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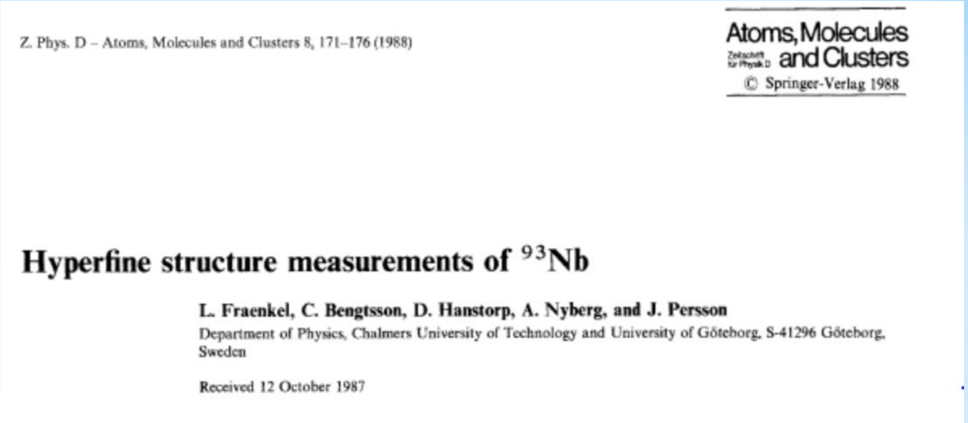
Dag Hanstorp

High Precision Spectroscopy of Negative Ions

Laser spectroscopy as a tool for nuclear theories
CEA, Orme des Merisiers Campus, Gif-sur-Yvette
October 7-11 2019

The first paper in my career:

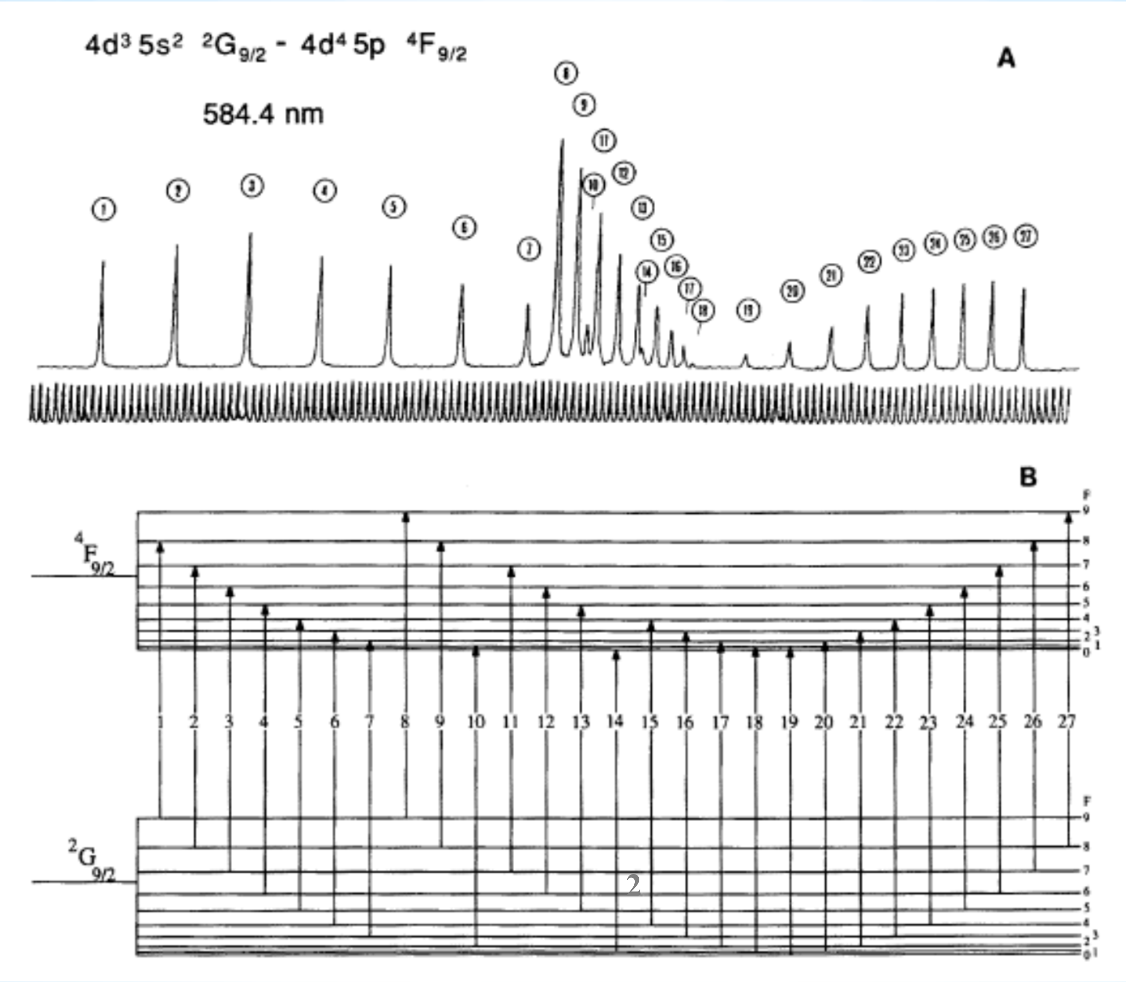

Z. Phys. D – Atoms, Molecules and Clusters 8, 171–176 (1988)

Atoms, Molecules and Clusters
Zeitschrift für Physik D

Hyperfine structure measurements of ^{93}Nb

L. Fraenkel, C. Bengtsson, D. Hanstorp, A. Nyberg, and J. Persson
Department of Physics, Chalmers University of Technology and University of Göteborg, S-41296 Göteborg, Sweden

Received 12 October 1987




new scientist
14 June 1973
Vol 58 No 850
Weekly 15p
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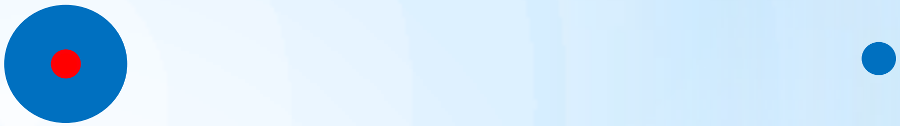
Canada 60 cents/
New Zealand 35 cents/
South Africa 35 cents/
USA (by air) 90 cents/
BF 25/FF 3/DM 2.80/
hfl 1.75/skr 3.00/
Are negative ions good for you?

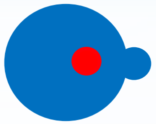
Long range forces in atomic systems

Coulomb force ~ $\frac{1}{r}$

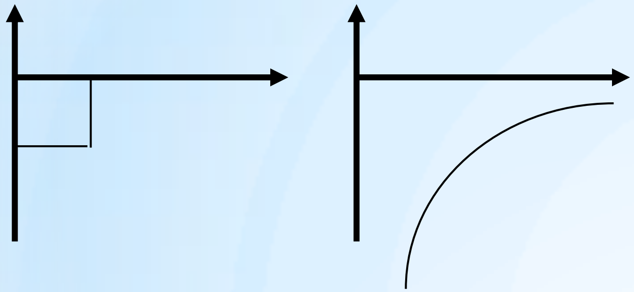


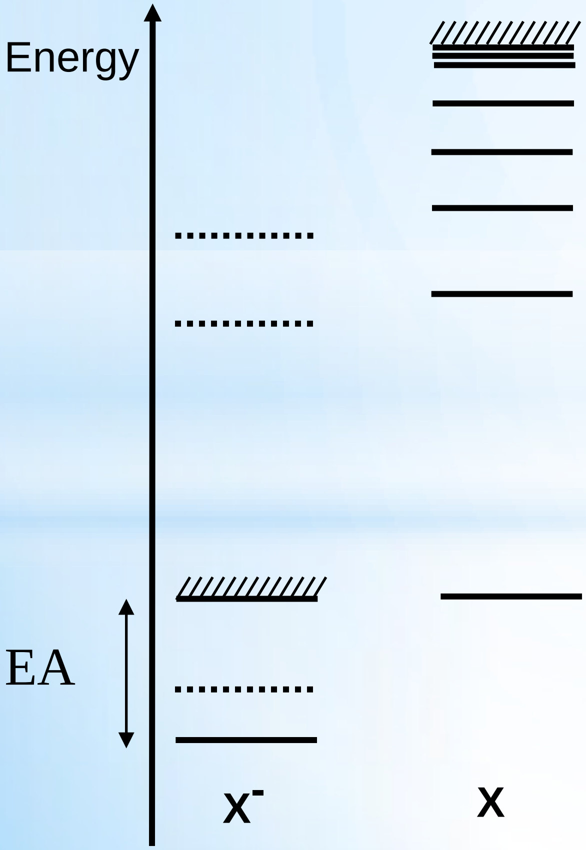
Polarisation ~ $\frac{1}{r^4}$

Penetration ~ $\frac{1}{e^r}$



Properties of Negative Ions





- Small binding energy (appr. 1 eV)
- Few (if any) excited states
- Almost no excited states with opposite parity (only observed in Os^-, Ce^- and La-)

→ Lack of optically allowed transitions

- Electron correlation of great importance

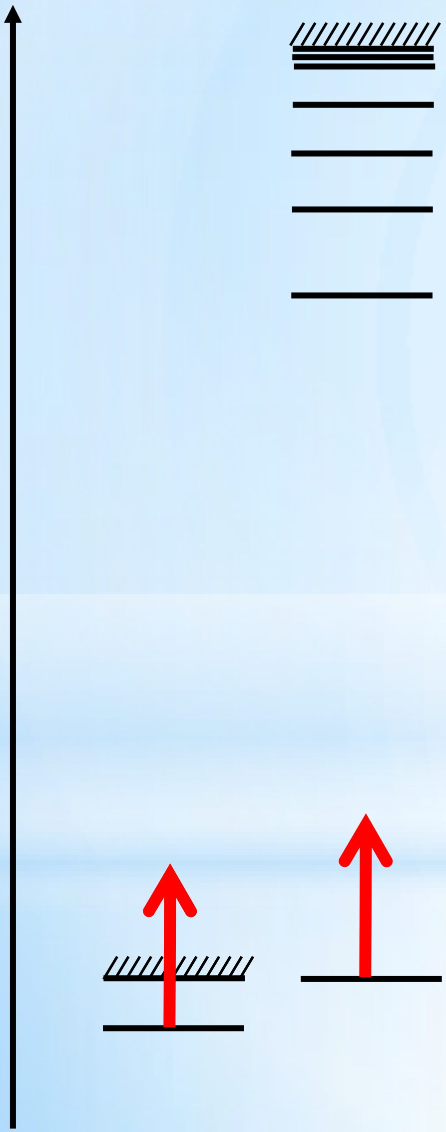
Why is the sun yellow?

