Electron-nucleus interactions and nuclear effects in atomic transitions

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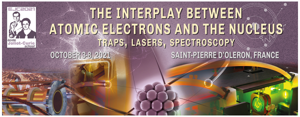
EJC Oleron, October 2021



FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

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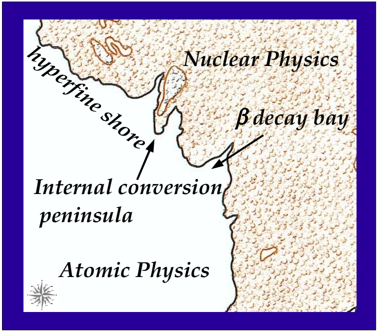
Bridging atomic and nuclear physics

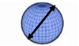
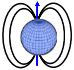
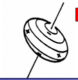


The borderline between atomic and nuclear physics

- exploring nuclear properties via atomic physics experiments YESTERDAY and leftovers
- nuclear processes directly involving atomic electrons TODAY

AP, Contemporary Physics 51, 471 (2010)

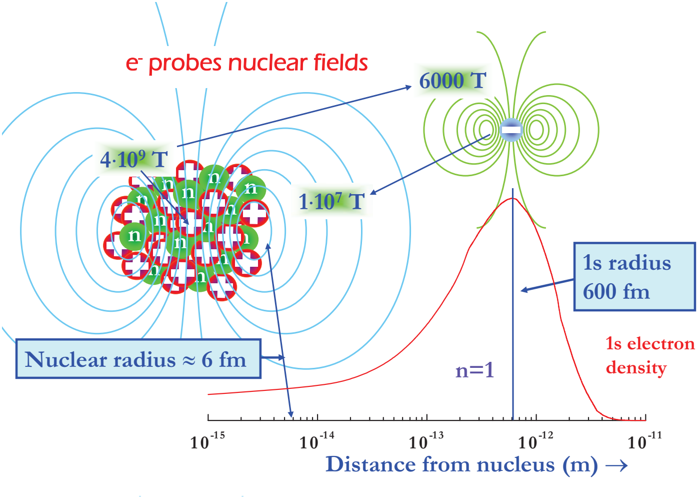
Nuclear effects in atomic transitions

NUCLEAR PROPERTY	EFFECT ON ATOMIC STRUCTURE
 size or radius $r_{RMS} = \sqrt{\langle r^2 \rangle}$	field (volume) shift
mass M, nuclear recoil	normal and specific mass shift
 spin and magnetic moment	magnetic hyperfine splitting
quadrupole moment 	quadrupole hyperfine splitting
polarizability	nuclear polarization shifts
weak interaction	parity non-conservation
excited states	nuclear transitions involving electrons

Outline

HFS

Nuclear magnetic moment and 1s electron in H-like Tl^{80+}

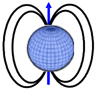


HFS

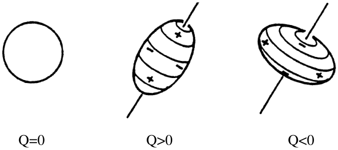
Splittings or shifts of fine structure levels due to the interaction of nuclear multipole moments with the electromagnetic field created by the electrons at the nucleus

- magnetic dipole moment associated to spin

$$\vec{F} = \vec{I} + \vec{J}$$



- electric quadrupole moment - deviation from spherical charge distribution



HFS

$$W(F) = \frac{A}{2}K + B\frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2(2I-1)(2J-1)I\cdot J}$$

where $K = F(F+1) - I(I+1) - J(J+1)$

Constant A:- magnetic dipole coupling

$$A = \frac{\mu_I H_e(0)}{I\cdot J},$$

$H_e(0) =$ magnetic field at site of nucleus

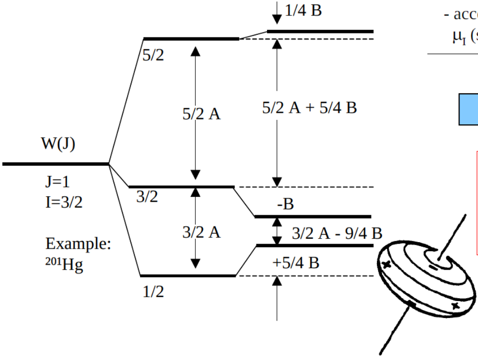
- access to nuclear parameters I (number of lines) and μ_I (size of splitting)

