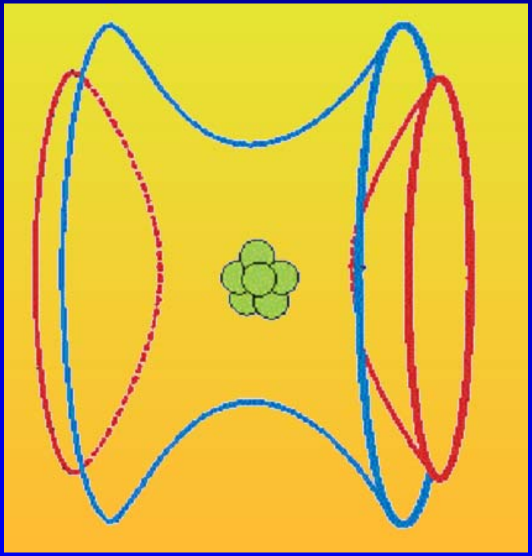
ClusterTrap: A Penning Trap for Cluster Research

(Ion Trapping for Cluster Research)



ClusterTrap

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Germany

ECTI, 2010-09, Redworth Hall

Overview

Other traps and applications

FT-ICR MS, precison MS of radionuclides, EBIT, (electrostatic ion-beam traps => Wada)

ClusterTrap

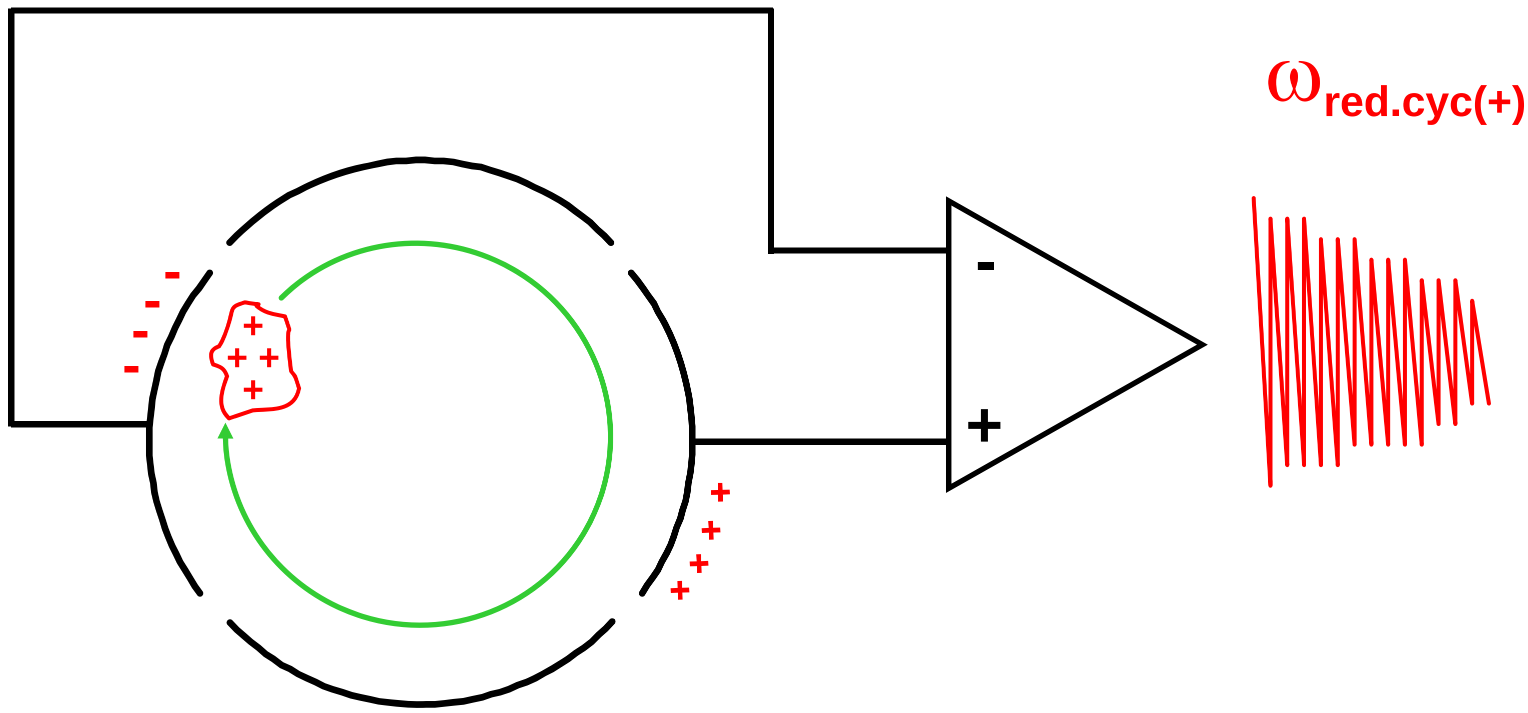
why? how? what?

Other cluster-storage devices

FT-ICR MS = FTMS

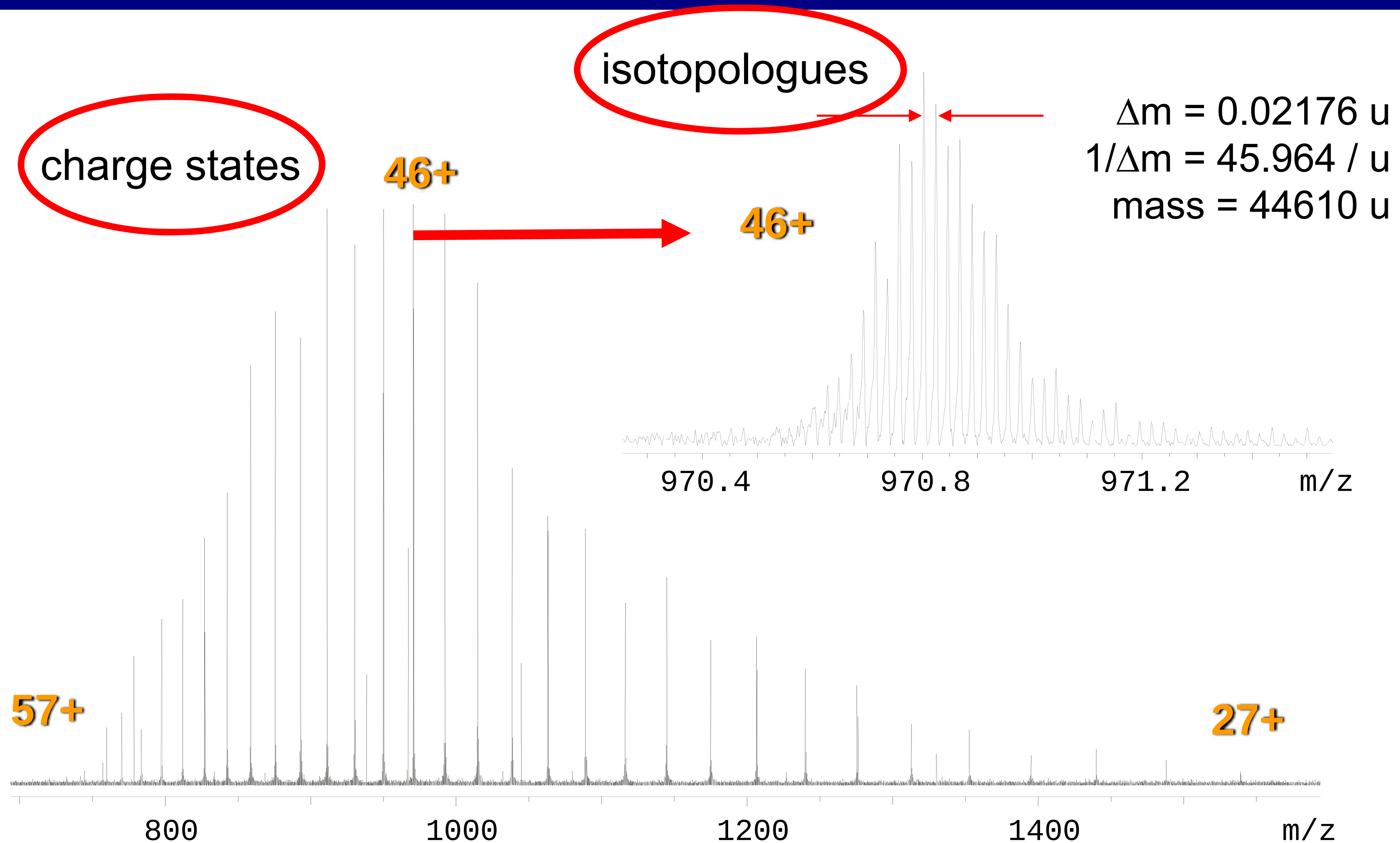
Fourier Transform (Ion Cyclotron Resonance) Mass Spectrometry

Detection of Ion Motion (after broad-band excitation)



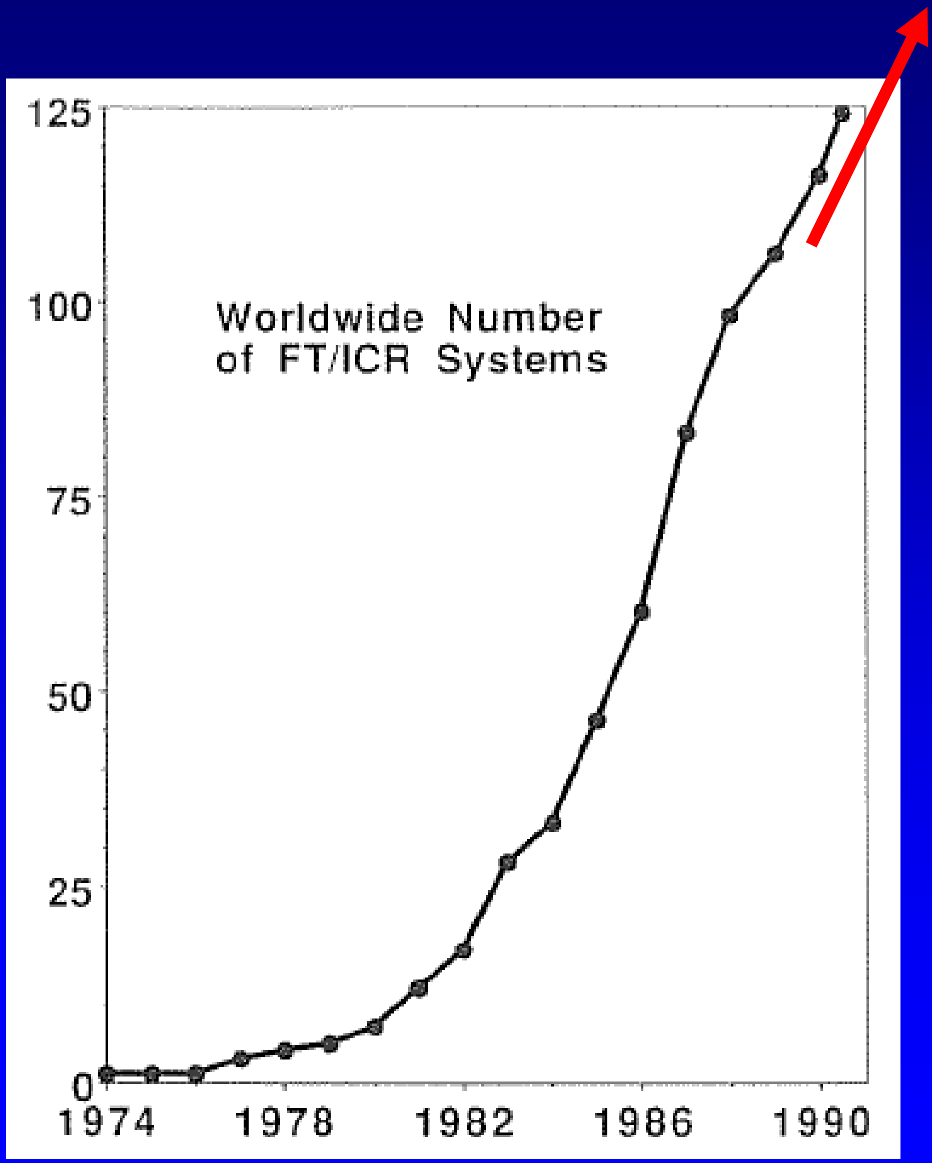
Courtesy of Roland Jertz, Bruker Daltonik/Bremen

Protein A (44 kDa) Broad-Band Spectrum



Courtesy of Roland Jertz, Bruker Daltonik/Bremen

FT-ICR MS systems in use
(as a function of time)



Typically > 500 k€ a piece

Three independent companies developing and selling FT-ICR systems

A.G. Marshall and LS, IJMS 118/119 (1992)

Overview

Other traps and applications

FT-ICR MS, precison MS of radionuclides,
EBIT, (electrostatic ion-beam traps => Wada)

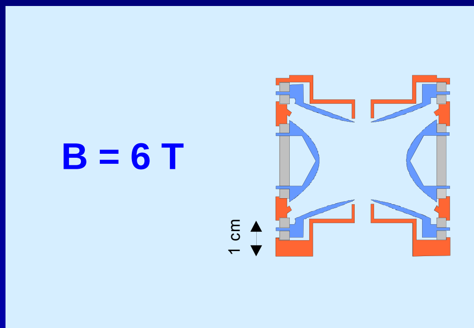
ClusterTrap

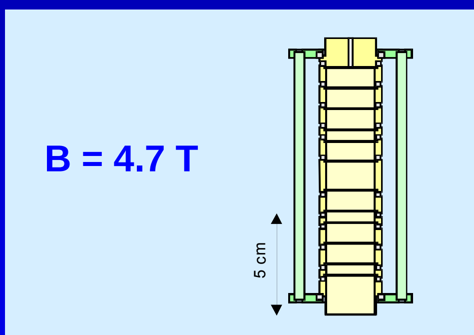
why? how? what?

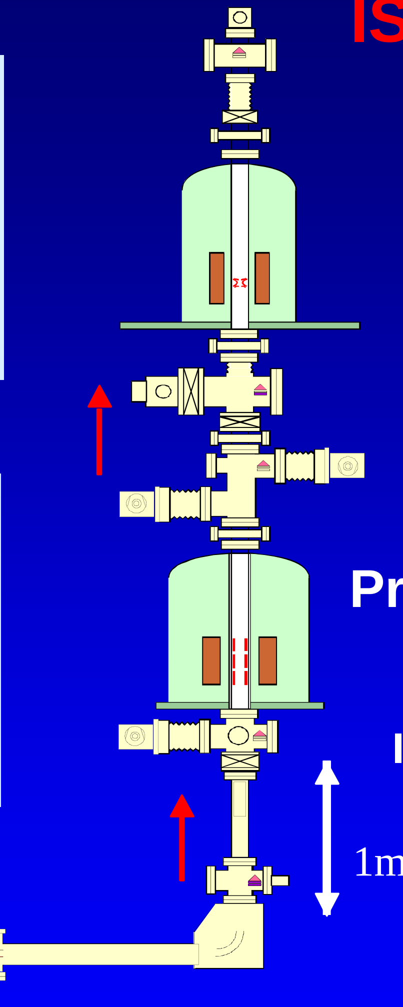
Other cluster-storage devices

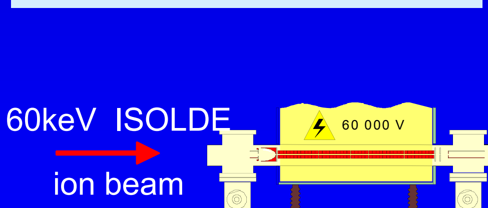
Precision mass measurements of short-lived nuclides

ISOLTRAP AT ISOLDE/CERN

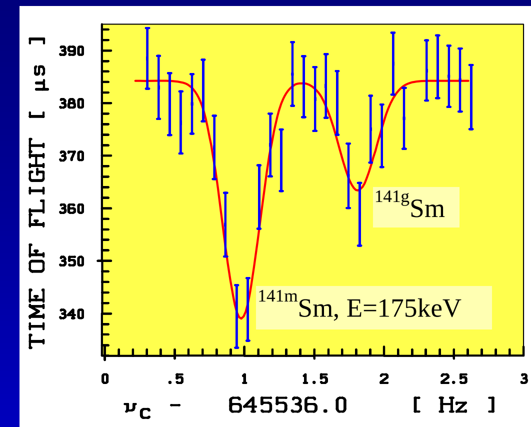




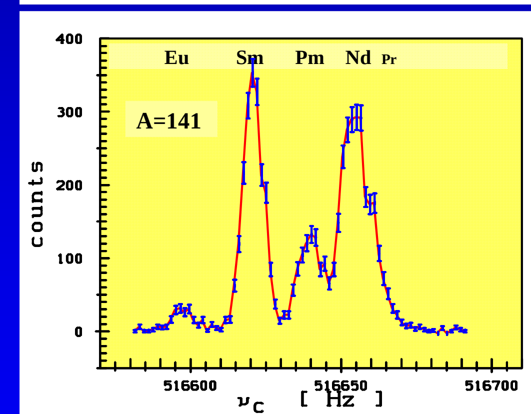


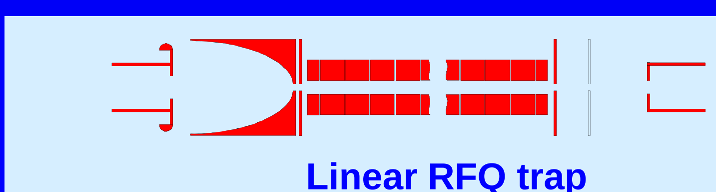


Precision Trap:
Determination of cyclotron frequency
Isomer separation



Preparation Trap:
Accumulation
Cooling
Isobar separation





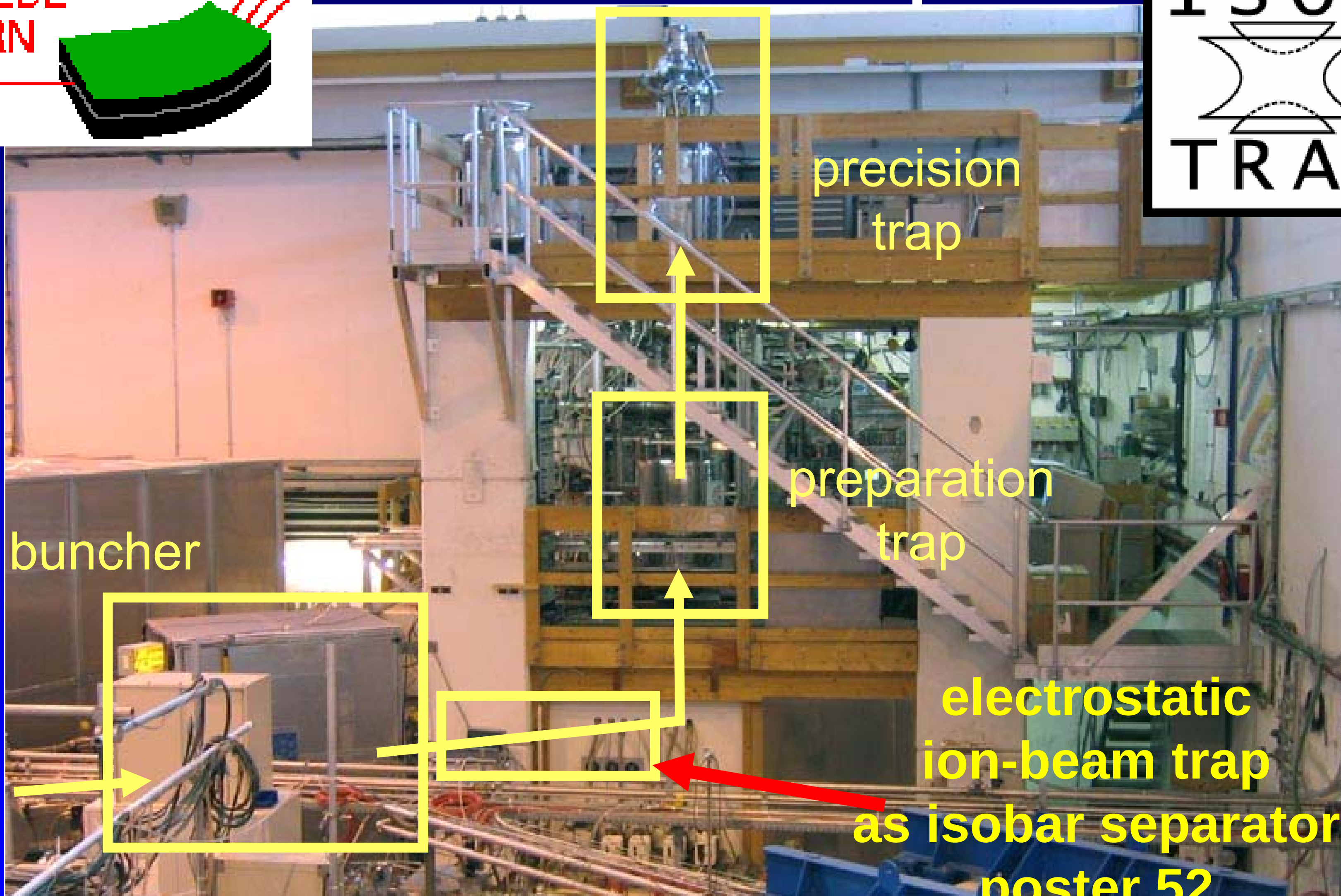
Retardation
Cooling
Accumulation
Bunching

Setup:
H. Stolzenberg et al., PRL 1990
G. Bollen et al., NIM A 1996
H. Raimbault-Hartmann et al., NIM B ‘97
F. Herfurth et al., NIM A 2001

ISOLDE
CERN

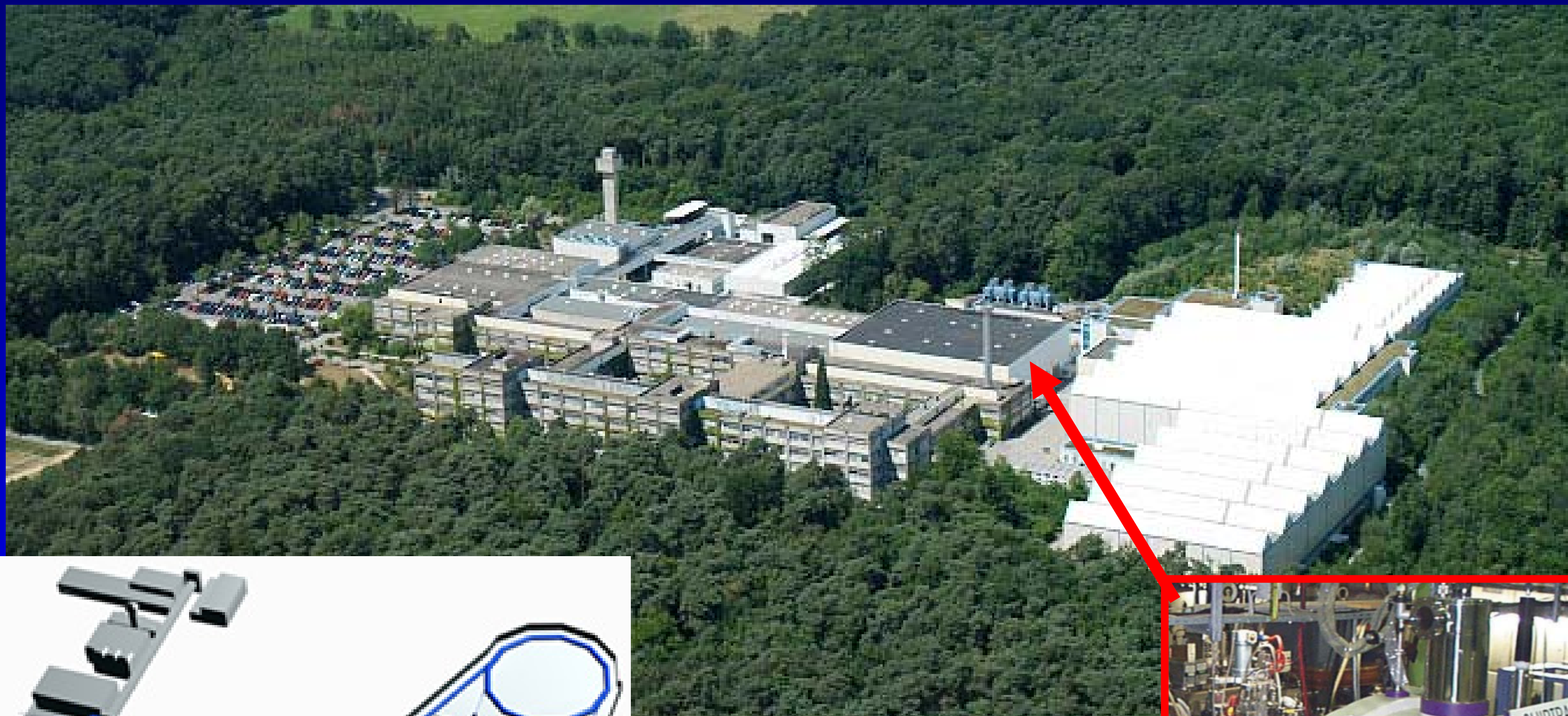
ISOLTRAP setup

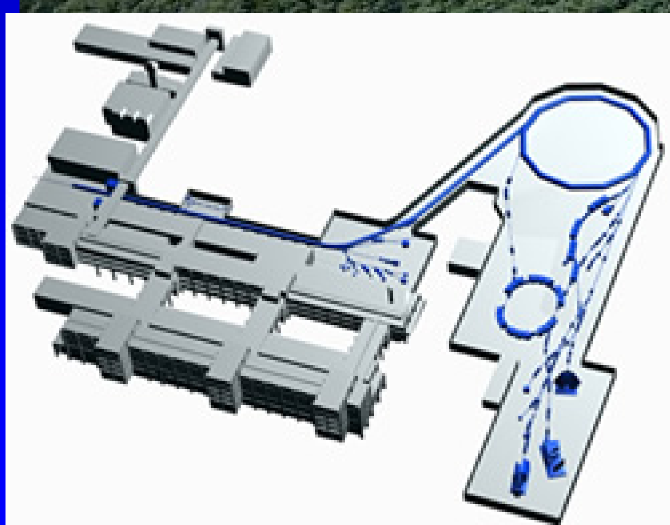
ISOL TRAP

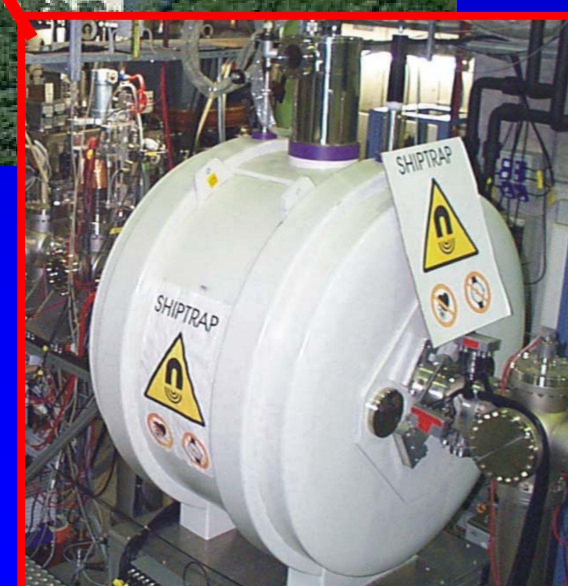


Recent exp. results, e.g.: PRL **98**, 162501(2007); **100**, 072501(2008); **101,** 252502(2008); **101**, 262501(2008); **102**, 112501(2009); **105**, 032502(2010)

One of the off-springs: **SHIPTRAP** at GSI/Darmstadt







First direct mass measurements above uranium

M. Block et al., **Nature** 463 (2010) 785

$^{252-254}$No (Z=102)

with production rates

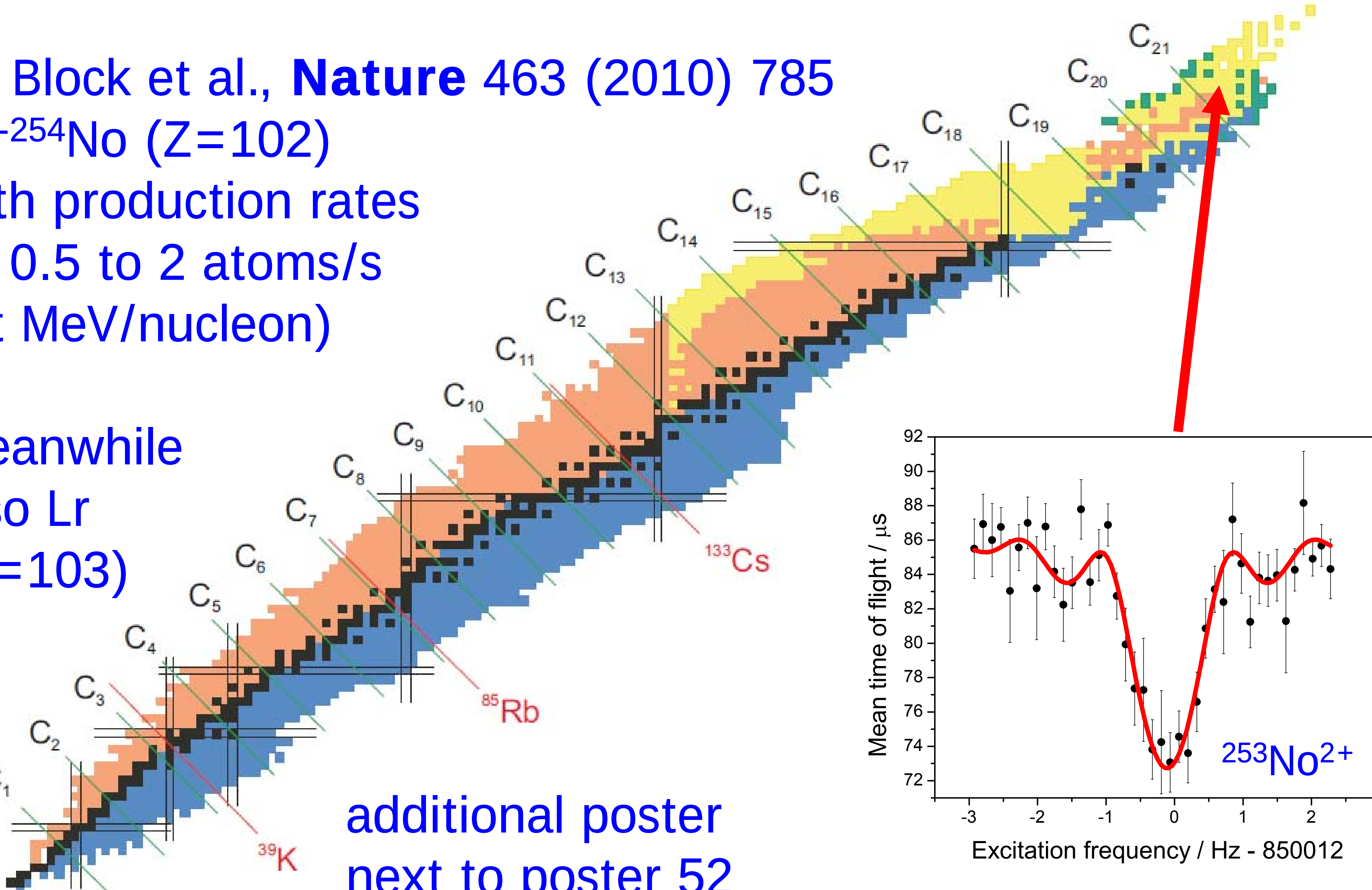
Of 0.5 to 2 atoms/s

(at MeV/nucleon)

meanwhile

also Lr

(Z=103)



additional poster

next to poster 52

Overview

Other traps and applications

FT-ICR MS, precison MS of radionuclides,

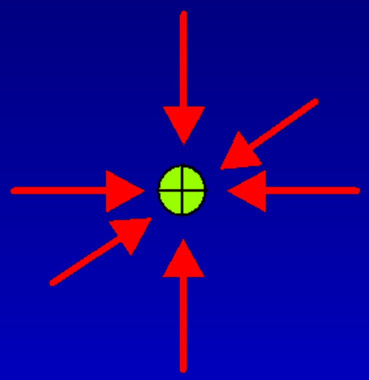
EBIT, (electrostatic ion-beam traps => Wada)

ClusterTrap

why? how? what?

