Atomic Cascade and X-Ray Yields in Light Exotic Atoms

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- Motivation
  - Precision measurements of πN and K^-p scattering length
  - Investigation of atomic cascade mechanisms
- New results for collisional cascade processes: elastic scattering and Stark mixing
- New cascade calculations
  - μp
  - $\pi^- p$
  - $K^- p$

Motivations

Precision measurements of the nuclear shifts and widths

$\Longrightarrow$ the scattering lengths $a_{\pi N}$, a_{K^-p}.

Pionic hydrogen $\pi^- p$

$\Delta E_{1S}/E_{1S} \sim 10^{-2}$, $\Delta\Gamma_{1S}/\Gamma_{1S} \sim 3 \cdot 10^{-2}$ (PSI)

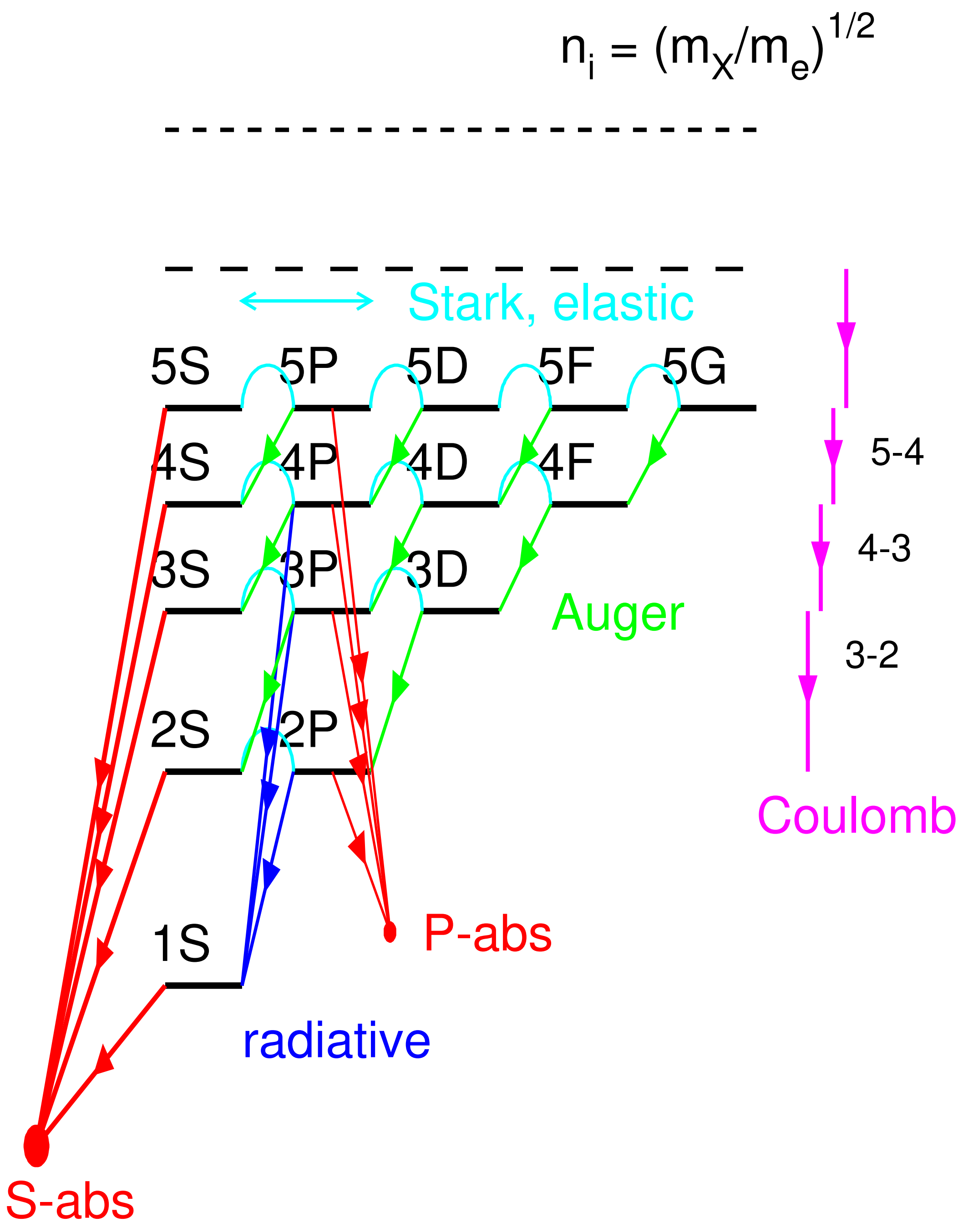
- Doppler broadening of the X-ray lines ($\Gamma_{1S} \sim 1$ eV)
- The energy distribution during the atomic cascade.
- Understanding acceleration and deceleration mechanisms.

Kaonic hydrogen $K^- p$

$\Delta E_{1S}/E_{1S} \sim 10^{-2}$, $\Delta\Gamma_{1S}/\Gamma_{1S} \sim 3 \cdot 10^{-2}$ (DEAR)

- The X-ray yields vs. density.
- The structure of the K X-ray complex.

The Kinetics of Atomic Cascade



The Monte Carlo kinetics code MCKin:

the number of states $\sim n_{max}^2/2$

the number of links $\sim n_{max}^3$

Cascade Models for the Exotic Atoms with $Z = 1$

Model	Rad.	Auger	Stark	Coul.	$p_{nl}(E,t)$
Leon, Bethe (1962)	+	+	+	−	−
Borie, Leon (1980)	+	+	+	−	−
V.M.(1981)	+	+	+	−	−
Landua, Klempt, Reinfenröter (1987)	+	+	+	−	−
Czaplinski, Gula, Kravtsov et al. (1990)	+	+	+	−	−
V.M.(1994)	+	+	+	+	+
Czaplinski, Gula, Kravtsov et al. (1994)	+	+	+	+	−
Aschenauer, V.M. (1996)	+	+	+	+	+
Terada, Hayano (1996)	+	+	+	−	−
Jensen, V.M. (2000)	+	+	+	+	+

The evolution of the **energy distribution** $p_{nl}(E,t)$ during the atomic cascade is important.

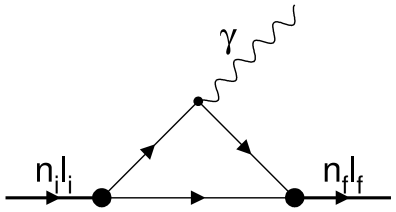
Cascade Mechanisms

- **De-excitation** $(n_f < n_i)$
  - Radiative
  - Auger
  - Coulomb
  - Molecular resonances

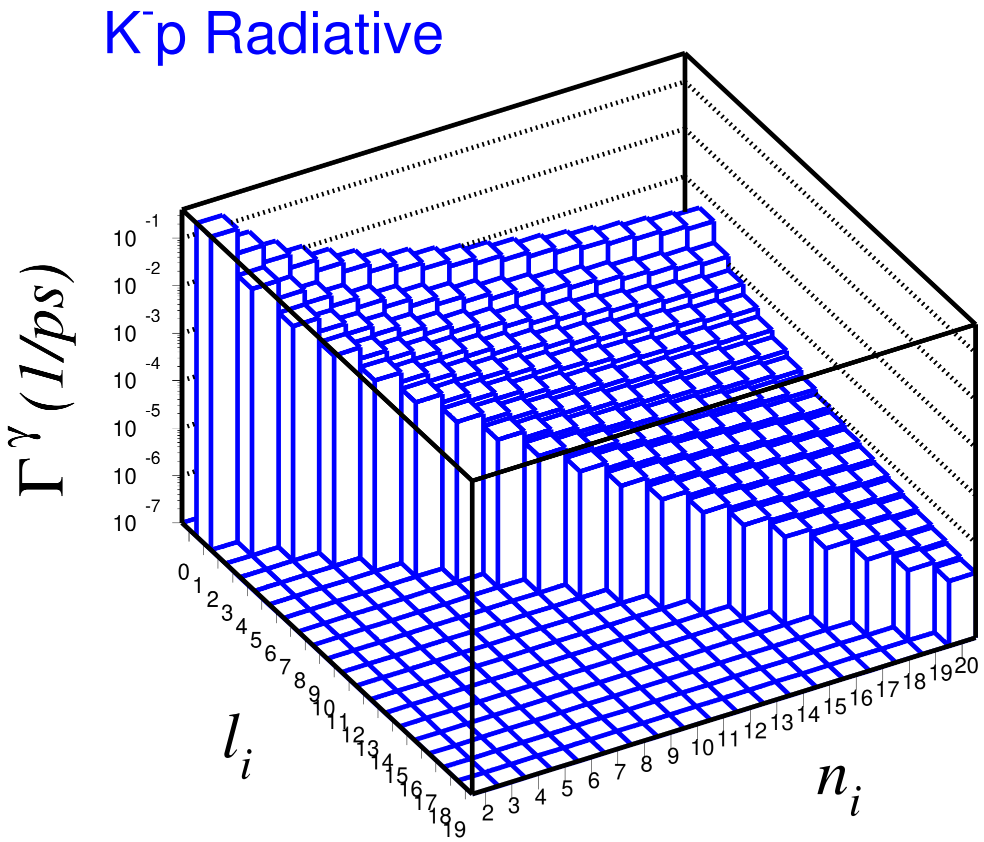
- **Elastic Scattering** $(n_f = n_i)$ *NEW*
  - Stark mixing
  - Deceleration