Blackbody radiation
At T = 5780 K

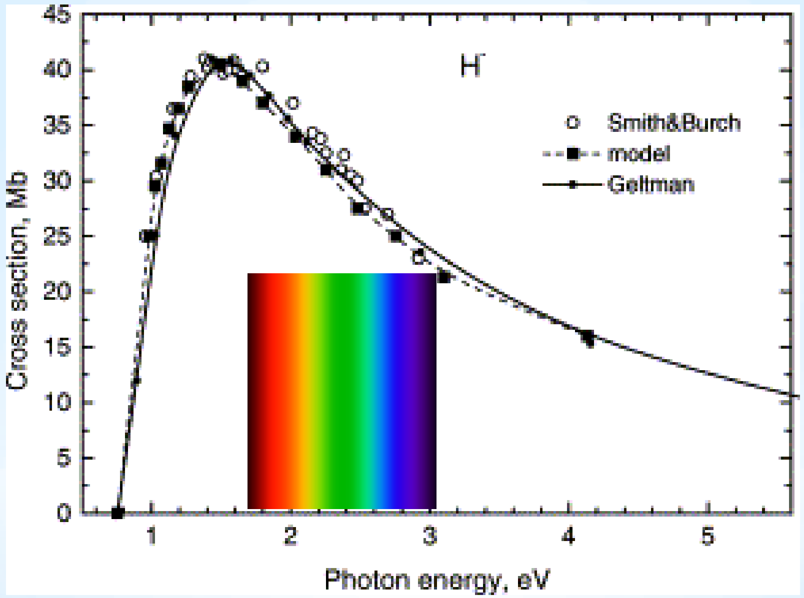
Fusion reactions
require

T = 100 MK

Energy



H^- H



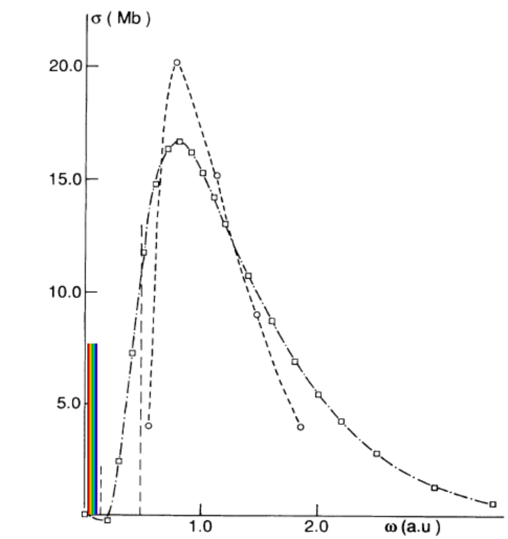


FIG. 2. Computed total absorption (photoionization) cross section for OH. □, present results; ○, Stephens and McKoy [7] (length form). The vertical dashed lines indicate the ionization threshold and the energy of the first excited $A\,^2\Sigma^+$ state, respectively.

Ivanov VK
RADIATION PHYSICS AND CHEMISTRY
70 (1-3): 345-370 MAY-JUN 2004

Veset L., Kelly, H. P.
PRA
45 (1991) 4621

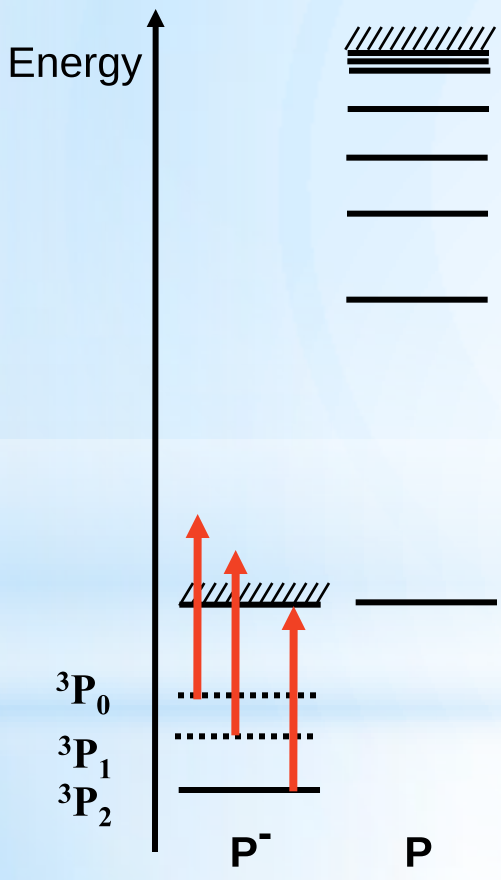
(Wildt, R. 1941, ApJ, 93, 502)

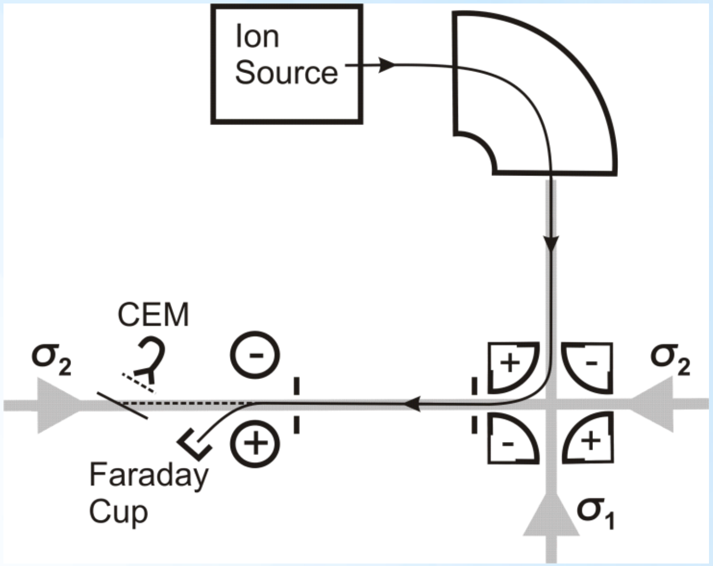
Why study negative ions?

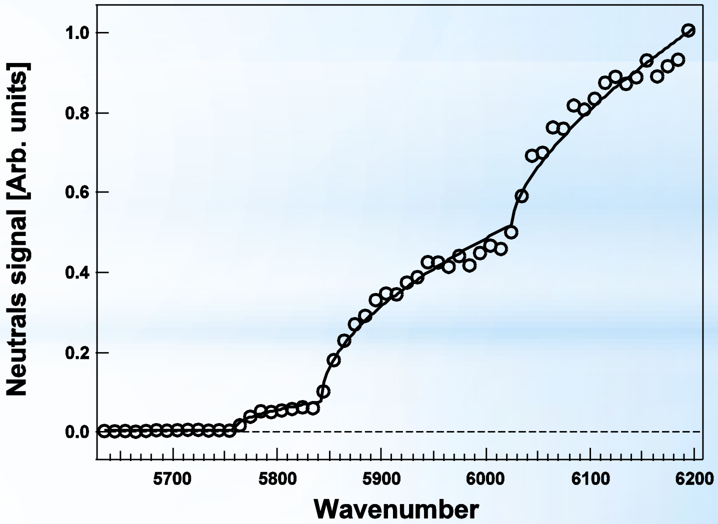
- Benchmark for electron correlation theory
- Single state system
- Efficient method to produce groundstate atoms
    - Heating of thermonuclear reactors
    - Accelerator Mass Spectrometry
- Sympathetic cooling of antiprotons

Laser photodetachment Threshold Spectroscopy

$$P^- + h\nu \rightarrow P + e^-$$







Andersson *et al.*
J. Phys. B **40** (2007) 4097.

The Wigner law: $\sigma = k\,(E-E_{EA})^{l+1/2}$

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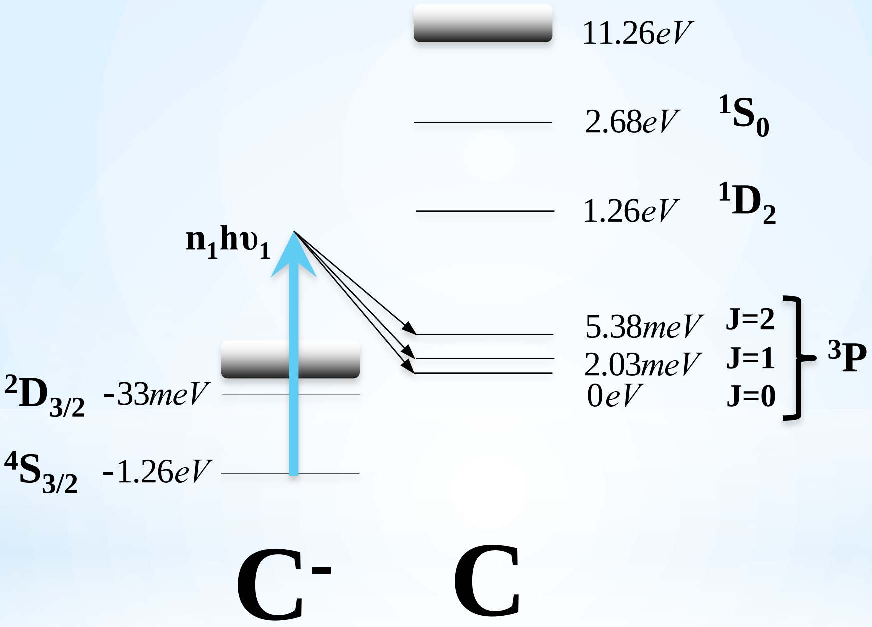
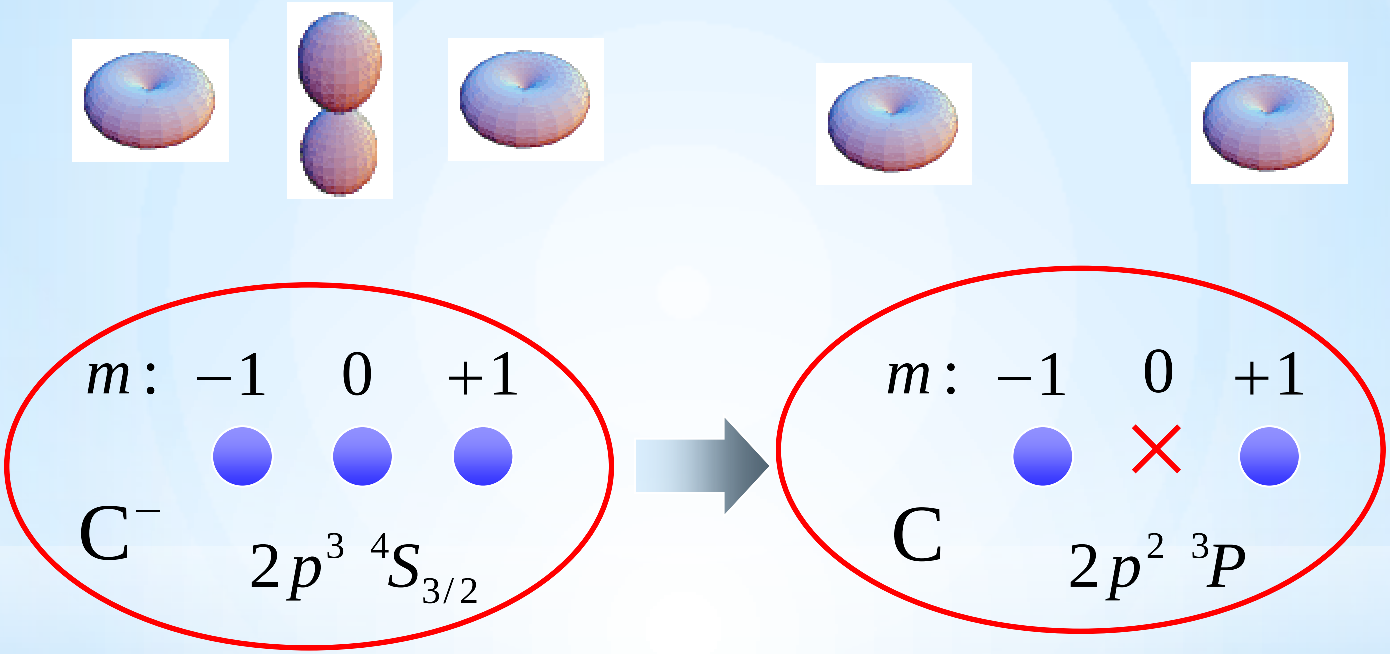
Visualization of electronic motion in an atomic ground state

