EU_FT-ICR_MS Short Course 3
Roma, 25-27 June 2019

FT-ICR ion chemistry lab classes: Reaction costants and ion-molecule reactions model interpretation

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Outline

1. Introduction: Ion molecule reactions
2. Equipment
3. Software
4. Experiments
5. Summary

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Introduction

There are several reasons why the development of ion-molecule reactions strategies offers a promising tool for solving fundamental/analytical problems.

- Speed
- Efficiency
- Small quantities of reagents are needed
- A wide set of analytes can be investigated
- Intermediates labile in solution can be isolated and examined

With the availability of MS^n , reaction pathways, mechanisms, thermodynamic parameters, kinetic aspects, and reactant/product structures can be explored in detail by multistep experiments.

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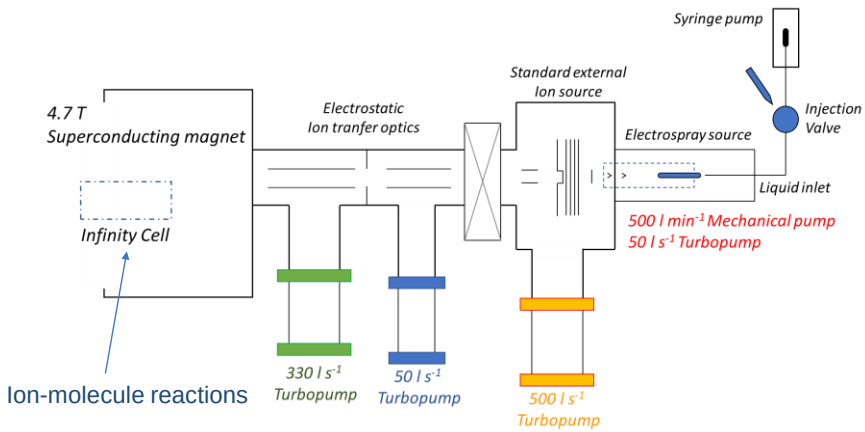
Hardware

Preparation of sample
↓
ESI FT-ICR MS injection
↓
Selection of target ion
↓
Introduction of neutral gas
↓
Ion-molecule reactions



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Experimental Overview

- Addition reaction
- Consecutive reactions
- FT-ICR MS equilibria
  - Test of achieving equilibrium: change the pressure
  - Test of achieving equilibrium: reversibility
- Equilibrium? No! An unreactive fraction!!!
- Advanced kinetics models
- H/D Exchange

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Outline
Introduction
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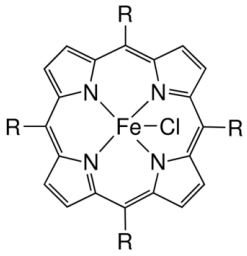
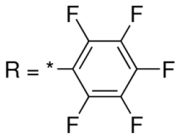
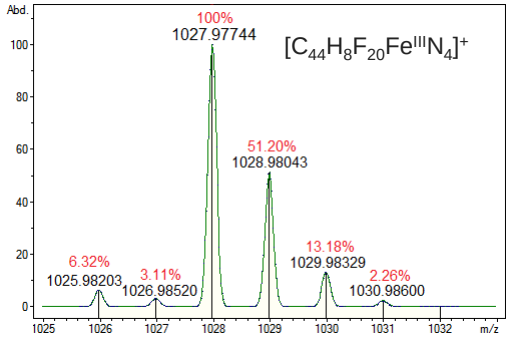
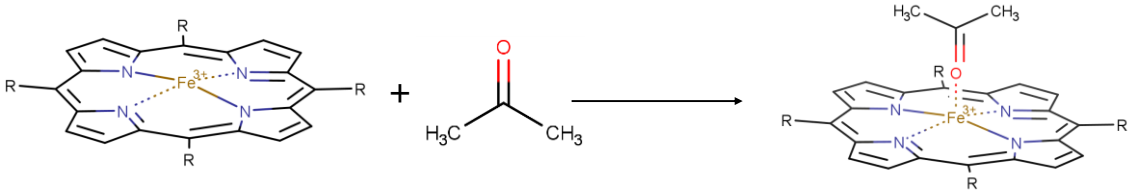
Subject





5,10,15,20-Tetrakis(pentafluorophenyl)-21*H*,23*H*-porphyrin iron(III) chloride = $[(TPFPP)Fe^{III}]^+$





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Outline
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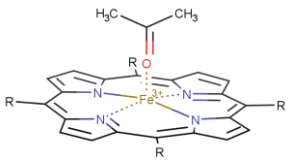
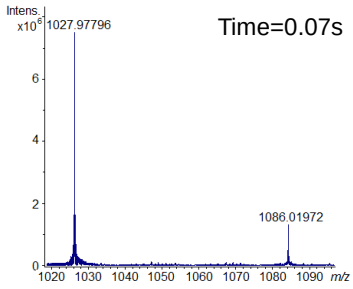
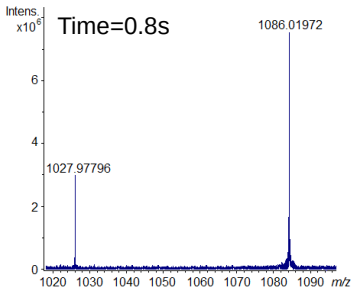
FT-ICR MS kinetics: data analysis