- **Absorption** $(\pi^- p,\ K^- p,\ (\bar{p}p))$ *NEW*

Radiative Transitions

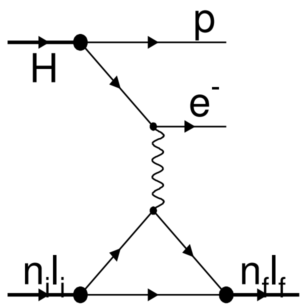


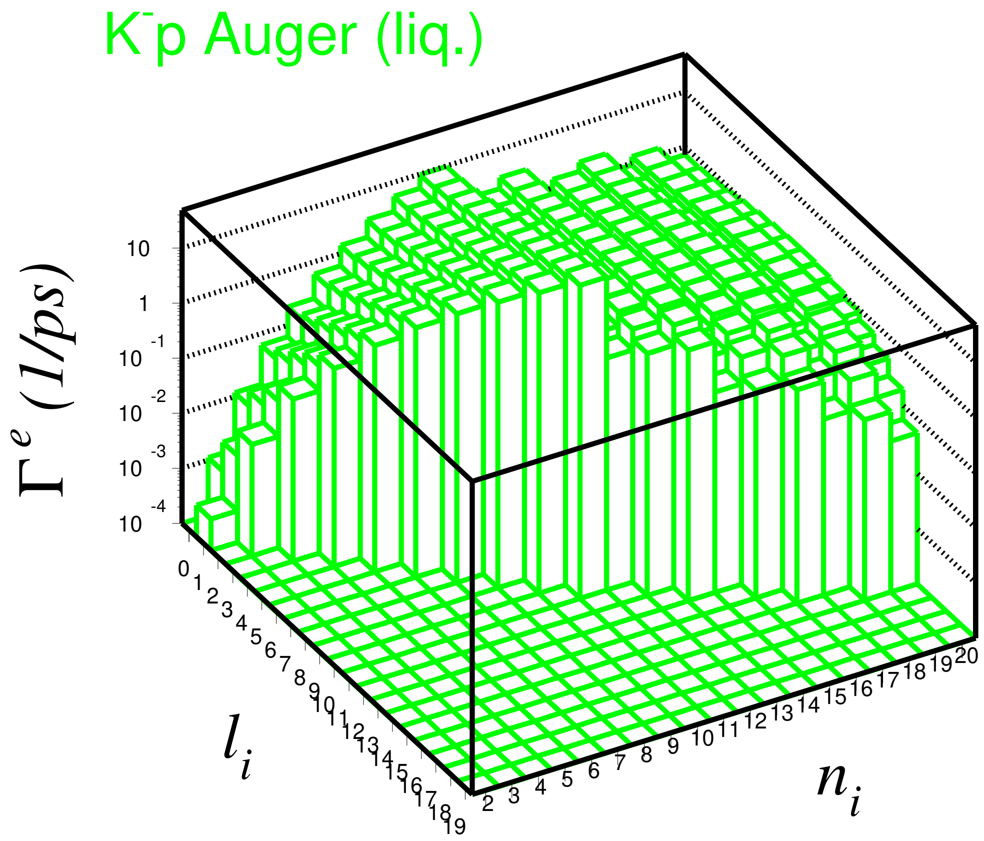
$$\Gamma^{\gamma}_{if} = \frac{4}{3}\alpha|R_{if}|^2(\Delta E_{if})^3$$



The total rates of radiative de-excitation.

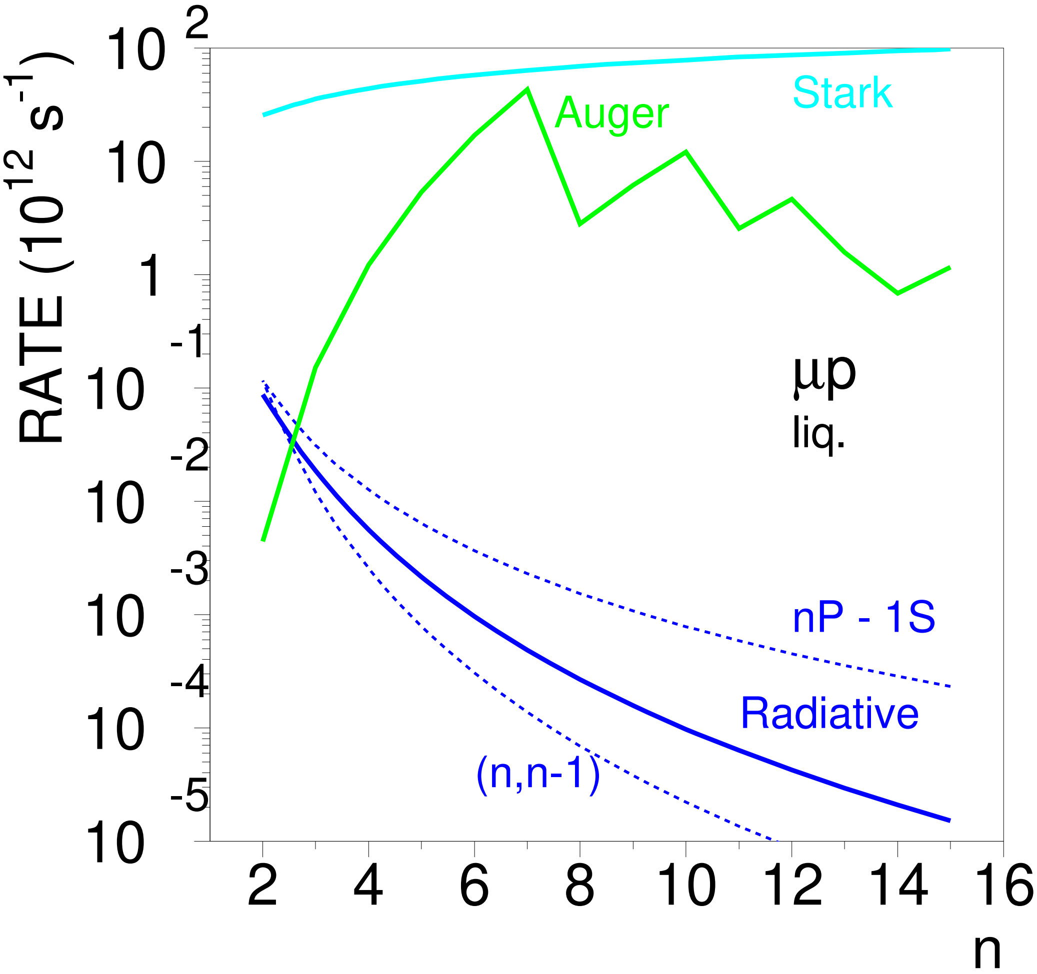
Auger Transitions



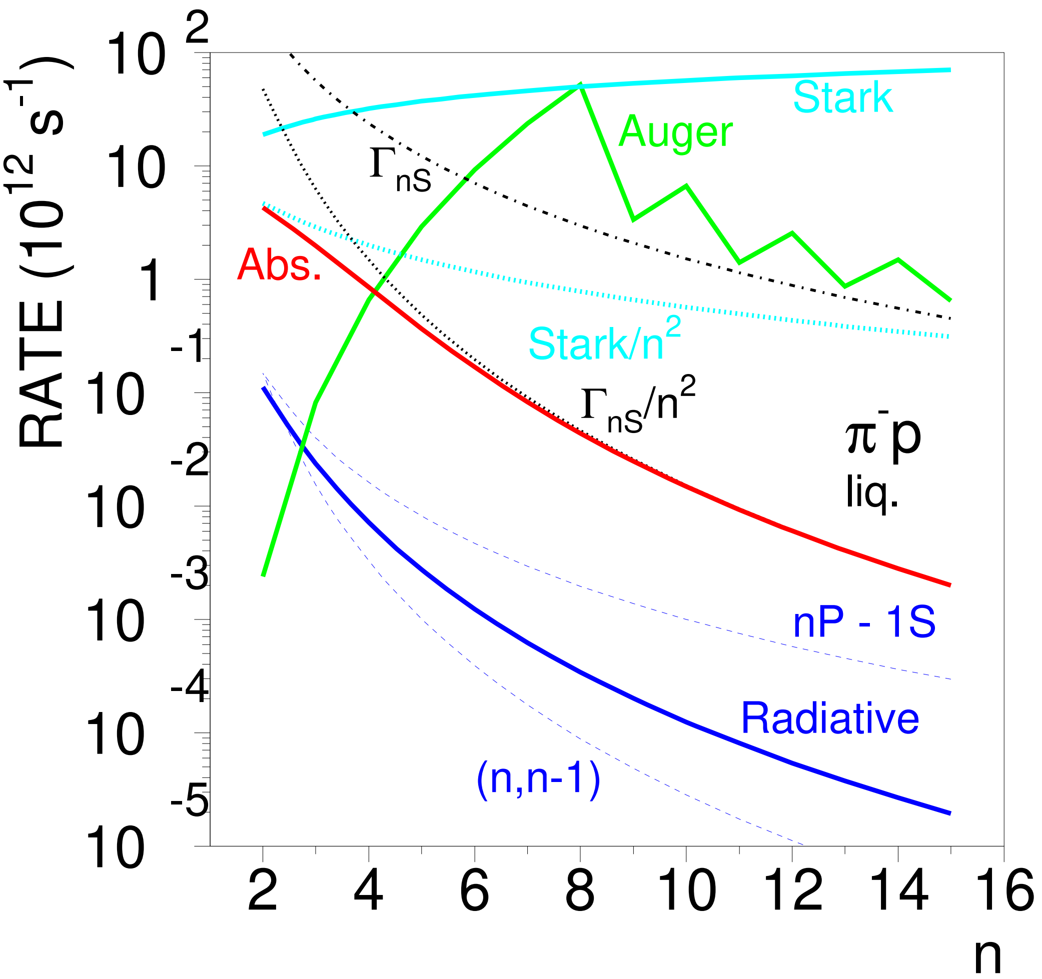


The total rates of Auger de-excitation (l.h.d.).

