Recombination from the Negative Continuum

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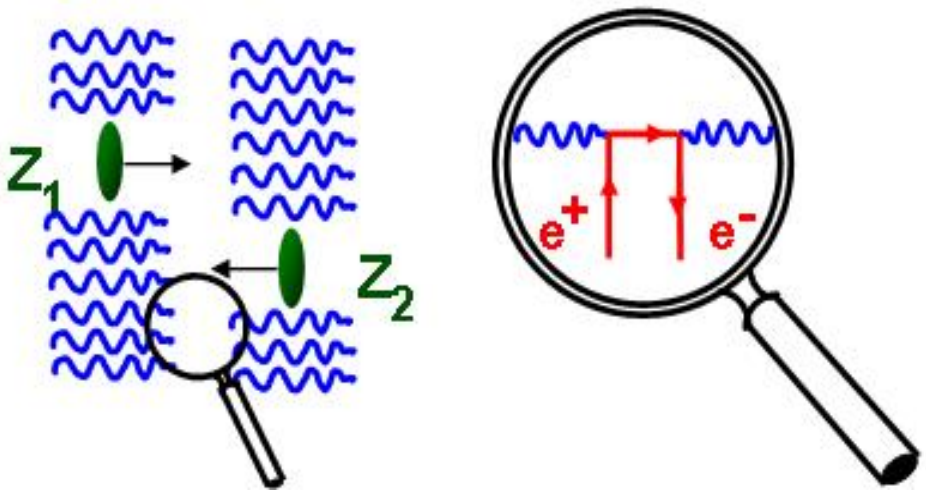
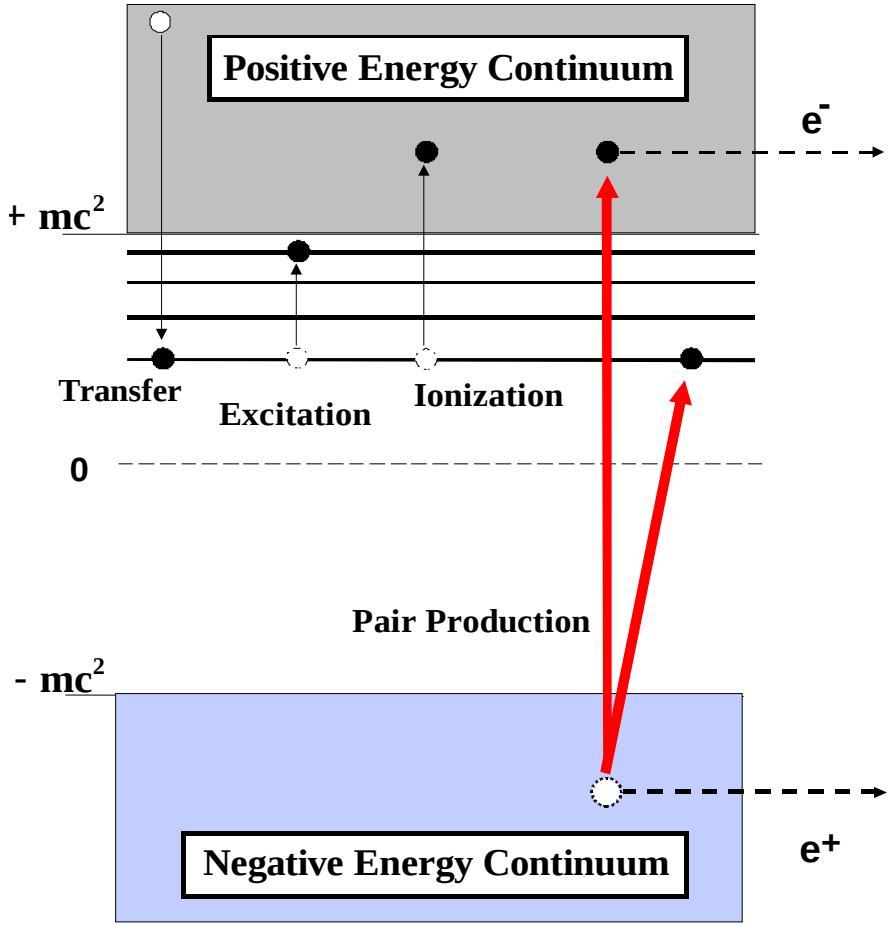
Recombination from the Negative Continuum

- **Introduction**: Electron-positron pair production in ion-ion collisions
  - Two-center Dirac problem
- Negative continuum dielectronic recombination
  - Theoretical background
  - Differential and total NCDR cross sections
- **Outlook**: Further NCDR studies
  - Scenarios for future experiments and “visibility” of the process

Relativistic ion-atom collisions

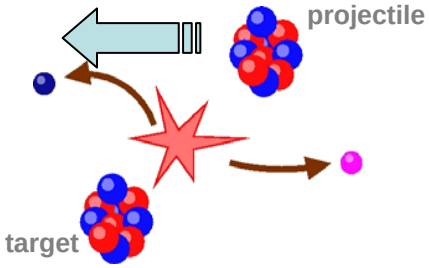
- Dynamically induced strong fields result in a large number of atomic processes.



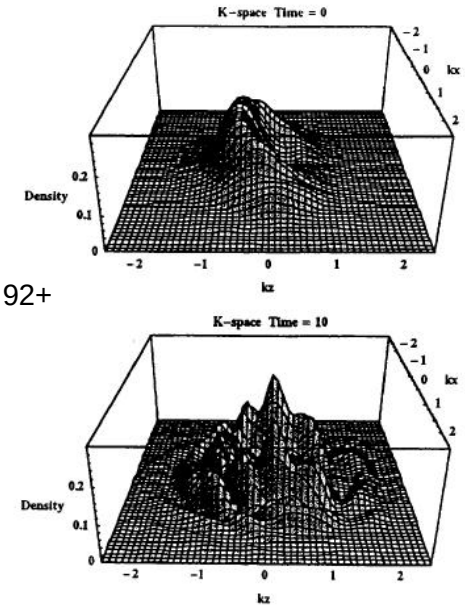


- We wish to consider process of electron-positron pair creation.

