UNIVERSITY OF GOTHENBURG

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Dag Hanstorp

Laser Spectroscopy of radioactive and stable negative ions

Solvay Workshop in honour of Michel Godefroid
'New Frontiers in Atomic, Nuclear, Plasma and Astrophysics'

Brussels, November 25 - 27, 2019

Charlotte Froese Fischer - Opening Remarks:
In the beginning

”It all began in the 60ies”

16th of May 1960

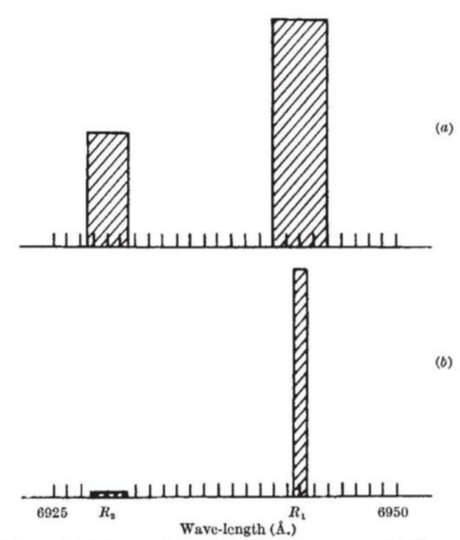


Fig. 2. Emission spectrum of ruby: *a*, low-power excitation; *b*, high-power excitation

T. H. Maiman Nature **187**, 493–494(1960)

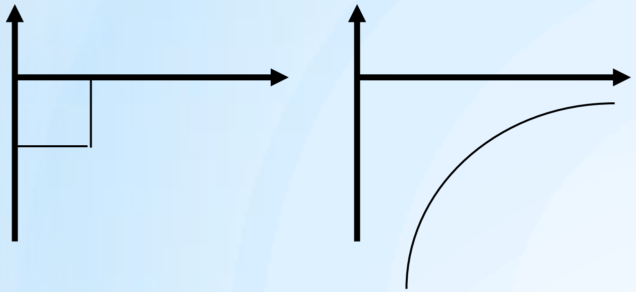
The negative ion of hydrogen: H^-

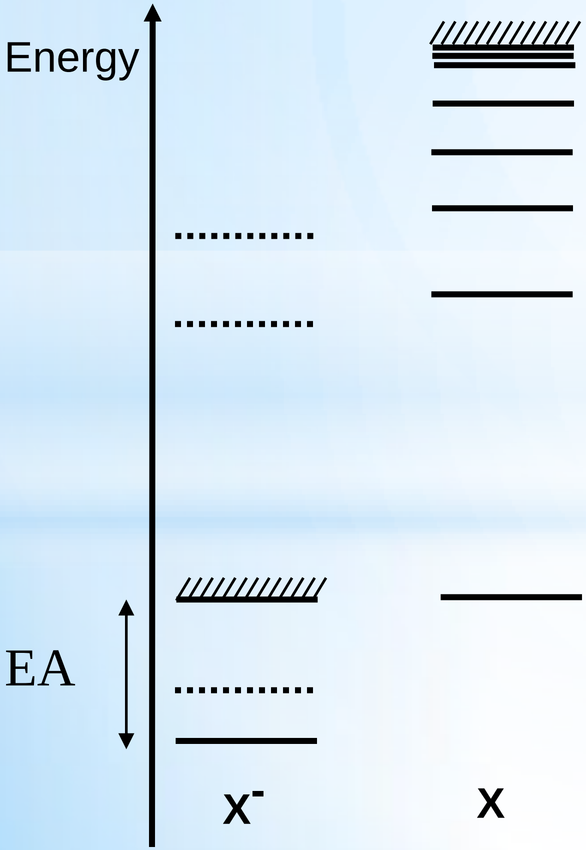
Hatree Fock predict H^- to be unstable

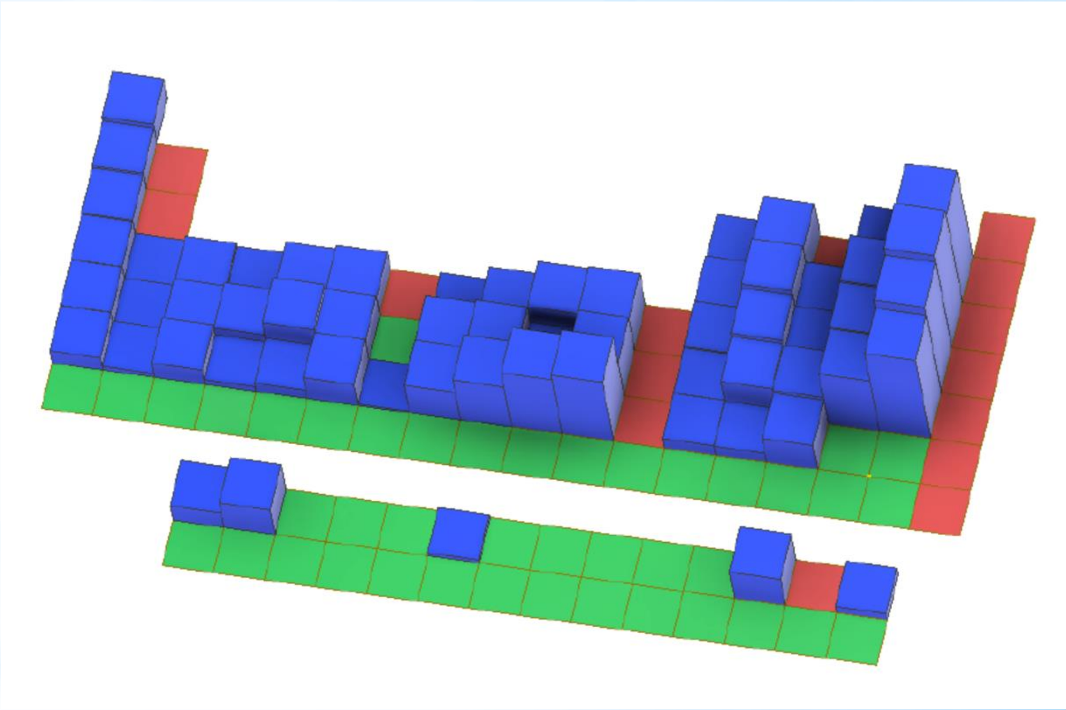
EA of H^- experimentally determined to be 0,75 eV

Can be predicted only by properly including electron correlation

Properties of Negative Ions







Why study negative ions?

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

Cerchiari, *et al*. PRL **123,** 103201 (2019), Tang *et al*. PRL **123**, 203002

Isotope shifts in the Electron affinity

Isotope shift

$$\mathbf{IS = NMS + SMS + VS}$$

Observable

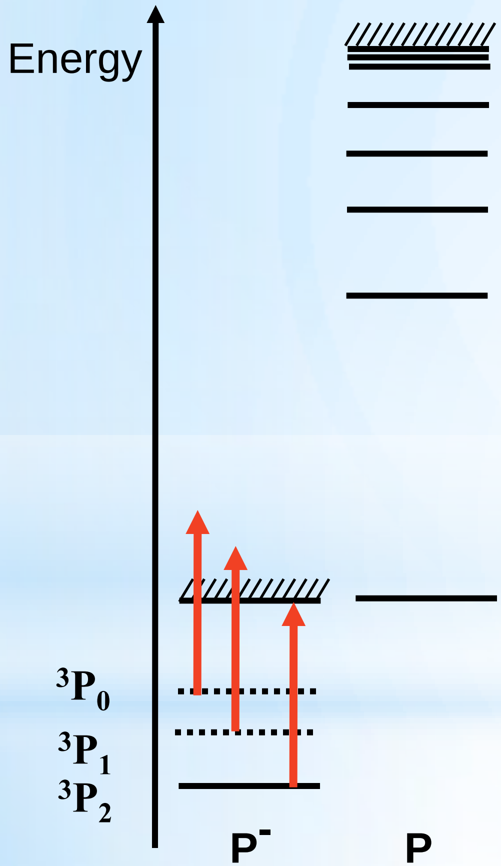
Trivial

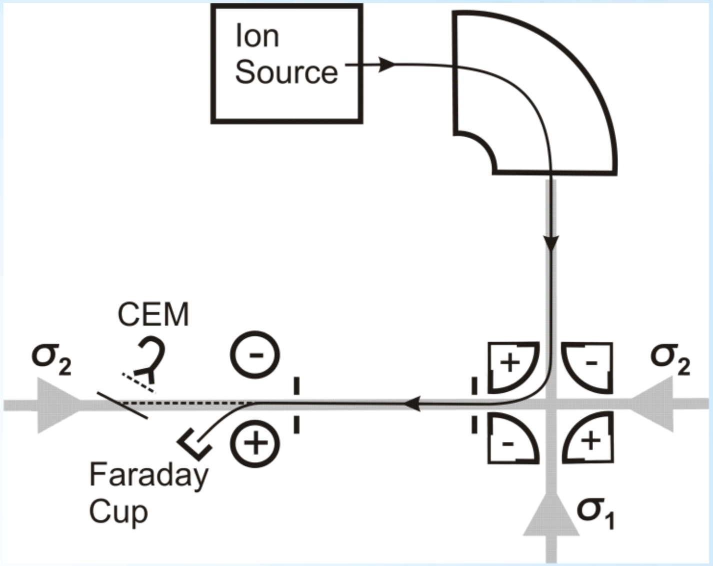
Atomic Physics

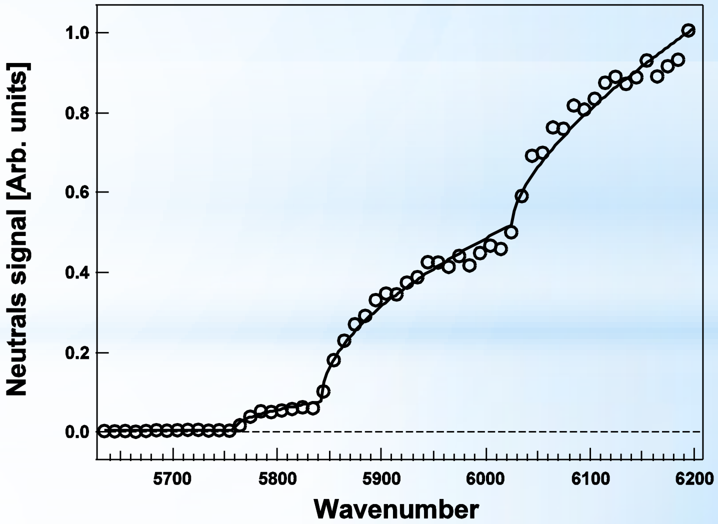
Nuclear Physics

Laser photodetachment Threshold Spectroscopy

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





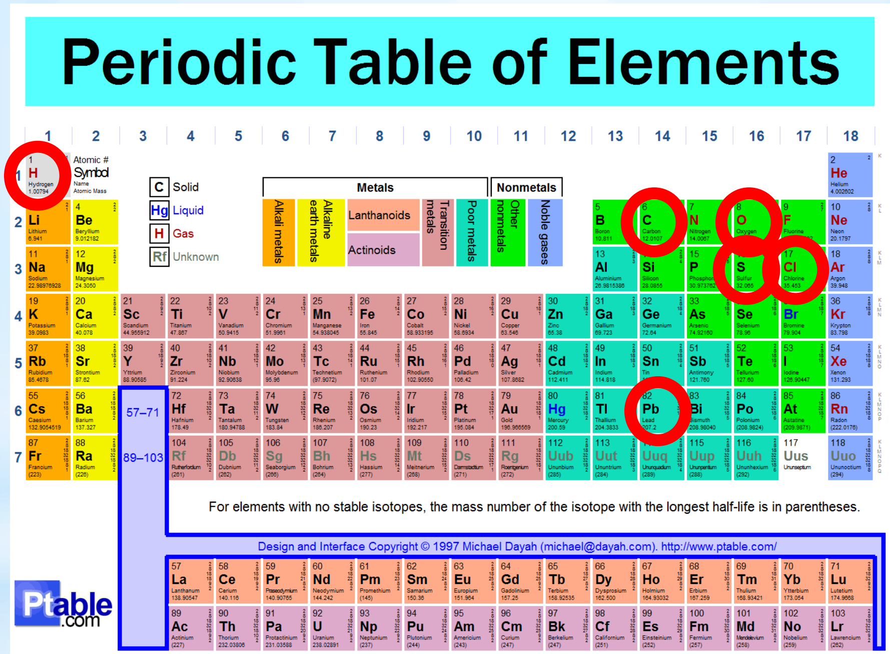


Andersson *et al.*
J. Phys. B **40** (2007) 4097.

