^{229m}Th at the interface of atomic physics and nuclear physics

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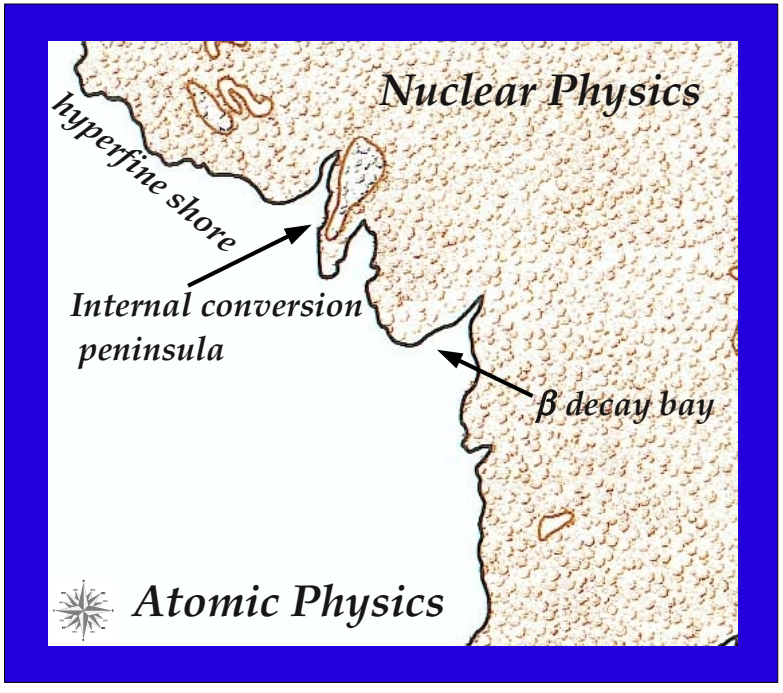
The Thorium Workshop, 25.09.2012

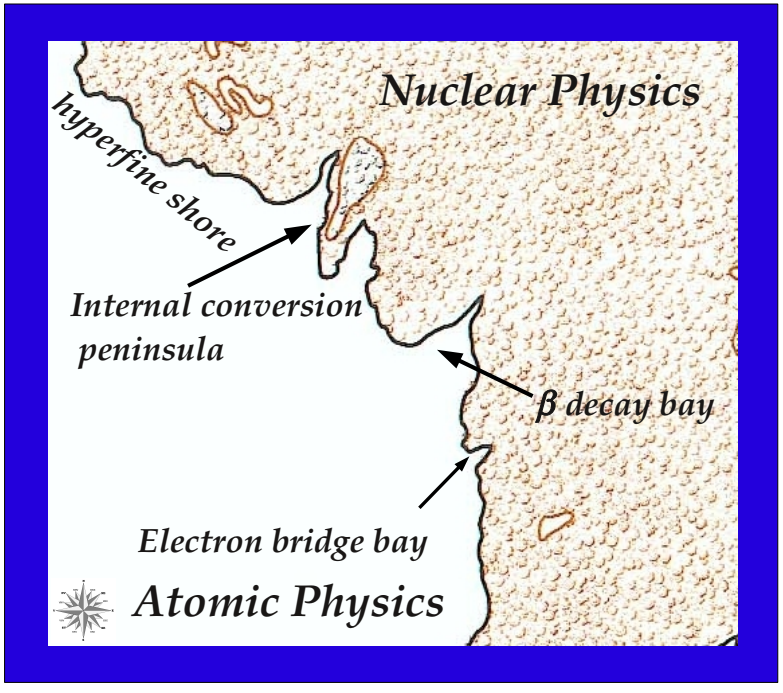
The interface of atomic and nuclear physics



The borderline between atomic and nuclear physics

- exploring nuclear properties via atomic physics experiments
- nuclear processes directly involving atomic electrons

The interface of atomic and nuclear physics



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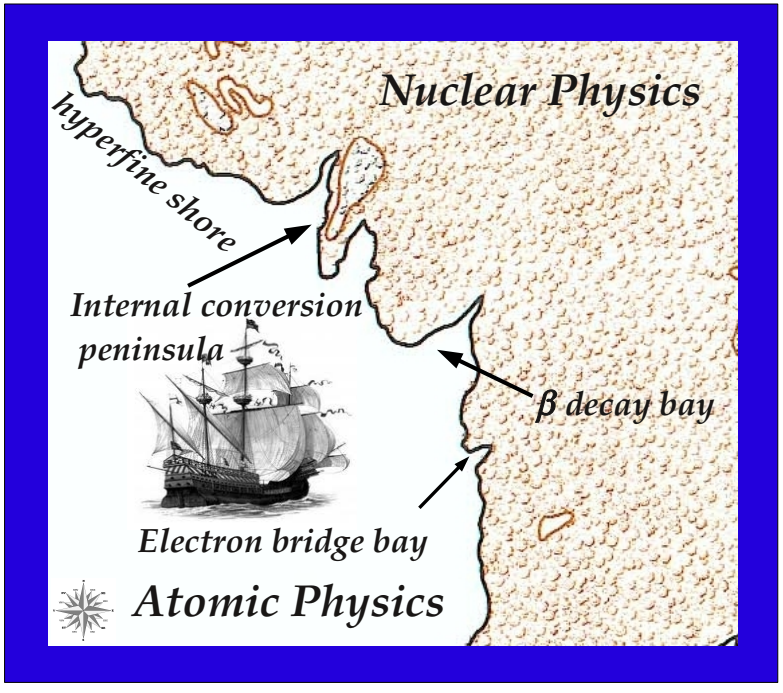

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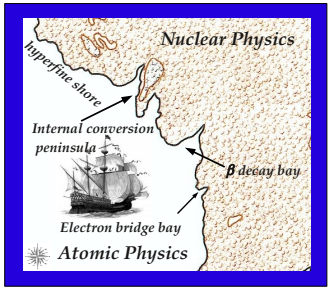
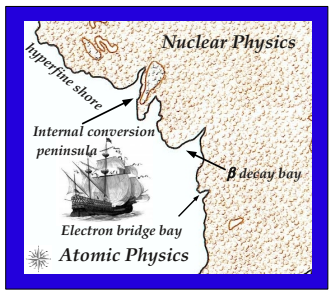


- exploring nuclear properties via atomic physics experiments

- hyperfine structure - high-precision laser spectroscopy - also of ^{229}Th
- muonic atoms
- isotope shifts and nuclear charge radii (precision laser spectroscopy, dielectronic recombination)

→ Storage ring experiments, talk by C. Kozhuharov!

The interface of atomic and nuclear physics



- nuclear processes directly involving atomic electrons

- electron capture (EC) + bound beta decay

$$p + e_b \rightarrow n + \nu_e$$

$$n \rightarrow p + e_b + \tilde{\nu}_e$$

- bound beta decay

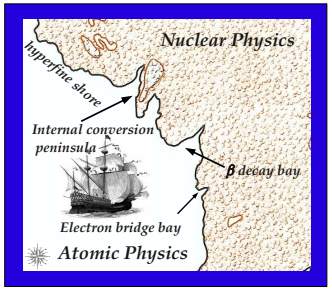
VOLUME 77, NUMBER 26 PHYSICAL REVIEW LETTERS 23 DECEMBER 1996

Observation of Bound-State β^- Decay of Fully Ionized ^{187}Re: ^{187}Re-^{187}Os Cosmochronometry

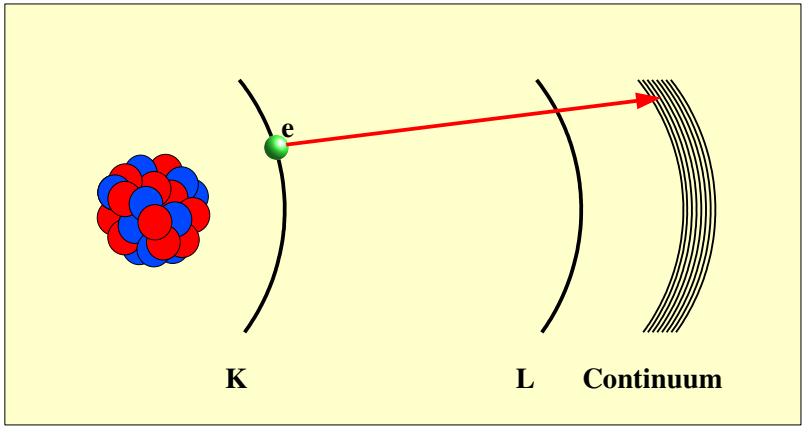
F. Bosch,[1] T. Faestermann,[2] J. Friese,[2] F. Heine,[2] P. Kienle,[2] E. Wefers,[2] K. Zeitelhack,[2] K. Beckert,[1] B. Franzke,[1] O. Klepper,[1] C. Kozhuharov,[1] G. Menzel,[1] R. Moshammer,[1] F. Nolden,[1] H. Reich,[1] B. Schlitt,[1] M. Steck,[1] T. Stöhlker,[1] T. Winkler,[1] and K. Takahashi[2,3]

The cosmic clocks, talk by F. Bosch!

The interface of atomic and nuclear physics

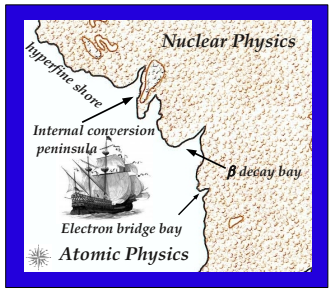


- nuclear processes directly involving atomic electrons
  AP, Contemporary Phys. 51 (2010) 471



internal conversion (IC) + inverse process
nuclear excitation by electron capture (NEEC)

The interface of atomic and nuclear physics



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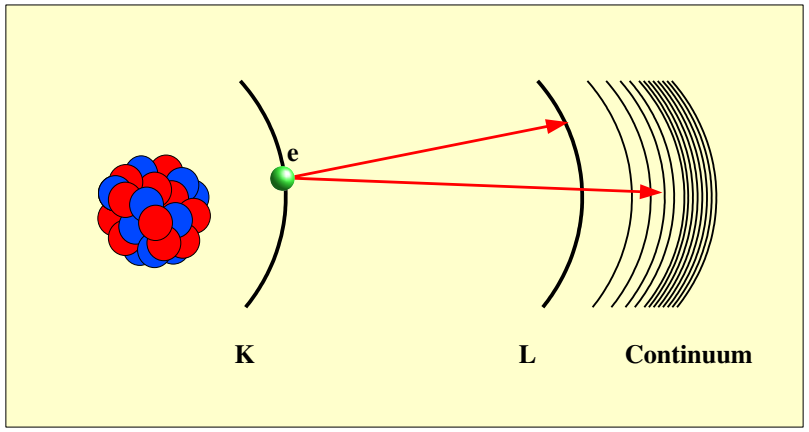

bound internal conversion (BIC) + inverse process

nuclear excitation by electron transition (NEET)

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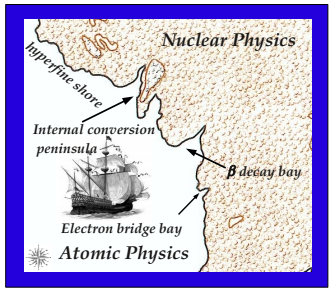
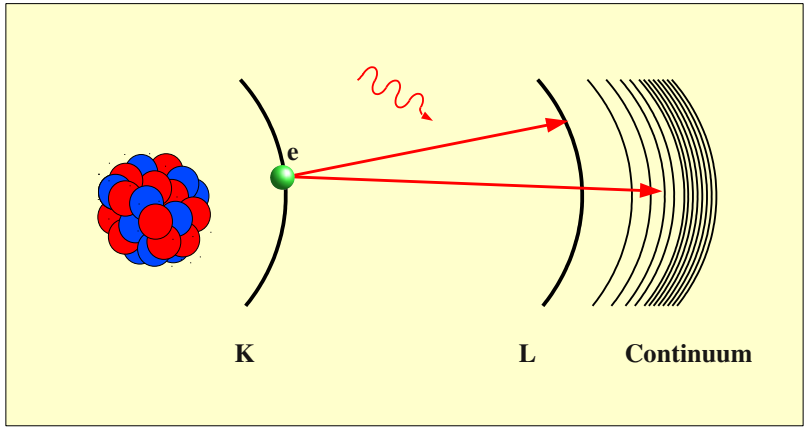
The interface of atomic and nuclear physics



- nuclear processes directly involving atomic electrons
  V. A. Krutov, 1958



the famous electron bridge (EB), both excitation and decay

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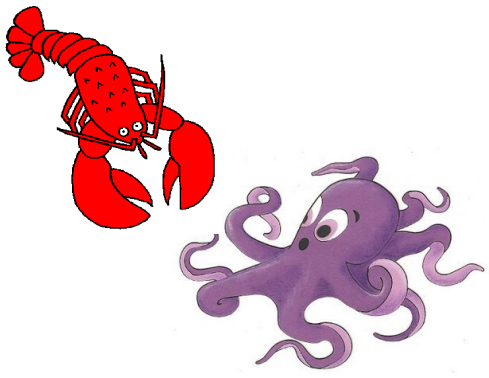
What are the ^{229}Th pirates looking for?

TREASURE

- Nuclear frequency standard based on the isomer
- Investigation of the temporal variation of fundamental constants
- Coherent control of a nuclear transition
- A nuclear gamma-ray laser

What are the ^{229}Th pirates looking for?



So far found

- Isomer energy 7.8 ± 0.6 eV
- Weak transition strength, theoretical value for B(M1) = 0.086 μ_N^2
- Hyperfine structure of the ground state

Beck et al., LLNL-PROC-415170 (2009), Dykhne and Tkalya, JETP Lett. 67, 251 (1998), Campbell et al., PRL 106, 223001(2011)

What are the ^{229}Th pirates looking for?

