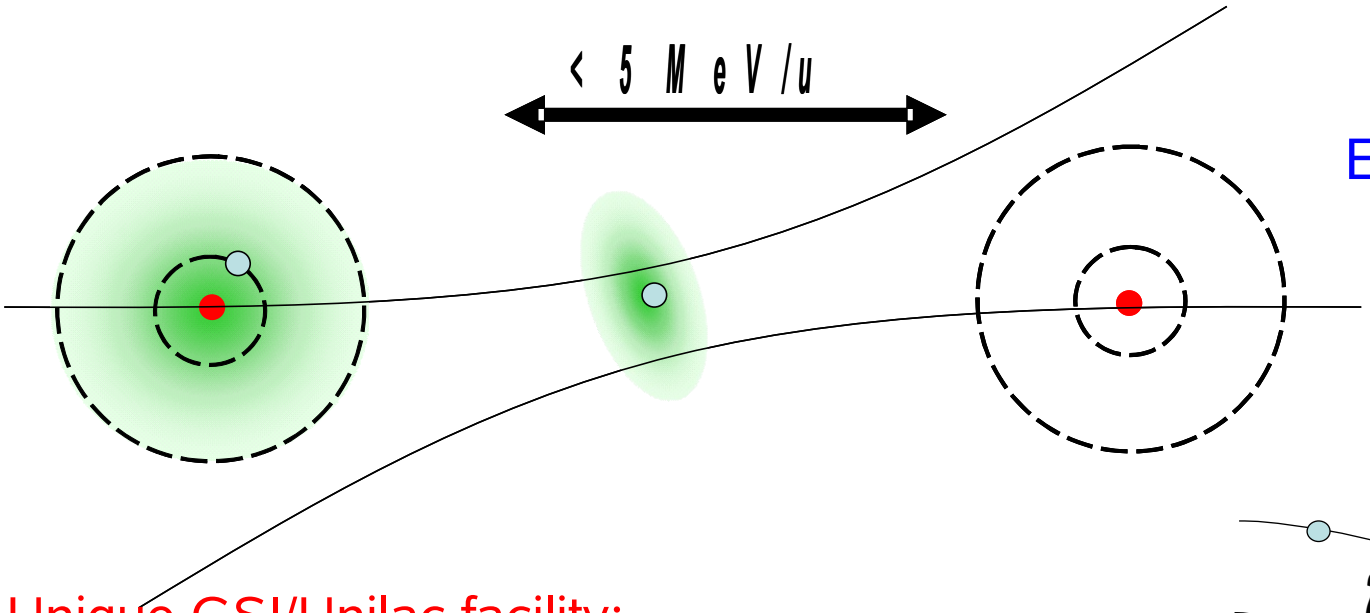
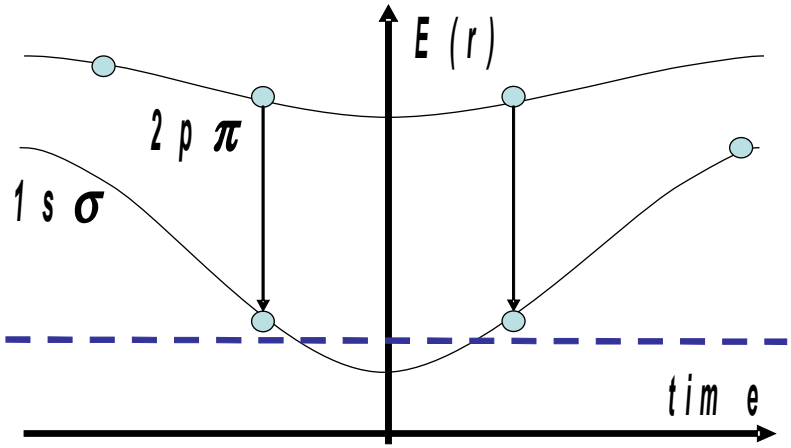
Quasimolecular radiation in heavy-ion collisions

-- Two-center description

S. Fritzsche
FIAS Frankfurt & GSI Darmstadt
18th July 2008



Experiments 1977-1981



Unique GSI/Unilac facility:

- (super-) strong em-fields
- $Z_{united} = Z_1 + Z_2 \sim$ 170..180, i.e. for $Z\alpha > 1$
- collision times 10^{-19} .. 10^{-21} s
- extremly short-lived superheavy „quasimolecules“
- closest approach < 150 fm as typical for K-shell

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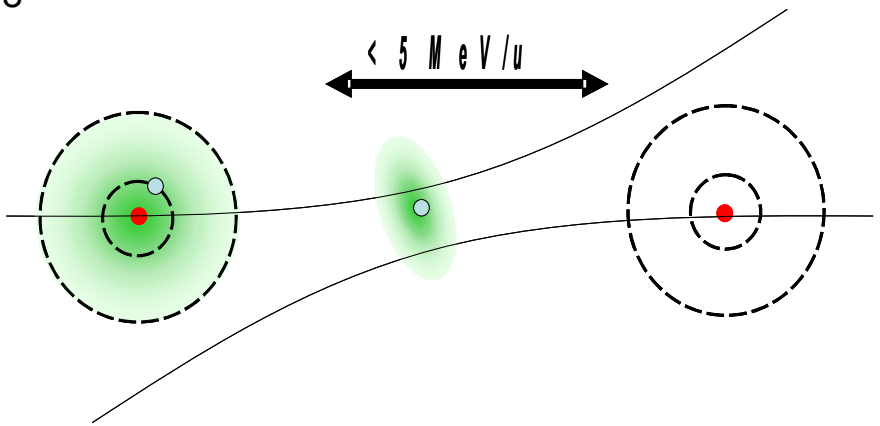
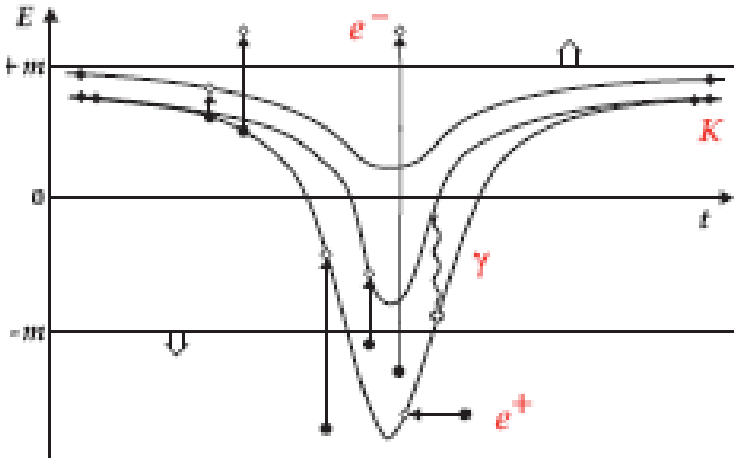
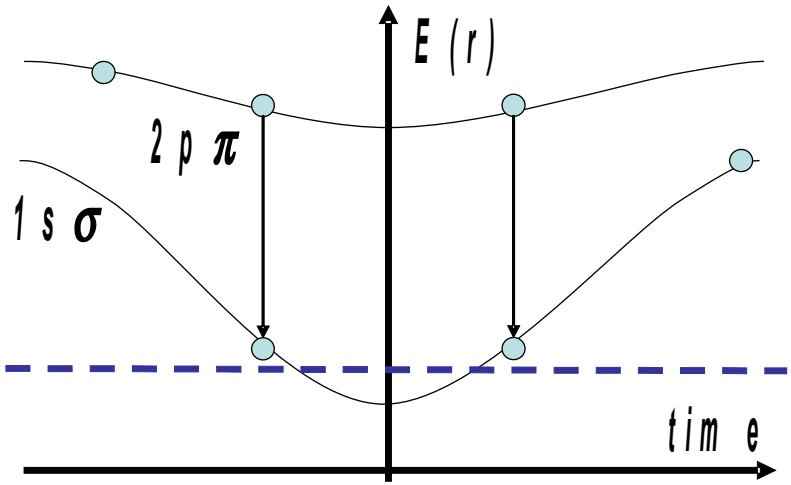


Creation of `positrons'

- spontaneous
- dynamical pairs (em field)
- induced by nuclear processes





Quasimolecular radiation in heavy-ion collisions

-- Two-center description

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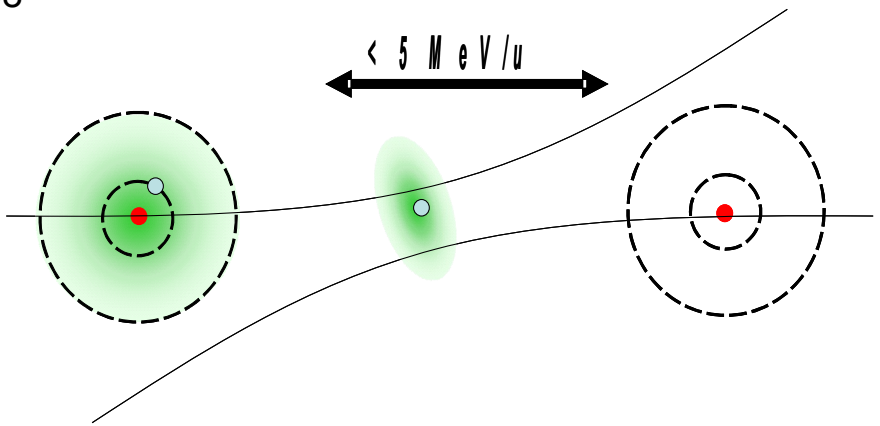


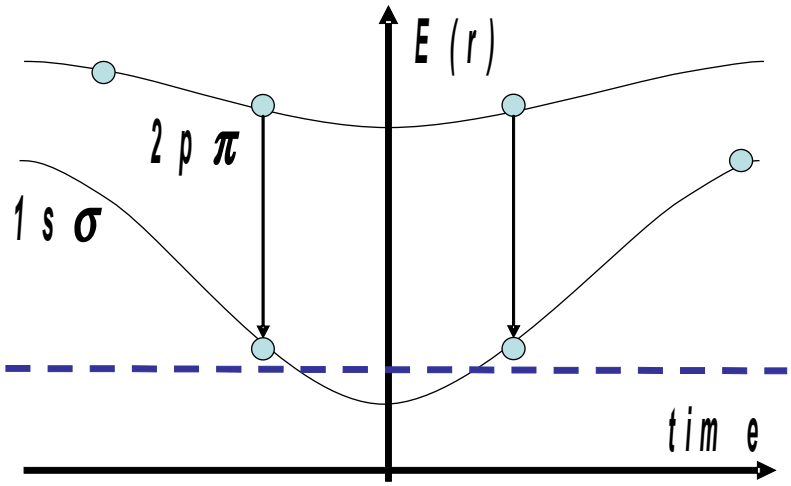
Outline of this talk:

i) Origin of quasi-molecular radiation

ii) Formation of super-heavy quasimolecules

iii) Adiabatic two-center description

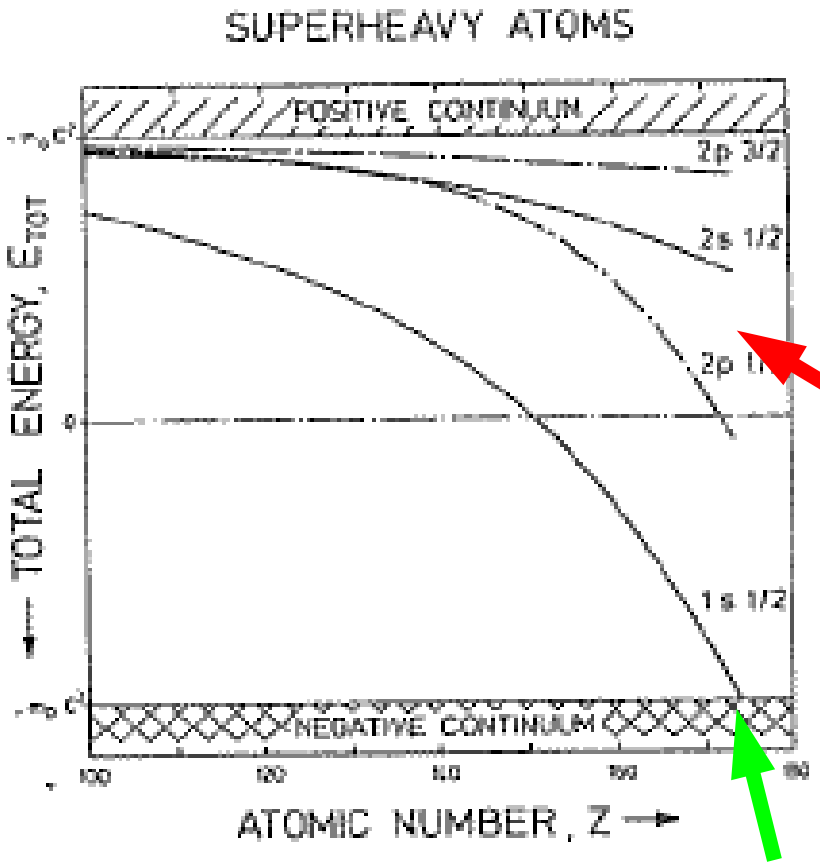
iv) Challenges and future chances



Thanks to: D. Liesen, F. Bosch & B. Fricke

Supercritical „static“ fields for atoms (I)

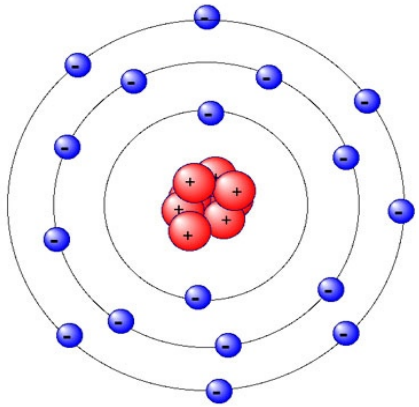
-- Relativistic motion and atomic notations



Fricke & Soff (1977)

strong spin-orbit splitting;
swapped `level order'

Z~ 173



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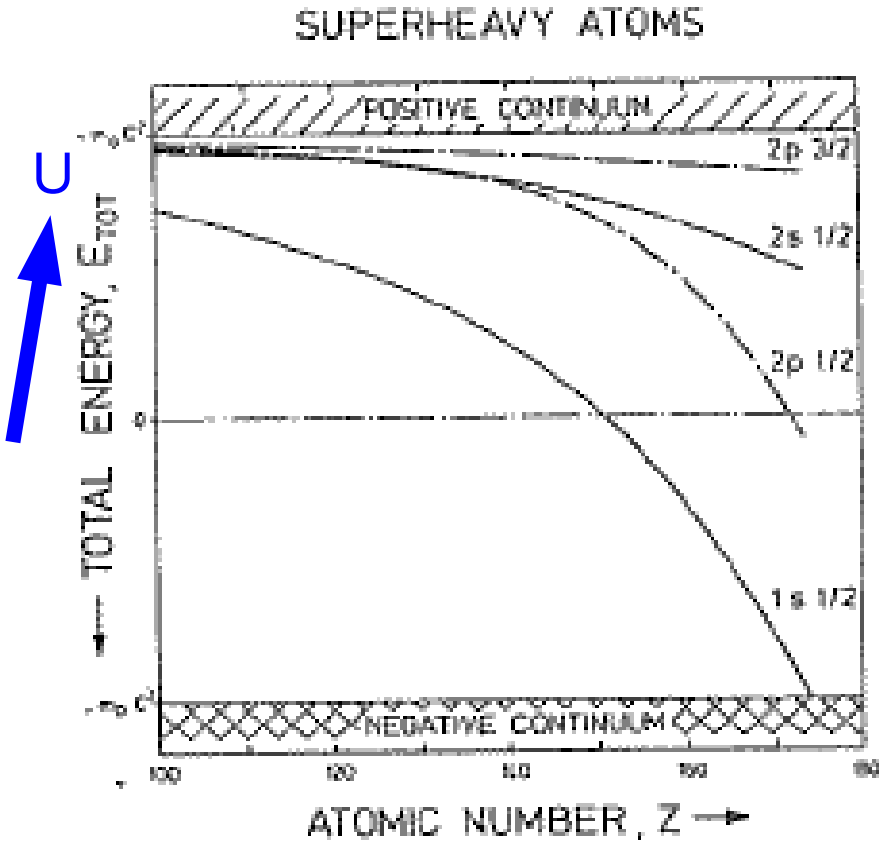