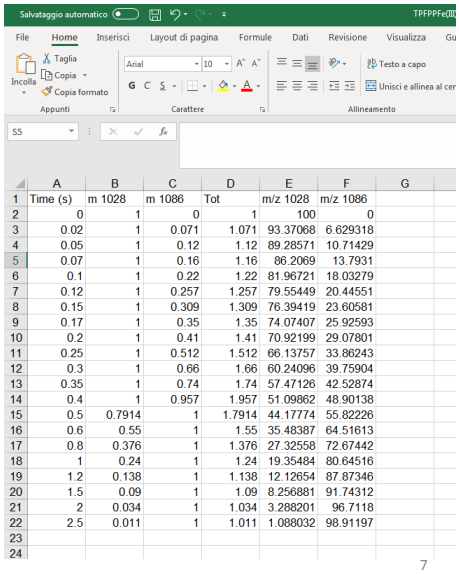


m/z_{theo} 1086.01931

Δppm=0.4







	A	B	C	D	E	F	G
1	Time (s)	m 1028	m 1086	Tot	m/z 1028	m/z 1086	
2	0	1	0	1	100	0	
3	0.02	1	0.071	1.071	93.37068	6.629318	
4	0.05	1	0.12	1.12	89.28571	10.71429	
5	0.07	1	0.16	1.16	86.2069	13.7931	
6	0.1	1	0.22	1.22	81.96721	18.03279	
7	0.12	1	0.257	1.257	79.55449	20.44551	
8	0.15	1	0.309	1.309	76.39419	23.60581	
9	0.17	1	0.35	1.35	74.07407	25.92593	
10	0.2	1	0.41	1.41	70.92199	29.07801	
11	0.25	1	0.512	1.512	66.13757	33.86243	
12	0.3	1	0.66	1.66	60.24096	39.75904	
13	0.35	1	0.74	1.74	57.47126	42.52874	
14	0.4	1	0.957	1.957	51.09862	48.90138	
15	0.5	0.7914	1	1.7914	44.17774	55.82226	
16	0.6	0.55	1	1.55	35.48387	64.51613	
17	0.8	0.376	1	1.376	27.32558	72.67442	
18	1	0.24	1	1.24	19.35484	80.64516	
19	1.2	0.138	1	1.138	12.12654	87.87346	
20	1.5	0.09	1	1.09	8.256881	91.74312	
21	2	0.034	1	1.034	3.288201	96.7118	
22	2.5	0.011	1	1.011	1.088032	98.91197	
23							
24							

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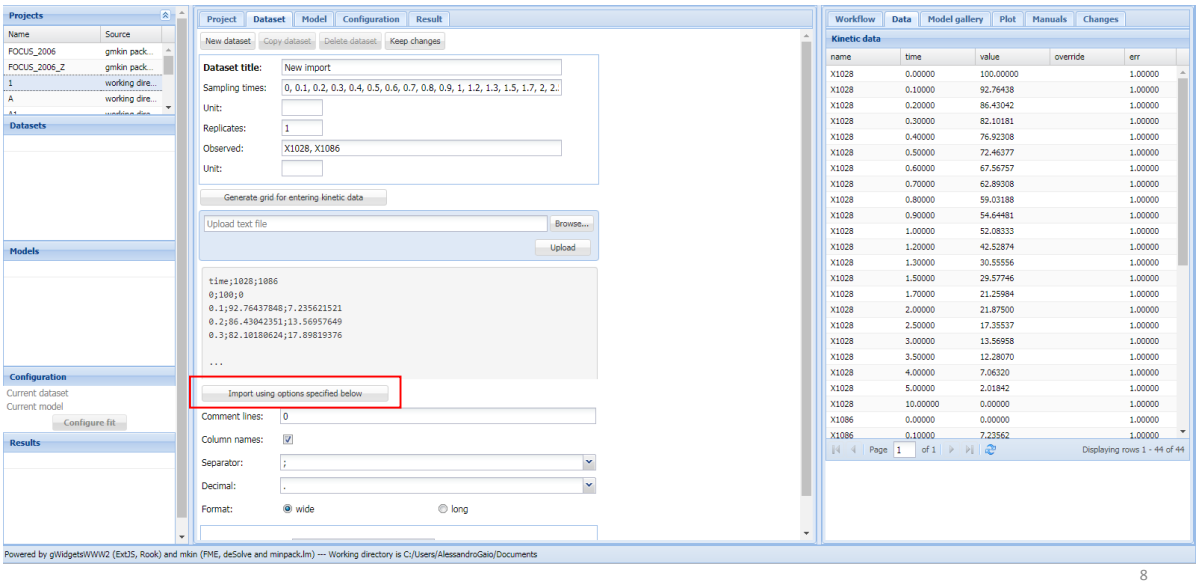
Dataset uploading in gmkin software