Other cluster-storage devices

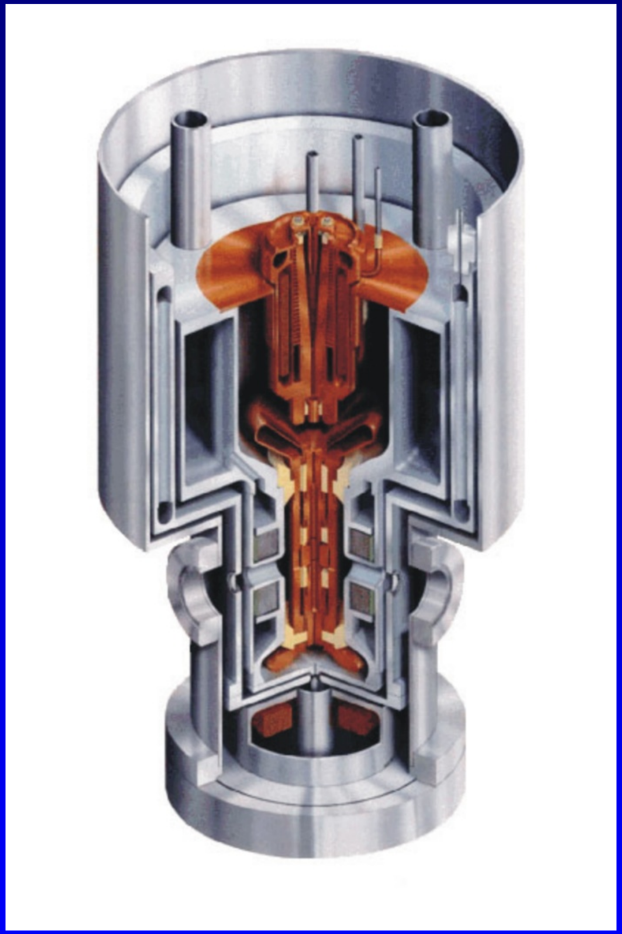
EBIT: Electro-Beam Ion Trap
or How to produce and confine highly-charged ions?



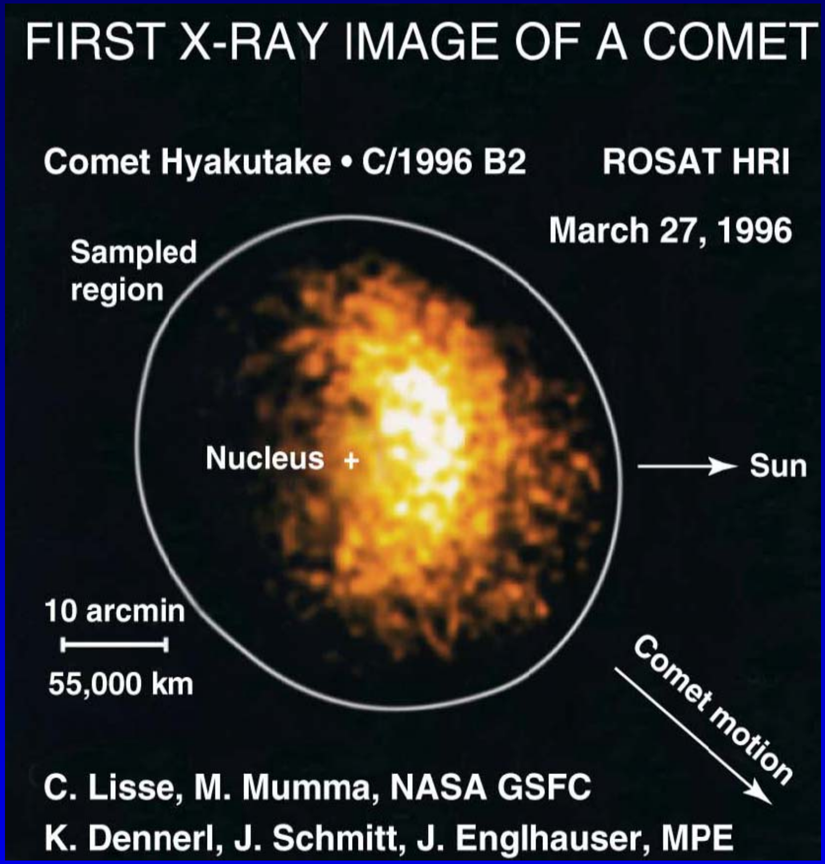
Electrostatic trapping
is not possible by
static electric fields only

unless space charge allowed

Here by compression
of an electron beam
by strong B-field



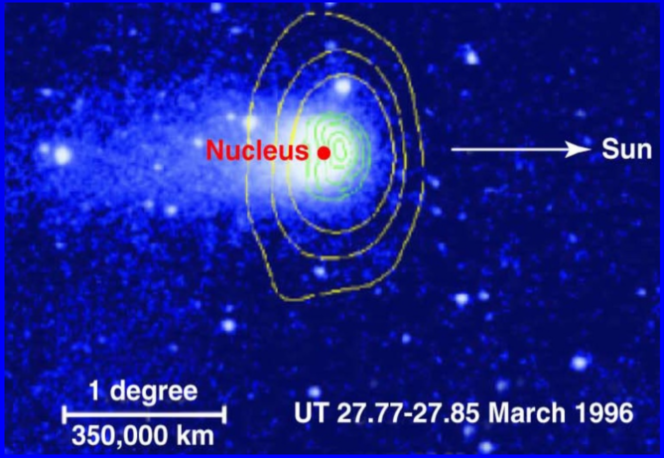
Replace Laplace: $\Delta\phi = 0$
by Poisson: $\Delta\phi = \rho/\varepsilon_0$



X-ray emission from comets

due to charge transfer
from highly-charged ions
of solar wind colliding with
neutral atoms of the comets

Such reactions as well as
lifetimes of metastable states
are studied in the
"magnetic-trapping mode"
of EBIT P. Beiersdorfer, LS et al.,
RSI **67**, 3818 (1996)



Lisse et al.,
Science 274, 205 (1996)

<u>Overview</u>

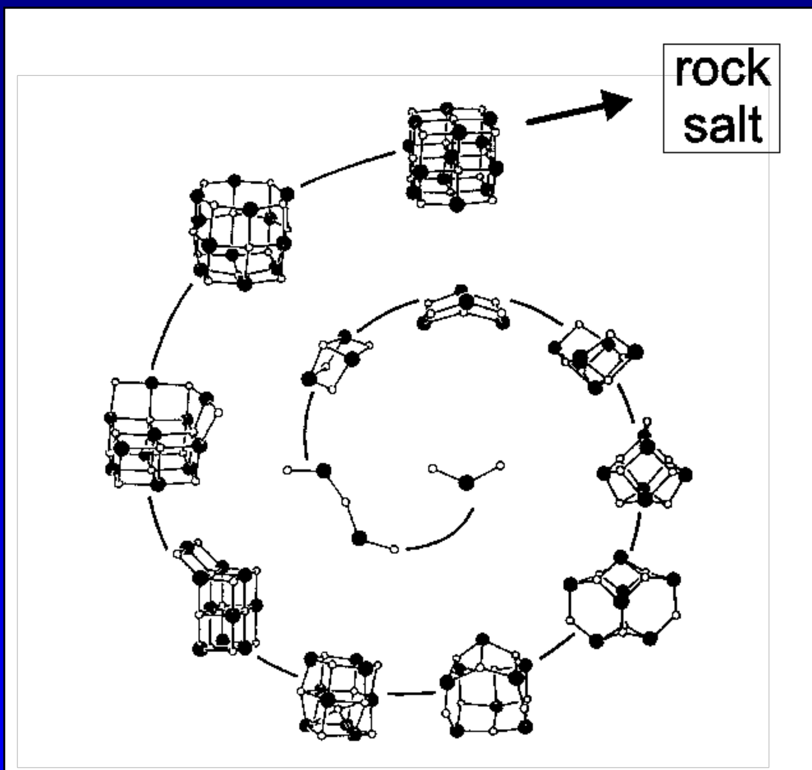
Other traps and applications

ClusterTrap

clusters? why? how? what?

Other cluster-storage devices

From Atoms to Bulk Matter: Clusters



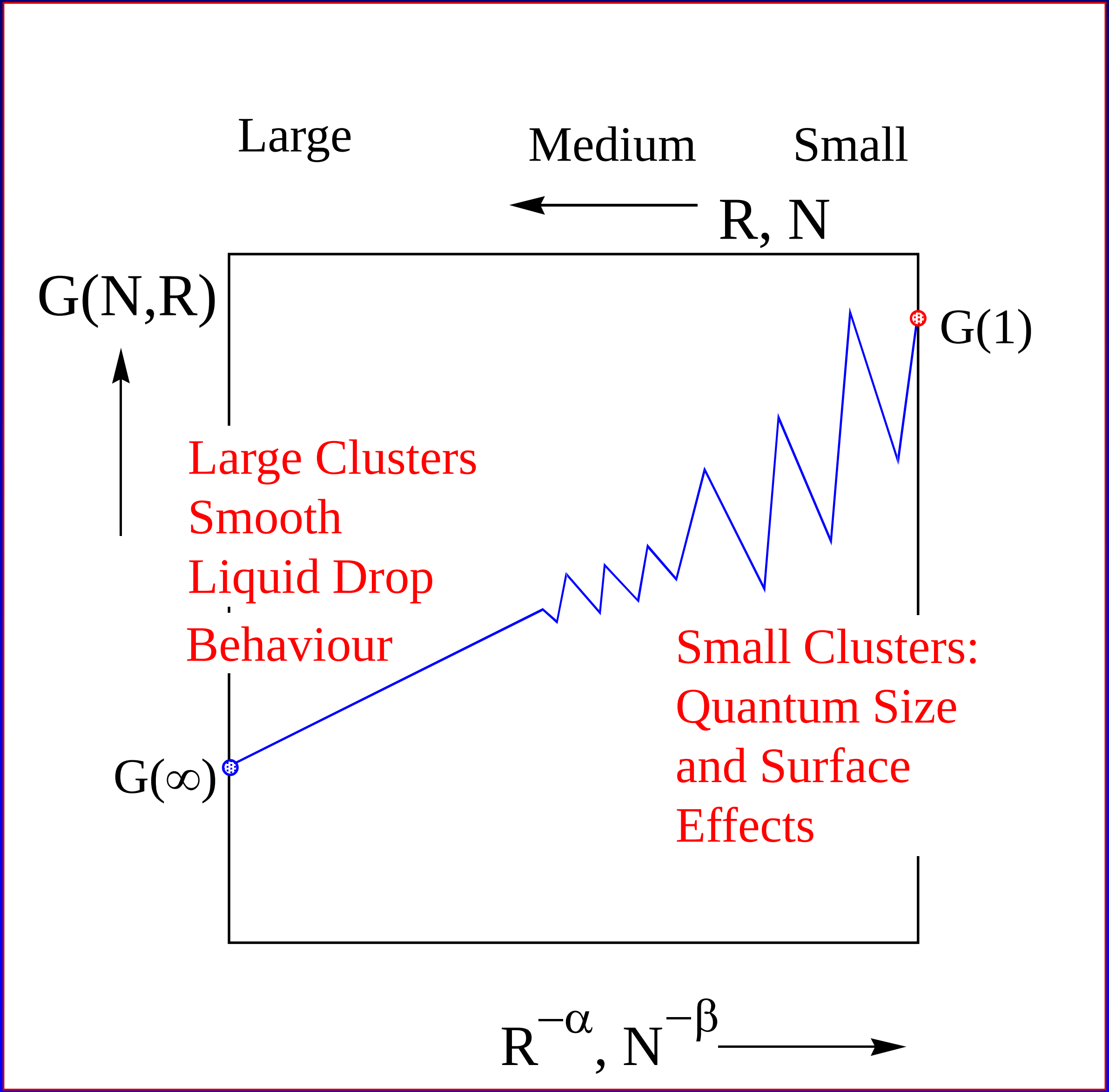
T.P. Martin (1984)

atom/molecule — one

surface ↔ CLUSTER — few

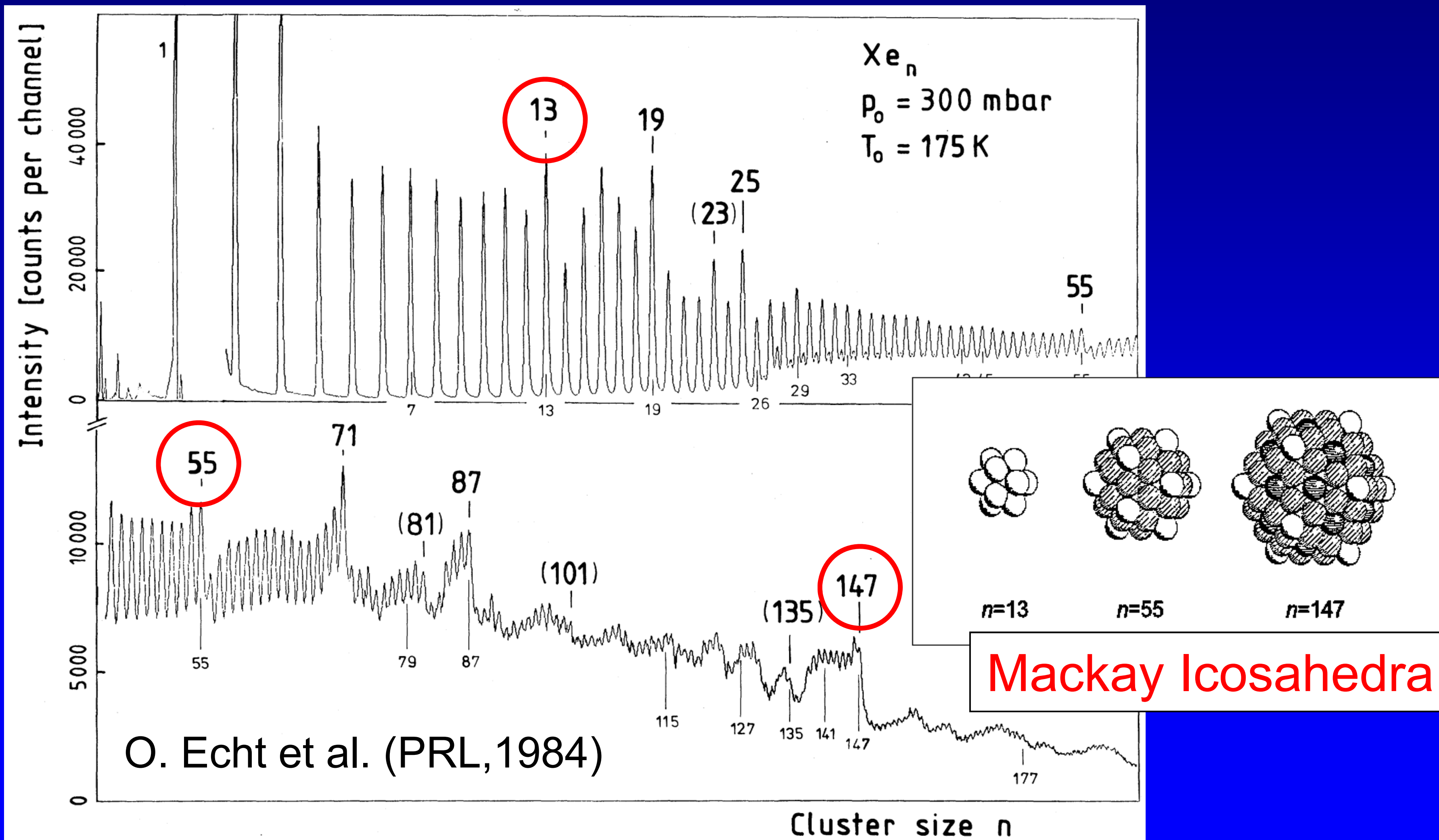
condensed matter — many

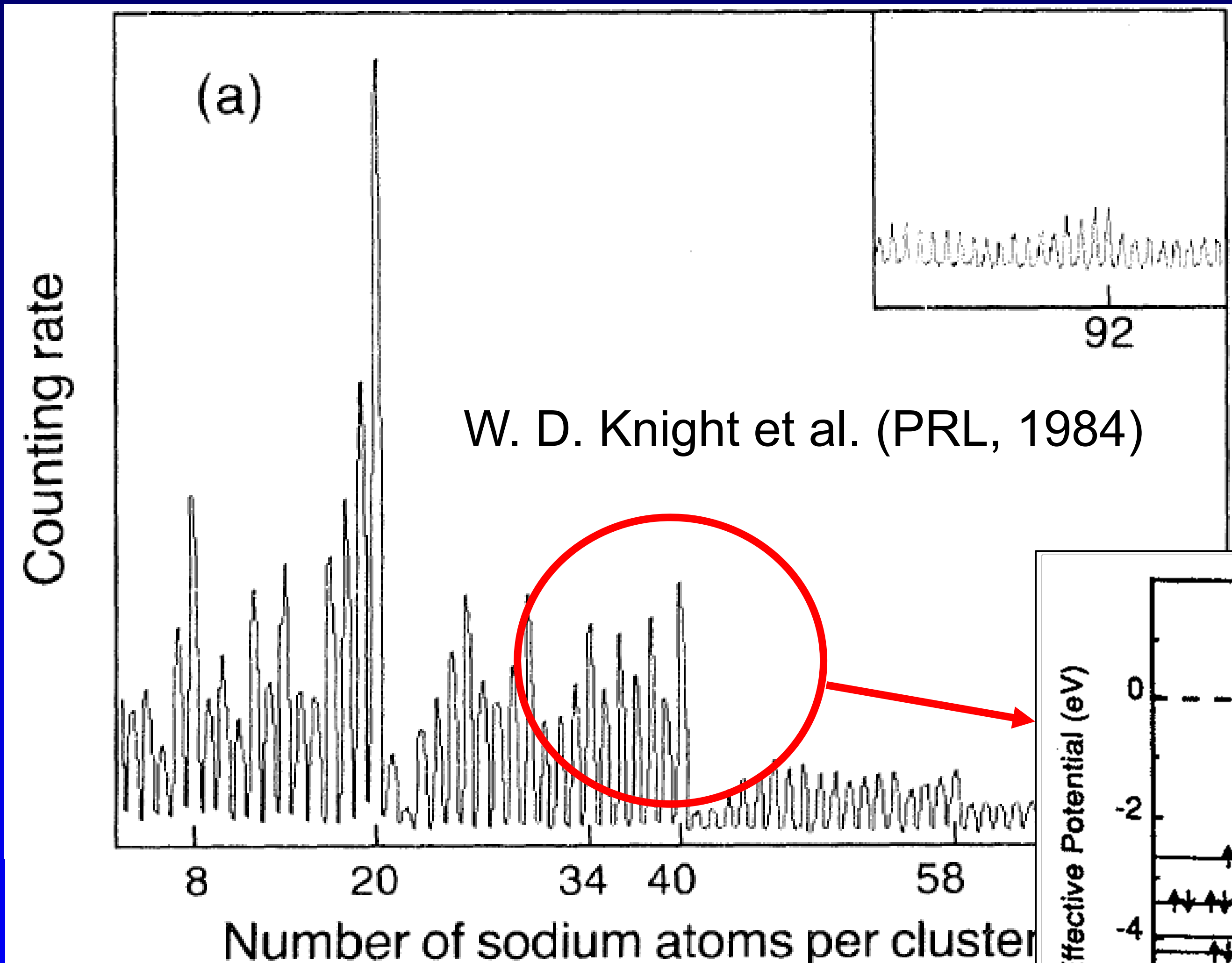
Scaling Laws



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

Noble gas clusters: geometric shells

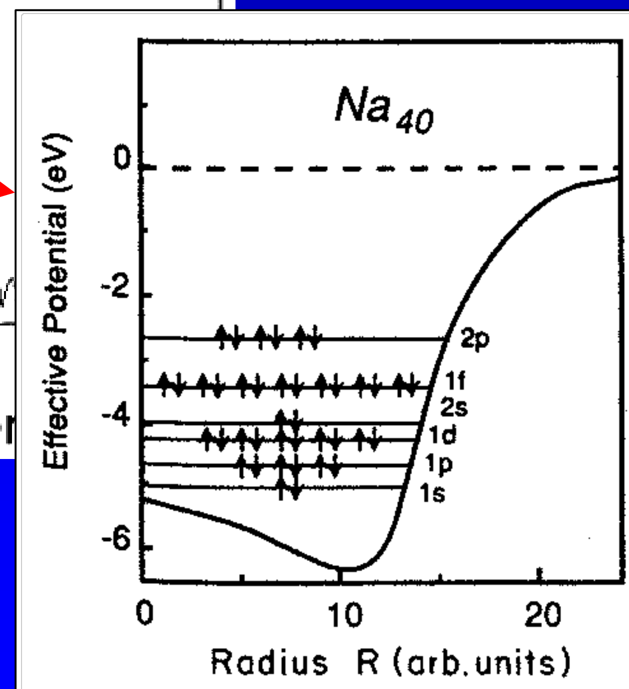




Metal clusters

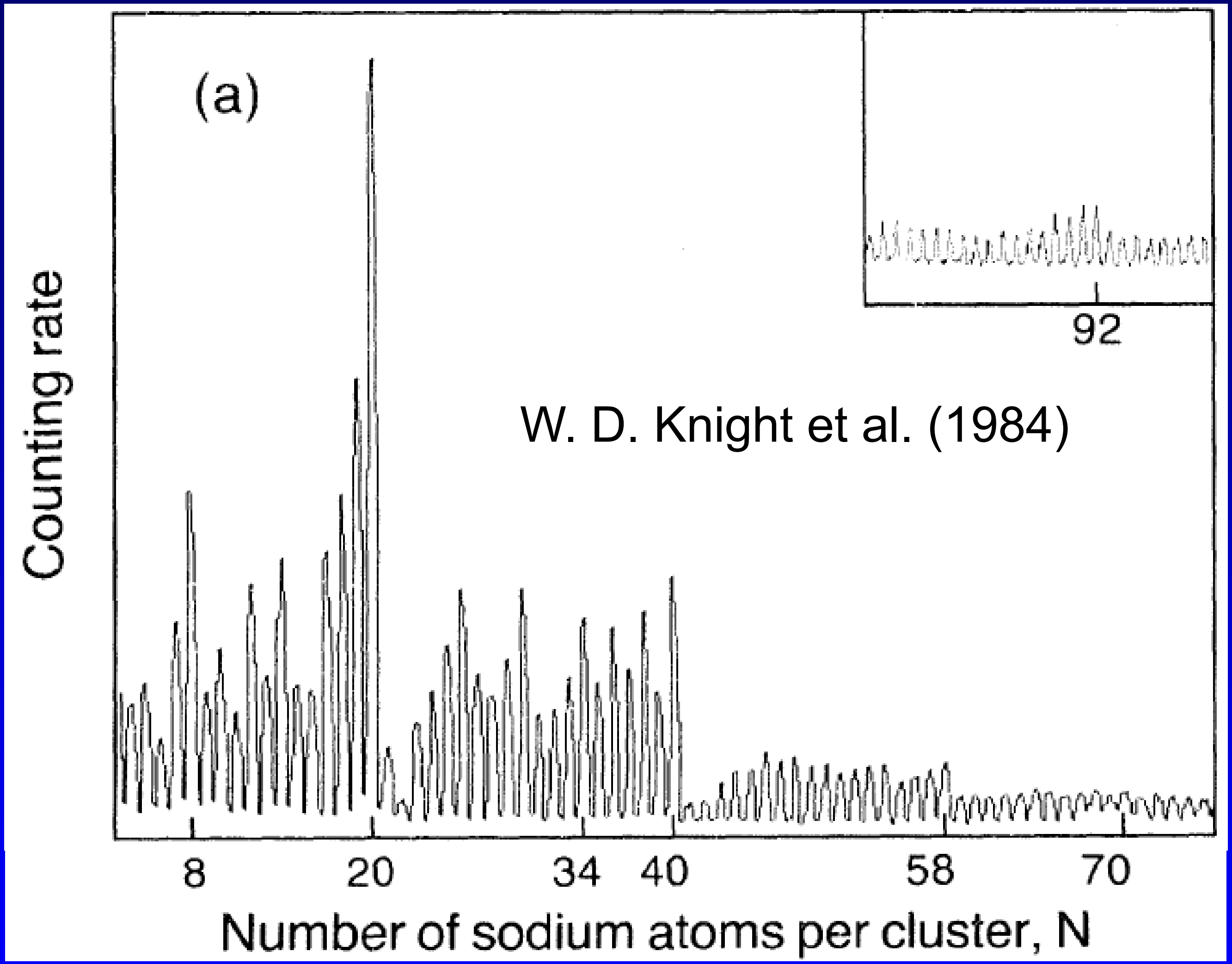
Jellium model

electronic shells



Experimental distinction betw. geom. and electr. effects:

charge-state dependence



Why cluster **ions**?

Size selection by **mass spec. as first step** for detailed studies !
mass spec. also for reaction **product analysis => MS-MS**

Overview

Other traps and applications

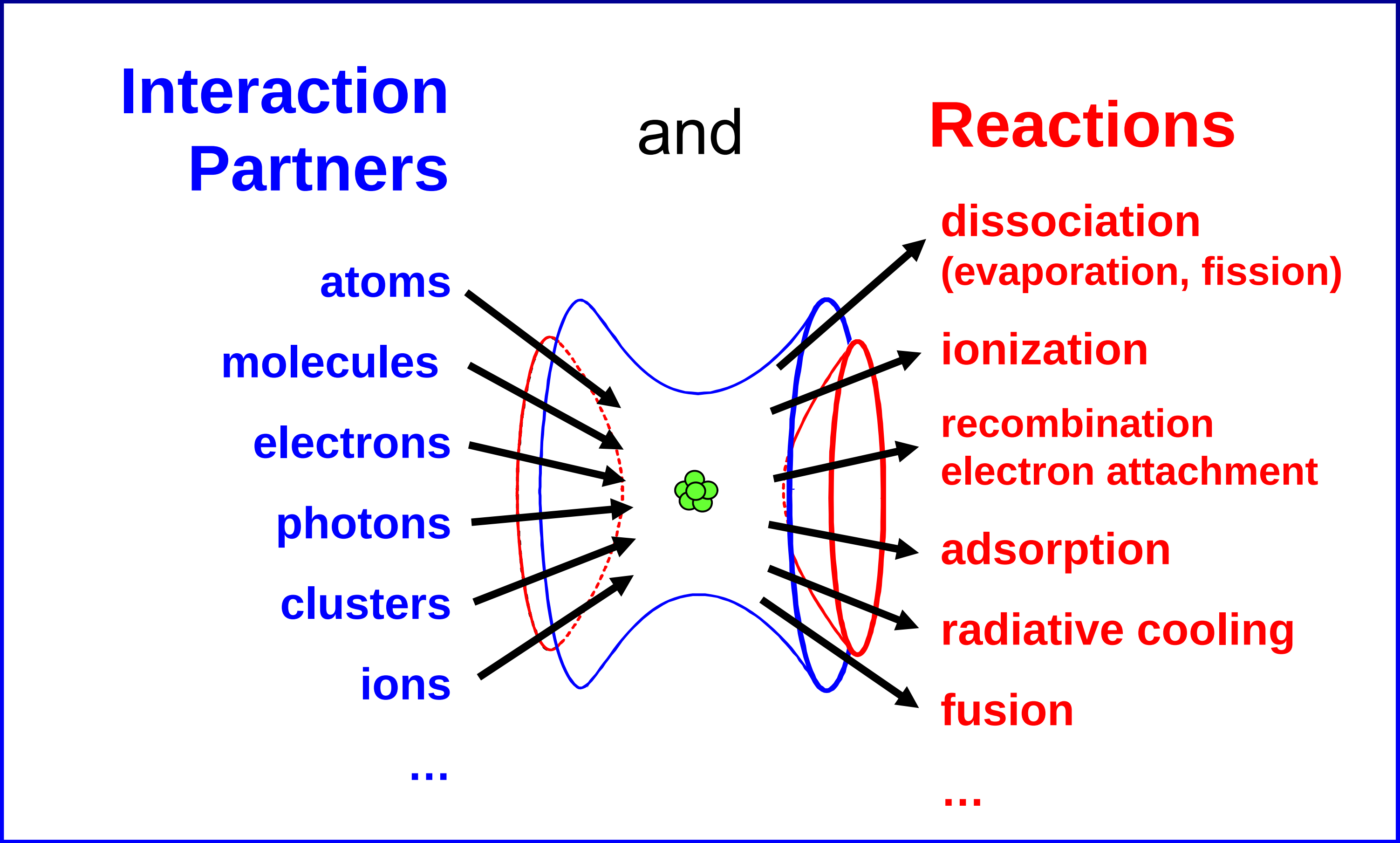
ClusterTrap

clusters? why? how? what?