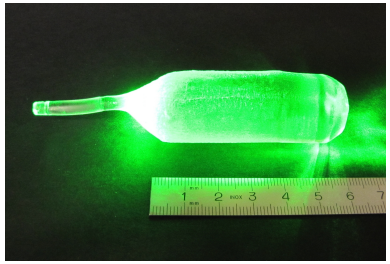
^{229m}Th ——— 7.8 eV

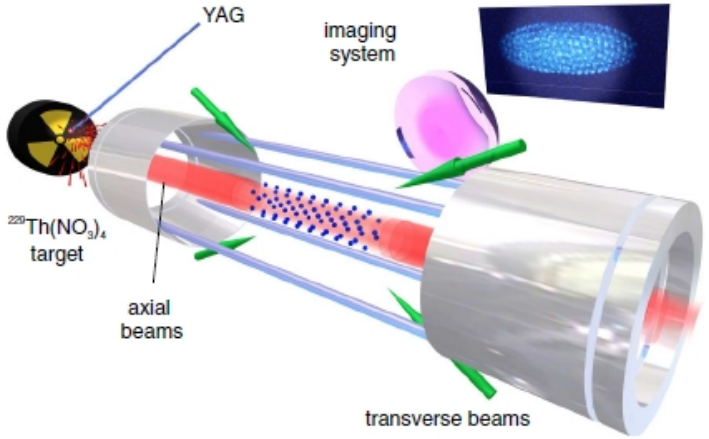
——— 0.0

Approaches

Trapped ions

Doped crystals





Outline

- Of IC and NEEC
- Of BIC and NEET
- EB for excitation and decay
- Conclusions

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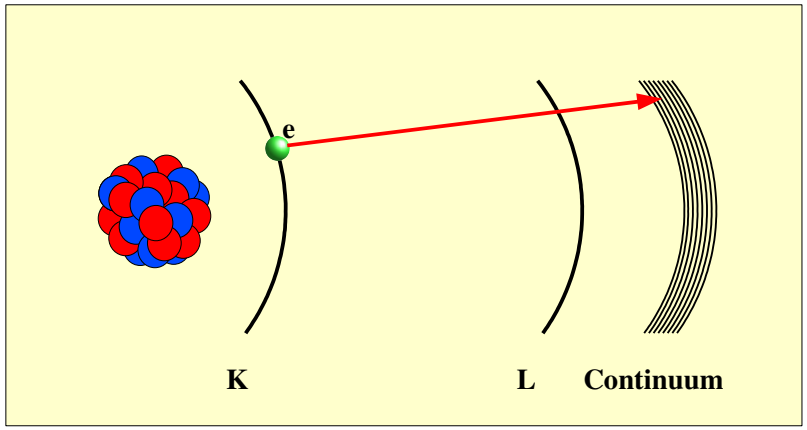
IC/NEEC in a nutshell

Internal conversion



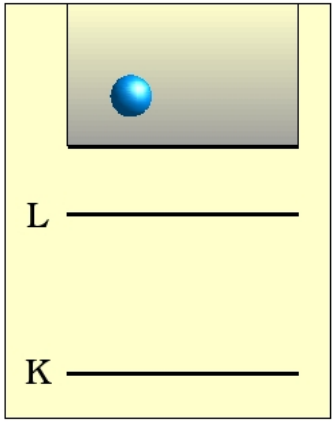
- for trapped $^{229}\mathrm{Th}^{3+}$ ions, IC is not energetically allowed
- in the doped crystals, the band gap of 10 eV forbids IC
- in other materials, IC may be possible and $\alpha = 10^{9}$ † $\rightarrow$ detect the emitted electrons? Talk by J. Burke tomorrow
- for such small excitation energies, coupling to the atomic shell works better* than photon emission/absorption!

† Karpeshin and Trzhaskovskaya, PRC 76, 054313 (2007)

* AP, Evers and Keitel, PRL 99, 172502 (2007)

Electron recombination processes

RR



- direct process
- any electron energy
- electron-radiation field

Electron recombination processes

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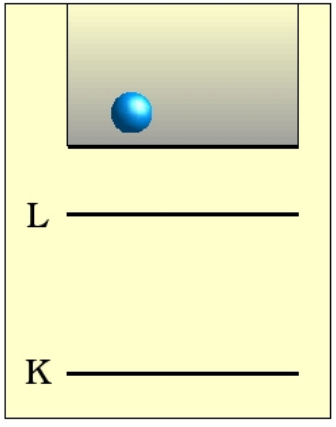

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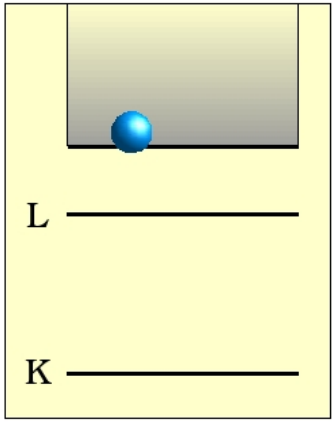

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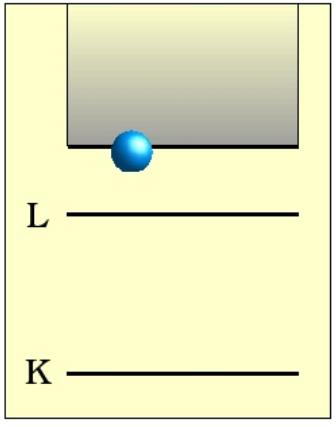

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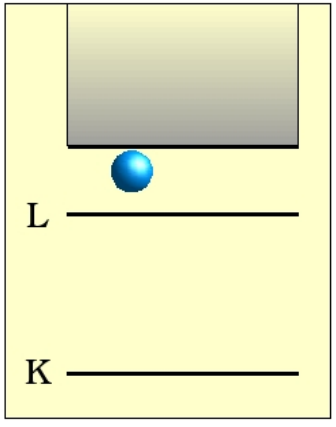

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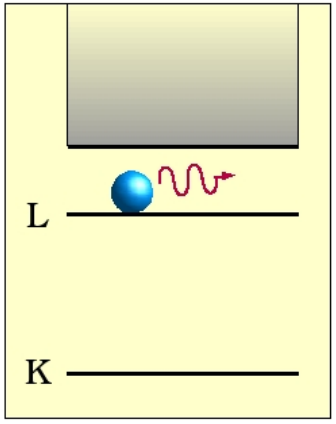

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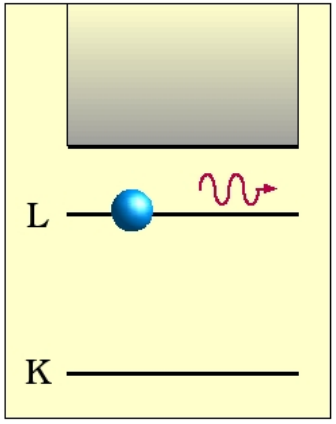

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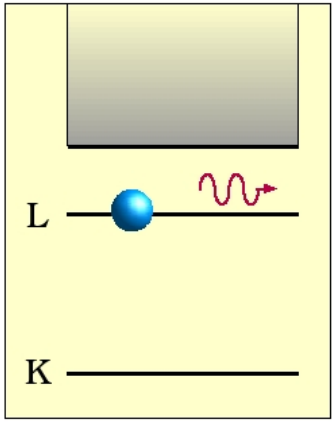

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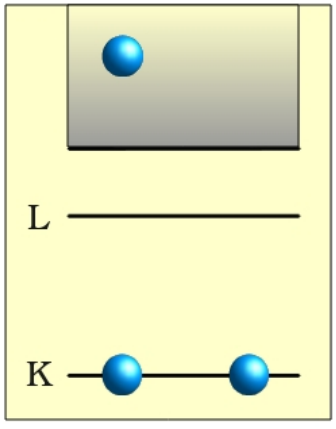

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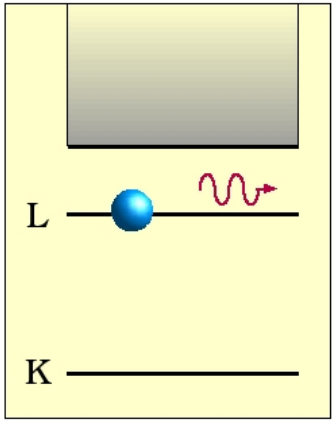

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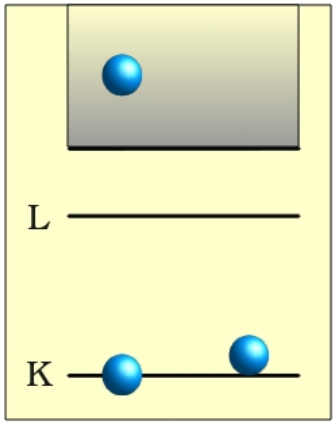

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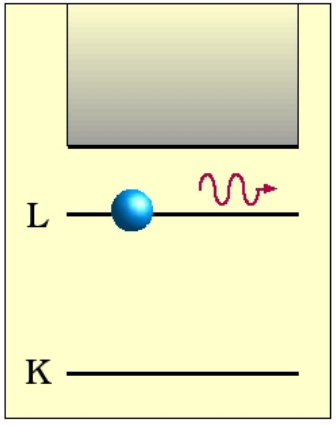

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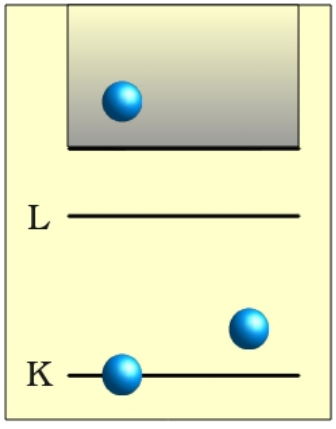

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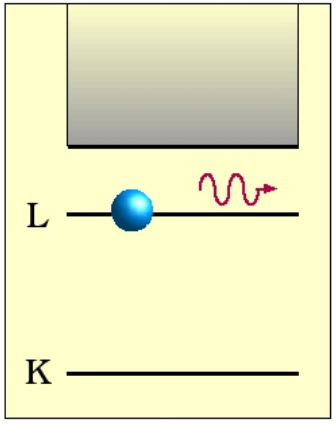

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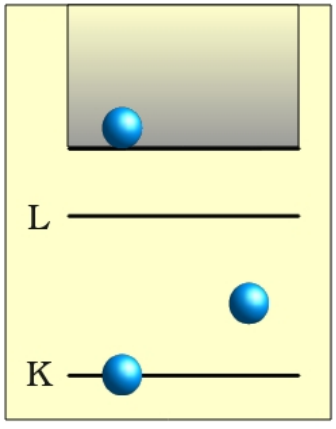

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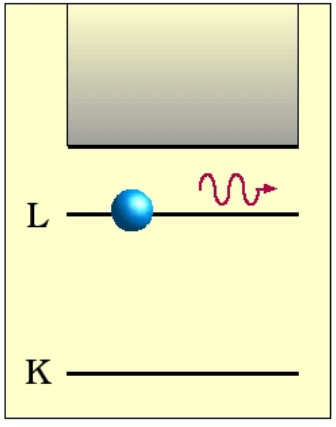

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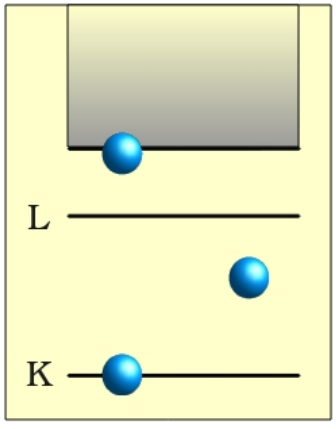

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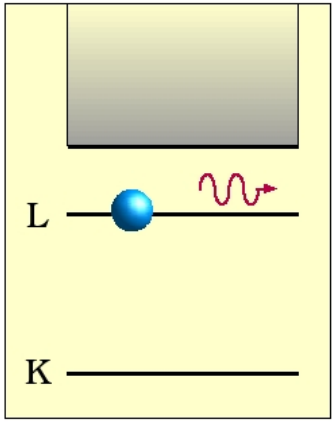

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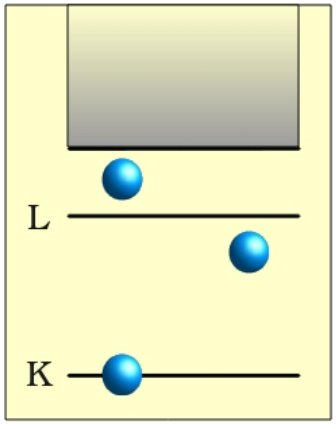

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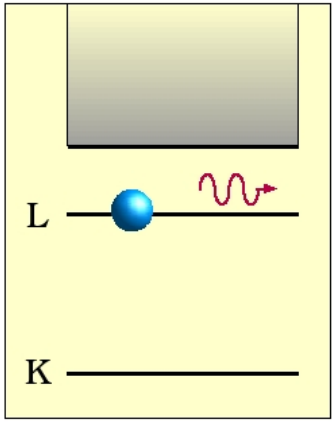

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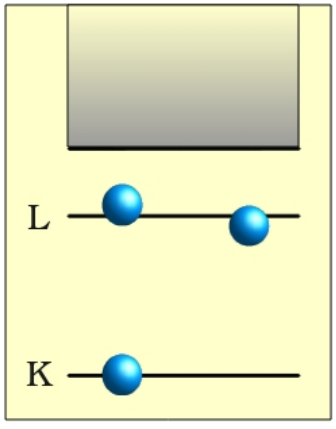

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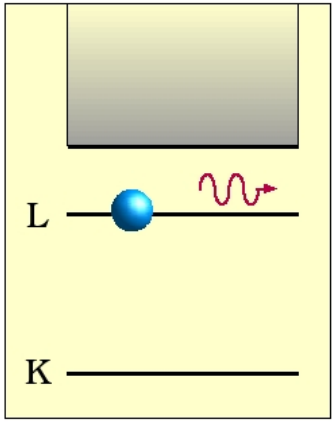

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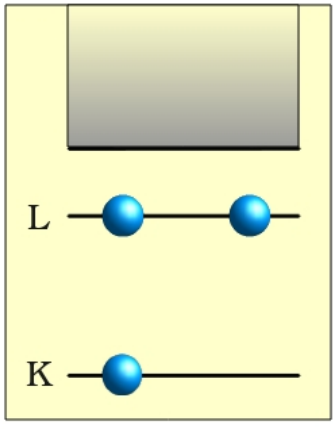

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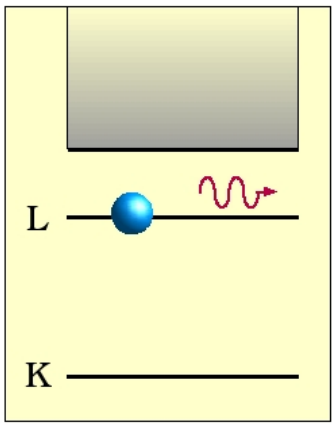

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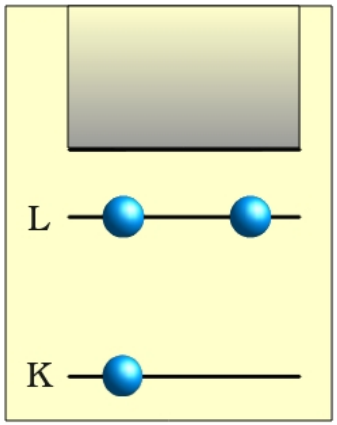

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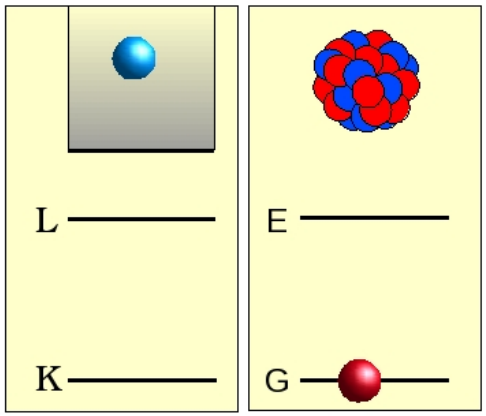

