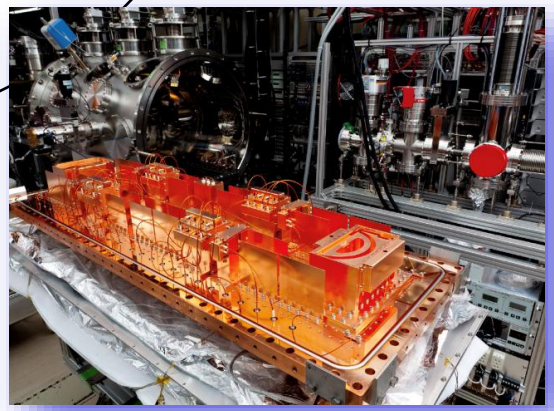
AMO physics

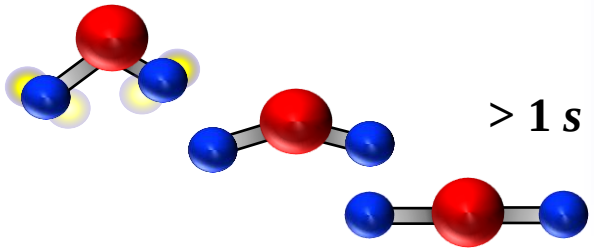


Plasma

Vacuum

~10^{-10} Pa





> 1 *s*

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Decay dynamics

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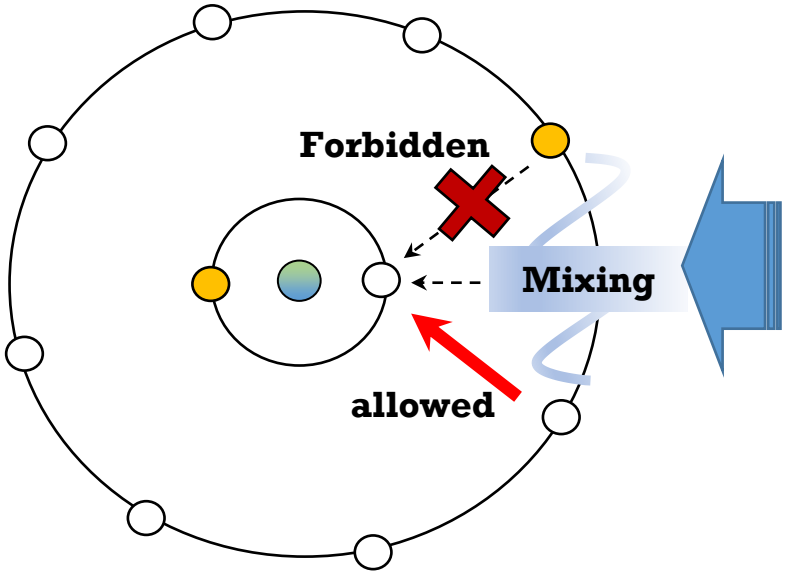
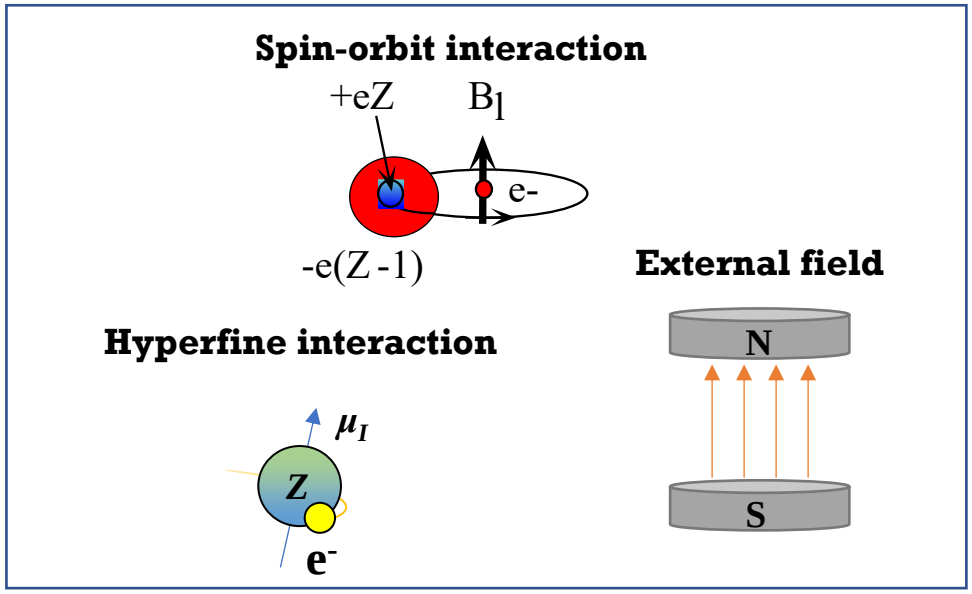
Decay dynamics : De-excitation processes in atom and molecules

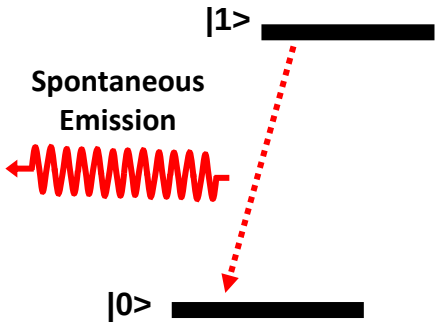
Reflecting the intrinsic property on atoms and molecules



Perturbation



Fundamental for various phenomena and applications



Astrophysical plasmas

Interstellar chemistry

Quantum metrology

Atomospheric chemistry

Laboratory plasmas

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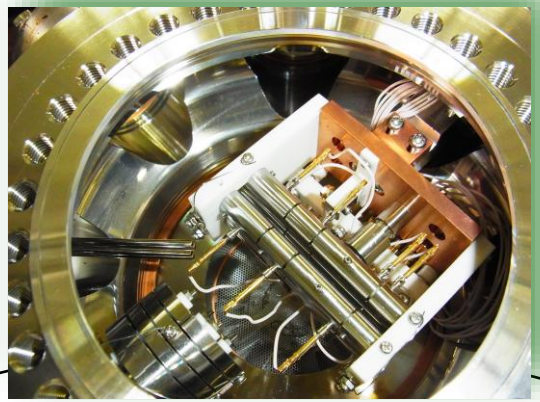


Gas phase

AMO physics

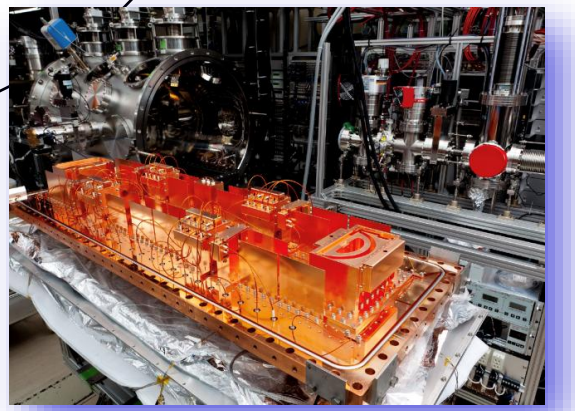
HCI

Plasma

EBIT

Vacuum

~10^{-10} Pa



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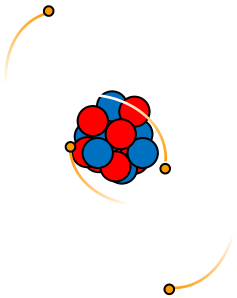
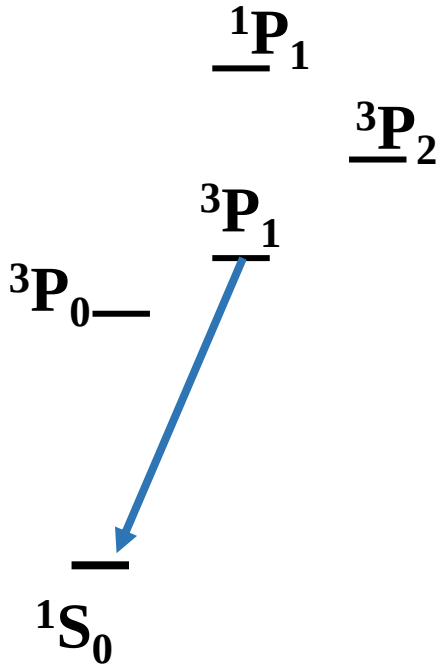
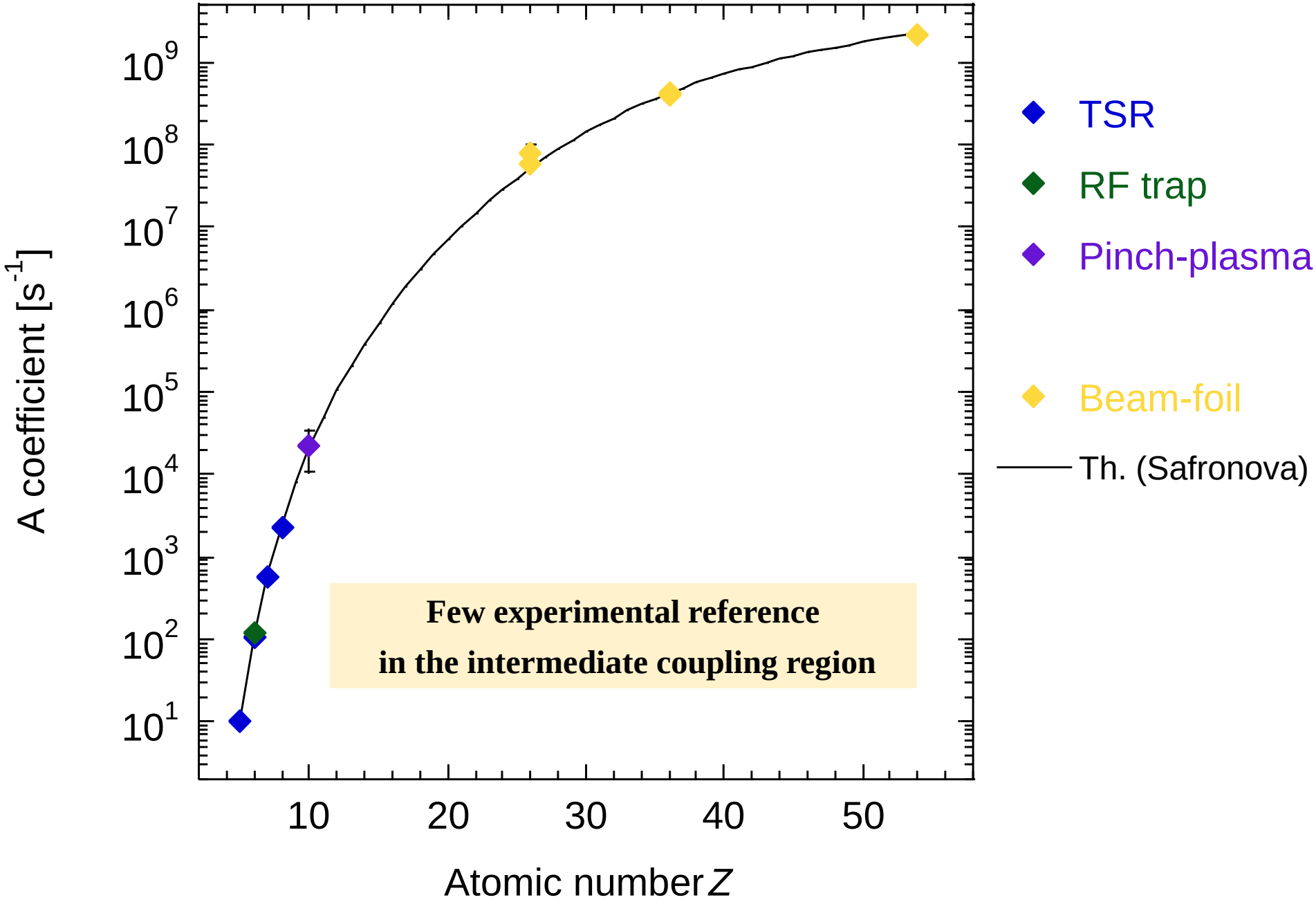
Be-like ions: the four electron atoms