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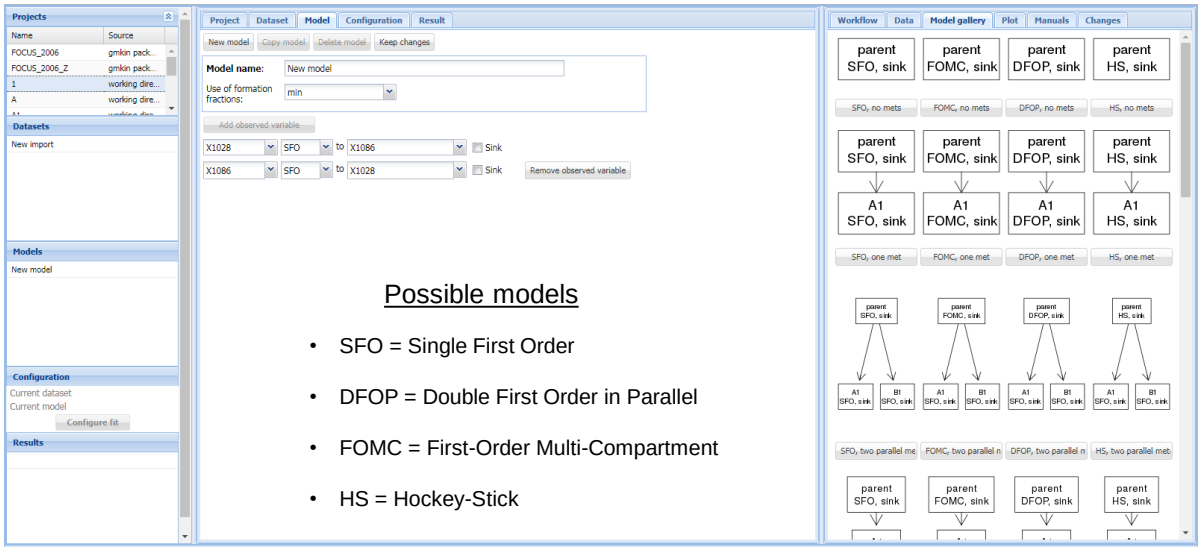
Model setting



Possible models

- SFO = Single First Order
- DFOP = Double First Order in Parallel
- FOMC = First-Order Multi-Compartment
- HS = Hockey-Stick

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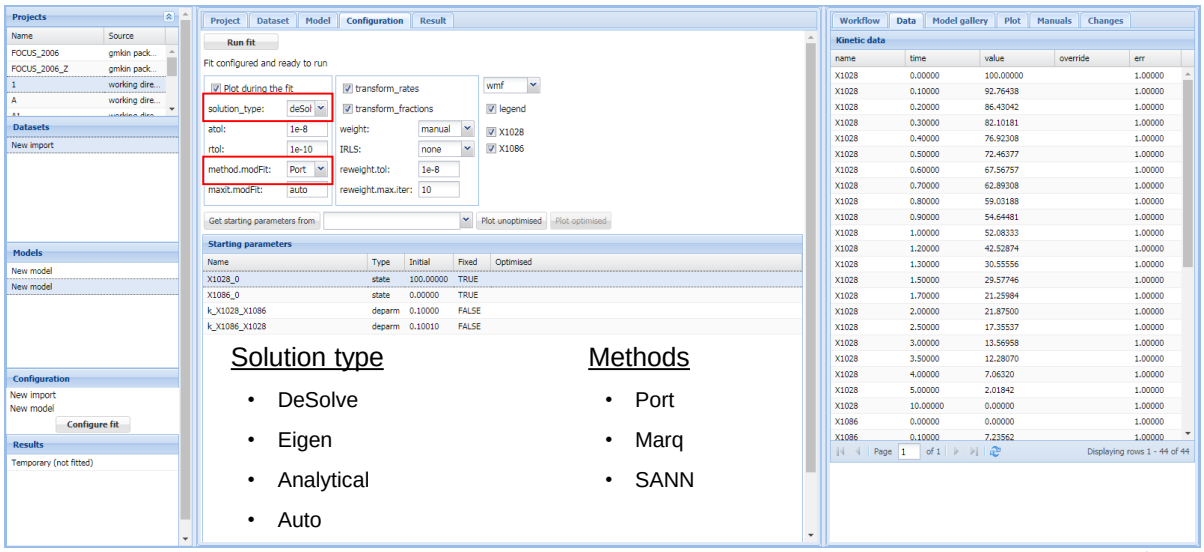
Fitting configuration



