Structural characterization under mass spectrometry conditions using IR specific activation

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Outline

- **Introduction**
  - **Fragmentation under MS, need for specific activation methods**
  - **Infrared background**

- **Organometallic Chemistry under MS/MS**
  - **Coordination mode of multidentate ligand?**
  - **Spin State of transition metals?**
  - **Structure of reactive intermediates?**

- **Integration of IR spectroscopy to MS**
  - **Historical background**
  - **Need for highly intense and tunable IR lasers, coupling with MS/MS instruments**

- **Organic Chemistry: mechanism of peptide fragmentation**
  - **StructureS of b_n and y_n ions, protonation site?**
  - **Isomerization of a_n ions, evidence for multiple isomers**

- **Isomer separation with Ion Mobility and Spectroscopy with IR lasers**
  - **IMS-MS/MS + Photodissociation**
  - **Separation of saccharide isomers and spectroscopy**

# 70 eV Electron Impact (Fragmentation) Mass Spectra : structural characterization
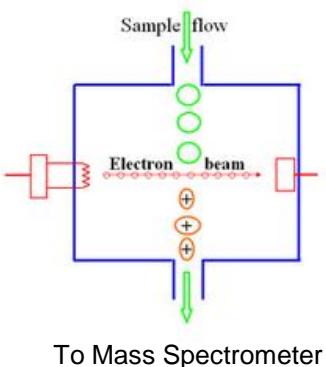
Electron ionization (EI) : one of the 1st ionization techniques developed for MS. EI uses high energetic (70 eV) e- to produce ions => extensive fragmentation. Structure determination useful for organic compounds (MW<600 Da).

M (sample molecule) + e- @70 eV → M+/• (radical cation) + 2 e-

+ Multiple (specific) fragment ions
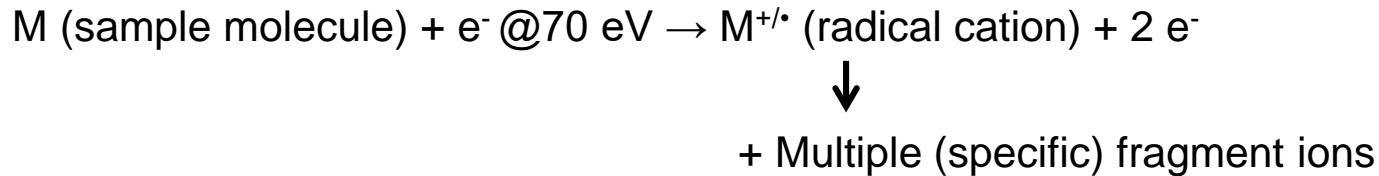
Very specific radical driven chemistry

[2-pentanone]+/•

[3-pentanone]+/•
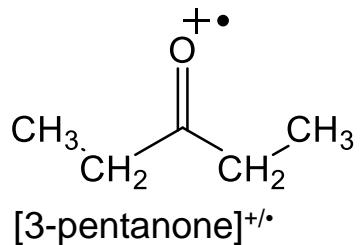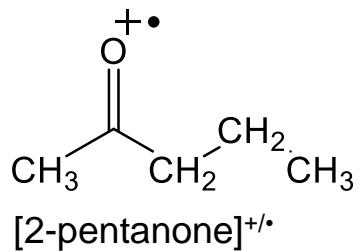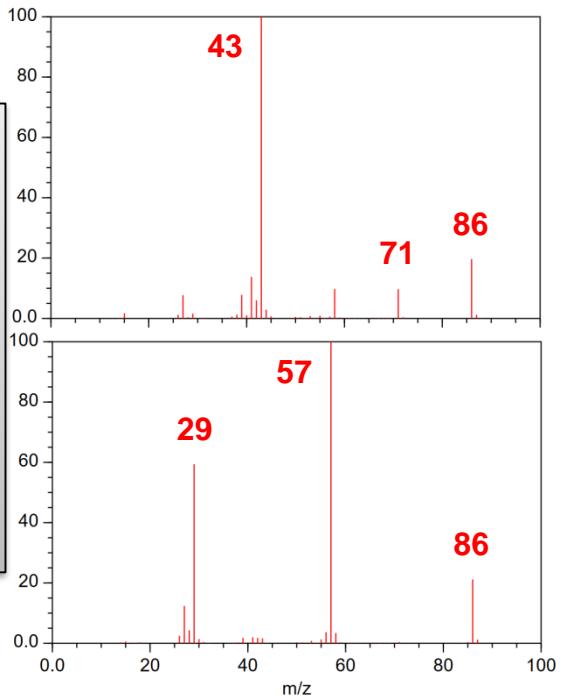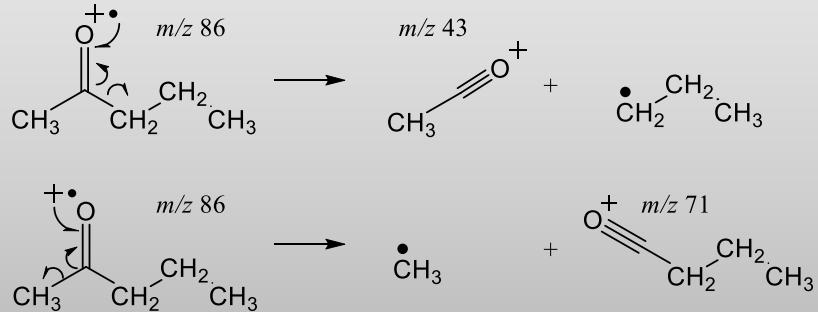
CID ESI-MS² spectra :
In some cases, isomers can be distinguished
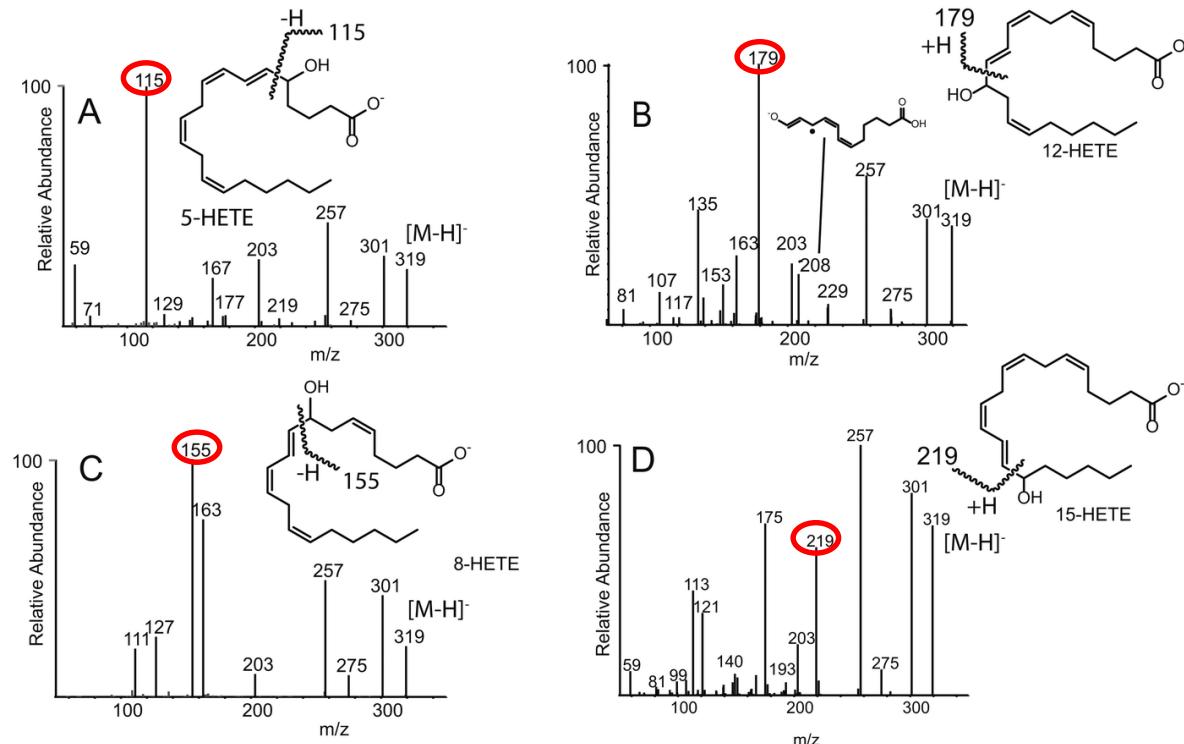
Electrospray ionization (negative ions) and tandem mass spectrometry of monohydroxy arachidonate metabolite isomers. CID mass spectra of [M − H]⁻ at *m/z* 319 using a tandem quadrupole mass spectrometer.

IR Spectroscopy integrated to Mass Spectrometry

- Need for structural information in MS/MS
  - Fragmentation mass Spectra, especially EI
  - Infrared Spectroscopy could be useful

- IR spectroscopy integrated to MS
  - It relies on SPECIFIC fragmentation of an **ion isomer** based on SPECIFIC activation
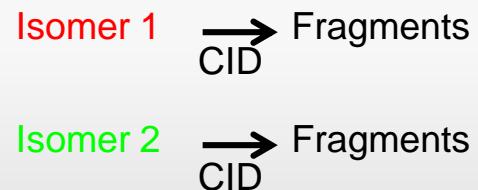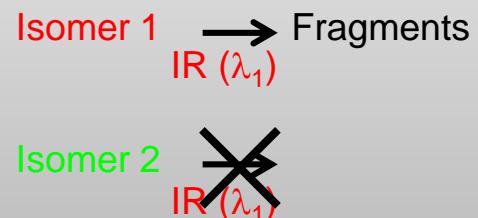
IR spectrum of formaldehyde (H$_2$CO)

Units used:

$E = h\,\nu$

$\quad = h * C * 1/\lambda$

$\quad = h * C * \overline{\nu}$
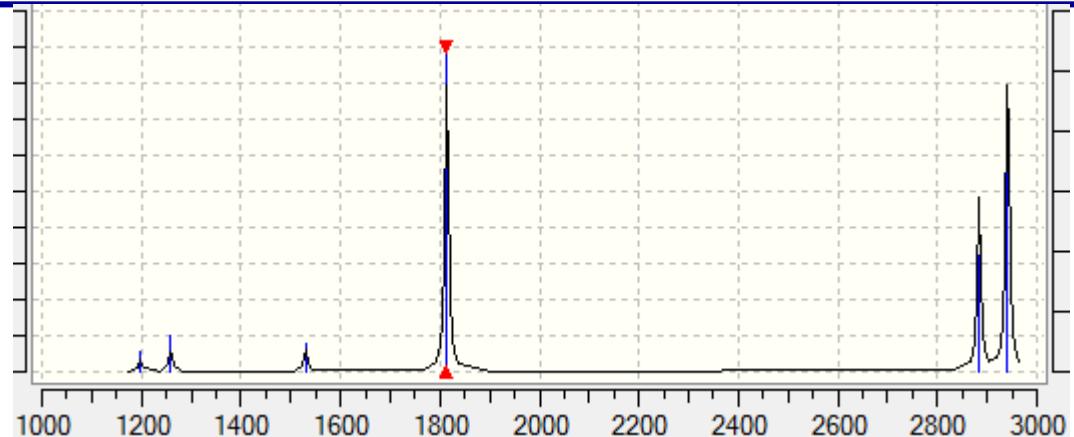
where λ is the wavelength (μm)
and $\overline{\nu}$ is the wavenumber per cm
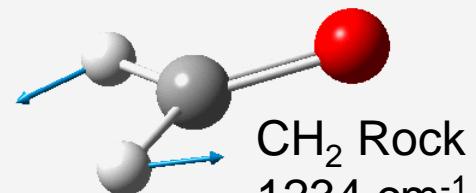
CH$_2$ Rock
1234 cm^{-1}
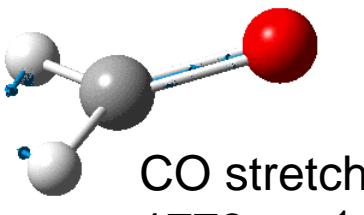
CO stretch
1778 cm^{-1}
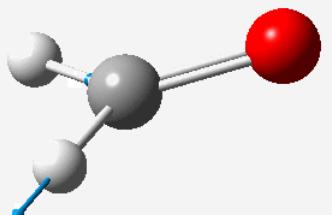
CH asym. stretch
2809 cm^{-1}
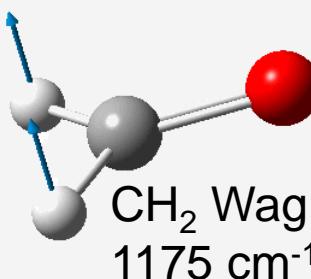
CH$_2$ Wag.
1175 cm^{-1}
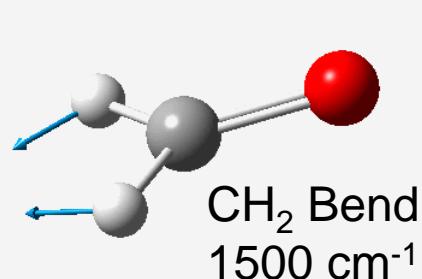
CH$_2$ Bend
1500 cm^{-1}
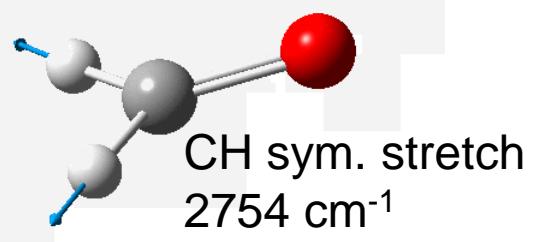
CH sym. stretch
2754 cm^{-1}

C=O carbonyl stretch (in cm^{-1}):
sensitive to electronic cyclic strain effects
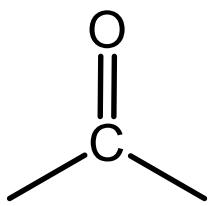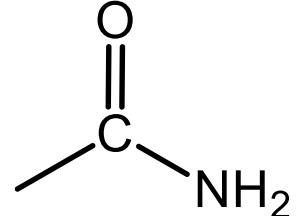
~1660   ~1650-1695   ~1735-1750   ~1810   ~1785-1815   ~1870
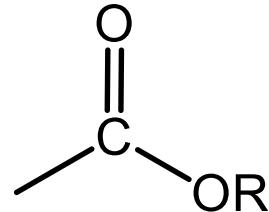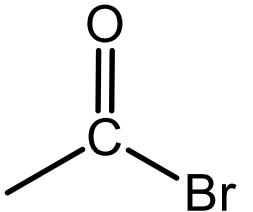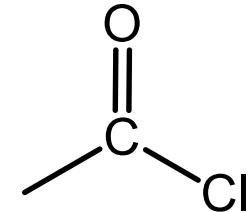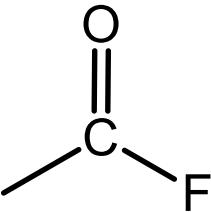
Attrative inductive effect$\nearrow$: $v_{C=O}$ $\nearrow$

Mesomeric effects (resonance) $\nearrow$: $v_{C=O}$ $\searrow$

Lactones: Conjugation and strain effects
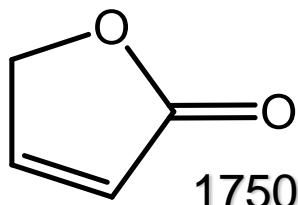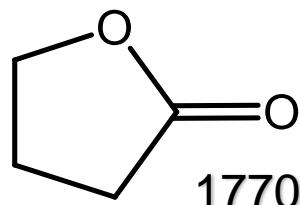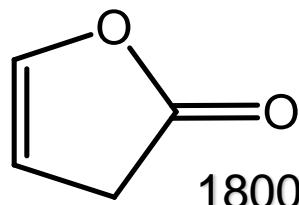
1750   1770   1800

Hydrogen bond effect on C=O and O-H stretches

Free (gas phase)

1788

3583

~1730
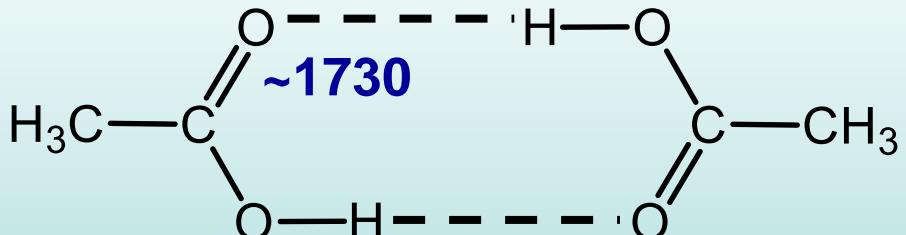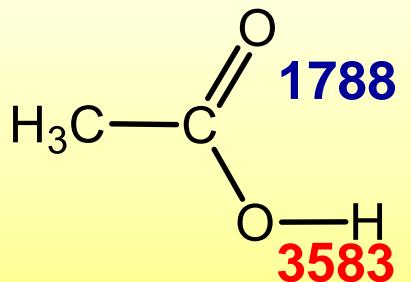
Free OH
3583 cm^{-1}

Free CO
3583 cm^{-1}

Acetic acid
INFRARED SPECTRUM (NIST)
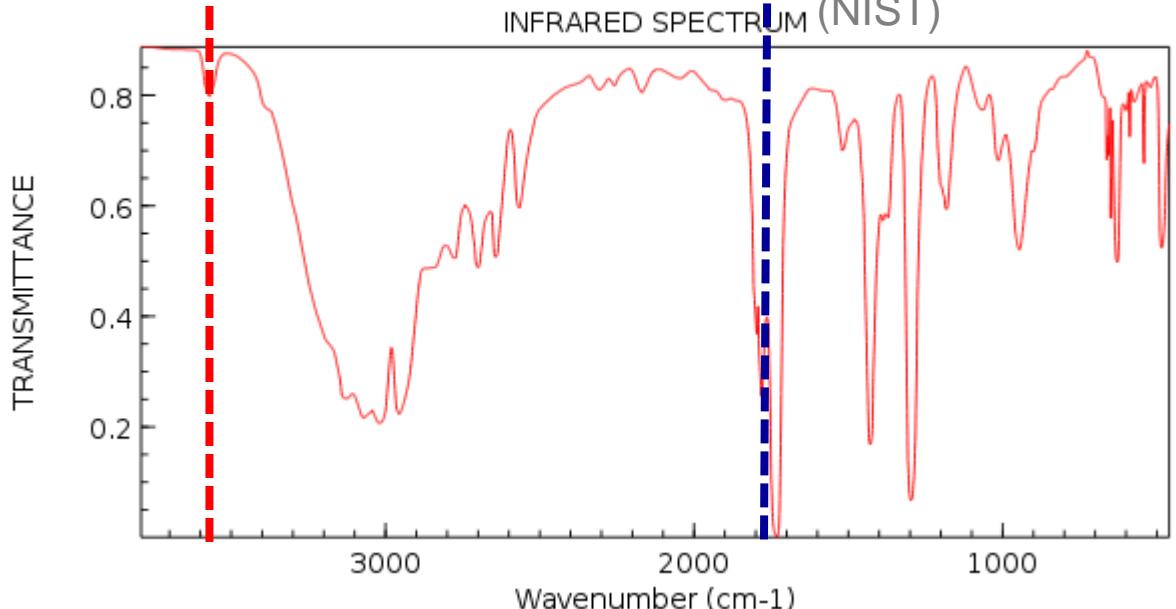
Upon formation of hydrogen bonds, red-shifts (i.e. bond weakening) are observed.