- resonant process
- Coulomb interaction
- current-current interaction

Electron recombination processes

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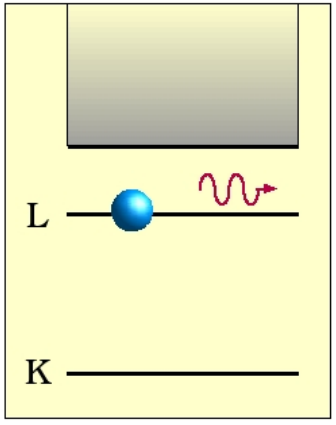

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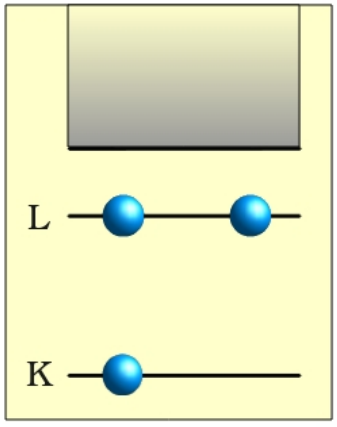

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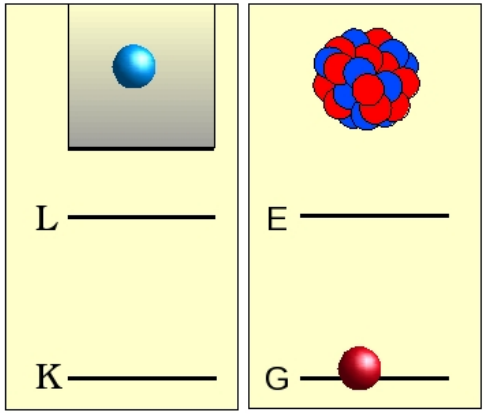

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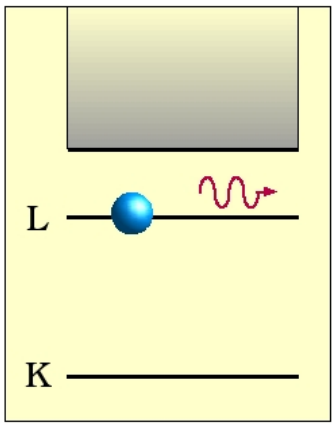

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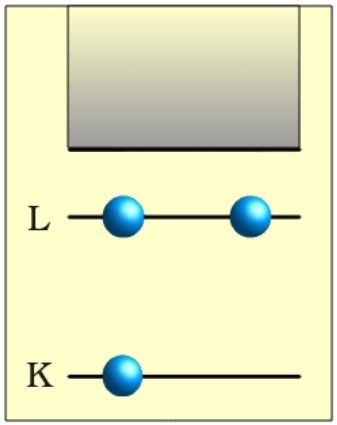

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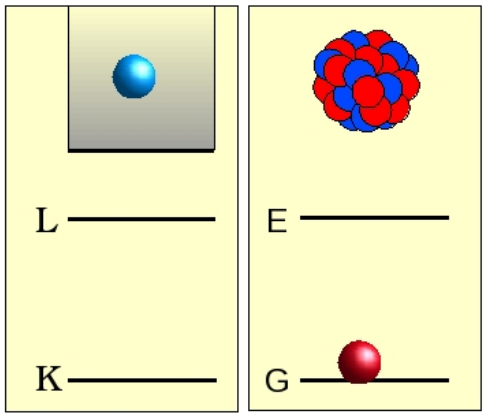

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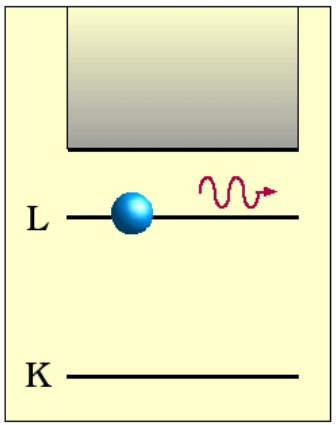

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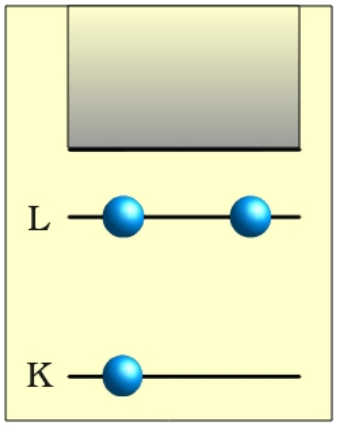

- resonant process
- Coulomb interaction
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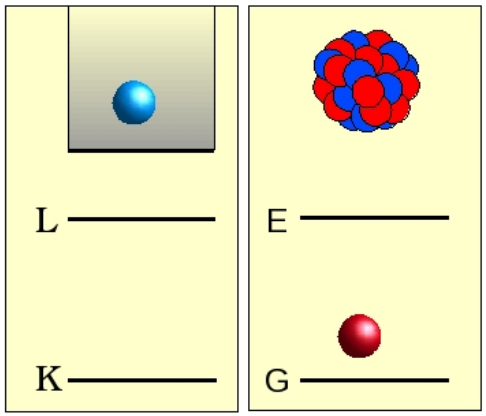
NEEC



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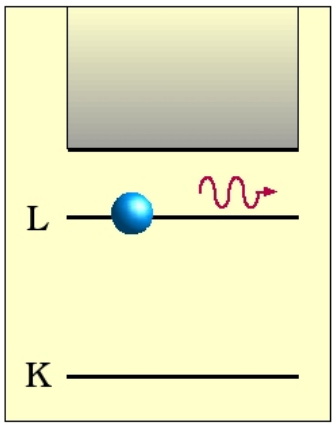
Electron recombination processes

RR



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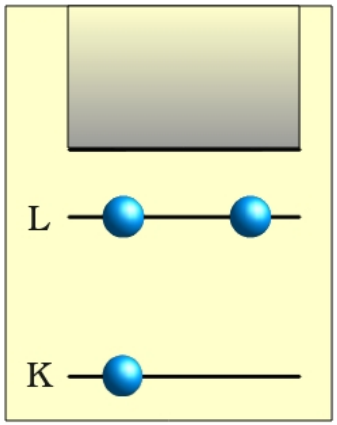

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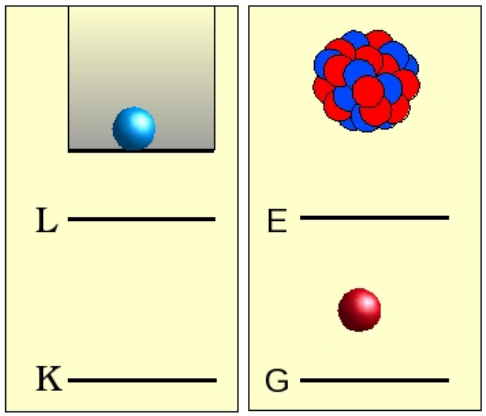

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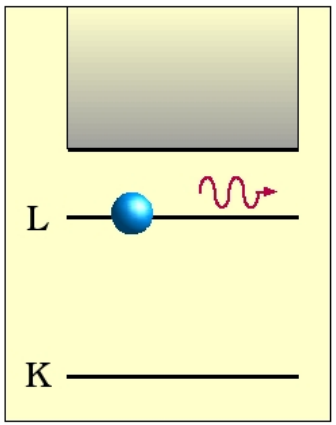

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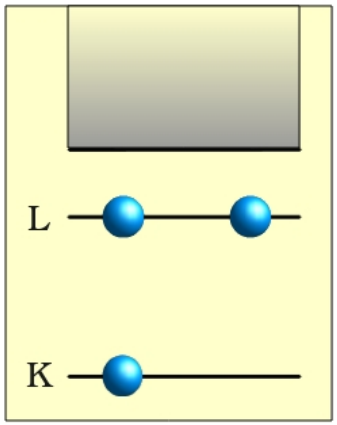

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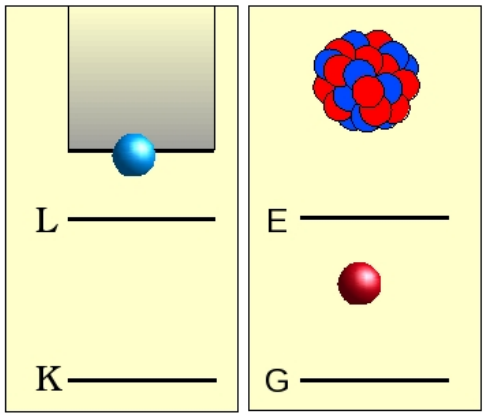

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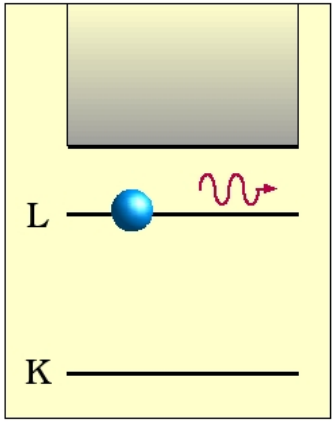

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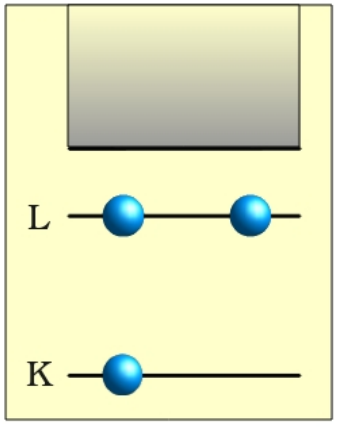

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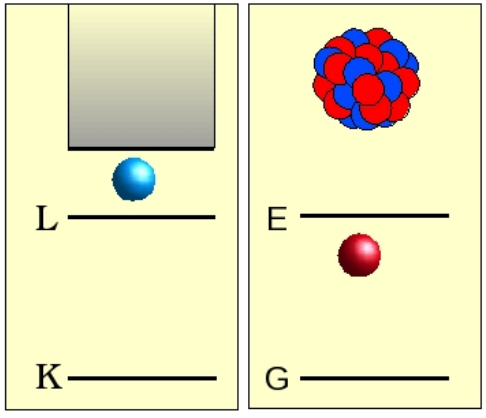

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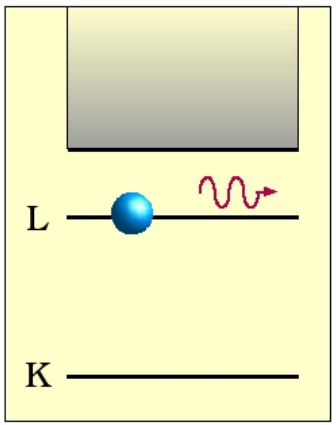

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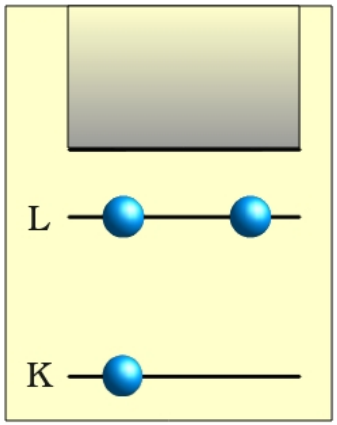

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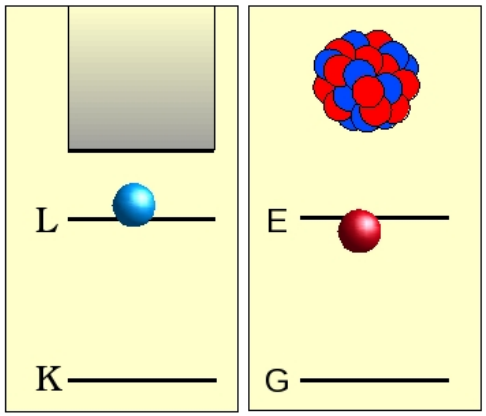

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Electron recombination processes

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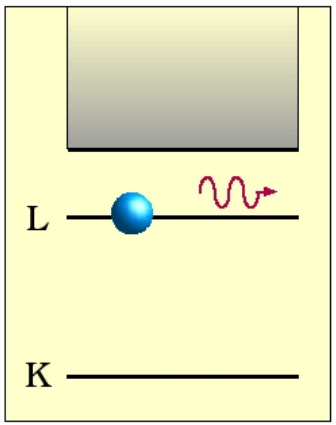

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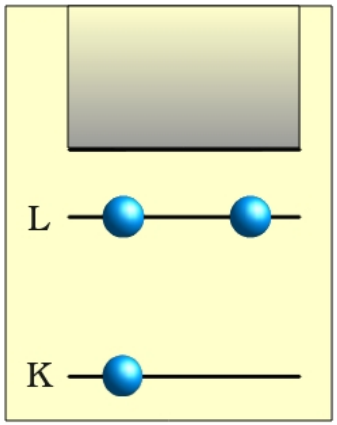

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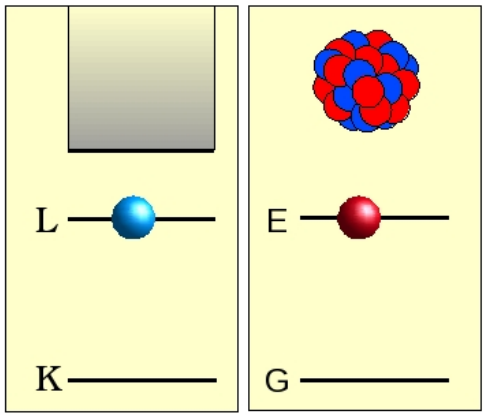