Solution type

- DeSolve
- Eigen
- Analytical
- Auto

Methods

- Port
- Marq
- SANN

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Solution types and Fitting methods

Solution Types

- If set to eigen, the solution type is based on the spectral decomposition of the coefficient matrix (where is possible)
- If set to deSolve, a numerical ode (ordinary differential equation) is used
- If set to analytical, an analytical method is applied to solve differential equations
- If set to auto, the best solution type is applied (arbitrary chosen by the software)

Fitting methods

- Marq: The purpose of Marq is to minimize the sum square of the vector returned by the given function, by a modification of the Levenberg-Marquardt algorithm. The user may also provide a function jac which calculates the Jacobian.
- Port: Unconstrained and box-constrained optimization using PORT routines.
- SANN: General-purpose optimization based on Nelder–Mead, quasi-Newton and conjugate-gradient algorithms. It includes an option for box-constrained optimization and simulated annealing

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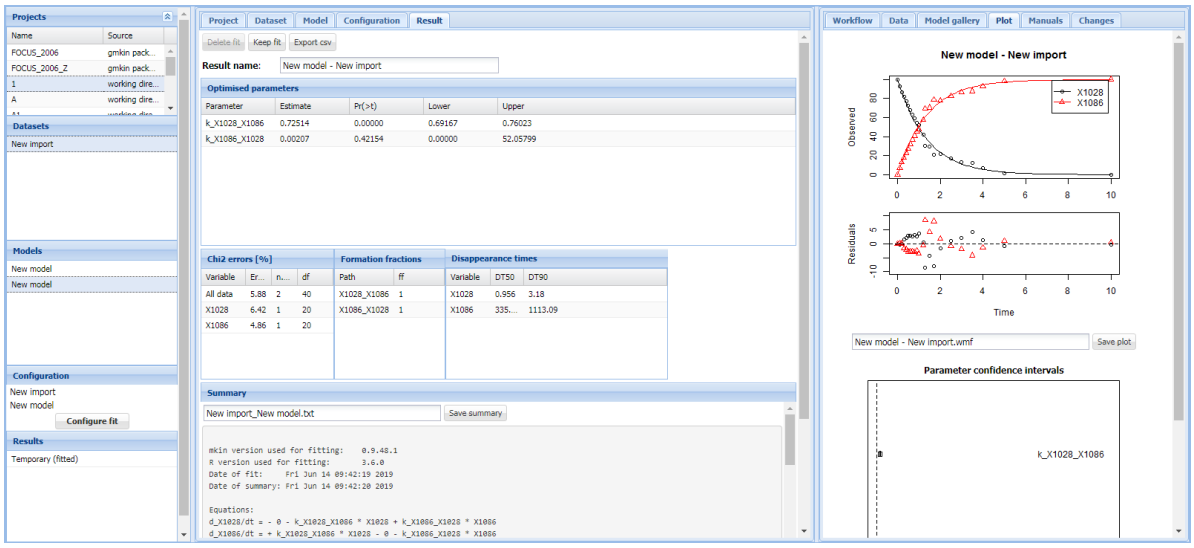
Outcome



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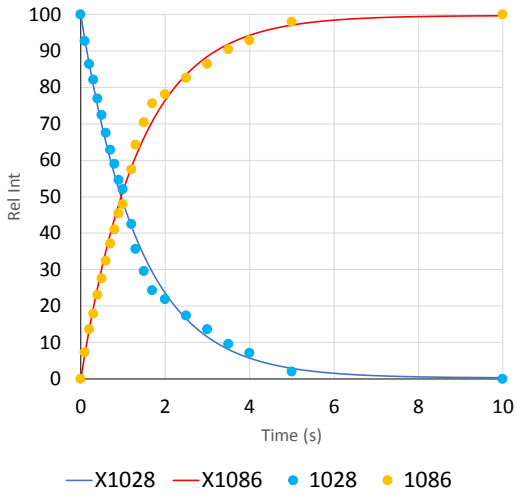
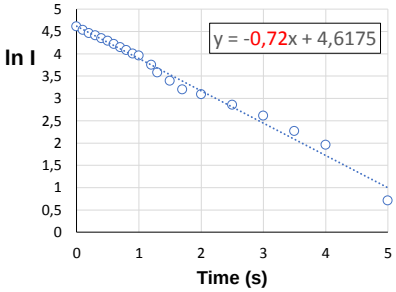
Addition reaction

$[(TPFPP)Fe^{III}]^+$ + Acetone (P_{obs}= 4.3 10^{-8} mbar)





$[1028]^+ + [58] \underset{k_{-1}}{\overset{k_{obs}}{\rightleftharpoons}} [1086]^+$