TRANSMITTANCE

Wavenumber (cm-1)

NIST Chemistry WebBook (http:..webbook.nist.gov/chemistry)

IRMPD spectroscopy: in practice

MS^2-chromatogram where each data point corresponds to one wavenumber
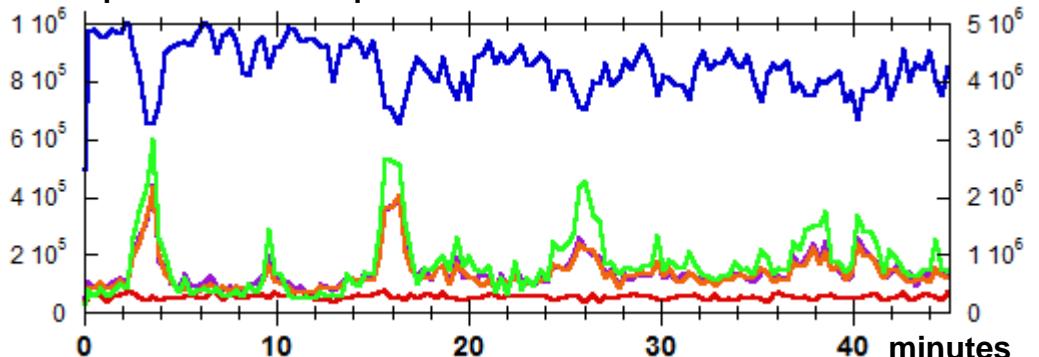
Parent ion : P$^+$

$\downarrow$ k(1st order rxn)

Multiple Fragments
F1$^+$ + F2$^+$ + F3$^+$ + F4$^+$

Exp.
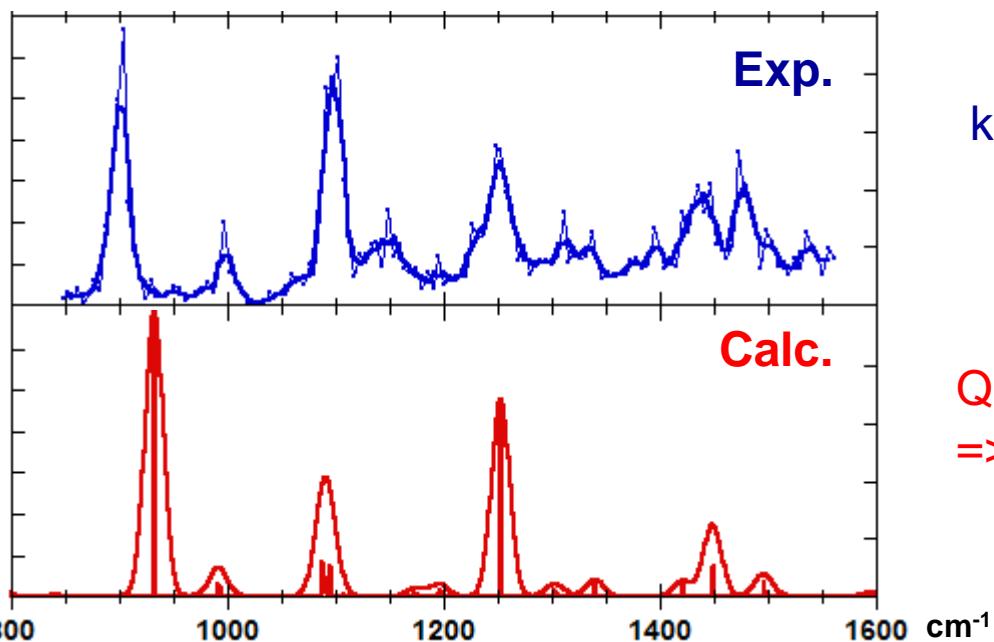
Calc.

$k*time=-\ln(P^+ /(F1^+ + F2^+ + F3^+ + F4^+)$

IRMPD=Multiple photon process

Quantum Chemical calc.
=> IR **absorption** spectrum

Absorption= 1 photon process

Structural assignment often relies on comparison with calc. Absorption spectra

- B3LYP with a saturated basis set (6-31+G**) is used.
  - Only the isomer with the lowest-energy (accessible under kinetic control) is observed
  - Harmonic IR bands are convoluted with gaussian profiles (fwhm=10 or 20 cm^{-1})

- Dual scaling factors to be applied to the calculated harmonic frequencies:
  - 0.98 for the fingerprint region
  - 0.955 for X-H (X=C, N, O) stretching region
- Expected performance (see Schlegel and coworkers, Theor. Chem. Acc. 2001)
  - B3LYP versus exptl frequencies: average absolute difference (AAD) ~25 cm^{-1}
  - B3LYP versus QCISD/Very large basis set intensities: AAD~10 km/mol

- Vibrational frequencies: Expections that prove the rule
  - Phosphorylated peptides: P-O and P=O stretches (scal. Factor ~1.0)
  - Perchlorate ligands: Cl-O stretches (scal. Factor > 1.0)
- Isomer relative energies:
  - Don Truhlar's M06-X density functionals (non covalent interactions)

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  - IMS-MS/MS + Photodissociation
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Solvation of metal ions: 1st versus 2nd coordination sphere?

Ni⁺(H₂O)ₙ Cluster produced by laser vaporisation: Mass Spectrum
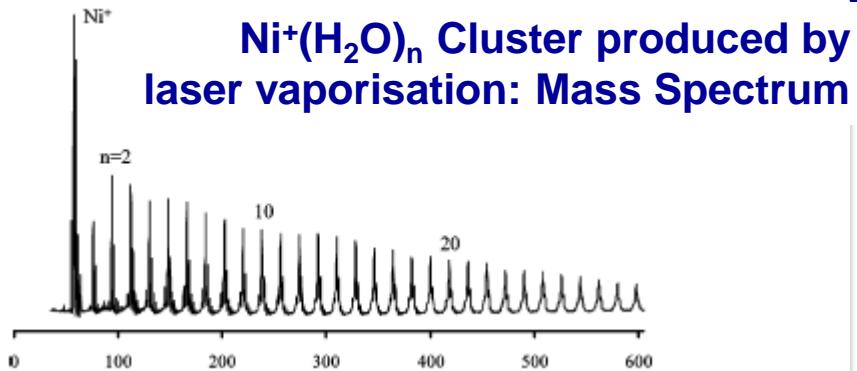
Up to n=3, only small red-shifts are observed with respect to the free water IR bands (3657 and 3756 cm⁻¹)
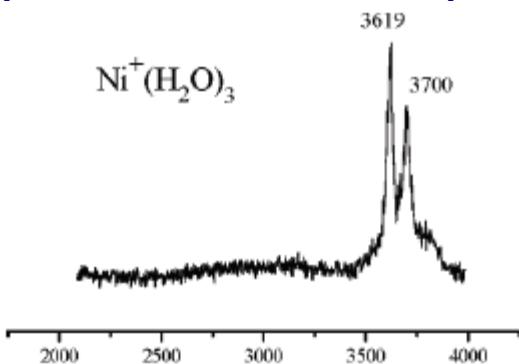
For n > 3, OH bands < 3400 cm⁻¹
⇒ **Signatures of Hydrogen bonds**
⇒ **H₂O in 2ⁿᵈ solvatation sphere**
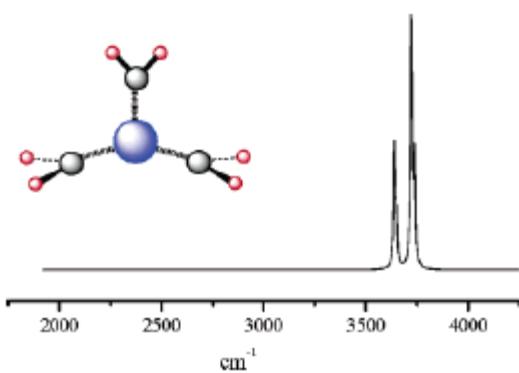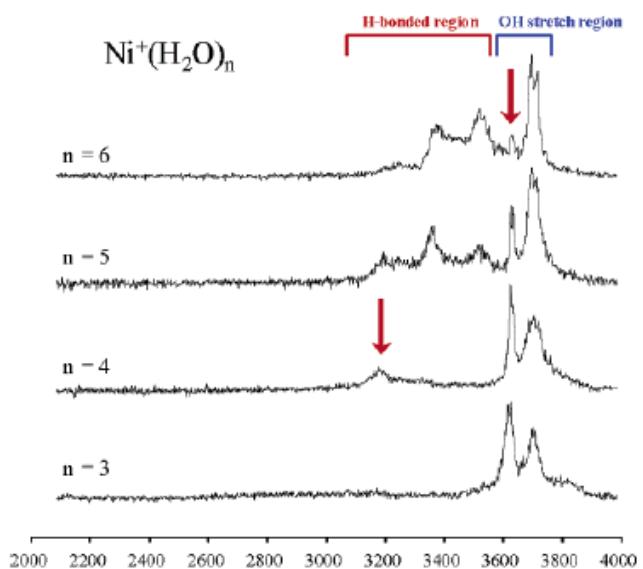
The red-shift values = signatures of the metal↔ligand charge transfers

Solvation of metal ions:
1st versus 2nd coordination sphere?

Ni+(H2O)n Cluster produced by laser vaporisation: Mass Spectrum
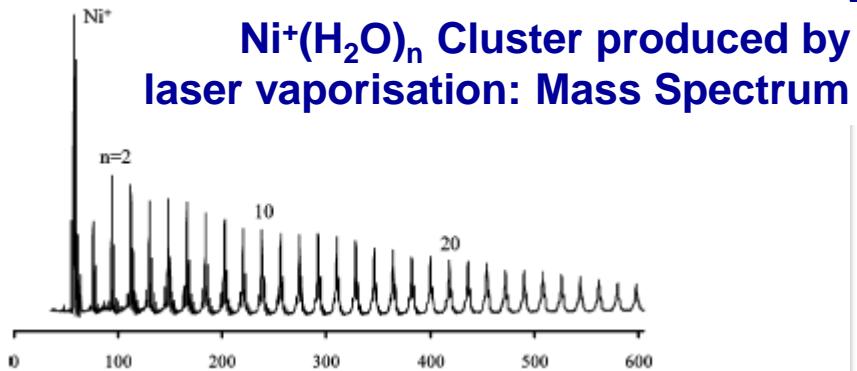
Starting with n=4, low wavenumber bands (@3180 cm-1 for n=4) are signatures of hydrong bonds (2nd solvation sphere)
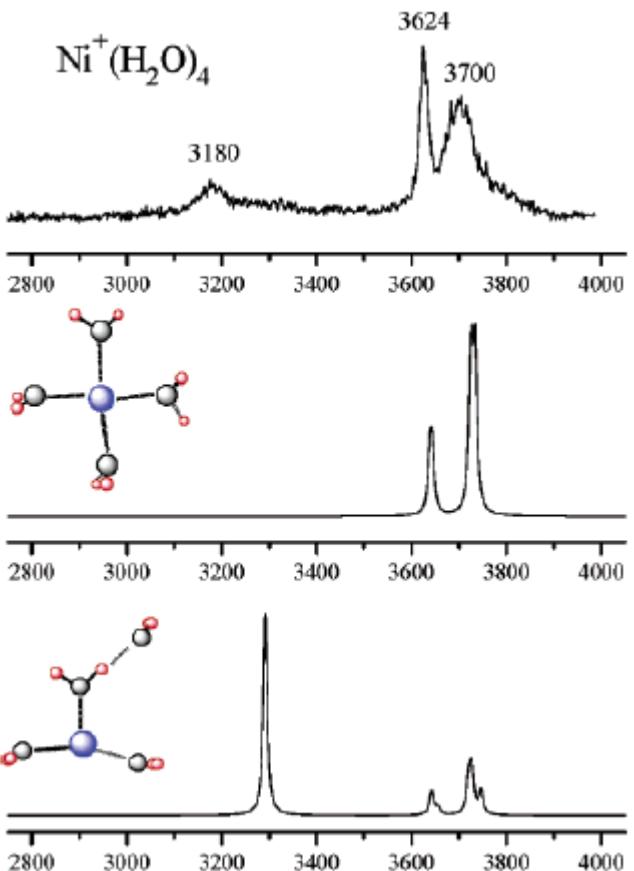
For n > 3, OH bands < 3400 cm-1
$\Rightarrow$ **Signatures of Hydrogen bonds**
$\Rightarrow$ **H2O in 2nd solvatation sphere**

M.A. Duncan et al. *JACS* **2005**, *127*, 16599
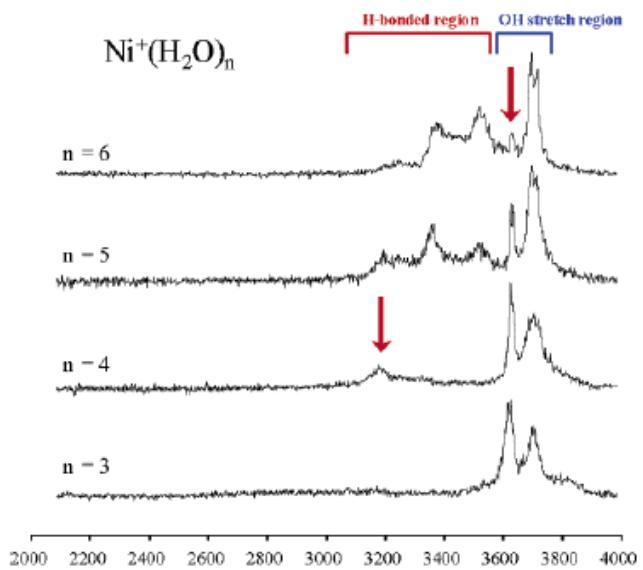
Optimization of HCO_2H dehydrogenation catalyzed by « Ag_2^+ core »: role of pincer diphosphine

- HCO_2H is recognized as one of the most promising materials for H_2 storage
- The effectiveness of direct formic acid fuel cells (DFAFC), however, relies on the selectivity of dehydrogenation ($HCO_2H \rightarrow H_2 + CO_2$) versus water shift ($HCO_2H \rightarrow H_2O + CO$)
- Pd catalysts have been shown to be very promising (Bulushev *et al*, Catal. Today **2010**, 154, 7
- Tandem Mass Spectrometry coupled with IR spectroscopy have been used to provide more insights into the role of ancillary (diphosphine) ligand / selectivity
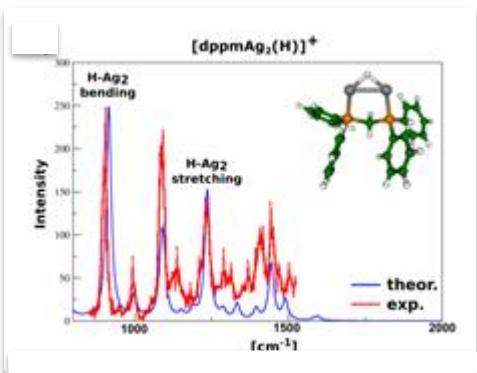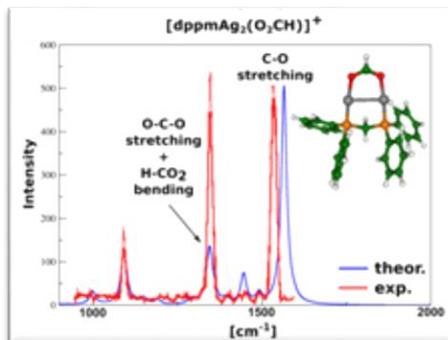
Several turn overs have been achieved under MS/MS conditions
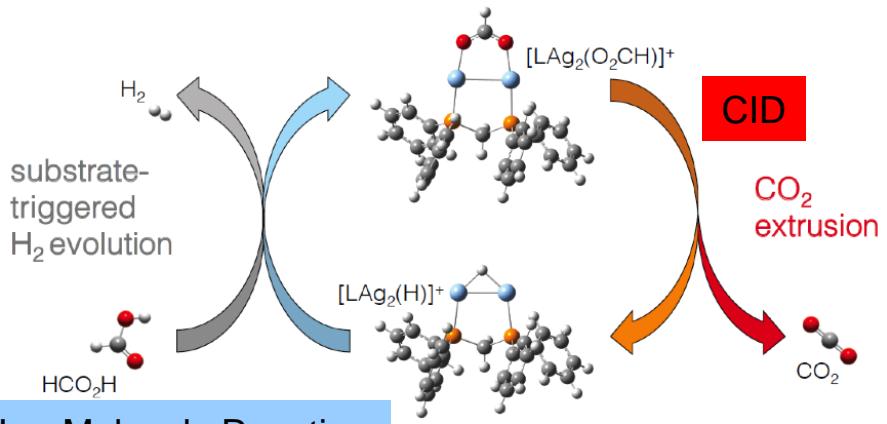
Proposed catalytic cycle for $HCO_2H \rightarrow H_2 + CO_2$

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IR spectroscopy of gas phase ions:
A need for highly intense and tunable lasers

- 1978: CO_2 laser, fixed photon energy at ~940 cm^{-1} (~10.6 μm)
  - First evidence for IRMPD under Tandem Mass Spectrometry conditions
  - J.L. Beauchamp and coworkers, *JACS* **1978**, *100*, 3248.

$$\text{Ion}^{\oplus} \;\rightarrow\; \text{Ion*}^{\oplus}\,(v=1)\ldots \rightarrow \ldots \rightarrow \ldots \rightarrow \text{Fragment}^{\oplus} + \text{Molecule}$$

$$\text{IR} \qquad\qquad \text{IVR} \quad \text{IR} \quad \text{IVR}$$
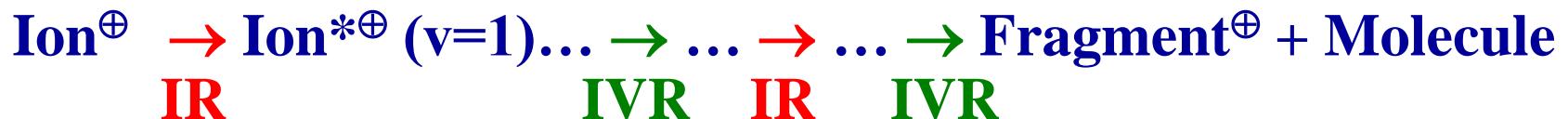
- 1985: IR spectra / 2000-4000 cm^{-1} range.

