The CRYRING Internal Gas-Jet Target

FYSIKUM

Henning Schmidt

Henrik Cederquist

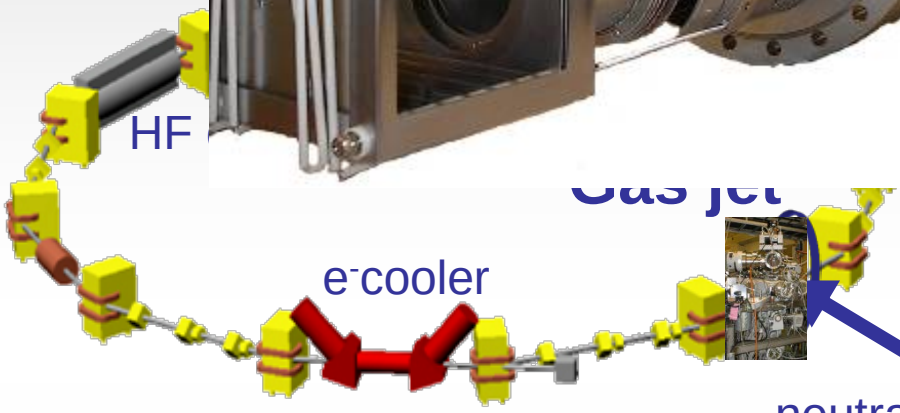
Magnus Gudmundsson, Kristian Støchkel

Deepankar Misra, Daniel Fischer

Reinhold Schuch, Horst Schmidt-Böcking, C. Lewis Cocke

Lars ”Bagge” Brännholm, Anders Källberg, Ansgar Simonsson

CRYRI



→Intense and narrow ion beam
→Ideal for low cross section measurements, e.g., ~ 10^{-22}cm^2

→Beam diameter ~ 1 mm for 1µA protons
→Gas jet diameter ~ 1 mm
→Gas jet density ~ 10^{11} - 10^{12} cm^{-3}
→Ultra High Vacuum ~10^{-12} mbar
→Temp T < 1 K

Single electron transfer. A generic COLTRIMS experiment

- Single electron transfer
  $H^+ + He \rightarrow H^0 + He^+$
  proton energies 1.3-12.5 MeV.

- Recoil ion momenta:

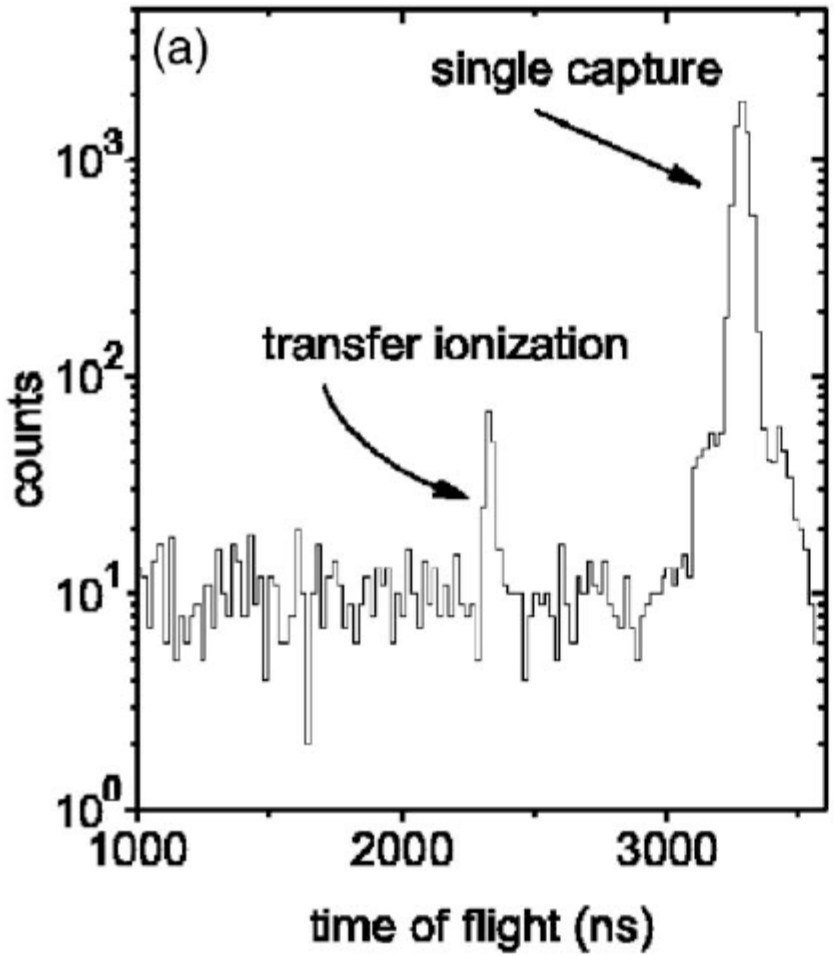
$$p_{\parallel} = -v/2 + Q/v$$

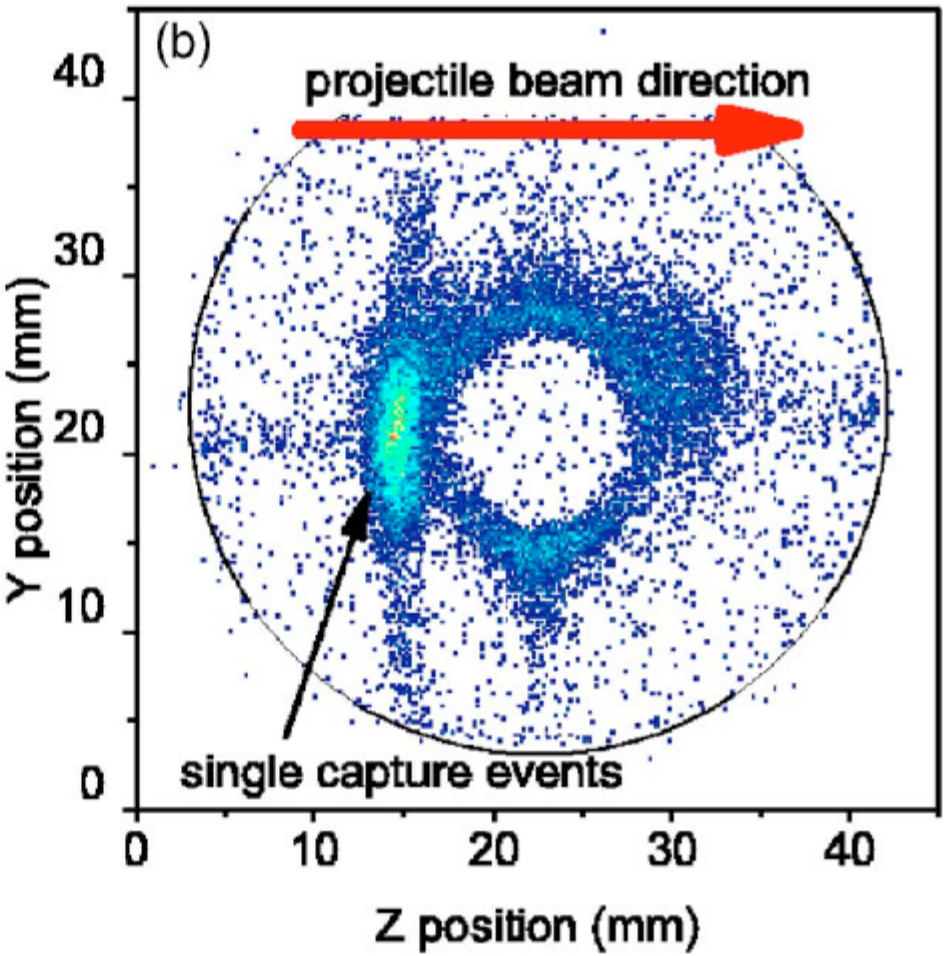
$$p_{\perp} = -Mv\tan\theta$$

i.e. we have access to very accurate projectile angular differential cross sections.

7.5 MeV p-He

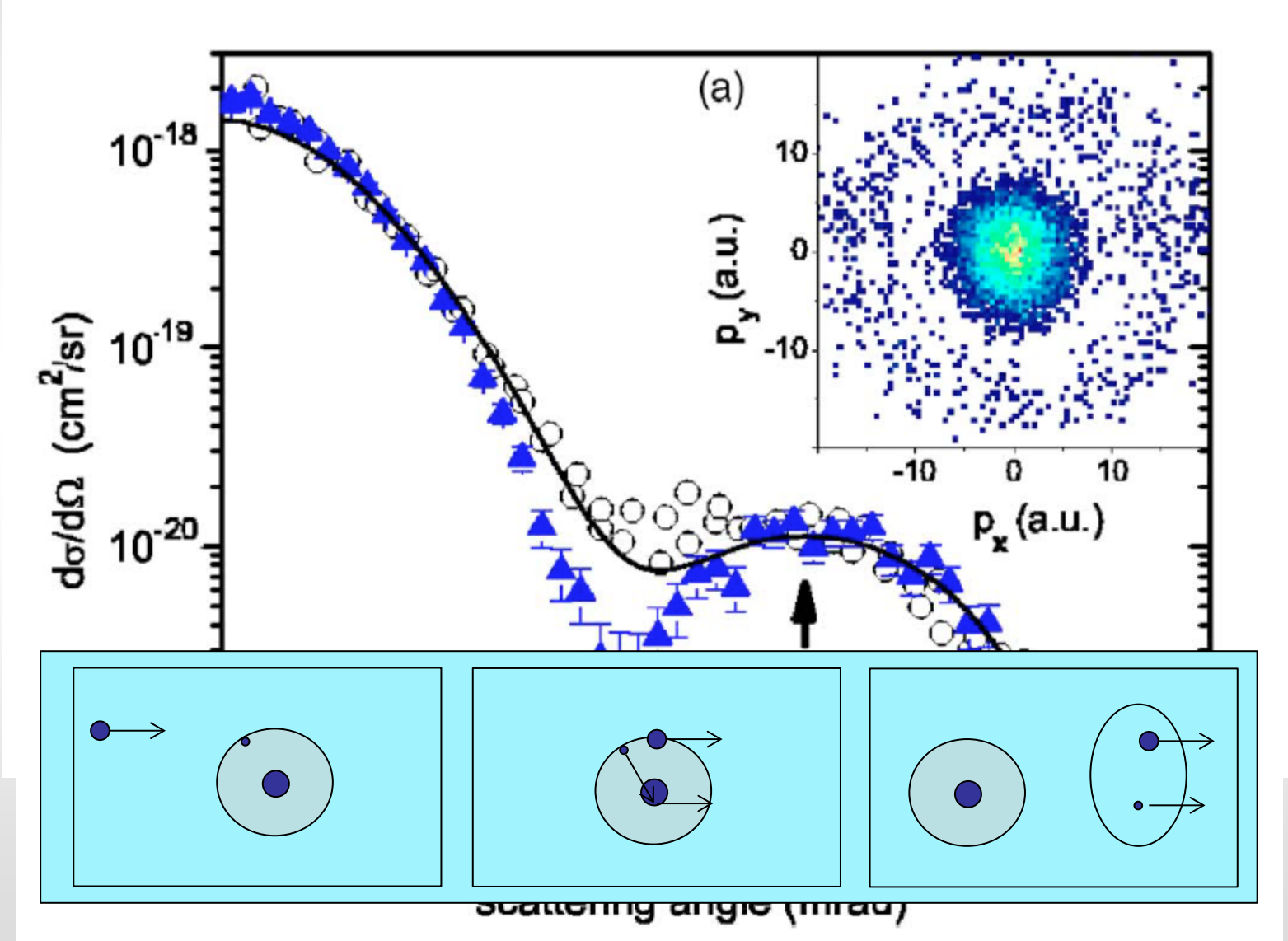
PRA **73**, 052713 (2006)





