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Study of cascade processes in $p\mu^-$ and pK^- atoms based on a new approach

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Atomic formation (initial stage):

$\{p\mu^-, pK^-\}$ (n_0, l_0, E_0)

$$n_0 \sim \sqrt{\frac{m}{m_e}}, \quad n_0^{(K)} \approx 30, \quad n_0^{(\mu)} \approx 14, \quad W \approx \frac{2l_0+1}{n_0^2}, \quad E_0 \sim 1\ eV.$$

Cascade processes (de-excitation stages):

$$(px^-)_{nl} + H_2 \to (px^-)_{n'l'} + H_2 \quad \begin{cases} \textit{elastic scattering } (n' = n,\ l' = l), \\ \textit{Stark transitions } (n' = n,\ l' \neq l), \\ \textit{Coulomb transitions } (n' \neq n), \end{cases}$$

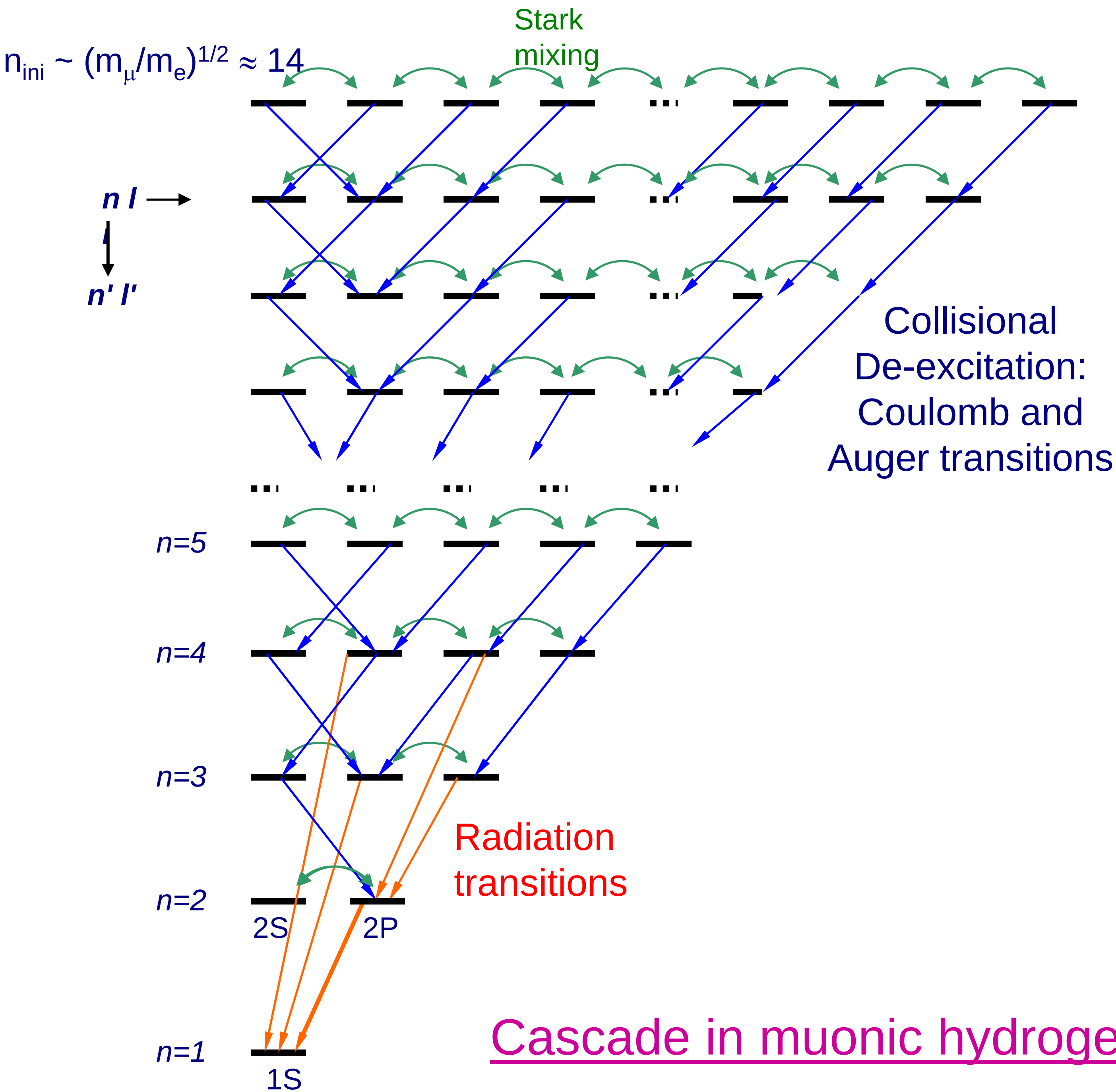
$$x^- = K^-, \mu$$

$$(px^-)_{nl} + H_2 \to (px^-)_{n'l'} + H_2^+ + e^- - \textit{Auger transitions } (n' < n),$$

$$(px^-)_{nl} \to (px^-)_{n'l'} + \gamma \quad - \quad \textit{radiative transitions } (n' < n).$$

Accompanying processes:
weak decay,
nuclear absorption.

Cascade in muonic hydrogen



Mechanisms of $(px^-)_{nl}$ exotic atoms acceleration

$$(px^-)_{nl}(E) + p \rightarrow (px^-)_{n'l'}(E') + p \quad - \textit{ Coulomb transitions } (n' < n,\ E' > E),$$

$$(px^-)_{nl}(E) + H \rightarrow (px^-)_{n'l'}(E') + p + e^- - \textit{ Auger transitions } (n' < n,\ \Delta = n_1 - n_2 \geq 0),$$

$$(px^-)_{nl} + H \rightarrow C' + e^-,\ C' \equiv \left[(px)_{n'l'}\, p\right] \quad - \textit{ Auger capture } (n' = n - 1,\ \Delta = n_1 - n_2 < 0),$$

$$C' \rightarrow C'' + \gamma,\quad C'' \equiv \left[(px)_{n''l''}\, p\right] \quad - \textit{ radiative deexcitation } (n' < n),$$

$$C' \rightarrow (px)_{n''l''} + p \quad - \textit{ predissociation } (n'' < n' = n - 1).$$

The general problem: $(px)_{nl} + H \rightarrow$ *all final states*

The existing approaches to solve this problem:

Quantum Mechanics (QM) methods:

- four-body problem;
- multi-channel Coulomb problem ($n^2 \sim 100 \div 1000$ muonic/kaonic states);
- total and differential cross sections, the most part of which are lacking.

Classical Mechanics (CM) description:

- four planets problem (classical collisions);
- Coulomb charged planets, including the muon motion;
- natural description of multi-quantum Coulomb transitions ($\Delta = n - n' > 1$);
- possibility to take into account protons chemical binding in H_2 molecule.

Good argument for solution of the QM problem by CM methods is successful description of electron charge exchange in collisions of multi-charged ions with hydrogen atoms (R. Olson and A. Salop, 1976): differences between calculated and experimental cross-sections are about ~20%.

Another argument is the Bohr Correspondence Principle: CM results coincide with QM ones at large n.

New Quantum-Classical Monte Carlo method

Proposed scheme **(NQCMC)** of cascade calculations:

- **Radiative transitions are considered by QM methods;**
- **Collisions are considered by methods of CM;**
- **Auger processes are treated semiclassically.**

The processes of Auger capture are negligible for heavy exotic atoms (e.g., pK^-), which become more and more energetic during the cascade due to multi-quantum Coulomb transitions.