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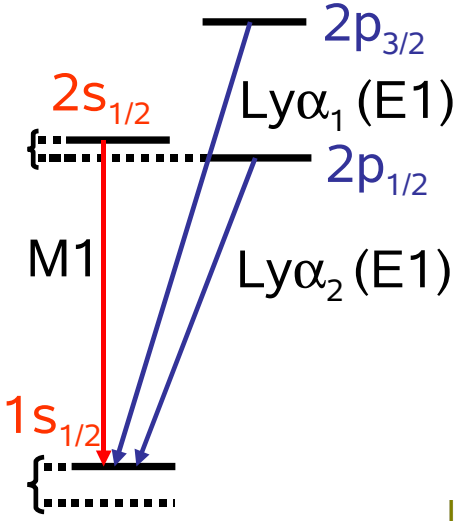
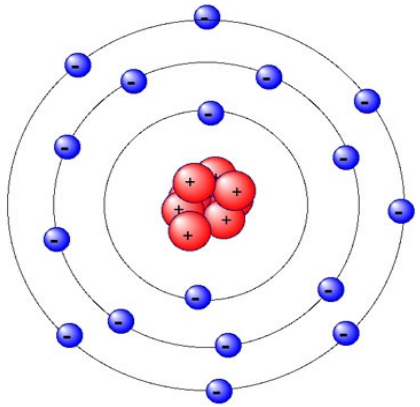
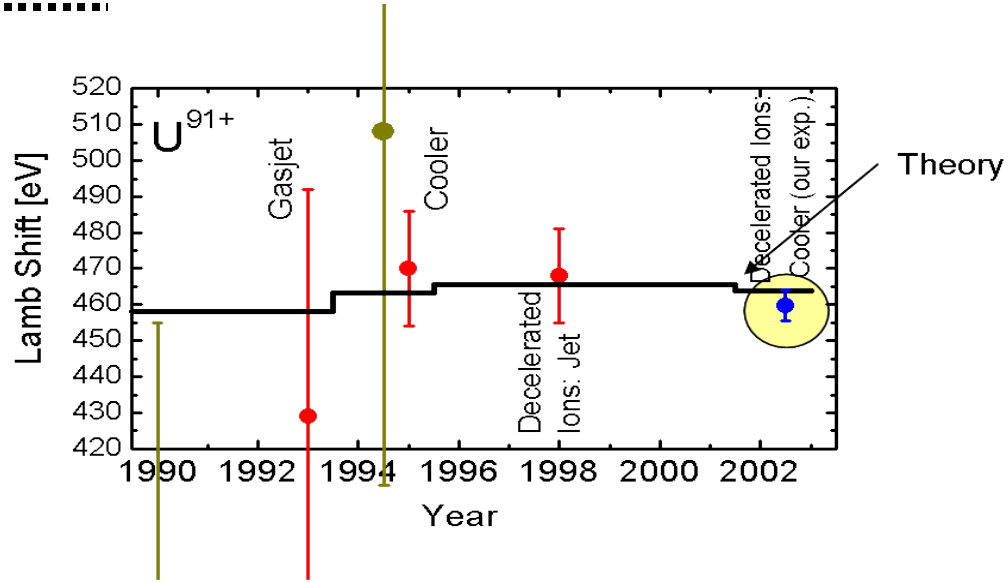
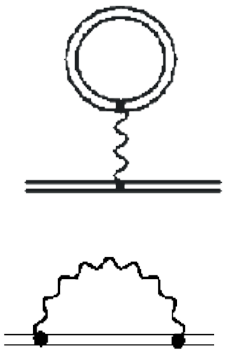






Main QED contributions:

- Electron self-energy (SE)
- Vacuum polarization (VP)
- Finite-size effects (FS)
- Higher-order contributions



Supercritical „static“ fields for atoms (II)

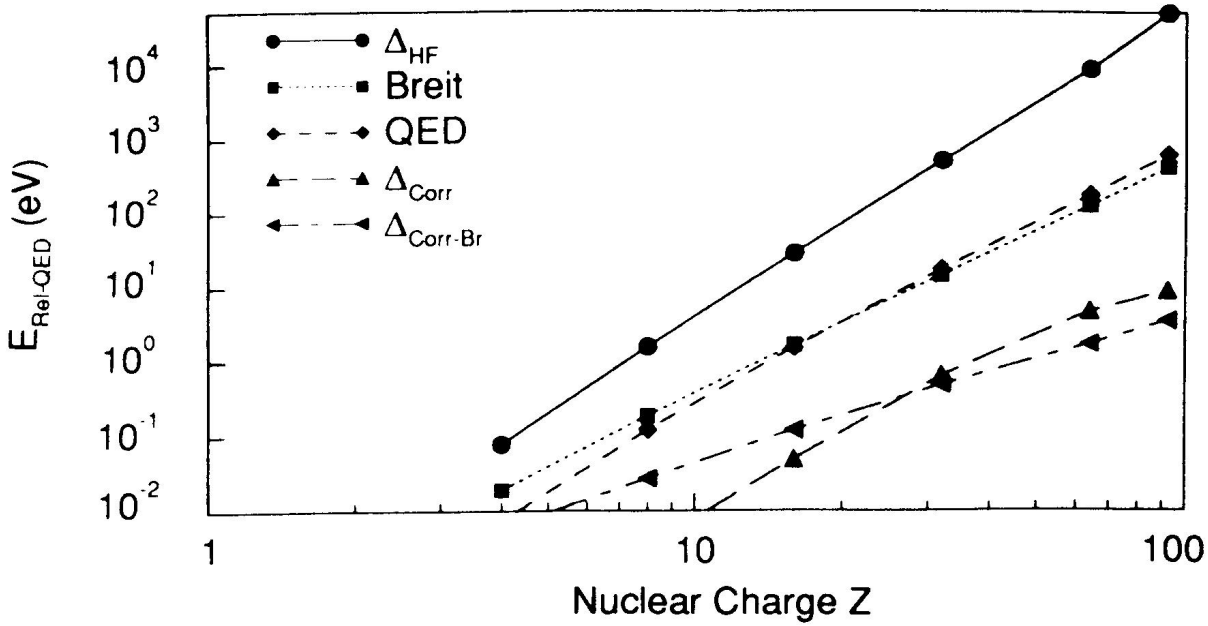
-- Relativistic motion and atomic notations

„Dirac see“ is visible in different properties

- energies
- transition probabilities (M1, ...)
- x-ray emission (angles & polarization)
- ...

Relativistic and correlation contributions to the ground-state energy of Be-like ions

W. R. Johnson (1994)



Supercritical „static“ fields for atoms (II)

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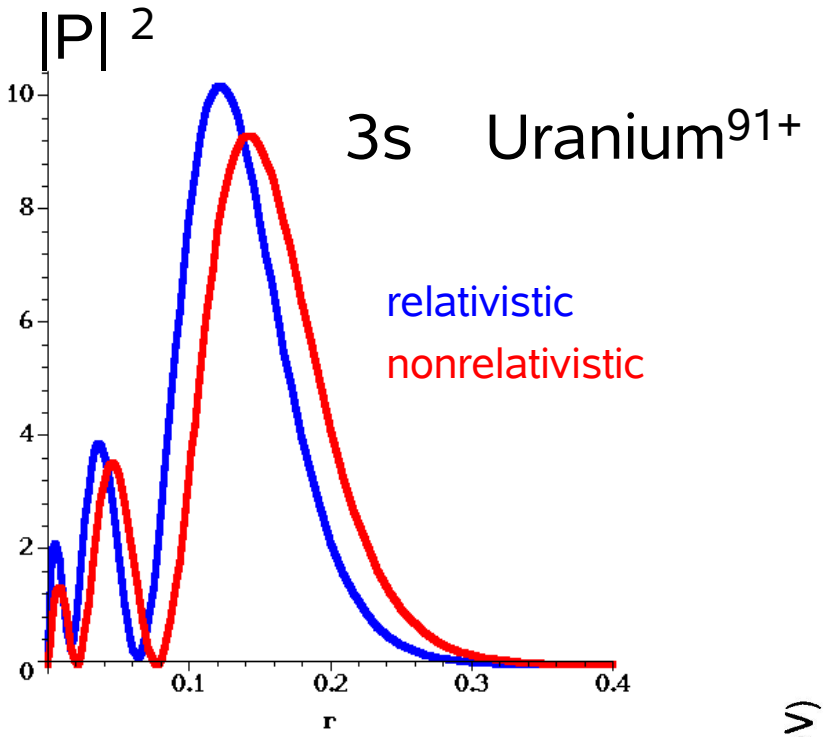

Relativistic contraction
of the wave functions

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Relativistic and correlation contributions to
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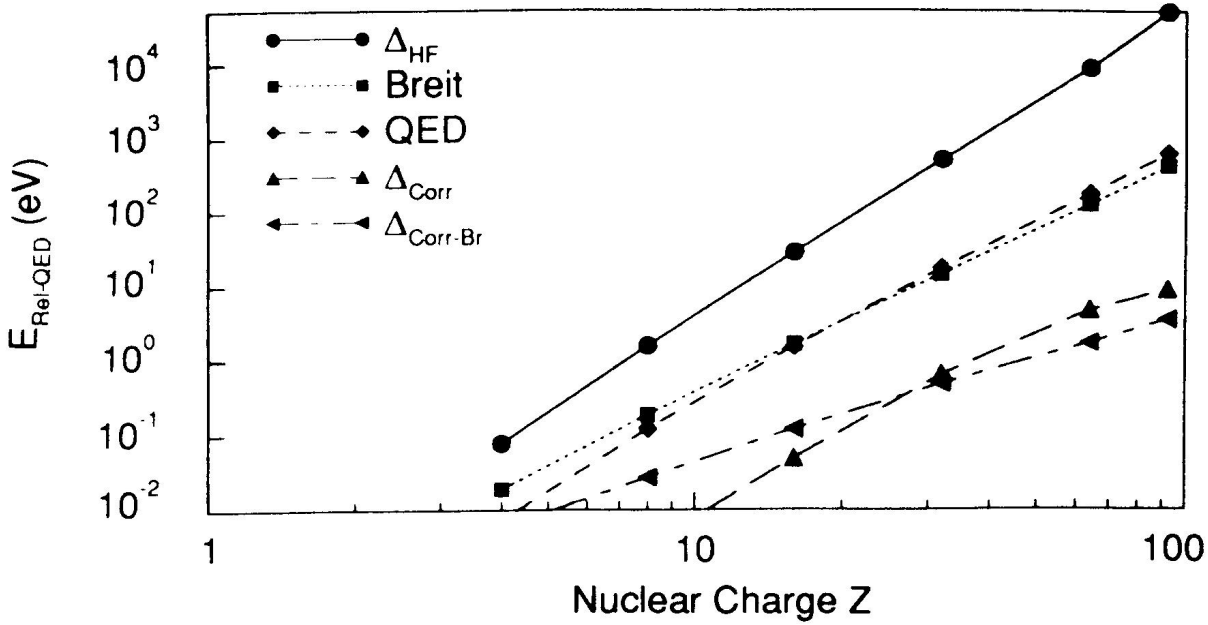

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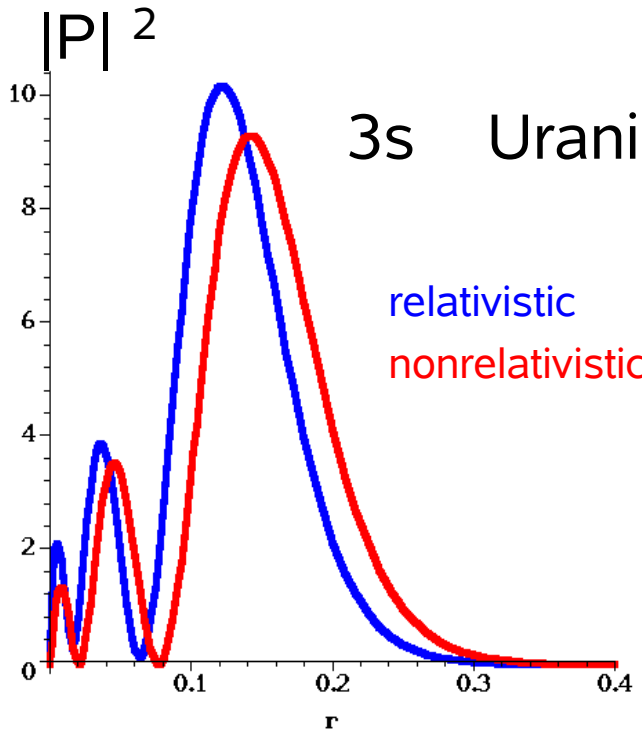
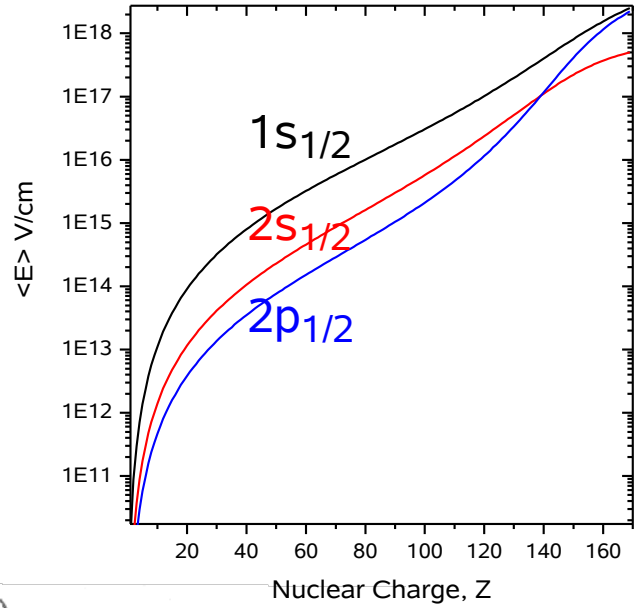
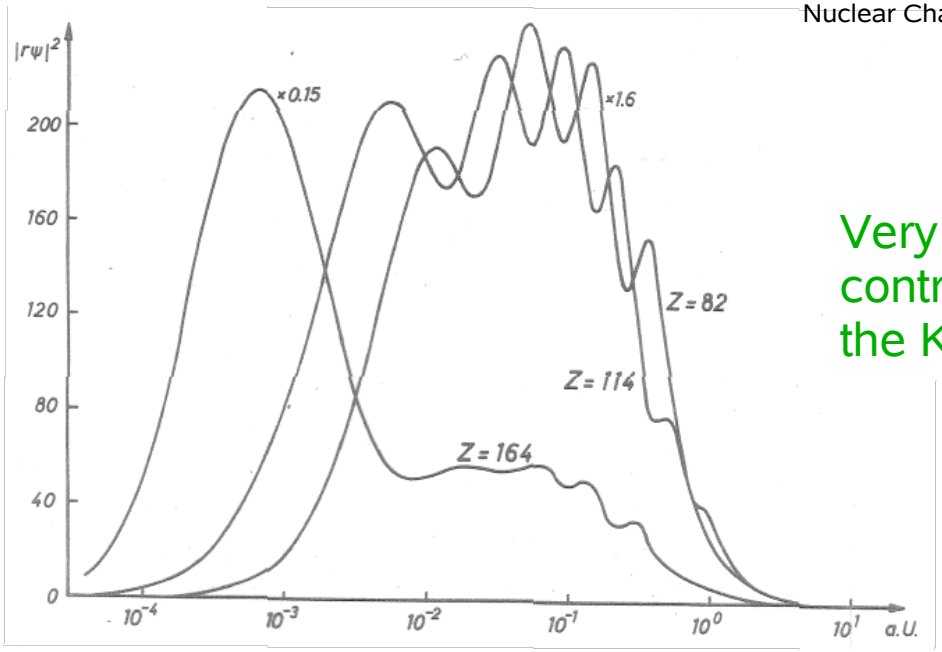


Relativistic contraction of the wave functions

Shrinkage of the electron density due to the Dirac operator.