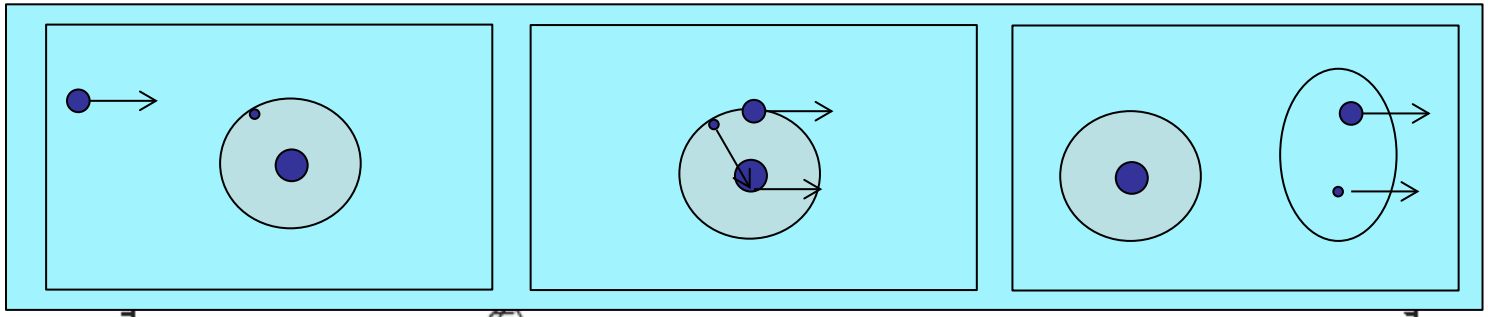
7.5 MeV

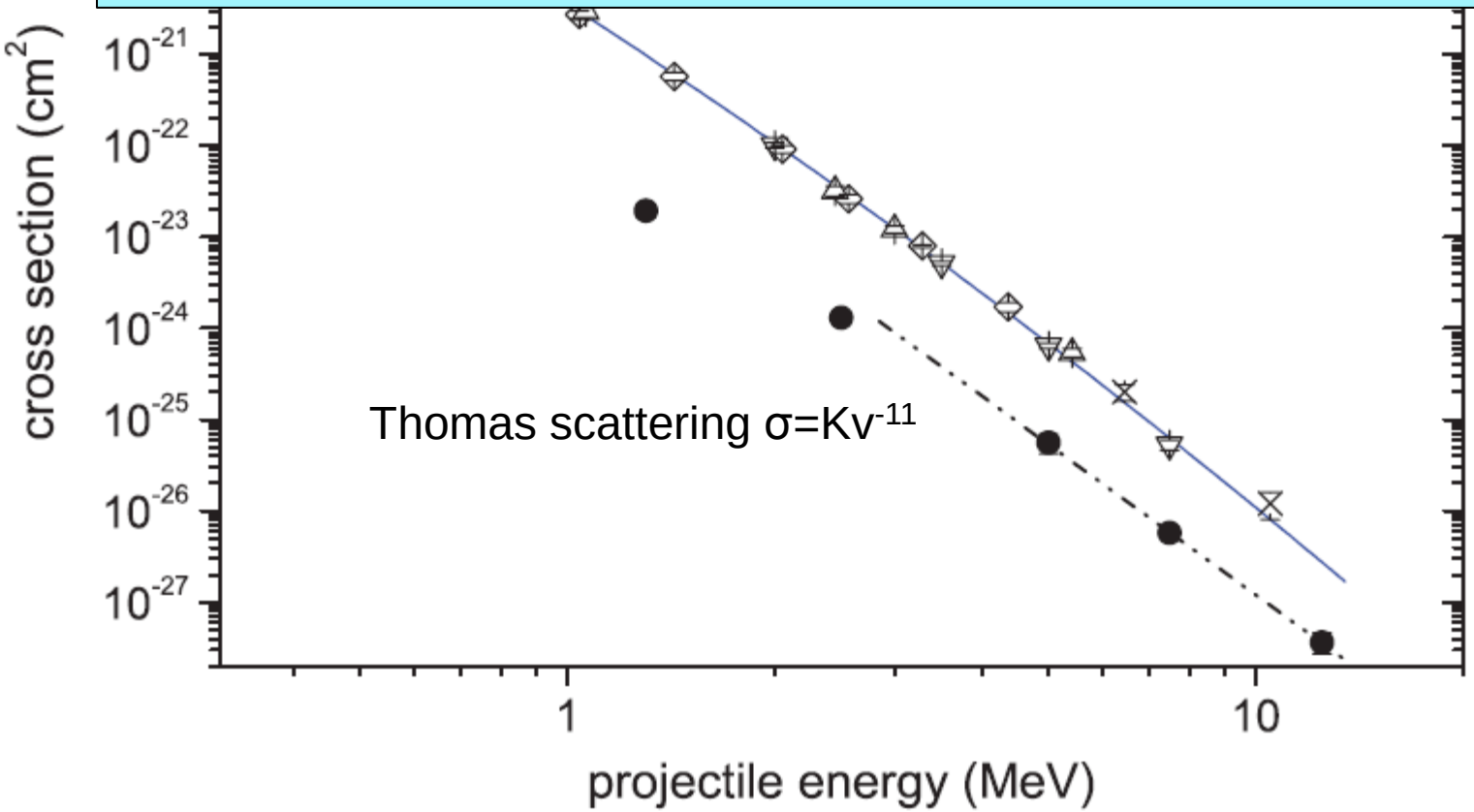
PRA **73**, 052713 (2006)



As function of energy

PRA **73**, 052713 (2006), PRA **81**, 012714 (2010)





We have studied molecular-axis orientation dependent cross sections for…

- Transfer excitation
  $H^+ + H_2 \rightarrow H^0 + (H_2^+)^* \rightarrow H^0 + (H + H^+)$
  proton energies 0.3-1.3 MeV.

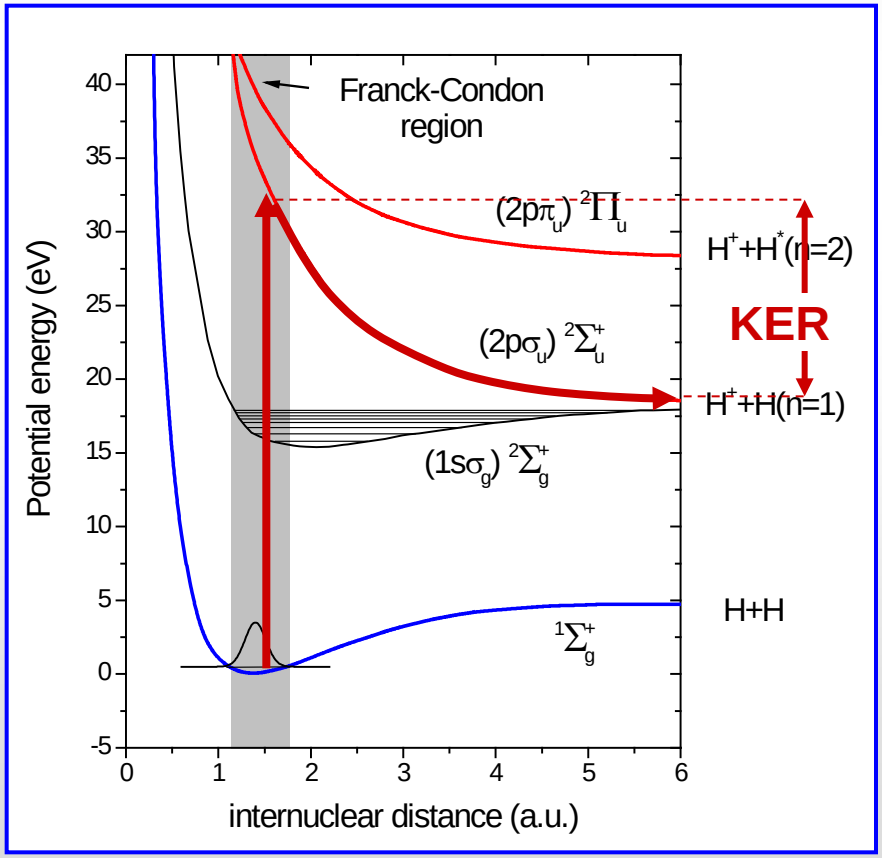
- Double Capture
  $He^{2+} + H_2 \rightarrow He + (H^+ + H^+)$
  alpha particle energies 1.2 and 2.0 MeV.

- Transfer (and ionization) 1.04 MeV
  $H^+ + N_2 \rightarrow H^0 + (N_2^+)^* \rightarrow H^0 + (N + N^+)$

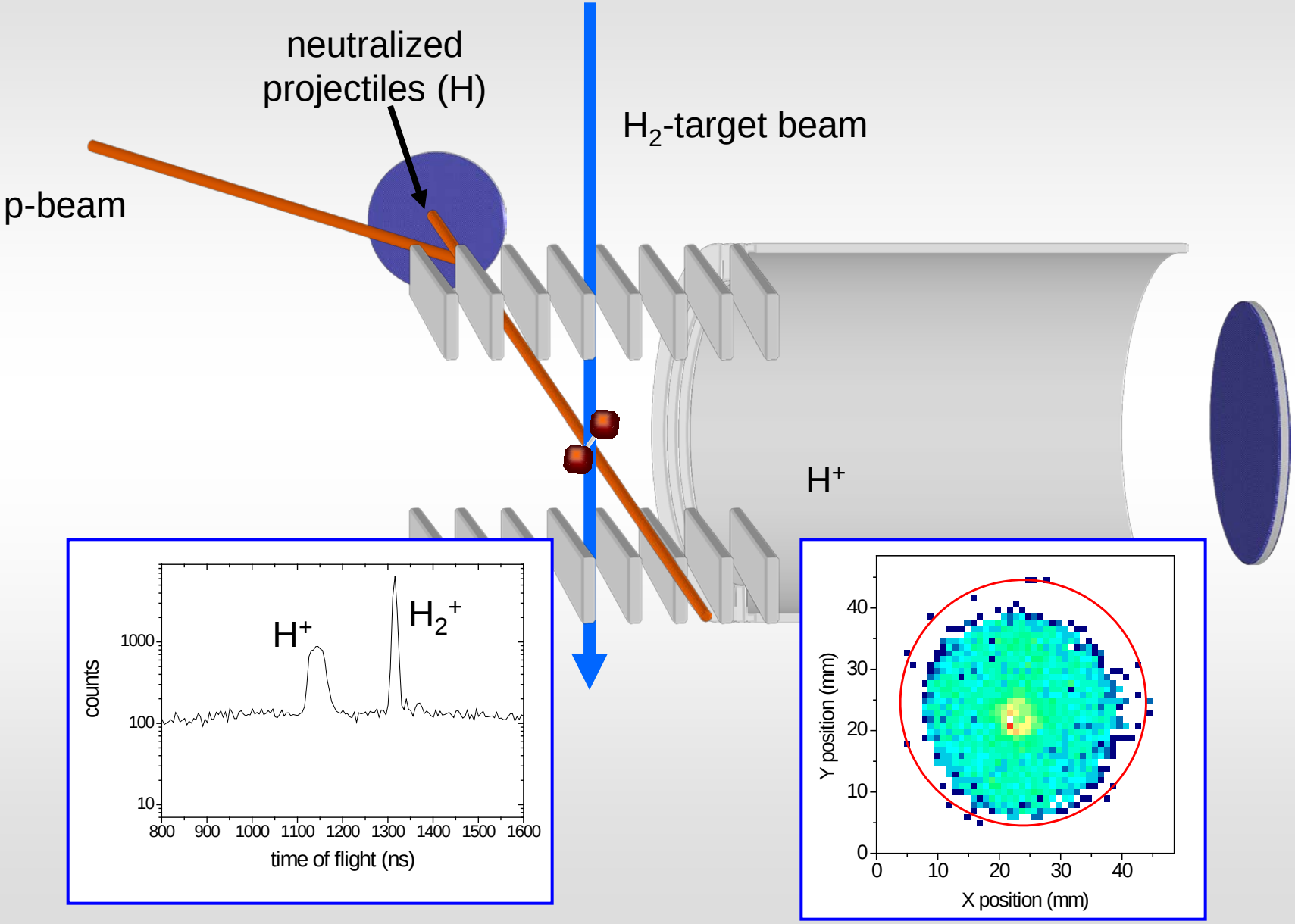
$$\rightarrow H^0 + (N_2^{q+})^* + (q\text{-}1)e^- \rightarrow H^0 + (N^{s+} + N^{t+})$$

