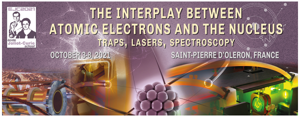
# Electron-nucleus interactions and nuclear effects in atomic transitions

Adriana Pálffy

Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

EJC Oleron, October 2021

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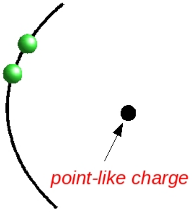
NATURWISSENSCHAFTLICHE FAKULTÄT

# “Nuclear” effects

- the nuclear charge $+Ze$ gives the binding energy!

*a nucleus’ odyssey from a* point-like *charge to its real size and properties*



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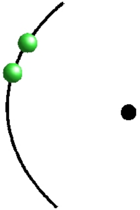

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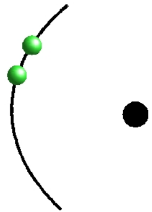

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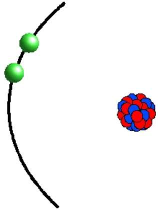

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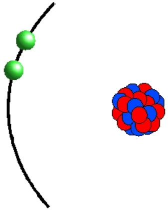

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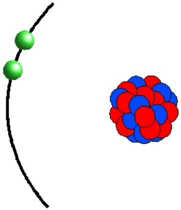

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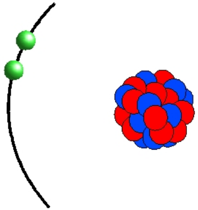

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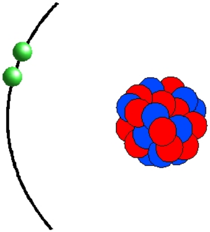

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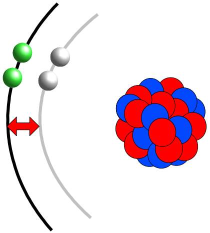
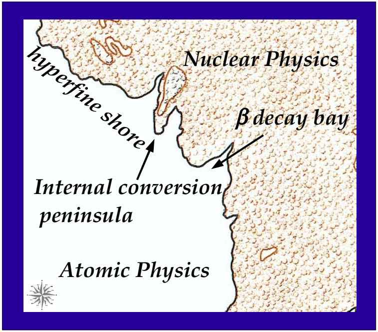


- small corrections to atomic level and transition energies
- best studied by comparing two different isotopes
  $\rightarrow$ measuring isotope shifts

# Bridging atomic and nuclear physics

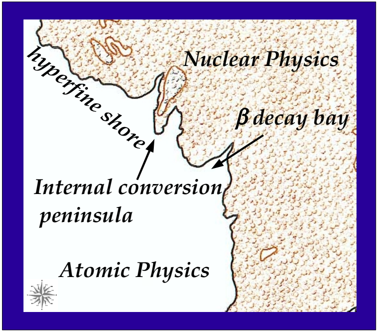



The borderline between atomic and nuclear physics

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

AP, Contemporary Physics 51, 471 (2010)

# Bridging atomic and nuclear physics




The borderline between atomic and nuclear physics

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

AP, Contemporary Physics 51, 471 (2010)

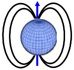
# Nuclear effects in atomic transitions

**NUCLEAR PROPERTY** → **EFFECT ON ATOMIC STRUCTURE**

size or radius → field (volume) shift

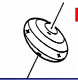
$$r_{RMS} = \sqrt{\langle r^2 \rangle}$$

mass M, nuclear recoil → normal and specific mass shift



spin and magnetic moment → magnetic hyperfine splitting

quadrupole moment → quadrupole hyperfine splitting



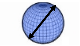
polarizability → nuclear polarization shifts

weak interaction → parity non-conservation

excited states → nuclear transitions involving electrons

# Nuclear effects in atomic transitions

**NUCLEAR PROPERTY** | **EFFECT ON ATOMIC STRUCTURE**

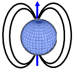


size or radius

$$r_{RMS} = \sqrt{\langle r^2 \rangle}$$

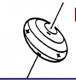
mass M, nuclear recoil

→ field (volu... ISOTOPE SHIFTS n... specific mass shift



spin and magnetic moment

quadrupole moment



→ magnetic hyperfine splitting; quadrupole ... e splitting; HFS

polarizability

weak interaction

excited states

→ nuclear polarization shifts; parity non-co...ervation; nuclear tran...s involving electrons; IC/NEEC