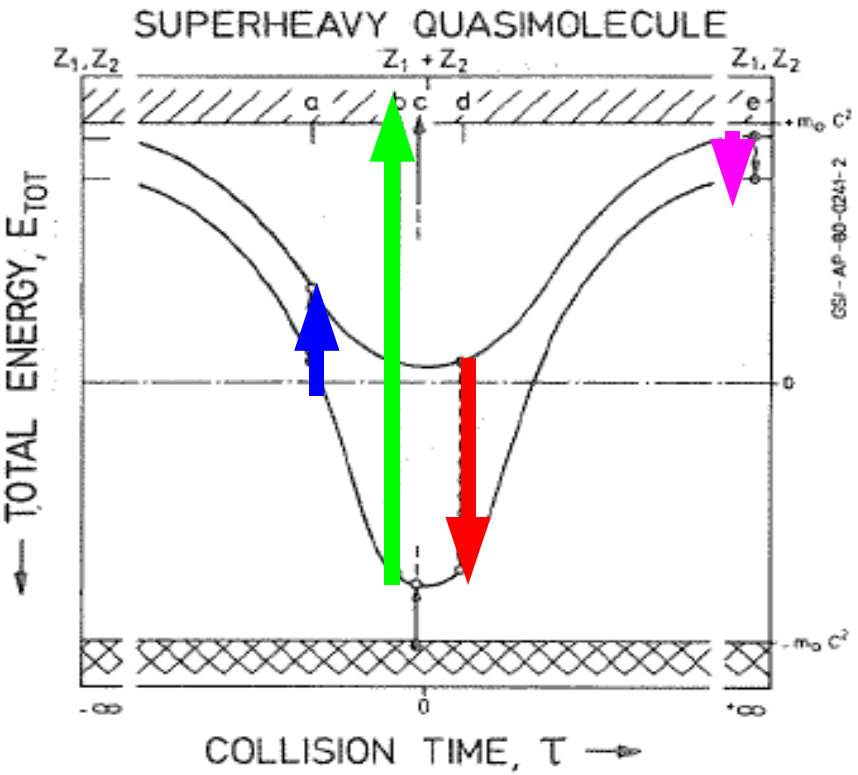


Very strong contraction for the K-shell

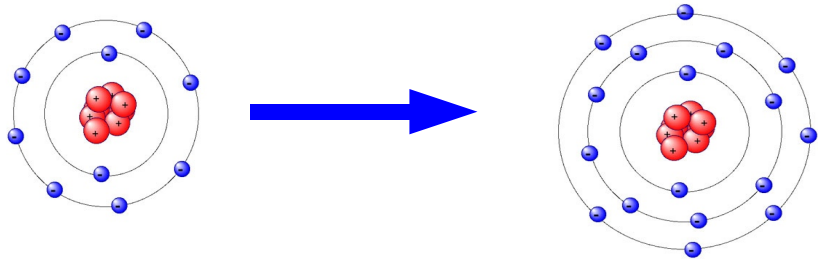
Fricke (1972)

Origin of quasi-molecular radiation (I)

-- Elementary processes and notations



Mokler & Liesen (1982)



multiple charged ion

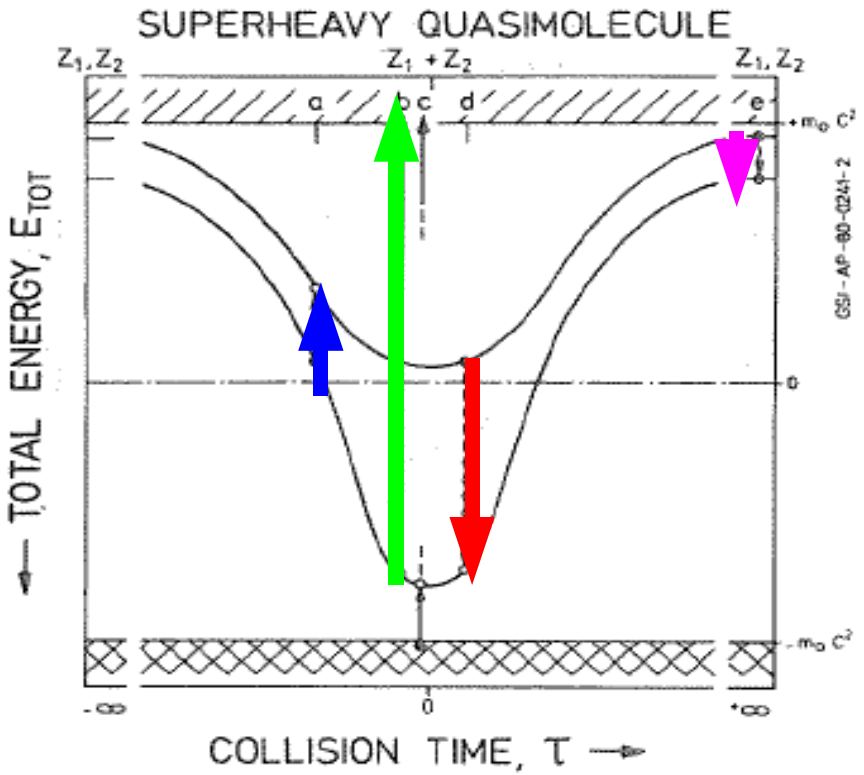
neutral target

Processes during the collision:

- excitation into higher shells
- ionization (δ-electrons)
- MO radiation
- characteristic x-rays

Origin of quasi-molecular radiation (I)

-- Elementary processes and notations



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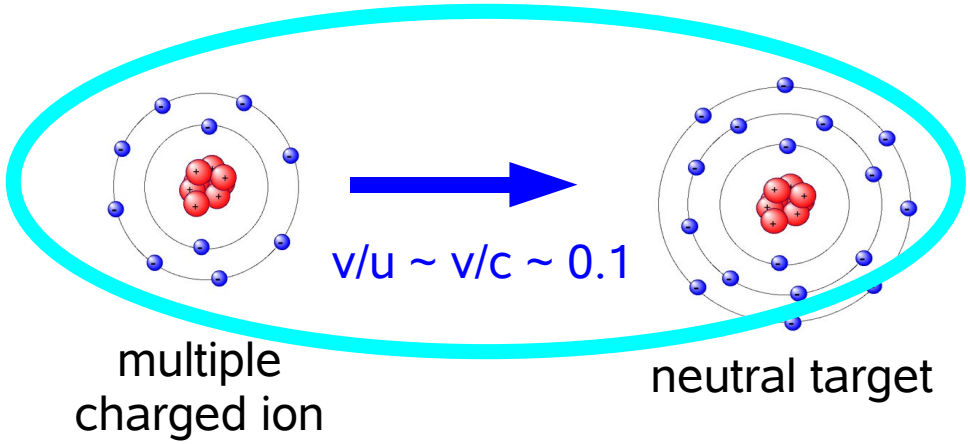

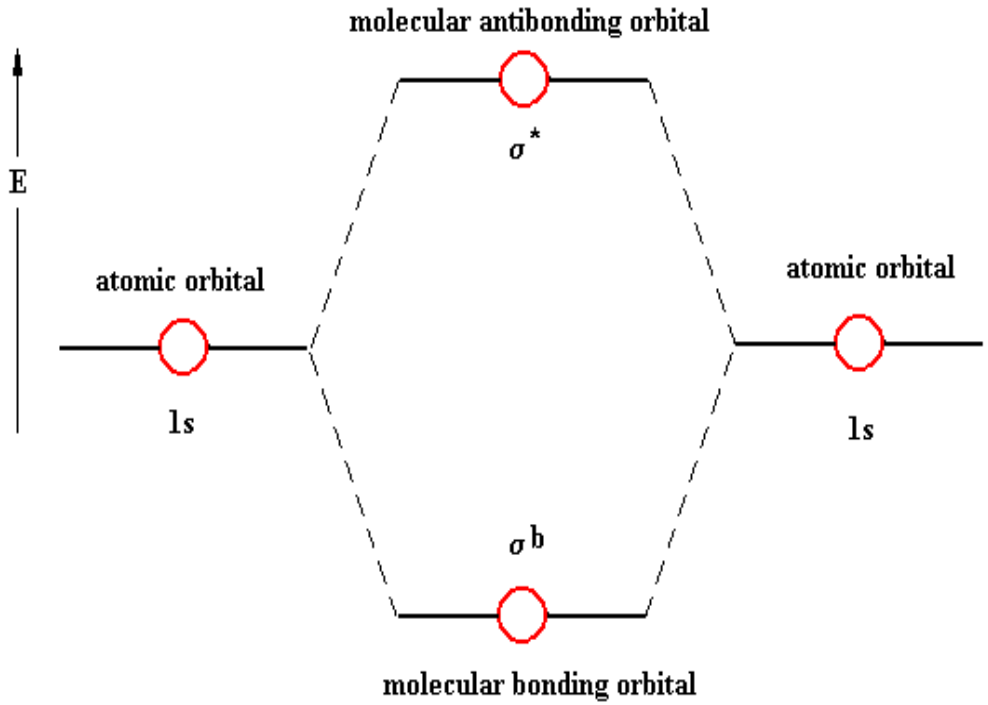

Processes during the collision:

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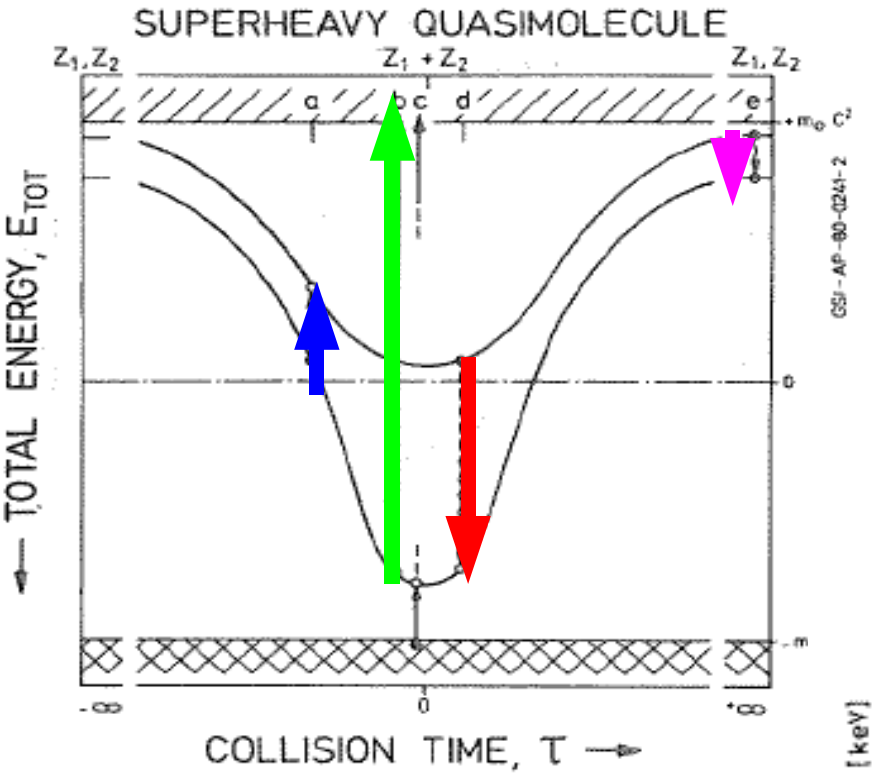
Origin of quasi-molecular radiation (II)

-- Quasistationary approach



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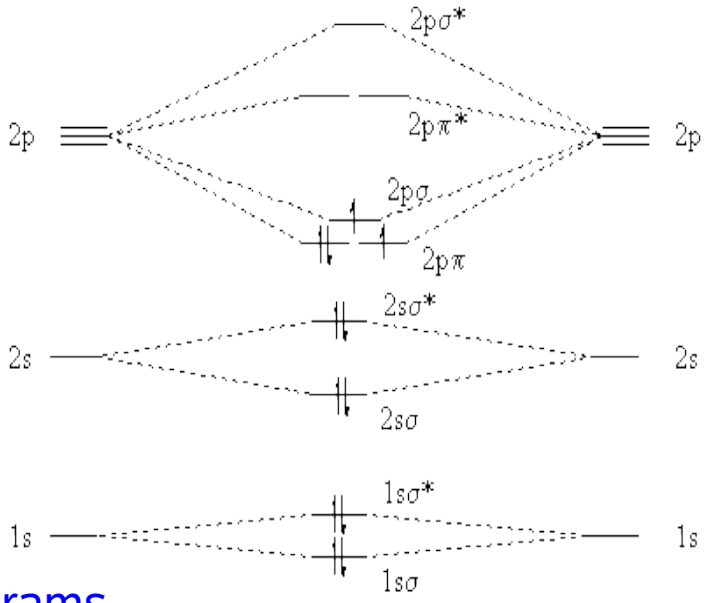
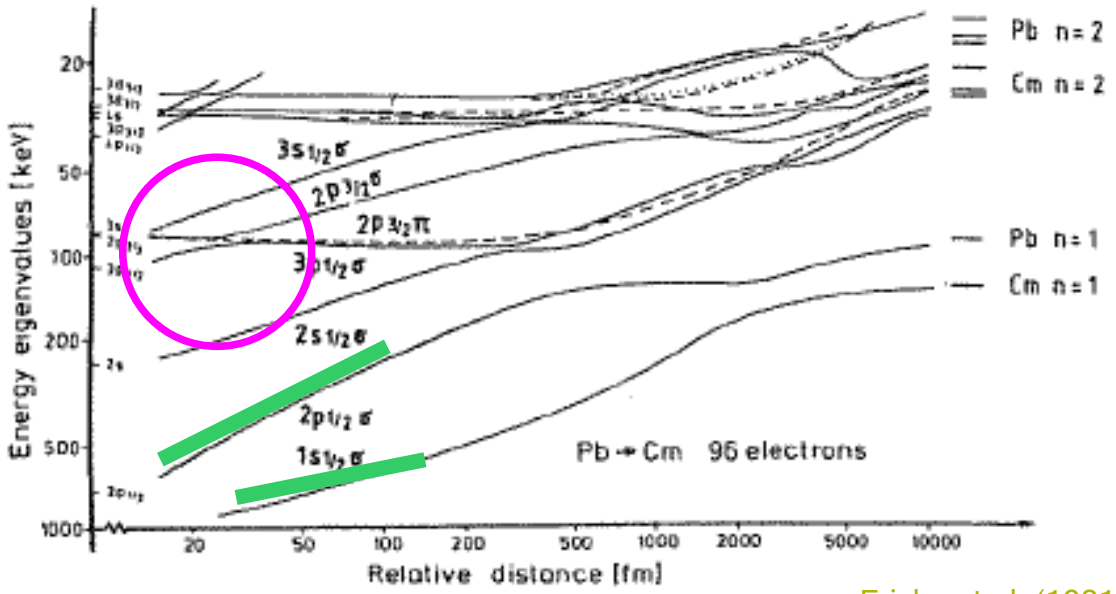


Correlation diagrams



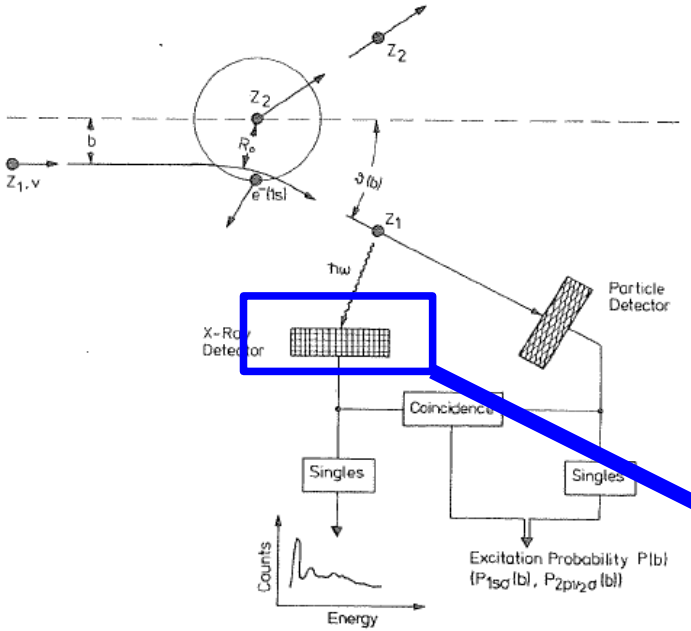
Fricke et al. (1981)

Two further relativistic effects:

- Deepest bound levels ($1s\sigma$, $2p_{1/2}\sigma$, ...) are not „flat“ at small R.
- Further levels crossings at small R that modify the inner-shell excitation.