Pair production in heavy ion collisions

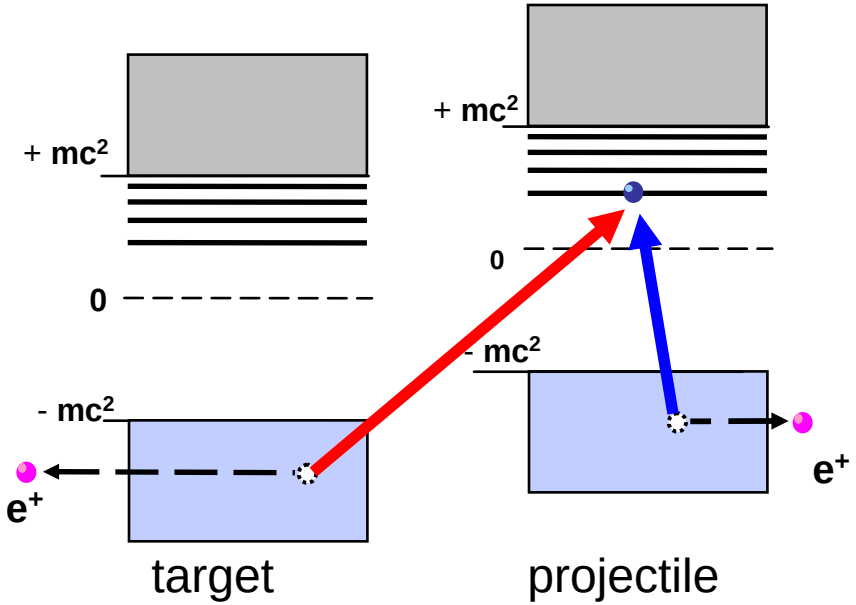


- Electron-positron pair production in ion-ion collisions (at moderate energies) has attracted much interest during last years.



$Au^{79+} + U^{92+}$

D. C. Ionescu and A. Belkacem, Phys. Scr. T80 (1999) 128



- Theoretical description of such a process requires an analysis of two-center Dirac problem:
  - Coupled-channel methods
  - Numerical integration on the grid

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Negative continuum dielectronic recombination

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Negative-continuum dielectronic recombination for heavy ions

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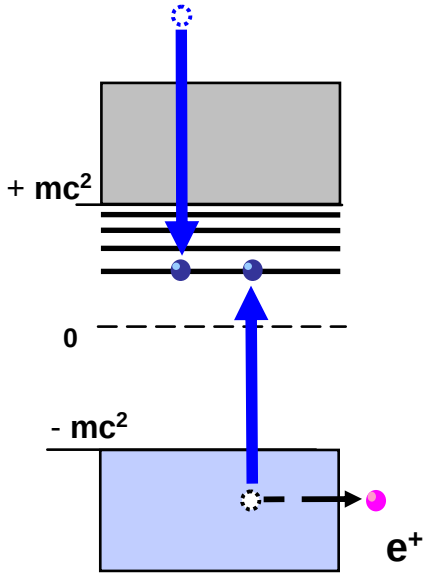
The process of recombination of an electron with a bare heavy nucleus via the creation of a free-positron–bound-electron pair is considered. This process is denoted as "negative-continuum dielectronic recombination" because it results in the capture of an incident electron into a bound state accompanied by a transition of a negative-continuum electron into a bound state. The calculations are performed for a wide range of incident electron energies for $Z=82$ and 92.

- In the negative continuum dielectronic recombination a free (or quasi-free) electron is captured by a heavy ion via the creation if a positron-electron pair.

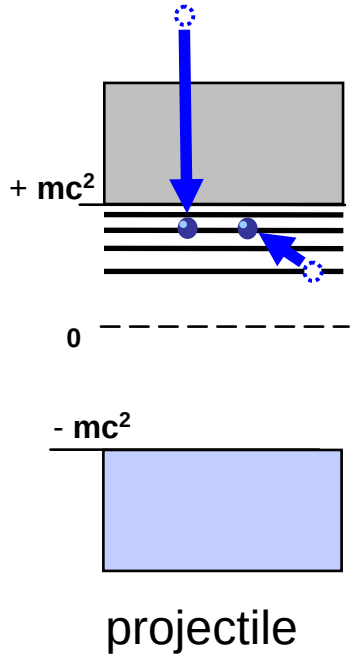
$$X^{Z+} + e^- \rightarrow X^{(Z-2)+} + e^+$$



projectile

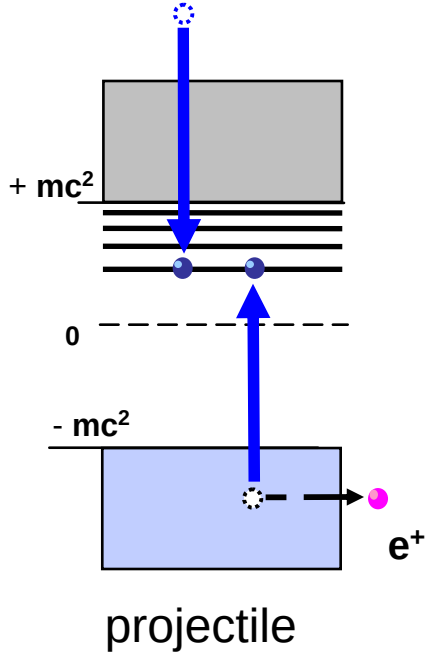
DR vs. NCDR

Dielectronic recombination (DR)



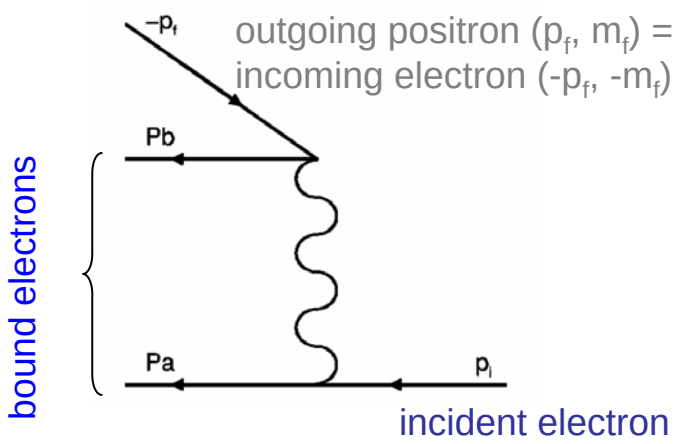
- Few-electron ion in initial state (before the capture).
- Resonant process.