Constant B: - electric quadrupole coupling

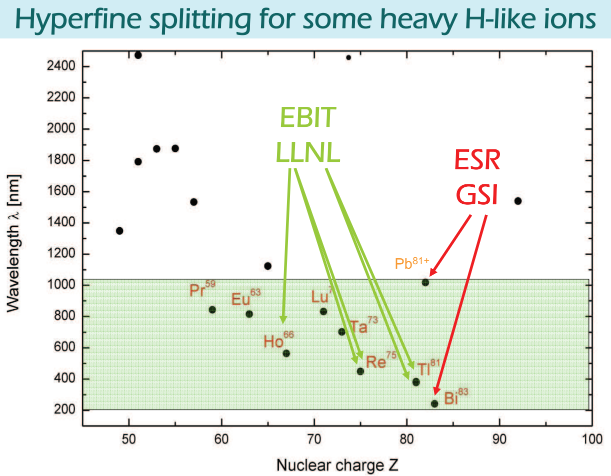
$$B = eQ_s\varphi_{jj}(0),$$

$\varphi_{jj}(0) =$ electric field gradient at the site of the nucleus

- access to spectroscopic quadrupole moment Q_s $\Rightarrow$ nuclear deformation parameters



Laser spectroscopy



DR very close to threshold

- HFS of $4s_{1/2}$ and $4p_{1/2}$ in $^{207}Pb^{53+}$ (comparing to $^{208}Pb^{53+}$) very low-energy electron captured in Rydberg state!
  R. Schuch, E. Lindroth *et al.*, PRL **95**, 183003 (2005)

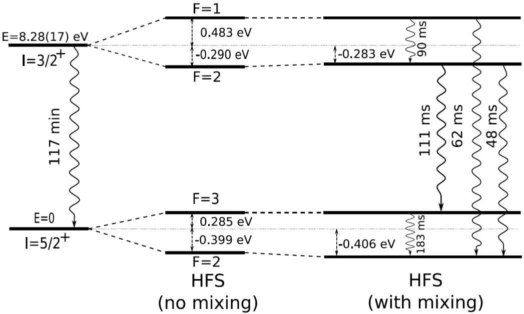
- HFS of $2s$ state in $^{45}Sc^{18+}$ using DR Rydberg resonances
  M. Lestinsky, E. Lindroth *et al.*, PRL **95**, 183003 (2005)

  TRICKS: low-energy electron and Rydberg state!

- hyperfine induced transitions: $2s2p\ ^3P_0 \rightarrow 2s^2\ ^1S_0$ in Be-like $^{47}Ti^{18+}$
  S. Schippers *et al.*, PRL **98**, 033001 (2007)

Nuclear hyperfine mixing in ^{229}Th

The lowest known excited nuclear state at only 8 eV in ^{229}Th



In ^{229}Th^{89+} the very strong 28 MT magnetic field of the unpaired electron mixes $F = 2$ states

V. M. Shabaev *et al.*, arXiv:2109.01642 [physics.atom-ph]

Disclaimer

So far the picture is not completely realistic!

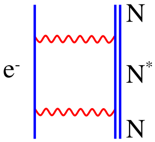
To include:

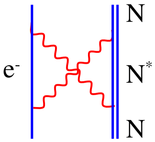
- effect of extended nuclear charge distributions on magnetic interactions (Breit-Rosenthal correction)
- the nuclear dipole moment is not point-like, but the nuclear magnetization distribution should be considered (Bohr-Weisskopf correction)

Nuclear polarization

What does this mean?