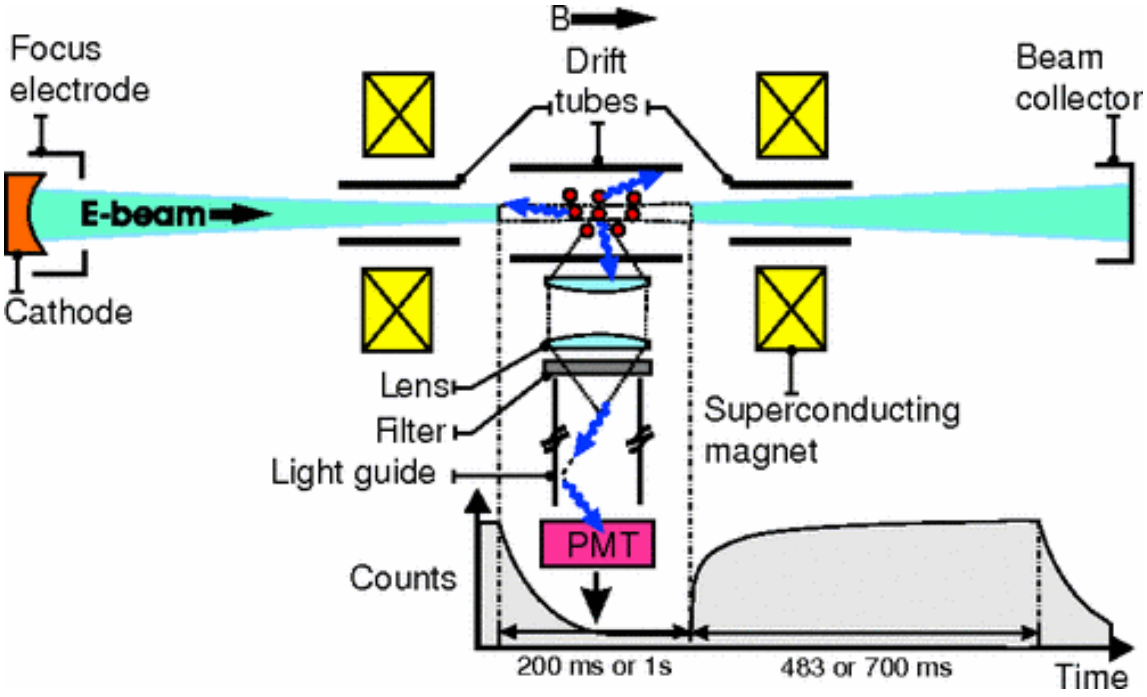


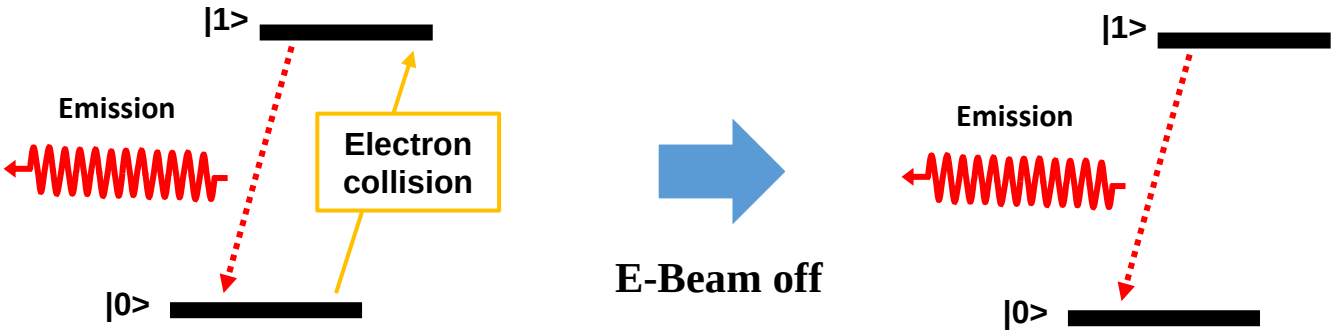
- **Simple example for many-bady quantum systems**
- **High abundance (Prominent emission) in plasmas**
  - **ex. Electron-temperature diagnostics using Be-like Ar^{14+}[APJ 338, 563 (1988)]**
- **Intercombination transition**
  - **Fundamental test for spin-orbit coupling with electron correlations**

The intercombination transition $^1S_0 - {}^3P_1$ in Be-like ions



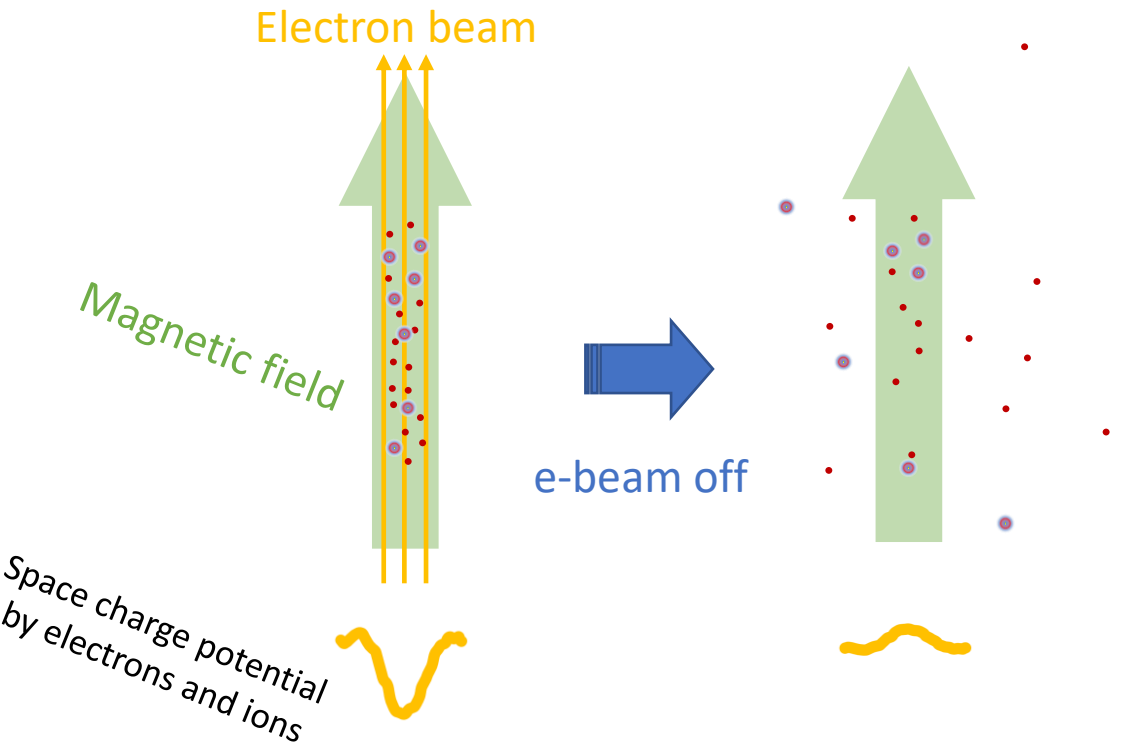
Conventional lifetime measurement using EBIT