Negative continuum dielectronic recombination (NCDR)



- Ion in initial state can be bare.
- Non-resonant process.
- There is threshold of the process.

NCDR: Basic theory (1)



- Differential cross section:

$$\frac{d\sigma}{d\Omega_f} = \frac{(2\pi)^4}{v_i}\, \boldsymbol{p}_f^2 \left|\tau_{if}\right|^2$$

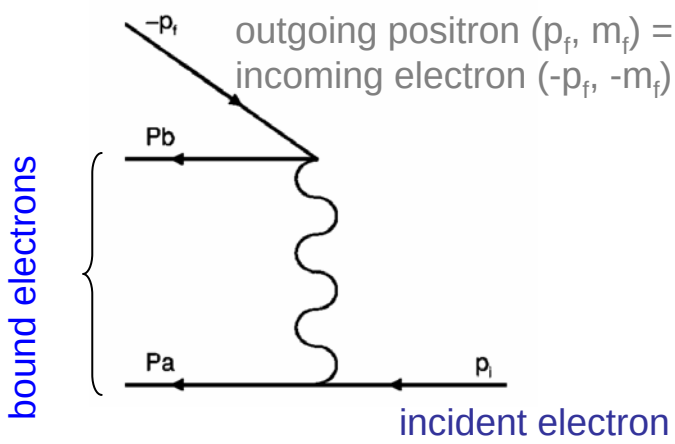
- With the transition amplitude:

$$2\,\pi\, i\, \delta\left(E_i - E_f\right)\tau_{if} = \left\langle \Psi_f \left| \alpha\left(1-\boldsymbol{\alpha}_1\boldsymbol{\alpha}_2\right)\frac{\exp\left(i\left|\omega\right|\left|\boldsymbol{r}_1-\boldsymbol{r}_2\right|\right)}{\left|\boldsymbol{r}_1-\boldsymbol{r}_2\right|}\right| \psi_{p_i m_i}, \psi_{-p_f -m_f} \right\rangle$$

electron-electron interaction (Feynman gauge)

- Electron-electron interaction operator includes not only Coulomb term but also magnetic interactions.

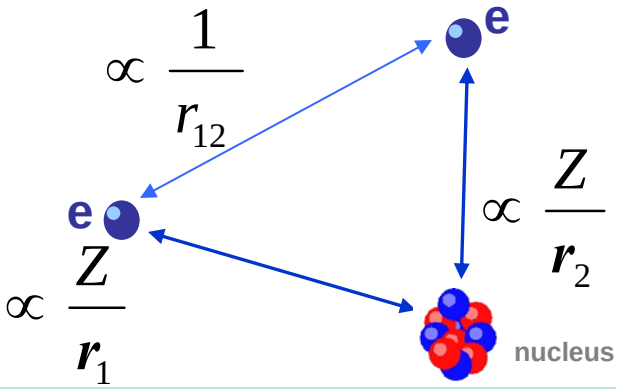
NCDR: Basic theory (2)



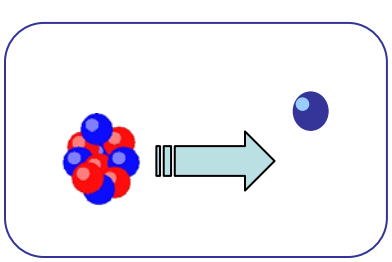
- Final-state wavefunction of helium-like ion is provided within the Independent Particle Model:

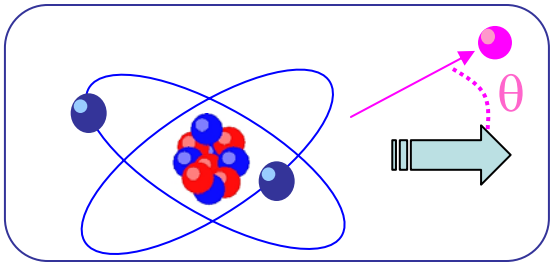
$$\Psi_f(\boldsymbol{r}_1,\boldsymbol{r}_2) = N \sum_{m_a,m_b} \left(j_a\, m_a \;\; j_b\, m_b \middle| JM \right) \begin{vmatrix} \psi_{n_a j_a m_a}(\boldsymbol{r}_1) & \psi_{n_b j_b m_b}(\boldsymbol{r}_1) \\ \psi_{n_a j_a m_a}(\boldsymbol{r}_2) & \psi_{n_b j_b m_b}(\boldsymbol{r}_2) \end{vmatrix}$$

- Good approximation for high-Z ions!

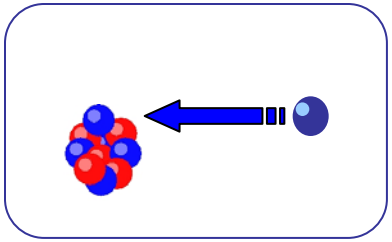


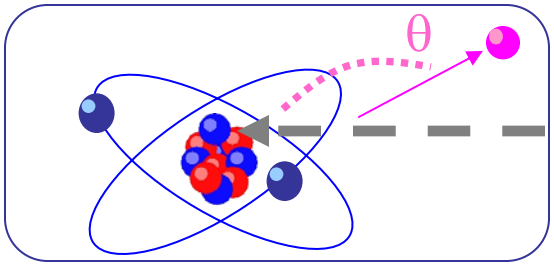
NCDR cross sections





laboratory frame





projectile frame

initial state

final state

- We like to study differential (in positron angle) NCDR cross section for the various collision energies.