  - OPO or DFG laser systems, limited to **weakly bound ions**.

  - NH and OH stretching region => H-bonding network

  - Y.T. Lee and coworkers, *J.Chem.Phys.* **1985**, *83*, 3705

- 2000: 800-2000 cm^{-1} Fingerprint spectra of **any ion**.

- Two IR Free Electron Lasers (FELs) available worldwide.

  - At FELIX (QIT), J. Oomens *et al*, *Astrophys. J.* 2000, *542*, 404.

  - At CLIO (FT-ICR), J. Lemaire *et al*, *Phys. Rev. Lett.* 2002, *89*, 273002

IR Multiple Photon Dissociation Process : How does it work?

« This method (IRMPD) employs an intense infrared laser to resonantly pump vibrational energy into the molecule in a **noncoherent** fashion, until it has sufficient energy to dissociate. »
R. C. Dunbar, D. T. Moore, and J. Oomens, *J. Phys. Chem. A* **2006,** *110,* 8316-8326

Step 1: Absorption
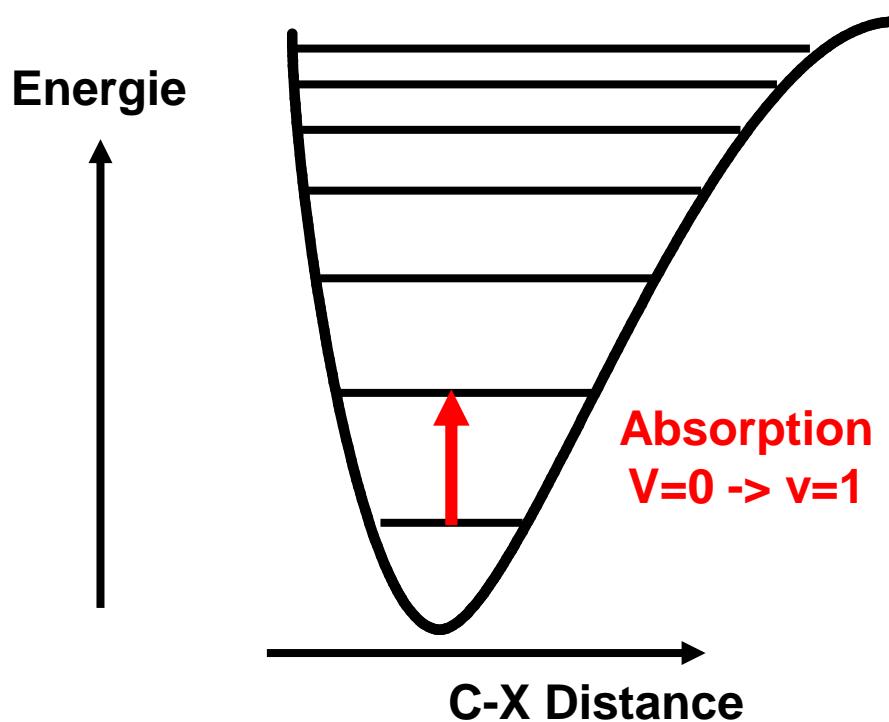
Step 2: Intramolecular Vibrational Redistribution (IVR)

Energie

Absorption
V=0 -> v=1

C-X Distance

IVR
V=1 -> v=0

$\tau \sim \text{ns}$
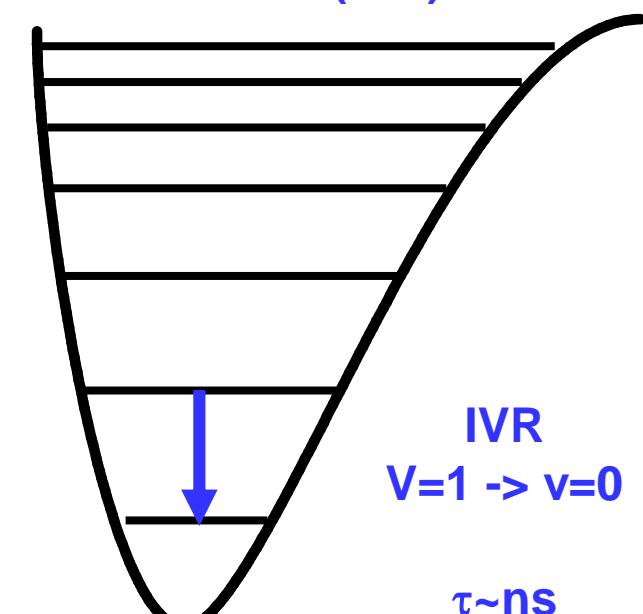
IR multiple photon absorption mechanism: a (too) simple image.

Energy (Resonance vibrational mode)

As under low energy CID conditions, the IR (or collisional) energy absorbed through one (resonance) vibrational mode is redistributed between two absorption events.

V=1

IR   IVR   IR   IVR

V=0

Energy (Ion internal)

2hν

hν

0

See G. von Helden, Optics Express **1999**, 4, 46
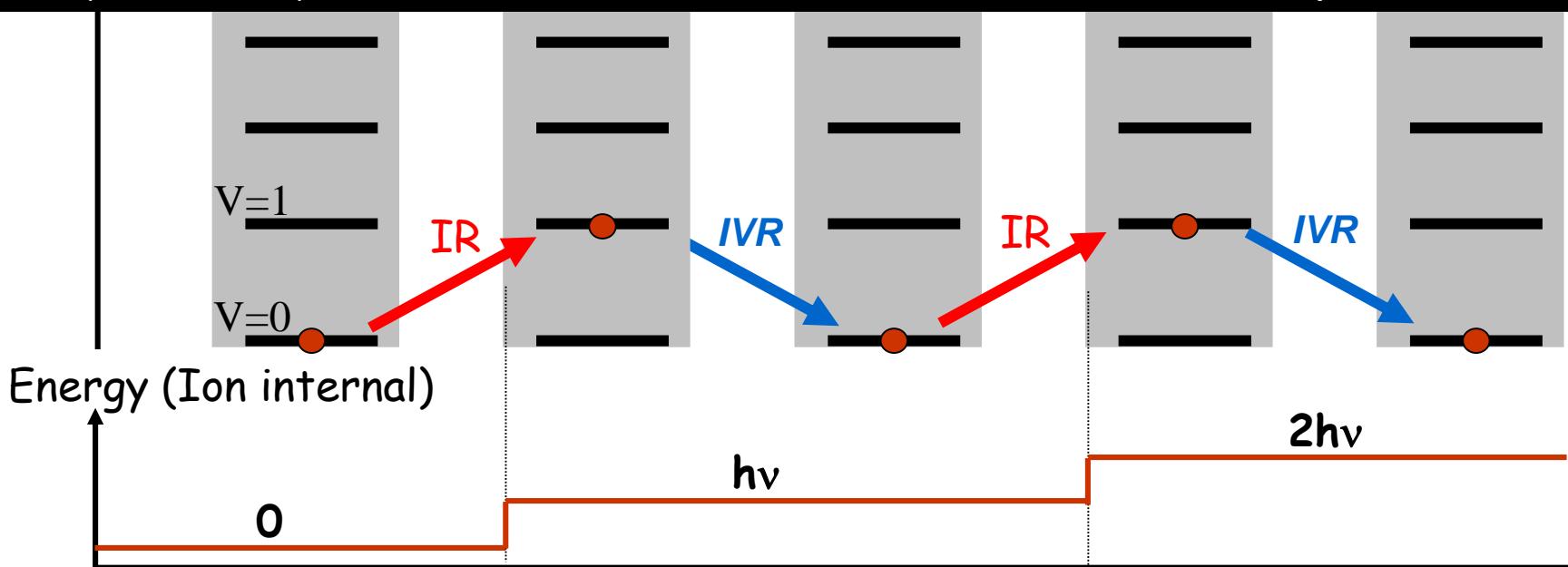
Infrared Free Electron Laser (FEL) at Orsay

IR FEL : High fluence (80μJ/ps pulse) and broad tunability (100-2500 cm^{-1})

IR FEL is based on an electron accelerator (16-48 MeV). IR beam is generated within the undulator placed in the optical cavity.

λ is tuned by adjusting the gap between the two sets of magnets of the undulator.

Typically, electrons at 40 MeV give access to the 800-2000 cm^{-1} IR fingerprint with a ~stable power.

$$\text{Ion}^{\oplus} \rightarrow \text{Ion*}^{\oplus} (v=1)… \rightarrow … \rightarrow … \rightarrow \text{Fragment}^{\oplus} + \text{Molecule}$$

IR   IVR   IR   IVR
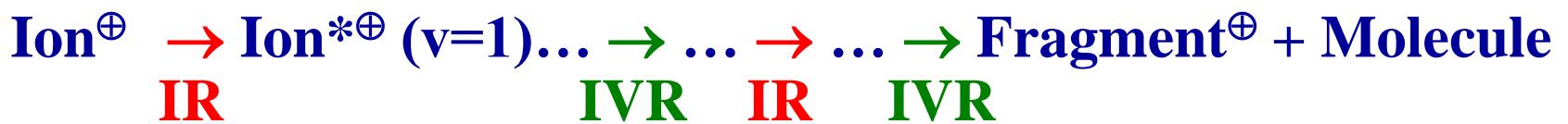
Macropulses (40 mJ) at 25 Hz

8 μs

40 ms

time

~1ps   16 ns
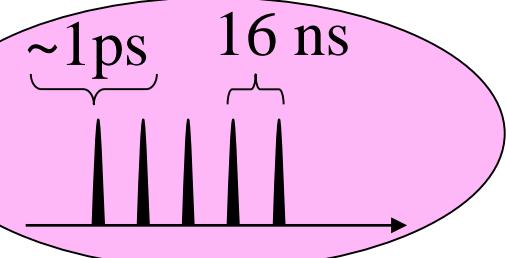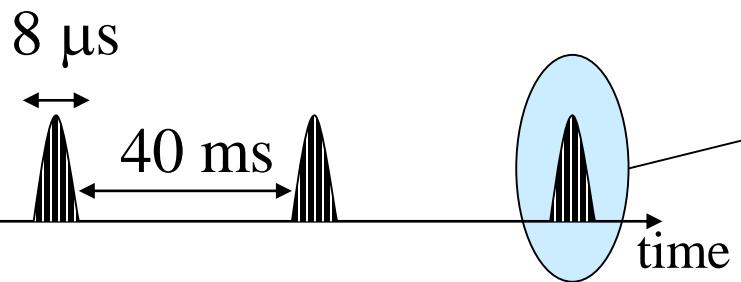
Pico-pulses (80 μJ)
Relative bandwidth Δλ/λ (fwhm) : ~0.5%

IR spectra recorded using commercial Tandem Mass Spectrometers @ Orsay

Bruker Esquire
QIT
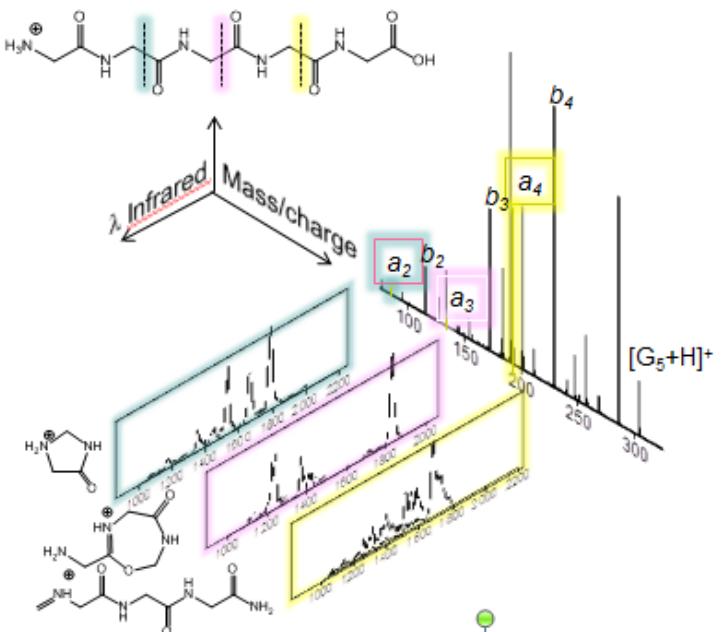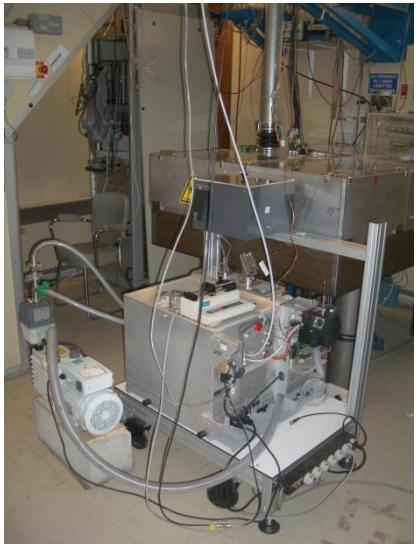
Bruker Apex IV
Hybrid FT-ICR
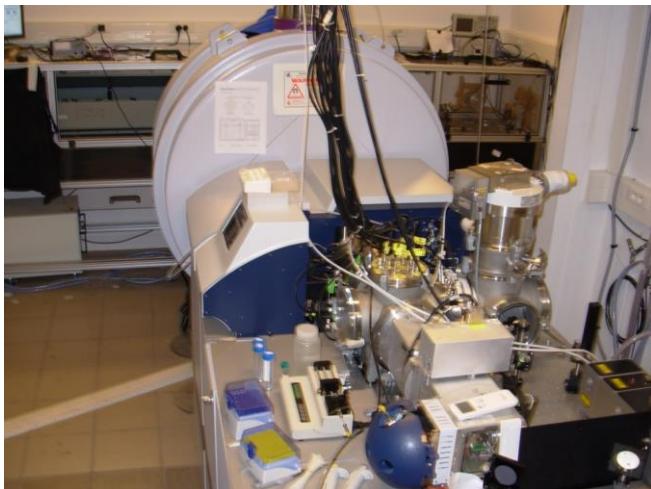
- Very simple implementation; Acquisition and Data Analysis using commercial software
- Room temperature ions: thermalization through collisions prior to IR irradiation
- Any kind of ions, including **strongly bound ions** are amenable
- MS^n sequences integrating IR activation can be achieved:
  IR spectroscopy of Ion fragments (CID+IR, ECD+IR)
  and of products of ion/molecule reactions (host-guest, H/D exchange (HDX))

Two MS/MS instruments: pros and cons

IR beam

Linear Hexapole Ion Trap (LIT) filled with Ar ~10^{-3} mbar

Ion Cyclotron Resonance (ICR) cell

Quadrupole

Gate valve

IR beam

Atm.