Due to exchange of virtual photons, nucleus undergoes virtual transitions to excited states!

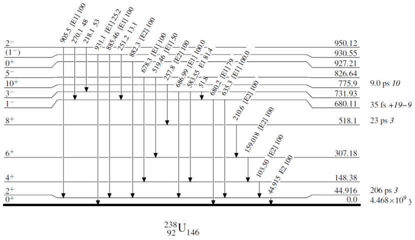


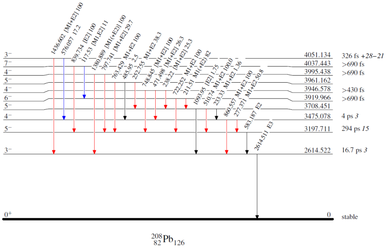


$$\Delta E \sim (E_n - E_a)^{-1}$$

Main theoretical challenge for high-precision tests of QED!

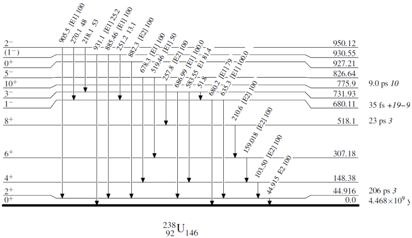
Nuclear level schemes

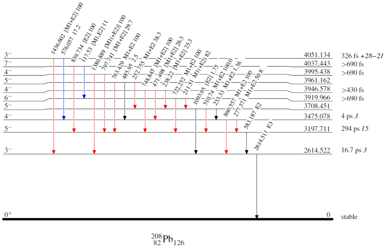




200 meV for K-shell electron

Nuclear level schemes

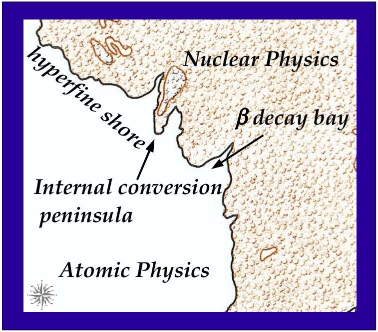




200 meV for K-shell electron

three orders of magnitude smaller!

Bridging atomic and nuclear physics



The borderline between atomic and nuclear physics

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- nuclear processes directly involving atomic electrons

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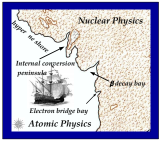
Nuclear processes involving electrons

The interface of atomic and nuclear physics



- nuclear processes directly involving atomic electrons

- electron capture (EC) + bound beta decay

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

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

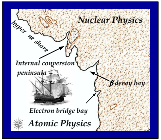
- bound beta decay

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]
[1]*Gesellschaft für Schwerionenforschung mbH, Planckstraße 1, D-64291 Darmstadt, Germany*
[2]*Physik Department E12, Technische Universität München, James-Franck-Straße, D-85748 Garching, Germany*
[3]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, D-85748 Garching, Germany*
(Received 20 September 1996)

The interface of atomic and nuclear physics



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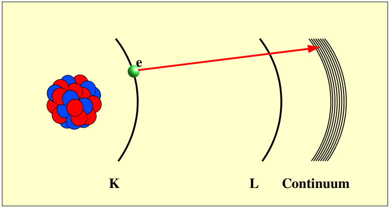
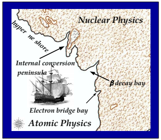


internal conversion (IC) + inverse process
nuclear excitation by electron capture (NEEC)

The interface of atomic and nuclear physics



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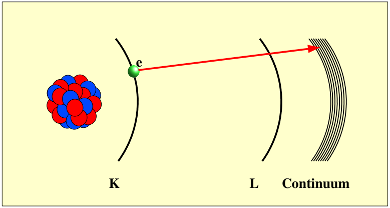
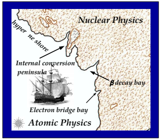