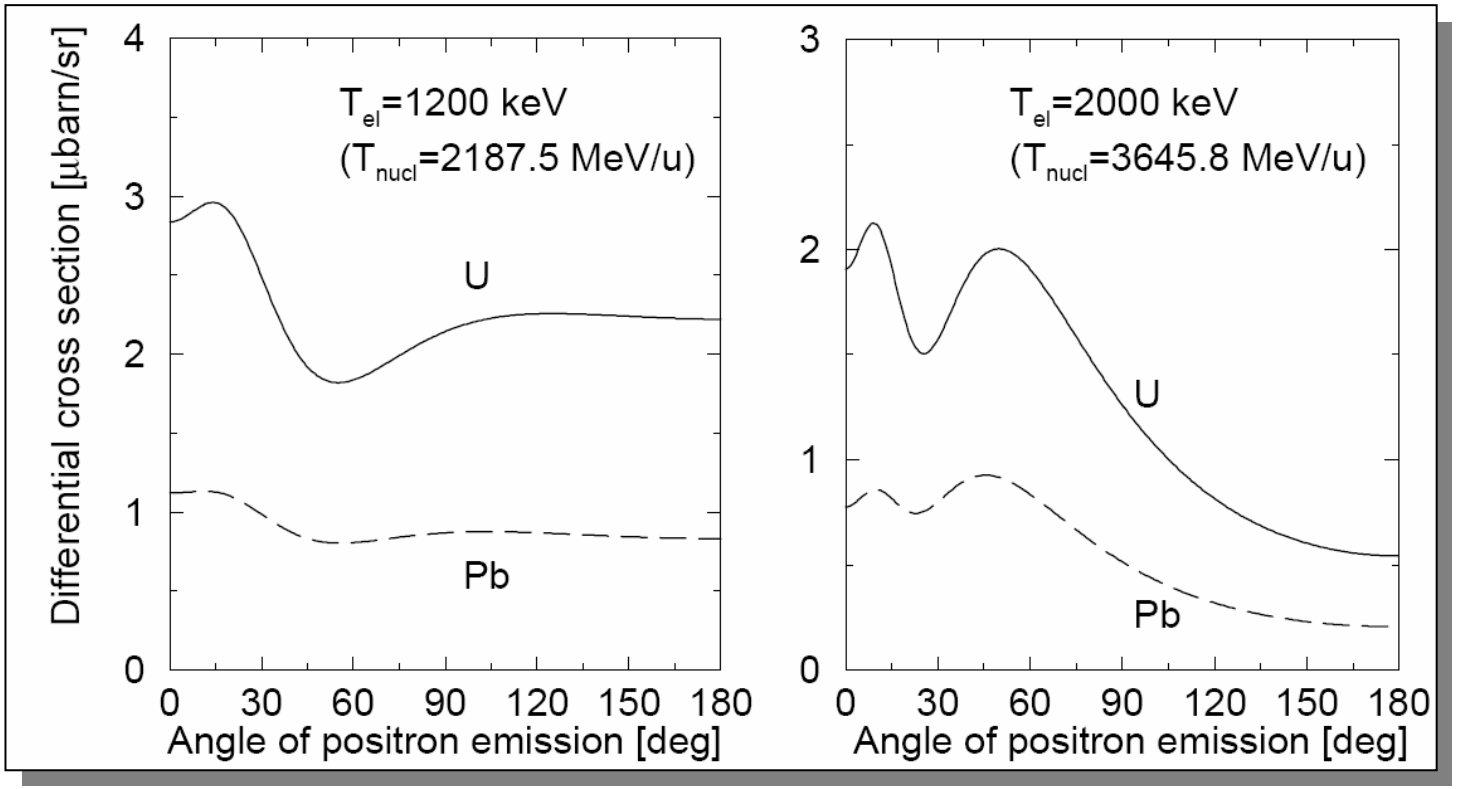
$$\frac{d\sigma}{d\Omega_f}\left(\theta_f, T_p\right) = \frac{(2\pi)^4}{v_i}\, \boldsymbol{p}_f^2 \left|\tau_{if}\right|^2$$

- Threshold for the process:

$$\varepsilon_i \geq E_{1s^2} + mc^2$$

total energy (with rest mass)

Differential cross sections in projectile frame



- Calculations have been carried out within the projectile frame.
- One need to perform Lorentz transformation to evaluate differential cross section in the laboratory frame.

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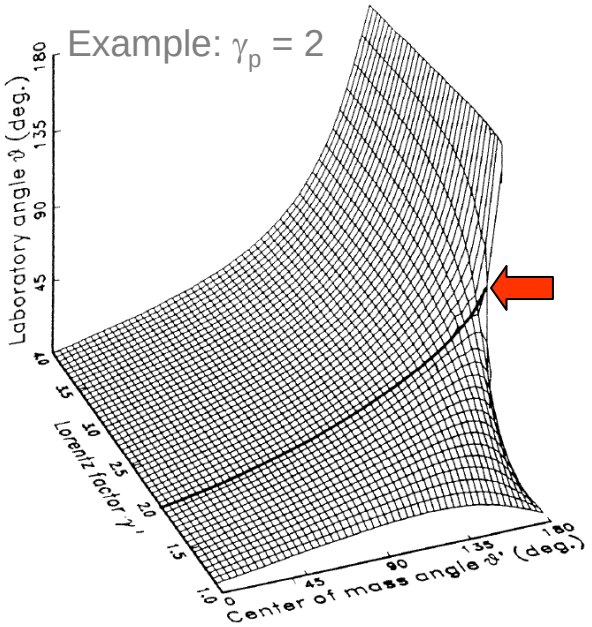
Lorentz transformation

- One has to transform the positron emission angle:

$$\tan\theta = \frac{\sin\theta'}{\gamma_p\left(\cos\theta' + \beta_p / \beta'\right)}$$

Note: in the laboratory frame there exists a maximal value of the angle θ for which emission is possible!

$$\sin\theta_{\max} = \frac{\beta'\gamma'}{\beta_p\gamma_p}, \quad \left(\beta' < \beta_p\right)$$



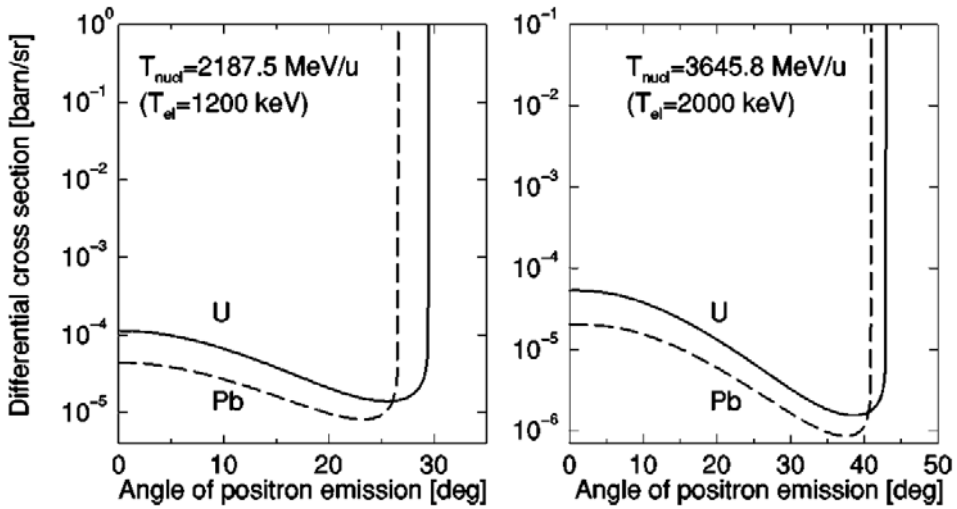
J. Eichler and W. Meyerhof,
Relativistic atomic collisions (1995)

- And the differential cross section:

$$\frac{d\sigma}{d\Omega} = \left|\frac{d\Omega'}{d\Omega}\right| \frac{d\sigma}{d\Omega'}$$

Note: when the emission angle reaches its maximum, the differential cross section (in lab. frame) becomes infinite!