Formation of super-heavy quasimolecules

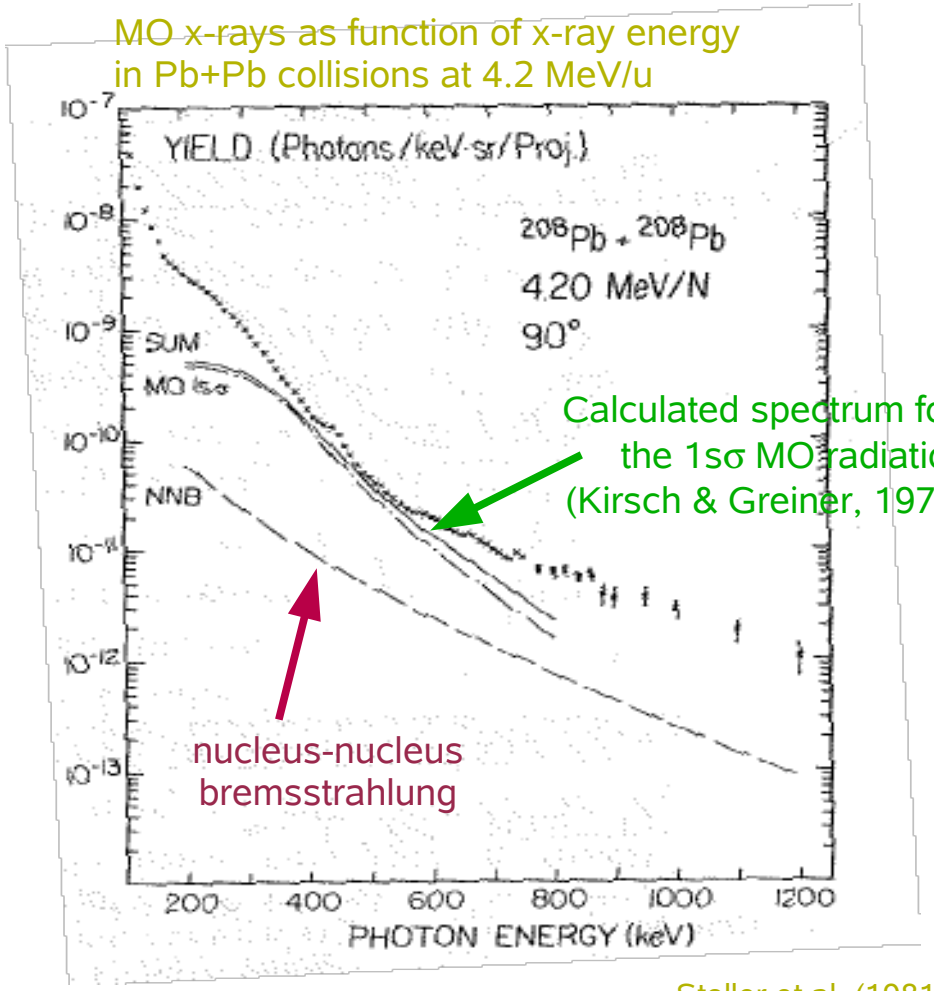
-- Previous ion-atom collisions



Pb + Pb (subcritical, Z = 164)

Pb + Cm (supercritical, Z = 178)

MO x-rays as function of x-ray energy in Pb+Pb collisions at 4.2 MeV/u



Stoller et al. (1981)

Formation of super-heavy quasimolecules

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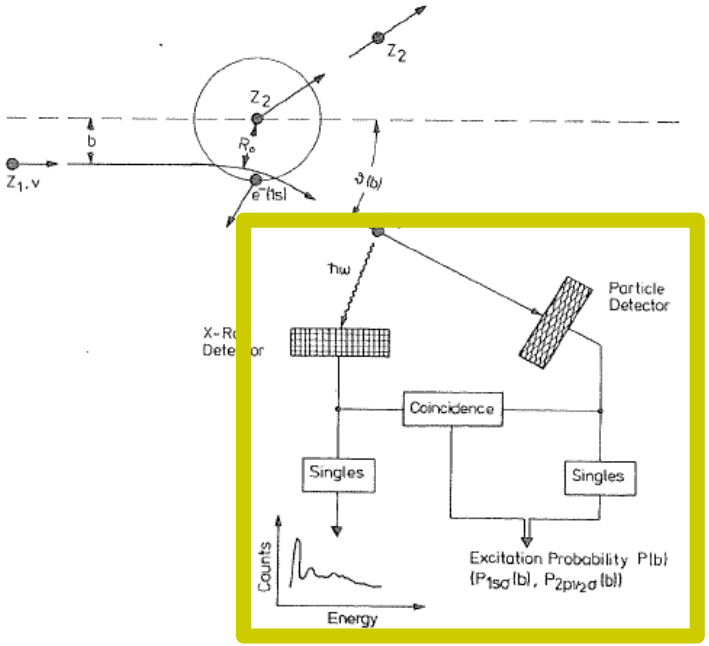
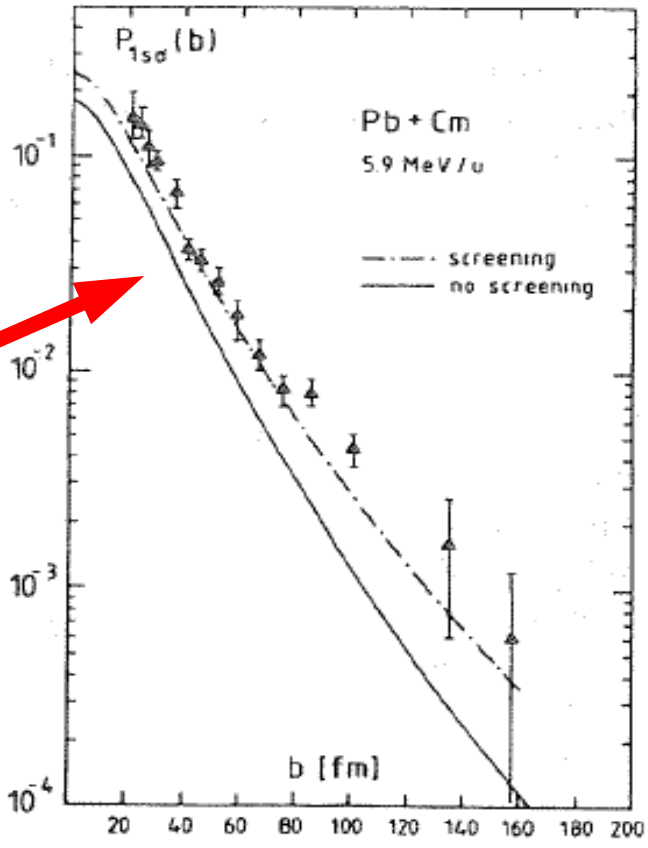


Pb + Pb (sub-critical, Z = 164)

Pb + Cm (supercritical, Z = 178)

Experimental vs. theoretical 1sσ excitation probability in Pb+Cm collisions at 5.9 MeV/u



Difficulties and requests (~1980):

- Creation of K-shell (1sσ) holes
- Theoretical prediction confirmed:
  increased K-shell ionization probability
- Proper subtraction of background
- Selected coincidence experiments
- Detailed studies on the P(b) dependence
- However, no „clean“ collision system !

Formation of super-heavy quasimolecules

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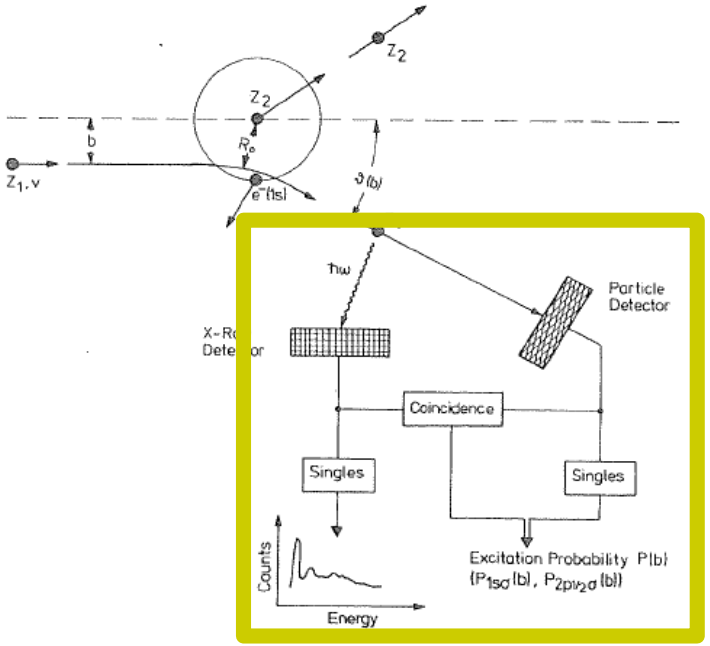

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VOLUME 44, NUMBER 15 PHYSICAL REVIEW LETTERS 14 APRIL 1980

Experimental Confirmation of a Scaling Law for the 1sσ Excitation Probability for $Z_1 + Z_2 > 120$, and its Breakdown in Pb + Cm Collisions at Very Small Internuclear Distances

D. Liesen, P. Armbruster, F. Bosch, S. Hagmann, P. H. Mokler, and H. J. Wollersheim
Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Federal Republic of Germany

and

H. Schmidt-Böcking
Institut für Kernphysik, D-6000 Frankfurt, Federal Republic of Germany

and

R. Schuch
Physikalisches Institut, Universität Heidelberg, D-6900 Heidelberg, Federal Republic of Germany

and

J. B. Wilhelmy
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

(Received 9 November 1979)

The excitation probability of the 1sσ-molecular orbital has been measured as a function of the impact parameter b for several collision systems in the region $129 \leq Z_1 + Z_2 \leq 178$ at the UNILAC. All published impact-parameter data agree with a simple scaling law except those for impact parameters $b \leq 40$ fm in the Pb + Cm system ($Z_1 + Z_2 = 178$).

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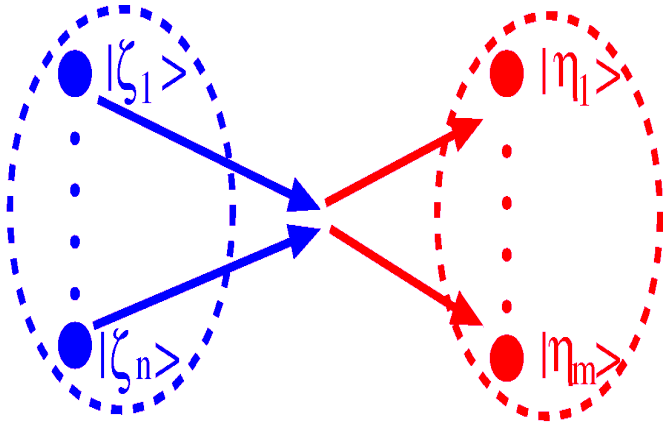
Perturbative description of ion-atom collisions

-- for instance, by means of the density matrix

Initial state

$(t \to -\infty)$

$\hat{\rho}_i$



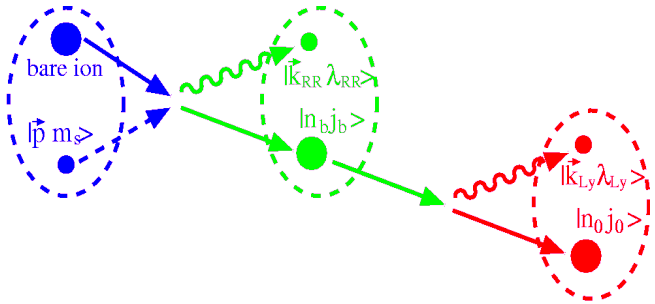
Final state

$(t \to +\infty)$

$\hat{\rho}_f$

$\hat{S}$ - scattering operator

$$\hat{\rho}_f = \hat{S}\,\hat{\rho}_i\,\hat{S}^+$$



Using the density matrix, a quantum system can be conveniently accompanied through several individual steps of the interaction but not for (quasi-) adiabatic processes !