How Auger processes is important for light exotic atoms $p\mu$?

Block-scheme of muonic atom cascade in hydrogen

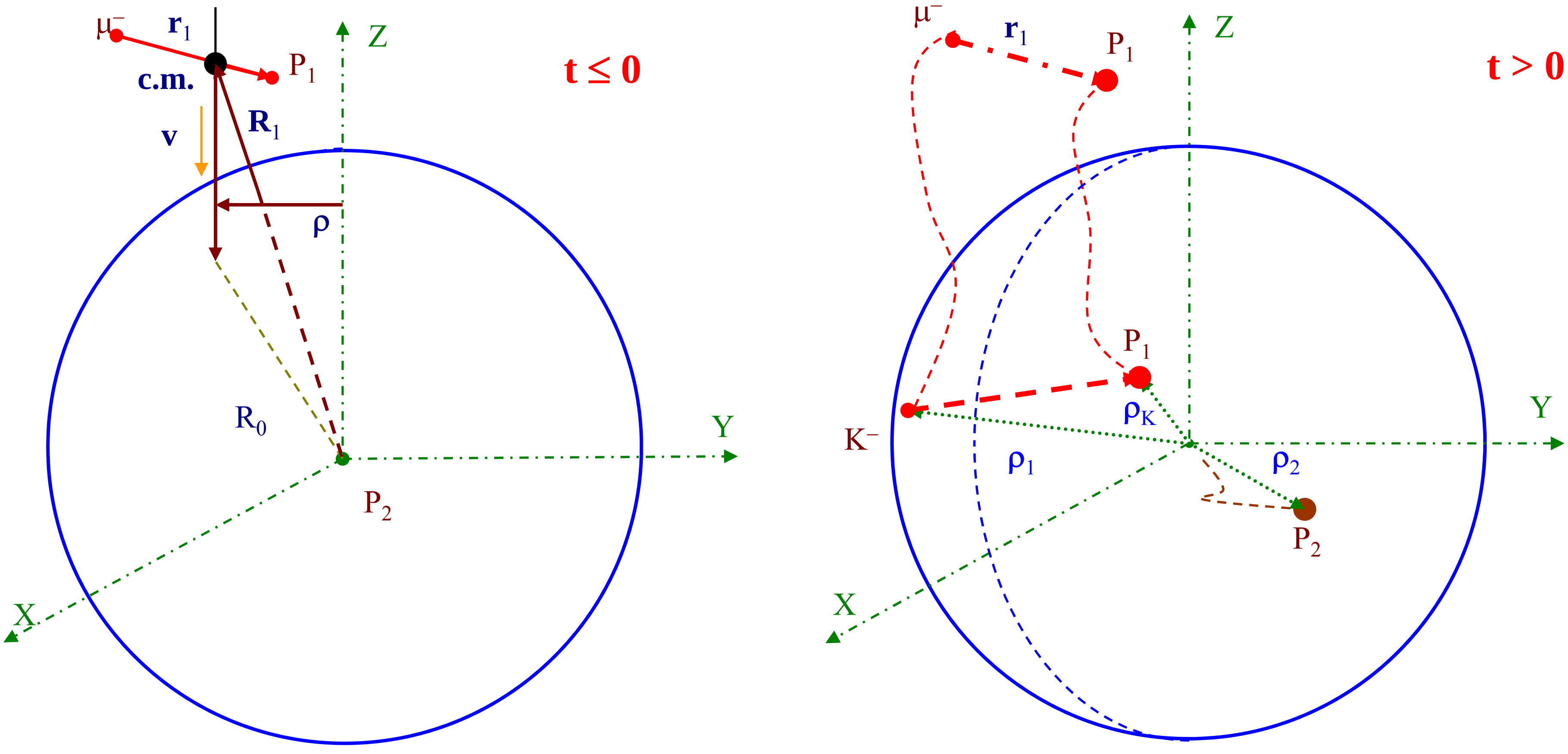
Output:

- cross-sections of Coulomb, Stark and Auger transitions;
- kinetic energy distributions;
- decay characteristics of the exotic molecular complex;
- cascade time in the exotic atom;
- Doppler broadening of the atomic {nl}-state;
- X-ray yields.

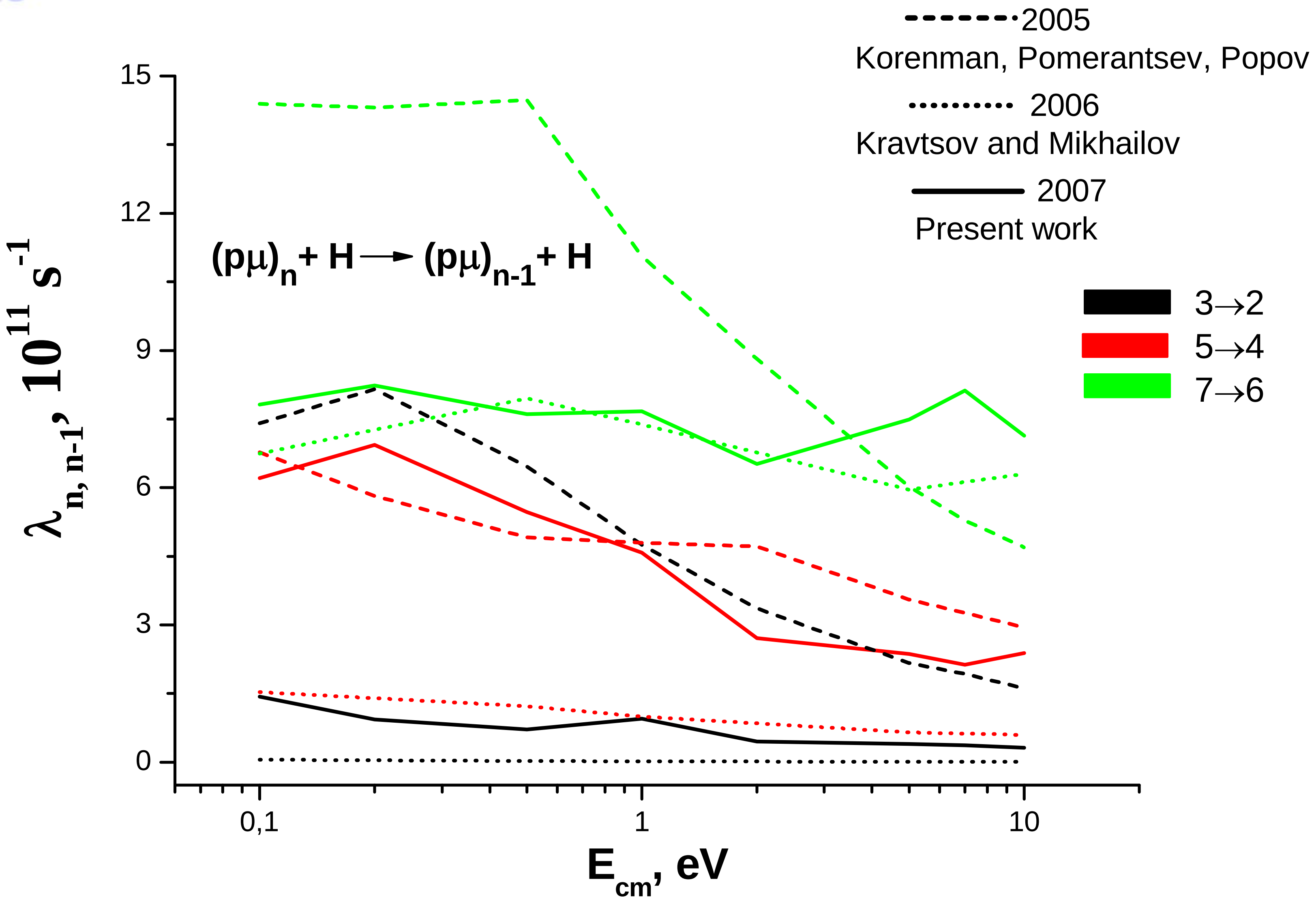
“Initial data” sphere

$\rho_1(t)$, $\rho_2(t)$, $\rho_K(t)$ – vector-coordinates of two protons and muon;

