Plan of lectures

- 1 15.04.2015 Preliminary Discussion / Introduction

- 2 22.04.2015 Experiments (discovery of the positron, formation of antihydrogen, ...)
- 3 29.04.2015 Experiments (Lamb shift, hyperfine structure, quasimolecules and MO spectra)
- 4 06.05.2015 Theory (from Schrödinger to Dirac equation, solutions with negative energy)
- 5 13.05.2015 Theory (bound-state solutions of Dirac equation, quantum numbers)
- 6 20.05.2015 Theory (bound-state Dirac wavefunctions, QED corrections)

- 7 27.05.2015 Experiment (photoionization, radiative recombination, ATI, HHG...)
- 8 03.06.2015 Theory (single and multiple scattering, energy loss mechanisms, channeling regime)
- 9 10.06.2015 Experiment (Kamiokande, cancer therapy, ….)

- 10 17.06.2015 Experiment (Auger decay, dielectronic recombination, double ionization)
- 11 24.06.2015 Theory (interelectronic interactions, extension of Dirac (and Schrödinger) theory for the description of many-electron systems, approximate methods)

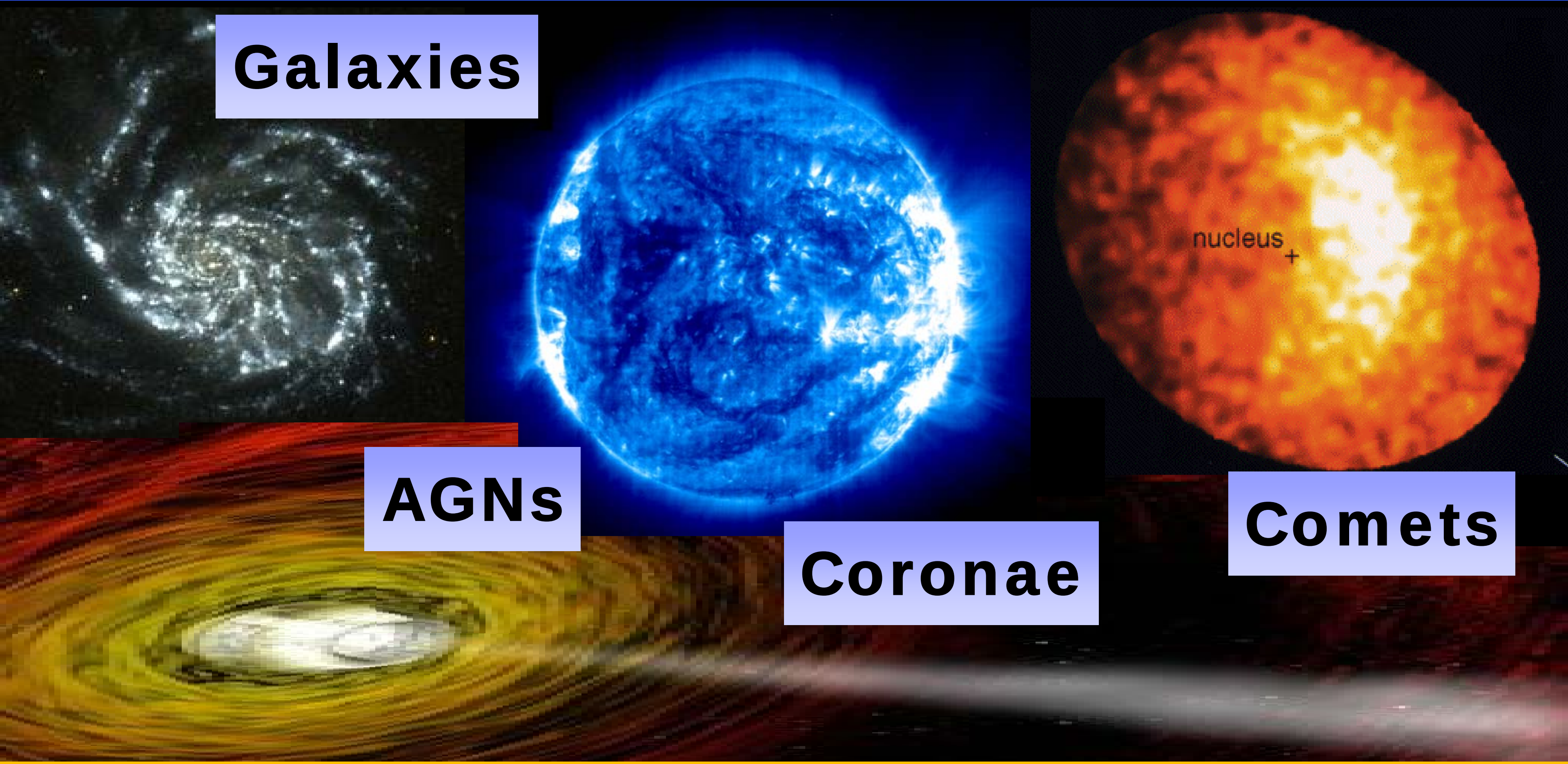
- 12 01.07.2015 Theory (atomic-physics tests of the Standard Model, search for a new physics)
- 13 08.07.2015 Experiment (Atomic physics PNC experiments (Cs,...), heavy ion PV research)

Motivation: Laboratory Astrophysics

Photoionization ⇔ Radiative Recombination

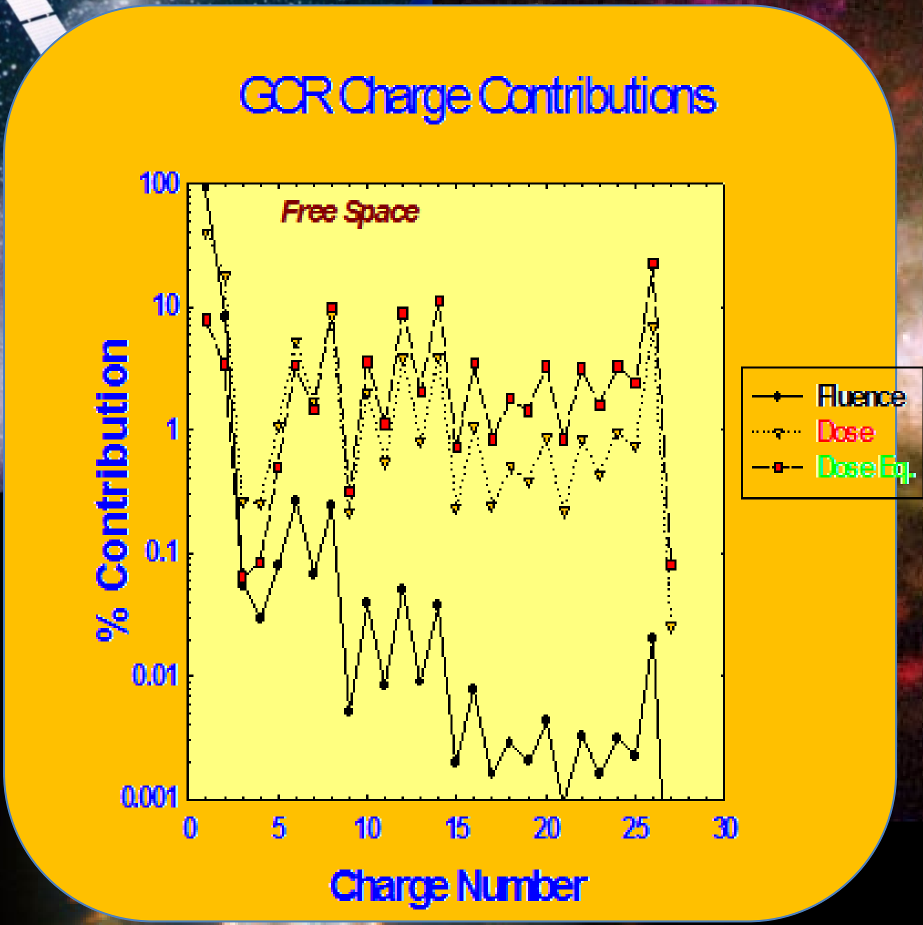
Experiment: Storage Rings

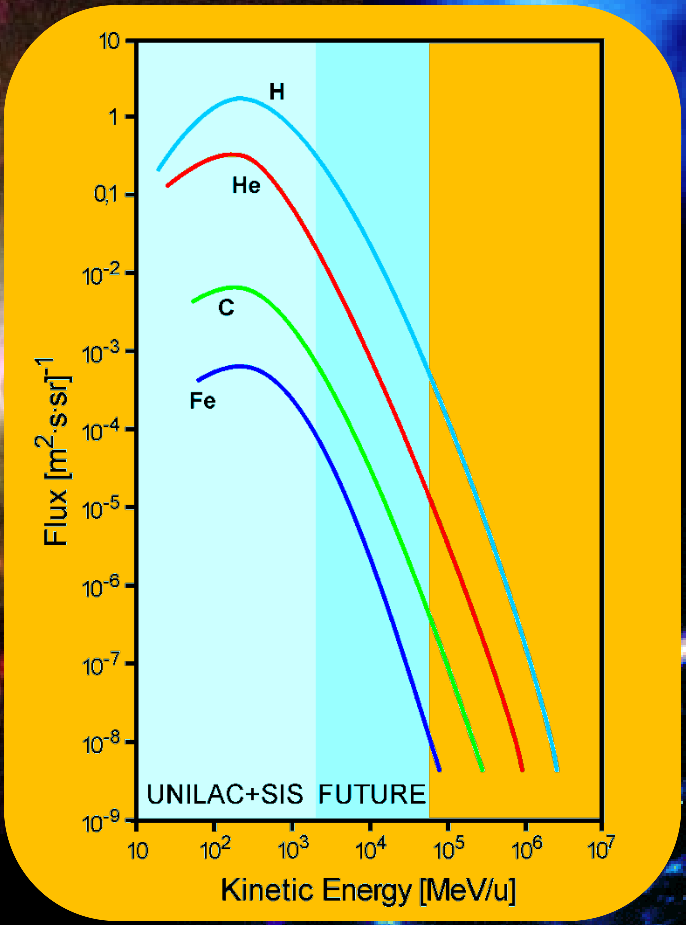
Highly Charged Ions / Strong EM Fields



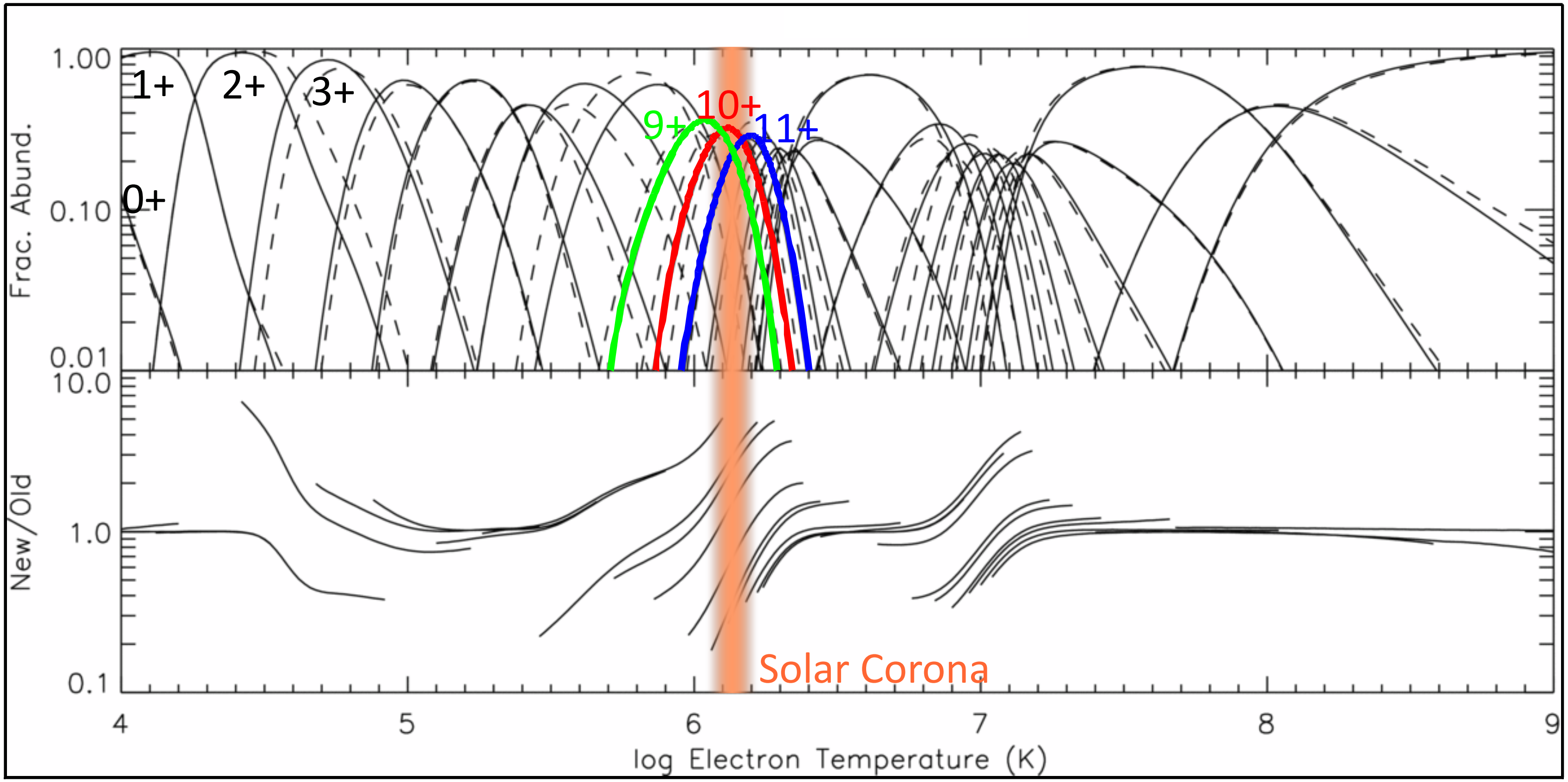
- Ionization and Particle Production Phenomena
- Radiative Processes

Relativistic Energies: Galactic Cosmic Radiation (GCR)



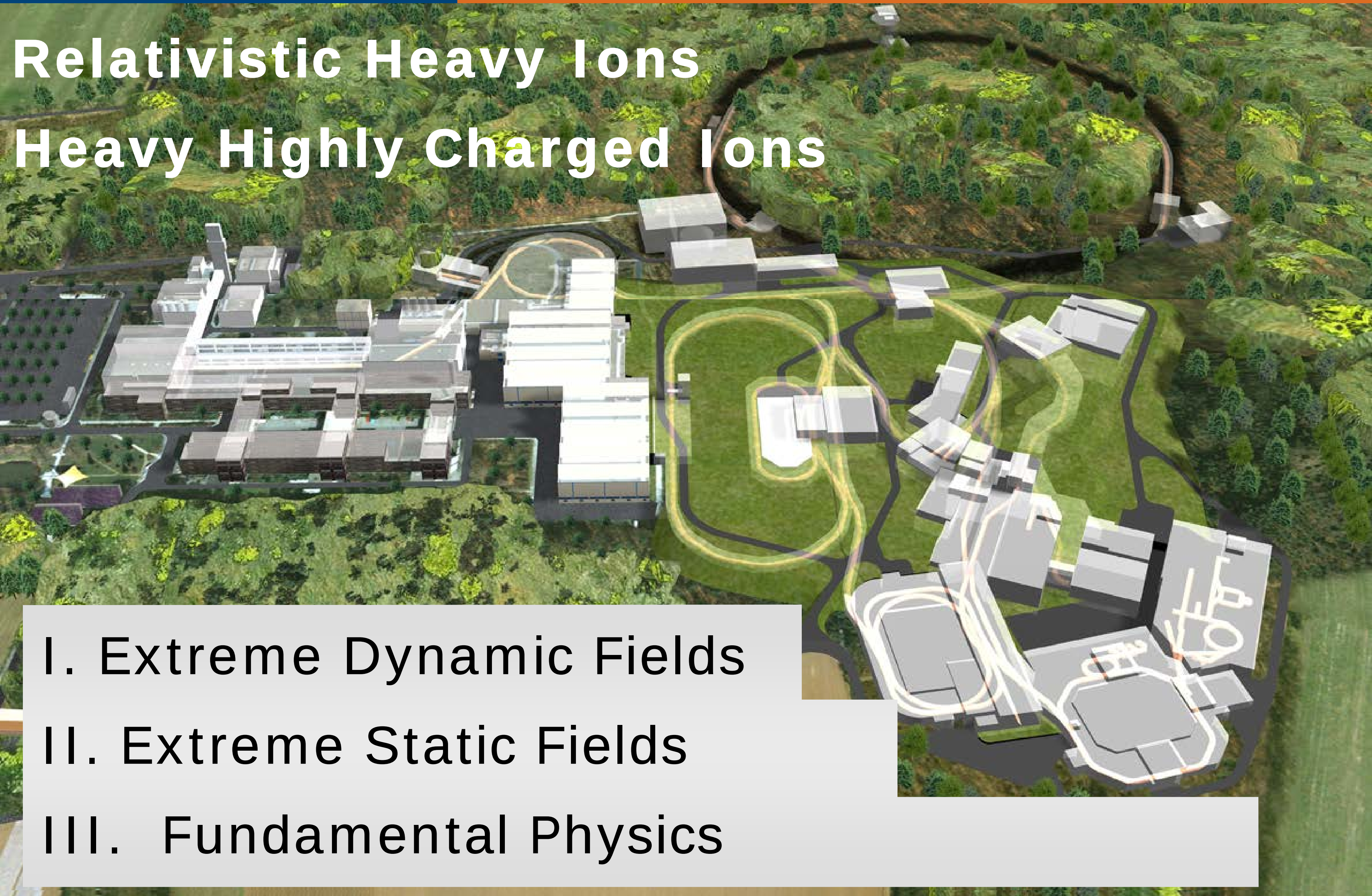


Charge State Distributions:
Collisions between Electrons and Ions only



"New": P. Bryans et al. (2009) "Old": Mazzotta, et al. (1998)

Charge state distribution is determined by the relative strength between the cross sections for electron impact ionization and recombination !