P 1 mbar

10^{-2} mbar

P 10^{-4} mbar

P 10^{-6} mbar

10^{-2} mbar (Ar)

P 10^{-8} mbar

10^{-10} mbar

Source | Qh-Unit | Transfer | ICR Cell

Quadrupole Ion Trap (QIT) filled with He ~10^{-3} mbar
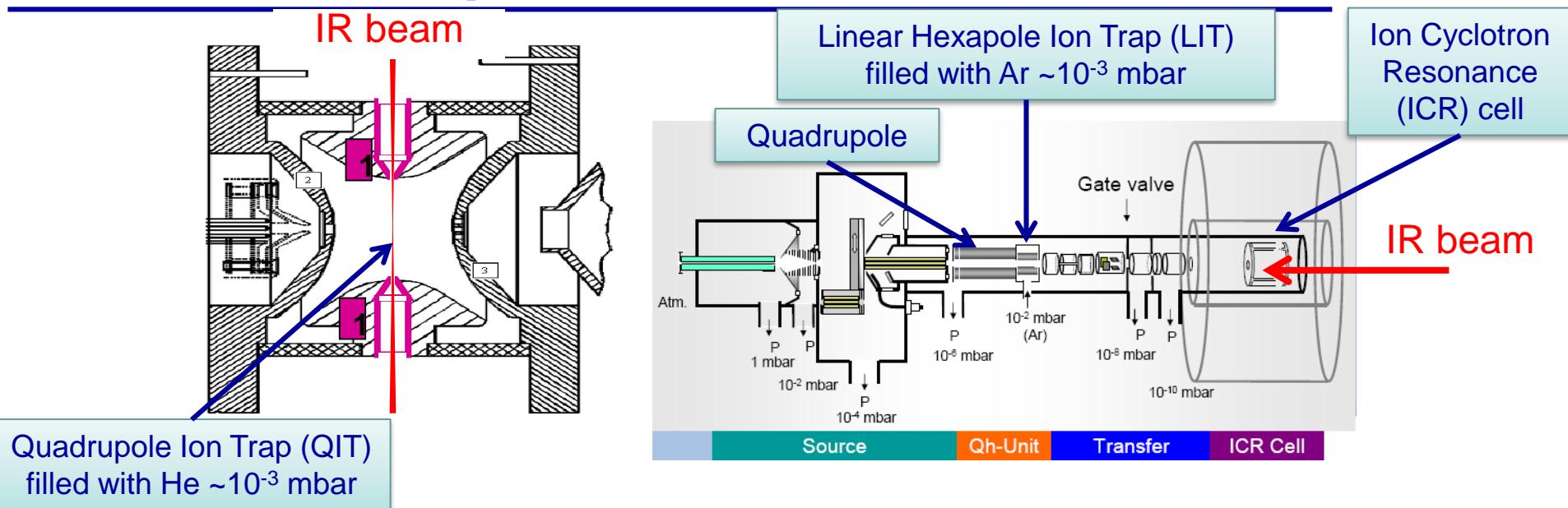
	Bruker Esquire (QIT)	Bruker Apex IV Hybrid FT-ICR
IR irradiation	QIT at 10^{-3} mbar (He)	ICR at <10^{-9} mbar
Collisional cooling	QIT	LIT at 10^{-3} mbar (Ar)
Mass Selection	QIT	Linear Hexapole or ICR
CID-MS/MS	QIT	LIT or ICR (SORI-CAD)
Ion-molecule reaction	QIT	LIT or ICR
Others		Electron Capture Dissociation (ECD)

IR Free Electron Laser coupled with Q-ion-trap : pros (overlap) and cons (thermalization)

IR-FEL delivers macropulses(40 mJ)@25 Hz

$8\ \mu s$

$40\ ms$

time

IR FEL beam

P(He) ~10^{-3} mbar
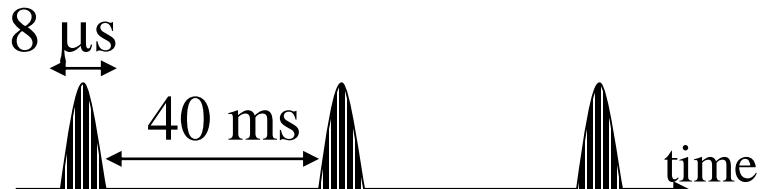
✓ **Helium pressure within the ion trap ≈ 10^{-3} mbar**

✓ **Confinement of the ion cloud => excellent ion/laser overlap (100% ion depletion using a single microsecond pulse)**
   Ion/laser overlap, see for example: Philip M. Remes; Gary L. Glish; JPC A 2009.

✓ **Efficient thermalisation of the ions through multiple low-energy collisions.**
   Typically ~10ms, see for example: Philip M. Remes; Gary L. Glish; IJMS 2007
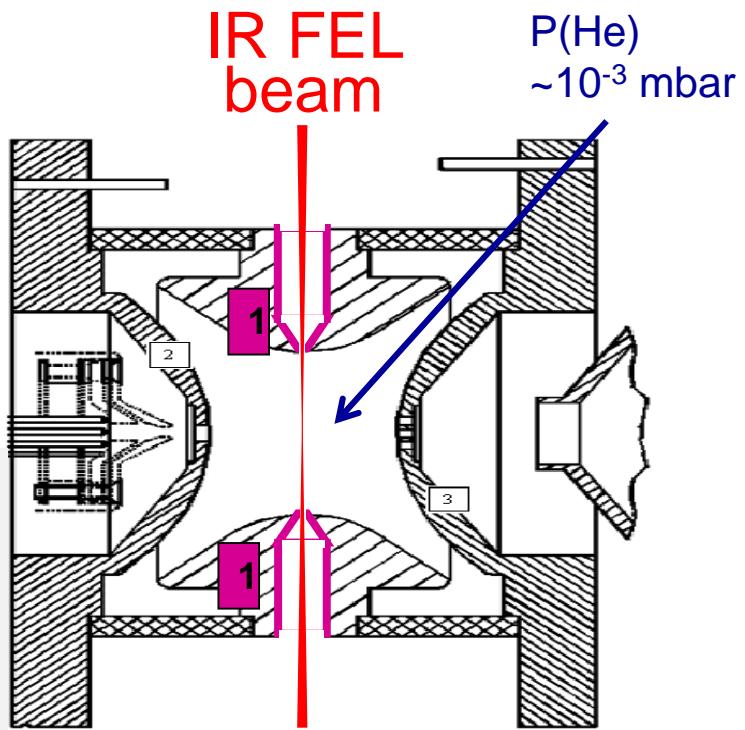
Performance and ion/laser overlap issues within the QIT versus ICR cell
Mac Aleese *et al*, *IJMS* **2006**.

IR spectra in the CH, NH, and OH stretching region: tabletop laser

Based on non-linear optical properties of crystal materials such as KTP, KTA, LiInS$_2$, AgGaSe$_2$

Optical Parametric Oscillator

**Optical Parametric Amplifier**

532 nm

OPO → signal (not used)

1064 nm

OPA → **2500-4000 cm^{-1}**

DFM → **600-2000 cm^{-1}**

LaserVision (Dean Guyer)
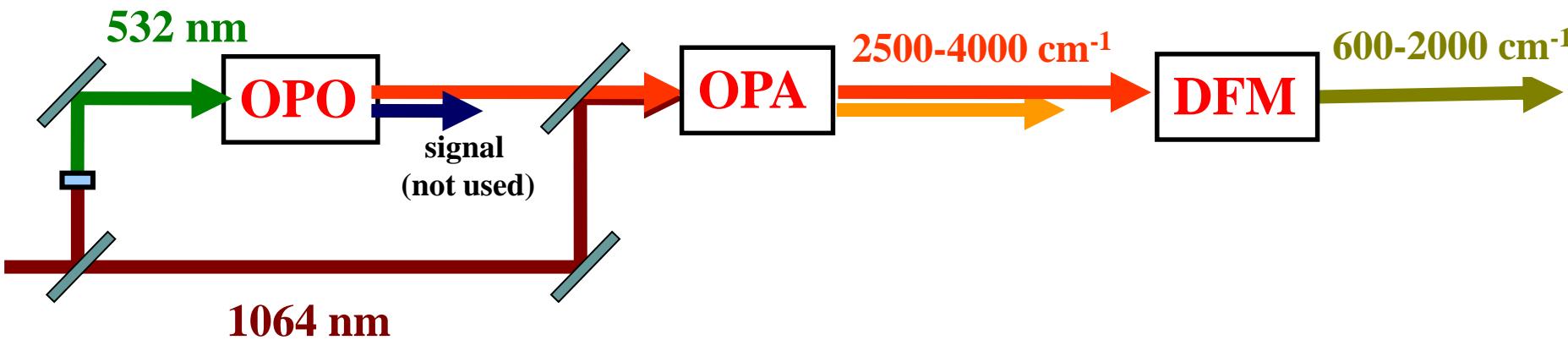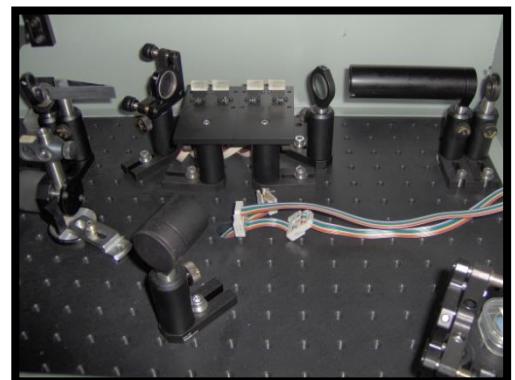
An auxiliary CO_2 laser can be used when IRMPD is not efficient (high dissociation E, low laser power)

m/z 262 pTyr(H+) -> m/z 216

200 ms IR

Ion Intensity

- CO$_2$ only
- I OPO only
- I OPO + CO$_2$

m/z
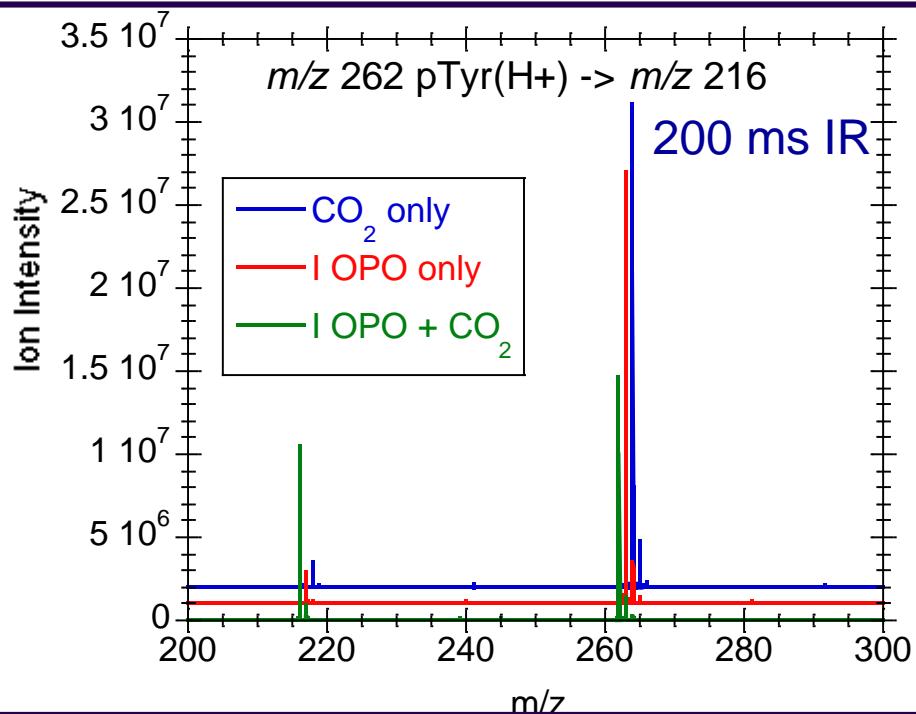
Phosphotyrosine+H$^+$: [pTyr+H]$^+$

OPO, on resonance with an O-H band

OPO+CO_2: significant amplification

CO_2 laser is synchronized with the OPO (delay ~ μs)
CO_2 irradiation time optimization: the irradiation time is increased up to the
using the CO_2-only fragmentation is obtained

OPO at 25 Hz
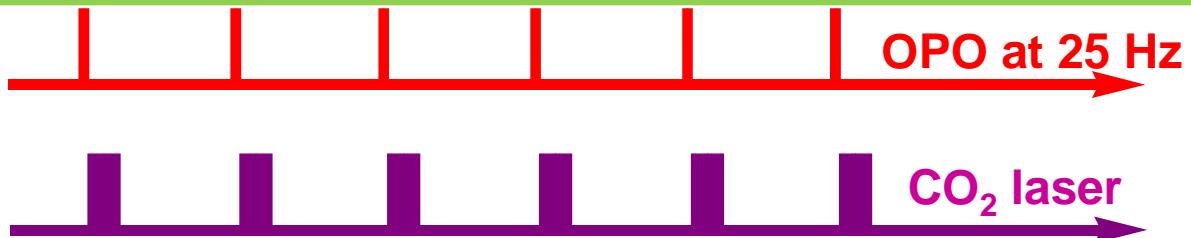
CO_2 laser

IRMPD at fixed wavelength (CO_2): analytically useful if CO_2-chromophore

CO_2 laser: 10.6μm (943 cm^{-1}).
Phosphate (P-O band) is a CO_2-chromophore
=> CO_2-IRMPD of Phosphorylated peptides
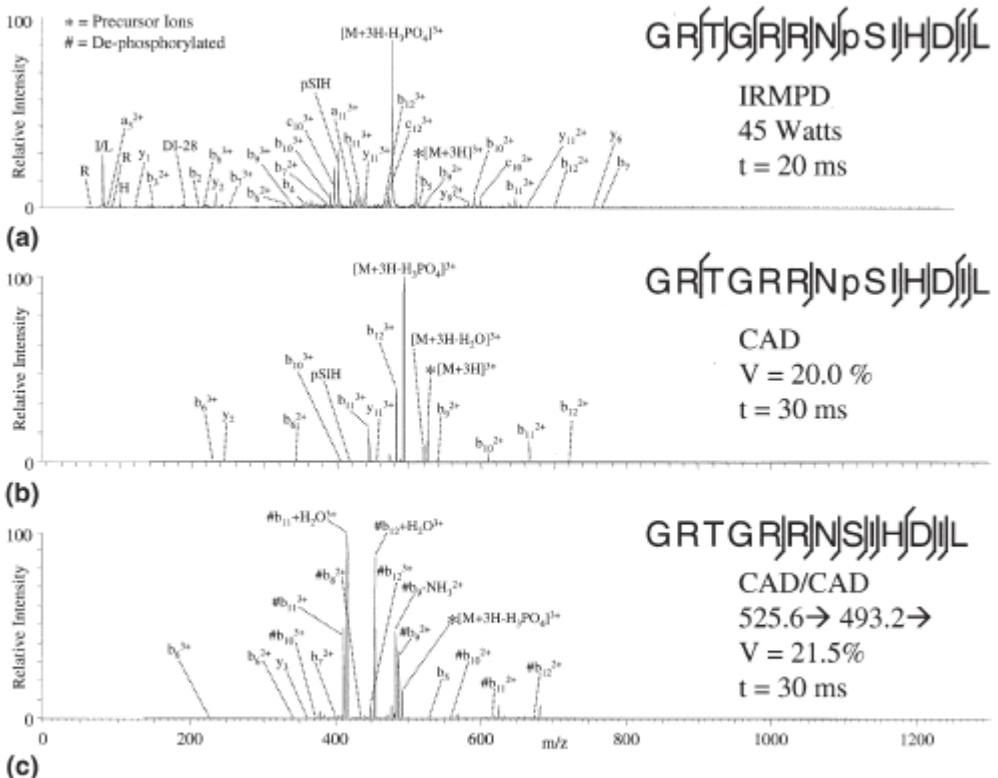
Figure 7. (a) IRMPD, (b) CAD MS^2, and (c) CAD MS^3 mass spectra of triply protonated GRT-GRRNpSIHDIL.

J.S. Brodbelt and coworkers, Anal. Chem. 2004

How that can be generalized?
Make a complex with the Analyte + Metal + Phosphate containing Ligand
=> Cu^{2+}(flavonoïde)(CO_2-chromophore)

CO_2-chromophores
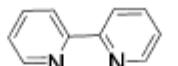
2,2'-bipyridine (156 Da)
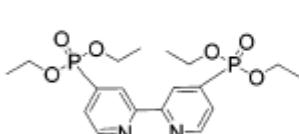
4,4'-(diethylphosphonate)-2,2'-bipyridine
IRAL-1 (428 Da)
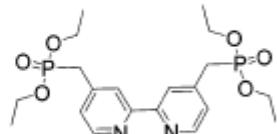
4,4'-bis(diethylmethylphosphonate)-2,2'-bipyridine
IRAL-2 (456 Da)

Their IR absorption spectra
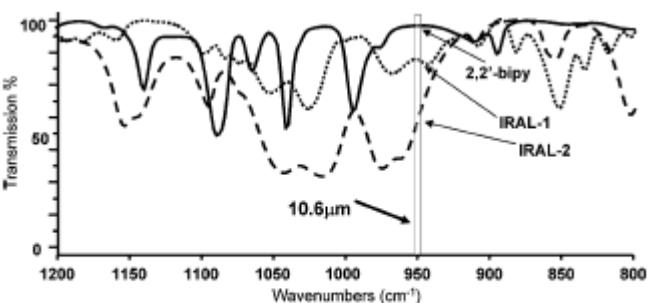
Figure 6. FTIR ATR spectra of the ligands used in the study, showing the enhanced absorption of the IR-active ligands, IRAL-1 and IRAL-2, at 10.6 μm as compared to 2,2'-bipyridine.

Outline

- **Introduction**
  - Fragmentation under MS, need for specific activation methods
  - Infrared background

- **Organometallic Chemistry under MS/MS**
  - Coordination mode of multidentate ligand?
 - Spin State of transition metals?
  - Structure of reactive intermediates?