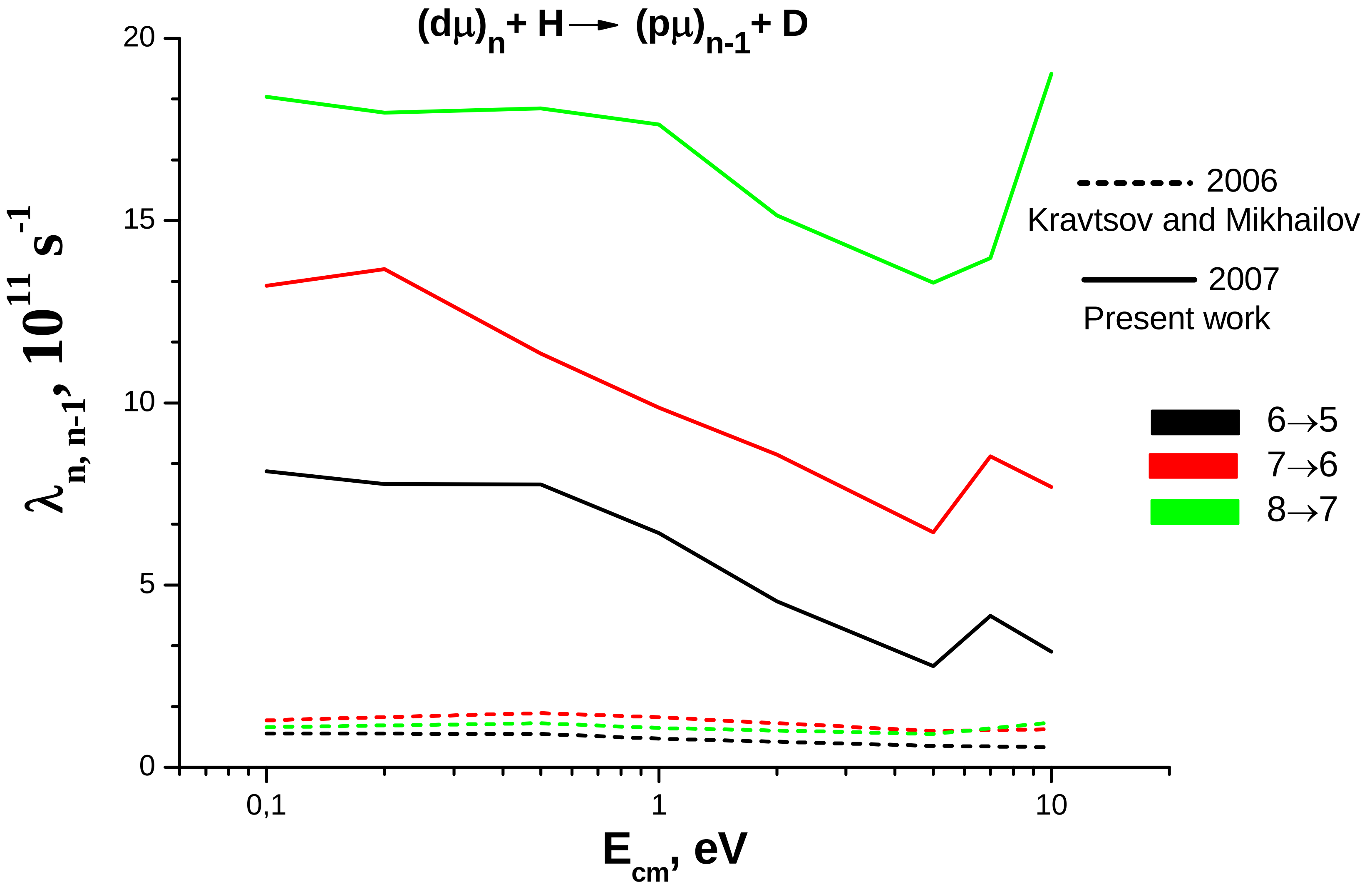
ρ – impact parameter; $\mathbf{R}_1 = \mathbf{R}_{c.m.} - \rho_2$.