Perturbative description of ion-atom collisions

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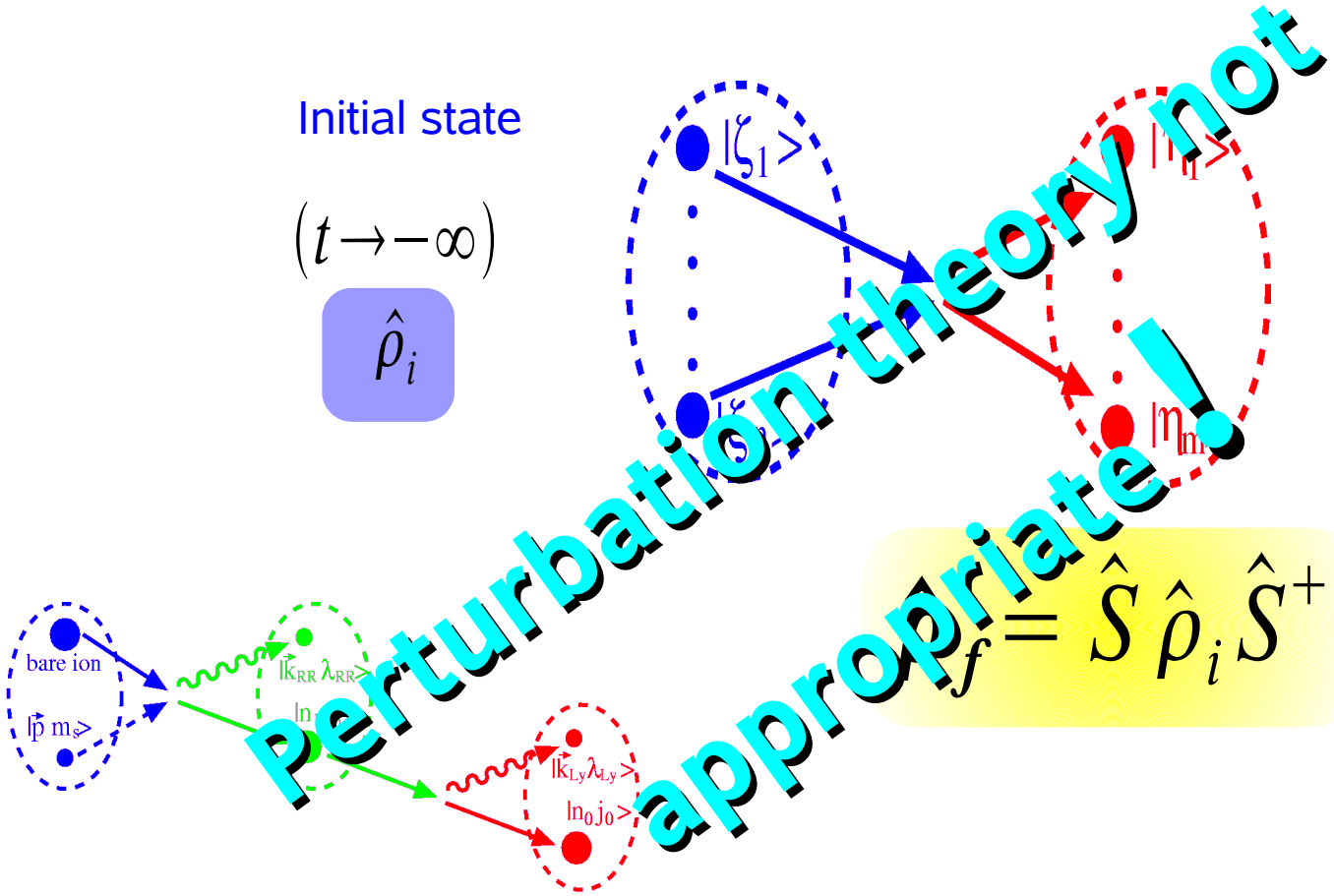

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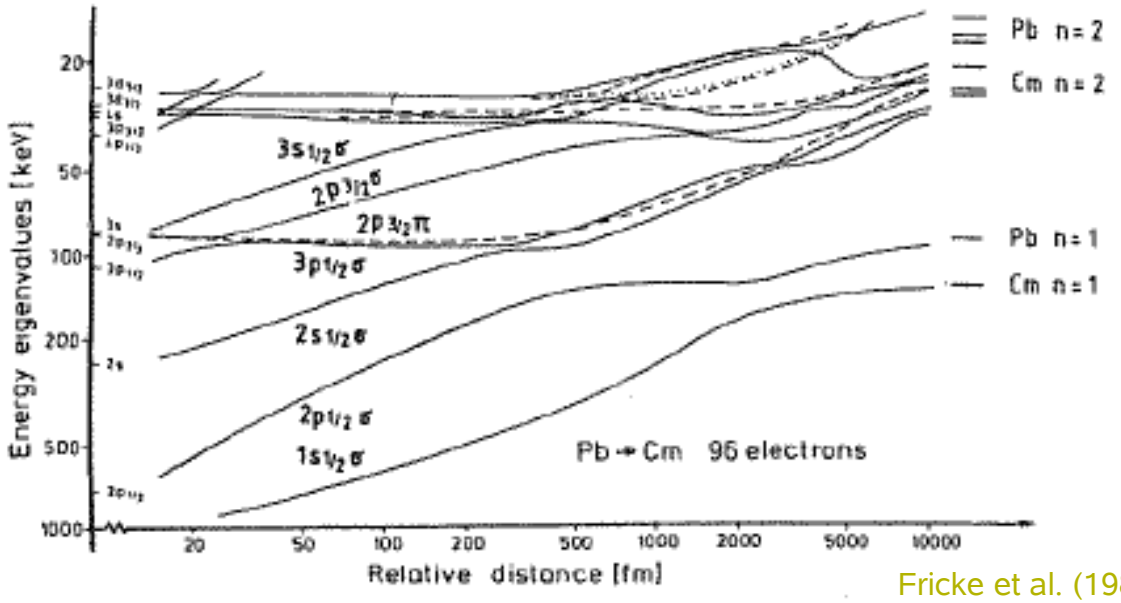
Adiabatic two-center description of ion-atom collisions

-- dynamics „along the diatomic correlation diagram“

$$i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}_1, \ldots, \vec{r}_N, t) = \hat{H}_{el} \Psi(\vec{r}_1, \ldots, \vec{r}_N, t)$$

One-electron treatment in quasimolecular basis:

(Müller ~ 1975: discrete
Rumrich, Soff ~ 80er: continuum)



Fricke et al. (1981)

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One-electron treatment in quasimolecular basis:

(Müller ~ 1975: discrete
Rumrich, Soff ~ 80er: continuum)

$$\Psi(\vec{r}_1, \cdots, \vec{r}_N, t) = \frac{1}{\sqrt{N!}} \begin{vmatrix} \psi_1(\vec{r}_1, t) & \cdots & \psi_1(\vec{r}_N, t) \\ \cdots & \cdots & \cdots \\ \psi_N(\vec{r}_1, t) & \cdots & \psi_N(\vec{r}_N, t) \end{vmatrix}$$

$$\psi_i(\vec{r}, t) = \sum_{j=1}^{M} a_{ji}(t)\, \phi_j(\vec{r}, R(t))\, e^{-\frac{i}{\hbar}\int^t \varepsilon_j dt'}$$

Coupled-channel equations

$$\dot{a}_{nk}(t) = -\sum_{j \neq k} a_{nj}(t)\, \langle \phi_k | \partial / \partial t | \phi_j \rangle\, e^{i(\chi_k - \chi_j)}$$

time-dependent molecular orbitals

fast oscillating translation factors

Adiabatic two-center description of ion-atom collisions

-- strongly dependent on the numerical basis

$$ih\, Sa'(t) = Ha(t)$$

$$S_{lj} = \langle \phi_l | \phi_j \rangle \; e^{-\frac{i}{\hbar}\int^t (\varepsilon_j - \varepsilon_l) dt'}$$

$$H_{lj} = < \phi_l | i\hbar \frac{\partial}{\partial t} + \varepsilon_j - \hat{h}^{TDDF} | \phi_j > \; e^{-\frac{i}{\hbar}\int^t (\varepsilon_j - \varepsilon_l) dt'}$$

Two- vs. three-center description

Adiabatic two-center description of ion-atom collisions

-- strongly dependent on the numerical basis

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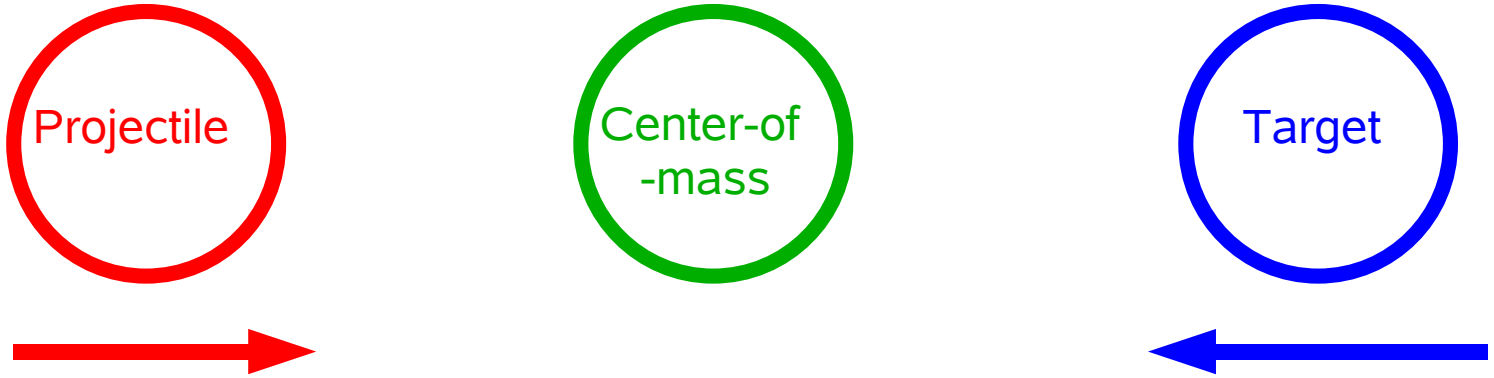
Radial and rotational coupling of matrix elements.

Two- vs. three-center description



Adiabatic two-center description of ion-atom collisions

-- strongly dependent on the numerical basis

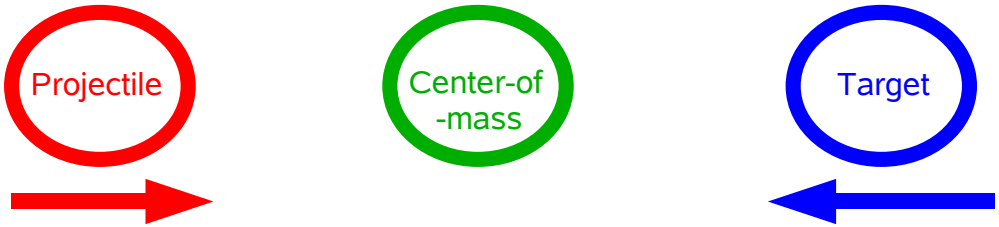
$$ih\,Sa'(t) = Ha(t)$$

$$S_{lj} = \langle \phi_l | \phi_j \rangle \; e^{-\frac{i}{\hbar}\int^t (\varepsilon_j - \varepsilon_l) dt'}$$

$$H_{lj} = < \phi_l | i\hbar \frac{\partial}{\partial t} + \varepsilon_j - \hat{h}^{TDDF} | \phi_j > \; e^{-\frac{i}{\hbar}\int^t (\varepsilon_j - \varepsilon_l) dt'}$$

Two- vs. three-center description

$$\begin{aligned}
\phi_j(\vec{r},\vec{R}) &= \sum_{\nu=1}^{S} d_{j\nu}^{P}(\vec{R})\,\varphi_\nu^{P}(\vec{\xi}(\vec{r},\vec{R}),\vec{R}) \cdot \exp\left\{\frac{i}{\hbar} m\vec{V}_P \cdot \vec{r}\right\} \\
&+ \sum_{\nu=1}^{S} d_{j\nu}^{T}(\vec{R})\,\varphi_\nu^{T}(\vec{\xi}(\vec{r},\vec{R}),\vec{R}) \cdot \exp\left\{\frac{i}{\hbar} m\vec{V}_T \cdot \vec{r}\right\} \\
&+ \sum_{\nu=1}^{S} d_{j\nu}^{C}(\vec{R})\,\varphi_\nu^{C}(\vec{\xi}(\vec{r}),\vec{R}) \\
&\equiv \sum_{K',\nu} d_{j\nu}^{K'}(\vec{R})\,\hat{S}_{K'} \left| \varphi_\nu^{K'} \right\rangle
\end{aligned}$$



- Ansatz for the molecular orbitals at a given time
  --> optimized basis (due to the molecular, i.e. diatomic treatment).
- Problem-adapted basis due to the explicit use of the electronic translation factors.
- For fast collisions ($v_{orbit} << v_{nuc}$), the Fock matrix is diagonal in atomic basis.
- Center-of-mass basis help describe `saddle-point' electrons.

Adiabatic two-center description of ion-atom collisions

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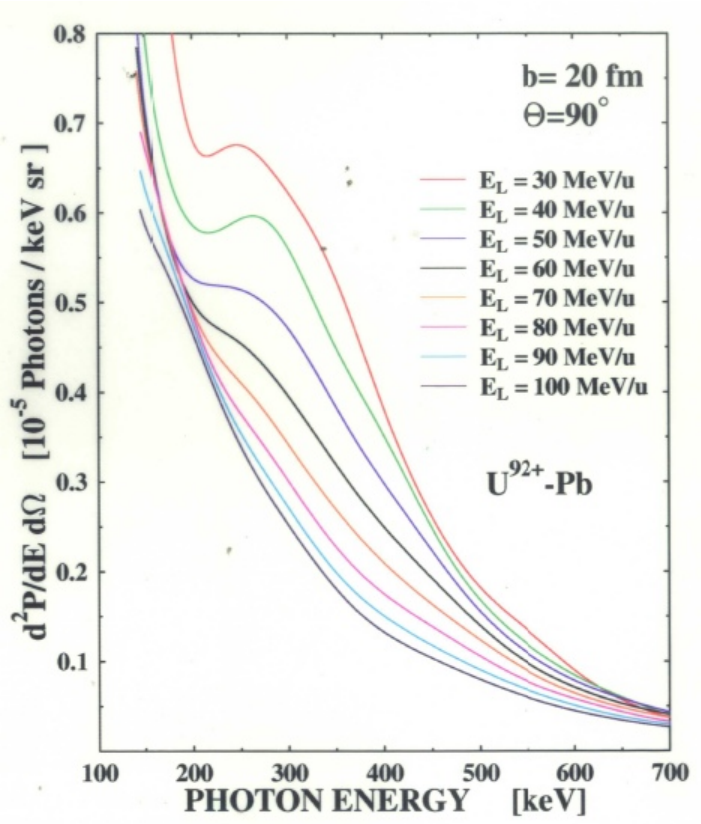

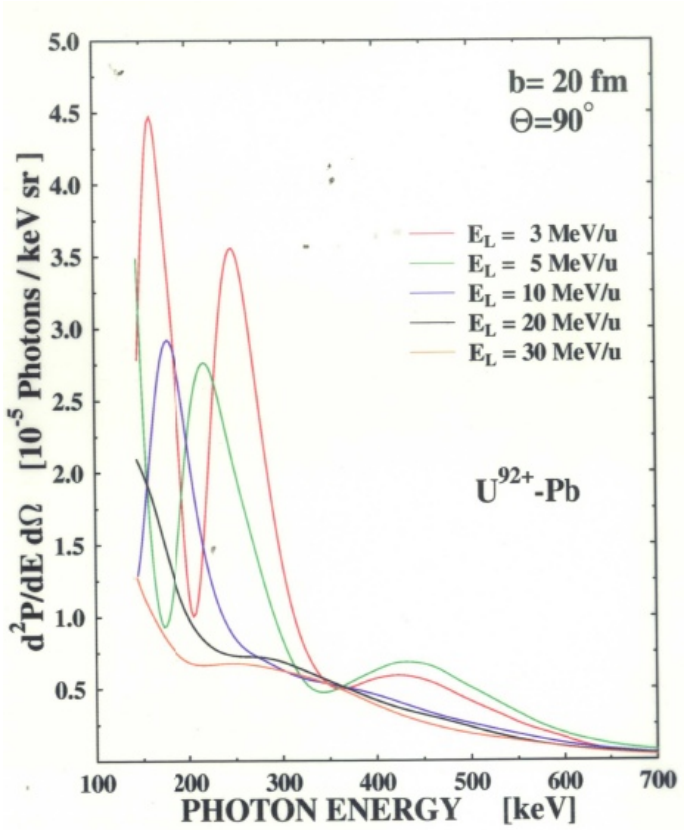

Initially filled K and L-shell of Pb and U.

Schulze, Anton & Fricke (1990ies)

Adiabatic two-center description of ion-atom collisions

-- strongly dependent on the numerical basis

$$ih\,Sa'(t) = Ha(t)$$

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Two- vs. thre

$$\phi_j(\vec{r},\vec{R}) = \sum_{\nu=1}^{S} d_{j\nu}^{P}(\vec{R}$$
$$+ \sum_{\nu=1}^{S} d_{j\nu}^{T}(\vec{R}$$
$$+ \sum_{\nu=1}^{S} d_{j\nu}^{C}(\vec{R}$$
$$\equiv \sum_{K',\nu} d_{j\nu}^{K'}(\vec{R}$$

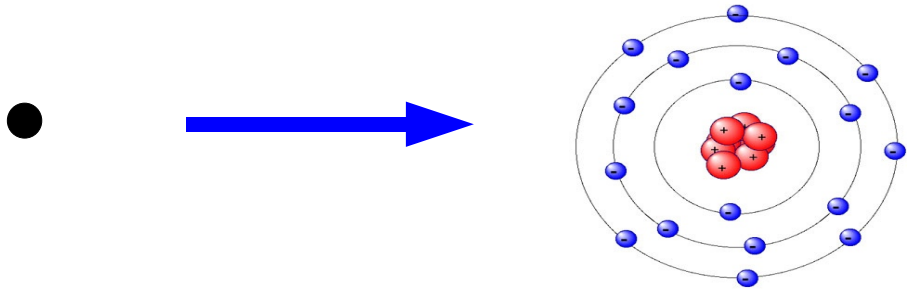
Previous successes

(AG Fricke, Kassel, until 1990ies)

- Solution of the time-dependent Dirac (HFS) equation for ion-atom collisions in sub- and supercritical fields.
- Unified description of excitation, transfer and ionization, including combined processes; incorporates the AO and MO picture as limit (sizeable programs; available ?)
- No correlation, so far, but expected to be small for inner-shell processes.
- Method of inclusive probabilities to find the proper orbital occupation after the collisions.
- Can be done but sophisticated and very time-consuming.