Relativistic Heavy Ions

Heavy Highly Charged Ions

I. Extreme Dynamic Fields

II. Extreme Static Fields

III. Fundamental Physics

Collisional photon-matter interaction processes exhibit distinct photon polarization features

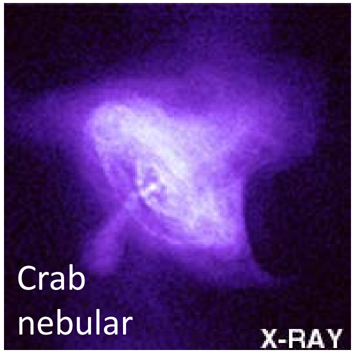
(Synchrotron Radiation, Bremsstrahlung, Recombination, Inverse Compton Scattering, Characteristic radiation, etc.)

But: the large Coulomb charge of heavy ions strongly affects the emission characteristics

Relativistic ion beams

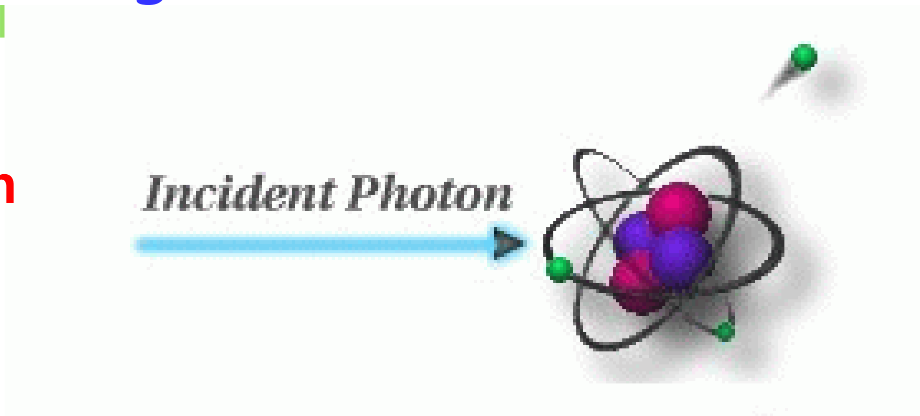
Relativistic electron beams

Celestial Plasmas

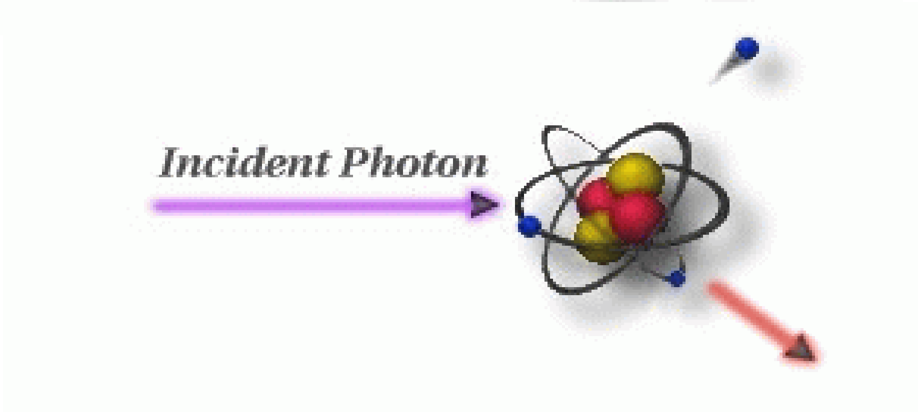


Interaction of photons and matter
x-ray and gamma-regime

photo-effect / photo-absorption



Compton-scattering



Pair production

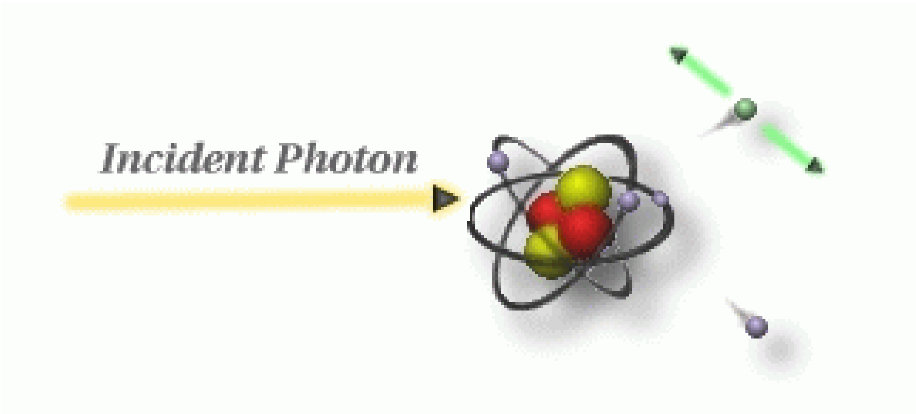


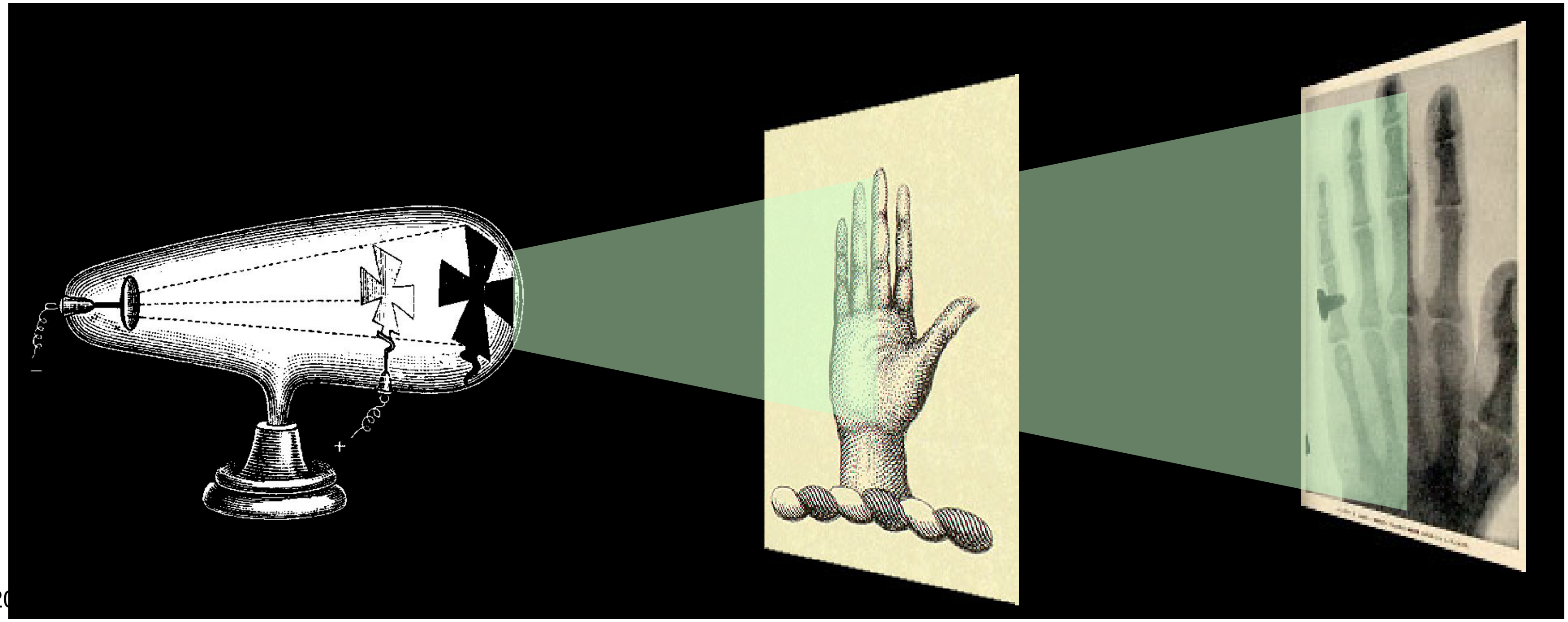
Photo-effect / Photo-absorption

Wilhelm Röntgen

first

X-ray picture

1895



The Nobel Prize in Physics 1901

"in recognition of the extraordinary services he has rendered b
discovery of the remarkable rays subsequently named after hi

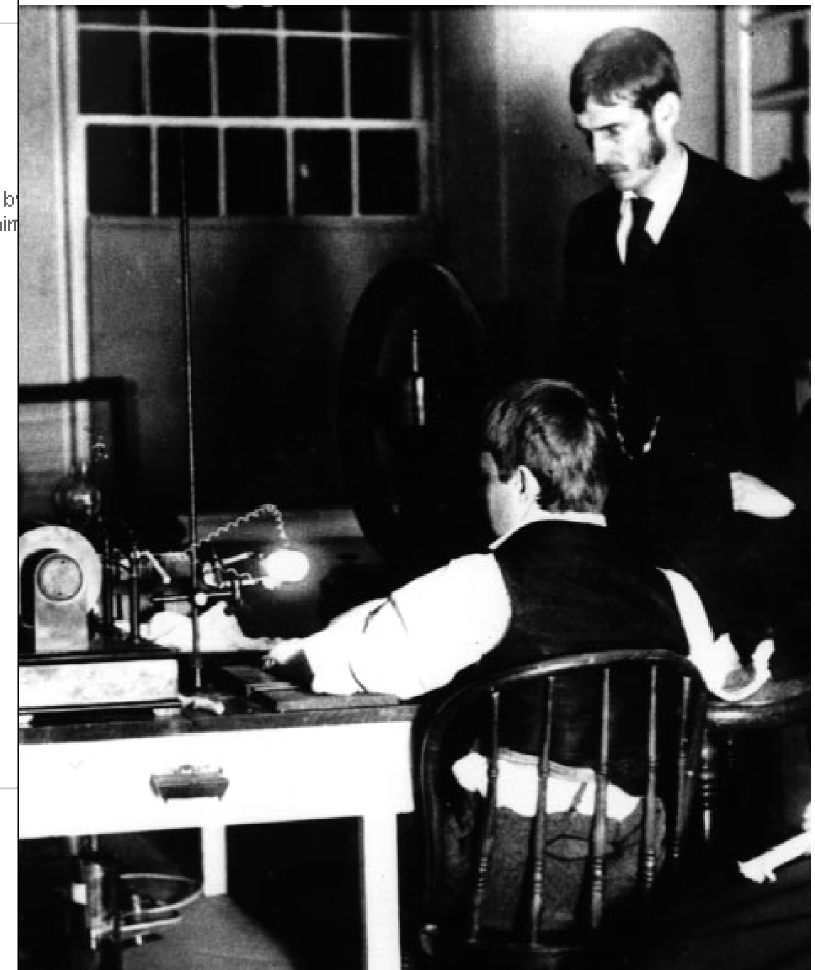
Wilhelm Conrad Röntgen

Germany

Munich University
Munich, Germany

b. 1845
d. 1923

http://www.nobel.se/
physics/laureates/1901/index.html



The New-York Times.

Wednesday
February 5-1896

PROF. ROENTGEN'S X-RAYS

May Be Due, He Says, to Longitudinal Vibrations of Ether.

HE WRITES OF HIS GREAT DISCOVERY

Difference Between His and the Kathode Rays of Lenard—Some of the Substances He Has Photographed.

The preliminary communication of Prof. Wilhelm Konrad Röntgen to the Würzberg Physico-Medical Society of his discovery of a new form of radiant energy appears this week translated in full in several of the English papers. As the chief interest of men of science is centred in the question of the nature of the rays, those portions of Prof. Röntgen's paper which deal with this aspect of the subject are here reproduced in full.

The name given by Prof. Röntgen to the newly discovered form of radiant energy is X-rays. The translation appended was made by Arthur Stanton, and appears in the current number of Nature. After describing his experiments in making shadow photographs of various substances, Prof. Röntgen says:

7. After my experiments on the transparency of increasing thicknesses of different media, I proceeded to investigate whether the X-rays could be deflected by a prism. Investigations with water and carbon bisulphide in mica prisms of 30° showed no deviation either on the photographic or the fluorescent plate. For comparison, light rays were allowed to fall on the prism as the apparatus was set up for the experiment. They were deviated 10 mm. and 20 mm. respectively in the case of the two prisms.

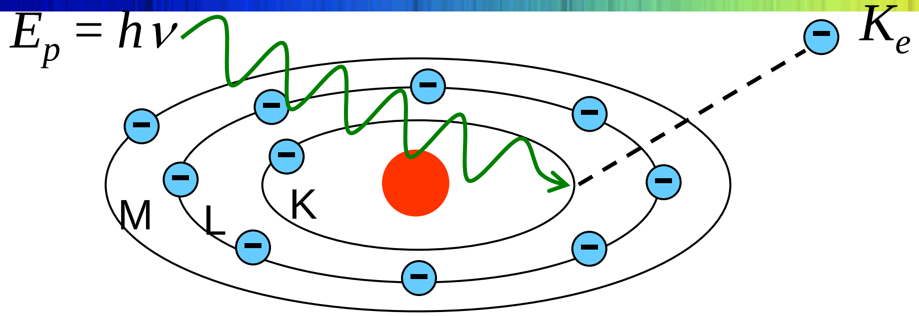
With prisms of ebonite and aluminium I have obtained images on the photographic plate which point to a possible deviation. It is, however, uncertain, and at most would point to a refractive index 1.05. No deviation can be observed by means of the fluorescent screen. Investigations with the heavier metals have not as yet led to any result, because of their small transparency and the consequent enfeebling of the transmitted rays.

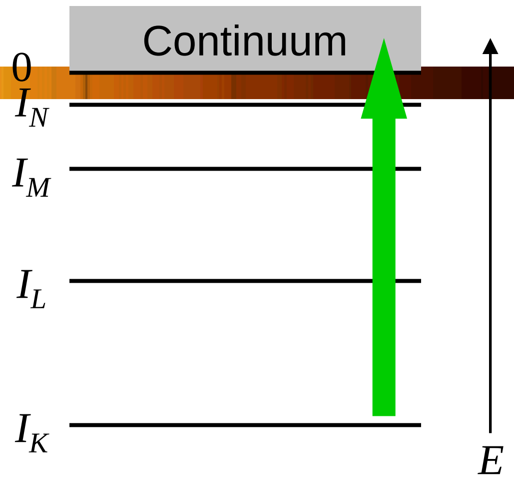
On account of the importance of the question it is desirable to try in other ways whether the X-rays are susceptible of refraction. Finely powdered bodies allow in thick layers but little of the incident light to pass through, in consequence of refraction and reflection. In the case of the X-rays, however, such layers of powder are for equal masses of substance equally transparent with the coherent solid itself. Hence we cannot conclude any regular reflection or refraction of the X-rays. The research was conducted by the aid of finely powdered rock salt, fine electrolytic silver powder, and zinc dust already many times employed in chemical work. In all these cases the result, whether by the fluorescent screen or the photographic method, indicated no difference in transparency between the powder and the coherent solid.

It is, hence, obvious that lenses cannot be looked upon as capable of concentrating the X-rays; in effect, both an ebonite and a glass lens of large size prove to be without action. The shadow photograph of a round rod is darker

http://www.slac.stanford.edu/pubs/beamline/beamline.html

Photo-effect





- ***Direct absorption of a photon by an atomic electron followed by the emission of the electron.***

- **Due to the conservation of energy the kinetic energy of the electron is defined by:**

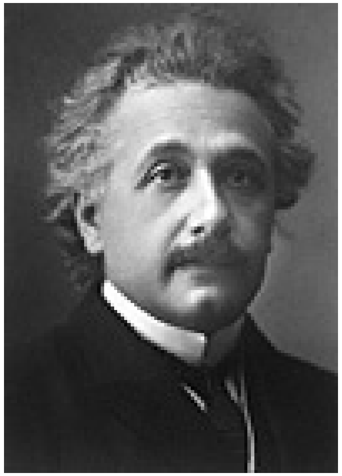
$$E_{kin} = \hbar \cdot \omega - I$$

- **Recoil momentum is absorbed by the atom**

- **Not possible for free electrons**

The Nobel Prize in Physics 1921

"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"



Albert Einstein

Germany and Switzerland

Kaiser-Wilhelm-Institut (now Max-Planck-Institut) für Physik
Berlin, Germany

b. 1879
(in Ulm, Germany)
d. 1955

Photo-effect: cross-section

For one electron-shell the **photo-ionisation cross-section is highest close to the threshold,** i.e. where the photon-energy equals the ionization-energy I (resonance or threshold behaviour):

$$\sigma_{\max} : \hbar \cdot \omega \approx I_K , I_L , I_M$$

The cross-section shows a **strong dependence on the photon-energy and the nuclear charge Z** :

$$\sigma_p \propto \frac{Z^{4-5}}{(\hbar \cdot \omega)^{7/2}}$$

At high photon-energies $\hbar \cdot \omega \gg I_K$ the ***ionisation of s-orbitals has the highest probability*** and the K-shell-ionization contributes most dominantly:

$$\sigma_{p_n} = \frac{1}{n^3} \cdot \sigma_K \qquad \sigma_p = \sigma_{p_K} \cdot \sum_{n=1}^{\infty} \frac{1}{n^3} = 1.2021 \cdot \sigma_{p_K}$$