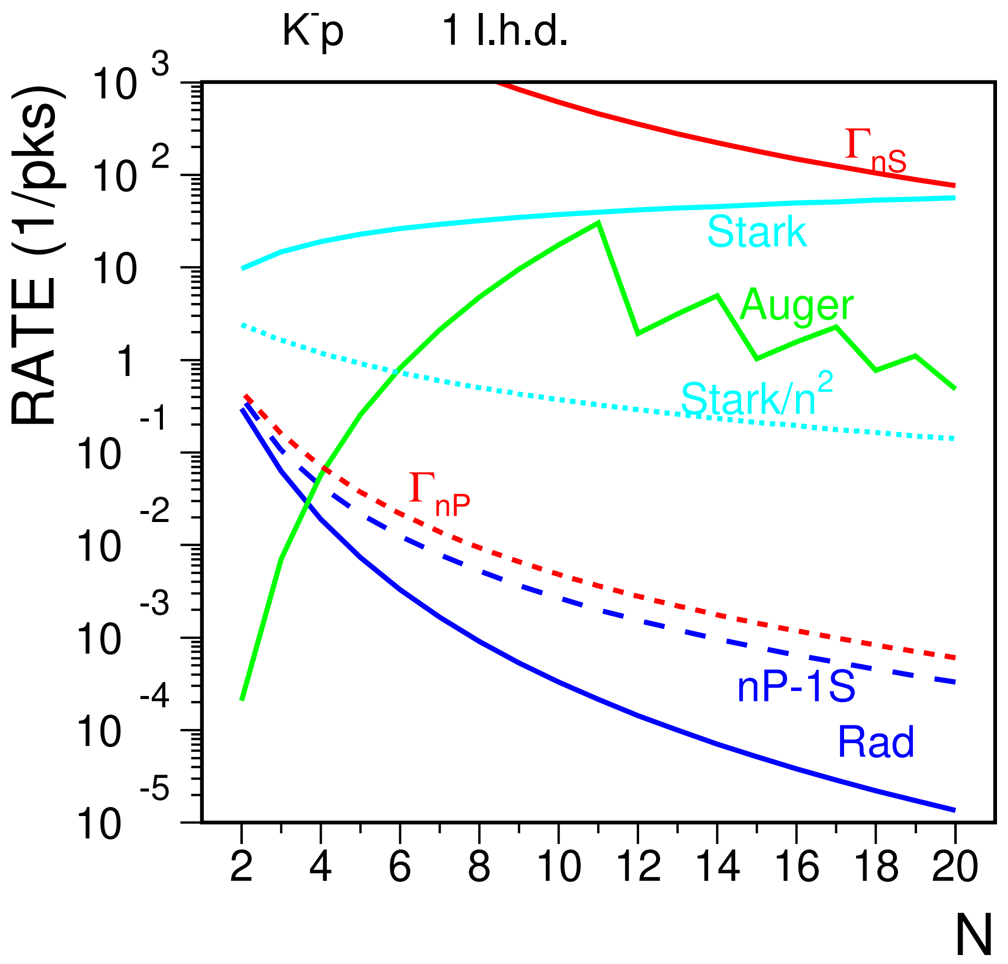
Muonic Hydrogen



Pionic Hydrogen



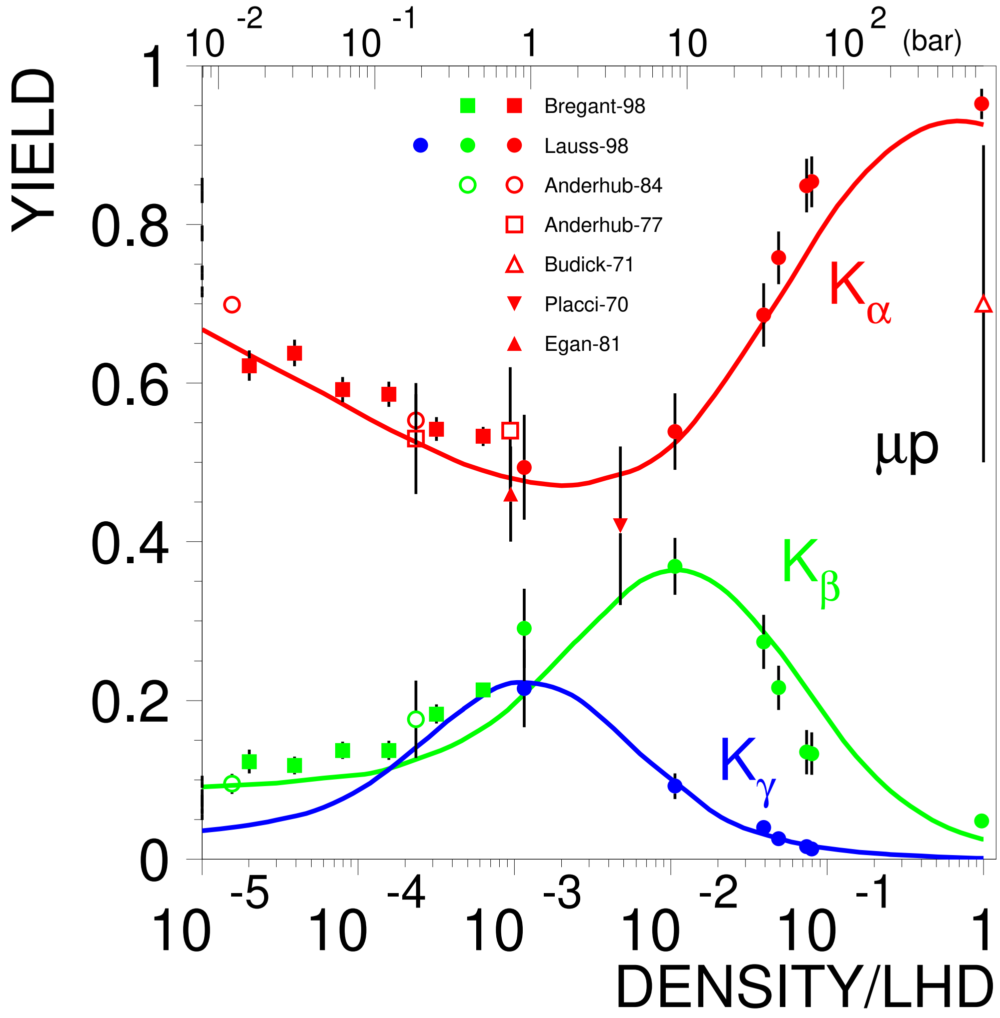
Kaonic Hydrogen



Muonic Hydrogen

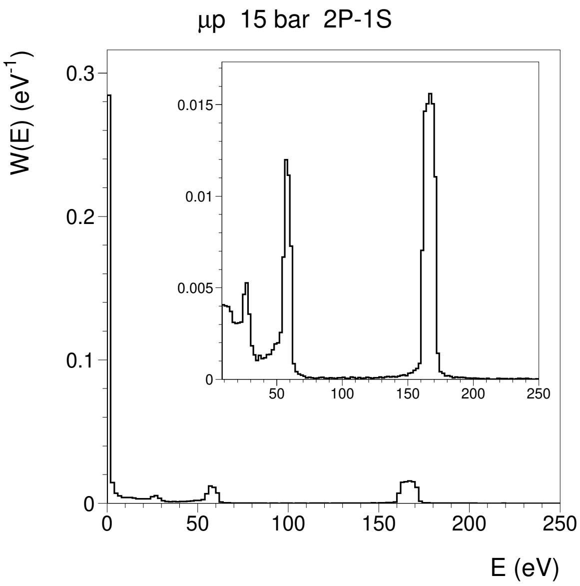
X-Ray Yields

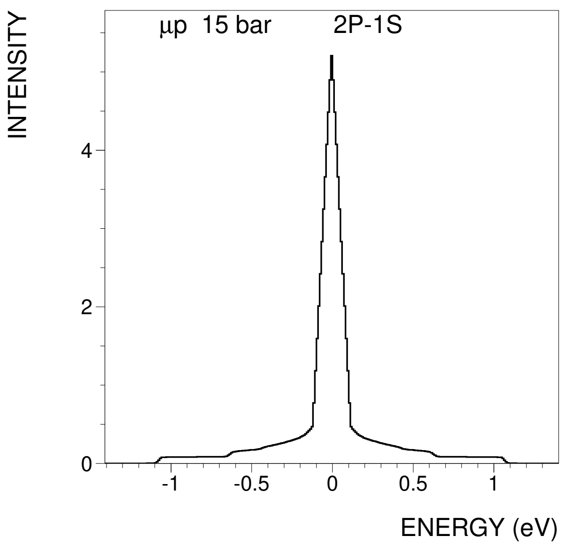
Theory *(V.M. 1996, 2000)* vs. Experiment



Kinetic Energy Distribution in Excited States

high-E component in the kinetic energy distribution of μp $\Longrightarrow$ Doppler broadening of the X-ray lines





Coulomb de-excitation

$\downarrow$

High kinetic energy $(\gg 1\mathrm{e}V)$

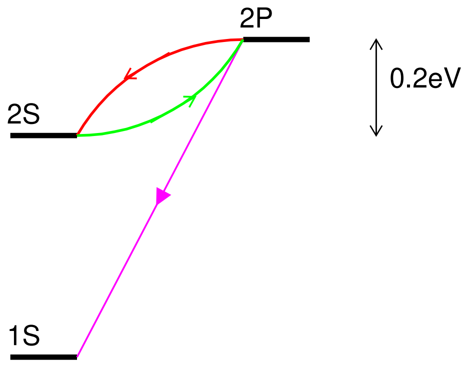
$\downarrow$

Doppler broadening of the X-ray lines

$\downarrow$

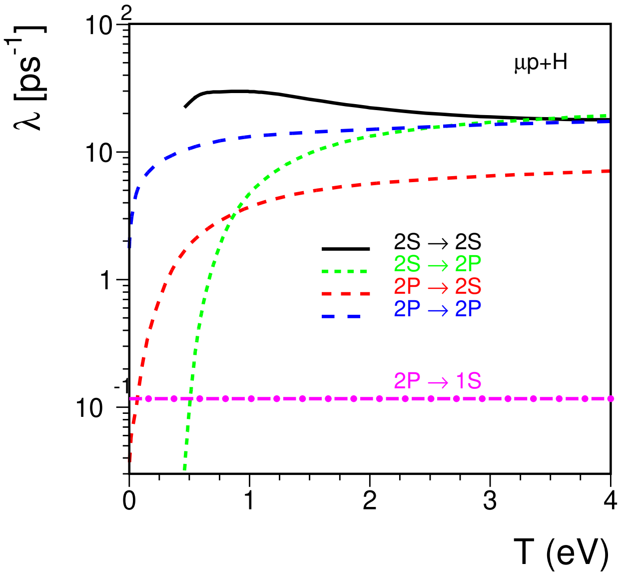
Measurement of the Coulomb transitions (PSI – in progress)

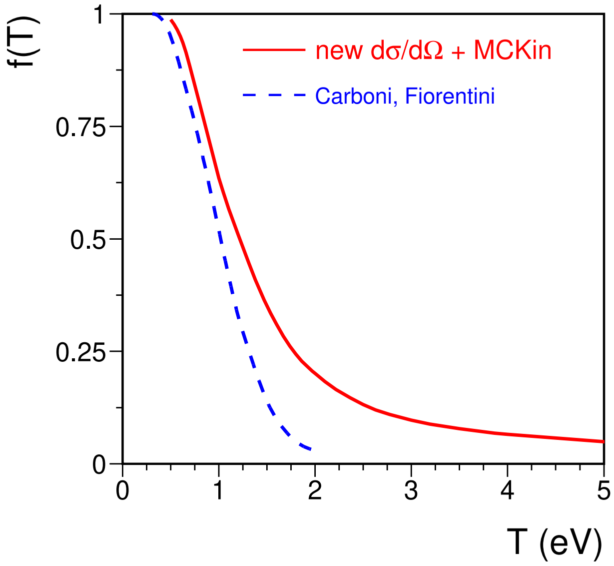
Metastable $2S$ Fraction in Muonic Hydrogen