# Outline

# Isotope shifts

# Isotope shifts

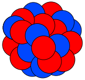
. . . frequency difference in an electronic transition between two isotopes

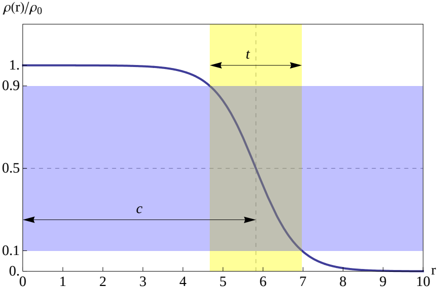
$$\Delta\nu_{IS} = \Delta\nu_{FS} + \Delta\nu_{MS}$$

# Field (volume) shift

Fermi two-parameter charge distribution

$$\rho_{nuc} = \frac{\rho_0}{1 + e^{(r-c)/a}}$$






- $\Delta\nu \sim Z^{5..6}$
- heavy nuclei $\Delta\nu/\nu = 10^{-5}$
- light nuclei $\Delta\nu/\nu = 10^{-8}$

numerical integration of the Dirac equation with $V_{nuc}$

# Mass shift

Relativistic nuclear recoil operator

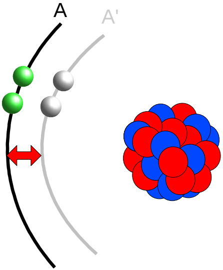
$$R_{ij} = \frac{\vec{p}_i \cdot \vec{p}_j}{2M} - \frac{Z\alpha}{2Mr_i}\left(\vec{\alpha}_i + \frac{(\vec{\alpha}_i \cdot \vec{r}_i)\vec{r}_i}{r_i^2}\right) \cdot \vec{p}_j$$

- normal mass shift correction $\langle \sum_i R_{ii} \rangle$
- specific mass shift term $\langle \sum_{i \neq j} R_{ij} \rangle$

in muonic atoms B. Fricke, PRL 30, 119 (1973)

QED theory V. M. Shabaev, Theor. Mat. Fiz. 63, 394 (1985)
Yad. Fiz. 47, 107 (1988)

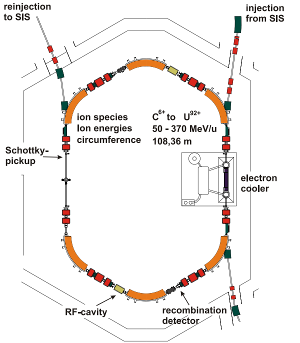
# How to measure isotope shifts?

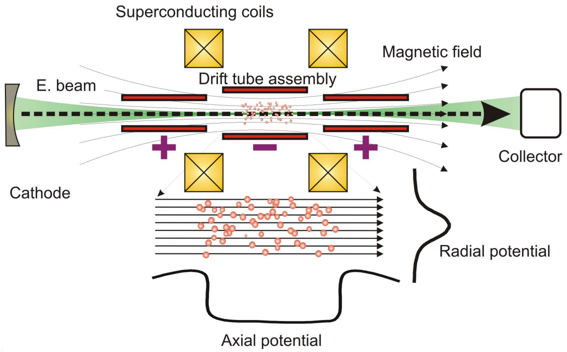



- muonic atoms
- electron scattering
- x-ray spectroscopy
- laser spectroscopy
- dielectronic recombination

Talks by Ruben and Iain!

# Highly charged ions




. . . storage ring . . .

or EBIT

# Isotopic shifts in x-ray transitions

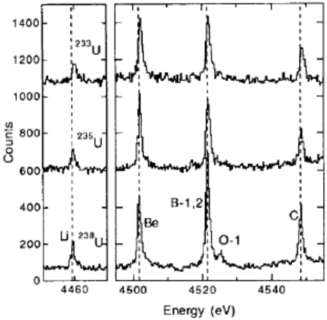



Figure 3. Spectra of the $2p_{3/2} \rightarrow 2s_{1/2}$ transitions in the highly charged $^{233}$U, $^{235}$U, and $^{238}$U isotopes. Individual lines are labeled by the charge state of the emitting ions: $C = \mathrm{U}^{86+}$, $B = \mathrm{U}^{87+}$, $Be = \mathrm{U}^{88+}$ and $Li = \mathrm{U}^{89+}$.

$$\delta\langle r^2\rangle^{233,238} = -0.457 \pm 0.043 \ \ \mathrm{fm}^2$$

Elliot, Beiersdorfer, Chen, PRL 76, 1031 (1996)