$k_{obs(fit)} = 0.73\ s^{-1}$ $k_{-1(fit)} = 2\ 10^{-3}\ s^{-1}$

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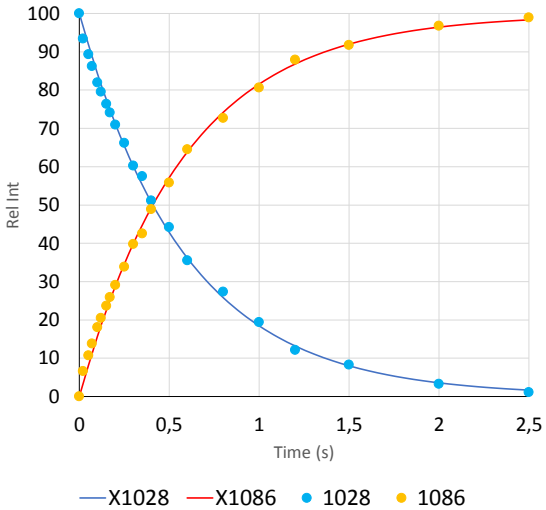
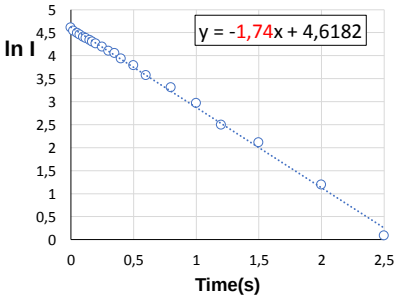
Addition reaction

$[(TPFPP)Fe^{III}]^+$ + Acetone (P_{obs}= 1.0 10^{-7} mbar)





$[1028]^+ + [58] \underset{k_{-1}}{\overset{k_{obs}}{\rightleftharpoons}} [1086]^+$

$k_{obs(fit)} = 1.70\ s^{-1}$ $k_{-1(fit)} = 5\ 10^{-3}\ s^{-1}$

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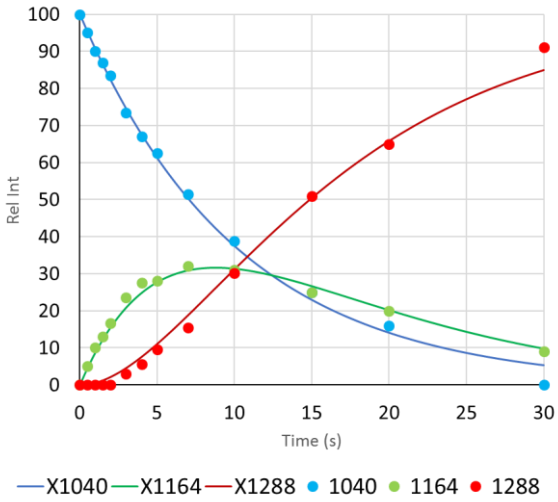
Consecutive reactions

$[(TPFPP)Cr^{V}O]^{+}$ + $P(OMe)_3$ (P_{obs}= 1.0 10^{-8} mbar)



$[1040]^+ + [124] \underset{k_{-1} = 2.9\ 10^{-11}}{\overset{k_{1obs} = 0.10\ s^{-1}}{\rightleftharpoons}} [1164]^+$

$[1164]^+ + [124] \underset{k_{-2} = 2.5\ 10^{-13}\ s^{-1}}{\overset{k_{2obs} = 0.13\ s^{-1}}{\rightleftharpoons}} [1288]^+$

$[1040]^+ \xrightarrow{[124]} [1164]^+ \xrightarrow{[124]} [1288]^+$

$[1164]^+ \xrightarrow[-\ PO(OMe)_3]{CID} [1024]^+$

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Law of mass action

$A^+ + B \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} C^+$

Equilibrium

$$\frac{d[C^+]}{dt} = k_1 \times [A^+] \times [B] - k_{-1} \times [C^+]$$

$$k_1 \times [A^+] \times [B] = k_{-1} \times [C^+] \longrightarrow K_{eq} = \frac{Int_{[C^+]}}{Int_{[A^+]}P_{[B]}} \longrightarrow K_{eq} = \frac{k_1}{k_{-1}}$$

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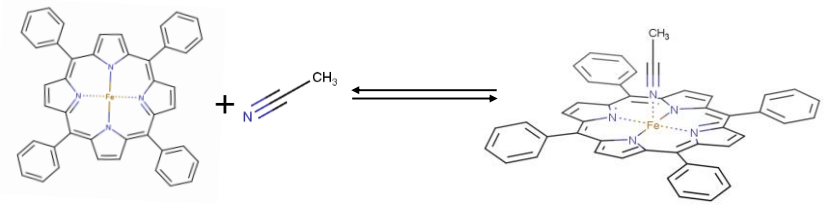
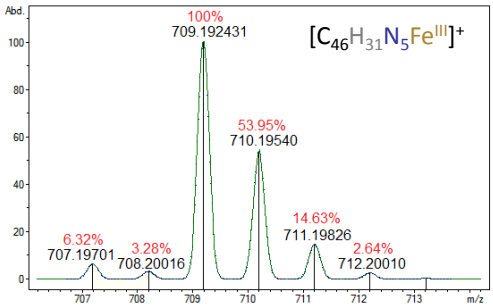
FT-ICR MS equilibria