Energy levels of C^- and C

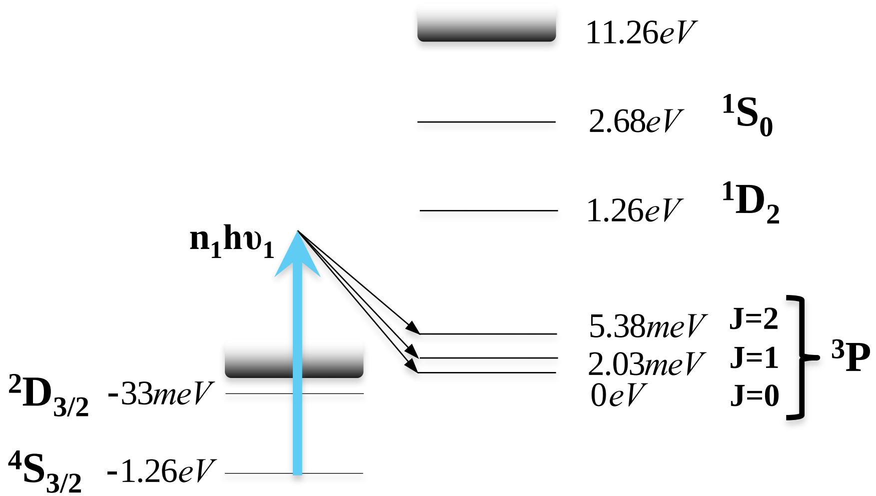


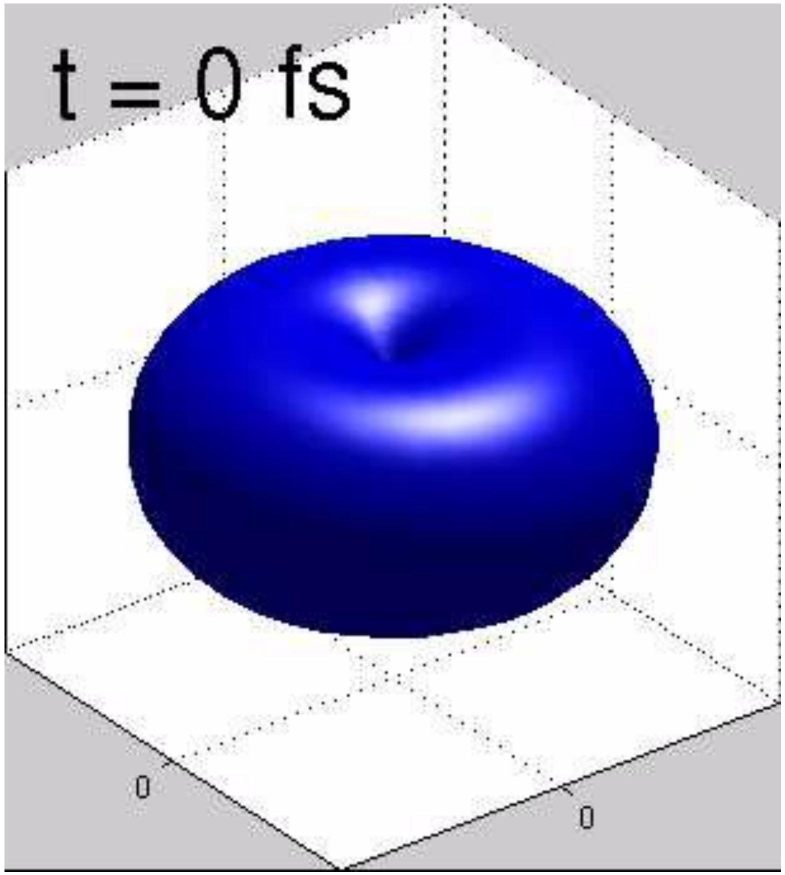
Photodetachment in a strong field:



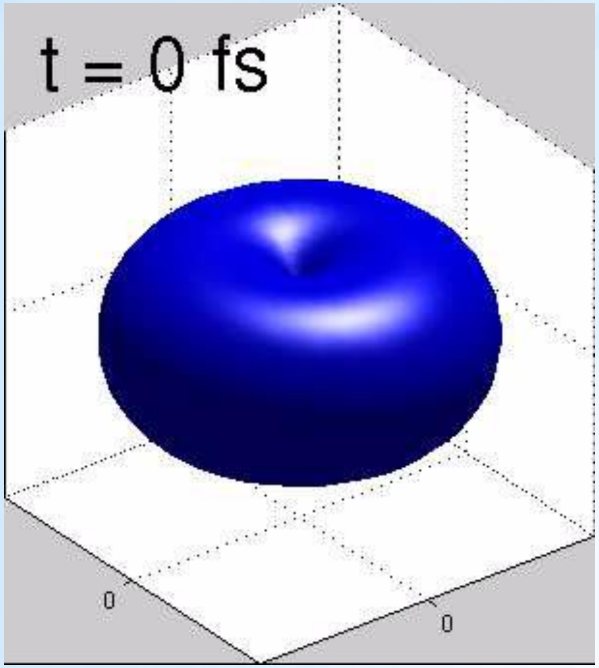
$$w_{m=0} >> w_{m=\pm 1}$$

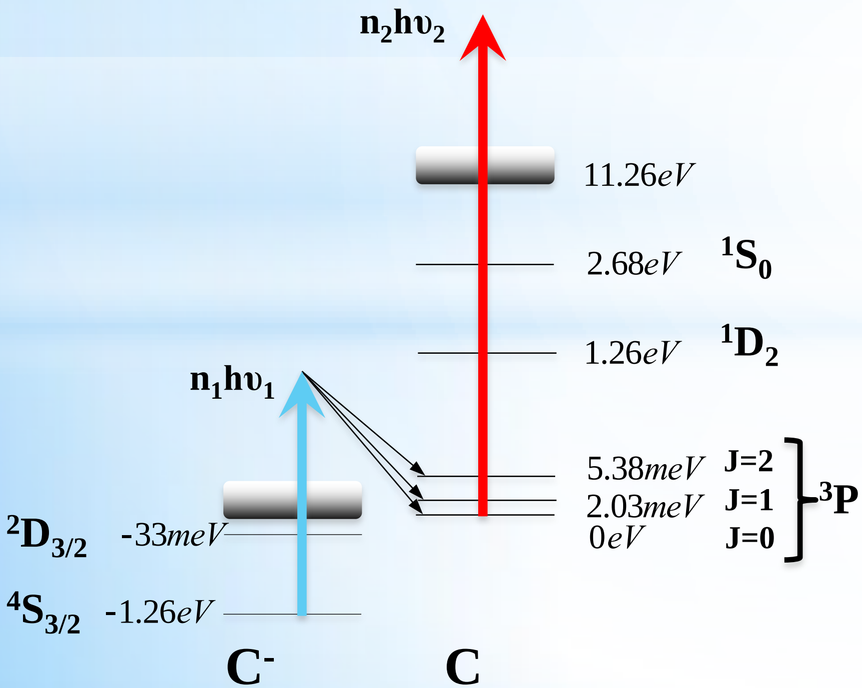
N. Rohringer and R. Santra, Phys. Rev. A **79**, 053402 (2009)