Other cluster-storage devices

Why cluster trapping?
(as compared to beams)

- extended interaction periods
- extended reaction periods
- multi-step preparation



Overview

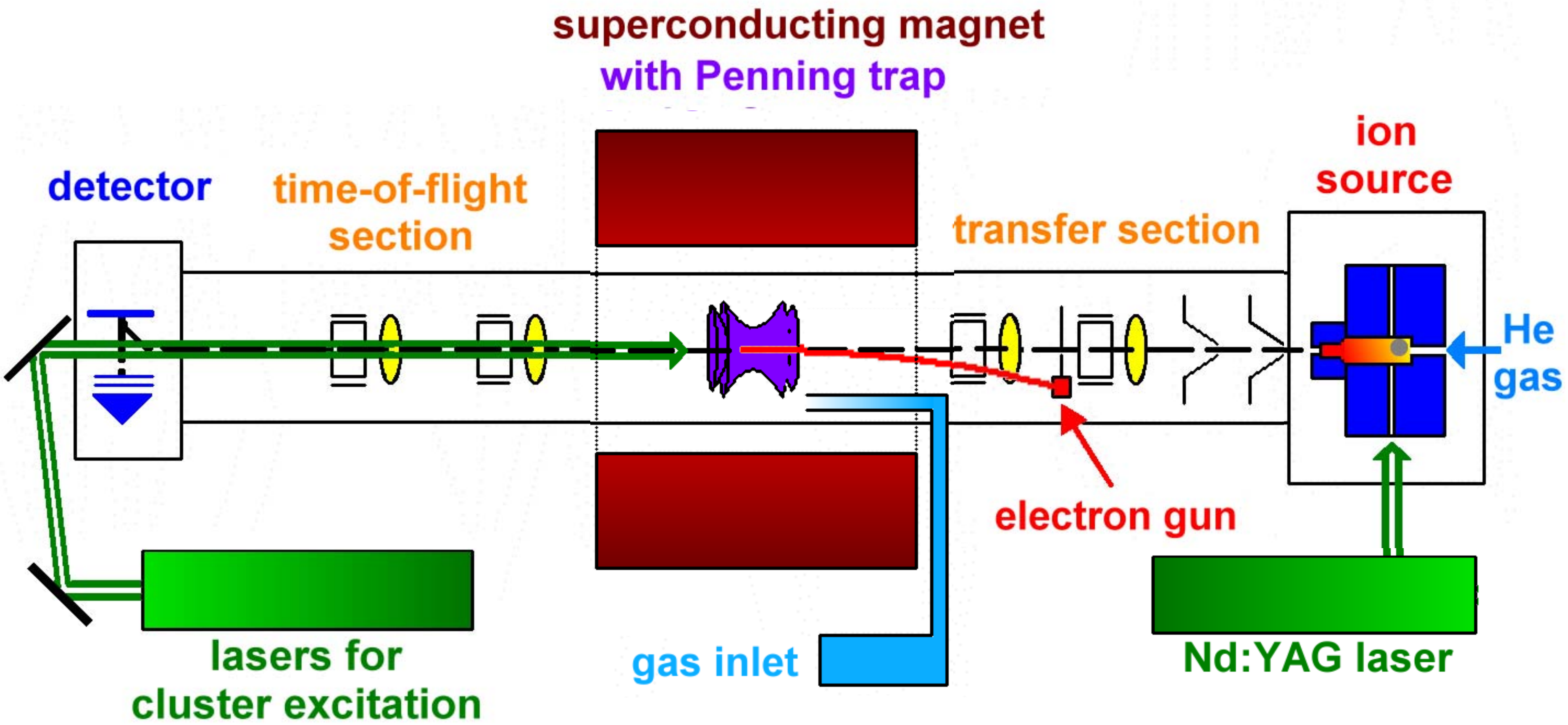
Other traps and applications

ClusterTrap

clusters? why? how? what?

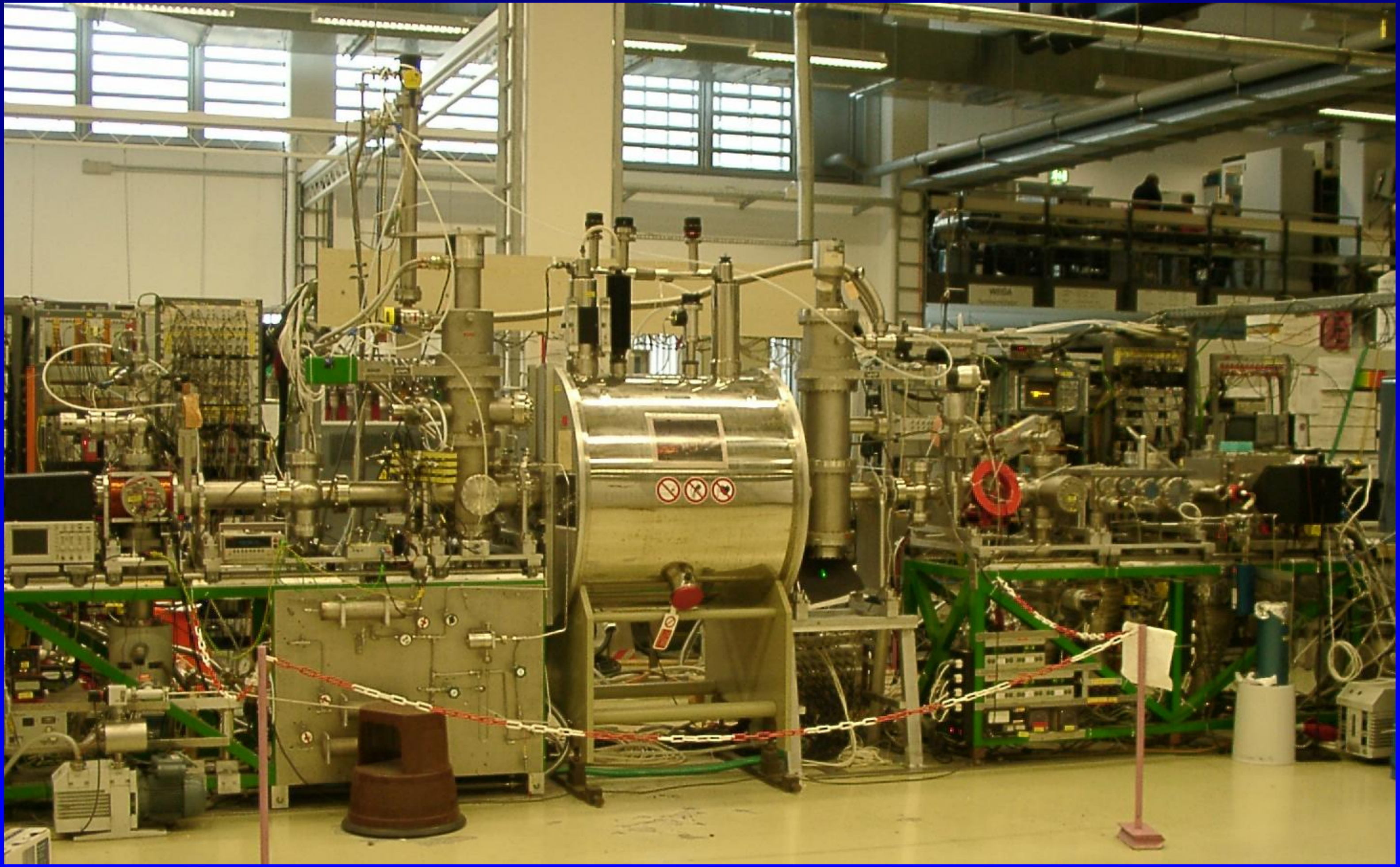
Other cluster-storage devices

Experimental set-up of ClusterTrap @ Greifswald



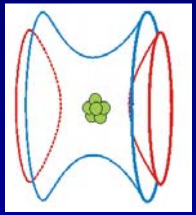
S. Becker et al., RSI (1995)
LS et al., EPJ D (2003)

Experimental set-up of ClusterTrap @ Greifswald



S. Becker et al., RSI (1995)
LS et al., EPJ D (2003)

ClusterTrap



at Univ. of Greifswald

founded in 1456
„full university“
ca. 12000 students

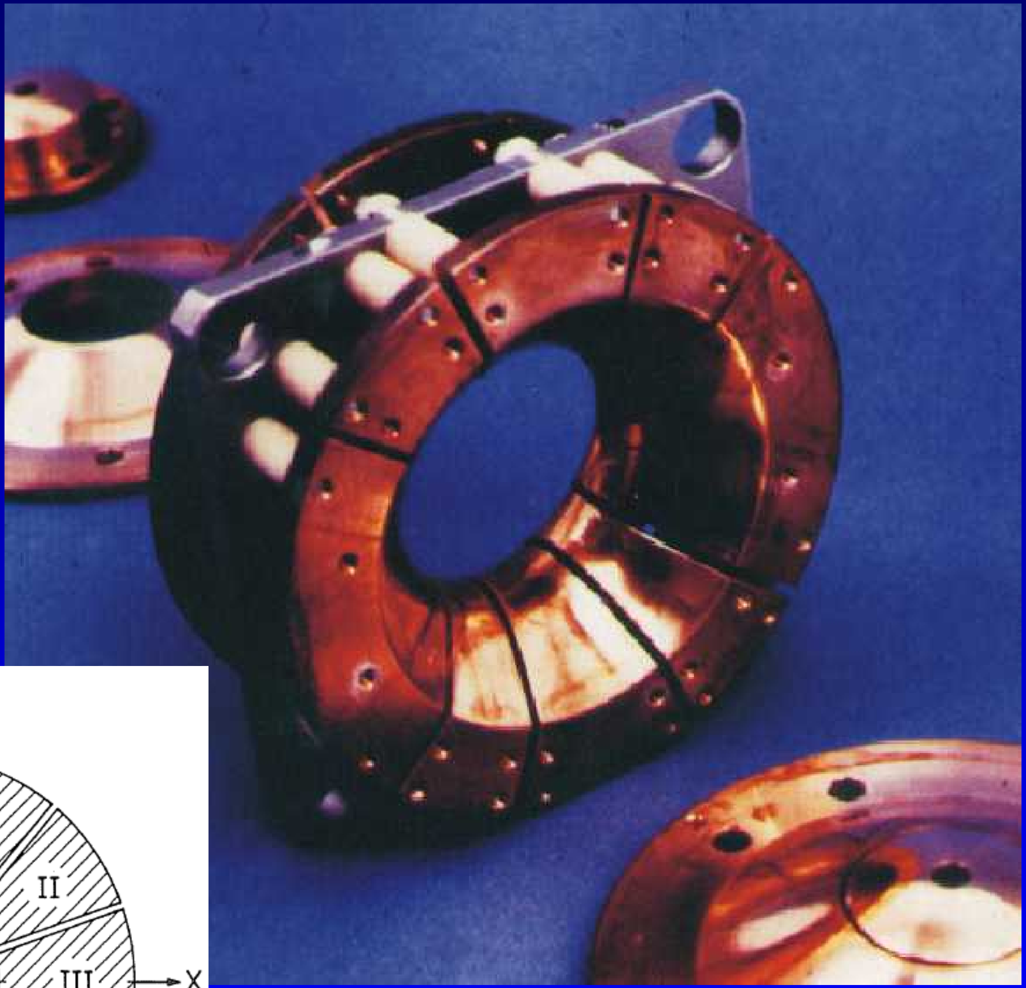
GSI

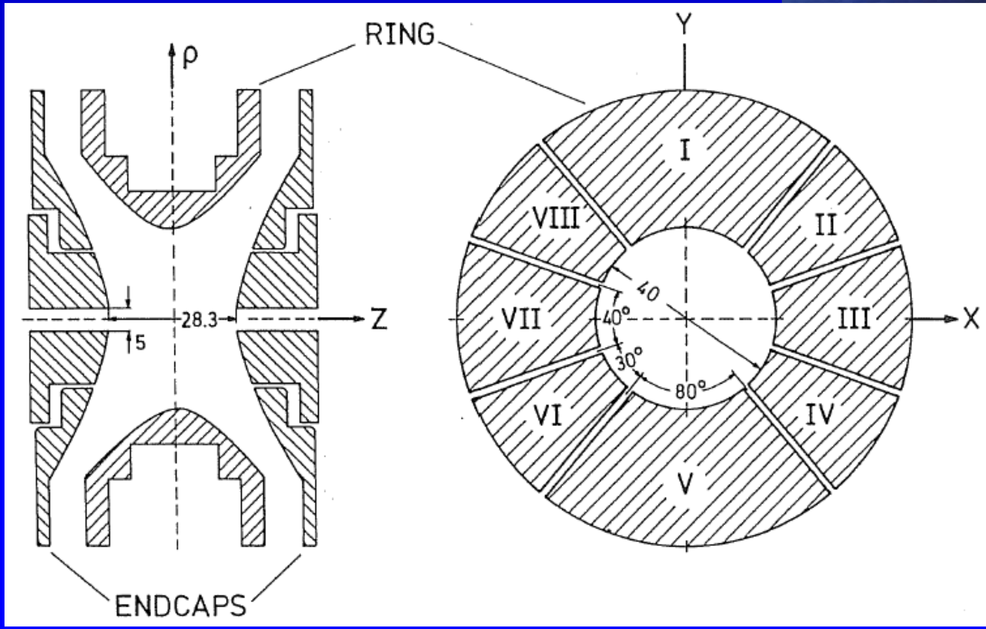
CERN

Obergurgl
Next ECTI

Trap Electrodes

inner diameter
of ring electrode
40 mm

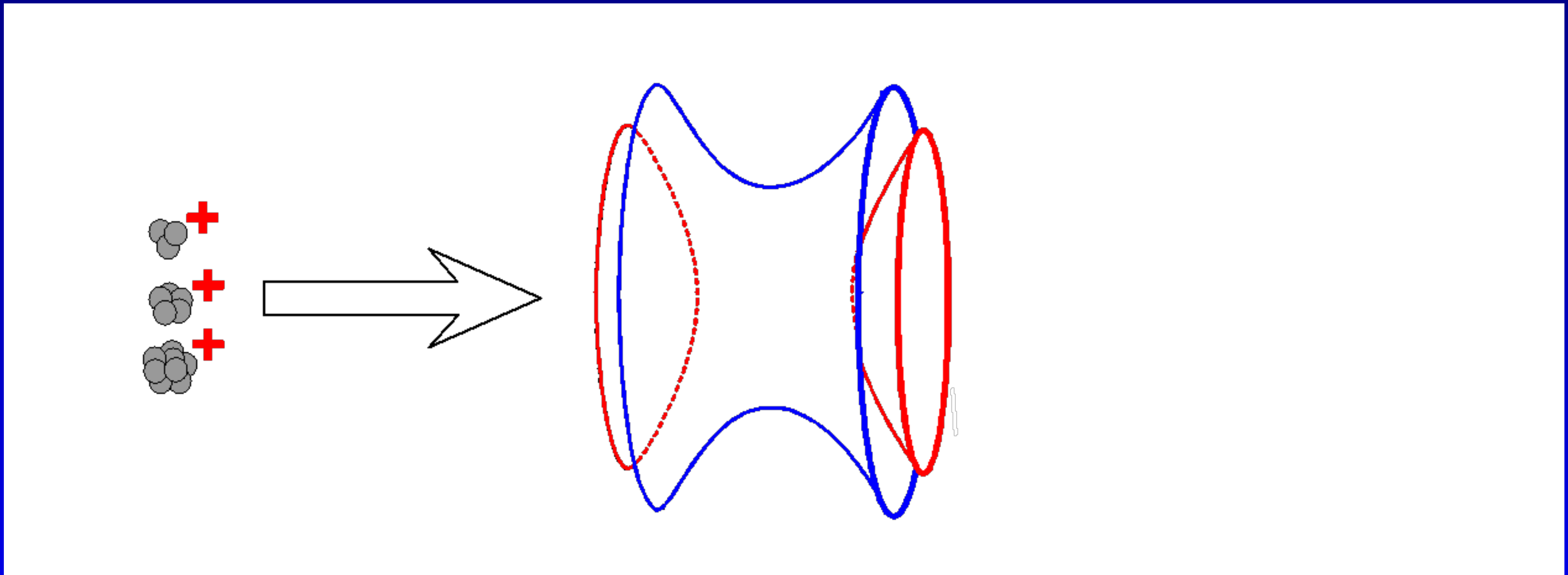




Note:

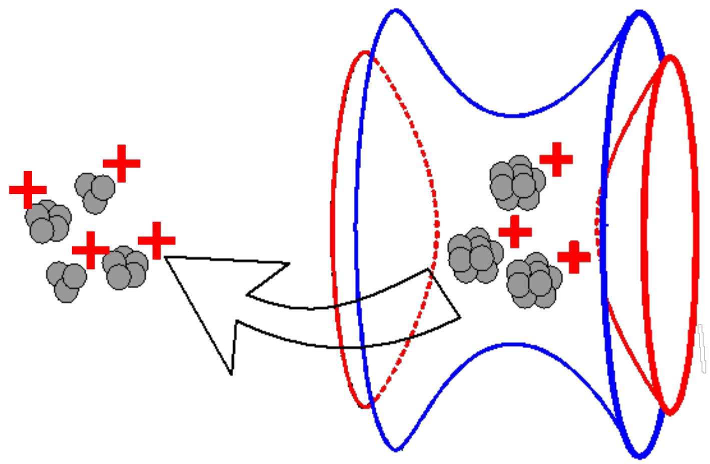
Miniaturization is not appreciated !

Typical experimental sequence



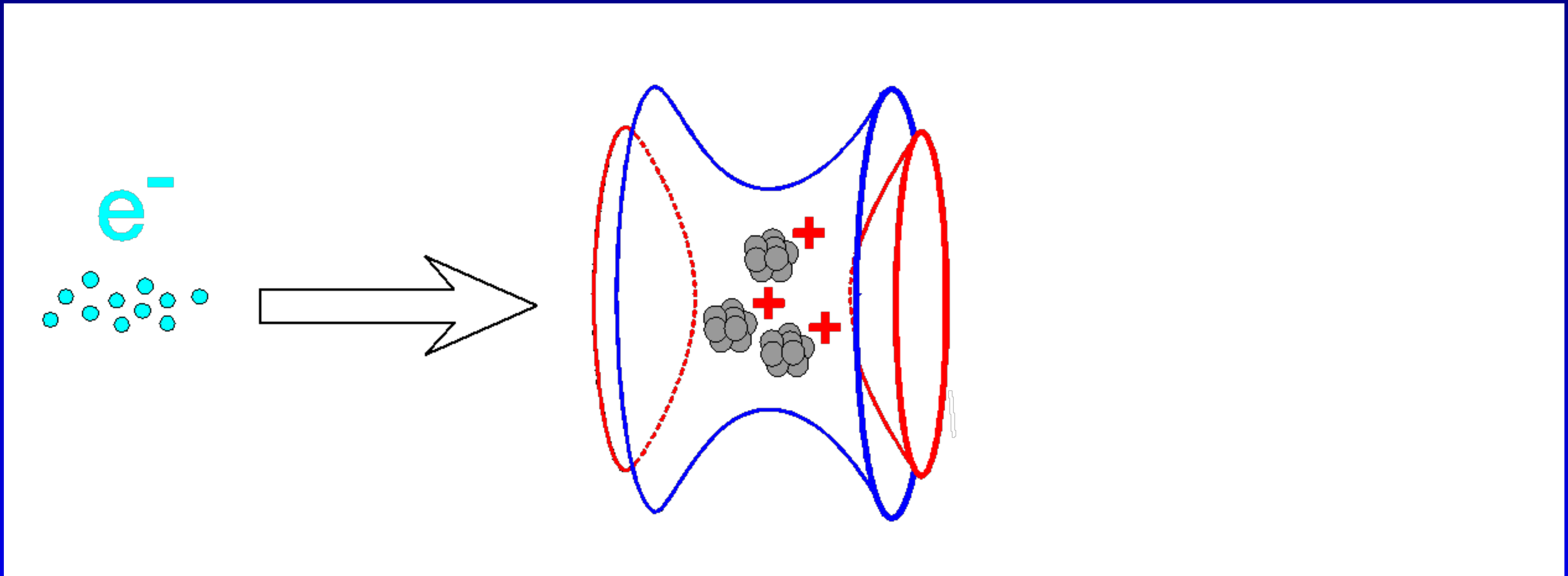
CAPTURE

Typical experimental sequence



SELECTION

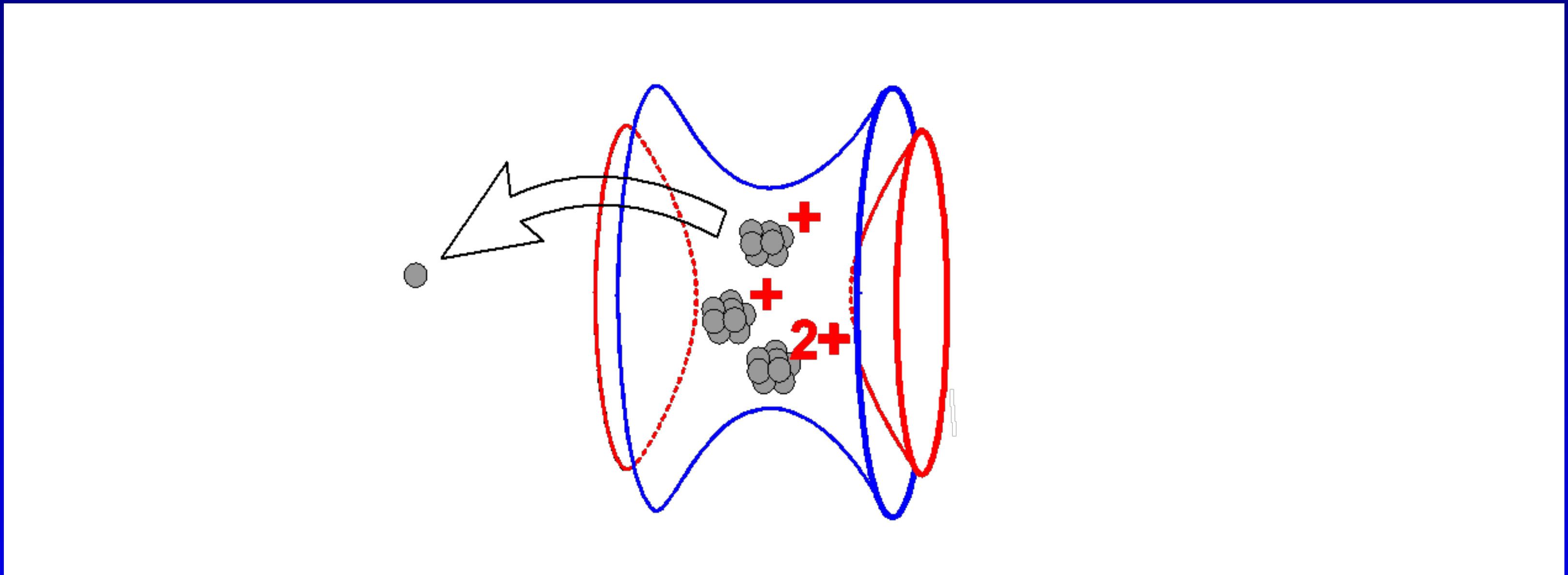
Typical experimental sequence



INTERACTION

(e.g. electron bombardment)

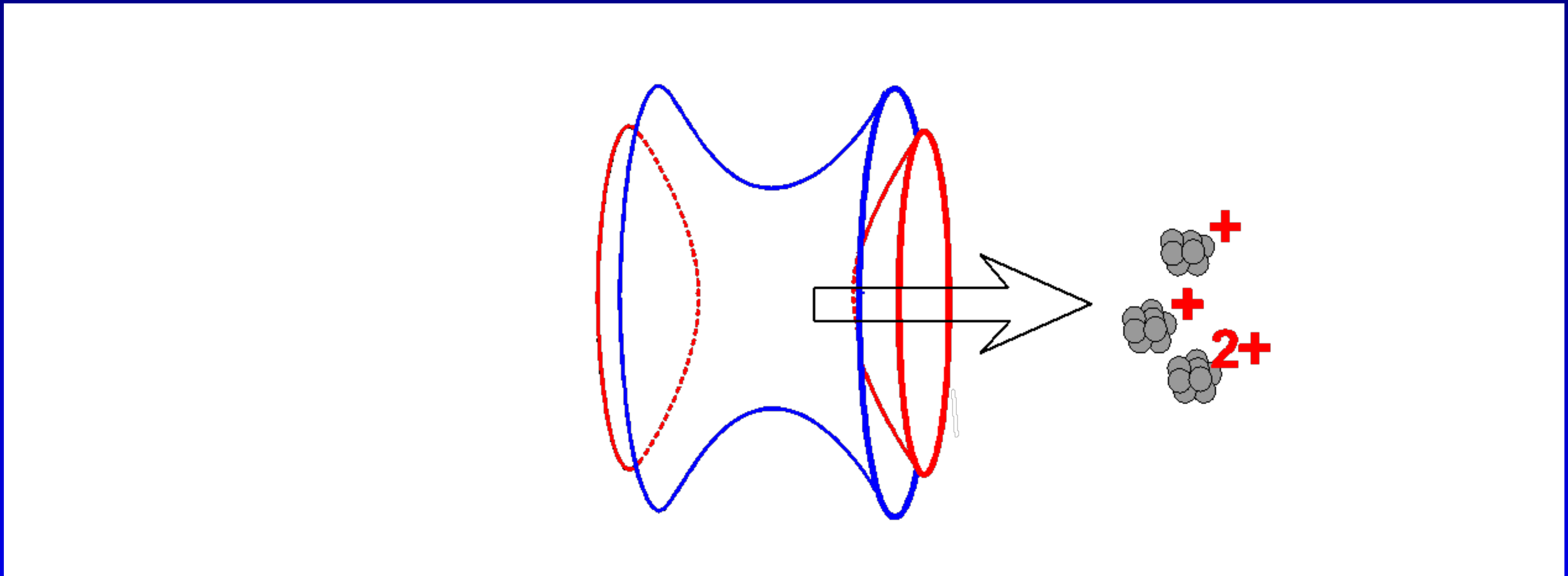
Typical experimental sequence



RE-ACTION

(e.g. ionization and dissociation)

Typical experimental sequence



EJECTION

for TOF mass analysis

Overview

Other traps and applications

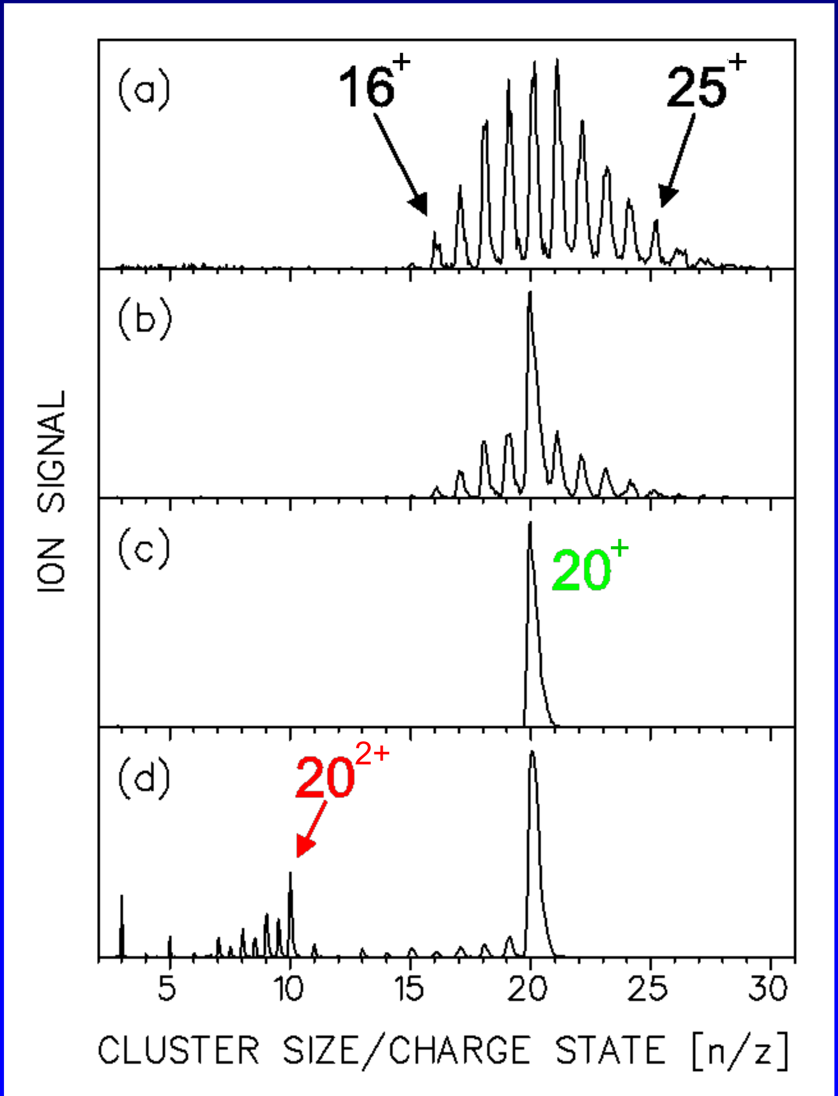
FT-ICR MS, precison MS of radionuclides, EBITs, electrostatic ion-beam traps

ClusterTrap

clusters? why? how? what?