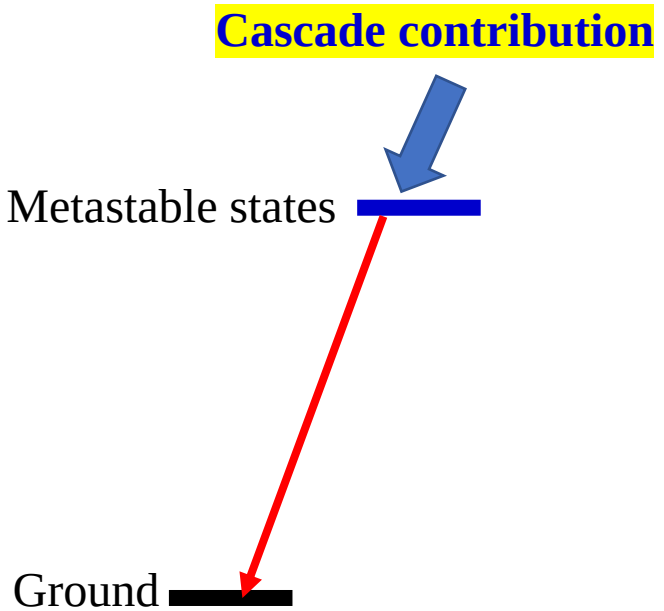




A. Lapierre, *et al.*, Phys. Rev. Lett. **95**, 183001 (2005).

Experimental difficulties of the μs-order lifetime measurement





Change of the number of trapped ions

Cascade re-population processes

These problems are significant in the short-time region

Concept: Time-resolved laser spectroscopy of Be-like Ar^{14+}

~inspired by the former proposals (Oxford & Stockholm)~

Hyperfine Interactions 114 (1998) 203–206 203

Laser spectroscopy of the $1s^2 2s2p\ ^3P_2–^3P_1$ transition in beryllium-like argon using the Oxford EBIT

T.V. Back [a], H.S. Margolis [a], P.K. Oxley [a], J.D. Silver [a] and E.G. Myers [b]

[a] *Clarendon Laboratory, University of Oxford, Parks Road, Oxford, OX1 3PU, UK*
E-mail: tekla.back@new.ox.ac.uk

[b] *Department of Physics, Florida State University, Tallahassee, FL 32306, USA*

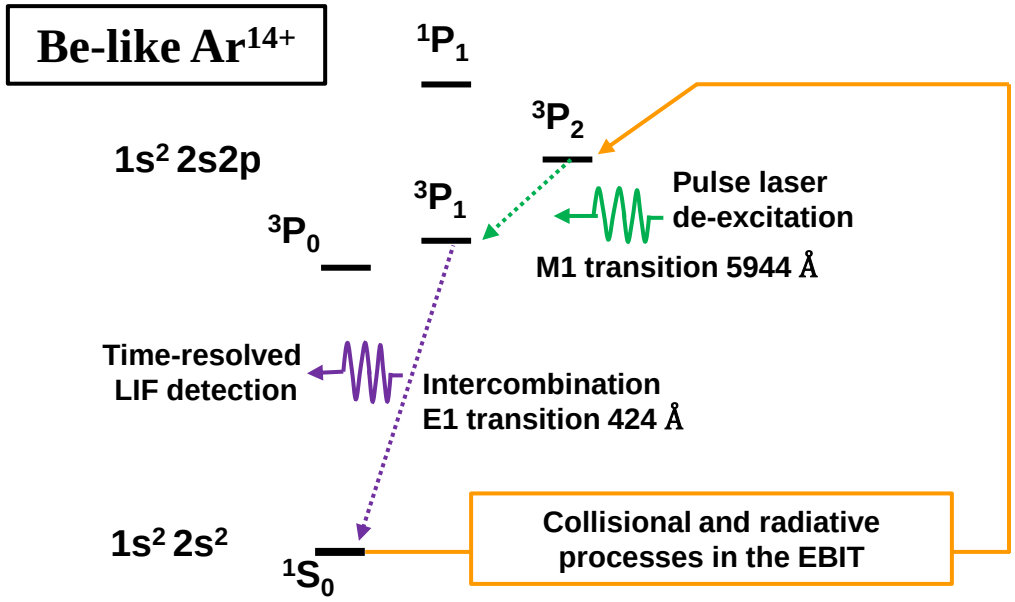
XXVII International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC 2011) IOP Publishing
Journal of Physics: Conference Series **388** (2012) 022049 doi:10.1088/1742-6596/388/2/022049

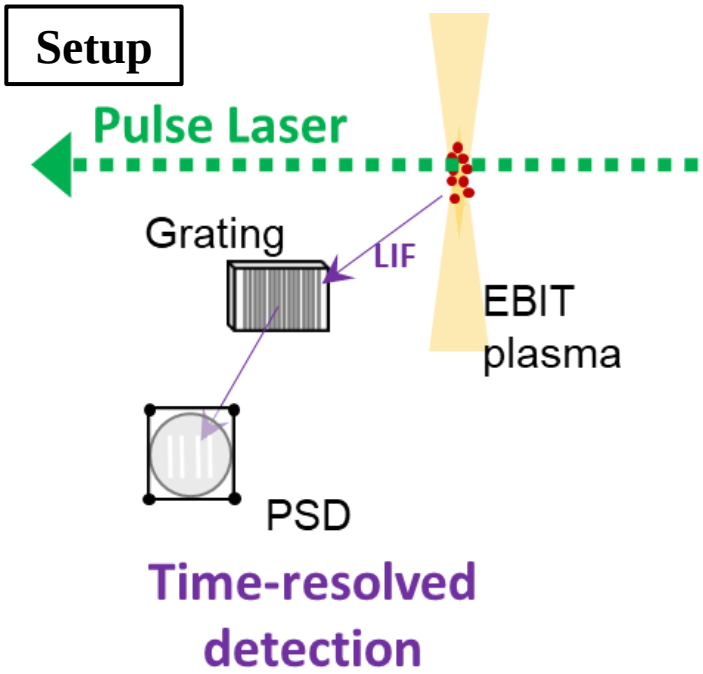
Laser spectroscopy of Be-like Ar at the Stockholm EBIT

S. Mahmood, S. Ali, I. Orban, S. Tashenov and R. Schuch

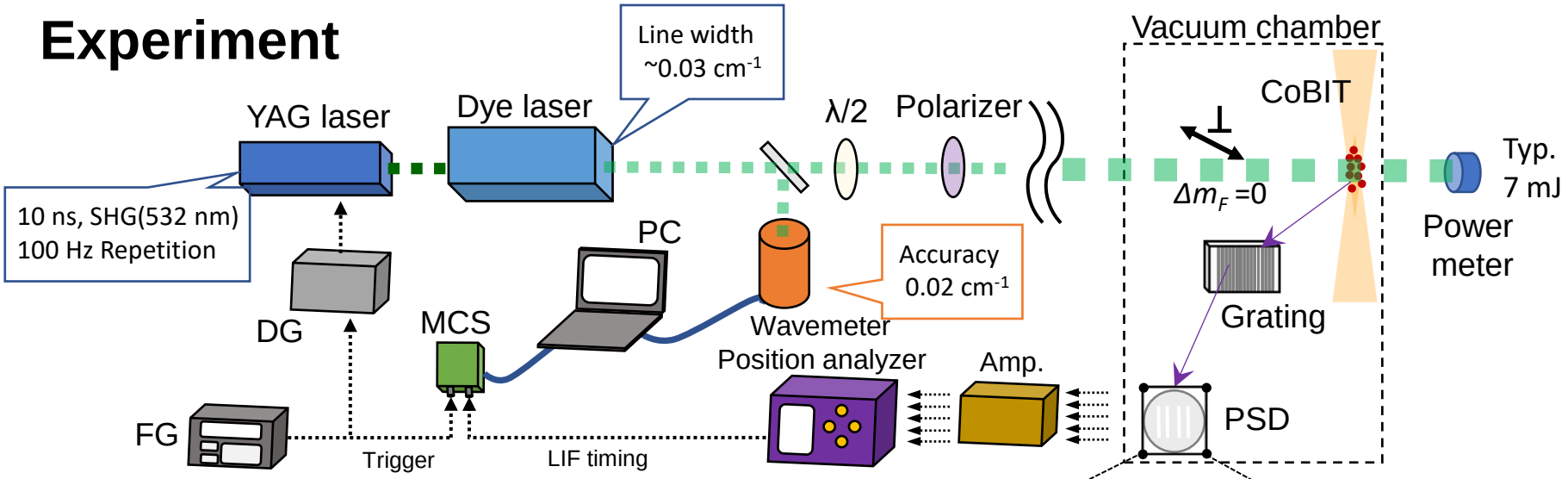
Department of Physics, Stockholm University, S-106 91 Stockholm, Sweden

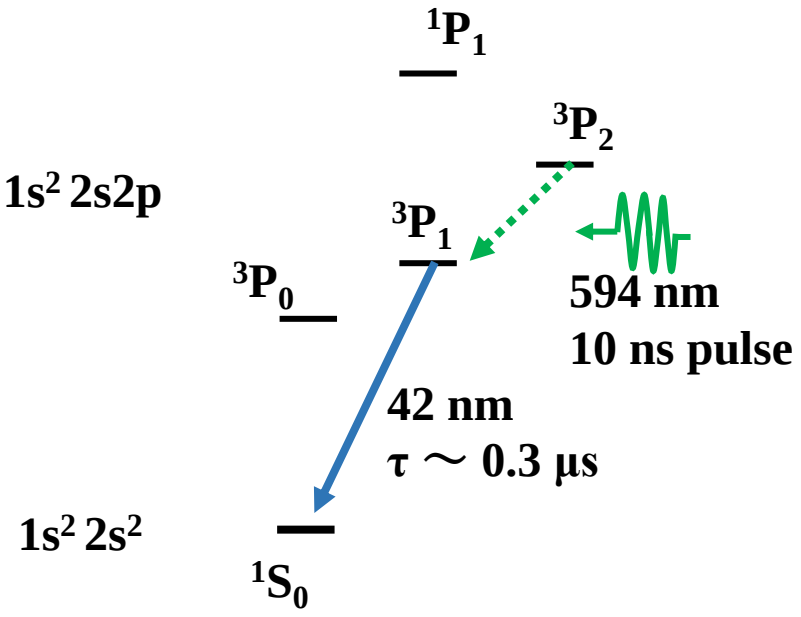
Synopsis We present here an experiment to precisely determine the $1s^2 2s2p\ (^3P_1–^3P_2)$ level splitting using laser excitation of Be-like Ar, at the Stockholm electron beam ion trap (R-EBIT). The wavelength of the above transition is in visible region of electromagnetic spectrum and accessible using a tunable laser system. The aim of the experiment is to develop precision laser spectroscopy of trapped highly charged ions.