Formation and observation of super-heavy quasimolecules

-- Future studies



bare ion

neutral target

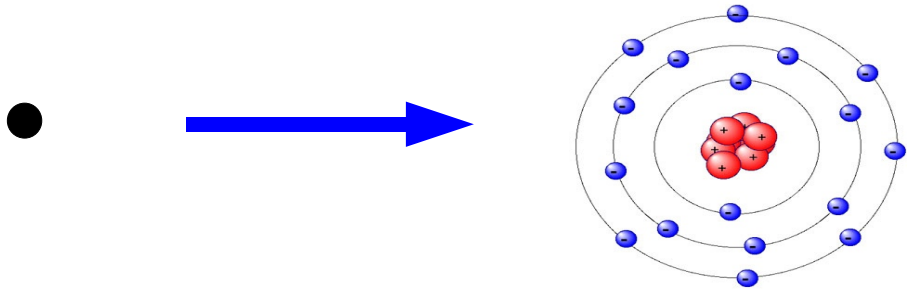
Suggestions for the future:

- Naked projectiles (U^{92+})
- No creation of K-shell holes required
  --> 10..100 x larger cross sections at small b
- Gas-jet target to ensure „clean system“

- Storage ring or „off-line“ at the Unilac ??
- Coincidence experiments with charge state ??
- Impact-parameter dependence ??

Formation and observation of super-heavy quasimolecules

-- Future studies



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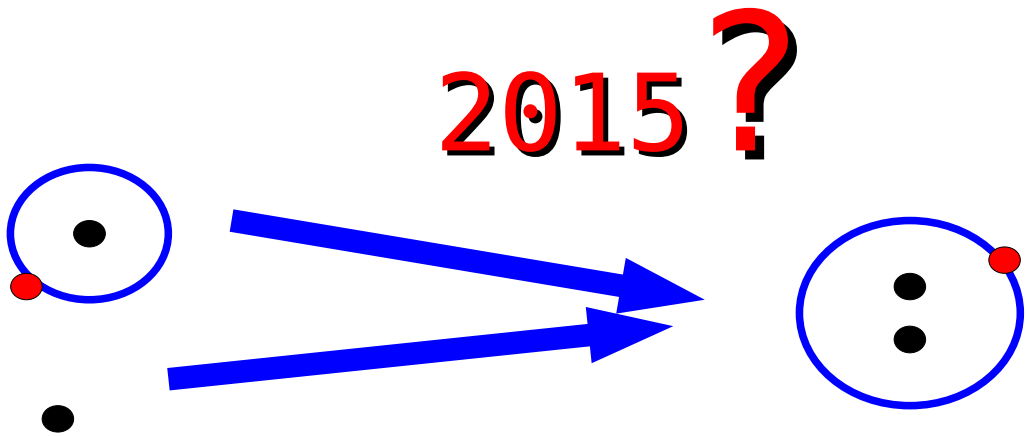
- Coincidence experiments with charge state ??
- Impact-parameter dependence ??

- Co-linear collisions with just a single electron involved !



Radiative potential for QED

$$\Phi_{\mathrm{rad}}(r)=\Phi_U(r)+\Phi_g(r)+\Phi_f(r)+\Phi_l(r)+\frac{2}{3}\Phi_{WC}^{simple}(r)$$

$$\Phi_g(r)+\Phi_f(r)+\Phi_l(r)=$$

$$\Phi_U(r)+\frac{2}{3}\Phi_{WC}^{simple}(r)=$$

$\Phi_g(r)$ – magnetic formfactor
$\Phi_f(r)$ – electric formfactor
$\Phi_l(r)$ – low energy electric formfactor
$\Phi_U(r)$ – Uehling potential
$\Phi_{WC}(r)$ – Wichmann-Kroll potential

$\Phi_f(r)$ and $\Phi_f(r)$ have free parameters which are chosen to fit QED corrections to the energies (Mohr, et al) and weak matrix elements (Kuchiev,Flambaum; Milstein,Sushkov,Terekhov; Sapirstein et al)

Systematic „routes“ to atomic structure

Multiconfiguration expansions

$$\psi_\alpha(P\,J\,M) = \sum_r^{n_c} c_r(\alpha)\,\gamma_r\,P\,J\,M>$$

Construct a basis in the N-electron Hilbert space

Shell-model all CSF including virtual single-, double-, ... excitations from occupied into the unoccupied(sub-) shells n, n+1, ...

Many-body perturbation theory

$H = H_0 + V$ Rest interaction to H_0 with known solutions

- order-by-order perturbation theory in V (MBPT) or
- decomposition in classes of „virtual excitations“ (all-order methods)

Systematic „routes“ to atomic structure

Multiconfiguration expansions

$$\psi_\alpha(P\,J\,M) = \sum_r^{n_c} c_r(\alpha)\,\gamma_r\,P\,J\,M>$$

Construct a basis in the
N-electron Hilbert space

Shell-model

all CSF including virtual single-, double-, ... excitations
from occupied into the unoccupied(sub-) shells n, n+1, ...

Many-body perturbation theory

$H = H_0 + V$

Rest interaction to H

- order-by-order perturbation theory in V
- decomposition in classes of „virtual excitati

Energies & Wave functions

- GRASP(-92)
- „Desclaux“
- Coupled-Cluster

„Electronic correlations“

-- Fine-structure of open-shell configurations

	Dimension of the Hilbert space
p^4	5
$p^3\ s$	10
d^8	9
$d^7\ p$	110
$f^7\ s^2$	327
$f^7\ sp$	3808
$f^7\ p^2$	4724
$f^6\ spd$	31804

$p^3\ s$

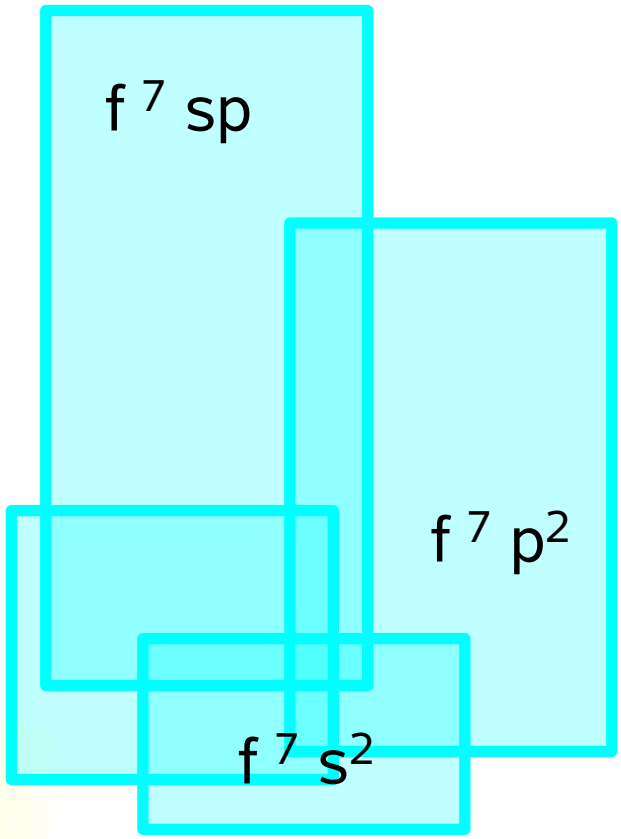
p^4

~ 1 .. 3 %

level and transition energies

~ 10 ... 500 %

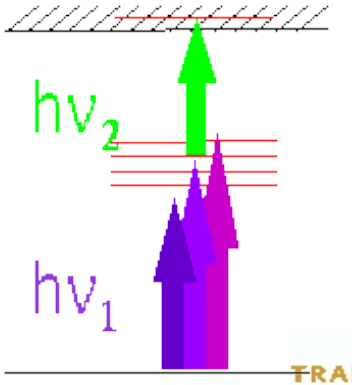
Computational requirements depend very critically on the shell structure of the atoms and ions !



Concept of electron configurations gets lost !

Optical spectroscopy at Fermium (Z = 100)

-- first observation and classification of atomic levels



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Phys. Rev. Lett. **90**, 163002
(issue of 25 April 2003)
Title and Authors

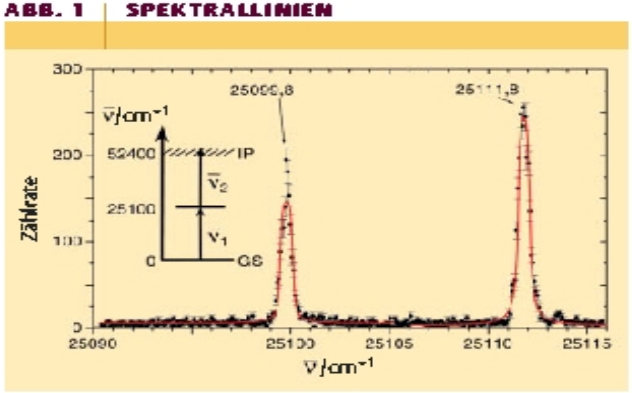
25 April 2003

TRANSURANE

Erstmalige Spektroskopie des Elements Fermium

Das Element Fermium (Z=100) wurde 1952 in den Überresten einer thermonuklearen Explosion entdeckt. Es ist das schwerste Element, das über sukzessiven Neutroneneinfang und Betazerfall hergestellt werden kann. Jetzt ließ sich erstmals die atomare Struktur spektroskopisch studieren. Dafür wurde eine 2 ng leichte Probe von ^{255}Fm (Halbwertszeit 20,1 Stunden) am Hochfluss-Kernreaktor des Oak Ridge National Laboratory, USA, produziert und nach Deutschland versandt [1].

ABB. 1 | SPEKTRALLINIEN



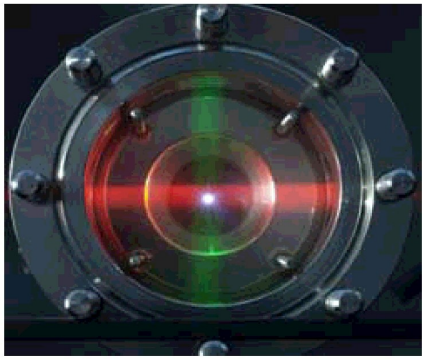
Beobachtete Spektrallinien von Fermium und das zweistufige Anregungsschema. Die rot eingezeichneten Kurven stellen theoretische Berechnungen der Spektrallinien dar.

relativistische Massenzunahme. Die Orbitale schrumpfen, was eine verstärkte Abschirmung des Coulomb-Potentials für die äußeren Leuchtelektronen zur Folge hat. Dadurch können sich die chemischen Eigenschaften der schweren Elemente so verändern, dass sie unerwartete, nicht mehr im Einklang mit der Extrapolation innerhalb einer Gruppe stehende Eigenschaften bekommen. Solche relativistischen Effekte äußern sich neben Änderungen in den chemischen Eigenschaften auch im Anregungsspektrum des Atoms und damit in seinen Spektrallinien.

Bei der Spektroskopie des Isotops ^{255}Fm traten zwei Probleme auf: Zum

nium Wins Heavyweight Title

n the 1952 detonation of the first nuclear bomb, the element m has since sat in a corner of the c table where few tools of try reach. Now a team has d a piece of its spectrum--the ngths of light it absorbs--making eaviest element ever to be so ed. The researchers rushed their ample of the short-lived element nuclear reactor in the US to ny, where they probed it with just atoms at a time. Appearing in April *PRL*, their findings shed the energies of fermium's ns and provide a way for theorists heir calculations for even heavier re elusive elements.



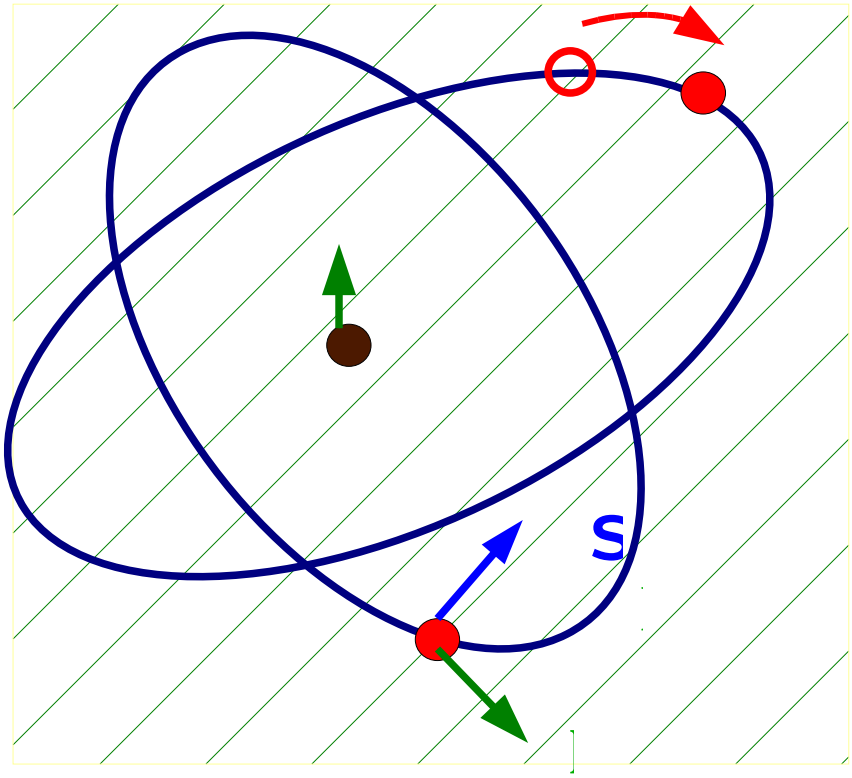
A. Zschau

Fermium, revealed. Lasers probed the spectrum of light absorbed by fermium atoms using this chamber, in which ionized atoms are drawn toward the exit hole (white) in back. The experiment makes fermium the heaviest element whose spectrum has been measured.

ailable energy levels for electrons om determine both what kind of t forms and what other elements it reacts with. Fermium is element x doors past plutonium in the periodic table--and calculating the energies of electrons is a tricky business. Einstein's relativity comes into play for the oving electrons of such an atom, changing the rules that usually indicate orbitals are most stable.

