Optically Trapped Atoms as an Ultracold Target for Ion and Antiproton Beams

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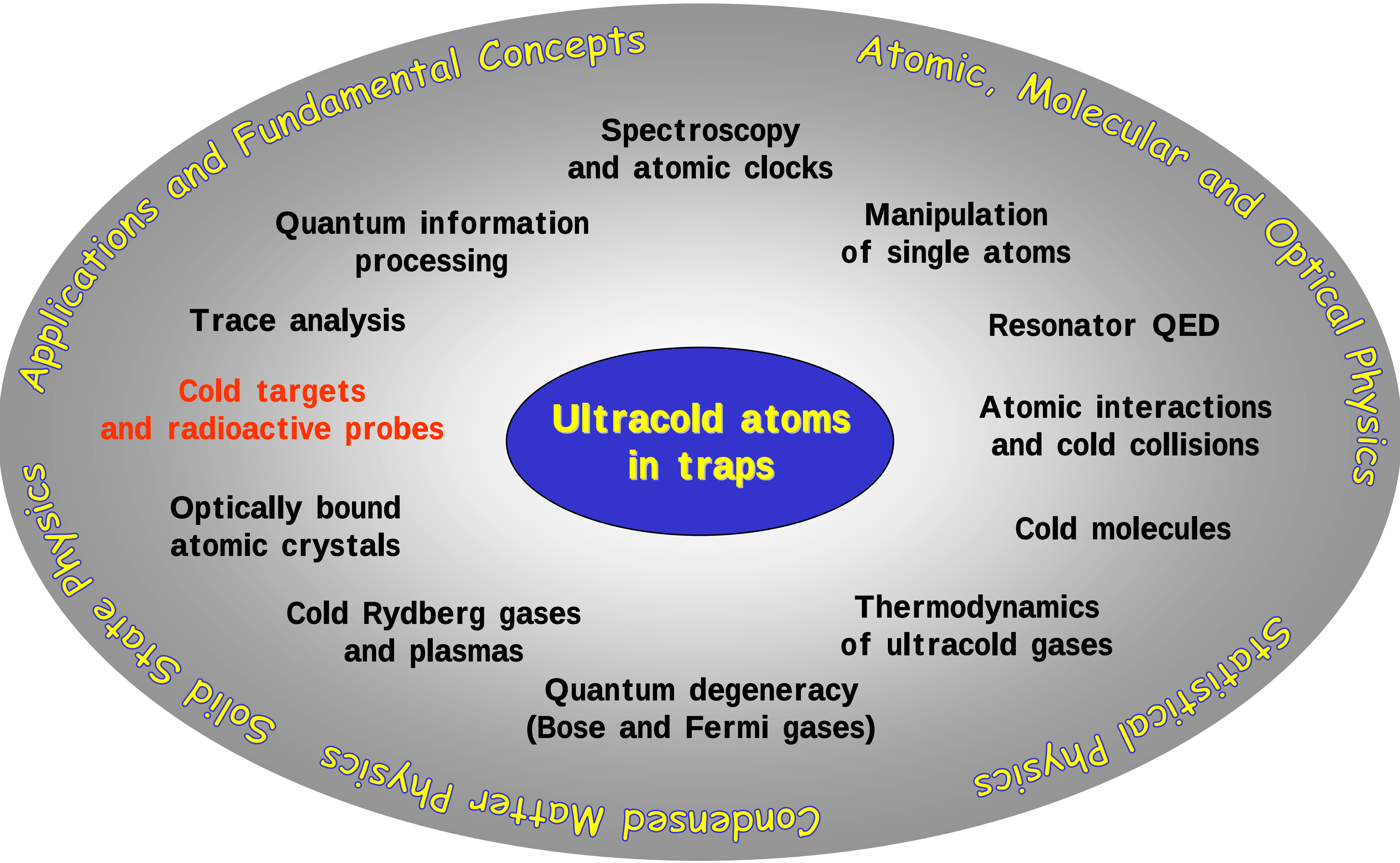
Ultracold atoms in traps

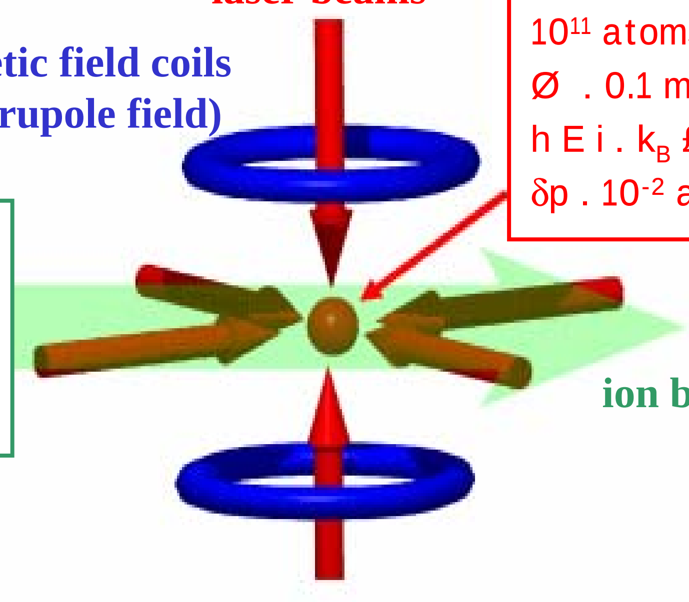


Ultracold atoms interacting with an ion beam

Magneto-optical trap (MOT) in a storage ring

Light-pressure force for confinement (Zeeman effect)
and
cooling (Doppler effect)

10^4 ... 10^9 stored atoms
10^{11} atoms / cm^3
Ø . 0.1 mm
h E i . k_B £ 100 µK ~ 10 neV
δp . 10^{-2} a.u.



10^6 stored ions
10^4 ions / cm^3
Ø ~ 1 mm
h E i ~ 1 MeV

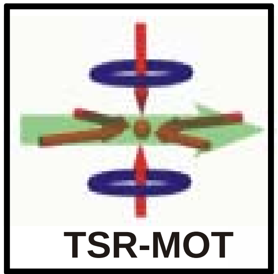
Cold-atom targets for ion beams: state of the art

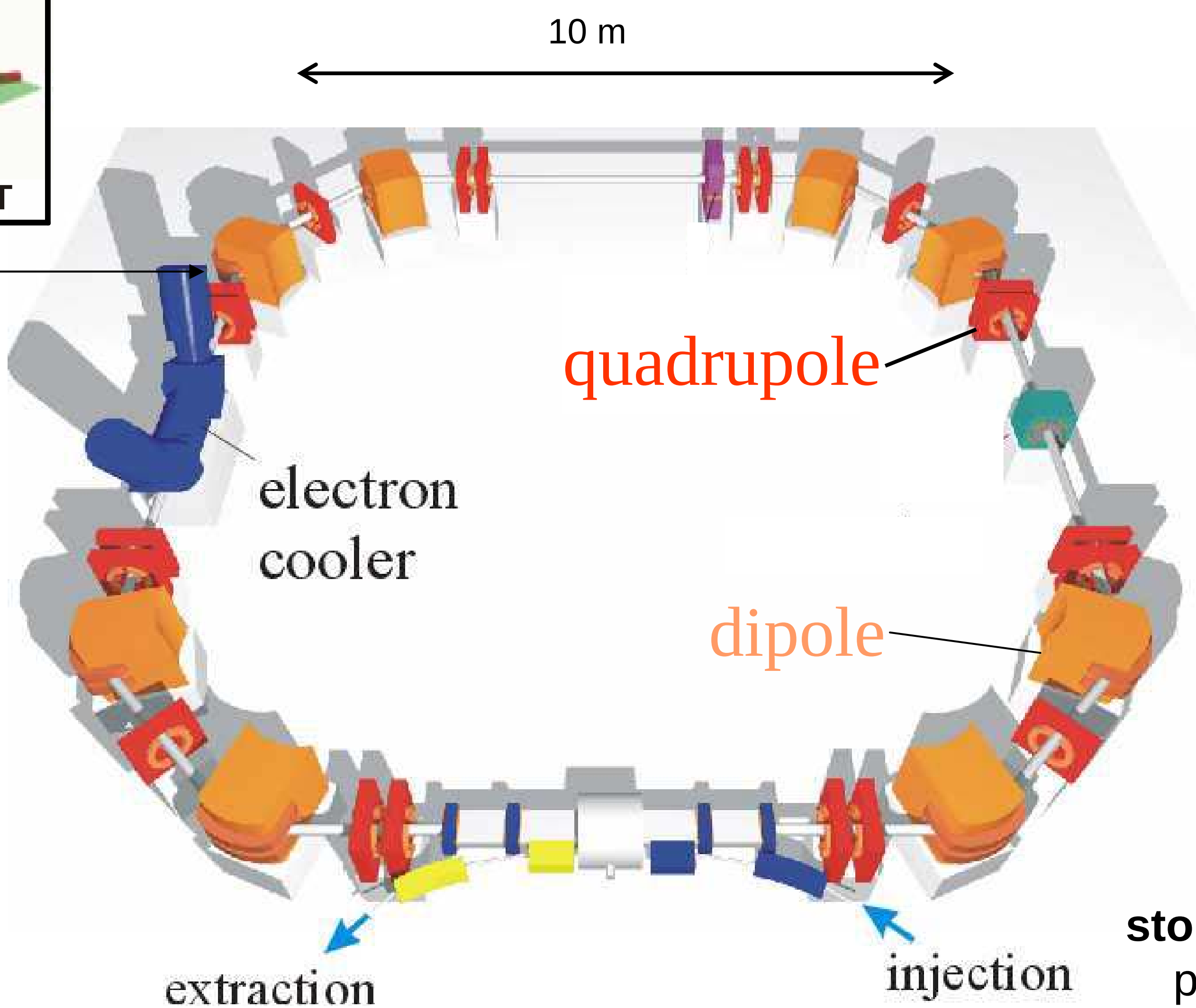
- **Recoil-ion momentum spectroscopy in single-pass experiments**
  - N. Andersen *et al.* (Niels Bohr Institute, Copenhagen)
    Na and singly-charged keV beams
  - B.D. dePaola *et al.* (Kansas State University, Manhattan)
    Rb and singly-charged keV beams
  - R. Morgenstern *et al.* (Kernfysisch Versneller Instituut, Groningen)
    Na and multiply-charged keV beams
- **Cold-atom target in a storage ring**
  - Our group, MPI for Nuclear Physics (Heidelberg)
    Cs and highly-charged MeV beams