σ_{p_K} **K-shell cross-section**

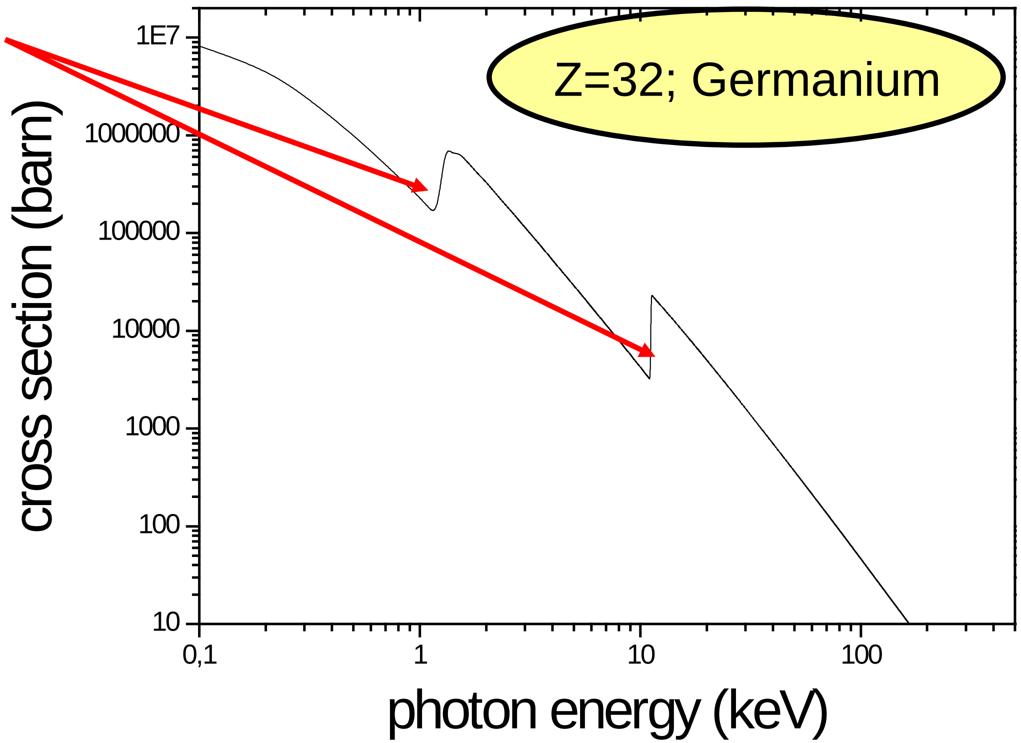
n **principal quantum number**

Cross-section for photo-ionization

$$\sigma_{\max} : \hbar \cdot \omega \approx E_K , E_L , E_M$$

binding energies

E_K, E_L, E_M... ionization energies



scaling law

$$\sigma_p \propto \frac{Z^{4-5}}{(\hbar \cdot \omega)^{7/2}}$$

Formular of Stobbe (1930):
photo-ionization of the K-shell in the dipole approximation

$$\sigma_{p_K} = \frac{8}{3} \cdot \pi \cdot r_e^2 \cdot \frac{2^7 \pi \cdot (137)^3}{Z^2} \cdot \left(\frac{E_K}{\hbar\omega} \right)^4 \cdot \frac{\exp(-4\kappa \cdot arc \cot \kappa)}{1 - \exp(-2\pi \cdot \kappa)}$$

$$\chi = \sqrt{\frac{E_K}{\hbar\omega - E_K}}$$

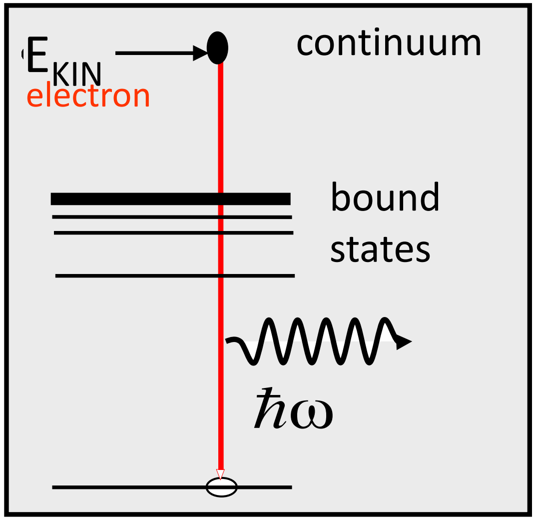
Recombination Processes

The main ionization and recombination processes in laboratory and astro physical plasmas:

- Electron impact excitation/ionization
- Radiative Recombination
- Dielectronic Recombination

Recombination processes of electrons with ions

Radiative Recombination/Electron Capture



- ***Electron capture into a bound ionic state by emission of a photon***

$$\hbar\omega = E_B + E_{KIN}$$

- ***Time-reversed photionization***
- ***Only possible capture/recombination process for bare ions colliding with electrons***

Radiative Recombination (RR)
/
Radiative Electron Capture (REC)

at High Energies

REC is the radiative electron capture of quasifree electrons

Quasifree electrons: *These electrons are electrons bound to a target atom with a target binding energy* E^B_T *much less than the collision energy*

$$E_{KIN} >> E^B_T$$

*Within the **impulse approximation**, quasifree electrons are treated as free electrons.*

Relation between REC and Photoionization

Relation between time reversed processes (detailed balance)

$$p_f^{\,2} \cdot g_f \cdot \sigma_{f\rightarrow i} = p_i^{\,2} \cdot g_i \cdot \sigma_{i\rightarrow f}$$

$$\sigma_{RR} = \left[\frac{E_{RR}}{\beta\gamma m_e c^2} \right] \cdot \sigma_{PI}$$

The REC cross sections are equal to the RR cross section for electrons times the amount of target electrons available

P_f: final state, momentum

P_i: initial state, momentum

g_f: final state, statistical weight

g_i: initial state, statistical weight

$\sigma_{f->i}$: cross section

$\sigma_{i->f}$: cross section

Radiative Electron Capture

Non Relativistic Dipole Approximation(Stobbe 1930):

$$\sigma_K^{REC} = 9.1\times10^{-21}\left(\frac{\kappa^3}{1+\kappa^2}\right)\frac{e^{-4\,arc\cot\kappa}}{1-e^{-2\pi\kappa}}[cm^2]$$

with $$\kappa = \frac{v_K}{v} = \sqrt{\frac{E_K}{E_{KIN}}}$$

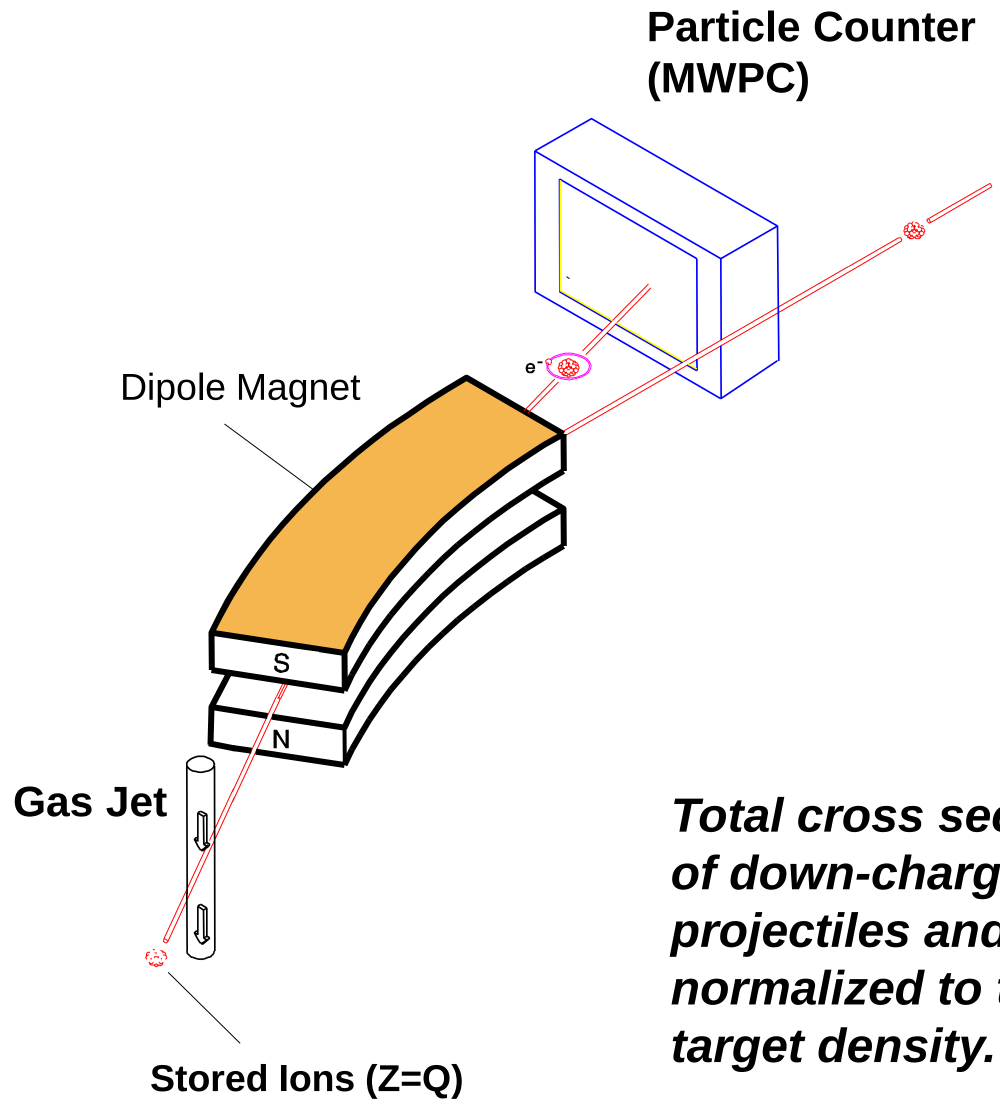
v: collision velocity
$E_{KIN}=m_e v^2/2$: kinetic electron energy
v_K: K-shell orbital velocity
E_K: K-shell binding energy

The cross section for radiative recombination does only depend on orbital and collision velocity

Adiabaticity parameter $$\eta = \frac{1}{\kappa^2} = \frac{E_{KIN}}{E_K}$$

Fast collisions: $\eta > 1$ **Slow collisions: $\eta < 1$**

Experiments at the Jet-Target



Electron transfer from the target atom into the HCI

$$Z^{Q+} + e^{-} \rightarrow Z^{(Q-1)+} + \hbar\omega + \ldots$$

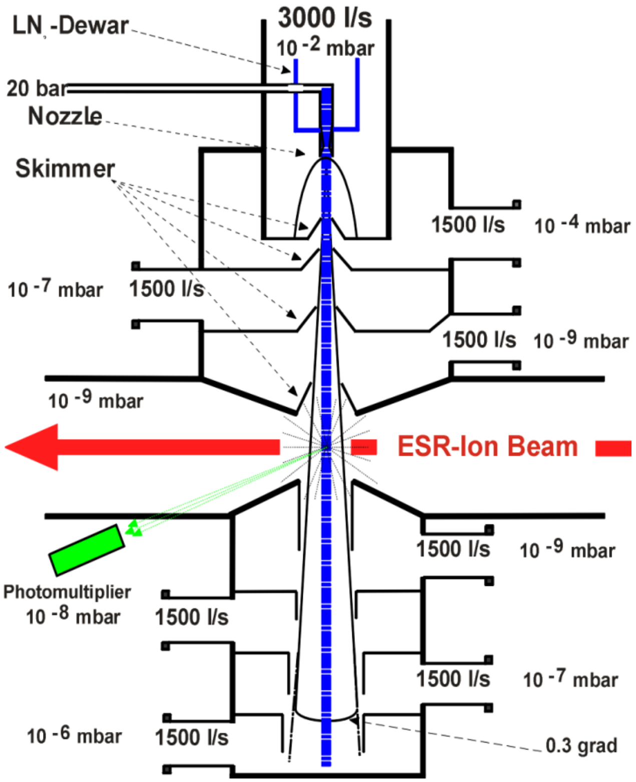
Total cross sections: Simply measure the amount of down-charged ions for different targets, projectiles and energies. The data must be normalized to the amount of ions stored and the target density.

The Jet-Target

The Jet-Target

Target species

H_2
CH_4
N_2
Ne
Ar
Kr
Xe



Target densities

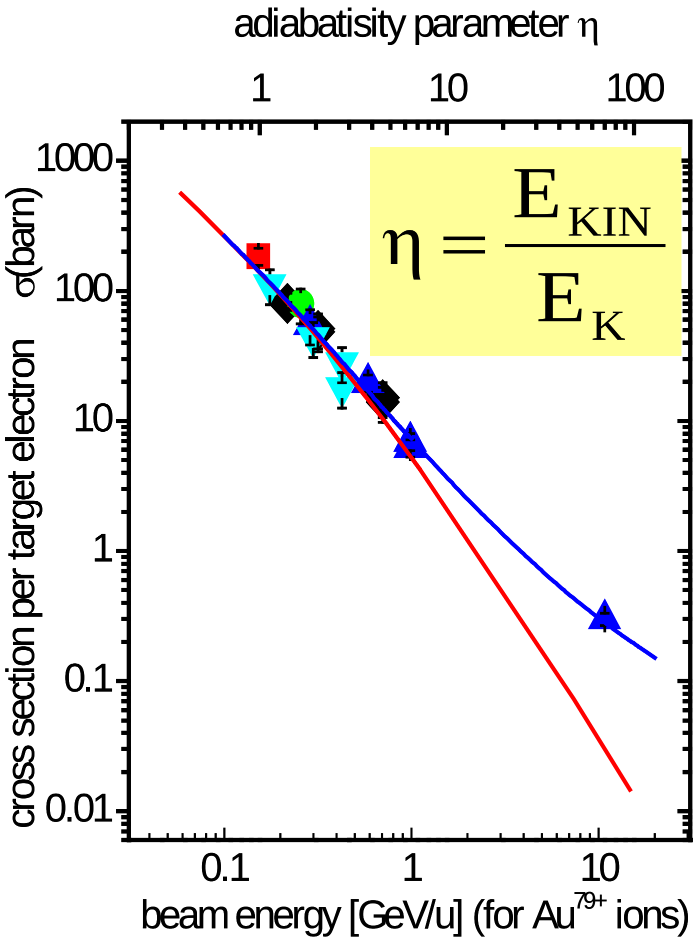
$10^{12} – 10^{14}$ p/cm^3

Single collision conditions

Supersonic jet, operates in ultra high vacuum enviroment (10^{-11} mbar)

A. Krämer et al, NIM B 174. 205 (2001)

Total cross section for recombination



dipole approximation

complete relativistic calculations for Au $^{79+}$ (Eichler et. al)

Data cover the Z range from 6 to 92 (BEVALAC, SIS/FRS/ESR, RHIC, CERN)

Highest energy: 33 TeV Pb^{82+}, γ=168

C. R. Vane, H. F. Krause, S. Datz, P. Grafström, H. Knudsen, C. Scheidenberger, R. Schuch PRA 62, 010701(R), 2000

Universal scaling law for all ion species and energies of up to 500 MeV/u, based on the non-relativistic dipole approximation

Cancellation of retardation and relativistic kinematics

E_{KIN} : kinetic projectile energy

E_K: K-shell binding energy

J. Eichler and Th. Stöhlker, Phys. Rep. 439, 1 (2007)

Multipole expansion

Hamiltonian of the photon–electron interaction: $H = e\frac{\vec{p}}{mc}\vec{A}$

The matrix element for a transition of an electron from the initial state Ψ_i to the final state Ψ_f is:

$$\left|M_{if}\right| = \int \Psi^*{}_i \, p e^{ikr} \Psi_f \, d^3 r$$

where **p** is the momentum of the electron, and **k** is the momentum of the emitted photon

The photon wavelength is: $\lambda = \frac{2\pi}{k}$

assumptions: plane wave,
vector potential, wave function:

$$A \propto e^{-i(kr-\omega t)}$$

$$e^{-ikr} = 1 - ikr + \frac{(kr)^2}{2} + \ldots$$

Multipole expansion

$$e^{-ikr} = 1 - ikr + \frac{(kr)^2}{2} + \dots$$

dipole approximation

$$k \cdot r << 1 \rightarrow r << \lambda$$

i.e. the wavelength is much larger than the size of the atom (orbit radius)

higher order multipoles

$$k \cdot r \approx 1 \text{ or } k \cdot r \geq 1$$

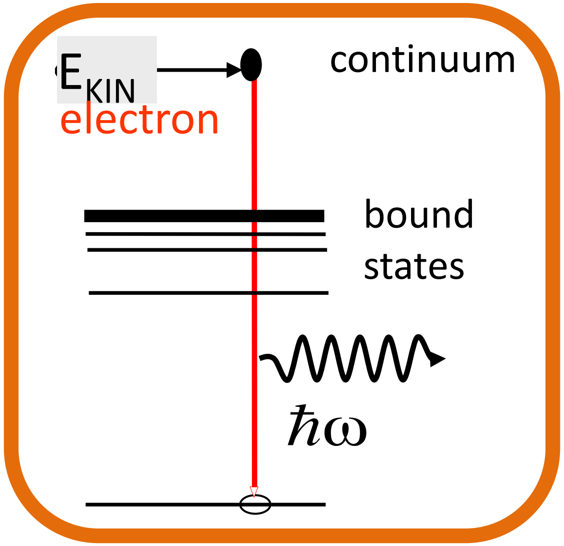
There will be higher order multipoles: Quadrupole, etc.
e.g.: nuclear decay, or atoms with high Z