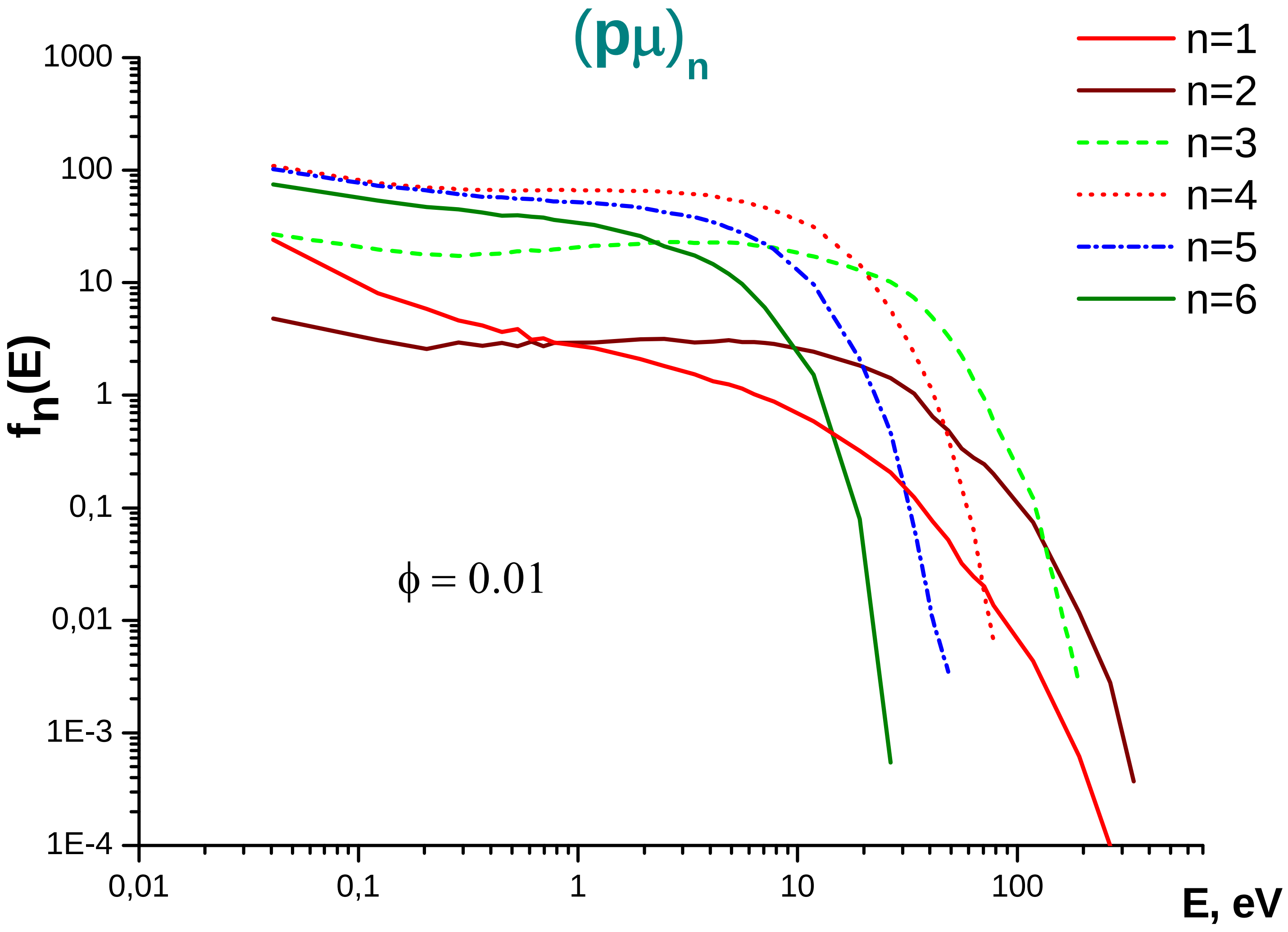


Coulomb de-excitation

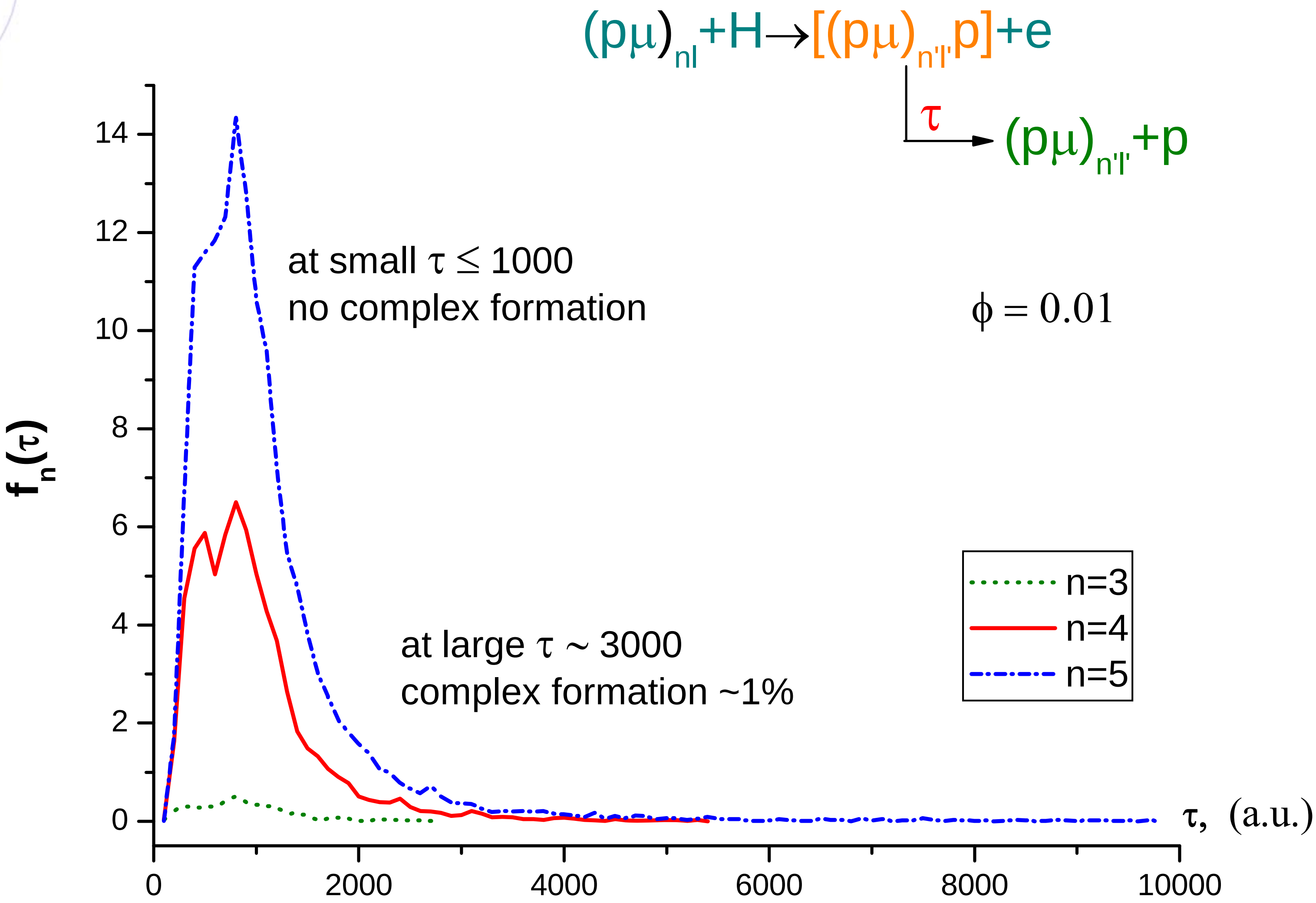


Charge exchange reaction

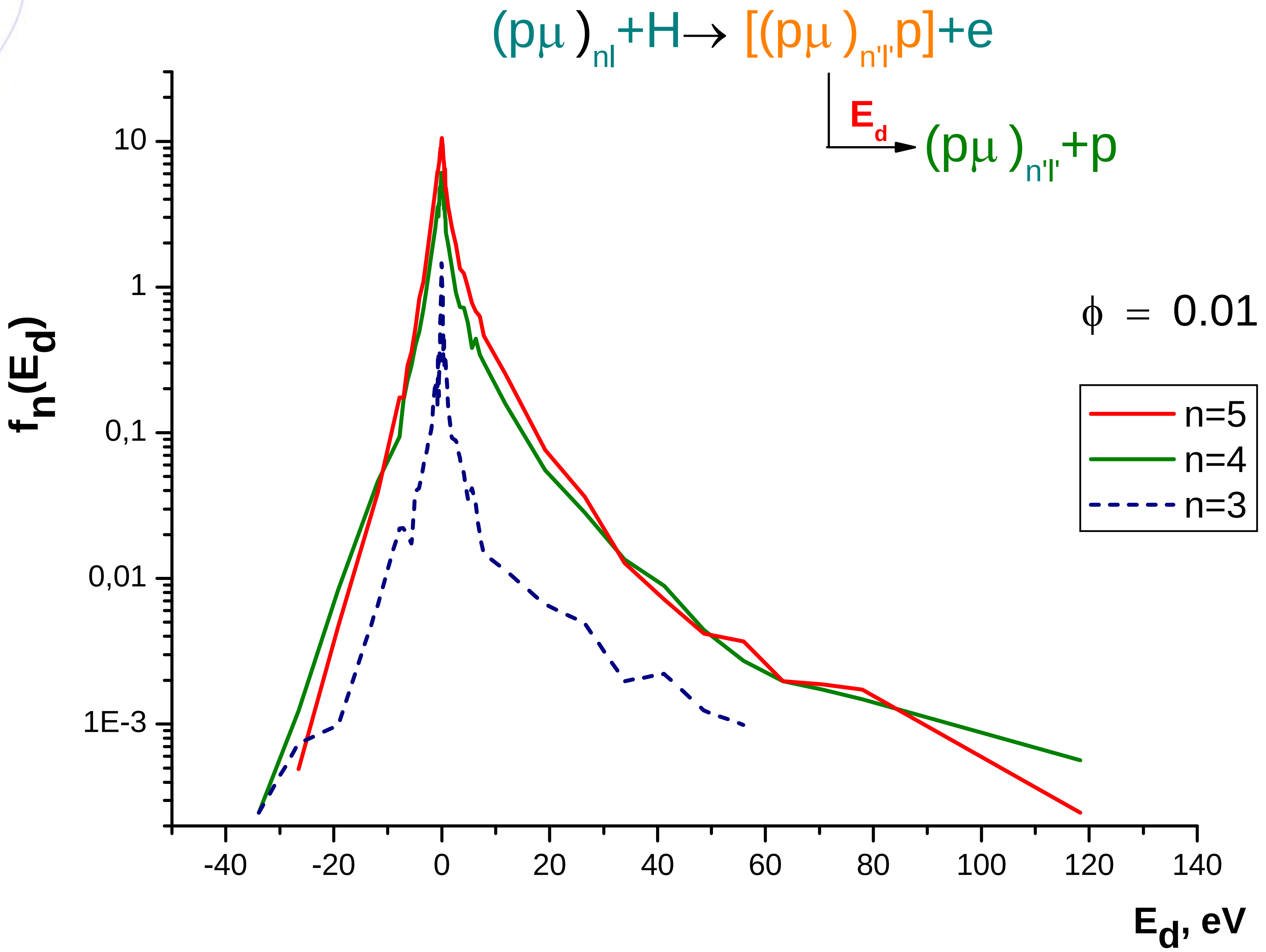




Kinetic energy distributions of (pμ) atoms in *n*-state at density ϕ=0.01 LHD.