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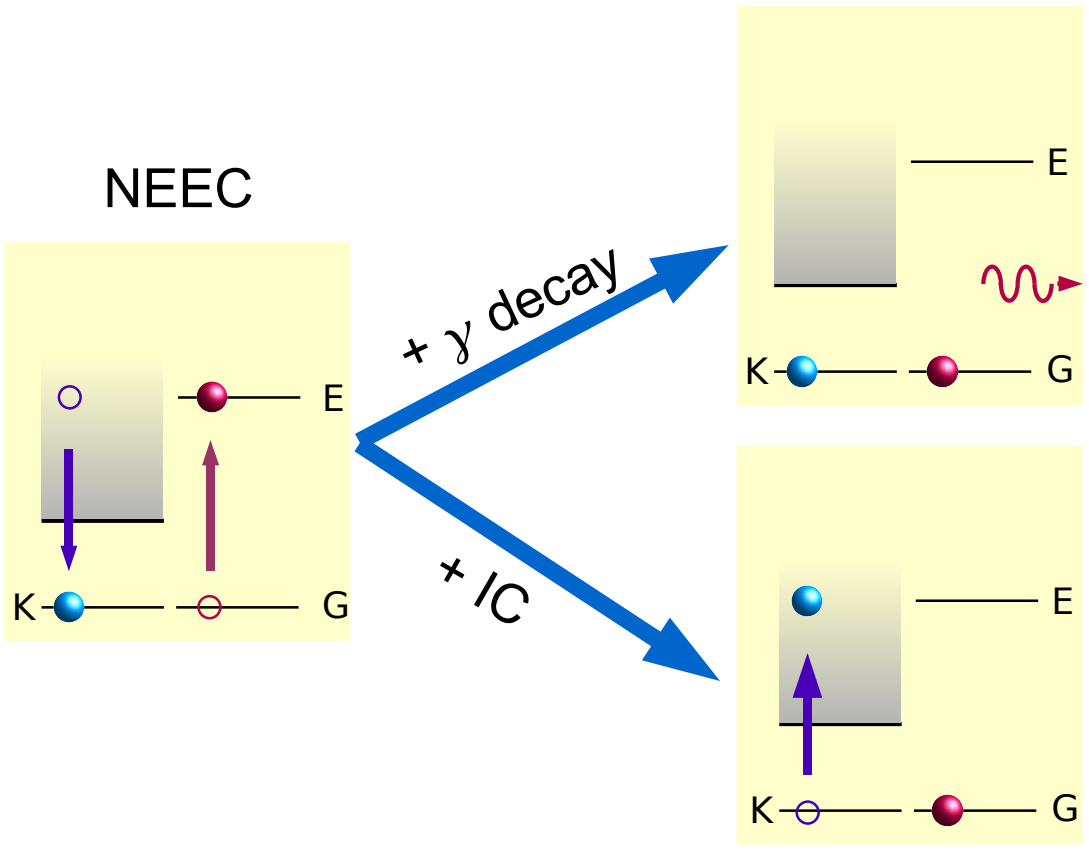
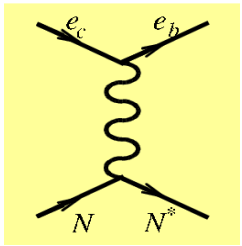
Nuclear decay channels



AP, Z. Harman, W. Scheid
PRA 73 (2006) 012715

AP, Z. Harman
PRA 77 (2008) 042704

Why NEEC?



- first proposed theoretically by Goldanskii & Namiot Phys. Lett. 62B (1976)
- not observed experimentally yet

why is it interesting?

Study of:

population mechanisms of excited nuclear levels

atomic vacancy effects on nuclear lifetime

nuclear decay rates

Relevant for:

dense astrophysical plasmas

triggering of isomers

NEEC in a nutshell

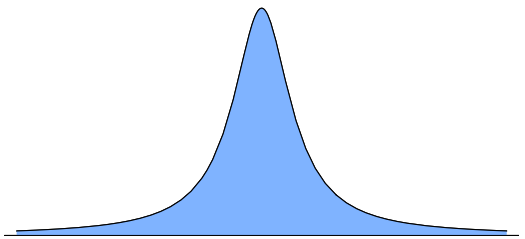
Total NEEC cross section

NEEC + γ total cross section as function of continuum electron energy

$$\sigma(E) = \frac{2\pi^2}{p^2} \frac{A_\gamma^{d\to f} Y_n^{i\to d}}{\Gamma_d} L_d(E - E_d)$$

$$\text{natural width } \Gamma_d \sim 10^{-5} - 10^{-8} \text{ eV}$$

$$\text{resonance strength } S \sim 1 \text{ b eV}$$



AP, Z. Harman and W. Scheid, PRA 73 (2006) 012715

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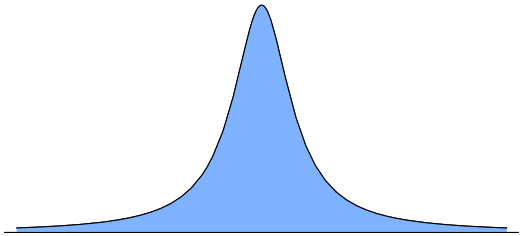

AP, Z. Harman and W. Scheid, PRA 73 (2006) 012715

Typical values

Typical values

Isotope
$^{174}_{70}\mathrm{Yb}$
$^{173}_{70}\mathrm{Yb}$
$^{185}_{75}\mathrm{Re}$
$^{187}_{75}\mathrm{Re}$

Typical values

Isotope	E_c(keV)
$^{174}_{70}$Yb	4.89
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Typical values

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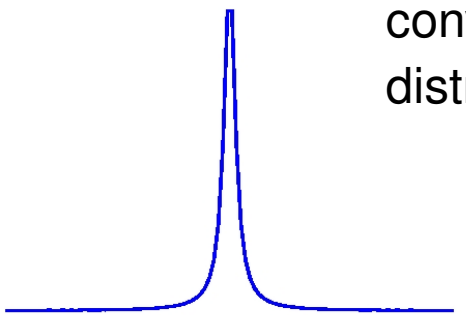

convolution with realistic electron energy distribution

$$\frac{1}{s\sqrt{2\pi}} \exp\left(-\frac{(E-E_0)^2}{2s^2}\right)$$

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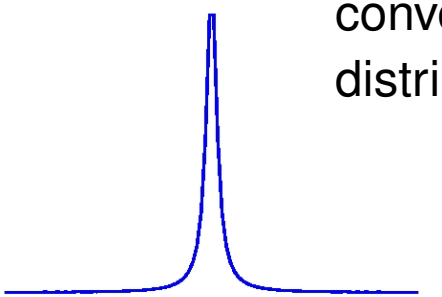

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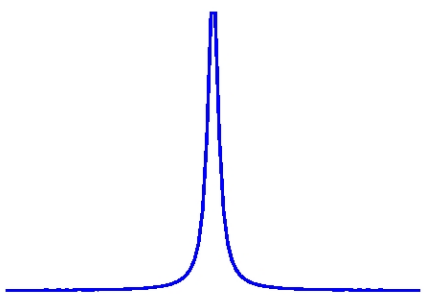

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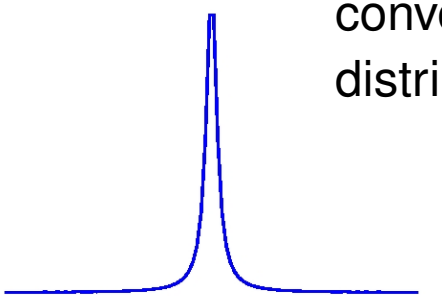

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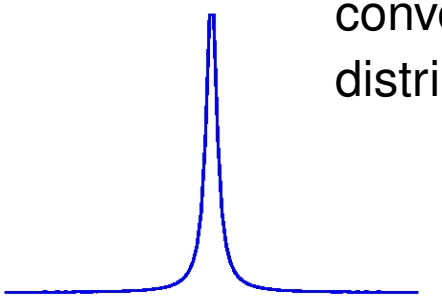

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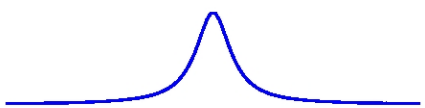

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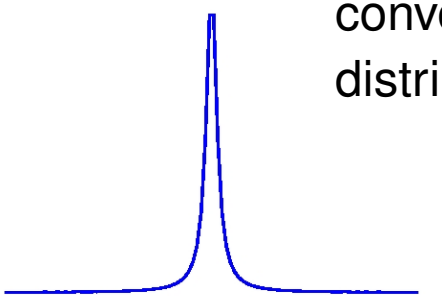

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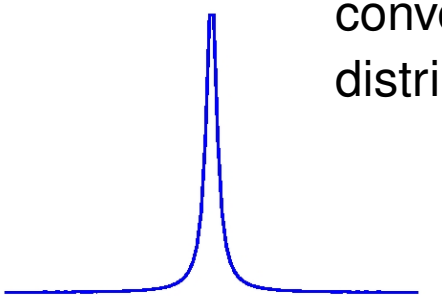

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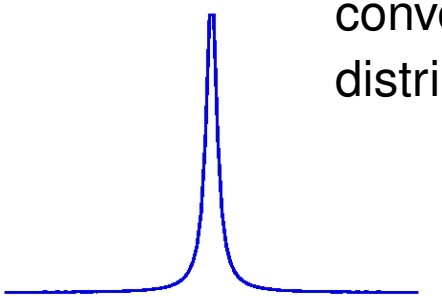

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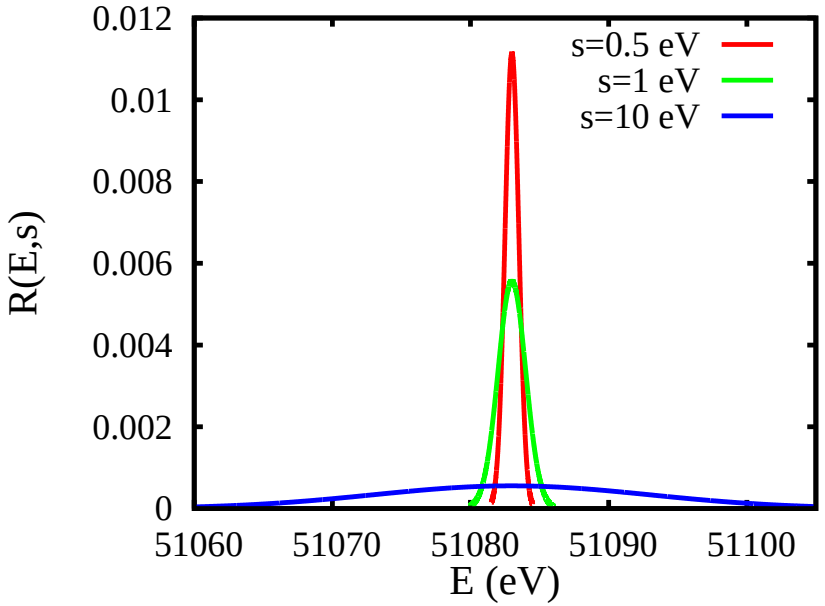
Why it hasn't been observed?

Ratio of the convoluted cross sections

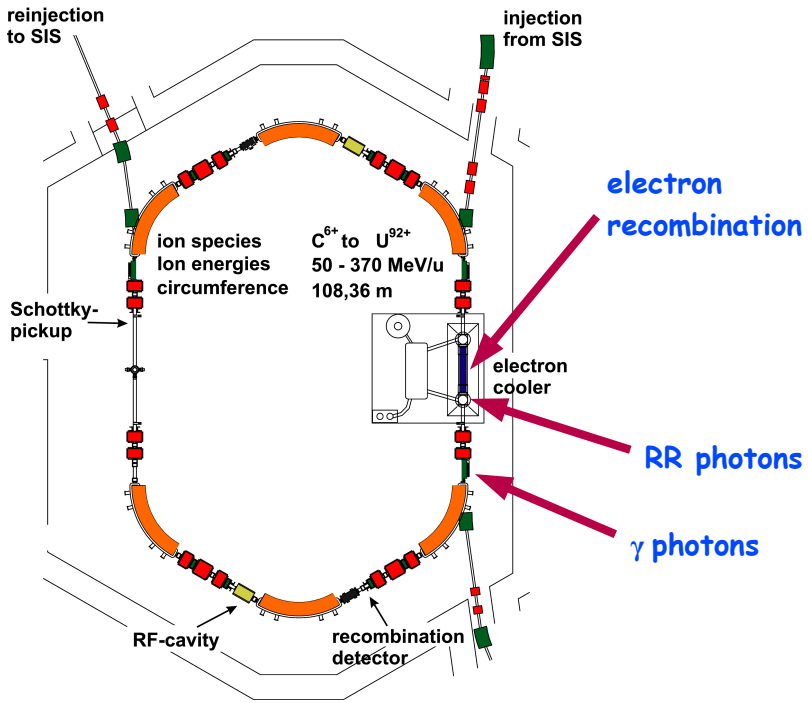
$$R(E,s) = \frac{\tilde{\sigma}_{\mathrm{NEEC}}(E,s)}{\tilde{\sigma}_{\mathrm{RR}}(E,s)}$$

for the case of $^{187}_{75}\mathrm{Re}$

s=10 eV, 1 eV, 0.5 eV



How can we tackle the problem?



- different time scales of NEEC and RR $\rightarrow$ spatial separation of emitted photons
- RR photons $\simeq 10^{-14} - 10^{-16}$
- γ photons $\simeq 10^{-9} - 10^{-11}$

$\tau \simeq 10 - 100$ ns $\rightarrow 2 - 20$ m

AP, Z. Harman, C. Kozhuharov, C. Brandau, C. H. Keitel, W. Scheid, T. Stöhlker
Phys. Lett. B 661 (2008) 330

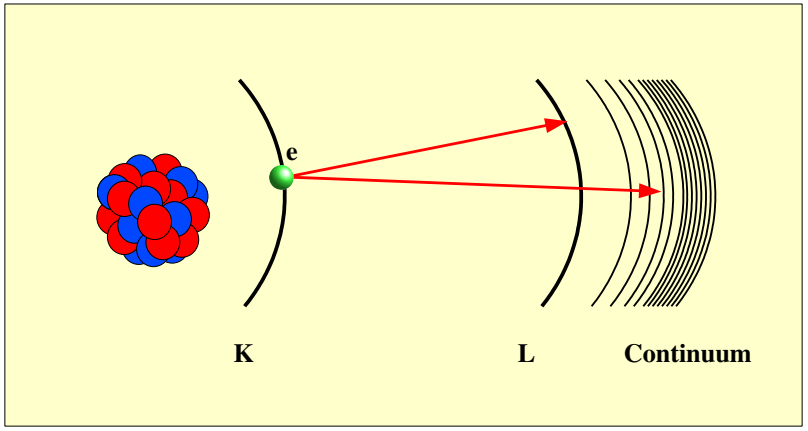
Max-Planck-Institut für Kernphysik

Why it wouldn't work for ^{229}Th

- very narrow transition width
- NEEC not so efficient for high orbitals in almost neutral atoms with many electrons
- monochromatic electron source?

BIC/NEET in a nutshell

Resonant processes



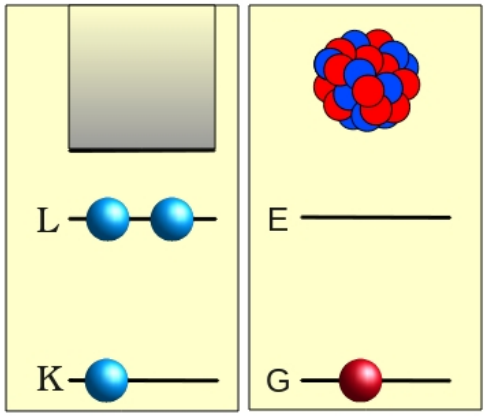
bound internal conversion (BIC) + inverse process

nuclear excitation by electron transition (NEET)

as it is not good for $^{229}\mathrm{Th}$! Resonance conditions are not fulfilled!