For higher order multipole radiation the following rules apply to the parity ℓ :

$$\pi = (-1)^{\ell}$$ **electric multipole radiation**

$$\pi = (-1)^{\ell+1}$$ **magnetic multipole radiation**

Dynamics in Strong Fields: Radiative Processes



Radiative Recombination

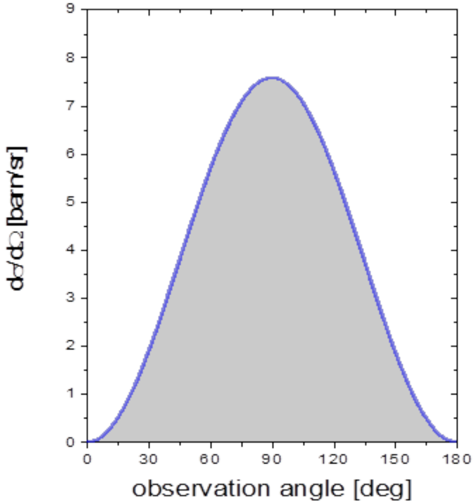
Electron capture into a bound ionic state by emission of a photon

$$\hbar\omega = E_B + E_{KIN}$$

Time-reversed photionization

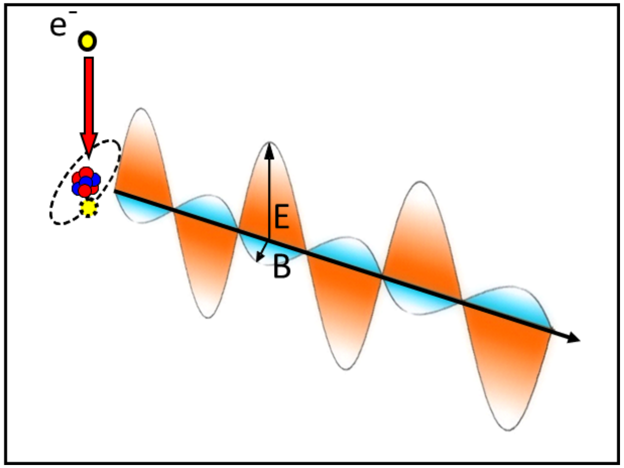
Schnopper et al., PRL 29, 898 (1972)

angular distribution

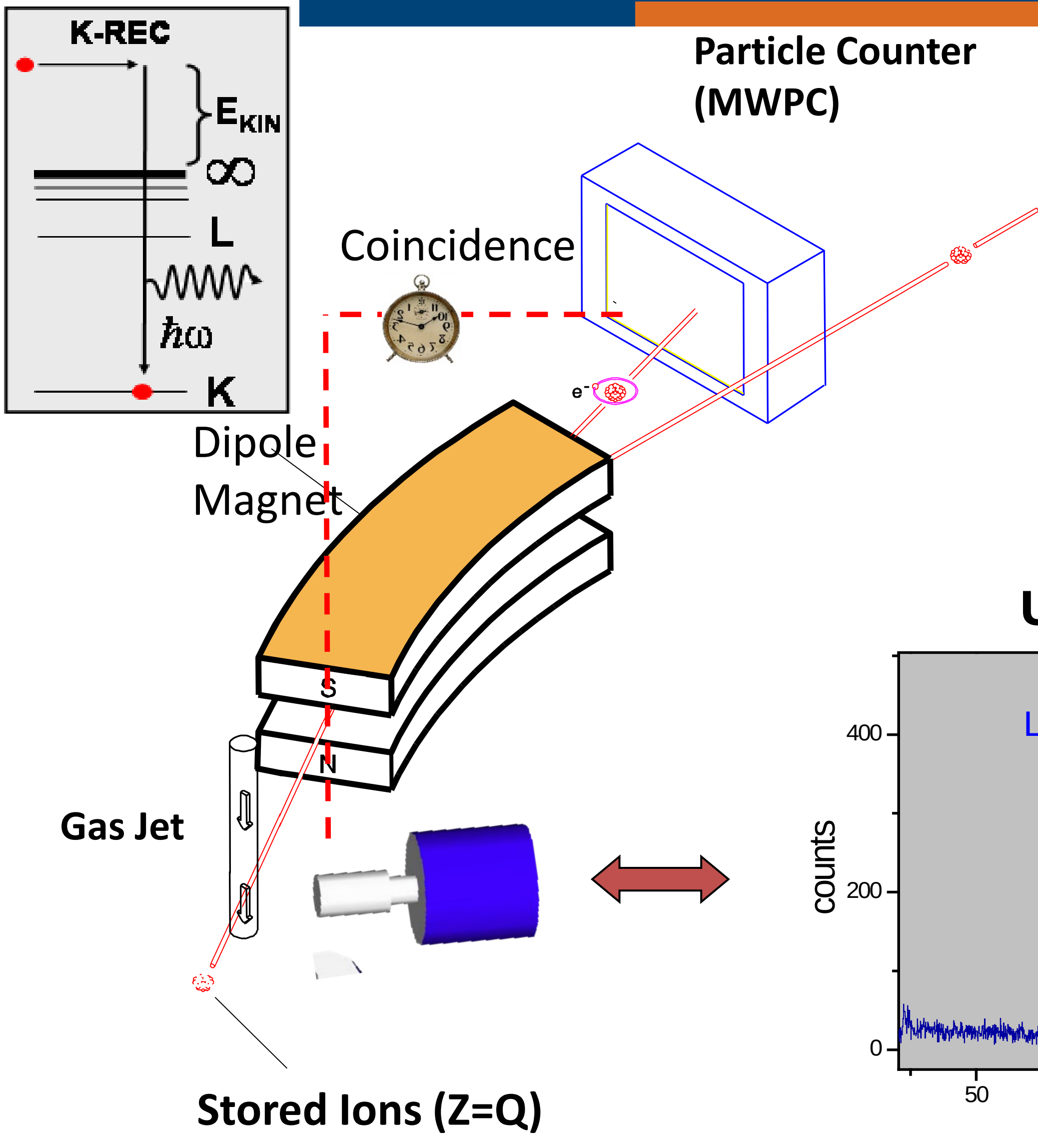


Spindler et al., 42, 832 (1979)

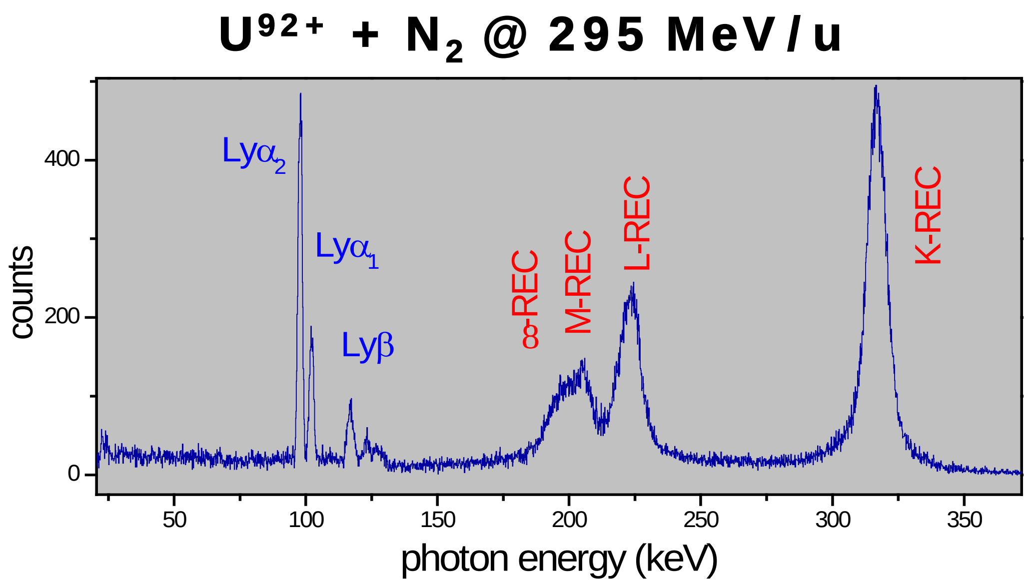
Polarization



Experimental REC-Spectra



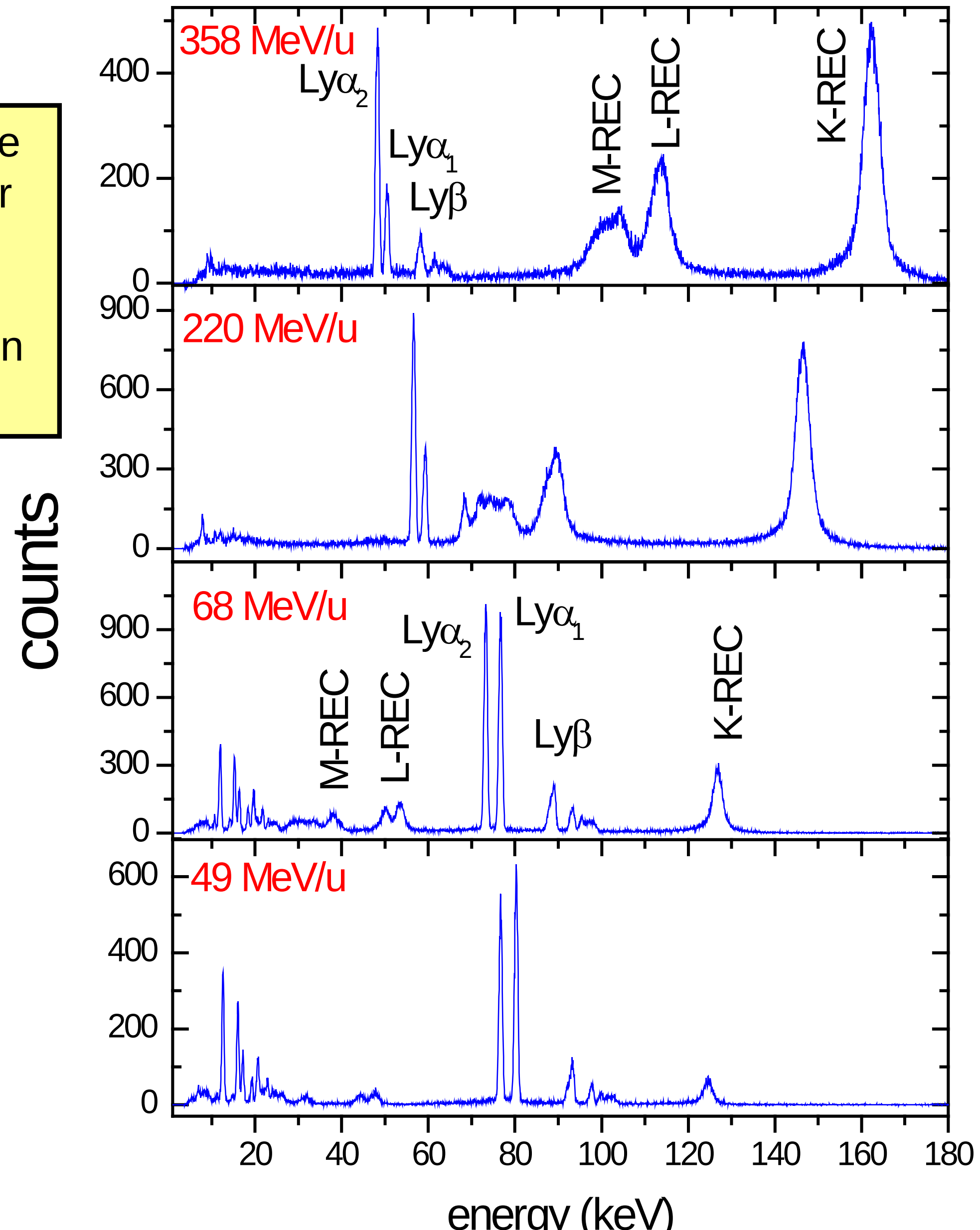
$$Z^{Q+} + e^{-} \rightarrow Z^{(Q-1)+} + \hbar\omega + \ldots$$



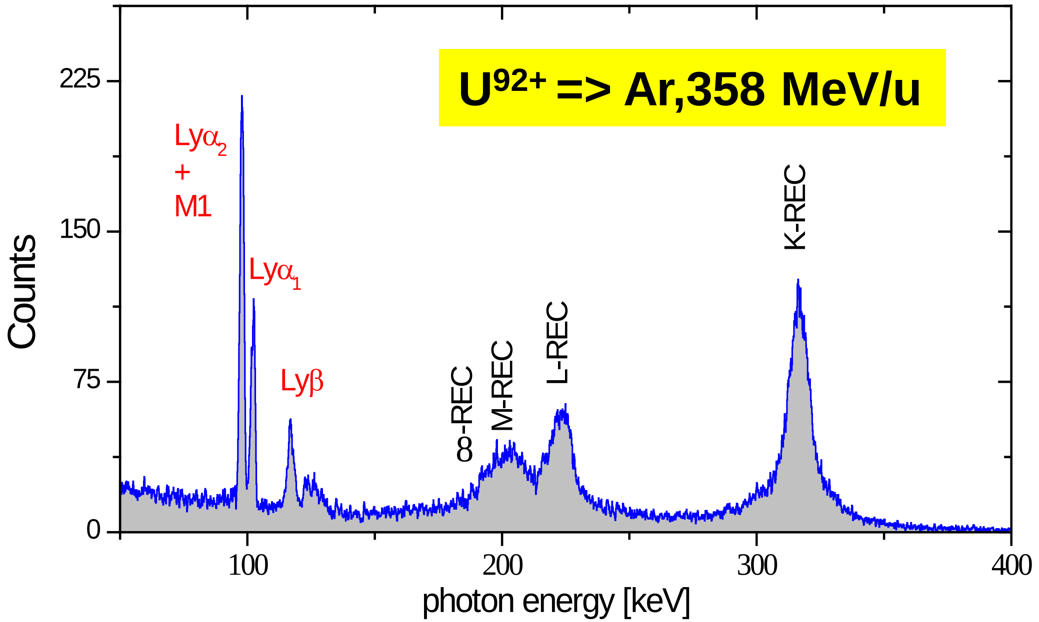
REC Cross Sections / U^{92+} => N_2

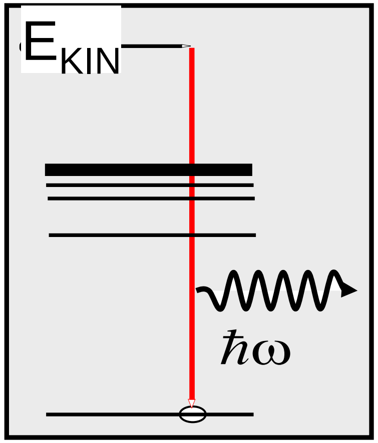
For high-Z ions and high energies REC is the most important charge exchange process for collisions with low-Z targets

REC populates predominately s-states and in particular the 1s ground state (80%)



REC Photon Energy: Compton Profiles





$$\hbar\omega_{REC} = E_B + m_e c^2(\gamma - 1) + \gamma(v_i p_z - E_T)$$

E_K : binding energy in the projectile

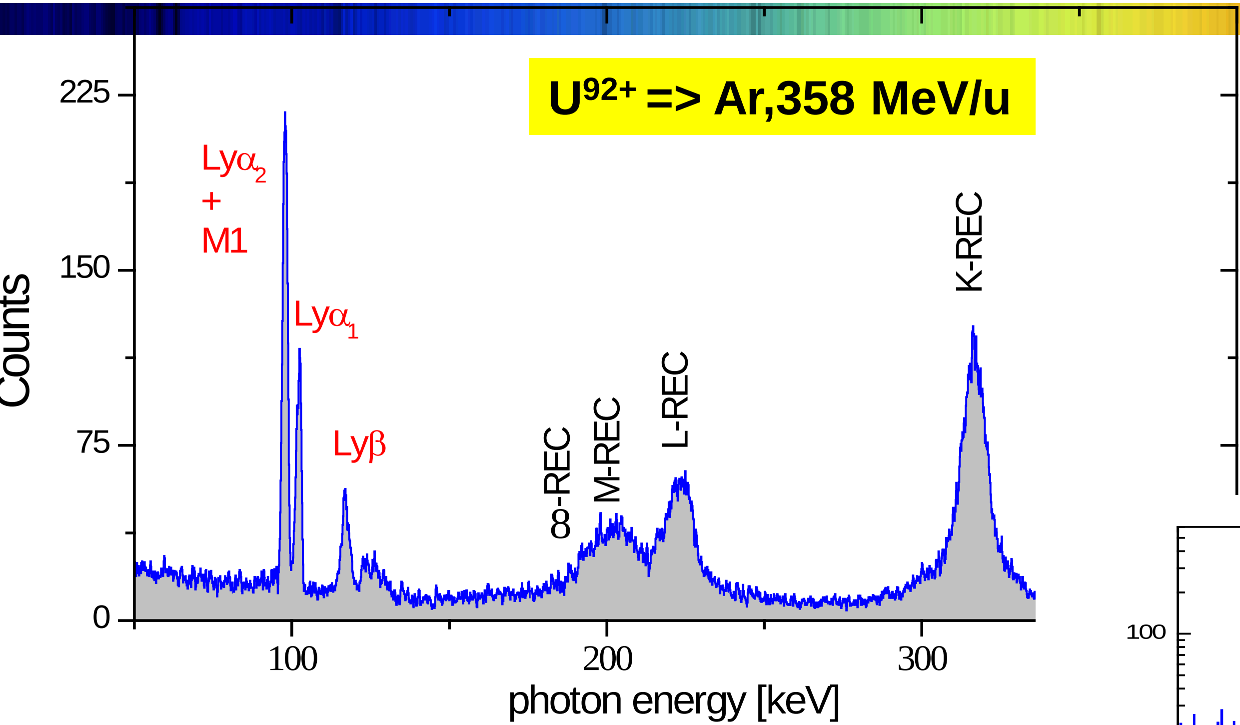
E^B_T: binding energy in the target

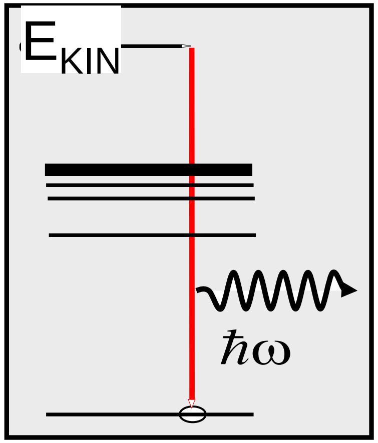
p_i: electron momentum in the target

v_0: projectile velocity

$m_e c^2(\gamma - 1)$: kinetic energy

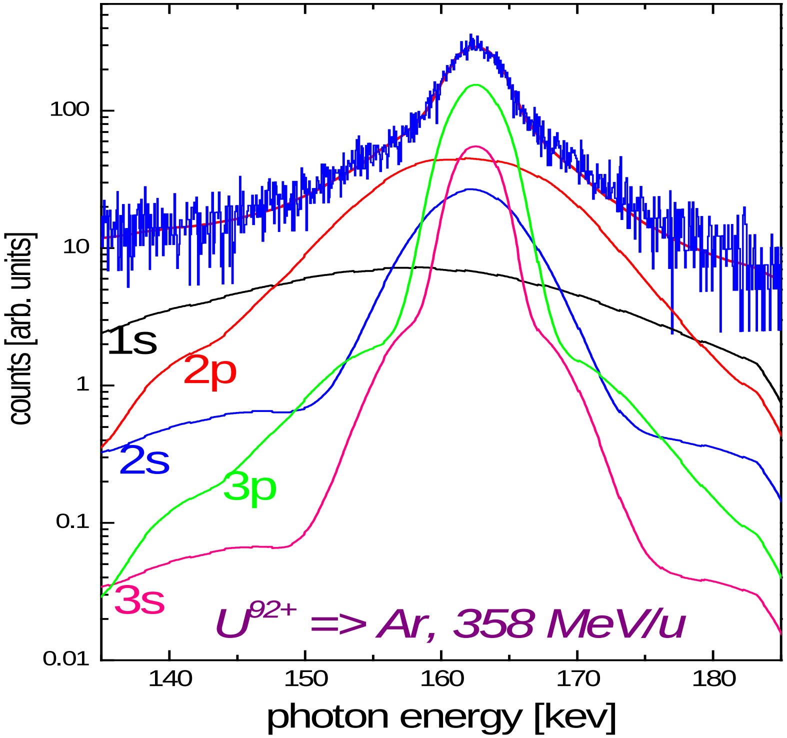
Radiative Electron Capture
Capture of Quasifree Targetelectrons