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

Isotope shift in electron affinity

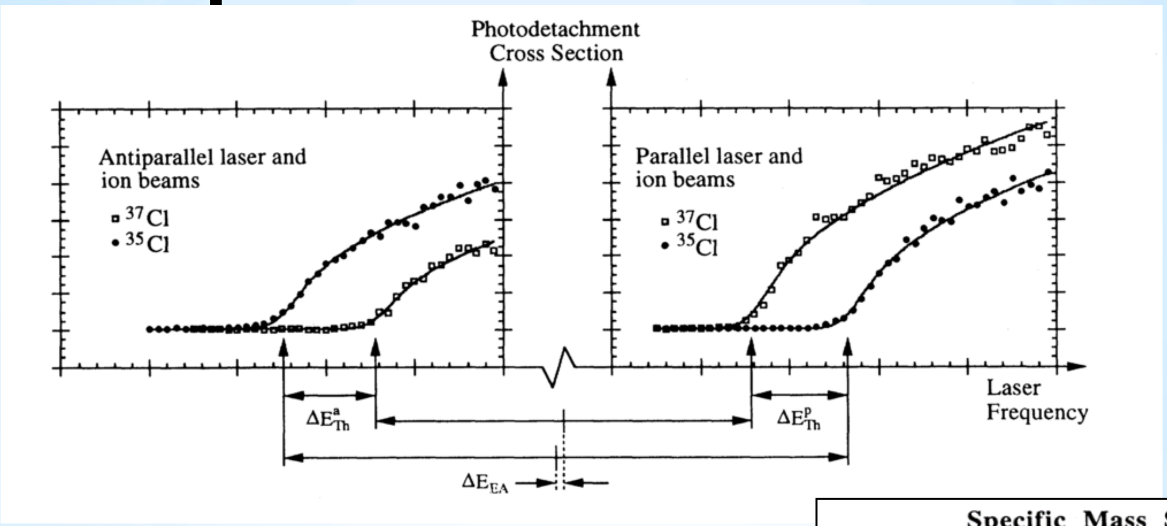
Ideal test case for electron correlation

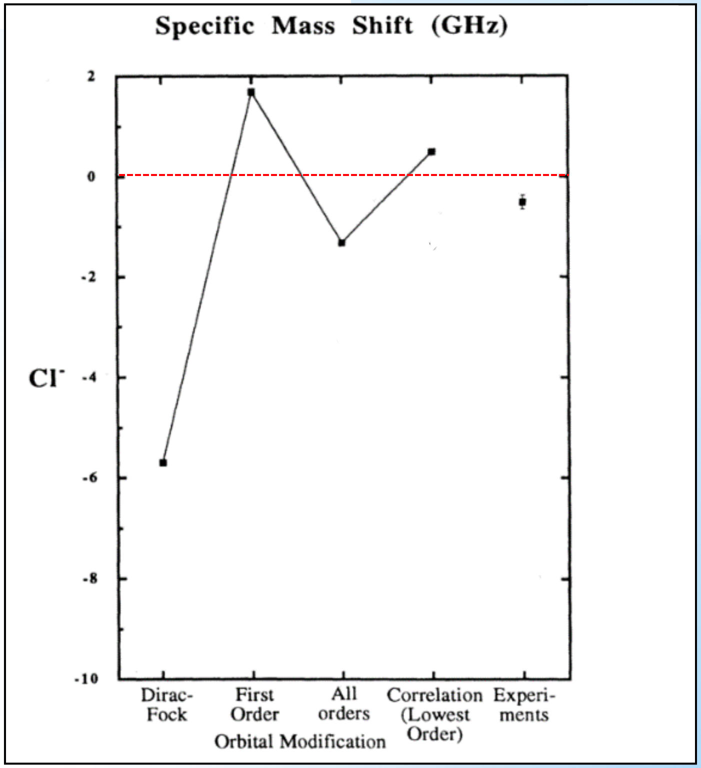


$^{1}H/\ ^{2}H$	Lykke, Murray and Lineberger, *Phys. Rev. A* **43** (1991) 6104
$^{35}Cl/37Cl$	Berzinsh et al. *Phys. Rev. A* **51**, (1995) 231
$^{16}O/\ ^{17}O\ /\ ^{18}O$	Blondel et al. *Phys. Rev. A* **64** (2001) 052504
$^{32}S/\ ^{34}S$	Carette, et al. *Phys. Rev. A* **81** (2010) 042522
$^{12}C/\ ^{13}C$	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

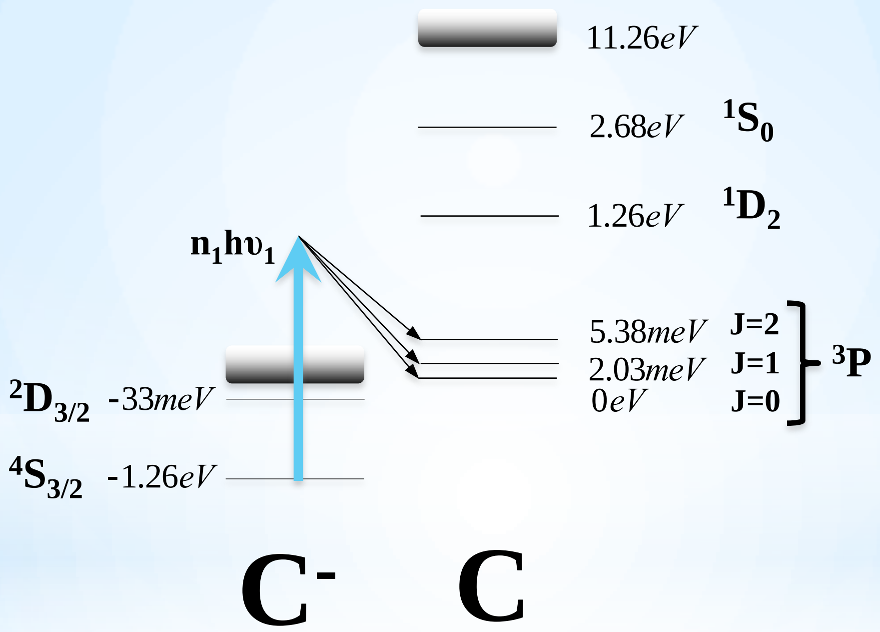
Isotope shift on the chlorine electron affinity revisited by an MCHF/CI approach

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

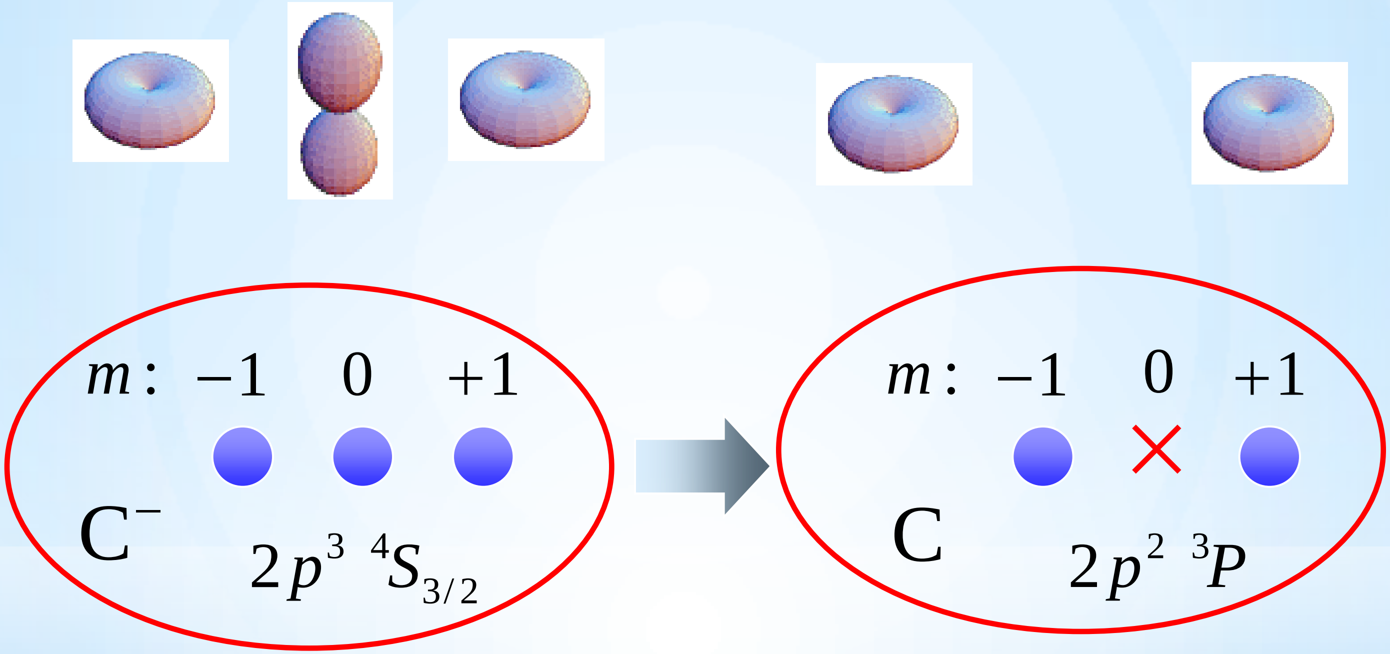
	SMS	MS	FS	RIS	IS
			This work		
HF	−1.348	−0.607	−0.003(22)	−1.351(22)	−0.610(22)
val. FC−MCHF	−0.674	+0.067	−0.002(20)	−0.676(20)	+0.065(20)
val. MCHF	−0.495	+0.246	−0.003(21)	−0.497(21)	+0.244(21)
final results	−0.535(51)	+0.206(51)	−0.003(22)	−0.538(72)	+0.203(72)
			Berzinsh *et al* [17]		
Exp.				−0.51(14)	+0.22(14)
DF	−1.3	−0.6	+0.014(14)	−1.5	−0.6
MB low corr.	+0.50	+1.24	+0.014(14)	+0.51(2)	+1.26(2)

Visualization of electronic motion in an atomic ground state

Energy levels of C^- and C

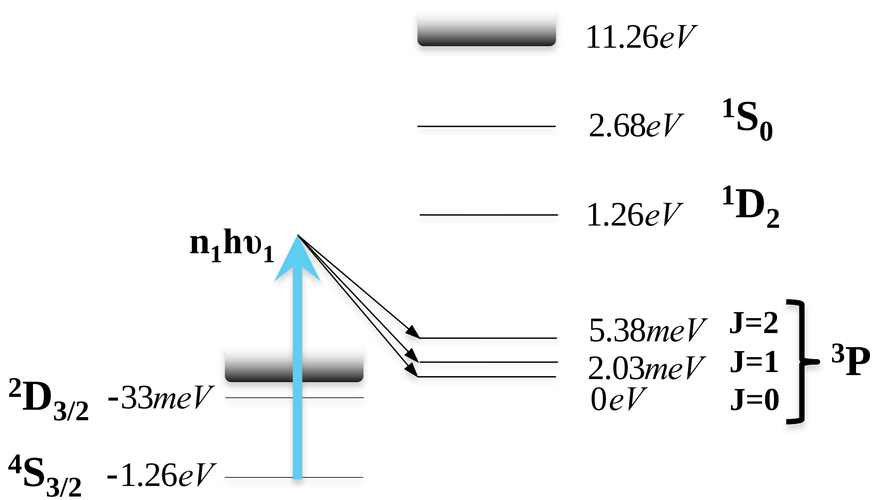


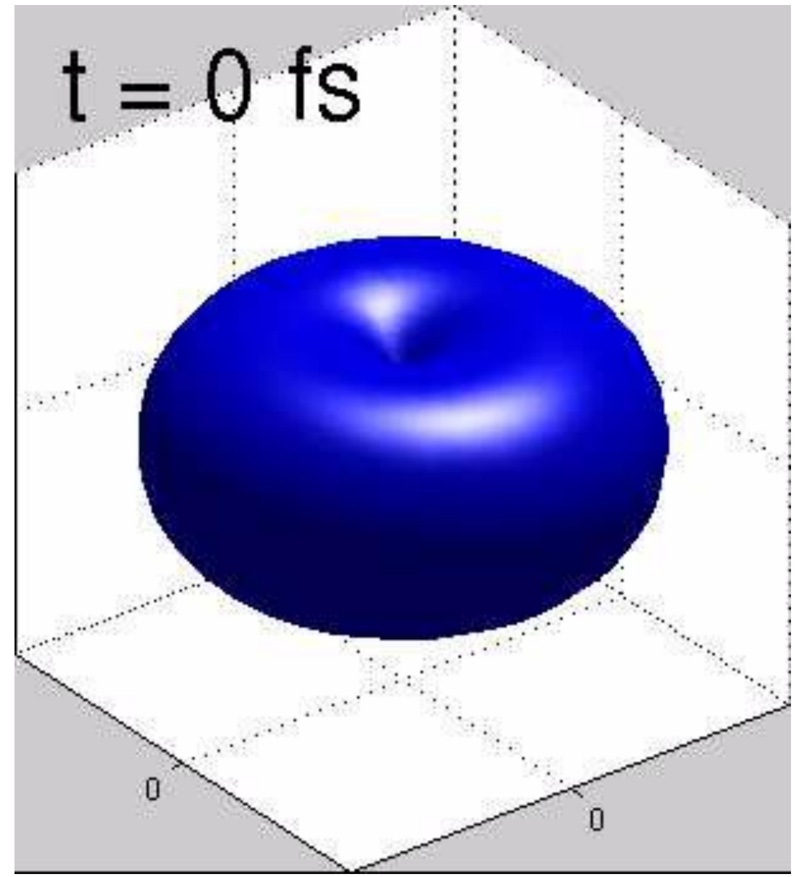
Photodetachment in a strong field:



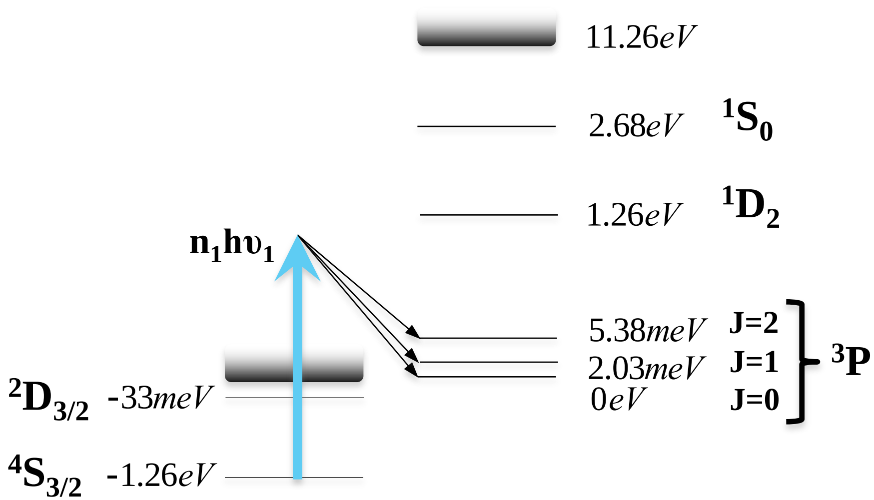
$$W_{m=0} >> W_{m=\pm 1}$$

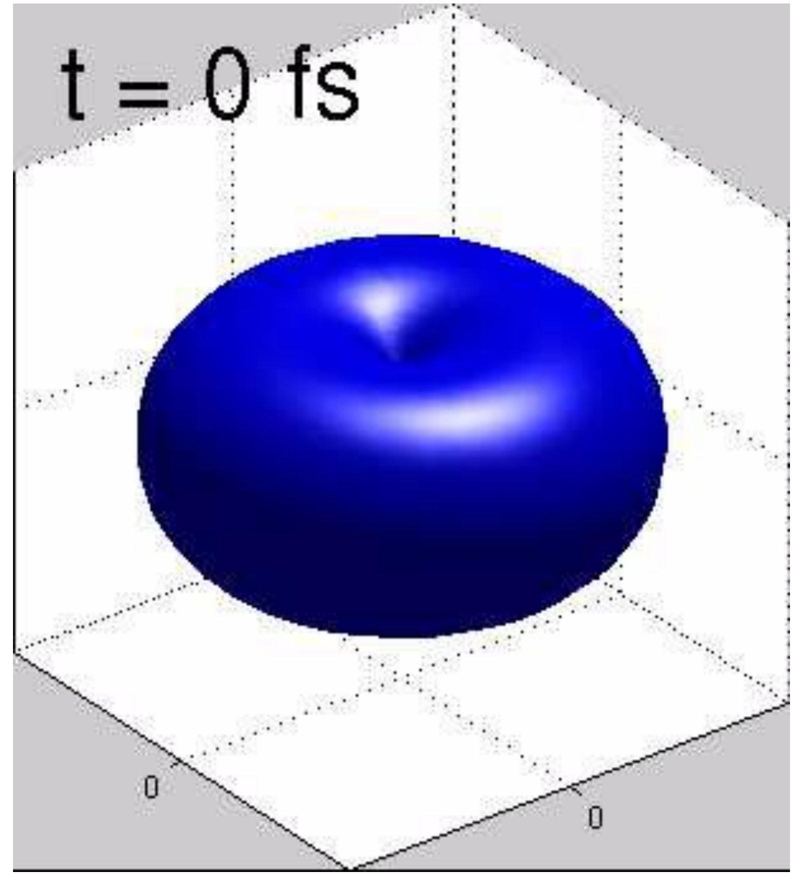
N. Rohringer and R. Santra, Phys. Rev. A **79**, 053402 (2009)



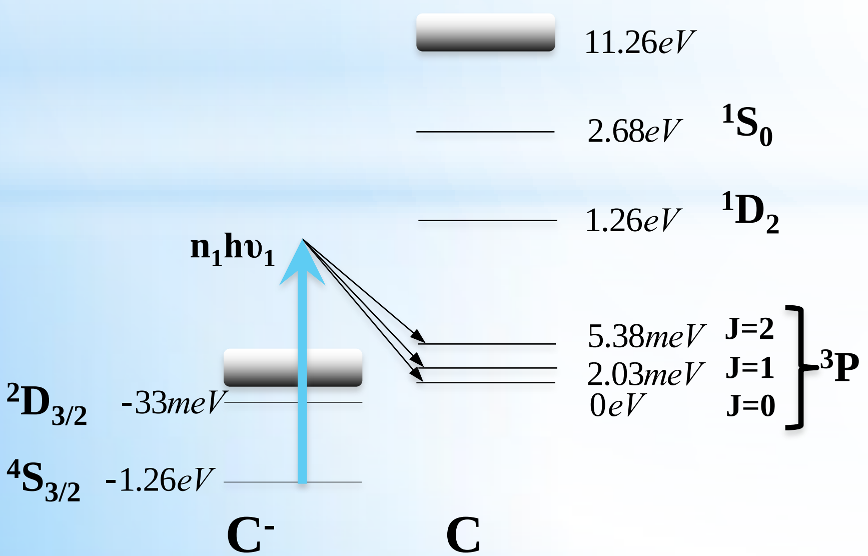


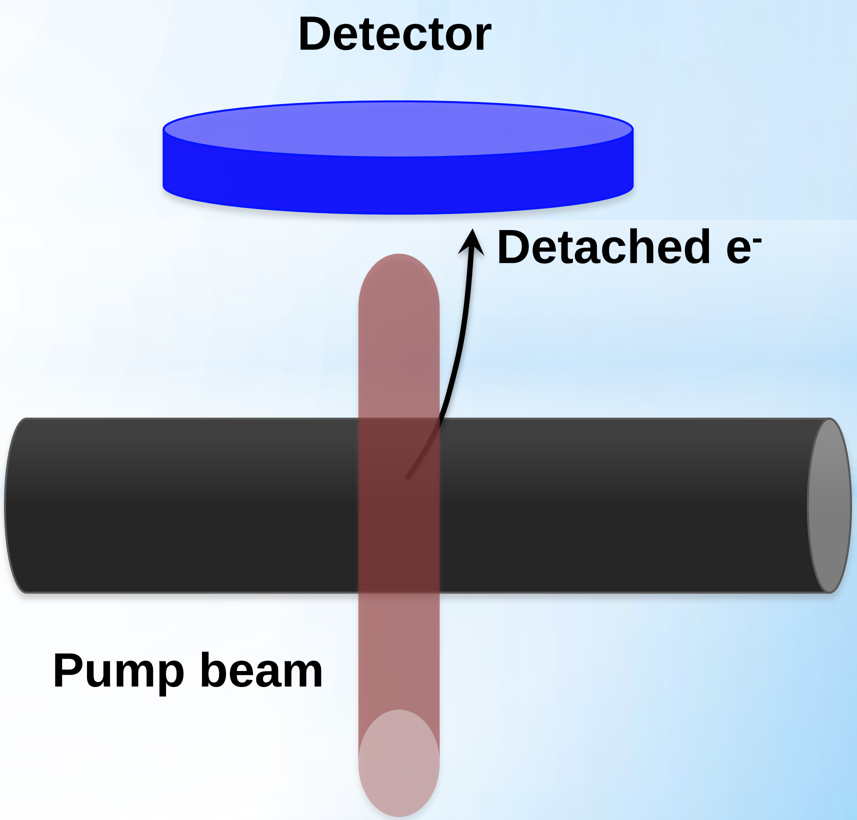
Bandwidth of laser > Fine structure splitting of C → Coherently populated states

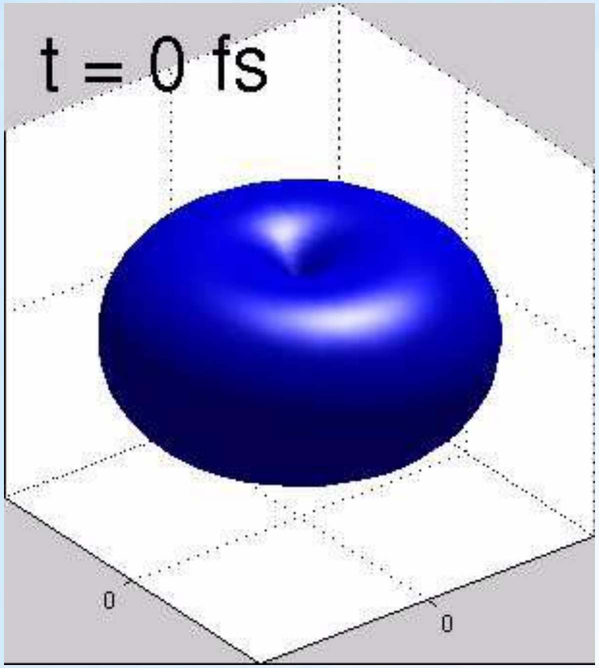


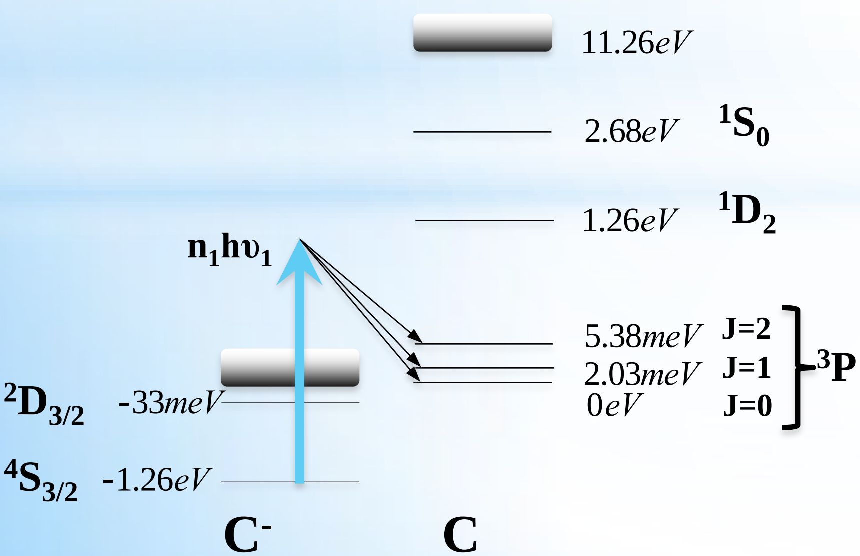


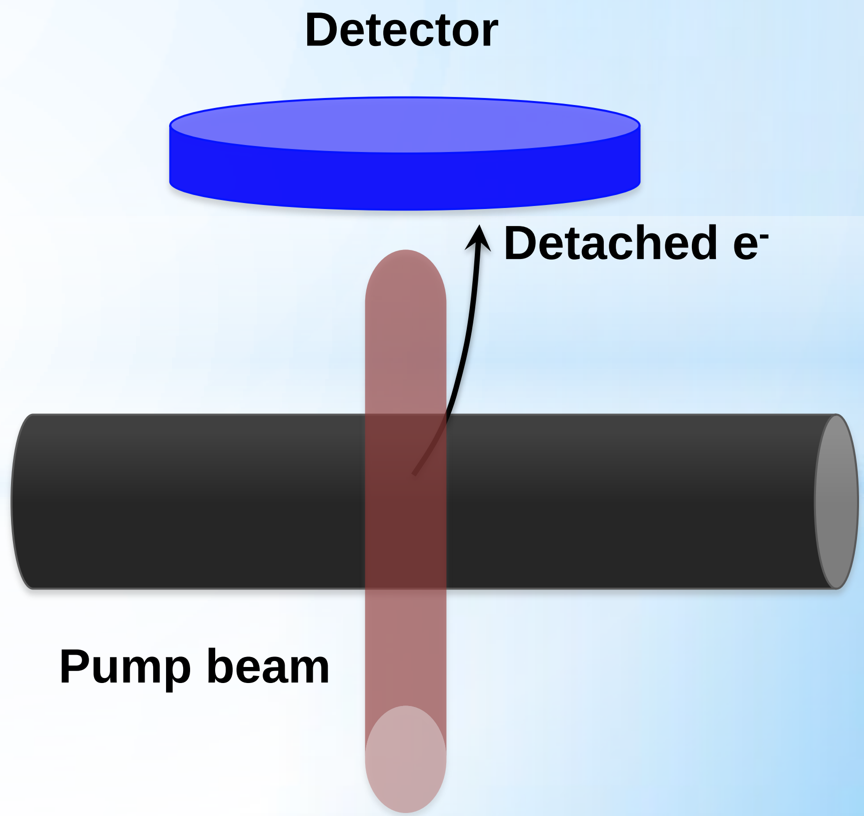
Bandwidth of laser > Fine structure splitting of C → Coherently populated states