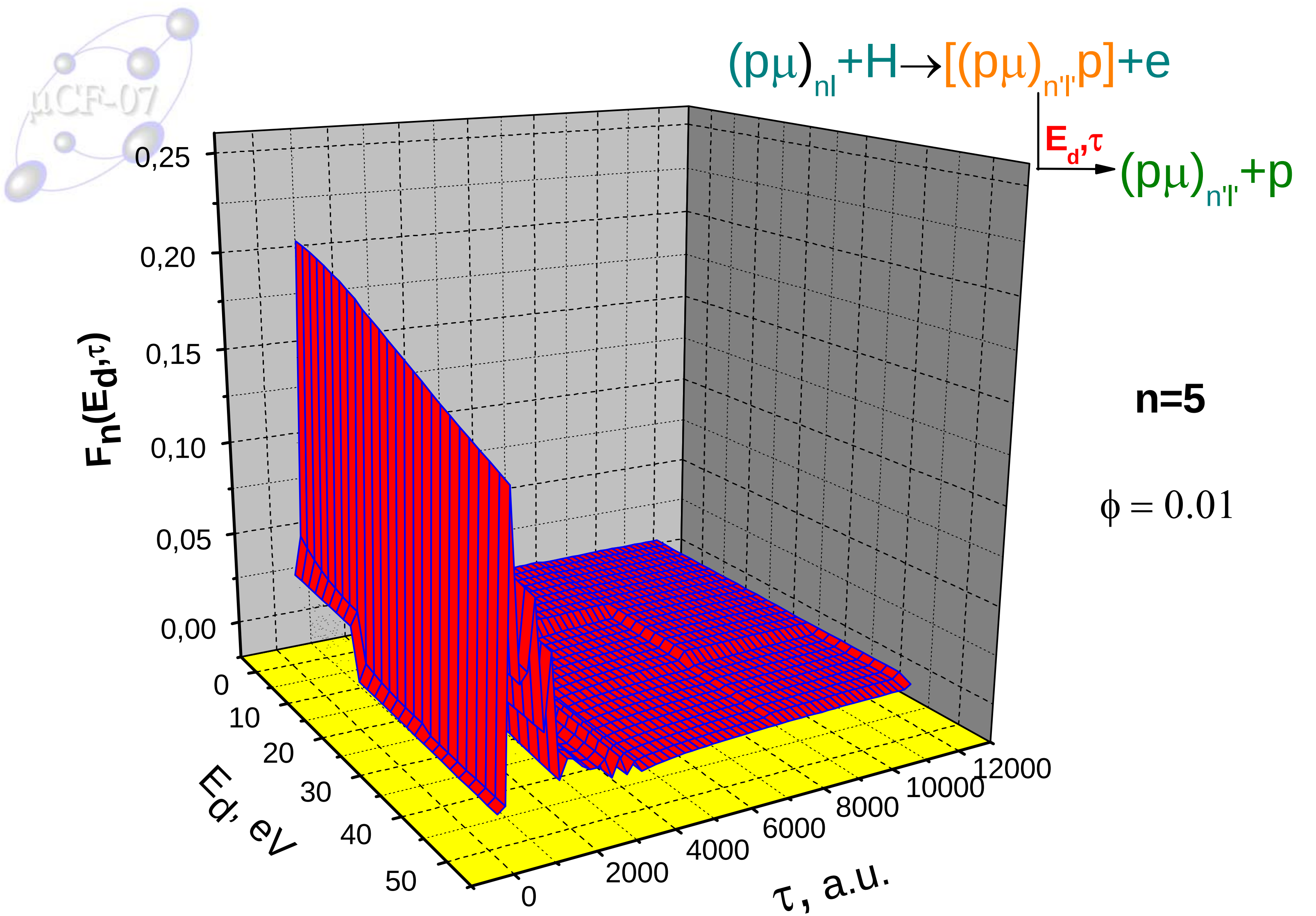


Time decay distributions of the muonic molecular complexes formed in Auger capture processes.



Distributions of (pμ) atoms over kinetic energy difference

$E_d = E_{p\mu(nl)} - E_{p\mu(n'l')}$ gained after Auger process.