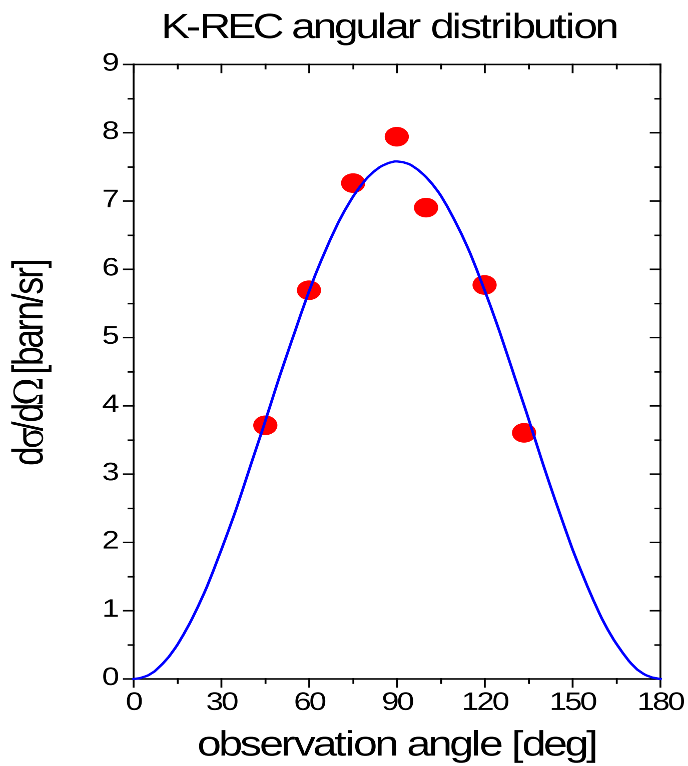
REC photon energy

$$\hbar\omega_{REC} = E_B + m_e c^2(\gamma - 1) + \gamma(v_i p_z - E_T)$$



Shape and width of REC lines are determined by the momentum distribution of the target electrons

K-REC Distribution for Xe^{54+} (200 MeV/u)

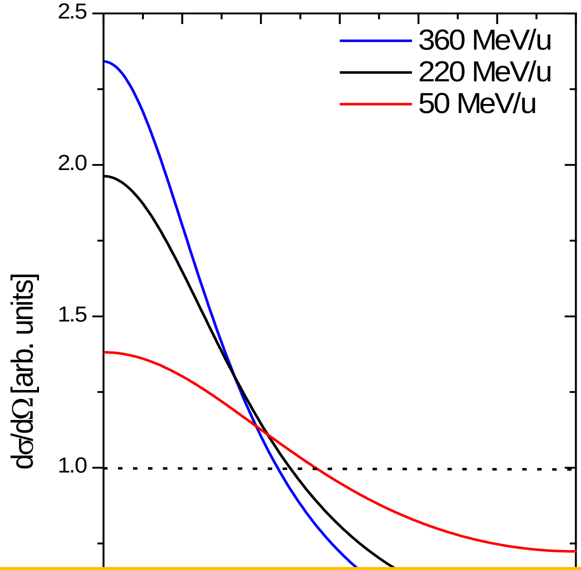


R. Anholt et al., PRL 53, 234 (1984)

BEVALAC experiment

$$\left.\frac{d\sigma}{d\Omega}\right|_{LAB} \propto \sin^2 \vartheta_{lab}$$

Lab. angular distribution of an isotropic transition



Using non-relativistic wave functions, complete cancellation between retardation and Lorentz transformation occurs (verified by Anholt for 197 MeV/u $Xe^{54+} \Rightarrow$ Be)

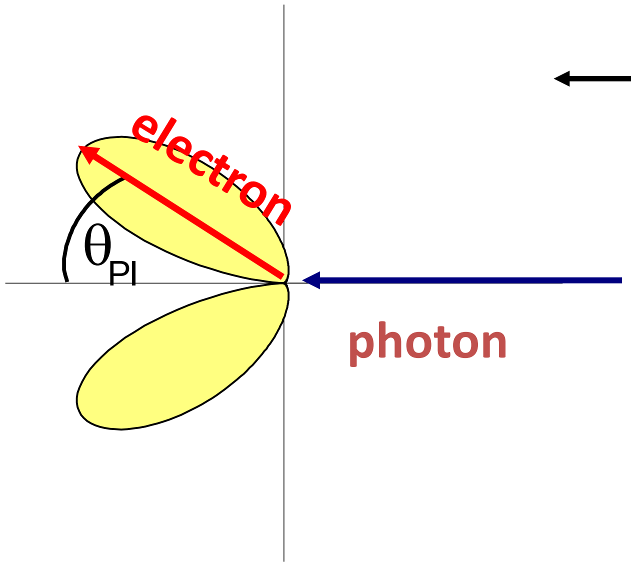
Recombination and Photoionisation of s-States

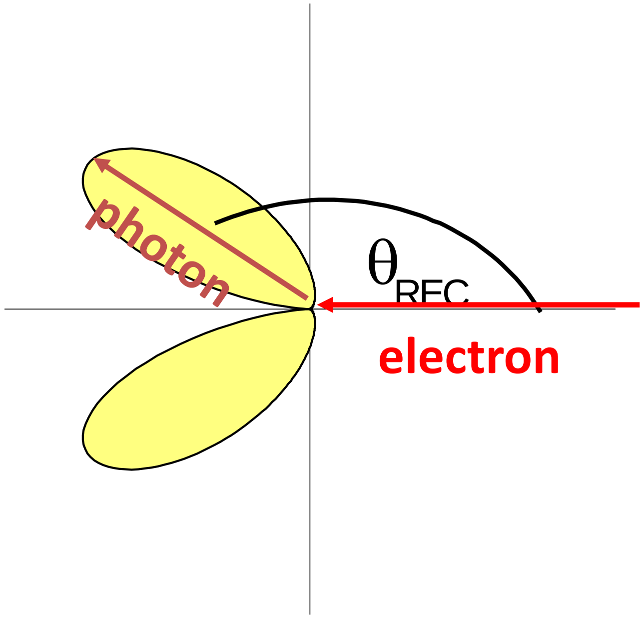
[non-relativistic theory]

photoionization (retardation)

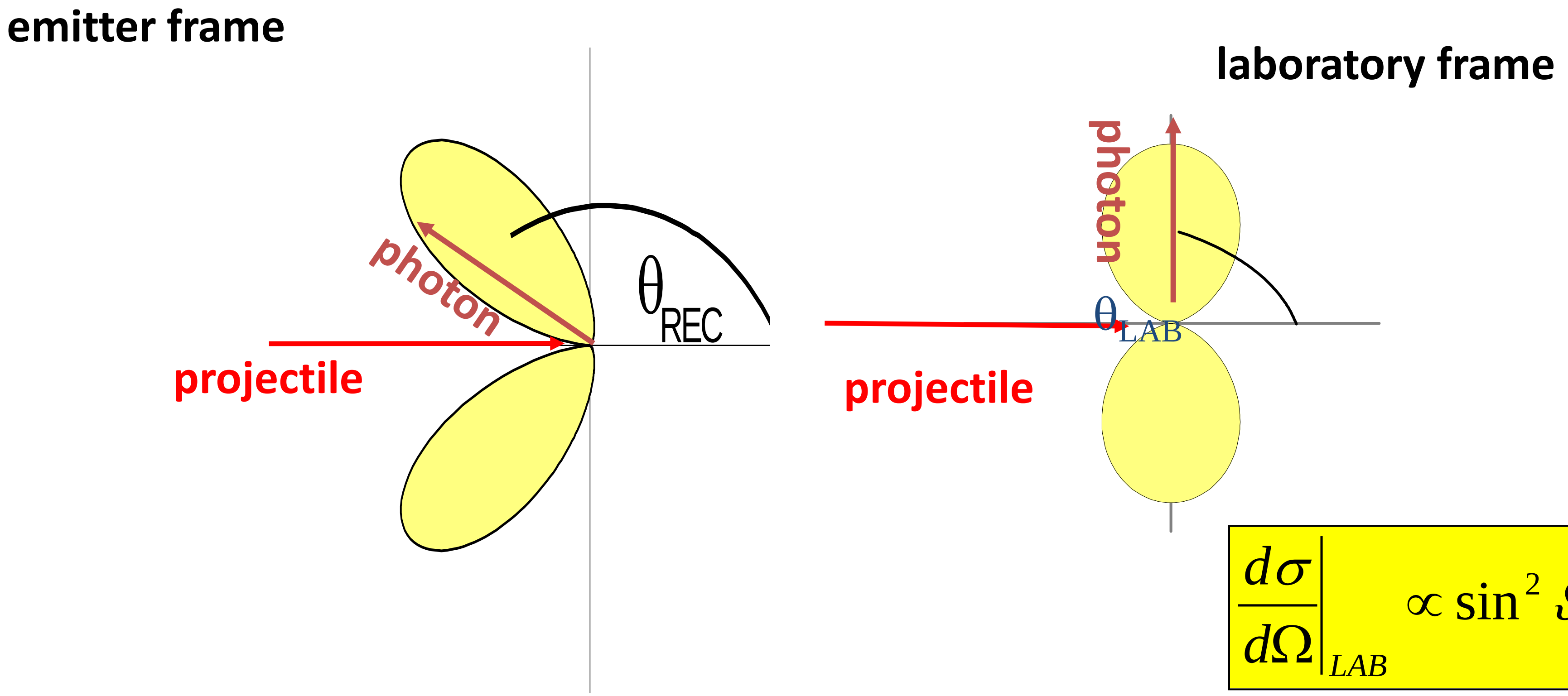
recombination (projectile frame)

$$\theta_{PI} = \pi - \theta_{REC}$$





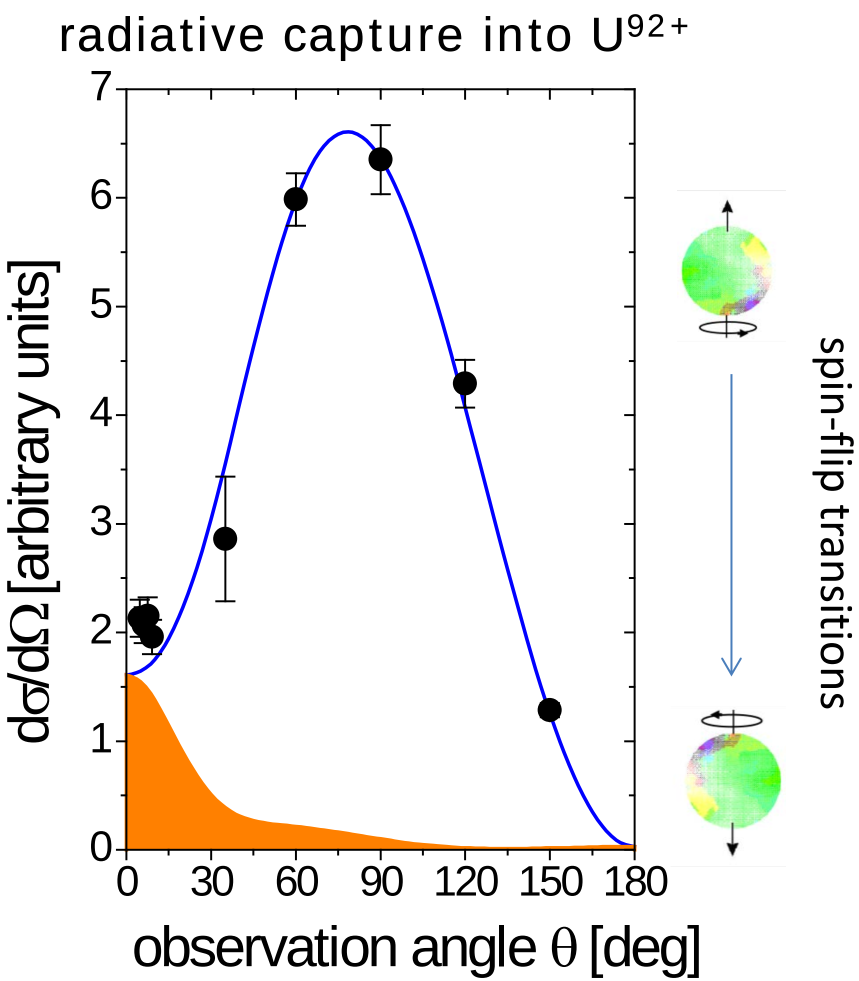
Effects of retardation and Lorentz transformation

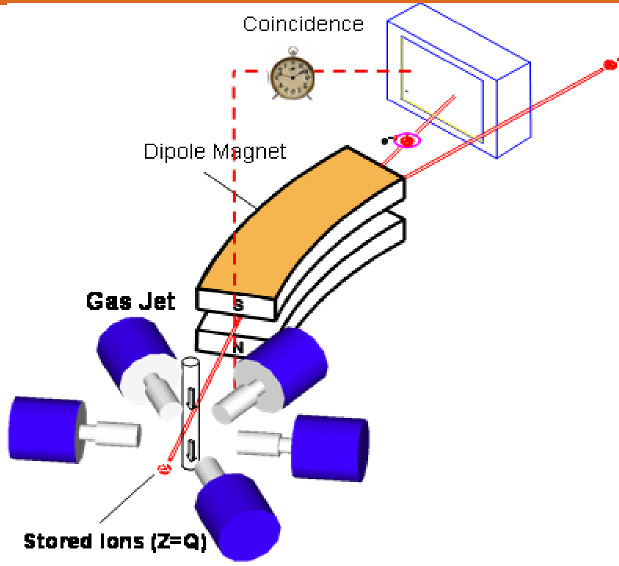


$$\left.\frac{d\sigma}{d\Omega}\right|_{LAB} \propto \sin^2 \vartheta_{lab}$$

don‘t forget: relativistic angle and solid angle transformation !

Photon Angular Distribution for REC into the K-shell (1s-state) (U^{92+}, 310 MeV/u)





At high-Z, the coupling of the magnetic moment of the electron to the radiation field leads to spin-flip transitions

→ 0 deg emission

observation at 0 deg allows for a kinematical identification of spin-flip transitions

Production of high charge states and ion storage rings

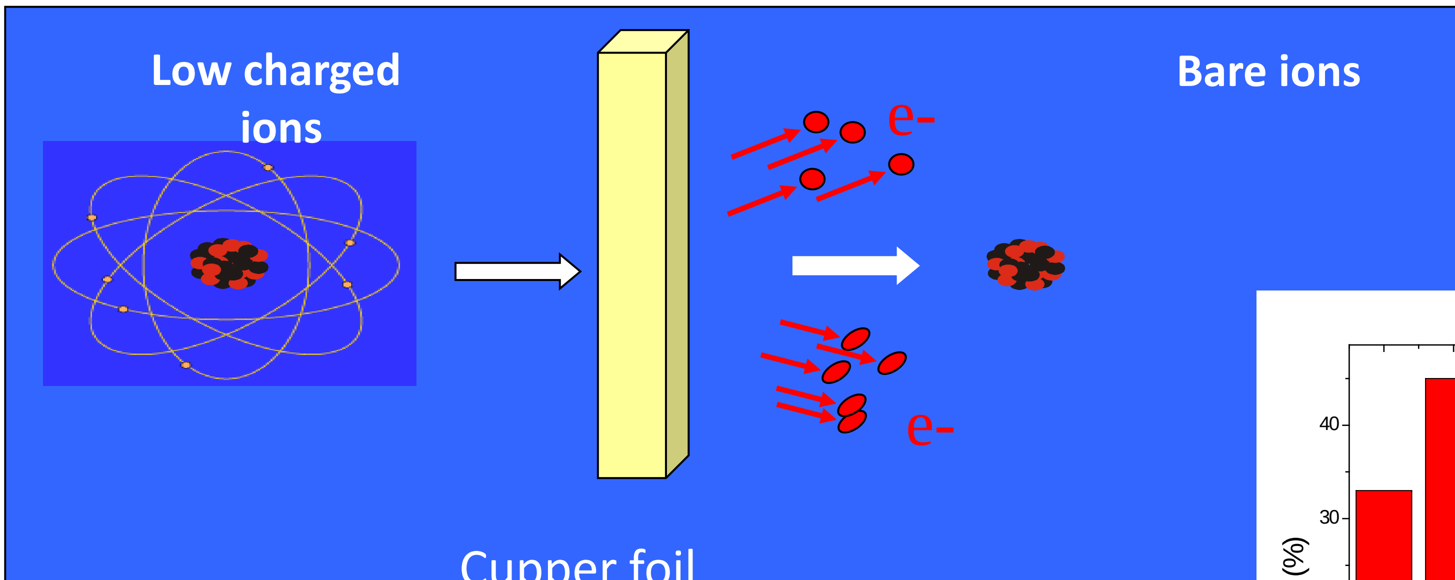
Why high velocities?