- **Integration of IR spectroscopy to MS**
  - Historical background
  - Need for highly intense and tunable IR lasers, coupling with MS/MS instruments

- **Organic Chemistry: mechanism of peptide fragmentation**
  - StructureS of b_n and y_n ions, protonation site?
  - Isomerization of a_n ions, evidence for multiple isomers

- **Isomer separation with Ion Mobility and Spectroscopy with IR lasers**
  - IMS-MS/MS + Photodissociation
  - Separation of saccharide isomers and spectroscopy

Peptide Fragmentation using CID: useful information for sequencing

y_1 y_2 y_3 y_4 y_5 y_6 y_7 y_8 M+H⁺

m/z

M+H⁺
1088.92

m/z
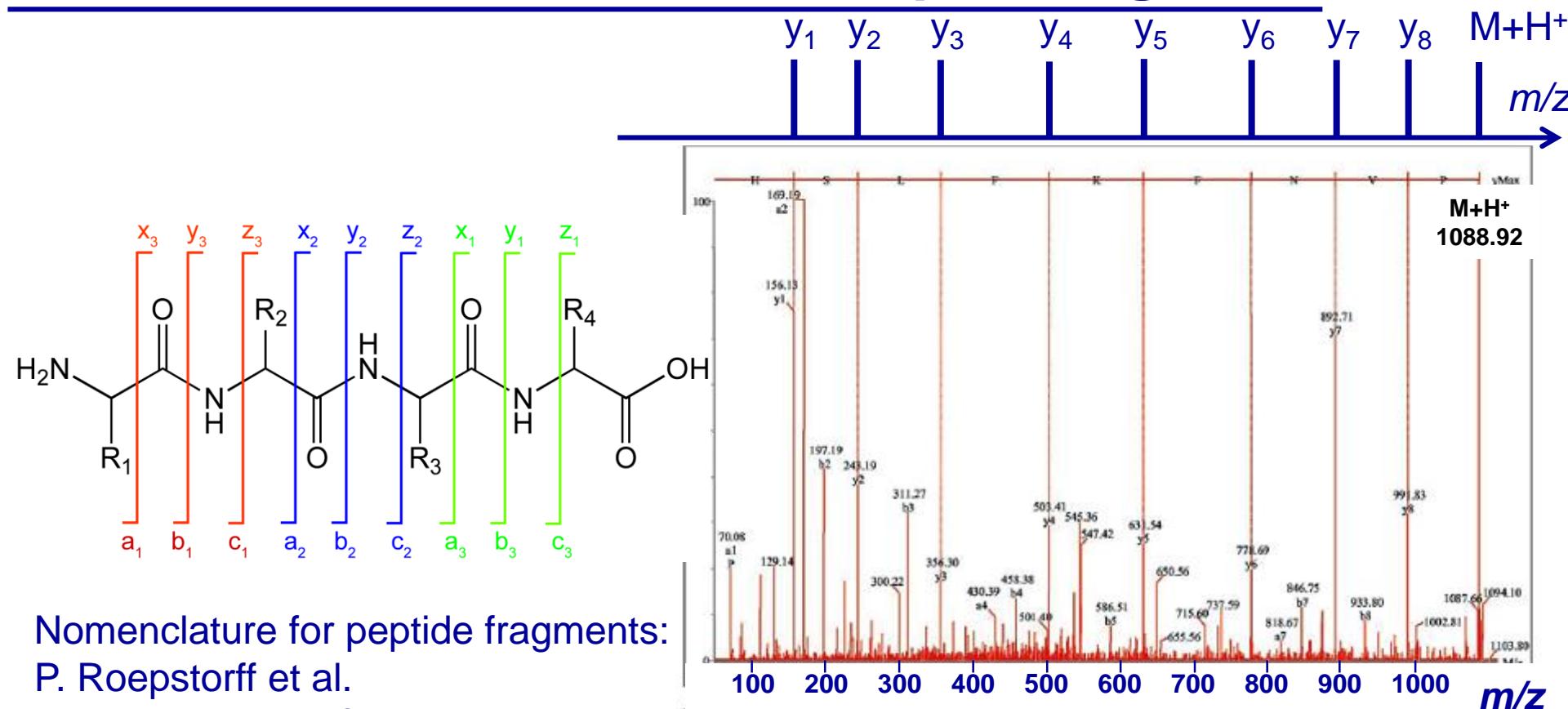
Nomenclature for peptide fragments:
P. Roepstorff et al.
J. Biomed. Mass Spectrom. **1984**

Collision Induced Dissociation (CID 26eV/Ar)
(ToF) Mass Spectrum of protonated
M=PVNFKFLSH nonapeptide

Questions:
What is the fragmentation mechanism?
Exceptions to the simple fragmentation scheme (induced sequence permutation)?

Formation and chemistry of b_n and a_n ions: reaction mechanism

Under collisional activation:
- Proton transfer(s)
- Fragmentation (a/x, b/y fragments)

And also rearrangement chemistry driven by (concerted or not) addition/elimination reactions of:
- **Nucleophilic sites**
- On **Electrophilic sites**

Proton Transfer

Fragmentation

- CO
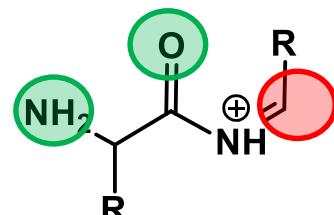
***a_2-ion
(imminium?)***

***b_2-ion
(acylium?)***
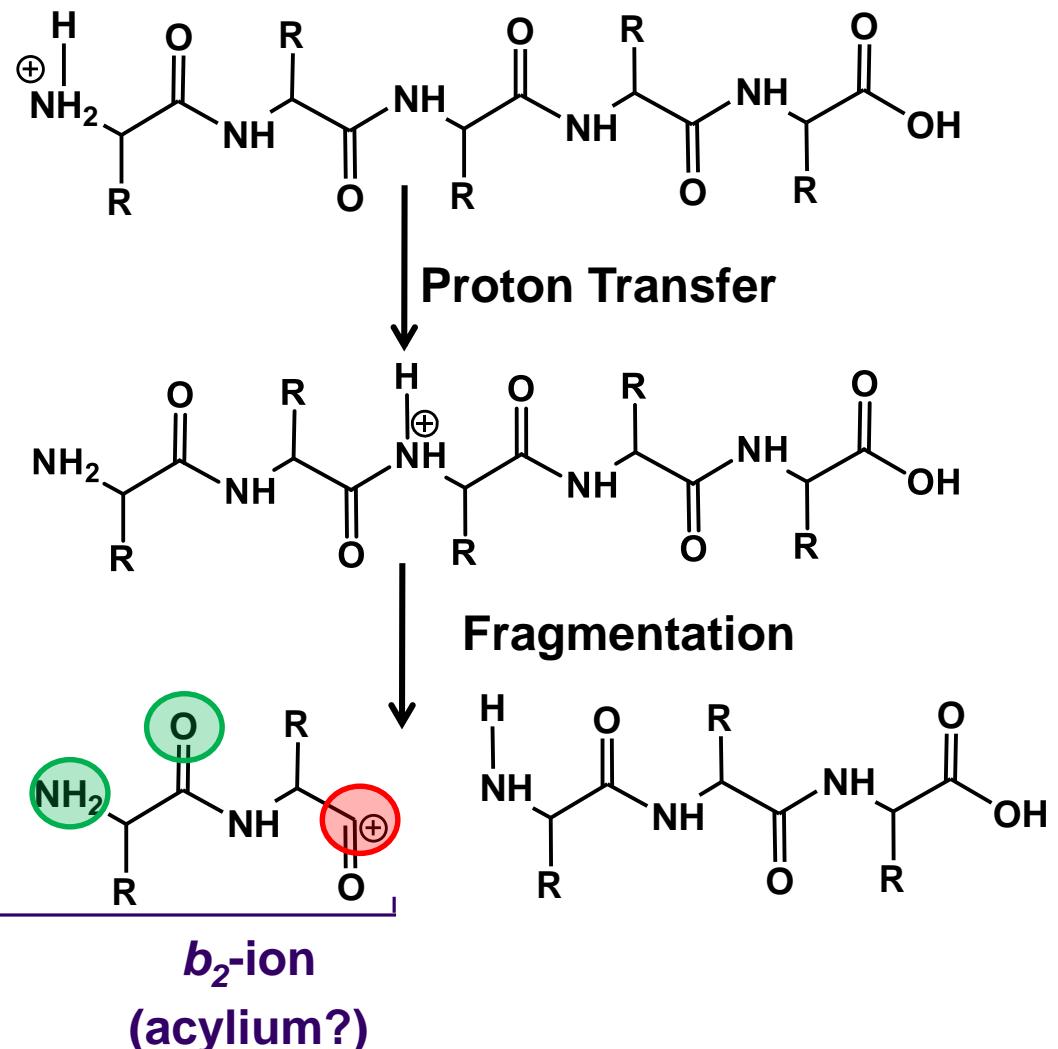
… on fragmentation efficiency: Evidence for the mobile proton model. Wysocki, V.H. and coworkers, *JACS* **1996**, *118*, 8365.

a_n fragment ions: formation and rearrangement (permutation) under CID conditions

Imine-Amide Rearranged structure

b_2 -13.1   17.6 a_2+CO   0.0 kcal/mol   11.9   -8.9   Lowest energy
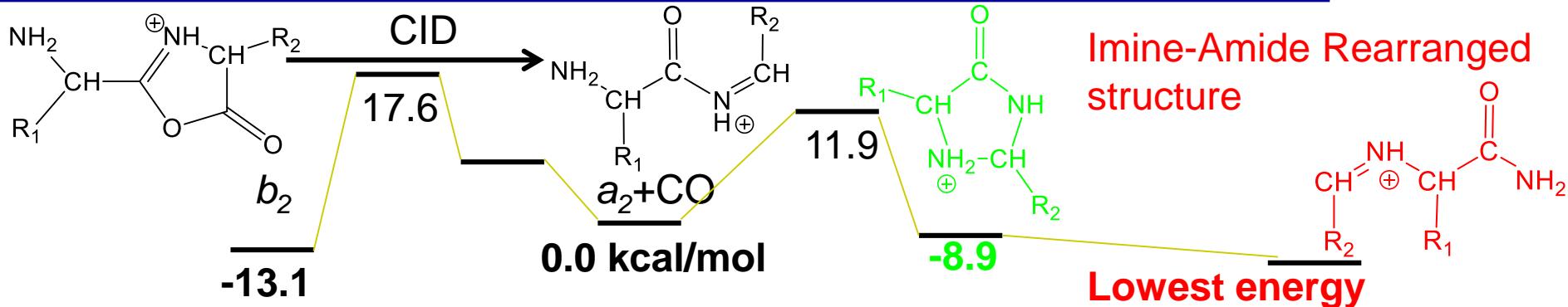
- The a_n ions are frequently observed under high- or low-energy CID conditions. Often more prevalent than the corresponding b_n ions (Zubarev JASMS'08)

- Structure? Iminium formation (Paizs et al RCMS 2000, energetic for R_1=R_2=H).
- Cyclisation: attack of terminal NH_2 on iminium C (Siu and coworkers JACS'03)

- Rearrangement?

  Indirect evidence (Vachet, Bishop, Erickson, and Glish, JACS'97):

       following a_4(YGGFL)$\rightarrow$NH$_3$+a_4*, loss of internal (Glycine) residue

  IRMPD spectroscopy for an fragments of [Gly$_n$+H]$^+$:

  - a_2 ion: Verkerk, Siu, Steill, El Aribi, Zhao, Rodriquez, Oomens, Hopkinson, and Siu, JPCLett' 10.
 - a_2-a_3-a_4 ions: Bythell, Maitre, and Paizs, JACS'10.

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cnrs
dépasser les frontières

CID

17.6

b_2

-13.1

a_2+CO

0.0 kcal/mol

11.9

Imine-Amide Rearranged structure

-8.9

Lowest energy
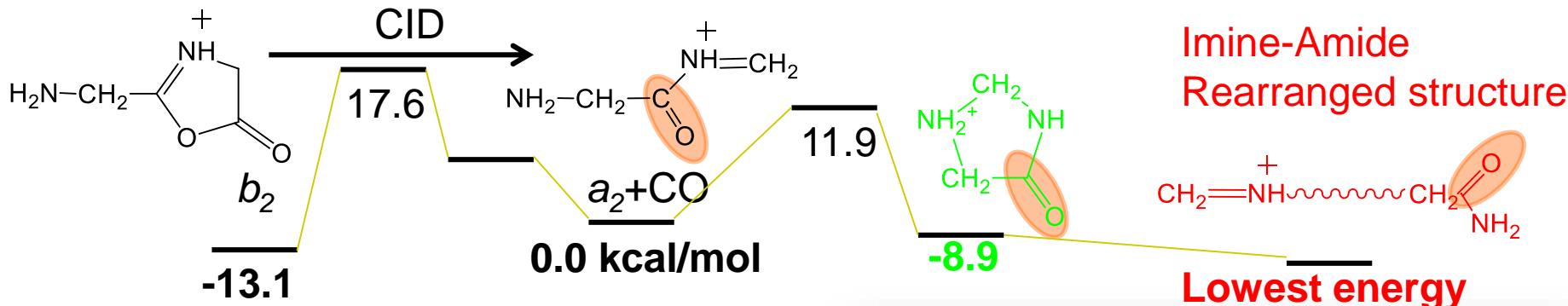
- Oligoglycine (R$_1$=R$_2$=..=H)

- Very different IR spectra for a_2, a_3, a_4 of protonated [G$_n$+H]$^+$.

- The C=O stretching region was the most structurally diagnostic.

- Consistency of theoretical and experimental results: rearrangement of a_n ions is kinetically controlled. The lowest energy isomer accessible through energy barriers lower than 10-12 kcal/mol is formed.

Bythell, Maître, Paizs, *JACS.* **2010**, *132*, 14766.

x 3

a_2

a_3

a_4

Wavenumber (cm^{-1})
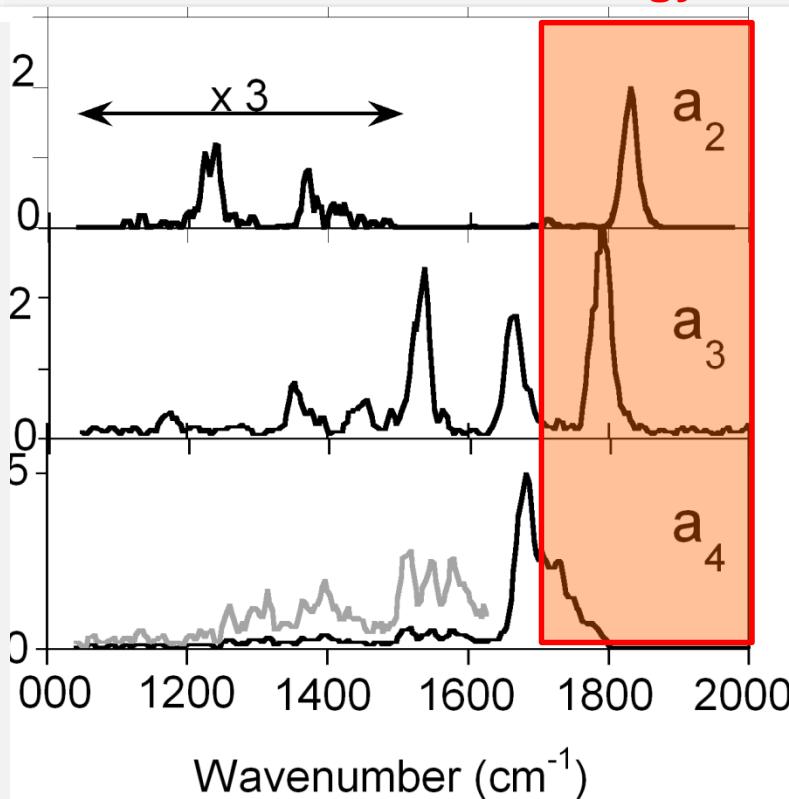
Fragment ion *a*$_2$ of [GGG+H]$^+$: Isomer(s) formed?

Relative Energies (kcal/mol)

Bythell, Maître, Paizs, *JACS.* **2010**, *132*, 14766.
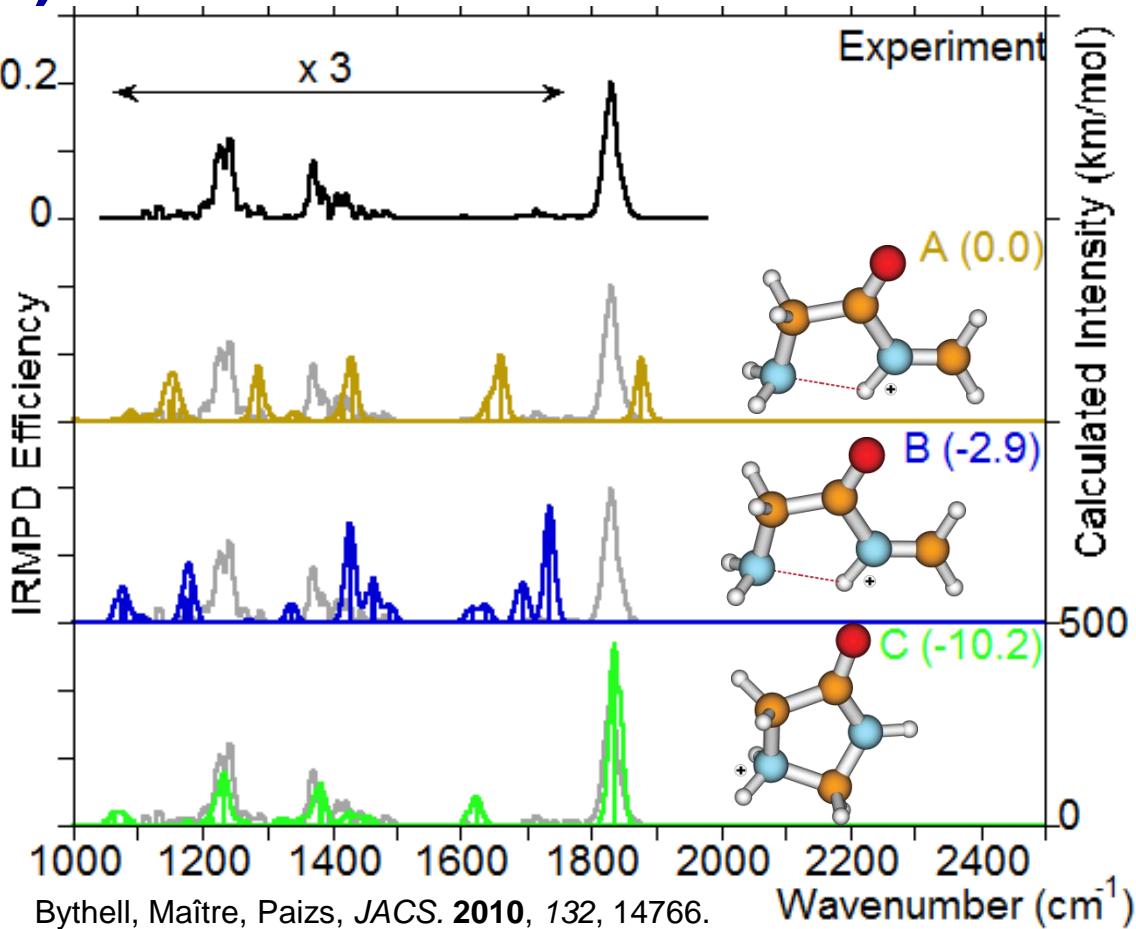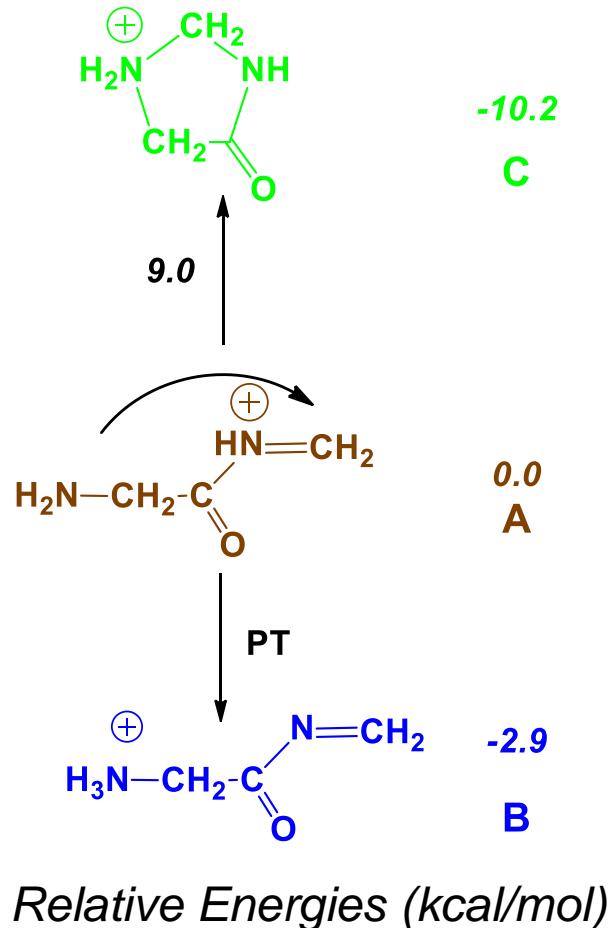
One (cyclic) or 2 isomers formed?
K.W M. Siu and co-workers (*JPC. Lett.* **2010**, *1*, 868): a second isomer (permuted sequence) also formed.