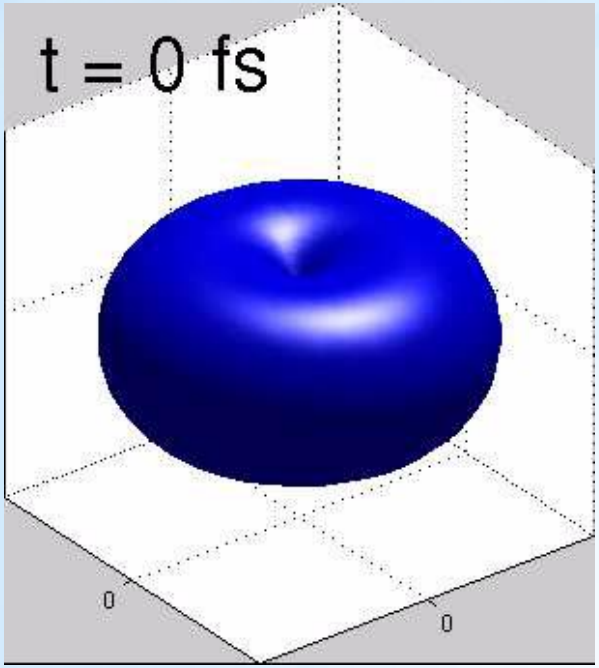

11.26eV
2.68eV
$^1S_0$
1.26eV
$^1D_2$
$n_1h\upsilon_1$
5.38meV
J=2
2.03meV
J=1
0eV
J=0
^3P
$^2D_{3/2}$
-33meV
$^4S_{3/2}$
-1.26eV
C^-
C

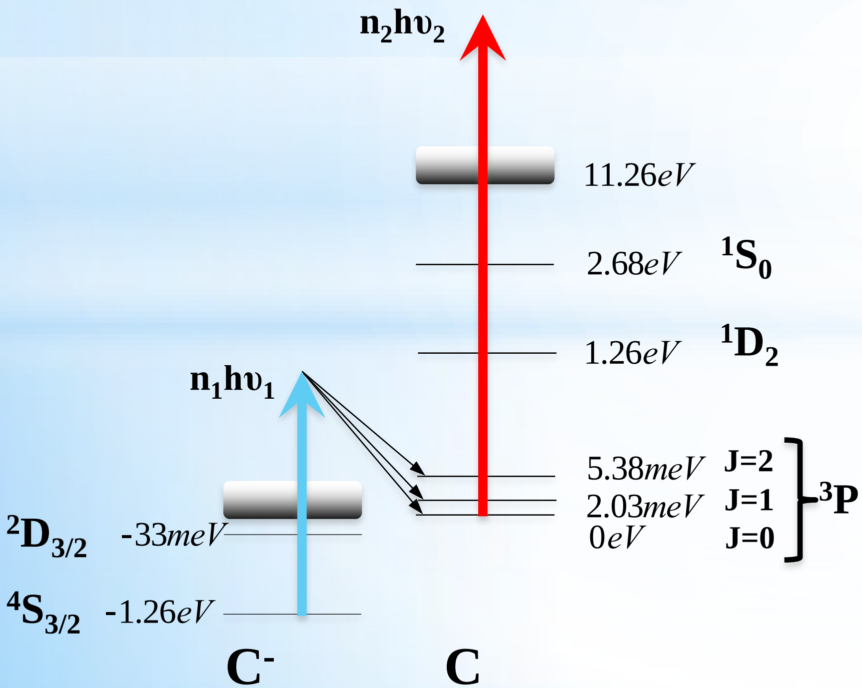

Detector
Detached e^-
Pump beam

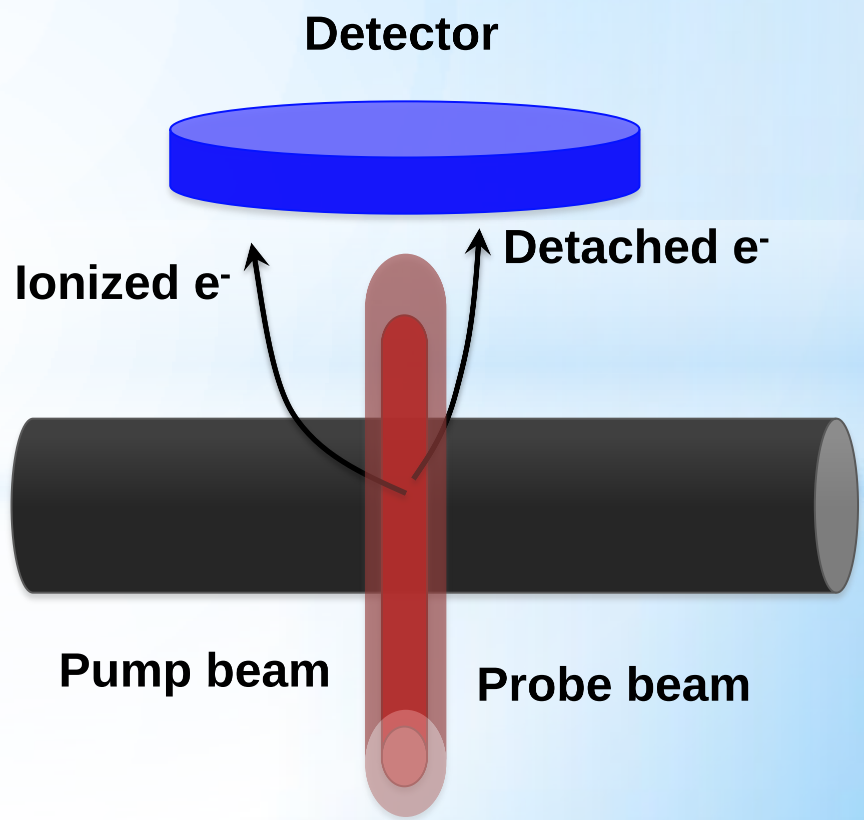

t = 0 fs
0
0

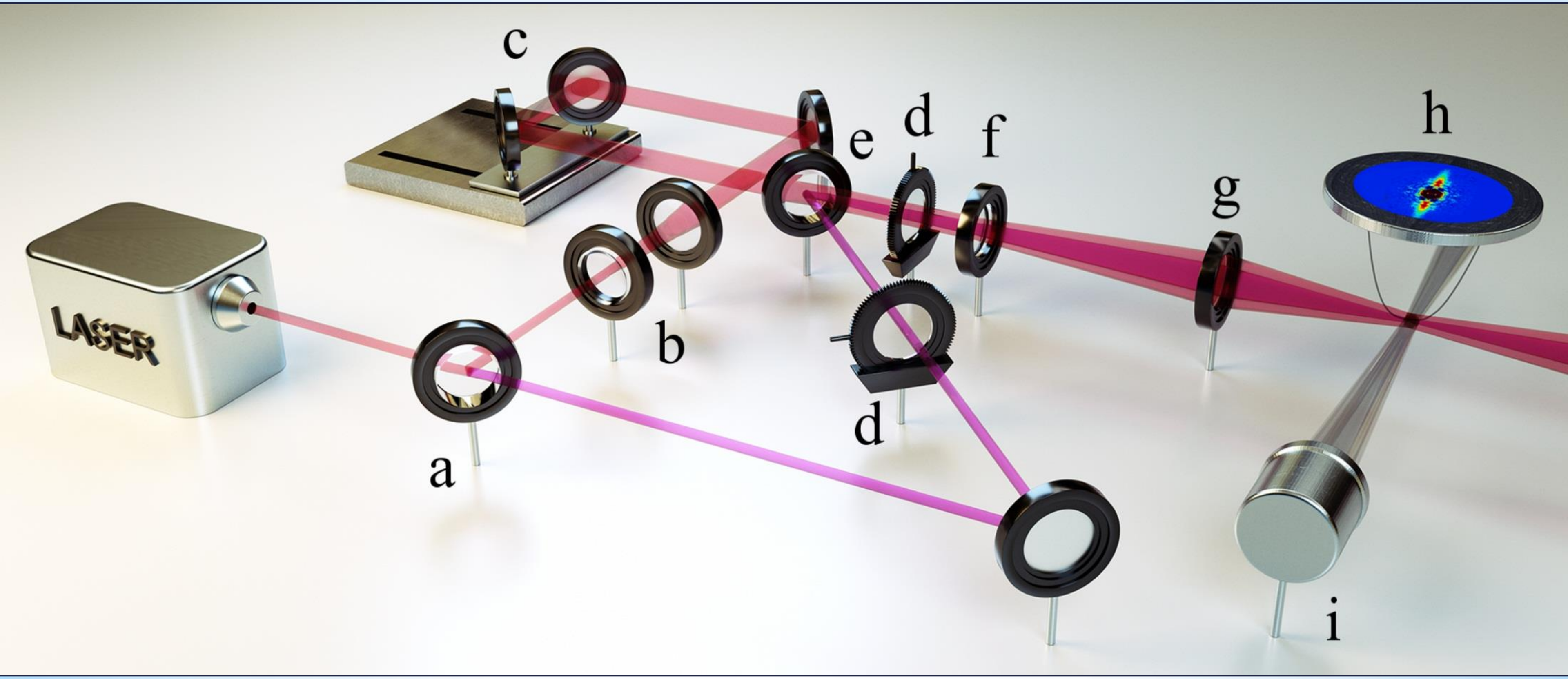

11.26eV
2.68eV
1S0
1.26eV
1D2
n1hυ1
5.38meV
J=2
2.03meV
J=1
3P
0eV
J=0
2D3/2
-33meV
4S3/2
-1.26eV
C-
C