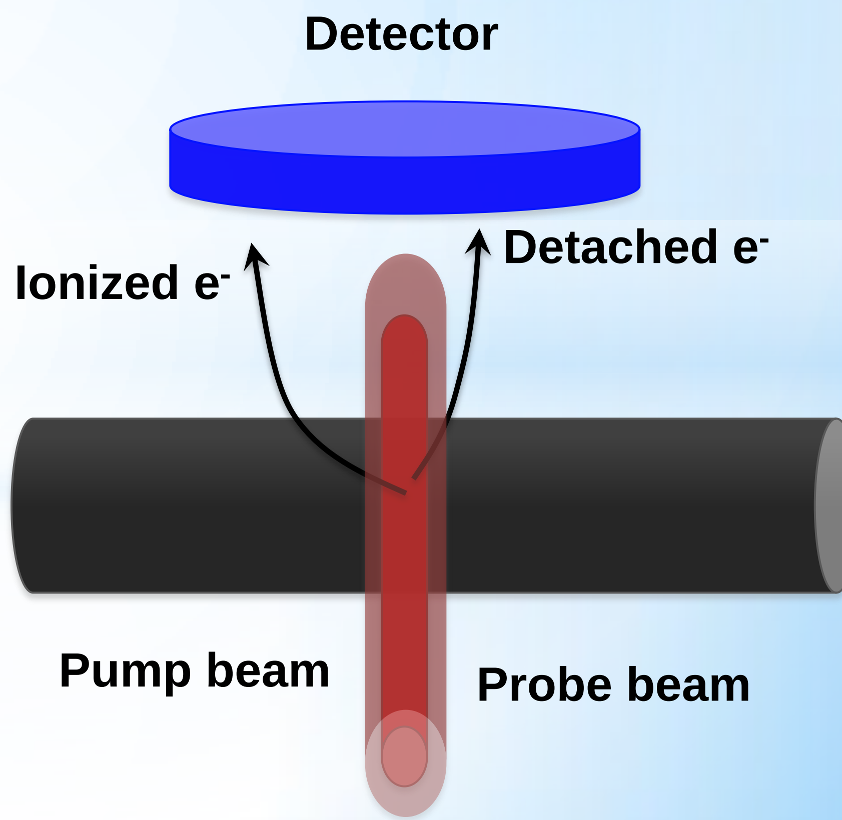


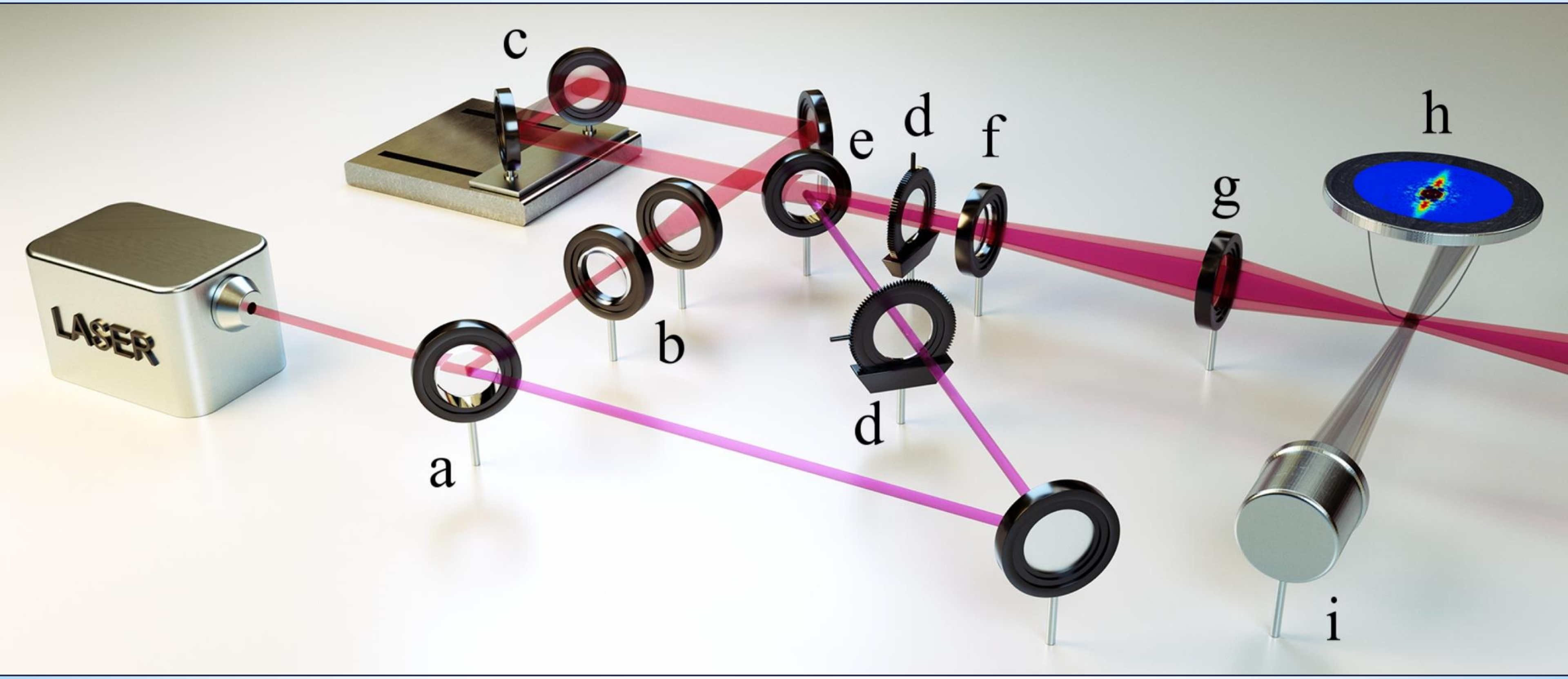


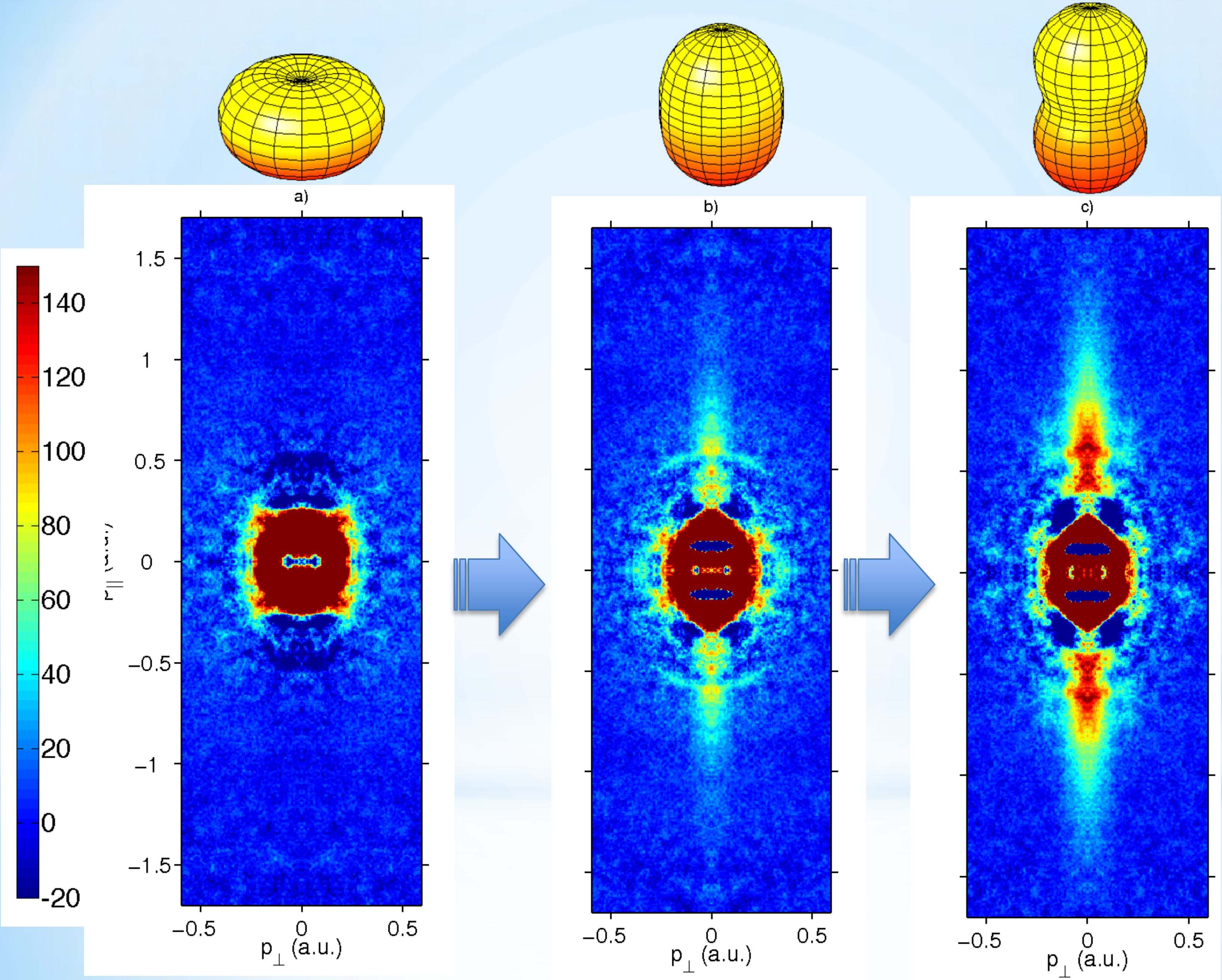
Bandwidth of laser > Fine structure splitting of C → Coherently populated states

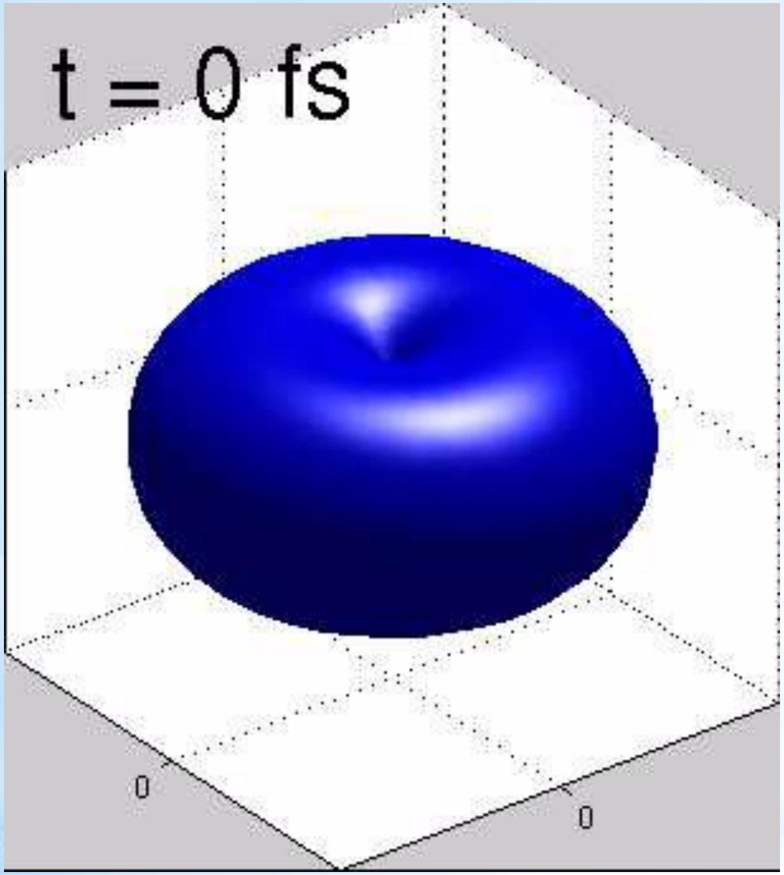

t = 0 fs
0
0


n₂hυ₂
11.26eV
2.68eV
¹S₀
1.26eV
¹D₂
n₁hυ₁
5.38meV
2.03meV
0eV
J=2
J=1
J=0
³P
²D3/2
-33meV
⁴S3/2
-1.26eV
C⁻
C

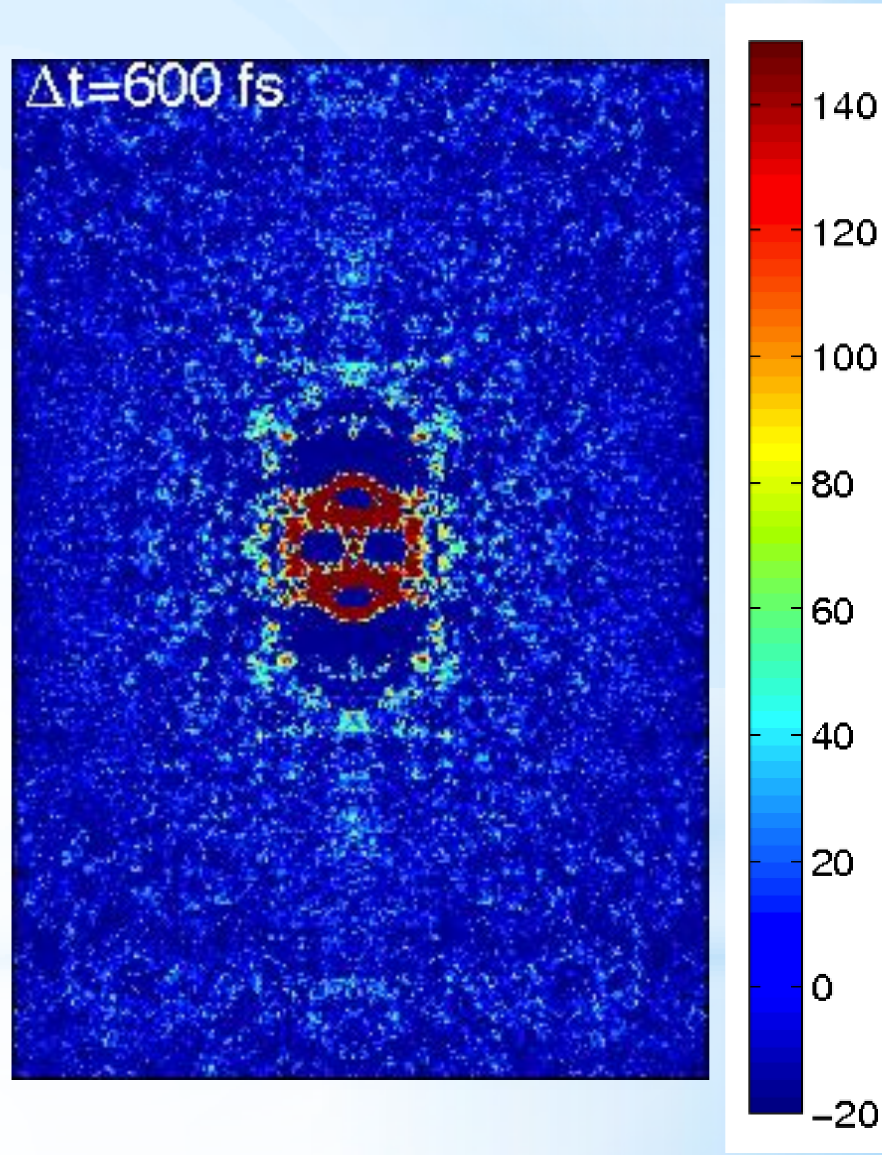

Detector
Ionized e⁻
Detached e⁻
Pump beam
Probe beam


c
d
e
f
h
g
LASER
b
d
a
i

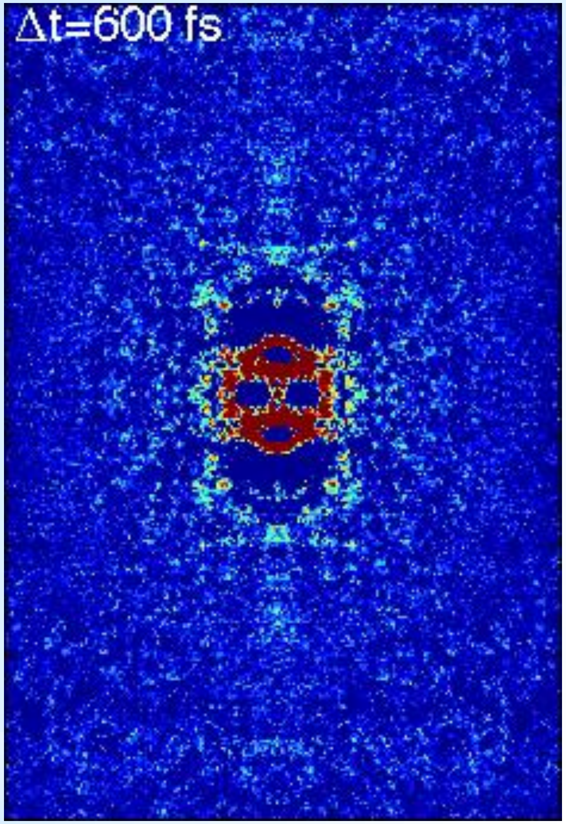

a)
b)
c)
140
120
100
80
60
40
20
0
-20
1.5
1
0.5
0
−0.5
−1
−1.5
−0.5
0
0.5
p⊥ (a.u.)
p⊥ (a.u.)
p⊥ (a.u.)