$[(TPP)Fe^{III}]^+ + CH_3CN \rightleftharpoons [(TPP)Fe^{III}CH_3CN]^+$

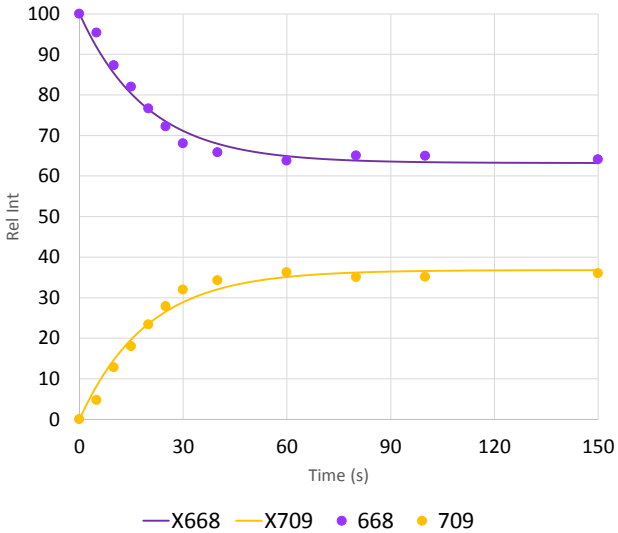




time	m/z 668	m/z 709
0	100	0
5	95.29	4.71
10	87.26	12.74
15	82.01	17.99
20	76.65	23.35
25	72.17	27.83
30	68.03	31.97
40	65.79	34.21
60	63.78	36.22
80	64.99	35.01
100	64.93	35.07
150	64.06	35.94

1. Test of achieving equilibrium: change the pressure

Addition reaction : $[(TPP)Fe^{III}]^+ + CH_3CN$ (P_{obs}=1.2 10^{-7} mbar)



$$[668]^+ + [41] \underset{k_{-1}}{\overset{k_{obs}}{\rightleftharpoons}} [709]^+$$

$k_{obs} = 0.019\ s^{-1}$ $k_{-1} = 0.032\ s^{-1}$

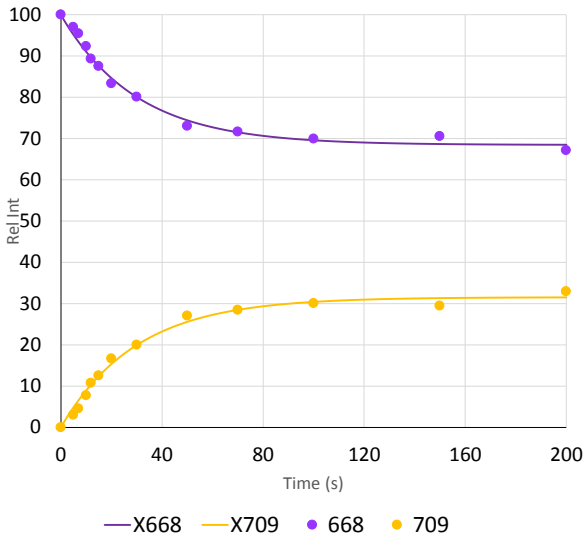
$$K_{eq} = \frac{I_P}{I_R\ P_{CH_3CN}} \qquad K_{eq} = \frac{k_{obs}}{k_{-1} P_{CH_3CN}}$$

$P_{CH_3CN} = 2.6\ 10^{-10}$ atm

$K_{eq\ (exp)} = 2.4\ 10^9$ $K_{eq\ (fit)} = 2.3\ 10^9$

1. Test of achieving equilibrium: change the pressure

Addition reaction : $[(TPP)Fe^{III}]^+ + CH_3CN$ (P_{obs}= 9.1 10^{-8} mbar)



$$[668]^+ + [41] \underset{k_{-1}}{\overset{k_{obs}}{\rightleftharpoons}} [709]^+$$

k_{obs} = 0.011 s^{-1} k_{-1} = 0.023 s^{-1}

$$K_{eq} = \frac{I_P}{I_R P_{CH_3CN}} \qquad K_{eq} = \frac{k_{obs}}{k_{-1} P_{CH_3CN}}$$

