The Magnetic(-)Trapping Mode
EBIT as a Penning trap

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20 Years of EBIT, Berkeley, Nov. 2006

20 Years of Spectroscopy with the Electron Beam Ion Trap
10 Years of/since the Magnetic-Trapping Mode
(a highly personal recollection)

- 1989 First visit to LLNL
- 1992 First (published) ICR-EBIT ideas (Schweikhard et al.)
- 1993 First detailed description (Elliott et al.)
- 1994 Proof of principle (Beiersdorfer et al.)
- 1995 Charge-state determination with FT-ICR MS
- 1996 Coining of the term in “FT-ICR Analysis of the Magnetic Trapping Mode of the Electron Beam Ion Trap”, Beiersdorfer et al., IJMSIP, (received Jan 02!)
- 1996, i.e. immediately afterwards: “The Magnetic Trapping Mode of EBIT - New Opportunities for Highly Charged Ion Research”, Beiersdorfer et al., RSI
- . . .

Overview

„History“

Aspects of Ion Trapping

Introduction to Penning Traps

Examples from

a) ISOLTRAP

b) FT-ICR MS

c) ClusterTrap

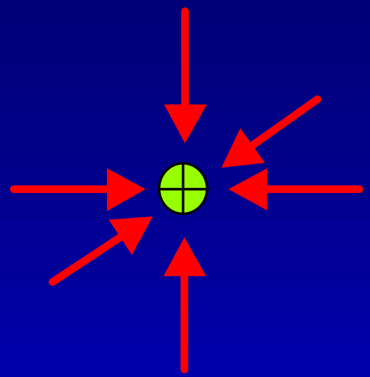
EBIT‘s Magnetic-Trapping Mode:

1) Mass Analysis

2) Charge-Transfer Reactions

3) Lifetimes of Metastable States

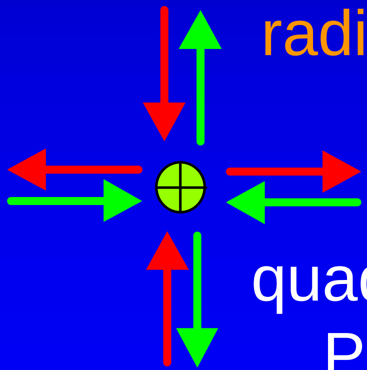
My standard introduction: How to trap ions?



~~electrostatic trapping~~

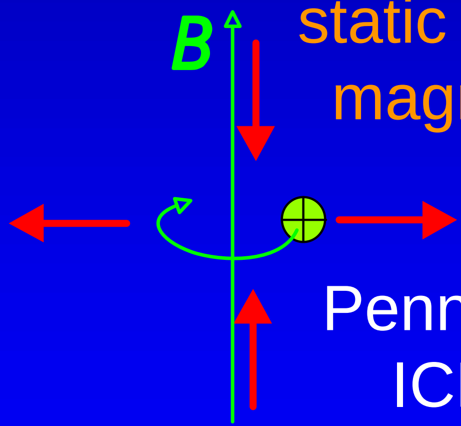
not possible due to
Laplace: $\Delta\phi = 0$

electric
radiofrequency
fields



quadrupolar potential:
Paul trap, rf trap,
QUISTOR, „ion trap“

static electric and
magnetic fields



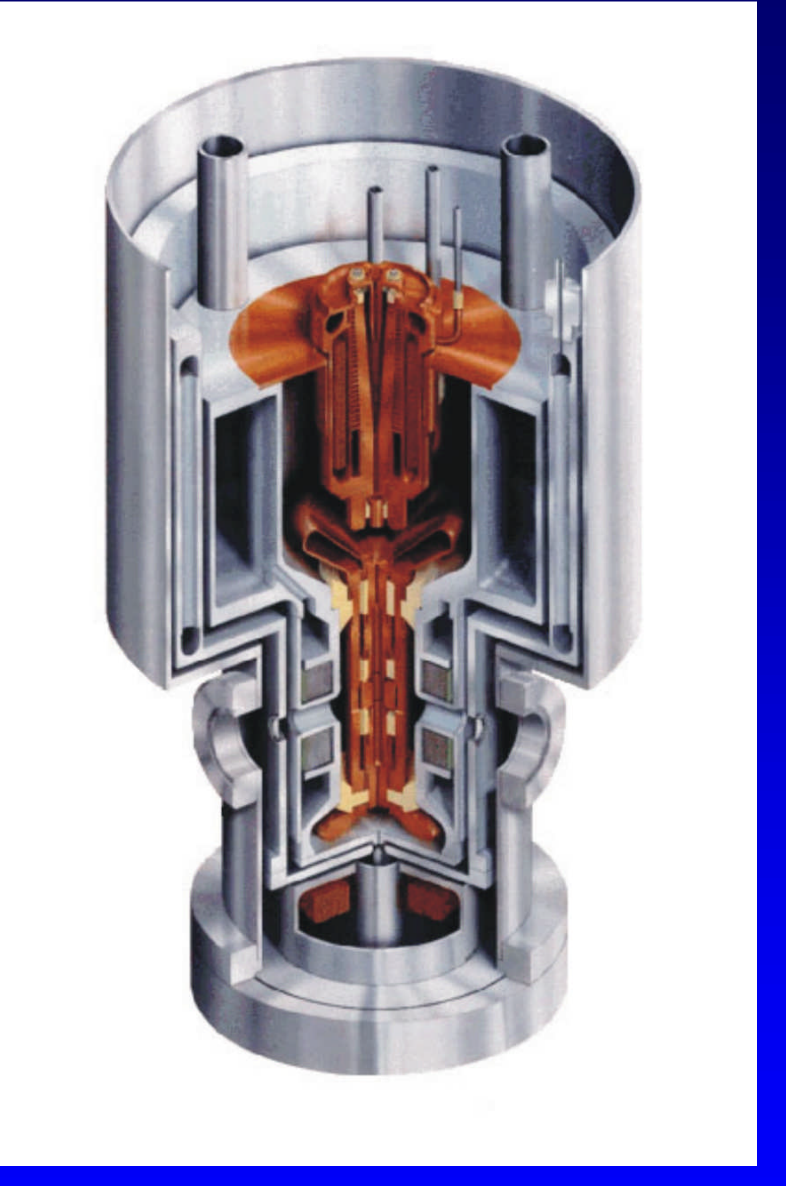
Penning trap
ICR cell
(ion cyclotron resonance)
FT-ICR MS, FTMS

An alternative approach to ion trapping

replace
Laplace: $\Delta\phi = 0$
by
Poisson: $\Delta\phi = \rho/\varepsilon_0$

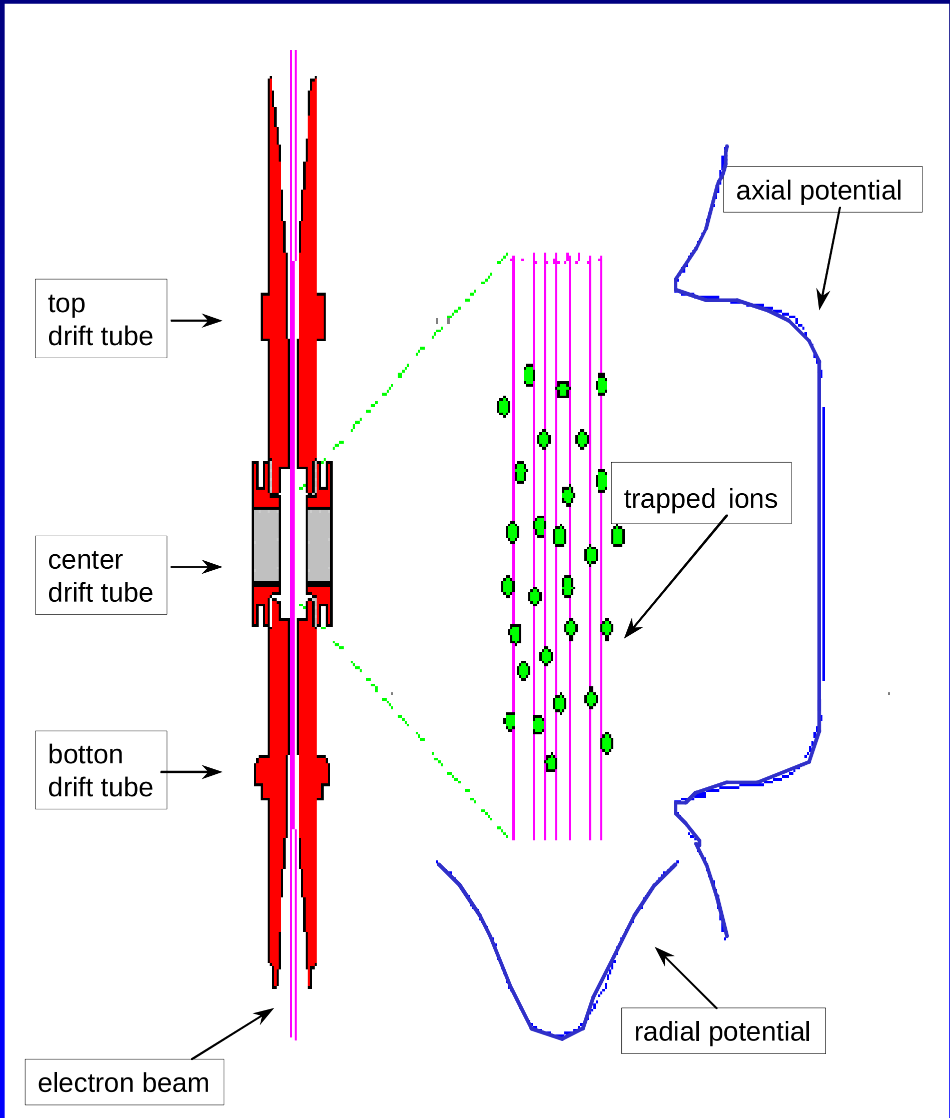
i.e. space-charge confinement in an

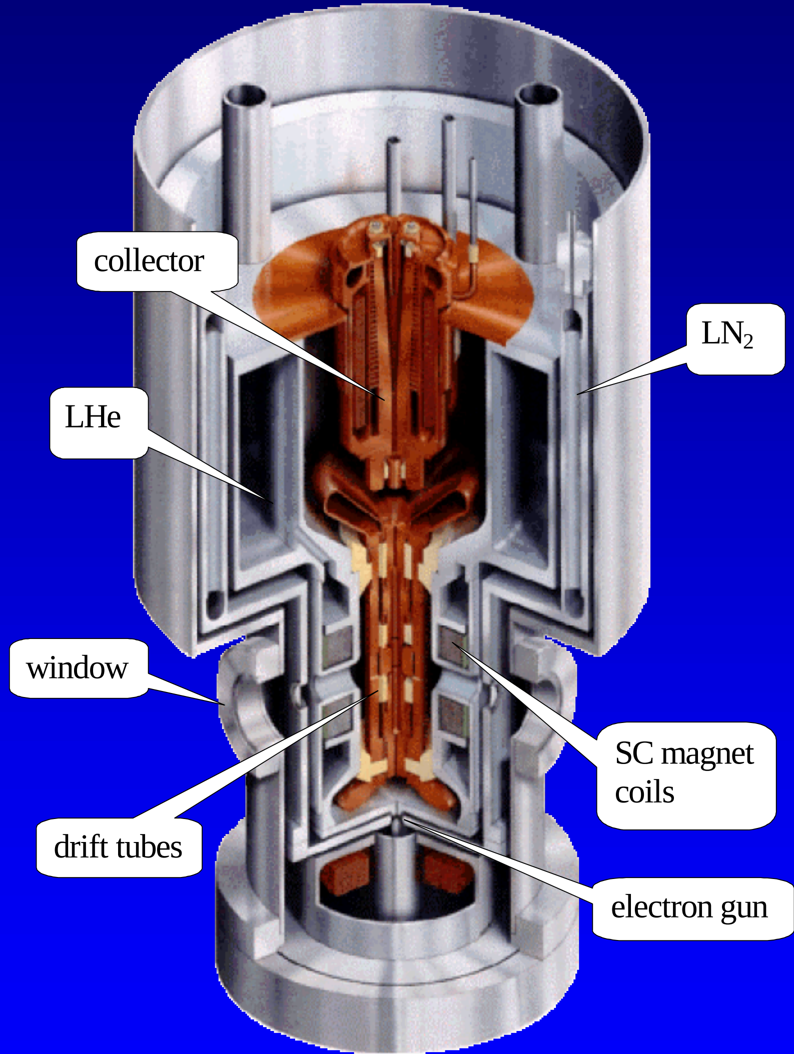
Electron Beam
Ion Trap
EBIT



LLNL, Livermore/CA

HCI production and confinement in an EBIT





EBIT II

Note:
The ions may
not stay continuously
right inside
the electron beam.

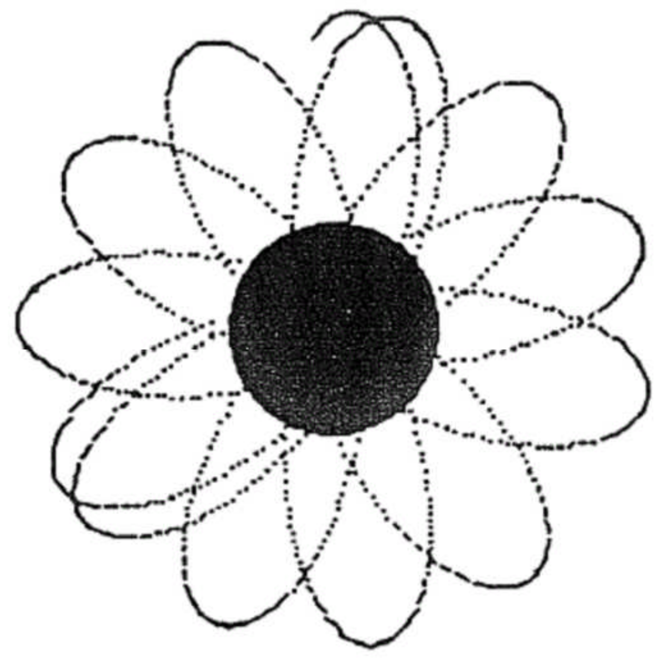


Fig. 2. Numerical simulation of an ion orbit through an electron beam

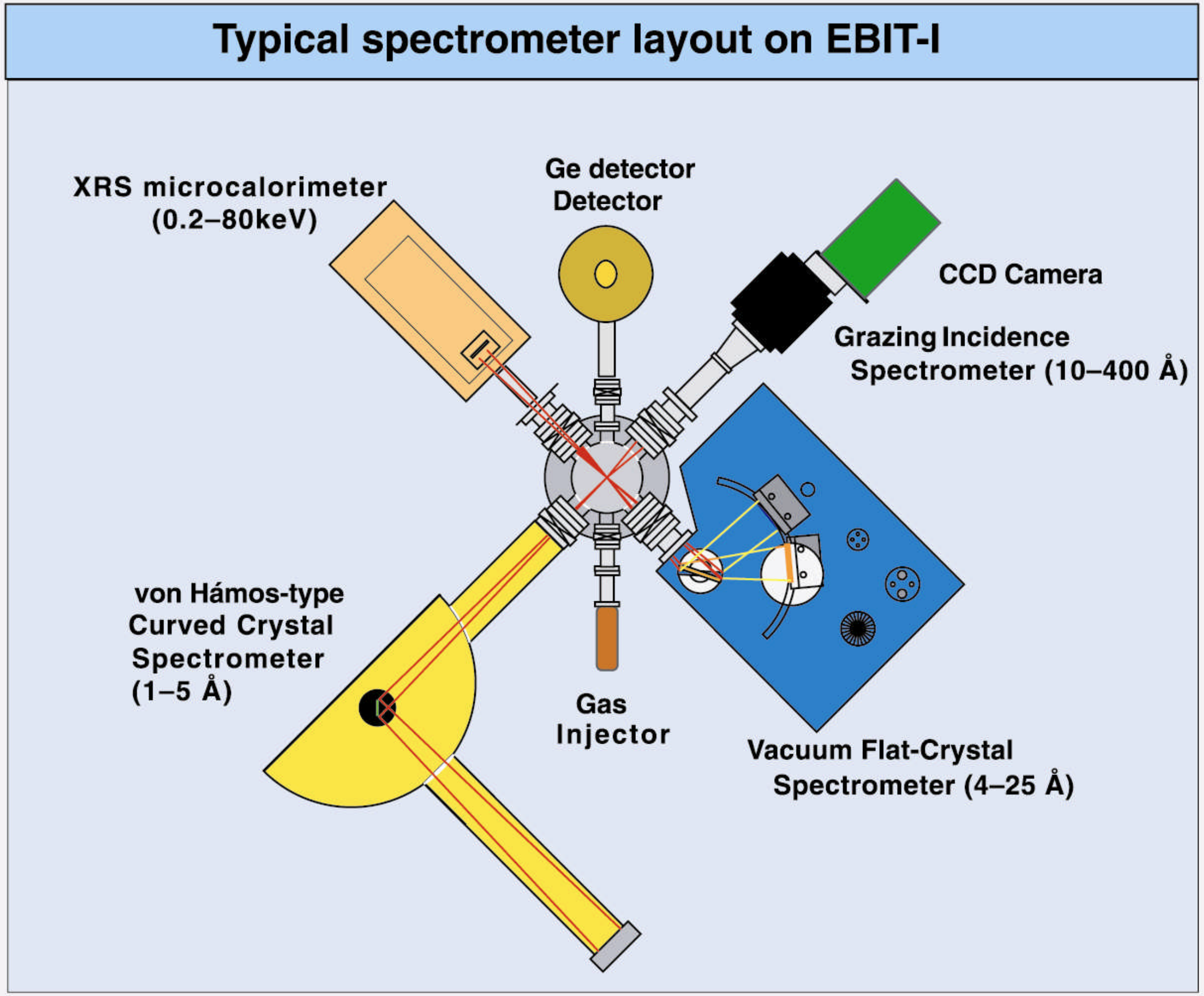
Gillaspy et al., Physica Scripta 1995

Nevertheless, they are effected with respect to

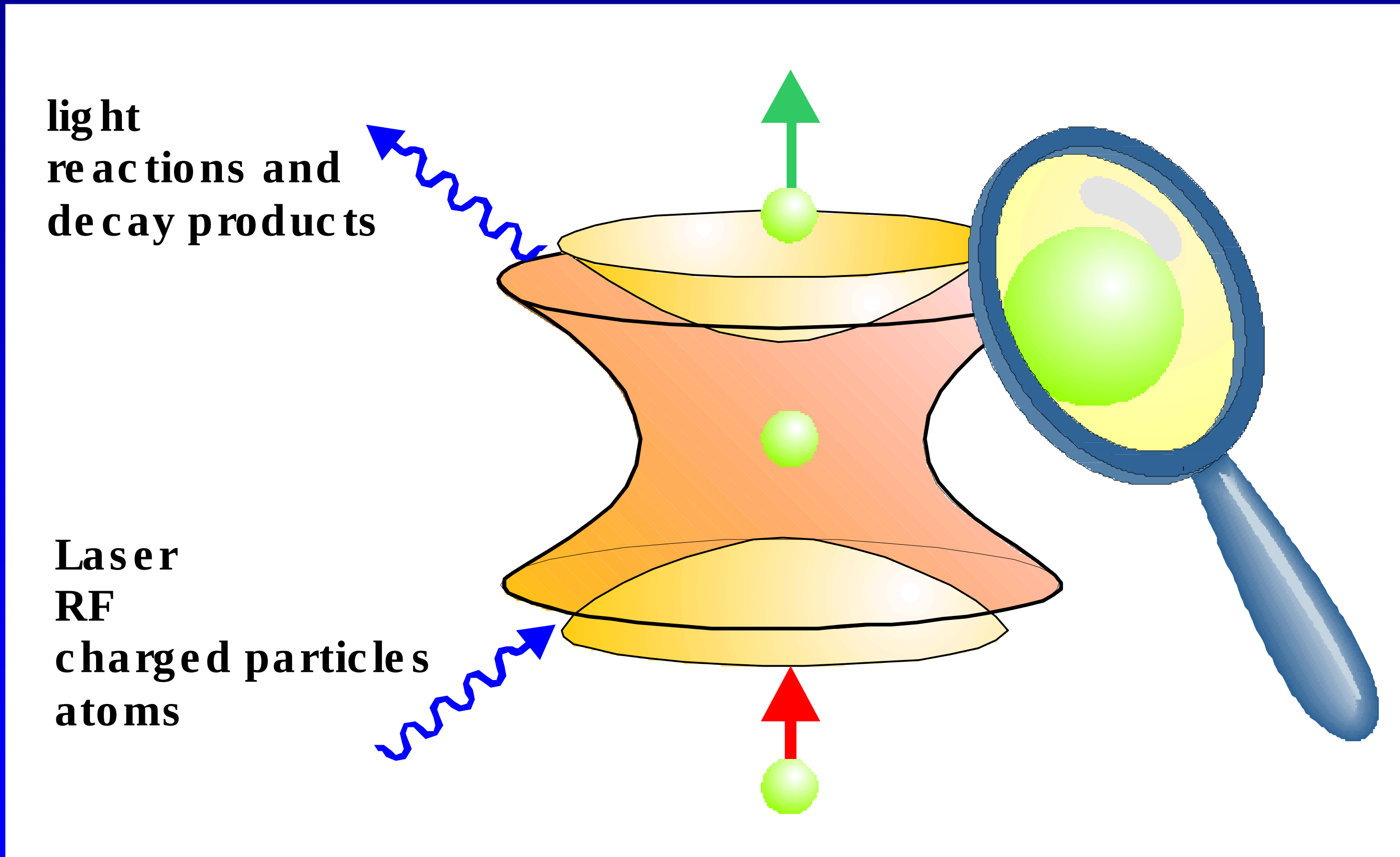
(a) their motional modes
and
(b) their internal structure

due to the short- and long-range interaction, resp., with the electron beam.

There are lots of interesting things to be done at EBIT



However, there are circumstances where ion trapping in a “wall-less container” is chosen to eliminate any interaction but only the one of interest, and in particular to study the re-action after a defined interaction



In more general terms ion trapping allows

extended preparations,
extended interactions,
extended re-action periods,
extended multi-step sequences.

Which leads to

- effective (non-destructive) (re-)use of rare species,
- easy manipulation of motion and internal modes,
- highly-accurate determination of *m*/*q*,
- selection by *m*/*q*-separation,
- accumulation & bunching ,
- charge breeding (ionization, electron attachment),
- cooling (again of motion and internal modes),
- ...

