Electron spectroscopy and fundamental processes in heavy-ion storage rings

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Outline

I. Fundamental quantum few-body problems: correlated quantum dynamics of electrons for ions up to transient superheavy quasi-atoms Z>100

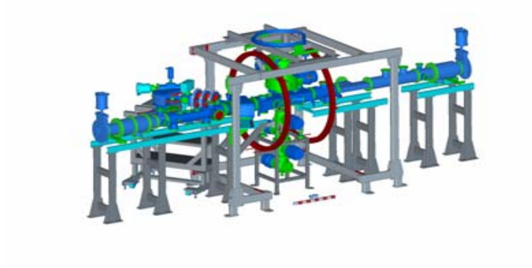
II. Electron Spectrometers:
  a) Toroidal electron branch for a reaction microscope in a storage ring
  b) Imaging forward electron spectrometer

III. First experimental results and agenda for coming experiments

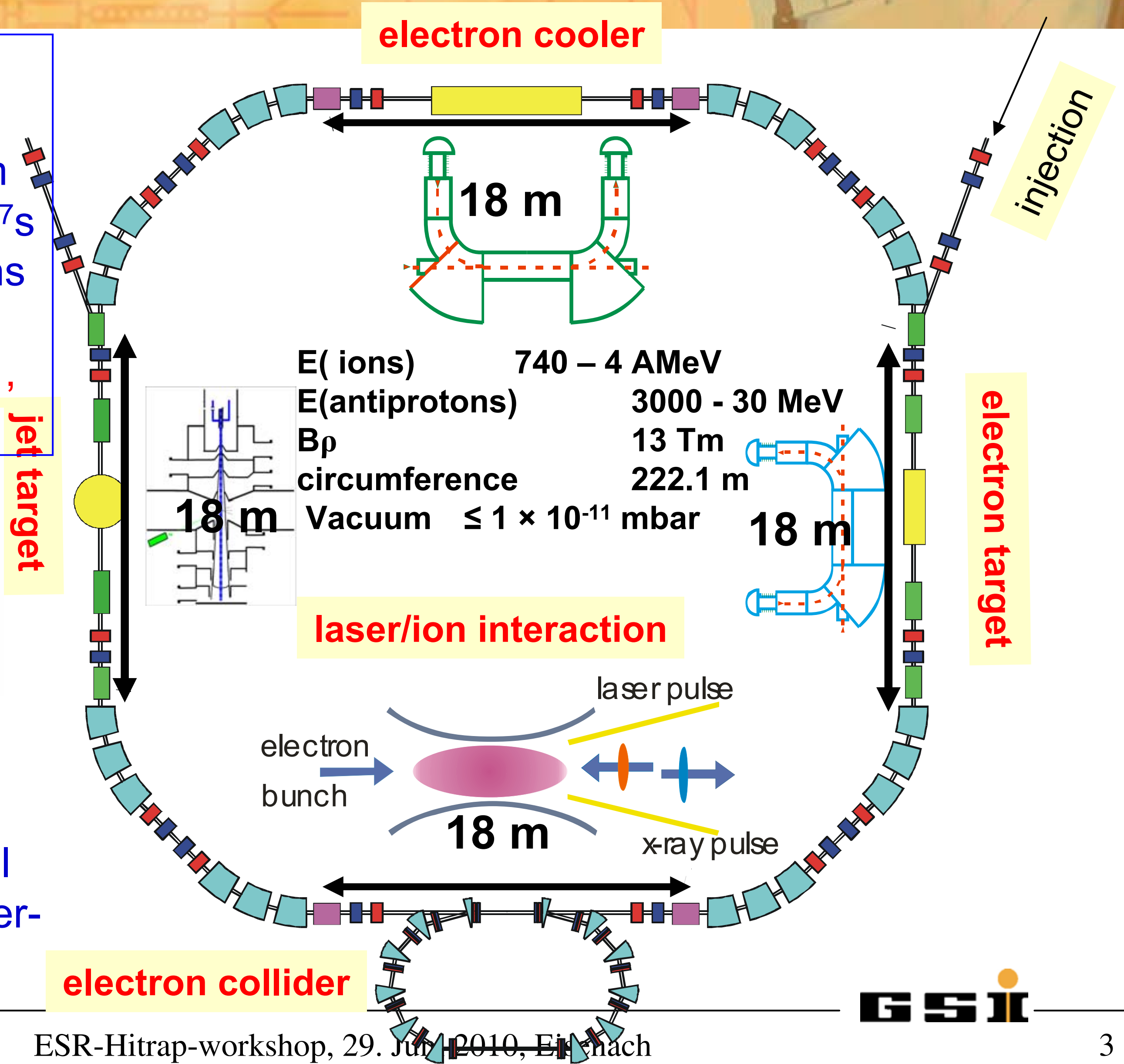
IV. Summary and Outlook

The New Experimental Storage Ring NESR
+ experimental facilities

- beams of high luminosity:
-extreme el-mag. Pulse
-high E-field up to 10^{16}V/cm
-short collision times $\tau \approx 10^{-17}$s
-bare, H-like very heavy ions
 at $v_{ion} << v_K$:
strong perturbations q/v »1,
adiabatic collisions



Unique tool for the study of dynamcis of fundamental processes in areas not otherwise accessible



E(ions)	740 – 4 AMeV
E(antiprotons)	3000 - 30 MeV
Bρ	13 Tm
circumference	222.1 m
Vacuum	≤ 1 × 10^{-11} mbar

I.Correlated Electron Dynamics: Fundamental processes accessible with ESR/NESR beams

a) Singular characteristics in near complete atomic fragmentation found in slow and strongly perturbing (q/v>>1) Collisions :

- pronounced (multi)-electron **continua in target and projectile;** **(these features are NOT present for swift collisions q/v<<1)**

In laboratory frame:

b) Radiative(RECC) and non-radiative(ECC) electron capture into the projectile continuum

↔

In projectile frame:

short–wavelength limit of **electron -nucleus bremsstrahlung**

E090

c) New avenues towards a spectroscopy of inner orbitals in transient superheavy quasiatoms Z>100

E102

d) first (e,2e) on ions in arbitrary charge states, e.g heavy He-like ions

E081

Evidence for topologically stable multi-electron transfer from target into projectile continuum

Strong perturbation q/v >1:

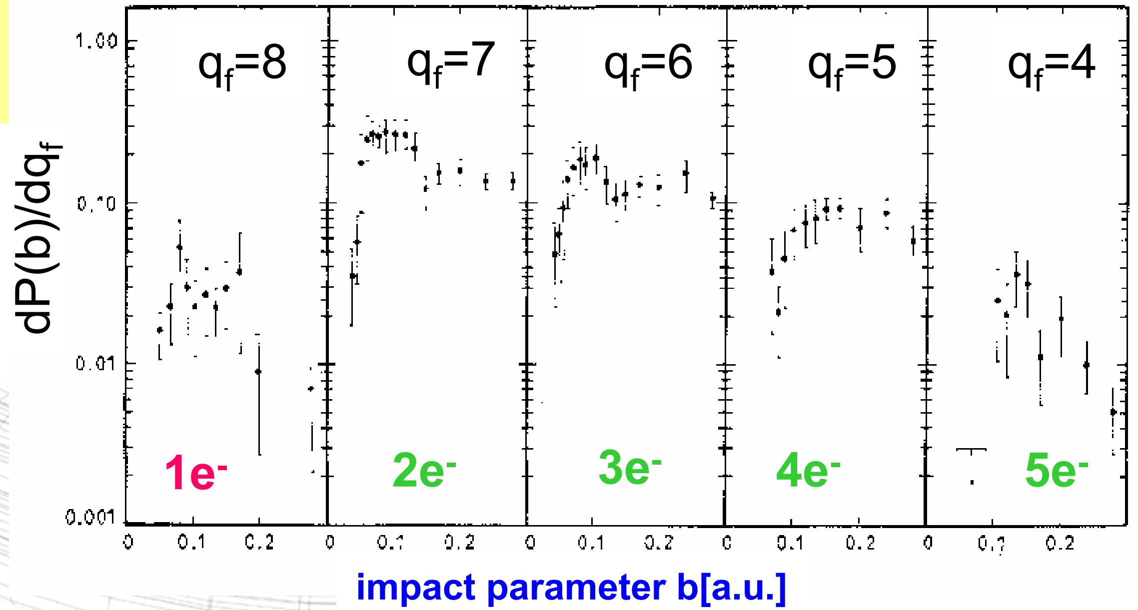
in projectile continua($\vec{v}_e \cong \vec{v}_{proj}$) 0.53AMeV F^{8+}+Ne$\rightarrow F^{q+}(\theta)$ + e_{cusp}

↑ coincidence ↑

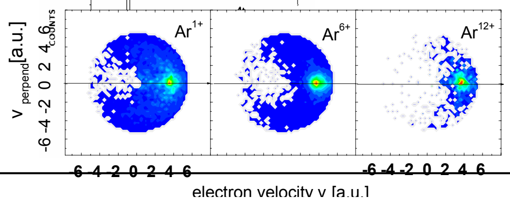
P(b) for **E**lectron **C**apture to **C**ontinuum (ECC) **/multiple TI**

Cusp:
fate of electrons does not
emerge until 5000 a.u.
(J. Macek, C. Reinhold)

(inhibited calculations
for P(b) for ECC to date)



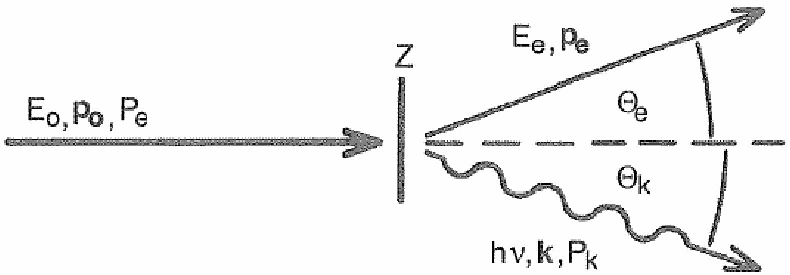
0.35AMeV I^{23+} +Ar: DDCS for electron emission coincident with Ar^{q+} recoil ions

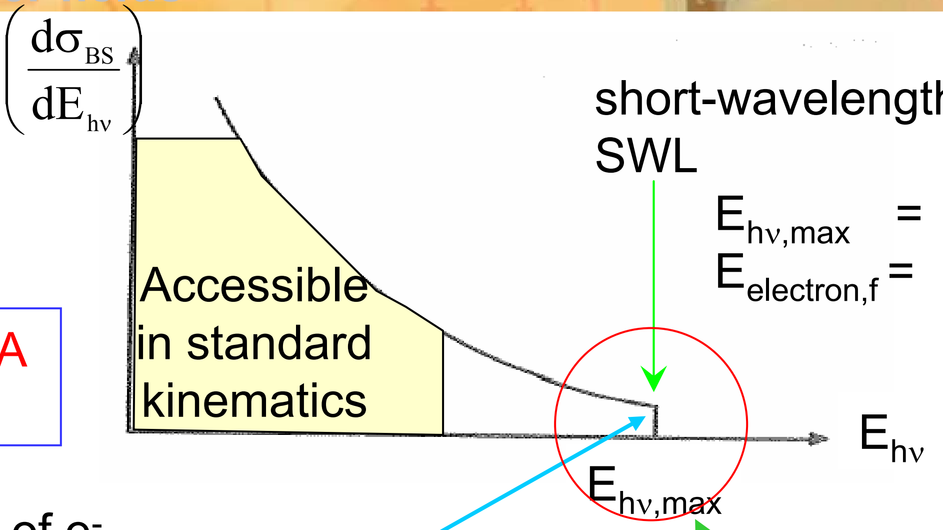


Collective effects in ECC and transfer ionization (TI),
A. Skutlartz et al. J.Phys.B

b) Electron-nucleus bremsstrahlung:

consequence of general coupling of e-m fields and matter fields





$e^-(E_0) + A \rightarrow e^-(E_e;\theta_e) + h\nu(E_x;\theta_k) + A$

↑coincidence↑

Quantum mechanical bremsstrahlung

i) Radiative process involves coupling of e^- and e-m field: p(radiation) $\sim\alpha$