$$q = s+t \leq 5$$

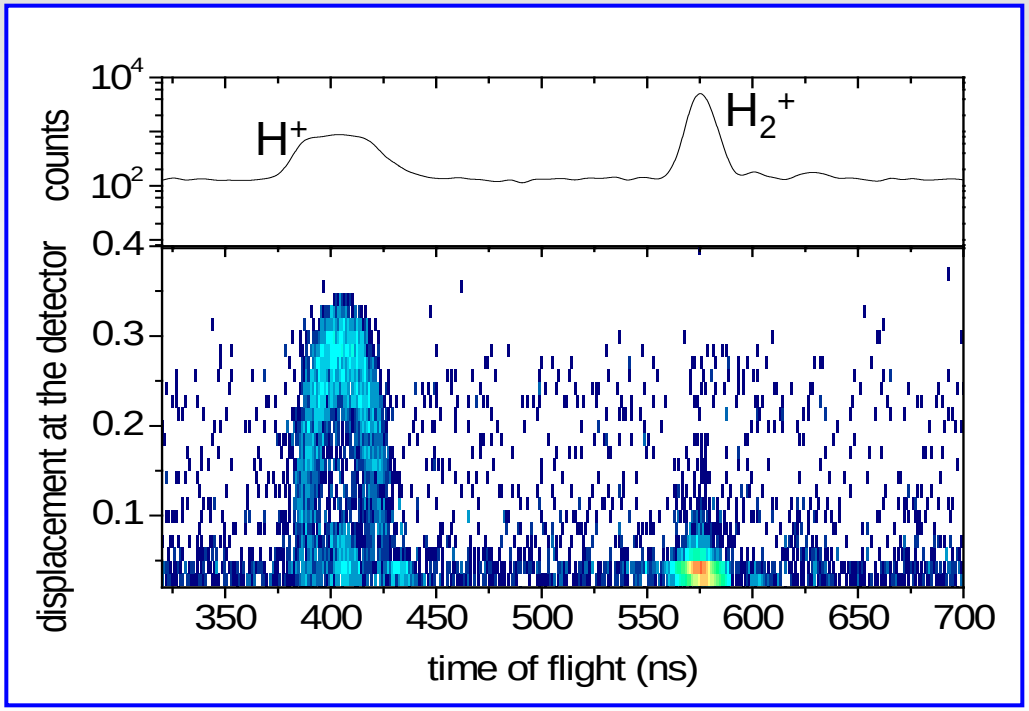
Electron capture from H_2



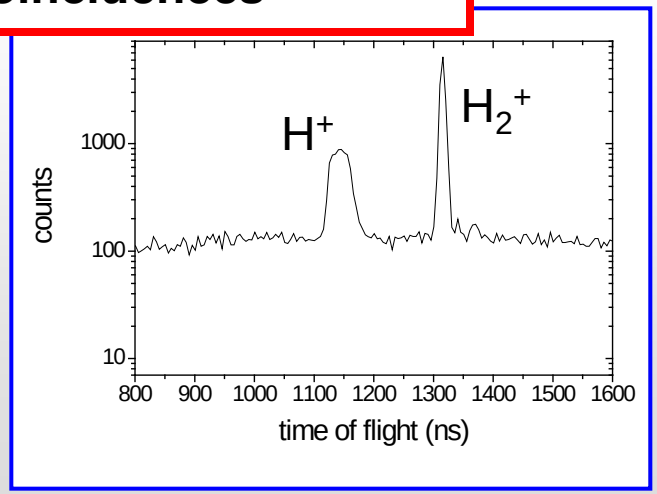
Experiment

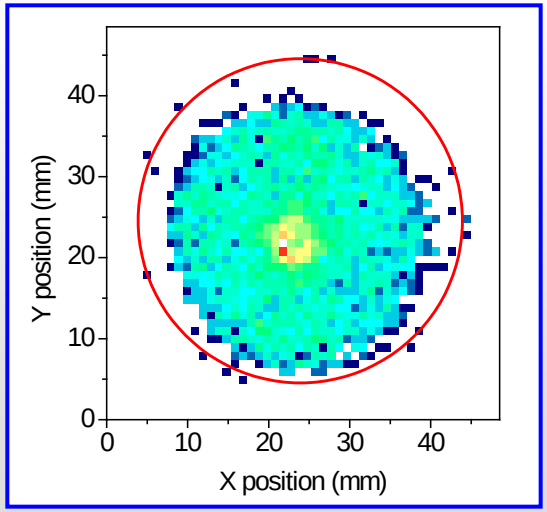

neutralized projectiles (H)
H_2-target beam
p-beam
H^+
counts
1000
100
10
H^+
H_2^+
800 900 1000 1100 1200 1300 1400 1500 1600
time of flight (ns)
Y position (mm)
0 10 20 30 40
X position (mm)
0 10 20 30 40

Experiment

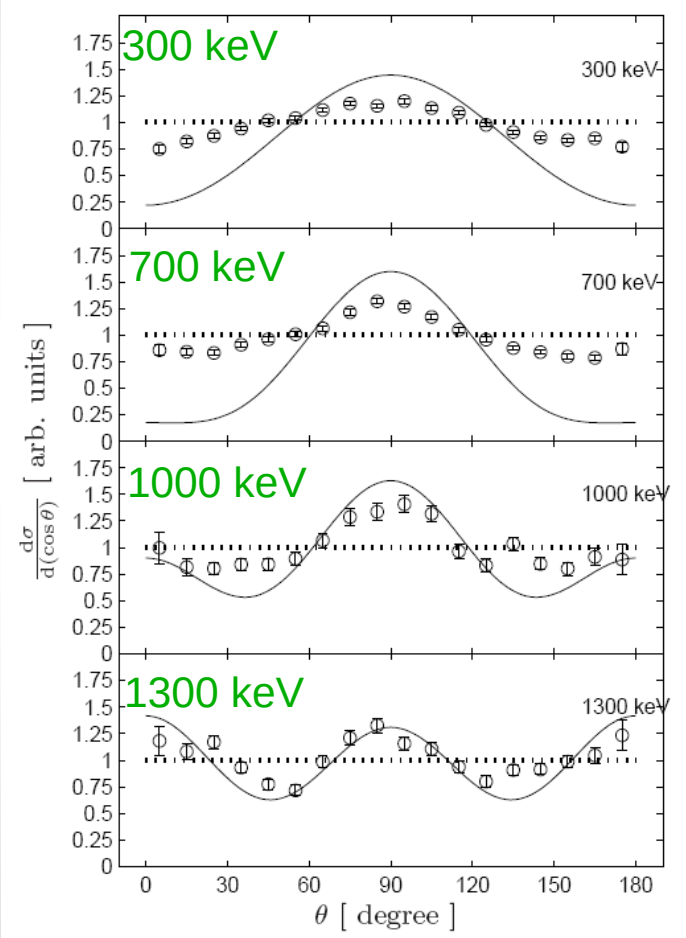


neutral projectile – recoil ion coincidences





Results for varying energies.



Experiment:

Støchkel et al. Phys. Rev. A **72**, 050703(R) (2005)

Theory:
Wang et al. Phys Rev. A **40**, 3673 (1989)

Interference for zero angle projectile scattering (1.3 MeV p-H_2)

As the proton captures the electron its momentum increases

$m_e v/2$

an equiva

de Broglie

The two parts of the

he

each

on

mic

he

pr

n

phase difference is accumulated over this distance.

Change in wave number upon capture (in atomic units):

$$\delta k = v/2$$

The phase difference of the two waves:

$$\delta\Phi = \delta k \cdot a\cos\theta = (va/2)\cos\theta = (7.2\times 1.4/2)\cos\theta = 5.0\cos\theta$$

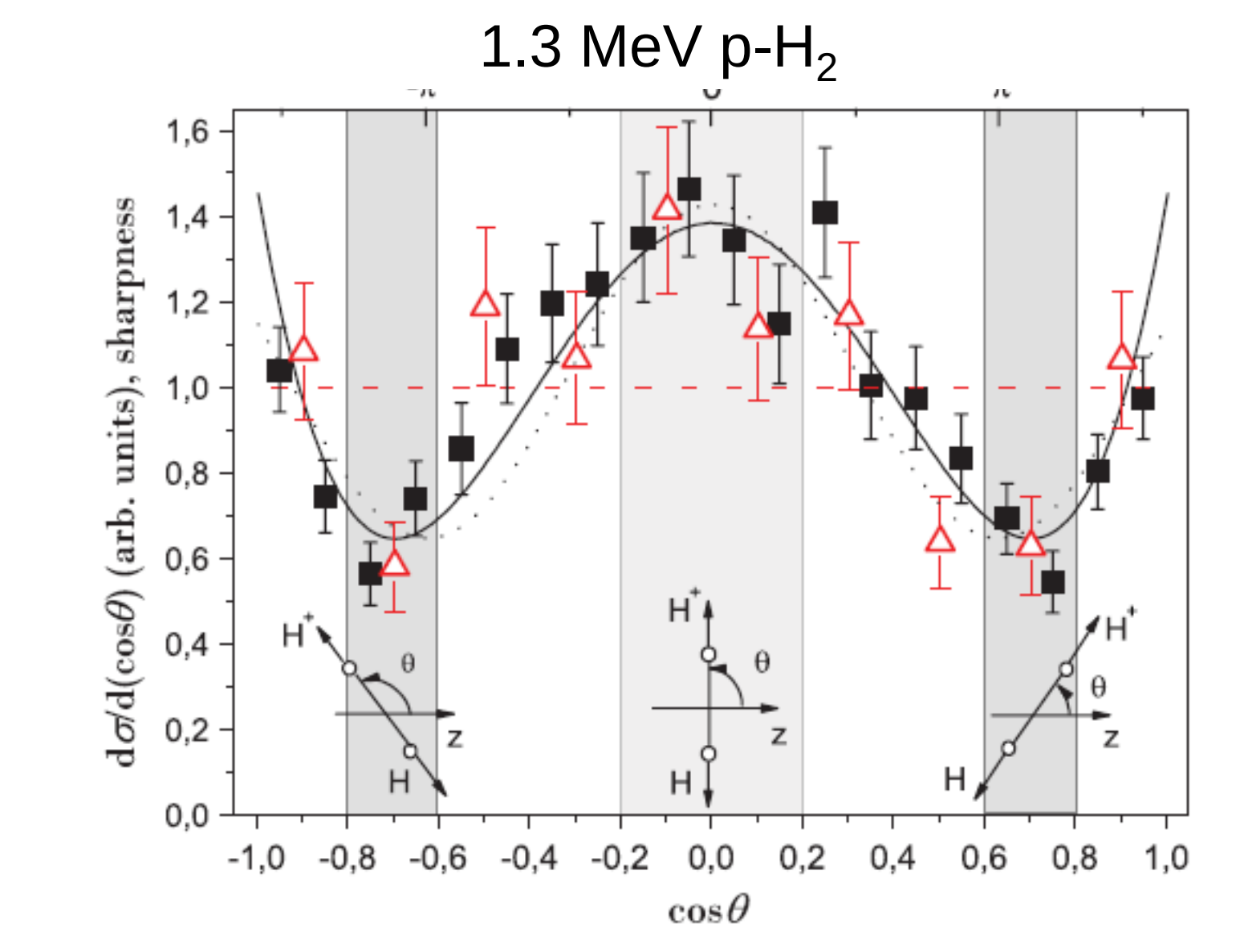
Destructive interference thus occurs for:

$$\delta\Phi = \pi$$

$$\Leftrightarrow$$

$$\cos\theta = \pi/5 = 0.63$$

PRL, **101**, 083201(2008)

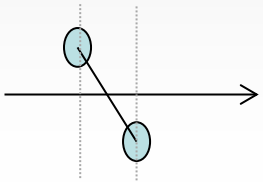


Model – addition of two plane waves with a phase shift

$$\text{Count rate} \propto \frac{1}{2\pi}\int_0^{2\pi}\left(\cos(\varphi+\delta\Phi)+\cos\varphi\right)^2 d\varphi = 1+\cos\delta\Phi$$

where

$$\delta\Phi = \delta k \cdot a \cos\theta$$

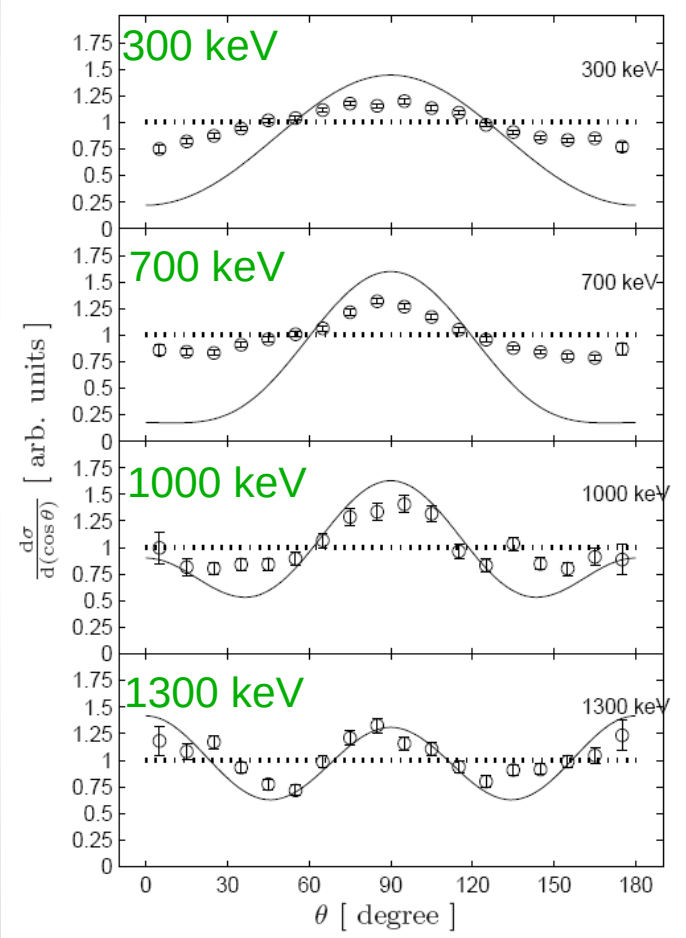


and the change in wave number is (in atomic units)

$$\delta k = v/2 + Q/v$$

For 1.3 MeV p+H_2: $\delta k \cdot a = 5.0$

Results for varying energies.