Prominent argument: Fourier Limit

Storage

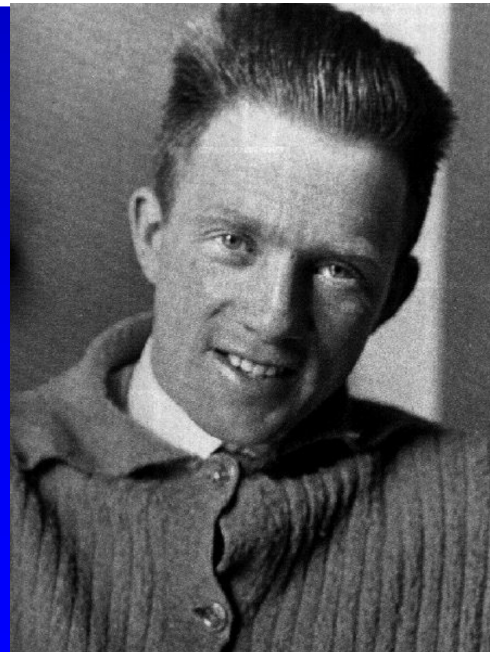
Resolving Power

$$\Delta t \cdot \Delta \upsilon > 1$$

$$\Delta t \cdot \Delta E > h$$

Important factor for

- all kinds of spectroscopy (laser, microwave, etc.)
- mass separation
- mass determination
  - analytical applications and
  - precision measurements



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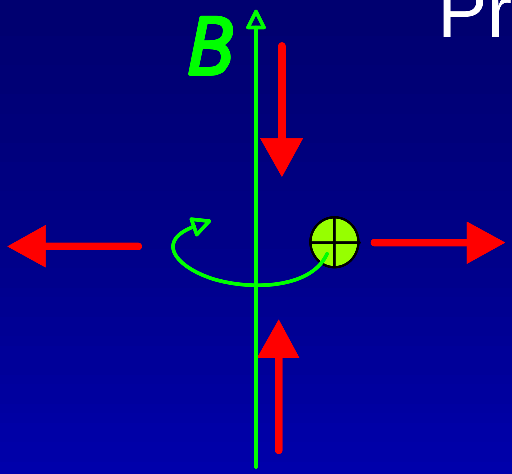
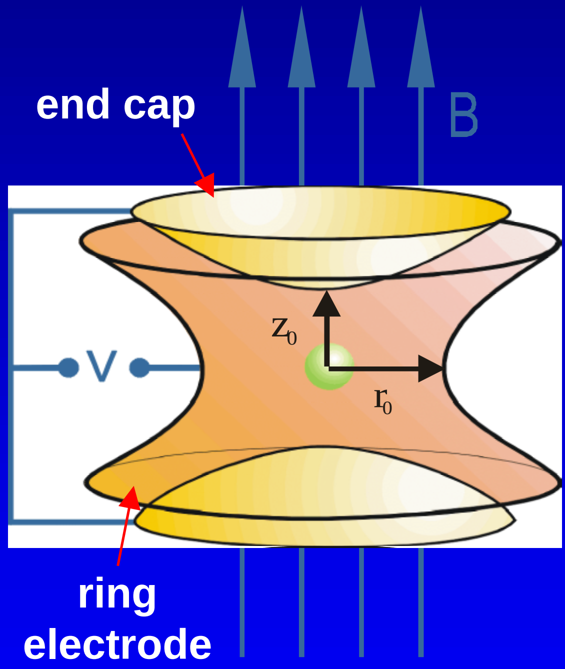
Principle of Penning traps



Cyclotron frequency: $\upsilon_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$



PENNING trap

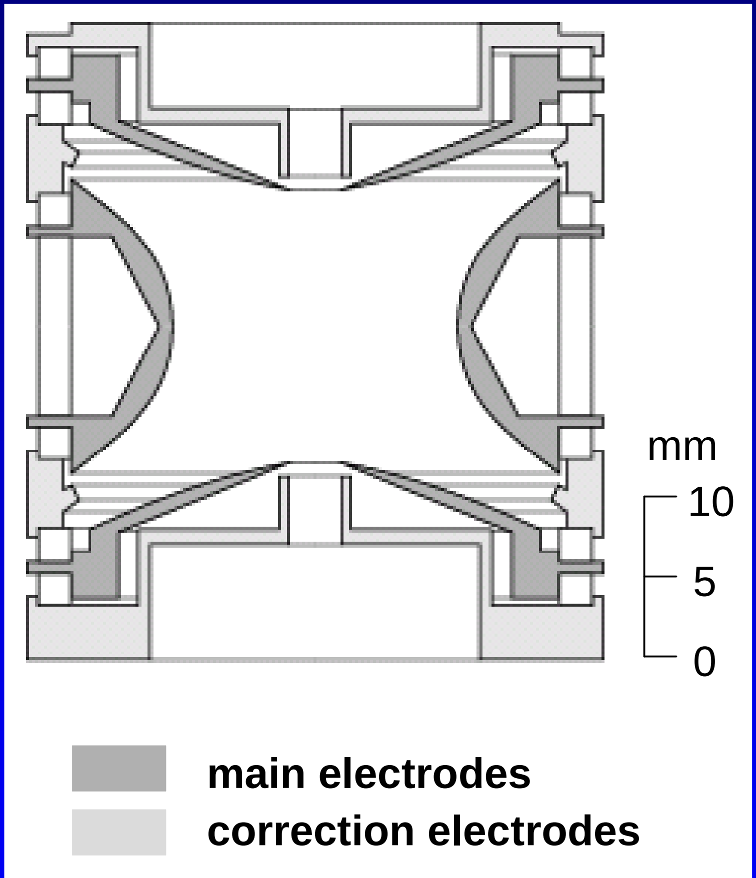
- Strong homogeneous magnetic field
- Weak electric 3D quadrupole field

Frans Michel Penning (Penning discharge at Philips 1936)

Hans G. Dehmelt (Nobel prize in physics 1989)

Penning trap configurations

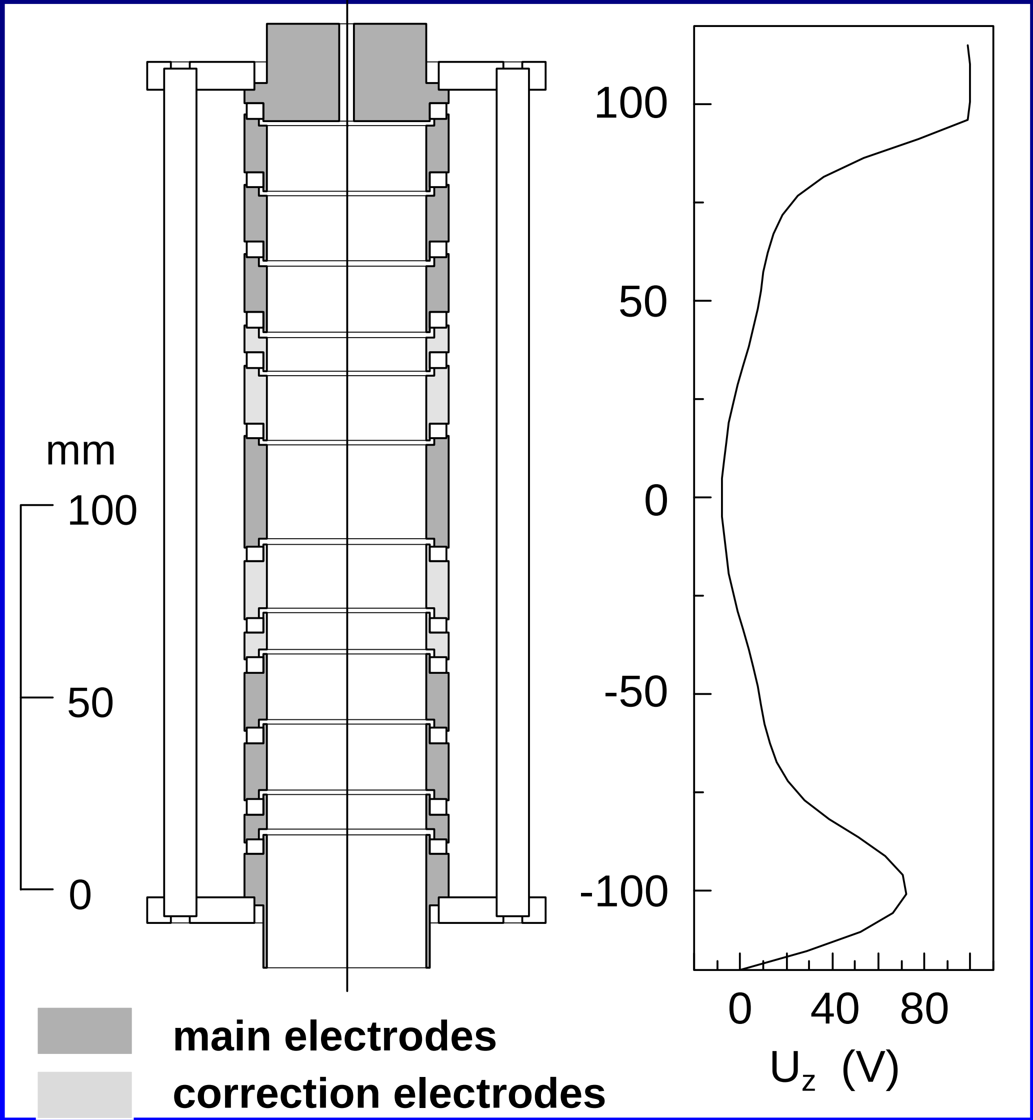
Hyperbolical Penning trap



$z_0 = r_0 / \sqrt{2}$ often used but not necessarily the best choice

Cylindrical Penning trap

Axial Potential



Equation of motion in a Penning trap

El. plus Lorentz force:

$$\vec{F} = -q\vec{\nabla}\phi(r) + q\vec{v}\times\vec{B}$$

equation of motion:

$$q\left(\vec{\nabla}\phi(r) + \vec{v}\times\vec{B}\right) + m\ddot{\vec{r}} = 0$$

axial oscillation

$$\frac{qU_0}{md_0^2}\cdot z + m\ddot{z} = 0$$

$$\omega_z = \sqrt{\frac{qU_0}{md_0^2}}$$

***z* or axial frequency**

radial oscillation

substitution: $u = x + iy$

$$\omega_c = \frac{e_0}{m}B$$

$$i\omega_c\dot{u} - \frac{\omega_z^2}{2}u + \ddot{u} = 0$$

$$u(t) = u_0 e^{-i\omega t}$$

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

modified or reduced cyclotron frequency

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

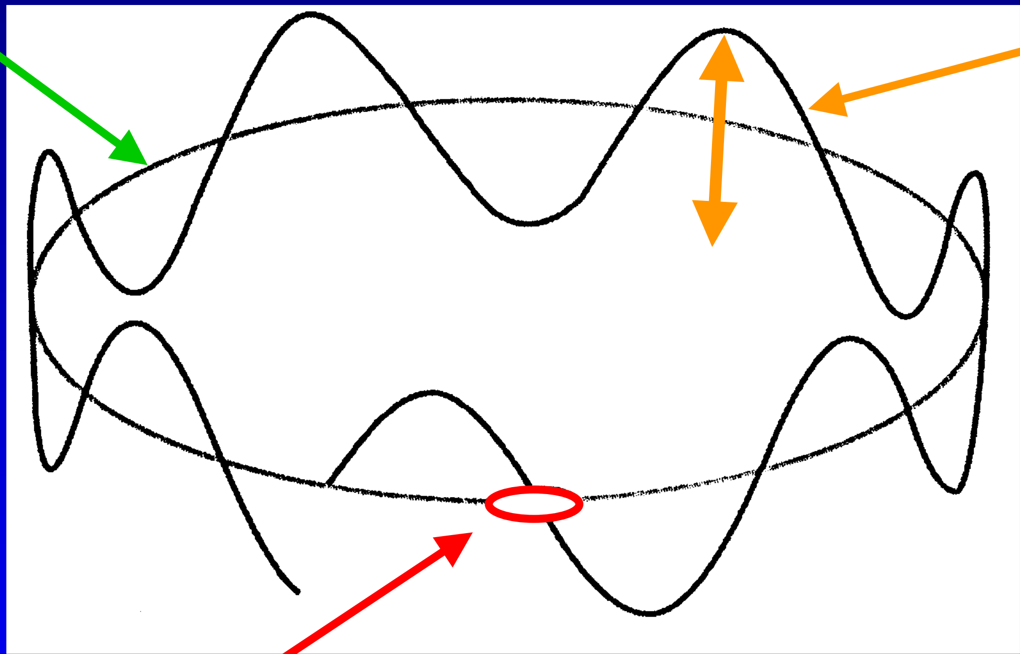
magnetron frequency

Ion motion in a Penning trap

magnetron motion

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\left(\frac{\omega_c}{2}\right)^2 - \frac{\omega_z^2}{2}}$$

kHz range



trapping motion

$$\omega_z = \sqrt{\frac{qU}{md^2}}$$

cyclotron motion

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\left(\frac{\omega_c}{2}\right)^2 - \frac{\omega_z^2}{2}}$$

MHz range

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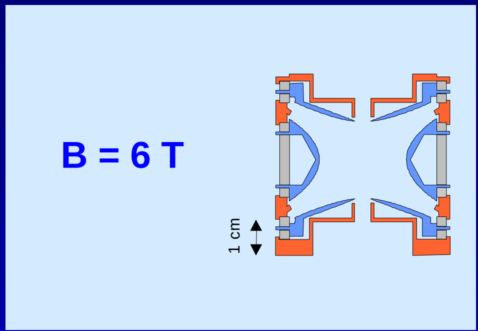
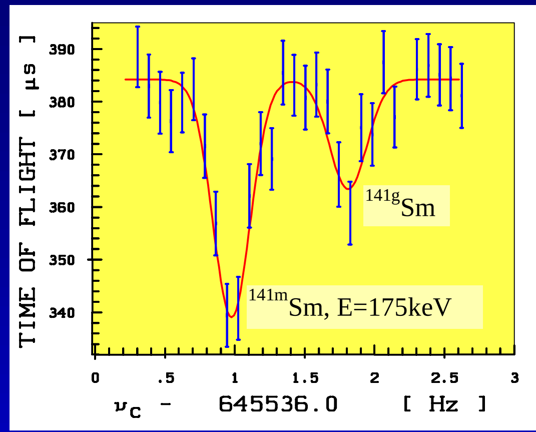
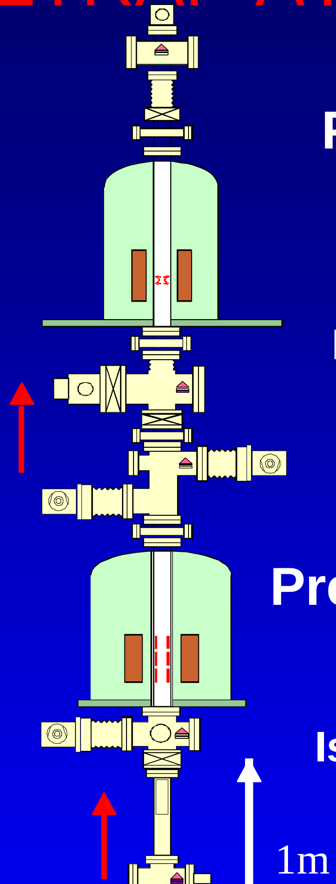
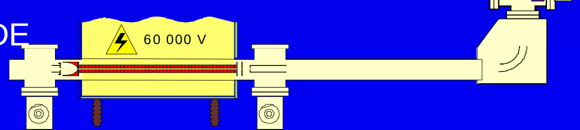
Example for Precision Mass Measurements:
ISOLTRAP AT ISOLDE/CERN



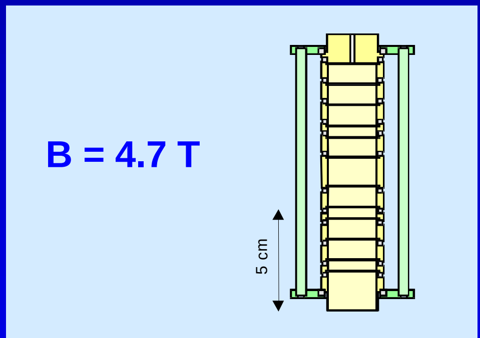
Precision Trap:
Determination of cyclotron frequency
Isomer separation



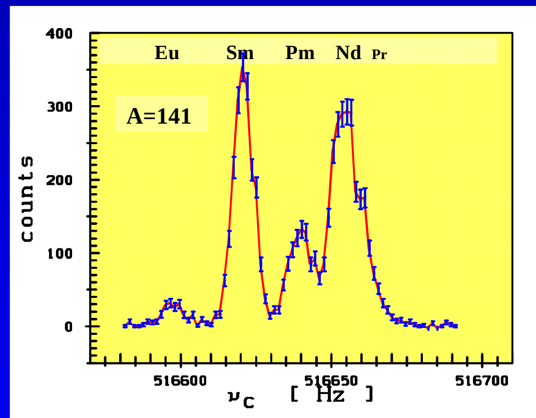


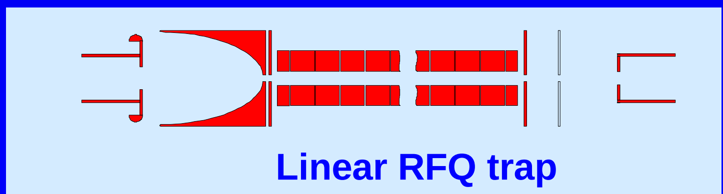


60keV ISOLDE ion beam



Preparation Trap:
Accumulation
Cooling
Isobar separation

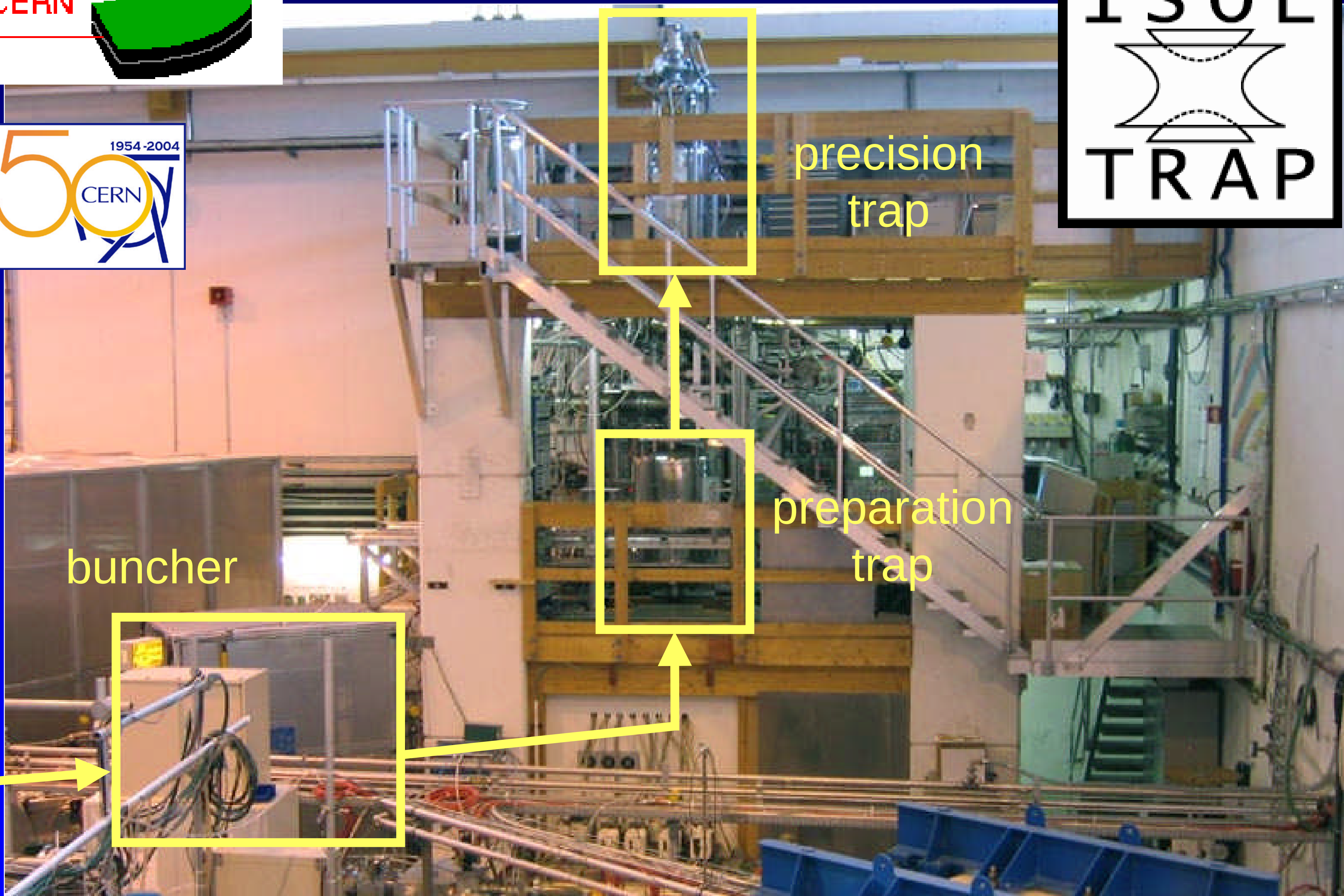




Retardation
Cooling
Accumulation
Bunching

H. Stolzenberg et al., PRL (1990)
G. Bollen et al., NIM A (1996)
F. Herfurth et al., NIM A (2001)

http://isoltrap.web.cern.ch



For some highlights see PRL **92**, 112501, **93**, 072502, **93**, 150801 (all 2004)

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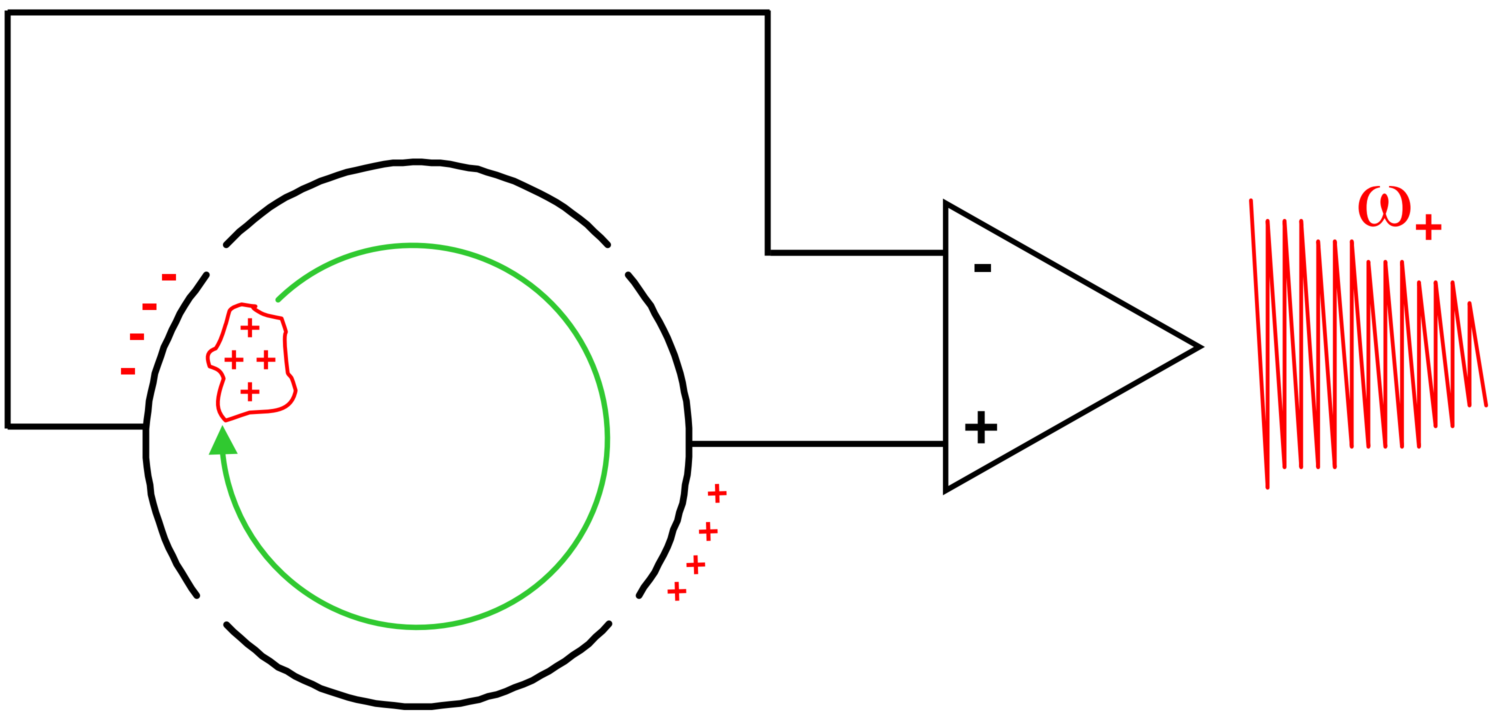
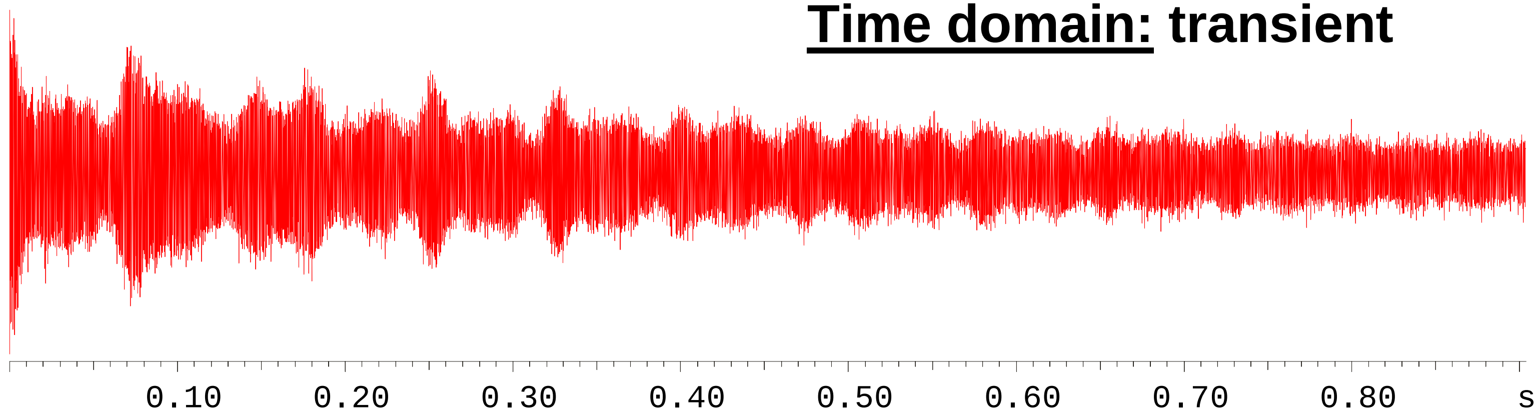
Mass Spectrometry for Analytical Chemistry:
Fourier Transform Ion Cyclotron Resonance Mass Spectrometry (FT-ICR MS or short **FTMS)**
Broadband excitation and detection