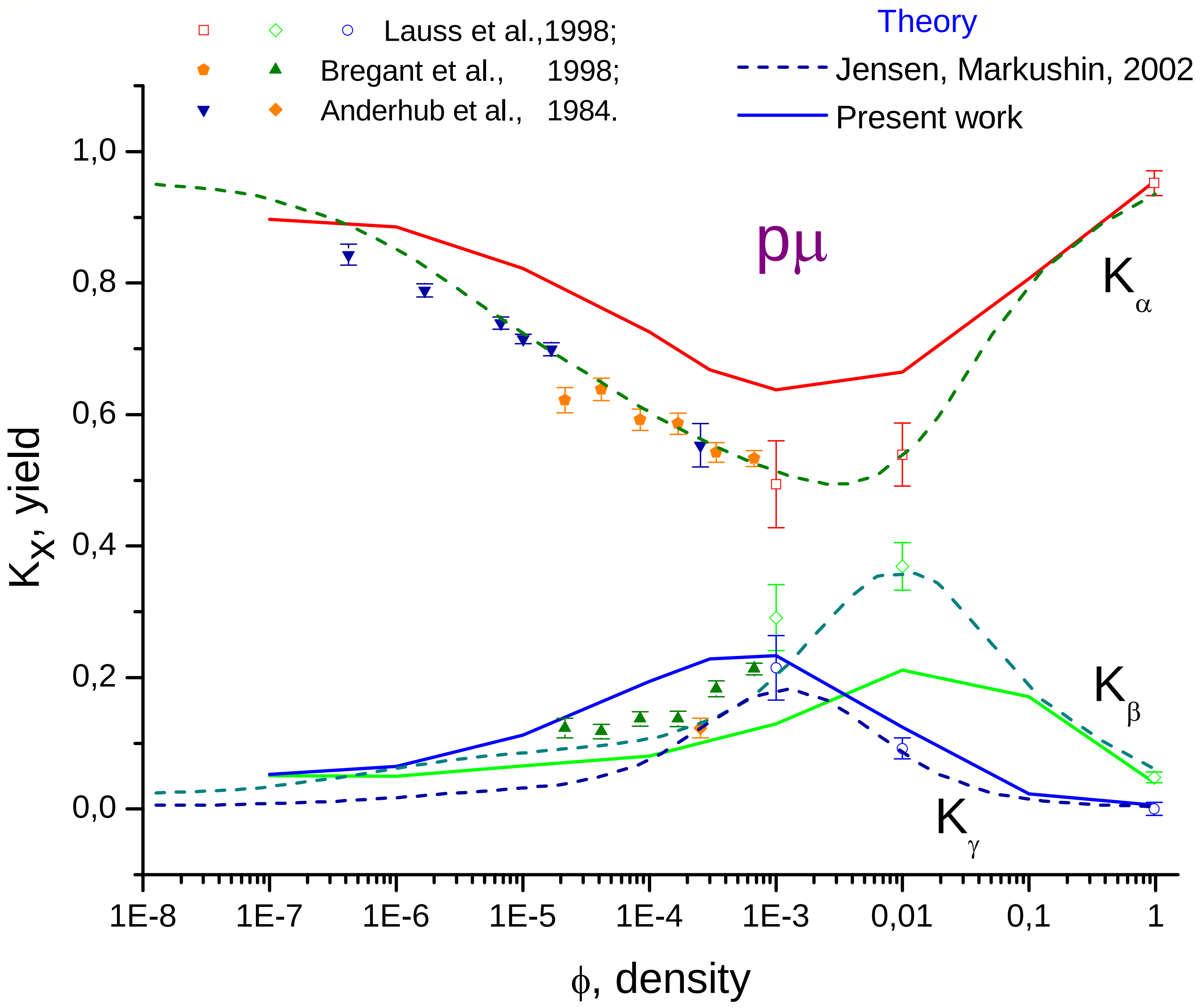


Distribution of (pμ) atoms over kinetic energy difference E_d and time decay τ after decay of the muonic molecular complex:

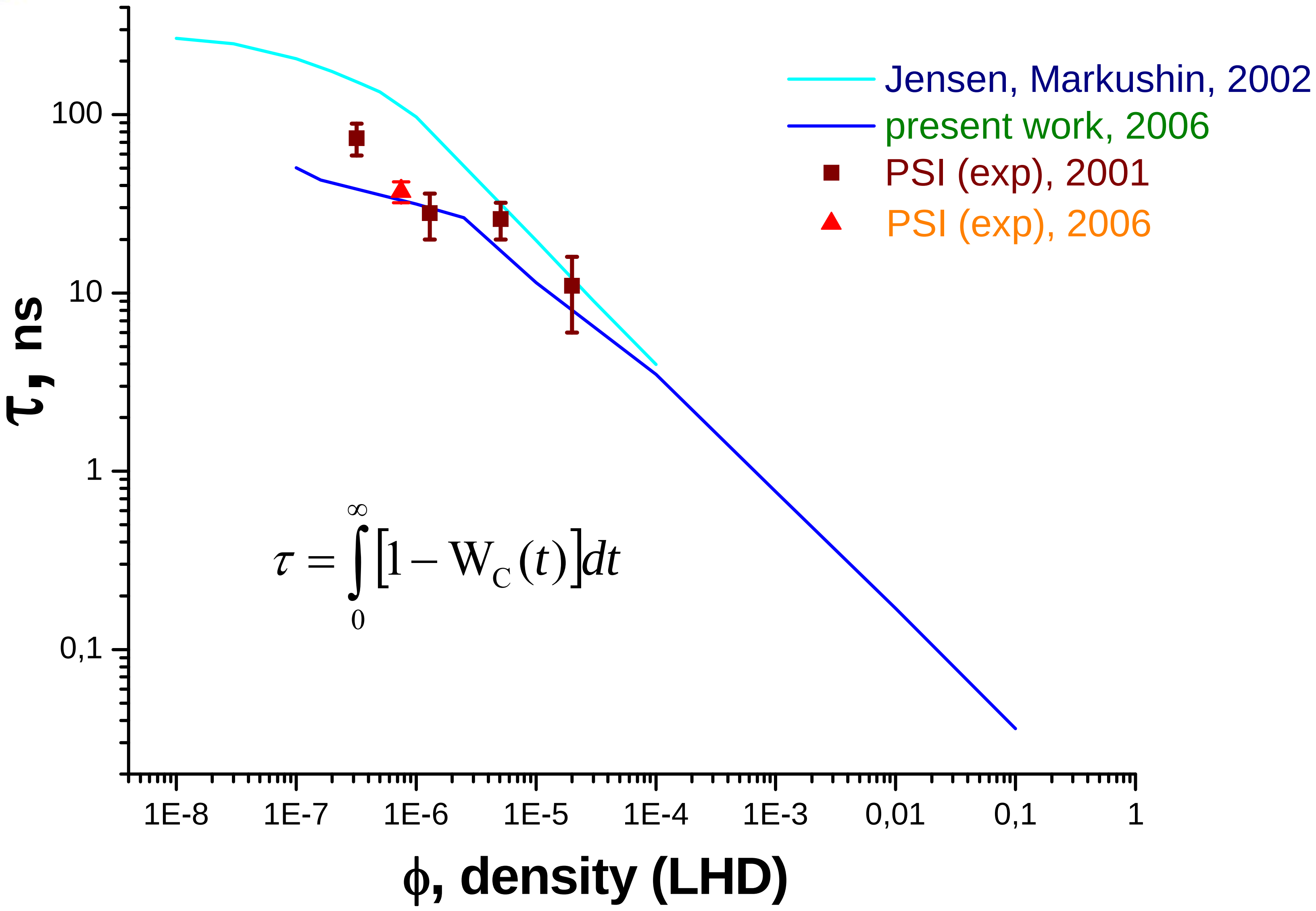
small τ, large E_d – Coulomb transitions;

large τ and E_d – predissociation (~1% of events)