$\sigma_{BS} \sim \alpha * \sigma_{el.scatt.}$

ii) Radiation spectrum has high-frequency limit,

Differential Cross Section ≠ 0

at SWL tip only for Coulomb case

(but: for screened atom $DCS|_{SWL}=0$)

iii) At SWL: Test of equivalence of

$DCS(BS)|_{SWL} \sim DCS(photoionization)$

U. Fano, R. Pratt

Accessible only in inverse kinematics:

$A^{q+} + N_2 \rightarrow A^{q+} + e^-(E_{cusp};0^0) + h\nu(E_x;\theta_k) + N_2^{*+}$

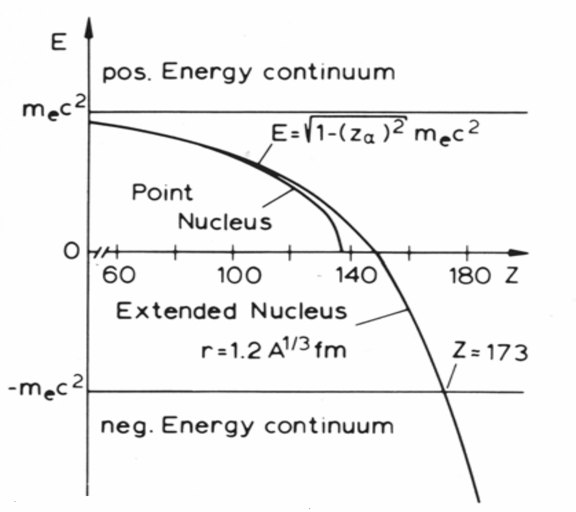
↑coincidence↑

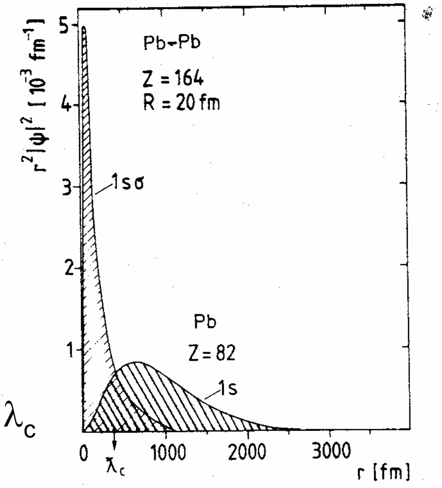
c) New Quest for electrons in extreme fields of superheavy quasiatoms

Flourishing experiments starting with availability of beams up to U in mid-70s and -80s at GSI
-present understanding of unique features of collision dynamics at high Z is largely owed to these experiments on inner-shell ionization.

Key findings: -strongly enhanced **relativistic shrinking of inner wavefunctions** controls ionization probabilities and δe^- - and e^+ - continua

Still open: - evolution of 1s-binding energies for $Z\alpha>1$ and as function of internuclear distance R
- experimental confirmation of diving of $1s\sigma$ into DIRAC-sea





inside λ_c

c) Derive $E_{1s\sigma}(R)$ from extrema of electron transfer probability $P_{1s\text{-}1s}(R)$

map energies E(R) of innermost molecular orbitals via resonant **1s to 1s** electron **transfer**

e.g. $Xe^{53+}(1s) + Xe \rightarrow Xe^{52+}(1s^2) + Xe^{n+}(1s) + e_A(KLL)$

↑coincidence↑

or $Pb^{81+}(1s) + Pb \rightarrow Pb^{80+}(1s^2) + Pb^{n+}(1s) + h\nu(K\text{-}X)$

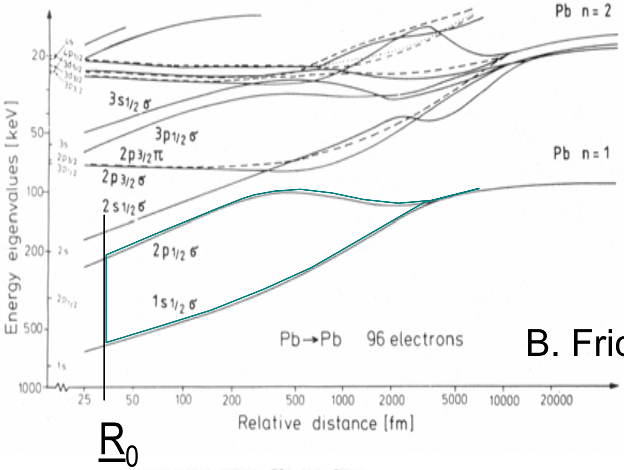
For probability of vacancy transfer P the amplitudes for two indistinguishable path must be added(2-state approximation):

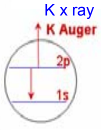
$$P = \sin^2\left(\frac{1}{v}\int \Delta(E_{1s\sigma} - E_{2p\sigma})\frac{R}{\sqrt{(R^2 - R_0^2)}}dR\right)$$

1s-1s resonant charge transfer has

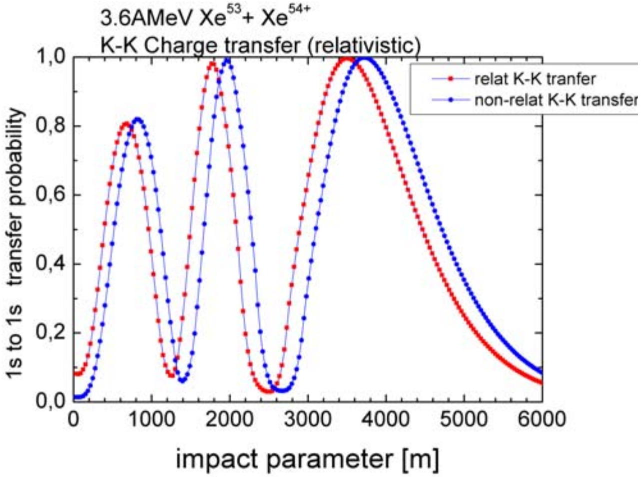
-strong and visible sensitive structure to be interesting

- sufficient simplicity (near 2-state approx.) to be intelligible



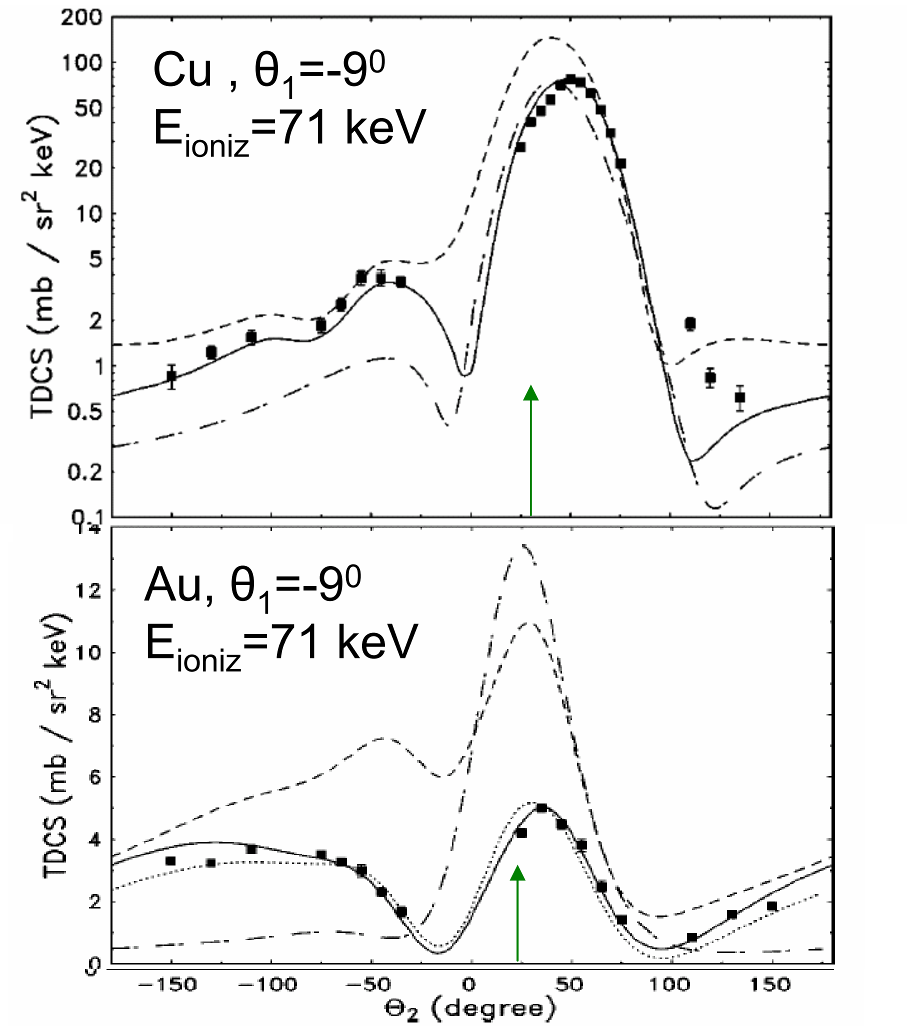


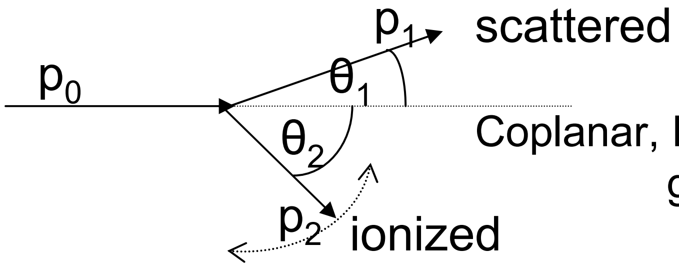
B. Fricke



V.Shabaev/I. Tupitsyn

Relativistic (e,2e) for 1s ionization: 300keV e^- + Cu and Au





scattered

Coplanar, Ehrhardt-geometry

ionized

-θ_{binary} > $\theta_{Momentum\ transfer}$
- strong relativistic effects for
- "same side“ electron emission

-RDWBA: S. Keller et al. PRA59(1999)

- Ambiguity: 1s ionization cannot
- be distinguished from 2-electron
- 2l- ionization event for $Au|_{solid}$ target :
- E_0-Q(1s)= $E_{1,scatt}$ + $E_{2,ionized}$
- E_0-Q(2p)= $E_{1,scatt}$ + $E_{2,ion.}$ +$E_{3,ion.}$

-only H-, He- like targets give clean
-access to relativistic and QED effects in collisions

II. ESR target zone with reaction microscope with toroidal electron branch: simultaneous mapping of low to intermediate electron energies

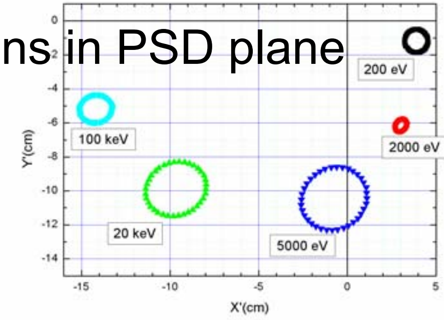
$Xe^{53+}(1s) + Xe \rightarrow Xe^{52+}(1s^2) + Xe^{n+}(1s)|_{E\text{-rec},\varphi\text{-rec}}$