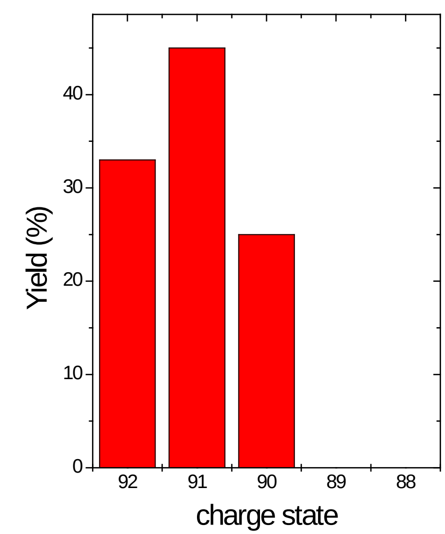
Bohr criteria: *Largest ionization cross section at* $v \approx v_K$

Uranium

$v_K / c \approx 0.67$

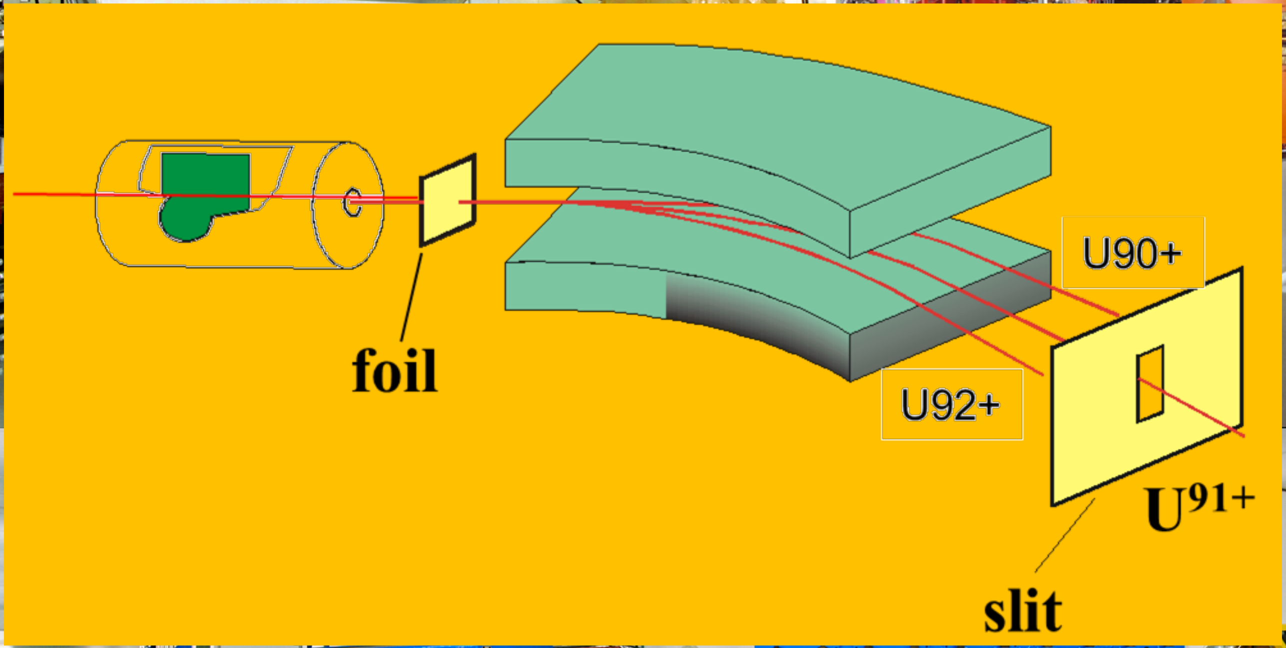
Beam energy ???

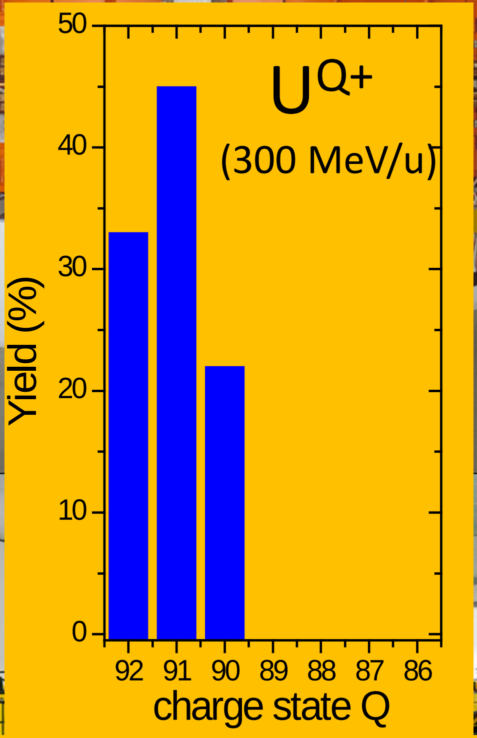




Storage Rings /Synchrotrons/ Charge State Separators

ESR/GSI

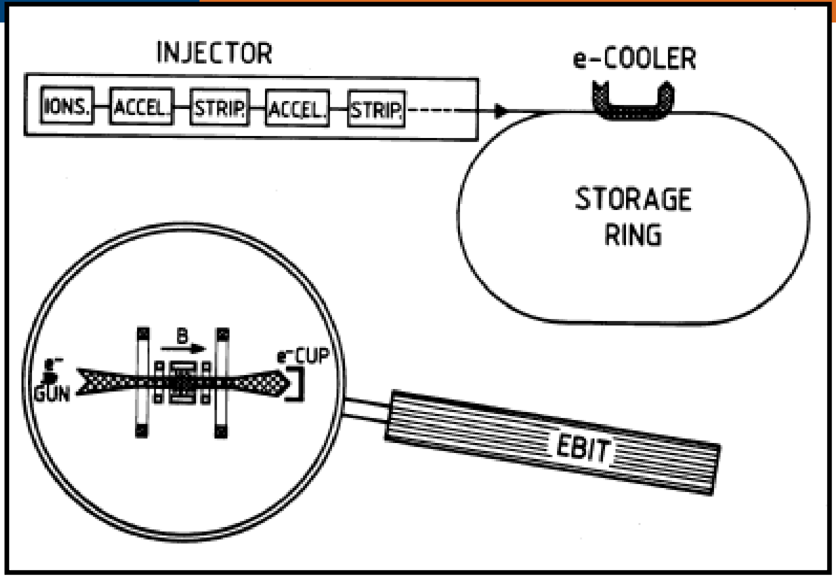




Every element in arbitrary charge state up to the heaviest bare elements are available for experiments

Production of Highly Charged Heavy Ions

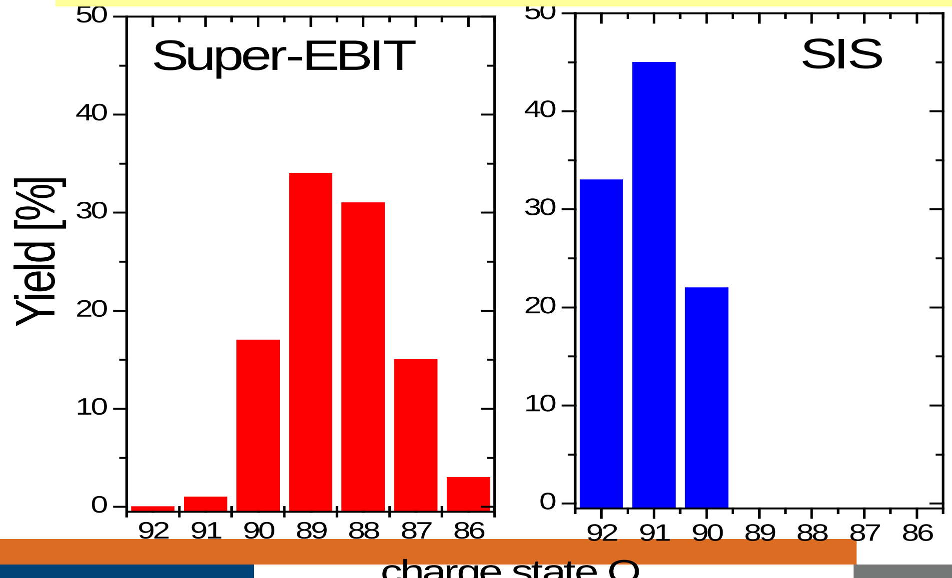
EBIT: Trapped, stationary ions; charge state production by electron bombardment



Accelerator: Fast moving ions, charge state production by penetration through stripper targets

Charge State Distributions for Uranium

200 keV electron energy (ion at rest)



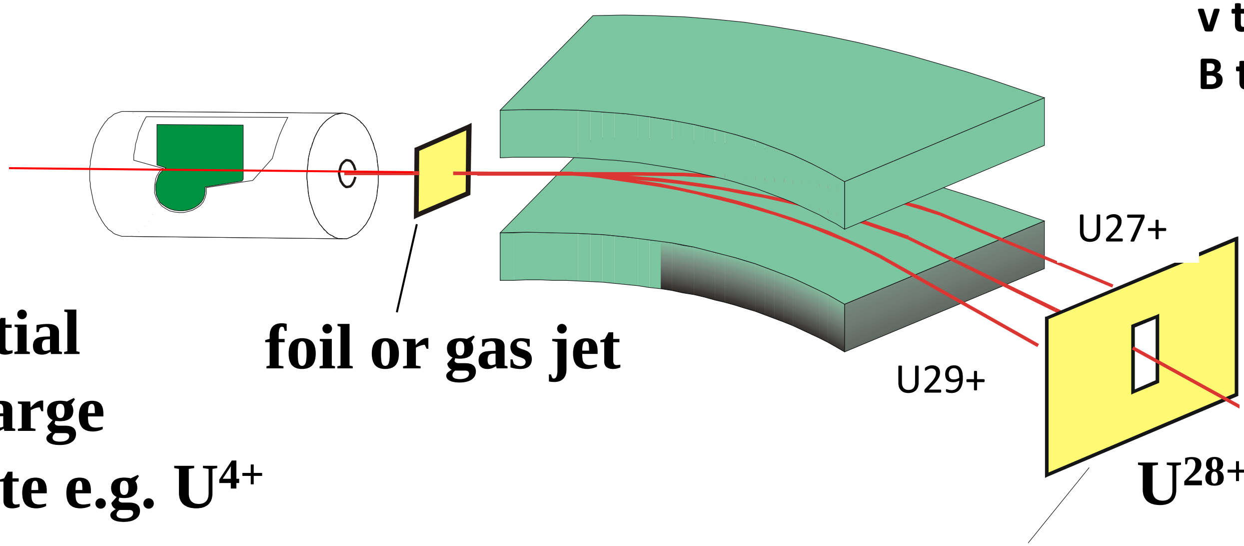
300 MeV/u (β ≈ 0.65)

Magnetic Charge Separation

Lorentz force

$$\vec{F}_L = q\left(\vec{v} \times \vec{B}\right)$$

q the charge of the ions
v the ion velocity
B the magnetic field



towards further acceleration

Ions in storage rings – some basics

- To store ions, a set of magnetic elements such as dipole, quadrupole, ... magnets is needed which form the ***lattice of the ring***

- Storage rings have a limited acceptance with respect to the ***size, angular divergence***, and ***momentum spread***

- The ions move on periodic orbits around the ideal trajectory (“Sollbahn”), performing ***betatron oszillations***. The ratio of the ring circumference to the betatron wavelength is called ***tune Q*** should not be an algebraic number such as 1, 2, ... or ½, ¾ in order to avoid beam losses.

Storage Rings: Magnetic Rigidity

$$\frac{mv^2}{r} = q\left(\vec{v} \times \vec{B}\right) \Rightarrow \frac{mv}{q} = B \cdot r$$

r the bending radius of the magents also called ρ
q the charge of the ions
v the ion velocity
m the mass of the ions
B the magnetic field

$$\frac{mv}{q} = B \cdot \rho$$

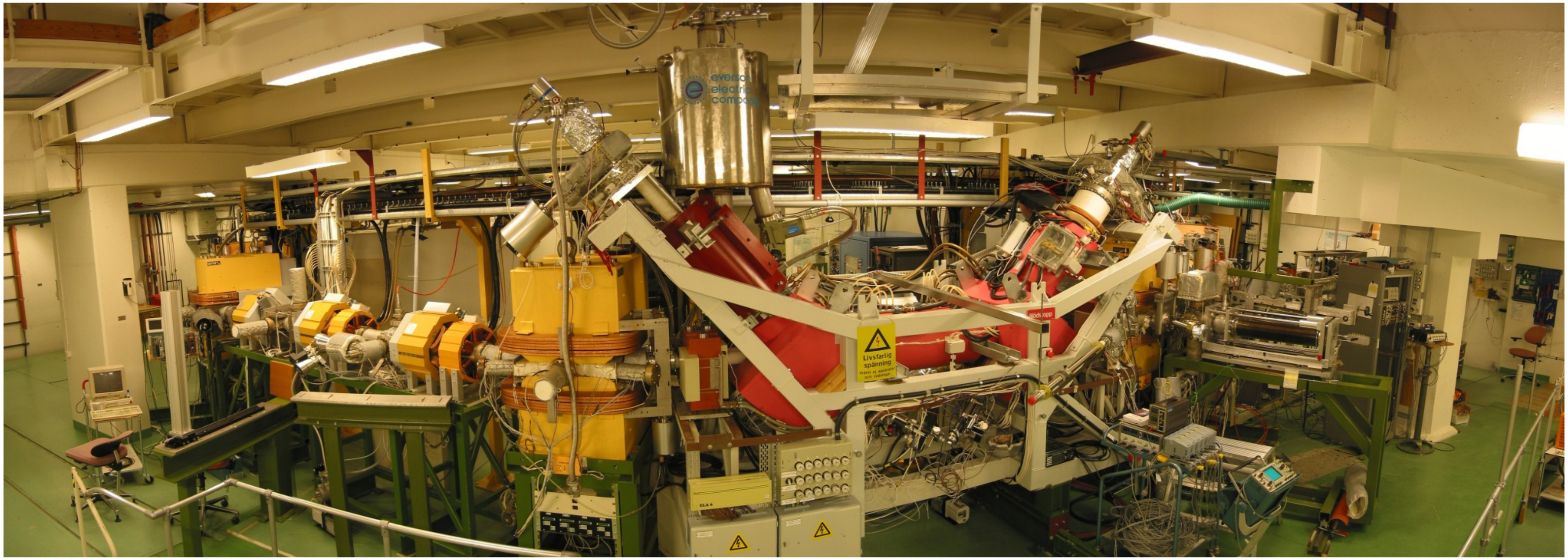
d.h. the magnetic rigidity (Bρ) is proportional to the ratio momentum to charge

Storage Ring	magnetic rigidity	Circumference
ESR	11 Tm	108 m
TSR	1.5 Tm	55 m
CRYRING	1.4 Tm	52 m
ASTRID	2 Tm	40 m

New ion storage rings were built/are in planning phase: Lanzhou, FAIR

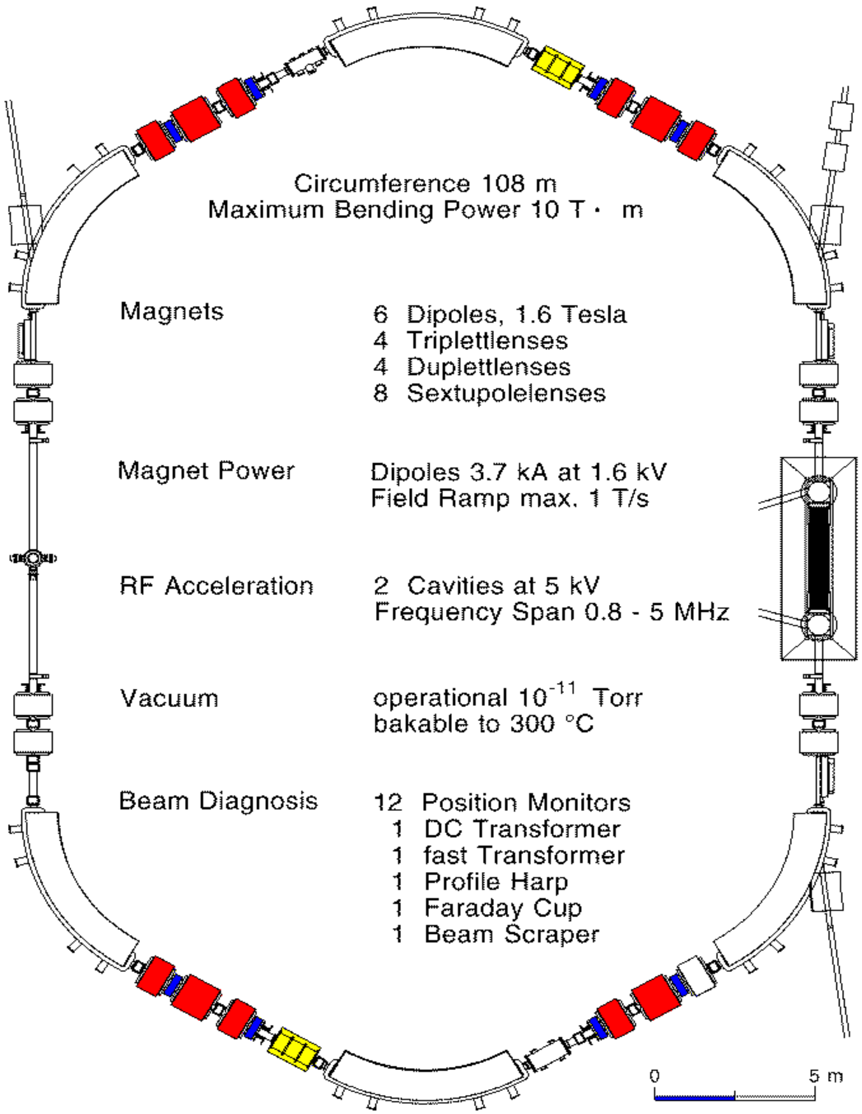
CRYRING

CRYRING is a small synchrotron and storage ring with electron cooling, built for research in atomic, molecular and nuclear physics



Heavy Ion Research Facility at Lanzhou (HIRFL)