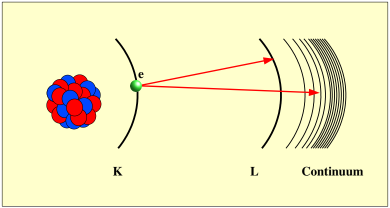
internal conversion (IC) + inverse process
nuclear excitation by electron capture (NEEC)

chronologically, IC - 1924, NEEC - 1976

The interface of atomic and nuclear physics



- nuclear processes directly involving atomic electrons

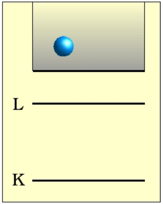


bound internal conversion (BIC) + inverse process
nuclear excitation by electron transition (NEET)

NEEC

Electron recombination processes

RR



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

Electron recombination processes

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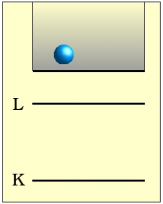

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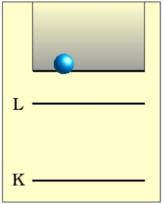

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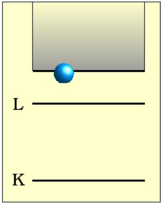

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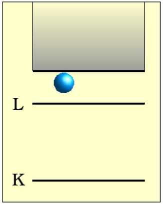

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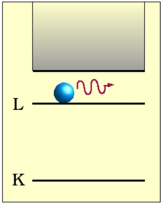

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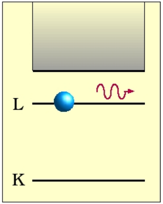

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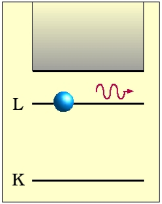

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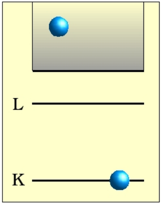

- resonant process
- Coulomb interaction
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Electron recombination processes

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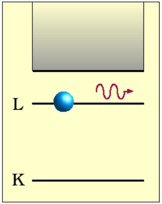

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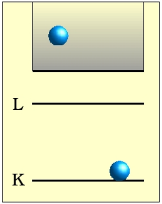

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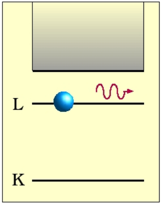

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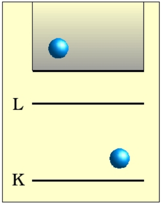

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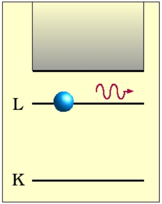

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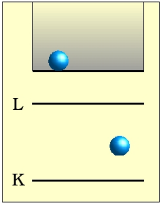

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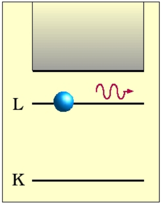

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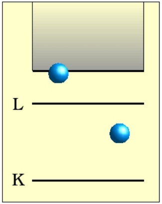

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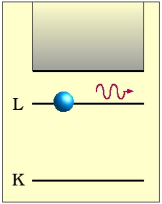

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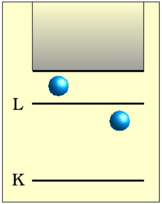

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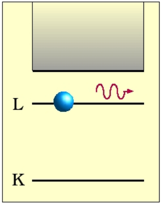

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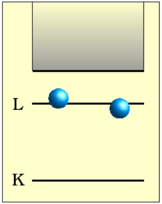

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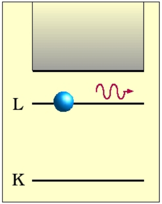

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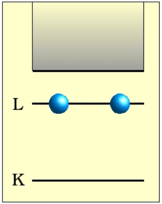

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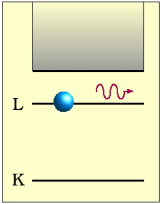

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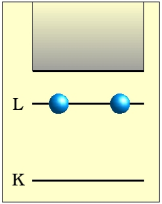