Reaction scheme:

NH$_2$–CH$_2$–C(=O)–NH$^+$=CH$_2$ →(9.0)→ **A (0.0)**

C (-10.2) (5-membered ring: NH$_2^+$–CH$_2$ / CH$_2$–C=O / NH)

→ **TS PT (32.1)** → **D (2.8)**

→(8.7)→ **E (-17.6)** CH$_2$=NH$^+$-CH$_2$–C(=O)–NH$_2$
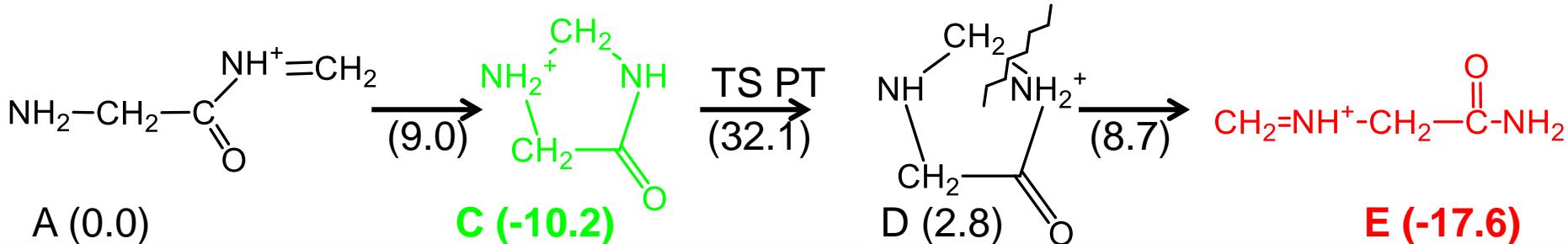
Under low-energy CID conditions, the high energy 1,3 proton transfer prevents from the rearrangement of a_2 ions of [G$_5$+H]$^+$.
Bythell, Maître, Paizs, JACS. 2010, 132, 14766.

Under other experimental conditions: **2 C=O bands (~1727 cm^{-1} for E, and ~1828 cm^{-1} for C)**
Siu and coworkers, JPC Lett, 2010, 1, 868

CID in the source region (high pressure)
Water and/or Methanol the 1,3-proton transfer
Siu and coworkers, IJMS, 2012, 330-332, 254

Experiment, A (0.0), C (-10.2), E (-17.6)
Wavenumber (cm^{-1})
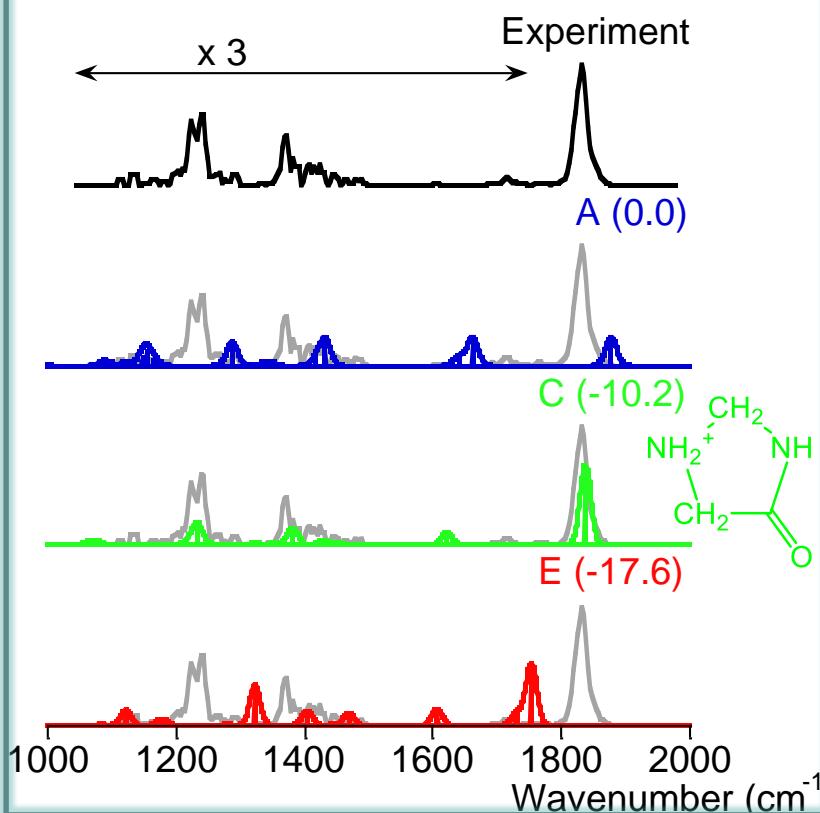
# IR signatures of imine-amide rearranged structure: role of aromatic side-chain

- a_2 of [YGGFL+H]$^+$: catalyzed 1,3 proton transfer: The interaction of the tyrosine side-chain with the proton significantly lowers the 1,3-PT TS (15.5 vs 32.1 kcal/mol, Bythell *et al*, IJMS **2012**, *316-8*, 227)

- Similar findings with Phe side-chain (Siu and coworkers, IJMS, **2012**, *330-332*, 254)

A (0.0)   C (-17.6)   TS 1,3-PT   D (-0.6)   E (-20.4)

(9.0)   (15.5)   (5.4)

Asymmetric NH$_2$ stretch

1600   1700   1800   1900

3400   3500   3600   cm^{-1}
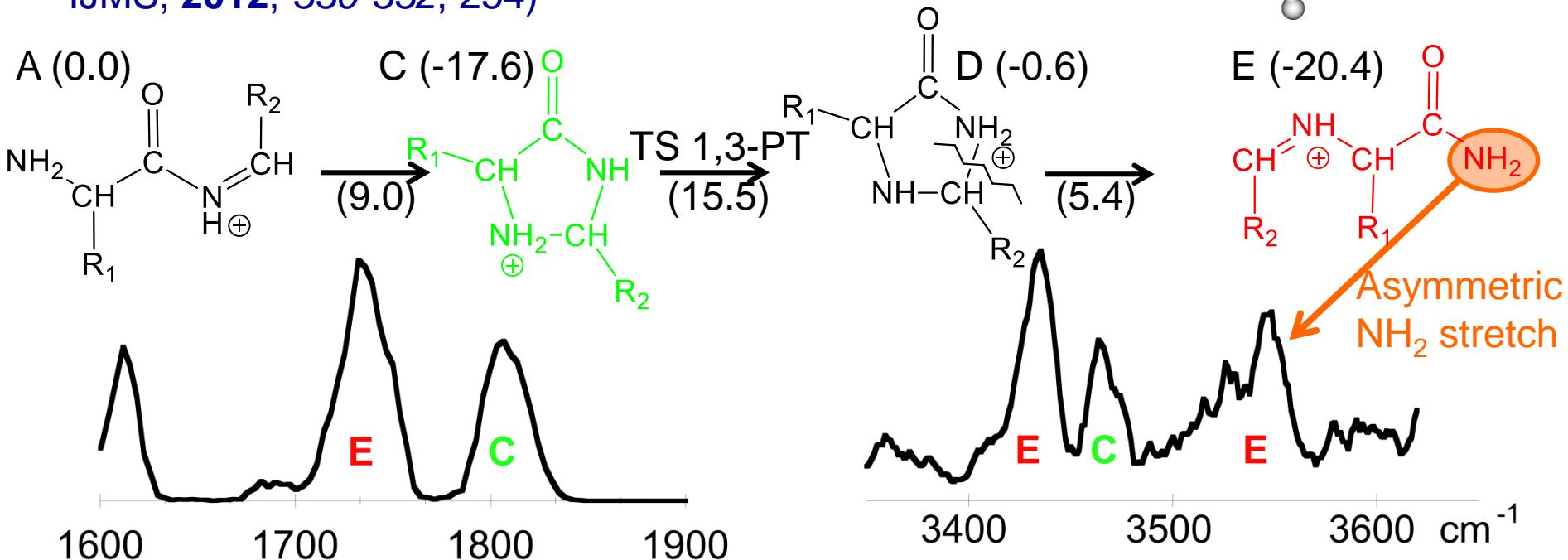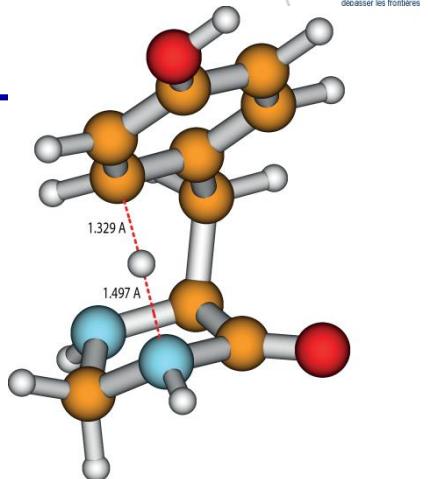
- **~3530 cm^{-1} IR signature of rearranged *a*$_n$ ions**:

- *a_2-a_4 of [G$_n$+H]$^+$ (to be submitted), [YGGFL+H]$^+$ (Wassermann; Boyarkin; Paizs; Rizzo, JASMS 2012, 23, 1029)*

Cyclic to imine-amide rearranged structure favored when increasing the collision time period
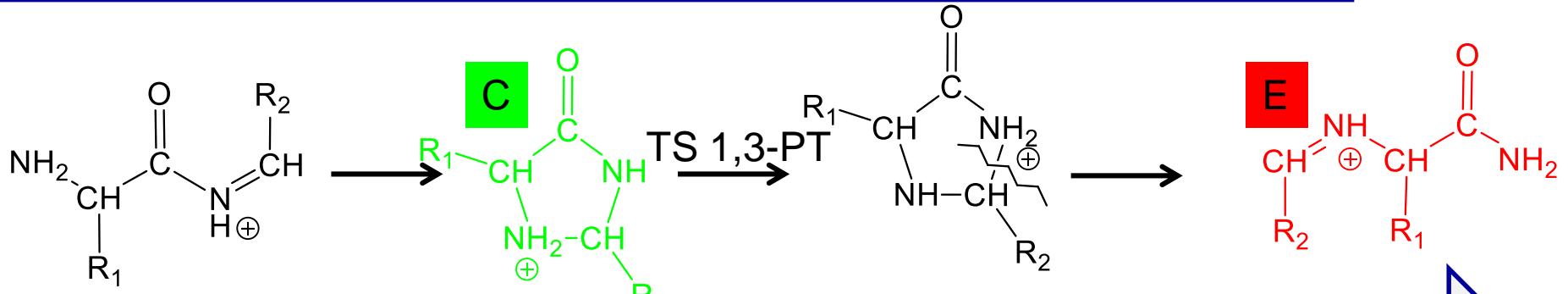
Increasing the CID time period favors the **C** -> **E** rearrangement

$[\text{YGGFL+H}]^+ \xrightarrow{\text{CID}} b_2 \xrightarrow{\text{CID}} a_2 \ (A\text{->}C\text{->}D\text{->}E)$

TS 1,3-PT
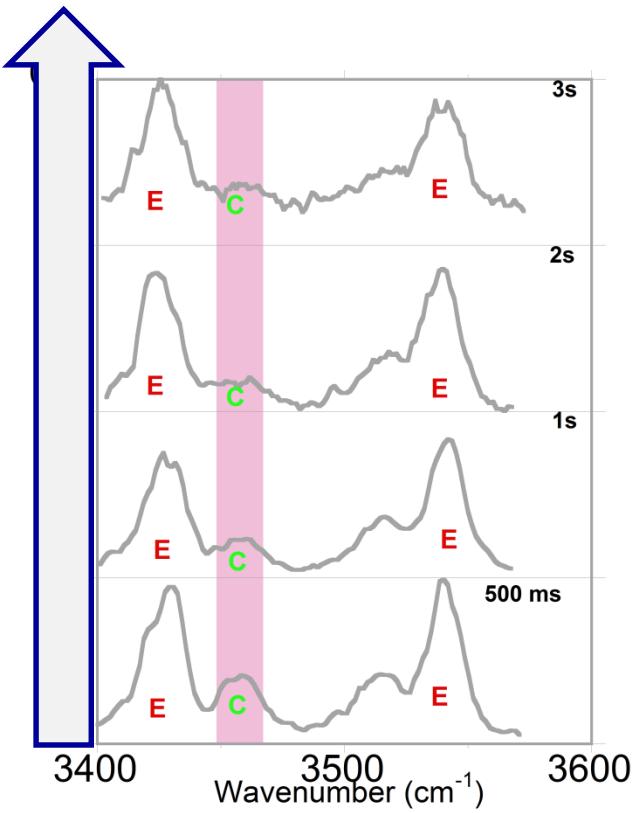
Probing Isomer population:
IRMPD Efficiency vs Irradiation Time

Hydration Isomers of Protonated Phenylalanine and Derivatives: Relative Stabilities from Infrared Photodissociation.
Prell, J.S., Chang, T.M., O'Brien, J.T., and Williams, E.R., *J. Am. Chem. Soc.* 2010, *132*, 7811-7819.
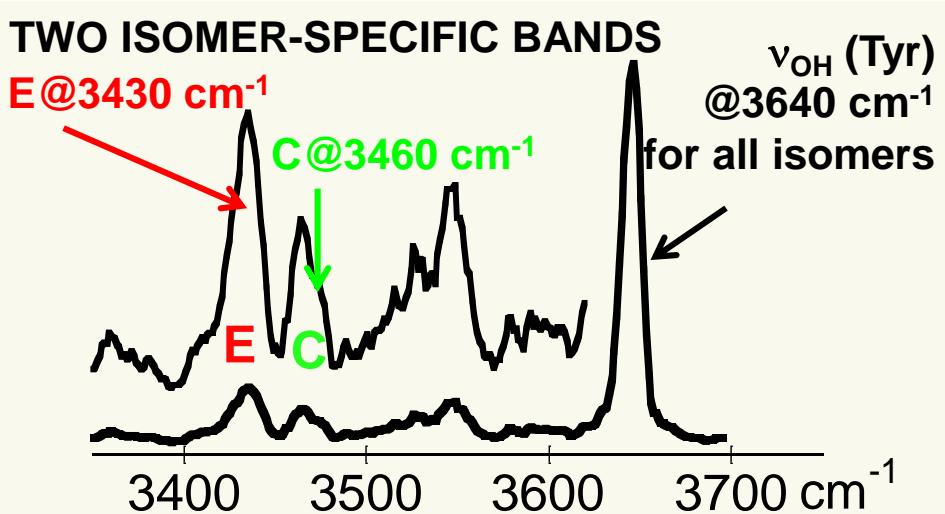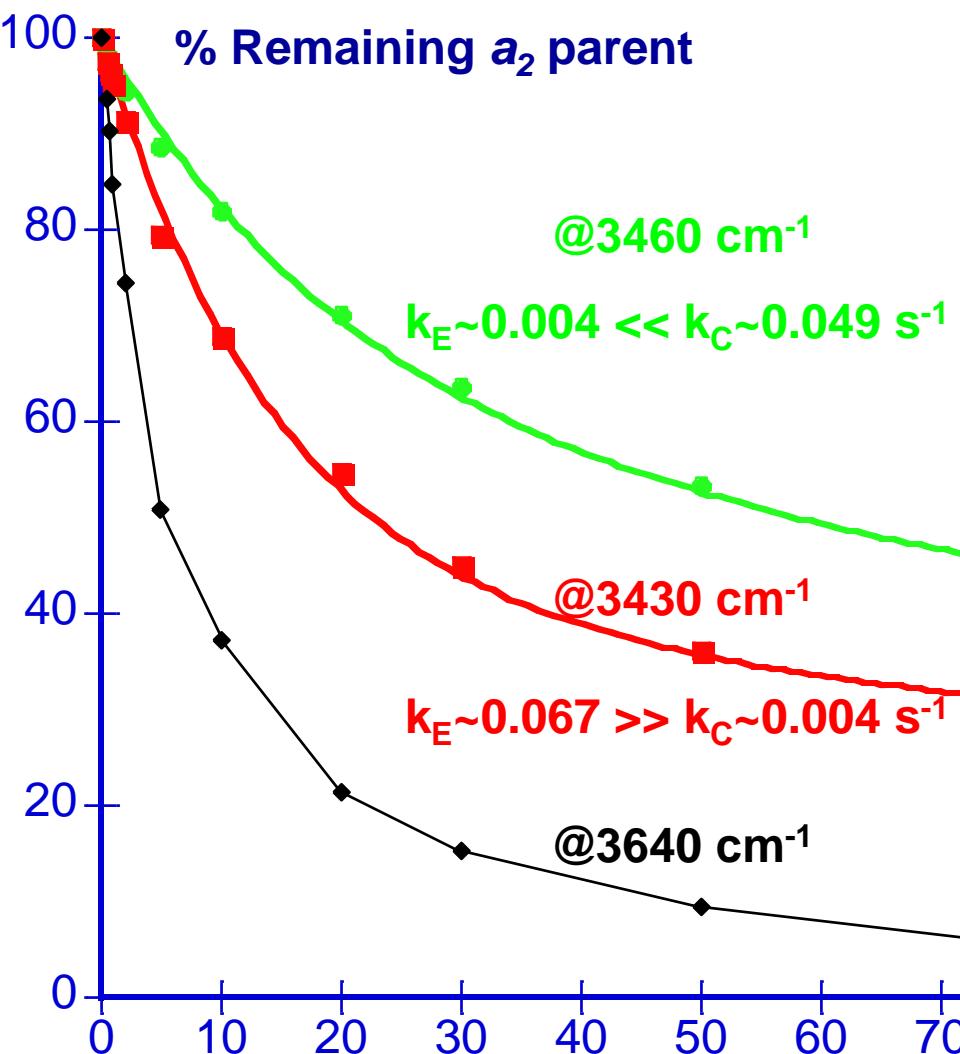
Isomer specific IR spectra:
IR-IR or IR-UV double resonance spectra