The ESR: fed by stable and exotic highly charged ions



magnetic rigidity: < 10 Tm

circumference: 108 m

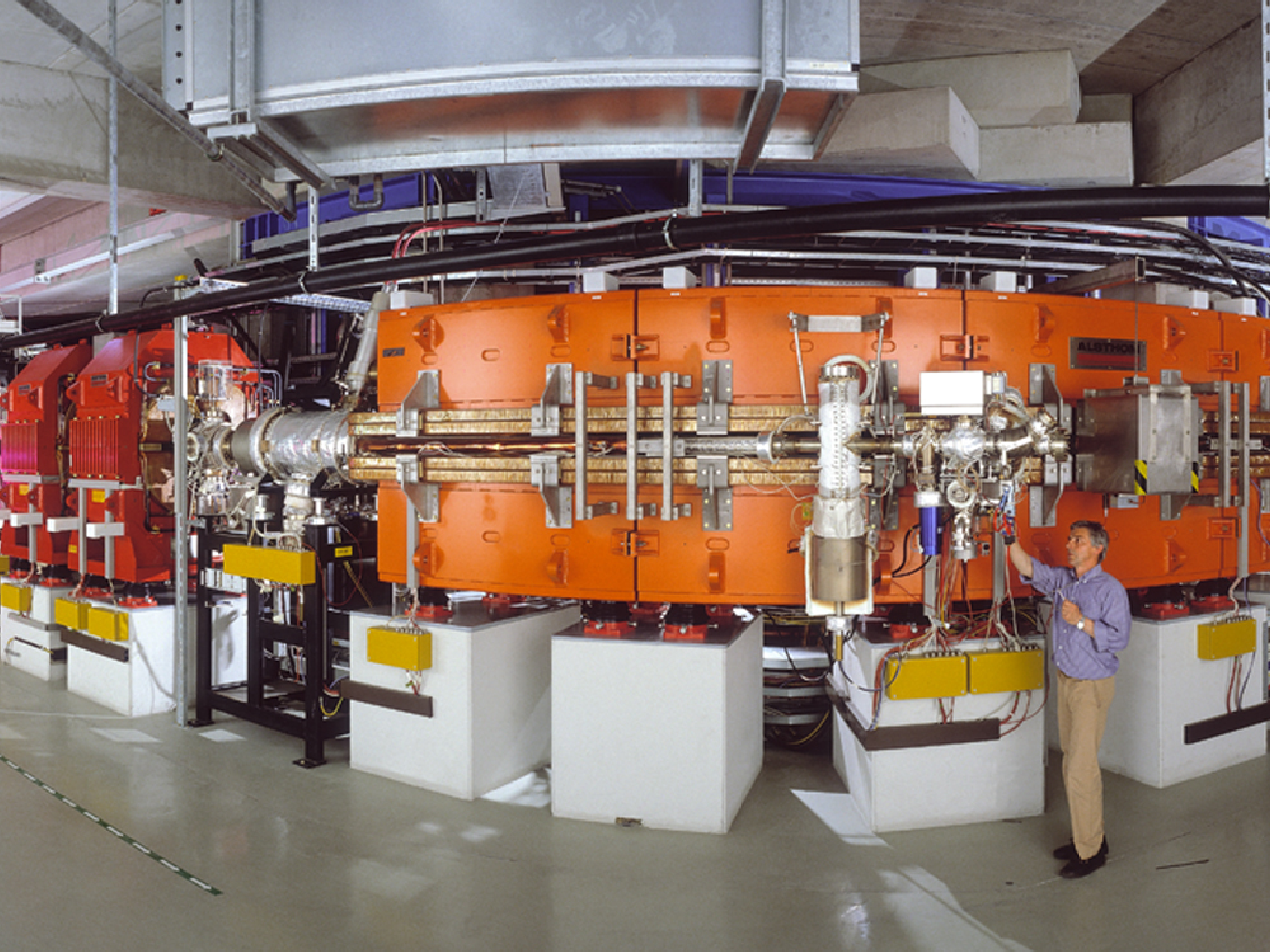
maximum velocity: v/c = 0.7

res. gas pressure: 10 (-11) mbar

electron and stochastic cooling

acceleration, deceleration

bakable to 300 C


ALSTHOM

Ions in storage rings – some basics

- To ***accelerate, decelerate, compress*** and inject the ions one needs RF-cavities (RF: radio frequency)

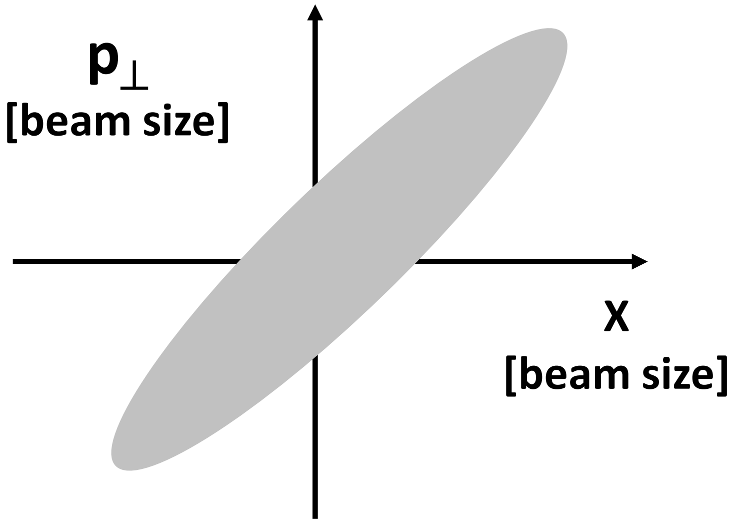
- To ***store highly charged ions for a long time*** (at least minutes) an excellent vacuum system (UHV: ultra high vacuum) of about 10^{-11} mbar is needed. In addition *cooling* is needed, the enhancement of the phase space density for the ions (*Liouville*)

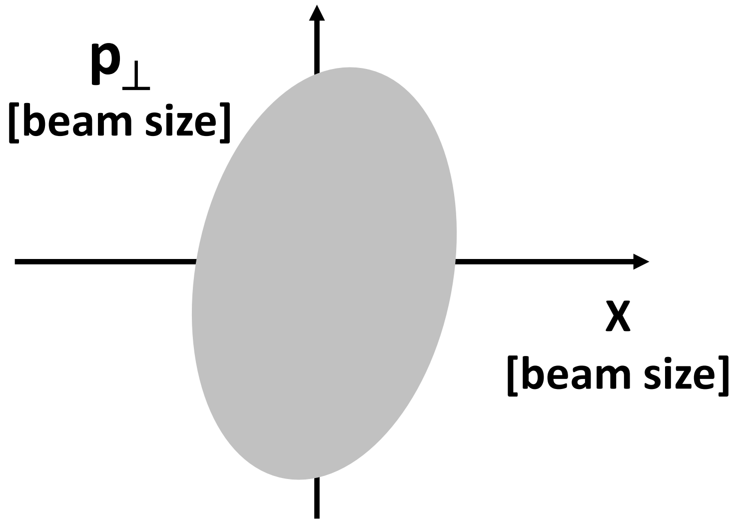
Cooling techniques: What is cooling ?

Cooling: ***Enhancement of the phase space density of the ion beam***. The beam remittance get's reduced, i.e. the beam size and the angular divergence is reduced simultaneously.

Liouville's theorem

For a given beam velocity, the emittance ε [mm x mrad] – the product of size (x) and angular divergence (transverse momentum **p**$\perp$*) – is constant if there are only conservative forces.*





Cooling techniques

One can only overcome Lioville by applying external forces

- **Laser cooling**
- **electron cooling**
- **stochastic cooling**

The Nobel Prize in Physics 1984

The Nobel Prize in Physics 1984

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

Carlo Rubbia

1/2 of the prize

Italy

CERN
Geneva, Switzerland

b. 1934

Simon van der Meer

1/2 of the prize

the Netherlands

CERN
Geneva, Switzerland

b. 1925

The Nobel Prize in Physics 1984
Press Release
Presentation Speech

Carlo Rubbia
Autobiography
Nobel Lecture
Banquet Speech

Simon van der Meer
Autobiography
Nobel Lecture

1983 1985

The 1984 Prize in:
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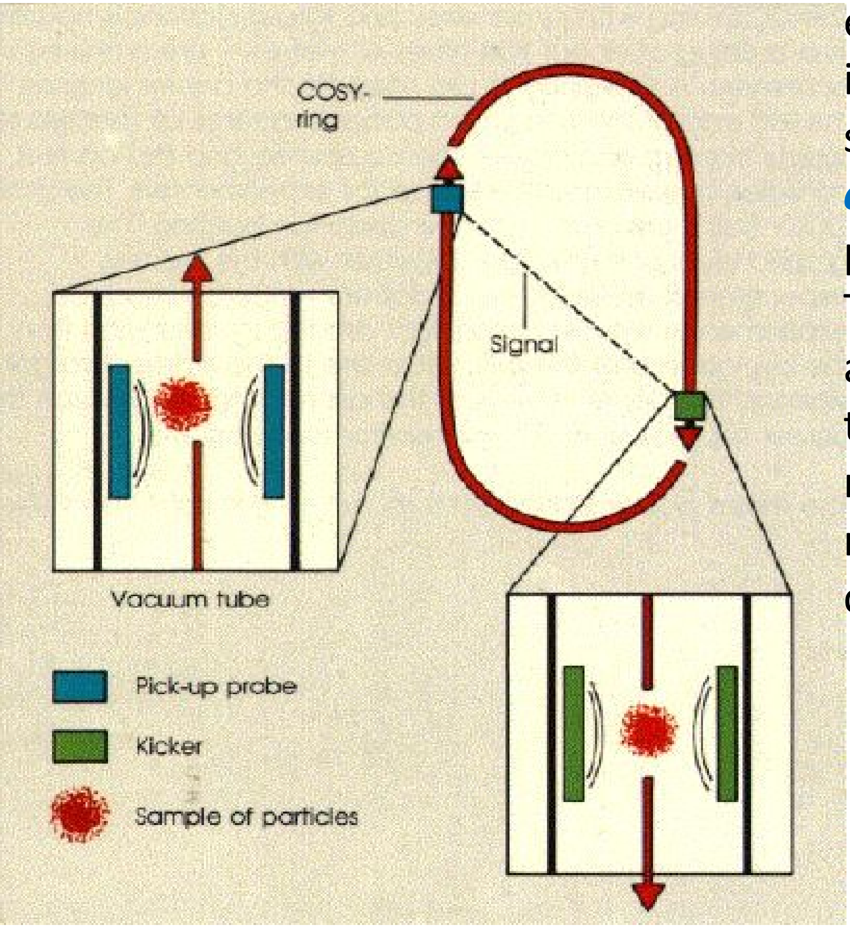
Prinziple of 'stochastic' cooling

Self correction of ion trajectory

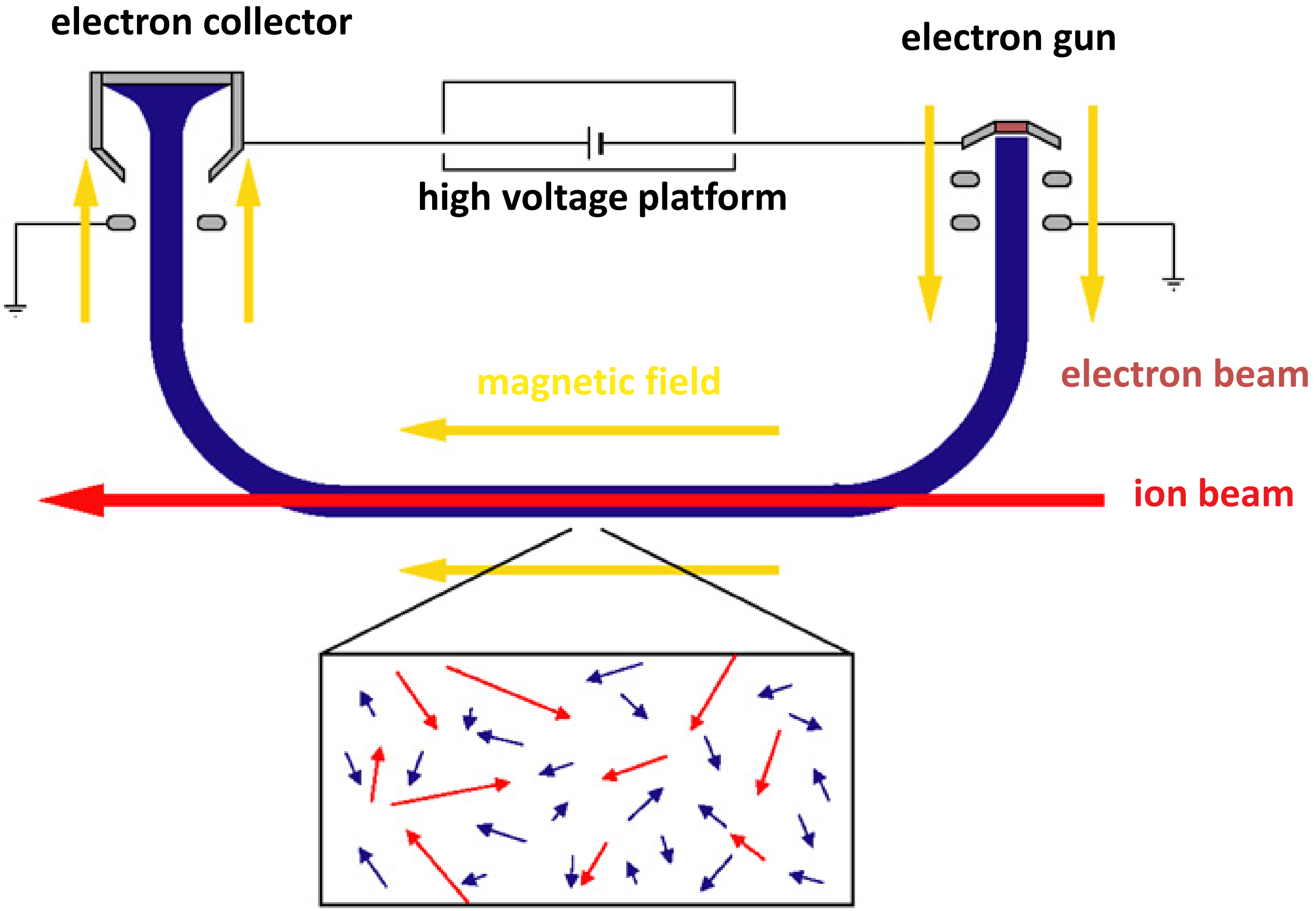


Using a ***pick-up probe***, the position of the ion beam can be measured at a fixed position via the induced electronic signal. A deviation of the beam from the ideal orbit can be correctd by the amplification of this signal. This ***amplified signal can now be used as a correction signal which acts on the beam*** at a second position via a ***„kicker“.***

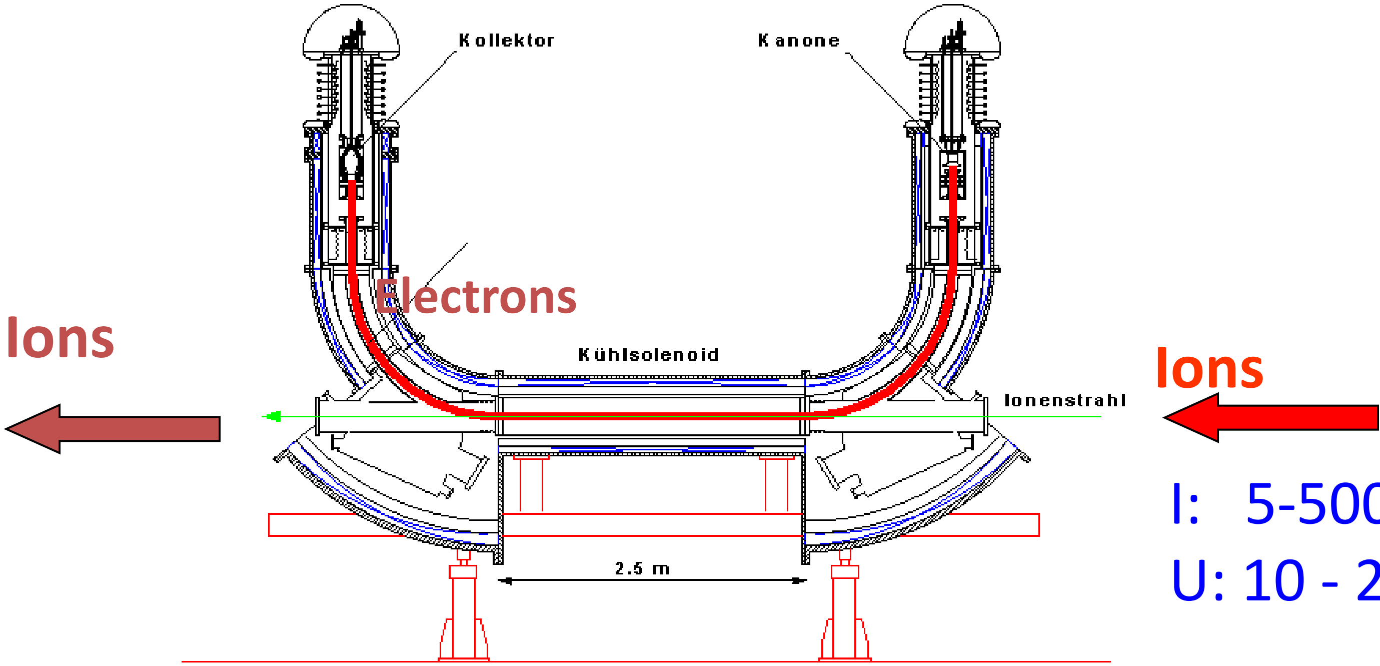
This method was invented for the cooling of hot antiprotons by Van der Meer. He was able to show that after a cooling time of $\tau \propto$ **N/C** (N: particle number, C = Bandwidth of the amplifier) a momentum width of the beam of about $\Delta p/p \approx 10^{-3}$ can be achieved by stochastic cooling

The Nobel Prize in Physics 1984
Simon van der Meer 1925*, CERN,

Electron Cooled Ion Beams



Electron Cooling



I: 5-500 mA

U: 10 - 200 kV

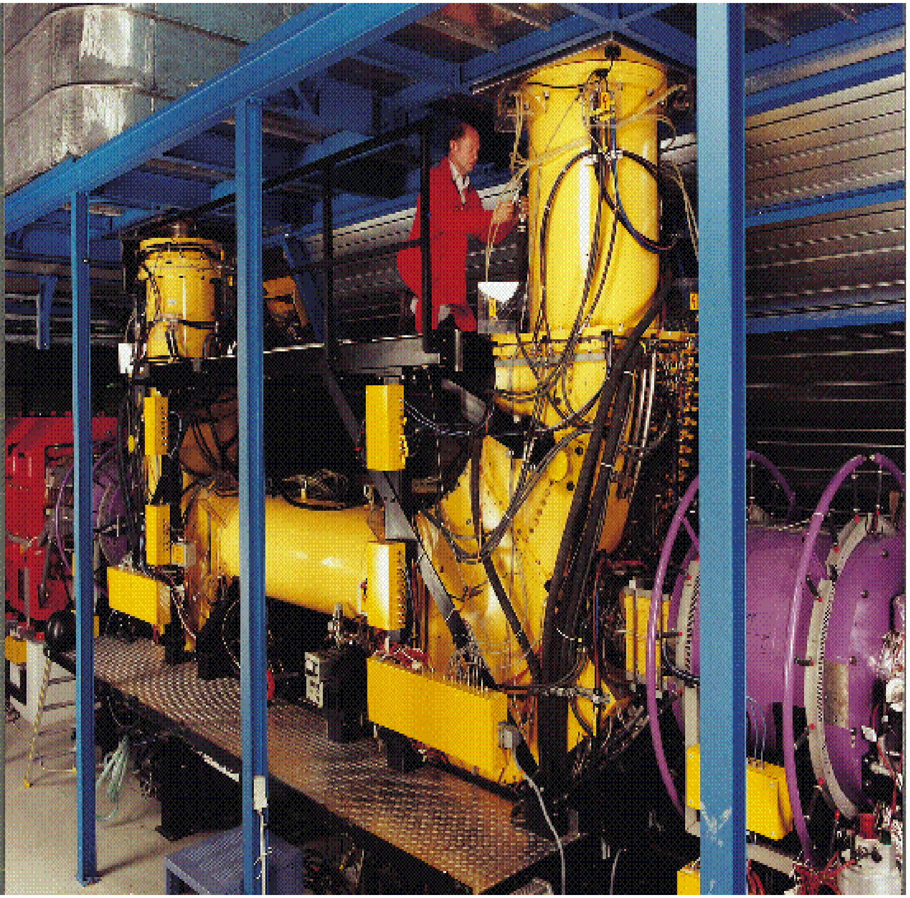
Ions interact 10^6 1/s with a collinear beam of cold electrons