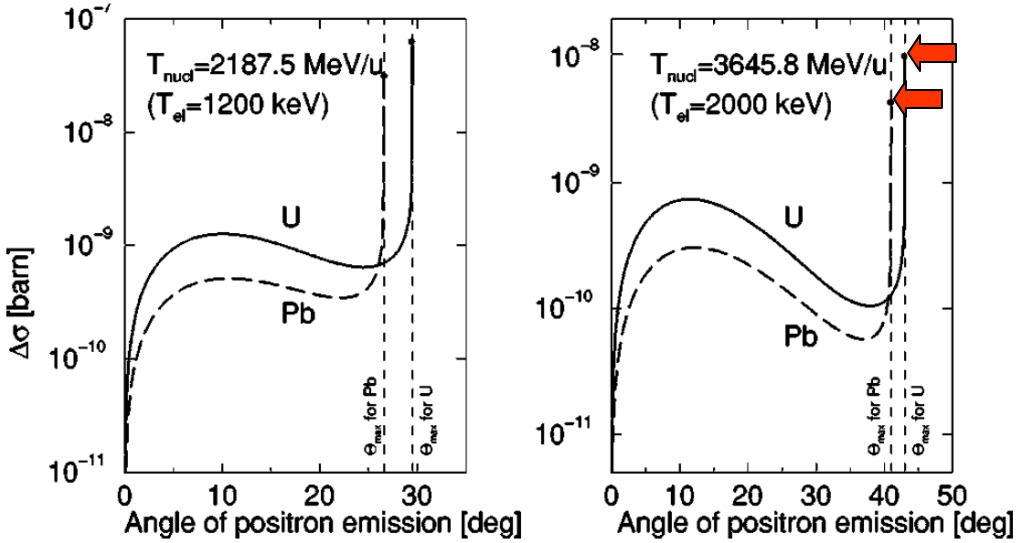
Differential cross sections in laboratory frame



- Despite the singularity, the integral of the differential cross section over the angle in both frames converges and yields the same value (i.e. the total NCDR cross section).

- Calculations have been done for the value:

$$\Delta\sigma(\theta) = 2\pi \int_{\theta}^{\theta+\Delta\theta} \frac{d\sigma}{d\theta} \sin\theta \, d\theta$$



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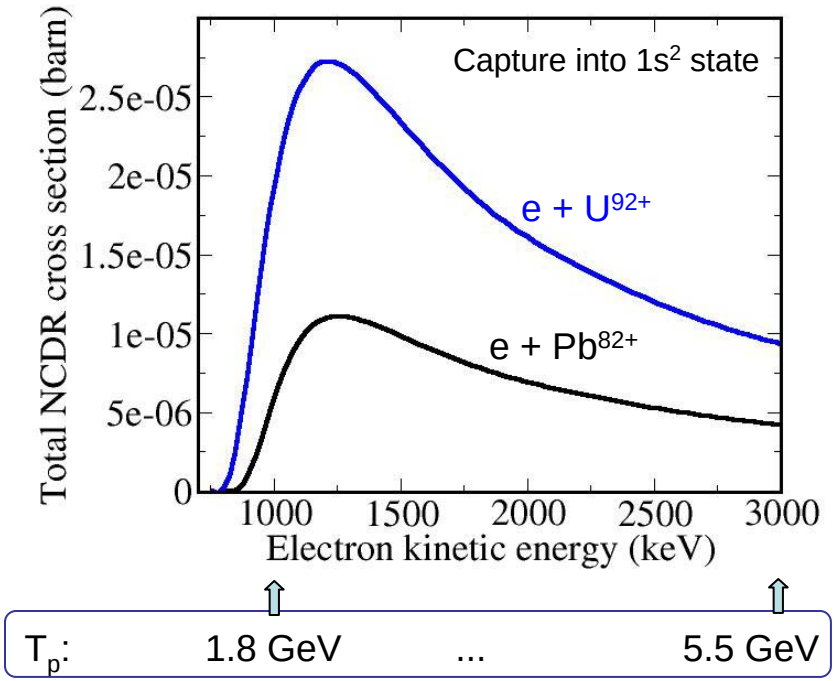
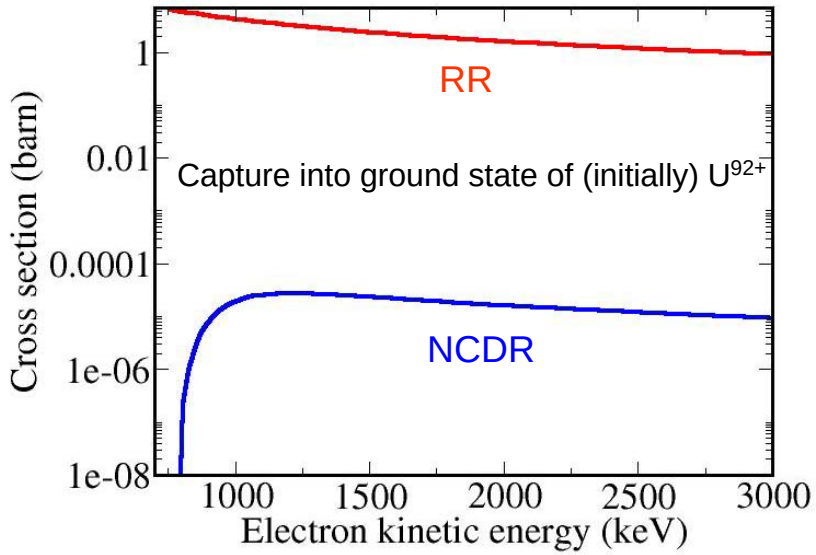
Total NCDR cross sections



- The NCDR cross section increases rapidly above the threshold and has a maximum slightly above the energy needed to create a free electron-positron pair.