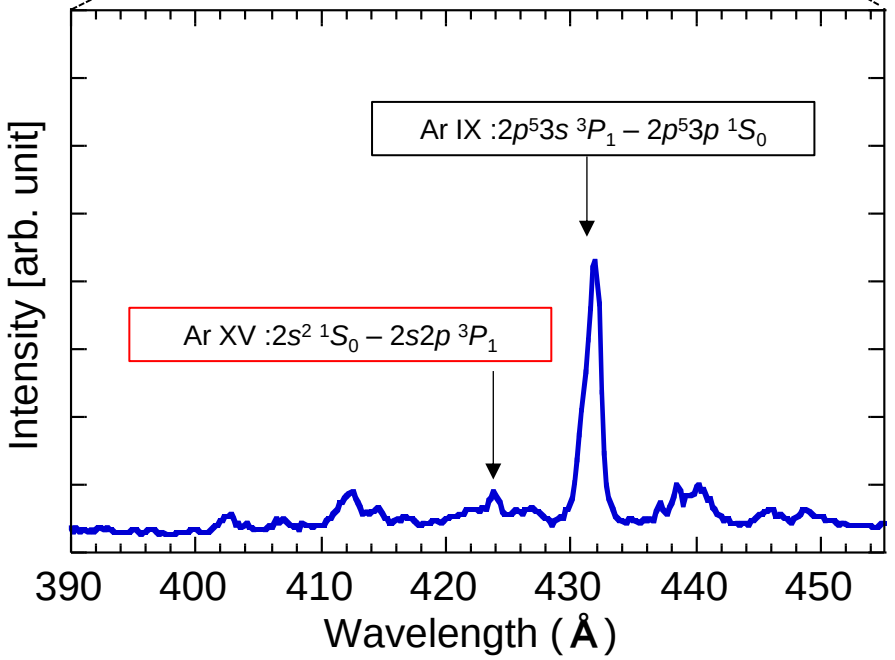




Experiment

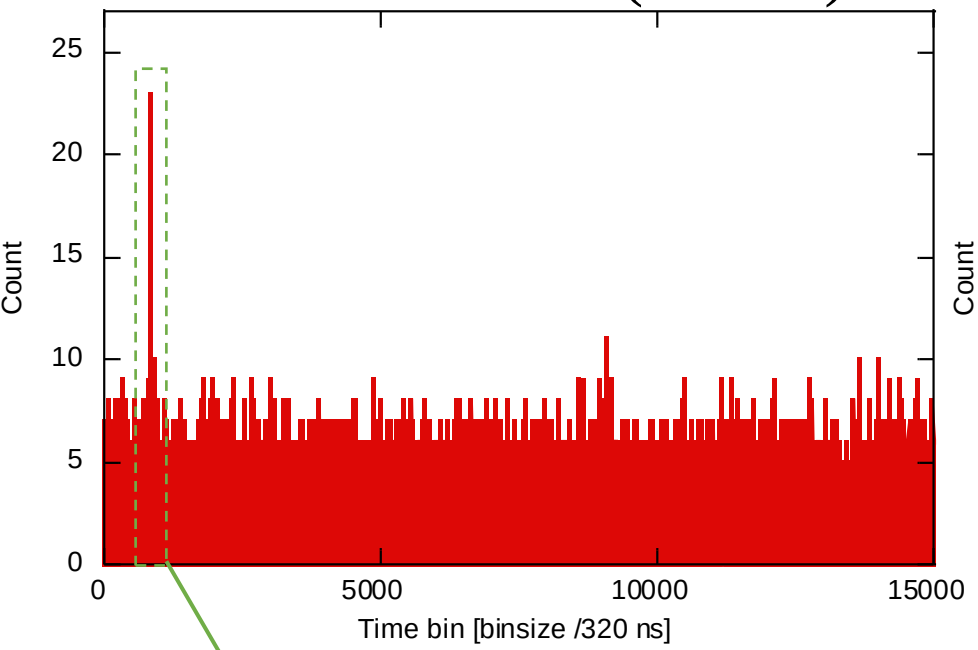

Line width
~0.03 cm-1
YAG laser
Dye laser
λ/2
Polarizer
Vacuum chamber
CoBIT
⊥
Δm_F =0
Typ.
7 mJ
Power
meter
10 ns, SHG(532 nm)
100 Hz Repetition
PC
Accuracy
0.02 cm-1
DG
MCS
Wavemeter
Position analyzer
Amp.
Grating
FG
Trigger
LIF timing
PSD


1P1
3P2
1s2 2s2p
3P1
3P0
594 nm
10 ns pulse
42 nm
τ ~ 0.3 μs
1s2 2s2
1S0

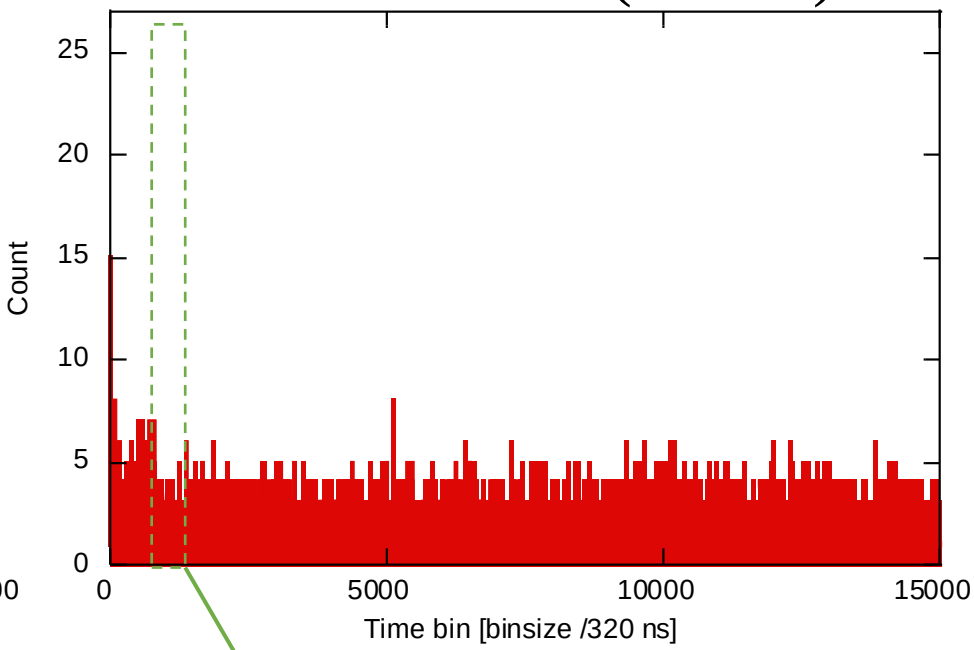

Ar IX :2p53s 3P1 – 2p53p 1S0
Ar XV :2s2 1S0 – 2s2p 3P1
Intensity [arb. unit]
390
400
410
420
430
440
450
Wavelength (Å)

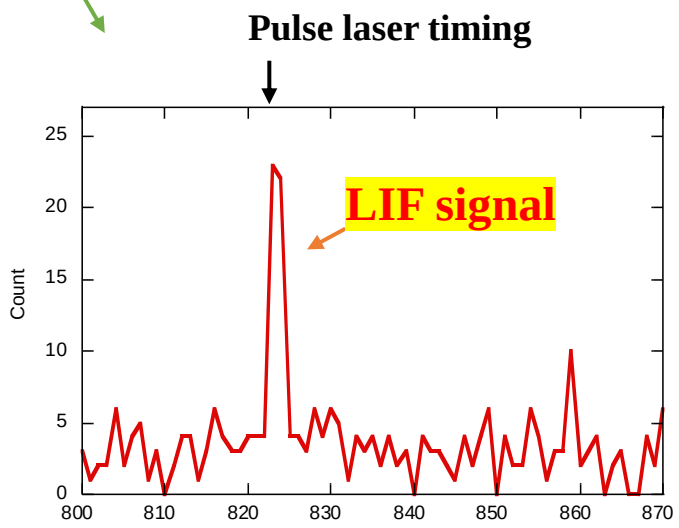
LIF signal of Ar^{14+} trapped in CoBIT

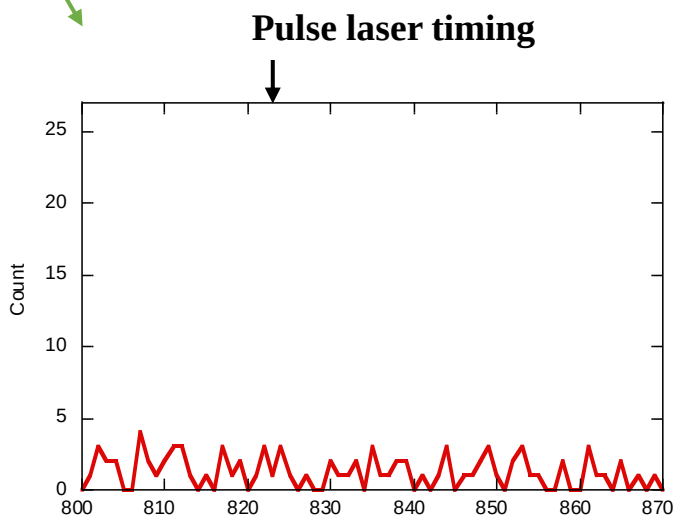
16819.36 cm^{-1} (60 min)