T. Jensen and V.M., nucl-th/0001009

New calculations of the cross sections $\mu p_{2l} + H \to \mu p_{2l'} + H$ $\Longrightarrow$ The surviving fraction f(T) of the $2S$ state vs. the initial energy T





The total population of the metastable $2S$ state

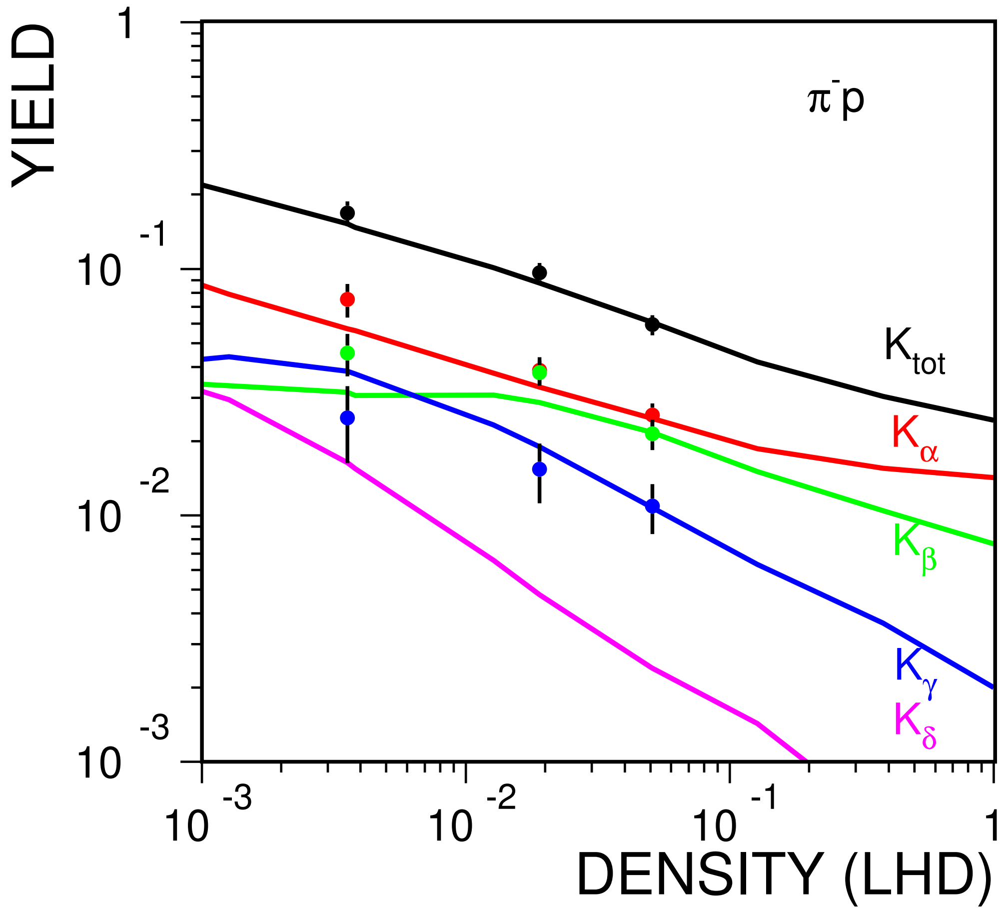
$$P_{2S} = \int w_{2S}(T) f(T) dT > 10^{-2}$$

$\Longrightarrow$ good news for the Lamb shift experiment at PSI (in progress).

Pionic Hydrogen

X-Ray Yields

Theory vs. Experiment *(PSI, 1995)*



Doppler Broadening of the X-Ray Lines

The Coulomb de-excitation

$\Longrightarrow$ the high-energy component ($T \gg 1$ eV)

$\Longrightarrow$ an important correction to the width of the $nP \to 1S$ transitions.

The kinetic energy distribution from the n-ToF experiment (PSI)

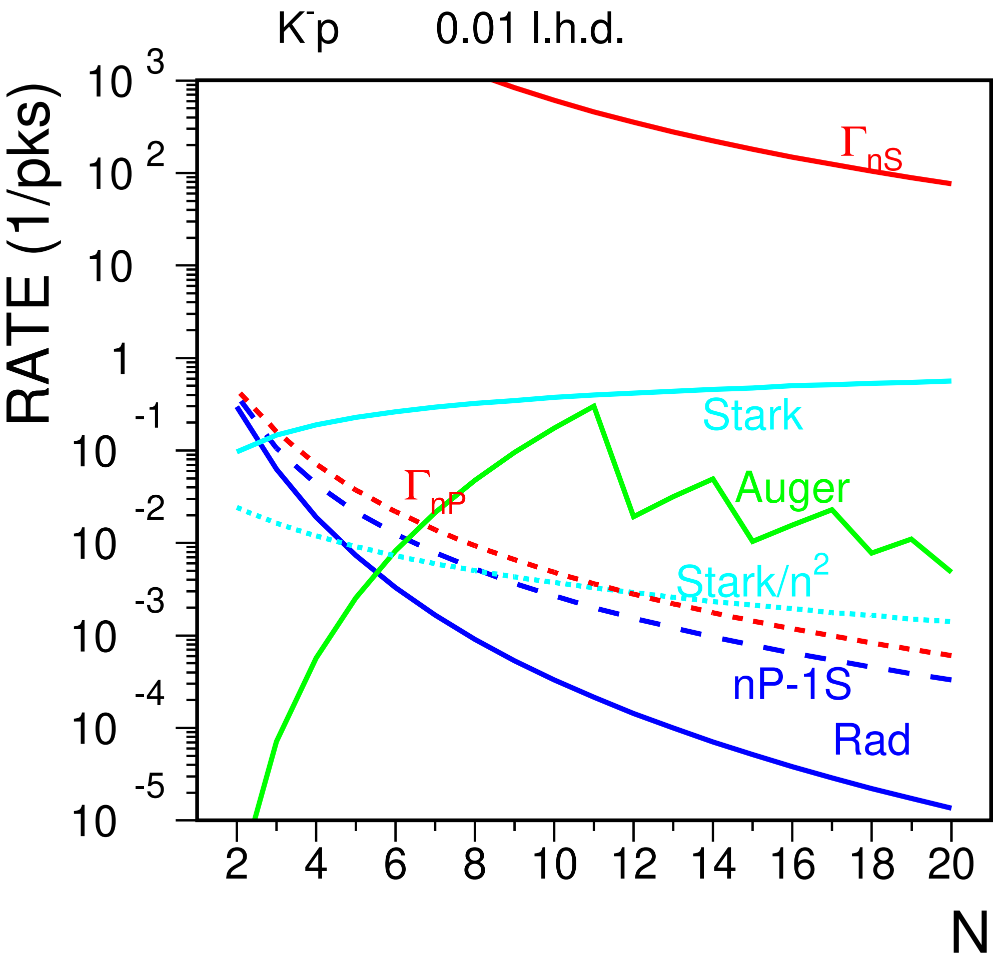
$$(\pi^- p)_{nS} \;\; \to \;\; \pi^0 + n$$

$\boxed{\text{PSI data}}$

The theoretical kinetic energy distribution — in progress.

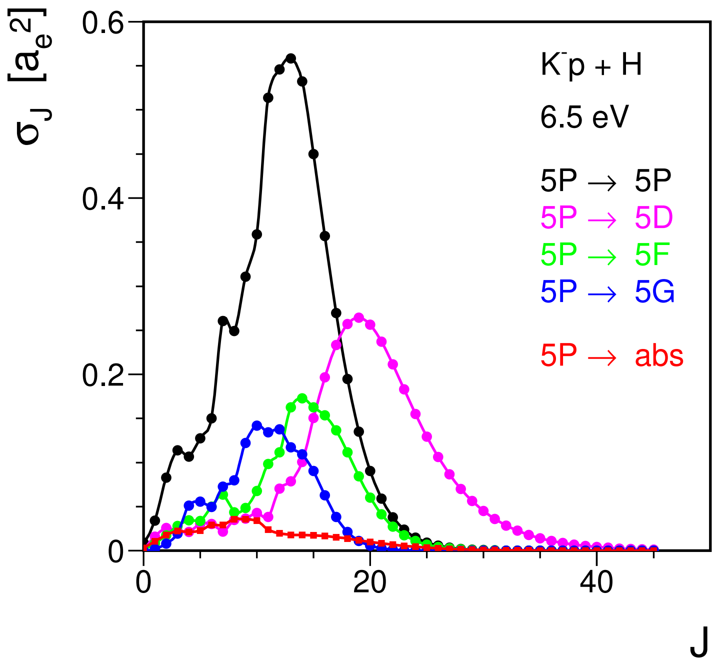
Atomic Cascade in Kaonic Hydrogen

The de-excitation vs. absorption



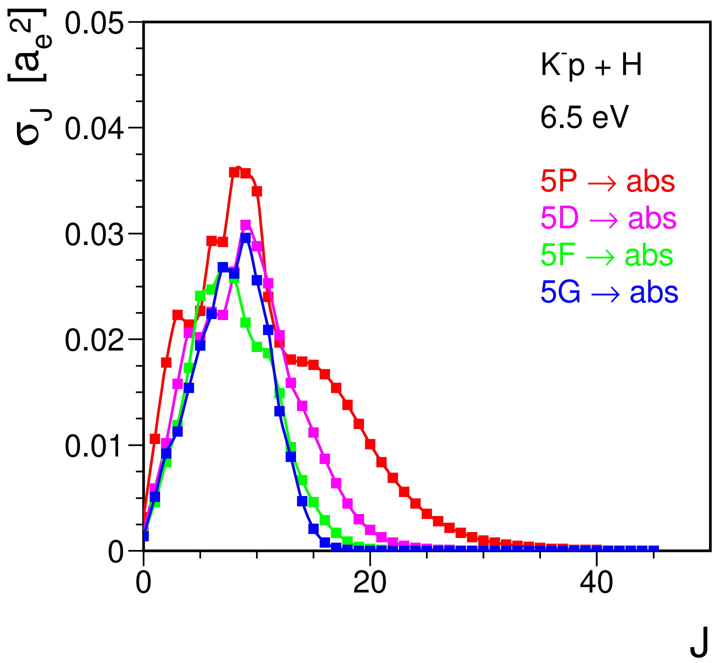
Collisional Cross Sections

New calculations of the elastic scattering, the Stark mixing, and the absorption cross sections *(T. Jensen, 2000)*