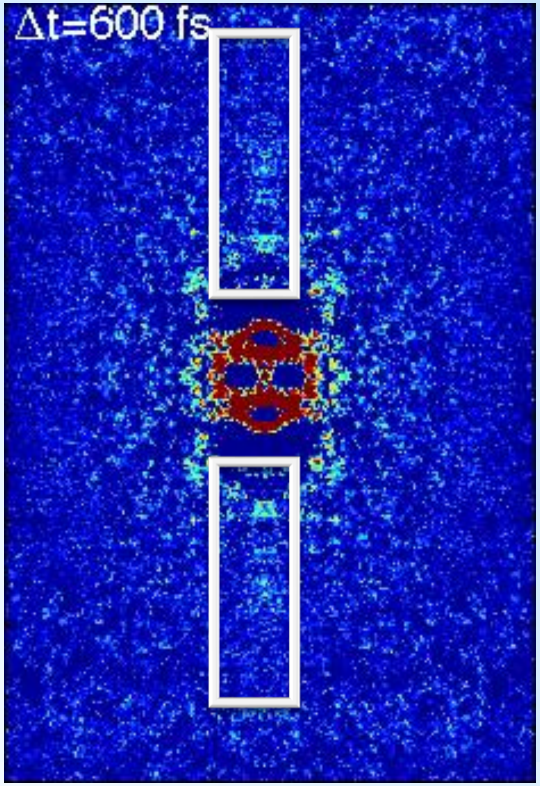


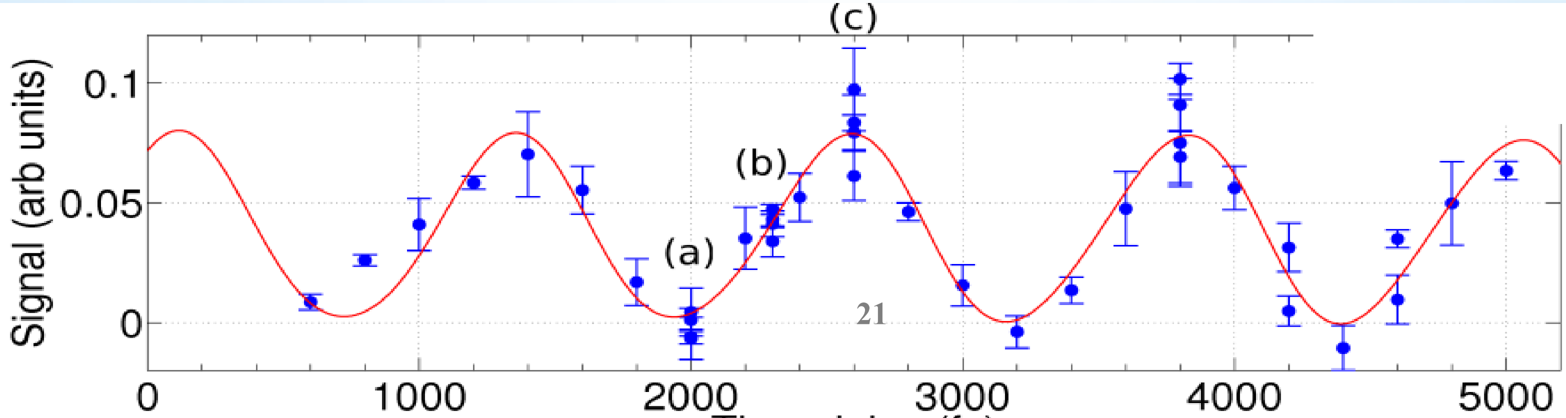
Laser Polarization



Laser Polarization







The electron affinity of Astatine

Astatine

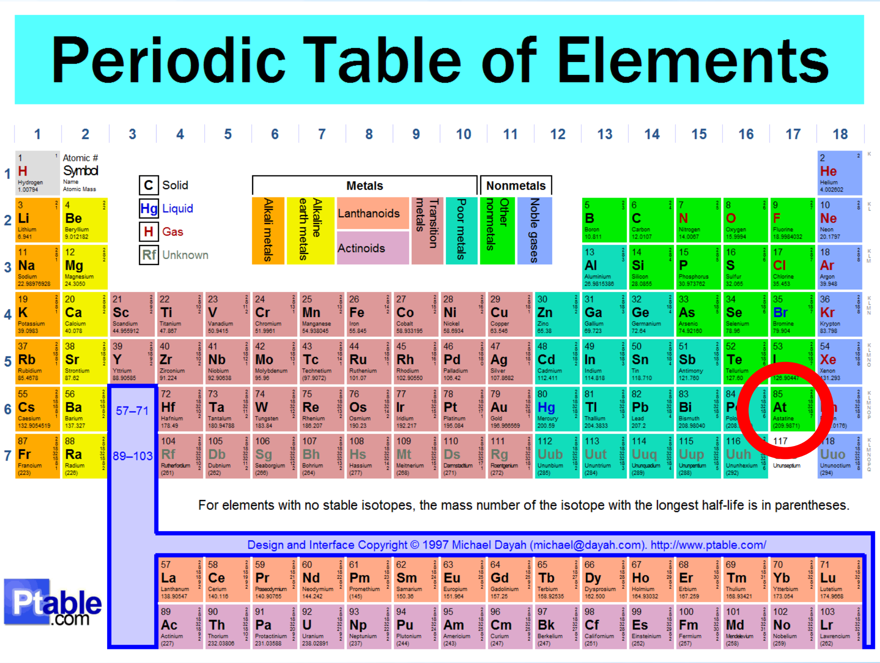
- Least abundant element on earth

- 70 mg in the crust of the earth
 (1 atom per 100 kg mass)

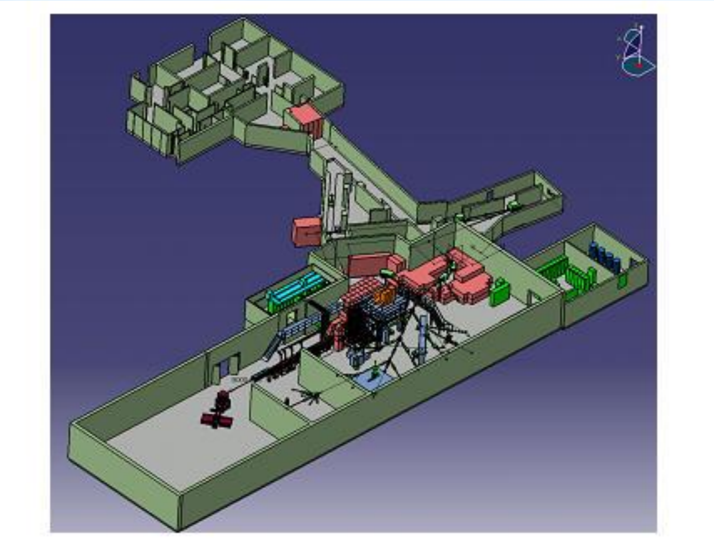
- Decays through α-decay

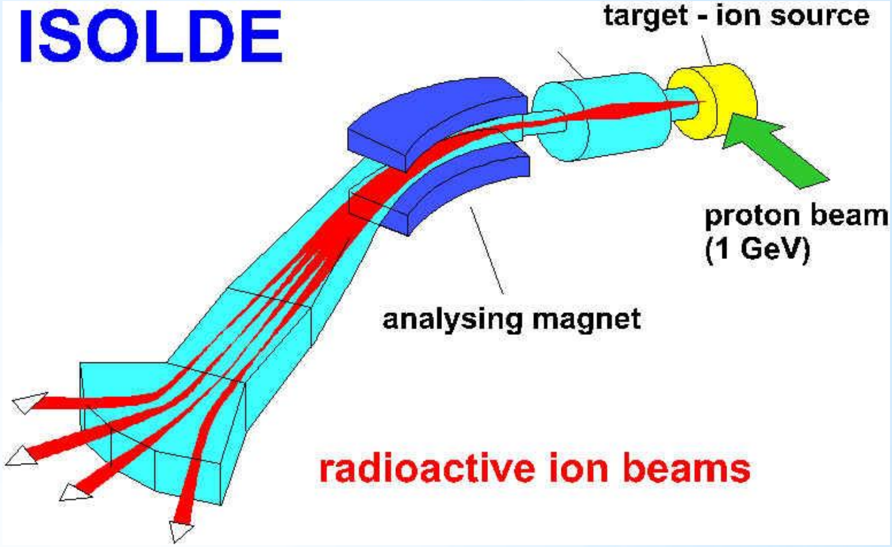
- Small knowledge about its
 chemical and physical properties

- Used in cancer treatment
 Targeted Alfa Therapy (TAT)
 (suitable lifetime and energy,
 non-toxic, non-radioactive daughters)



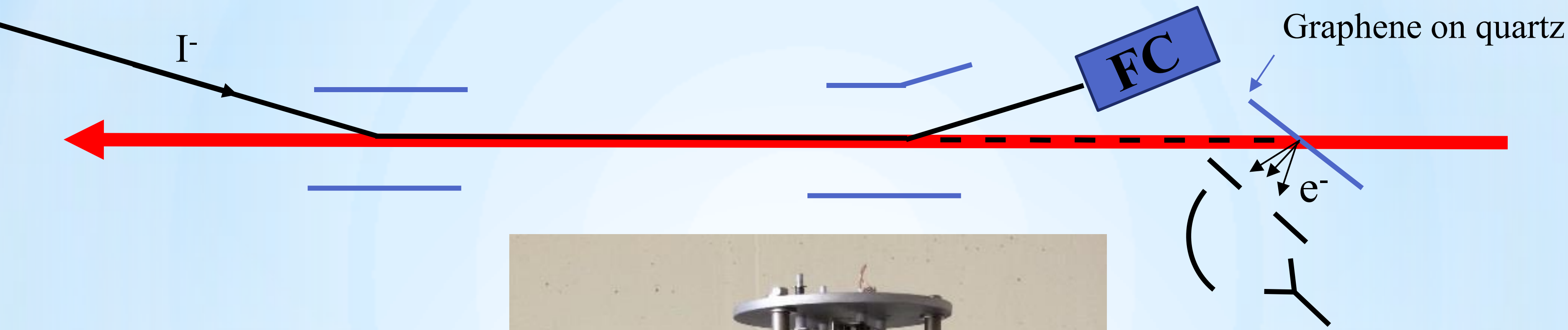
Experimental program at ISOLDE





GANDALPH

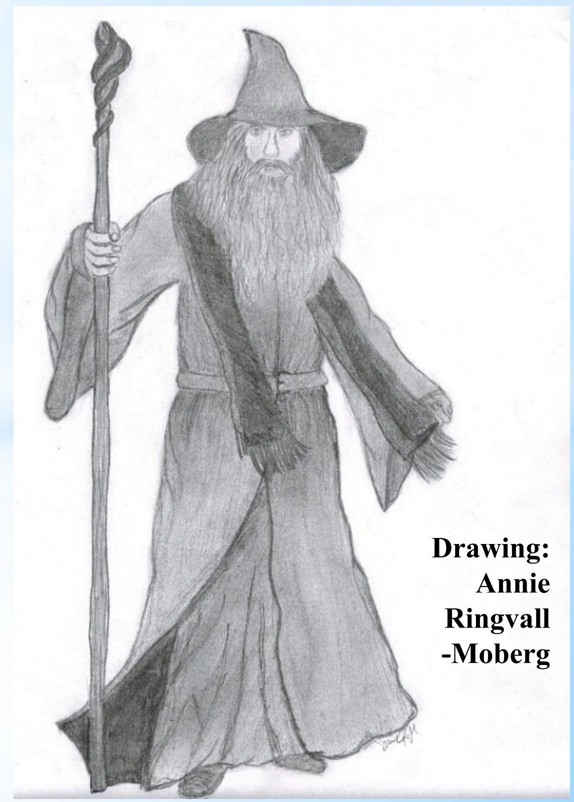
Gothenburg **AN**ion **D**etector for **A**ffinity measurements by **L**aser **PH**otodetachment



For each laserpuls:

Signal:
0.01 atom

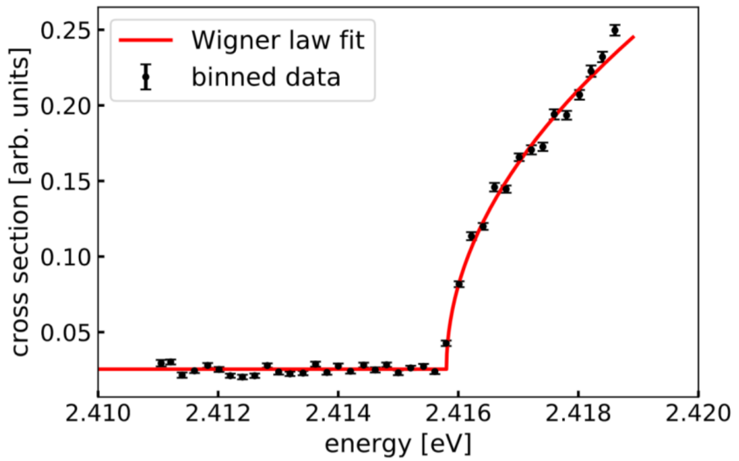
Background:
10^{14} photons



Drawing: Annie Ringvall -Moberg

The animated Astatine experiment!