Other cluster-storage devices

electron bombardment of cations
time-of-flight spectra (gold clusters)



CAPTURE

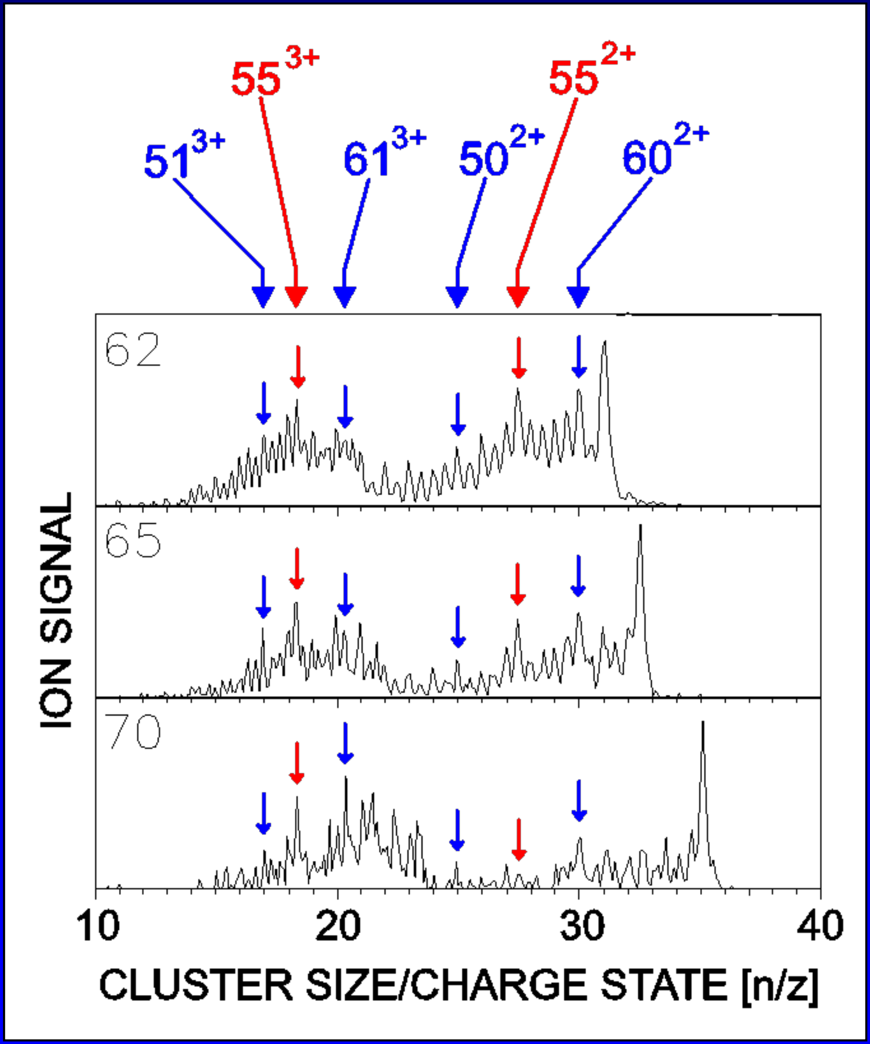
ACCUMULATION

SELECTION

ELECTRON BOMBARDMENT

A. Herlert et al.,
J. Electron.Spectrosc. (2000)

Electron Impact Ionization/Dissociation of Ag-clusters



S. Krückeberg et al. (1999)

observation of both

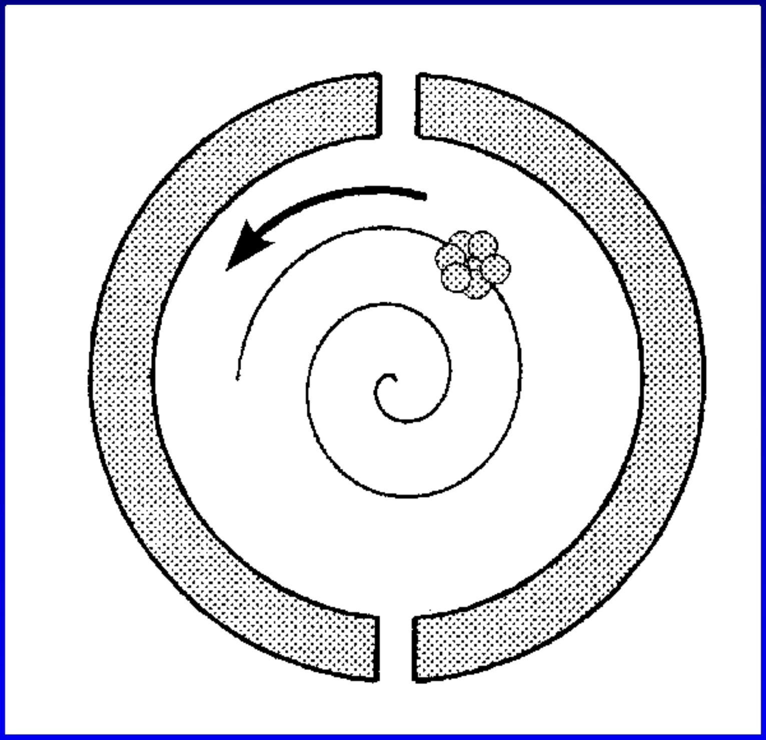
ELECTRONIC

and

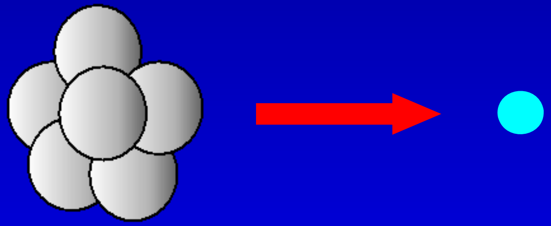
GEOMETRIC

shells

Collision Induced Dissociation (CID)

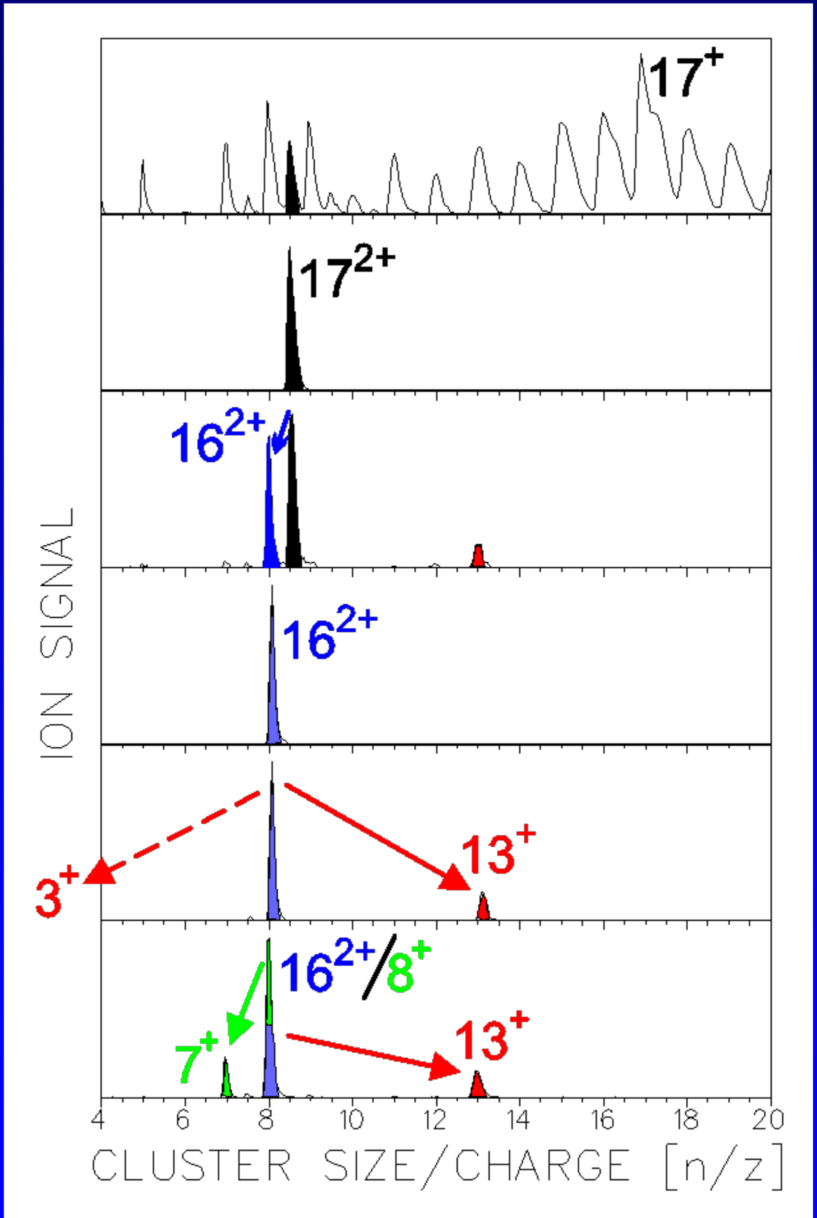


dipole excitation



(Many) collisions
with noble-gas atoms

CID of product ions: How do they break apart ?
=> decay channels



capture/accumulation and electron bombardment

1. selection

CID

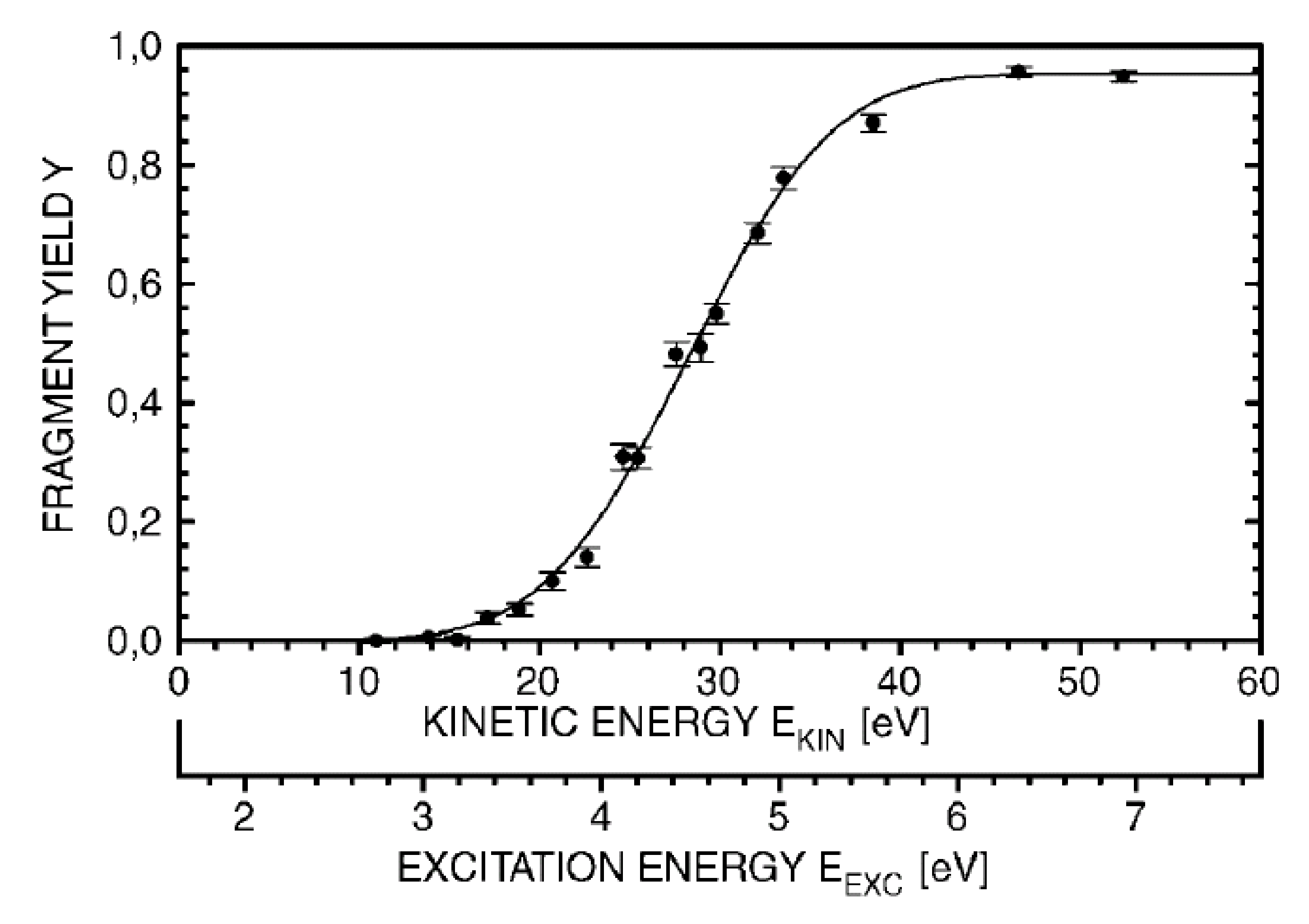
2. selection

CID

CID after first selection

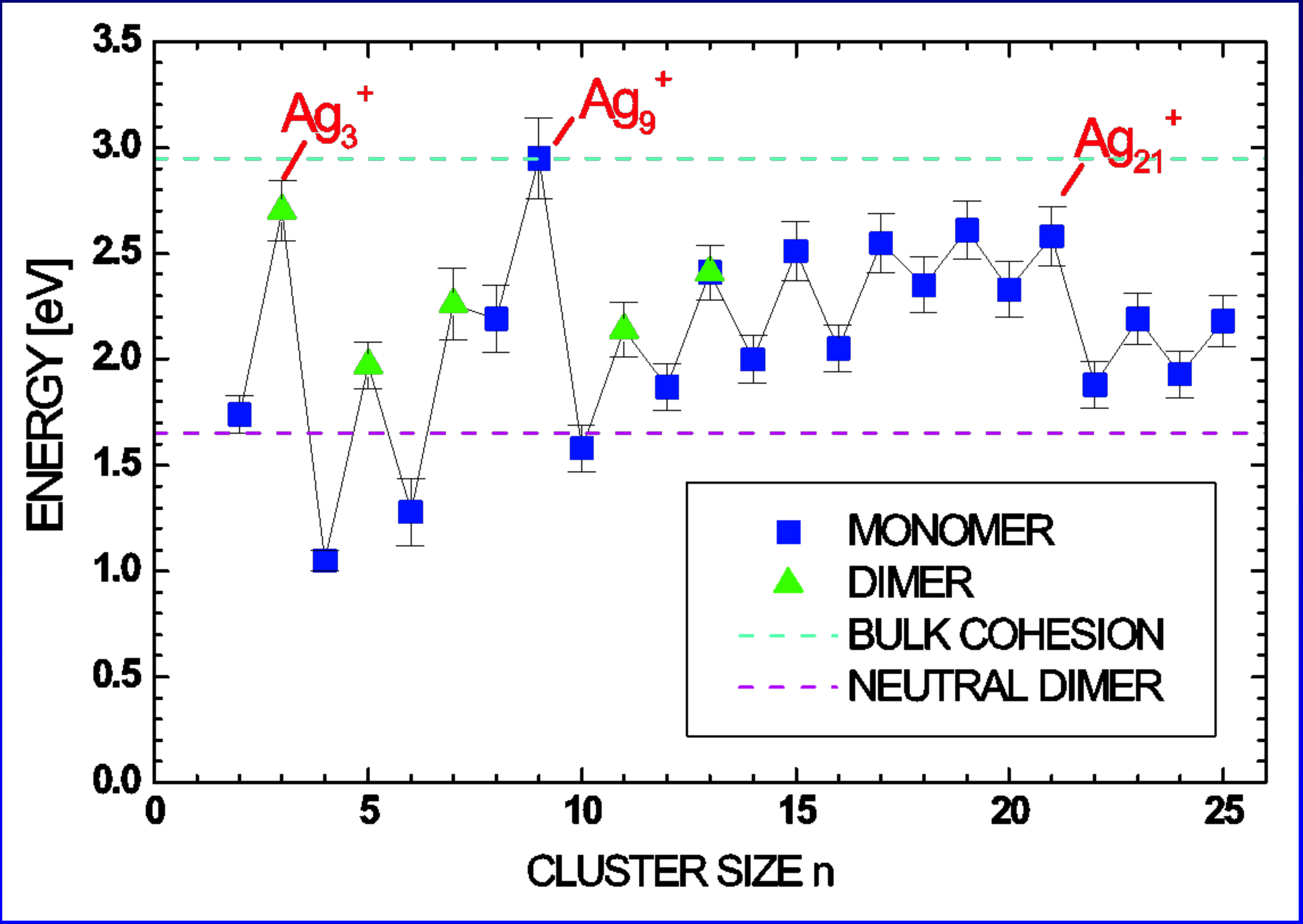
S. Krückeberg et al., ZPD (1997)

CID revisited: At what energy do they break apart ?
=> dissociation energies



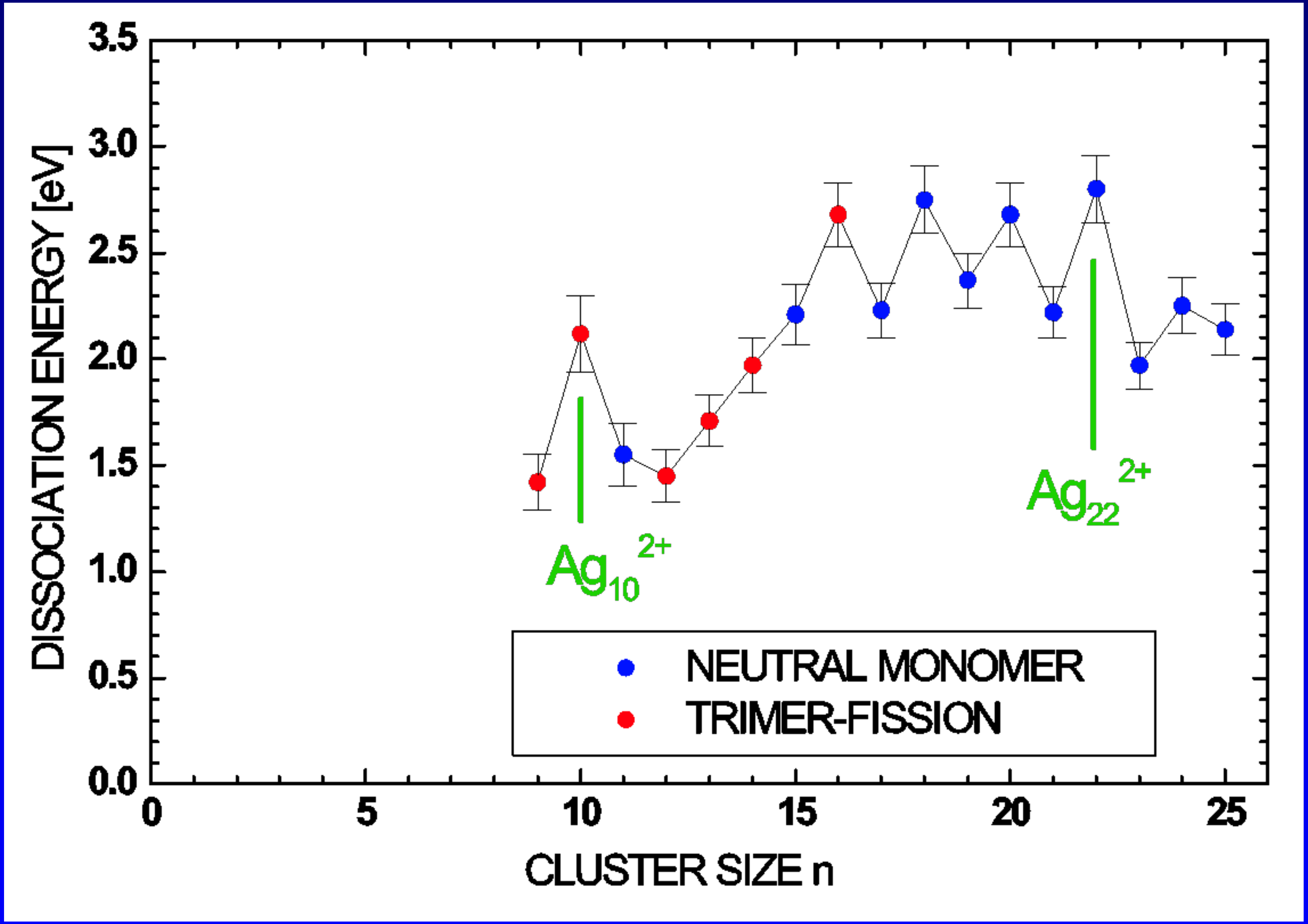
Krückeberg (EPJD, 1999)

Dissociation energies from CID



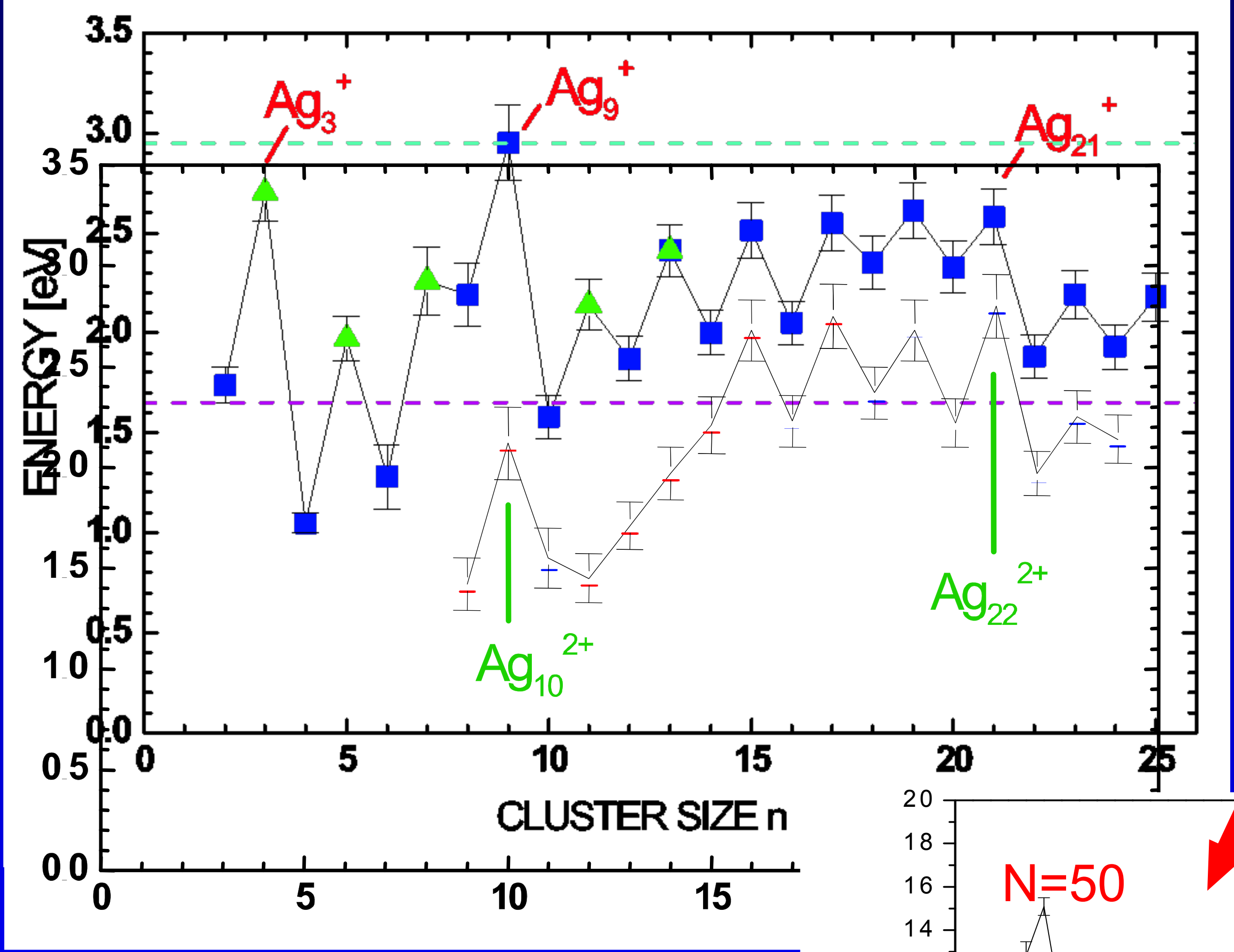
S. Krückeberg et al., JCP (1999)

Dissociation energies from CID

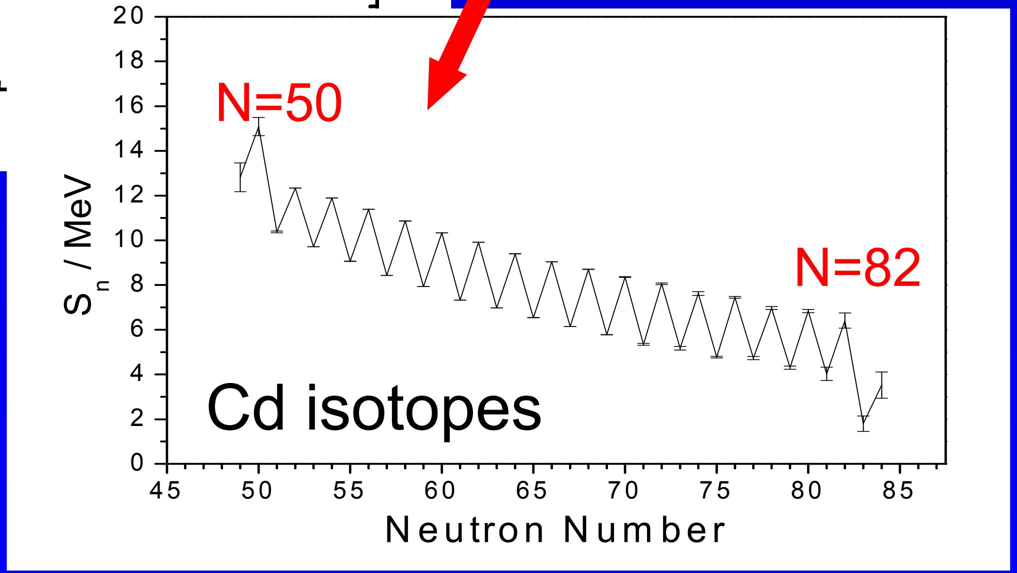


S. Krückeberg et al., PRA (1999)

Dissociation energies from CID



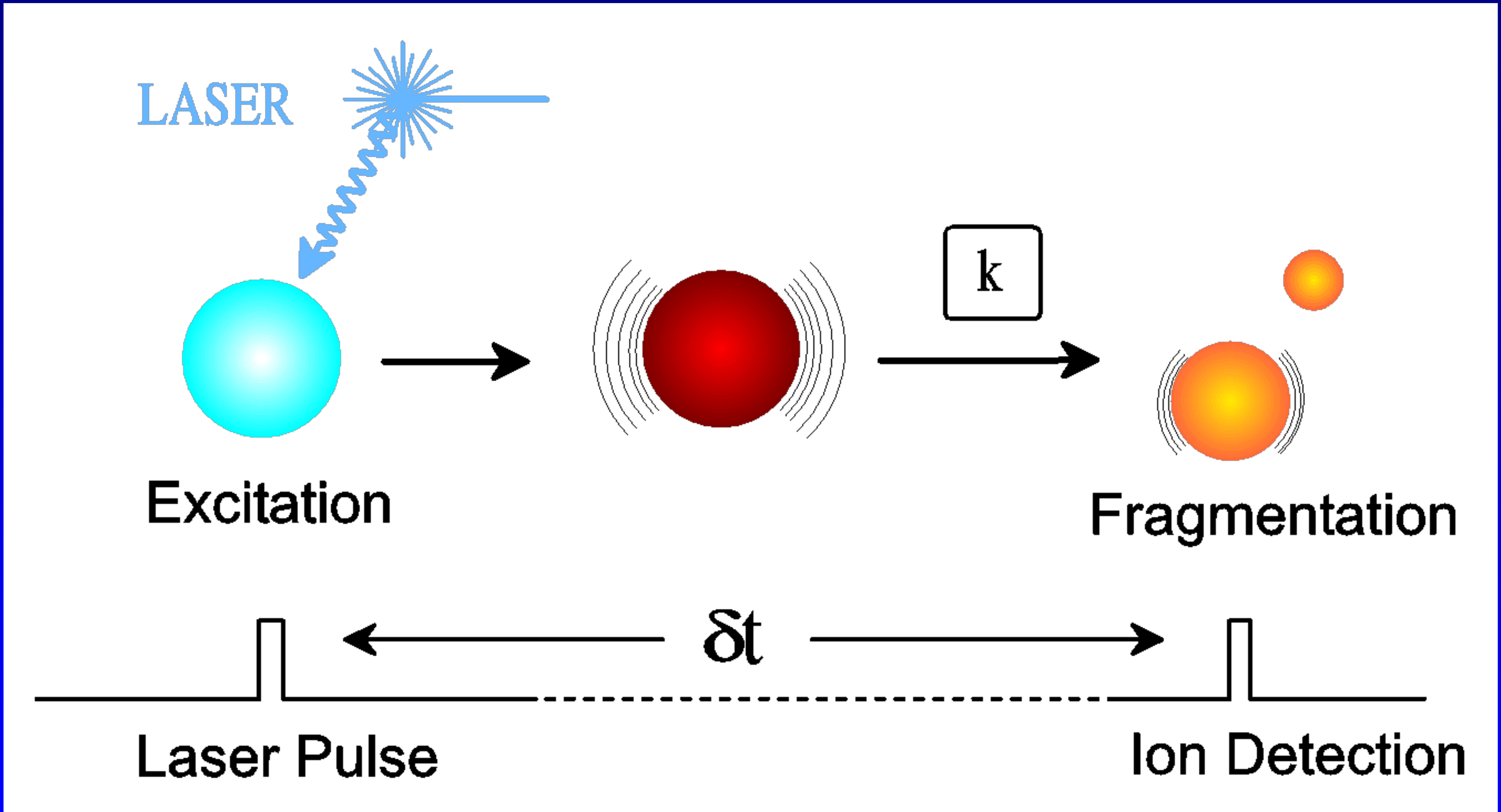
cf. neutron-separation energies from mass meas.