$(K^-p)_{nl} + H$

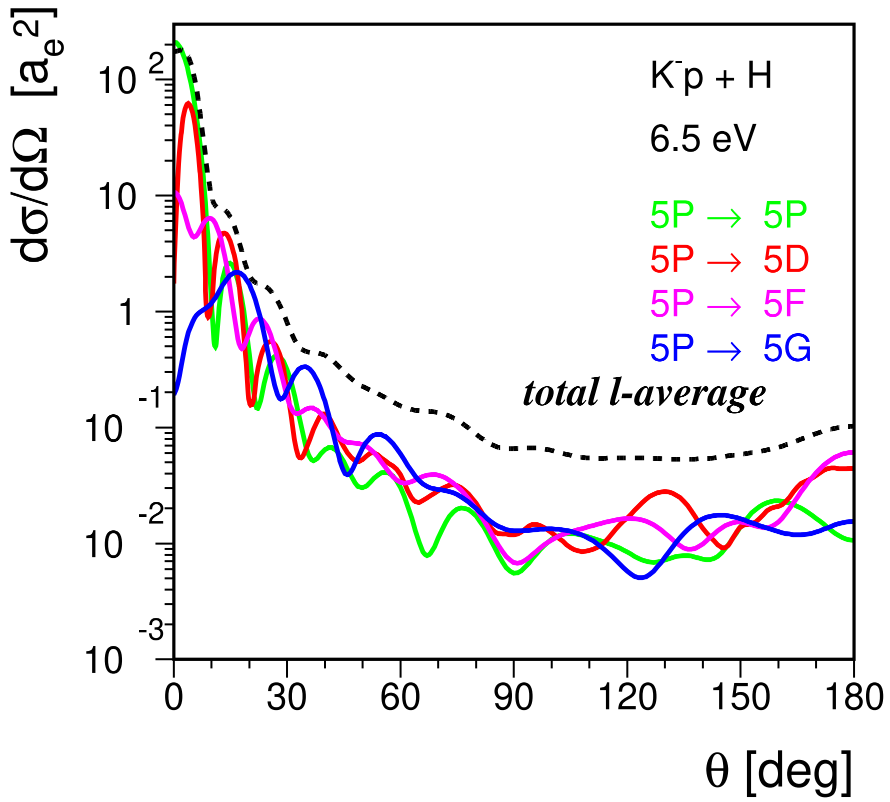
the partial wave cross sections $\sigma_J^{nl\to f}(E)$ of the Stark mixing ($f = nl'$) and the absorption ($f = nS \to$abs.)



$(K^-p)_{nl} + H$

the partial wave absorption cross sections

The Differential Cross Sections



$(K^-p)_{nl} + H$

an example of the differential cross sections $d\sigma_{nl \to nl'}/d\Omega$

A complete set of the cross sections $d\sigma_{nl\to nl'}(E)/d\Omega$ that are needed for the Monte Carlo kinetics (about 10^3 functions) has been calculated.

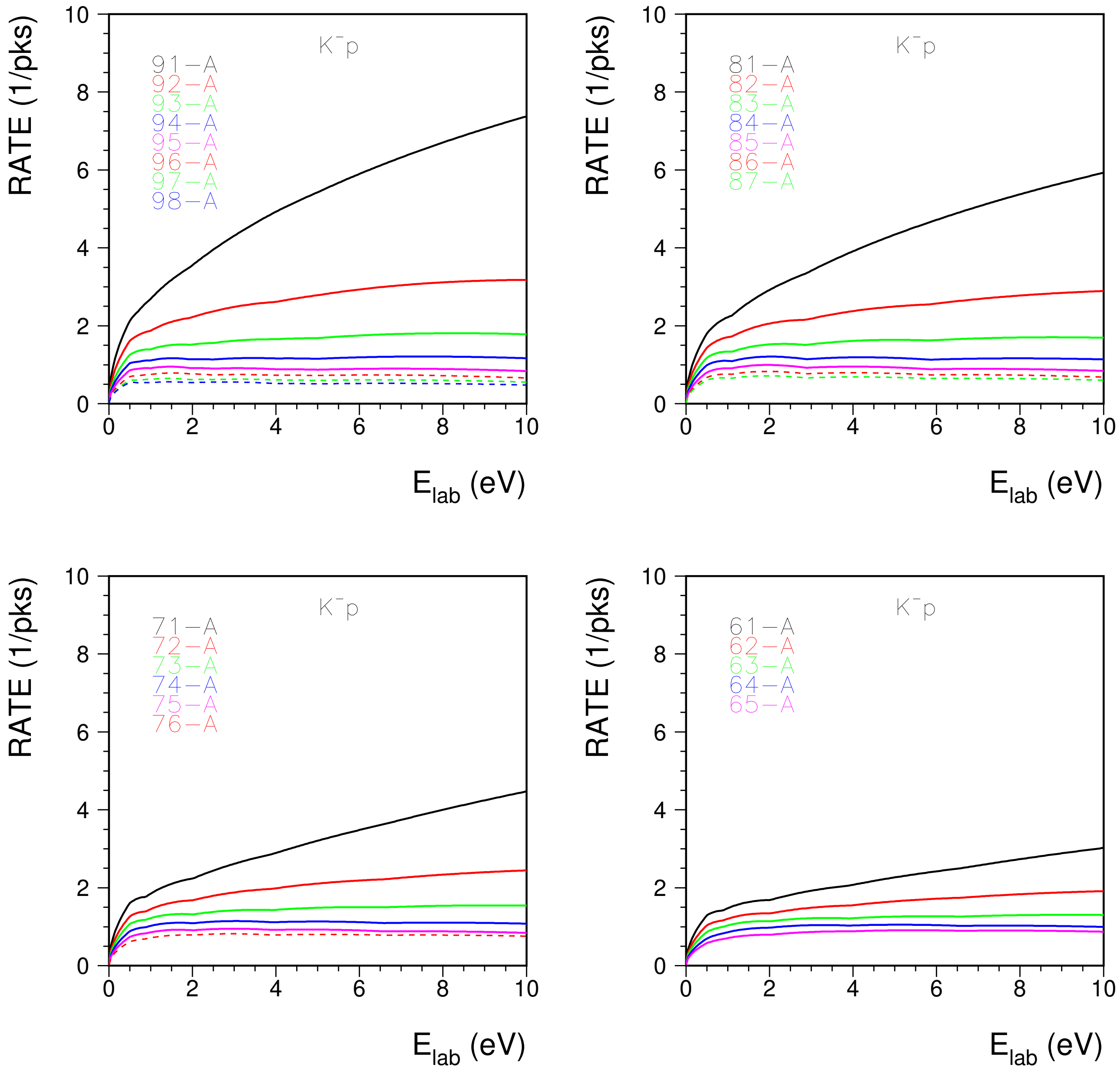
The methods used:

- A quantum mechanical coupled–channel model $(n = 2, 3, 4, 5)$.

- A semiclassical solution with the full angular coupling between the internal K^-p and the external $K^-p + H$ motion $(n > 5)$.

The $K^- p$ absorption via Stark mixing

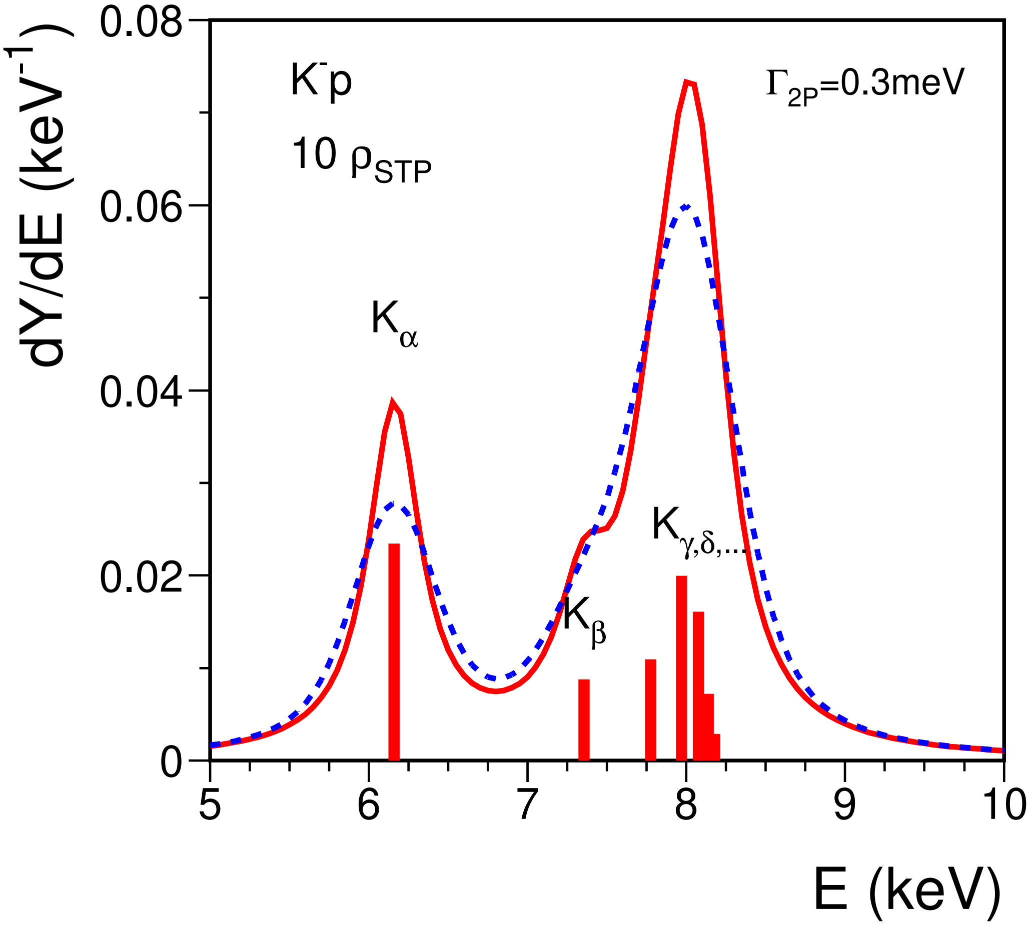
The rates of the absorption from the nl states vs. lab. energy (l.h.d)



Cascade Calculations

- Input:
  - The nuclear shift ΔE_{1S} and width Γ_{1S} of the $1S$ state.
  - The nuclear width Γ_{2P} of the $2P$ state.
  - The initial kinetic energy distribution $w(E)$.
- Output:
  - The X–ray yields vs. density.
  - The population (and the energy distribution) of the nl states during the cascade.
  - The S–wave and P–wave absorption.