RESUTLS



Method	EA/eV	Ref.
CBS-DC-CCSDT(Q)+Breit+QED	2.414(16)	this work
2c-DFT[1]	2.30	43
MCDHF+SE corr.[2]	2.38(2)	44
MCDHF	2.416	10
DC-CCSD(T)+Breit+QED	2.412	45
MCDHF+Extrap. [3]	2.3729(46)	7
CBS-DC-CCSD(T)+Gaunt+QED	2.423(13)	8
Experiment	2.415 78(5)	this work

Property	Definition	Value
Electron affinity	EA	$2.415\,78(5)$ eV
Ionization energy	IE	$9.317\,51(8)$ eV[20]
Electronegativity	$\chi_M = \frac{IP+EA}{2}$	$5.866\,65$ eV
Hardness	$\eta = IE - EA$	$6.901\,72(13)$ eV
Softness	$S = \frac{1}{\eta_2}$	$0.144\,89(2)$ eV^{-1}
Electrophilicity	$\omega = \frac{\chi^2}{2\eta}$	$2.493\,41(8)$ eV

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Isotope shifts in the Electron affinity

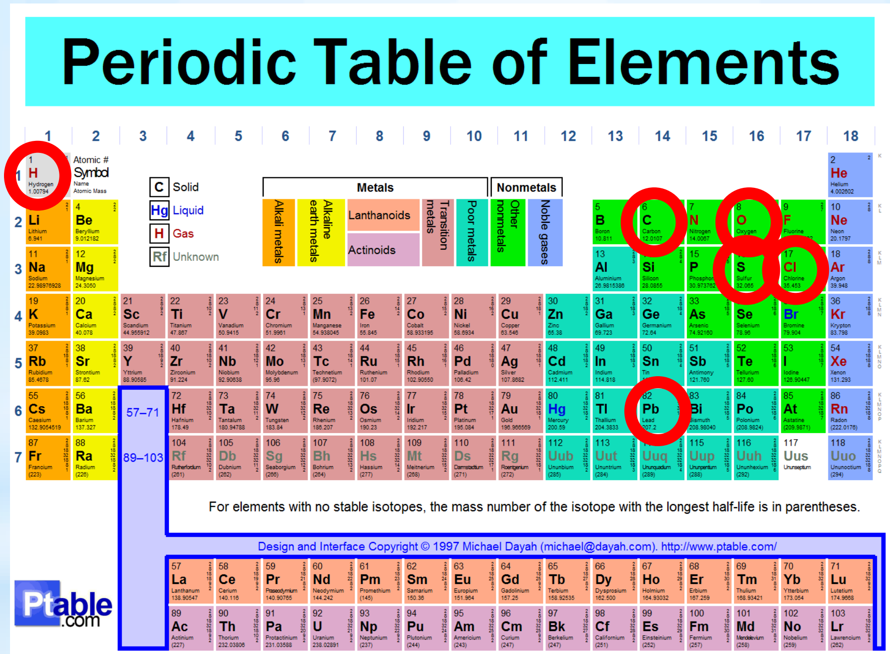
Isotope shift

IS = NMS + SMS + VS

Observable — Trivial — Atomic Physics — Nuclear Physics

Isotope shift in electron affinity

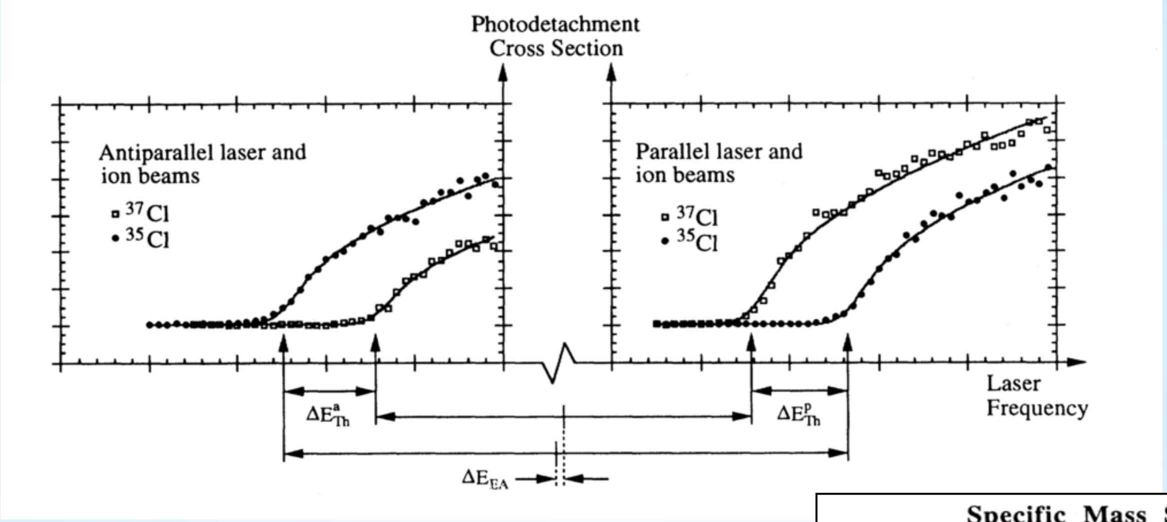
Ideal test case for electron correlation

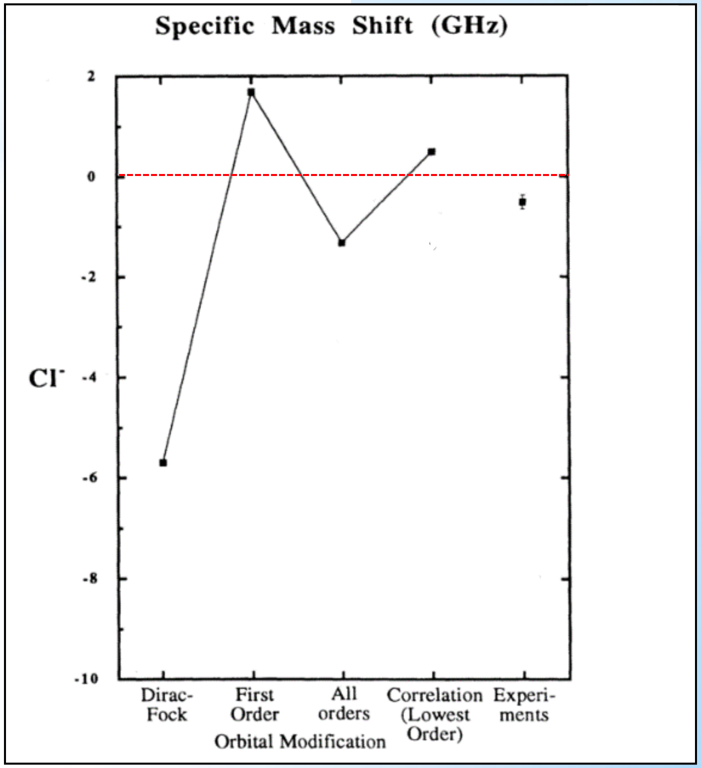


^{1}H/ ^{2}H	Lykke, Murray and Lineberger, *Phys. Rev. A* **43** (1991) 6104
^{35}Cl/37Cl	Berzinsh et al. *Phys. Rev. A* **51**, (1995) 231
^{16}O/ ^{17}O / ^{18}O	Blondel et al. *Phys. Rev. A* **64** (2001) 052504
^{32}S/ ^{34}S	Carette, et al. *Phys. Rev. A* **81** (2010) 042522
^{12}C/ ^{13}C	Bresteau, Drag and Blondel, *Phys. Rev. A* **93** (2016) 013414
^{206}Pb / ^{208}Pb	Chen and Ning, *J. Chem. Phys.* **145** (2016) 084303

Only stable isotopes investigated

Isotope shift in EA of $^{35/37}Cl$





SMS = — 0.51(14) GHz

Berzinsh et al. *Phys. Rev. A* **51**, (1995) 231

Isotope shift in EA of $^{35/37}$Cl

IOP PUBLISHING — JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS
J. Phys. B: At. Mol. Opt. Phys. **46** (2013) 095003 (10pp) — doi:10.1088/0953-4075/46/9/095003

Isotope shift on the chlorine electron affinity revisited by an MCHF/CI approach

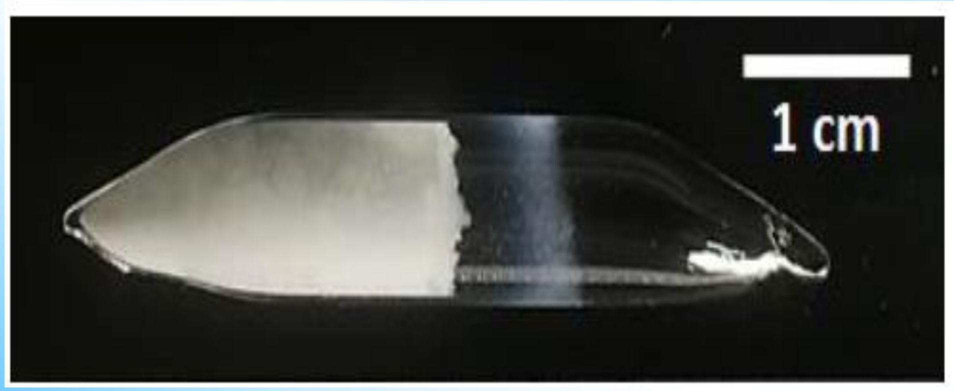
T Carette[1,2] and M R Godefroid[2]

	SMS	MS	FS	RIS	IS
			This work		
HF	−1.348	−0.607	−0.003(22)	−1.351(22)	−0.610(22)
val. FC−MCHF	−0.674	+0.067	−0.002(20)	−0.676(20)	+0.065(20)
val. MCHF	−0.495	+0.246	−0.003(21)	[illegible]	+0.244(21)
final results	−0.535(51)	+0.206(51)	−0.003(22)	−0.538(72)	+0.203(72)
			Berzinsh *et al* [[illegible]7]		
Exp.				−0.51(14)	+0.22(14)
DF	−1.3	−0.6	+0.014(14)	[illegible]	−0.6
MB low corr.	+0.50	+1.24	+0.014(14)	+0.51(2)	+1.26(2)