X-ray yields in the muonic hydrogen

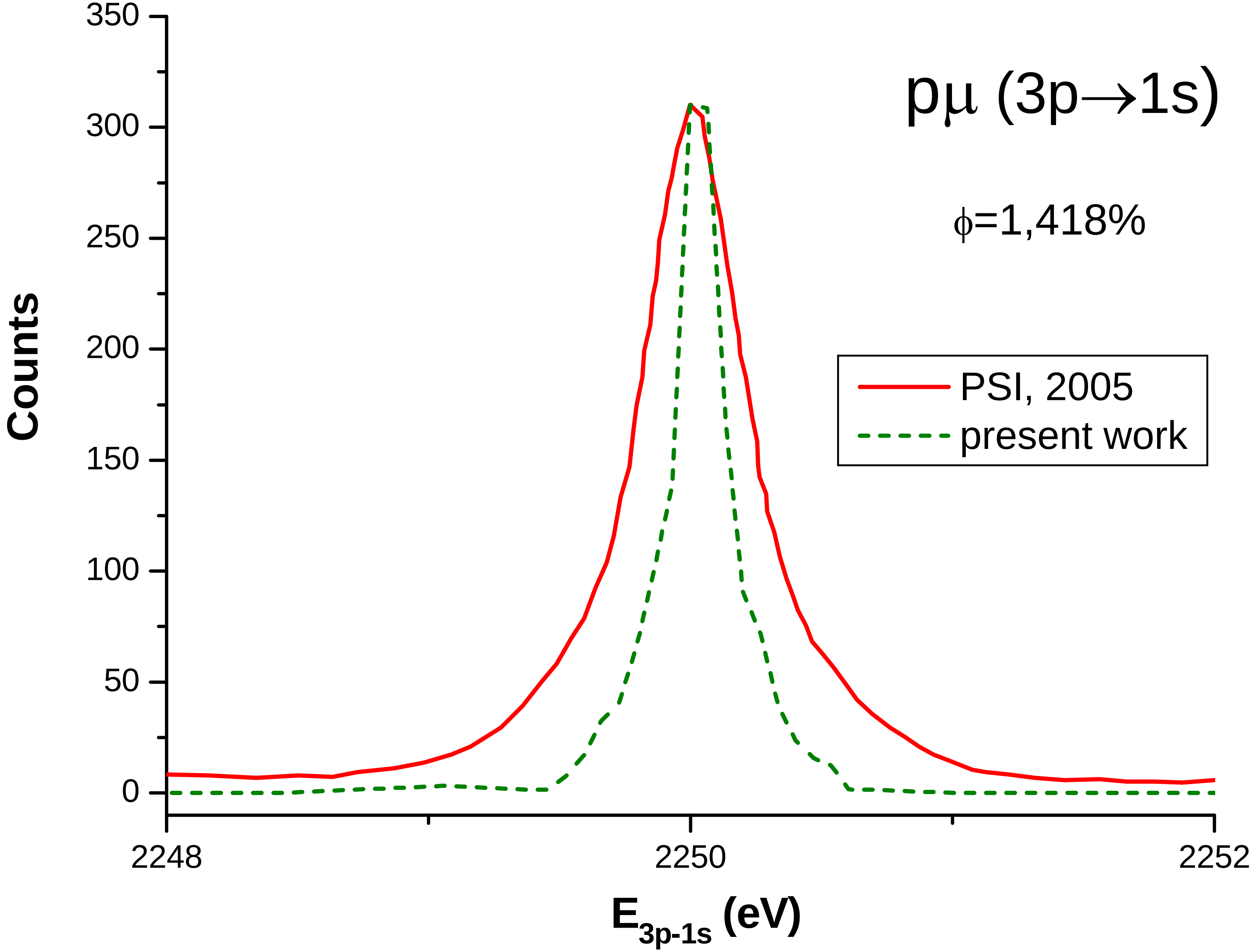


pμ atomic cascade time

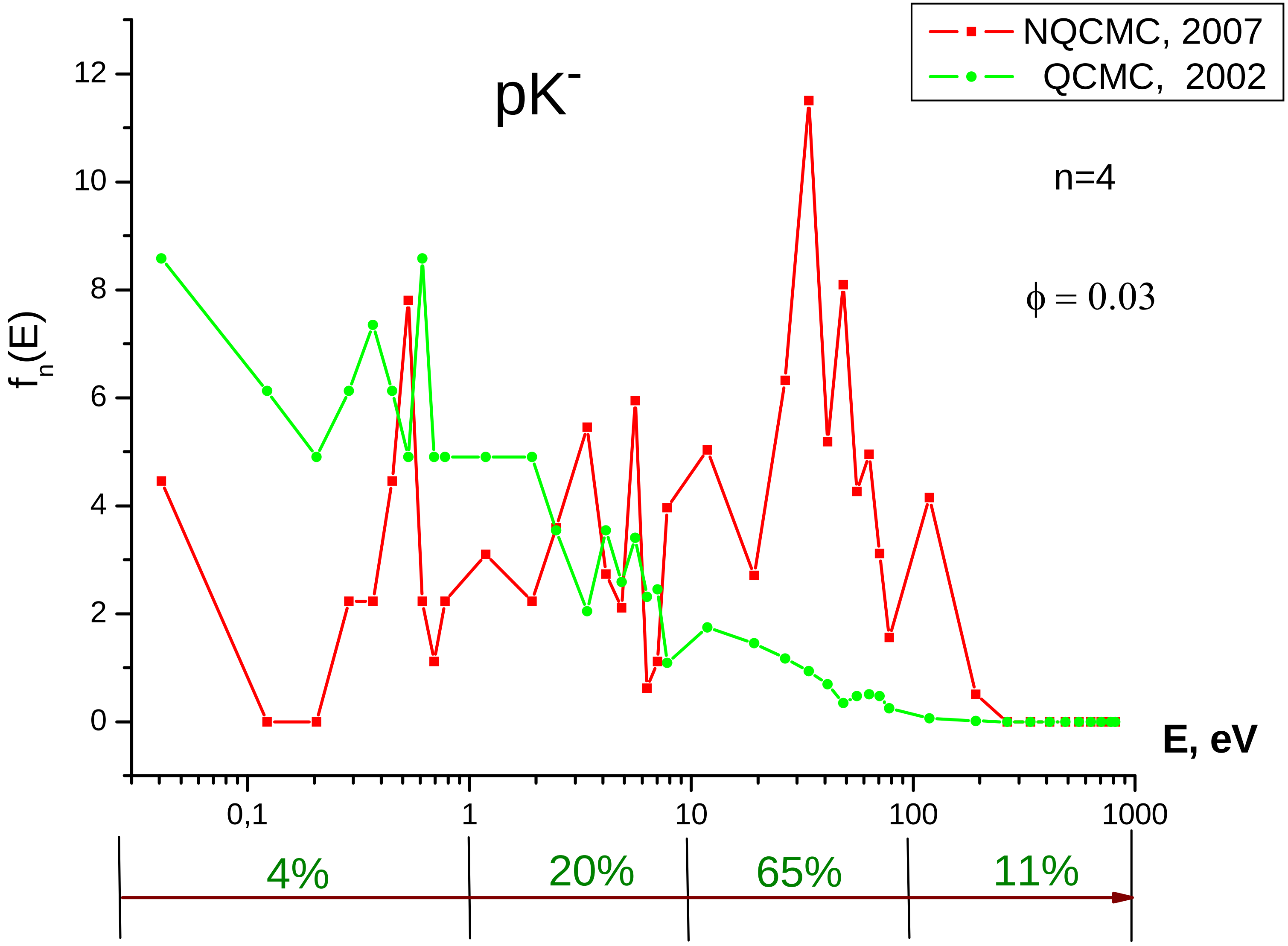


$$\tau = \int_0^\infty [1 - W_C(t)]dt$$

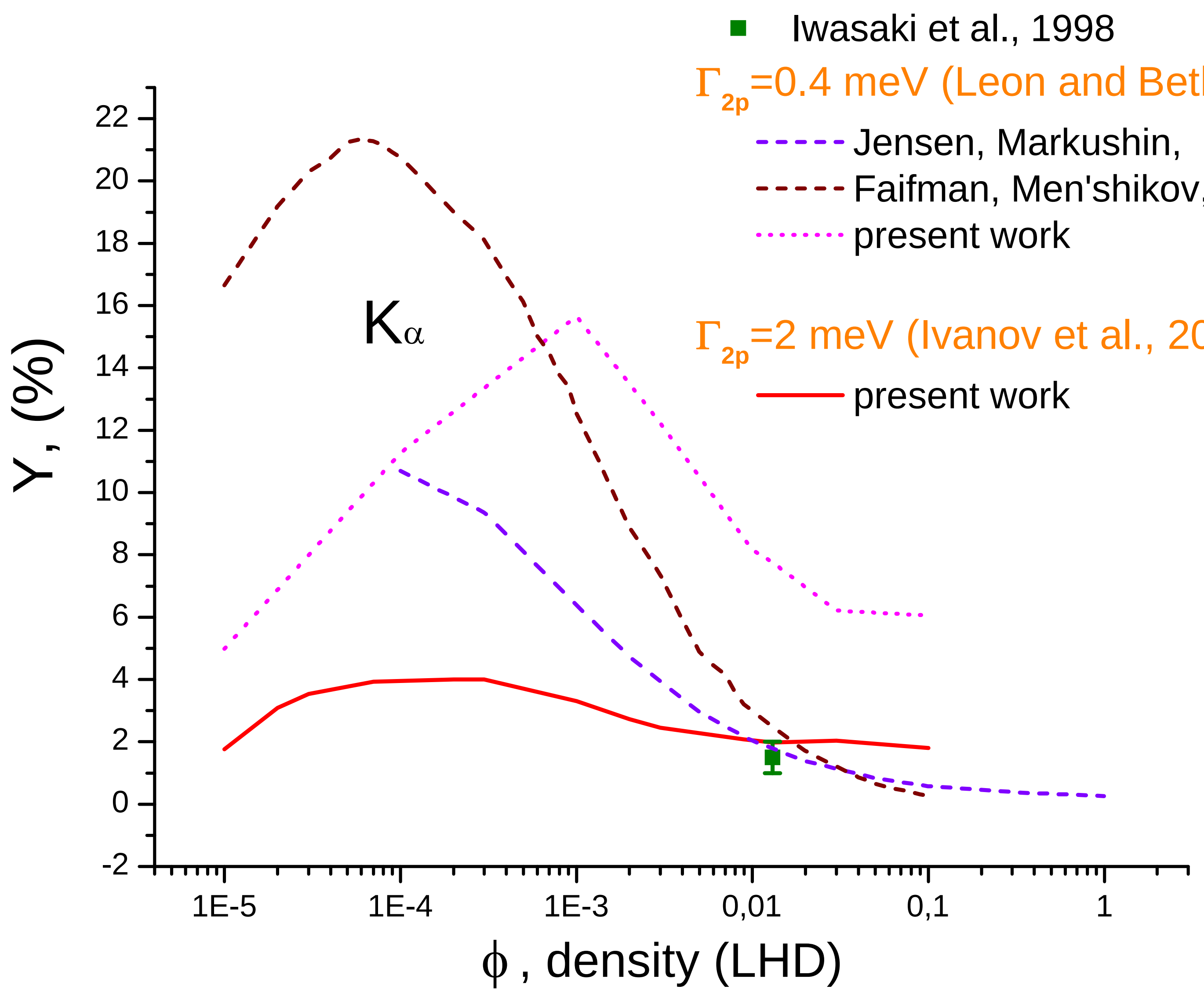
Doppler broadening



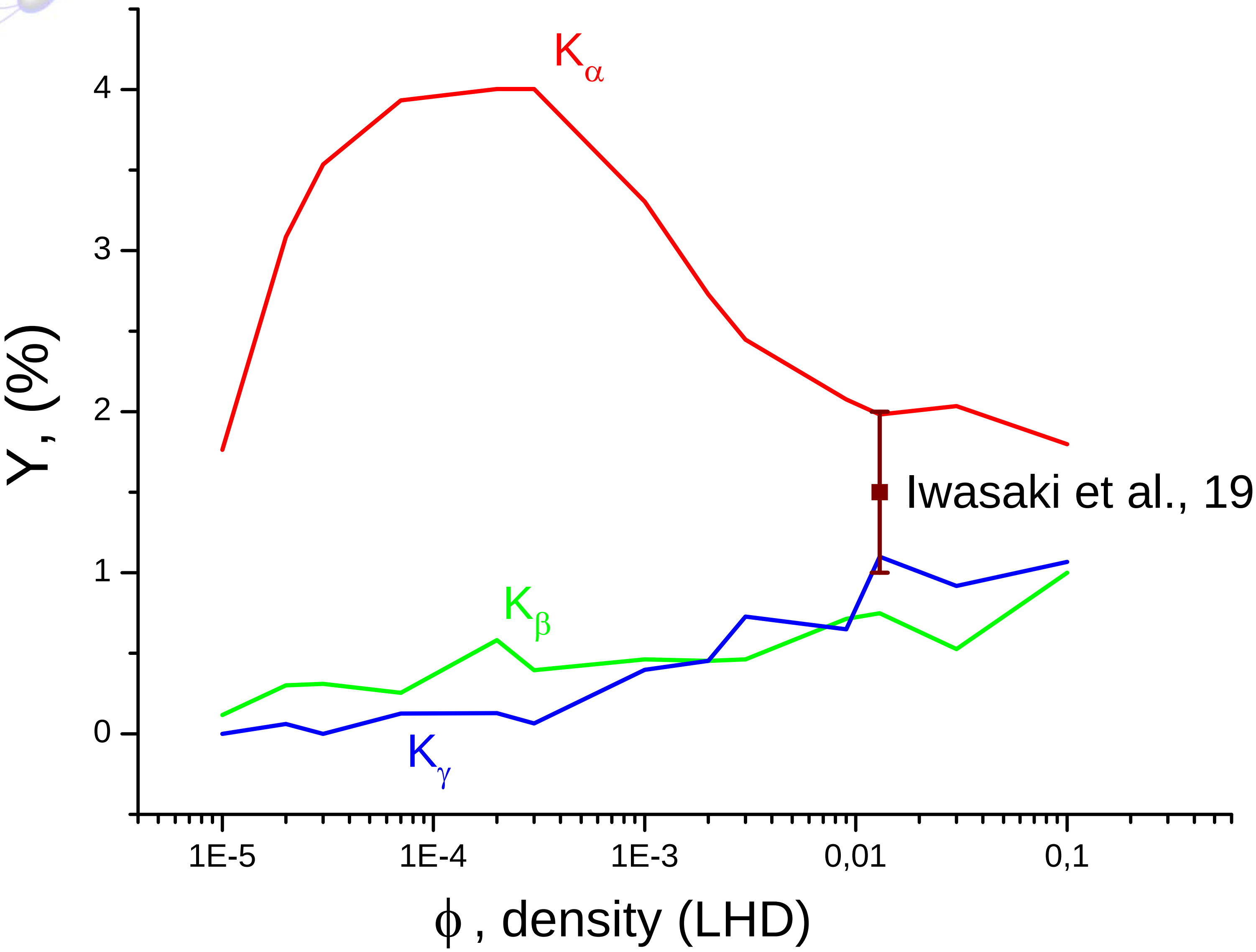
Fractions of pK^- atoms in the selected energy intervals



Calculated K_α-ray yields of pK^- atoms at Γ_{2p}=0.4 meV and Γ_{2p}=2 meV



X-ray yields of kaonic hydrogen atoms



Summary

❖ A new NQCMC code for *ab initio* calculations of cascade in exotic hydrogen atoms is developed.

❖ The analysis of the kinetics of cascade processes in muonic and kaonic hydrogen atoms leads to conclusion, which is important for simplifying the cascade calculations:

Auger acceleration is negligible for all exotic hydrogen atoms.

❖The obtained results have demonstrated good agreement between theory and experiment.

❖ The developed code enables to carry out calculations (with sufficient accuracy ~ 30% and less) of main characteristics of cascade processes:

- **cross-sections of Coulomb, Stark and Auger transitions;**
- **kinetic energy distributions;**
- **cascade time in the exotic atom;**
- **Doppler broadening of the atomic states;**
- **X-ray yields.**