Coupling nuclei to the atomic shell

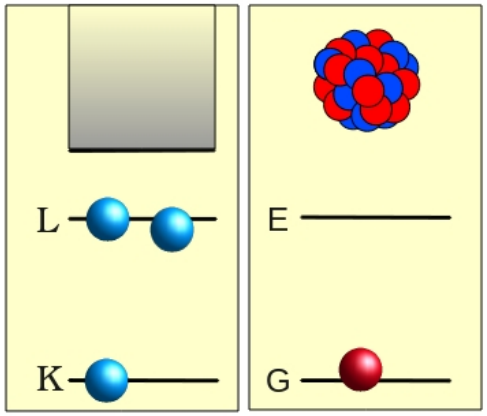
NEET



- electronic hole
- electronic and nuclear transition energy match

Coupling nuclei to the atomic shell

NEET



- electronic hole
- electronic and nuclear transition energy match

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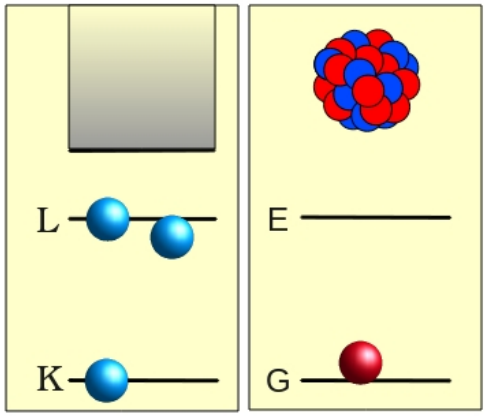

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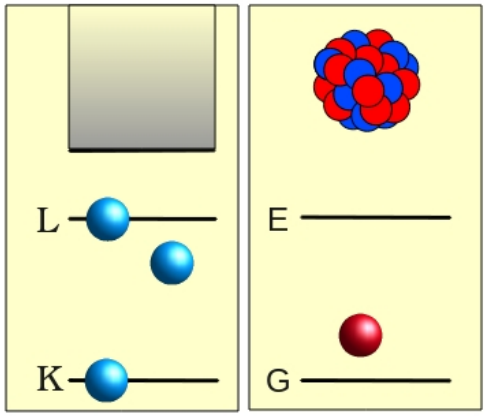

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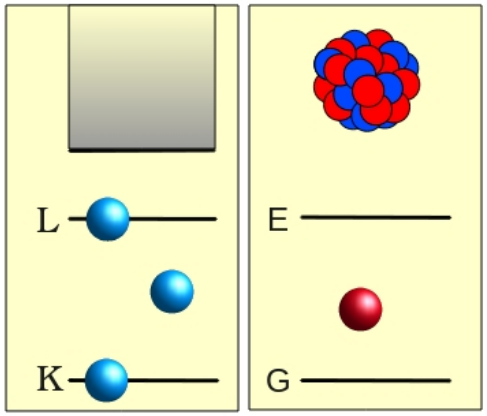

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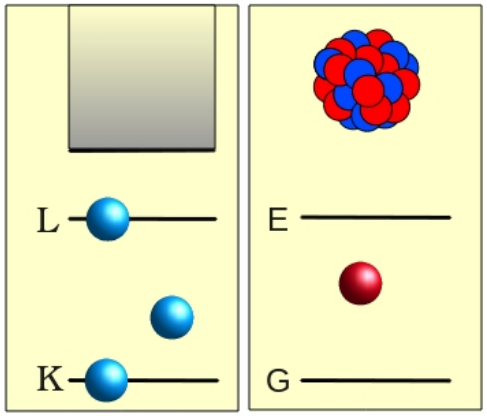

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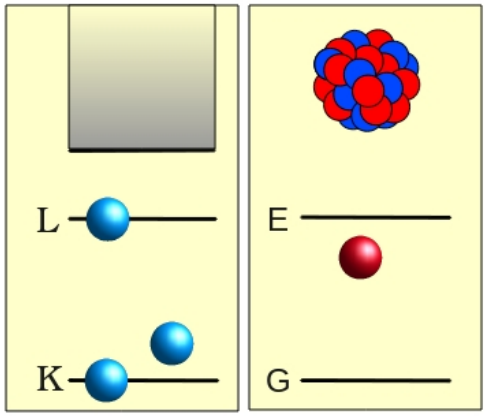

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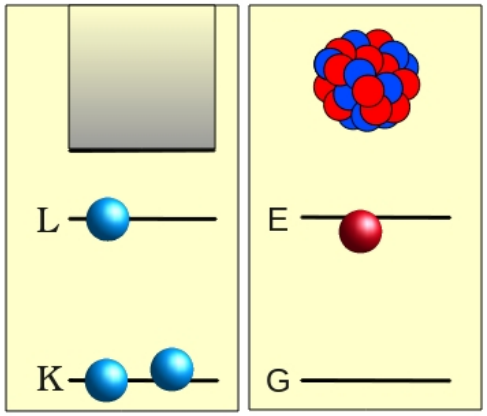

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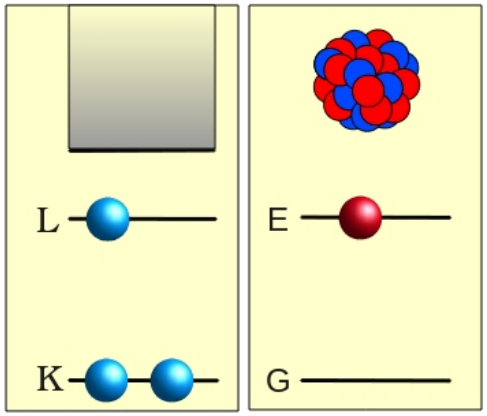

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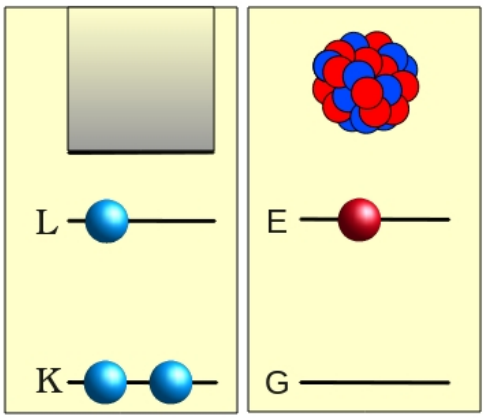

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VOLUME 85, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 2000

Observation of Nuclear Excitation by Electron Transition in ^{197}Au with Synchrotron X Rays and an Avalanche Photodiode

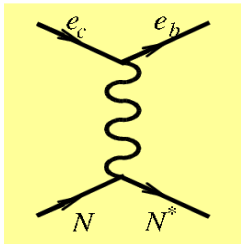
S. Kishimoto,[1] Y. Yoda,[2] M. Seto,[3] Y. Kobayashi,[3] S. Kitao,[3] R. Haruki,[3] T. Kawauchi,[4] K. Fukutani,[4] and T. Okano[4]
[1]*Institute of Materials Structure Science, KEK, Tsukuba, Ibaraki 305-0801, Japan*
[2]*Japan Synchrotron Radiation Research Institute, Mikazuki, Sayo, Hyogo 679-5198, Japan*
[3]*Research Reactor Institute, Kyoto University, Kumatori, Sennan, Osaka 590-0494, Japan*
[4]*Institute of Industrial Science, University of Tokyo, Roppongi, Minato-ku, Tokyo 106-8558, Japan*
(Received 7 December 1999)

atomic ^{197}Au
monochromatized x-rays
$M \rightarrow K$ shell transition
$\mathcal{P}_{NEET} = (5 \pm 0.6) \times 10^{-8}$

Few perfect energy matches in nature!

$\rightarrow$ use highly charged ions instead of atoms!

Why NEET?



- first proposed theoretically by
  M. Morita, Prog. Theor. Phys. 49 (1973)
- observed experimentally

why is it interesting?

Study of:

population mechanisms of excited nuclear levels

atomic vacancy effects on nuclear lifetime

nuclear decay rates

Relevant for:

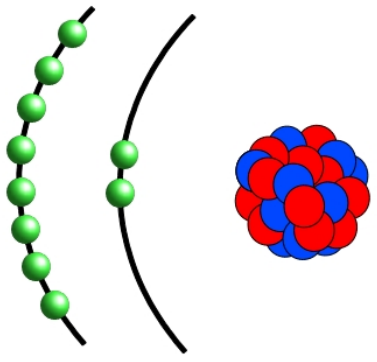
dense astrophysical plasmas → highly charged ions

NEET in highly charged ions

Tunability of electronic transition energy:

ionic charge state modifies the electronic energy levels!

$$\Delta E_{HCI} > \Delta E_{atom}$$



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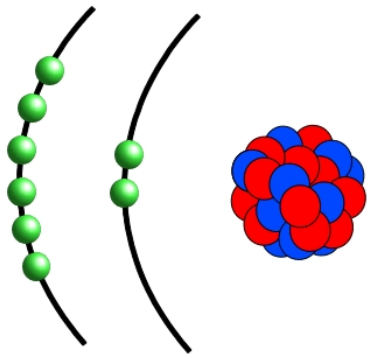

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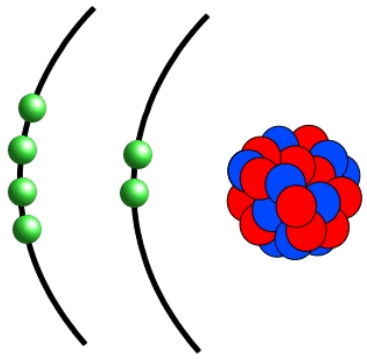

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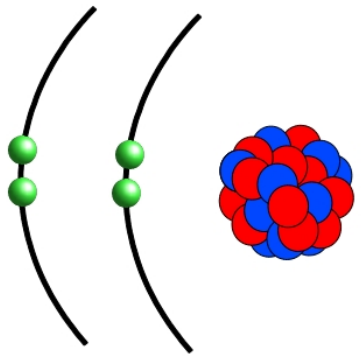

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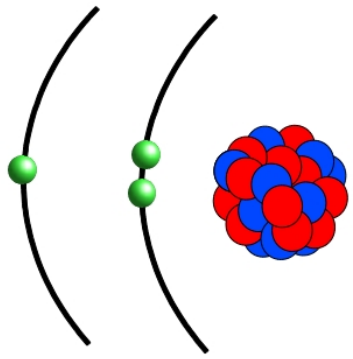

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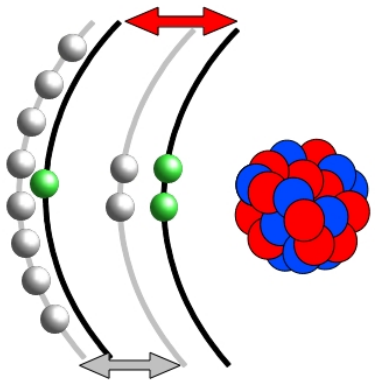
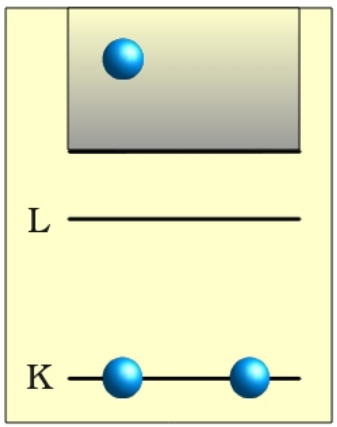


DC in highly charged ions

. . . another way to create the electronic hole, predominant in plasmas

DC



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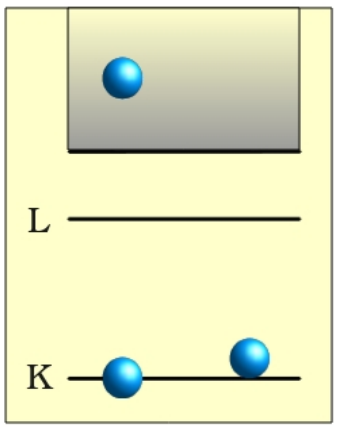

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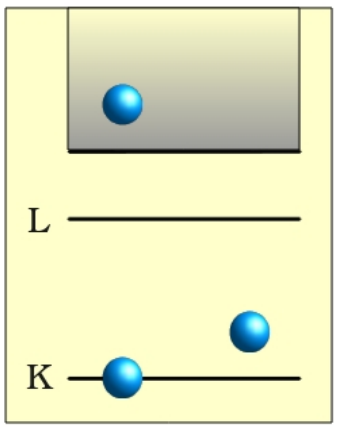

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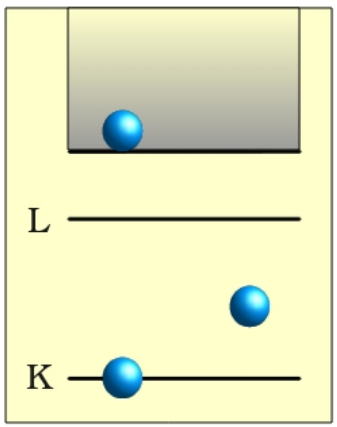

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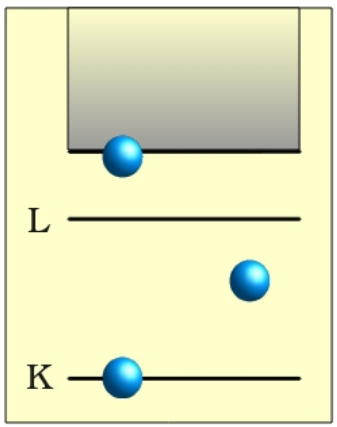

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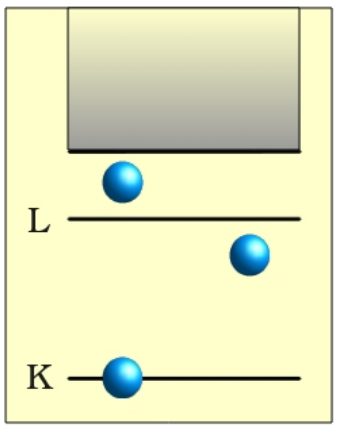

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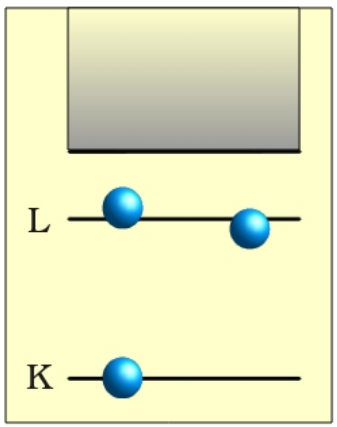