Experiment:

Støchkel et al. Phys. Rev. A **72**, 050703(R) (2005)

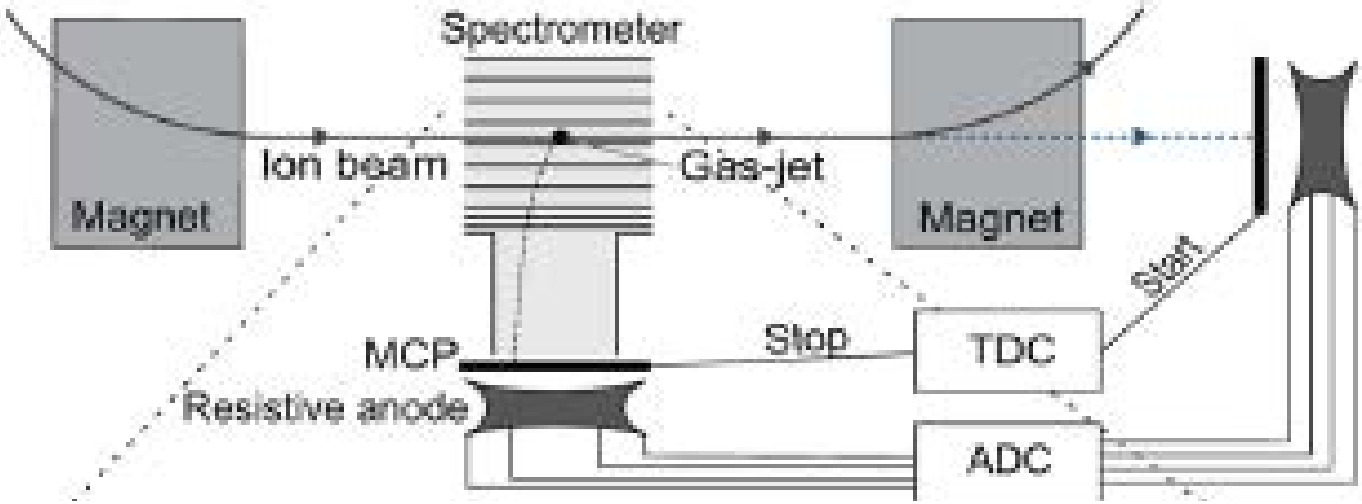
Schmidt et al. Phys. Rev. Lett. **101**, 083201 (2008)

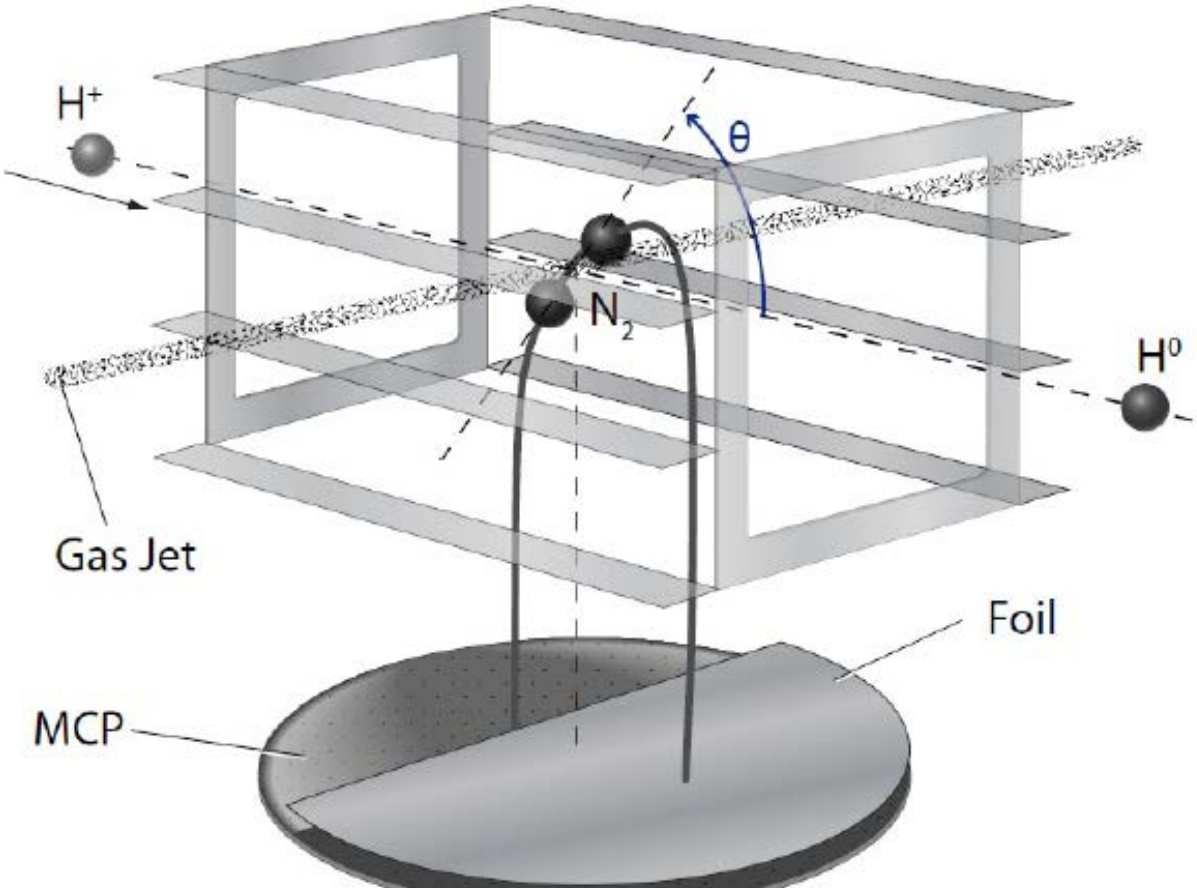
Misra et al. Phys. Rev. Lett. **102**, 153201 (2009)

Theory:
Wang et al. Phys Rev. A **40**, 3673 (1989)

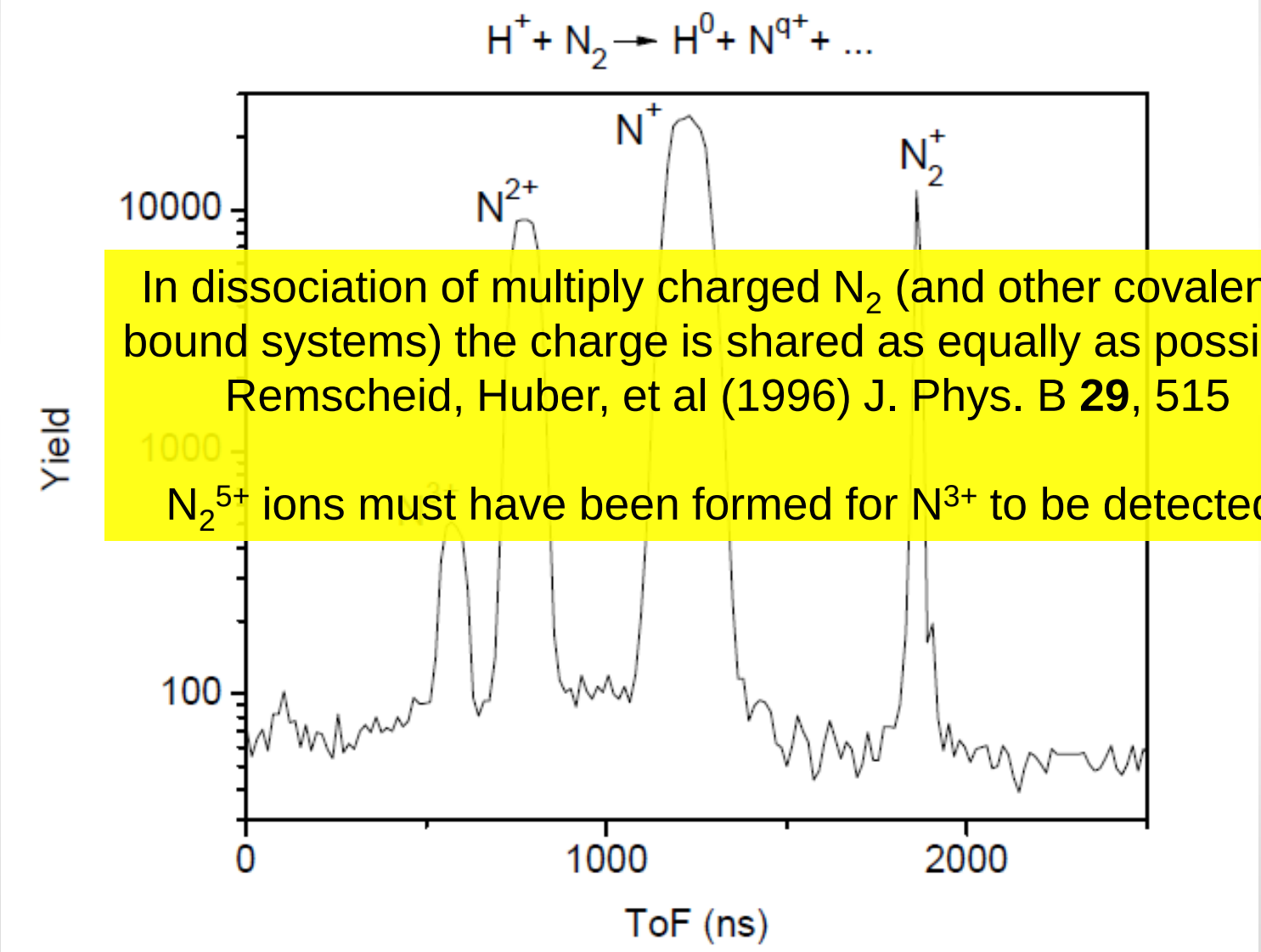
p-N_2

M. Gudmundsson et al., J. Phys. B, **43**, 185209 (2011)


Spectrometer
Ion beam
Gas-jet
Magnet
Magnet
Start
Stop
MCP
TDC
Resistive anode
ADC


H+
θ
N2
H0
Gas Jet
Foil
MCP

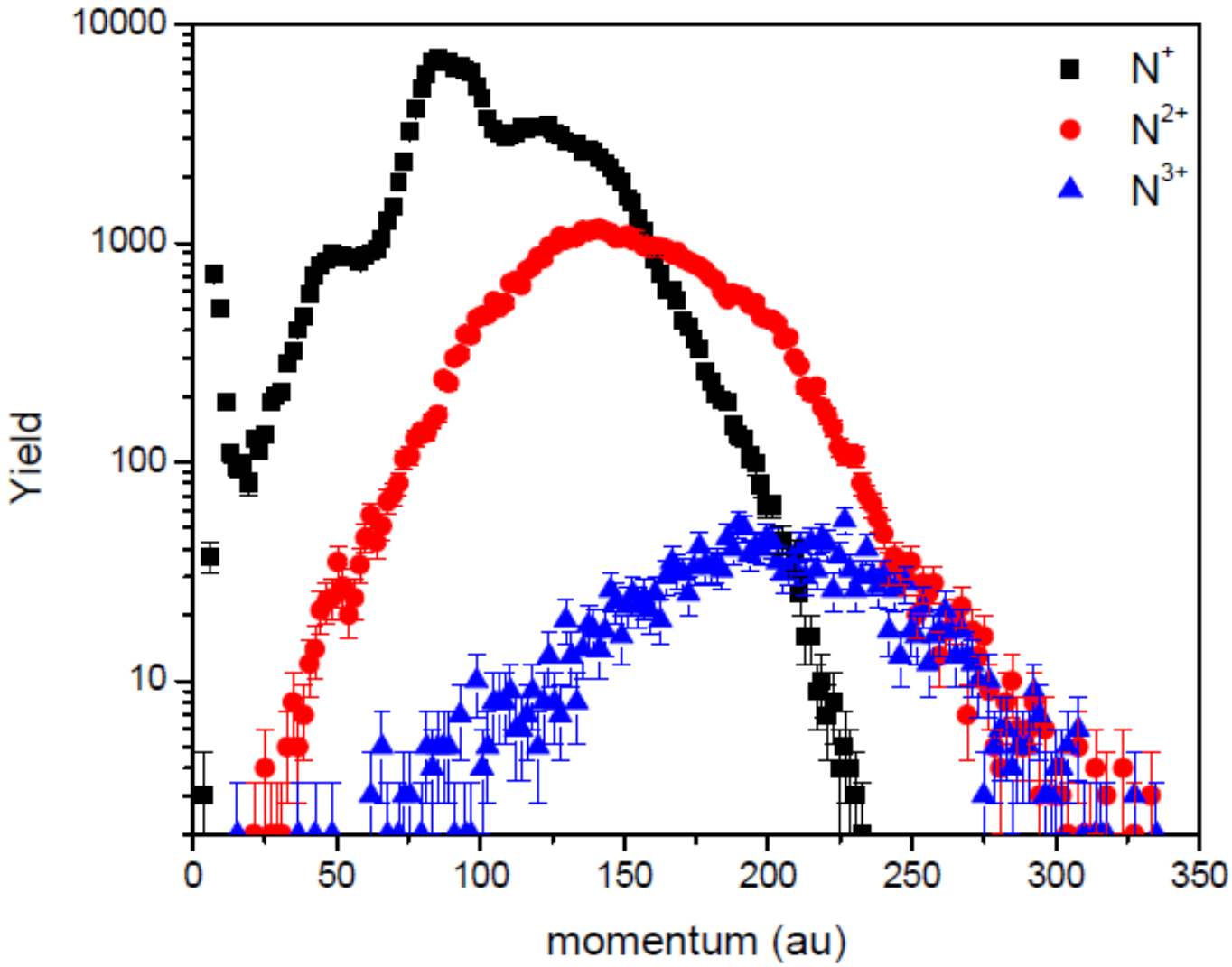
ToF of recoil ions/fragments



In dissociation of multiply charged N_2 (and other covalently bound systems) the charge is shared as equally as possible.
Remscheid, Huber, et al (1996) J. Phys. B **29**, 515

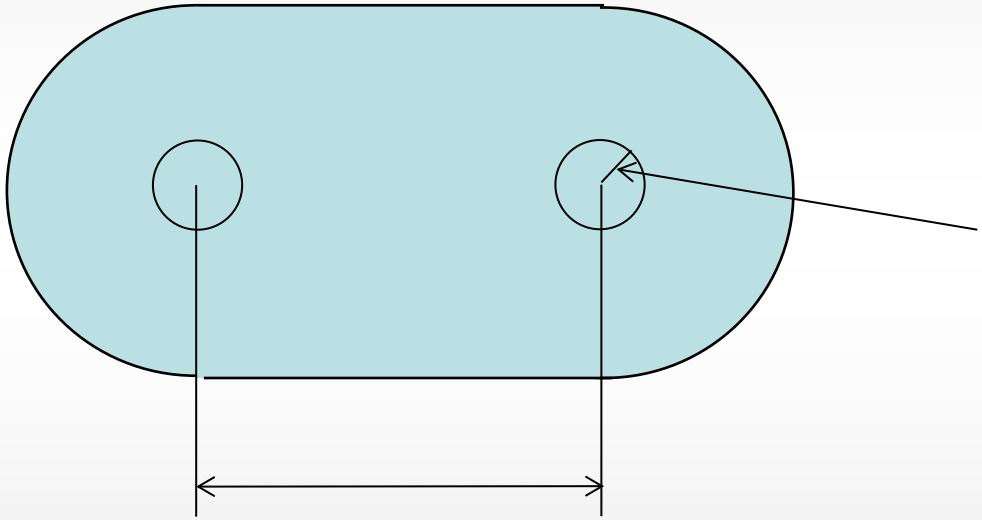
N_2^{5+} ions must have been formed for N^{3+} to be detected.