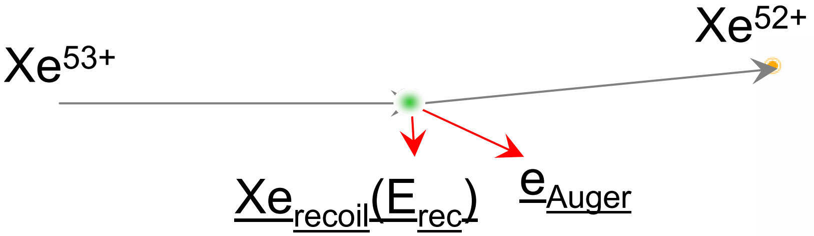
↓

$Xe^{(n+1)+}(1s^2) \quad +e_A(KLL)$

↑ coincidence↑

electrons in PSD plane

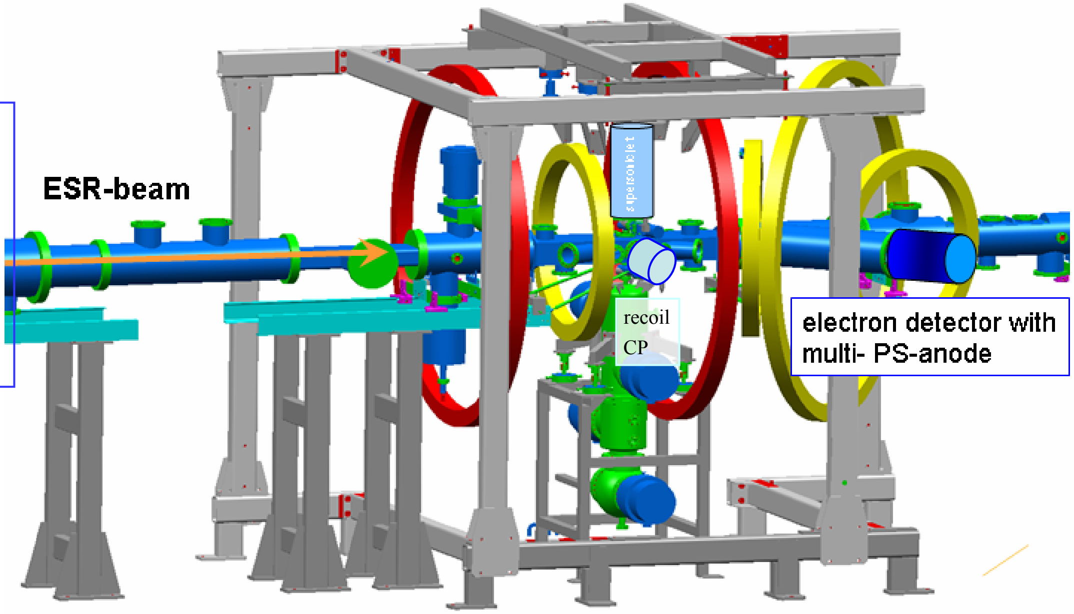




The interesting impact parameter range 1000fm<b<4000fm can in the ESR only be covered by recoil ion TOF at near 90^0 recoil angle:

100ns to 2.2 µs for recoil TOF

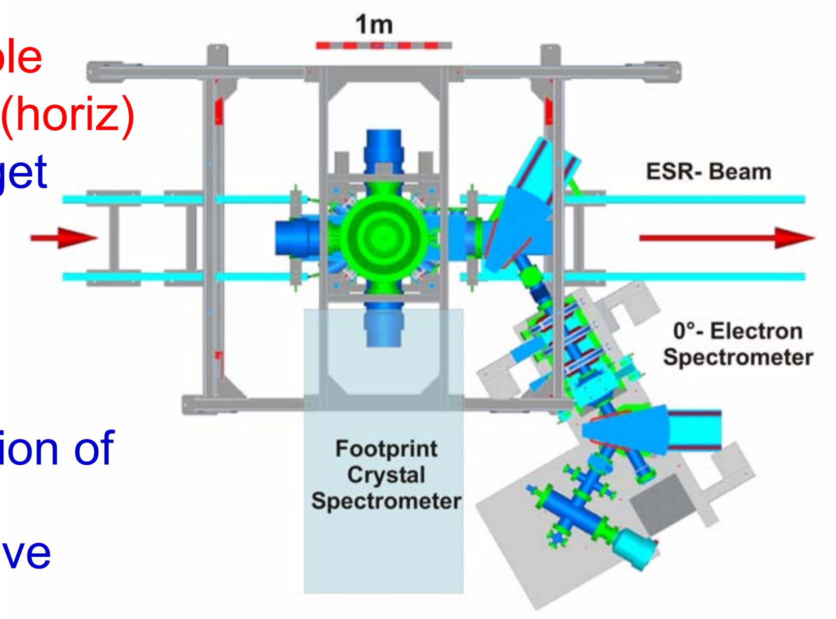
ESR- target-zone with supersonic- jet and reaction-microscope with toroidal electron branch



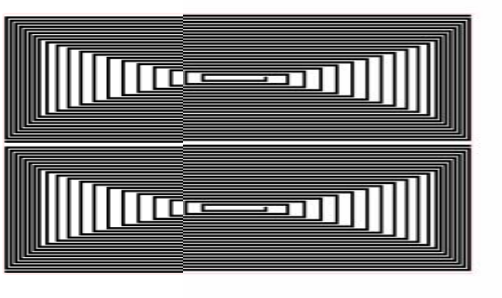
electron detector with multi- PS-anode

II. Parameters of current 0^0- Electron spectrometer in ESR

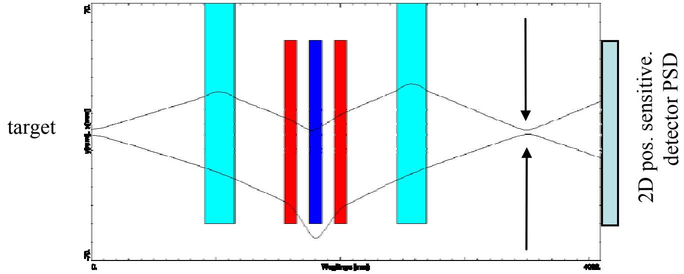
- Configuration: 60^0dipole-quad.-triplett-60^0dipole
  aperture :100mm(vert)x250mm(horiz)
- in telescope mode: maps electrons from target zone below jet onto 2D PSD
  with magnification $|M_x|=|M_y|=1$;
  resolving power $p/\Delta p$ up to 1600.
- for kinematically complete experiments:
  momentum analysis of electrons; reconstruction of scattering plane, i.e. the primordial
  direction of emissions, on 2D position sensitive detector



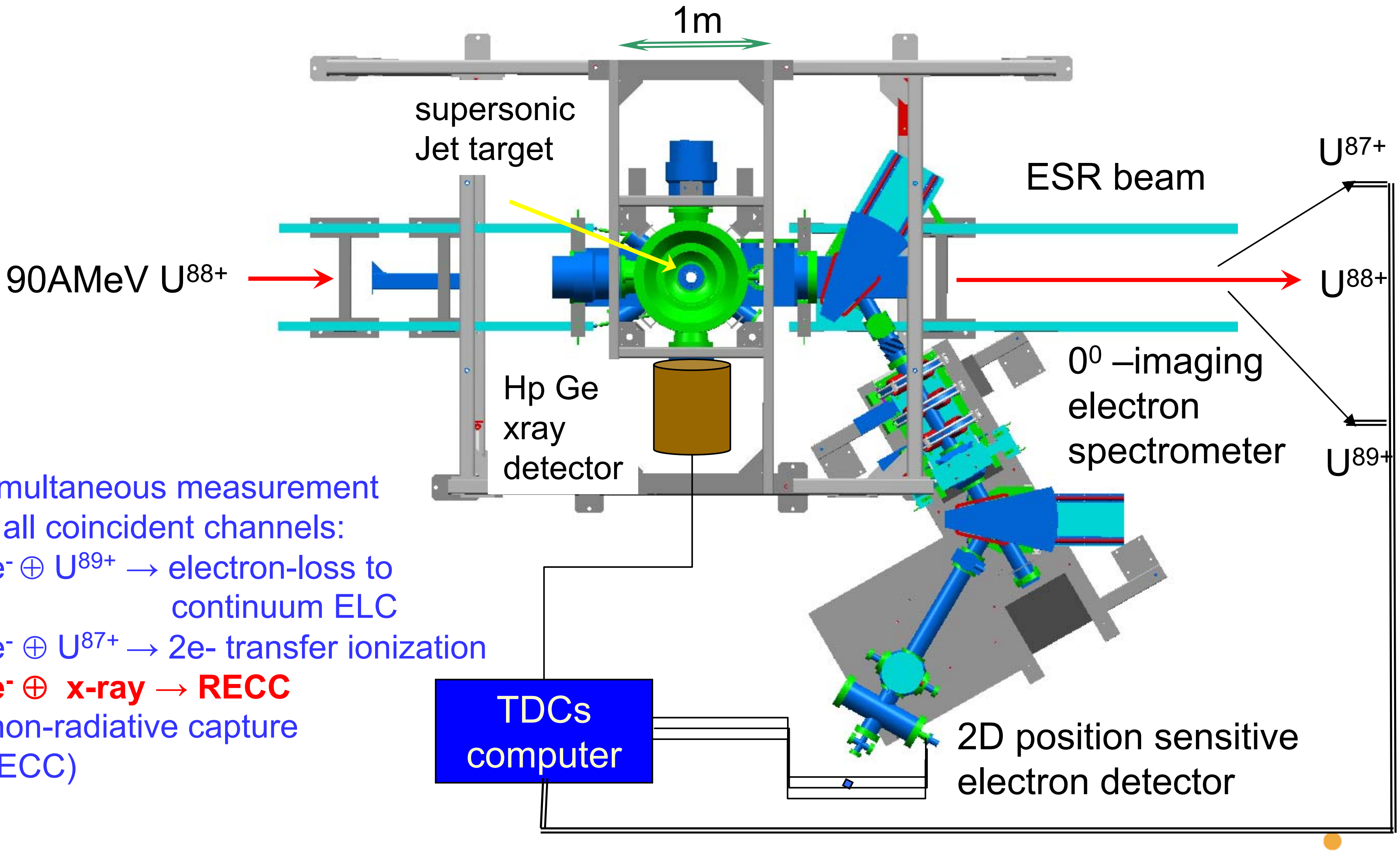
Electron detector:
80mm∅ with 2D-PSD
delayline anode



layout of new ironfree cos-2-theta coils for quadupole triplett of 150 mm∅



III. Experimental Configuration at Internal Target of ESR for measurement of radiative capture to continuum cusp(RECC) and e-N Bremsstrahlung



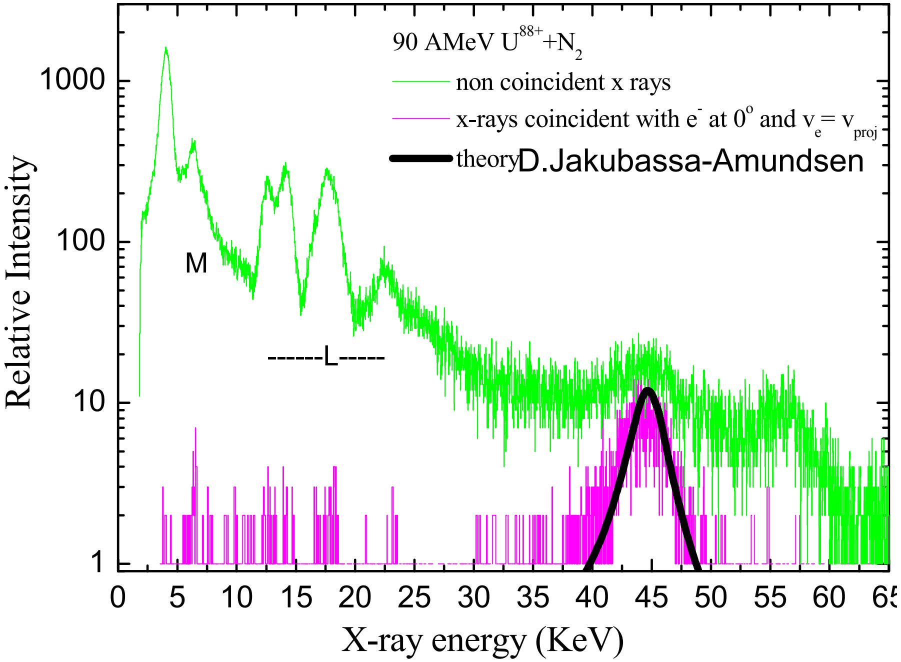
Simultaneous measurement of all coincident channels:

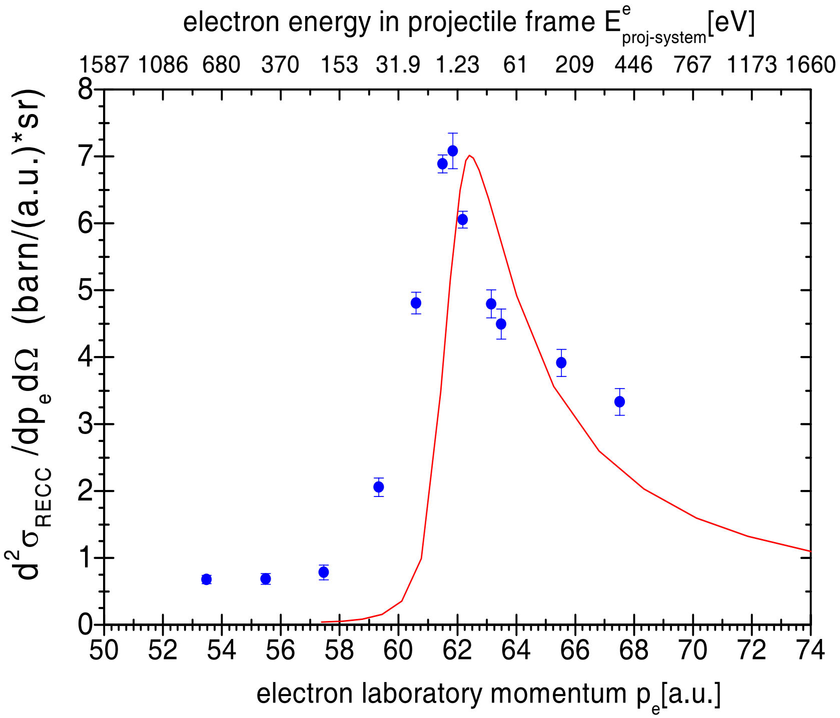
- $e^- \oplus U^{89+} \rightarrow$ electron-loss to continuum ELC
- $e^- \oplus U^{87+} \rightarrow$ 2e- transfer ionization
- **$e^- \oplus$ x-ray → RECC**
- non-radiative capture (ECC)

Radiative Electron Capture RECC and e N Bremsstrahlung

90AMeV $U^{88+}(1s^2 2s^2) + N_2 \rightarrow U^{q+} + \{N^{+*}\} + e_{Cusp} + h\upsilon(\varphi_{lab})$

$\Leftrightarrow$ **49.4 keV $e^- + U^{88+} \rightarrow U^{88+}$ $e(\theta) + h\upsilon(\varphi_{proj\text{-}sys})$ inverse kinematics**





a) In the xray spectrum coincident with forward electrons only **x rays** from the **shortwavelength limit of Bremsstrahlung** appear

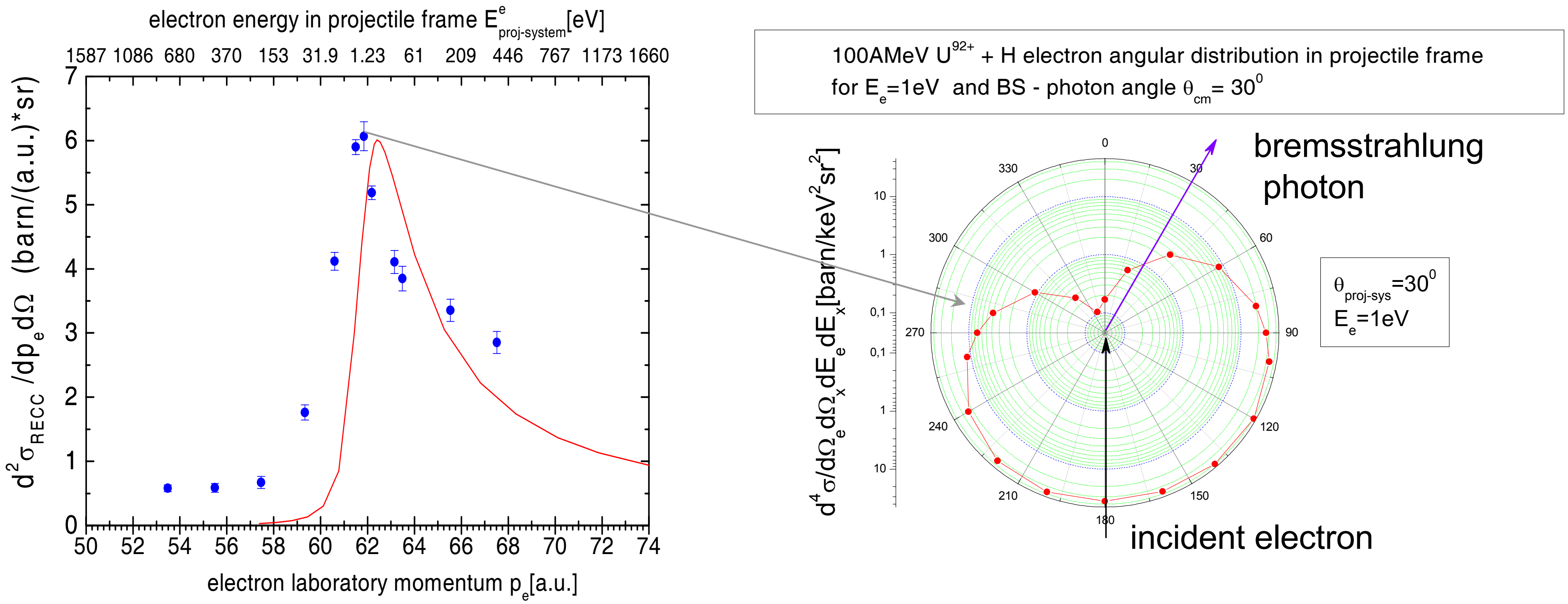
b) The asymmetry of the cusp peak is skewed to **high electron energies**

PRL 99

theory- Jakubassa-Amundsen

Towards kinematically complete triple differential cross sections for eN-Bremsstrahlung in the projectile frame:

For every electron momentum in Cusp:



100AMeV U^{92+} + H electron angular distribution in projectile frame for E_e=1eV and BS - photon angle θ_{cm}= 30^0

For every point of $\frac{d^2\sigma_{RECC}}{dp_e d\Omega_e}$ the polar angular distribution on the 2D-position sensitive detector of the forward spectrometer must be mapped onto the triple differential cross section in the projectile frame(=next step)

Derive $E_{1s\sigma}(R)$ from extrema of electron transfer probability $P_{1s-1s}(R)$

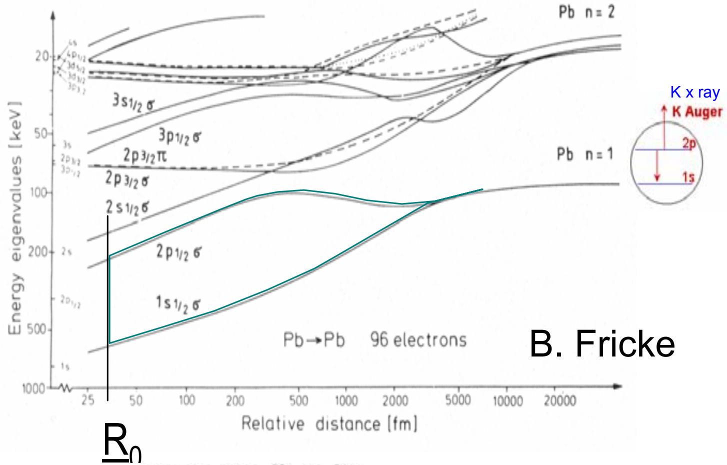
map energies E(R) of innermost molecular orbitals via resonant **1s to 1s** electron **transfer**

e.g. $Xe^{53+}(1s)$ + Xe ➔ $Xe^{52+}(1s^2)$+ $Xe^{n+}(1s)$ +e_A(KLL)

↑coincidence↑

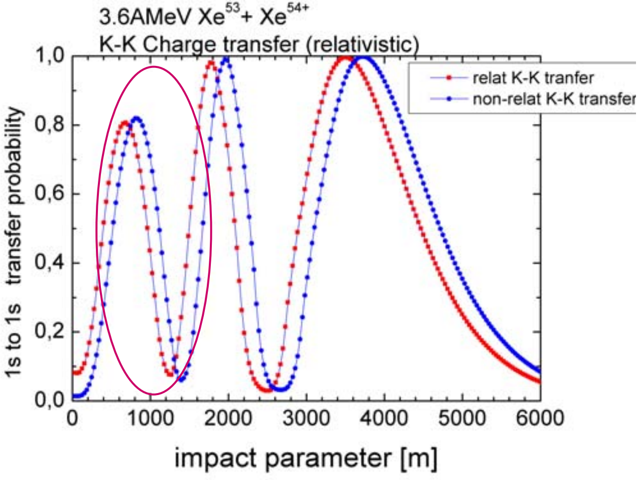
or $Pb^{81+}(1s)$ + Pb ➔ $Pb^{80+}(1s^2)$+ $Pb^{n+}(1s)$ +hν(K-X)

For probability of vacancy transfer P the amplitudes for two indistinguishable path must be added(2-state approximation):



B. Fricke

$$P=\sin^2\left(\frac{1}{v}\int\Delta(E_{1s\sigma}-E_{2p\sigma})\frac{R}{\sqrt{(R^2-R_0^2)}}dR\right)$$



V.Shabaev/I. Tupitsyn

1s-1s resonant charge transfer has

-strong and visible sensitive structure to be interesting

- sufficient simplicity (near 2-state approx.) to be intelligible

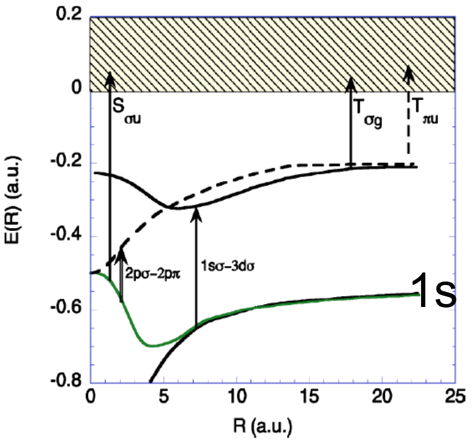
Dynamics of electrons in transient high E-fields during heavy ion-atom collisions:

mechanisms for adiabatic ionization 1s➔ εl (near-continuum)

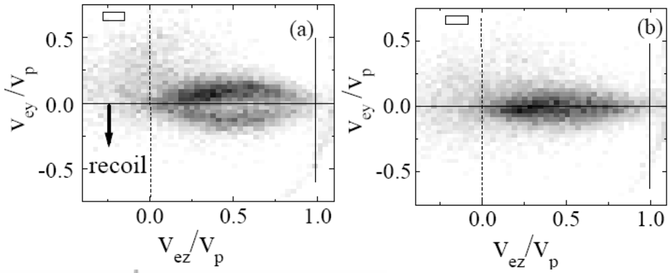
- ionization in symmetric systems for strong perturbation q/v>>1

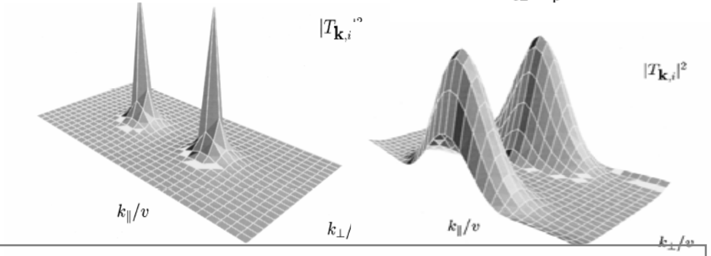
Theory offers diverse solutions for electron continua

theory :
(J. Macek et al.)