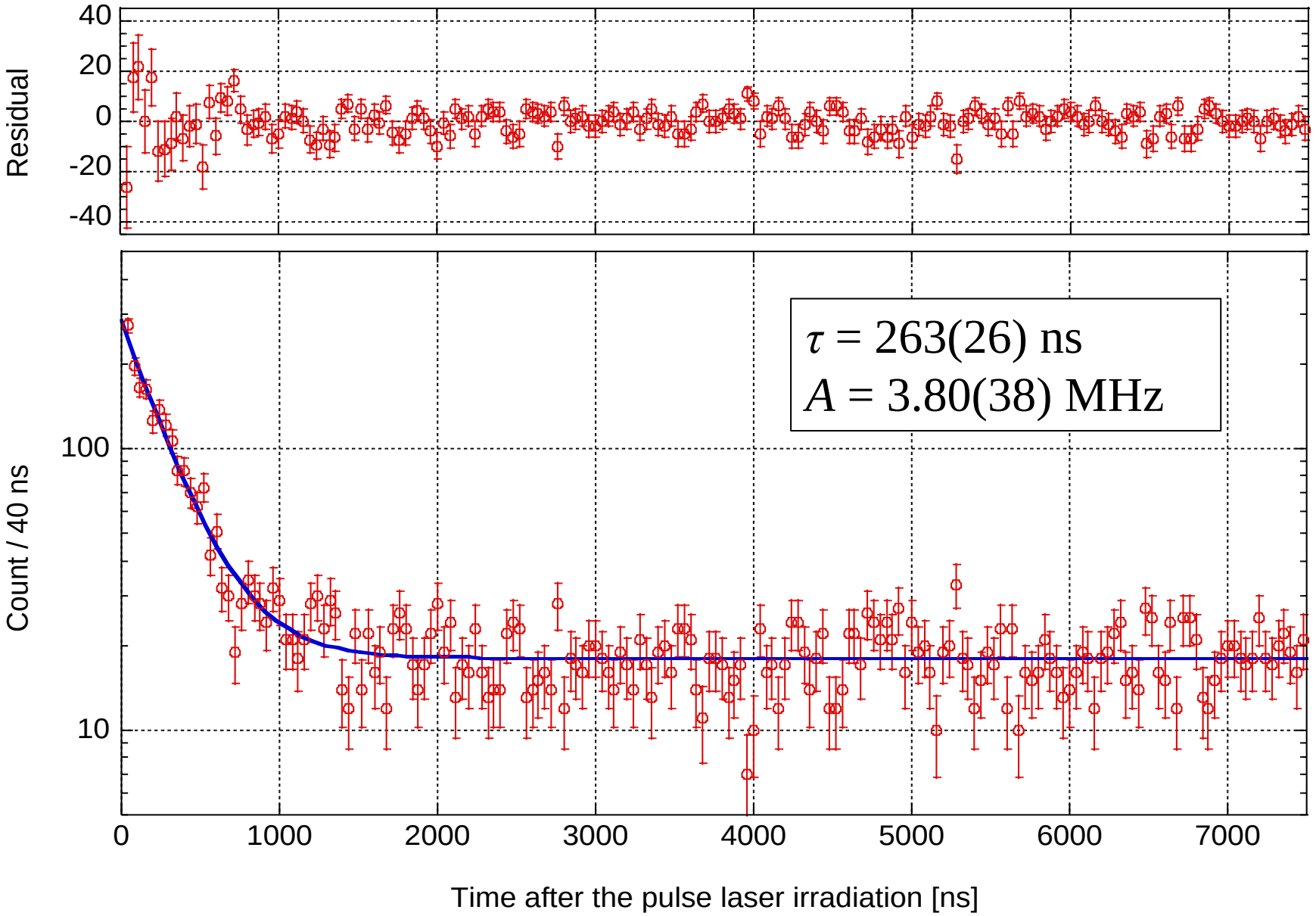
16819.06 cm^{-1} (30 min)





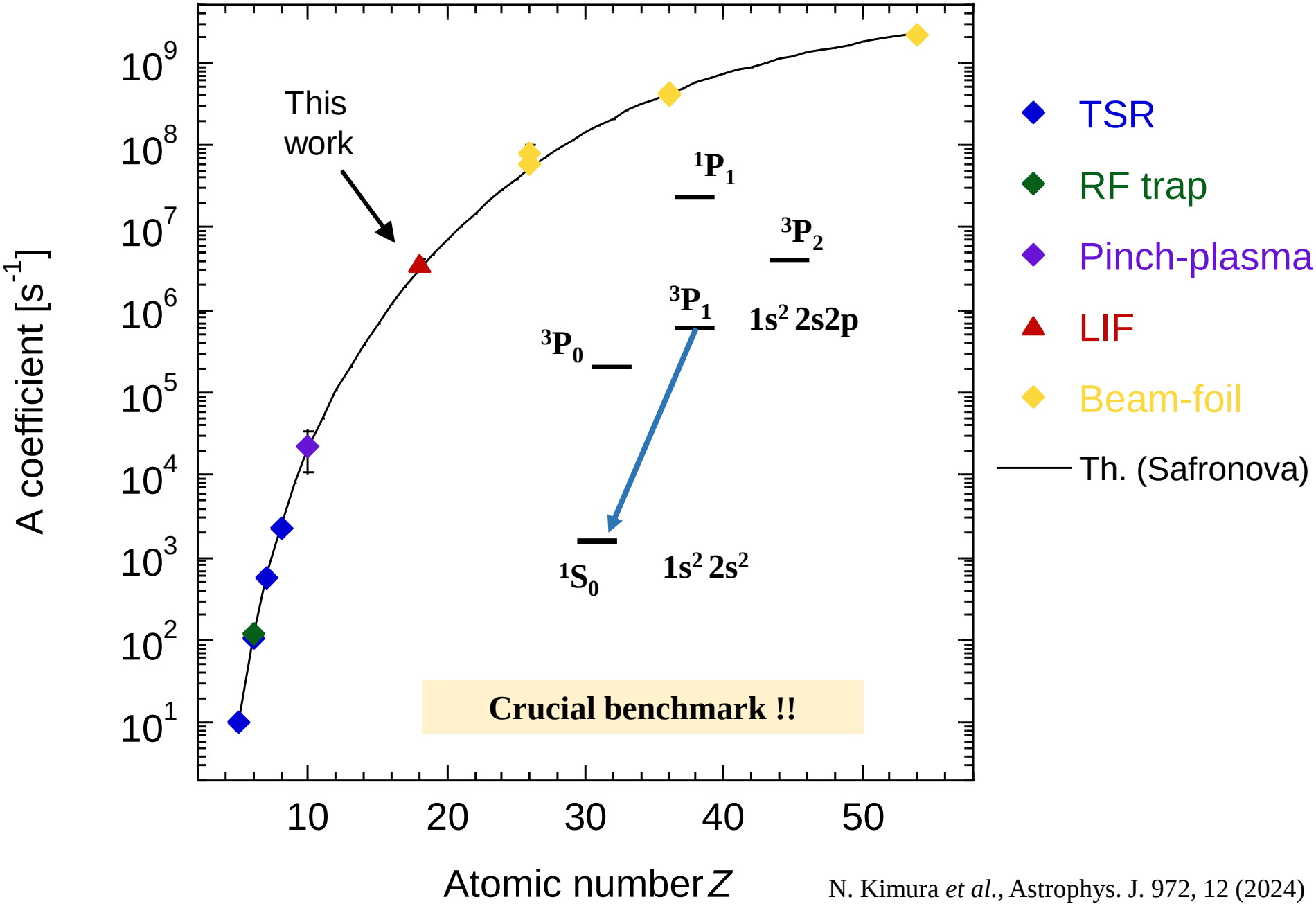


Lifetime (Transition-rate) measurement ~ 48 hours



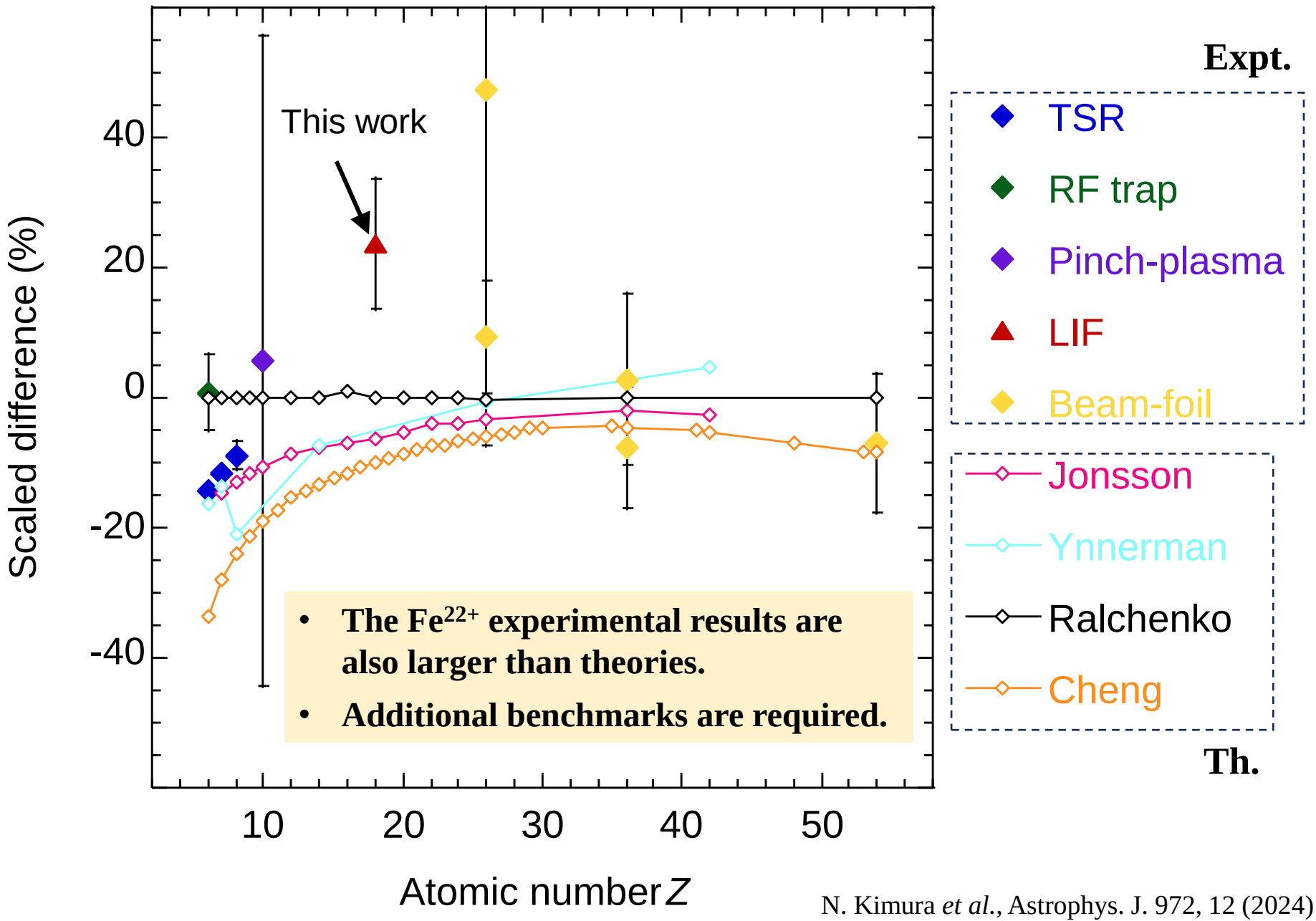
N. Kimura *et al.*, Astrophys. J. 972, 12 (2024)