Overview

- Implementation of a cold atom target into a complex storage ring
- Ultracold atoms as an in-situ current and beam profile monitor
- Ultracold atoms as a precision target for collision studies
- Prospects @ GSI

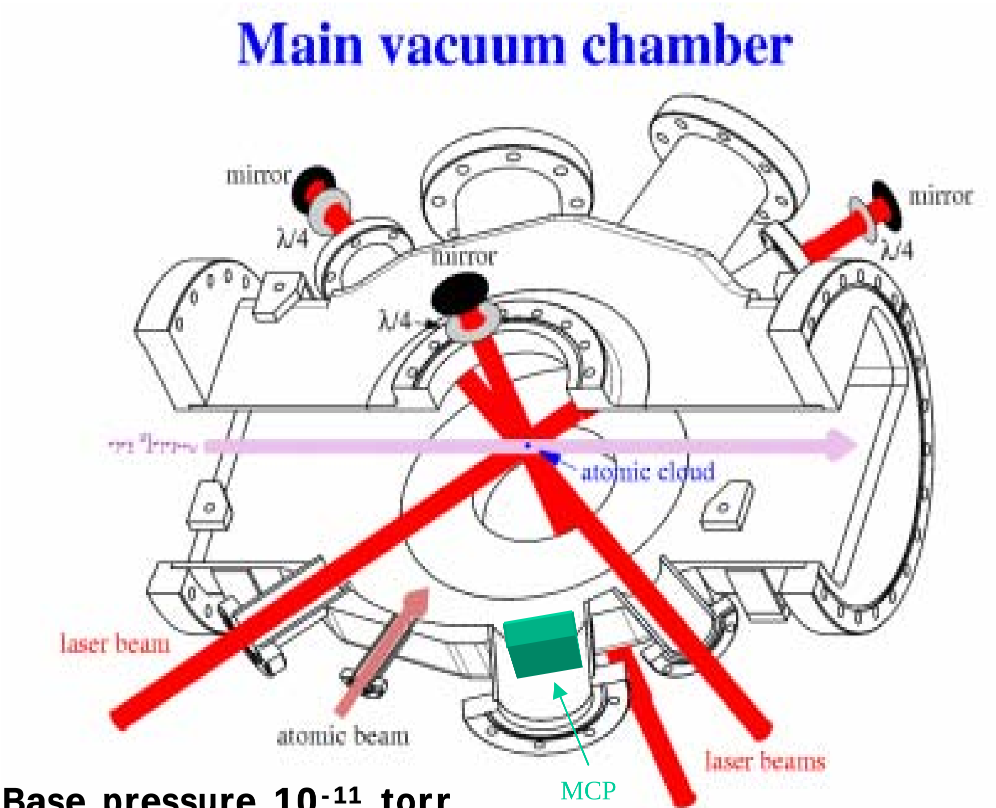
Heidelberg Test Storage Ring



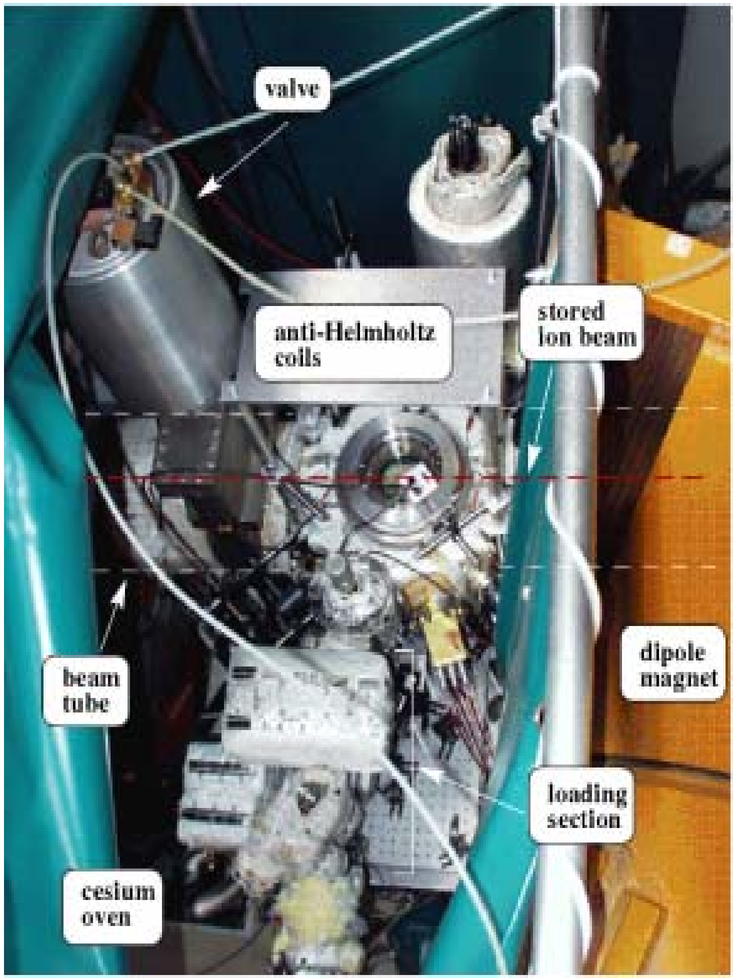


storable ions:
p … Au^{79+}
@ some MeV/u

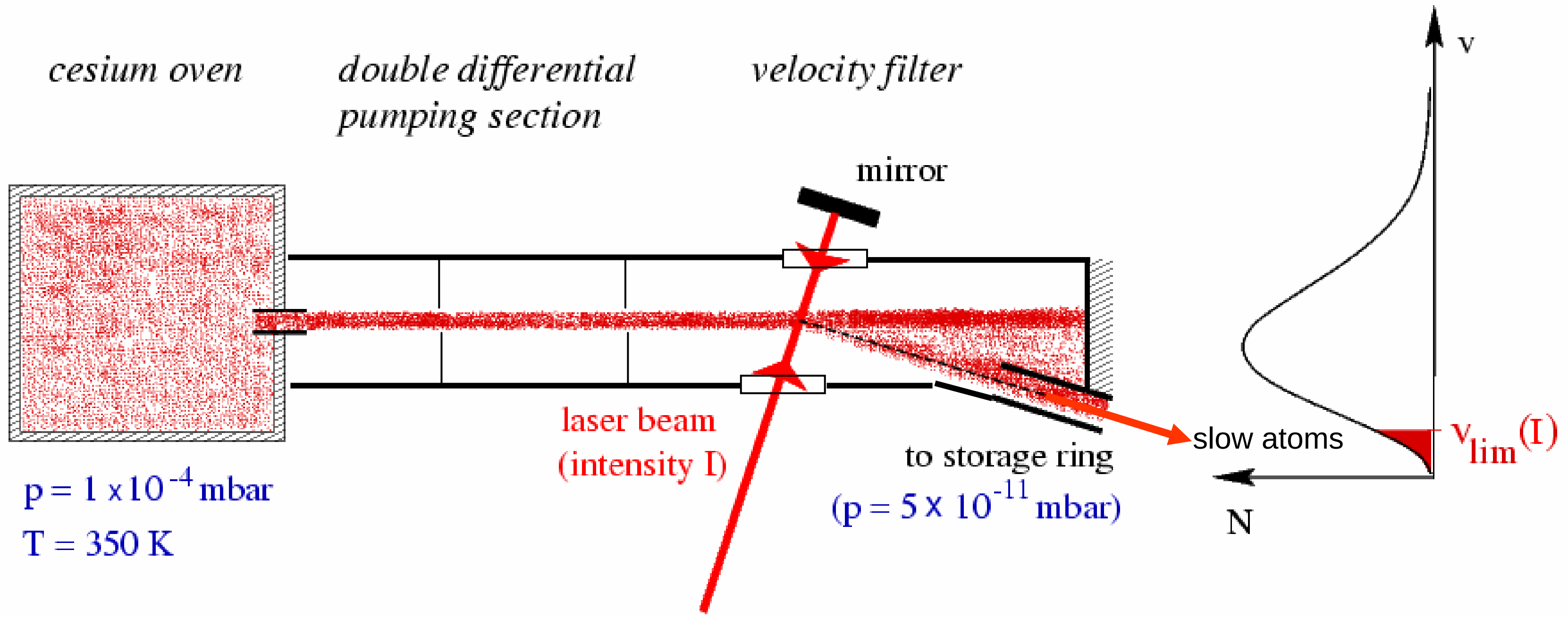
Implementation into the storage ring



Base pressure 10^{-11} torr

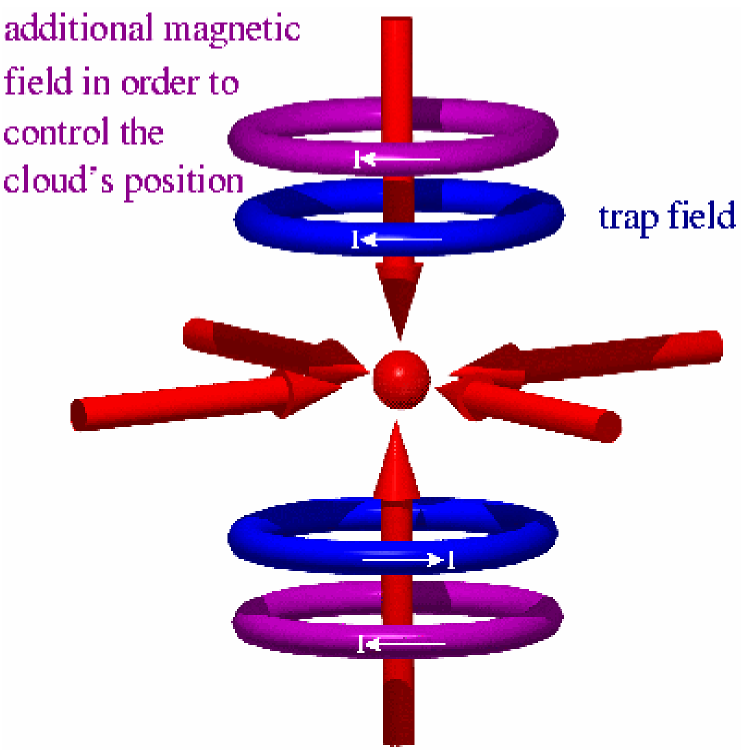


Loading concept

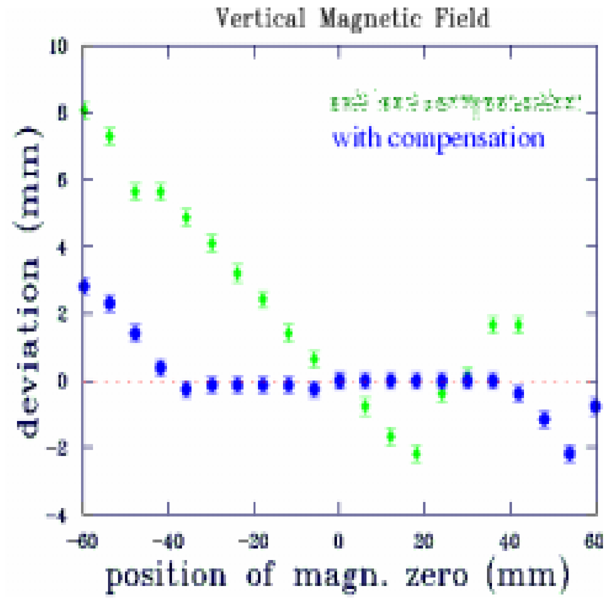