Momentum (magnitude) distributions



How can we get such high charges?

Schematic N_2 molecule.



$\langle r \rangle_{1s} = 0.23\ a_0$

$\langle v \rangle_{1s} = 5.7\ v_0$

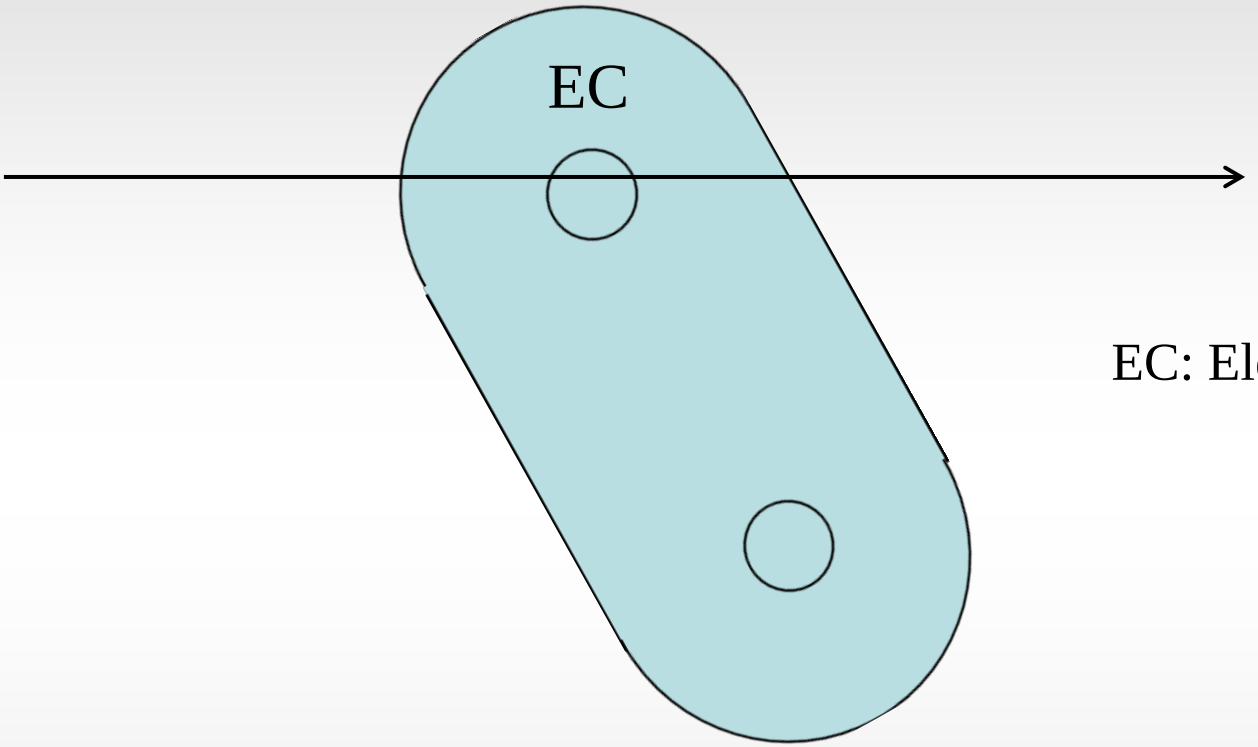
$\langle v \rangle_{val} \approx 1 v_0$

$v_{proj} = 6.45\ v_0$

Internuclear distance $a = 2.1\ a_0$

It is more likely to capture a core electron than a valence electron

Semiclassical picture.



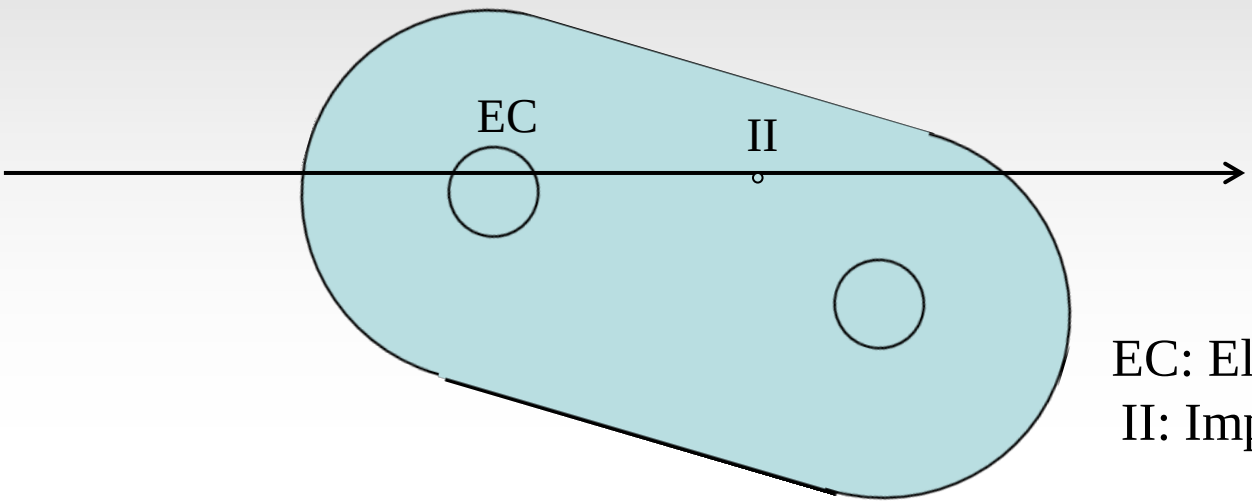
EC: Electron Capture

$$p + N_2 \rightarrow H + N_2^+(1s^{-1})$$

$$N_2^+(1s^{-1}) \rightarrow N_2^{2+} + e^-$$

$$N_2^{2+} \rightarrow N^+ + N^+$$

Semiclassical picture.



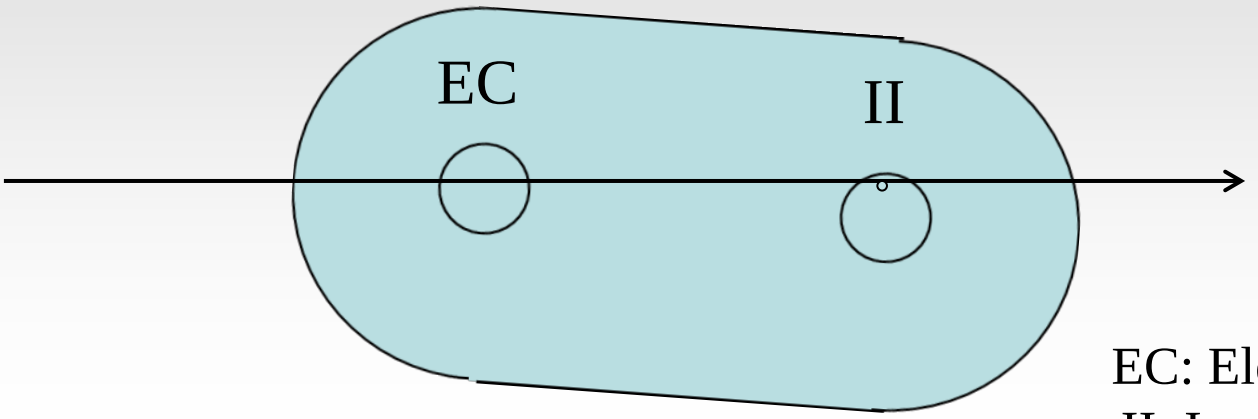
EC: Electron Capture
II: Impact Ionization

$$p + N_2 \rightarrow H + N_2^{2+}(1s^{-1}) + e^-$$

$$N_2^{2+}(1s^{-1}) \rightarrow N_2^{3+} + e^-$$

$$N_2^{3+} \rightarrow N^{2+} + N^+$$

Semiclassical picture.



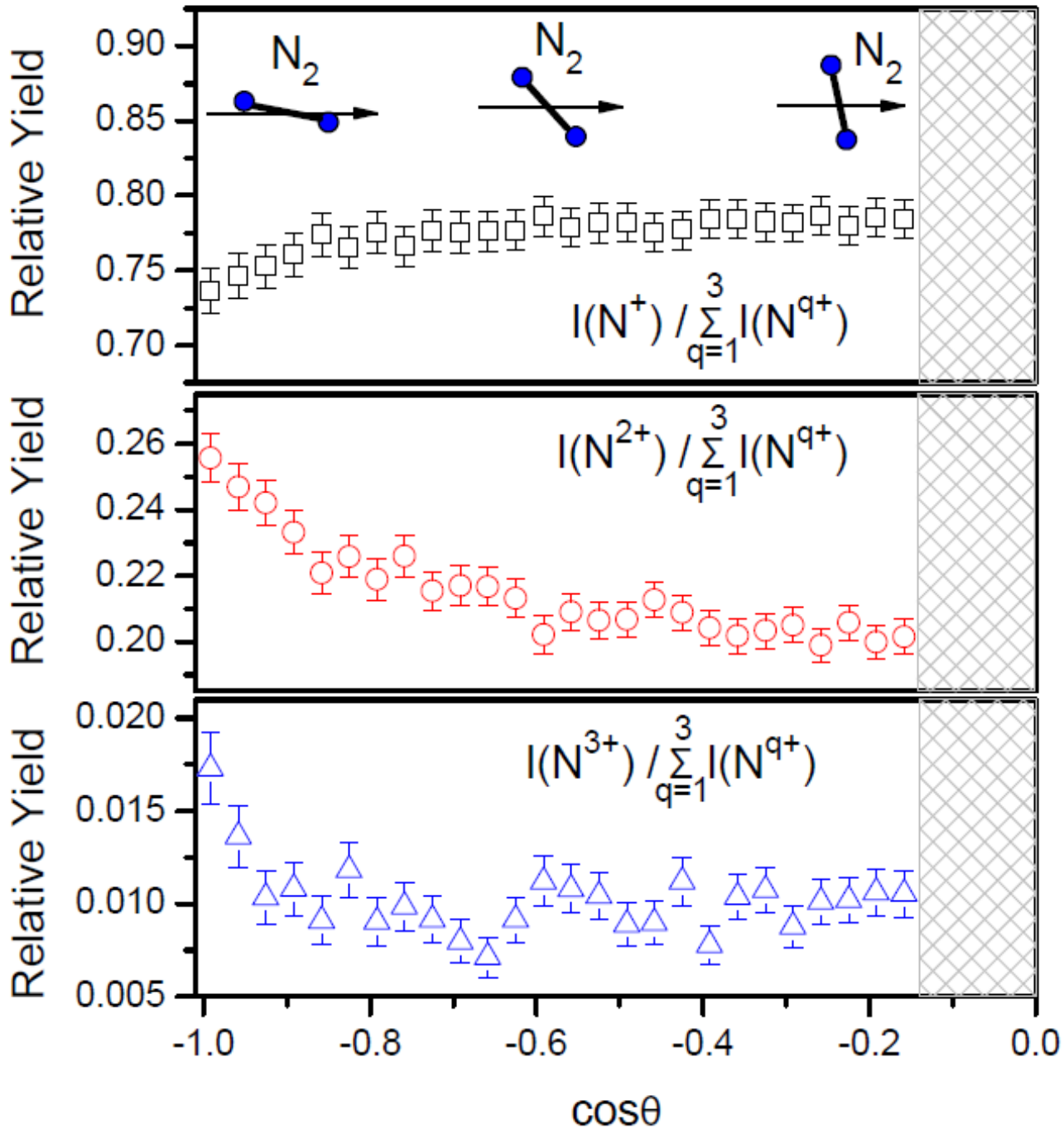
EC: Electron Capture
II: Impact Ionization