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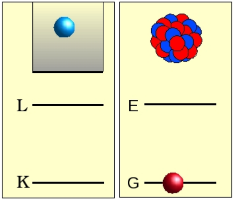
NEEC



- resonant process
- Coulomb interaction
- current-current interaction

Electron recombination processes

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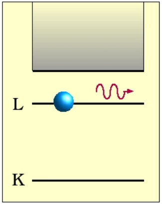

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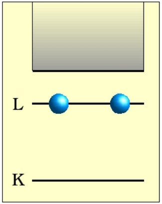

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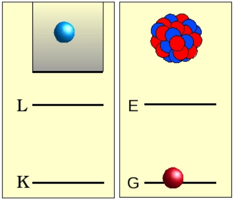

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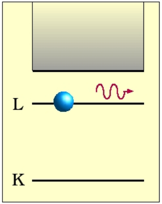

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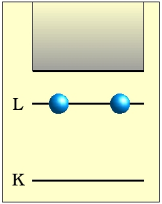

- resonant process
- Coulomb interaction
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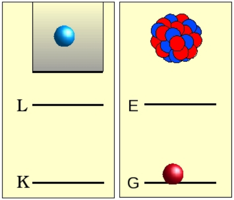
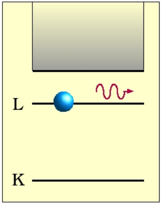
NEEC



- resonant process
- Coulomb interaction
- current-current interaction

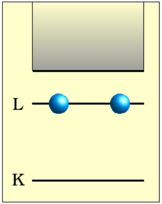
Electron recombination processes

RR



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

DR



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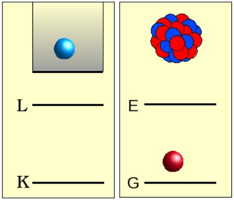

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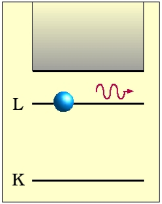

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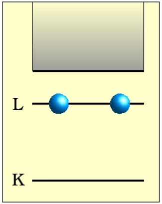

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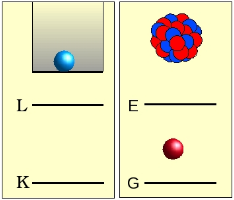

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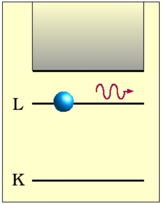

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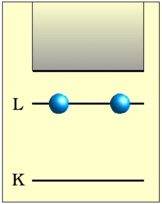

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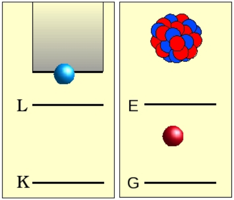

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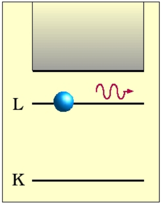

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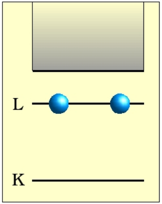

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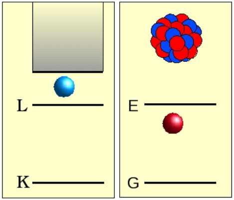

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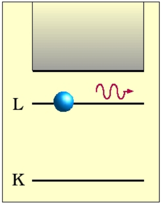

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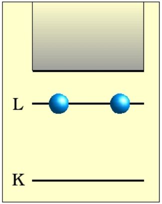

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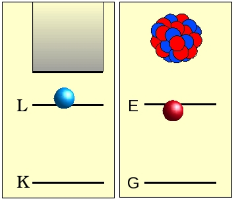

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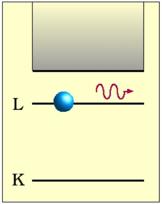

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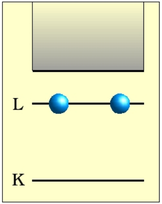

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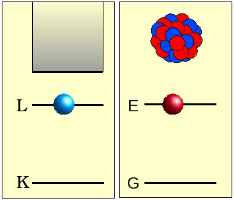

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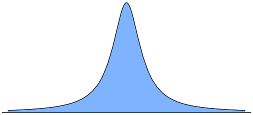
Total NEEC cross section

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

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

$$\begin{aligned} \text{natural width} \;\; \Gamma_d &\sim 10^{-5} - 10^{-8}\ \text{eV} \\ \text{resonance strength} \;\; S &\sim 1\ \text{b eV} \end{aligned}$$



Pálffy, Scheid, Harman, PRA 73 (2006) 012715

Continuum electrons have a narrow resonance condition to fulfill!