The K^-p X-ray Spectrum at $10\ \rho_{STP}$

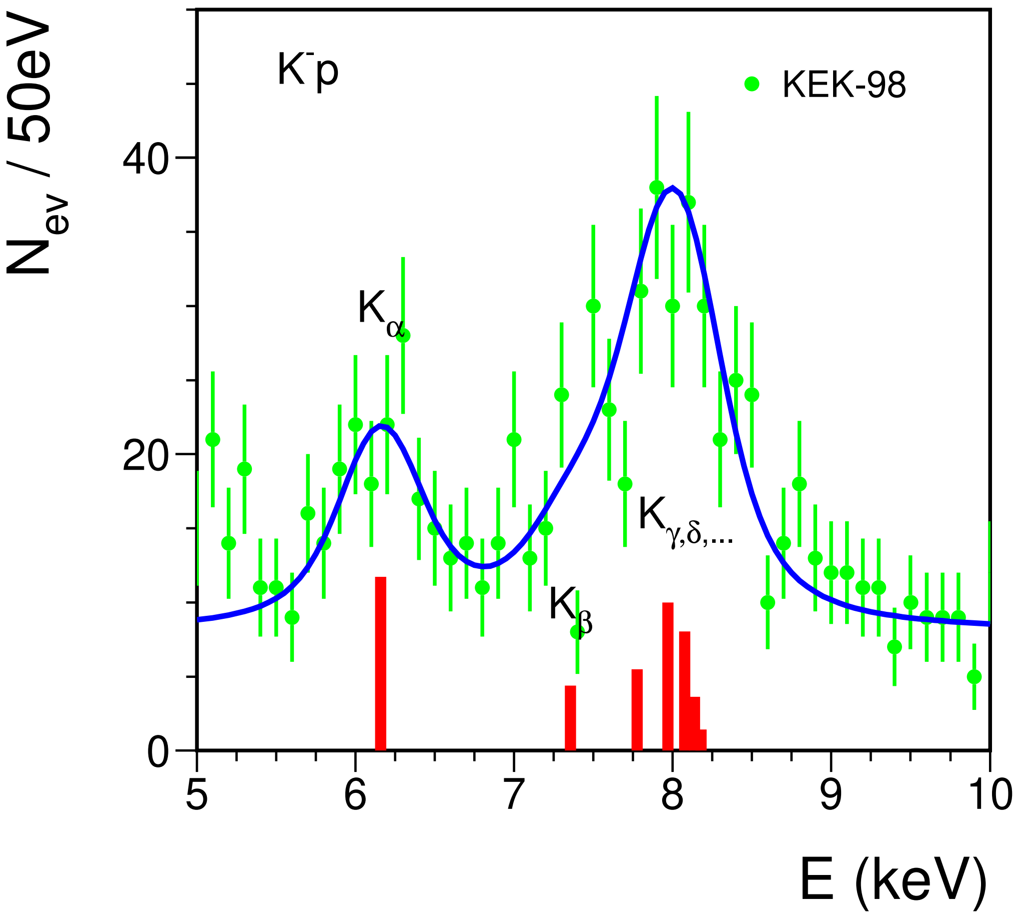


$\Delta E_{1S} = -320$ eV

$\Gamma_{1S} = 400$ eV

$\mathbf{FWHM} = 400$ eV

The $K^- p$ X-ray Spectrum at $10\ \rho_{STP}$



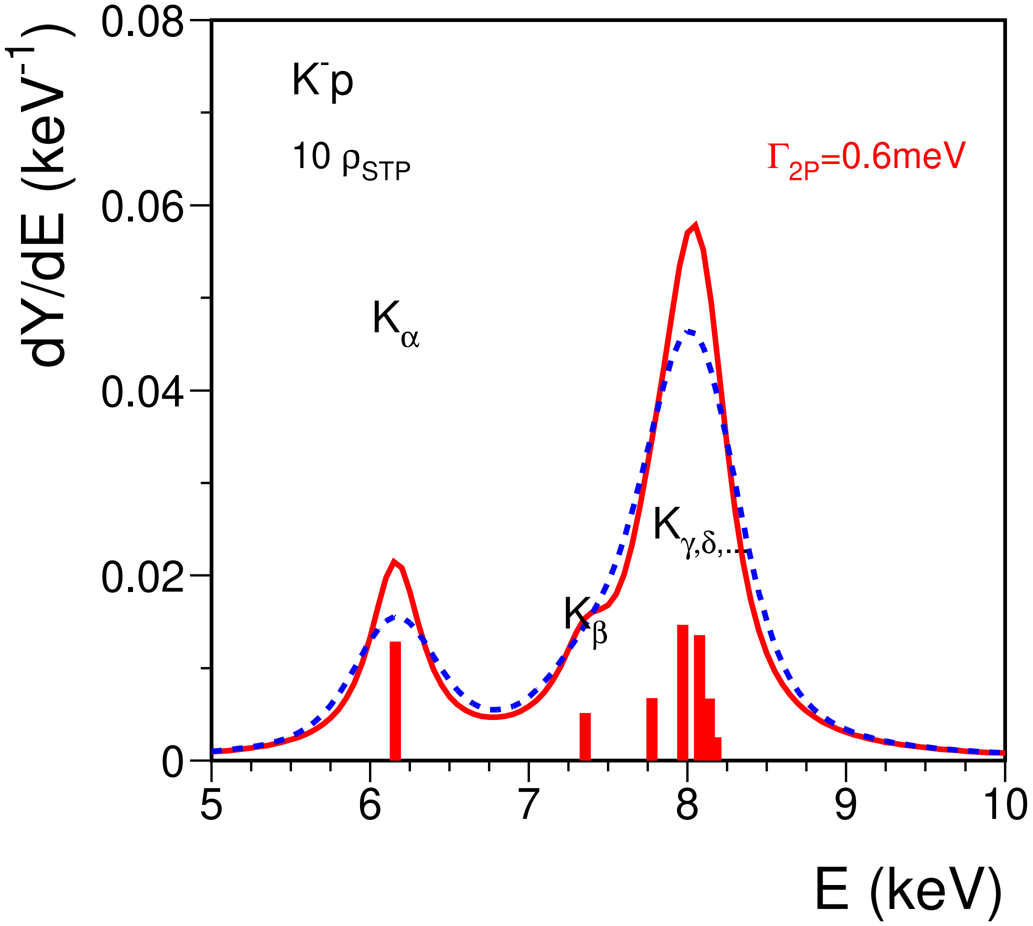
The experimental data — KEK (1998):