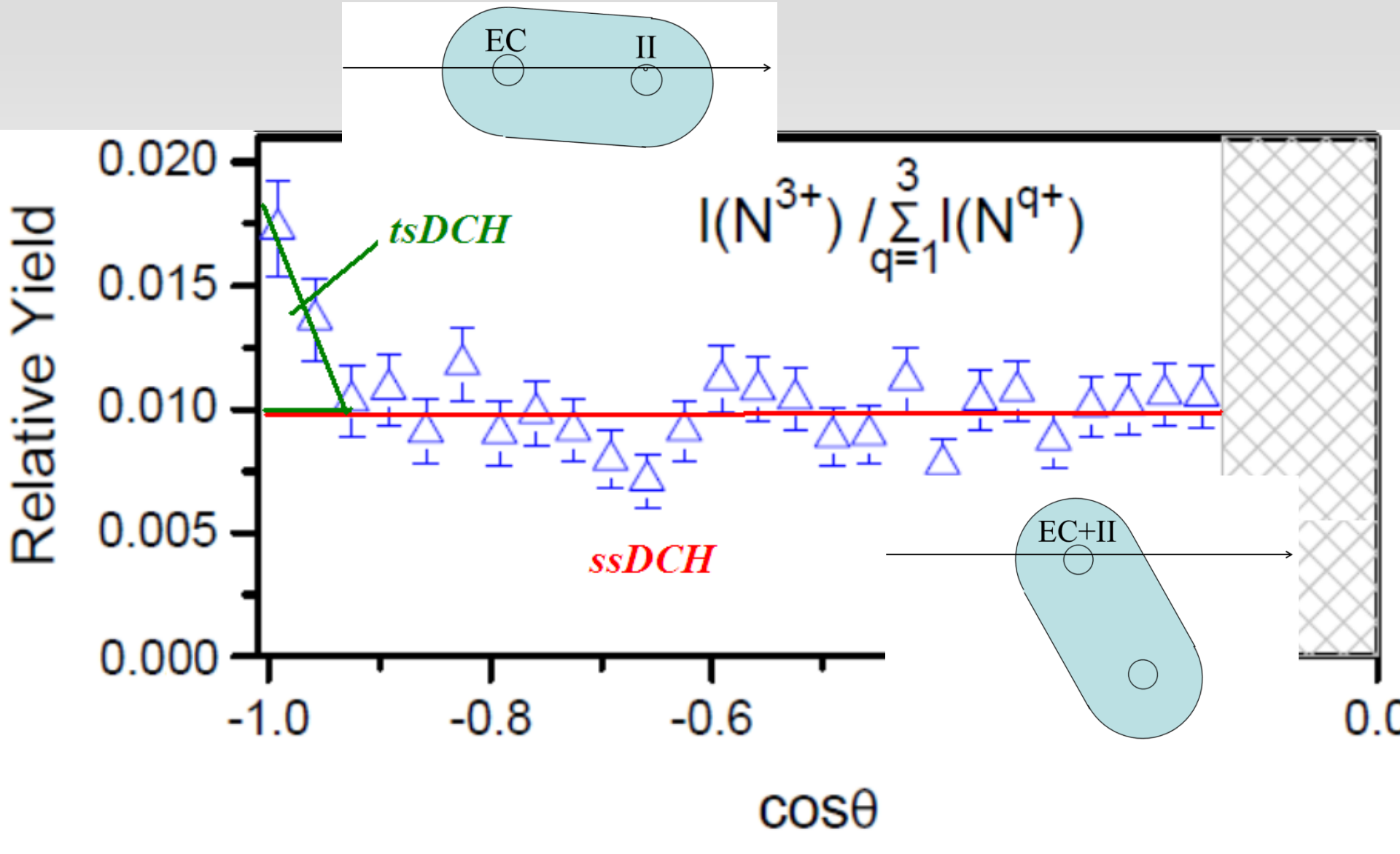
$$p + N_2 \rightarrow H + N_2^{2+}(1s^{-2}) + e^-$$

$$N_2^{2+}(1s^{-2}) \rightarrow N_2^{4+} + 2e^-$$

$$N_2^{4+} \rightarrow N^{2+} + N^{2+}$$

To reach N_2^{5+} requires an additional impact ionization or shake-off or…

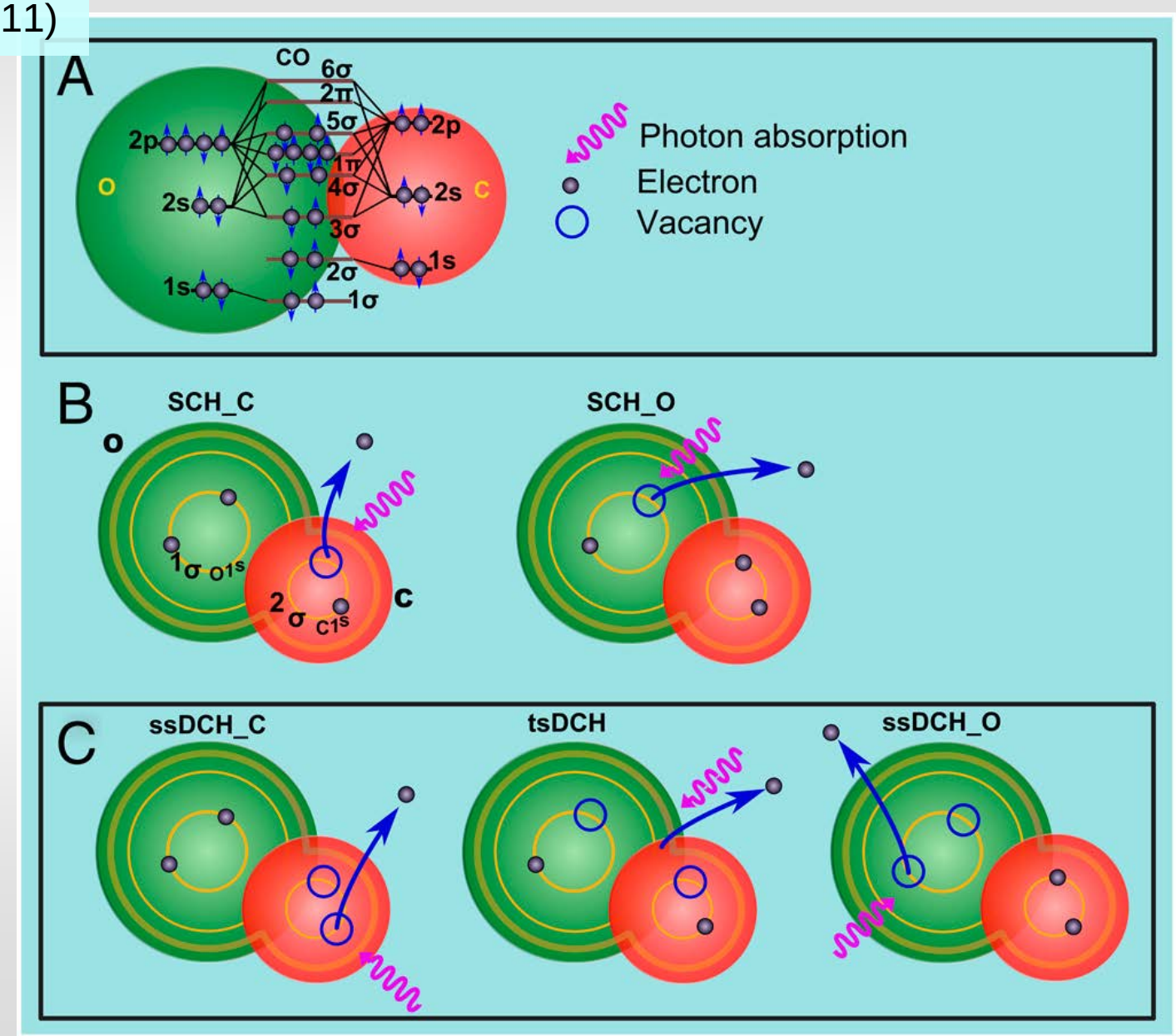

N2
N2
N2
Relative Yield
0.90
0.85
0.80
0.75
0.70
I(N+) / Σ I(Nq+)
q=1
3
Relative Yield
0.26
0.24
0.22
0.20
I(N2+) / Σ I(Nq+)
q=1
3
Relative Yield
0.020
0.015
0.010
0.005
I(N3+) / Σ I(Nq+)
q=1
3
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
cosθ


EC
II
EC+II
tsDCH
ssDCH
$I(N^{3+}) / \sum_{q=1}^{3} I(N^{q+})$
Relative Yield
0.020
0.015
0.010
0.005
0.000
-1.0
-0.8
-0.6
0.0
cosθ

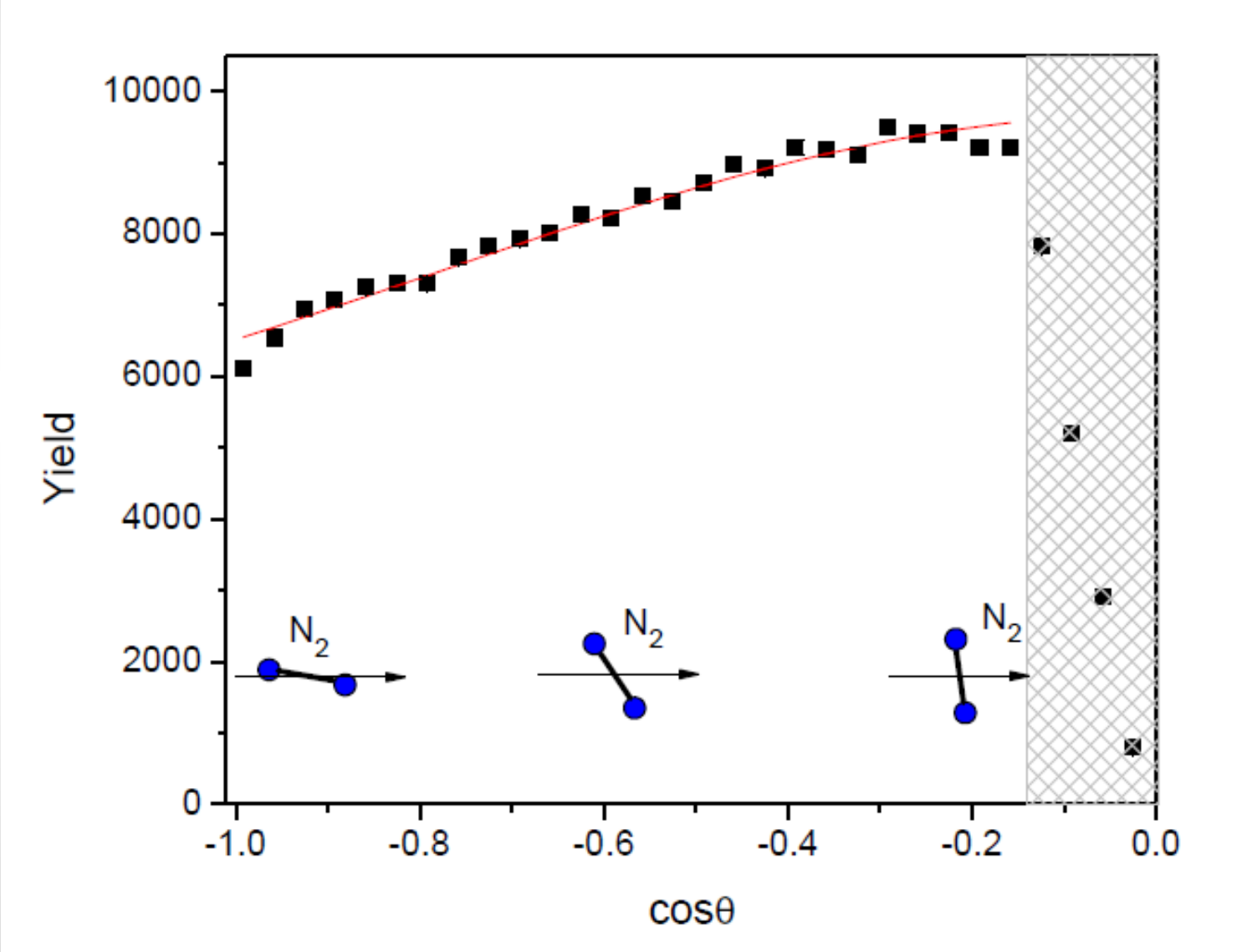
Double-core-hole spectroscopy for chemical analysis with an intense X-ray femtosecond laser

Nora Berrah, Li Fang, Brendan Murphy, Timur Osipov, Kiyoshi Ueda, Edwin Kukk, Raimund Feifel, Peter van der Meulen, Peter Salen, Henning T. Schmidt, Richard D. Thomas, Mats Larsson, Robert Richter, Kevin C. Prince, John D. Bozek, Christoph Bostedt, Shin-ichi Wada, Maria N. Piancastelli, Motomichi Tashiro, and Masahiro Ehara