BUT: experiment: H⁺ + H, Dörner, Cocke





diverse molecular promotion mechanisms:

ESR at high Z: Xe^{53+} + Xe is still adiabatic at >6 AMeV : v/v_{1s} =0.3

1s projectile ionization: $Xe^{53+}(1s)+Xe \rightarrow Xe^{54+}(1s^0) + Xe^{n+} + e_{cusp}(0^0,\varphi)$

in inverse kinematics ↑--coin----↑--cidence -↑

coincidence can provide clean seperation from capture channel

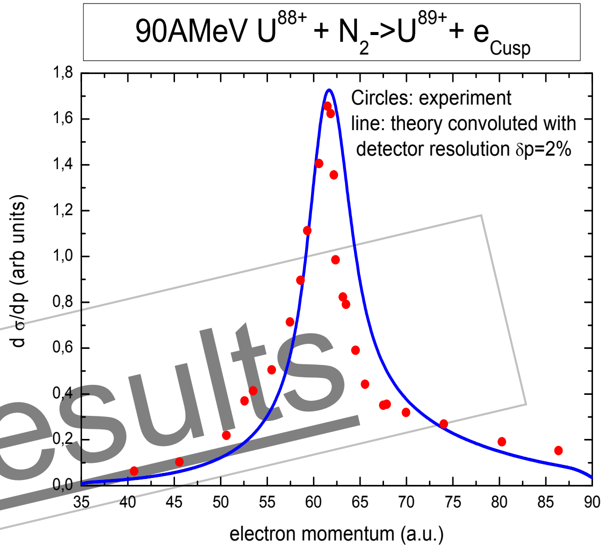
(to be measured with new configuration imaging 0^0 imaging spectrometer)

Electron loss to continuum ELC: towards kinematically complete cross sections for adiabatic 1s-ionization

as proof of principle for adiabatic 1s ionization of projectile:

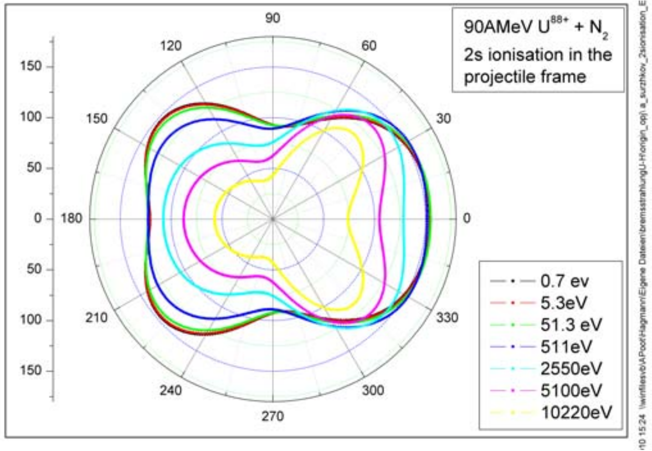
90AMeV $U^{88+}(1s^2 2s^2) + N_2 \rightarrow U^{89+}(1s^2 2s) + e_{cusp}(0^0)$

↑-- coincidence--↑



The electron loss to continuum of the projectile is identified via concidences of cusp electron and charge exchanged projectile U^{89+}.

The FWHM =5.6a.u. is significantly narrower than the 2p-Comptonprofile of U(2s).



2s ionization in projectile frame

Theory: A. Surzhykov, S. Fritzsche

Summary and Outlook

a) We have introduced a new configuration for the electron branch for a reaction microscope for improved adaption to operation in a heavy ion storage ring and

b) an imaging forward electron spectrometer for reconstruction of the primordial vector momenta for establishing collision planes in collisions involving projectile continua

c) we have presented first experimental results for differential cross sections for an electron-nucleus Bremsstrahlung ⊗Cusp-electron experiment with U^{88+} at the ESR ; the RECC allows for the first time to study the short-wavelength limit of electron-nucleus Bremsstrahlung

d) The new instrumentation will permit to investigate the dynamics of multi-electron continua in target and projectile originating in strongly perturbing collisions of highly charged heavy ions from NESR

Correlation and Dynamics of electrons in transient high E-fields during heavy ion-atom collisions:

correlation in electron resonant 1s-1s charge transfer

unmatched sensitivity to electron correlation in 1s -1s electron transfer

for H-like projectiles, e.g. Xe^{53+}(1s^1):

vacancy transfer probability P

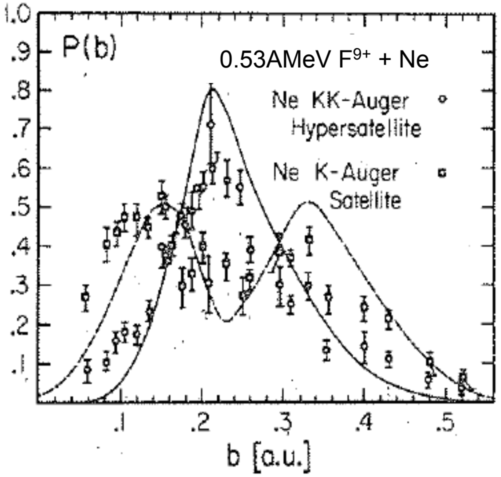
$$P = \sin^2\left(\frac{1}{\mathrm{v}}\int \Delta(E_{1s\sigma} - E_{2p\sigma})\frac{R}{\sqrt{(R^2 - R_0^2)}}dR\right)$$

for bare projectiles, e.g. Xe^{54+}(1s^0):

Xe^{54+}(1s^0) + Xe ➔ Xe^{53+}(1s^1)+ Xe^{n+}(1s) +e$_A$(KLL)

-transfer of exactly one electron: $P_{1\text{-electron}}=2P(1-P)$

when uncorrelated; (satellite Auger/ x-ray)



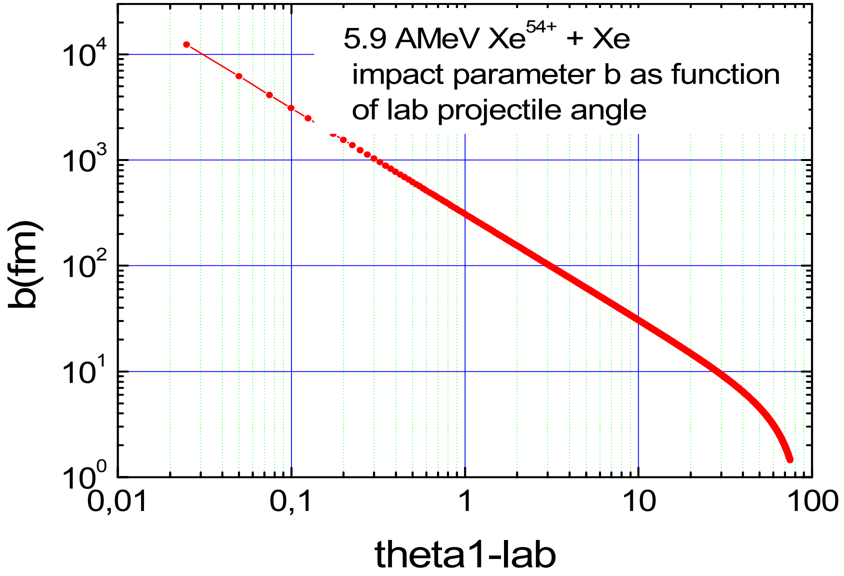
Xe^{54+}(1s^0) + Xe ➔ Xe^{52+}(1s^2)+ Xe^{n+}(1s^0) +e$_{HA}$(KK-LL)

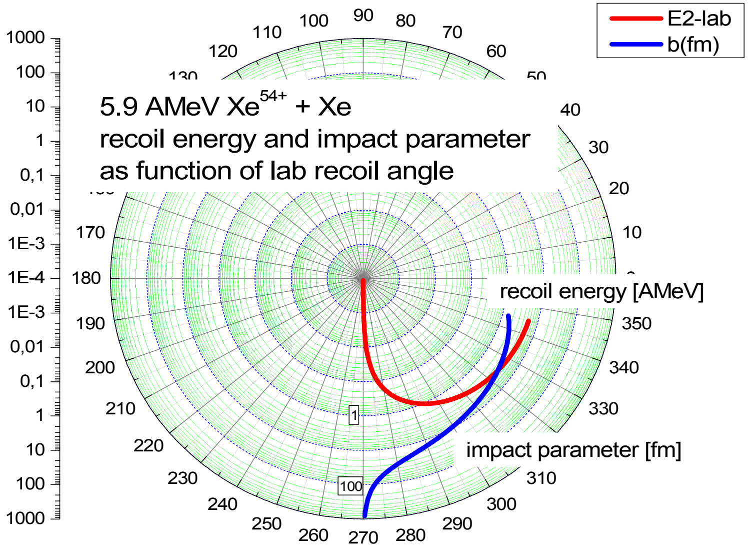
-transfer of both electrons: $P_{2\text{-electron}}=P^2$

(hyper-satellite Auger/ x-ray)

➔any deviation of experimental impact parameter dependence P(b) shows electron correlation as function of internuclear separation R

Kinematic considerations for relevant impact parameters: Shabayev: 100fm to 4000 fm





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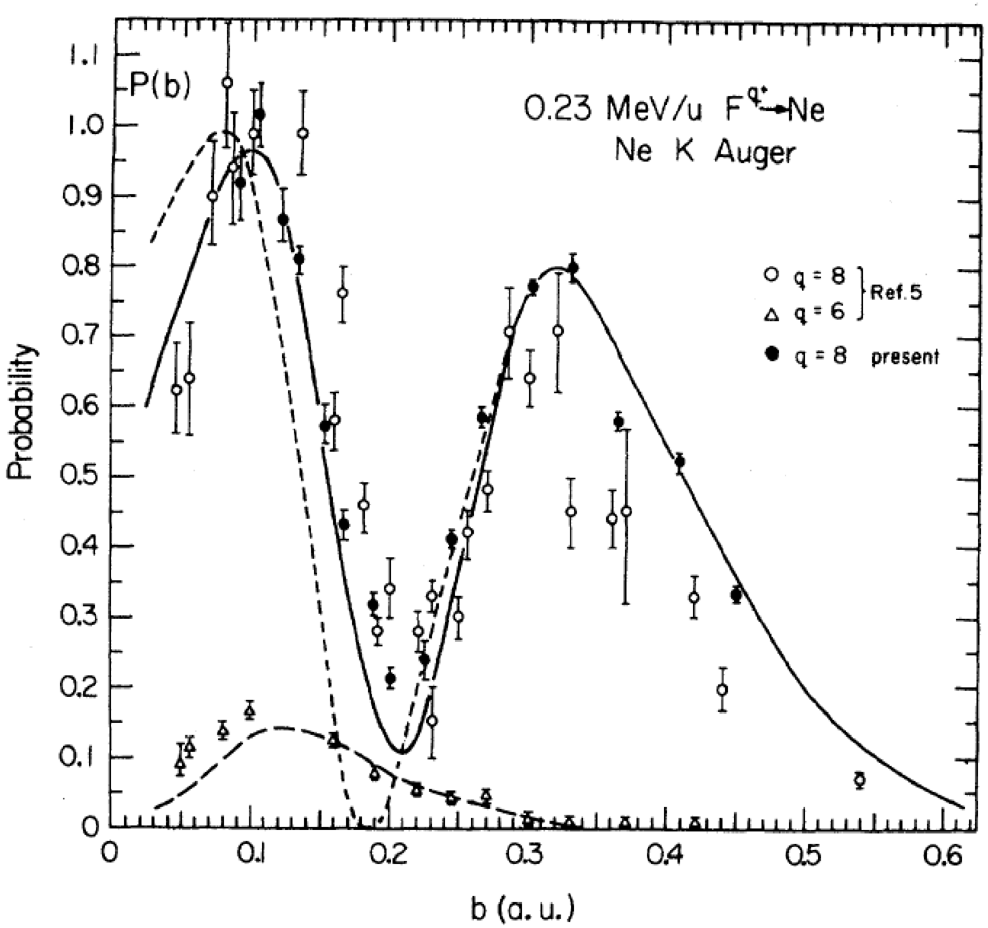
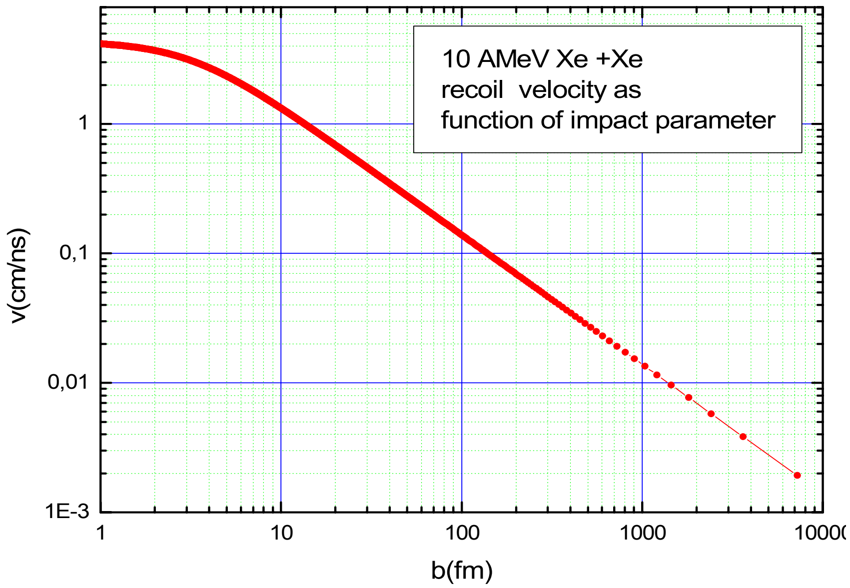
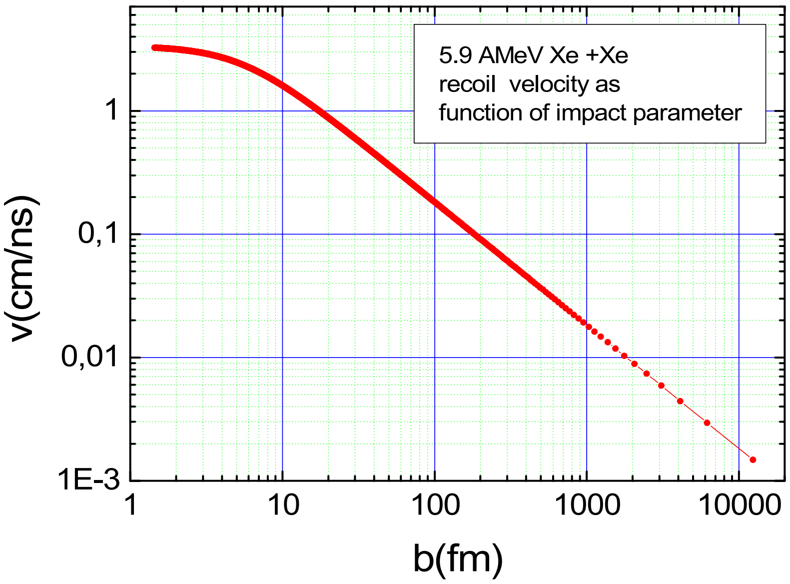