* Isotope shift of chlorine - offline

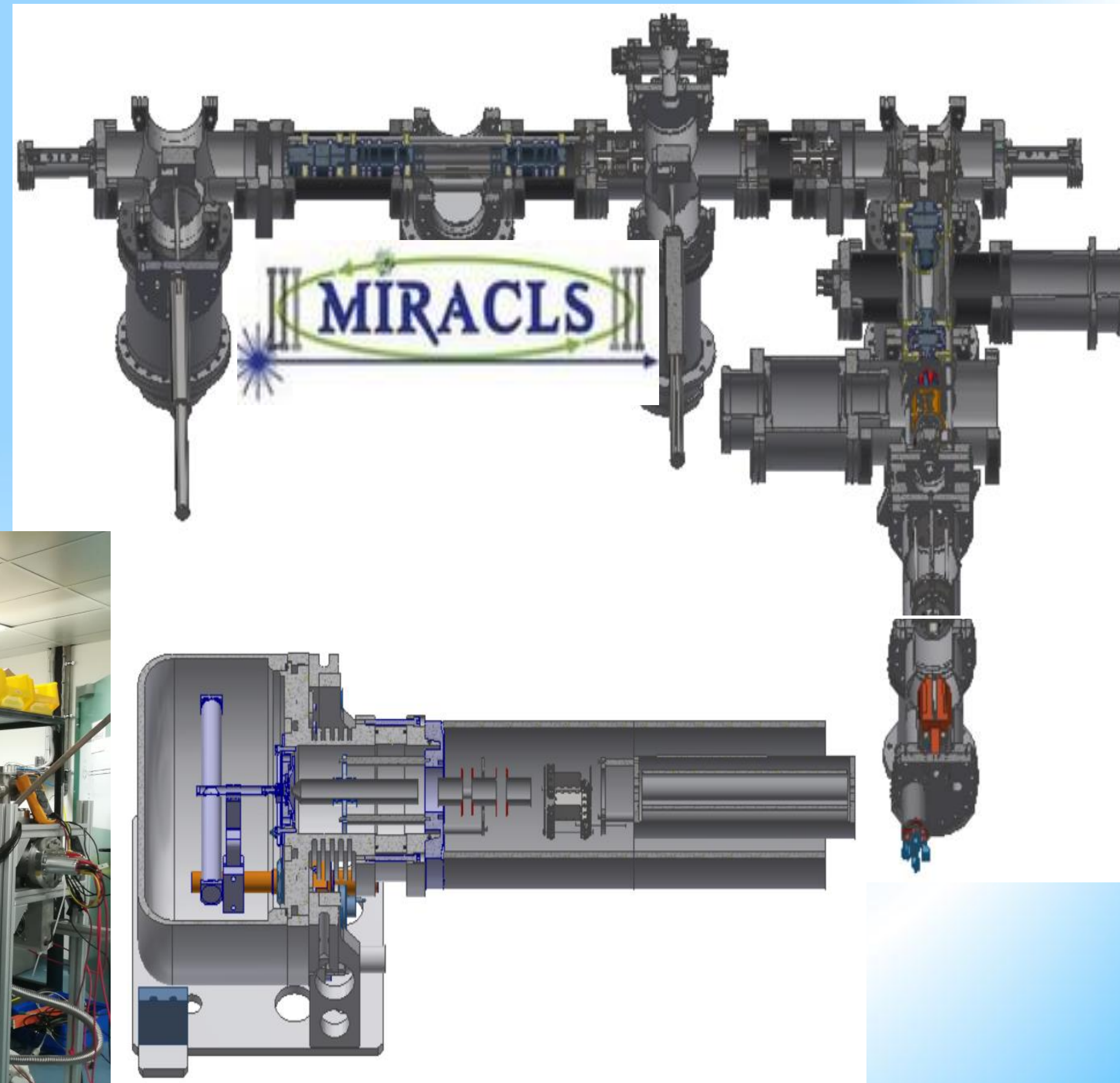
First goal: measure IS for ^{35}Cl, ^{36}Cl, ^{37}Cl

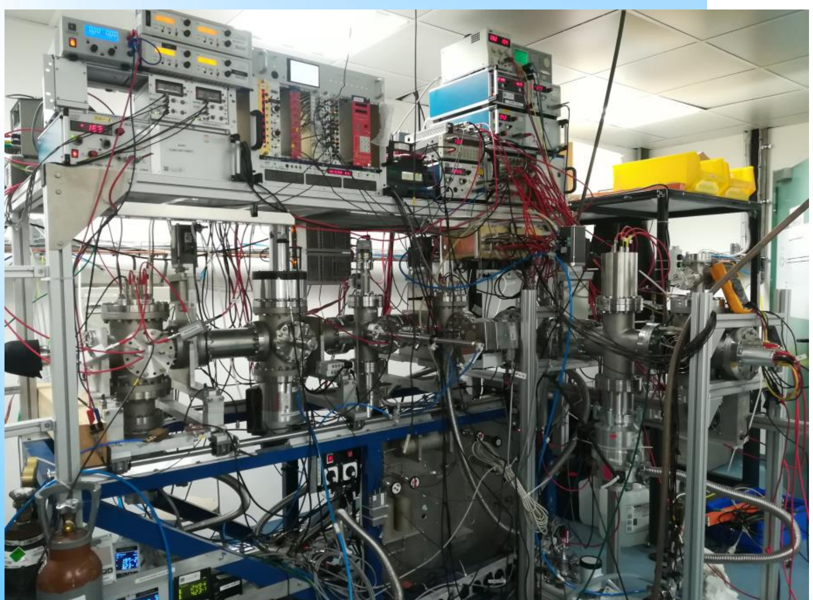
* Preparation of irradiation of $MgCl_2$ at ILL ongoing
    * 1mg $MgCl_2$ results to ~14µAh beam of ^{36}Cl



* Isotope shift of chlorine - offline

^{35}Cl, ^{36}Cl, ^{37}Cl





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Stockholm University

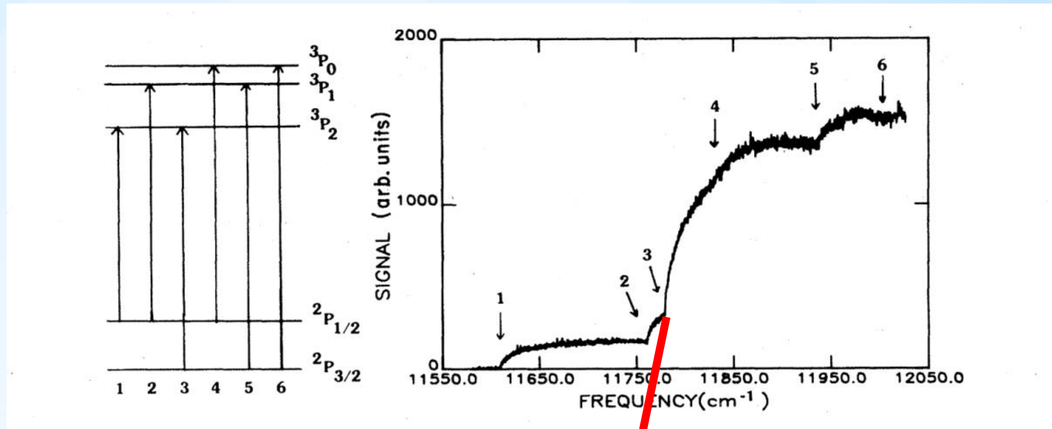
Photodetachment using an electrostatic storage ring

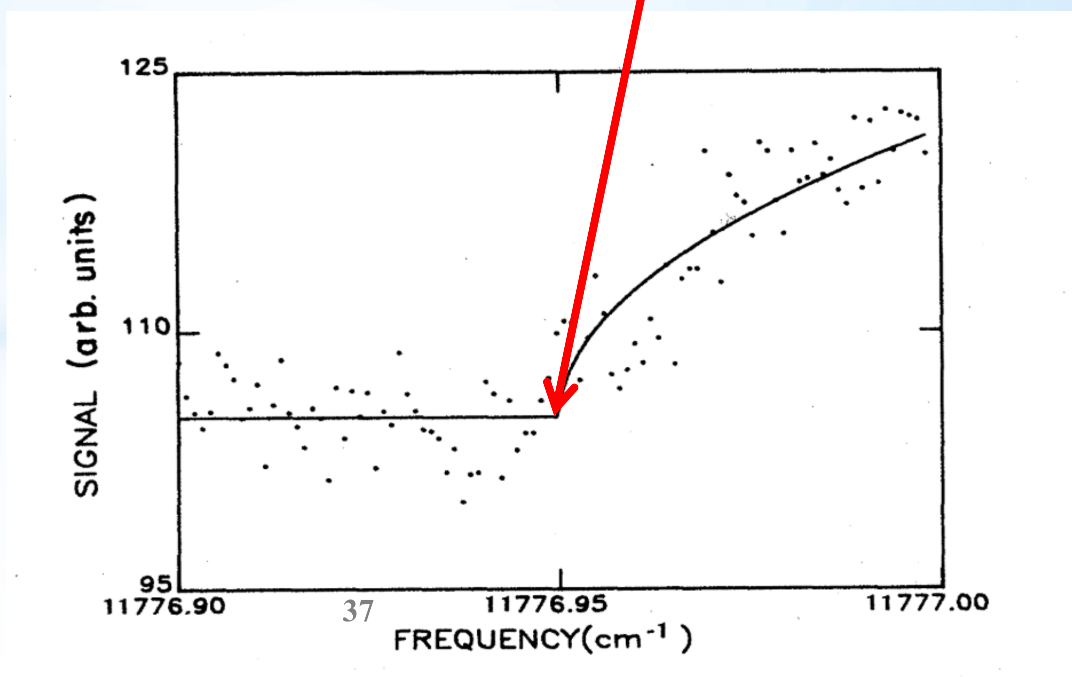
PHYSICAL REVIEW A VOLUME 32, NUMBER 3 SEPTEMBER 1985