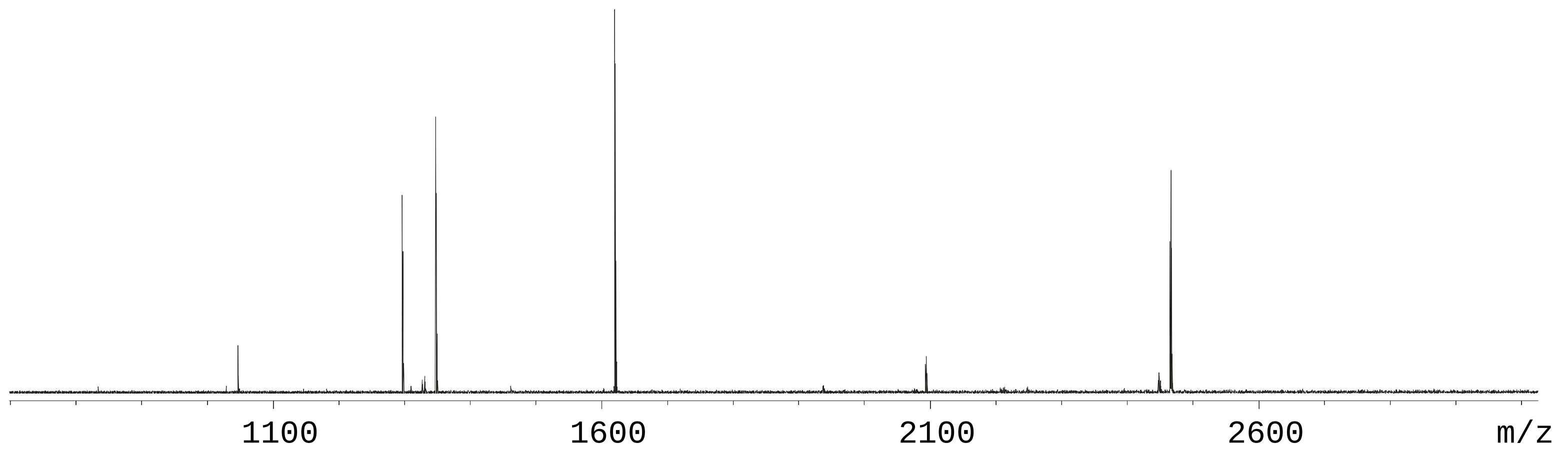
Comisarow & Marshall, 1974

Fourier Transformation

<u>Time domain:</u> transient

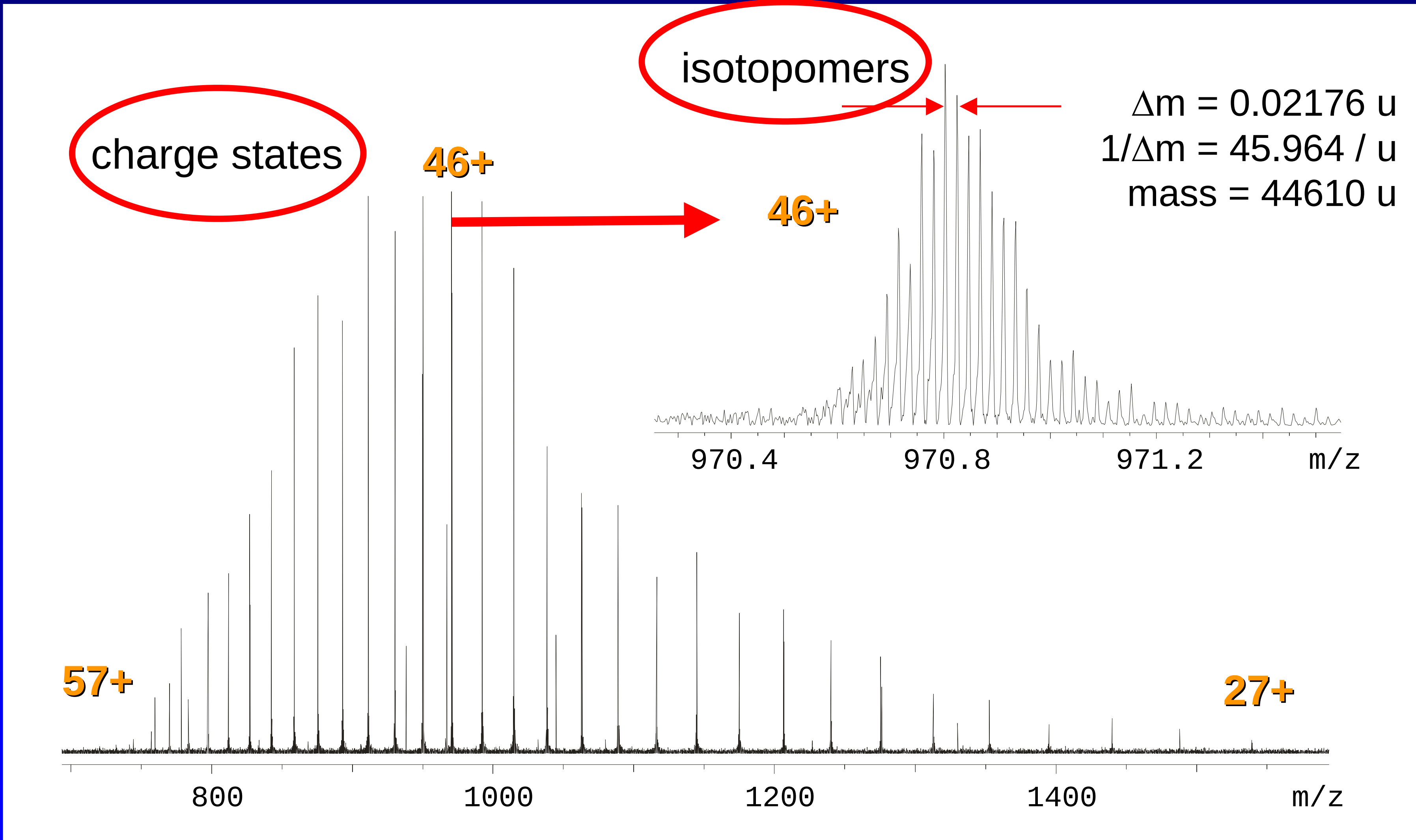


<u>Frequency domain:</u> mass spectrum



Boom since early 1990s in bio-chemistry

Example: Protein A (44kDa) Broadband Spectrum



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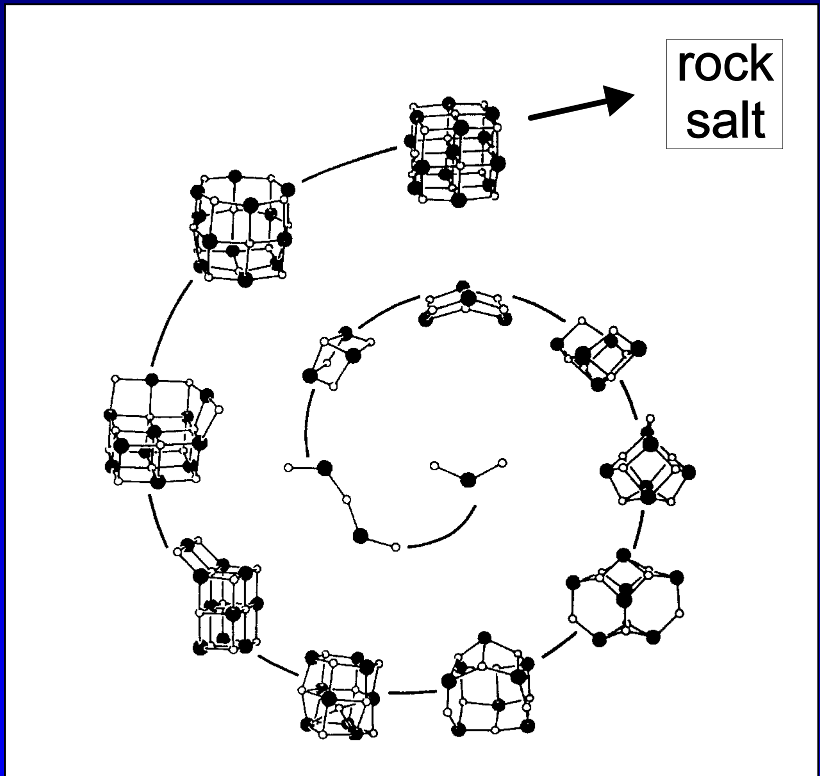
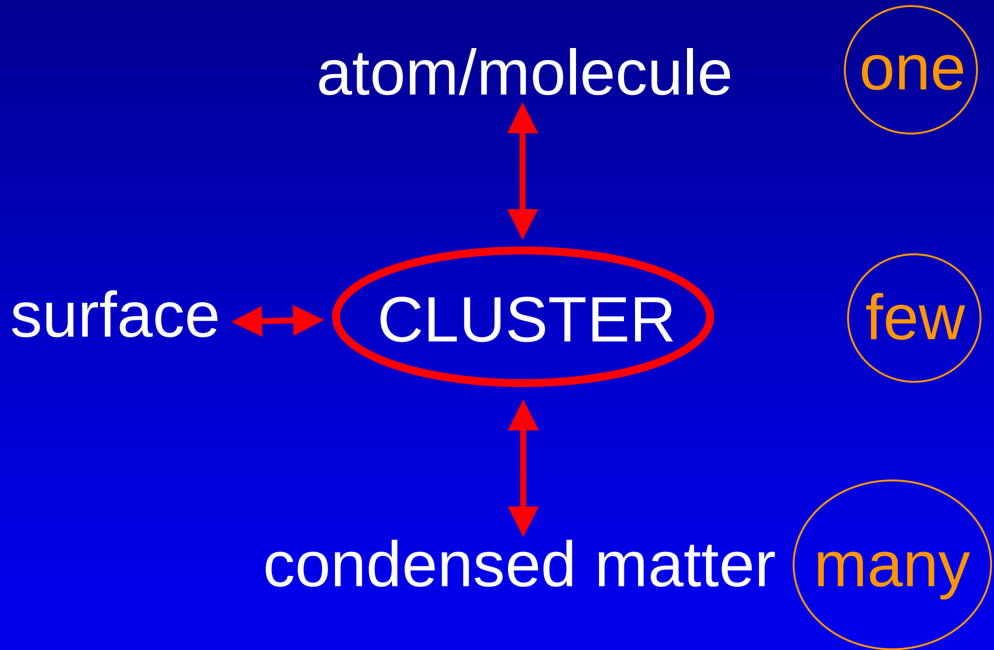
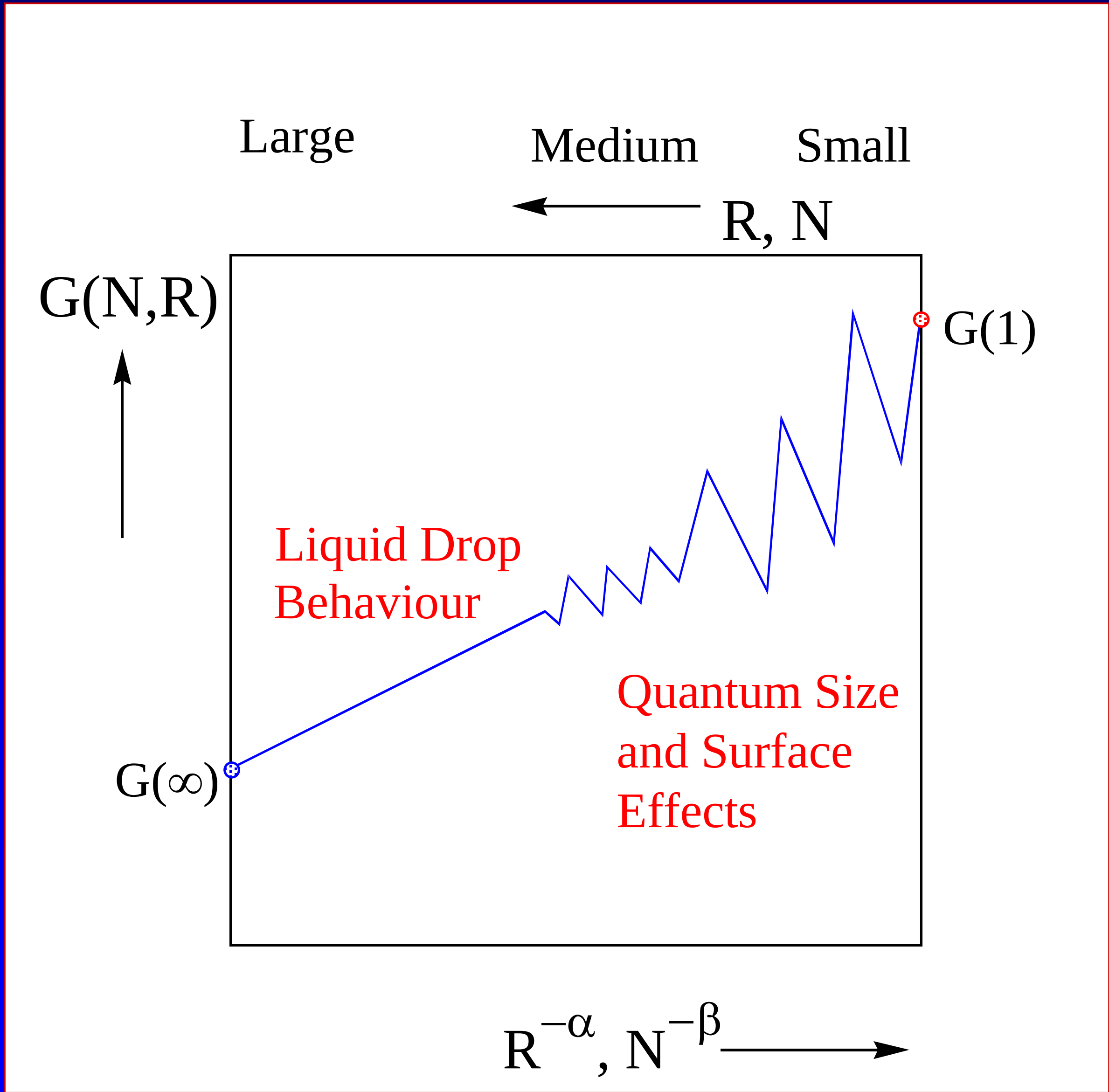
From Atoms to Bulk Matter: Clusters



T.P. Martin (1984)

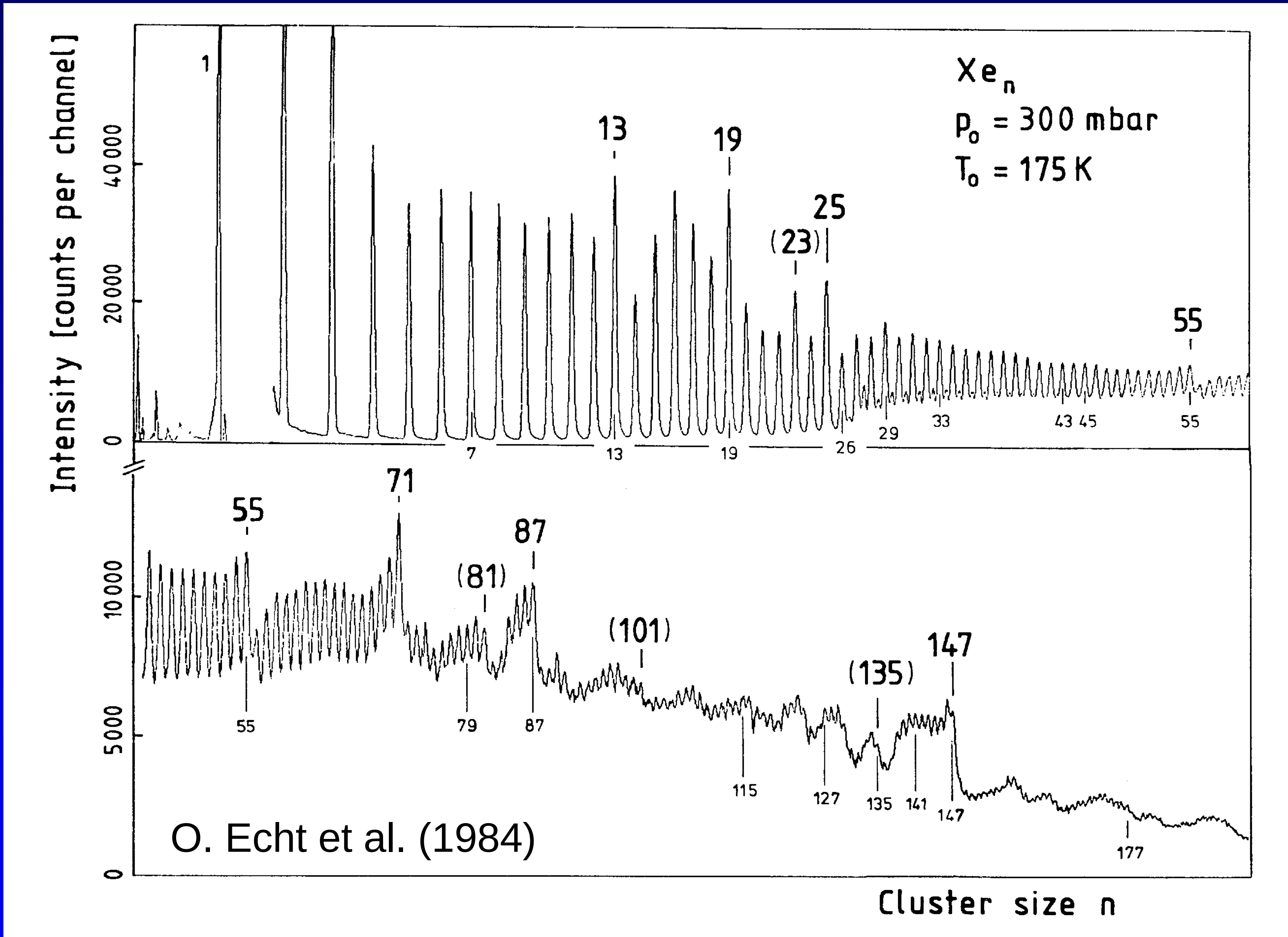


Scaling Laws

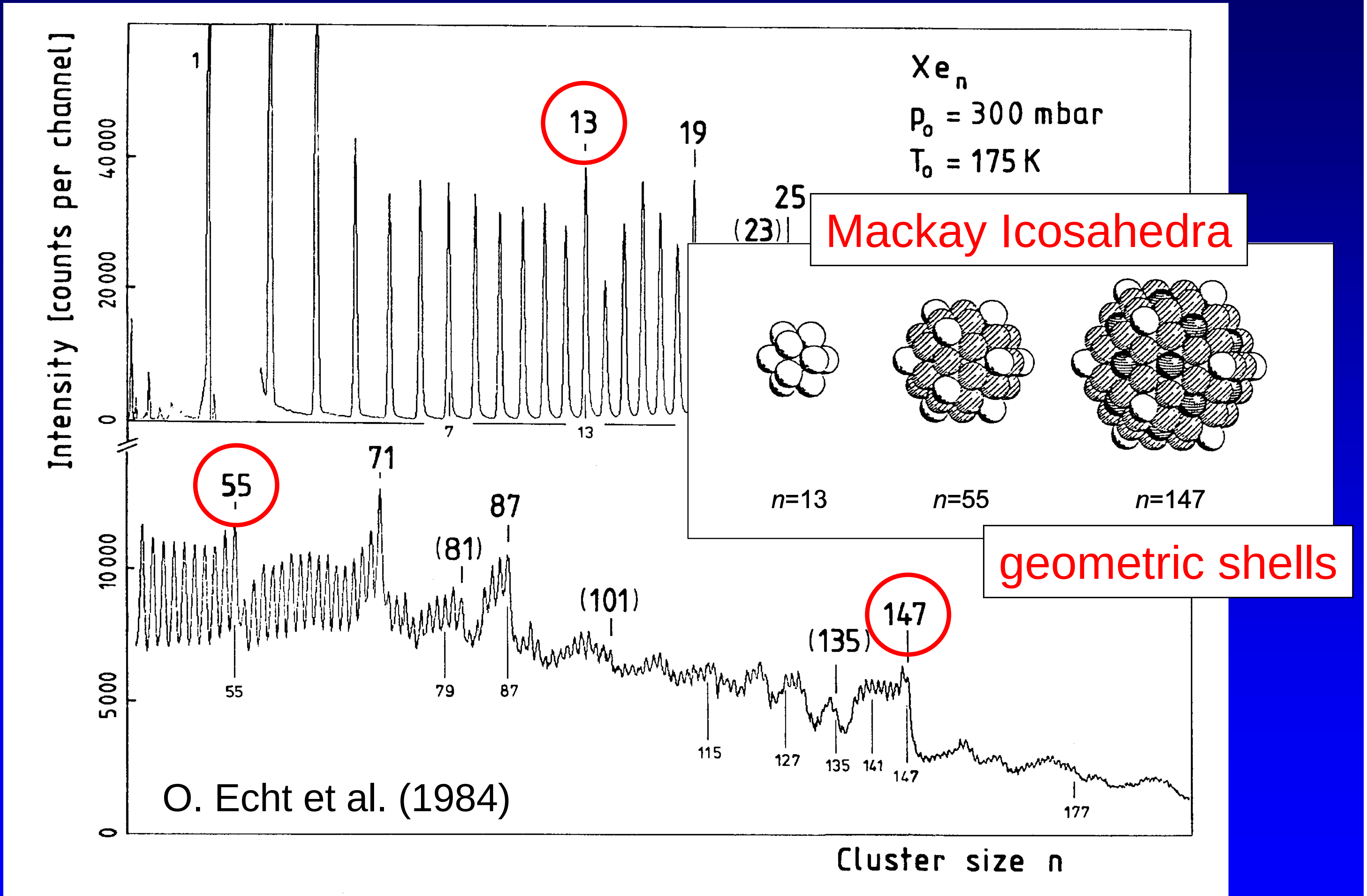


Roy L. Johnston: Atomic and Molecular Clusters
(London, New York, 2002)