Hierarchy of inner-atomic interactions

-- Self-consistent field calculations



External fields

- Nuclear potential
- Instantaneous Coulomb repulsion between all pairs of electrons
- Spin-orbit interaction
- Relativistic electron velocities; magnetic contributions and retardation

- QED: radiative co… …s
- Hyperfine st…
- Electric… …netic nuclear m… …otopes)

Perturbation theory

★ Motion of the nucleus: Reduced mass and mass polarization

Methods of solution:
- Direct numerical integration of PDE
- Expansion w.r.t. atomic basis
- Expansion w.r.t. adiabatic basis

Expansion of the wavefunction:

$$\psi_n^{(+)}(\vec{r},t) = \sum_k a_{nk}(t)\,\phi_n(\vec{r},\vec{R}(t))\,\mathrm{e}^{-\mathrm{i}\chi_k(t)} \quad \text{with the phase} \quad \chi_k(t) = \int^t dt'\,E_k(R(t))$$

Coupled channel equations

$$\dot{a}_{nk}(t) = -\sum_{j\neq k} a_{nj}(t)\,\langle\phi_k|\partial/\partial t|\phi_j\rangle\,\mathrm{e}^{\mathrm{i}(\chi_k-\chi_j)}$$

to be integrated with the initial condition $a_{ik}(t\to-\infty)=\delta_{ik}$

Coupling operator: $\dfrac{\partial}{\partial t} = \dot{R}\dfrac{\partial}{\partial R} - \mathrm{i}\,\vec{\omega}\cdot\vec{J}$

Strong radial couplings between $s_{1/2}$ or $p_{1/2}$ states in the limit $R\to 0$.

Multi-step processes are important. 1st order perturbation theory not sufficient.

$$\dot{a}_{nk}(t) = -\sum_{j\neq k} a_{nj}(t)\,\langle\phi_k|\partial/\partial t|\phi_j\rangle\,\mathrm{e}^{\mathrm{i}(\chi_k-\chi_j)}$$

Field theoretical description

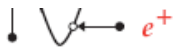
Field operator: $\hat{\psi}(x) = \sum_{n>F} \hat{b}_n^{\rm in}\, \psi_n^{(+)} + \sum_{n<F} \hat{d}_n^{\rm in\dagger}\, \psi_n^{(+)}$

The state vector $|F\rangle$ is prepared as $\begin{cases} \hat{b}^{\rm in}|F\rangle &= 0 \quad , \quad n > F \\ \hat{d}^{\rm in}|F\rangle &= 0 \quad , \quad n < F \end{cases}$

Expansion in terms of out-operators: $\hat{\psi}(x) = \sum_{n>F} \hat{b}_n^{\rm out}\, \psi_n^{(-)} + \sum_{n<F} \hat{d}_n^{\rm out\dagger}\, \psi_n^{(-)}$

Canonical transformation: $\hat{b}_n^{\rm out} = \sum_{k>F} \hat{b}_k^{\rm in}\, a_{kn} + \sum_{k<F} \hat{d}_k^{\rm in\dagger} a_{kn}$

- **K-hole production**



High ionisation rates: $P_{1s\sigma} \simeq 10\%$.
Approximate scaling behaviour:

$P_{1s\sigma}(b) \simeq D(Z)\, {\rm e}^{-2R_{\rm min}q_{\rm min}}$ where $q_{\rm min} = \dfrac{E^B_{1s\sigma}(R_{\rm min})}{\hbar v_{\rm ion}}$ (minimum momentum transfer)

→ "Spectroscopy" of superheavy quasimolecules.

- **δ-electron production**

The high-energy tail (up to $E_e > 2\,{\rm MeV}$) probes the high-momentum components of the the quasimolecular wave functions.

- **Quasimolecular X rays (MOX)**

Broad photon spectra. No "end point", quasistatic picture not applicable.

- **Positron creation**
  - Drastic increase of positron yield with nuclear charge Z : $P_{e^+} \propto Z^{20}$
  - *No qualitative signal* for level diving expected. (Collisional broadening)
  - Good quantitative agreement with experiments: $P(b), P(Z), dP/dE_{e^+}$.

Summary

- This method allows an ab-initio solution of the time-dependent Dirac equation for the ion-atom collision process.

- It allows to calculate excitation, transfer and ionization or any combined process for many electrons in a unified way. What is needed is just the electron-electron and electron-nucleus 1/r-interaction.

  Personally I would not speak of correlated processes because this correlation depends on the simple Pauli correlation and a relatively good treatment of the 1/r-interaction between the electrons.

- Because one needs separate calculations

  – at all internuclear distances
  – for all energies
  – and all impact parameters

  an actual calculation is very time-consuming and complicated.

  But it can be done!

Folgende Fortschritte sind in den letzten Jahren erzielt worden:

1. Konstruktion einer auch qualitativ neuen zeitabhängigen 3-Zentren Basis zur Beschreibung eines Ion-Atom Stoßes

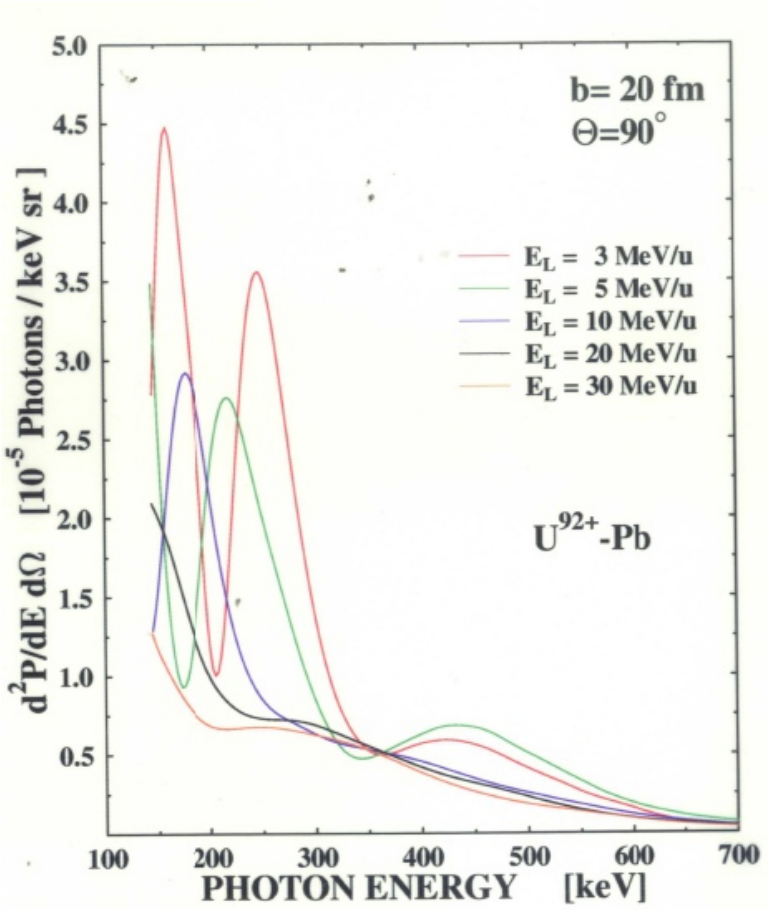
2. Einbau expliziter zeitabhängiger Translationsfaktoren

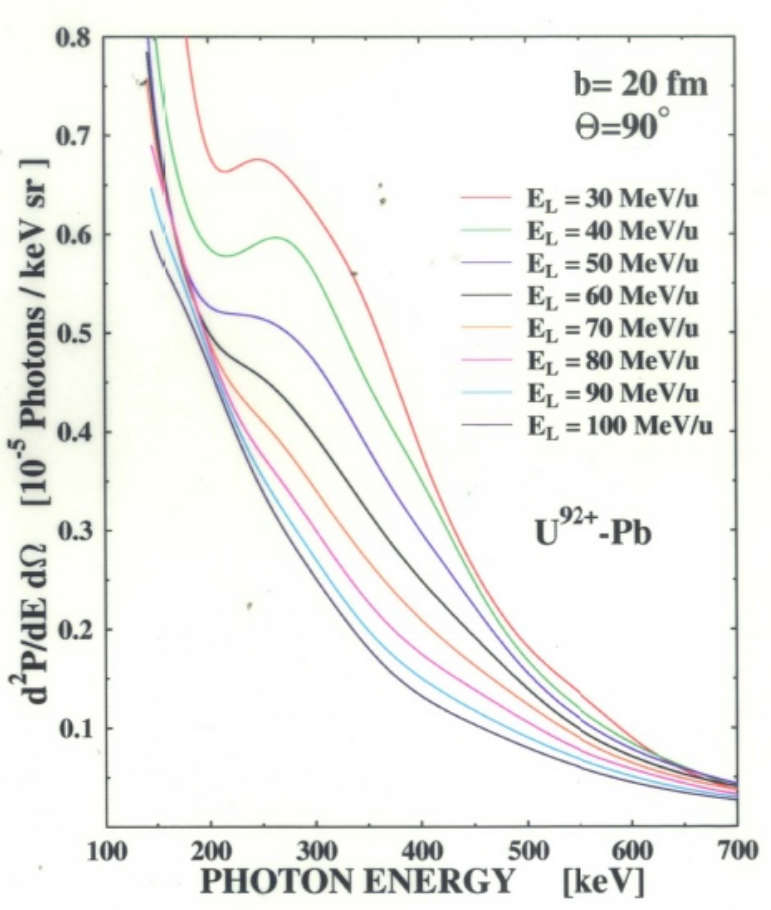
3. Universelle Beschreibung des Ion-Atom Stoßes für alle Stoßenergien mit dem AO- und MO-Bild als Grenzfälle

4. Erstmalige direkte nicht-störungstheoretische Berechnung einer Ionisation für einfache Mehr-Elektronen Stoßsysteme

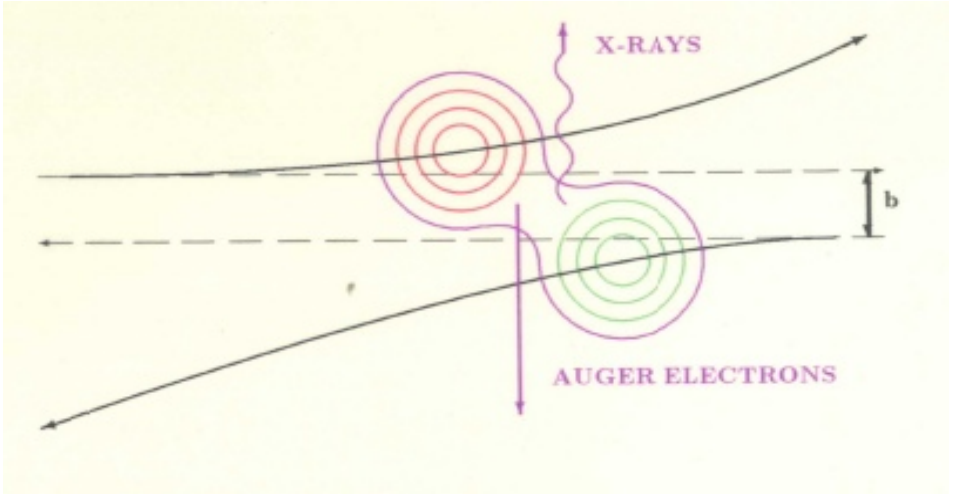
Vorgehen:

1. Lösung der atomaren DFS Gleichungen
2. Auswahl der Basisfunktionen für die Molekülläufe
3. Molekülrechnungen für alle internuklearen Abstände – dabei auch Berechnung aller Matrixelemente
4. Ausschreiben aller notwendigen Ergebnisse auf File
5. Test auf relativen Vorzeichen für alle MO's für verschiedene R.
6. Auswahl der MO's oder Konfigurationen
7. Erzeugung des Input für die gekoppelten Kanäle Rechnungen
8. Gekoppelte Kanäle Rechnungen für alle Energien und Stoßparameter (und beteiligte Elektronen)
9. Vielteilcheninterpretation mit den gefundenen Satz a.i.s. entsprechend der physikalischen Fragestellung