- ## IR-IR: K. Asmis (FHI Berlin)
  - See review on metal oxide clusters, PCCP **2012**, 14, 9270

- ## IR-IR: M.A. Johnson (Yale)
  - A. B. Wolk, C. M. Leavitt, E. Garand, M. A. Johnson, Ac
  - Applied on small peptides, J. Phys. Chem. Lett. **2012**, 3

- ## IR-IR: J. Roithova (Praha)
  - J. Jašík, J. Žabka, J. Roithová., D. Gerlich, IJMS **2013**, 3
  - Applied on organometallic chemistry, Angew. Chem. **201**
  - A review: J. Roithová, A. Gray, E. Andris, J. Jašík, D. Ge
    49, 223 – 230.

- ## IR-UV: T. R. Rizzo (Lausanne)
  - Stearns, J. A.; Boyarkin, O. V.; Rizzo, T. R. J. Am. Chem. Soc. **2007**, 129, 13820.

VIP

Juraj Jašík

Outline

- **Introduction**
  - Fragmentation under MS, need for specific activation methods
  - Infrared background

- **Organometallic Chemistry under MS/MS**
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  - IMS-MS/MS + Photodissociation
 - Separation of saccharide isomers and spectroscopy

Towards the IR spectroscopy of mobility selected isomers

- Coupling IMS and laser activation:
  - First: Dugourd, Jarrold and coworkers, *J. Chem. Phys.* **1999**, *111*, 7865.
  - IMS+UV: Reilly, Clemmer and coworkers, *JASMS* **2011**, *22*, 1477
  - IMS+UV/IR: Rizzo and coworkers, *Faraday Discuss.* **2011**, *150*, 243
  - IMS+UV: Bieske and coworkers, *PCCP* **2013**, *15*, 9540
  - IMS+IR: von Helden and coworkers, *JACS* **2014**

- In our lab at Orsay, integration of IMS and IR on Quadrupole Ion Trap
  - Differential Ion Mobility Spectrometry (DIMS)
  - Developed by Gary L. Glish (Chapel Hill, NC, USA), in collaboration with Bruker
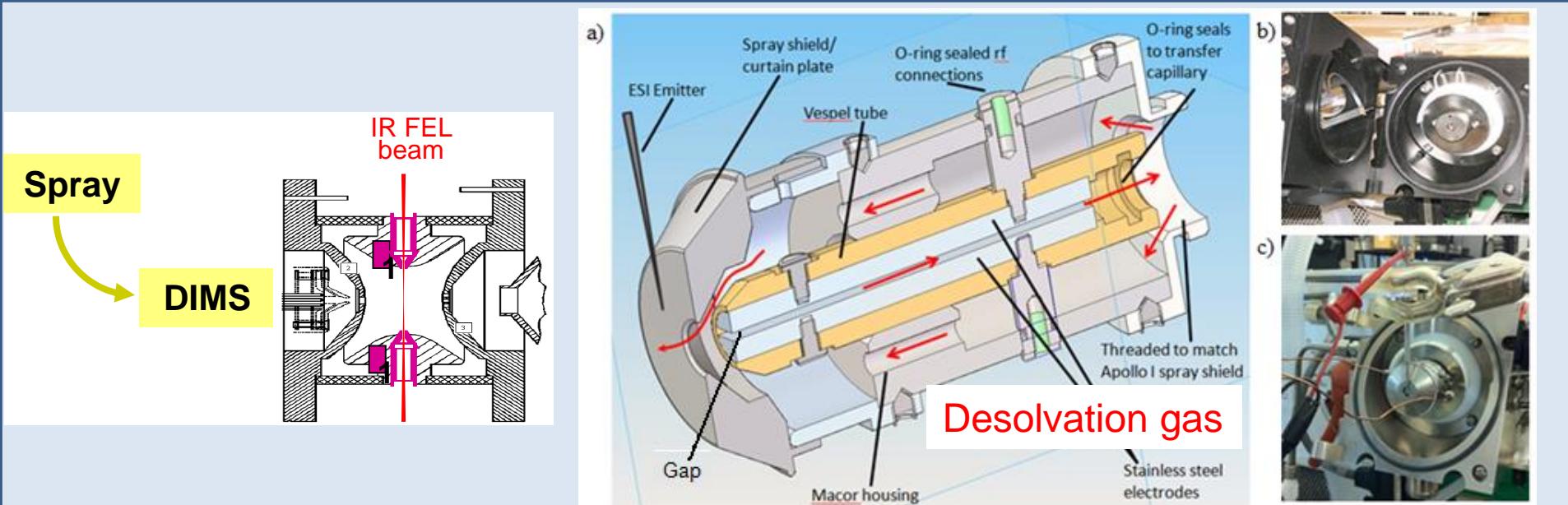
DMS-Ion trap-IR activation experimental

Differential ion Mobility Spectrometry (DMS)

Ion generation   Tra

ElectroSpray
Ionisation
(ESI)

Gla
cap

BRUKER

B
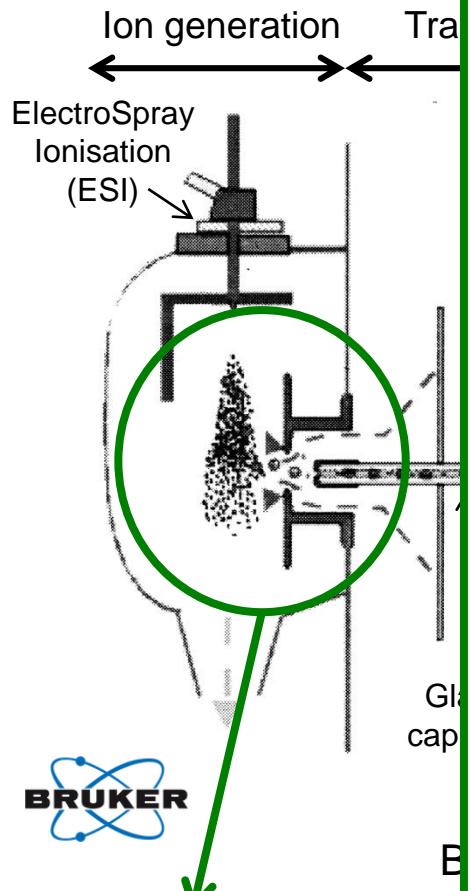
**Separation by
Ion Mobility**
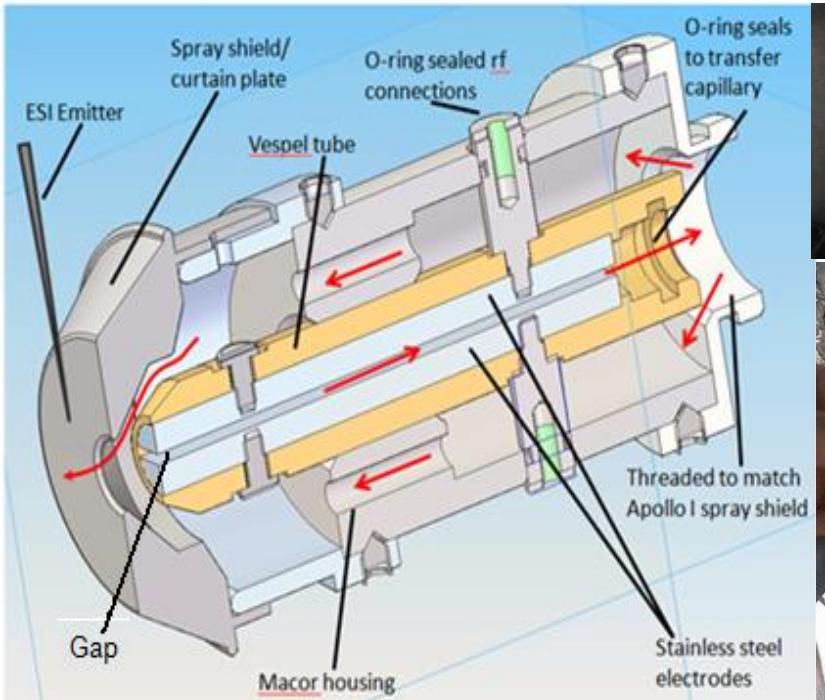
- DMS cell is inserted between the ESI emitter and the capillary transfer.
- The N_2 desolvation gas is partially redirected through the outer housing of the DMS assembly to serve as an ion carrier gas as well as for ion desolvation.
- Modifiers can be added to the N_2 carrier gas flow for improving ion separation.

Isenberg SL, Armistead PM, Glish GL. Optimization of peptide separations by differential ion mobility spectrometry. J Am Soc Mass Spectrom. 2014;25(9):1592-9

Separation principle and D...

Carrier gas (N₂)

Electrode

K, ion mobility coefficient

V = K x E   V = K(E) x E

DIMS Spectrum

Low field re...

...tric field, E

Intensity

CV

⟨CV₁⟩ ⟨CV₂⟩ ⟨CV₃⟩

--▶ To the mass-spectrometer

High-voltage asymmetric RF

Compensation Voltage, CV
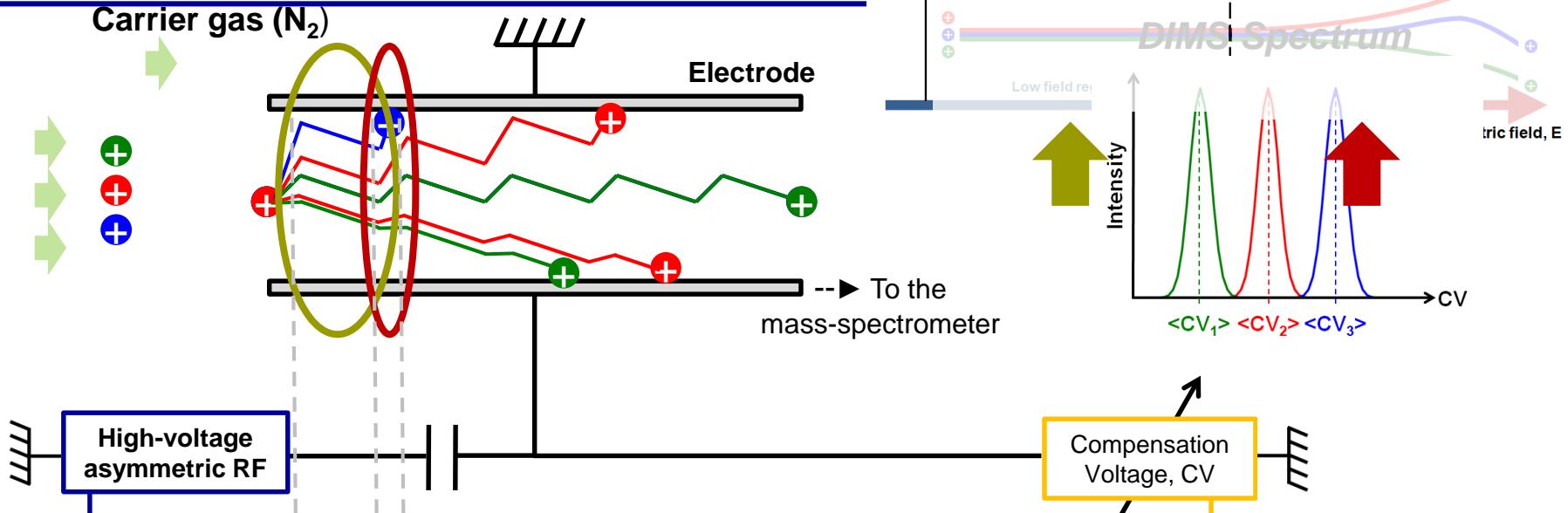
- ➤ **Reduction of background signal.**
- ➤ **DMS filtered ions can be accumulated: high signal-to-noise => MS/MS analysis**
- ➤ **DMS-selected isomers can be characterized**

- ○ **No clear understanding of the ion mobility under high electric field.**
- ○ **No cross section measurement.**

Separation of Saccharides using DIMS: effect of M⁺(M=Li, Na, K) ionizing cation
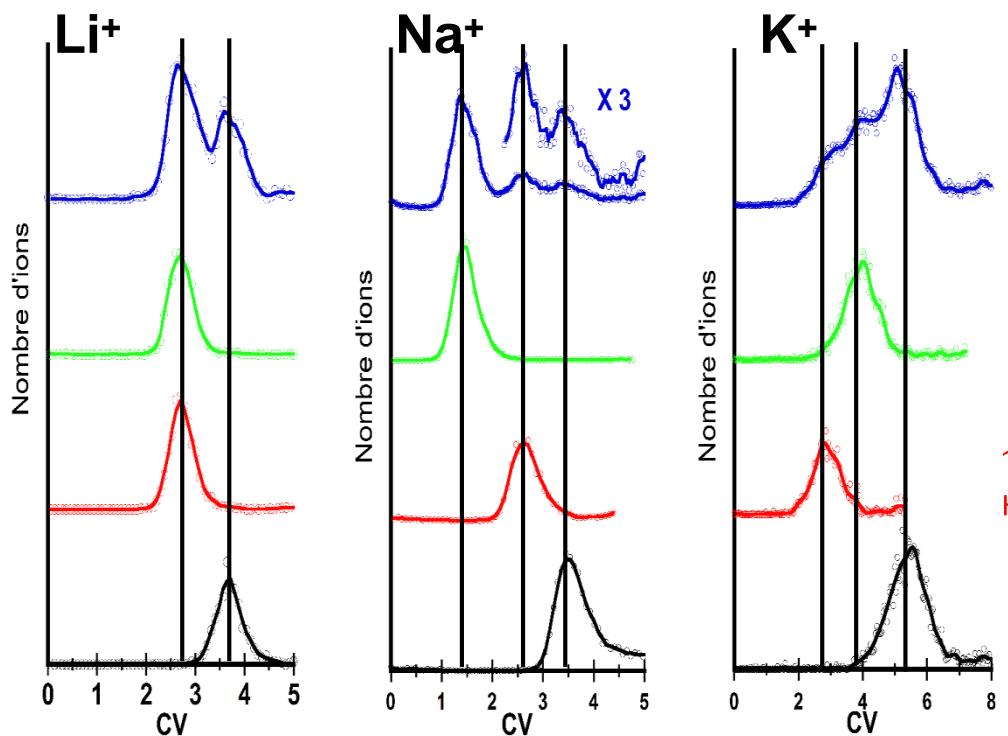
Iso-mixture of 3 sugars

Me-α-glucose

Me-β-glucose
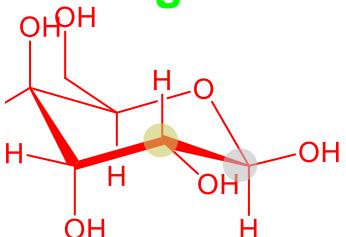
Me-α-mannose
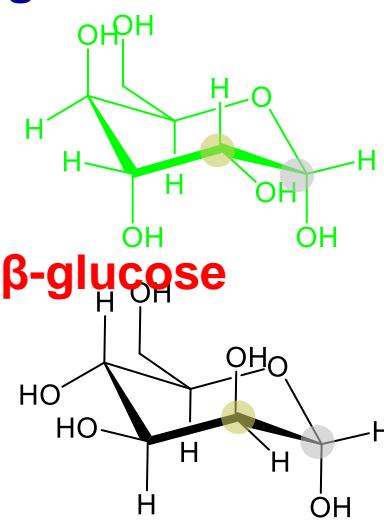
- **For each metal/sugar adduct: a single peak (fwhm~0.5 V)**

- **Two glucose α/β anomers best separated with Na⁺; resolution for anomer separation (R=1.41), to be compared to 1.12 (DTIMS) or 0.44 (TWIMS), see Hill and coworkers,** *Anal. Chem. 2012, 84 (7), 3231-3239*