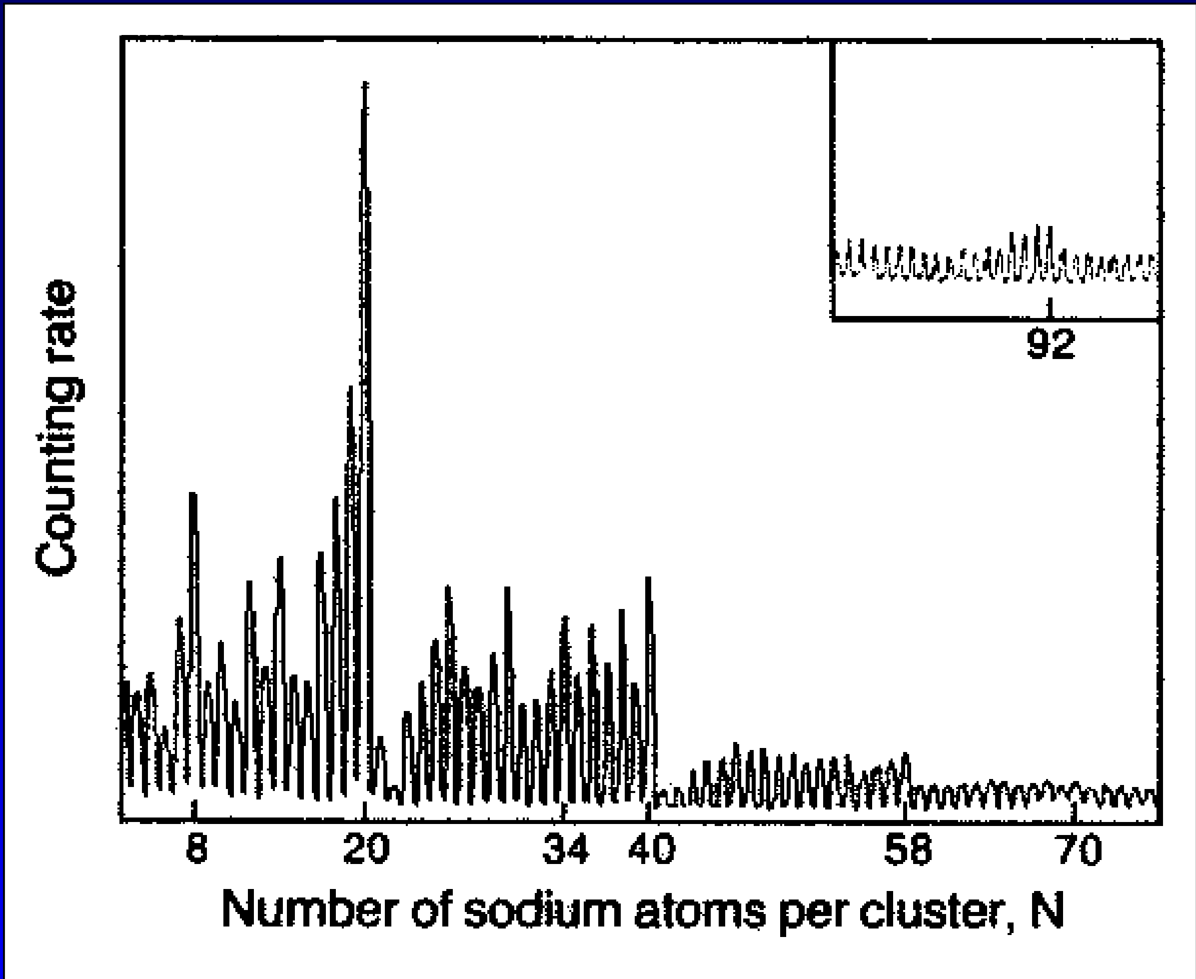
Noble gas clusters: Van der Waals force



Noble gas clusters: Van der Waals force

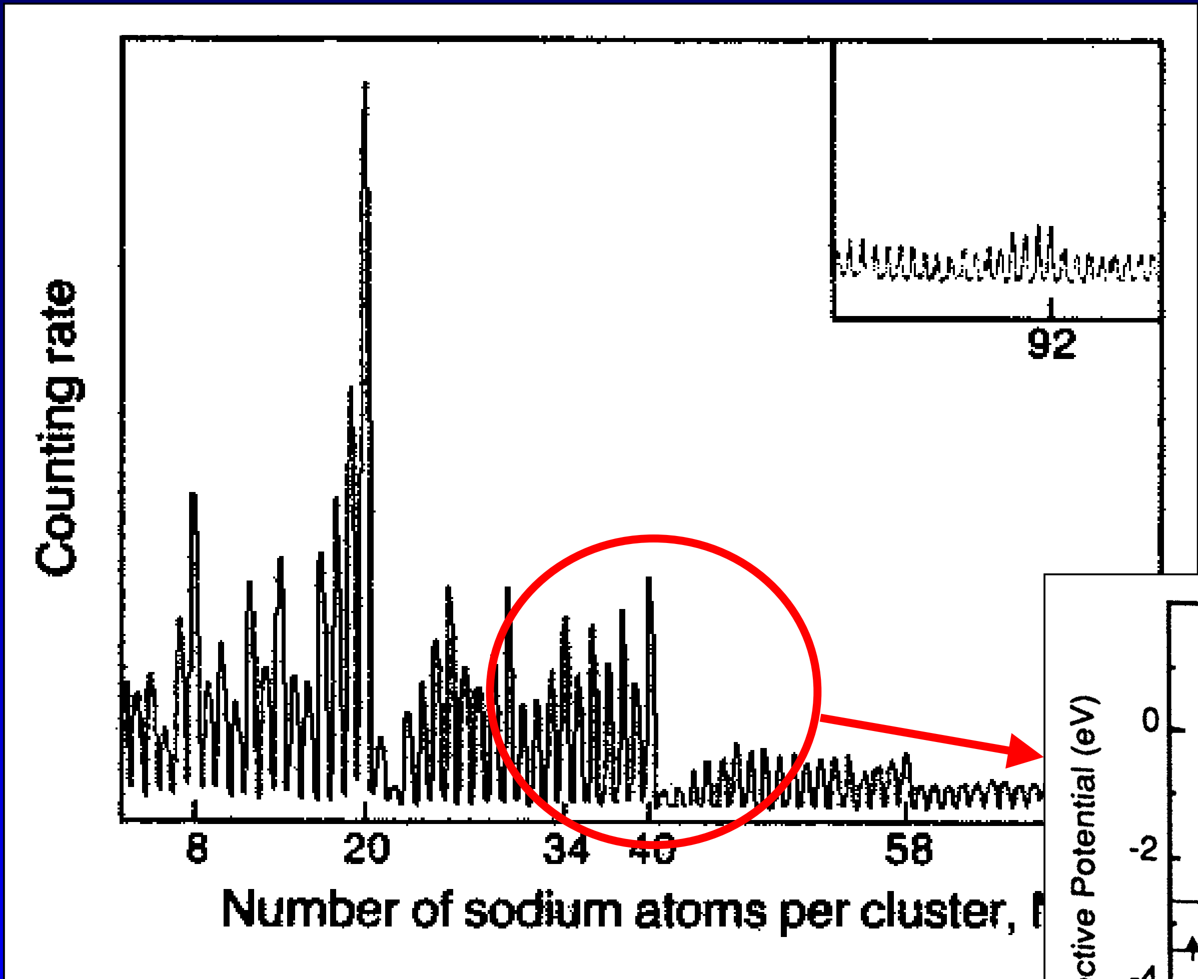


Metal clusters



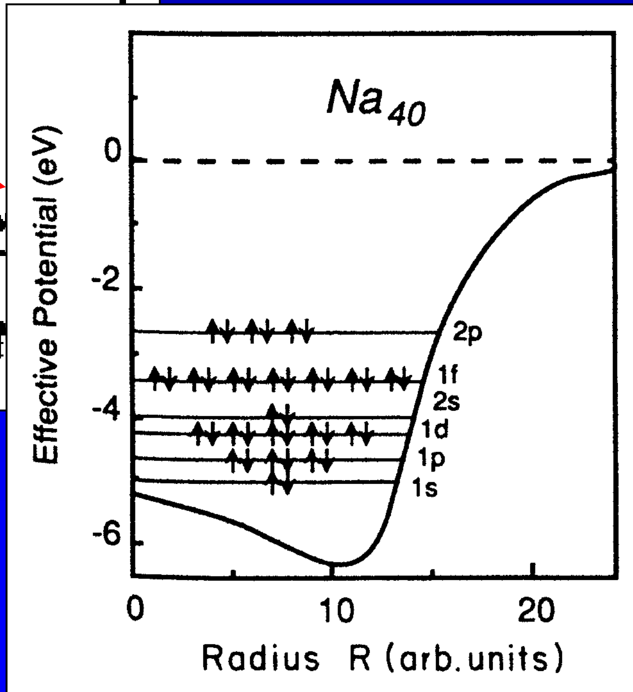
W. D. Knight et al. (1984)

Metal clusters



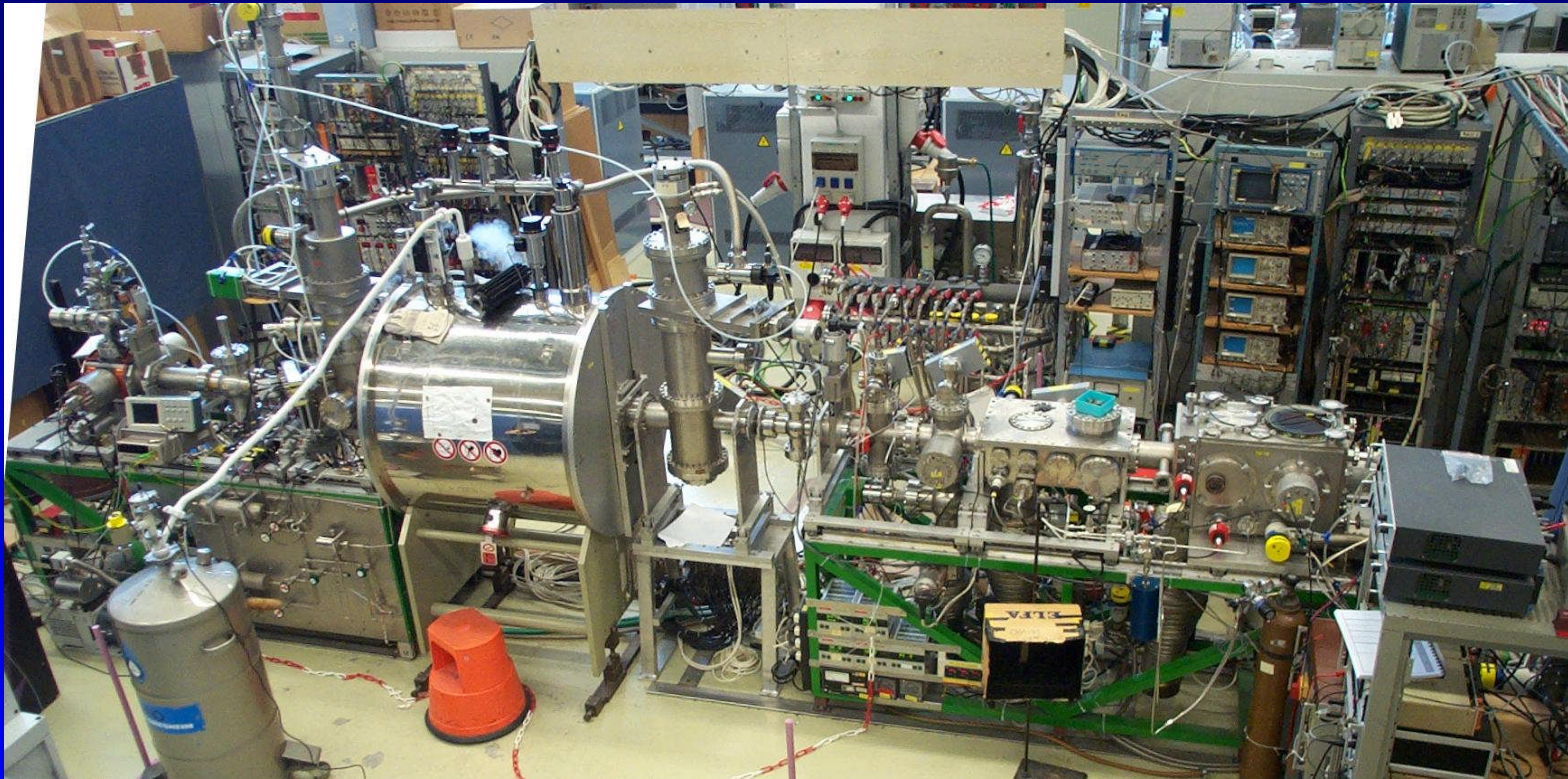
Closed electronic shells

at n=8,20,40,58,92



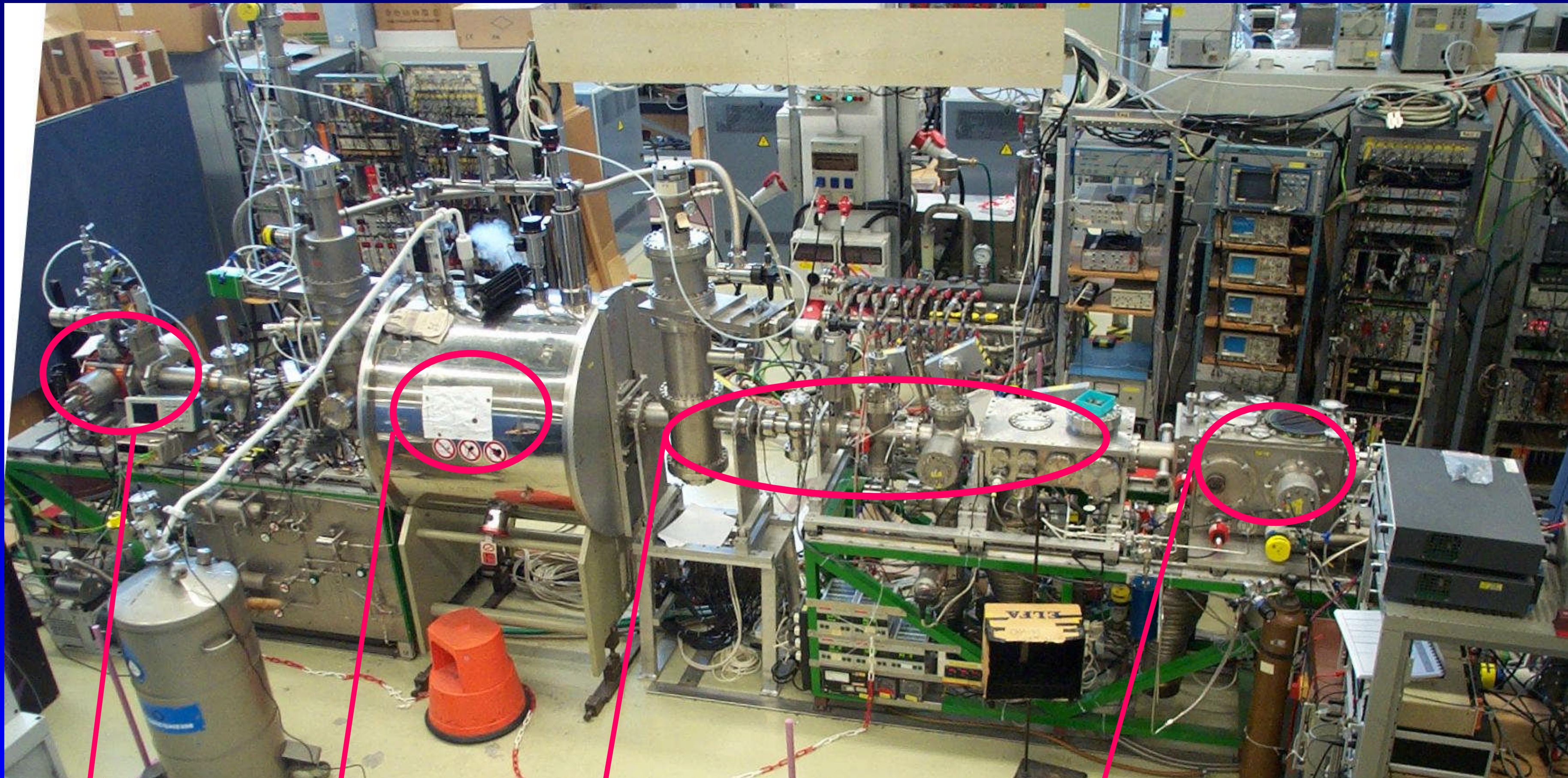
W. D. Knight et al. (1984)