P(b)
0.23 MeV/u F^{q+}→Ne
Ne K Auger
○ q = 8 } Ref.5
△ q = 6 }
● q = 8 present
Probability
b (a.u.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
0
0.1
0.2
0.3
0.4
0.5
0.6


10 AMeV Xe +Xe
recoil velocity as
function of impact parameter
v(cm/ns)
1
0,1
0,01
1E-3
1
10
100
1000
1000
b(fm)


5.9 AMeV Xe +Xe
recoil velocity as
function of impact parameter
v(cm/ns)
1
0,1
0,01
1E-3
1
10
100
1000
10000
b(fm)

a) Atomic fragmentation and (multi)-electron **continua in target and projectile**

Strong perturbation q/v >1:

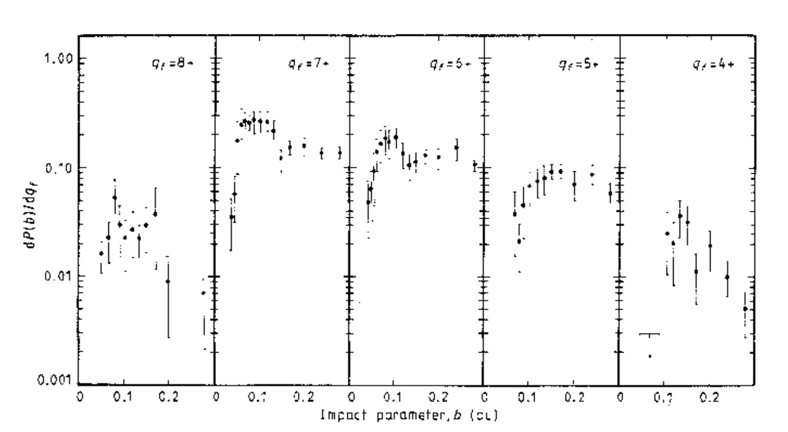
in projectile

0.5AMeV F^{8+}+Ne

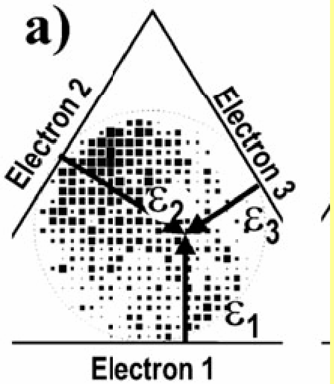
P(b) for electron capture to continuum (ECC) /multiple TI

in target

3.6AMeV Au^{53}+ Ne



Collective effects in ECC and transfer ionization (TI)
A. Skutlartz et al. J.Phys.B



J. Ullrich et al.
Rep.Pr.Phys.
66(2003)1463

Strong correlation in multi-electron continua: E_{kin} (e_1), E_{kin} (e_3) >> $E_{kin}(e_2)$

There are NO theoretical calculations for these multi-electron processes

(Multi)-electron continua in target and projectile: Dynamics of electron transfer

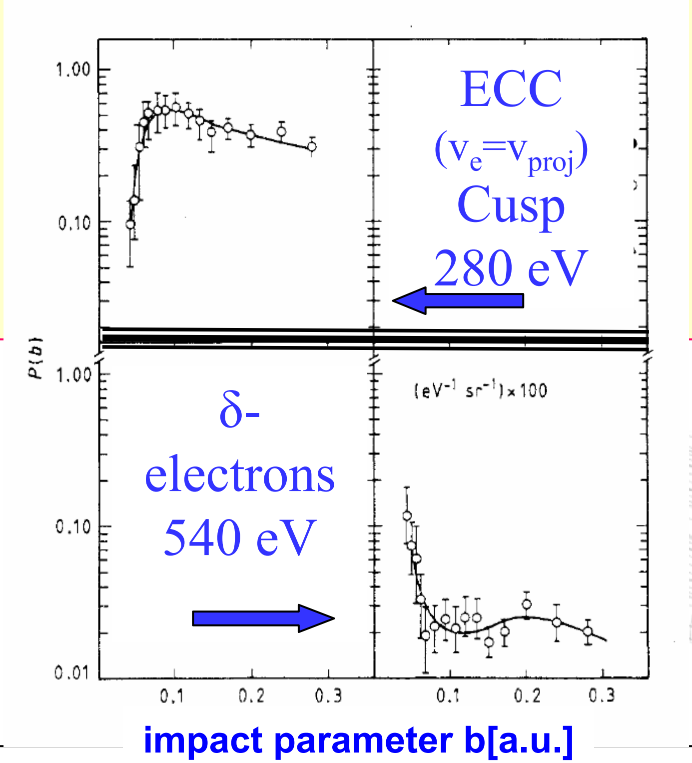
Strong perturbation q/v >1:

in projectile continua($\vec{v}_e \cong \vec{v}_{proj}$)

0.5AMeV F^{8+}+Ne ➔F(θ) + e_{cusp}

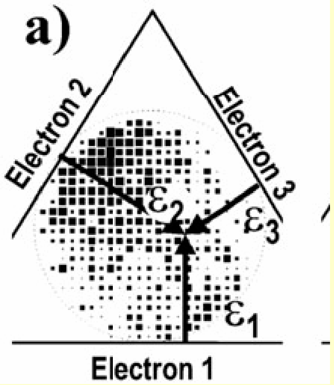
↑ coincidence ↑

P(b) ECC and 0^0 δ-electrons



in target continua (v_e«v_{proj})

3.6AMeV Au^{53}+ Ne



$\theta_1<\theta_2<\theta_3$

J. Ullrich et al.
Rep.Pr.Phys.
66(2003)1463

Strong correlation in multi-electron continua:

E_{kin} (e_1), E_{kin} (e_3) >> E_{kin}(e_2)

There are NO theoretical calculations for these multi-electron processes

a) (Multi)-electron continua in target and projectile:

topologically stable multi-electron transfer from target into projectile continuum

Strong perturbation q/v >1:

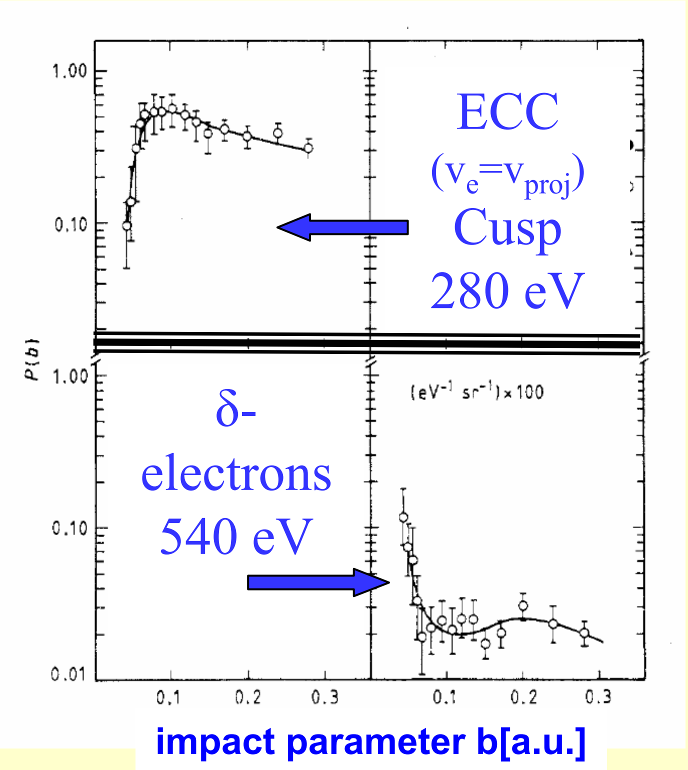
in projectile continua($\vec{v}_e \cong \vec{v}_{proj}$)

0.5AMeV F^{8+}+Ne ➔F**(θ)** + e_{cusp}

↑ coincidence ↑

P(b) ECC and 0^0 δ-electrons

P(multi-ECC)» P($1e^-$ ECC)



Cusp:
the fate of electrons does not emerge until 5000 a.u.
(J. Macek, C. Reinhold)

(this inhibited calculations for P(b) for ECC and TI to date)

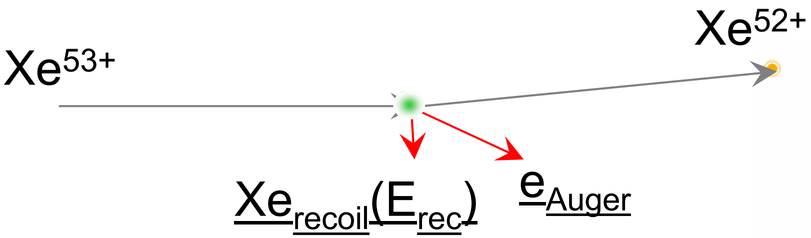
II. ESR target zone with reaction microscope with toroidal electron branch: simultaneous mapping of low to intermediate electron energies

$$Xe^{53+}(1s) + Xe \rightarrow Xe^{52+}(1s^2) + Xe^{n+}(1s)|_{E\text{-rec},\varphi\text{-rec}}$$

$$\downarrow$$

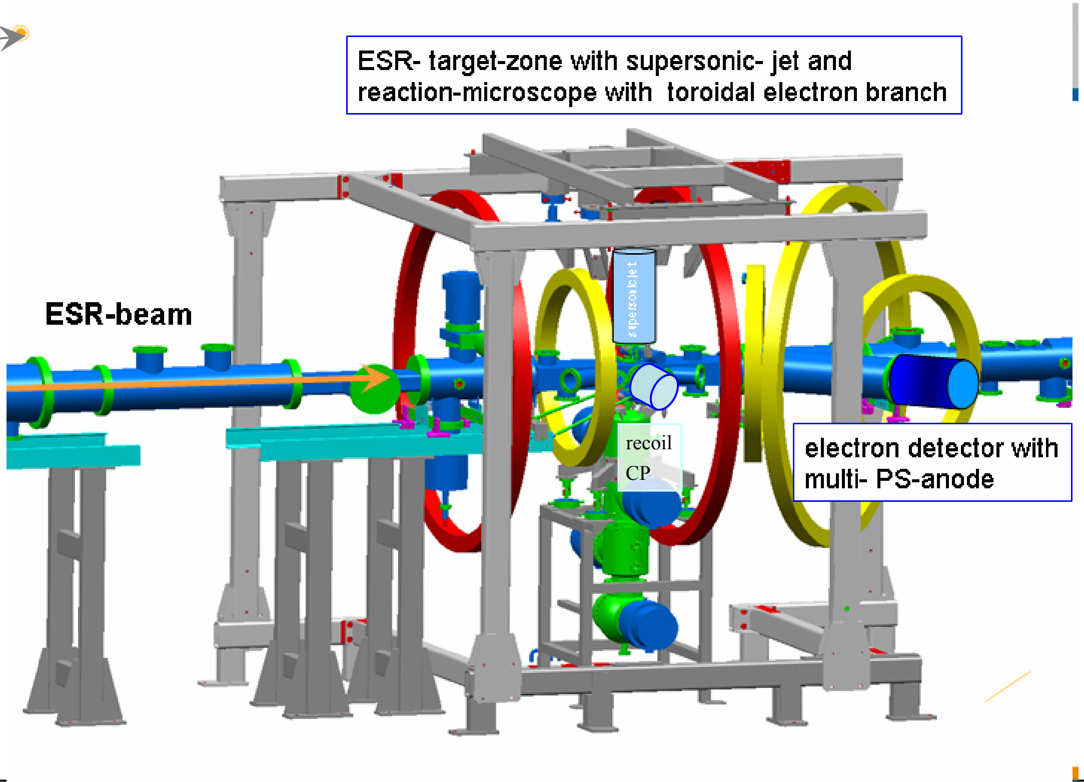
$$Xe^{(n+1)+}(1s^2) \quad + e_A(KLL)$$

↑ coincidence↑



The interesting impact parameter range can in the ESR only be covered by recoil ion TOF at near 90^0 recoil angle: 100ns to 2.2 μs for recoil TOF