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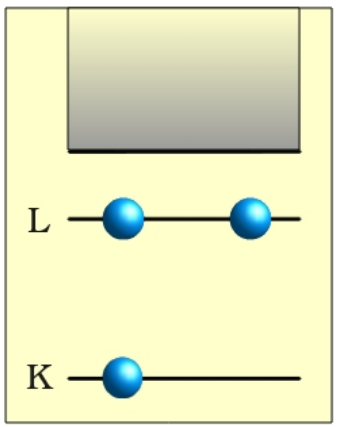

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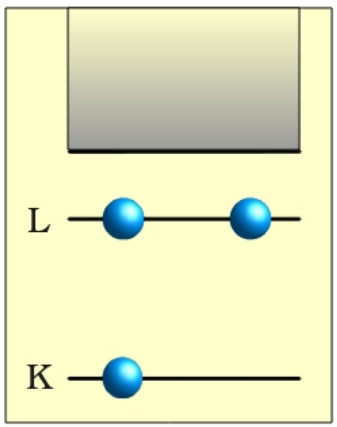
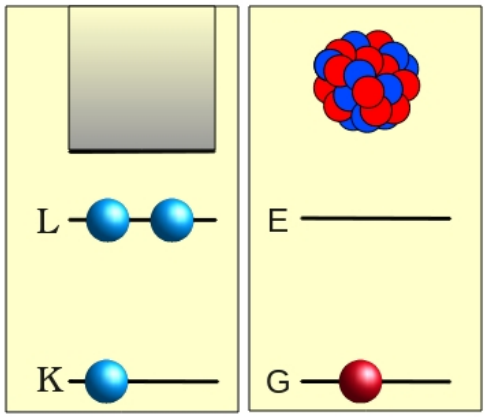


NEET



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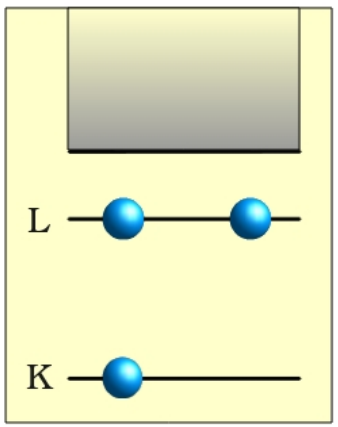

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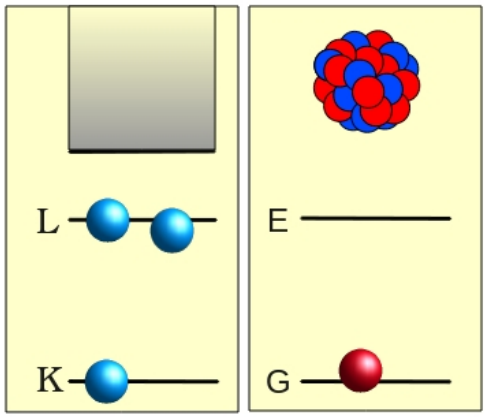

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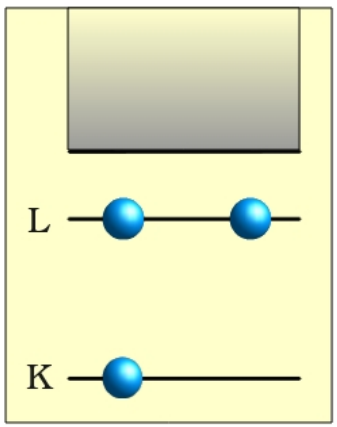

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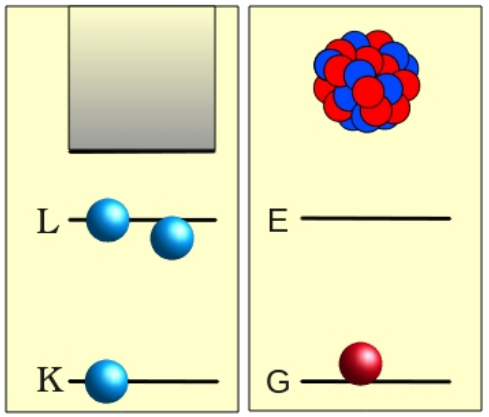

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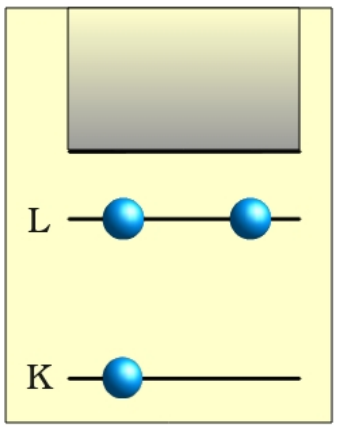

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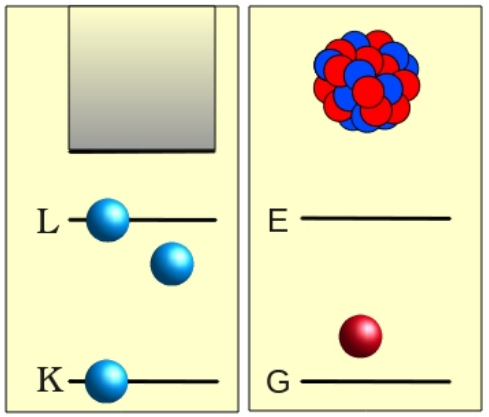

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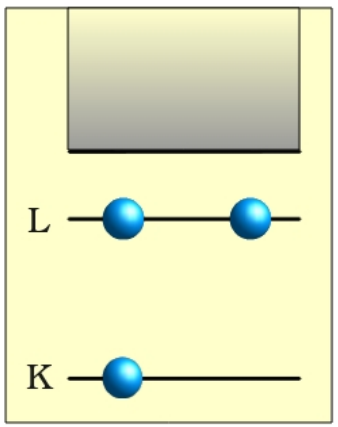

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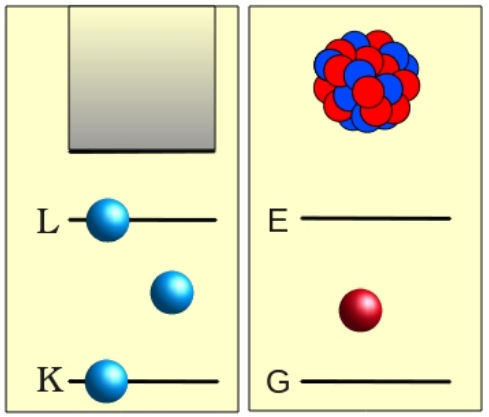

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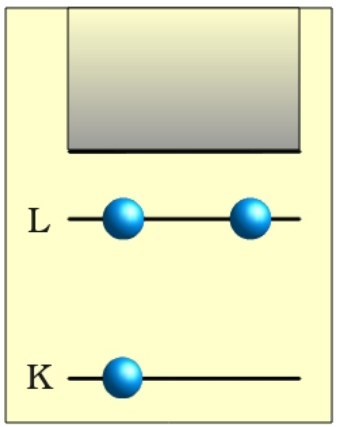

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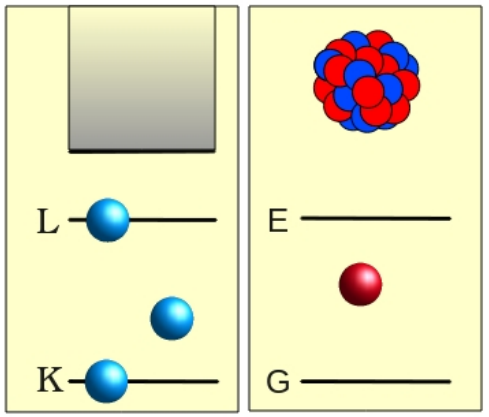

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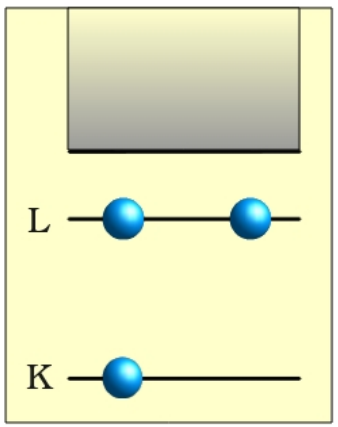

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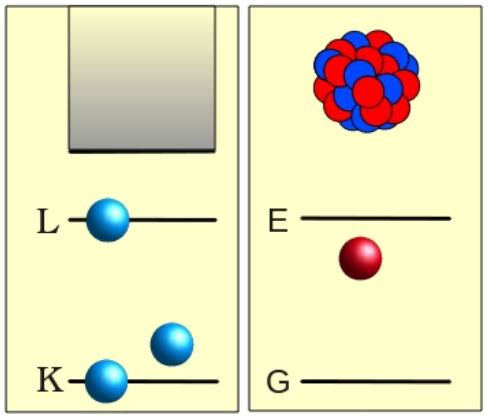

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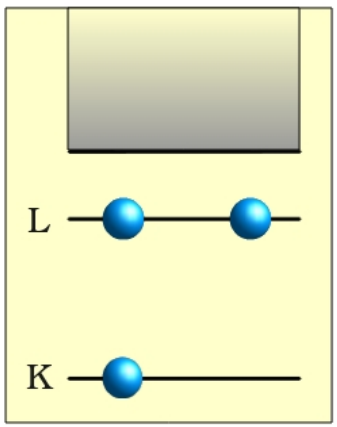

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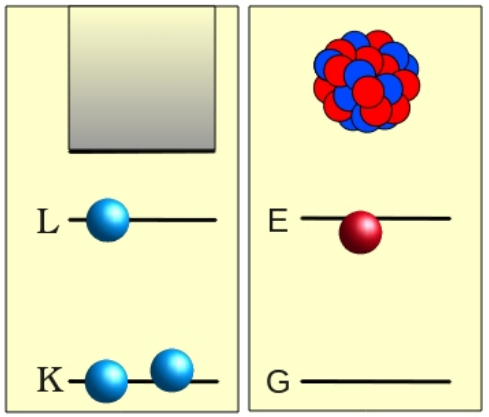

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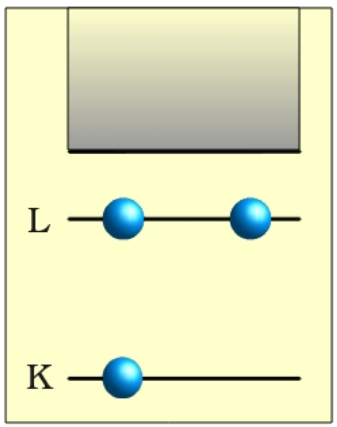

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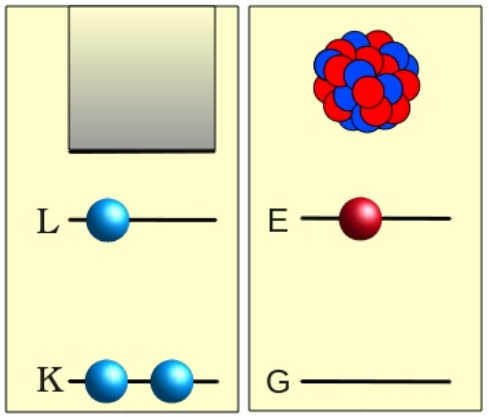

DC followed by NEET and γ decay

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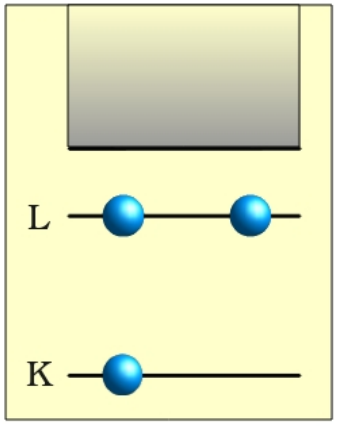
DR



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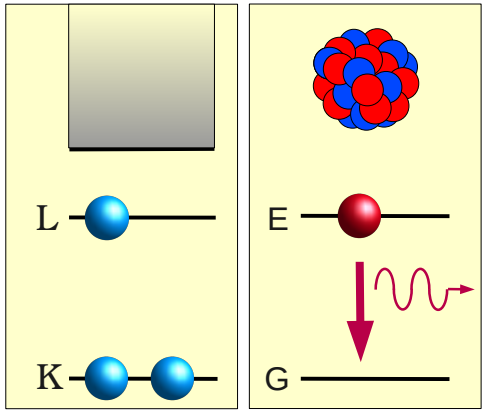

Total resonance strength

DC + NEET + γ total cross section as function of continuum electron energy

$$\sigma(E) = \frac{\pi^2}{p^2} \frac{A_{DC} |\langle f|H_{en}|i\rangle|^2 A_\gamma}{\left((E-E_a)^2 + \frac{\Gamma_a^2}{4}\right)\left((E-E_n)^2 + \frac{\Gamma_n^2}{4}\right)}$$

$$S = \frac{\pi^2}{p^2} \frac{A_{DC}\ \mathcal{P}_{NEET}\ A_\gamma}{\Gamma_n}$$

- dielectronic capture rate A_{DC}
- gamma decay rate A_γ
- NEET probability $\mathcal{P}_{NEET} \sim \frac{|\langle f|H_{en}|i\rangle|^2}{(E_n - E_a)^2 + \frac{\Gamma_a^2}{4}}$

perfect match
$E_n - E_a = 0$
narrow electronic width Γ_a

S. K. Arigapudi and AP, PRA 85, 012710 (2012)

Test case $^{237}_{93}\mathrm{Np}$

... neutral atoms:

Isotope	Type	E_n (keV)	$\bar{e}$ transition	E_a (keV)	ΔE (keV)
$^{237}_{93}\mathrm{Np}$	E1	102.96	K-L	101.07	1.89

... tunable transitions:

Configuration	E_a (keV)	ΔE (keV)	Γ_a (eV)
$[1s^1 2s^2 2p^2_{1/2} 2p^4_{3/2}]_{1/2+}$	101.664	1.295	70
$[1s^1 2s^2 2p^2_{1/2} 2p^3_{3/2}]_{1-}$	101.701	1.258	76
$[1s^1 2s^1 2p^1_{3/2}]_{1/2-}$	102.879	0.080	30
$[1s^1 2s^1 2p^1_{3/2}]_{3/2-}$	102.999	-0.040	22
$[1s^1 2p^1_{3/2}]_{1-}$	103.279	-0.320	29