$\Delta E_{1S} = -323 \pm 63 \pm 11$ eV

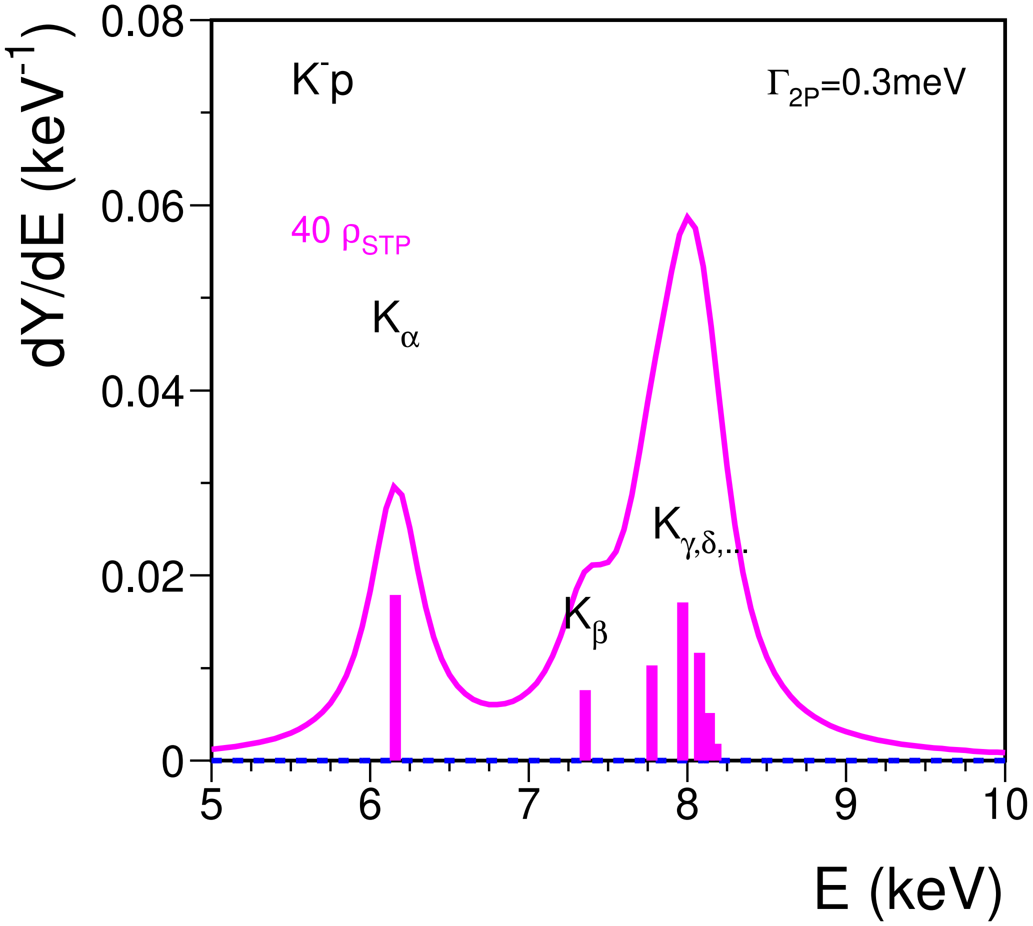
$\Gamma_{1S} = 407 \pm 208 \pm 100$ eV

$\mathrm{FWHM} = 400$ eV

The $K^{-}p$ X-ray Spectrum at $10\ \rho_{STP}$

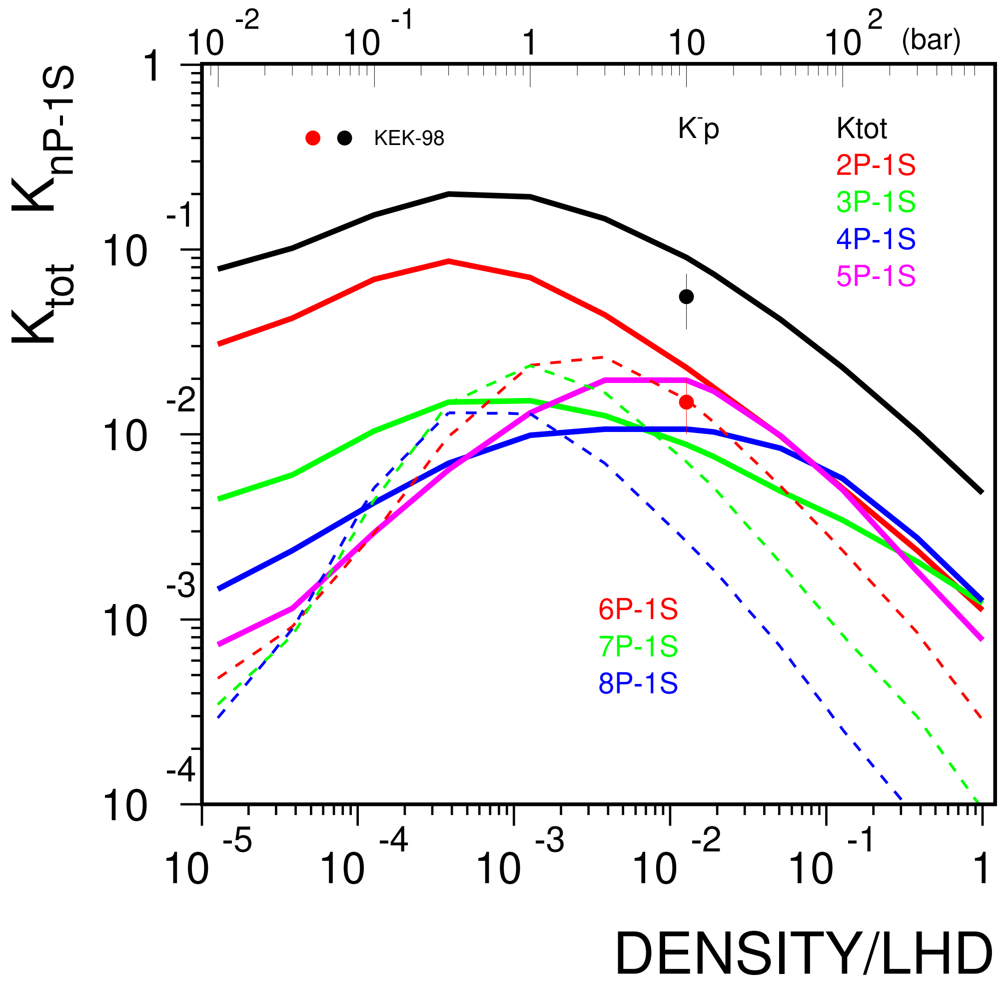


The $K^- p$ X-ray Spectrum at $40\ \rho_{STP}$



The Kaonic Hydrogen

The X-Ray Yields



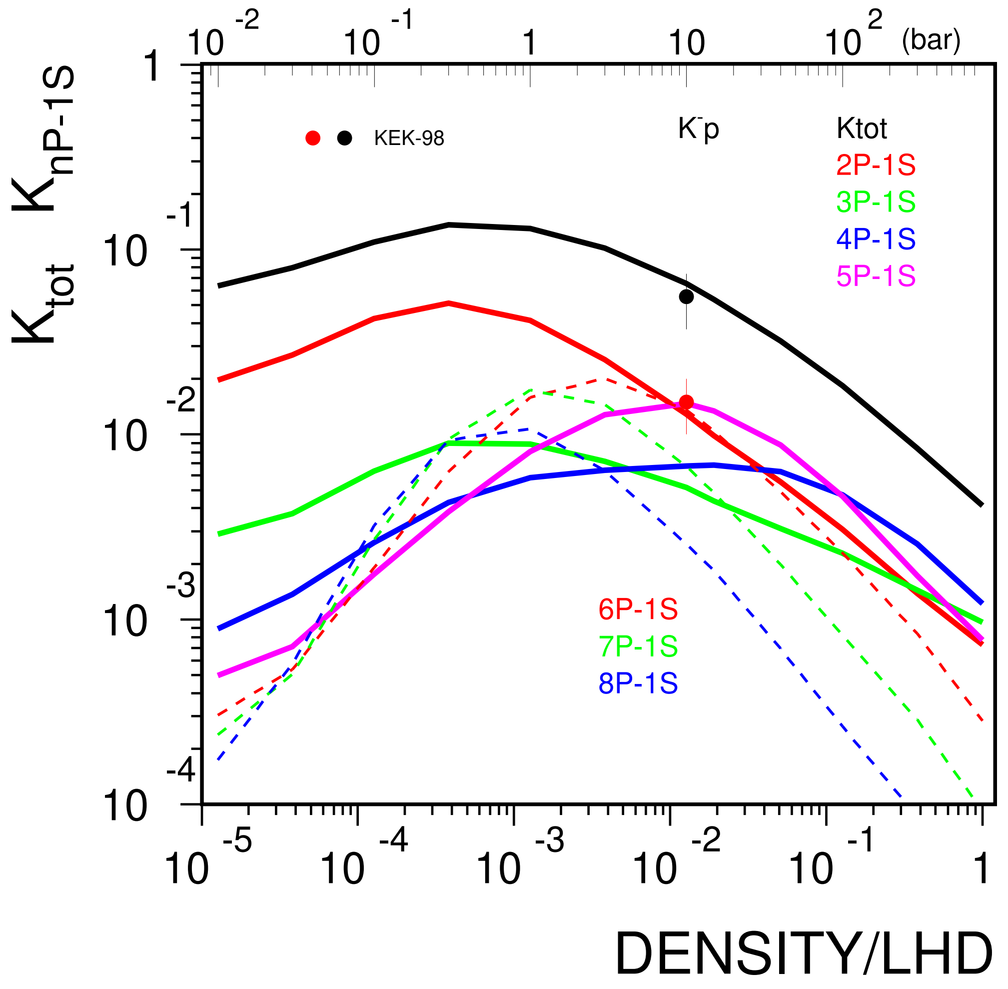
$\Gamma_{2P} = 0.3$ meV

$\Delta E_{1S} = -320$ eV, $\Gamma_{1S} = 400$ eV

$\langle T \rangle = 1.5$ eV

The Kaonic Hydrogen

The X-Ray Yields



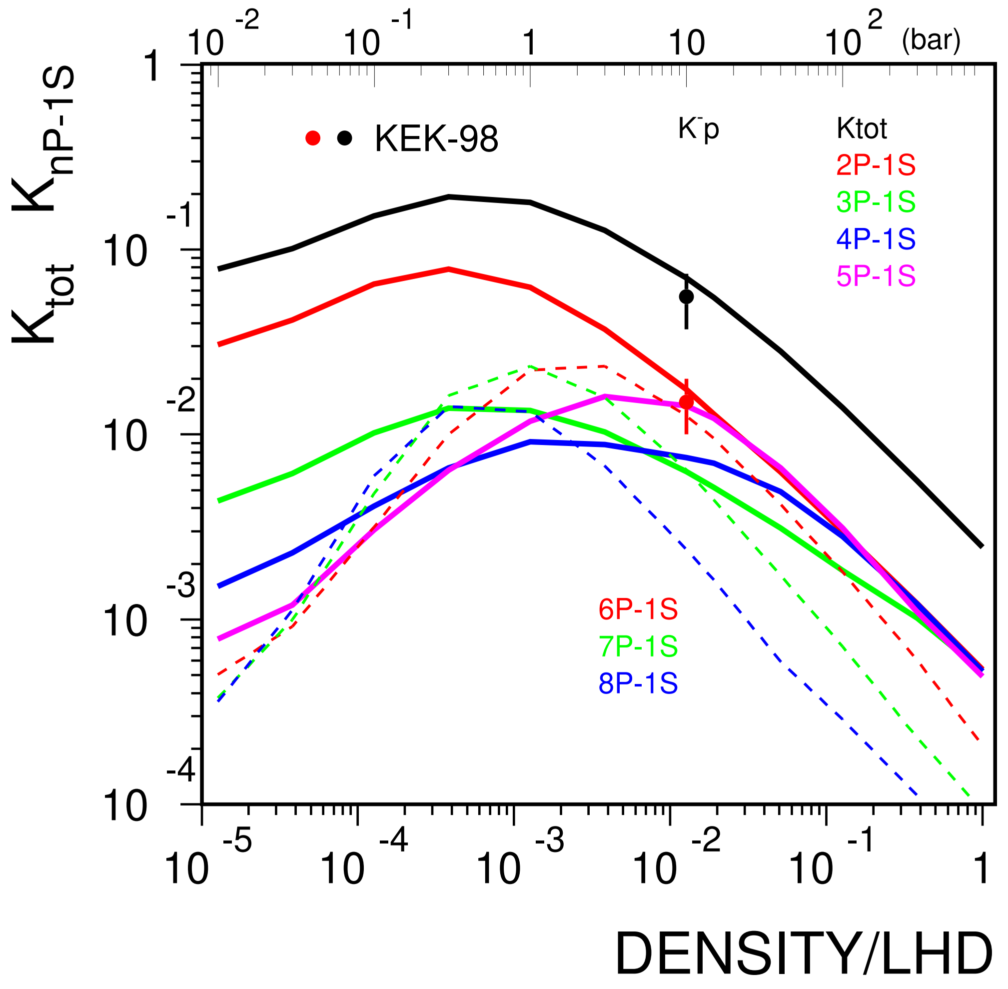
$\Gamma_{2P} = 0.6$ meV

$\Delta E_{1S} = -320$ eV, $\Gamma_{1S} = 400$ eV

$\langle T \rangle = 1.5$ eV

The Kaonic Hydrogen

The X-Ray Yields



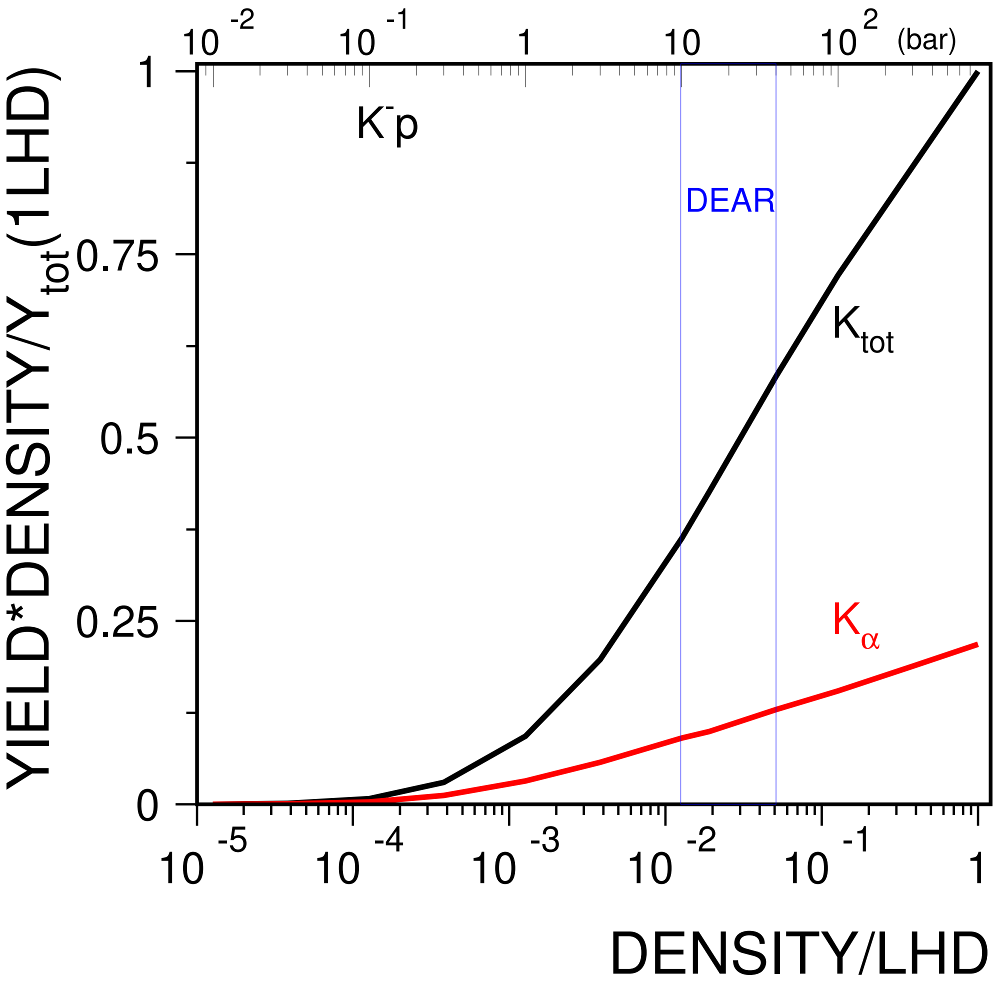
$\Gamma_{2P} = 0.3$ meV

$\Delta E_{1S} = -320$ eV, $\Gamma_{1S} = 400$ eV

$\langle T \rangle = 5$ eV

The Kaonic Hydrogen

The X-Ray Yields $\times$ Density

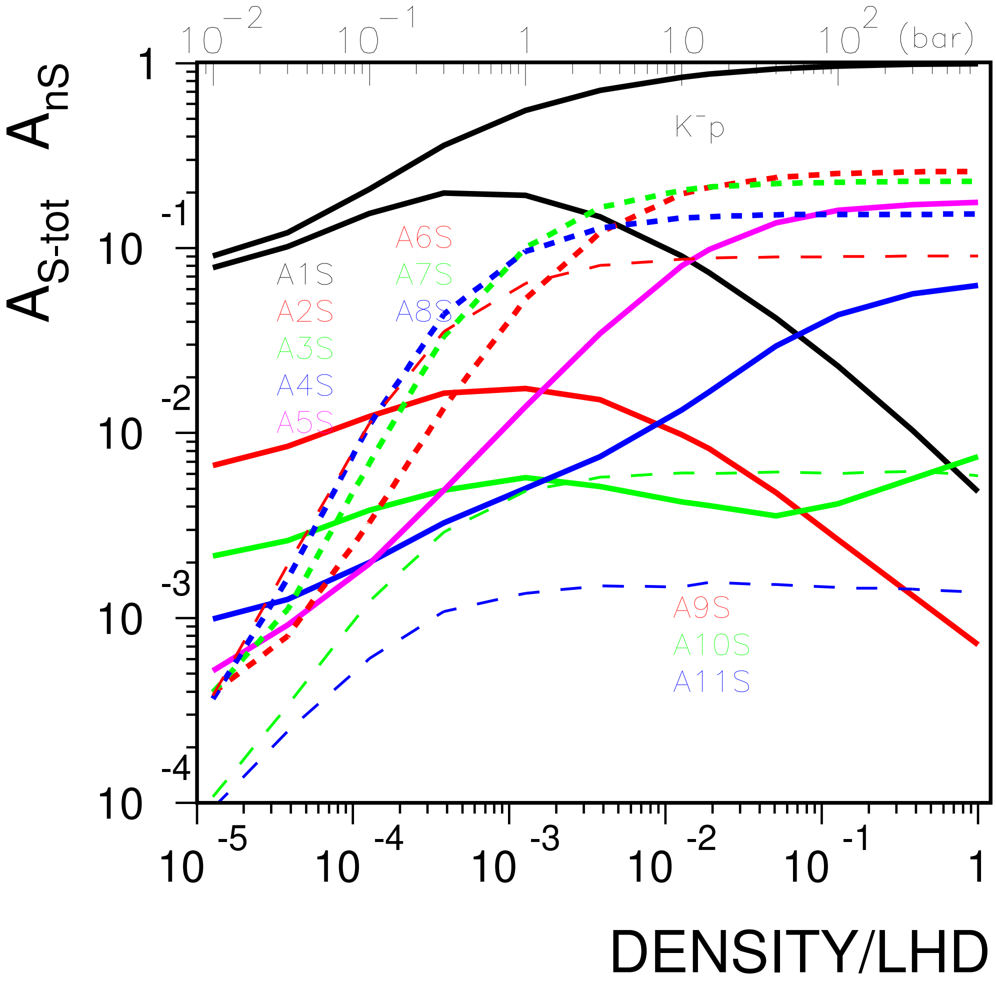


$\Gamma_{2P} = 0.3$ meV

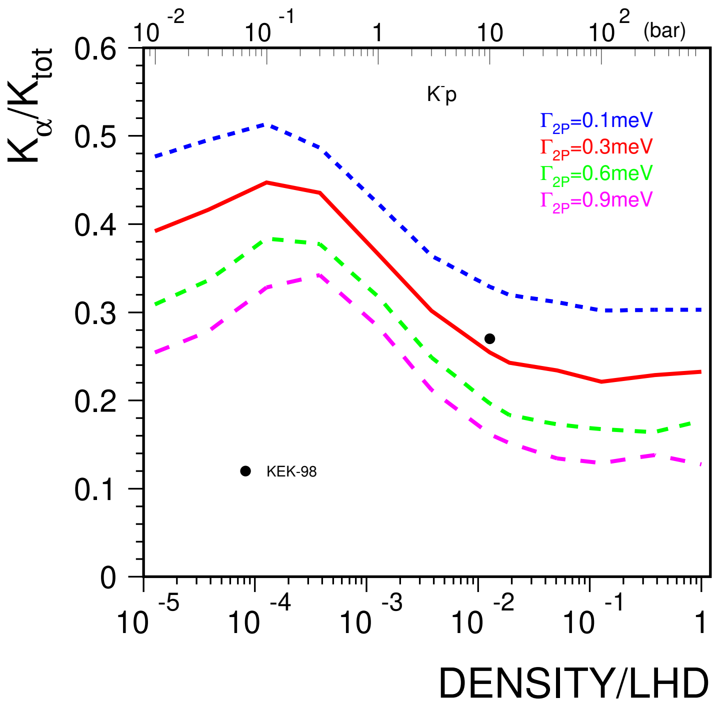