The ClusterTrap setup



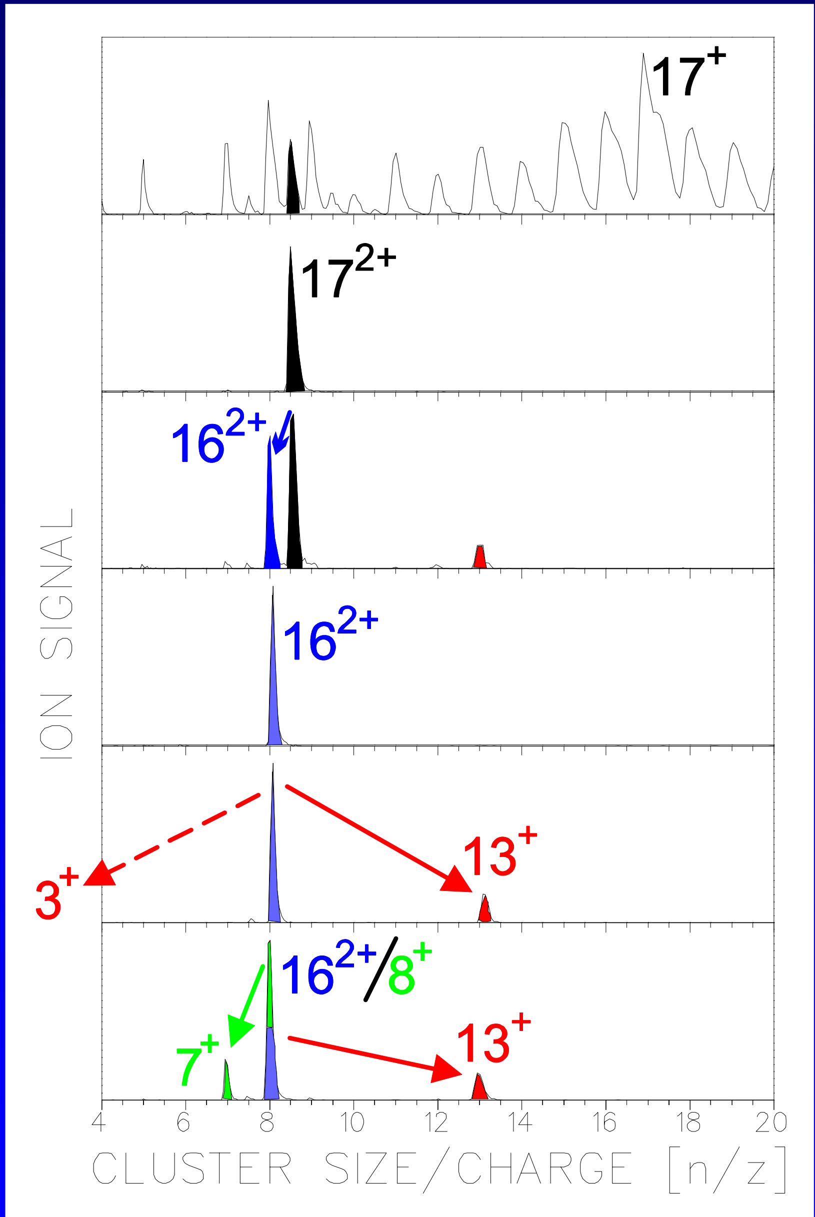
Max-Planck-Institut für Plasmaphysik

The ClusterTrap setup



IPP Max-Planck-Institut für Plasmaphysik

CID of product ions



capture/accumulation and electron bombardment

1. selection

CID

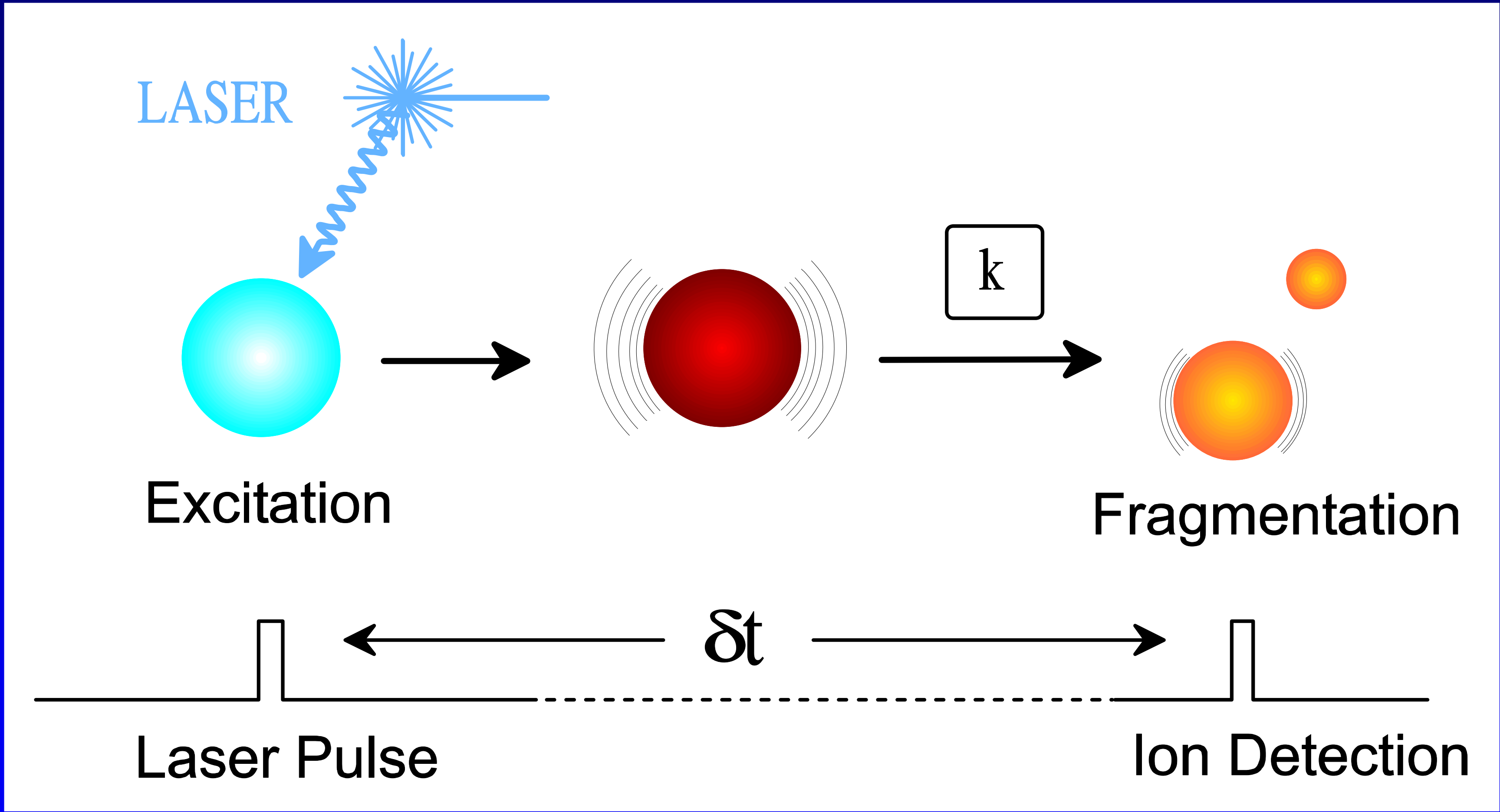
2. selection

CID

CID after first selection

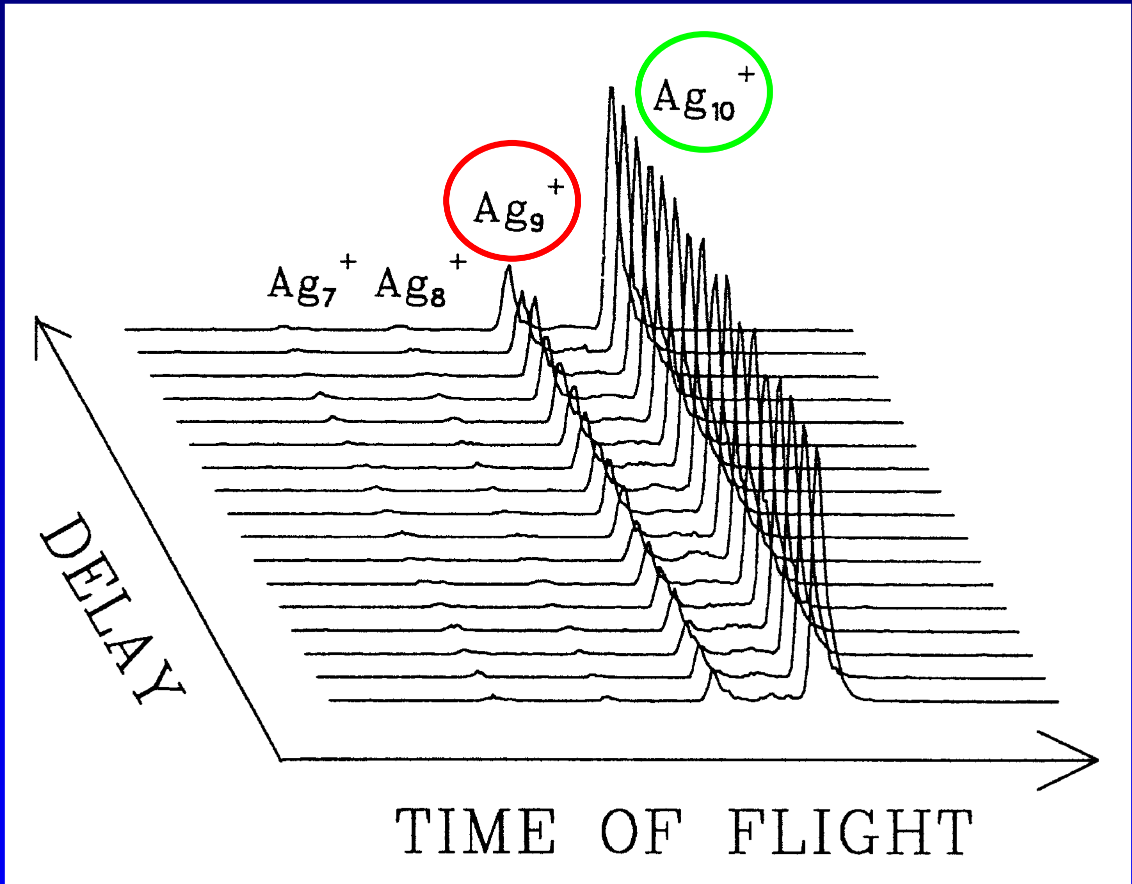
S. Krückeberg et al., ZPD (1997)

Time – resolved photodissociation

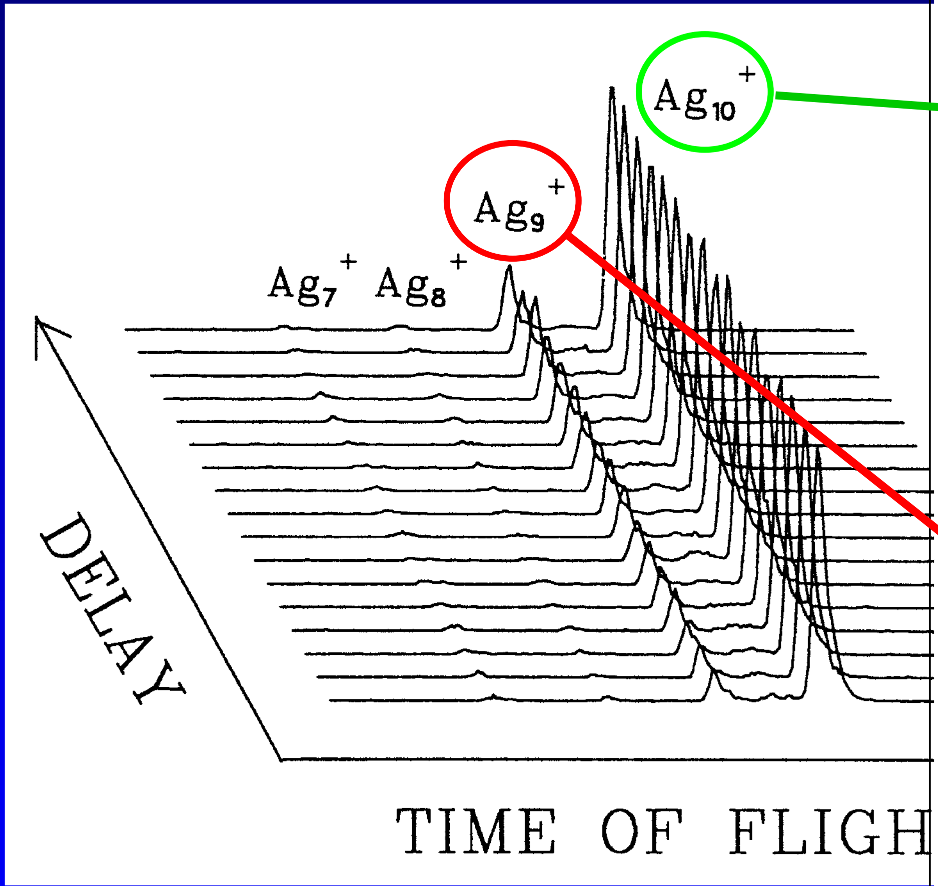


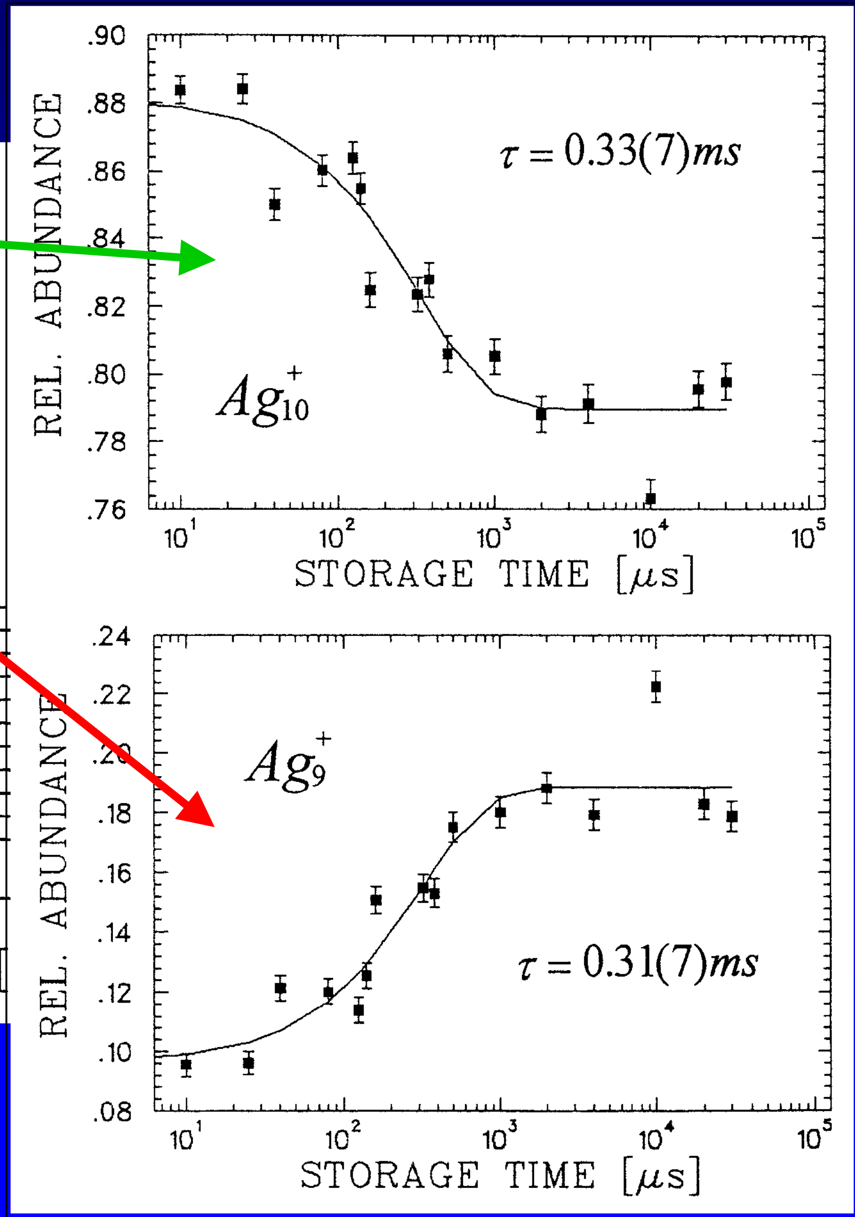
C. Walther et al., CPL (1996), M. Lindinger et al., ZPD (1997)

Time – resolved photodissociation



Time – resolved photodissociation

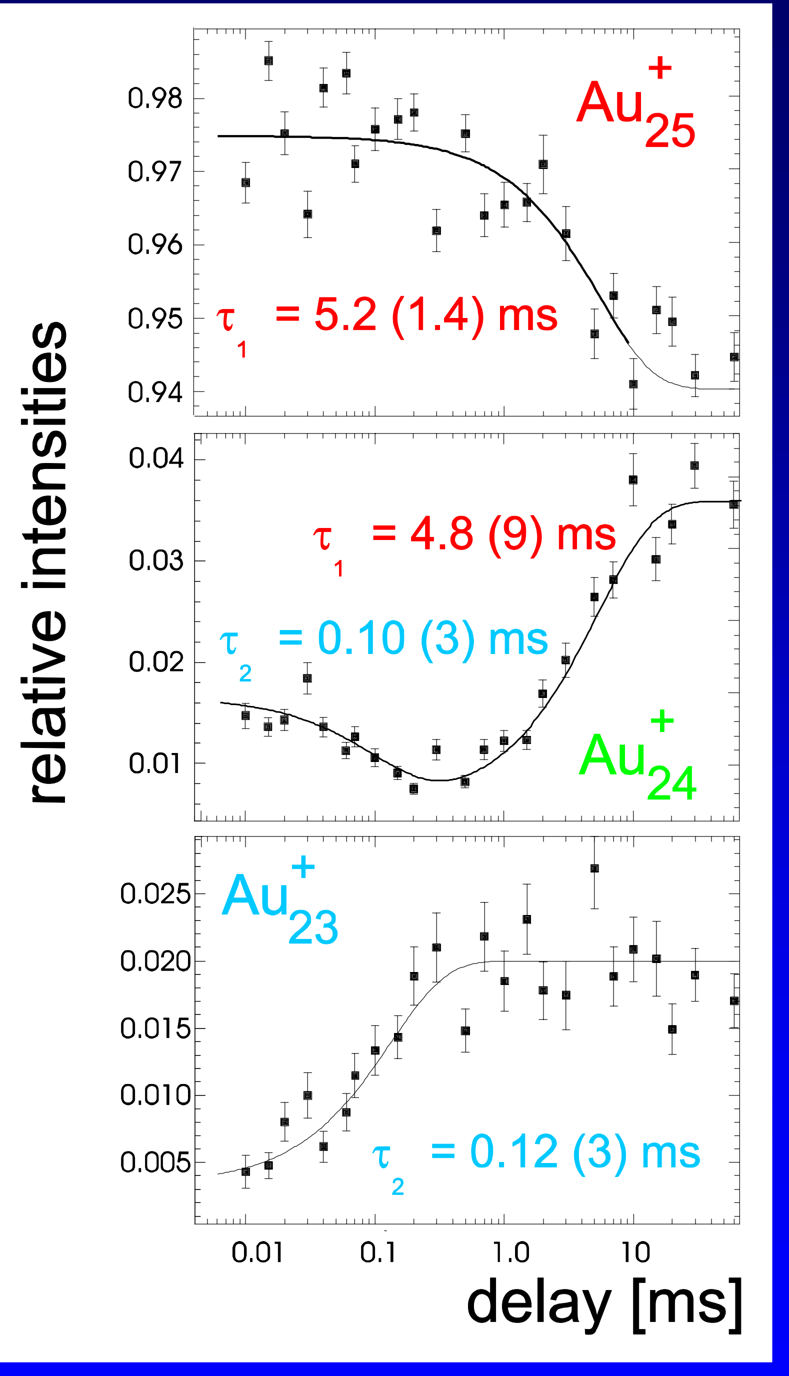




L.S. et al., RCMS (1997)
U. Hild et al., PRA (1998)

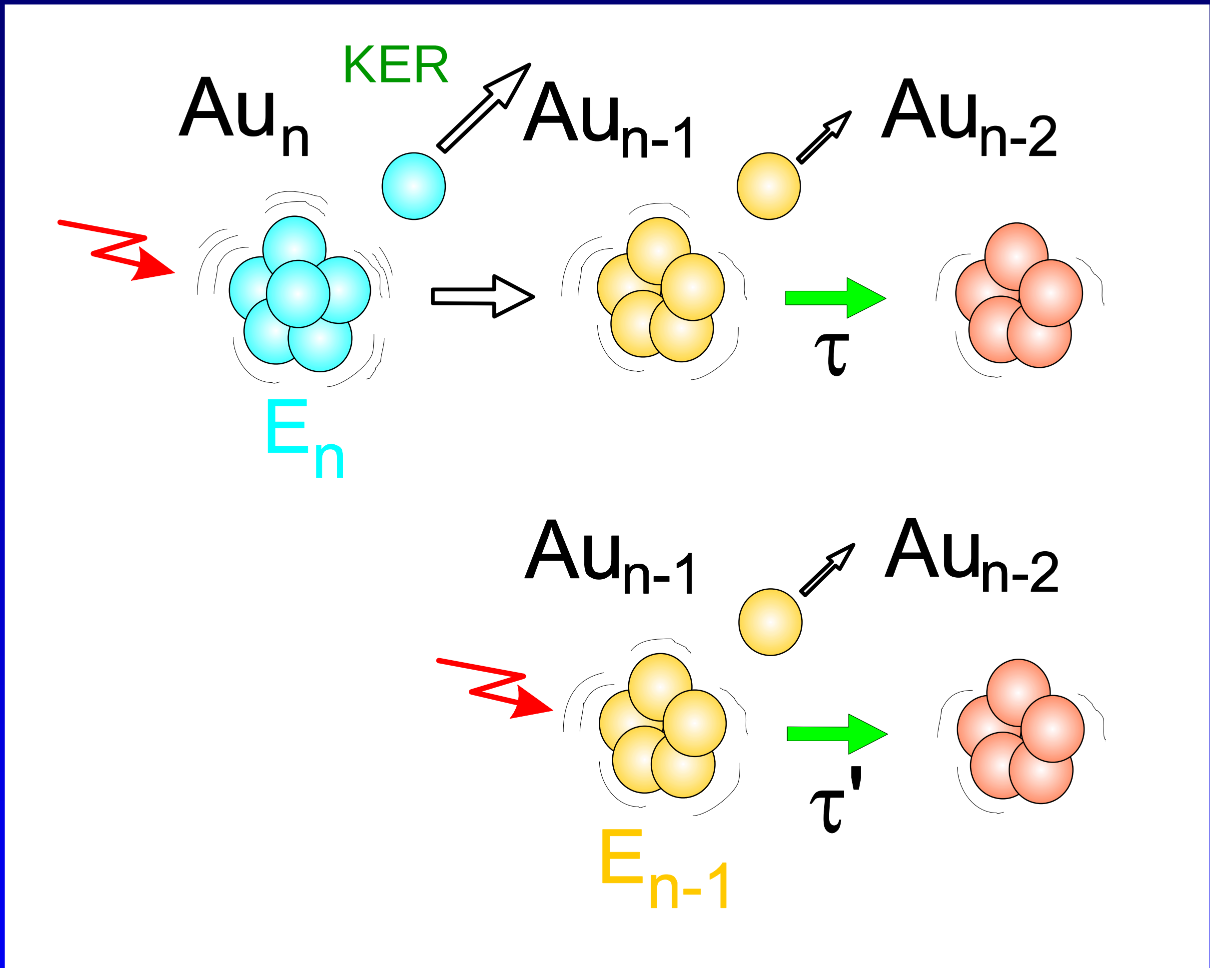
decay cascades

i.e.
sequential
time – resolved
decays



U. Hild et al., PRA (1998)
M. Vogel et al., PRL (2001)

=> model-free determination of **dissociation energy D**



M. Vogel et al.
PRL (2001)

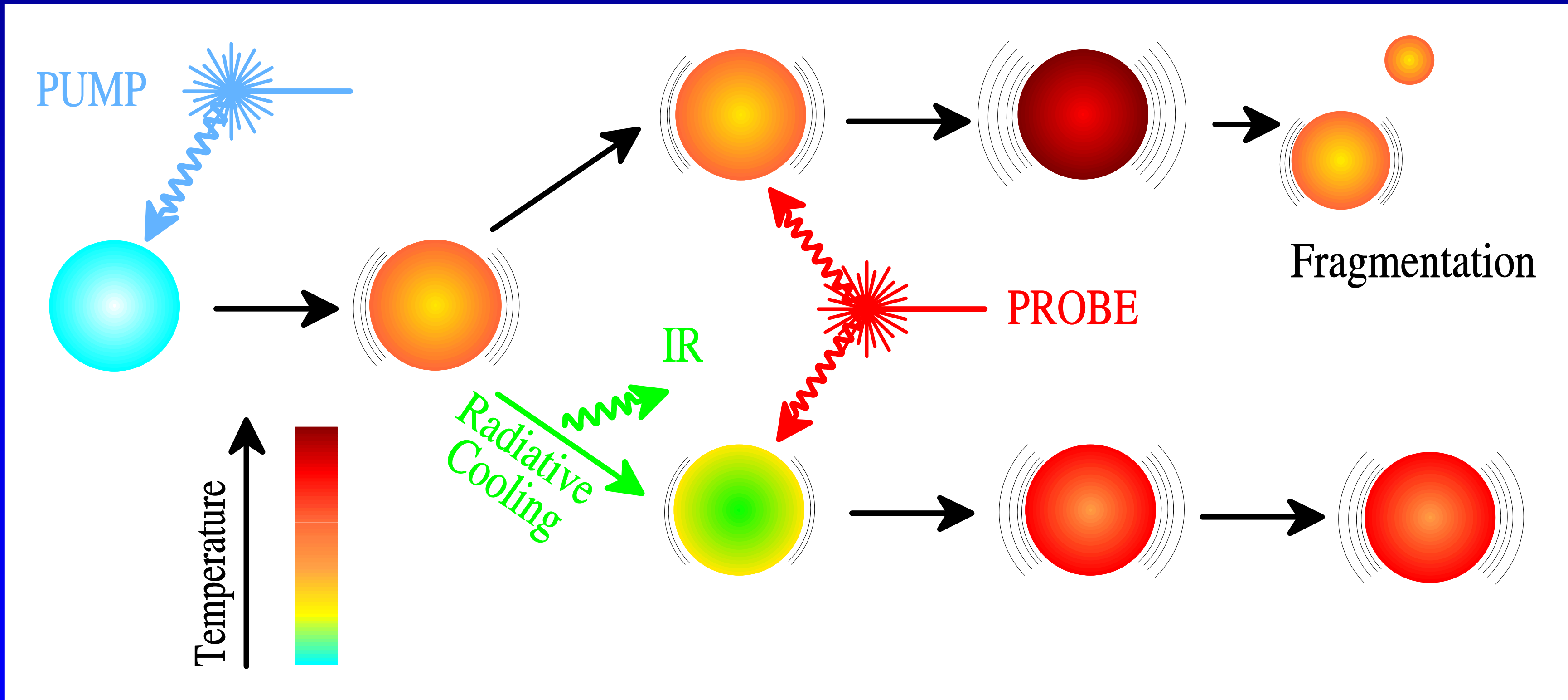
for $\tau = \tau'$: $E_n - D_n - KER = E_{n-1}$

→ $D_n = E_n - E_{n-1} - KER$

Sequential photoexcitation

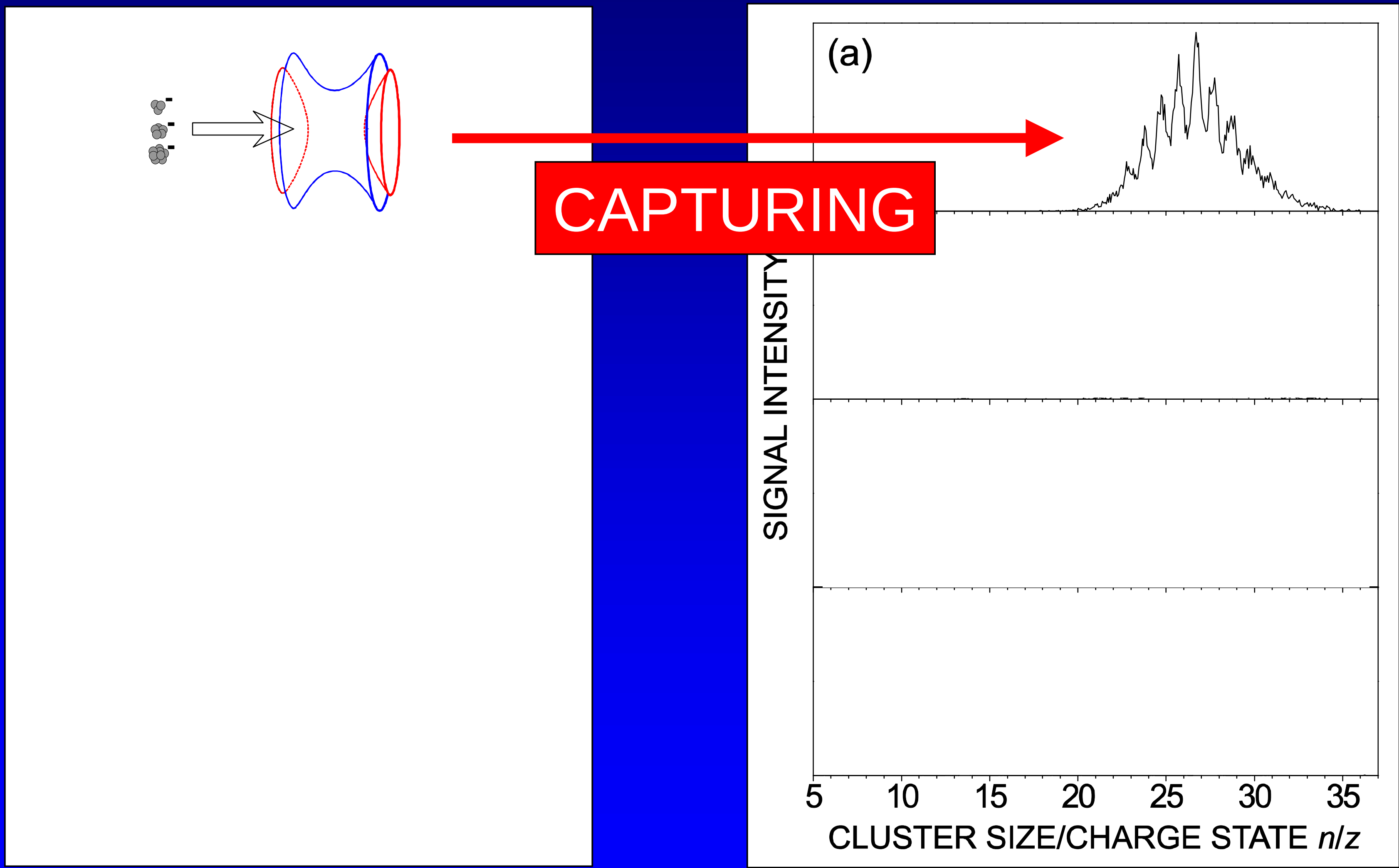
=> Study of **Radiative Cooling**

(„blackbody“ radiation in the limit of small particles)