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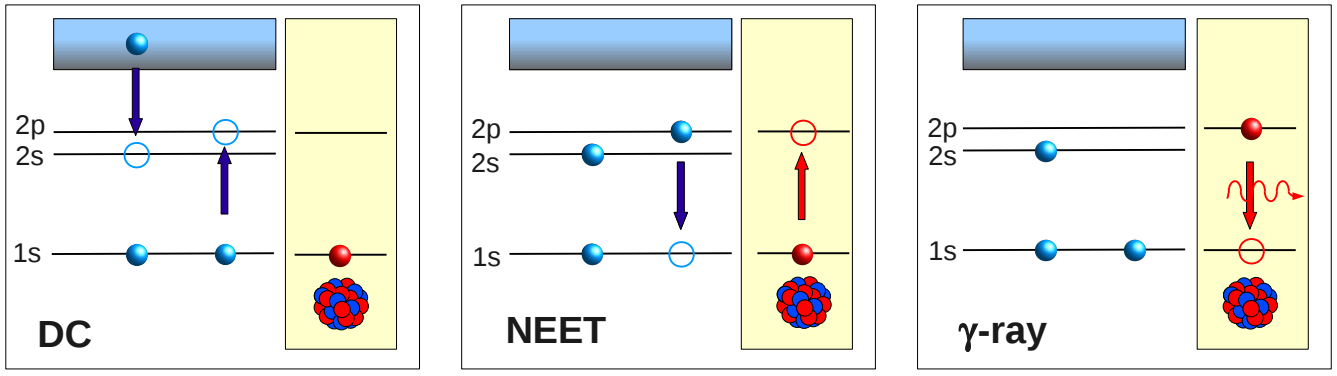
$^{237}_{93}\mathrm{Np}$	E1	102.96	K-L	101.07	1.89

... tunable transitions:

Configuration	E_a (keV)	ΔE (keV)	Γ_a (eV)	$\mathcal{P}_{NEET}$
$[1s^1 2s^2 2p^2_{1/2} 2p^4_{3/2}]_{1/2+}$	101.664	1.295	70	
$[1s^1 2s^2 2p^2_{1/2} 2p^3_{3/2}]_{1-}$	101.701	1.258	76	
$[1s^1 2s^1 2p^1_{3/2}]_{1/2-}$	102.879	0.080	30	7.2×10^{-10}
$[1s^1 2s^1 2p^1_{3/2}]_{3/2-}$	102.999	-0.040	22	2.8×10^{-9}
$[1s^1 2p^1_{3/2}]_{1-}$	103.279	-0.320	29	

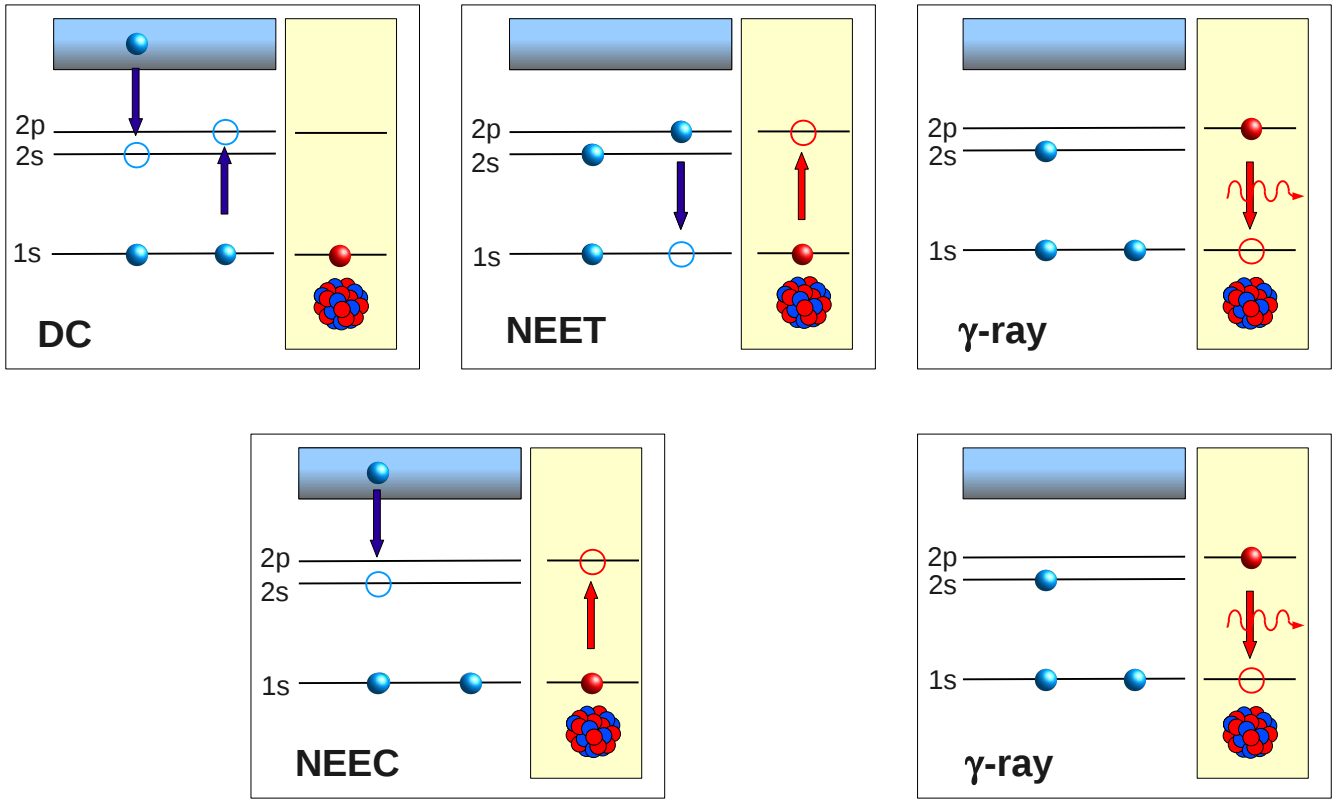
S. K. Arigapudi and AP, PRA 85, 012710 (2012)

Interference possibilities for $^{237}_{93}\mathrm{Np}$



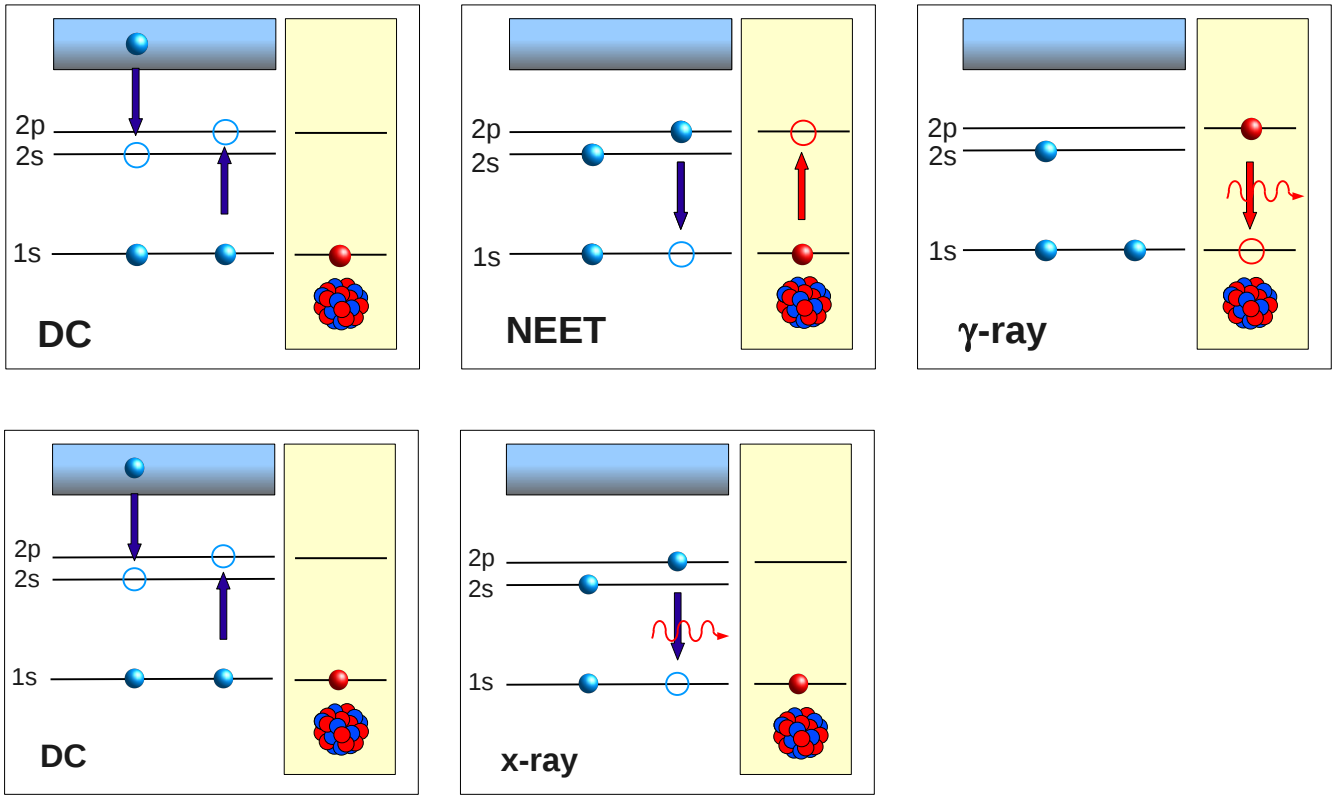
S. K. Arigapudi and AP, PRA 85, 012710 (2012)

NEET and NEEC



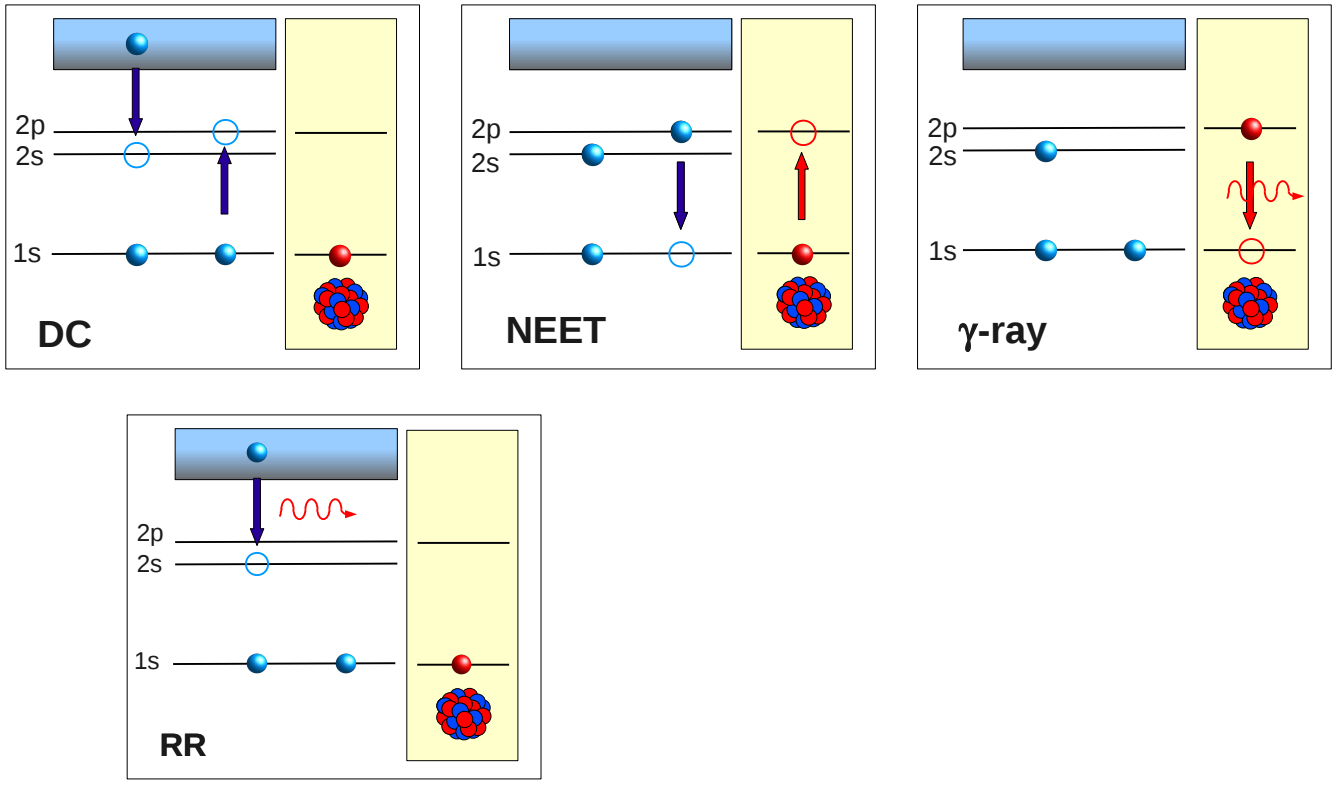
S. K. Arigapudi and AP, PRA 85, 012710 (2012)

NEET and DR



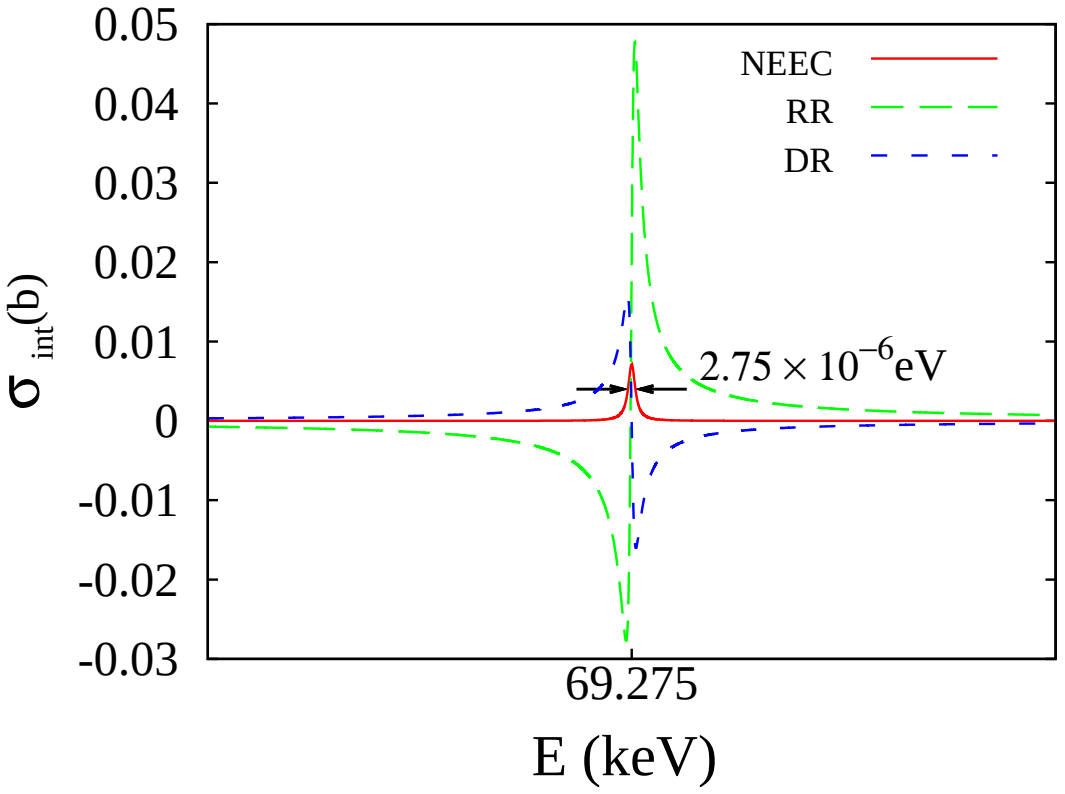
S. K. Arigapudi and AP, PRA 85, 012710 (2012)