P_{CH_3CN} =1.9 10^{-10} atm

$K_{eq\ (exp)}$ = 2.4 10^9 $K_{eq\ (fit)}$ = 2.3 10^9

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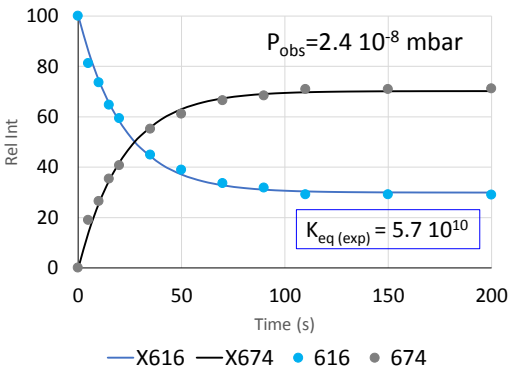
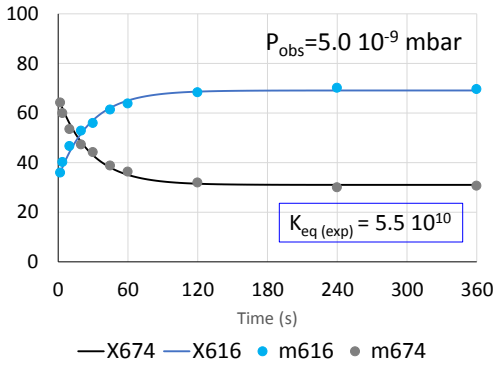
2. Test of achieving equilibrium: reversibility

Addition reaction: $[Fe^{III}\text{-heme}]^+$+ Acetone





$$[616^+] + [58] \underset{k_{-1} = 0.014\ s^{-1}}{\overset{k_{obs} = 0.03\ s^{-1}}{\rightleftharpoons}} [674^+]$$

$K_{eq\ (fit)}$ = 5.2 10^{10}

$$[674^+] \underset{k_{obs}=0.025\ s^{-1}}{\overset{k_{-1} = 0.011\ s^{-1}}{\rightleftharpoons}} [616^+] + [58]$$

$K_{eq\ (fit)}$ = 5.2 10^{10}

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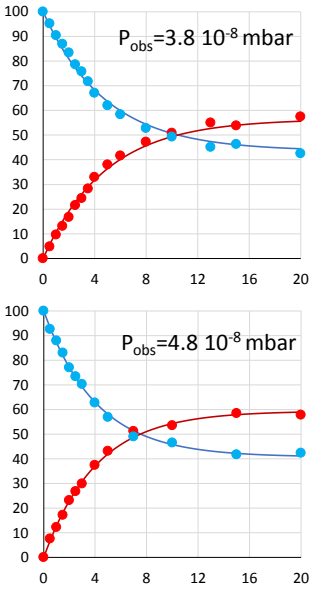
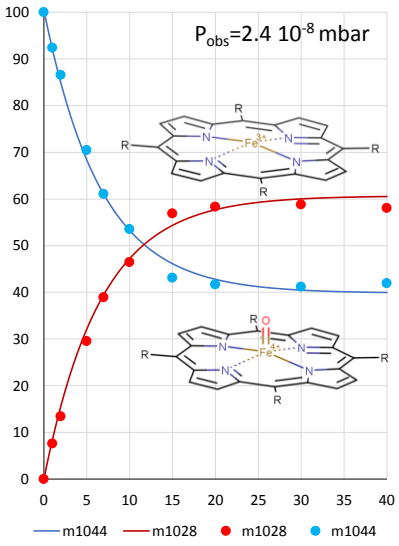
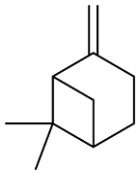
Equilibrium? No! An unreactive fraction!!!



$[(TPFPP)Fe^{III}O]^+$ + β-pinene





$[1044]^+ + [136] \xrightarrow{k_1,k_2} [1028]^+ + [152]$

P_{obs}	k_{obs} (s^{-1})	k_2 (s^{-1})	NRF (%)
2.4 10^{-8} mbar	0.15	6.6 10^{-13}	40
3.8 10^{-8} mbar	0.21	2.6 10^{-12}	43
4.8 10^{-8} mbar	0.25	1.9 10^{-12}	41

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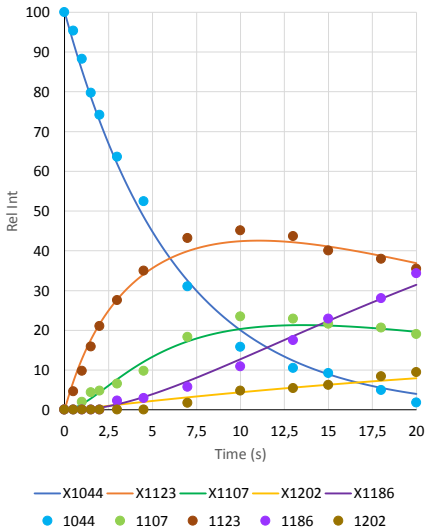
Advanced kinetics models

$[(TPFPP)Fe^{III}]^+$ + pyridine (P_{obs}=1.2 10^{-7} mbar)



$[1044]^+ \xrightarrow[OAT]{py} [1123]^+ \underset{}{\overset{py}{\rightleftharpoons}} [1202]^+$