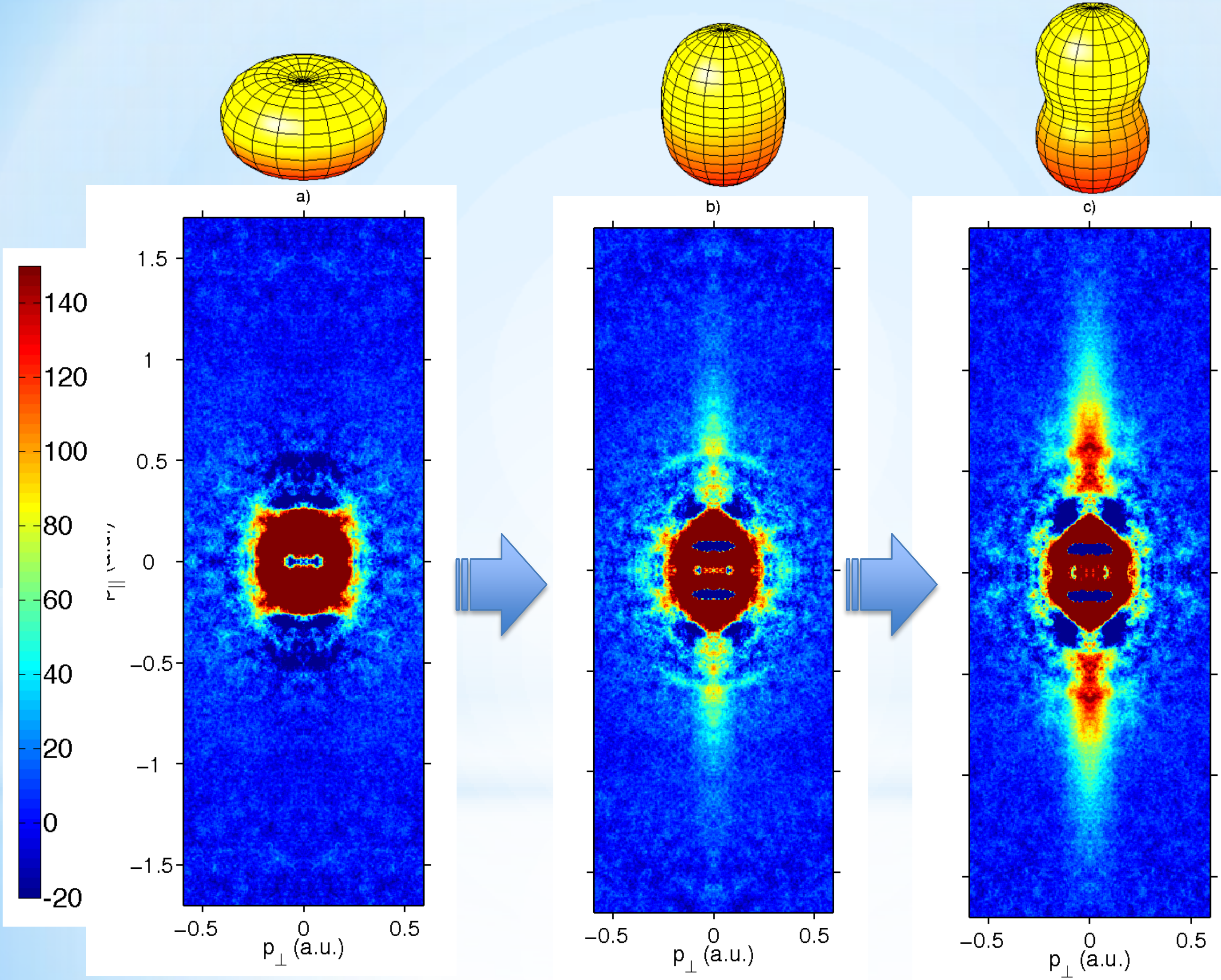

Detector
Detached e-
Pump beam


t = 0 fs
0
0

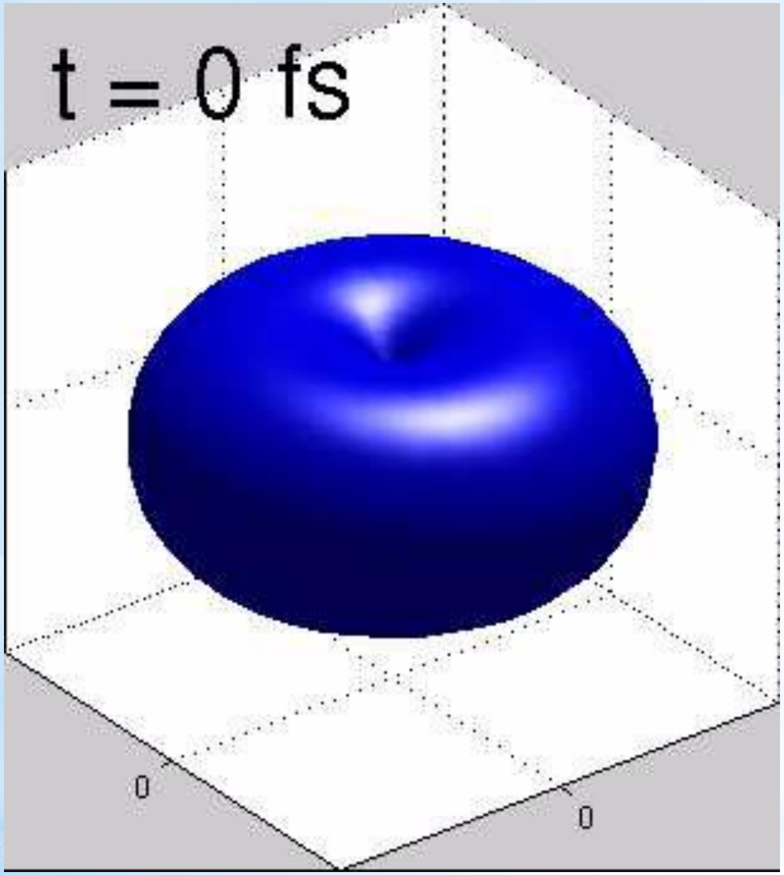

$n_2 h\upsilon_2$
$11.26eV$
$2.68eV$ $^1S_0$
$1.26eV$ $^1D_2$
$n_1 h\upsilon_1$
$5.38meV$ J=2
$2.03meV$ J=1
$0eV$ J=0
^3P
$^2D_{3/2}$ $-33meV$
$^4S_{3/2}$ $-1.26eV$
C^-
C


Detector
Ionized e^-
Detached e^-
Pump beam
Probe beam

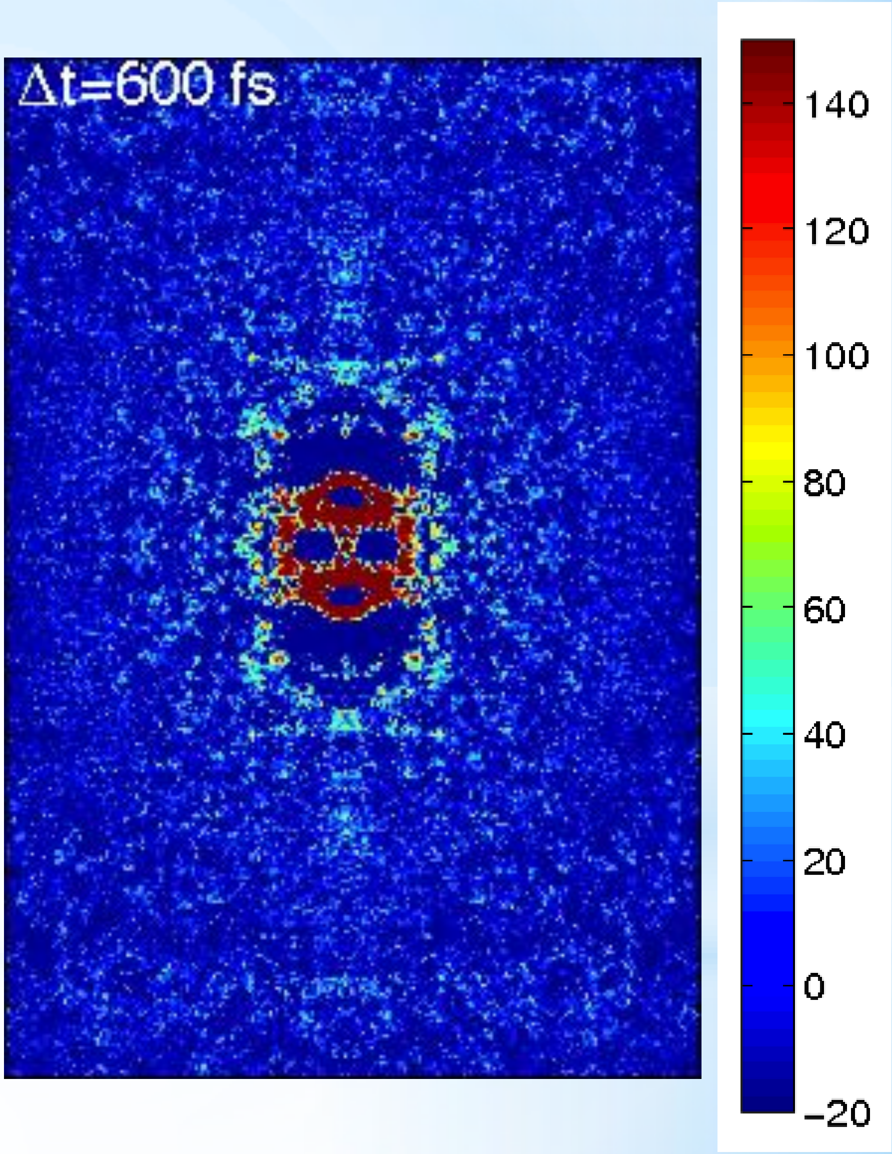

c
d
f
h
e
g
LASER
b
d
a
i



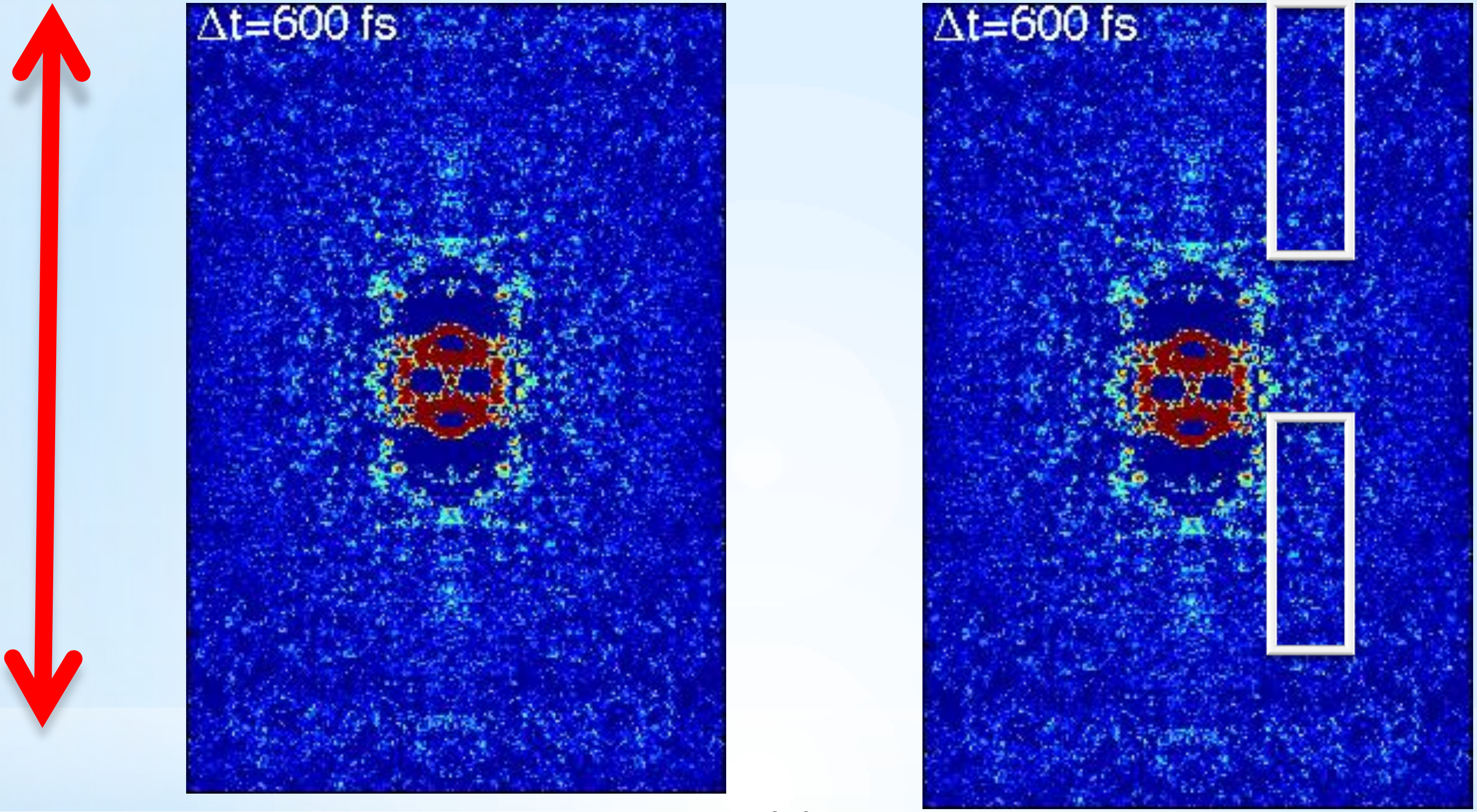
a)
b)
c)
140
120
100
80
60
40
20
0
-20
1.5
1
0.5
0
−0.5
−1
−1.5
−0.5
0
0.5
p⊥ (a.u.)