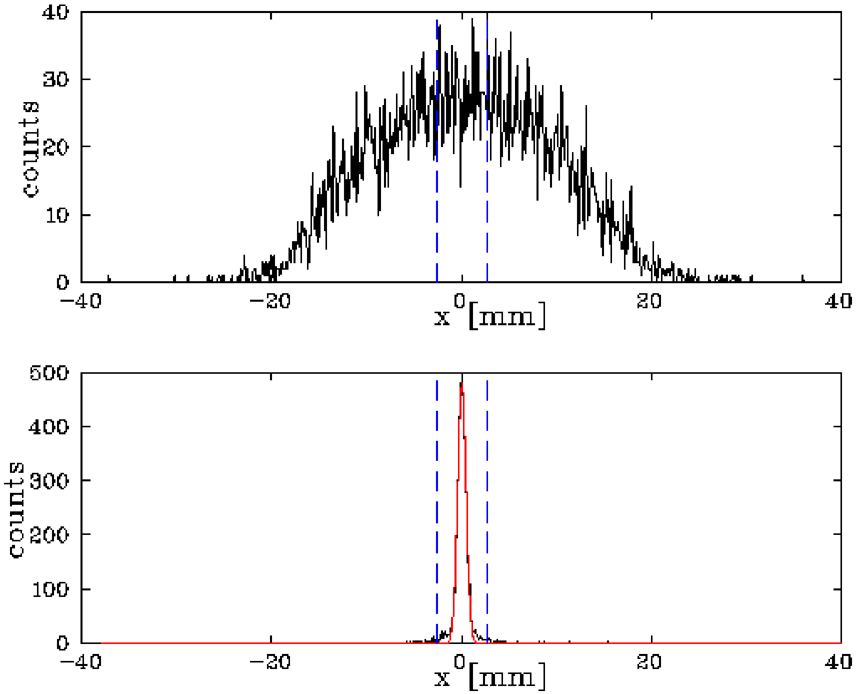
Properties of the cold ions

Momentum spread	$\Delta p/p$: $10^{-4} - 10^{-5}$
Diameter	2 mm

'Cooling': narrowing velocity, size and divergence of the stored ions

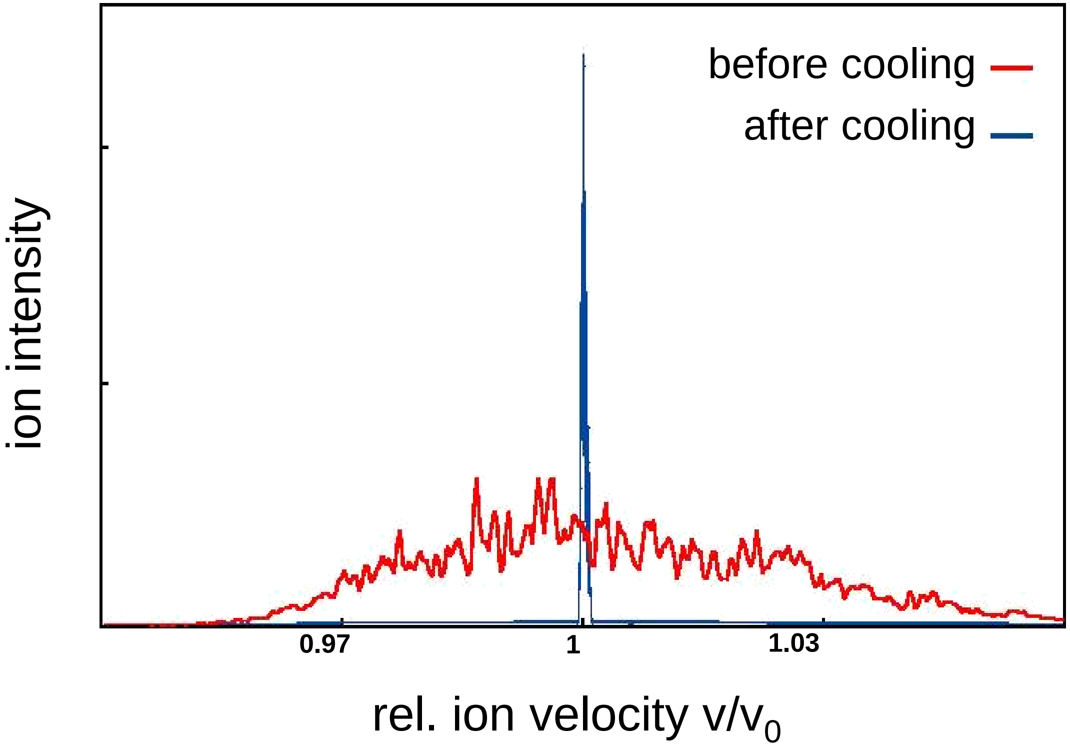
Electron cooling: Budker, 1967 Novosibirsk





momentum exchange
with 'cold', collinear e- beam. The ions get the **sharp velocity** of the electrons, small size and divergence

Electron cooling provides



- Brilliant ion beams
- Constant energy
- Long storage times
- Small velocity spread for all ions
- Operation of targets within the ring
- Very cold beams

- But long cooling times (10 s)

Coulomb cooling: electron cooling

Cooling by electrons can be treated in analogy to energy loss of ions in matter

$$\frac{dE}{dx} \propto \rho \frac{Z^2}{m_e v^2}$$

What acts against cooling ?

a) "***intra beam scattering***"
Ion-ion scattering

b) ***Collisions*** (scattering) of ions with the ***residual gas atoms***

c) ***Charge exchange losses*** of the ions in collisions with the residual gas atoms or cooler electrons

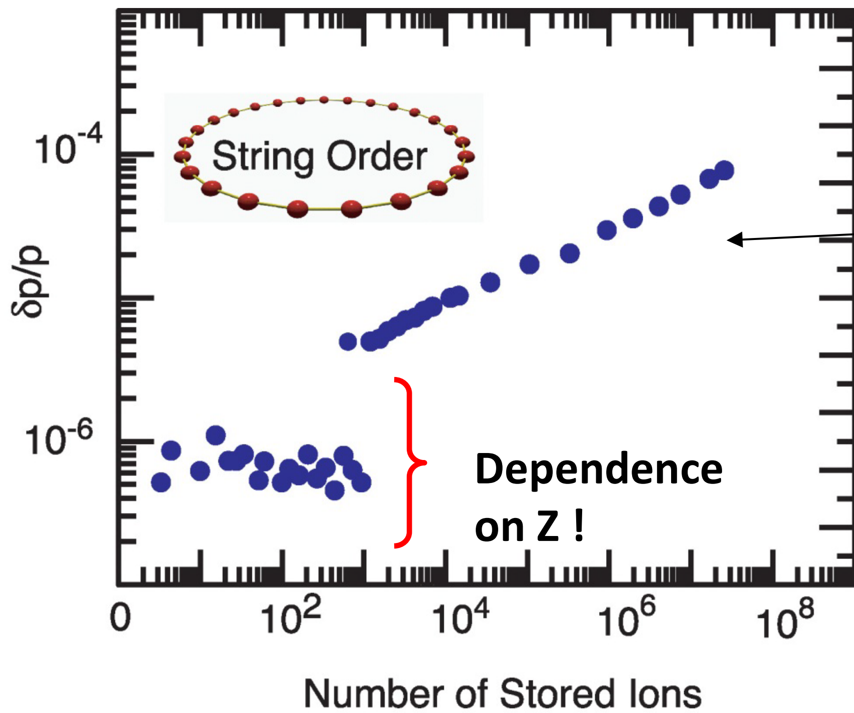
All processes (a, b, c) scale with Z^2
(Z is the nuclear charge of the stored ions)

Intra beam scattering

ESR: circumference about 10^4 cm

With 10^4 ions, the mean distacane amounts to about <d>≈ 1 cm

At distances of about 1 cm and larger intra-beam-scattering was not observed



$N^{1/3}$

Temperature of the ions dependence on intra beam scattering

Recombination Processes

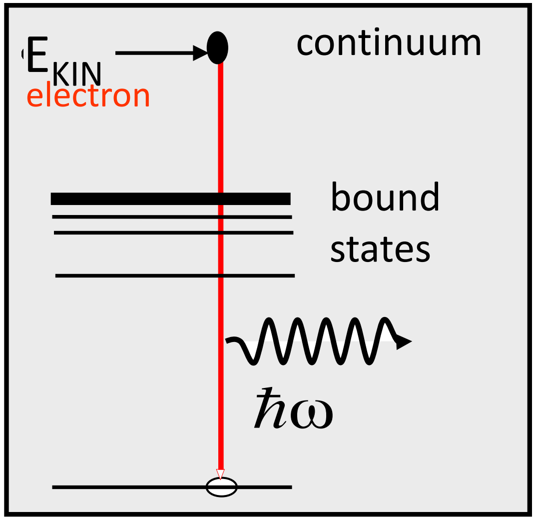
Charge changing collisions of ions with matter

Electron-Ion-Collisions

- Radiative Recombination

Electron Pickup Processes of HCI in Collisions with Electrons (Dynamic Processes)

Radiative Recombination/Electron Capture

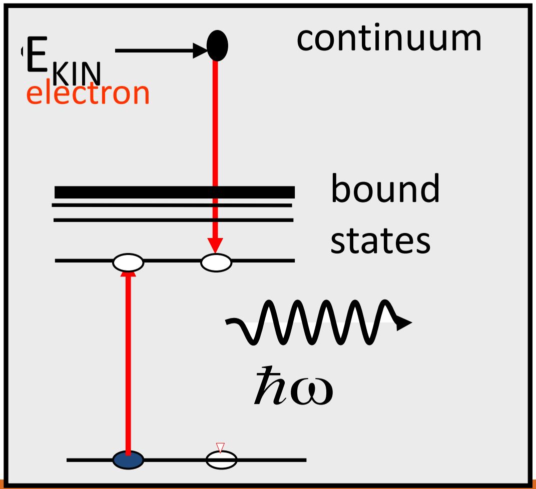


- *Electron capture into a bound ionic state by emission of a photon*

$$\hbar\omega = E_B + E_{KIN}$$

- *Time-reversed photionization*
- *Only possible capture/recombination process for bare ions colliding with electrons*

Dielectronic Recombination/Electron Capture



- *Resonant (non-radiative) capture of an electron into a bound state*
- *Time-reversed Auger process*
- *Important charge exchange process for multi-electron ions*

Beam lifetimes at ESR

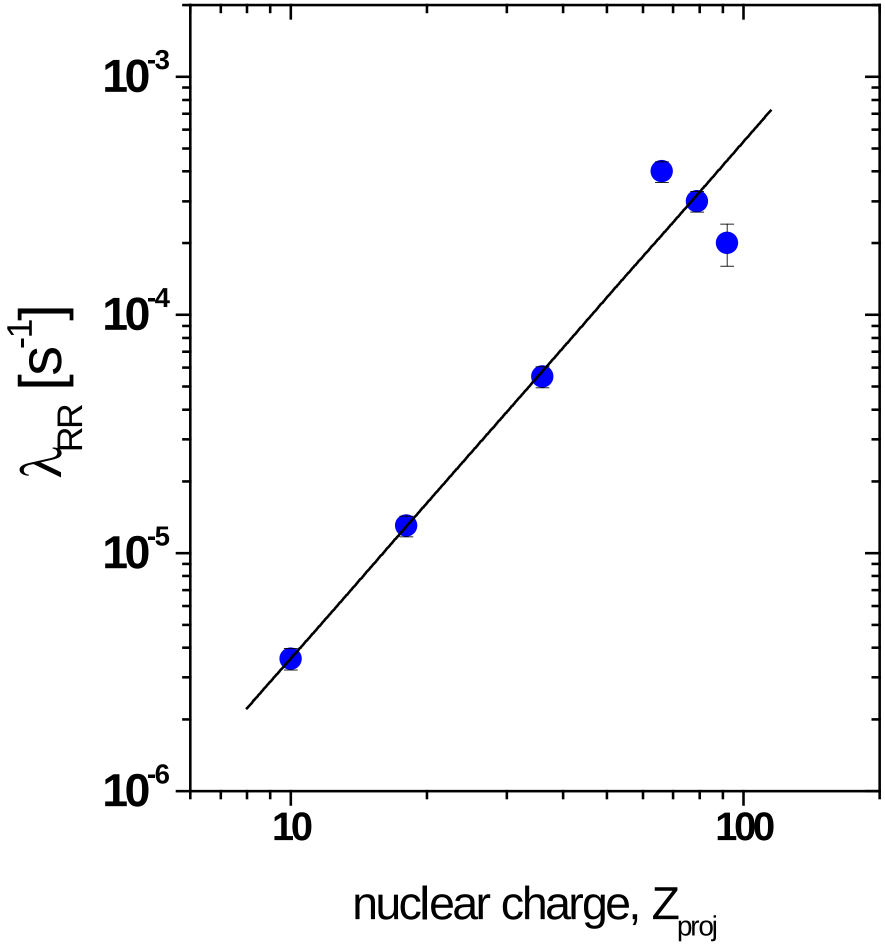
Recombination rate

$$\lambda_{RR} \propto N \cdot \rho \cdot \alpha_{RR}$$

N: number of stored ions
ρ: electron density

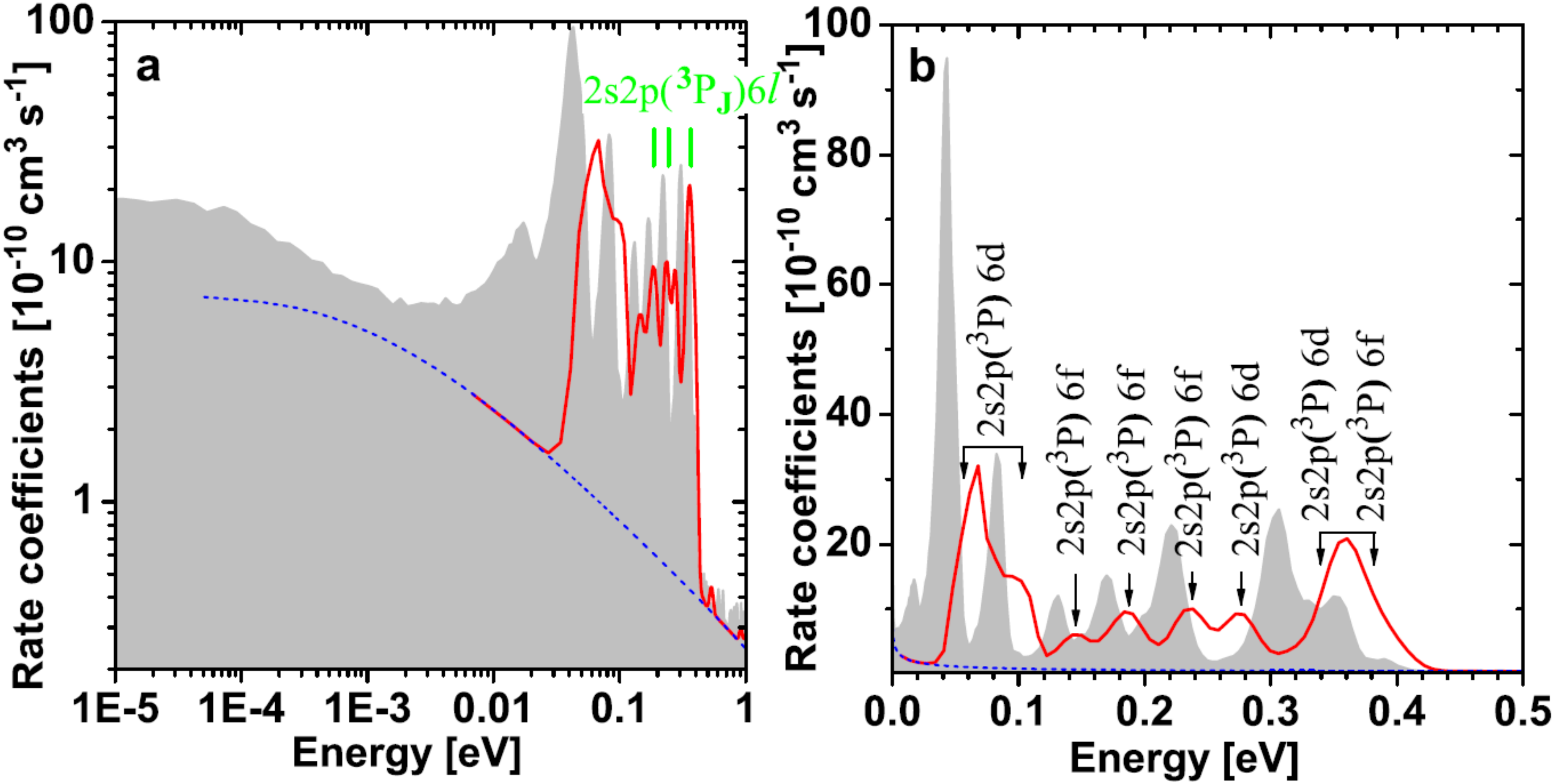
Recombination coefficient

$$\alpha_{RR} = \int f(v) \cdot v \cdot \sigma_{RR} \cdot d^3v$$



Low-energy DR of Be-like Ne^{6+}

CRYRING experiment vs. AUTOSTRUCTURE theory



I. Orban et al.,
A&A (2008) in print