Total NEEC cross section

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

$$S = \frac{2\pi^2}{p^2} \frac{A_\gamma^{d\to f} Y_n^{i\to d}}{\Gamma_d}$$

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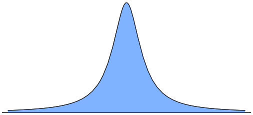


Pálffy, Scheid, Harman, PRA 73 (2006) 012715

Continuum electrons have a narrow resonance condition to fulfill!

Interaction mechanisms

- Coulomb interaction (E transitions)

$$H_{en} = \int d^3 r_n \frac{\rho_n(\vec{r}_n)}{|\vec{r}_e - \vec{r}_n|}$$

- Virtual photon exchange (M transitions)

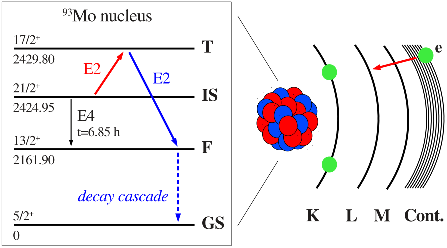
$$H_{magn} = -\frac{1}{c}\vec{\alpha} \int d^3 r_n \frac{\vec{j}_n(\vec{r}_n)}{|\vec{r} - \vec{r}_n|}$$

Matrix elements:

- nuclear via reduced transition probability $B(E/ML)$
- electronic wavefunctions via GRASP92 for bound electrons
  Dirac equation with effective charge for continuum electrons.

NEEC in isomers

- excitation mechanism via gateway state above the isomer

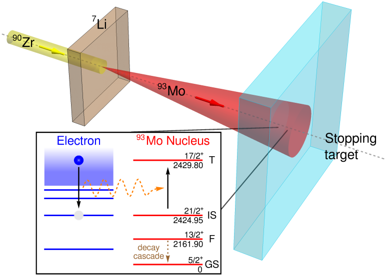


Isomer depletion

Pálffy, Evers, Keitel, Phys. Rev. Lett. 99, 172502 (2007)
Gunst, Litvinov, Keitel, Pálffy, Phys. Rev. Lett. 112, 082501 (2014)

NEEC in a beam-target scenario

- First experimental evidence of NEEC was reported in a beam-target scenario



- Depletion probability $P_{exc} = 0.01$ per ^{93m}Mo was reported

C. J. Chiara *et al.*, Nature, 554, 216 (2018)

- Observed excitation probability was attributed to NEEC process

- A theoretical analysis of NEEC rates for the experimental setting reports $P_{exc} = 10^{-11}$!

Wu, Keitel, Pálffy, Phys. Rev. Lett. 122, 212501 (2019)

- Debate is still in progress.

IC

Inverse process of NEEC

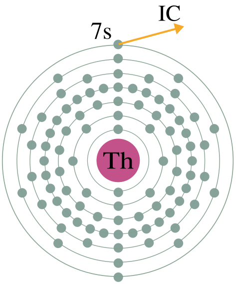
Fermi's golden rule

$$\Gamma_{\mathrm{IC}} = \frac{2\pi}{N_{\mathrm{init}}} \sum_{\mathrm{init.states}} \sum_{\mathrm{fin.states}} \left| \langle \Psi_{\mathrm{fin}} | \hat{H} | \Psi_{\mathrm{init}} \rangle \right|^2 \rho_{\mathrm{fin}}$$

The same Hamilton operators as for NEEC, $\hat{H}_{en}$ or $\hat{H}_{magn}$.