Z-dependence of the transition-rate $^1S_0 - {}^3P_1$ in Be-like ions



N. Kimura *et al.*, Astrophys. J. 972, 12 (2024)

Scaled differences of the intercombination transition rate from the Safronova's calculation



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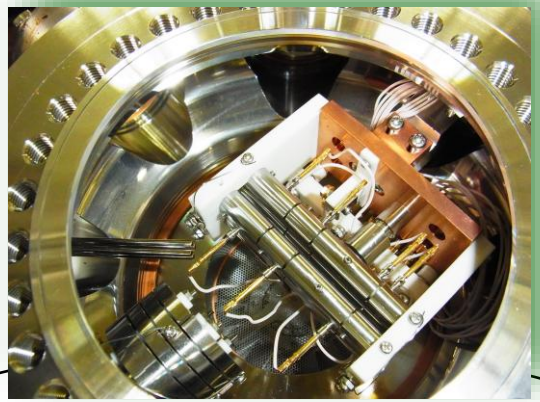

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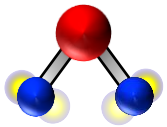
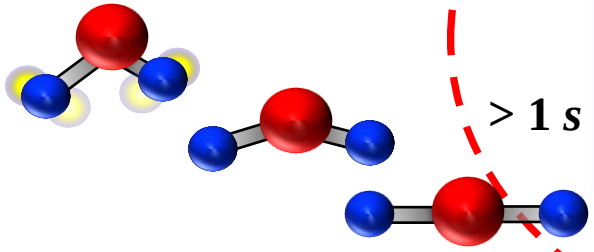
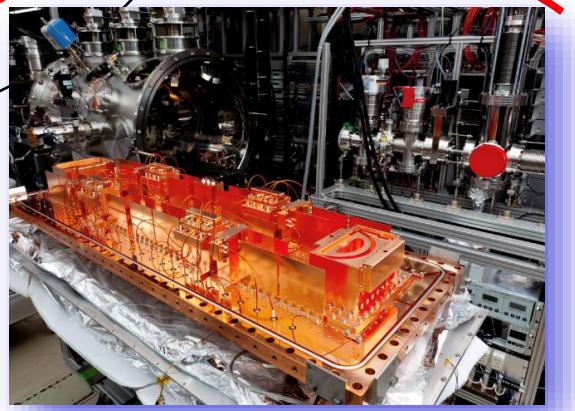




> 1 *s*

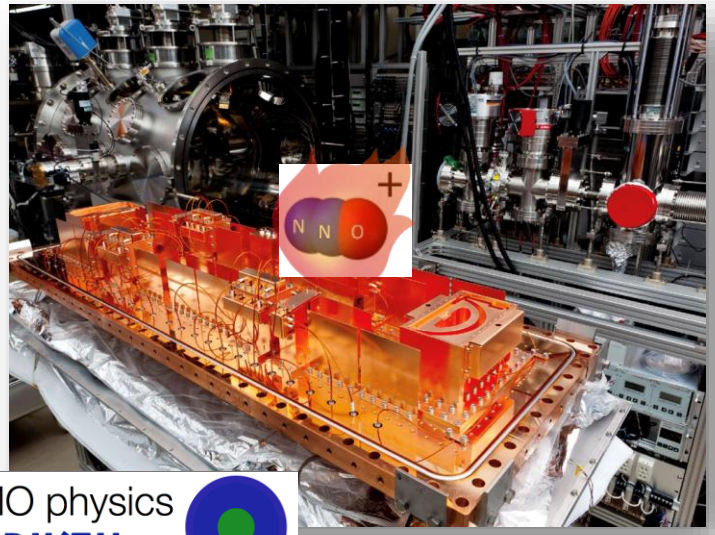


EBIT

Cooling dynamics

RICE

RICE ~ RIken Cryogenic Electrostatic ion storage ring



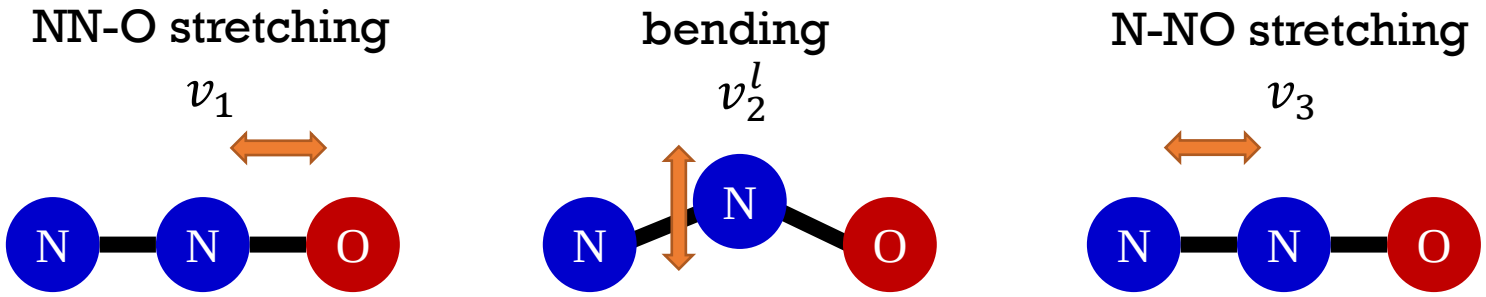
AMO physics
RIKEN

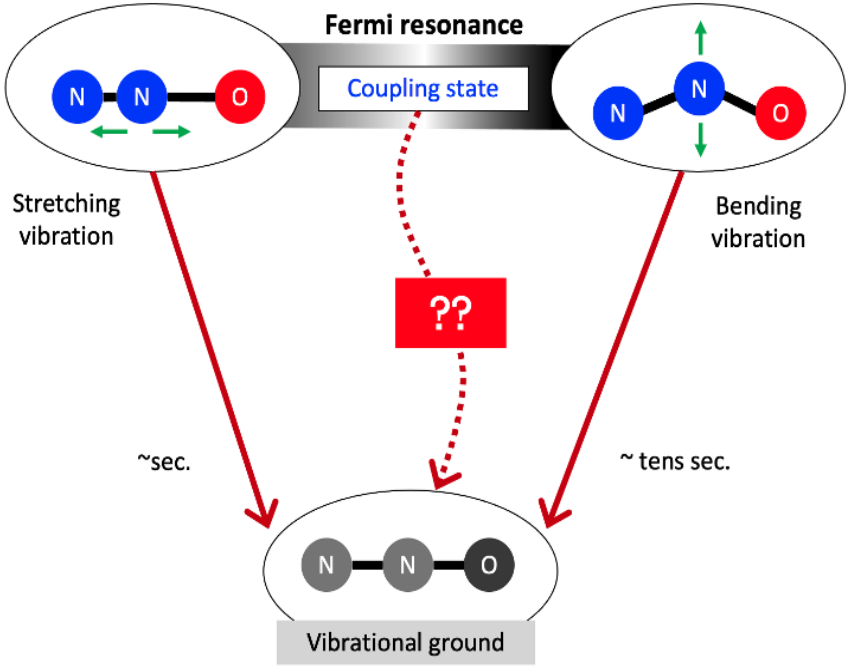
Y. Nakano *et al.*, Rev. Sci. Instrum. 88, 033110 (2017)

- Ion beam storage : 2 ~ 20 keV
- Magnetic field : ~ 0 gauss
- Cryogenic : 4.2 K
- Vacuum : ~ 10^{-10} Pa
  - ➢ Long Time Trapping ~ 1000 sec !!