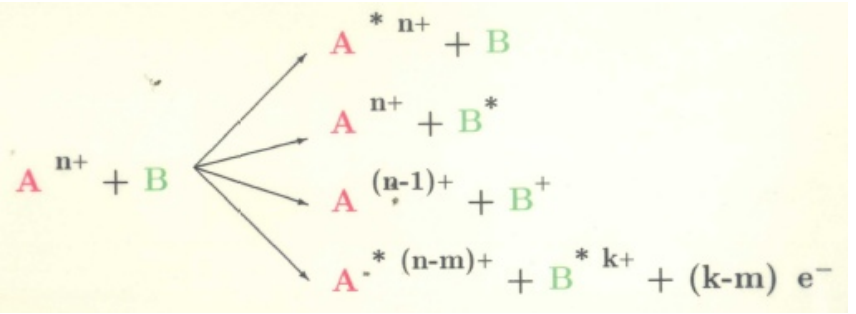
10 electrons in the K and L-shell of Pb



Energy

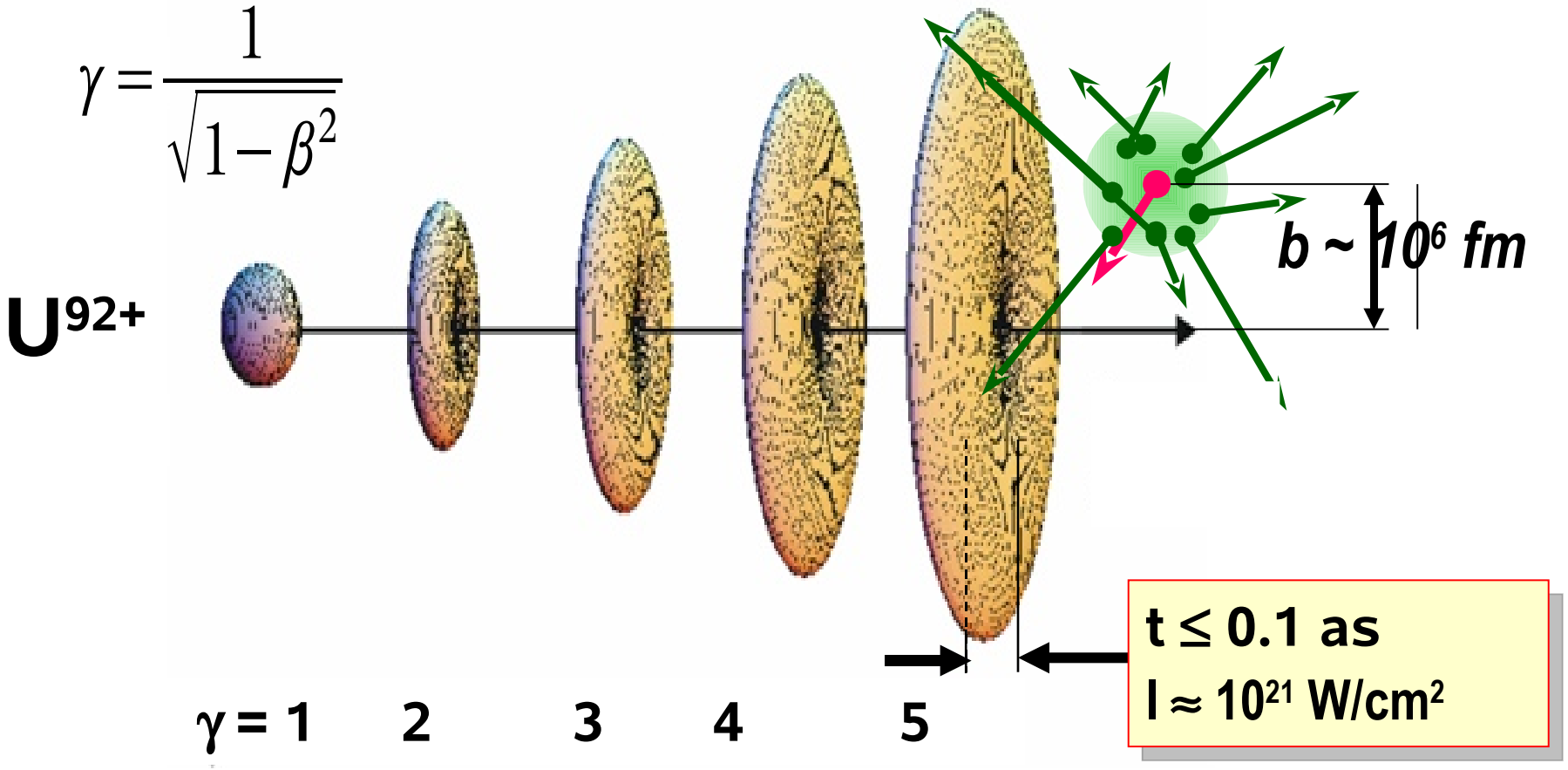
Scattering angle resp. impact parameter

State selective

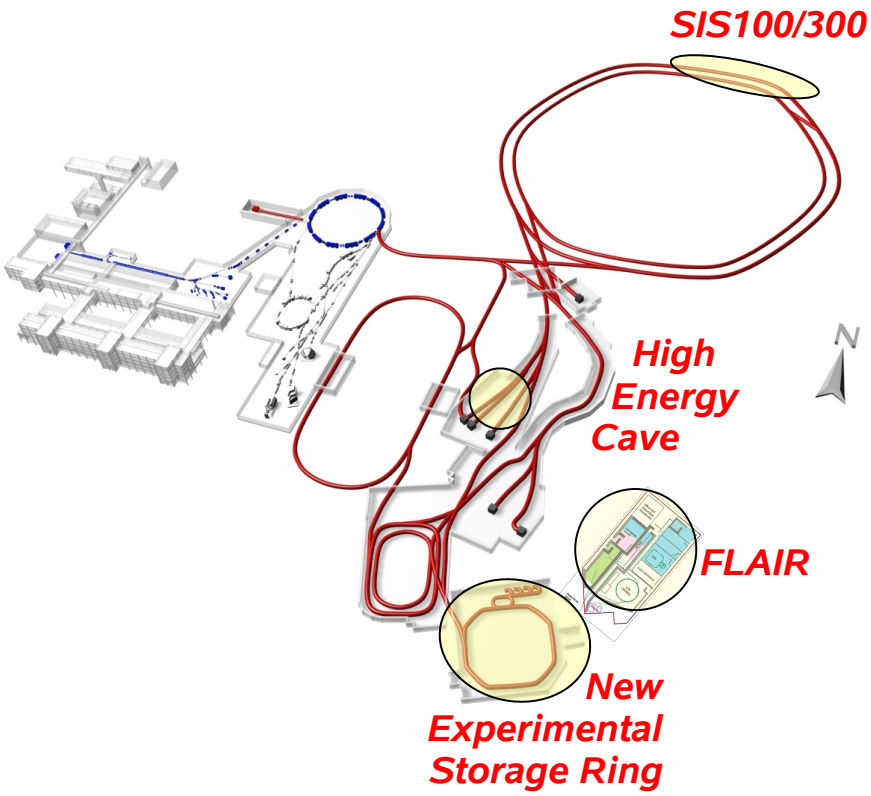


Reactions of relativistic projectiles in extreme dynamical fields

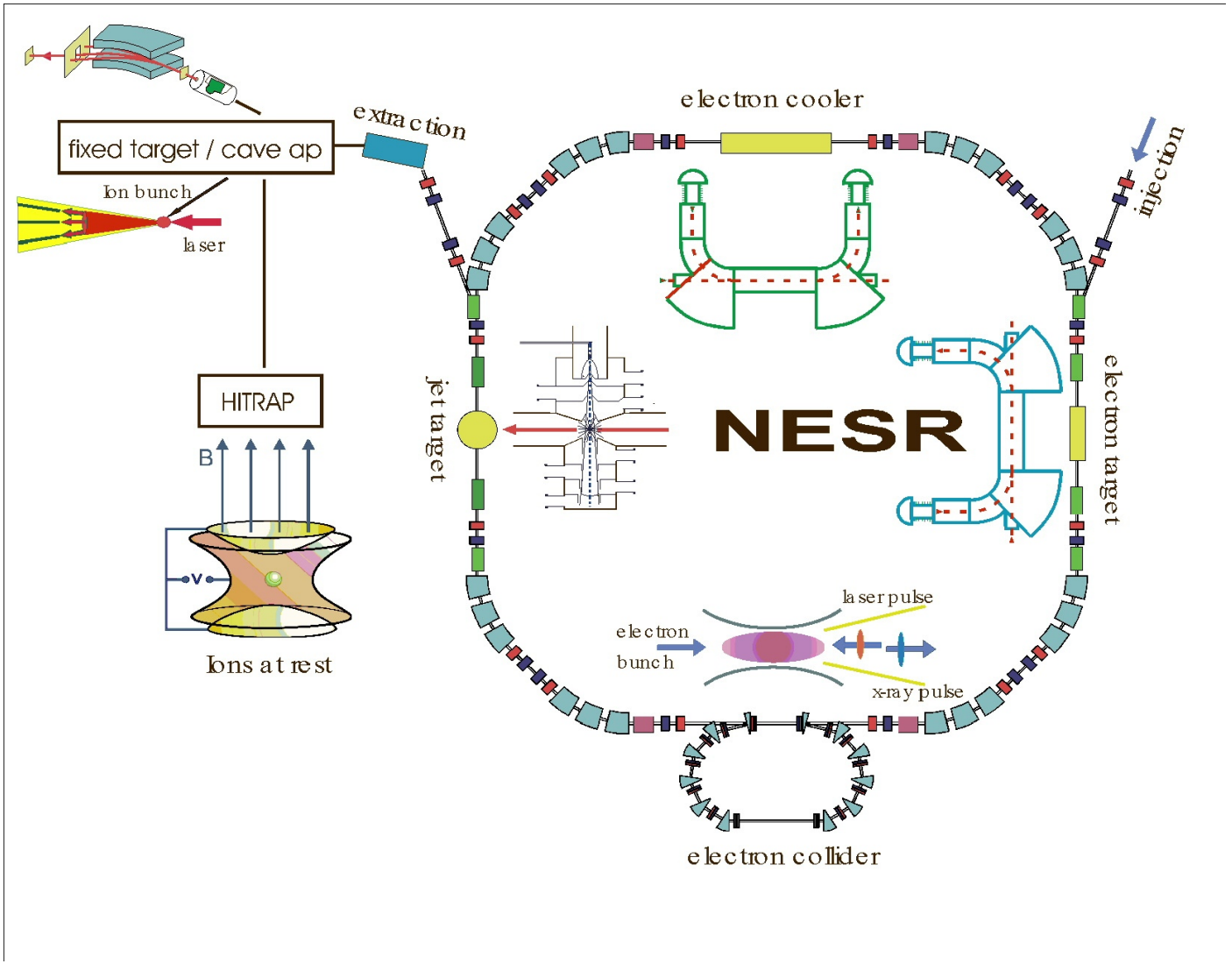
$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$



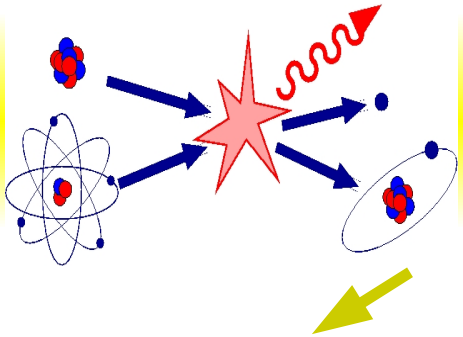
intense fields
ultra-short electromagnetic pulses
pair production



Novel Instrumentation


fixed target / cave ap
extraction
electron cooler
injection
Ion bunch
laser
HITRAP
B
Ions at rest
jet target
NESR
electron target
laser pulse
electron
bunch
x-ray pulse
electron collider

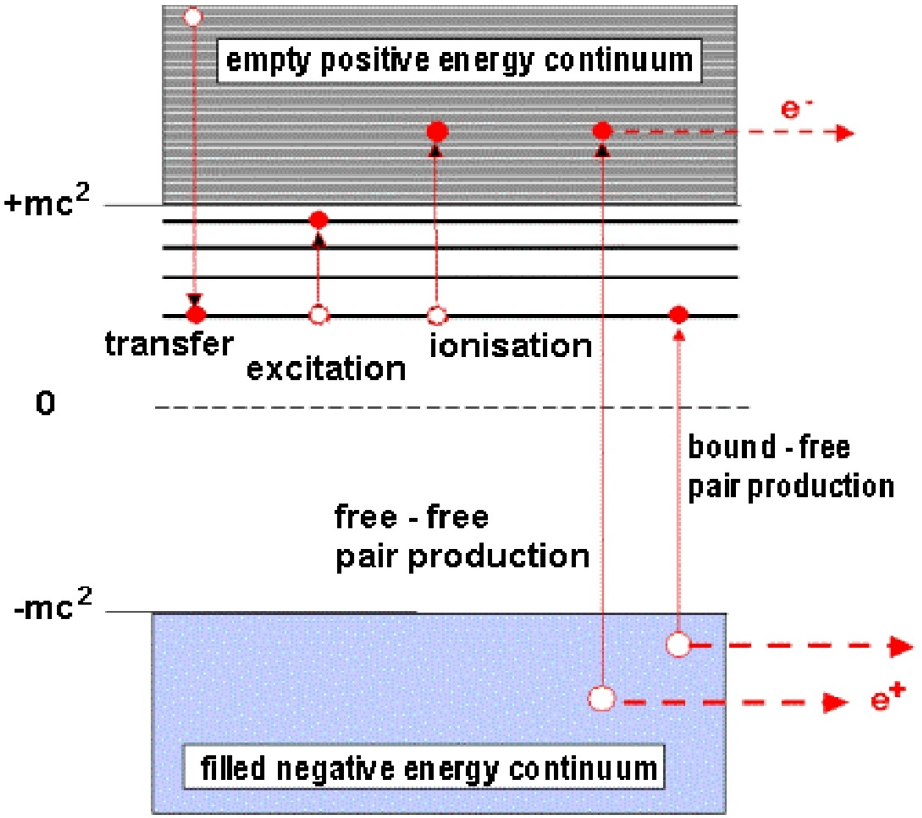
Ion-Atom Stöße



schnelle Stöße

„Einteilchenbild“

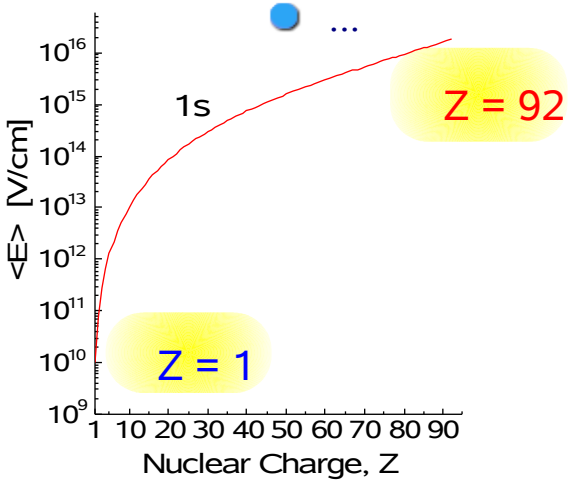
- Hochgeladene Ionen sind sehr gut geeignet, um die elementaren Prozesse in (extrem) starken Feldern zu verstehen.



langsame Stöße

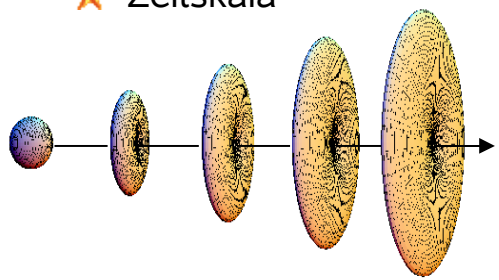
„Vielteilchenbild“

- Besseres Verständnis der Vielteilchendynamik erforderlich.
  - Verstärkung des REC bei langsamen Ionen (!)
  - Resonante (dielektronische) Rekombination.
  - Abbremsen und Einfang in Fallen.
  - Wichtig für Ionen-Oberflächen Prozesse.
  - ...



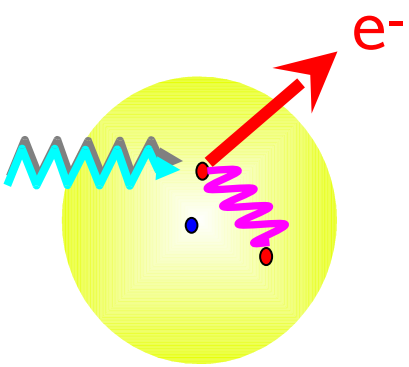
Ionen sind variabel:

- Feldstärke
- Zahl der Elektronen
- Zeitskala



Summary

- There has been great progress in the multiple ionization of noble gases due to FEL radiation and high-resolution electron spectroscopy.
- For present-day intensities (< 10^{16} W/cm^2), ionization can be well described by perturbation theory; if appropriate for the 'first' electron, than also suitable for all subsequent steps (since IP increases).
- Parametrization of the sequential photoionization enables one to understand the ionization dynamics of the individual steps and to help reveal dynamical correlations in the electron-photon interaction.



Weak radiation fields: Perturbative approaches

- cross sections
- angular distributions
- „complete“ experiments
- spin polarization
- entanglement

No information about the second electron
but the knowledge of the state of the final photoion !

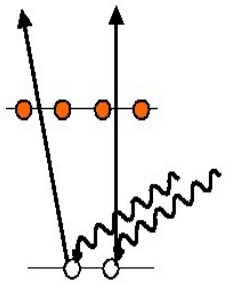
P. Corkum and coworkers (2005)

Two-photon double ionization (TPDI) of atomic neon

-- with resolved electron-momentum distributions

Many-particle photoionization amplitudes <J, lj || D || J'>

$$\psi_\alpha(P\,J\,M) = \sum_r^{n_c} c_r(\alpha)\,|\gamma_r\,P\,J\,M\rangle$$



RATIP

Relativistic Atomic Transition and Ionization Properties

(CPC library)

Wave function expansions:

- Construction and classification of N-particle Hilbert spaces
- Shell model: Systematically enlarged CSF basis

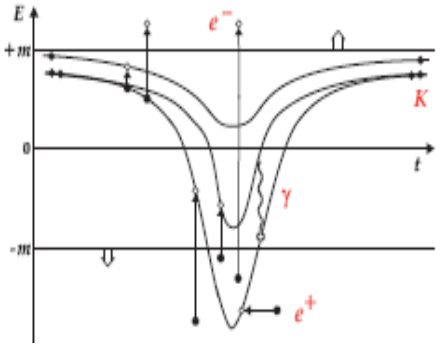
S. Fritzsche, JESRP 114-116 (2001) 1155
Phys. Scr. T100 (2002) 46

Spontaneous pair creation

Charged vacuum

Heavy ion collisions

Dynamics of e^+e^- creation, ...



Frankfurt group

Greiner, Müller, Soff, Reinhardt, Müller-Nehler, ...

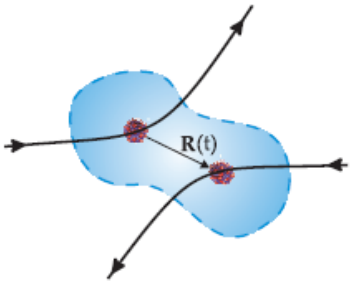
Two Center Dirac Hamiltonian:

$$H_{\mathrm{TCD}}(\vec{R}) = -\mathrm{i}\vec{\alpha}\cdot\vec{\nabla} + \beta m + V_1(\vec{r},\vec{R}) + V_2(\vec{r},\vec{R})$$

Semiclassical approximation: $\vec{R}(t) =$ Rutherford trajectory.

If the velocity $\dot{\vec{R}}$ is "small" the electrons follow the adiabatic quasimolecular basis

$$H_{\mathrm{TCD}}(\vec{R})\,\phi_n = E_n(R)\,\phi_n$$



TCD solutions:	Discrete states:	B. Müller	$\sim$ 1975
	Continuum:	Wietschorke, Rumrich, Soff	$\sim$ 1985

Critical distance for U+U R_{cr} = 37 fm (point nuclei, unscreened)

R_{cr} = 26 fm (extended nuclei, HFS screening)