IC coefficient $\alpha = \frac{\Gamma_{\mathrm{IC}}}{\gamma\text{-decay rate}}$

IC for ^{229}Th



Unique nuclear isomer with
$E_m = 8.2$ eV

- M1 transition at $E \simeq 10$ eV
  γ-decay rate $\propto E^3$ is small
  $\Rightarrow \alpha$ is large
- In neutral atoms $\alpha \simeq 10^9$
  F. F. Karpeshin *et al.* PRC **76**, 054313 (2007)

Ion charge	0	1+	2+	3+	4+
Ion. threshold (eV)	6.3	12.1	20.0	28.7	58

Isomer energy

$E_m = 8.28 \pm 0.17$ eV by IC electron spectroscopy

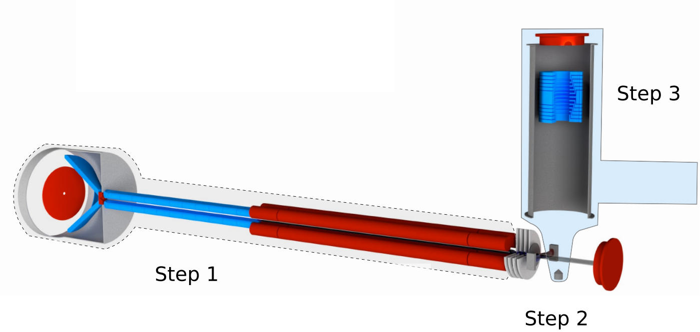
Cover image: Daria Bilous

- LMU Munich
  Benedict Seiferle,
  Lars von der Wense,
  Ines Amersdorffer, Peter G. Thirolf
- MPIK
  Pavlo V. Bilous, Adriana Pálffy
- TU Wien
  Christoph Lemell, Florian Libisch,
  Thorsten Schumm
- Uni Bonn
  Simon Stellmer
- Uni Mainz
  Christoph E. Düllmann