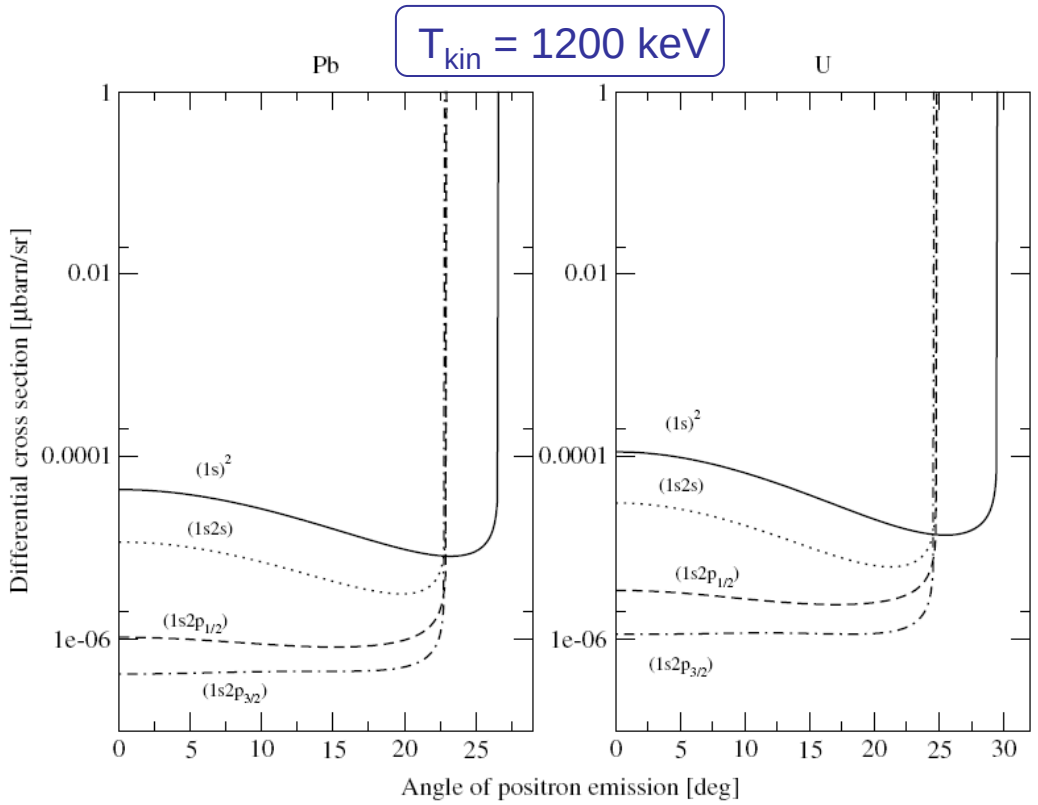
$$X^{Z+} + e^- \rightarrow X^{(Z-1)+} + e^+ + e^-$$



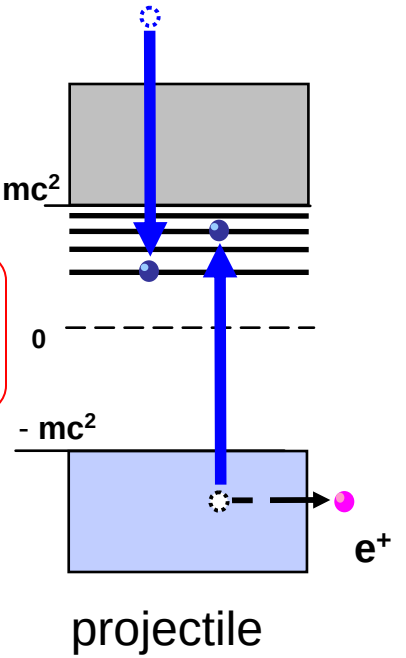
- The NCDR cross sections are by (about) six orders of magnitude smaller than the RR cross sections.

Capture into excited ionic states (1)

- Calculation have been also performed for the NCDR into excited states of (finally) helium-like ions.