$[1123]^+ \xrightarrow[-pyO]{py} [1107]^+ \xrightarrow{py} [1186]^+$

$[1044]^+ + [py] \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} [1123]^+$ $\quad k_{1obs} = 0.15\ s^{-1}$ $\quad k_{-1} = 6.2\ 10^{-16}\ s^{-1}$

$[1123]^+ + [py] \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} [1107]^+ + [pyO]$ $\quad k_{2obs} = 0.08\ s^{-1}$

$[1123]^+ + [py] \underset{k_{-3}}{\overset{k_3}{\rightleftharpoons}} [1202]^+$ $\quad k_{3obs} = 0.03\ s^{-1}$ $\quad k_{-3} = 0.17\ s^{-1}$

$[1107]^+ + [py] \underset{k_{-4}}{\overset{k_4}{\rightleftharpoons}} [1186]^+$ $\quad k_{4obs} = 0.12\ s^{-1}$ $\quad k_{-4} = 5.11\ 10^{-11}\ s^{-1}$

$[1123]^+ \xrightarrow[-\ pyO]{CID} [1028]^+$

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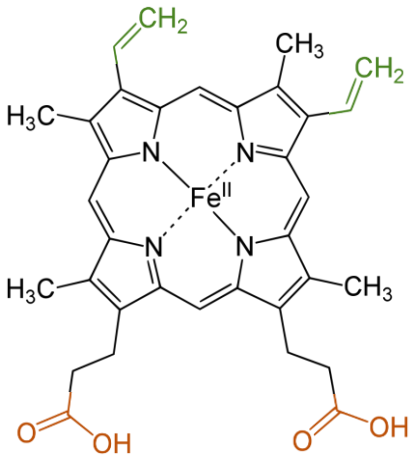
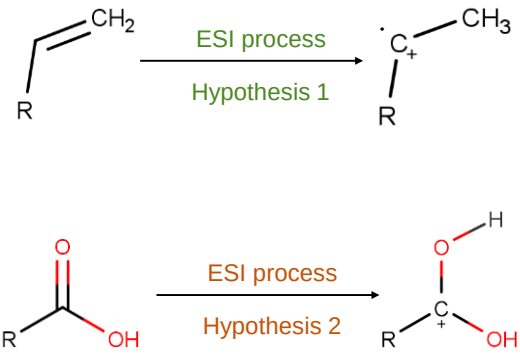
H/D exchanges

$[Fe^{II}\text{-hemeH}]^+ + ND_3$





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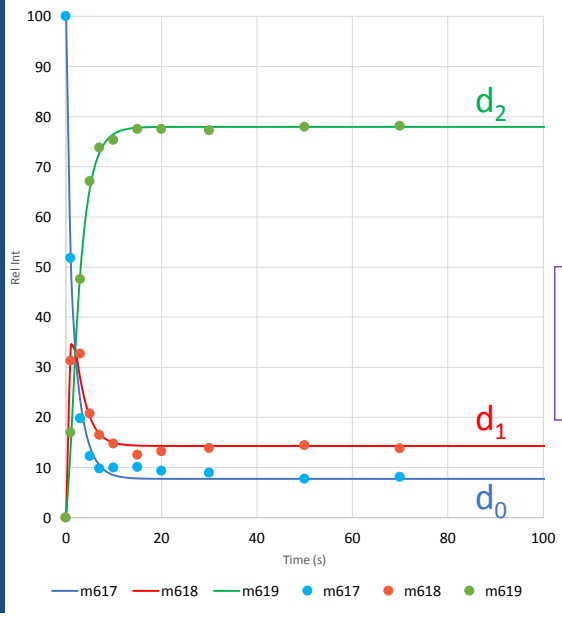
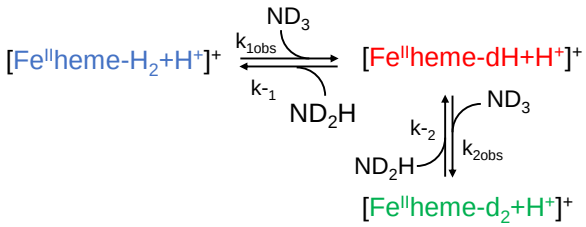
H/D exchange reactions: $[Fe^{II}\text{-hemeH}]^+ + ND_3$ ($P_{obs}=3.0\ 10^{-8}$ mbar)





$$R^+CO_2H + ND_3 \rightarrow [R^+CO_2H\ ND_3] \rightarrow [R^+CO_2^-\ ND_3H^+]$$

$$\rightarrow [R^+CO_2D\ ND_2H] \rightarrow R^+CO_2\ D + ND_2H]$$

$k_{1obs} = 0.84\ s^{-1}$ $k_{2obs} = 0.66\ s^{-1}$

$k_{-1} = 0.46\ s^{-1}$ $k_{-2} = 0.12\ s^{-1}$

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Summary and Conclusions

Doubts?

Questions?

Any ideas?

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