Control of the target position

Shift of the quadrupole magnetic field center
by additional homogeneous magnetic field

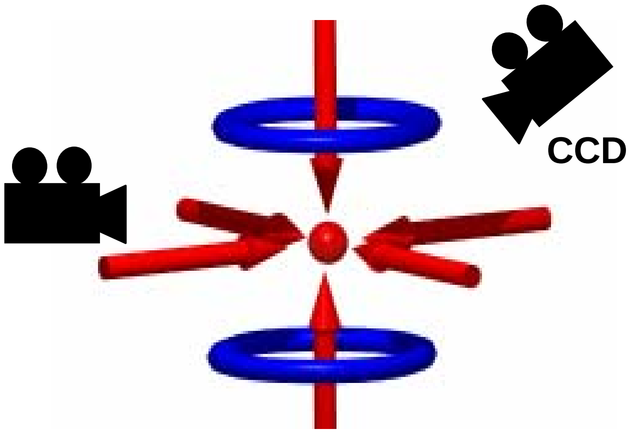


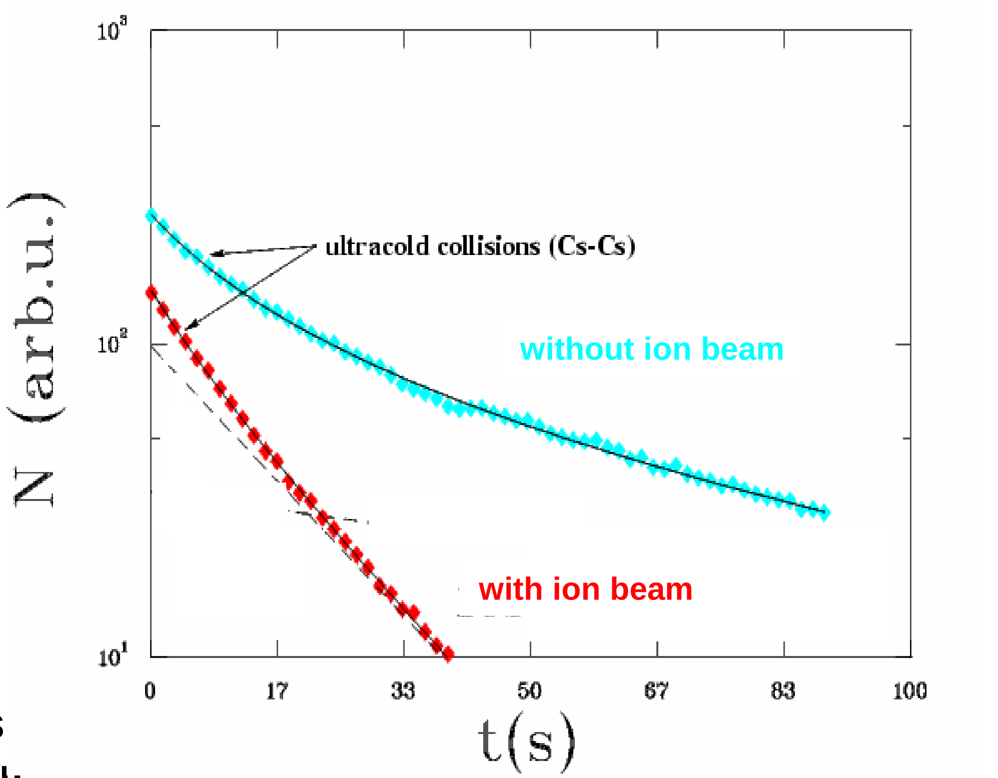
Reaction of the ion beam
on the MOT control field:



Detection of interactions: Fluorescence

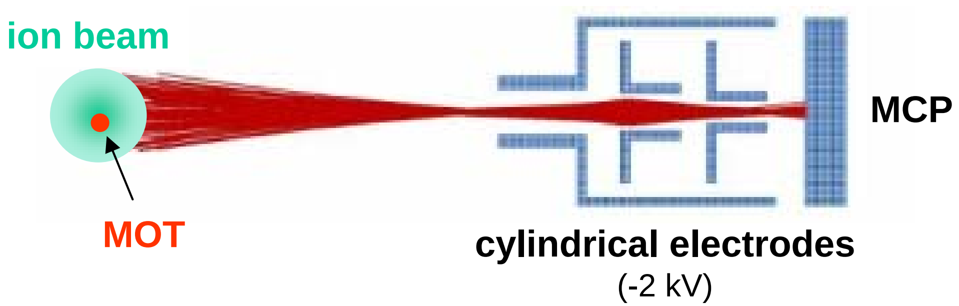
Detection of fluorescence light
$\propto$ number of trapped atoms



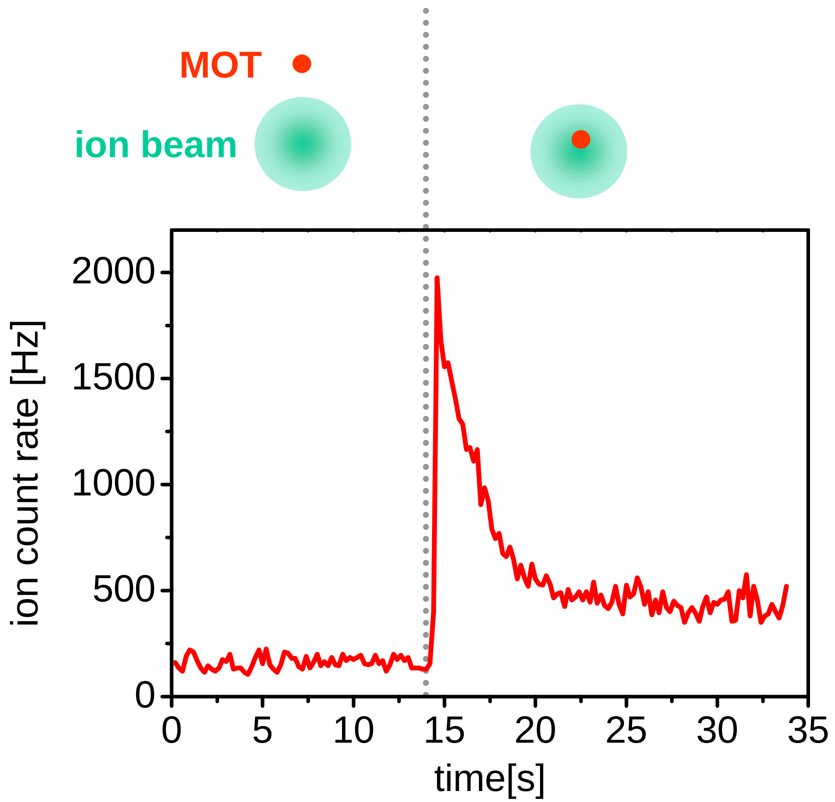


Stereoscopic detection with two cameras for determination **of atom cloud's position**

Detection of interactions: Ionized atoms



Ion signal:



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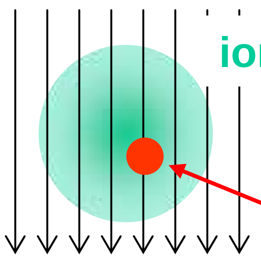
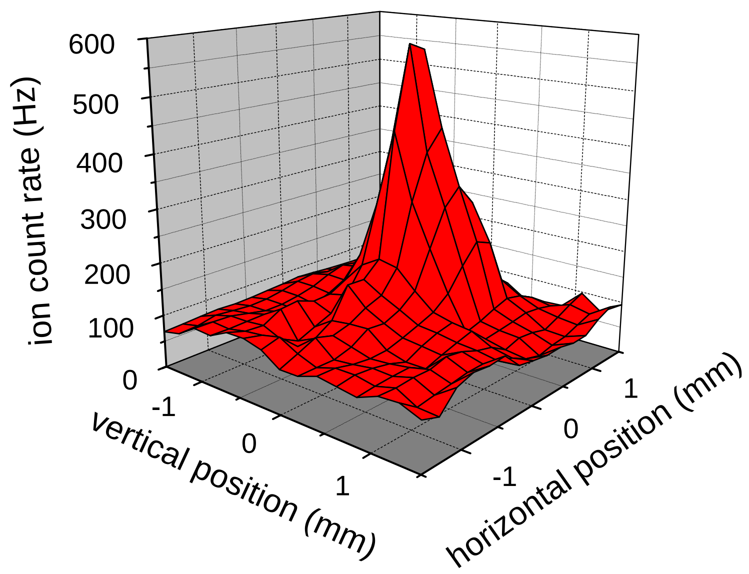
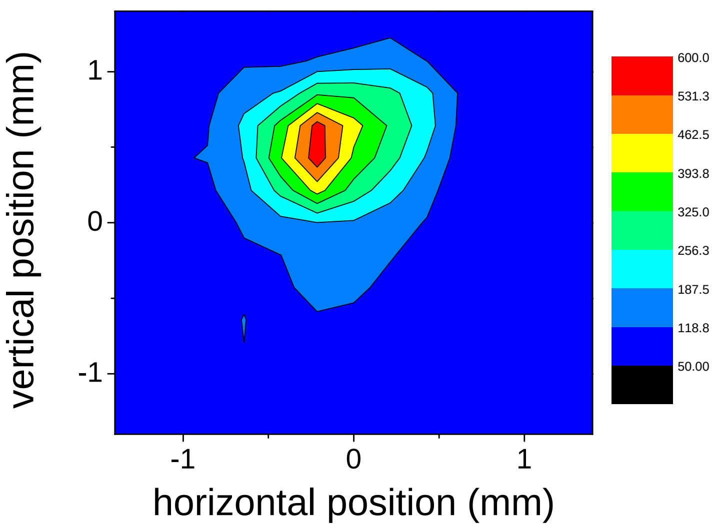
TSR-MOT as a beam profile monitor

Ion count rate for a 2D scan of atom cloud position

(cloud dia. ~ 100 μm)

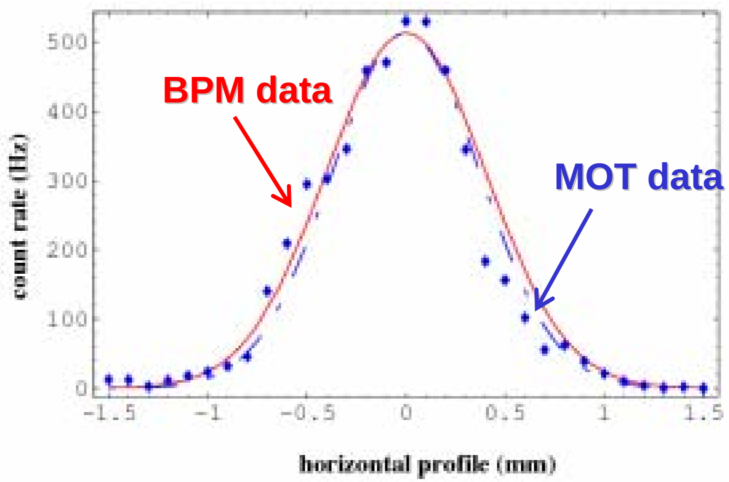




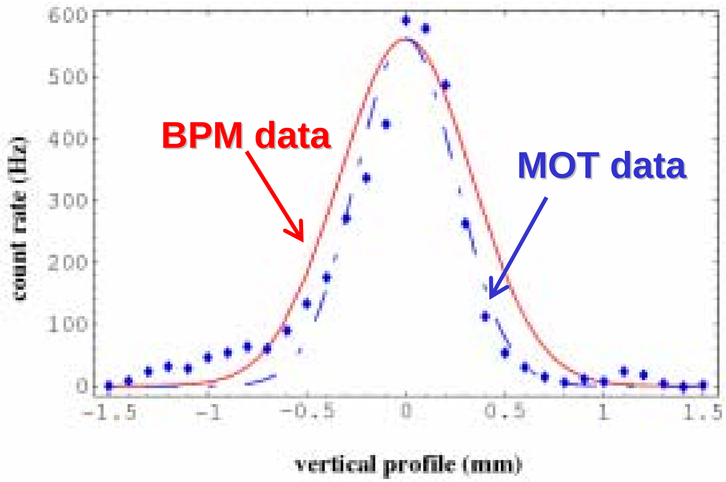


Comparison with rest-gas BPM

horizontal integrated profile



vertical integrated profile



ADVANTAGES of the cold-atom BPM

- Sensitivity down to low ion currents (<10 nA)
- Better resolution than rest-gas BPM
- Direct 2D beam profile

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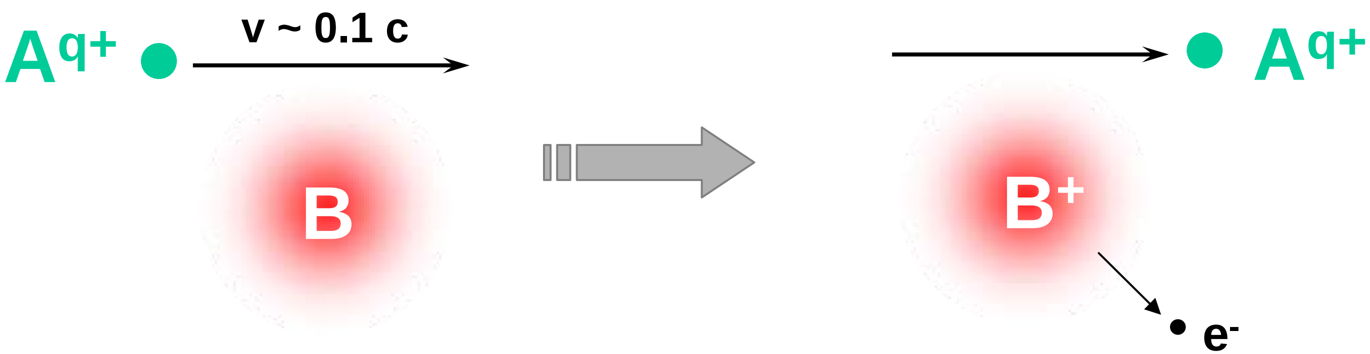
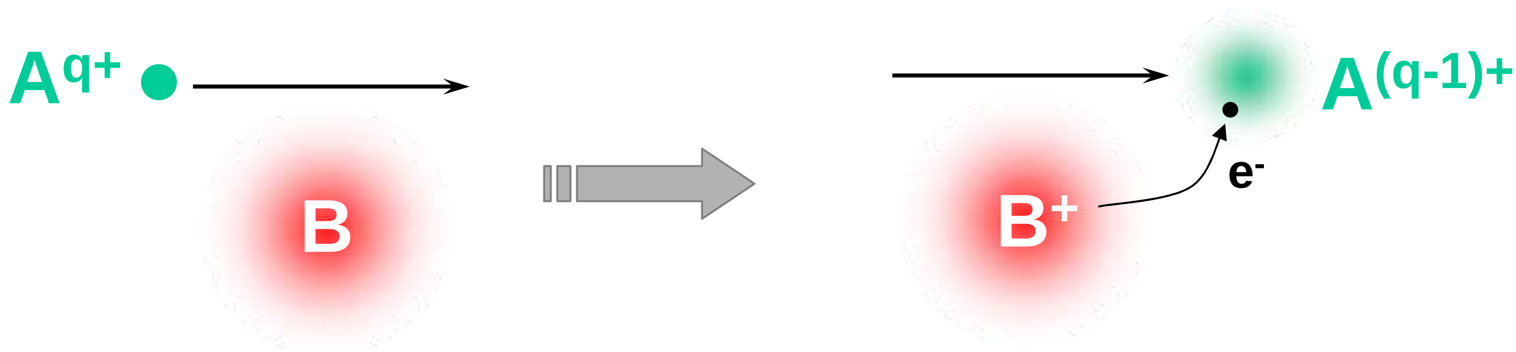
Interaction of fast ions with atoms

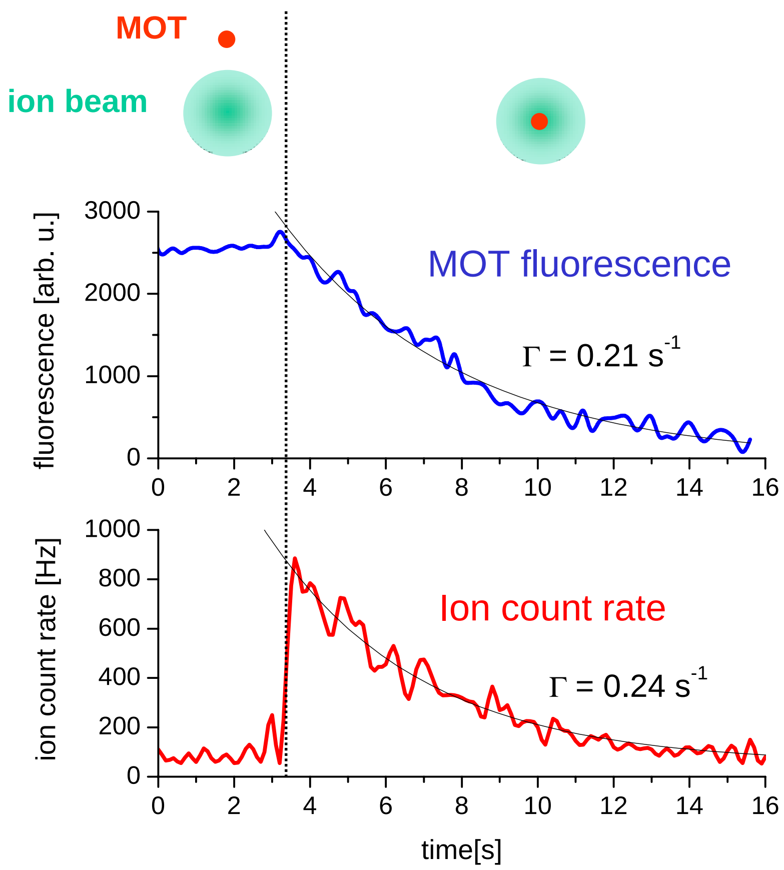
Impact ionization:



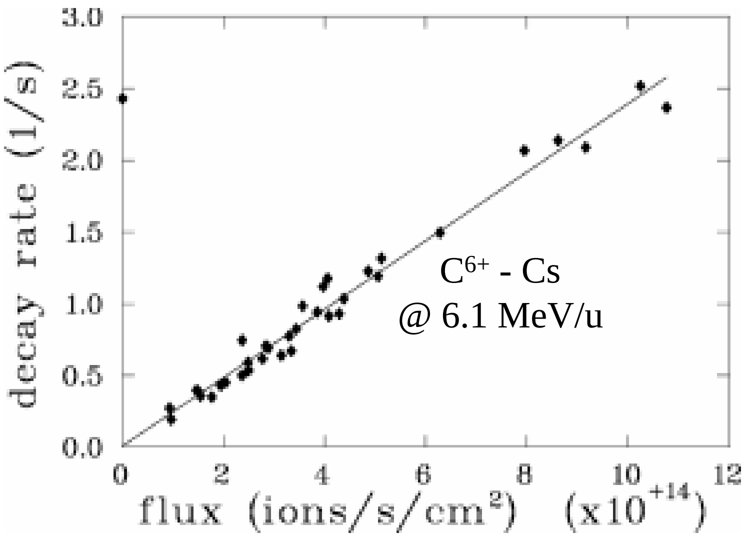
Electron capture:



Total collision cross sections



Decay rate versus ion flux

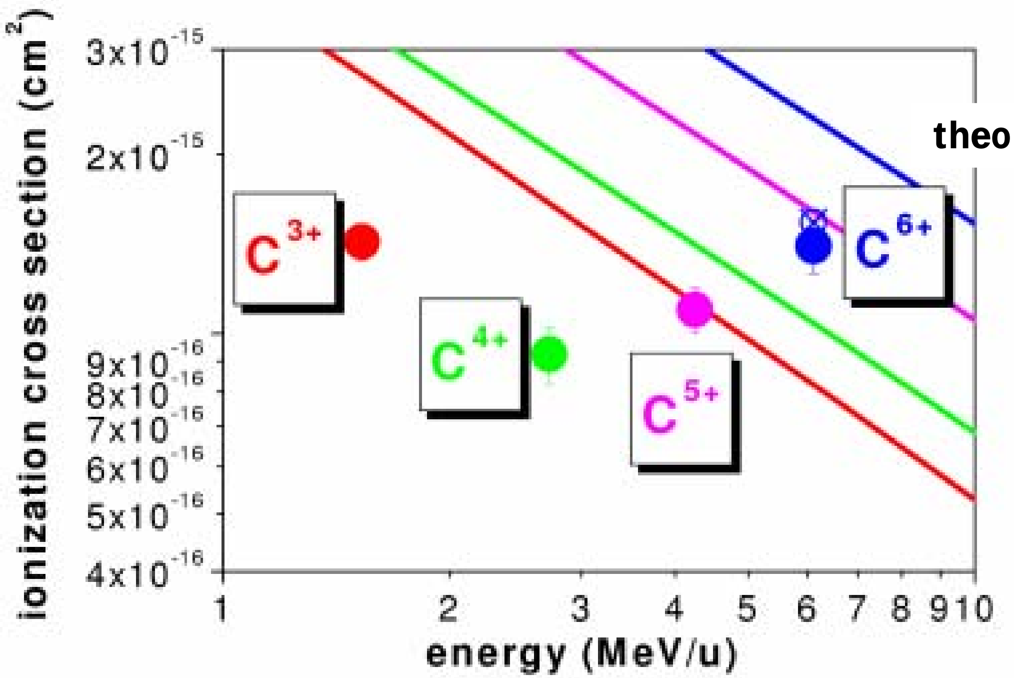


Ion flux determined from calibrated BPM count rate

$$\text{cross section } \sigma = \frac{\text{decay rate } \Gamma}{\text{ion flux } \eta}$$

Dependence on charge state

Dependence of the cross section on the charge state

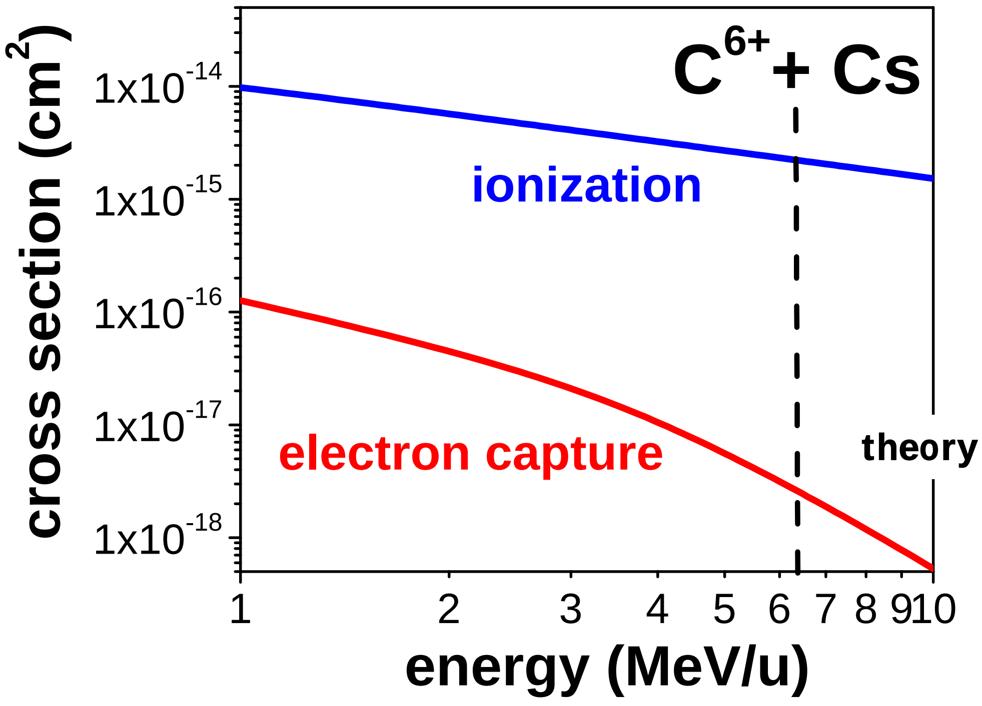


theory by V.P. Shevelko

Ionization vs. electron capture

main contribution to total cross section:

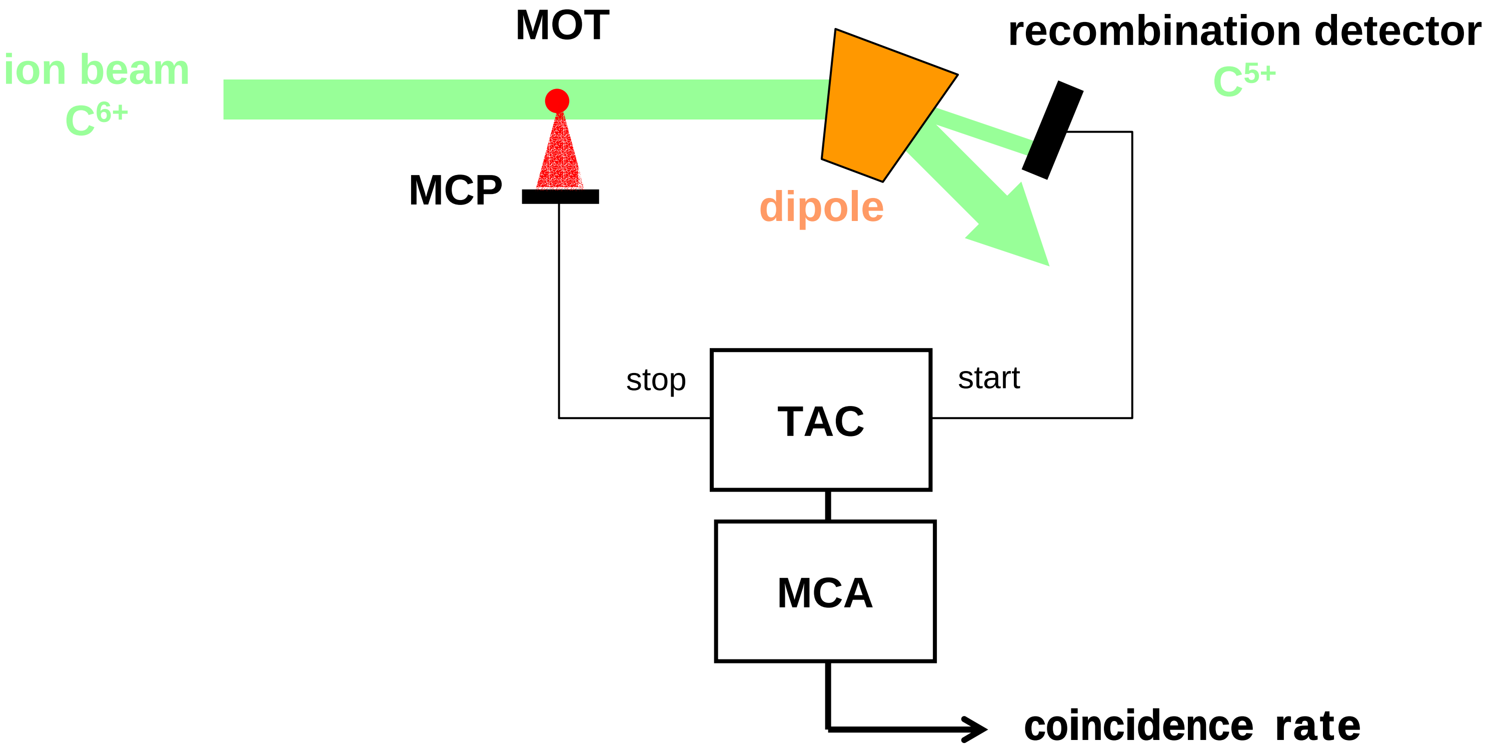
ionization of the cesium target



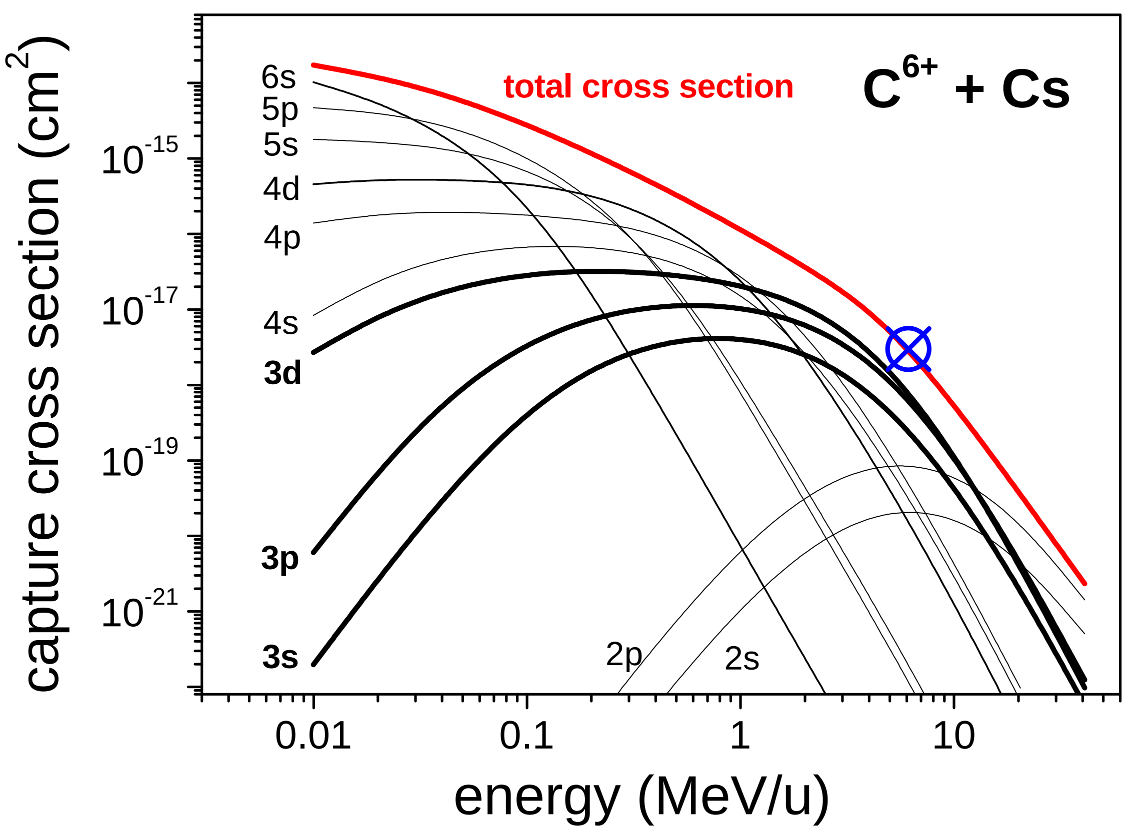
theory by V.P. Shevelko

Detection of electron capture

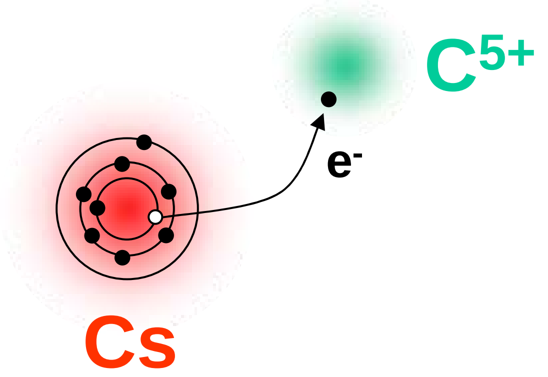
$$C^{6+}(6.1\ \text{MeV/u}) + \mathbf{Cs} \rightarrow C^{5+} + \mathbf{Cs}^{q+}$$



Electron capture cross section

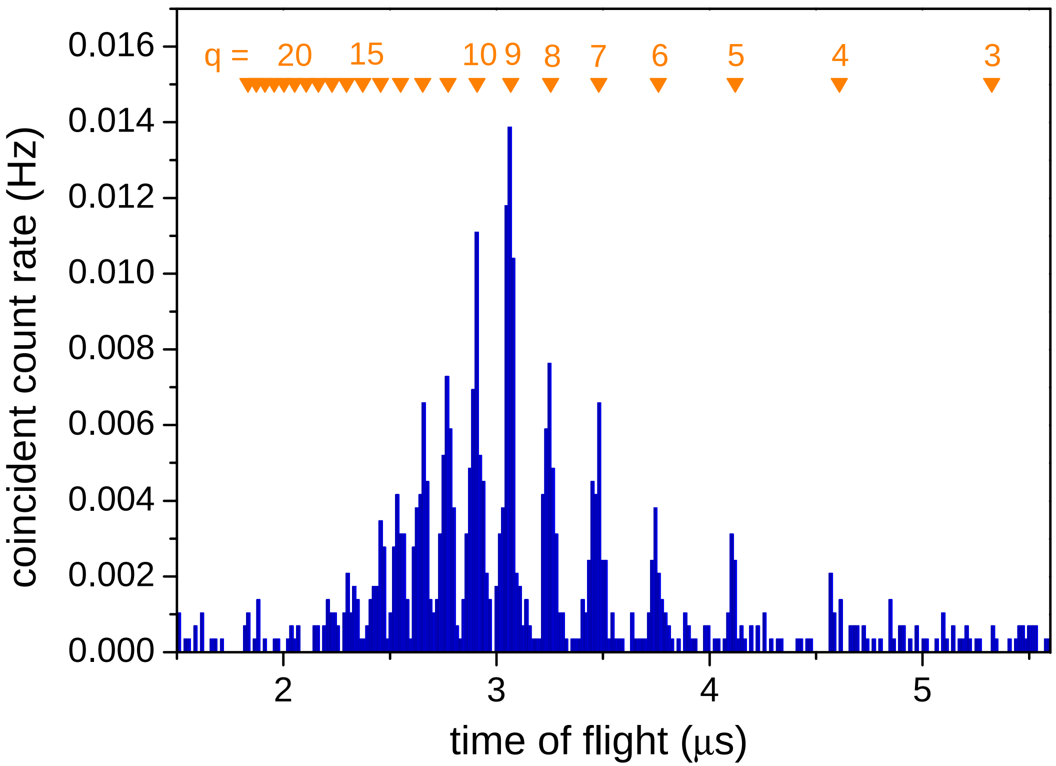


mainly **M-shell** electrons are captured



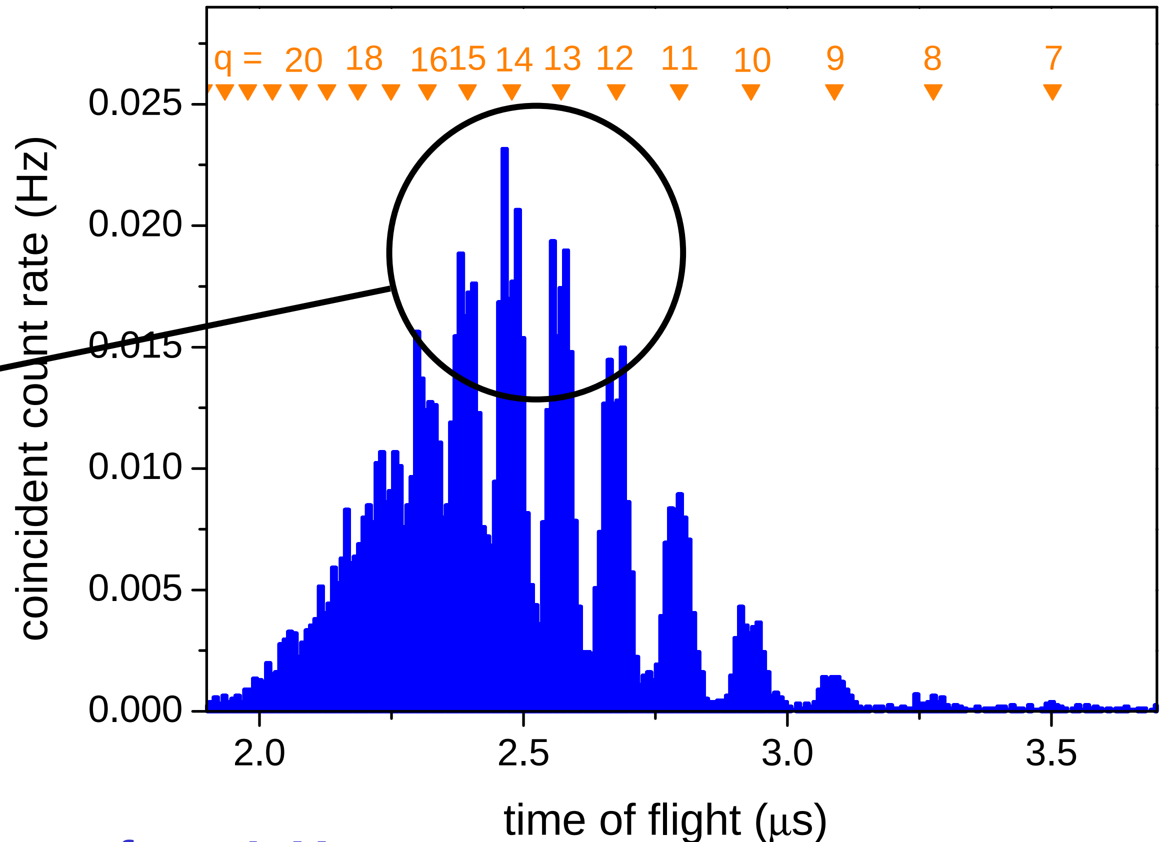
Distribution of final charge states

Electron capture: $C^{6+} + Cs \rightarrow C^{5+} + Cs^{q+}$ @ 6.1 MeV/u

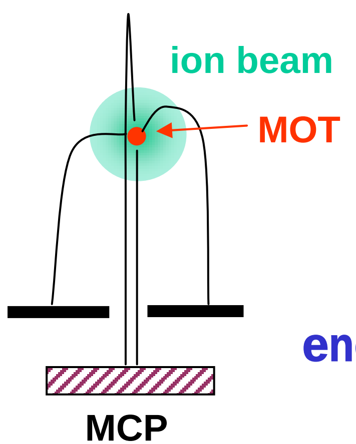


Momentum transfer

Electron capture: O^{8+} + Cs ! O^{7+} + Cs^{q+} @ 8.3 MeV/u



double peak structure



energy transfer ~1eV

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Properties of cold-atom targets