- **N_2O^+**
  - ➢ R. Igosawa *et al.*, J. Chem. Phys. 153, 184305 (2020)
  - ➢ A. Hirota *et al.*, Phys. Rev. A 102, 023119 (2020)
  - ➢ S. Harayama *et al.*, Phys. Rev. A accepted [editors' suggestion]
- **C_2^-**
  - ➢ M. Iizawa *et al.*, J. Phys. Soc. Jpn. 91, 084302 (2022)

Decay dynamics on the triatomic molecule N_2O^+

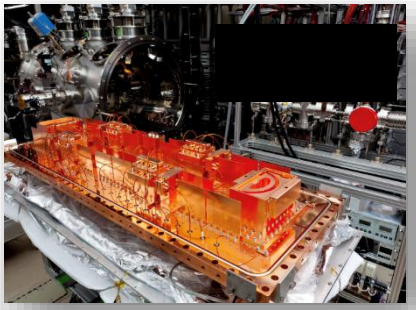




- ***Important molecule for atomospheric chemistry***
- ***Good example for vibrational decay with multiple modes***
- ***Fermi resonance effect on the vibrational decay dynamics***

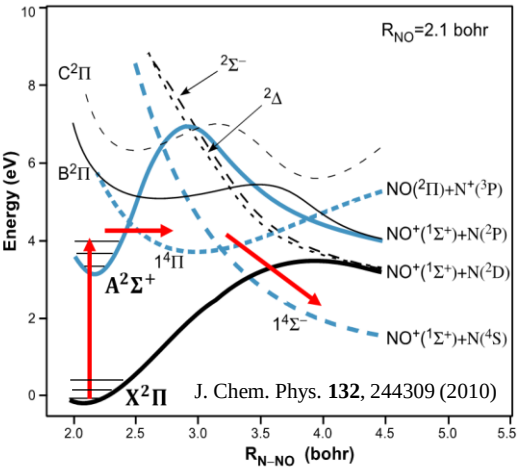
N_2O^+ Experiment with RICE

Wavelength tunable pulsed laser



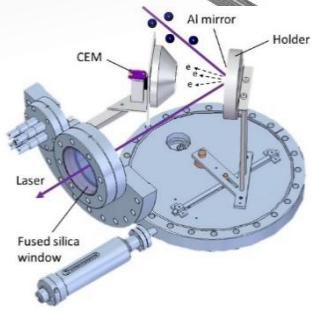
4 K, 10^{-10} Pa

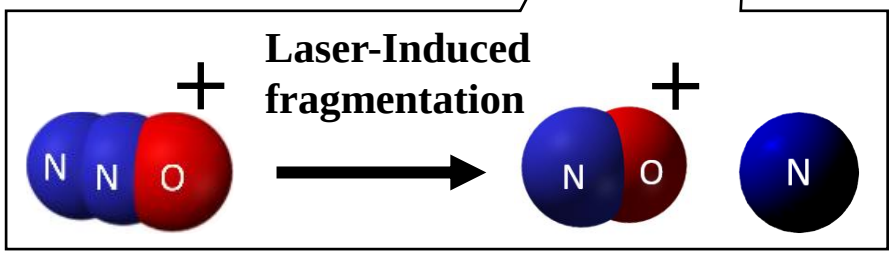
ECRIS



J. Chem. Phys. **132**, 244309 (2010)

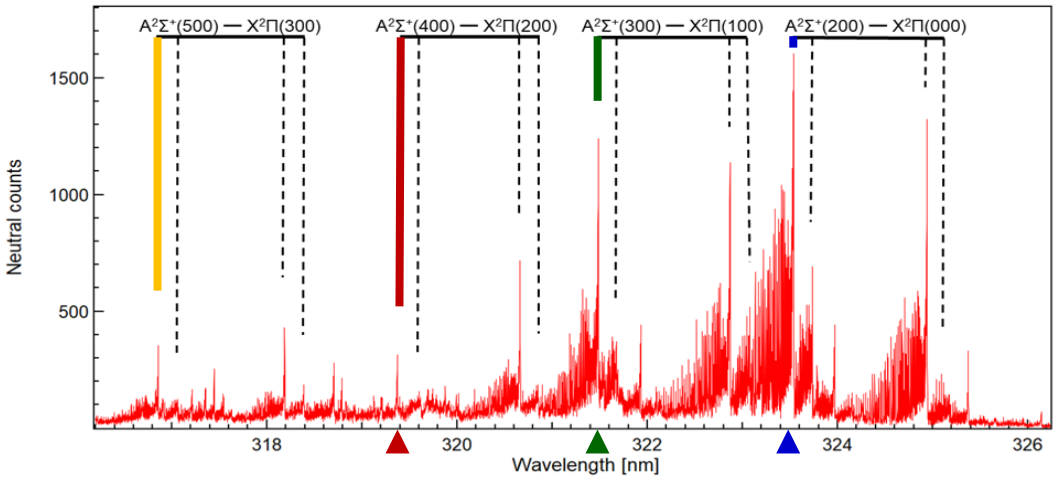
Mass selection Magnet

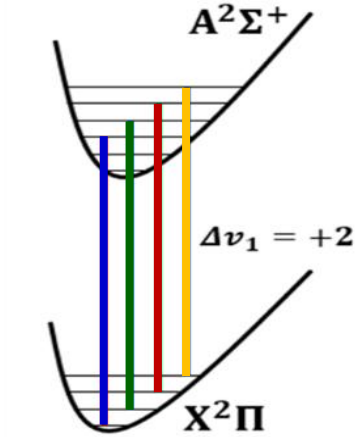




Neutral Particle Detector

N_2O^+ Experiment with RICE

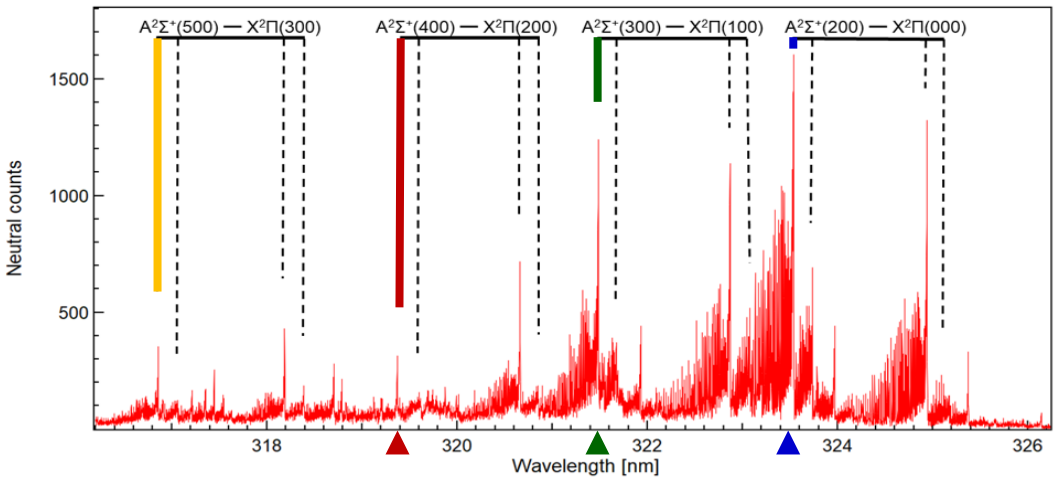


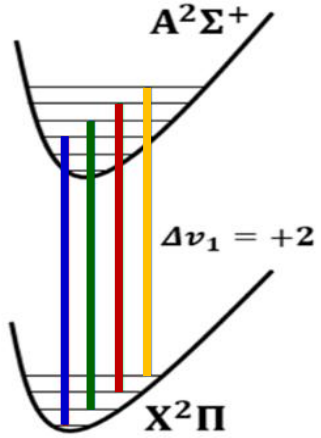


NN-O stretching
(v_1 0 0)

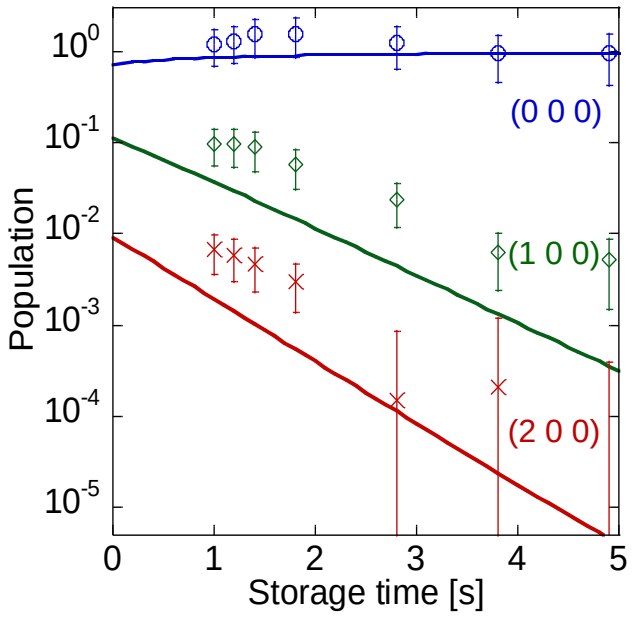
A. Hirota *et al.*, PRA 102, 023119 (2020)

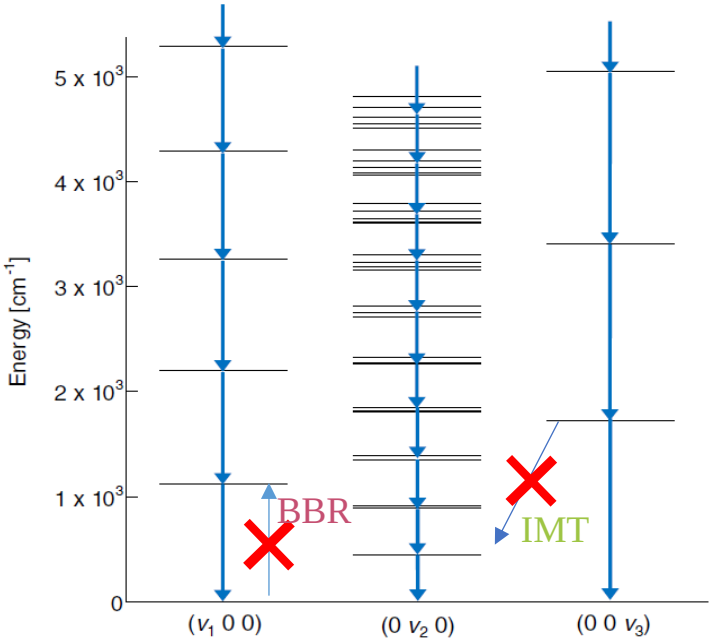
N_2O^+ Experiment with RICE





NN-O stretching
(v_1 0 0)