However:

- impact parameter?
  => energy?
- time of collision?

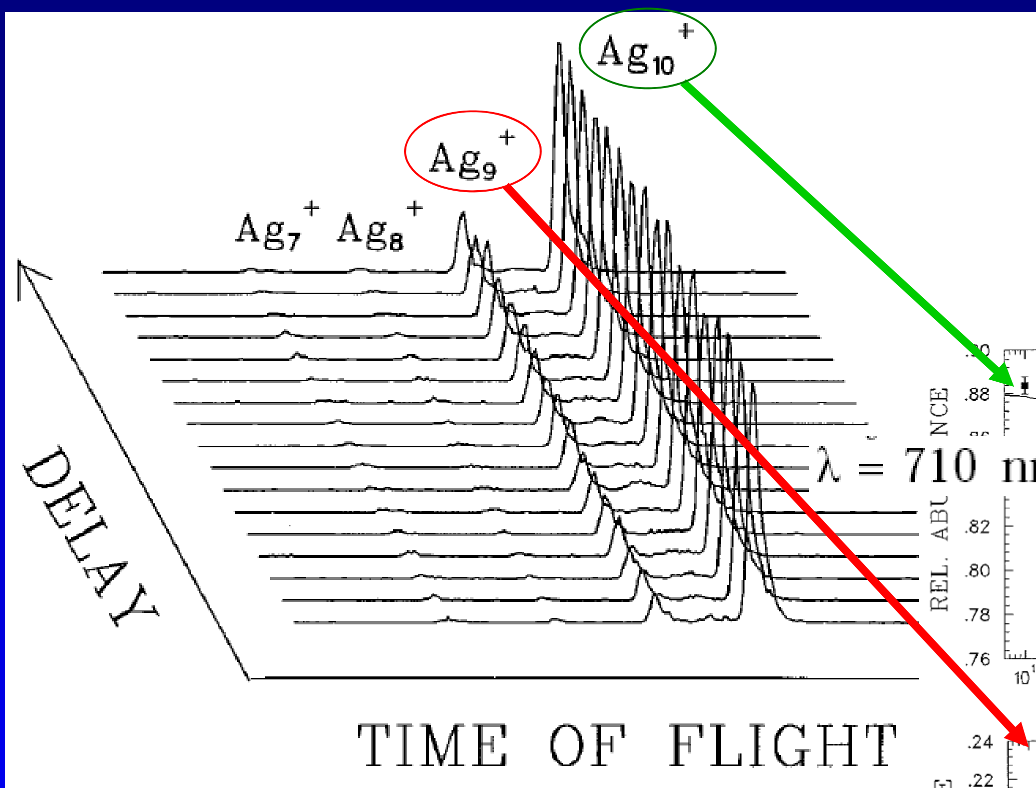
Dissociation energies from Time – resolved photodissociation

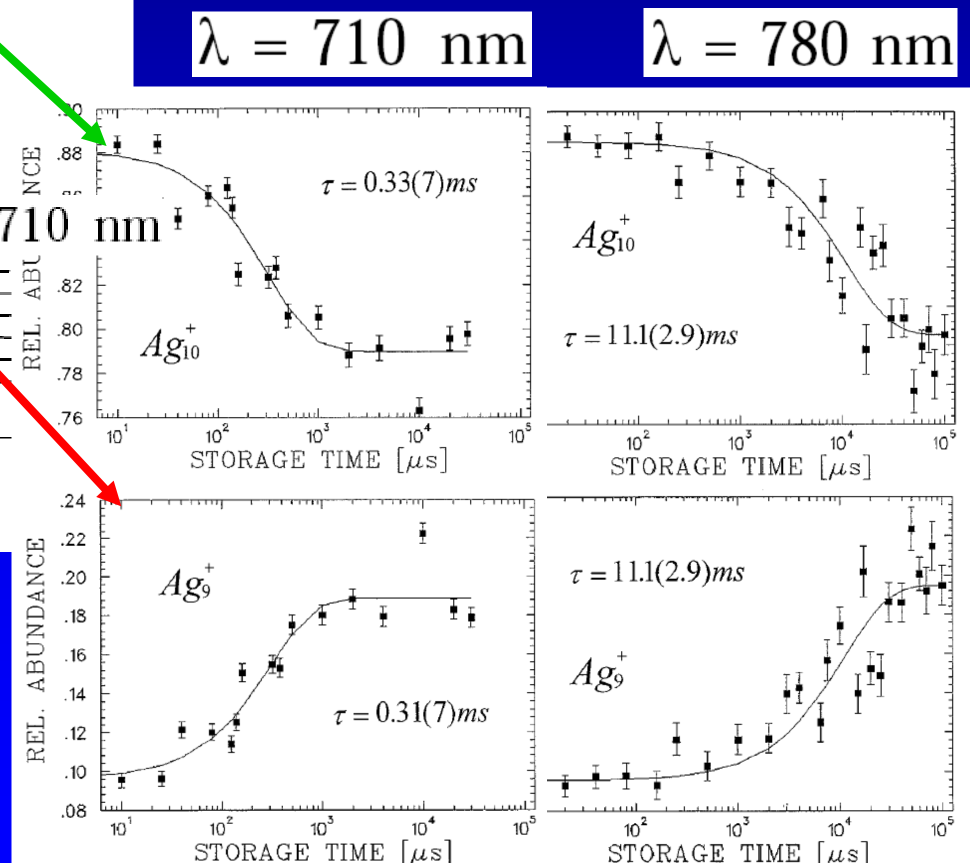


C. Walther et al., CPL (1996), M. Lindinger et al., ZPD (1997)

Time – resolved photodissociation

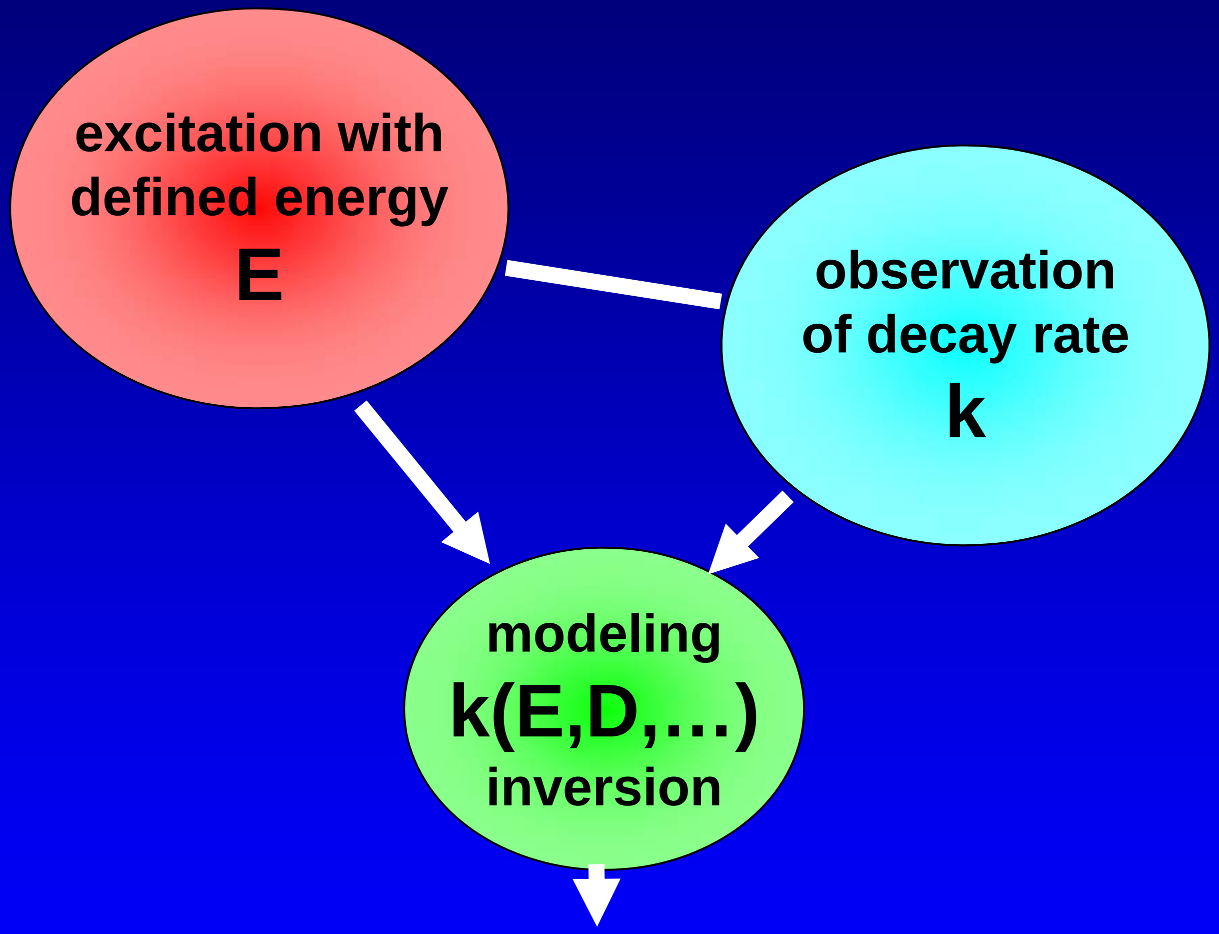
Defined
- exitation time and
- exitation energy





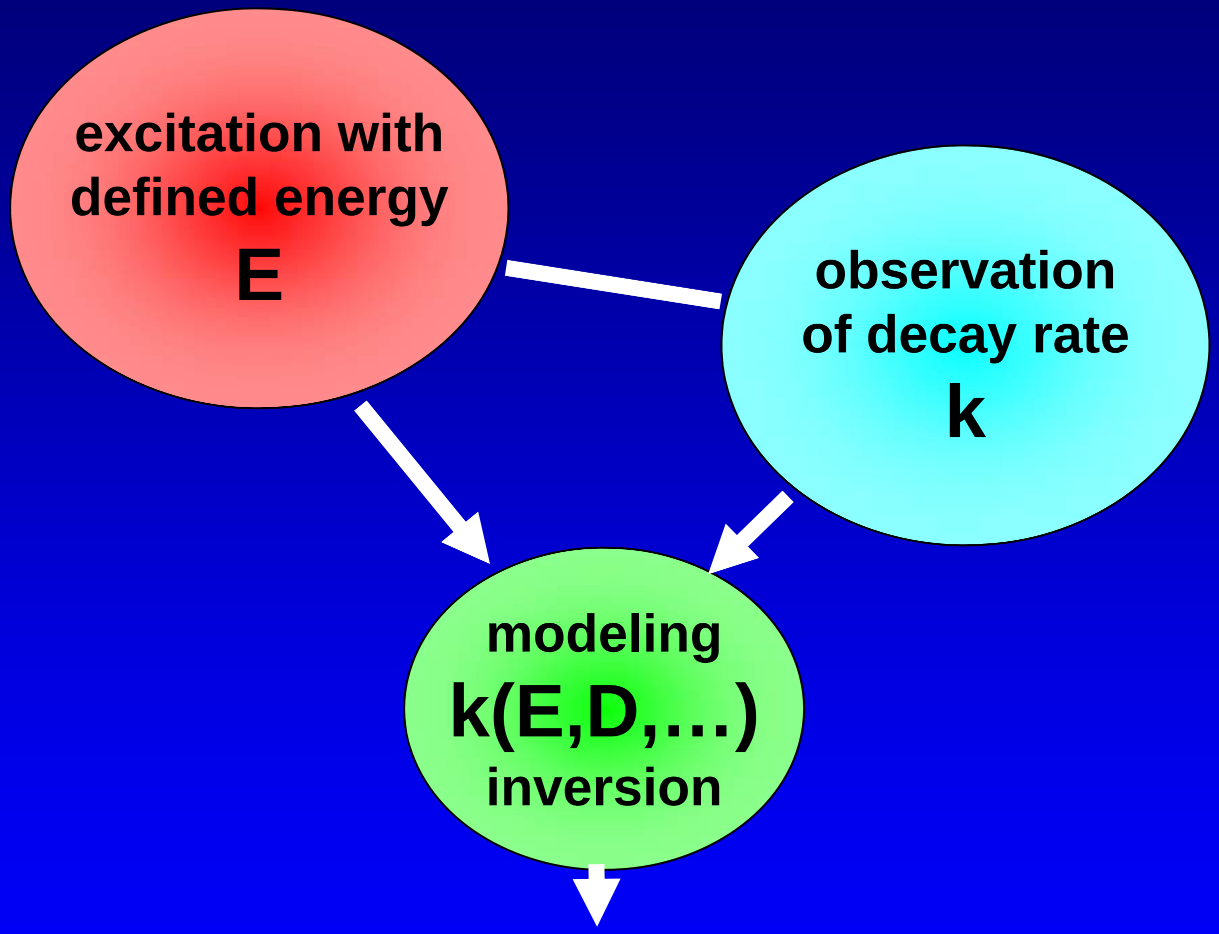
Walther et al., Z. Phys. D., 1996
Lindinger et al., Z. Phys. D., 1997
Hild et al., Phys. Rev. A, 1998

Determination of dissociation energy – in principle



dissociation energy D

Determination of dissociation energy – in principle



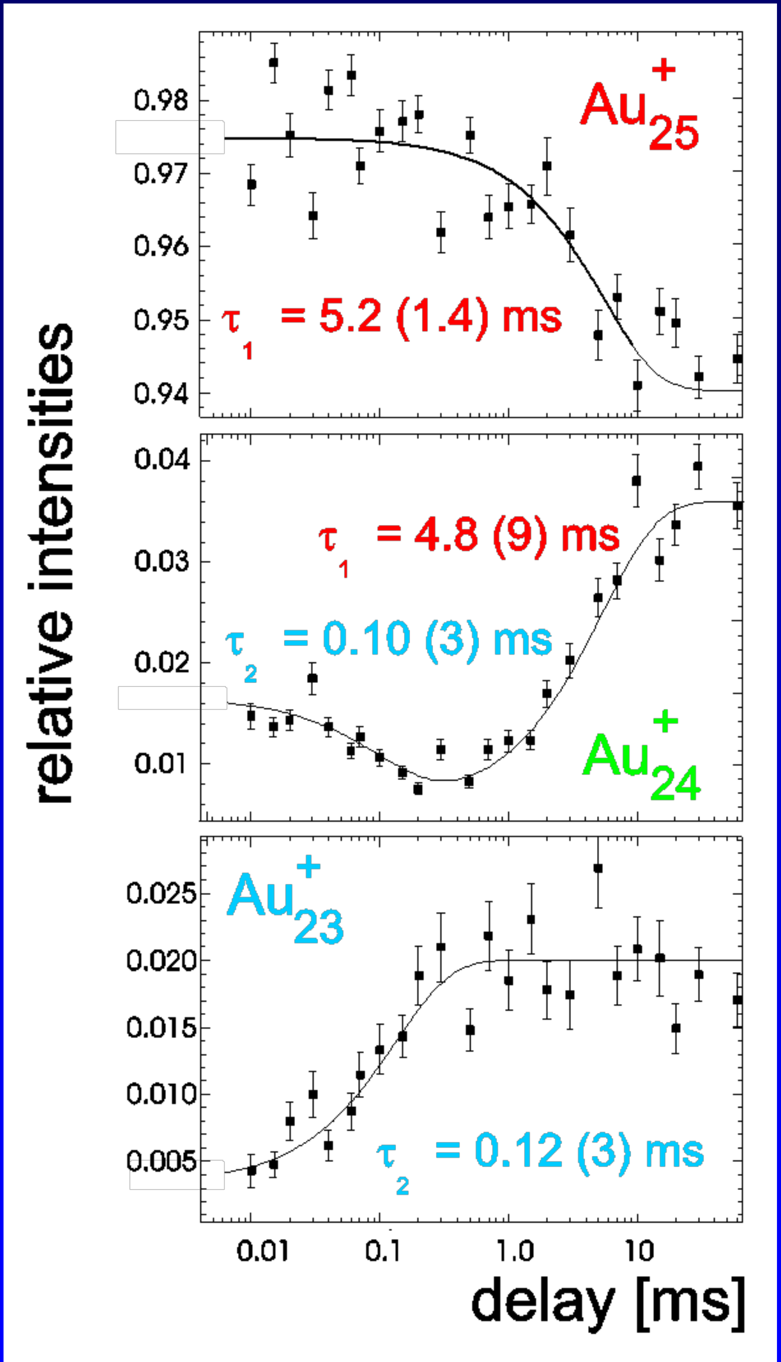
and in praxis: - value of D is model-dependent

- value of D is dep. on exc. energy E

Observation of precursor and product(s)

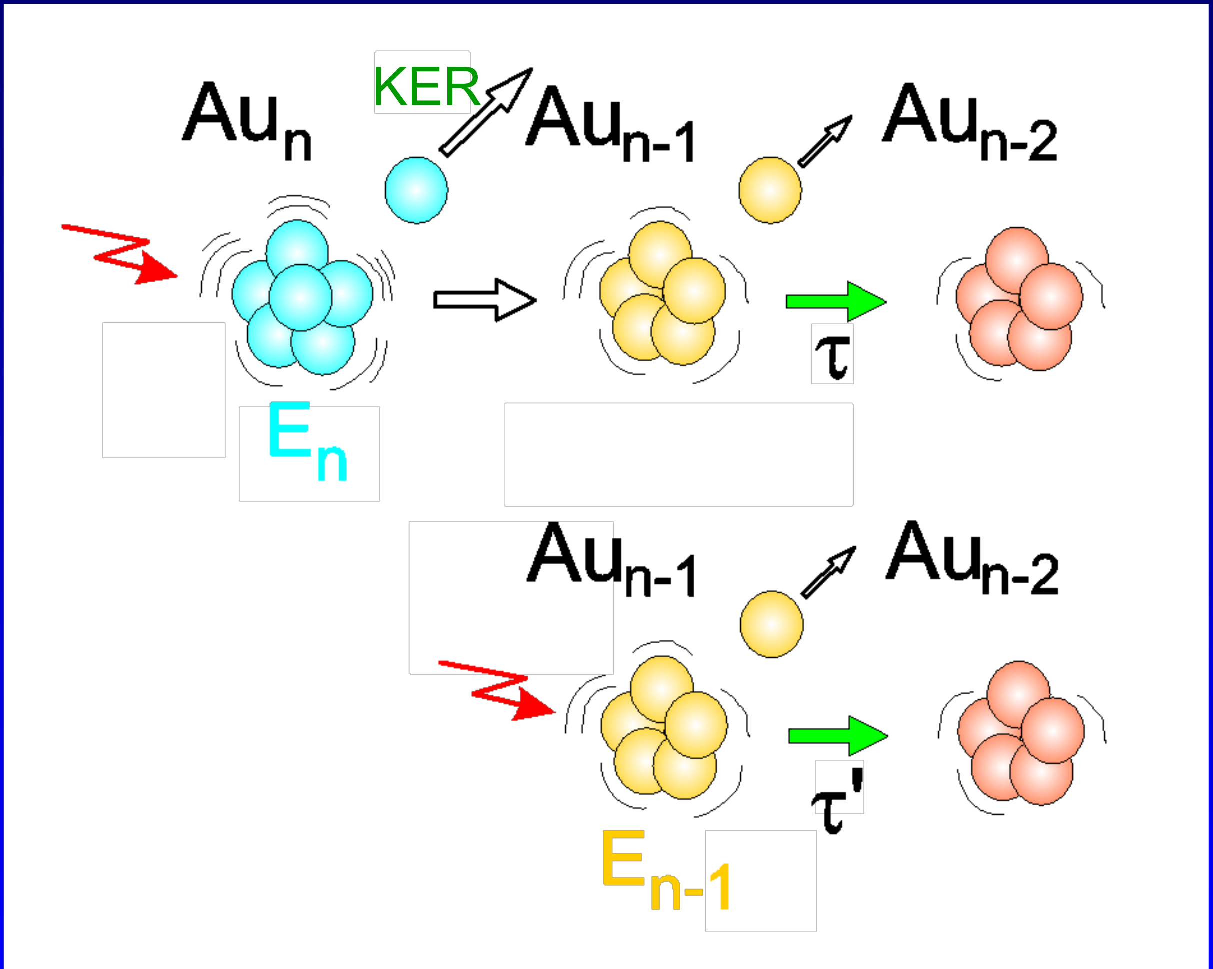
allows

observation of sequential decay



M. Vogel et al., PRL (2001)

Quasi model-free determination of D



What‘s the trick?

no need to model the residual excitation energy left after the dissociation

What‘s the pay-off?

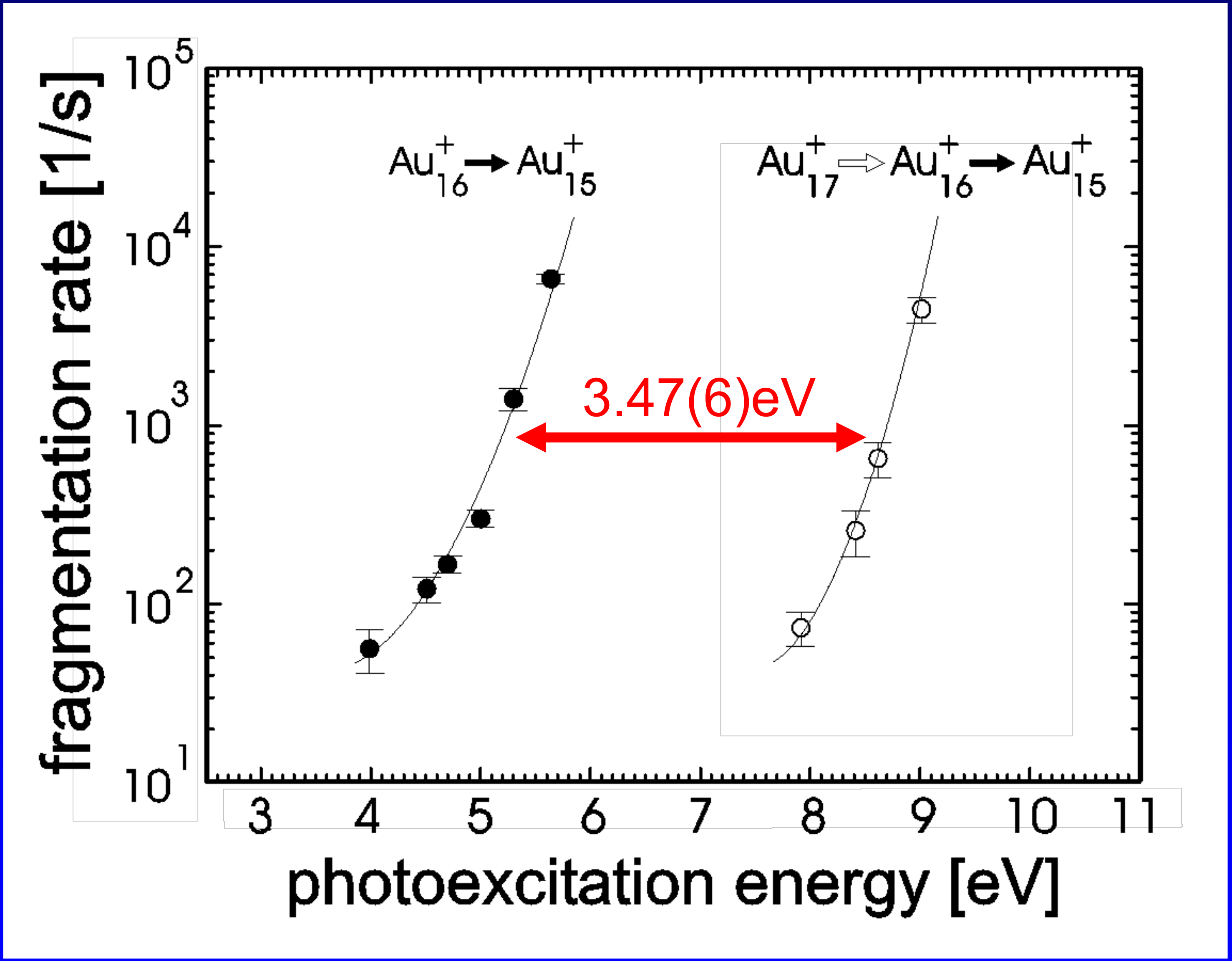
two coordinated measurements needed

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

$\longrightarrow$ $D_n = E_n - E_{n-1} - KER$

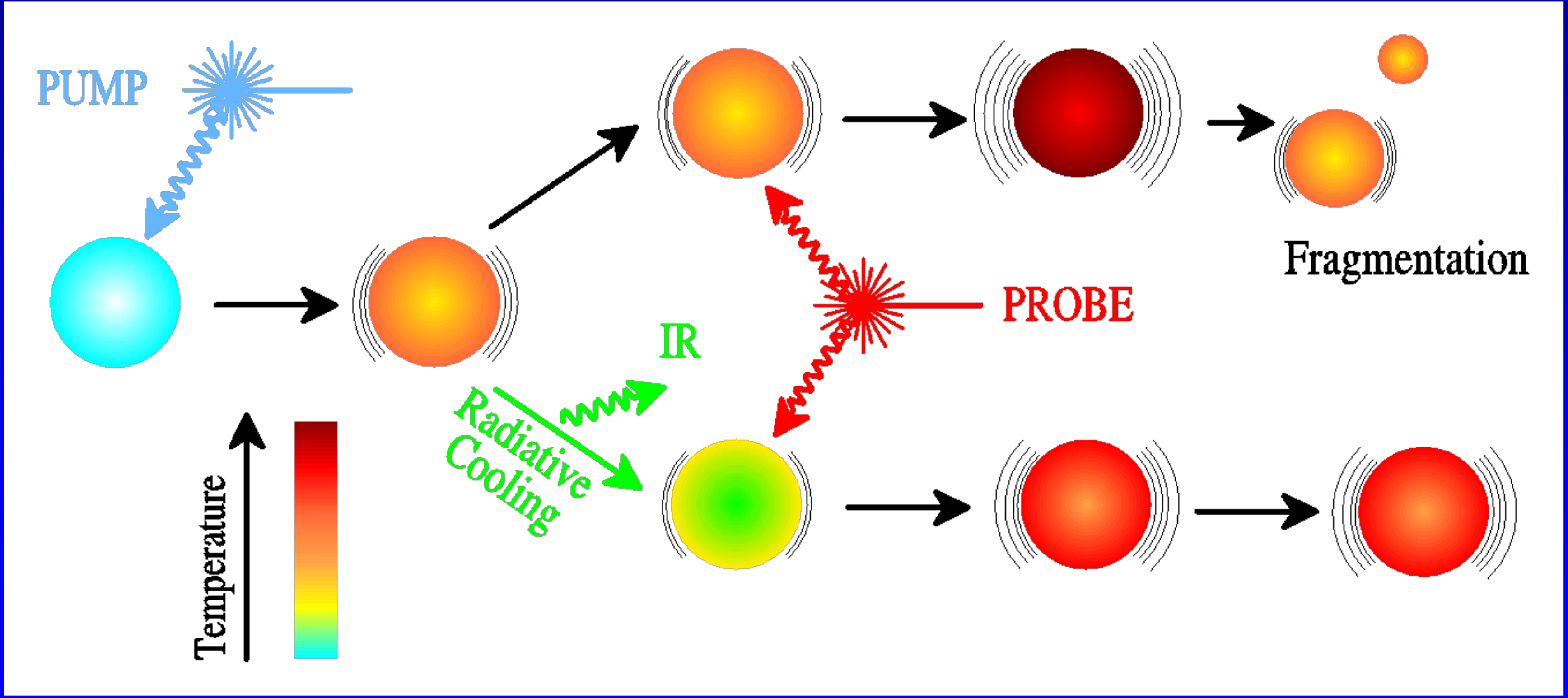
M. Vogel et al., PRL (2001)