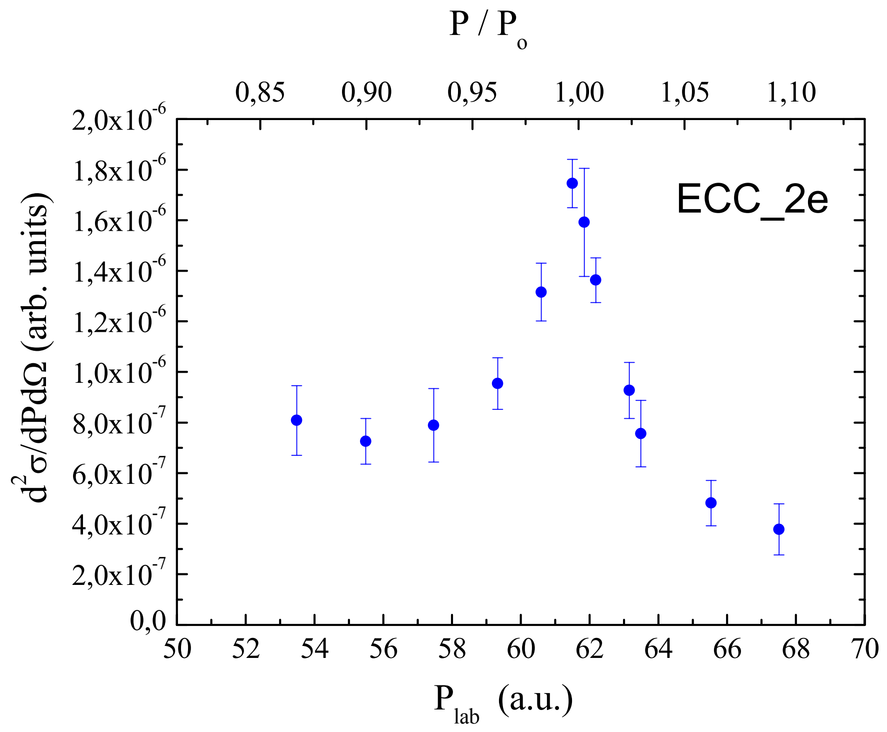
1s- ionization channel and 1s-1s resonant capture can be studied simultaneously



2-electron cusp ECC2

$$U^{88+}(1s^2 2s^2) + N_2 \rightarrow \underbrace{U^{87+}\,(1s^2 2s^2 2p) + \{N_2^{q+*}\} + e_{Cusp}}_{\text{coincidence}}$$

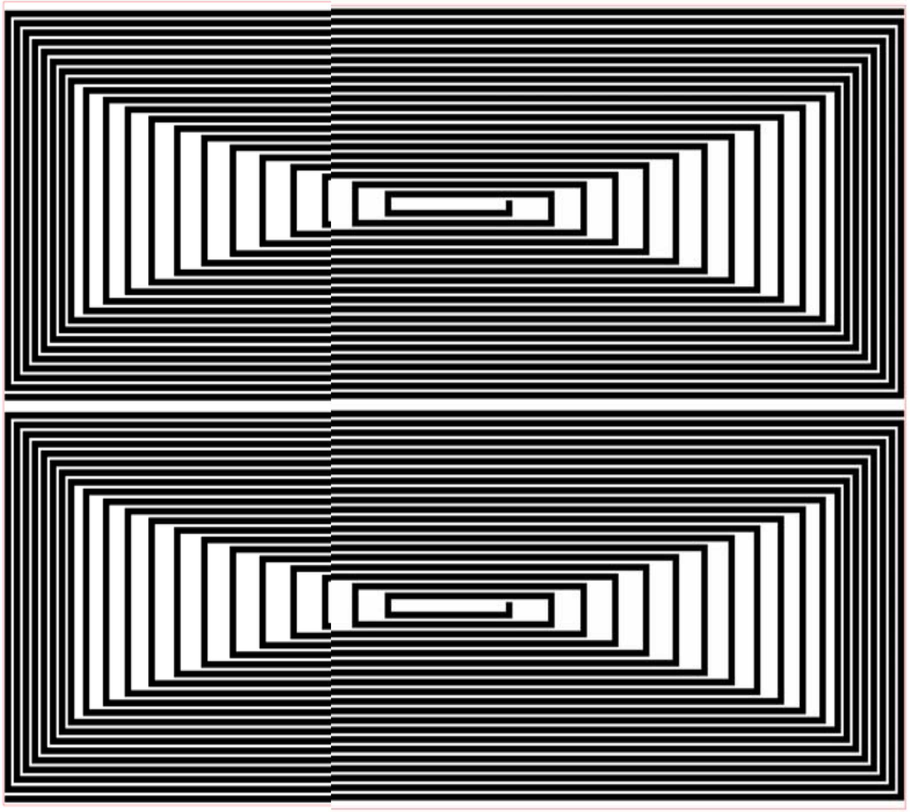
ECC2 2e-electron capture to bound **and** to continuum state of projectile



The non-radiative capture into projectile-continuum is accompanied by a simultaneous capture into a bound state of the projectile.

ECC2 and ECC have same-sense asymmetry on low-momentum side

ECC2 is NOT double-capture followed by autoionisation (AI produces symmetr.cusp)



Dynamics of electrons in transient high E-fields during heavy ion-atom collisions:

THEN: only high-Z beams with full K-shell – all vacancies are created around R_0,

i.e. only single pass probabilities for vacancy transfer at localized couplings between molecular orbitals

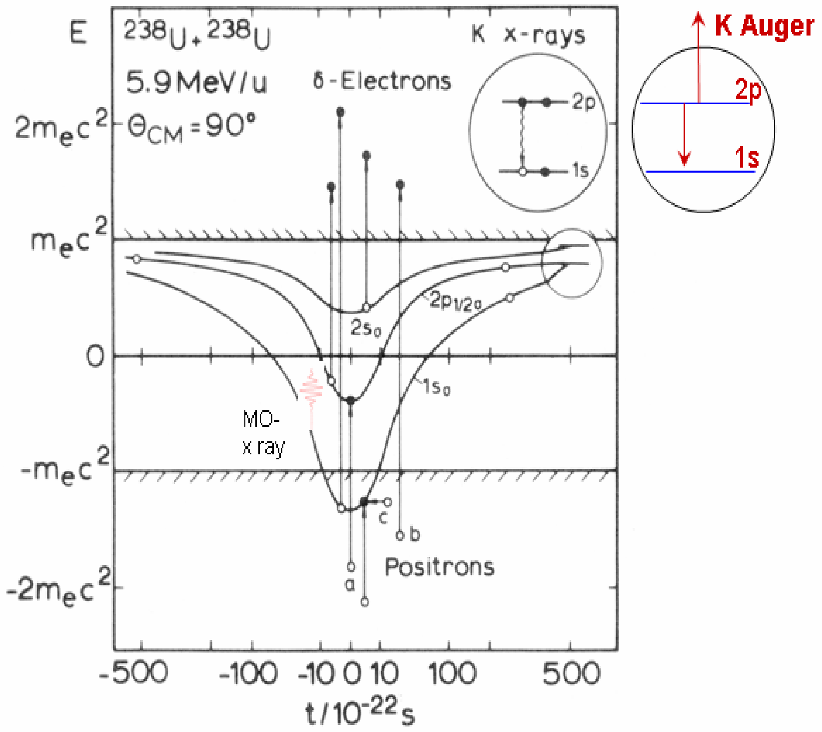
NOW:

bare and H-like decelerated HI-beams like $Xe^{53+,54+}$ and $U^{91+,92+}$ in ESR :

-huge enhancements in probability for deexcitation- permits use gas targets,

-unambiguous electronic configurations; (condition for high-res spectroscopy)

-appeareance of interference effects from two possible and indistinguishable path/MOs of e^- during collisions



Electron transfer into projectile continuum for $U^{88+}(1s^2 2s^2)$

OPEN CHANNELS for electron transfer into projectile continuum:

$$U^{88+} + N_2 \rightarrow \underbrace{U^{89+}(1s^2 2s^1) + \{N_2^{+*}\} + e^-_{Cusp}}_{\text{Coinc.}}$$

ELC electron loss to continuum

(nearly symmetric cusp)

$$\rightarrow U^{88+}(1s^2 2s^2) + \{N_2^{+*}\} + e^-_{Cusp}$$

ECC electron capture to continuum

$$\rightarrow U^{88+}(1s^2 2s^2) + \{N_2^{+*}\} + \underbrace{e^-_{Cusp} + h\nu}_{\text{Coinc.}}$$

RECC radiative electron capture to continuum

$$\rightarrow \underbrace{U^{87+}(1s^2 2s^2 2p) + \{N_2^{q+*}\} + e^-_{Cusp}}_{\text{Coinc.}}$$

ECC2 2e-electron capture to bound and to continuum

Electron transfer into projectile continuum for heavy multi-electron $A^{q+}(1s^2 2s^2)$

OPEN CHANNELS for electron transfer into projectile continuum:

$$A^{q+} + He \rightarrow A^{(q+1)+}(1s^2\underbrace{2s^1) + \{He^{+*}\} + e^-_{Cusp}}_{\text{Coinc.}}$$

ELC electron loss to continuum

(nearly symmetric cusp)

$$\rightarrow A^{q+}(1s^2 2s^2) + \{He^{+*}\} + e^-_{Cusp}$$

ECC electron capture to continuum

$$\rightarrow A^{q+}(1s^2 2s^2) + \{He^{+*}\} + \underbrace{e^-_{Cusp} + h\nu}_{\text{Coinc.}}$$

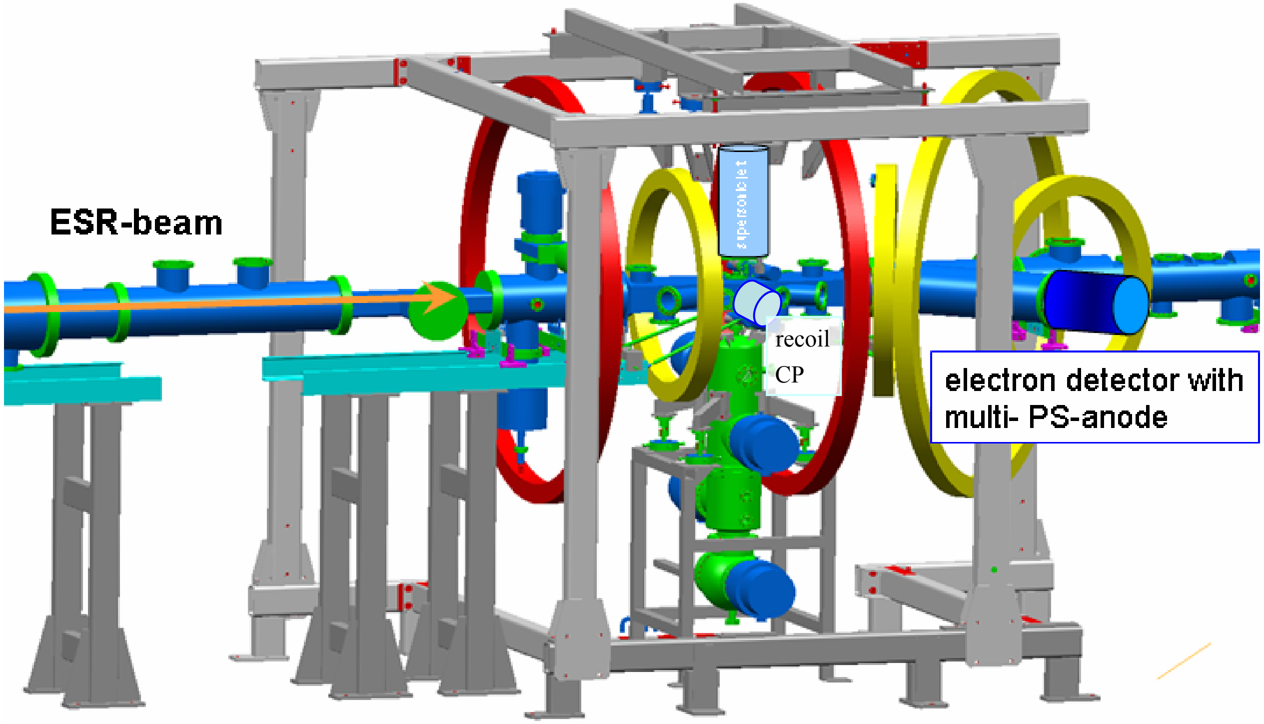
RECC radiative electron capture to continuum

$$\rightarrow A^{(q-1)+}(1s^2\underbrace{2s^2 2p) + \{He^{q+*}\} + e^-_{Cusp}}_{\text{Coinc.}}$$