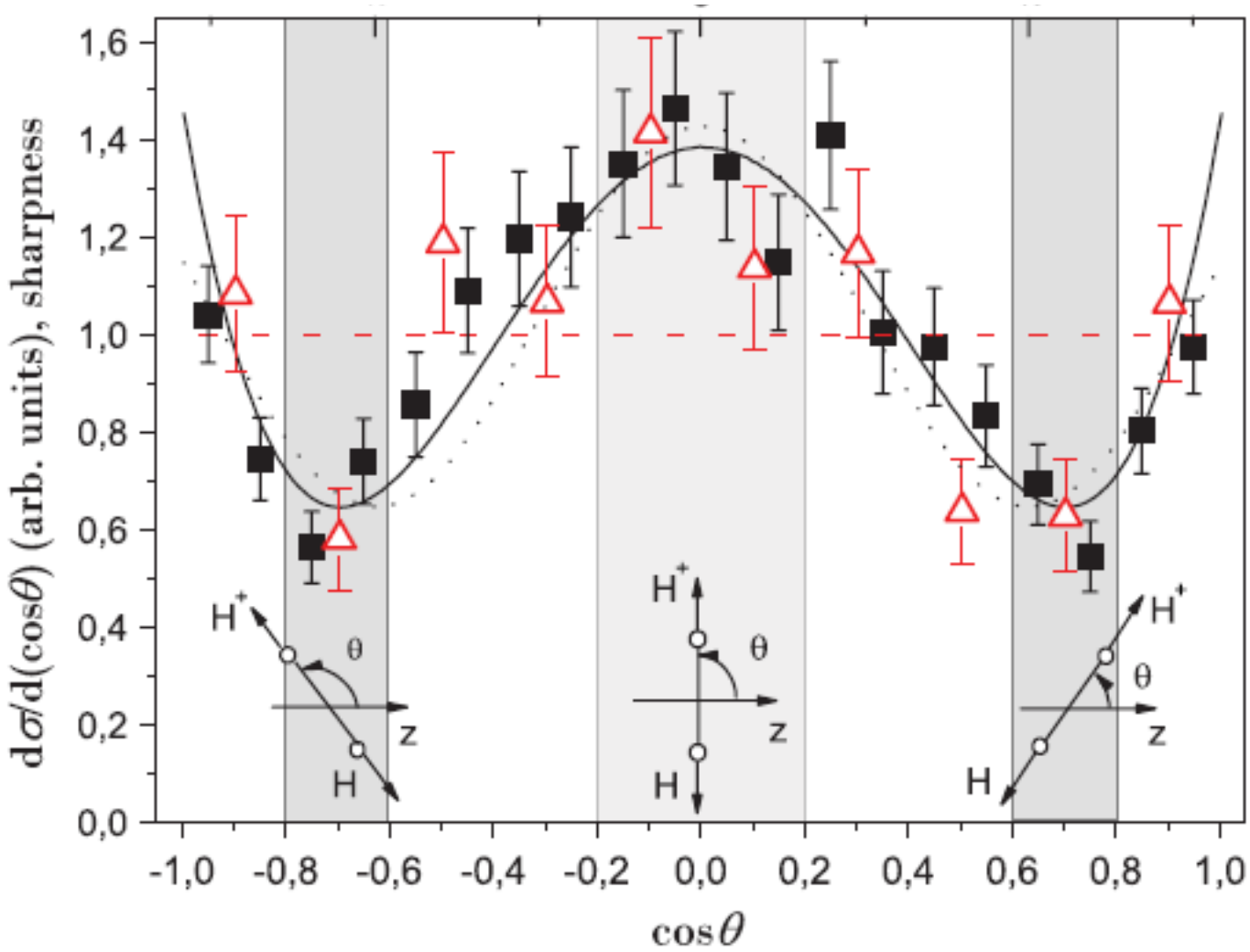
PNAS, 108, 16912 (2011)



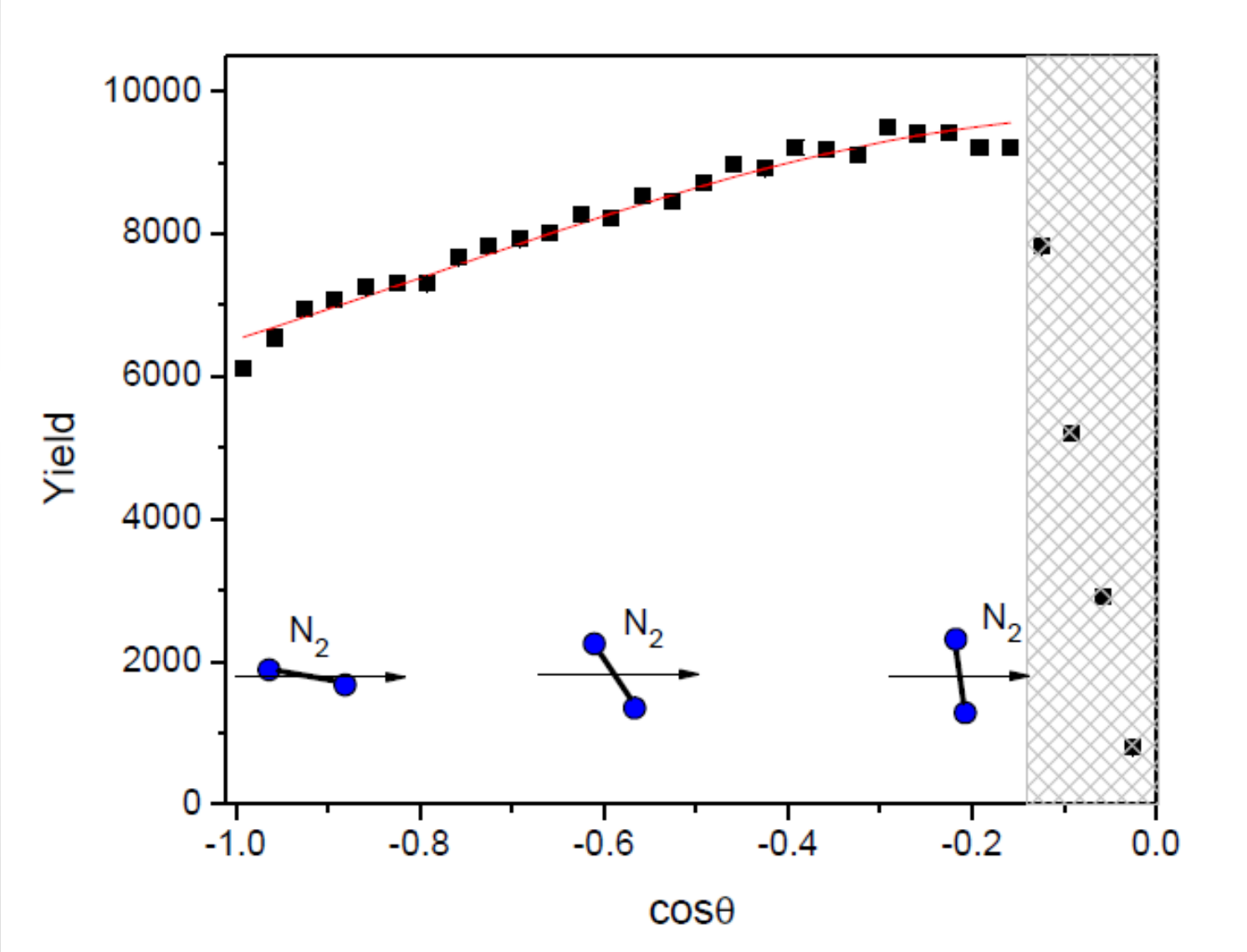
Orientation dependence of total cross section



1.3 MeV p-H_2


1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
dσ/d(cosθ) (arb. units), sharpness
-1,0
-0,8
-0,6
-0,4
-0,2
0,0
0,2
0,4
0,6
0,8
1,0
cosθ
H+
θ
z
H
H+
θ
z
H
H+
θ
z
H

Orientation dependence of total cross section

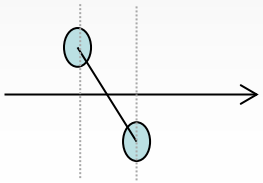


Model – addition of two plane waves with a phase shift

$$\text{Count rate} \propto \frac{1}{2\pi}\int_0^{2\pi}\left(\cos(\varphi+\delta\Phi)+\cos\varphi\right)^2 d\varphi = 1+\cos\delta\Phi$$

where

$$\delta\Phi = \delta k \cdot a\cos\theta$$



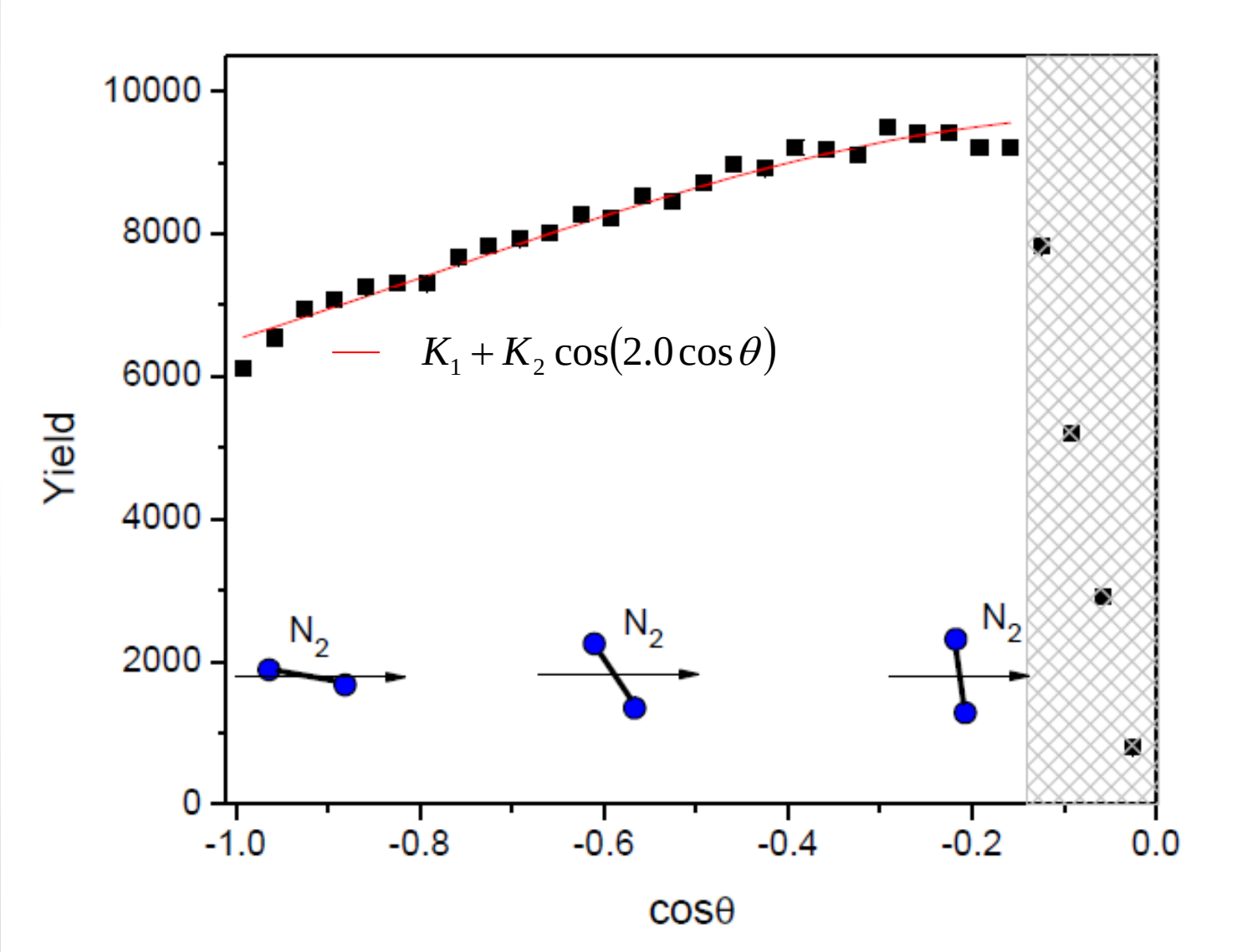
and the change in wave number is (in atomic units)

$$\delta k = v/2 + Q/v$$

~~Capture of valence electron:~~ $\cancel{\delta k \cdot a = 6.7}$

Capture of core electron: $\delta k \cdot a = 2.0$

Orientation dependence of total cross section

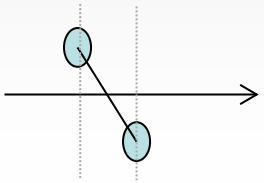


Model – addition of two plane waves with a phase shift

$$\text{Count rate} \propto \frac{1}{2\pi}\int_0^{2\pi}\left(\cos(\varphi+\delta\Phi)+\cos\varphi\right)^2 d\varphi = 1+\cos\delta\Phi$$

where

$$\delta\Phi = \delta k \cdot a\cos\theta$$



and the change in wave number is (in atomic units)