$\Delta E_{1S} = -320$ eV, $\Gamma_{1S} = 400$ eV

$\langle T \rangle = 5$ eV

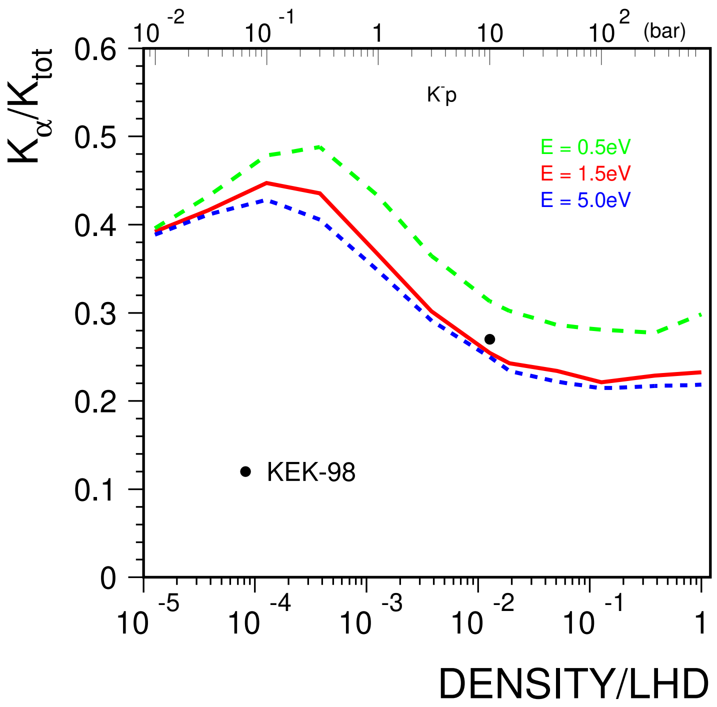
The S-wave Absorption



The K_α/K_{tot} Ratio



$\Leftarrow$ the dependence on the width Γ_{2P}



$\Leftarrow$ the dependence on the kinetic energy distribution $E = \langle w(T) \rangle$

Conclusions

- A significant improvement of the atomic cascade model based on the **new calculations** of the **collisional cross sections** (elastic, Stark mixing, absorption).

- The **energy evolution** during the atomic cascade is important for the **precision spectroscopy** of pionic and muonic hydrogen.

- The **Doppler broadening corrections** to the X-ray widths of $\pi^- p$ can be calculated to the required level of precision.

- The **X-ray yields of kaonic hydrogen** and their dependence on the ΔE_{1S}, Γ_{1S}, and Γ_{2P} have been calculated.

- More detailed studies of the cascades in μp, $\pi^- p$, $K^- p$ are in progress (Coulomb acceleration, molecular resonances, etc.).