Laser photodetachment measurement of the electron affinity of atomic oxygen

D. M. Neumark, K. R. Lykke, T. Andersen,* and W. C. Lineberger

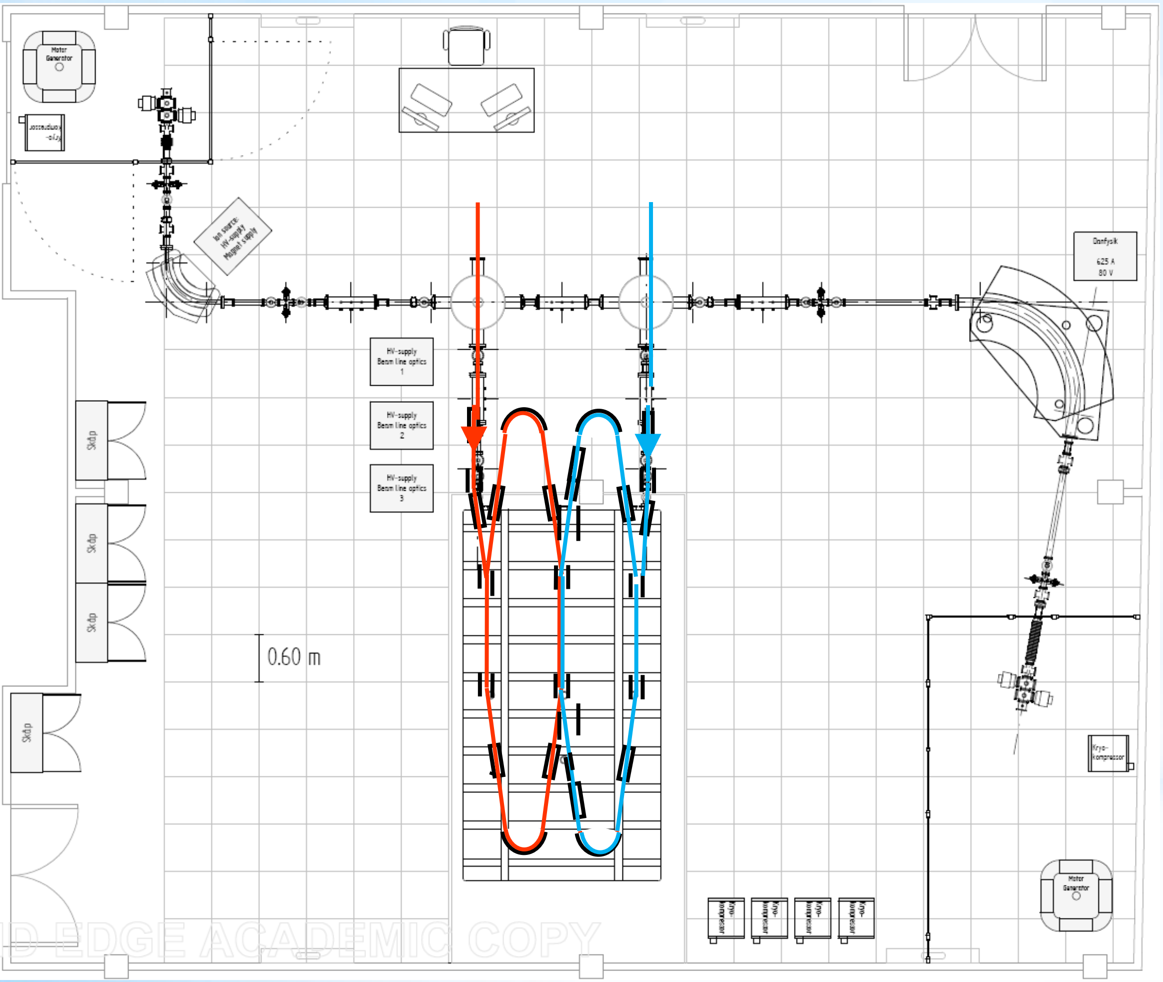
$O^- + h\nu \rightarrow O + e^-$





DESIREE – Double Electrostatic Ion Ring Experiment

A Swedish national facility at Stockholm university



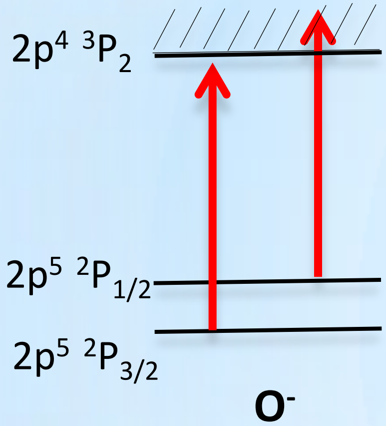
T = 13 Kelvin
p = 10^{-14} mbar
ρ = 10^{4} H_2 per cm^3
E_{kin} = 10-30 keV
Mass range 1 – thousands amu
(so for up to Cu_{33})
Storage times > 1 hour
Kollissions energies
(center-of-mass) = meV - keV

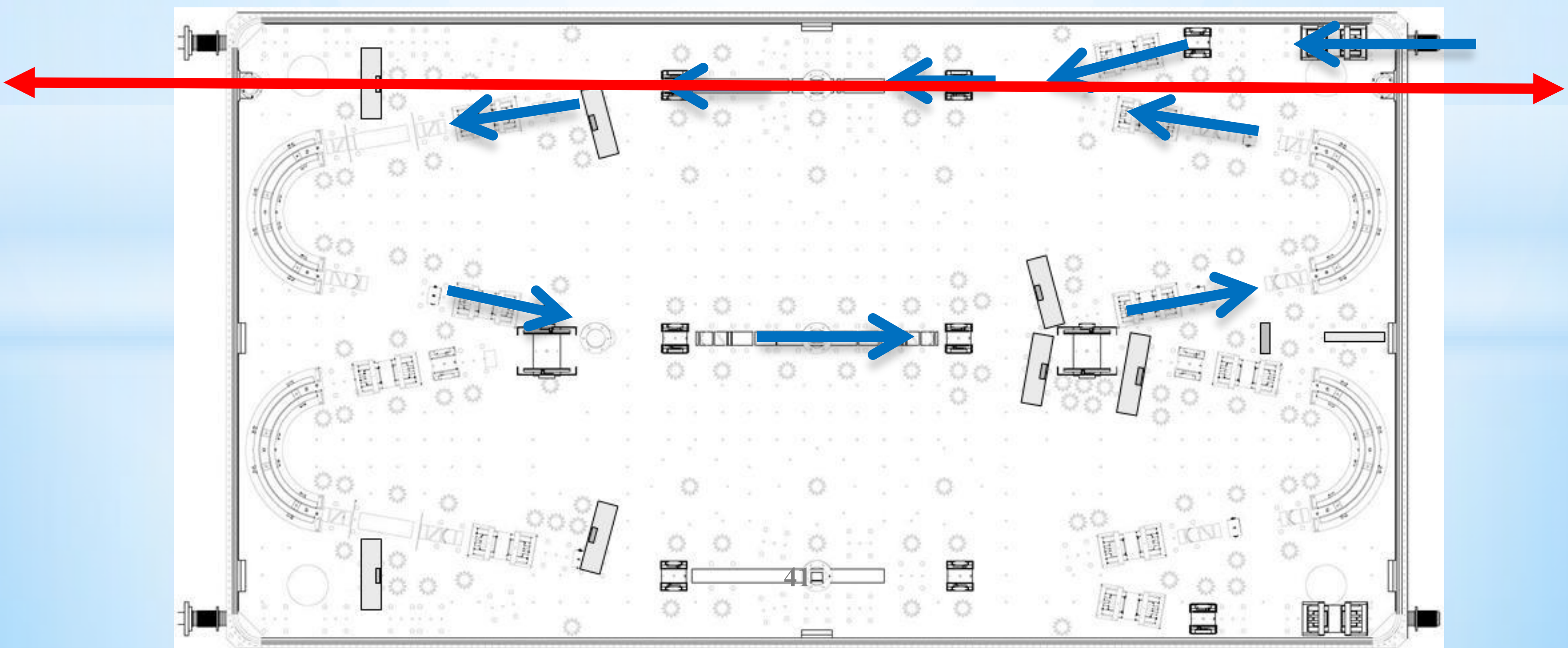
Construction time ≈10 years
Construction cost ≈ 15MEURO

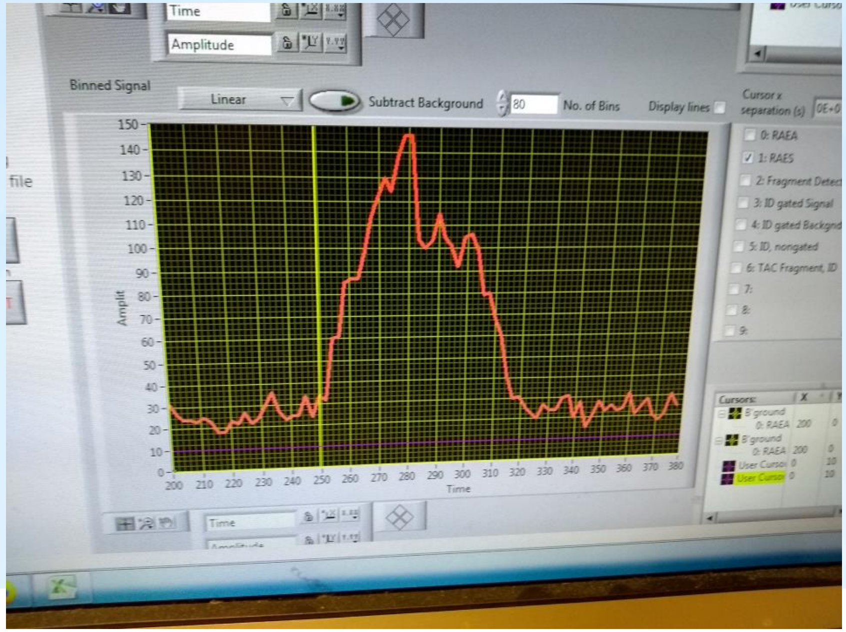
→ ***Physics at conditions of the interstellar media***

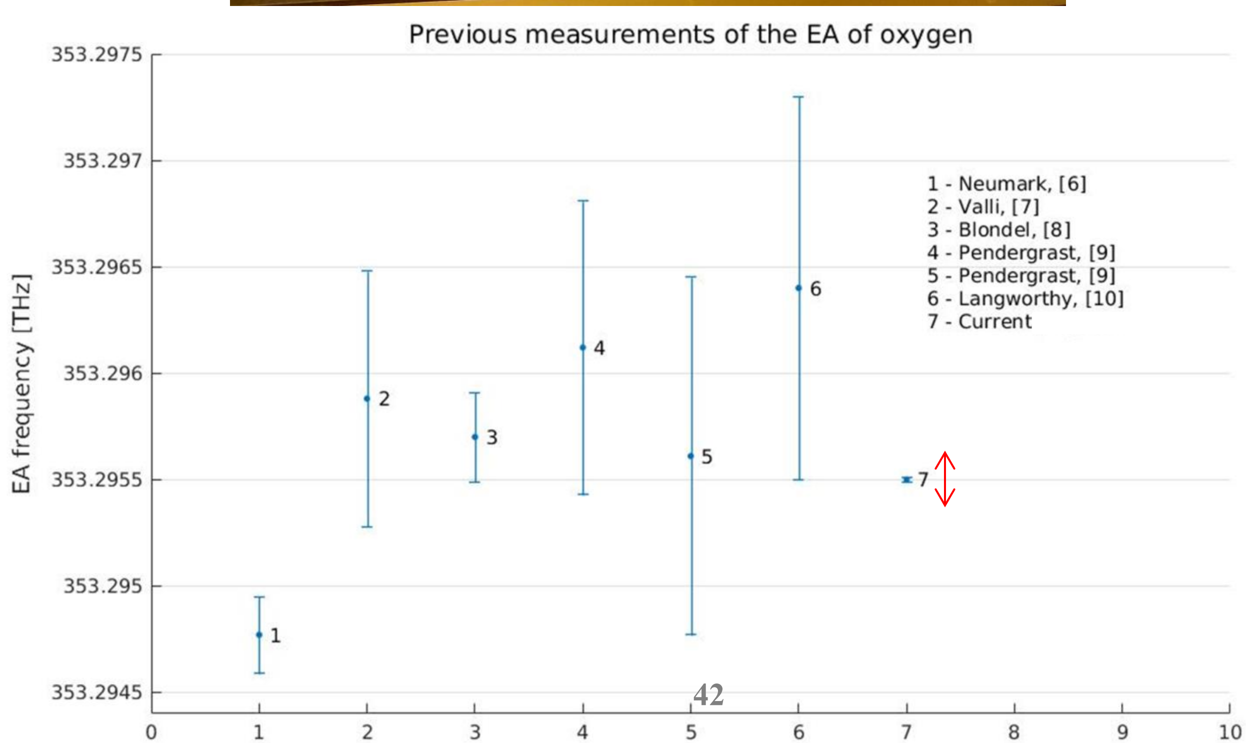
Measuring the EA of O^-

$$O^- + h\nu \rightarrow O + e^-$$






Time
Amplitude
Binned Signal
Linear
Subtract Background
80
No. of Bins
Display lines
Cursor x separation (s)
0: RAEA
1: RAES
2: Fragment Detec
3: ID gated Signal
4: ID gated Backgnd
5: ID, nongated
6: TAC Fragment, ID
Amplit
Time
Cursors:


Previous measurements of the EA of oxygen
EA frequency [THz]
353.2975
353.297
353.2965
353.296
353.2955
353.295
353.2945
0
1
2
3
4
5
6
7
8
9
10
1 - Neumark, [6]
2 - Valli, [7]
3 - Blondel, [8]
4 - Pendergrast, [9]
5 - Pendergrast, [9]
6 - Langworthy, [10]
7 - Current


new scientist
14 June 1973
Vol 58 No 850
Weekly 15p
Australia 35 cents/
Canada 60 cents/
New Zealand 35 cents/
South Africa 35 cents/
USA (by air) 90 cents/
BF 25/FF 3/DM 2.80/
hfl 1.75/skr 3.00/
Are negative ions good for you?

ACKNOWLEDGEMENT

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Anton Lindahl
Pontus Andersson
Johan Rohlén
Jakob Welander
Julia Sundberg
Annie Moberg-Ringwall

Stockholm University
Henrik Cederquist
Henning Schmidt
Moa Kristiansson
Erik Bäckström

University of Freiburg
Freiburg, Germany
Igor Kiyan
Hannes Hultgren
Mikael Eklund
Hanspeter Helm

Mainz, Germany
Klaus Wendt

University of Tennessee,
Tennessee, USA
David Pegg

CERN
Sebastian Rothe
David Leimbach