ECC2 2e-electron capture to bound + to continuum

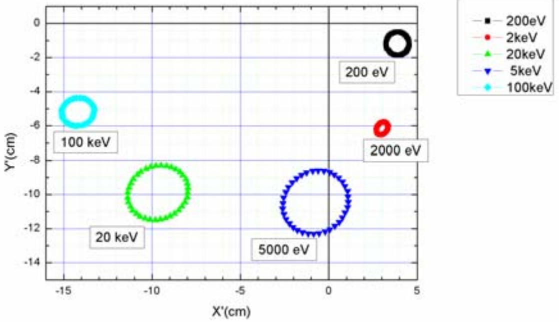
II. ESR target zone with reaction microscope with toroidal electron branch: simultaneous mapping of low to intermediate electron energies

ESR- target-zone with supersonic- jet and reaction-microscope with toroidal electron branch



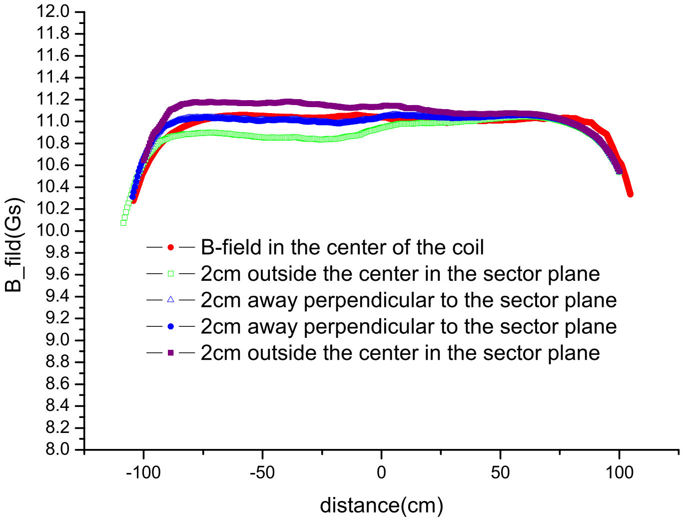
electron detector with multi- PS-anode

electrons in PSD plane



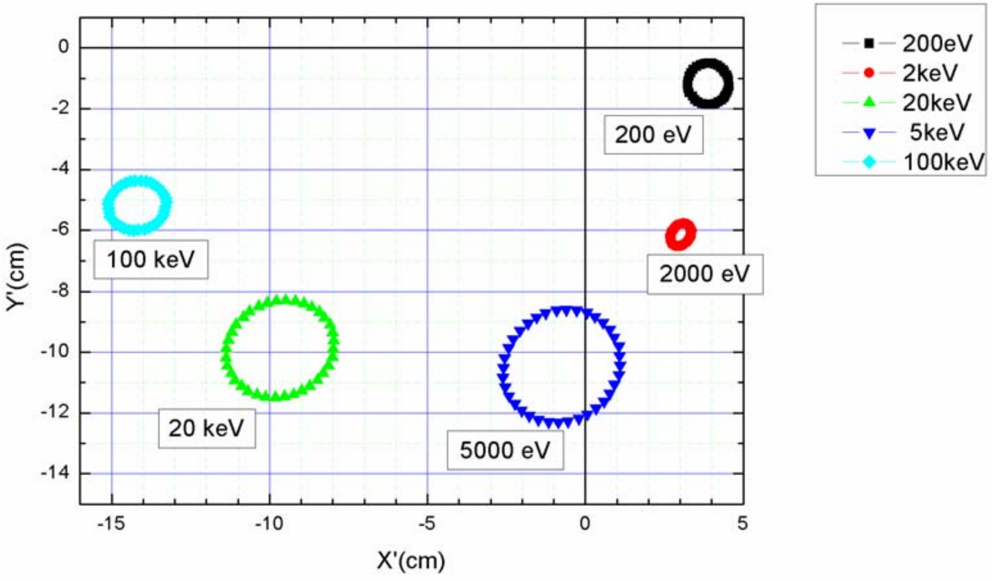
1s- ionization channel and 1s-1s capture can be studied simultaneously

Toroidal electron branch for a longitudinal reaction microscope: OPERA optics calculation



Magnitude of magnetic B field for selected trajectories around the central ray

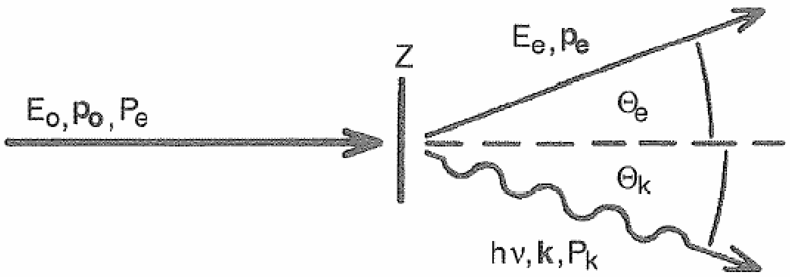
Location of fast and slow electrons on e$^-$ - detectors at end of toroidal sector

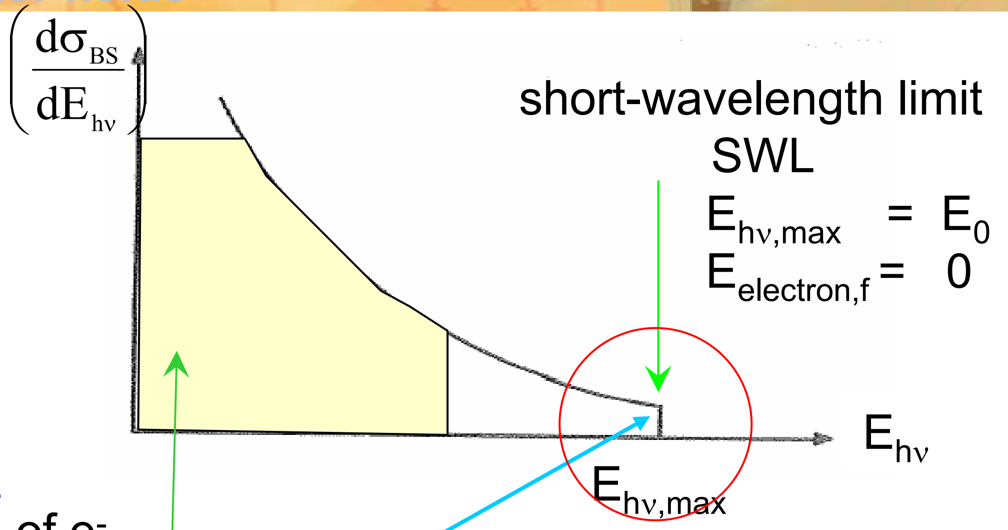


View from back onto electron detector

III. Electron-nucleus bremsstrahlung:

consequence of general coupling of e-m fields and matter fields





short-wavelength limit
SWL
$E_{h\nu,max} = E_0$
$E_{electron,f} = 0$

Quantum mechanical bremsstrahlung

i) Radiative process involves coupling of e^- and e-m field: p(radiation) ~α

$\sigma_{BS} \sim \alpha * \sigma_{el.scatt.}$

ii) Radiation spectrum has high-frequency limit,

Differential Cross Section ≠ 0

at SWL tip only for Coulomb case

(for screened atom $DCS|_{SWL}=0$)

iii) Test of equivalence of

$DCS(BS)|_{SWL}$ ~DCS(photoionization)

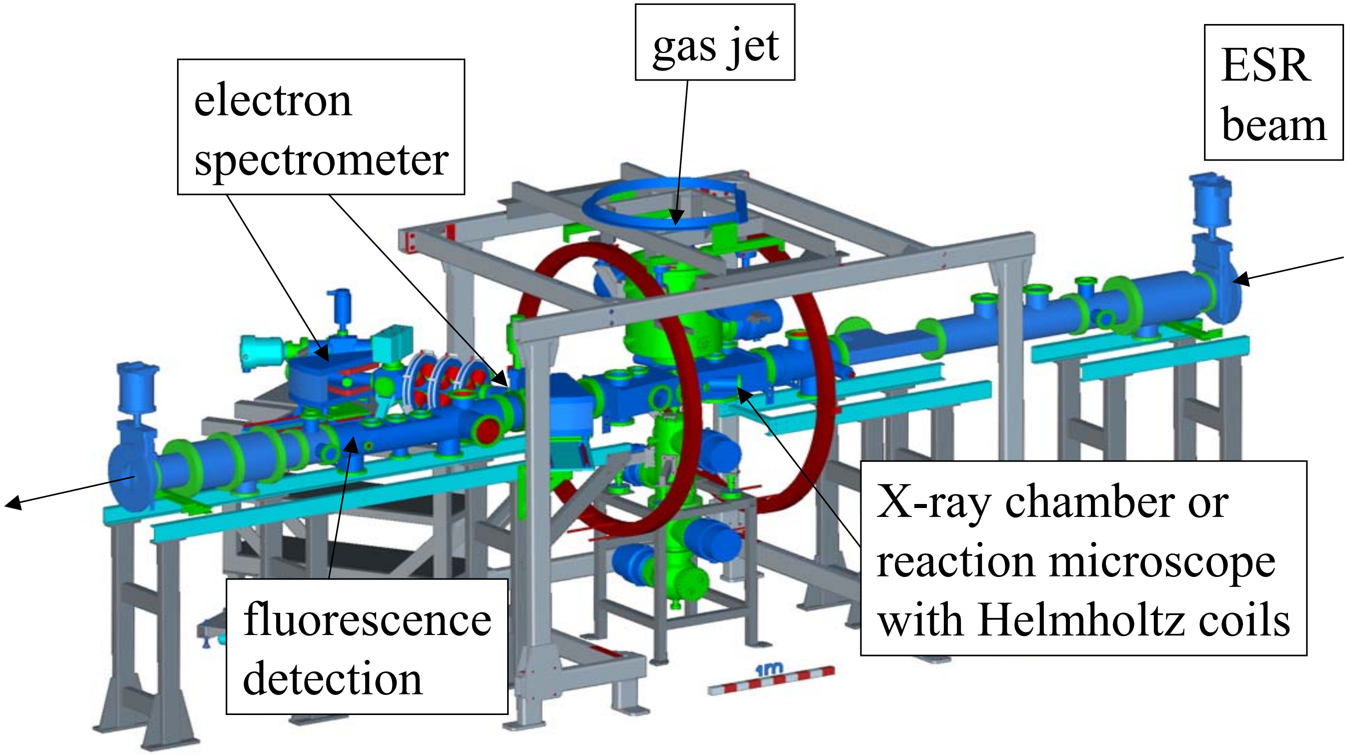
U. Fano, R. Pratt

$e^-(E_0) + A \rightarrow e^-(E_e\,;\theta_e) + h\nu(E_x;\theta_k) + A$

↑coincidence↑

- kinematically complete experiments can be performed only in long- and medium wavelength range of x rays, not in theoretically interesting short-wave length limit

II. Internal Target Area at the ESR with forward electron spectrometer



Electron spectrometer shall allow to reconstruct primordial electron momenta i.e. scattering plane