✓ **Full control over important target parameters**
(number of target atoms, density, target position and size)

✓ **Full control over internal degrees of freedom**
(spin polarization, ground state vs. Rydberg states)

- **Limited number of elements**
(Laser-coolable species: alkali, alkali-earth, metastable rare gases
and some exotic elements like chromium)

✓ **High isotope selectivity**

- **Limited loading flux and densities**

✓ **Large repertoire in cooling, trapping and manipulation techniques**

Prospects at GSI (personal view)

1. **Trapped atoms as a probe**
   for precision experiments with dilute beams (e.g. at SIS200 and NESR)

   Improved copy of the TSR concept (enhanced loading flux, improved position control)

2. **COLTRIMS with an ultracold Li target**
   for kinematically complete collision experiments

   Combination of COLTRIMS technology with Li manipulation techniques (e.g. high-flux source)

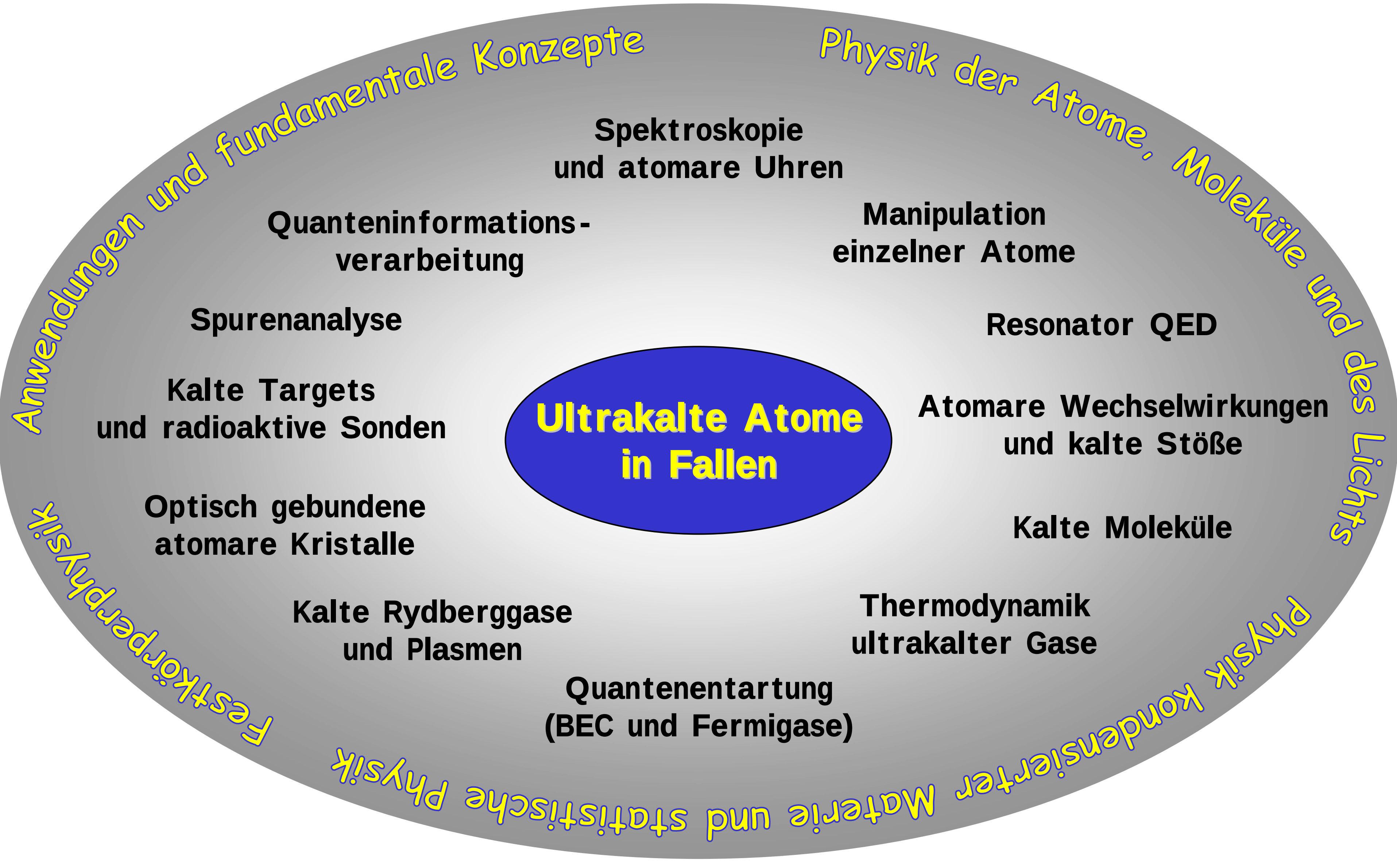
3. **Cold Rydberg atoms as an electron target**
   for studies of ion-electron interactions

   Two- or three-step laser excitation of trapped alkali atoms into highly-excited states

4. **Trapping and manipulation of radioactive isotopes**
   for studies of fundamental questions

   Application of state-of-the-art trapping and manipulation techniques to exotic elements

Ultrakalte Atome in Fallen



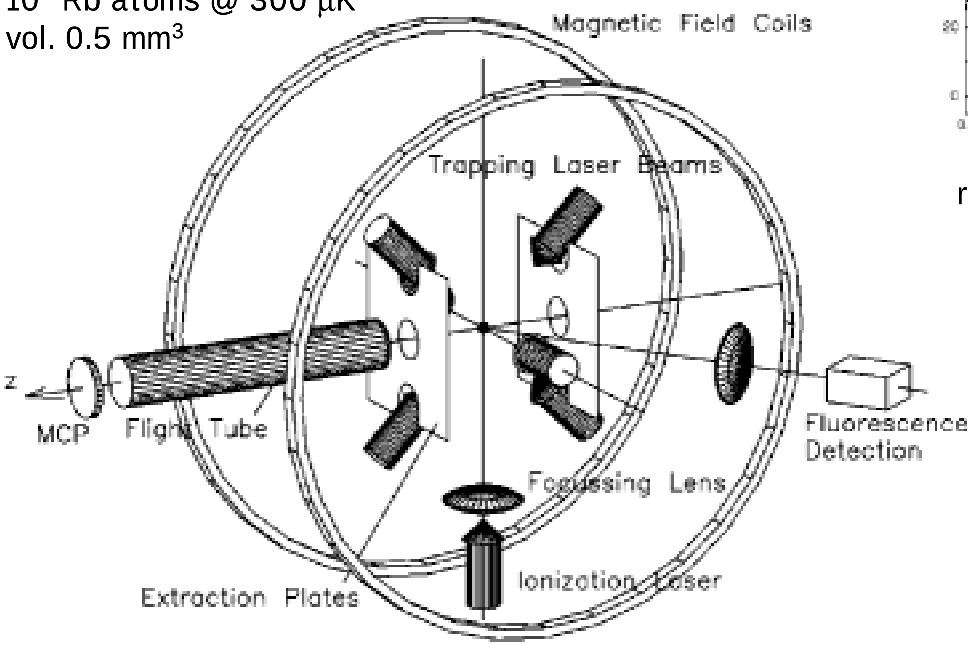
COLTRIMS of photoionization in a MOT

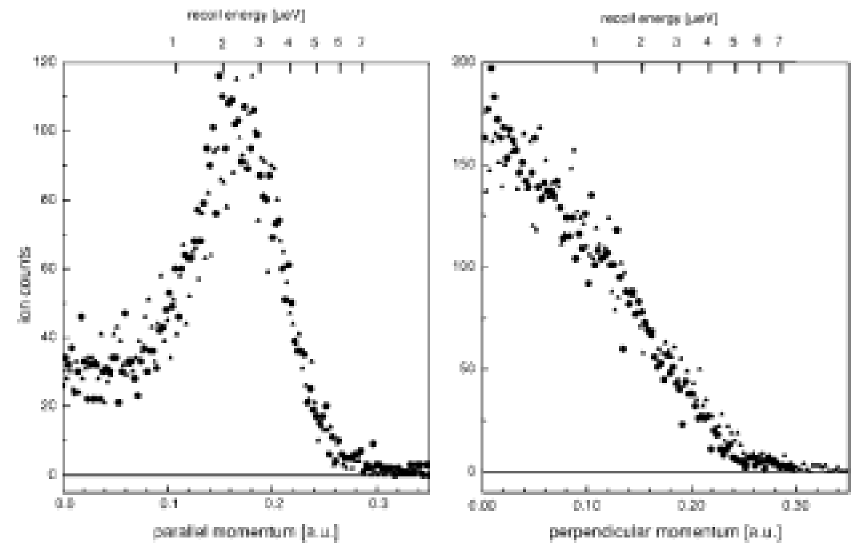
S. Wolf and H. Helm, Phys. Rev. A **56**, R4385 (1997); *ibid.* **62**, 043408 (2000). [Uni Freiburg]

Photoionization of Rb with a 150-fs Ti:Saph laser

$Rb(^2P_{3/2}) + 2\,h\,\nu\ !\ Rb^+(^1S_0) + e + \Delta E$

10^6 Rb atoms @ 300 μK
vol. 0.5 mm^3





recoil momemtum k el. field   recoil momemtum ? el. field

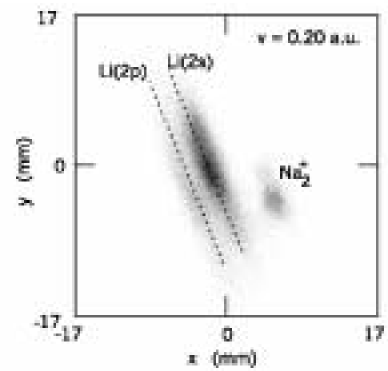
- Investigation of systematic broadening effects (e.g., space-charge, laser bandwidth, imperfect time focusing)
- Momentum resolution 0.05 a.u.
  energy resolution 1 μeV