In practise: perform a couple of measurements



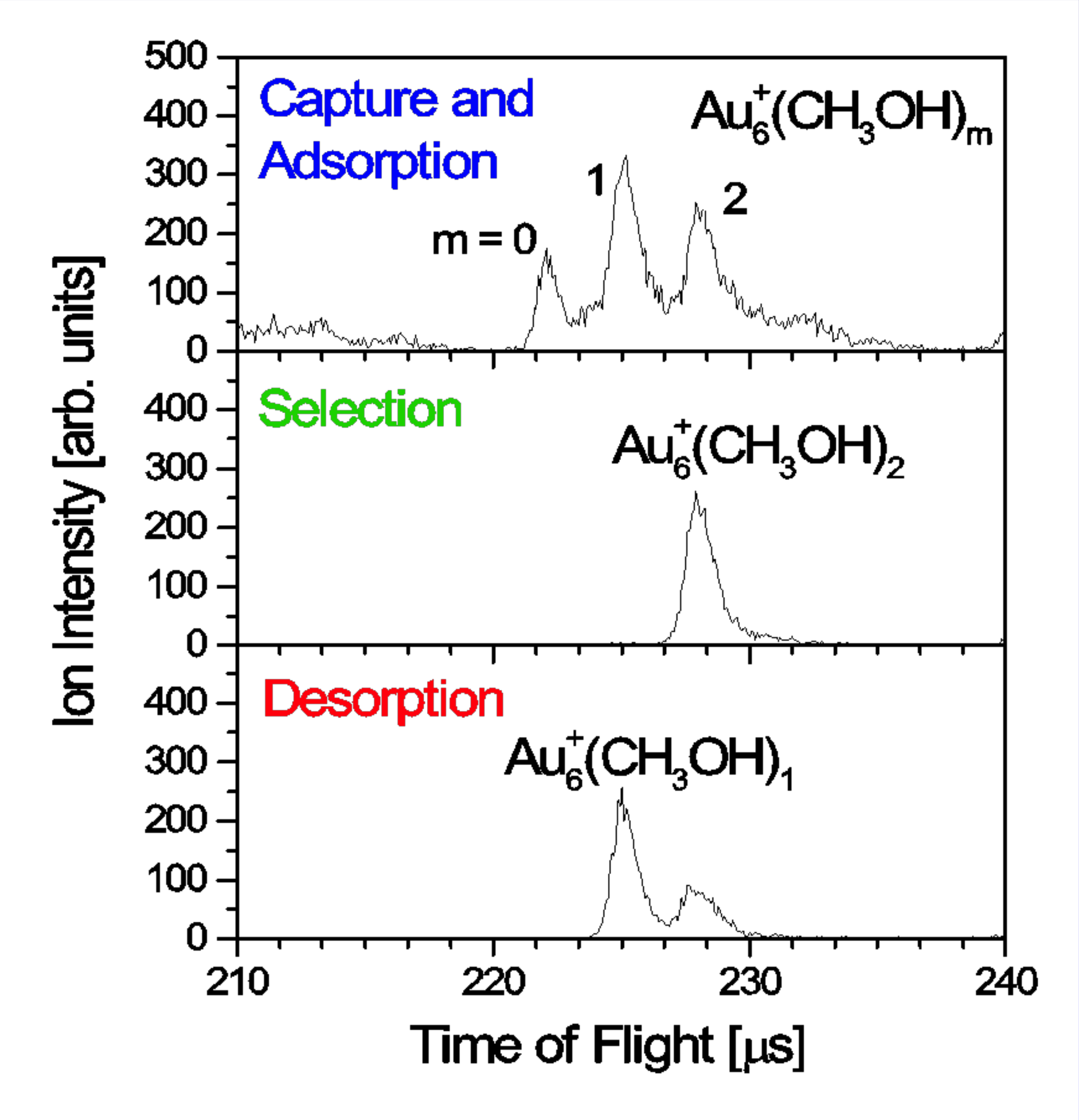
Sequential Excitation
i.e. pump – probe at up to tens of milliseconds

=> Investigation of Radiative Cooling



C. Walther et al., PRL (1999)

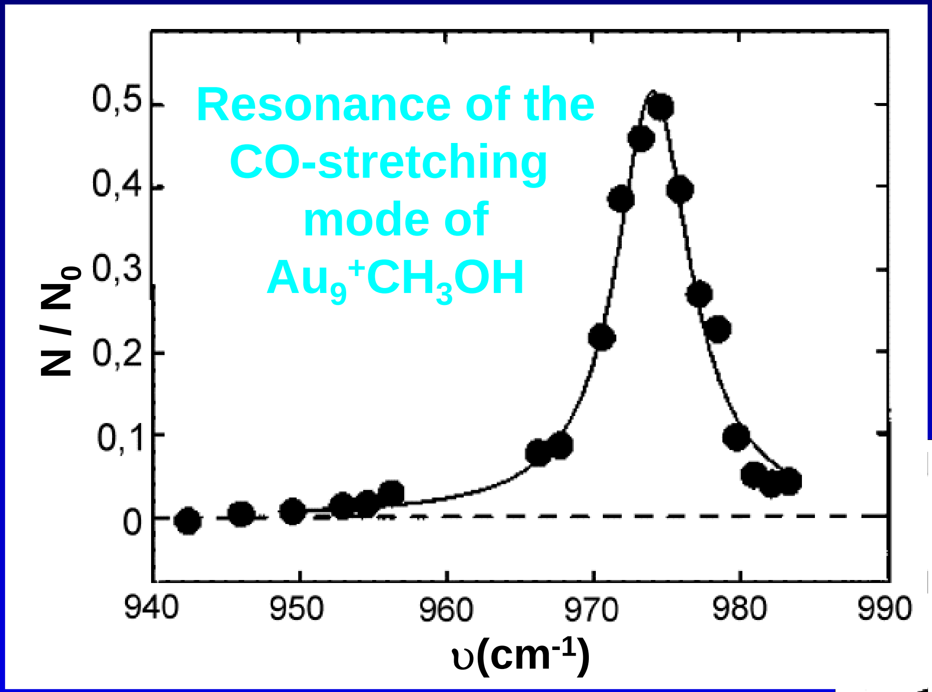
Attachment and photodetachment of methanol



G. Dietrich et al., CPL (1996), … JCP (2000)

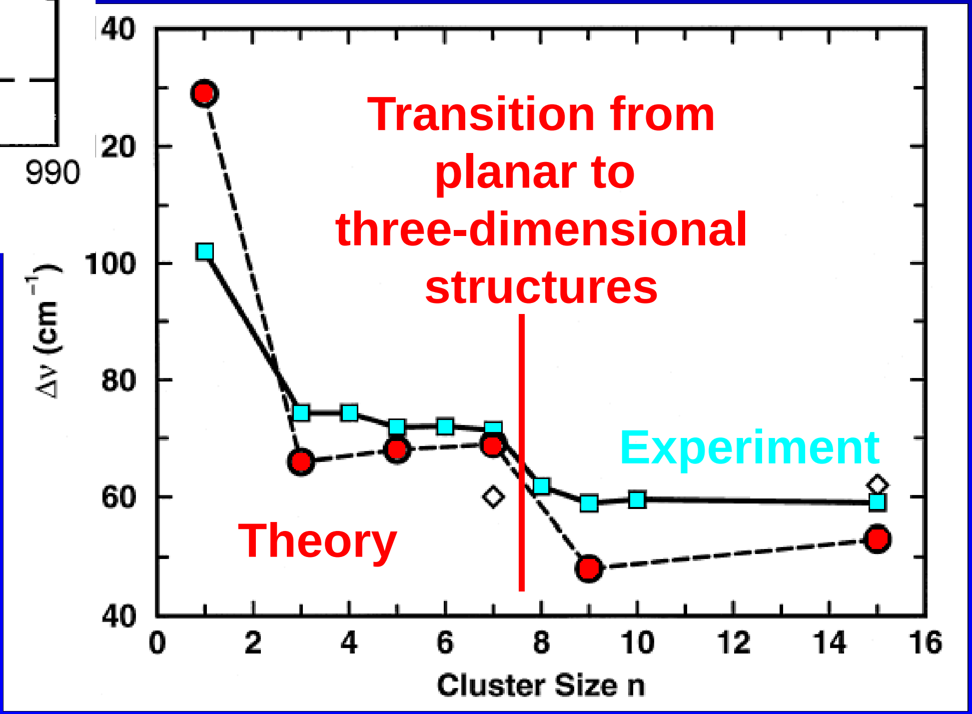
Infrared Spectroscopy

Photodetachment
of methanol



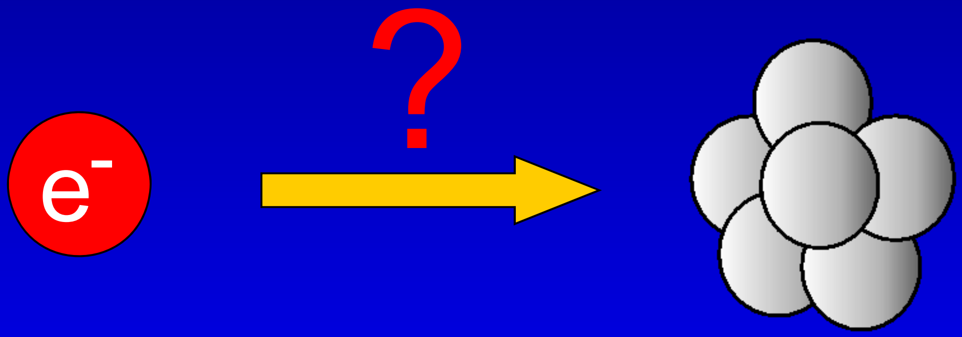
G. Dietrich et al., JCP (2000)

R. Rousseau et al., CPL (1998)



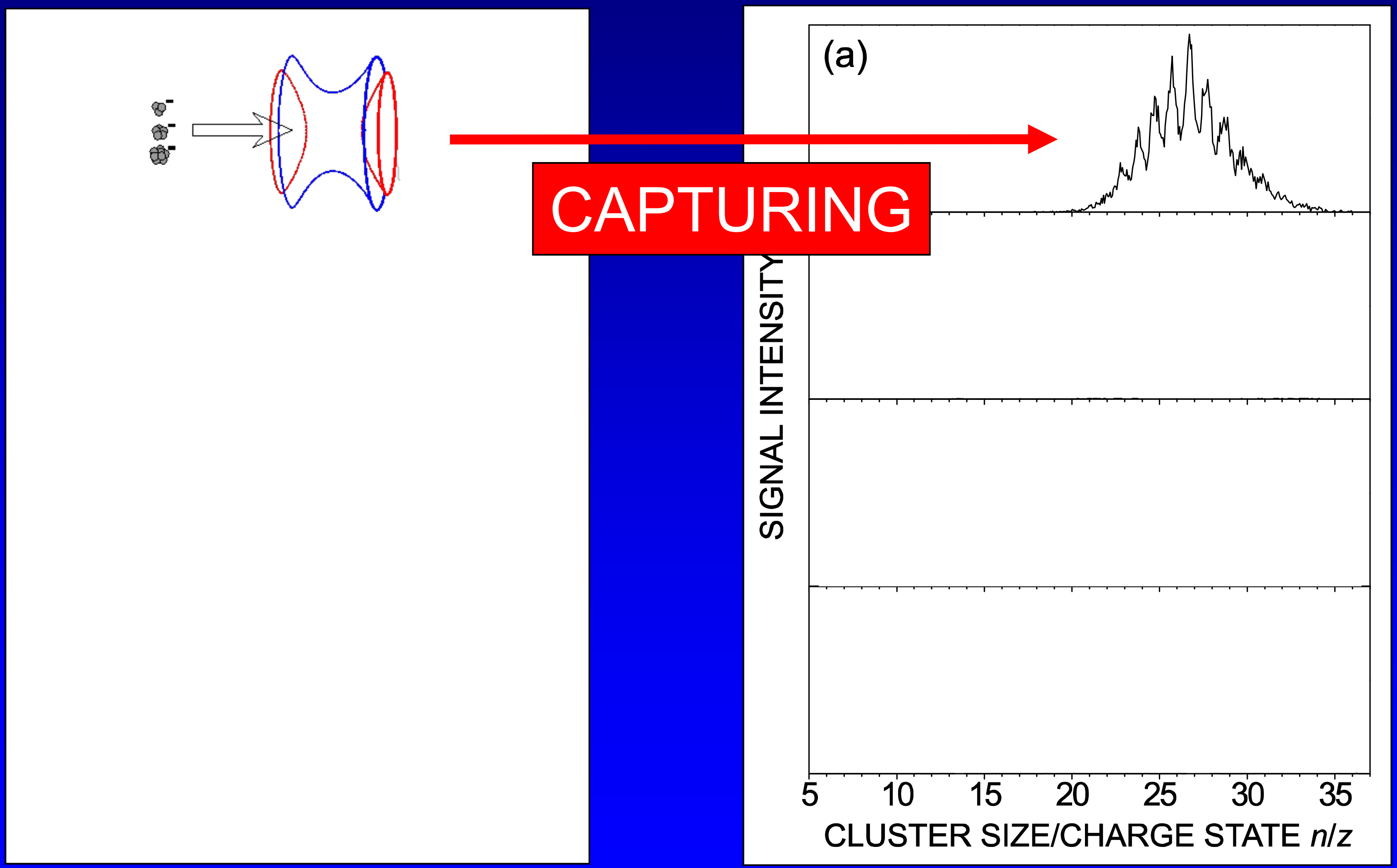
Detachment energies:
M. Vogel et al., JCP (2002)

Moving on to further charge states by electron-cluster interaction:

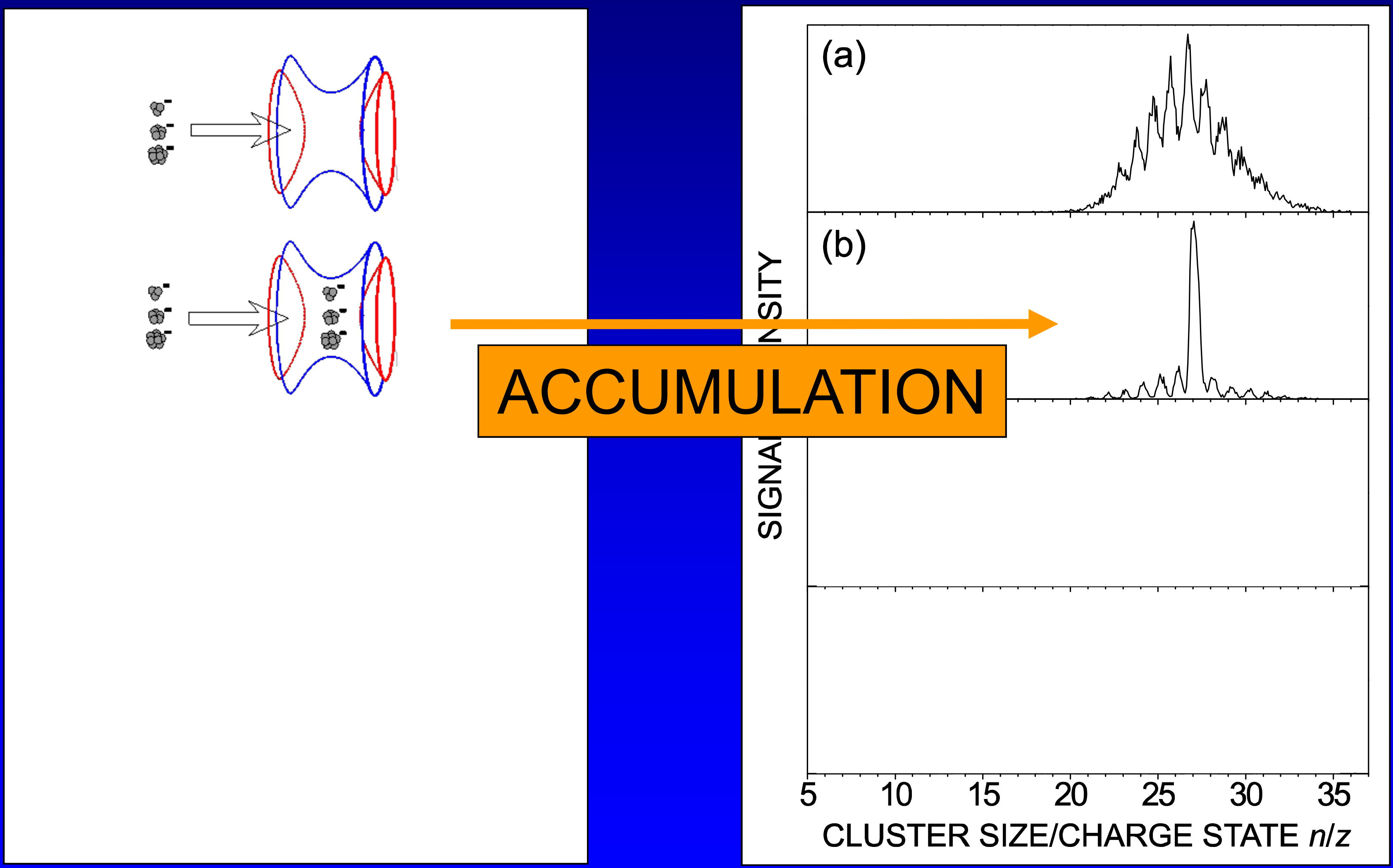


- Electron-impact ionisation for cationic clusters (see above)
- Electron attachment for anionic clusters

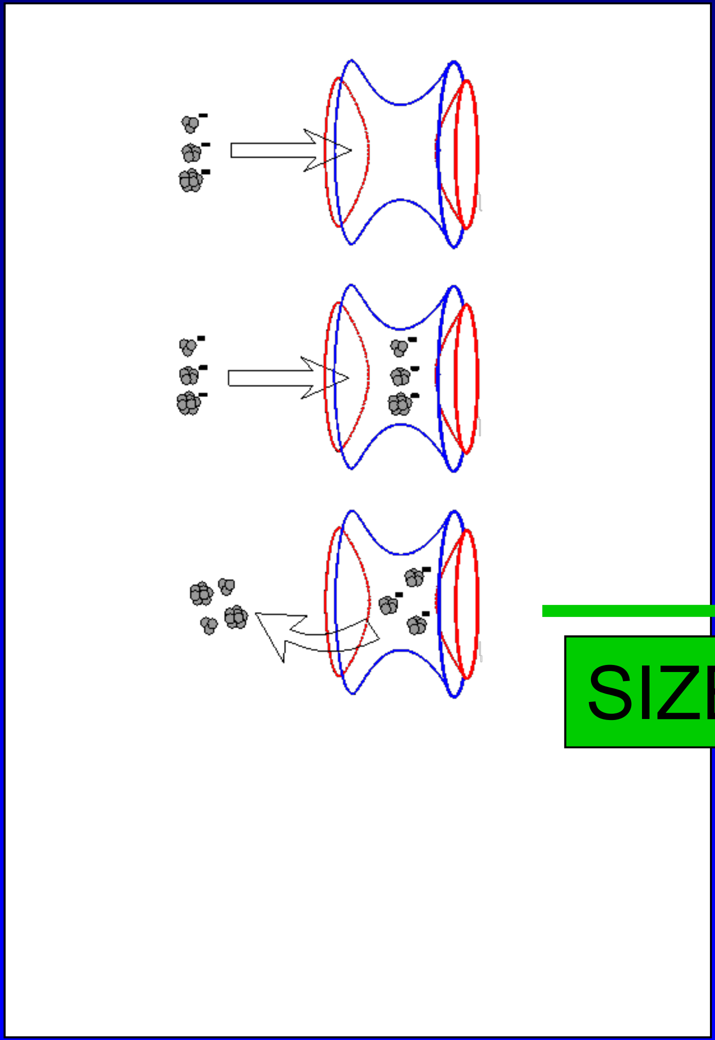
Dianion production

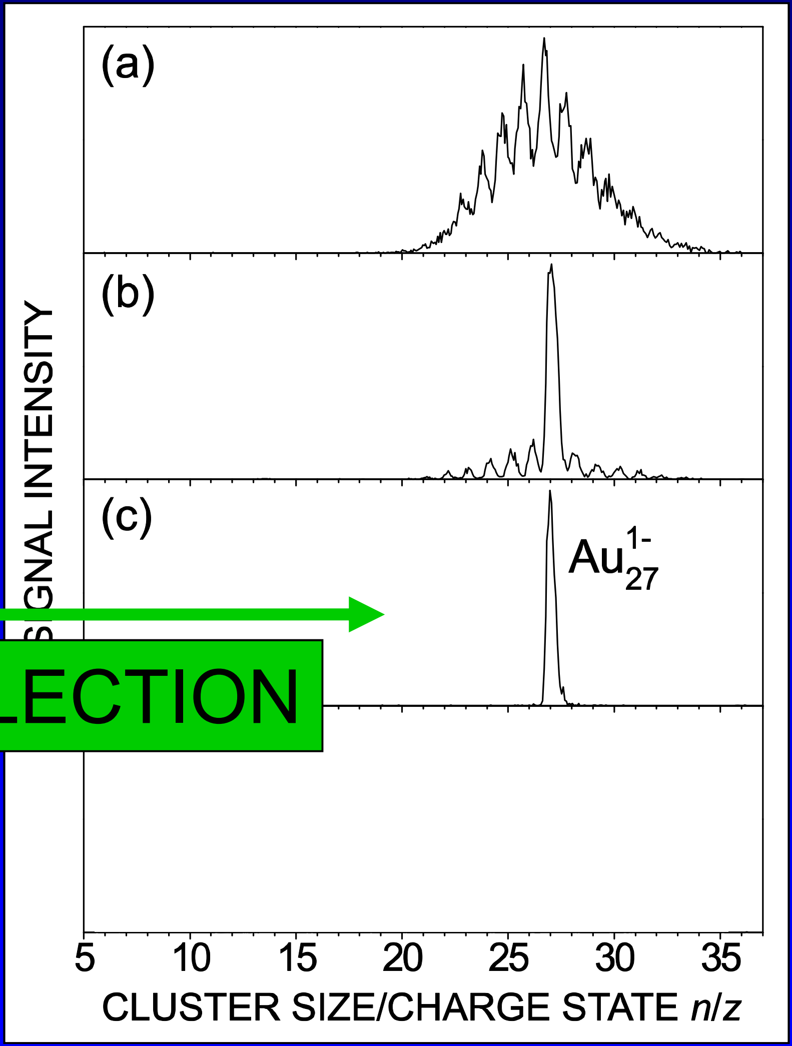


Dianion production



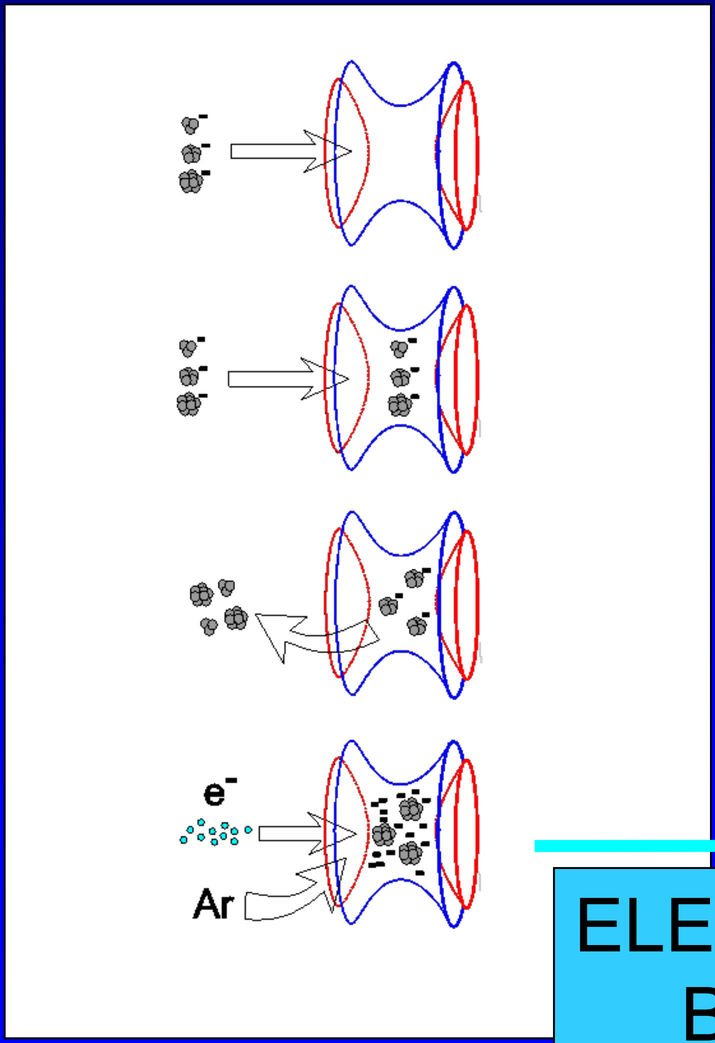
Dianion production

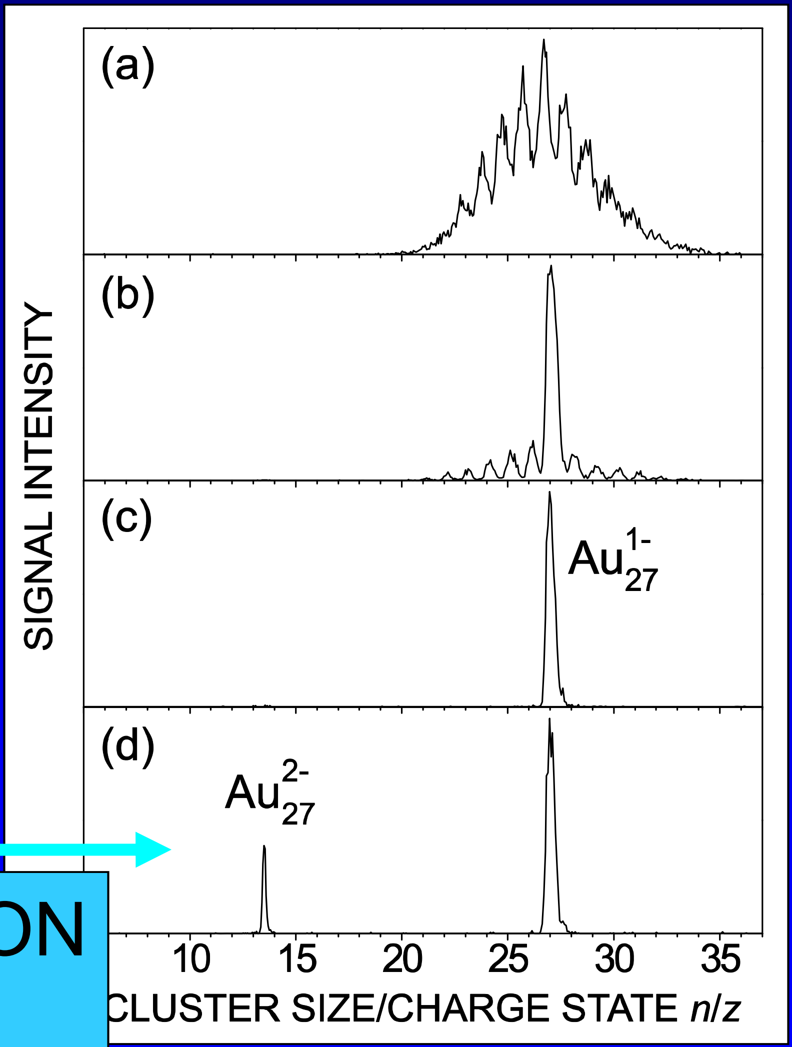




SIZE SELECTION

Simultan. storage of clusters, $m_{cluster} \approx 5000$ u and electrons, $m_e \approx 1/2000$ u

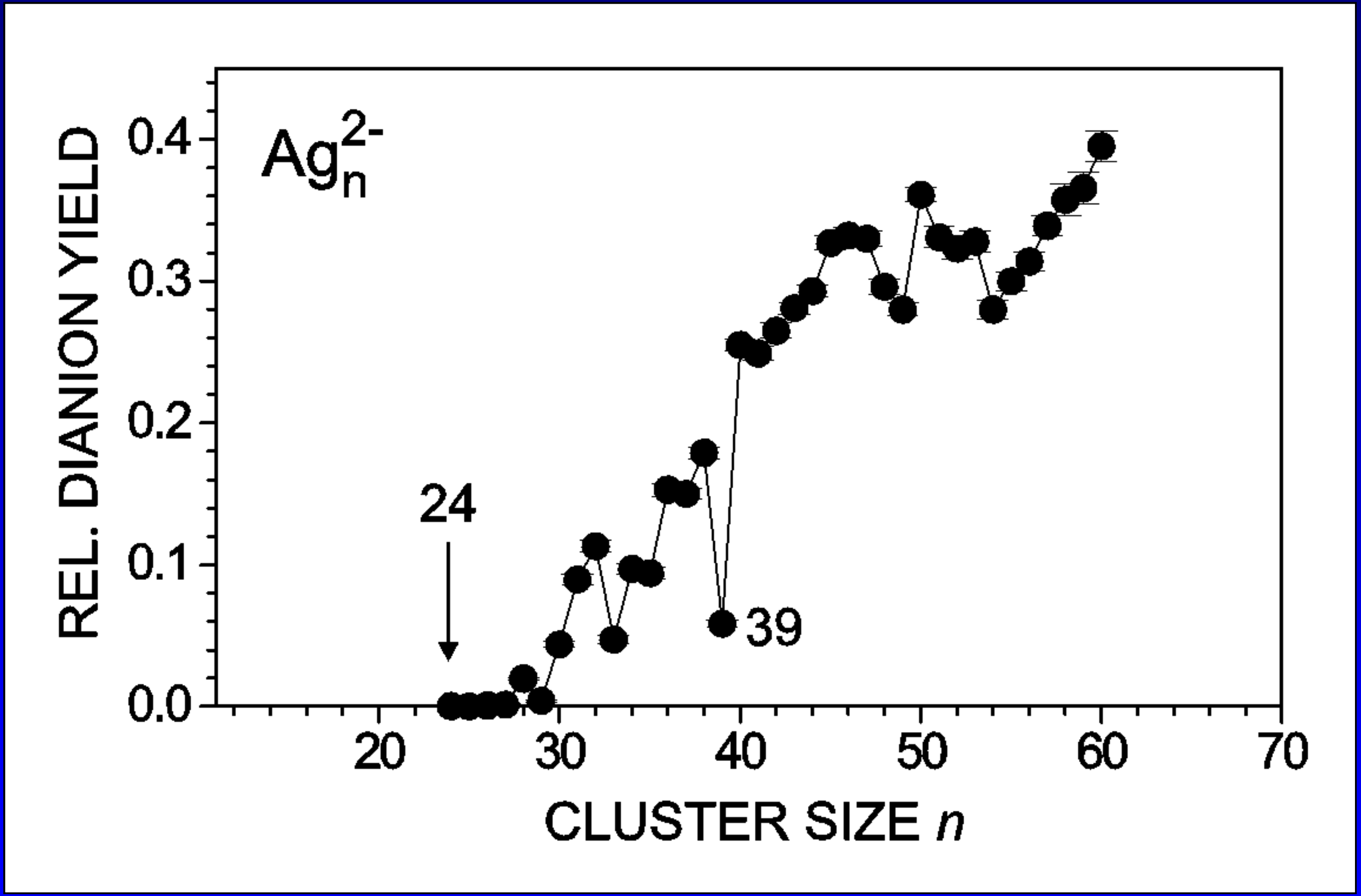




ELECTRON BATH

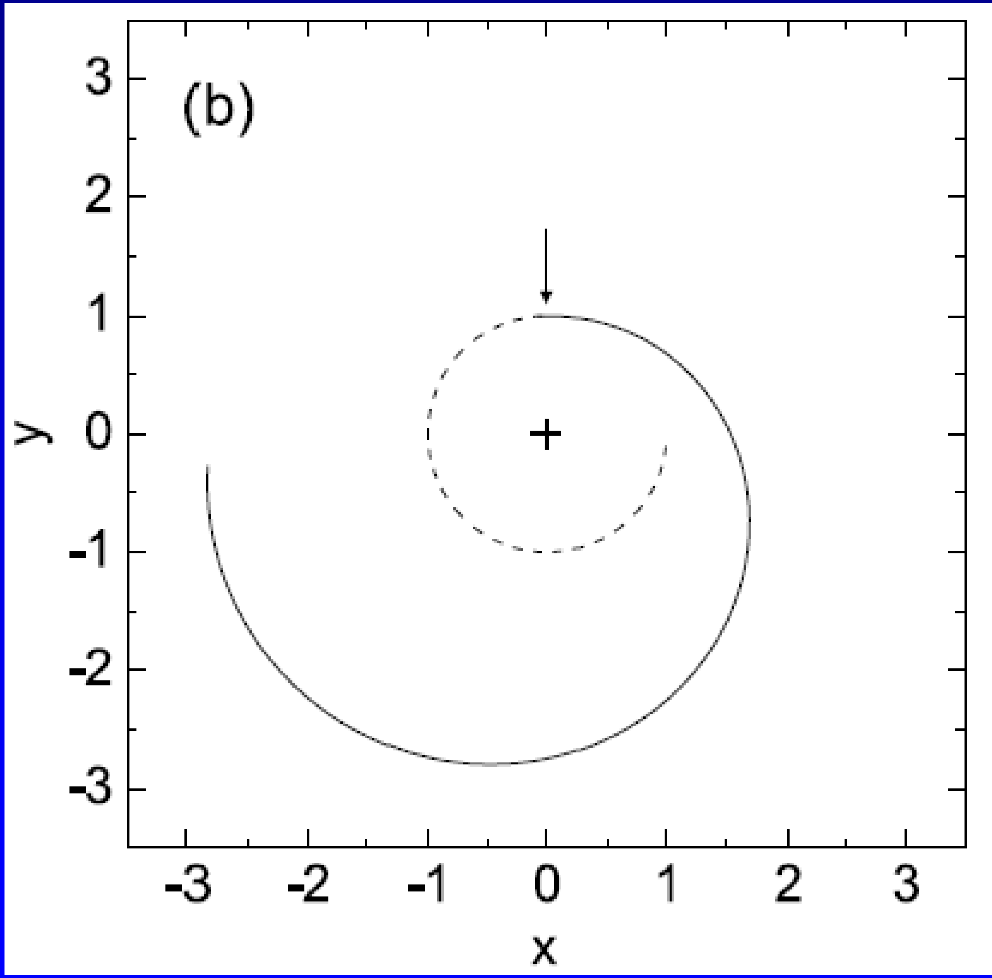
A. Herlert et al. (1999)