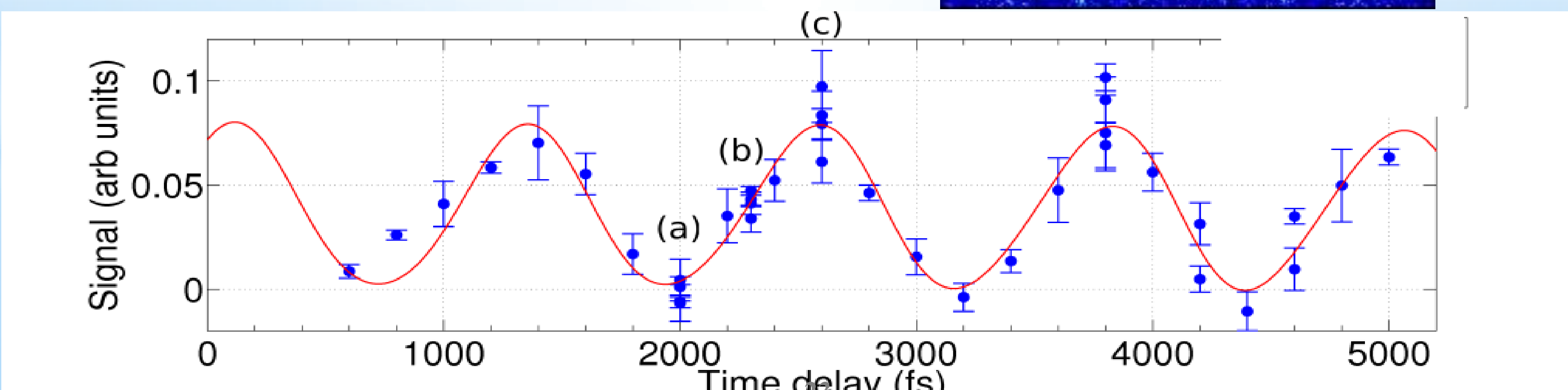


Laser Polarization



Laser Polarization



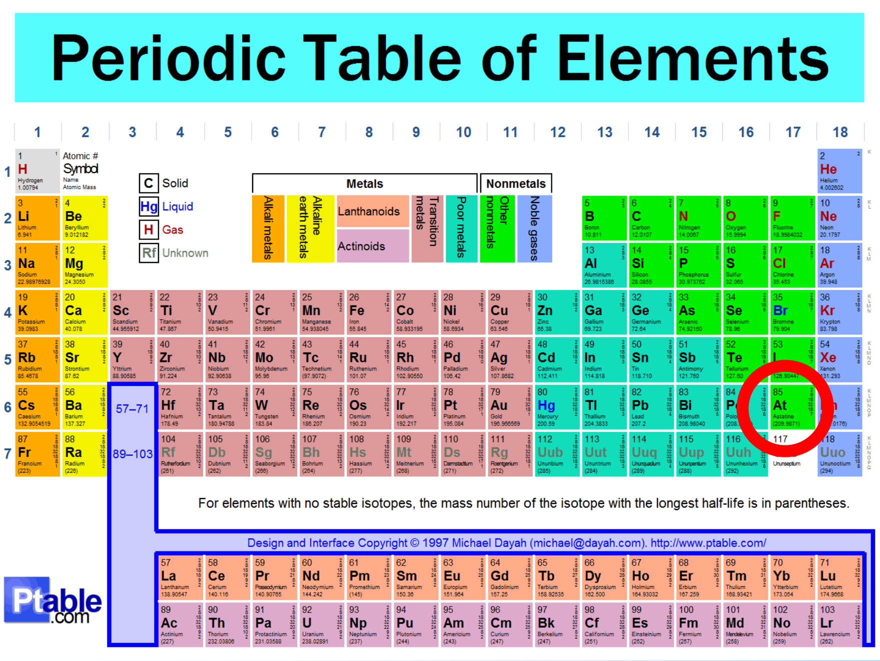


Hultgren *et al.* PRA 87 (2013) 031404

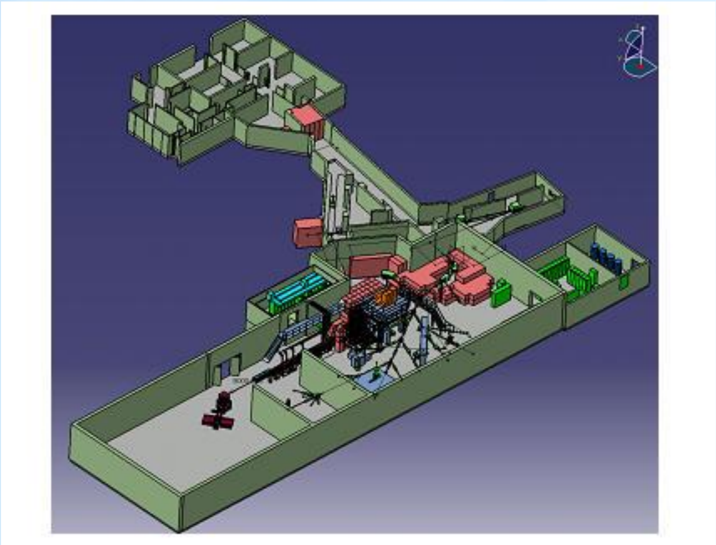
The electron affinity of Astatine

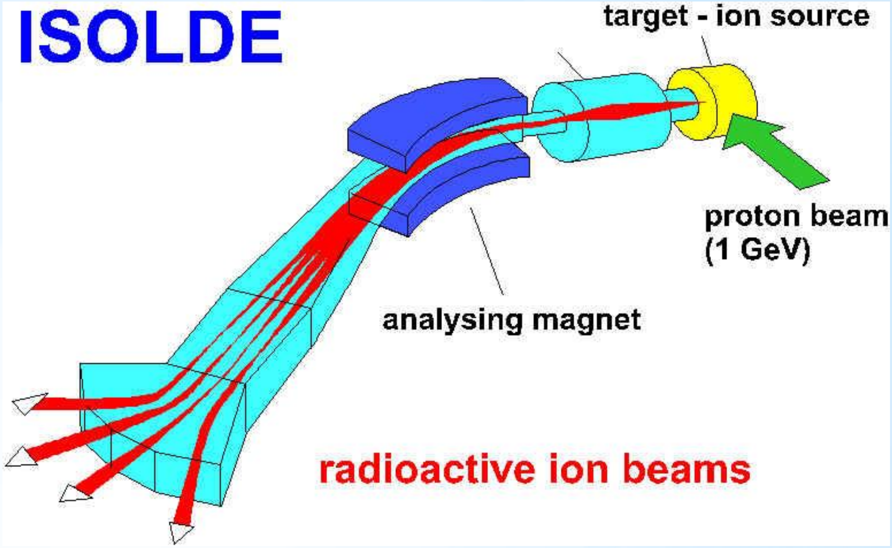
Astatine

- 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)



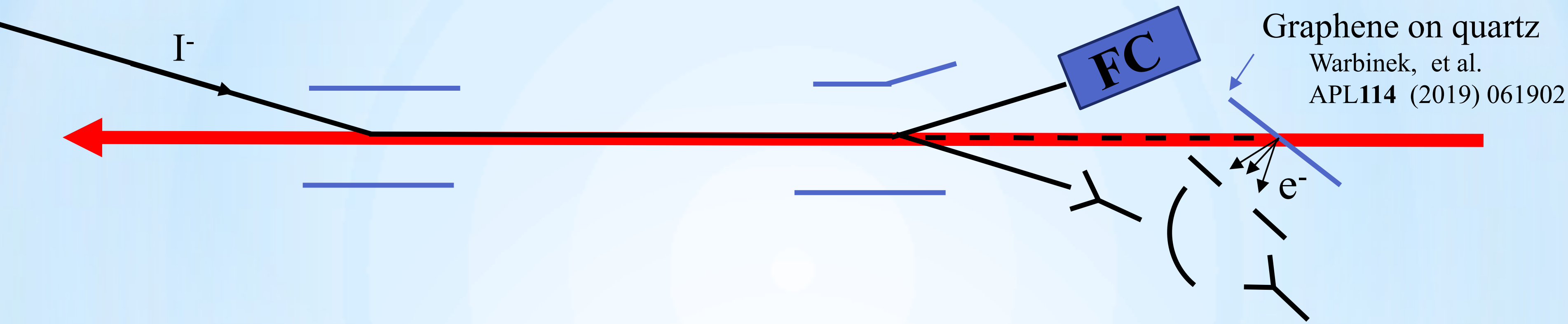
Experimental program at ISOLDE





GANDALPH

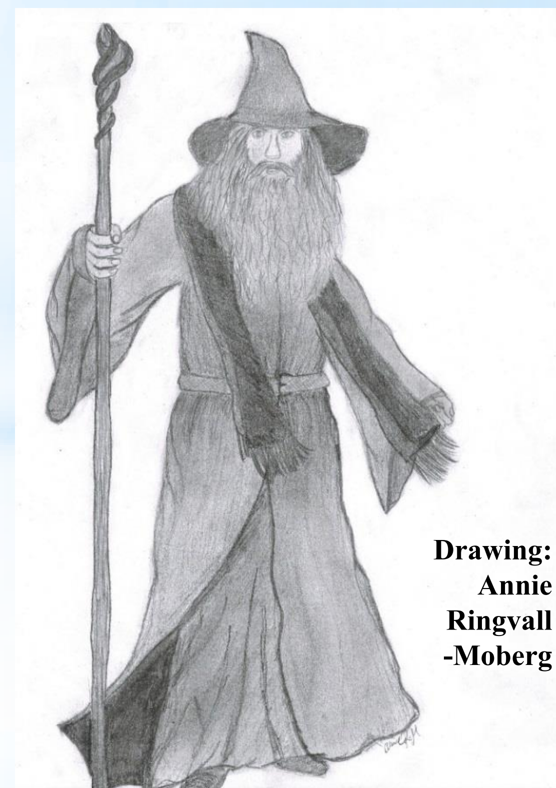
Gothenburg **AN**ion **D**etector for **A**ffinity measurements by **L**aser **PH**otodetachment



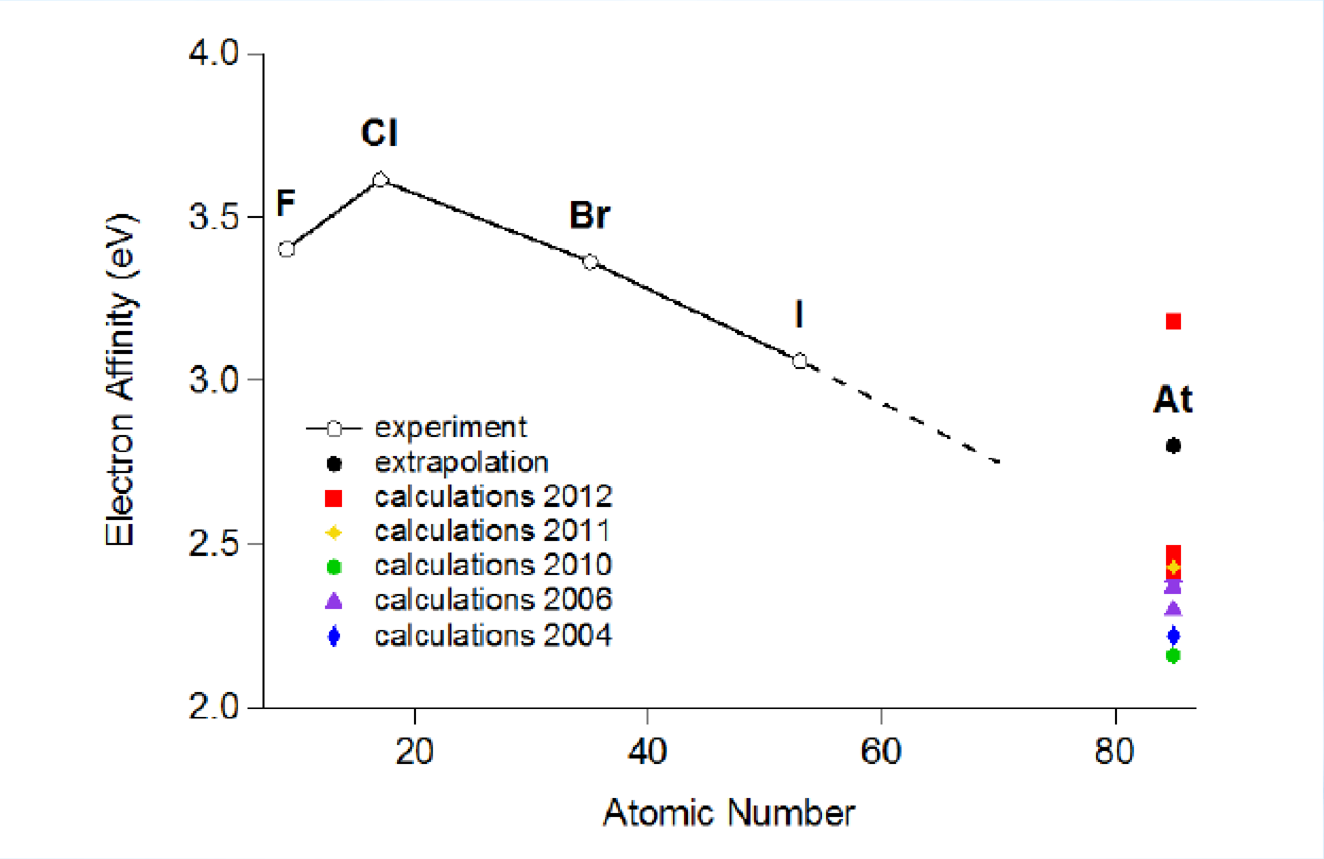
For each laserpuls:

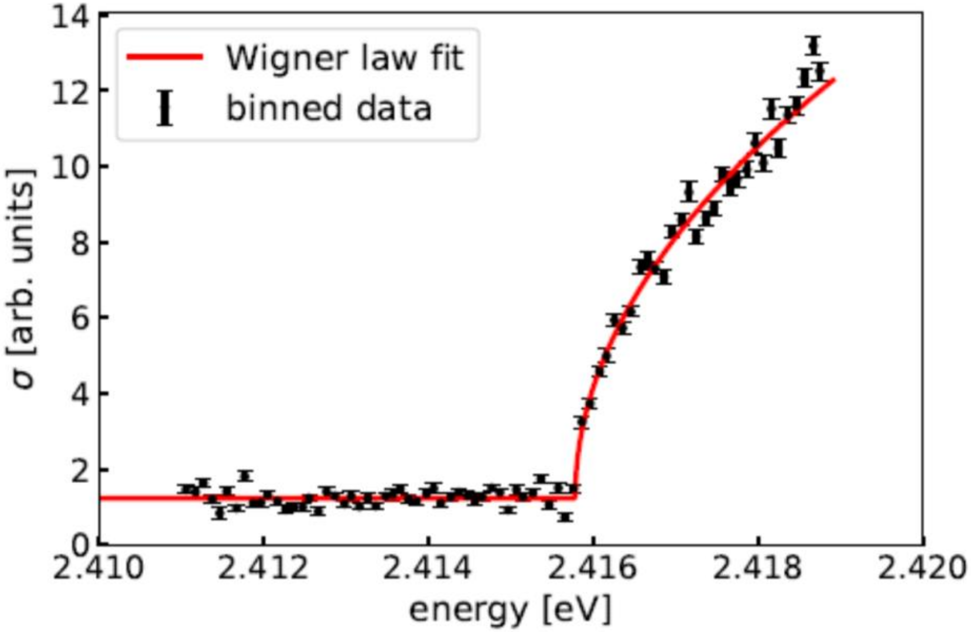
Signal:
0.01 atom

Background:
10^{14} photons



Drawing: Annie Ringvall -Moberg


4.0
3.5
3.0
2.5
2.0
Electron Affinity (eV)
F
Cl
Br
I
At
experiment
extrapolation
calculations 2012
calculations 2011
calculations 2010
calculations 2006
calculations 2004
20
40
60
80
Atomic Number

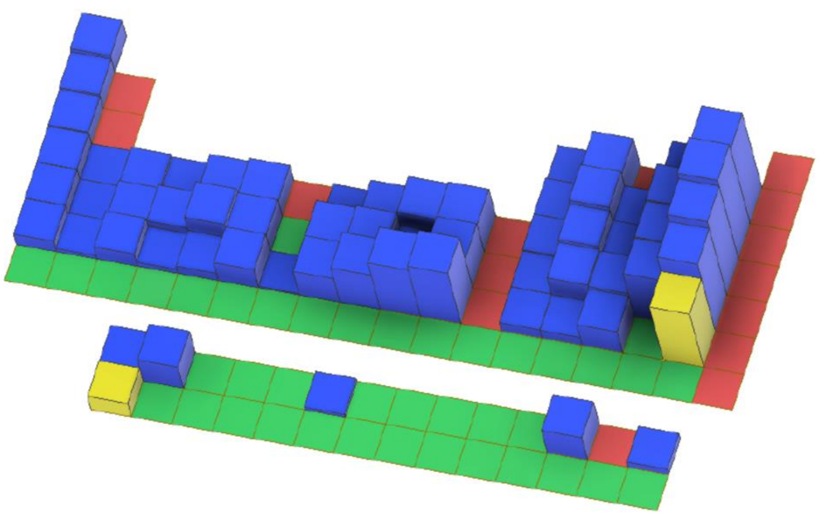


The electron affinity of astatine

David Leimbach[1,2,3], Julia Sundberg[2], Yangyang Guo[4], Rizwan Ahmed[5], Jochen Ballof[1,6], Lars Bengtsson[2], Ferran Boix Pamies[1], Anastasia Borschevsky[4], Katerina Chrysalidis[1,3], Ephraim Eliav[11], Dmitry Fedorov[7], Valentin Fedosseev[1], Oliver Forstner[8,9], Nicolas Galland[10], Ronald Fernando Garcia Ruiz[1], Camilo Granados[1], Reinhard Heinke[3], Karl Johnston[1], Agota Koszorus[1], Ulli Köster[13], Moa K. Kristiansson[14], Yuan Liu[15], Bruce Marsh[1], Pavel Molkanov[7], Lukáš F. Pašteka[12], Joao Pedro Ramos[1], Eric Renault[10], Mikael Reponen[16], Annie Ringvall-Moberg[1,2], Ralf Erik Rossel[1], Dominik Studer[3], Adam Vernon[17], Jessica Warbinek[2,3], Jakob Welander[2], Klaus Wendt[3], Shane Wilkins[1], Dag Hanstorp[2] and Sebastian Rothe[1]

[1] *CERN, Geneva, Switzerland*
[2] *Department of Physics, University of Gothenburg, Gothenburg, Sweden*
[3] *Institut für Physik, Johannes Gutenberg-Universität, Mainz, Germany*
[4] *Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Groningen, The Netherlands*
[5] *National Centre for Physics (NCP), Islamabad, Pakistan*
[6] *Institut für Kernchemie, Johannes Gutenberg-Universität, Mainz, Germany*
[7] *Petersburg Nuclear Physics Institute - NRC KI, Gatchina, Russia*
[8] *Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, Germany*
[9] *Helmholtz-Institut Jena, Jena, Germany*
[10] *CEISAM, Université de Nantes, CNRS, Nantes, France*
[11] *School of Chemistry, Tel Aviv University, Tel Aviv, Israel*
[12] *Department of Physical and Theoretical Chemistry & Laboratory for Advanced Materials, Faculty of Natural Sciences, Comenius University, Bratislava, Slovakia*
[13] *Institut Laue-Langevin, Grenoble, France*
[14] *Department of Physics, Stockholm University, Stockholm, Sweden*
[15] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA*
[16] *Department of Physics, University of Jyväskylä, Jyväskylä, Finland*
[17] *School of Physics and Astronomy, The University of Manchester, Manchester, UK*

Method	Author	Year	EA
Experiment			2.41578(5)
CBS-DC-CCSDT(Q)+Breit+QED			2.414(16)
MCDHF+SE corr.	Chang et al	2010	2.38(2)
MCDHF	Zhao et al	2012	2.416
DC-CCSD(T)+Breit+QED	Broschevsky et al	2015	2.412
MCDHF+Extrap.+Breit+QED	Si and Fischer	2018	2.3729(46)
CBS-DC-CCSD(T)+Gaunt+QED	Finney and Peterson	2019	2.423(13)



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	$S = \frac{1}{\eta}$	0.144 89(2) eV^{-1}
Electrophilicity	$\omega = \frac{\chi^2}{2\eta}$	2.493 41(8) eV

The At-H molecule should be called **astatine hydride**
(not hydrogen astatide)

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Stockholm University

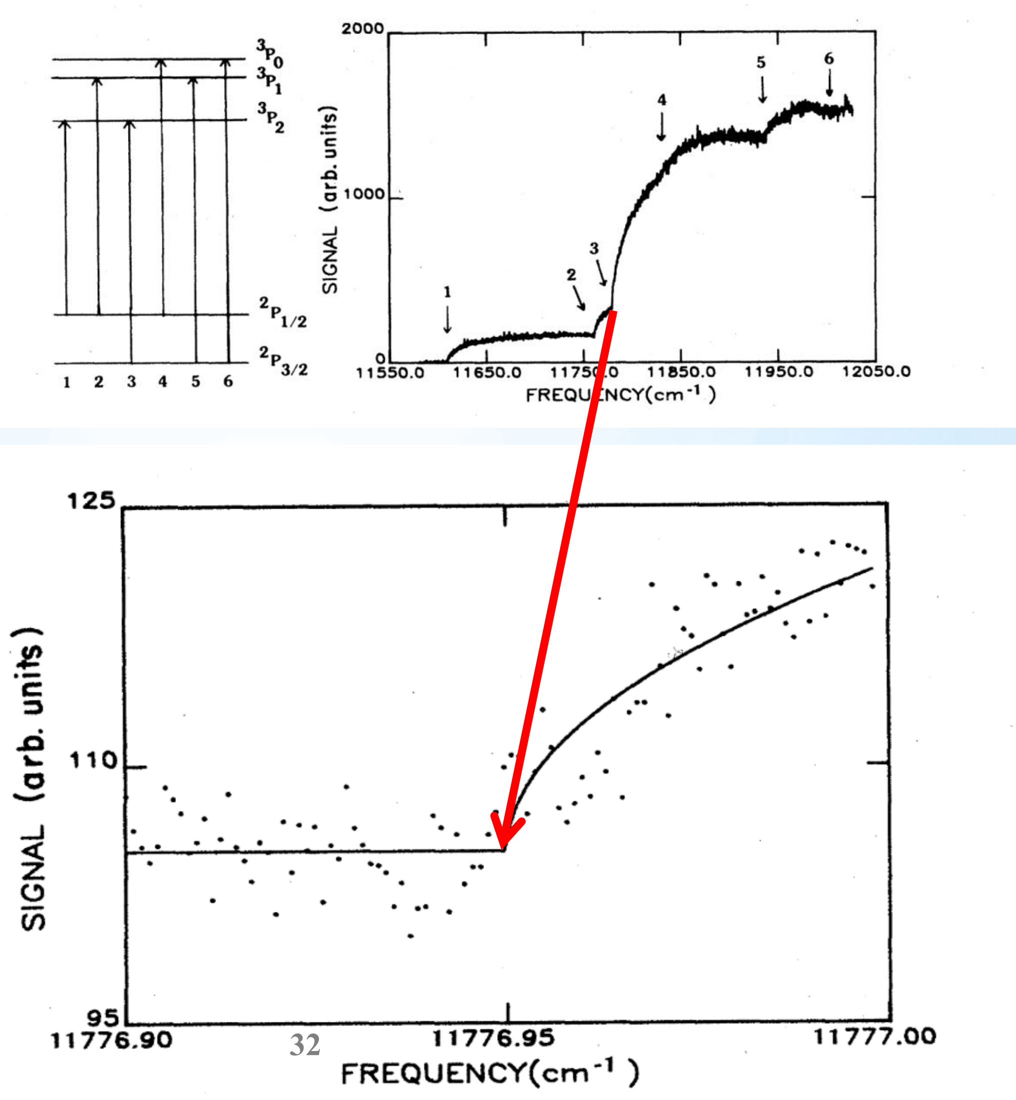
Photodetachment using an electrostatic storage ring

PHYSICAL REVIEW A VOLUME 32, NUMBER 3 SEPTEMBER 1985

Laser photodetachment measurement of the electron affinity of atomic oxygen

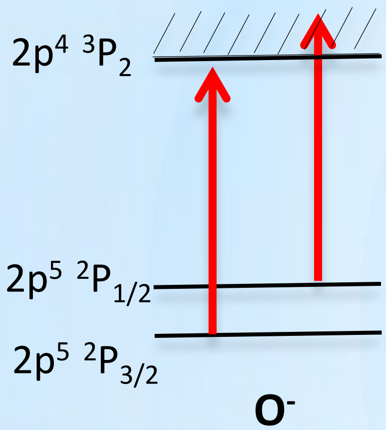
D. M. Neumark, K. R. Lykke, T. Andersen,* and W. C. Lineberger