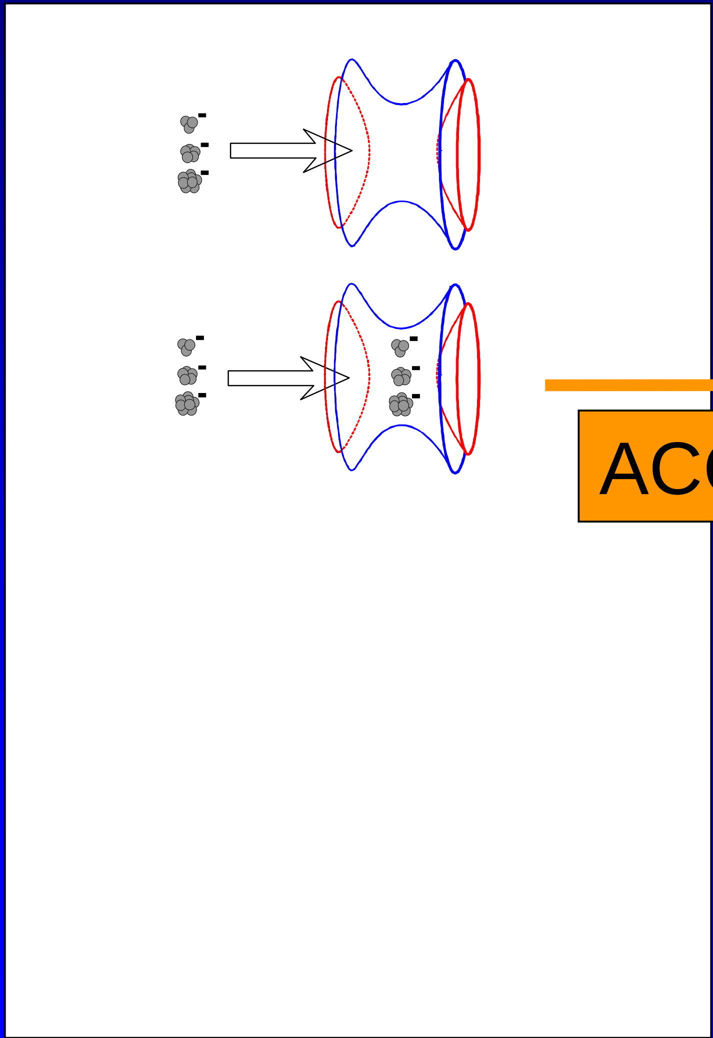


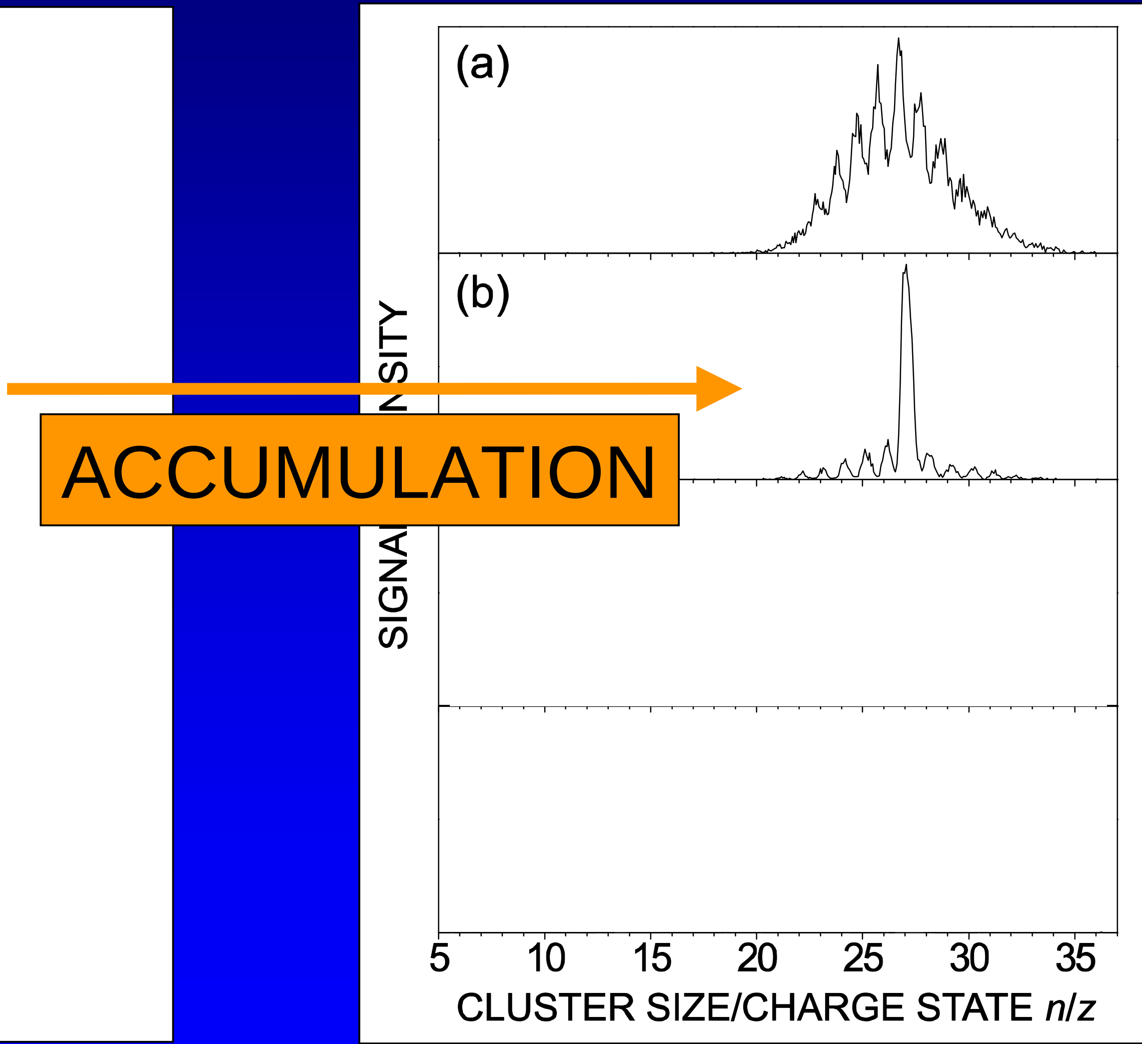
C. Walther et al., PRL (1999)