B. Seiferle *et al.*, Nature **573**, 243 (2019)

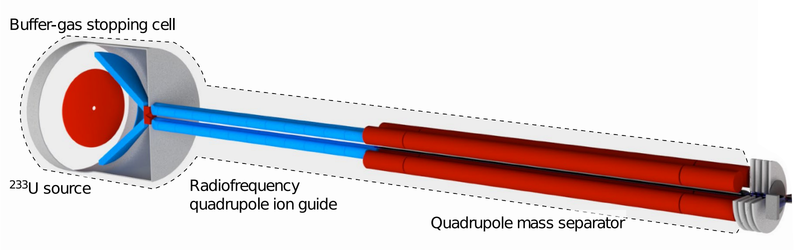
Experimental scheme

Experimental setup at LMU Munich



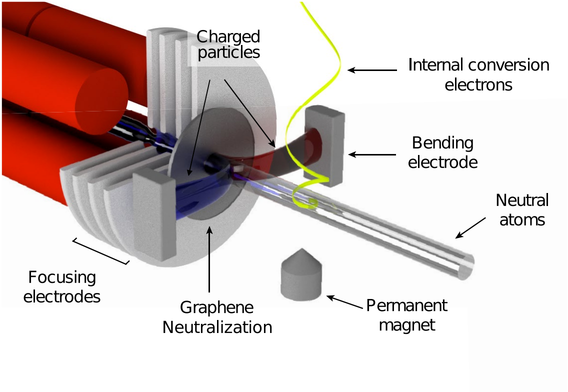
Experimental scheme

Step 1: Generation of Th ions in the isomeric state



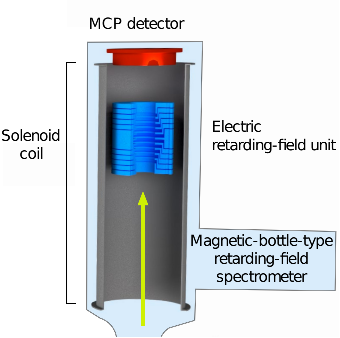
Experimental scheme

Step 2: Th neutralization and collecting of IC electrons



Experimental scheme

Step 3: Measurement of the IC electron energies



Experimental scheme

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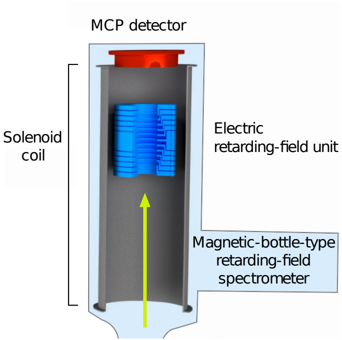
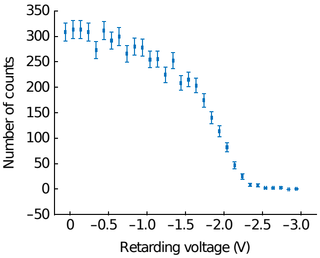
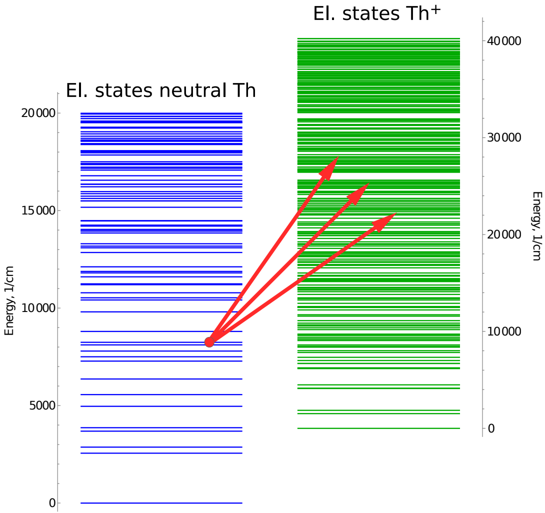




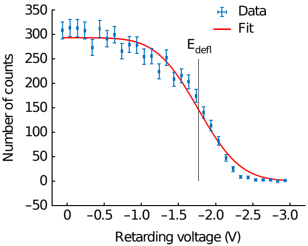
E_m – ?

IC at low energies



Theory to include

- initial excited electronic states
- all possible final excited electronic state of ion
- angular momenta couplings in the electronic shells



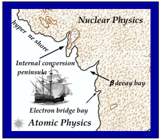
$$f(U) = a\left\{1 - \mathrm{erf}\left[\frac{U - E_{\mathrm{defl}}}{b}\right]\right\}$$

$$E_{\mathrm{defl}} = 1.77 \pm 0.03 \text{ eV}$$

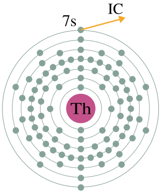
$$E_{\mathrm{m}} = E_0 + E_{\mathrm{defl}}$$

$$E_m = 8.28 \pm 0.17 \text{ eV}$$

Summarizing



- high-precision atomic physics reveals information about nucleus
- theory challenge to separate the respective contributions from nuclear mass, volume, shape, spin, magnetization, and polarization



- especially low-energy nuclear transitions have a strong interplay with the atomic shell
- exotic examples: isomer depletion or nuclear clock

Mingle-mangle

mass shift
field shift

nuclear spin

laser
spectroscopy

Isotope shifts

laser
spectroscopy

X-ray
spectroscopy

DR

DR

EBIT

ESR

HFS

halo nuclei

nuclear
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Rydberg
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astrophysics

Atomic physics
experiments

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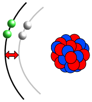

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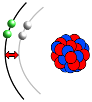

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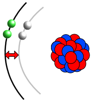

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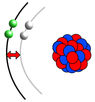

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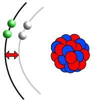

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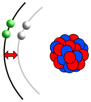

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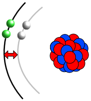

Thank you!