Electron-nucleus interactions and nuclear effects in atomic transitions

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Bridging atomic and nuclear physics

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

The borderline between atomic and nuclear physics

AP, Contemporary Physics 51, 471 (2010)
Nuclear effects in atomic transitions

**NUCLEAR PROPERTY**  

- size or radius  
  \[ r_{RMS} = \sqrt{\langle r^2 \rangle} \]  
- mass M, nuclear recoil

**EFFECT ON ATOMIC STRUCTURE**

- field (volume) shift
- normal and specific mass shift
- magnetic hyperfine splitting
- quadrupole hyperfine splitting
- nuclear polarization shifts
- parity non-conservation
- nuclear transitions involving electrons
Outline

1. Introduction
2. HFS
3. Nuclear Polarization
4. Nuclear processes involving electrons
5. NEEC
6. IC
7. Conclusions
HFS
Nuclear magnetic moment and 1s electron in H-like $^{110+}$

- $e^{-}$ probes nuclear fields
- Nuclear radius $\approx 6$ fm
- 1s electron density
- 1s radius $600$ fm
- Distance from nucleus (m)
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

Q=0

Q>0

Q<0
HFS

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

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 \( \mu_i \) (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 \( Q_s \) => nuclear deformation parameters

Example: \(^{201}\text{Hg} \)
Laser spectroscopy

Hyperfine splitting for some heavy H-like ions
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: $2s2p\,^3P_0\rightarrow2s^2\,^1S_0$ 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

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
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

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

The borderline between atomic and nuclear physics

AP, Contemporary Physics 51, 471 (2010)
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

**Observation of Bound-State \( \beta^- \) Decay of Fully Ionized \( ^{187}\text{Re} \): \( ^{187}\text{Re}-^{187}\text{Os} \) 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. Takahashi2,3

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(Received 20 September 1996)
The interface of atomic and nuclear physics

- nuclear processes directly involving atomic electrons

internal conversion (IC) + inverse process
nuclear excitation by electron capture (NEEC)
The interface of atomic and nuclear physics

- nuclear processes directly involving atomic electrons

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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Electron recombination processes

RR

L

K

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Electron recombination processes

- **RR (Direct Process)**
  - Any electron energy
  - Electron-radiation field

- **DR (Resonant Process)**
  - Coulomb interaction
  - Breit interaction
Electron recombination processes

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- Coulomb interaction
- current-current interaction
Electron recombination processes

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- Coulomb interaction
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Electron recombination processes

- **RR**: Direct process, any electron energy, electron-radiation field.
- **DR**: Resonant process, Coulomb interaction, Breit interaction.
- **NEEC**: Resonant process, Coulomb interaction, current-current interaction.
Electron recombination processes

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- direct process
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Total NEEC cross section

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

\[ \sigma(E) = \frac{2\pi^2}{p^2} \frac{A_{d\rightarrow f}^d Y_{n\rightarrow d}^i}{\Gamma_d} L_d(E - E_d) \]

natural width \( \Gamma_d \sim 10^{-5} - 10^{-8} \) eV
resonance strength \( S \sim 1 \) b eV

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

Continuum electrons have a narrow resonance condition to fulfill!
Total NEEC cross section

NEEC + $\gamma$ total cross section as function of continuum electron energy

$$S = \frac{2\pi^2}{p^2} \frac{A_{d\rightarrow f} Y_{n\rightarrow d}}{\Gamma_d}$$

natural width $\Gamma_d \sim 10^{-5} - 10^{-8}$ eV
resonance strength $S \sim 1$ b eV

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)**

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

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

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

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


Observed excitation probability was attributed to NEEC process.

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


Debate is still in progress.
IC
Inverse process of NEEC

Fermi’s golden rule

\[ \Gamma_{\text{IC}} = \frac{2\pi}{N_{\text{init}}} \sum_{\text{init. states}} \sum_{\text{fin. states}} \left| \langle \psi_{\text{fin}} | \hat{H} | \psi_{\text{init}} \rangle \right|^2 \rho_{\text{fin}} \]

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

IC coefficient \( \alpha = \frac{\Gamma_{\text{IC}}}{\gamma\text{-decay rate}} \)
IC for $^{229}\text{Th}$

Unique nuclear isomer with $E_m = 8.2$ eV

- M1 transition at $E \simeq 10$ eV
  - $\gamma$-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)

<table>
<thead>
<tr>
<th>Ion charge</th>
<th>0</th>
<th>1+</th>
<th>2+</th>
<th>3+</th>
<th>4+</th>
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</thead>
<tbody>
<tr>
<td>Ion. threshold (eV)</td>
<td>6.3</td>
<td>12.1</td>
<td>20.0</td>
<td>28.7</td>
<td>58</td>
</tr>
</tbody>
</table>
Isomer energy

\[ E_m = 8.28 \pm 0.17 \text{ eV} \] by IC electron spectroscopy

- **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

Cover image: Daria Bilous

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

Experimental setup at LMU Munich

Step 1

Step 2

Step 3
Experimental scheme

Step 1: Generation of Th ions in the isomeric state
Step 2: Th neutralization and collecting of IC electrons
Step 3: Measurement of the IC electron energies
Step 3: Measurement of the IC electron energies

$E_m - ?$
IC at low energies

![Graph showing energy levels of Th and Th+ ions](image-url)
Theory to include

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

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

\[E_{\text{defl}} = 1.77 \pm 0.03 \text{ eV} \]

\[E_m = E_0 + E_{\text{defl}} \]

\[E_m = 8.28 \pm 0.17 \text{ eV} \]
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
Mingle-mangle

- Isotope shifts
- X-ray spectroscopy
- Nuclear properties
- EBIT
- HCl
- DR
- Halo nuclei
- Nuclear spin
- HFS
- Isomers
- Laser spectroscopy
- Atomic physics experiments
- NEEC
- IC
- Conclusions
- Mass shift field shift
-astrophysics

- DR
- Nuclear lifetimes
Mingle-mangle
Thank you!