Silver - cluster dianions



Herlert et al., EPJ D (2001)

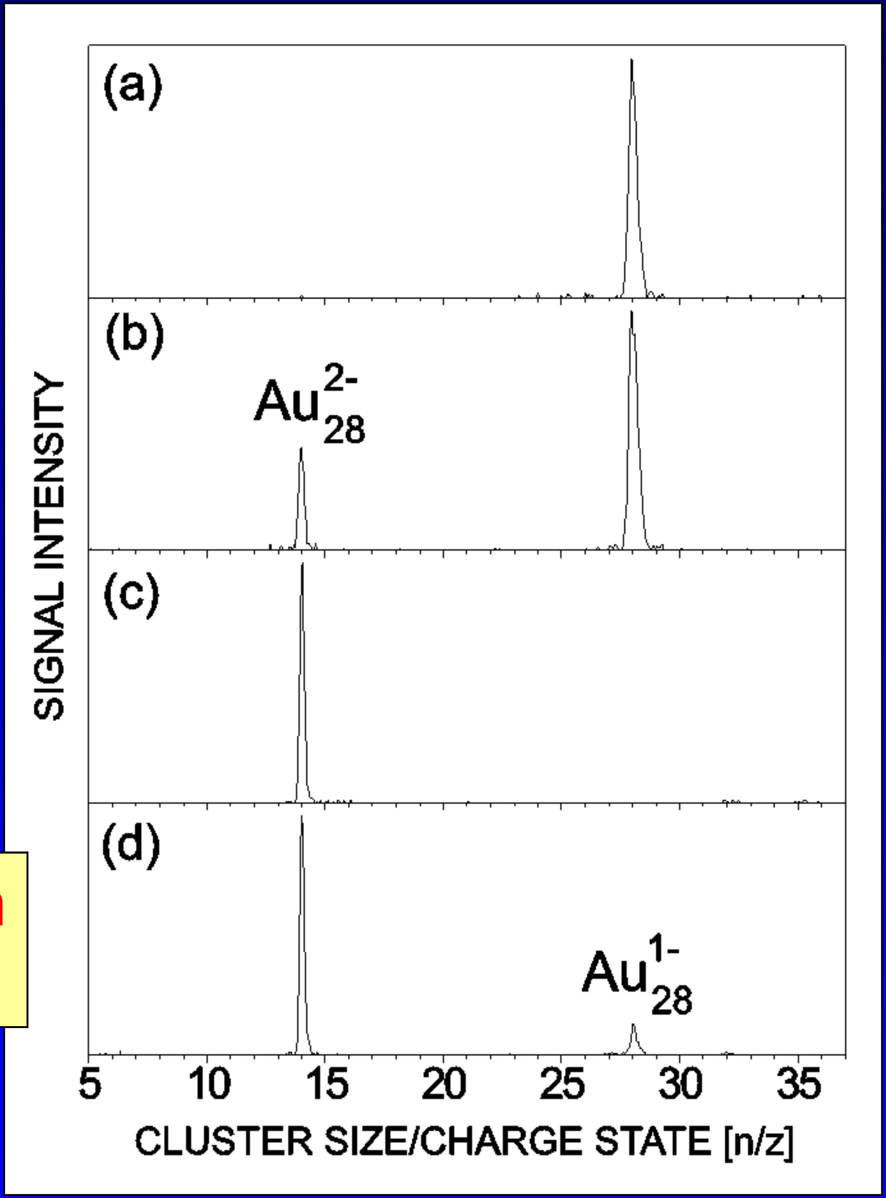
CID (collision-ind. dissociation) is not always a good idea



as charge-changing reactions
(here electron emission)
can lead to ion loss due to increased motional amplitudes

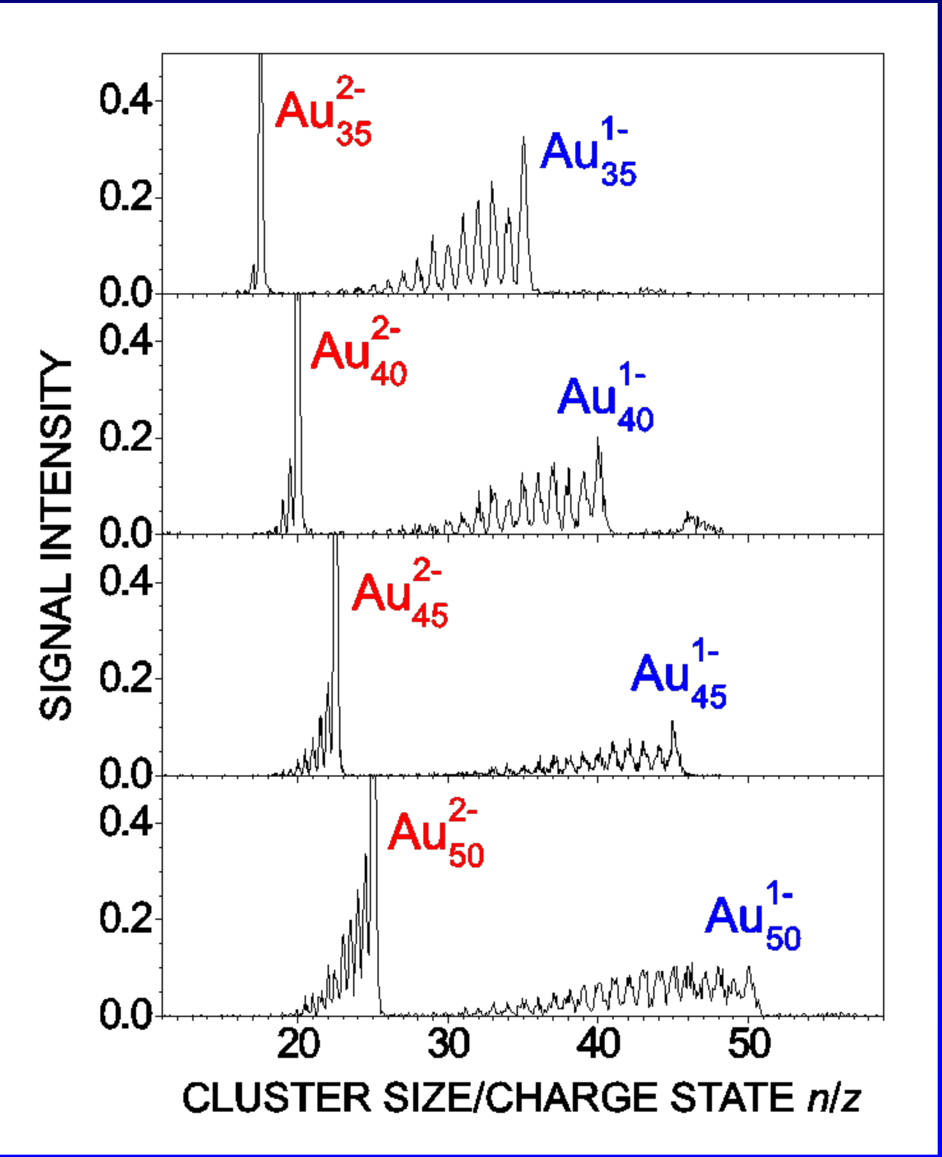
Herlert et al.
IJMS 2004

Photoexcitation of dianions

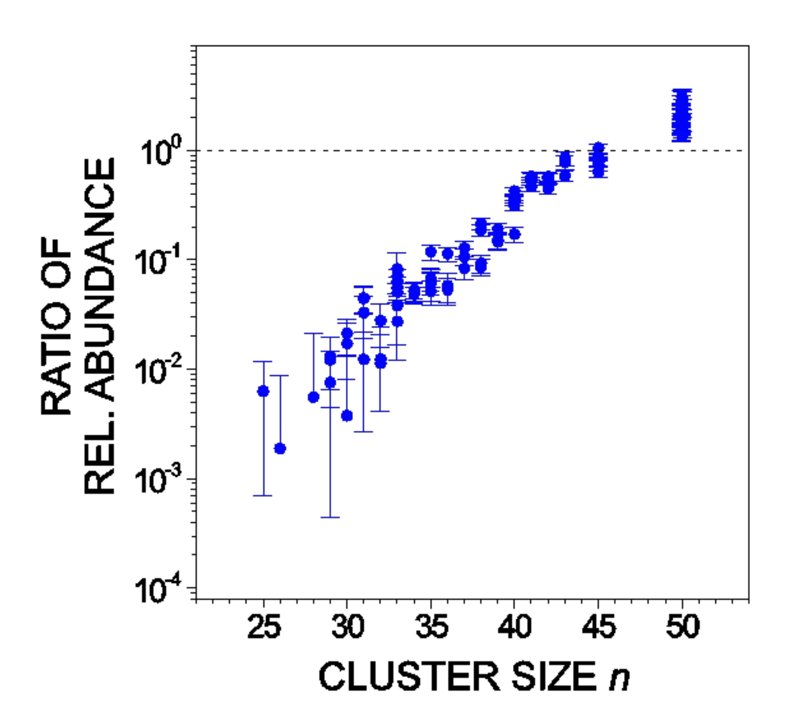


10 ns pulse, λ=355nm
E=1mJ

Photoabsorption of dianions

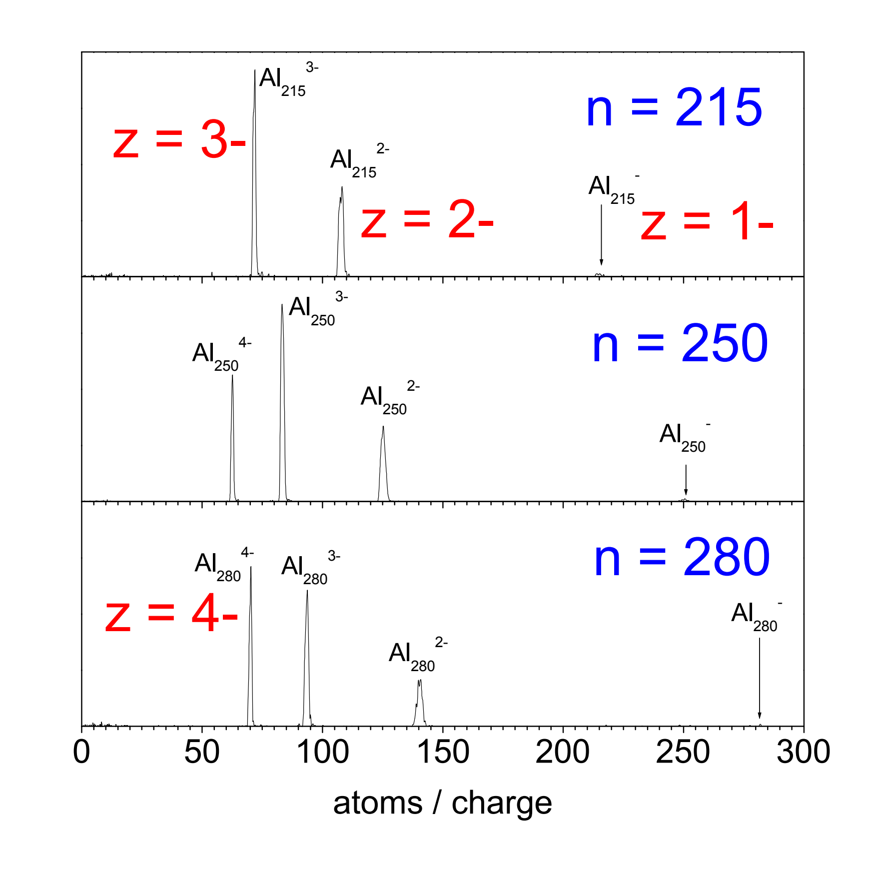


branching ratio
of decay pathways
(monomer vs.
electron emission)

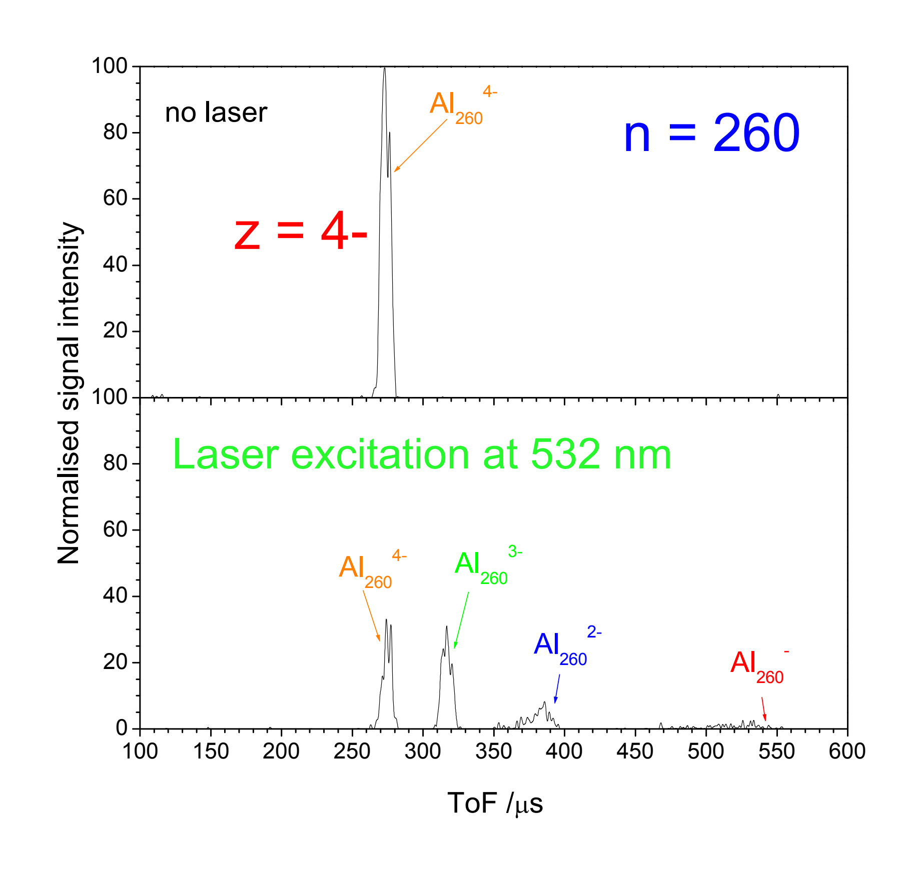


Tetra-(quad-)anionic aluminum clusters

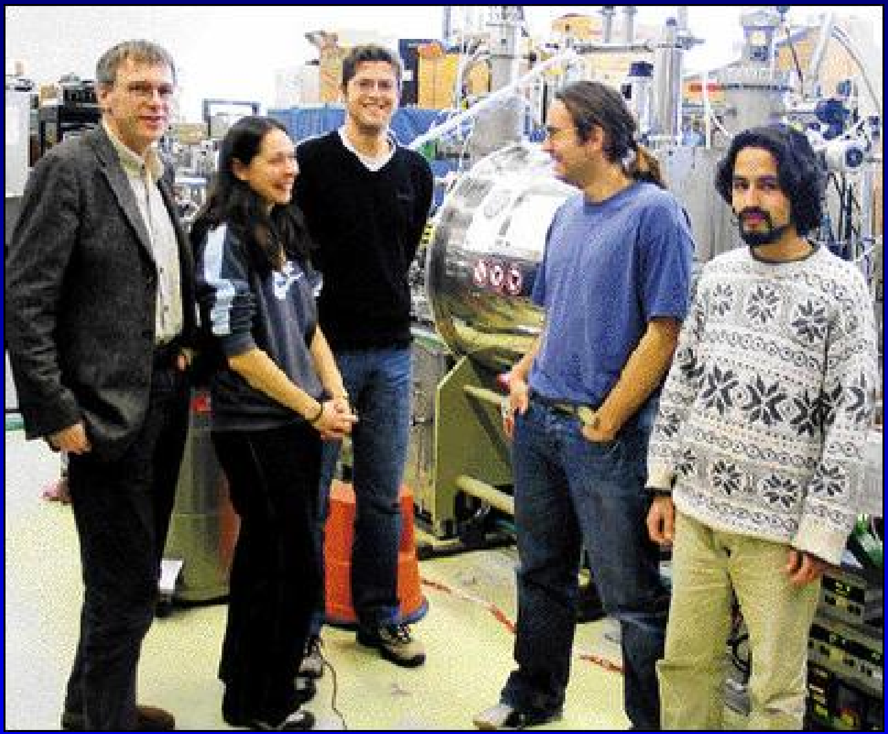
production



photoexcitation



N. Walsh et al., J. Phys. B 42 (2009) 154024



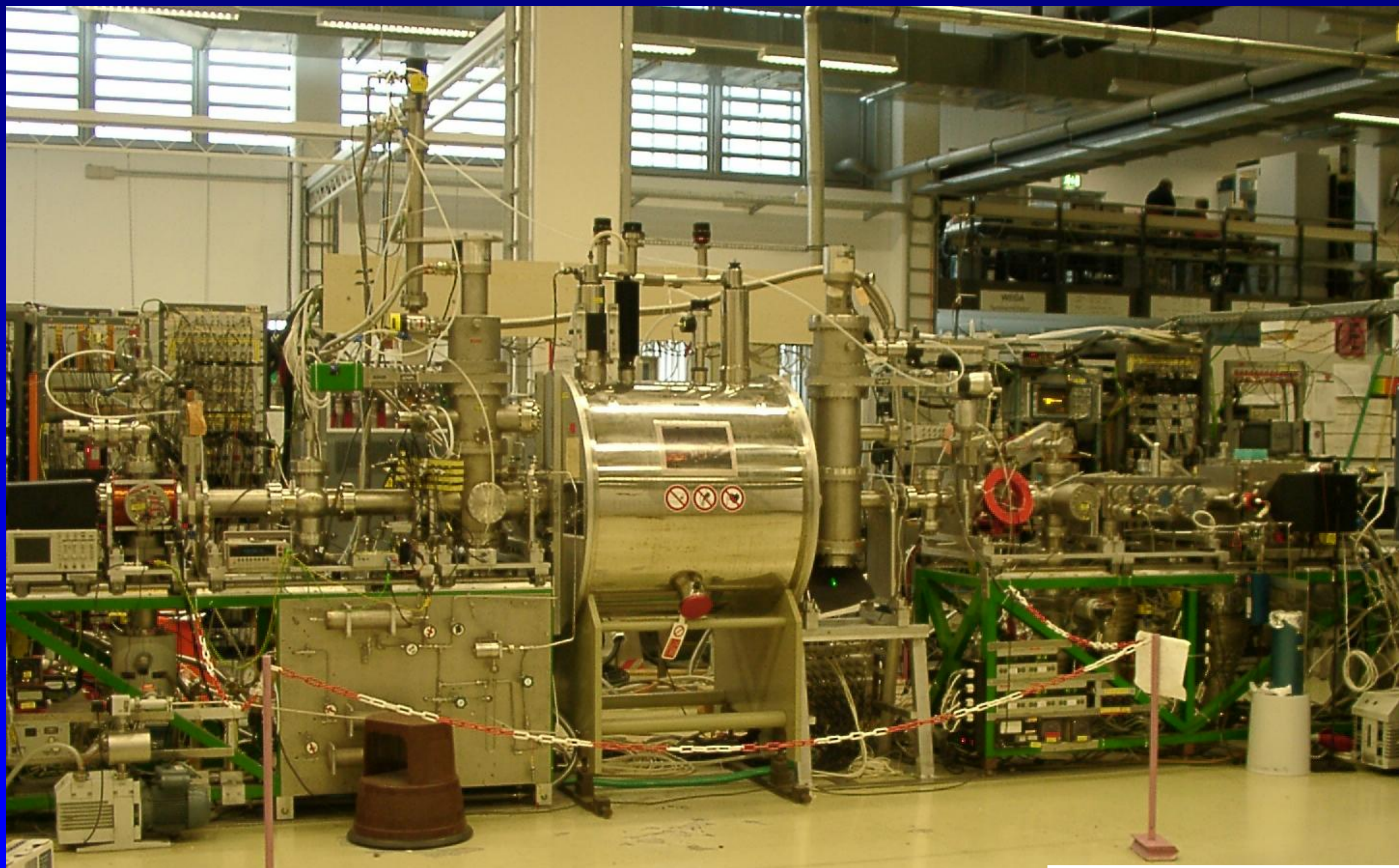
Current Ion Trappers at Greifswald
(and at CERN and GSI)

M. Arndt (Paul trap)
S. Bandelow (Paul trap)
Ch. Droese (SHIPTRAP/GSI)
F. Martinez (ClusterTrap)
Dr. G. Marx (almost all)
M. Rosenbusch (ISOLTRAP/CERN)
L. S.
A. Vass(ClusterTrap)
B. F. Wienholtz (just started)
R. Wolf (ISOLTRAP/CERN)
F. Ziegler (ClusterTrap)

Diploma/Master students:
Ch. Breitenfeldt, S. Gierke, S. Knaur

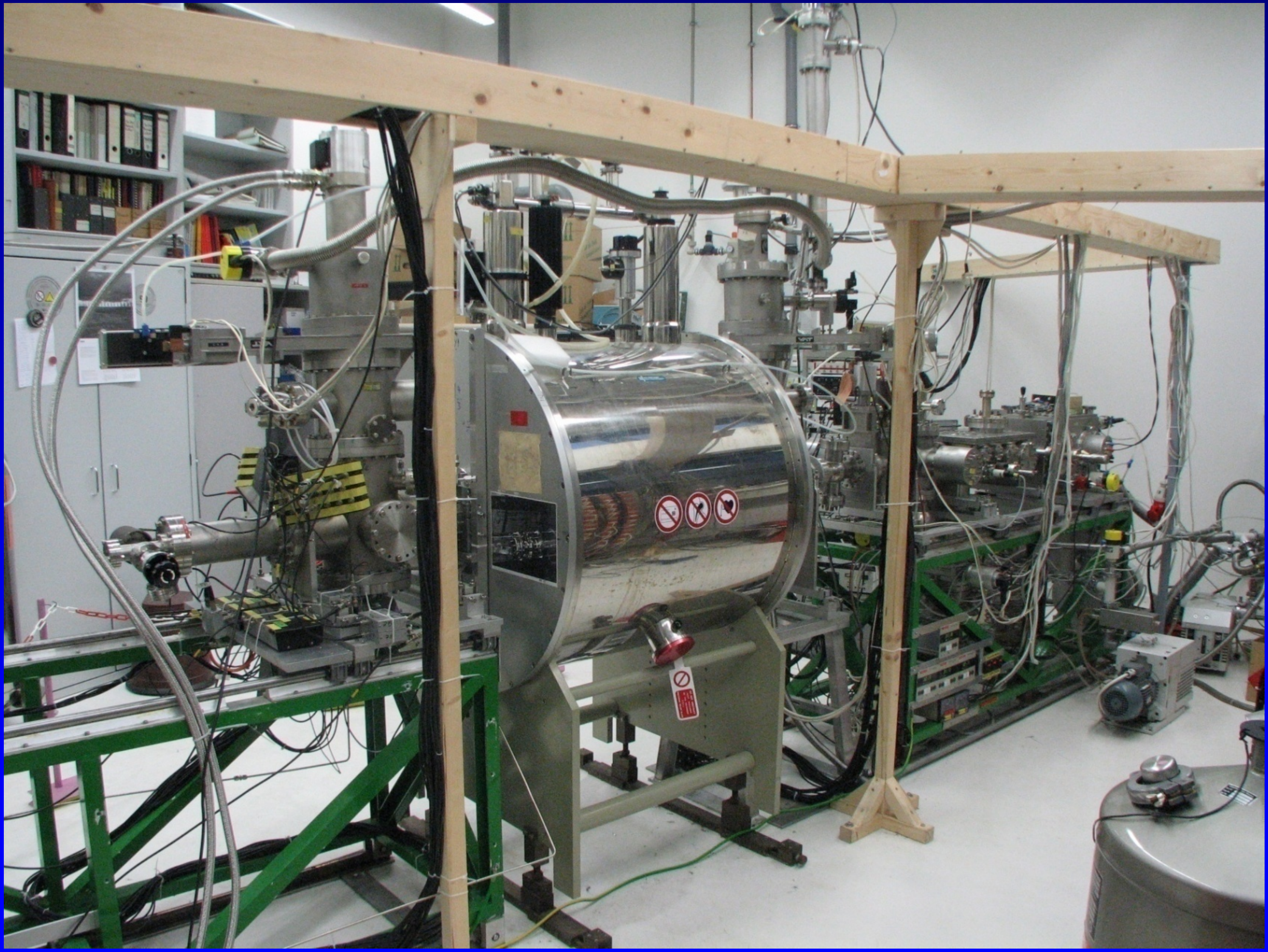
Thanks also to
DFG, BMBF, EU, …

We have moved from

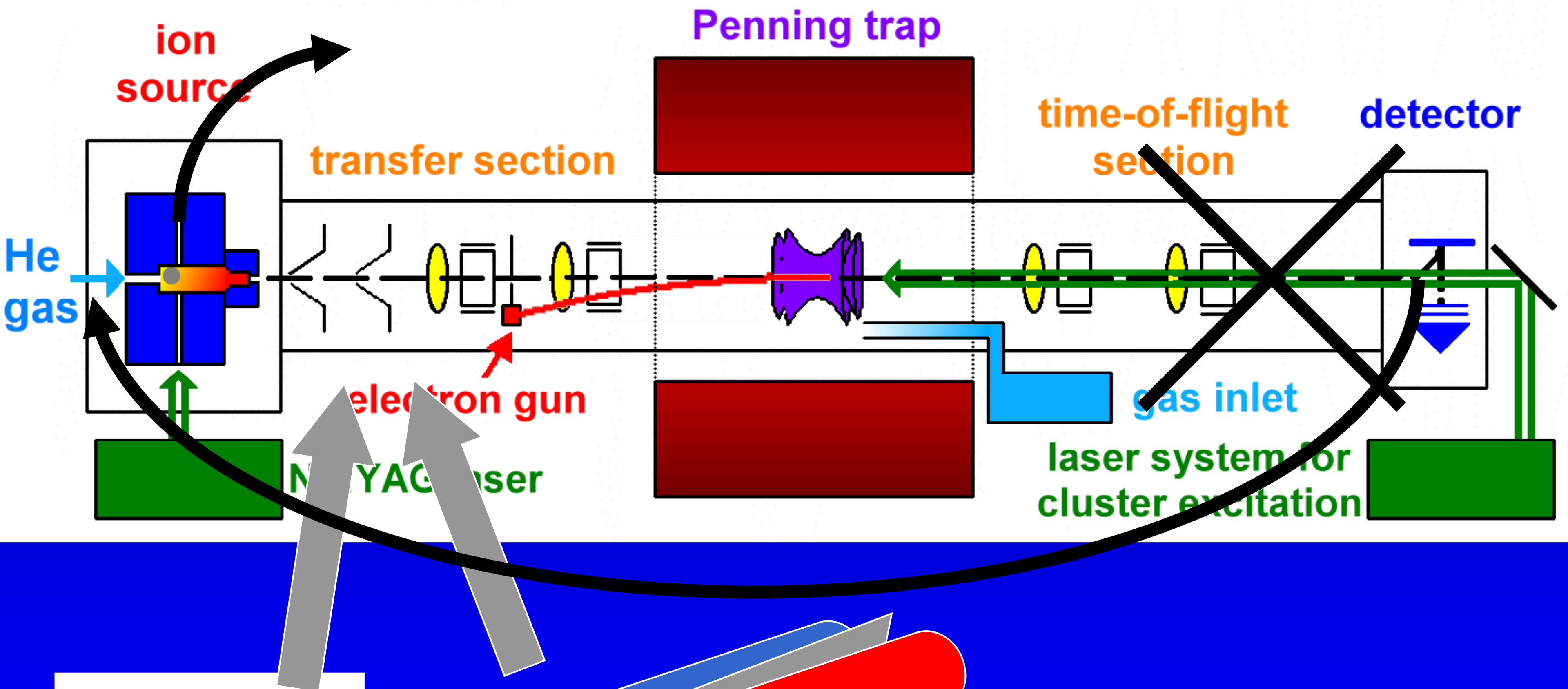


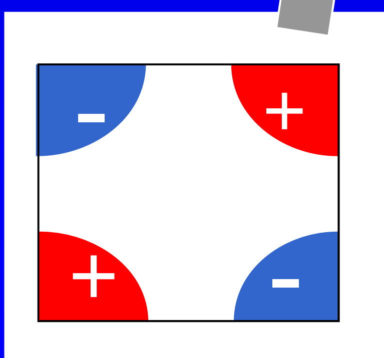
IPP Max-Planck-Institut für Plasmaphysik

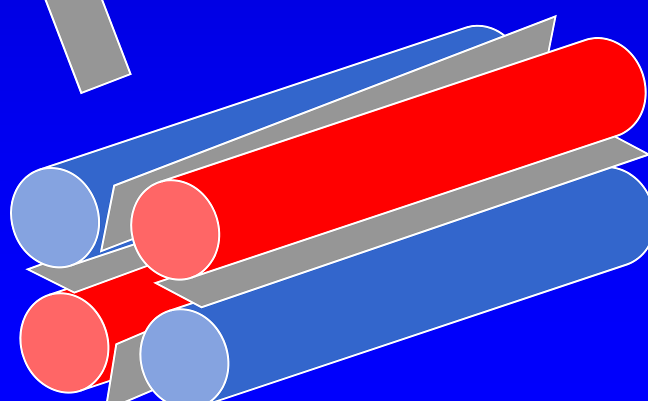
We have moved to the new building of the Inst. of Physics



Current modifications







under way i.e.
„construction site“

<u>Overview</u>

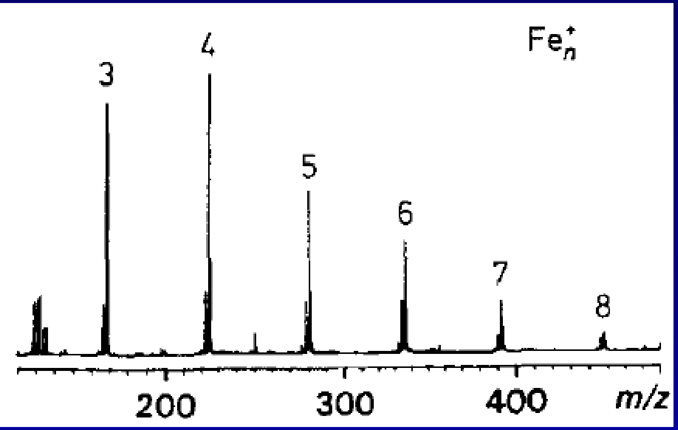
Other traps and applications

ClusterTrap

clusters? why? how? what?