Dianion production

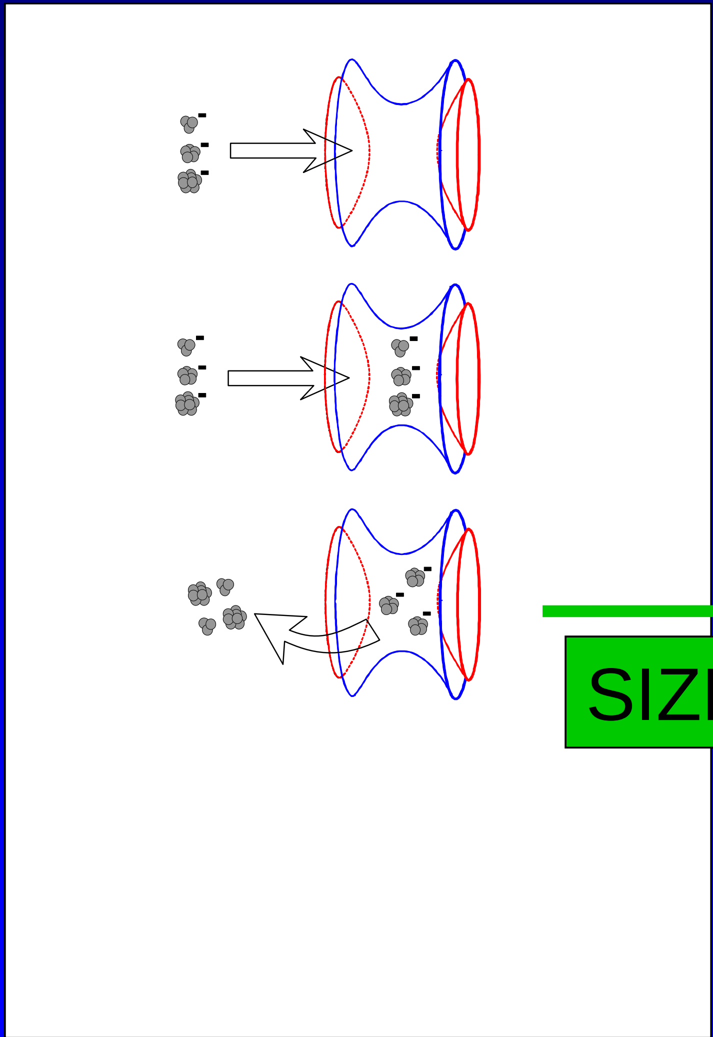


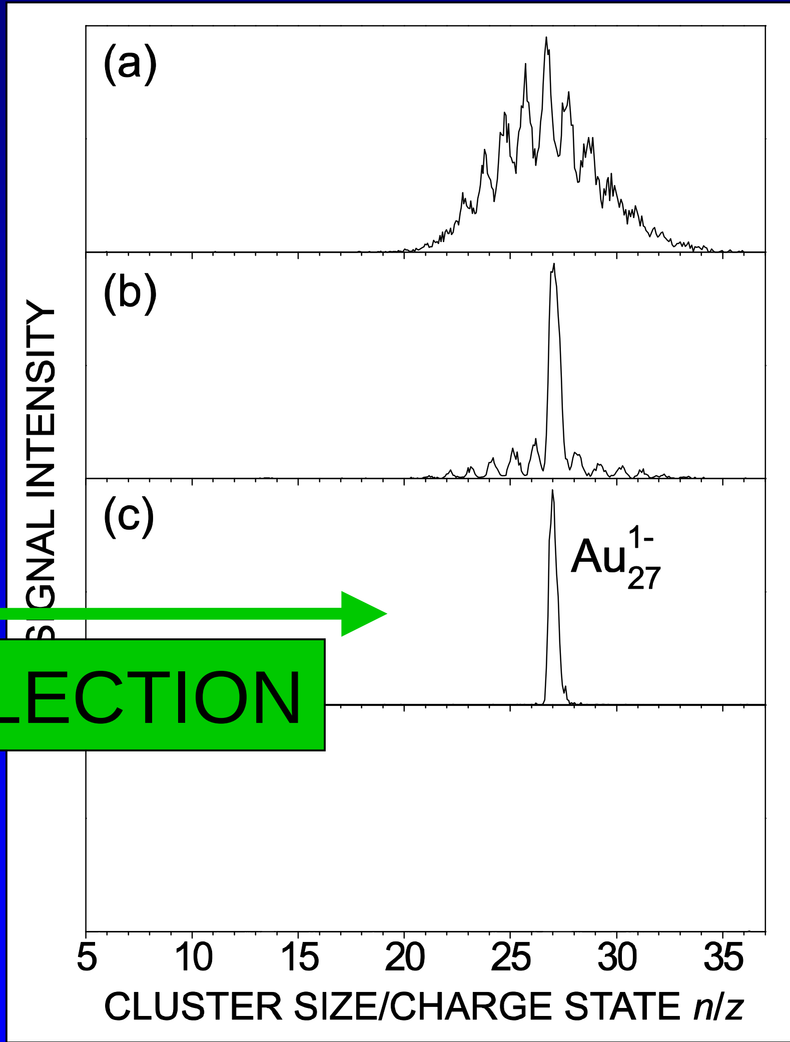
Dianion production





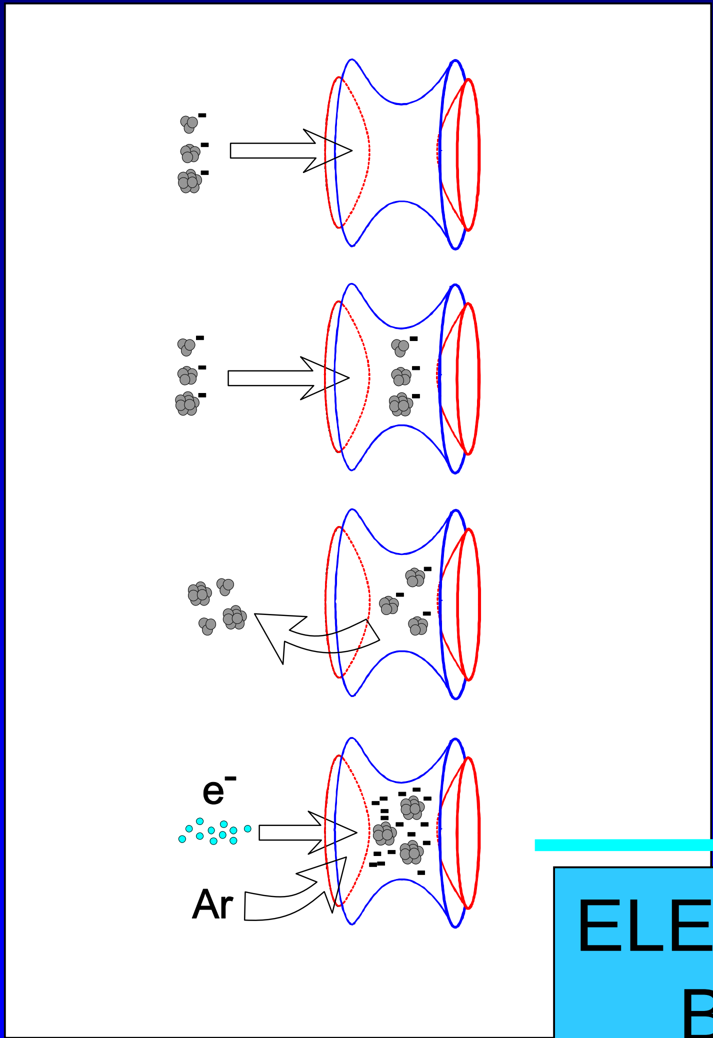
Dianion production



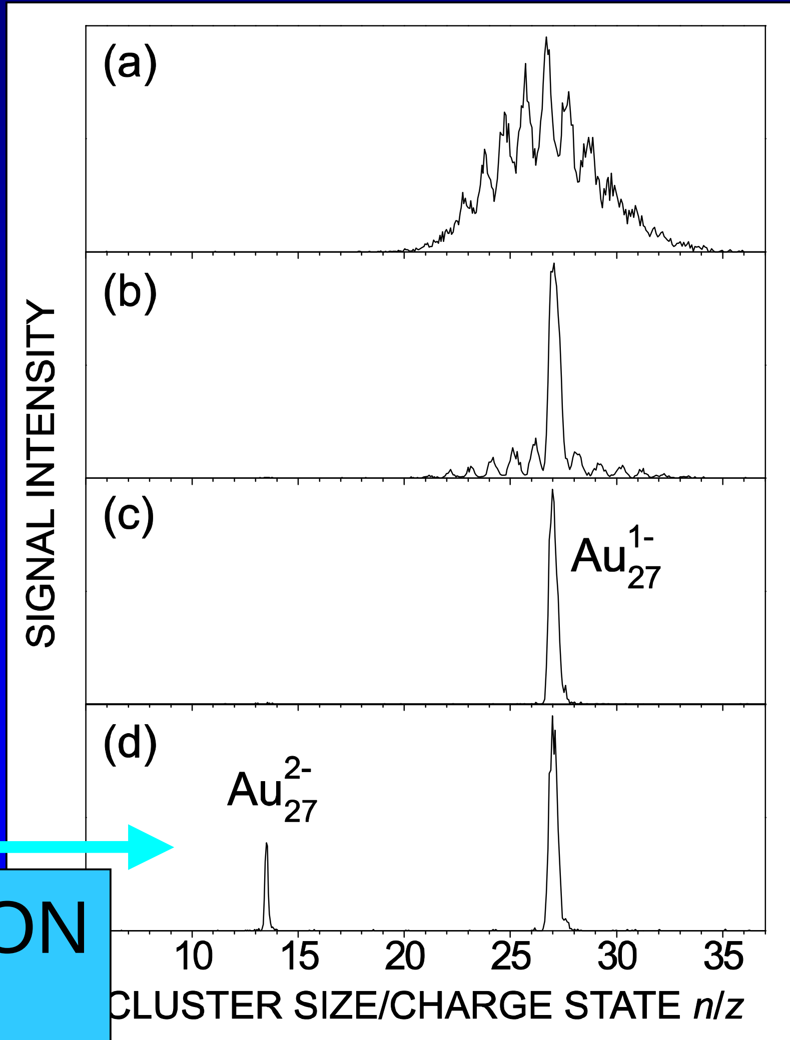


SIZE SELECTION

Dianion production



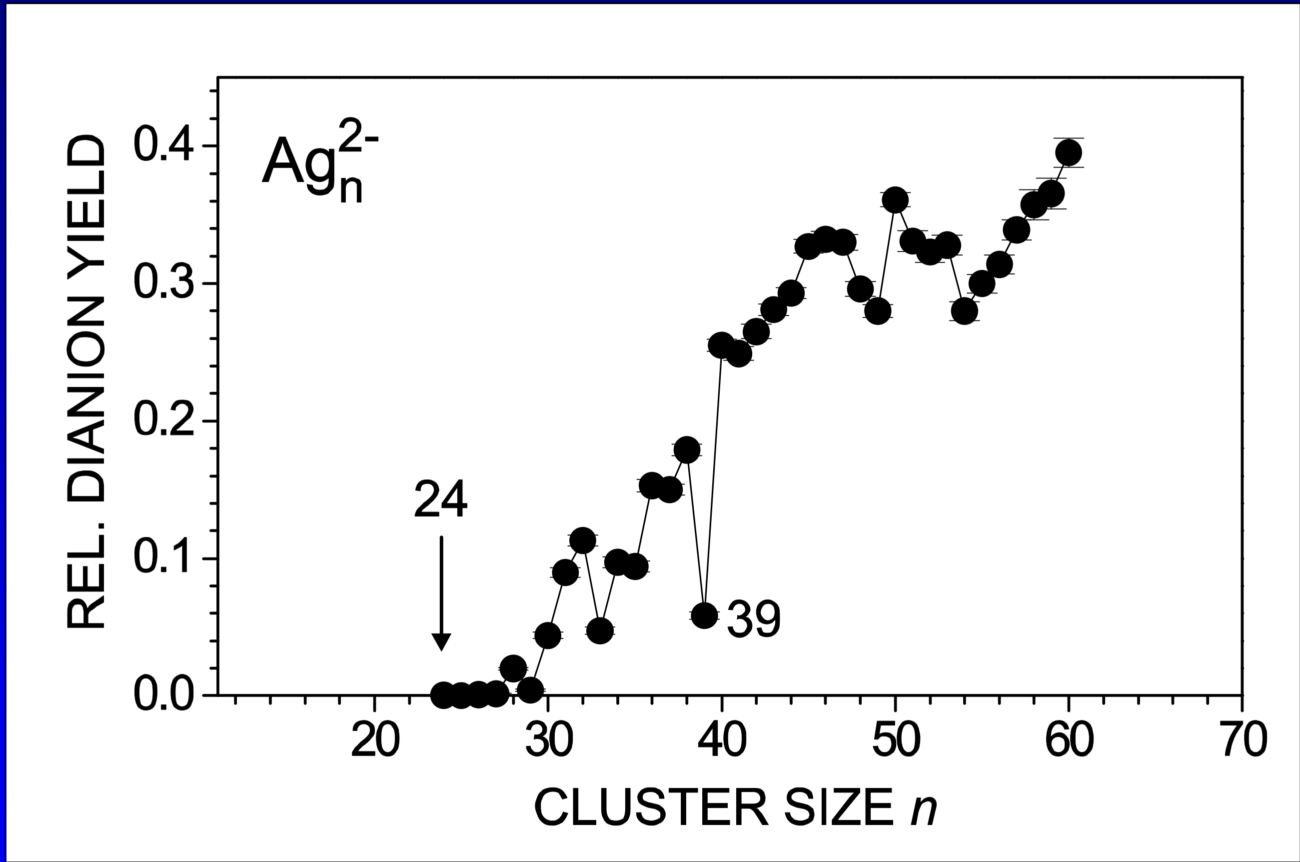
ELECTRON BATH



A. Herlert et al. (1999)

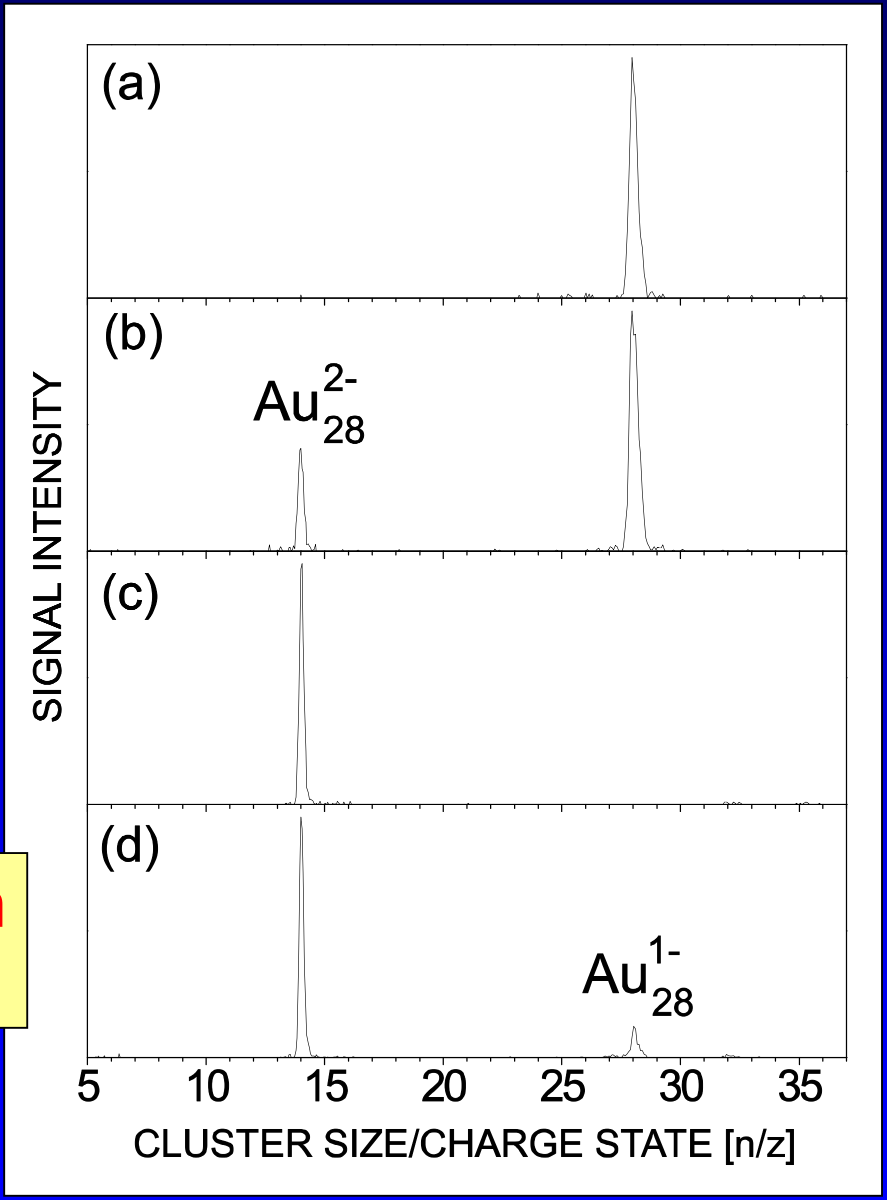
Dianion abundancies

A. Herlert et al.
EPJ D (2001)



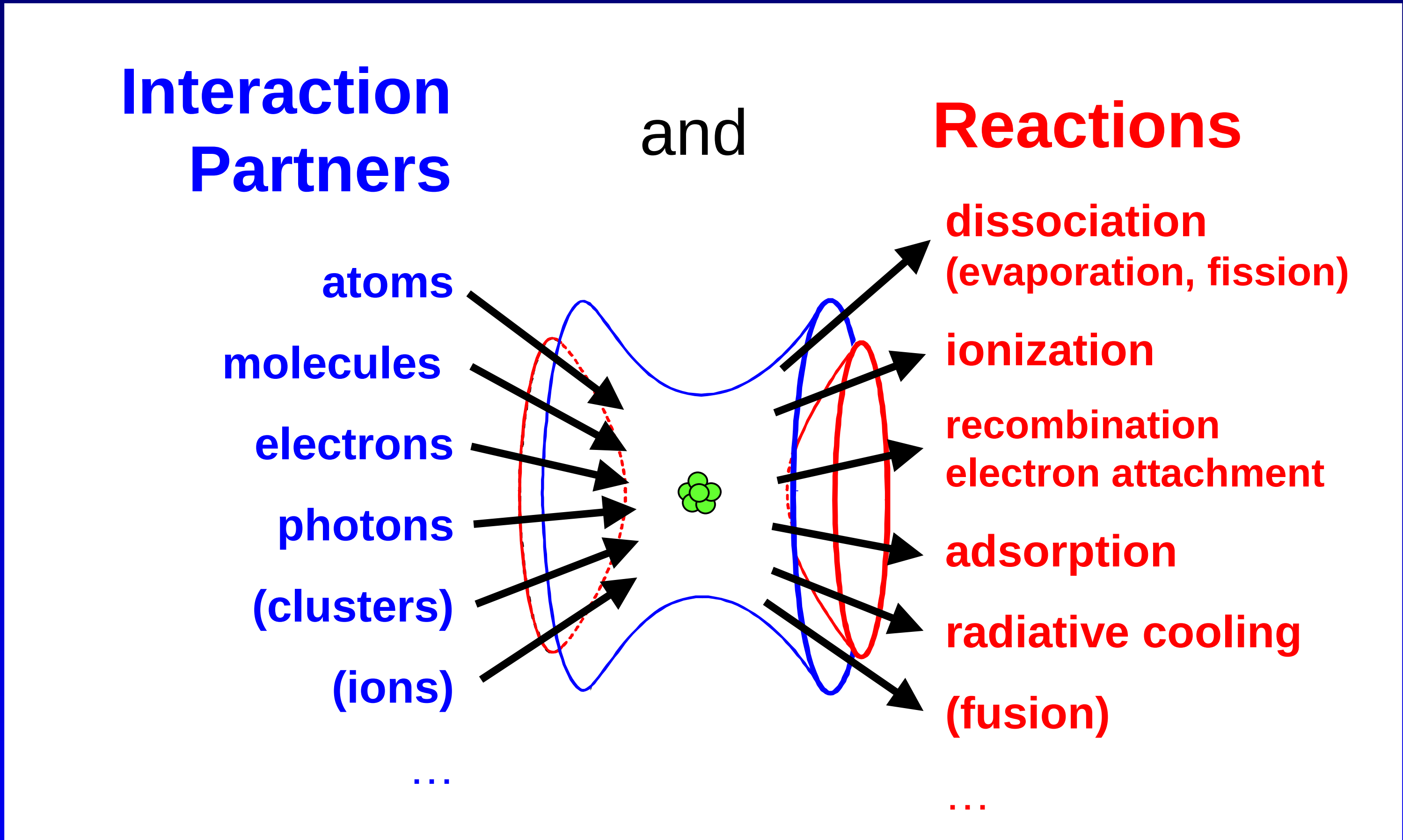
For gold di- and trianions see L.S. et al., Phil. Mag. B 1999
C. Yannouleas et al., PRL 2001

photoexcitation of dianions



10 ns pulse, λ=355nm
E=1mJ

Ion trapping for cluster research



Why cluster trapping?

- extended interactions
- extended reaction periods
- multi-step preparation

Overview

„History“

Aspects of Ion Trapping

Introduction to Penning Traps

Examples from

a) ISOLTRAP

b) FT-ICR MS

c) ClusterTrap

EBIT‘s Magnetic-Trapping Mode:

1) Mass Analysis

2) Charge-Transfer Reactions

3) Lifetimes of Metastable States

In-situ analysis by FT-ICR MS

What you want

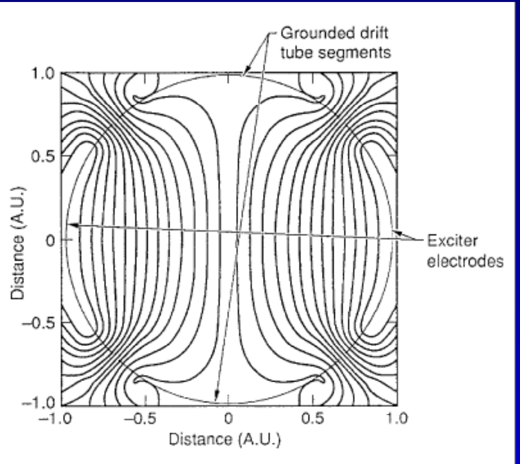


Fig. 4. Equipotential curves for (infinitely long) cylindrical trap segmented into four 90° sectors.

Elliot et al.
Hyp. Int. 1993

What you get

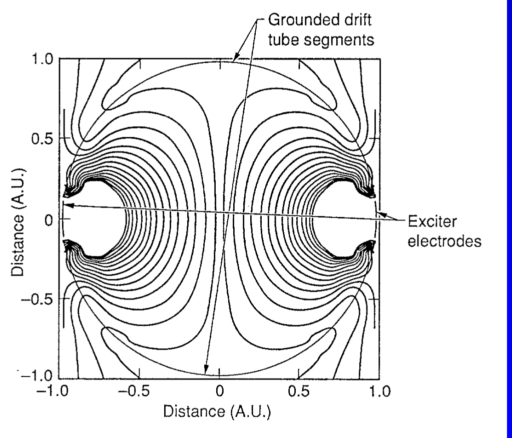
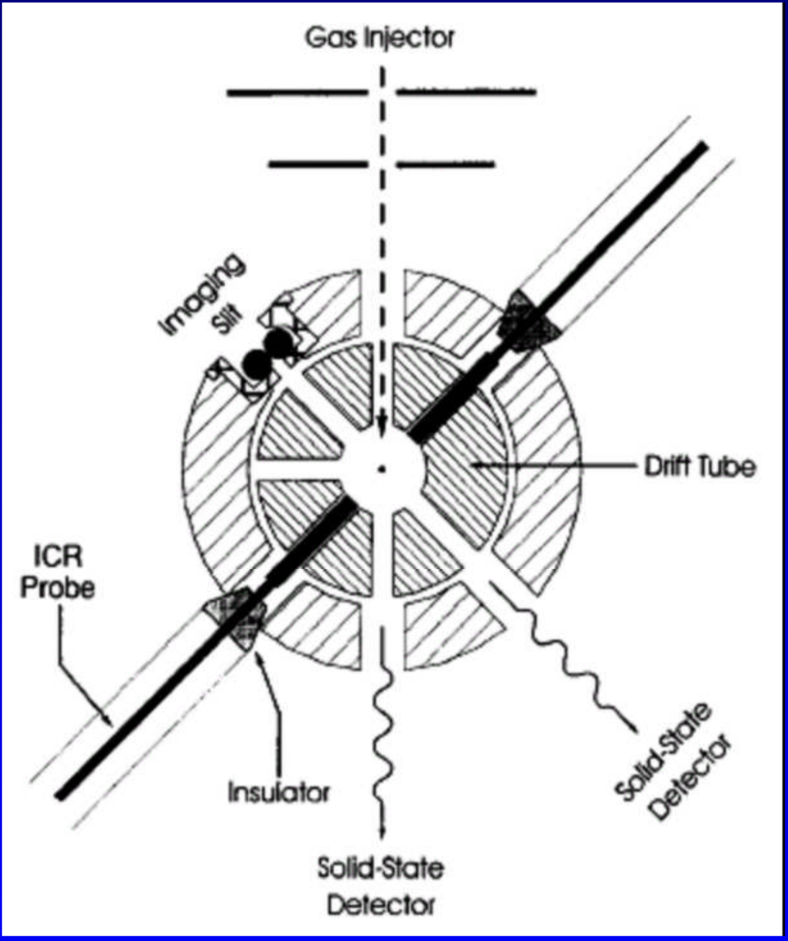


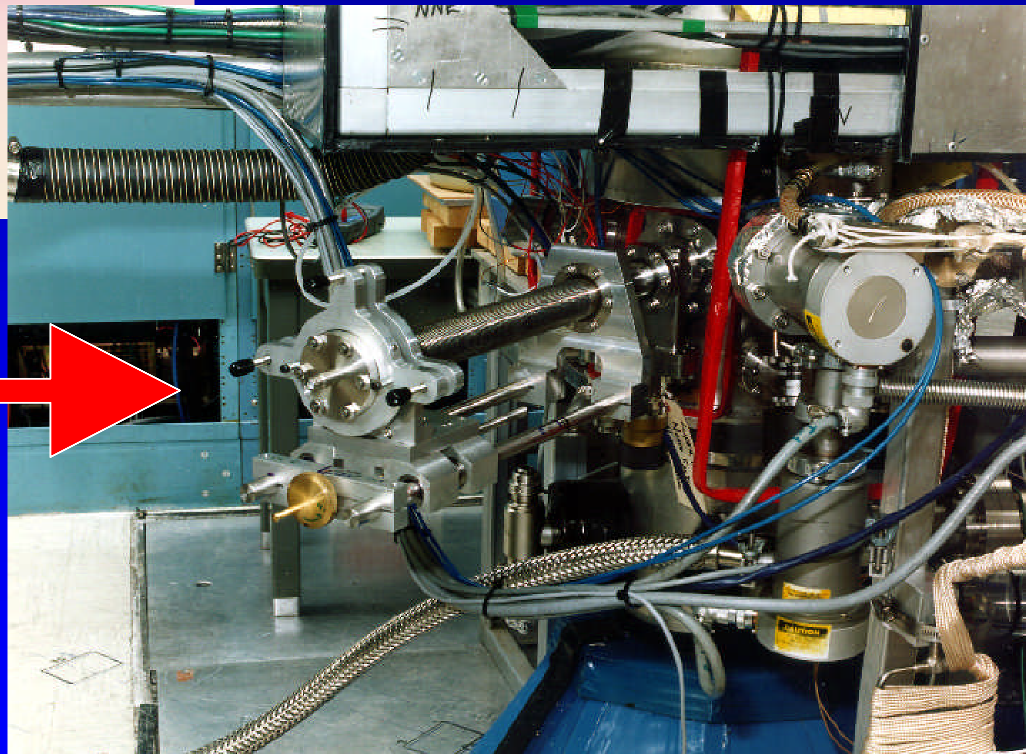
Fig. 5. Equipotential curves for (infinitely long) cylindrical trap at ground excited by two 15° wide excitor electrodes.

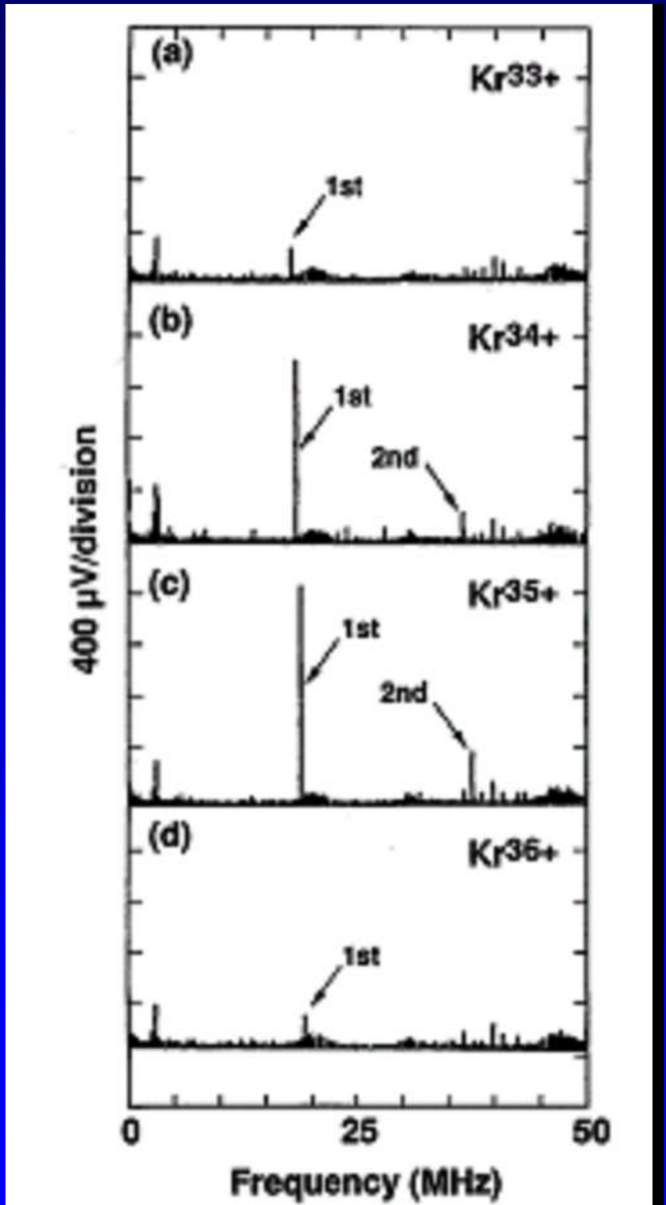
Note: Similar inhomog. with respect to B



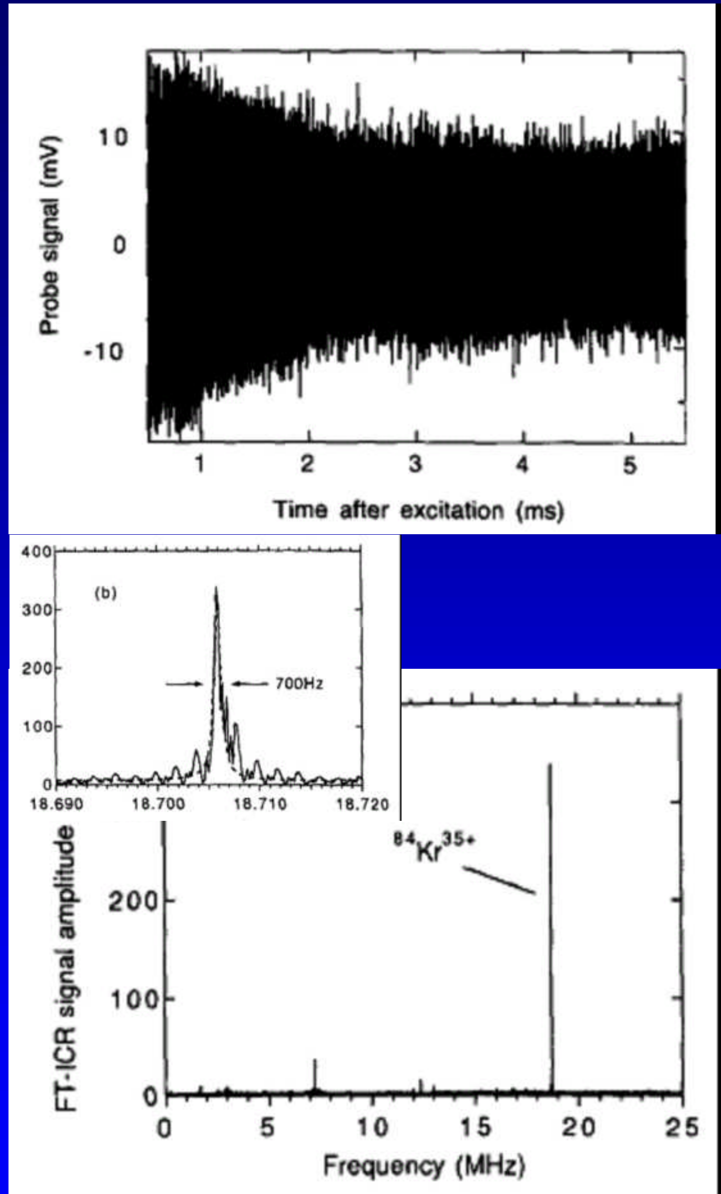
Beiersdorfer et al.
IJMSIP 1996

Excitation and Detection Electrodes





Beiersdorfer et al., RCMS 1994



Beiersdorfer et al., IJMSIP 1996

Broad-band FT-ICR MS

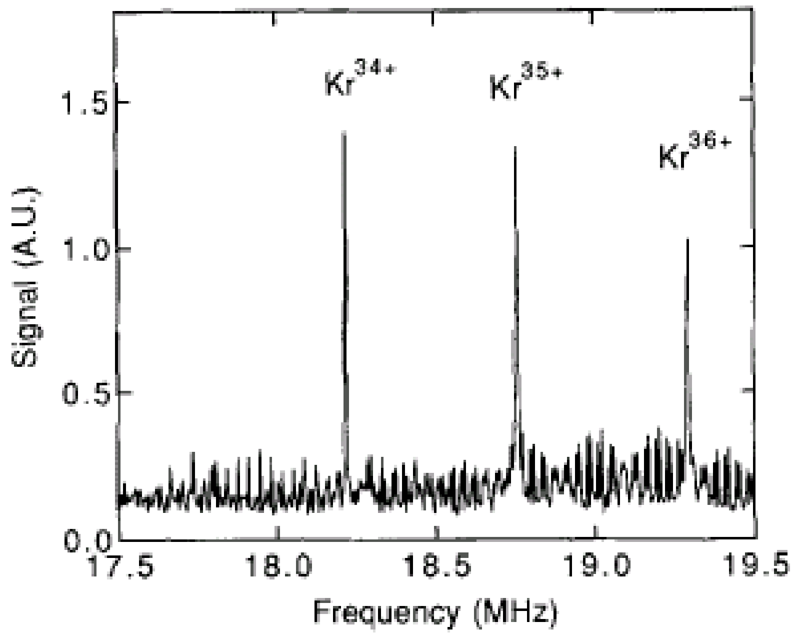


Fig. 2. FT–ICR spectrum of heliumlike, hydrogenlike, and bare ^{84}Kr ions excited by a 300 μs broadband sweep from 17.5 to 19.5 MHz.

Beiersdorfer et al.
NIM B 1995

confirmed by x-ray meas.
but 20 times faster !

Relative charge-state abundances

e.g. as a function of breeding time

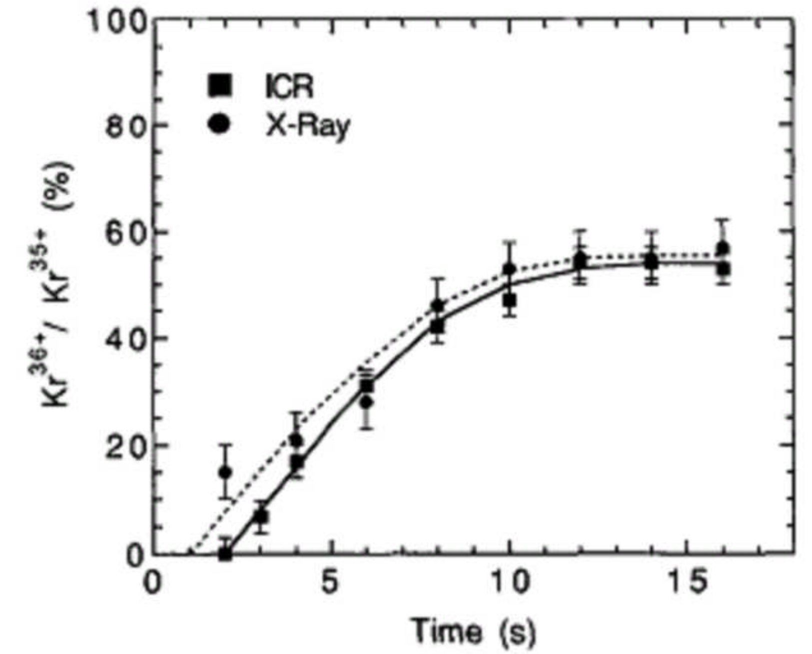


Fig. 3. Relative abundance of hydrogenlike Kr^{35+} and bare Kr^{36+} as a function of time after injection into the EBIT trap. The ions were produced at an electron beam current of 100 mA and a beam energy of 90 kV. Measurements were made with the FT–ICR method and an X-ray technique as discussed in the text. The solid and dashed lines are drawn to guide the eye.