- **Anomers separated, but reverse ordering using Na⁺ and K⁺**

 - **=> Change of structure (M⁺ coordination and/or hydrogen bonding)?**

Hernandez, Isenberg, Steinmetz, Glish, Maitre, J. Chem. Phys. A 2015

Selective ion-molecule reactions of DIMS- and mass-selected ions with water

DIMS- and Mass-Selected Li⁺(Sugar) adduct is allowed to react with water

Depletion of Li⁺(Sugar) / time

Mass Spectra at 1.5 sec. reaction time
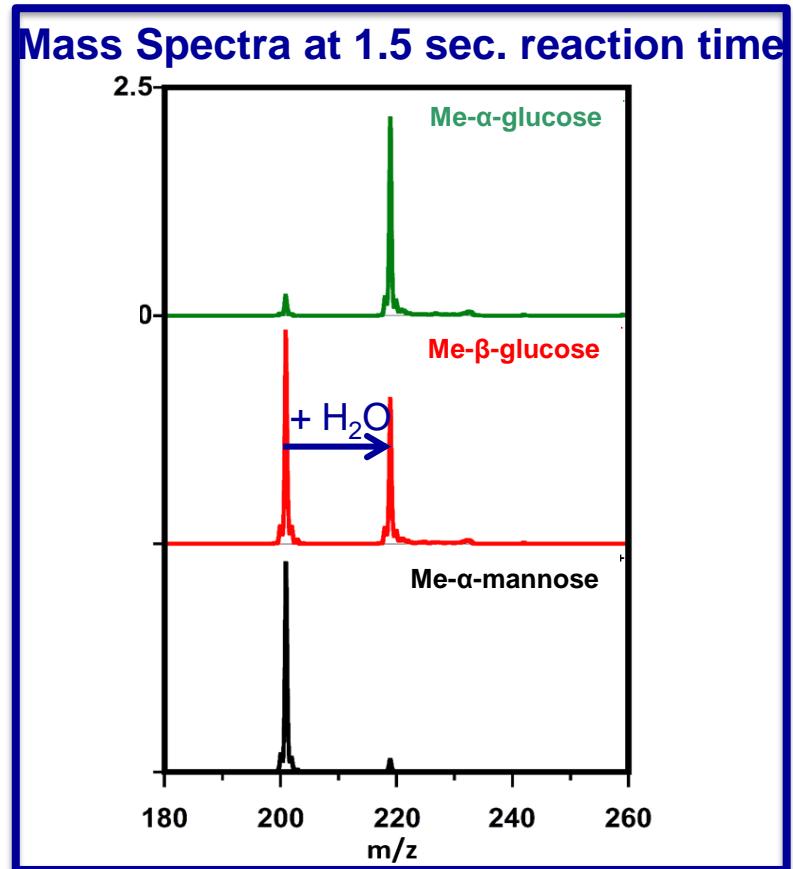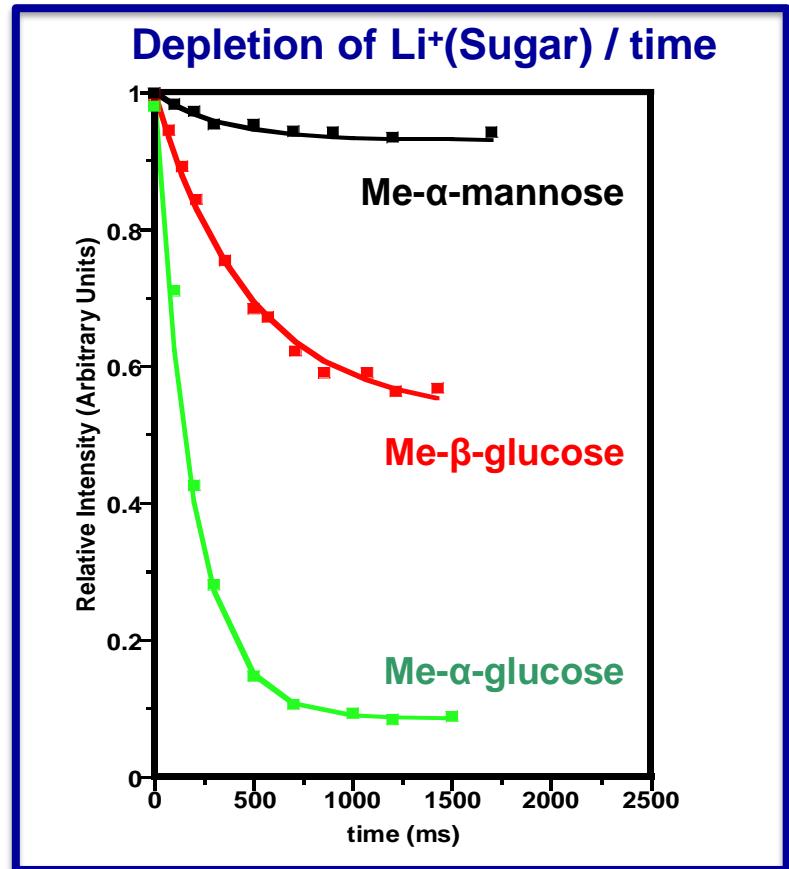
- **Reaction yields: α-Glucose $\geq$ β-Glucose >> α-Mannose**
- **Assuming that water binds to Li⁺, this may suggest that the denticity of sugar (Coordination Number (CN) of Li⁺) is different (2 or 3?)**

Infrared Spectroscopy of singly-hydrated DIMS-selected isomers

1a) Li⁺(H₂O)(MeβGlu)

1b) Li⁺(H₂O)(MeαGlu)

1c) Li⁺(H₂O)(MeαMan)

IRMPD Efficiency

Wavenumber (cm⁻¹)
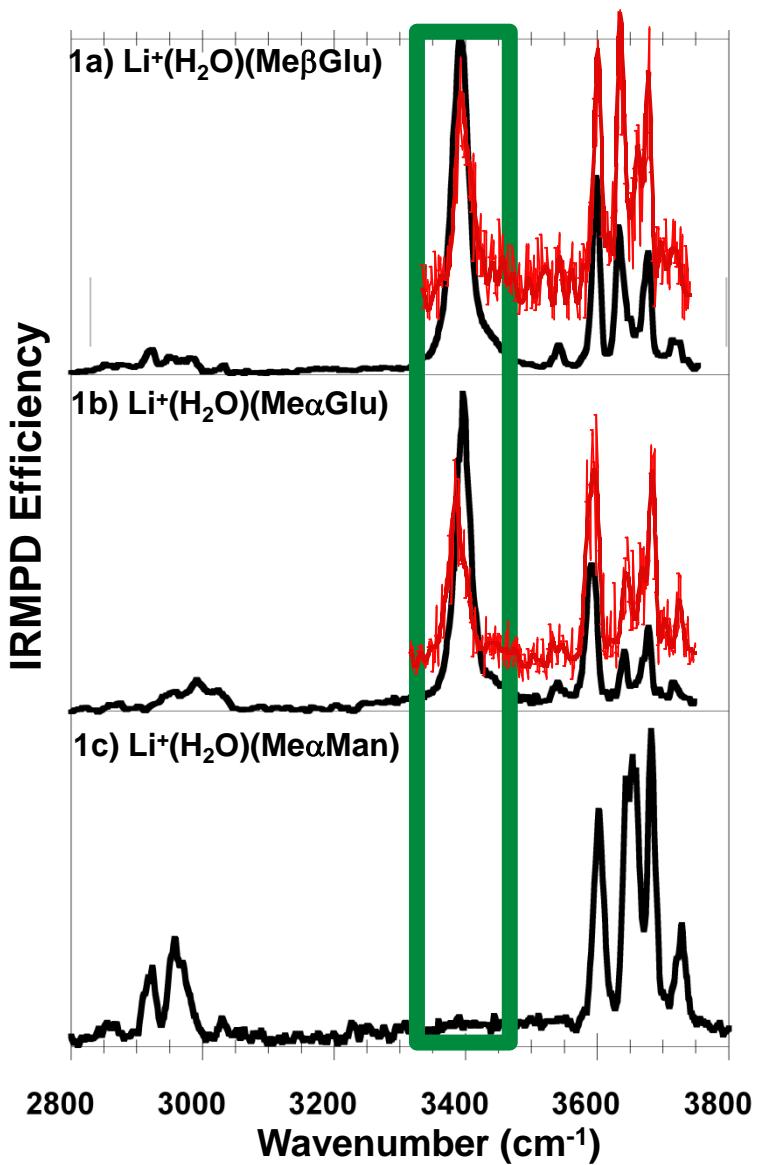
- **IR spectroscopy performed in water tagged DIMS-selected ions**
- **Reference spectra, i.e. ESI of:**

    Li⁺(H₂O)(MeβGlu),
    Li⁺(H₂O)(MeαGlu),
    Li⁺(H₂O)(MeαMan).

- **IR spectra of DIMS- and Mass-Selected isomers**

- **Band assignment?**
    - **6 OH stretches (sugar and water)**
    - **Multiple weak CH (~3000 cm⁻¹) can be seen**

- **Band at ~3400 cm⁻¹ (α/β-glucose)**
   - **Signature (=>specific IR activation)?**
    - **Signature of which bonding motif?**

Structure of Li$^+$(Me-α-Glucose) without and with H$_2$O
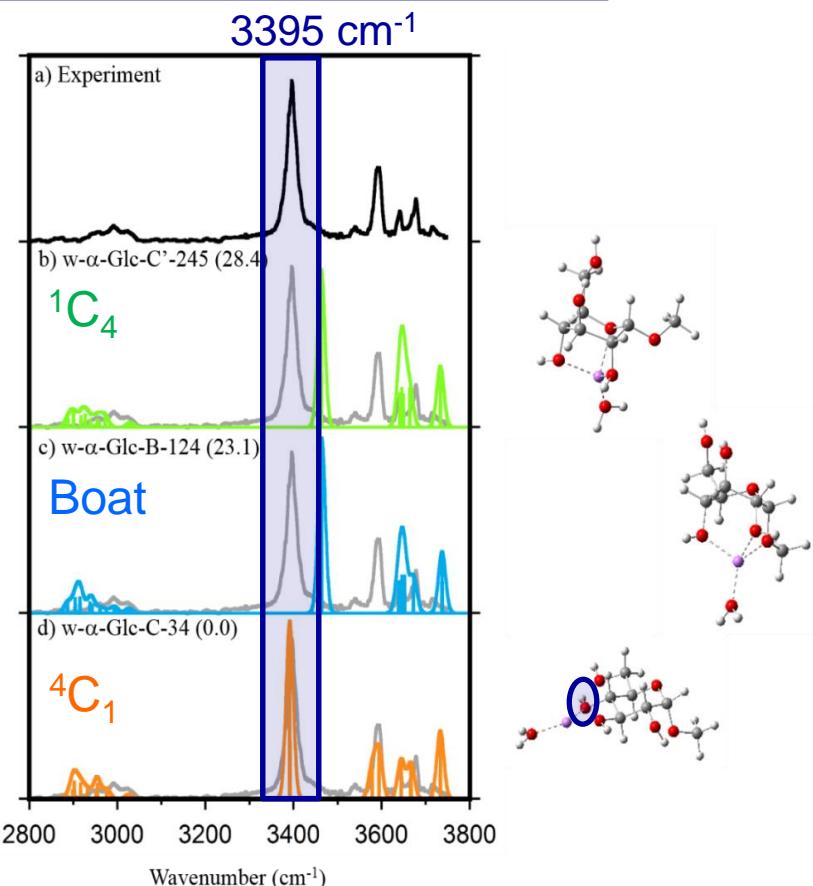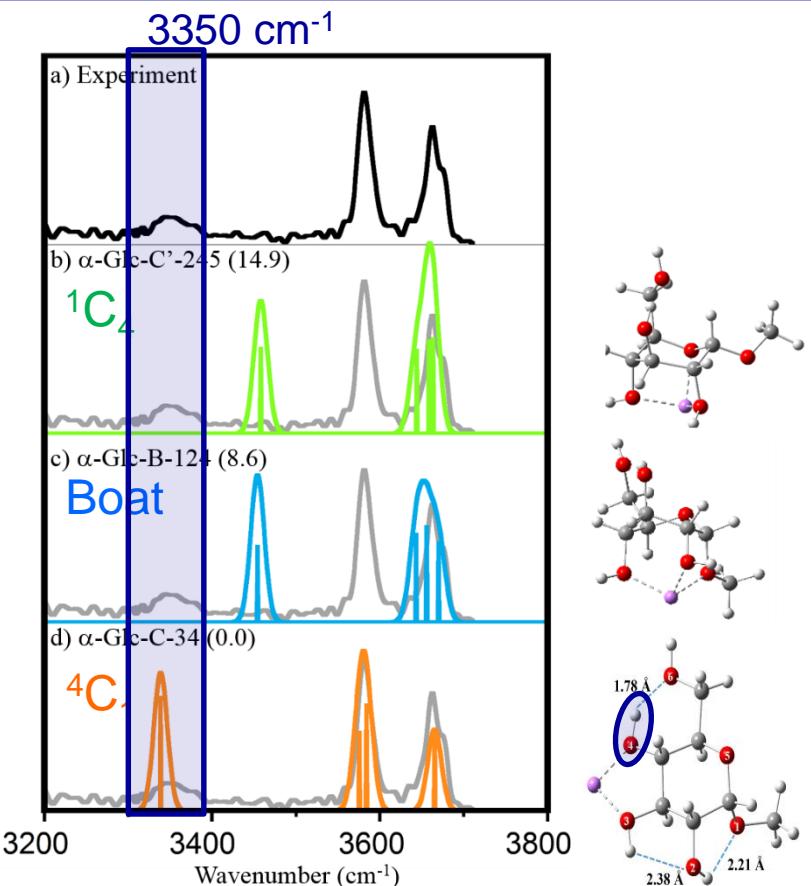
- Observed IR spectra is consistent with the predicted spectrum of the lowest-energy structure
- Position of the bands: exp/theory agreement to within 1%
- IR diagnostic band (HB DA OH stretch) slightly blue shifted upon water addition: consistent with decreased charge on lithium

Glucose/mannose structural difference consistent with IRMPD and DIMS
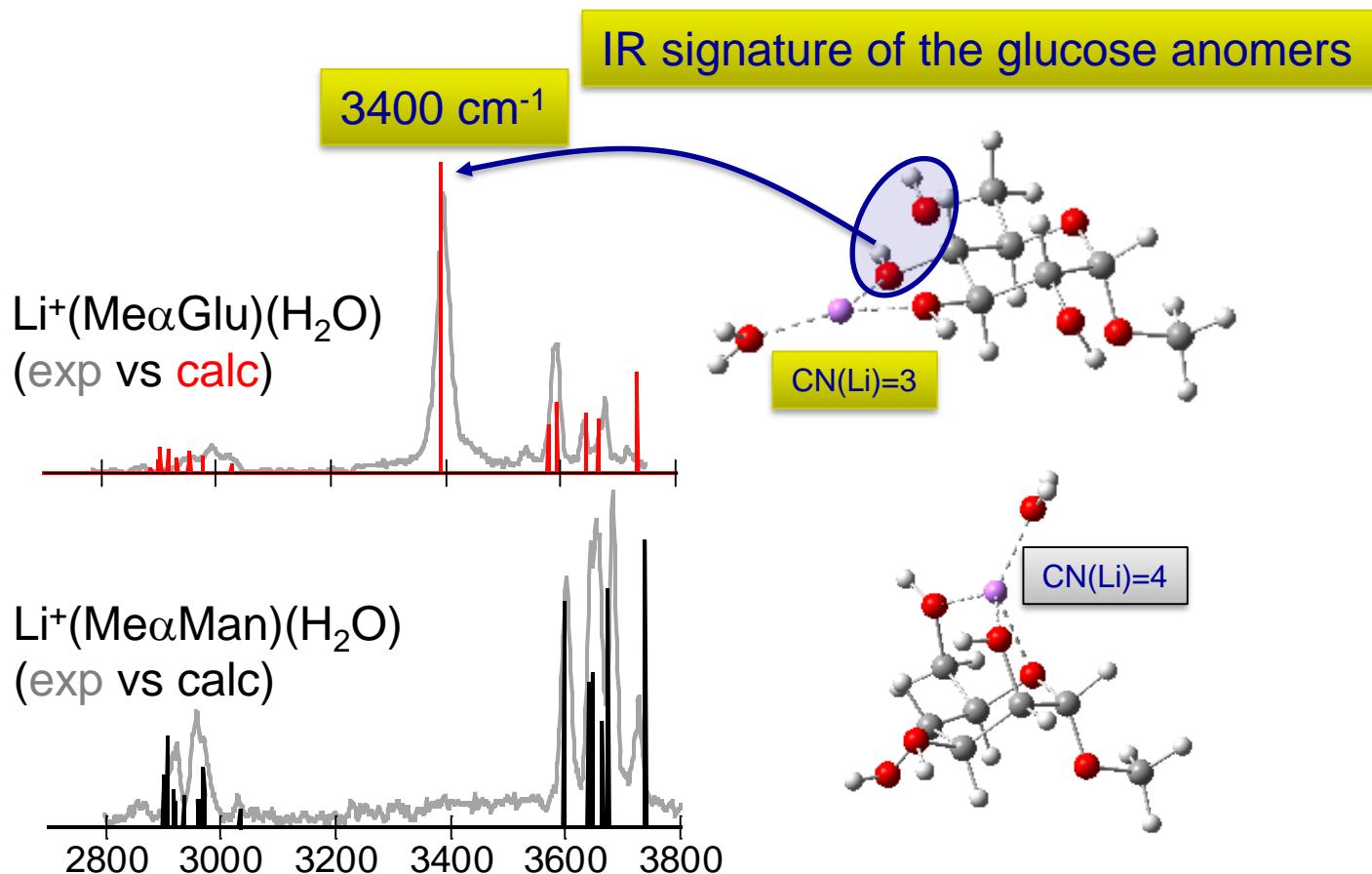
IR signature of the glucose anomers

3400 cm^{-1}

Li$^+$(MeαGlu)(H$_2$O)
(exp vs calc)

CN(Li)=3

Li$^+$(MeαMan)(H$_2$O)
(exp vs calc)

CN(Li)=4

2800 3000 3200 3400 3600 3800

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