$$\sin\theta_{\max} = \frac{\beta'\gamma'}{\beta_p\gamma_p}$$



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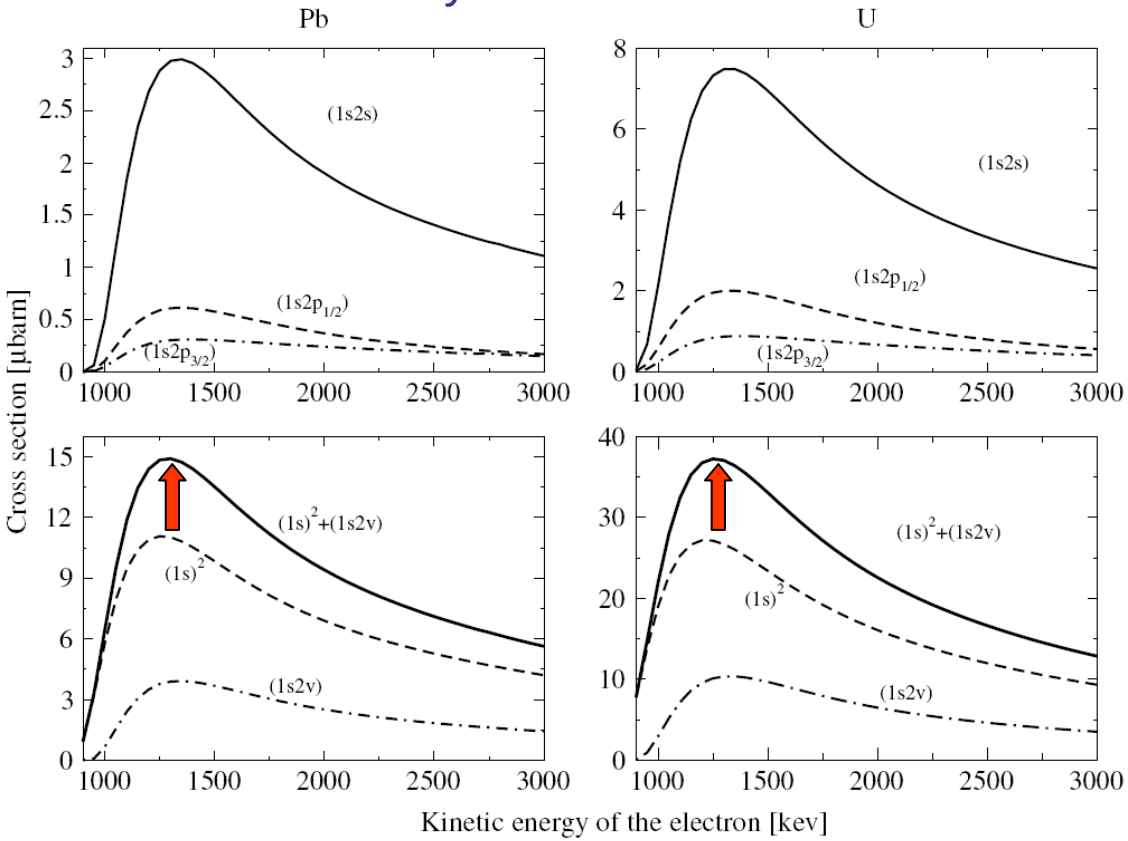
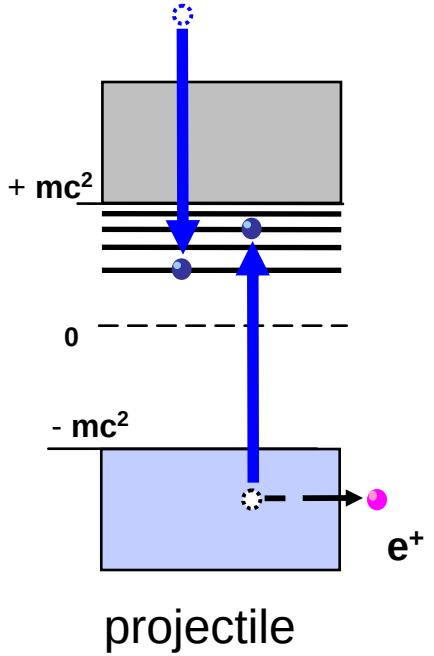
A. N. Artemyev *et al.*, to be published

- The maximum scattering angle will be different for NCDR into bound states with different angles.

Capture into excited ionic states (2)

- Calculation have been also performed for the NCDR into excited states of (finally) helium-like ions.
- Capture into excited states enhance the total NCDR cross section by about 25 %.





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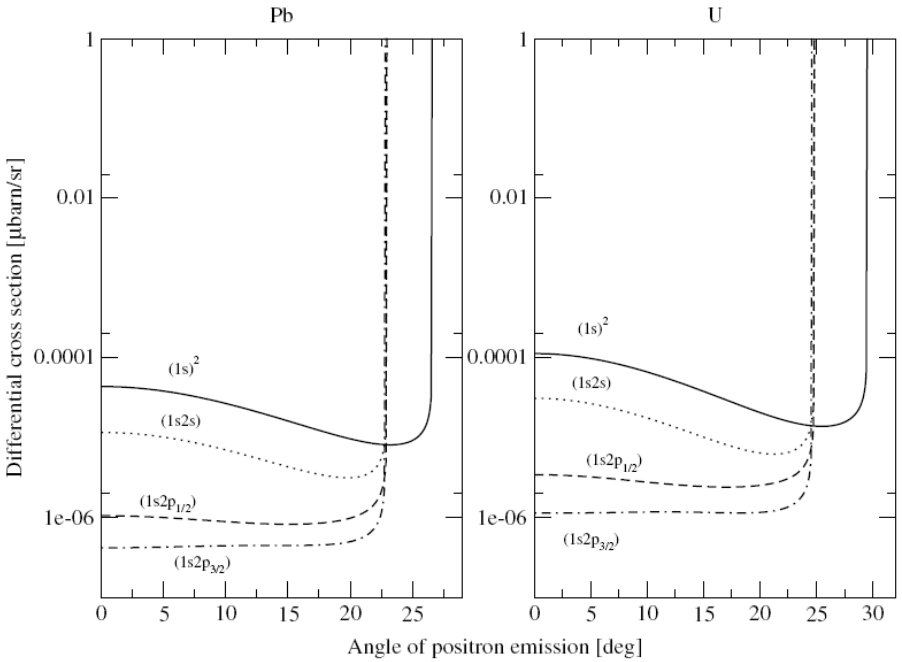
The role of Compton profile

- So far calculations have been performed for the “delta-function-like” energy distribution of the incoming electrons and ion beam.

- If incident electrons or ions have some energy distribution that is expected to remove the singularity in the differential cross section.



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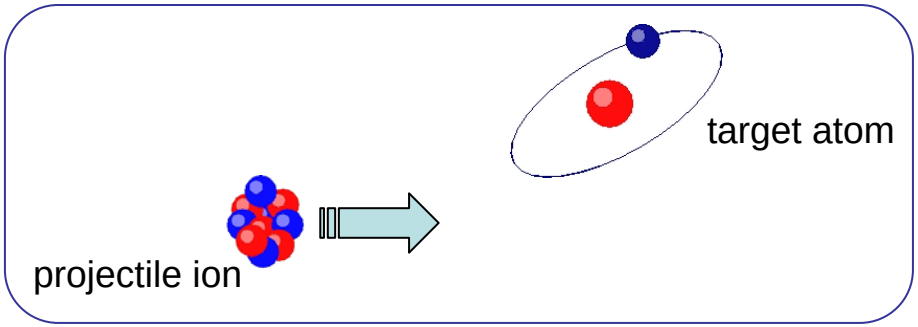
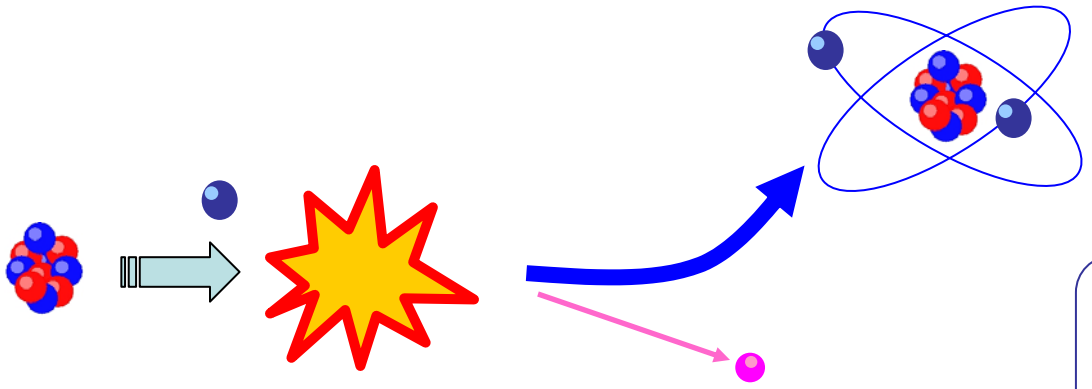


- Experiments at:
  - Electron target (cooler) ?
  - Jet target ?
  - Foil target ?