A. Hirota *et al.*, PRA 102, 023119 (2020)

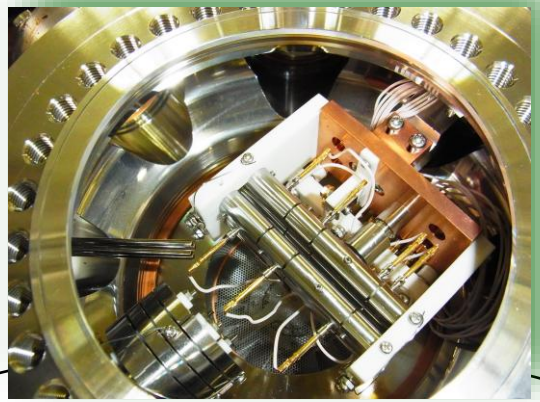
様々なイオントラップ実験で覗く 原子分子の個性と可能性

核融合科学研究所 プラズマ量子プロセスユニット
木村 直樹

1. Introduction
2. Property（個性）～Decay dynamicsの研究を例に～
   - Intercombination transition in Be-like Ar^{14+}
   - Fermi resonance in vibrational decay of N_2O^+
3. Prospect （可能性）　～基礎物理への貢献を目指して～
   - Ultracold ion (Coulomb crystal)
   - Future plan toward HCI clocks
4. Summary

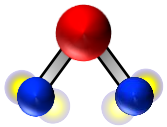
Our ion traps

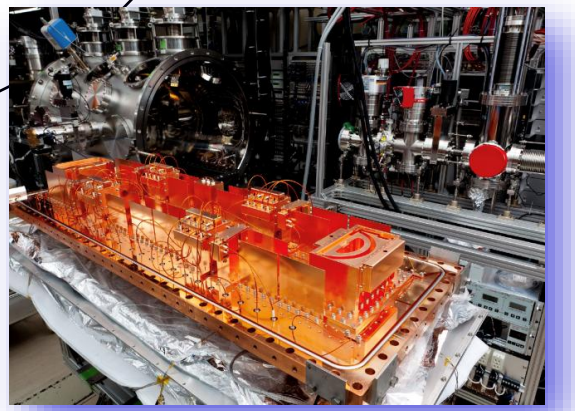
RF trap



Gas phase

AMO physics



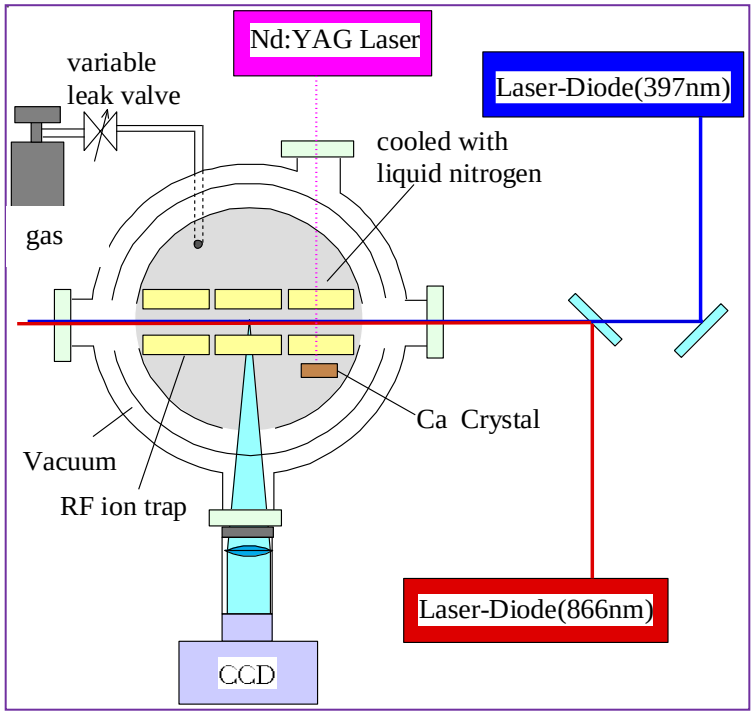


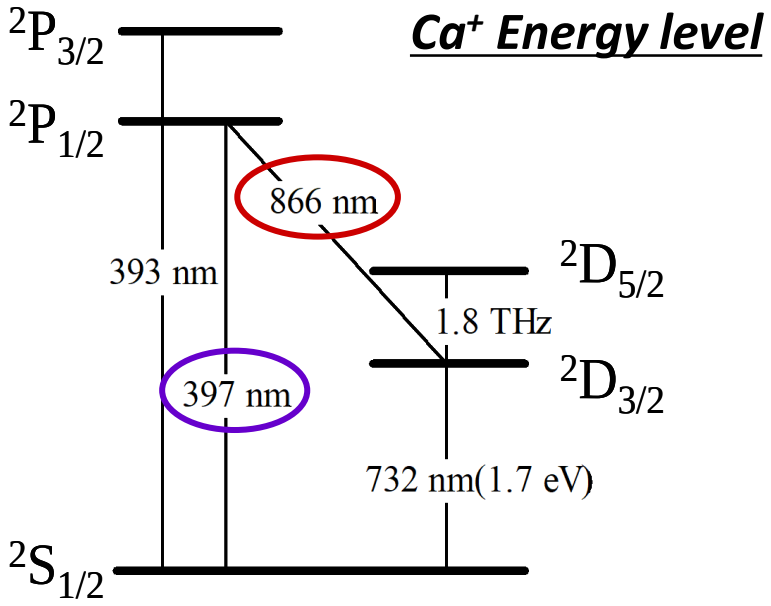
EBIT

RICE

Ca^+ Coulomb crystal @ Sophia Univ.

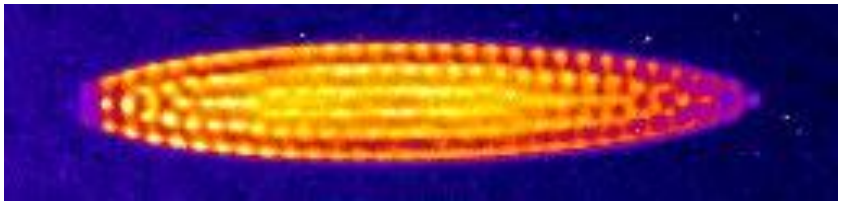
Experimental Setup





Ca^+ Energy level

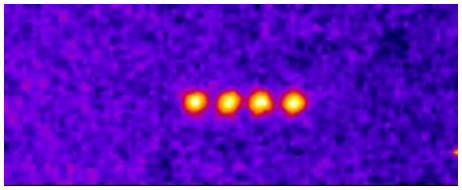
Typical Ca^+ crystal (~500 Ca^+)



1.0 mm

Sympathetic crystallization **(共同冷却)**

4 Ca^+ ⇒ 3 Ca^+, 1 CaH^+



0.39 mm

N. Kimura, *et al.*, Physical Review A 83, 033422 (2011)

様々なイオントラップ実験で覗く 原子分子の個性と可能性

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New application !! ~ Highly charged ion clock ~

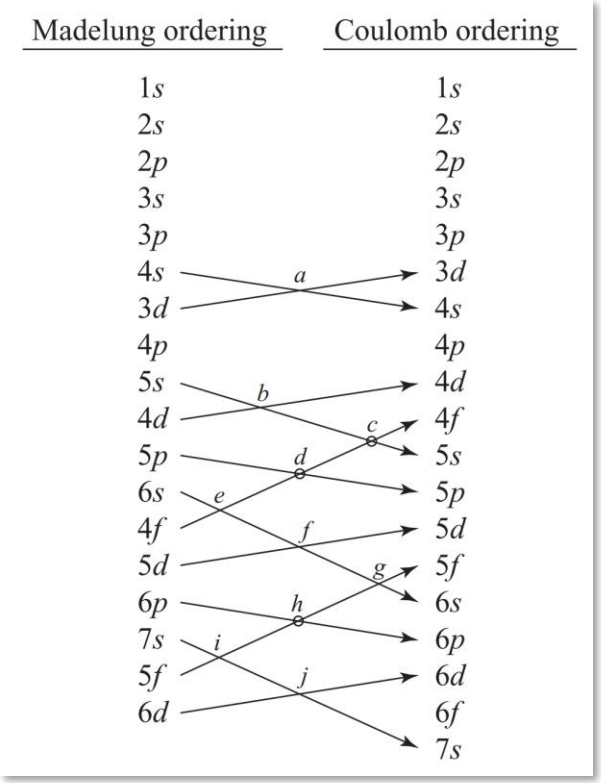
PRL **105,** 120801 (2010) PHYSICAL REVIEW LETTERS week ending 17 SEPTEMBER 2010

Enhanced Laboratory Sensitivity to Variation of the Fine-Structure Constant using Highly Charged Ions

J. C. Berengut, V. A. Dzuba, and V. V. Flambaum

School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia

(Received 8 July 2010; published 14 September 2010)



- **Particular many-electron heavy HCIs possess optical transitions**
  - **Fine-structure transition**
  - **Level crossing**
- **Insensitive to perturbations**
  - **Small Stark shift**
- **High sensitivity to the *a*-variation**

Many proposal papers for HCI clocks have been published !!

J. C. Berengut *et al.*, Phys. Rev. A 86, 022517 (2012)

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Summary

- Decay dynamics の研究を例に、独自の装置と手法を駆使して原子分子の個性を観る実験を紹介した
- これまで経験した幅広いイオントラップ技術を組み合わせ、HCI分光を周波数計測へ昇華させる研究に挑戦したい

Thank you for your attention !!