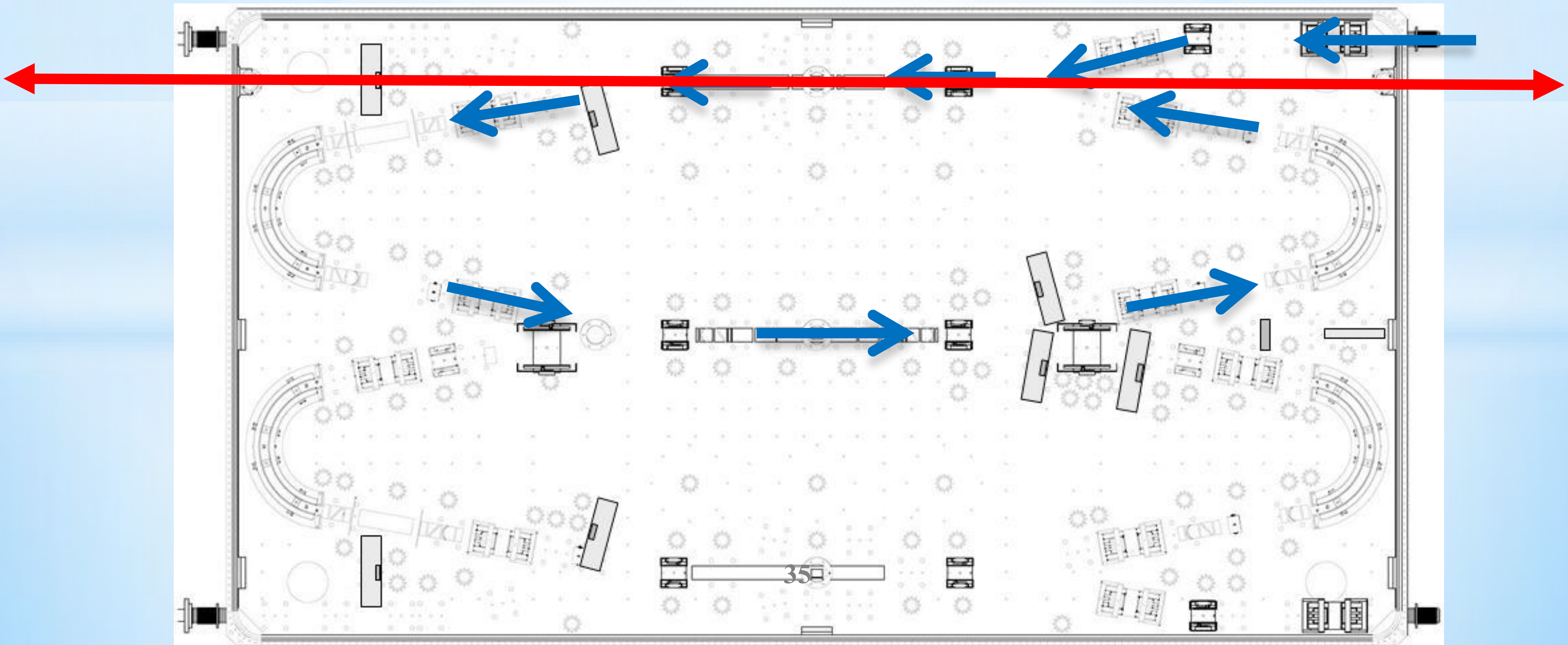
$$O^- + h\nu \rightarrow O + e^-$$



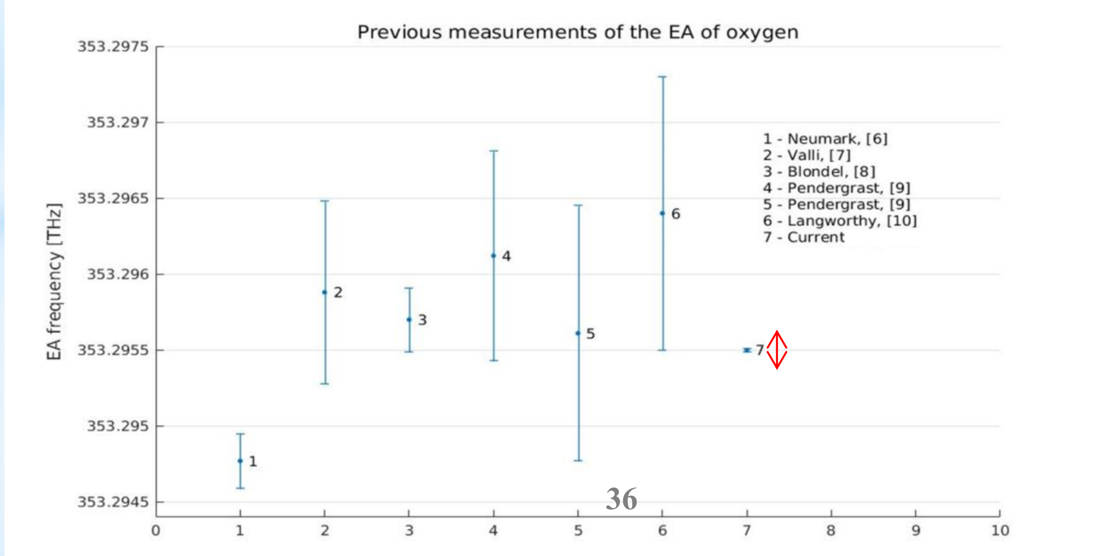
Measuring the EA of O^-

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






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


Previous measurements of the EA of oxygen
EA frequency [THz]
1 - Neumark, [6]
2 - Valli, [7]
3 - Blondel, [8]
4 - Pendergrast, [9]
5 - Pendergrast, [9]
6 - Langworthy, [10]
7 - Current

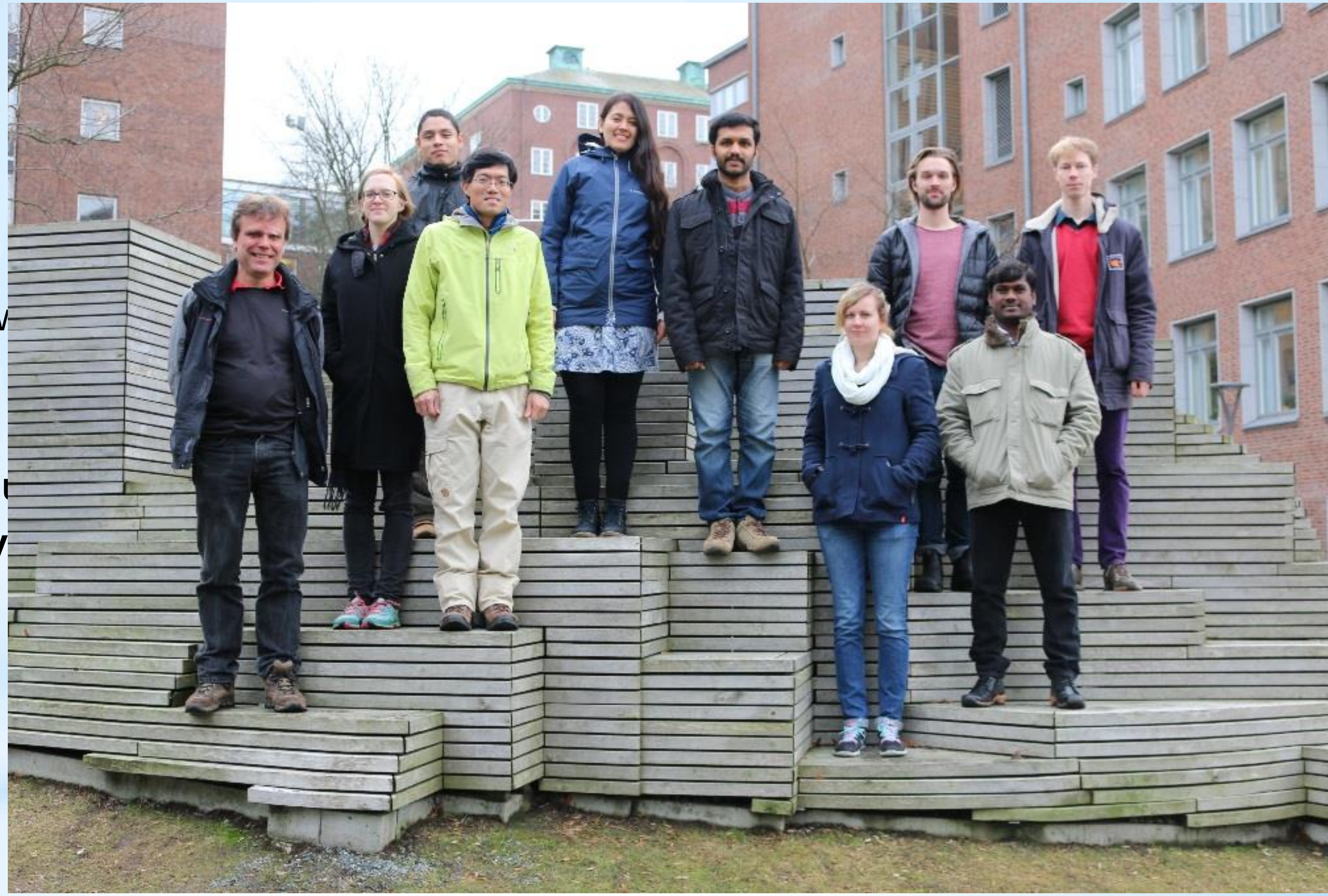
ACKNOWLEDGEMENT

University of Gothenburg **Stockholm University**

Anton Lindahl
Pontus Andersson
Johan Rohlén
Jakob Welander
Julia Sundberg
Annie Moberg-Ringw
Moa Kristiansson

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

CERN
Sebastian Rothe
David Leimbach



Charlotte Froese Fischer - Opening Remarks:
In the beginning

”It all began in the 60ies”

”2019 is not the end, but the beginning of the future!”

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of shifts in the electron affinities of chlorine isotopes

Dag Hanstorp[1], Jakob Welander[1], David Leimbach[1], Annie Ringvall-Moberg[1,2], Michel Godefroid[3], Per Jönsson[4], Jörgen Ekman[4], Tomas Brage[5], Klaus Wendt[6], Reinhard Heinke[6], Oliver Forstner[7], Yuan Liu[8], Ronald Garcia Ruiz[9], Shane Wilkins[9], Adam Vernon[9], Cory Binnersley[9], Kieran Flanagan[9], Gerda Neyens[10], Agi Koszorus[10], Kara Lynch[2], Sebastian Rothe[2], Tim Giles[2], Katerina Chrysalidis[2,6], Pierre Larmonier[2], Valentin Fedosseev[2] and Bruce Marsh[2].

[1] Department of Physics, University of Gothenburg, SE 412 96 Gothenburg, Sweden
[2] CERN, CH-1211 Geneva 23, Switzerland
[3] Université libre de Bruxelles, B 1050 Brussels, Belgium
[4] Materials Science and Applied Mathematics, Malmö University, 205 06 Malmö, Sweden
[5] Division of Mathematical Physics, Department of Physics, Lund University, Box 118, SE-221 00 Lund,
[6] Institut für Physik, Johannes-Gutenberg Universität, Mainz, Germany
[7] Friedrich Schiller Universität, Jena, Germany
[8] Physics Division, Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee, USA
[9] School of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, United Kingdom
[10] Institute for Nuclear and Radiation Physics, Celestijnenlaan 200d - box 2418, 3001 Leuven, Belgium

Spokesperson: D. Hanstorp (dag.hanstorp@gu.se)
Co-spokesperson: J. Welander (jakob.welander@gu.se)
Contact persons: S. Rothe (sebastian.rothe@cern.ch)

Abstract

We propose to conduct measurements of the isotope shift in the electron affinity (EA) for chlorine isotopes. The specific mass shift is sensitive to electron correlation that is particularly pronounced in negative ions and neutral atoms. Hence, a study of isotope shifts in electron affinities is an excellent method to obtain benchmark data for theoretical models that go beyond the independent-particle model. The treatment and interpretation of the experimental data will be supported by multiconfiguration Dirac-Hartree-Fock (MCDHF) calculations performed by leading specialists in the field of theoretical atomic physics. The collinear laser photodetachement spectroscopy will be conducted using the GANDALPH experimental beam line at GLM using the RILIS laser system in narrow linewidth configuration.

This proposal is based on the letter of intent I-177

Requested shifts: 8 shifts

Solvay Workshop in honour of
Michel Godefroid

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Thanks to

the organizers for an excellent conference

Michel for a career where you have combine scientific excellence with friendship

you for your attention