NEET and RR



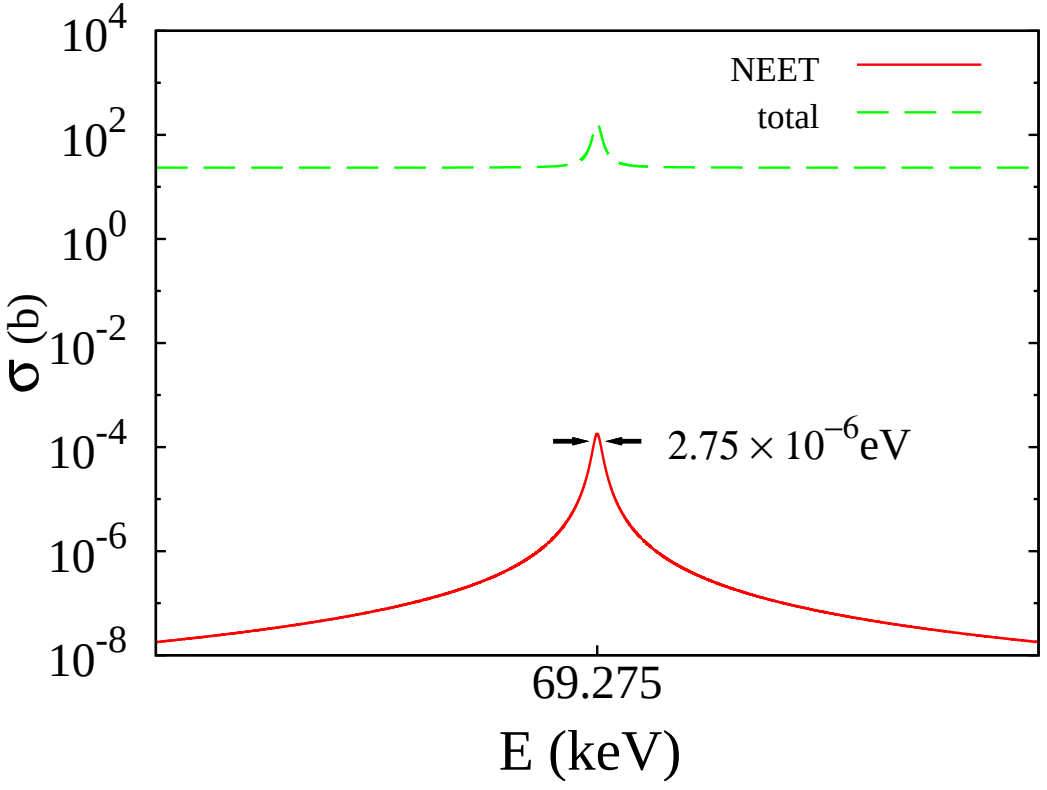
S. K. Arigapudi and AP, PRA 85, 012710 (2012)

Interference cross sections



- Very narrow peaks determined by nuclear width!

Total cross sections



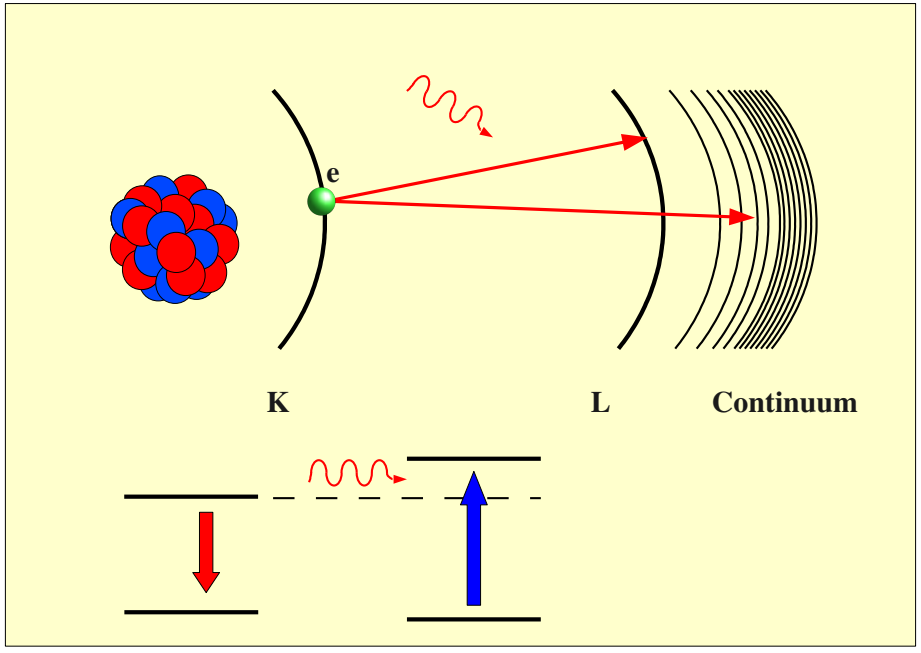
- Surprise! For highly charged ions, NEEC cross section larger than NEET one!
- At the resonance, NEEC term dominates (143 b), far from the resonance the RR (27 b) and DR (2 b) terms.

Why it wouldn't work for ^{229}Th

- mismatch between atomic and nuclear transition - this is solved in the EB by an additional photon!
- very narrow transition width - signal washed out compared to other electronic processes
- NEET also not so efficient for high orbitals in almost neutral atoms with many electrons

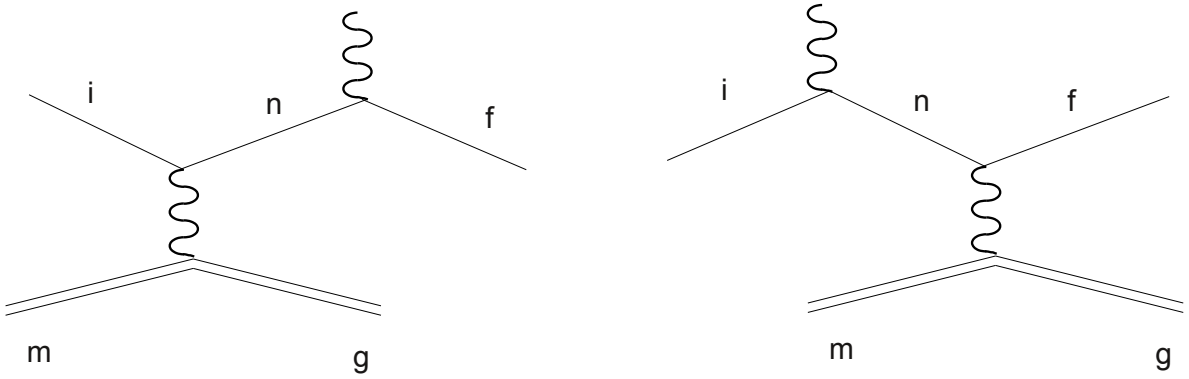
EB in a nutshell

Electronic bridge



- higher order process
- sometimes also called bound internal conversion or resonant electron bridge

Electronic bridge

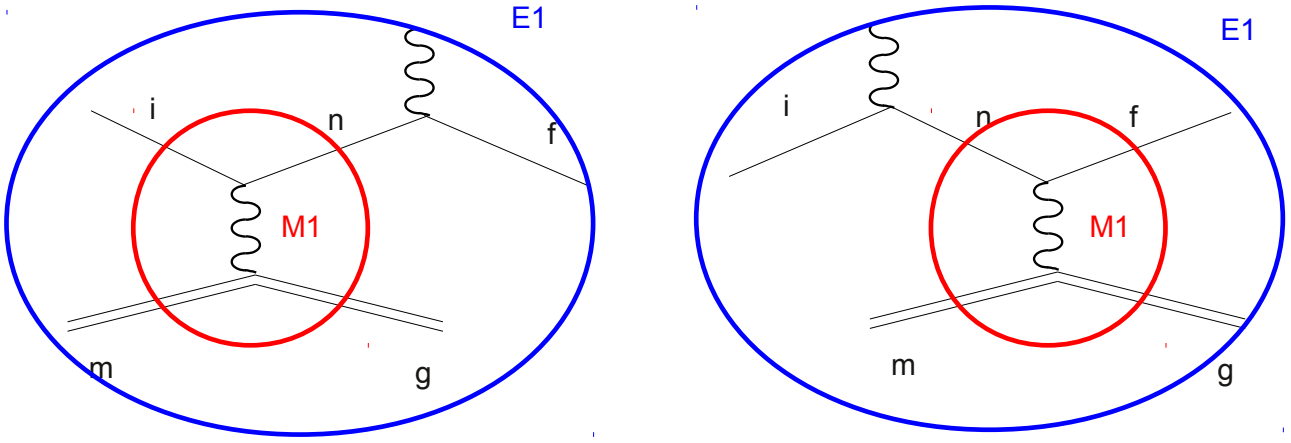


$$\mathcal{D}_{EB} = \sum_n \frac{\langle f|\mathcal{D}|n\rangle\langle g,n|H_{int}|m,i\rangle}{\varepsilon_i + E_m - \varepsilon_n - E_g + i\Gamma_n/2}$$

$$+ \sum_k \frac{\langle g,f|H_{int}|m,k\rangle\langle k|\mathcal{D}|i\rangle}{\varepsilon_f + E_g - \varepsilon_k - E_m + i\Gamma_k/2}$$

Porsev and Flambaum, PRA 81, 032504, 042516 (2010)

Electronic bridge



$$\mathcal{D}_{EB} = \sum_n \frac{\langle f|\mathcal{D}|n\rangle\langle g,n|H_{int}|m,i\rangle}{\varepsilon_i + E_m - \varepsilon_n - E_g + i\Gamma_n/2}$$

$$+ \sum_k \frac{\langle g,f|H_{int}|m,k\rangle\langle k|\mathcal{D}|i\rangle}{\varepsilon_f + E_g - \varepsilon_k - E_m + i\Gamma_k/2}$$

Porsev and Flambaum, PRA 81, 032504, 042516 (2010)

Electronic bridge

$$\Gamma_{EB} = \frac{4}{3}\left(\frac{\omega}{c}\right)^3 |\mathcal{D}_{EB}|^2$$

$$\beta_{M1} = \frac{\Gamma_{EB}}{\Gamma_{rad}}$$

TABLE IV. The coefficients β_{M1} obtained for several values of ω_N for the $7s \to 7p_{1/2}$ transition in the DHF + RPA approximation are presented.

i	f	ω_N (eV)	β_{M1}
$7s_{1/2}$	$7p_{1/2}$	5.0	0.21
		6.0	4.3
		7.0	13
		7.6	19
$7s_{1/2}$	$7p_{3/2}$	7.0	1.0
		7.6	4.4

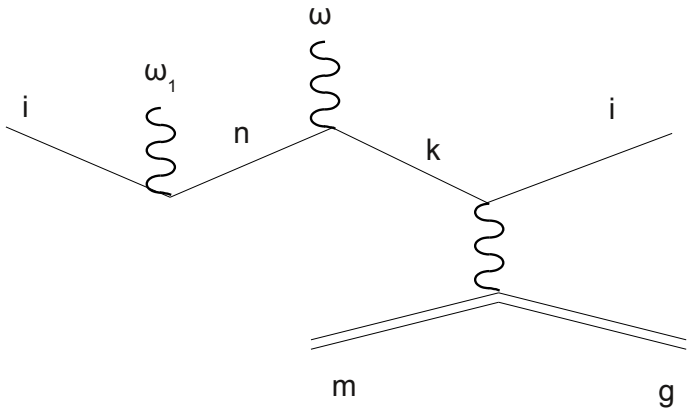
Effect of atomic electrons on the 7.6 eV nuclear transition in $^{229}\mathrm{Th}^{3+}$.

Porsev and Flambaum, PRA 81, 032504 (2010)

Excitation via EB

Porsev et al., PRL 105, 182501 (2010)

"The process relies on the excitation of the electron shell by two laser photons whose sum frequency is equal to the nuclear transition frequency."



$^{229}\mathrm{Th}^{+}$ depending on the position of the involved atomic levels, one can achieve $\beta_{M1} \sim 30$!

→ experimental proposal to use this process as excitation mechanism for the isomeric state!

Excitation via EB

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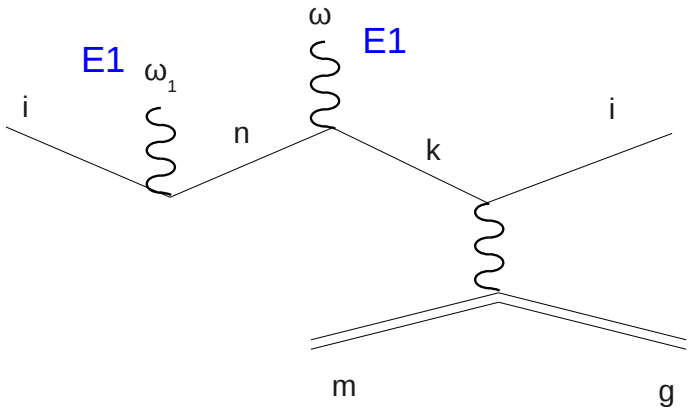


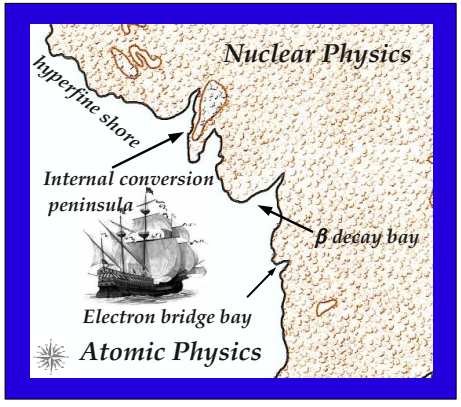
$^{229}\mathrm{Th}^{+}$ depending on the position of the involved atomic levels, one can achieve $\beta_{M1} \sim 30$!

→ experimental proposal to use this process as excitation mechanism for the isomeric state!

Difficulties with EB

- the hyperfine splitting so far disregarded
- difficult to rely on theoretical atomic structure values for such many-electron ions
- also a factor of 10 will not make the experiment much easier...

Conclusions



- several possibilities for coupling the nuclear transition in $^{229}\mathrm{Th}$ to atomic electrons: IC/NEEC, EB

- are atomic electrons easier to handle than photons?
- the narrow nuclear transition width (the treasure) remains the challenge