$$\delta k = v/2 + Q/v$$

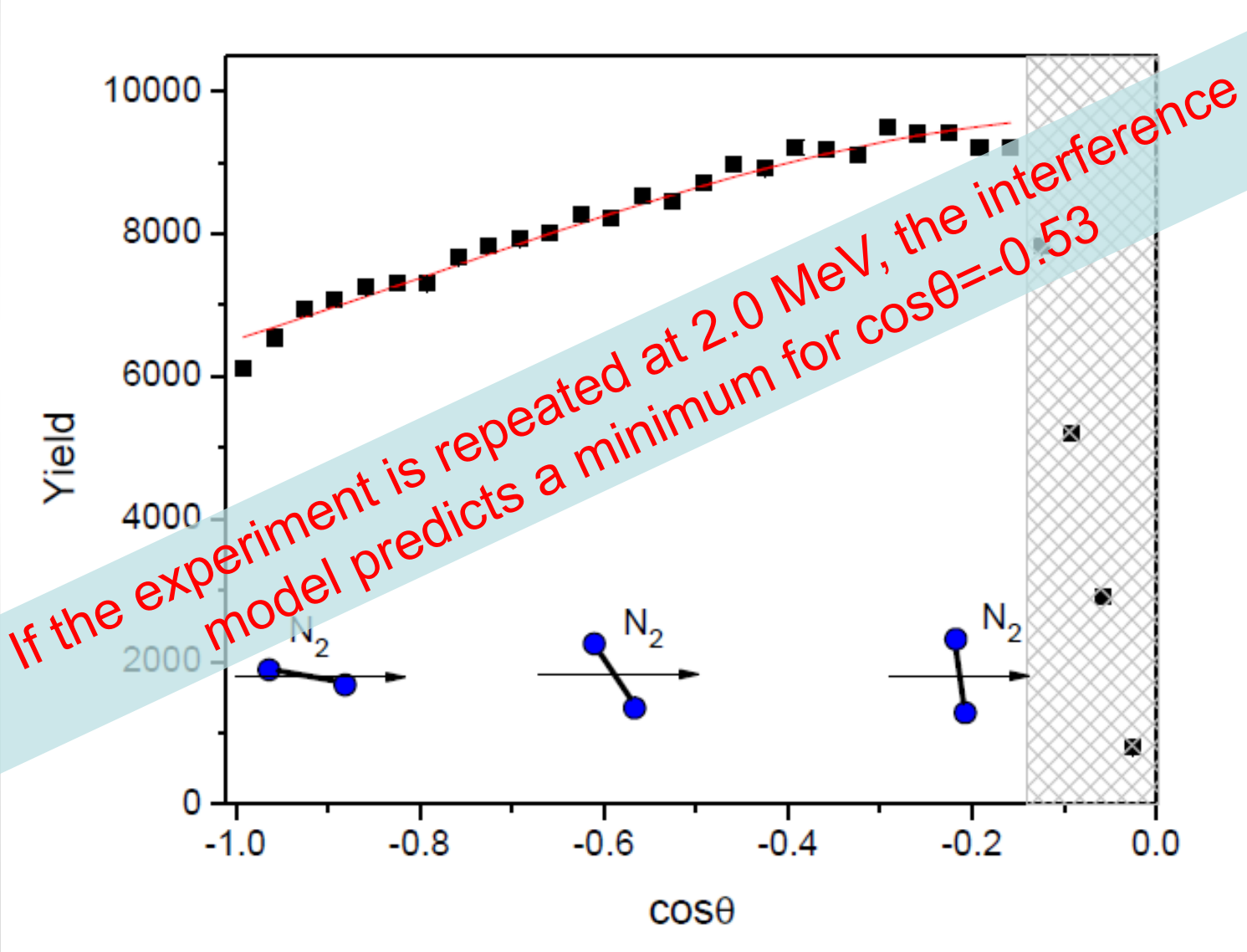
~~Capture of valence electron:~~ $\cancel{\delta k \cdot a = 6.7}$

Capture of core electron: $\delta k \cdot a = 2.0$

If we would change the projectile energy to 2.0 MeV

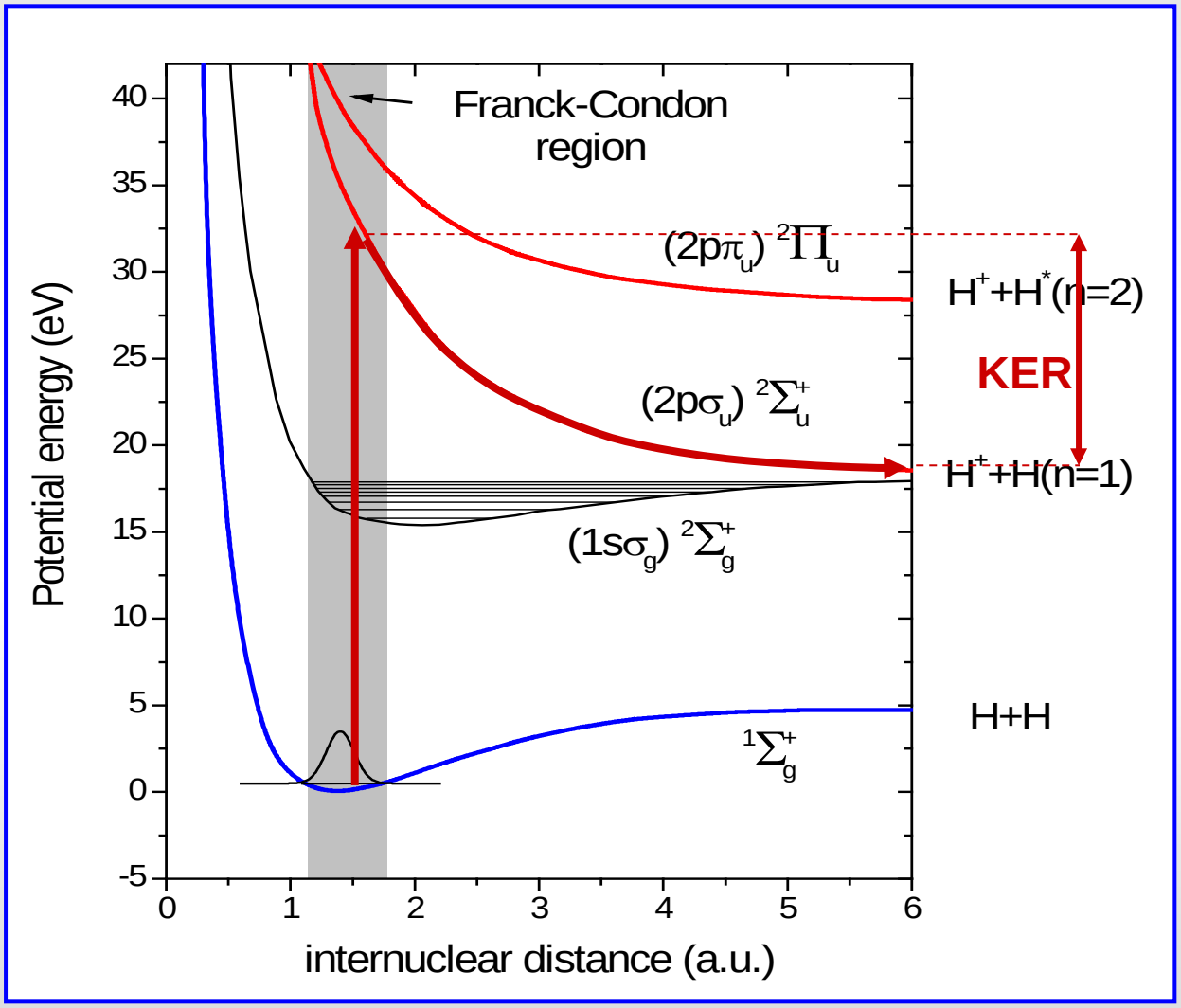
$$\left(\delta k \cdot a\right)_{1s}^{2MeV} = 6.0$$

Orientation dependence



If the experiment is repeated at 2.0 MeV, the interference model predicts a minimum for cosθ=-0.53

p-H_2 mechanism

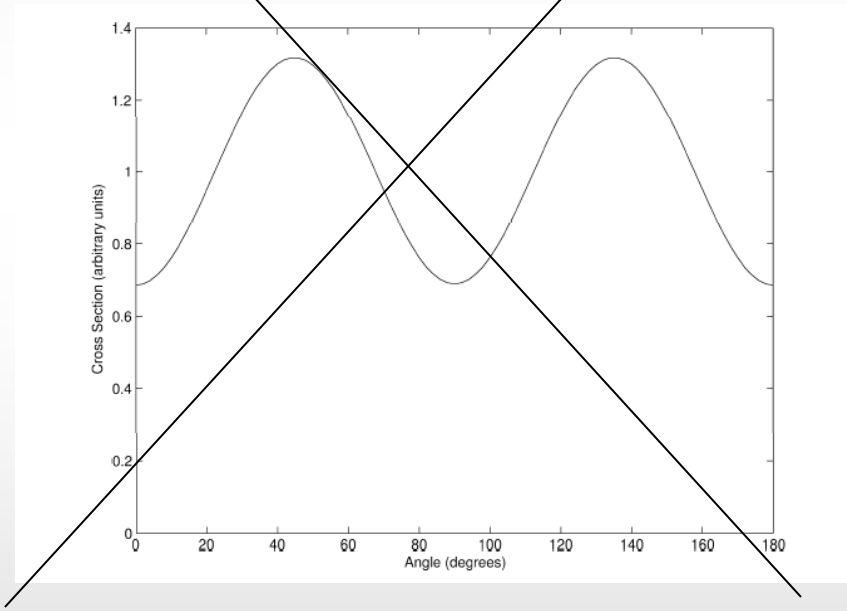


p-H_2 mechanism

Mechanism for excitation to antibonding ungerade H_2^+ state

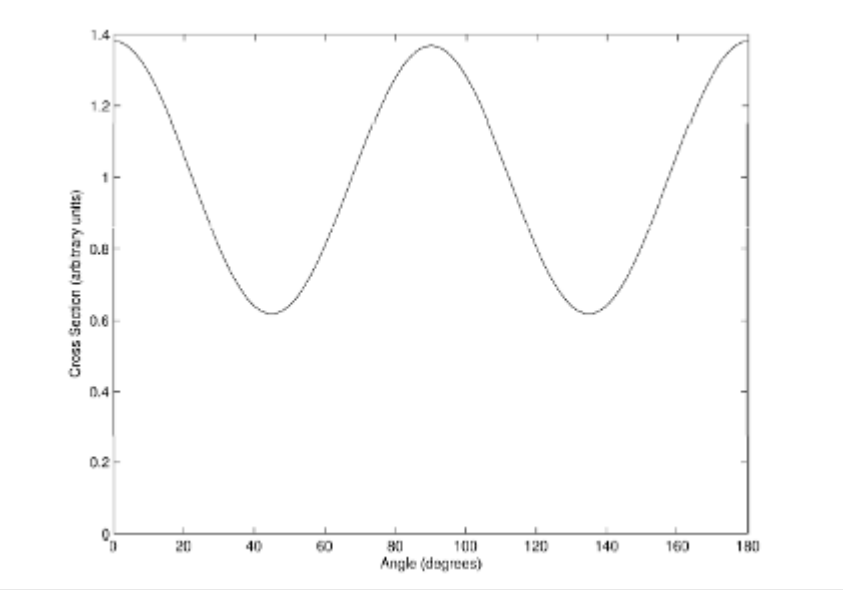
~~"Promotion" due to Configuration Interaction~~

~~Initial ungerade symmetry~~



Separate exciting interaction

Initial gerade symmetry



2008, L. Ph. Schmidt et al. PRL **101**, 173202: H_2^+ + He capture. Capture TO ungerade state gives dissociating projectiles which are observed.

In N_2 we have equal population of core states of either symmetry and should not see an effect, but we do!!

What have we learned?

- We can measure electron transfer cross sections in p-N_2 collisions as function of the molecular orientation.
- We produce molecular ions in charge states up to q=5.
- This may be explained by formation of single- and two-site Double Core Hole states.
- Total cross section show orientation dependence that can be explained by interference as found earlier in p-H_2 collisions.
- This is unexpected due to equal population of gerade and ungerade initial states.
- Interference issue may be resolved by going to slightly higher collision energy. (CRYRING@GSI).

Another issue:

- Schulz *et al* have pointed to the importance of the transverse coherence properties of the projectile beam in ion-impact ionization.
  (Phys. Rev. A **86**, 022706; Phys. Rev. Lett. **110**, 113201).
- According to this recent analysis our observed orientation dependencies are relying on the macroscopic collimation of the projectile beam.
- With a less well-cooled ion beam the orientation dependence (which does not require very high momentum resolution in our COLTRIMS system) should vanish.

What we would like to do at CRYRING@FAIR (phase 0)

- p-N_2 orientation dependent at 2 MeV to look for the interference we have seen more clearly in p-H_2.

- p-H_2 orientation dependent at 1.3 MeV with varied projectile beam transverse coherence properties.

What we would like to do at CRYRING@FAIR

- Reaction microscopy. Free electrons and recoiling ions in coincidence.
- HCI@modest velocities. Approach non-perturbative regime in ion/atom collisions.

Co-workers:

p-N_2:
M. Gudmundsson, D. Fischer, D. Misra, A. Källberg, A. Simonsson, K. Støchkel, H. Cederquist

and some youngsters involved in earlier work on H_2:
P. Reinhed, R. Schuch, C. L. Cocke and H. Schmidt-Böcking

and THANK YOU