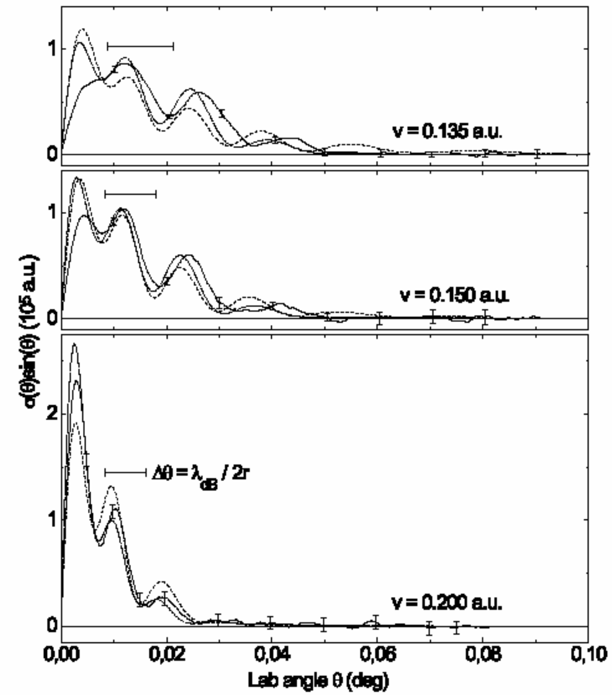
COLTRIMS of electron transfer with a MOT I

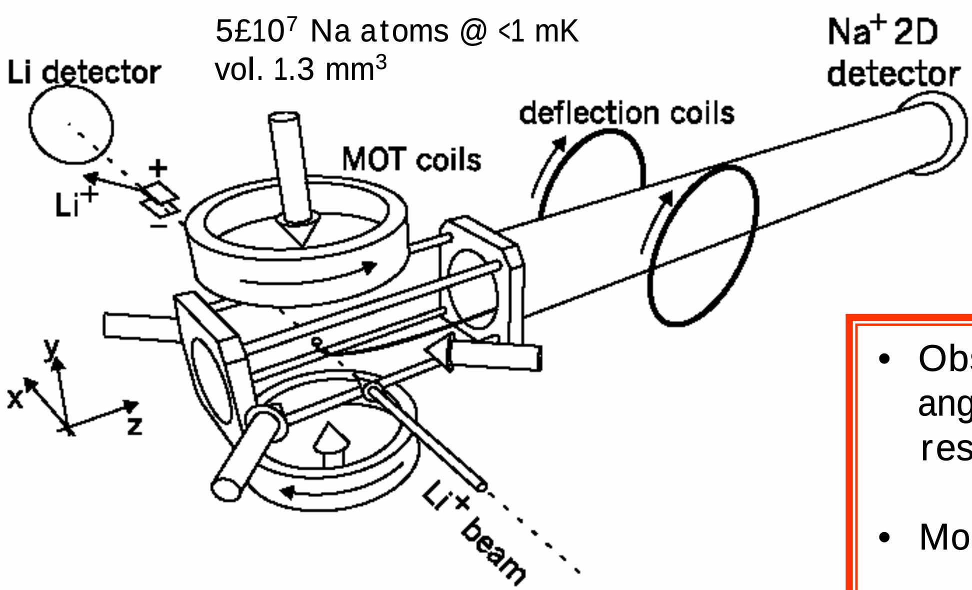
M. van der Poel *et al.*, Phys. Rev. Lett. **87**, 123201 (2001). [Niels Bohr Institute, Copenhagen]

Charge-exchange collisions of a 6 keV Li^+ beam with cold Na atom

Li^+ + Na ! Li + Na^+







- Observation of Fraunhofer diffraction in the angular dependency of the cross section (angular resolution » 0.003º)
- Momentum resolution 0.12 a.u. (δp_z)
  0.80 a.u. (δp_y) [MOT field]

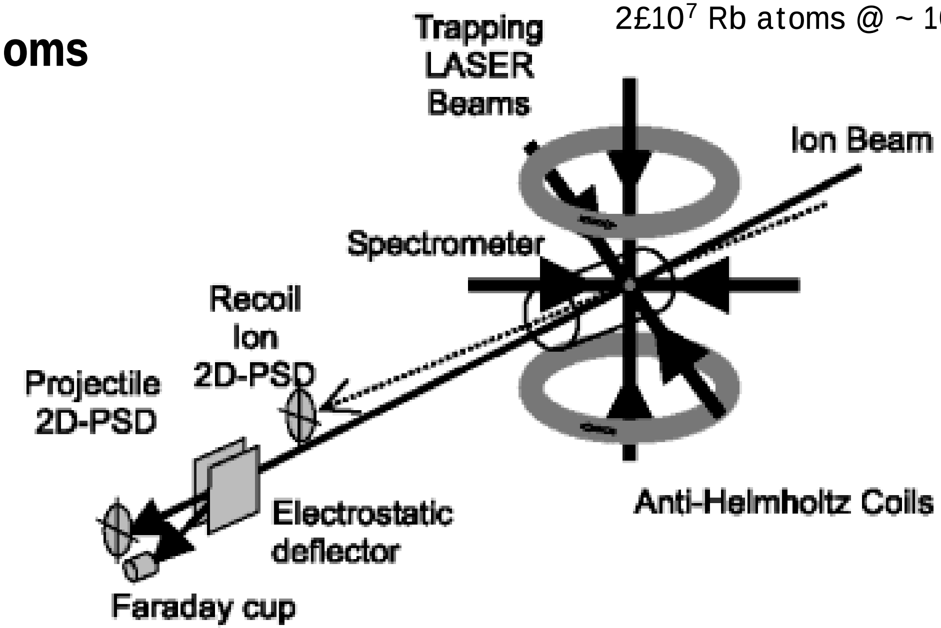
COLTRIMS of electron transfer with a MOT II

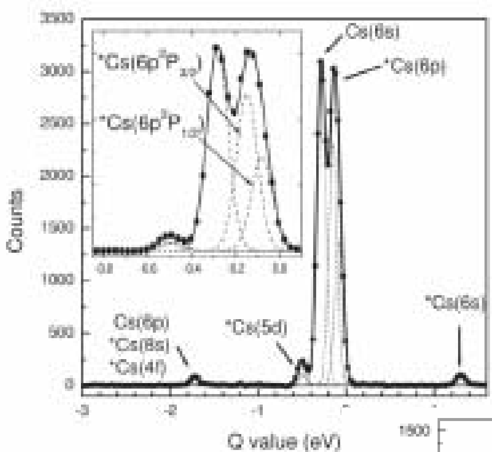
X. Flechard *et al.*, Phys. Rev. Lett. **87**, 123203 (2001). [Kansas State University, Manhattan]

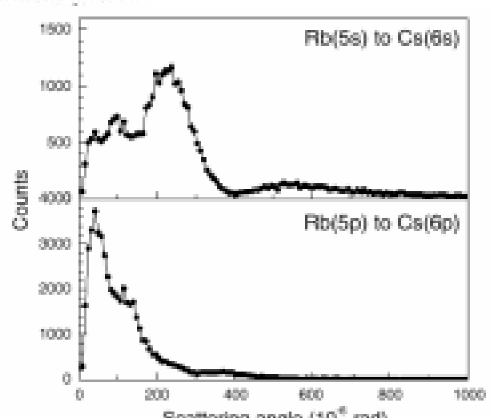
Charge-exchange collisions of a 6 keV Cs^+ beam with cold Rb atoms

$Cs^+ + Rb ! Cs + Rb^+$

$2£10^7$ Rb atoms @ ~ 100 μK







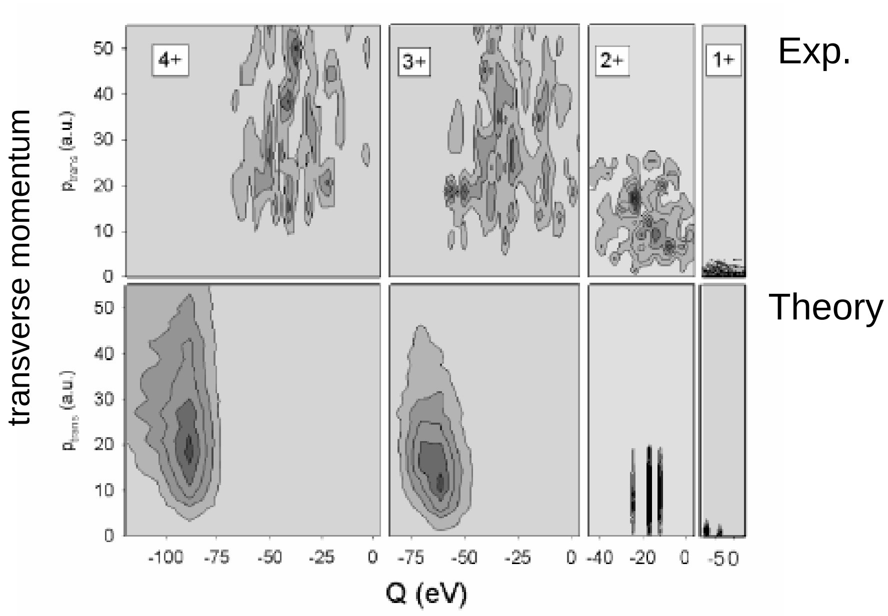
- Charge-capture from Rb(5s) and Rb(5p) by Cs^+ projectiles with resolved final state.
- Momentum resolution 0.08 a.u. (δp_z) angular resolution » 0.002º

COLTRIMS of highly-charged ion collisions with a MOT

J.W. Turkstra *et al.*, Phys. Rev. Lett. **87**, 123202 (2001). [KFI, Groningen]

Charge-exchange collisions of a keV highly-charged ion beam with cold Na atoms

O^{6+} + Na ! $O^{(6-q)+}$ + Na^{q+}



- Investigation of multielectron capture processes
- Momentum resolution 0.25 a.u.