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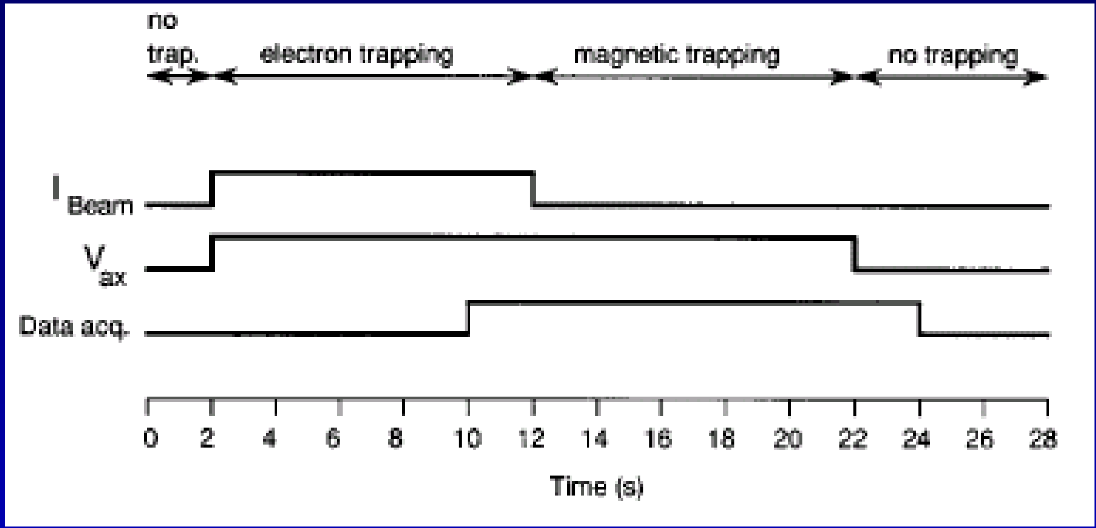
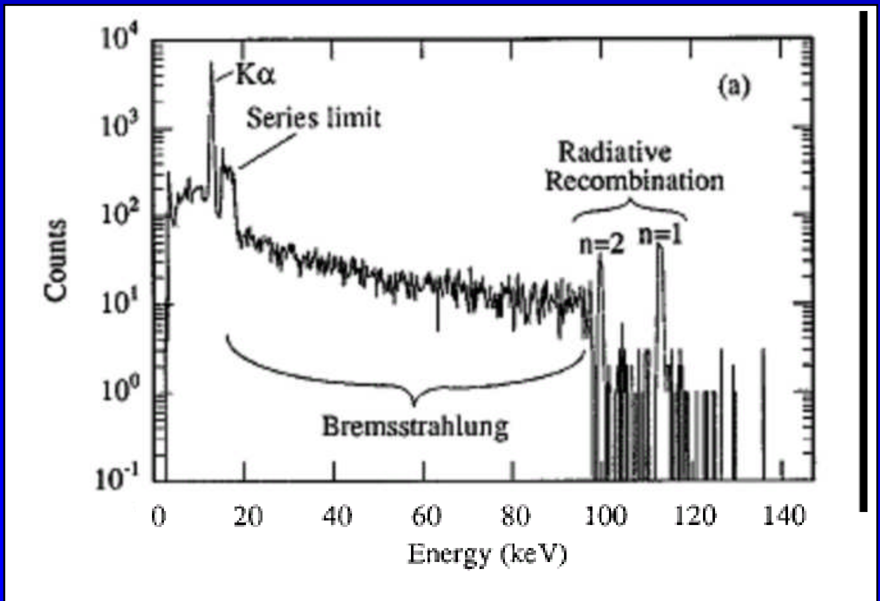
Beiersdorfer et al., RSI 1996:

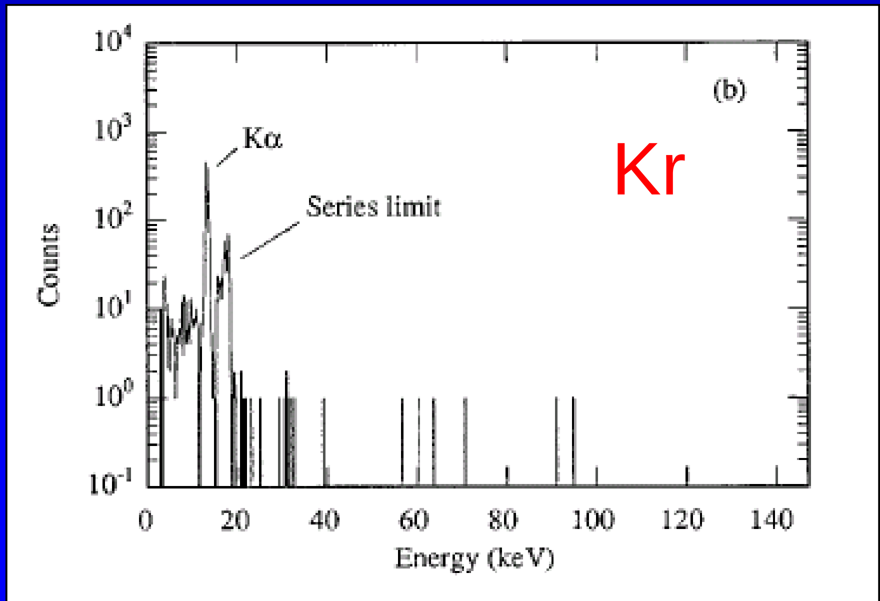
The magnetic trapping mode of an electron beam ion trap: New opportunities for highly charged ion research



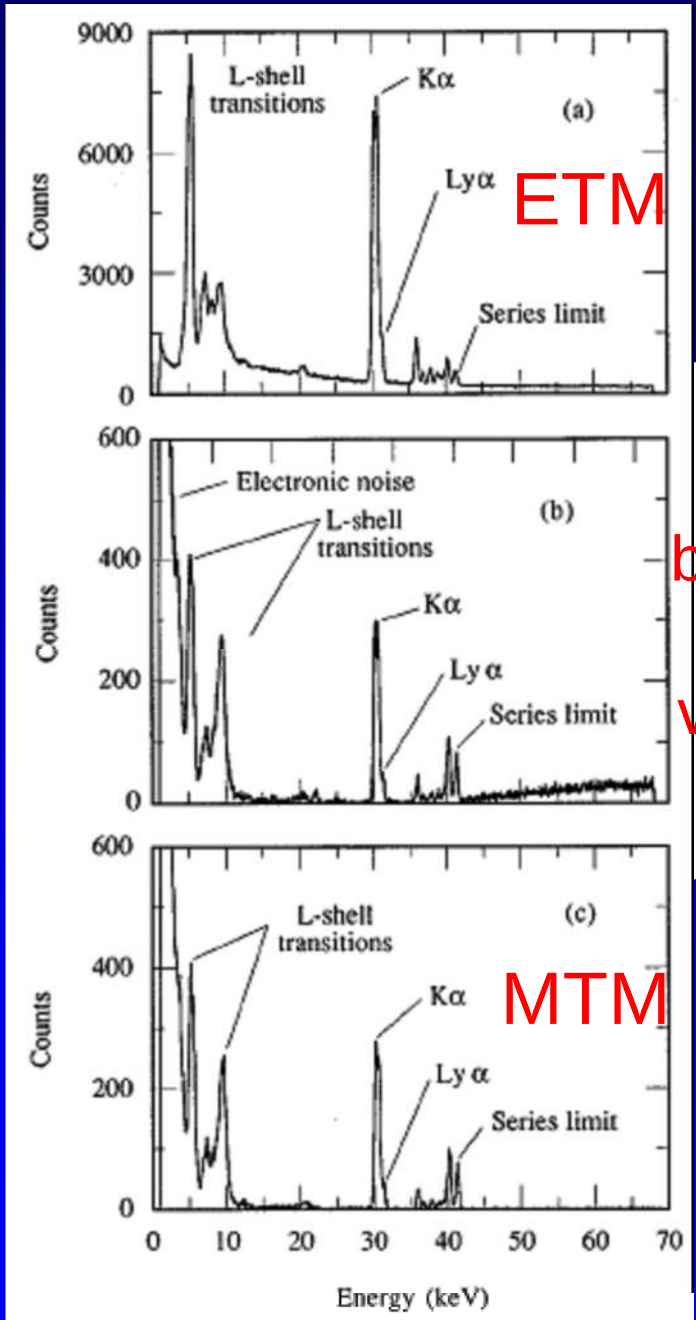
electron trapping mode

magnetic trapping mode

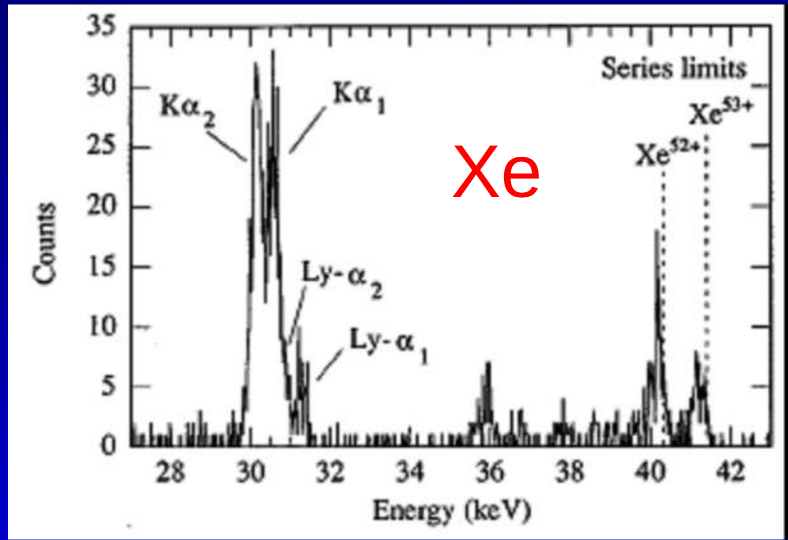


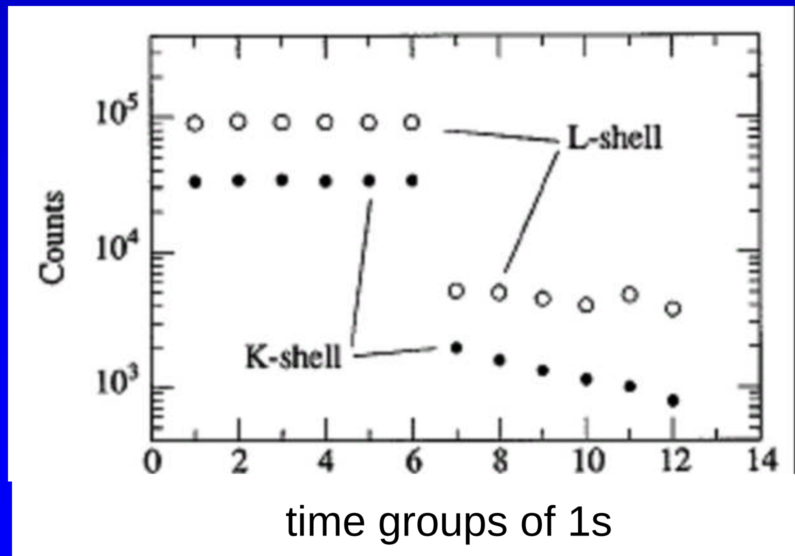


Beiersdorfer et al., RSI 1996, cont.

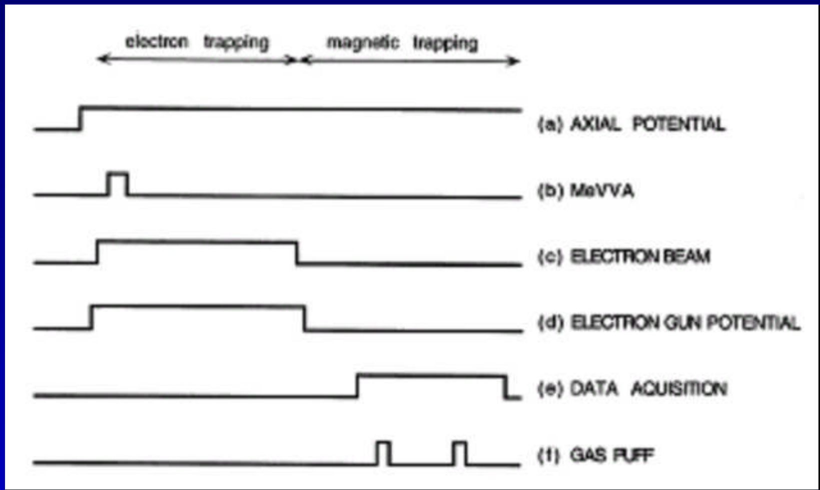


MTM but with e-gun voltage on





S/N enhancement by Pulsed Gas Injection



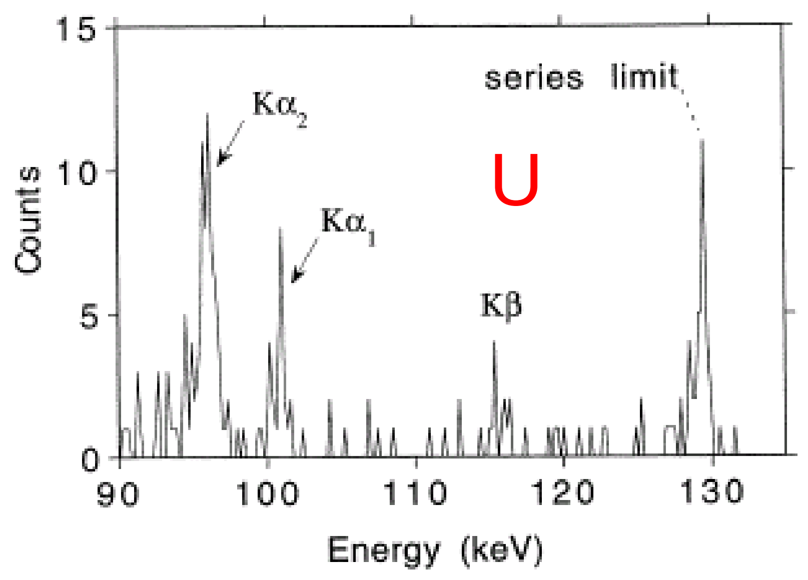


Fig. 8. K-shell spectrum of U^{90+} observed in the magnetic trapping mode.

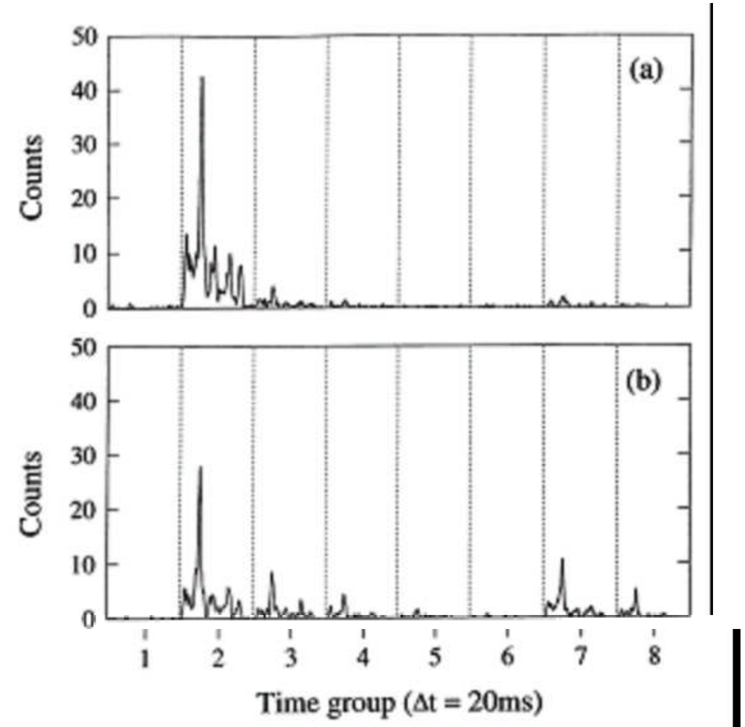


Fig. 5. Uranium L-shell transitions signals as a function of time, 8 time bins of 20 ms each, with gas puffs in second and seventh time bin. (a) X-ray spectra (cf. inset of Fig. 4) after 700 ms of magnetic trapping time. (b) X-ray spectra after 2500 ms of magnetic trapping time.

LS et al., NIM B 1998

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Already in Beiersdorfer et al., RSI 1996

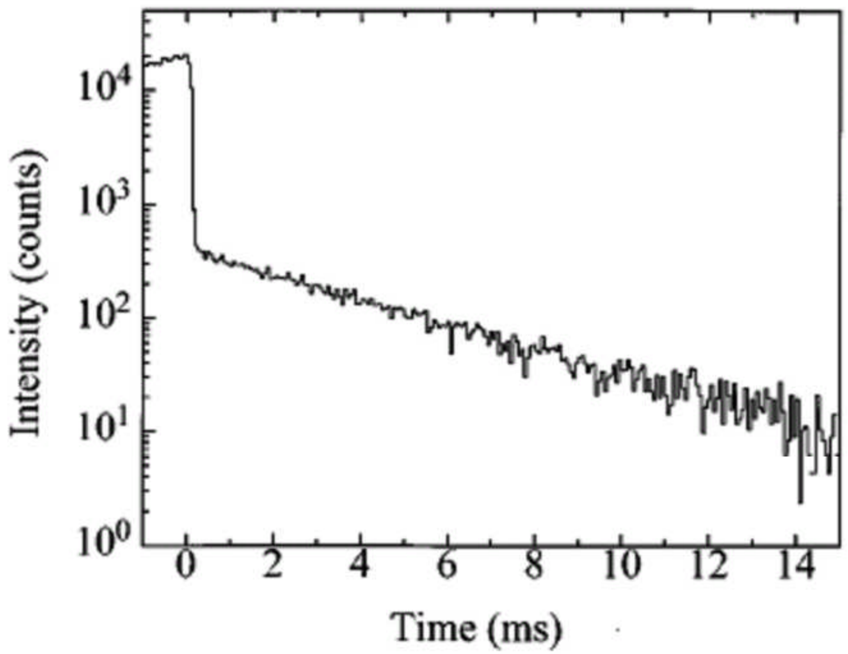
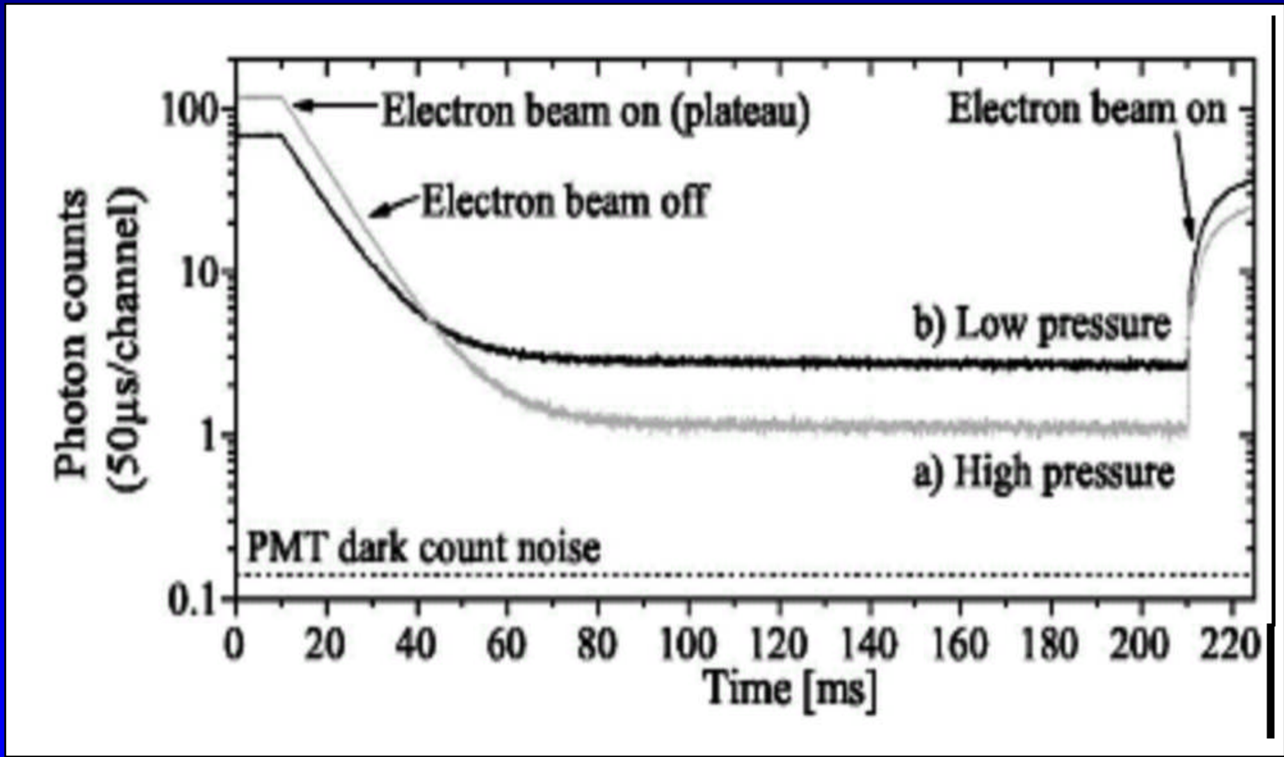


FIG. 10. Time dependence of the K-shell x-ray emission from N^{5+}. At $t=0$ ms, EBIT operation is switched from the electron to the magnetic trapping mode. The x rays observed in the magnetic mode are the result of the fluorescent decay of the $1s2s\ ^3S_1$ level in heliumlike N^{5+}. An exponential decay in the signal intensity evident.

Lifetimes from time-resolved fluorescence measurements in the x-ray regime

Also: Lifetimes from
time-resolved fluorescence
Measurements in the optical regime

e.g.
boron-like
Ar XIV
as studied
at Heidelberg



Lapierre et al., PRA 2006 / PRL 2005

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Peter Beiersdorfer

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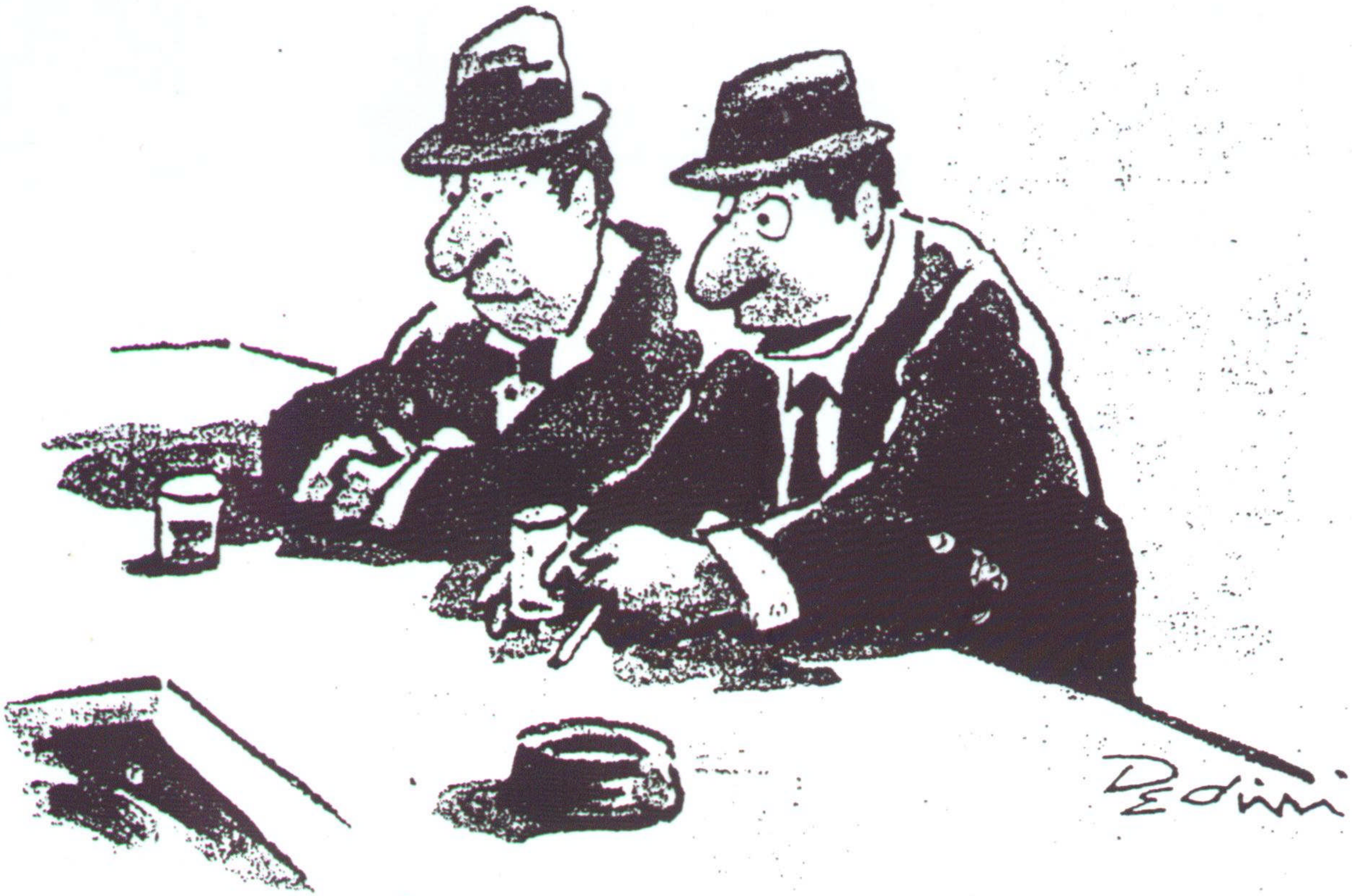
Klaus Widmann (at the time graduate student at LLNL)

Elmar Träbert

plus lots of further people I met at LLNL

€ $ € $ € - DAAD - $ € $ € $ - NATO Collaborative Research Grant - € $ € $ €



"Everything's a trap if you're not careful."

Well, sometimes a trap may not be that bad, after all.