Scenarios for the future experiments

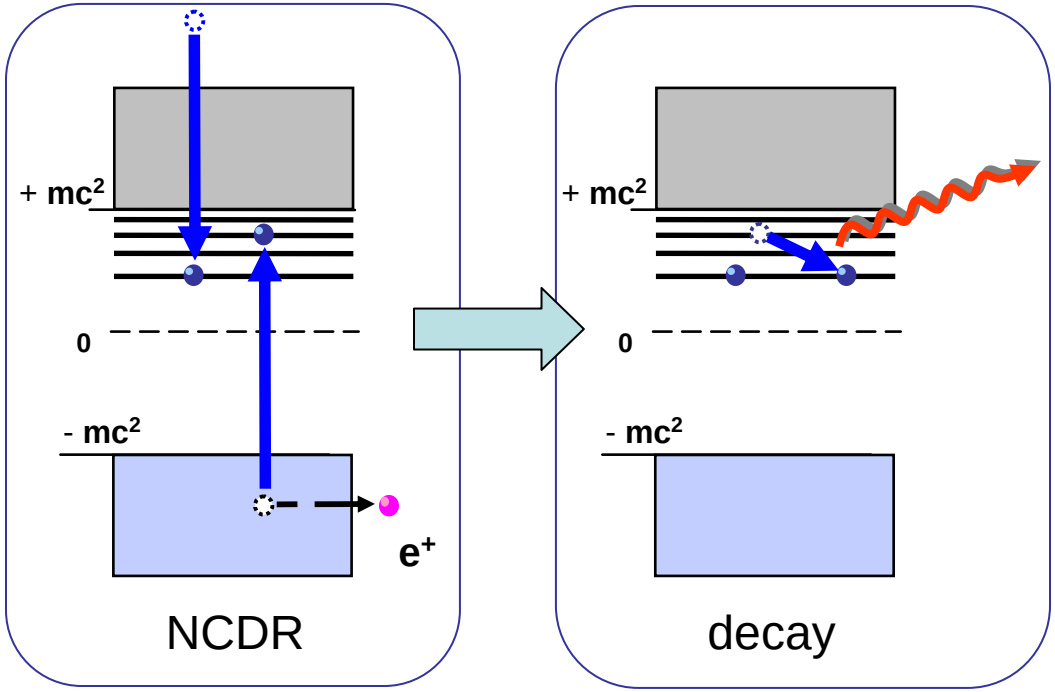
- Probable scenario is “coincidence experiment” in which emitted positron is detected in coincidence with $X^{(Z-2)+}$ ion.
- The “signature” of the process is: forward positron emission (in lab. frame) associated with projectiles that captured two electrons.



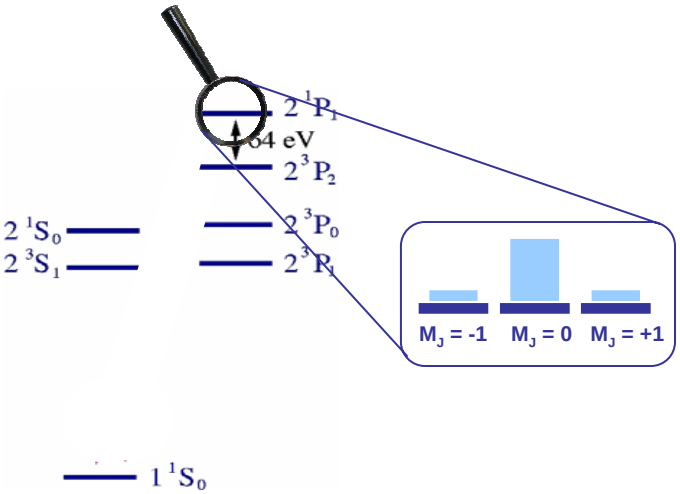
Competitive processes? (RDEC and DREC, pair production)

Can we employ positron angular distributions to separate out experimentally competitive processes?

Radiative stabilization following NCDR



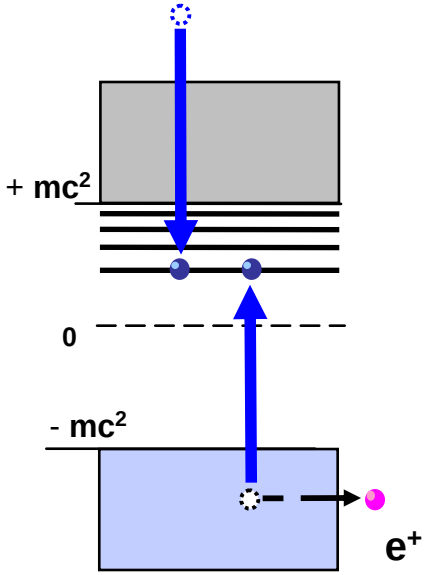
- Can we use emission pattern of characteristic radiation following NCDR as another “signature” of the process?
- Can we study magnetic terms of electron-electron interactions?



- Analysis is to be performed for the magnetic sublevel population (alignment) of residual He-like ions following NCDR.

Summary

- We have recalled the NCDR process which provides a new mechanism for production of electron-positron pairs in heavy ion collisions.
- Total and differential cross sections of this process have been discussed in detail both for the capture into ground and excited states.



- Future studies are to be performed towards more realistic NCDR scenarios.
- We plan to explore properties of characteristic x-ray emission following NCDR.

Thank you for your attention!