Other cluster-storage devices

multi-step reactions

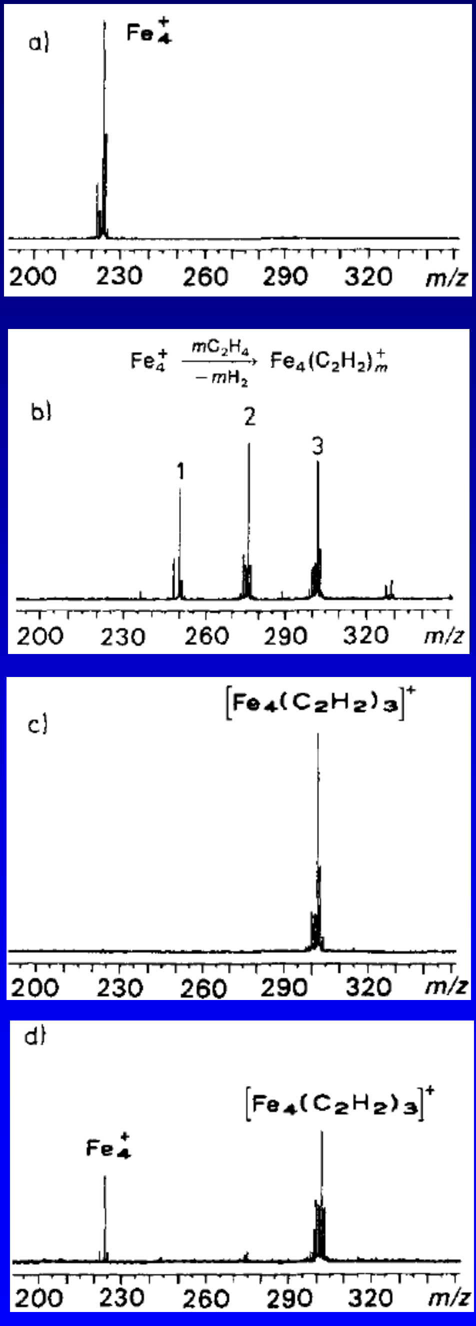


growth of benzene from ethylene on iron tetramers

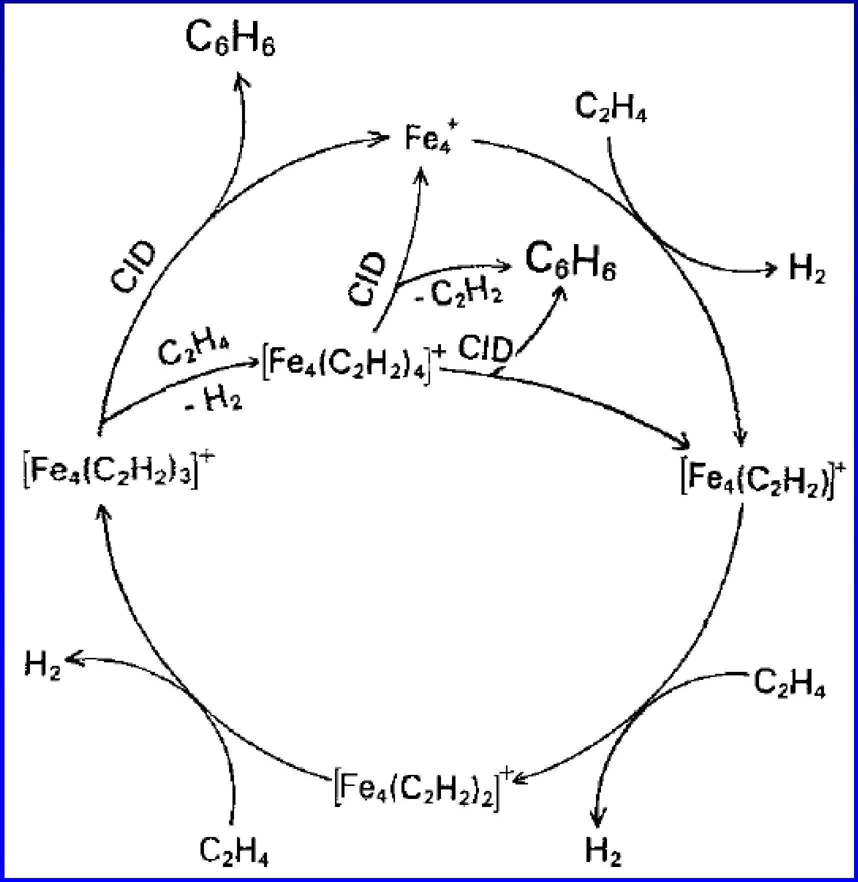
Schnabel et al. (Irion)

J. Chem., 1991

Angew. Chem., 1992



repeated selection and further reaction



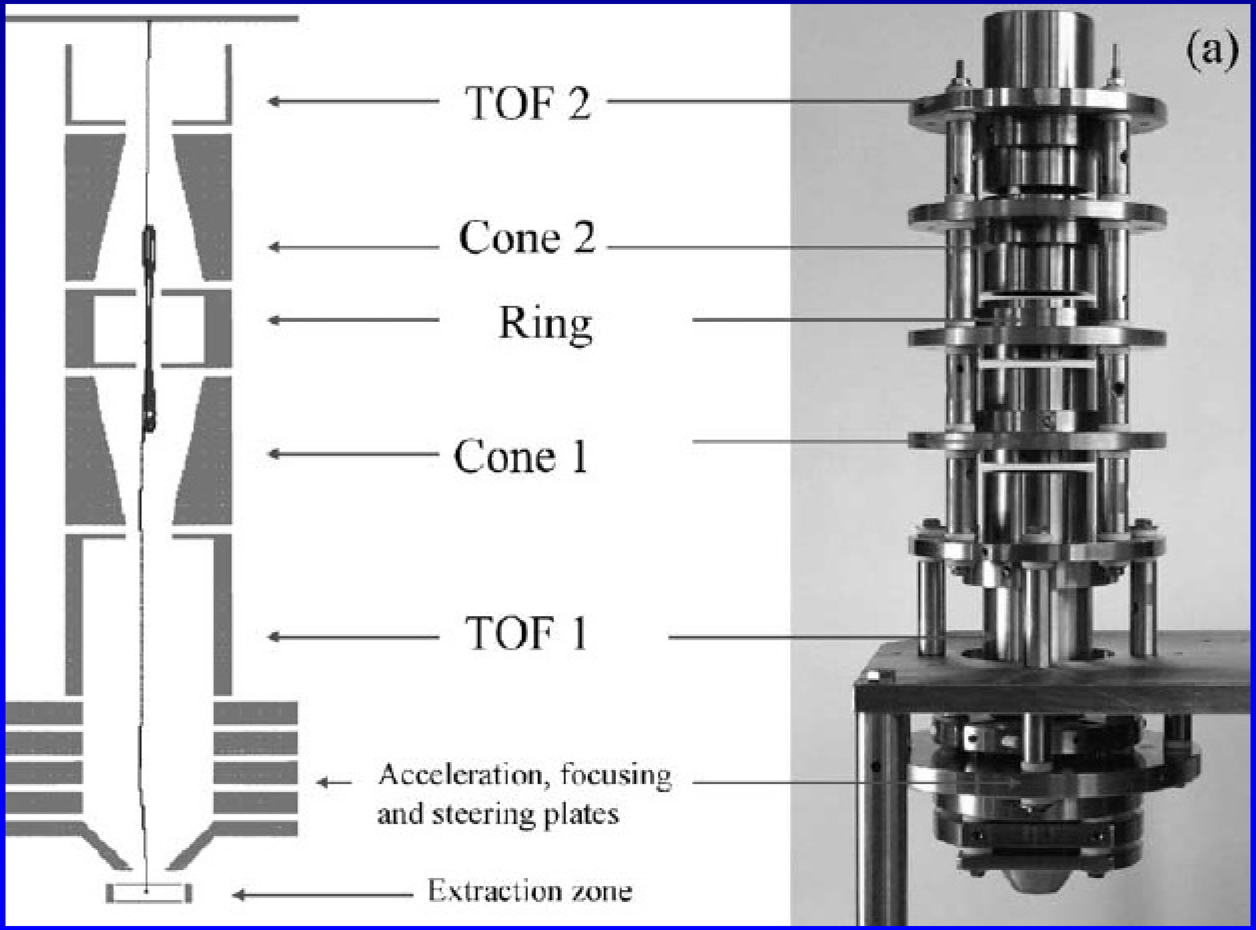
two [!] cycles such as shown

⇒ catalysis research

Use of other types of traps:

Electrostatic ion beam traps

(detection of neutral products)



„Cone Trap“

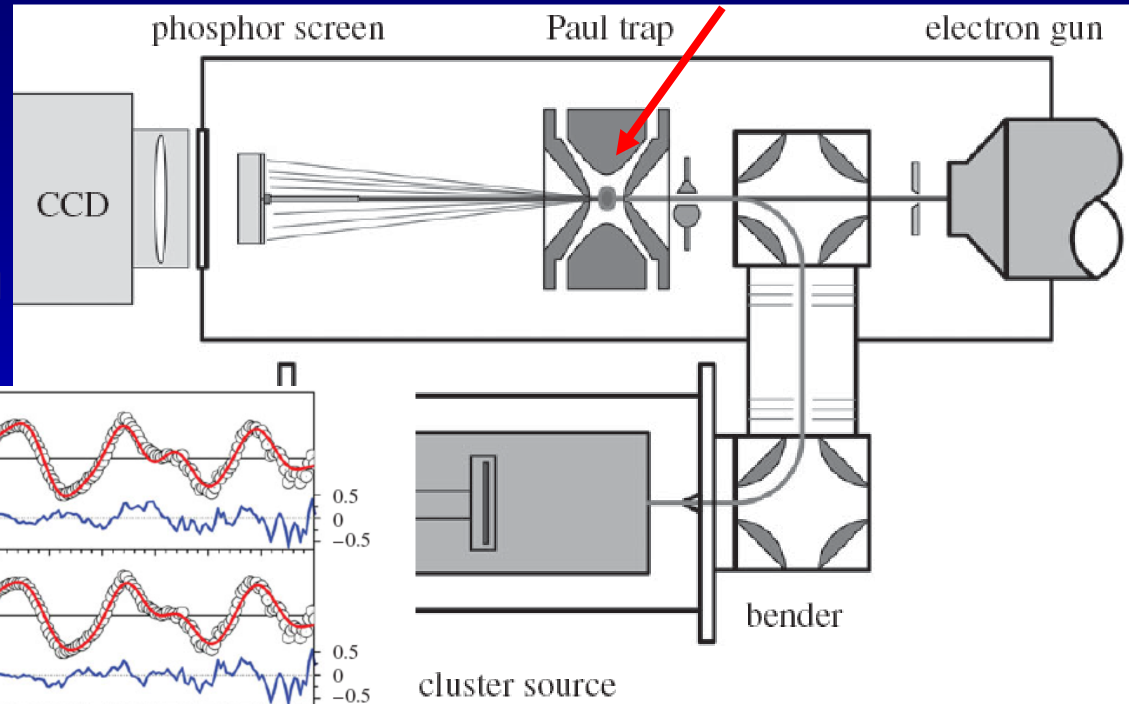
Bernard et al.
NIM B, 2003
Trapping of C_{60}^{3+}

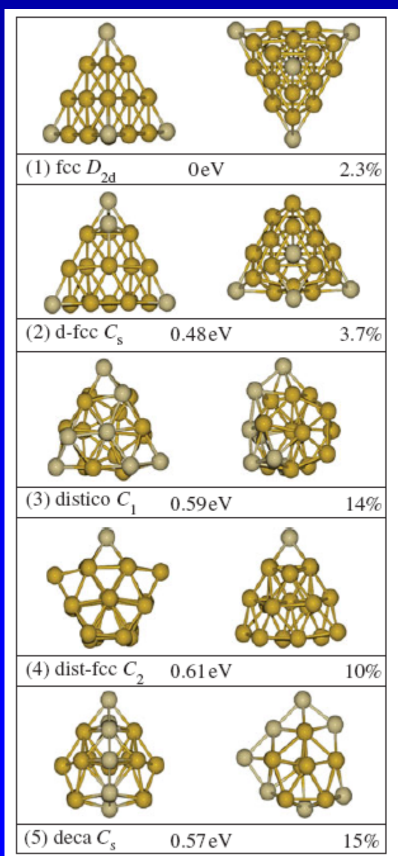
Inspired by
Zajfman & Co.

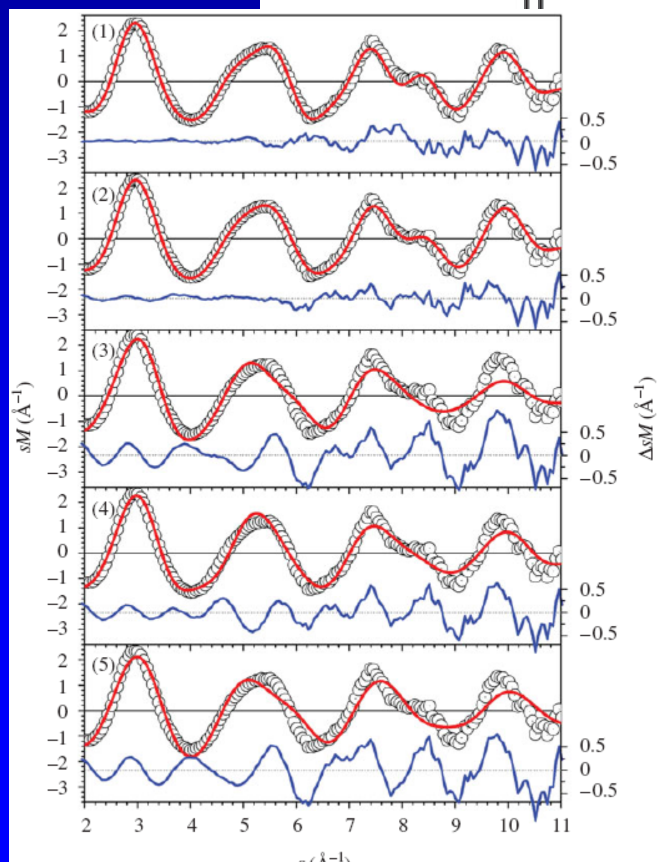
Use of more exotic probes:

Trapped ion electron diffraction

Paul trap







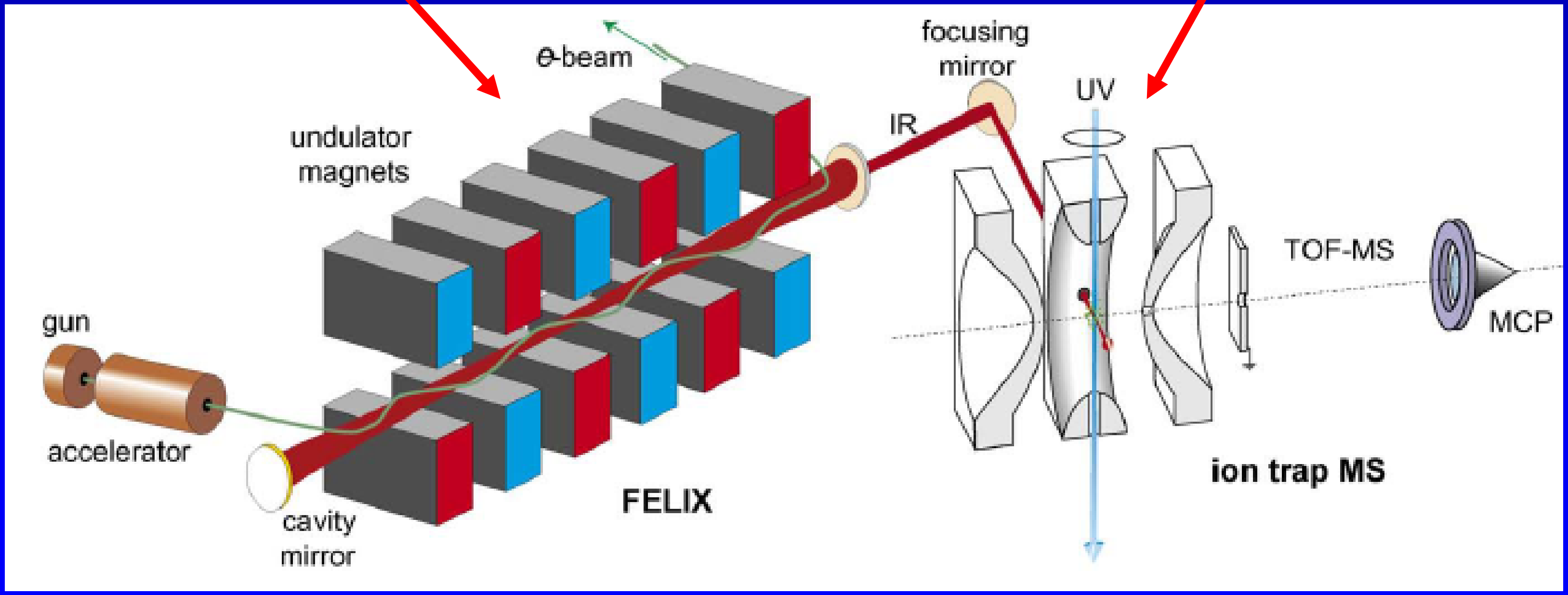
Schooß et al. (Kappes) Phil. Trans. Royal Soc. 2010

based on
J.H. Parks & Co
Maier-Borst et al., PRA 1999
Krückeberg et al., PRL 2000

IR-MPI (infrared multiple photon dissociation) spectroscopy of mass-selected clusters (etc.)

IR-FEL at FOM (Nieuwegein) coupled to 3D rf trap

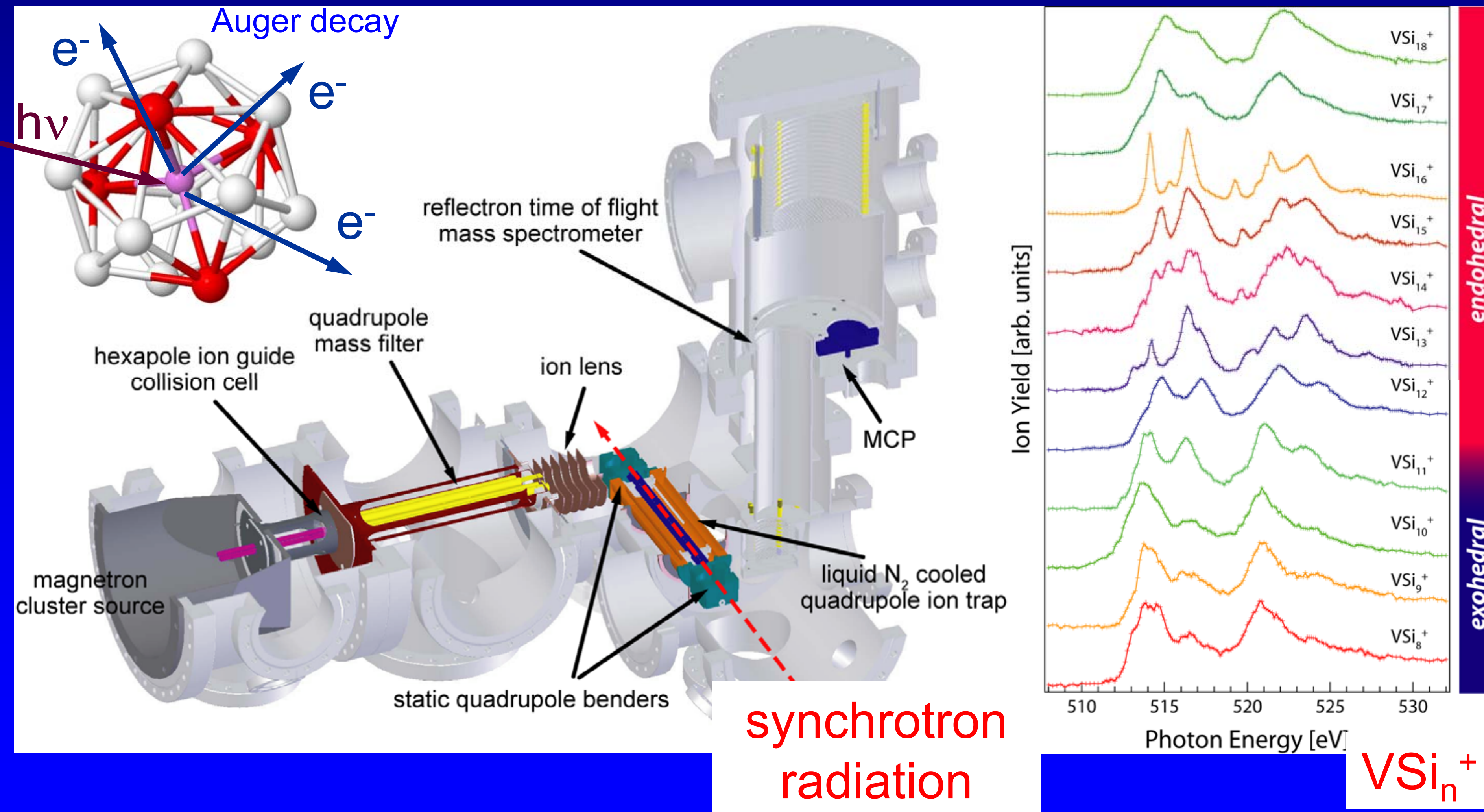
or rather the other way



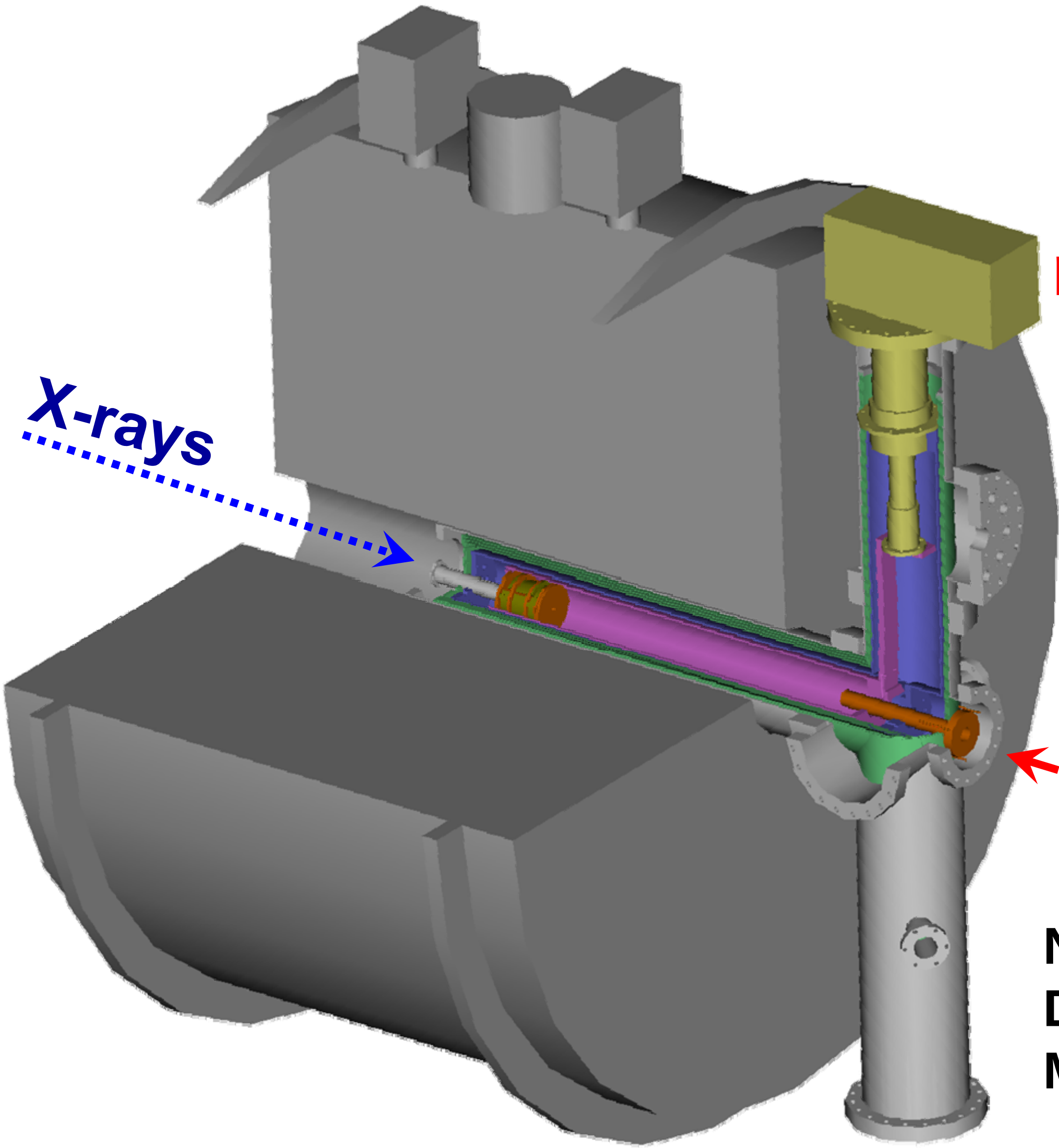
Oomens et al. (von Helden, Meijer) IJMS 2006

X-ray spectroscopy on size-selected clusters in an ion trap (at BESSY/Berlin)

Lau & Co.
PRL 101, 2008
PRB 79, 2009
JPhysB 42, 2009
PRA 79, 2009



A novel concept for the storage of cold ions (20 K)
within an FT-ICR spectrometer



XMCD
x-ray absorption
magnetic dichroism

100 K Ron Heeren
100 K Martin Beyer
100 K Evan Williams
30 K Christine Joblin
16 K FRITZ prototype
16 K GAMBIT prototype

Niedner-Schatteburg
DPG (AMOP) meeting
March 2010

Overview

Other traps and applications

ClusterTrap

clusters? why? how? what?

Other cluster-storage devices

The End

Thanks for your attention !