# Relativistic recoil and isotopic shifts in $^{40}Ar/^{36}Ar$

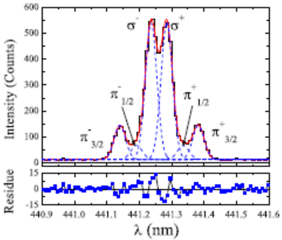



FIG. 1 (color online). A typical spectral line obtained from the $1s^22s^22p\ ^2P_{1/2} - ^2P_{3/2}$ transition in B-like $^{40}Ar^{13+}$. The six dashed curves represent a fit to the Zeeman components.

$$Ar^{13+} \quad 1s^22s^22p\ ^2P_{1/2} - ^2P_{3/2}$$
$$Ar^{14+} \quad 1s^22s2p\ ^3P_1 - ^3P_2$$

sub-ppm accuracy: Soria Orts *et al.* PRL 97, 103002 (2006)

# Isotopic shifts $^{40}Ar/^{36}Ar$

This experiment confirms the newest treatment of relativistic recoil effect

| Ion | Theory $\lambda$ (nm, air)* | $\lambda_{Observed}$ (nm) | Isotopic shifts ($^{40}Ar/^{36}Ar$) | |
|---|---|---|---|---|
| | | | theory (nm) | experiment (nm) |
| $Ar^{13+}$ | 441.16(27) | 441.2556(1) | 0.00123(5) | 0.00123(6) |
| $Ar^{14+}$ | 594.24(30) | 594.3879(2) | 0.00122(5) | 0.00120(10) |

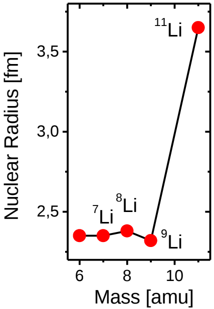
Normal and specific mass shifts and their relativistic corrections are of similar sizes.

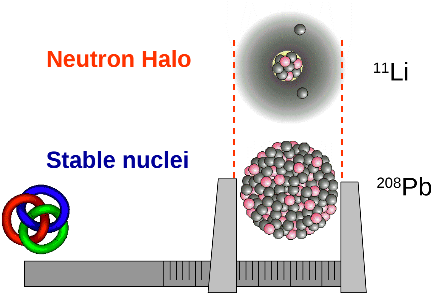
This relativistic few-body quantum problem can only be solved consistently within a full QED treatment.

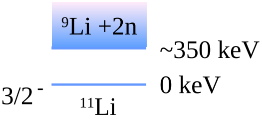
**courtesy J. Crespo**

Soria Orts *et al.* PRL 97, 103002 (2006)

# Isotope shifts and nuclear halos



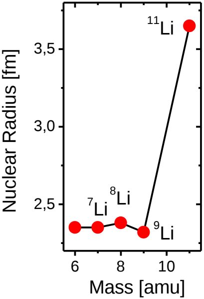

How to probe that $^{11}$Li is a neutron halo?

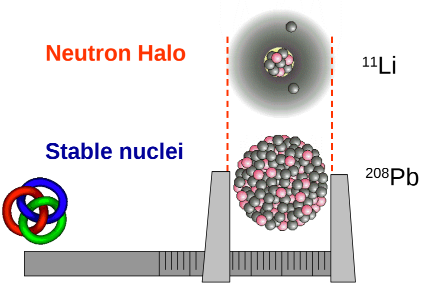
Mass measurements
→ Two-neutron separation energy

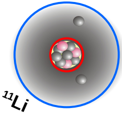
Laser spectroscopy
→ Nuclear charge radii, moment

**courtesy K. Blaum**

# Isotope shifts and nuclear halos



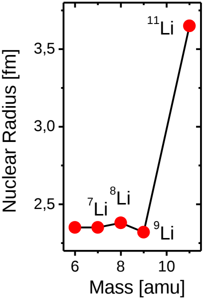




isotope shift

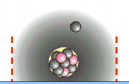
Halo "=" $R_{Matter} - R_{Charge}$

nuclear reactions

# Isotope shifts and nuclear halos




**Neutron Halo**





$^{6,8}$He – P. Müller *et al.*, PRL 99, 252501 (2007)
$^{11}$Li – R. Neugart *et al.*, PRL 101, 132502 (2008)
$^{11}$Be – W. Nörteshäuser *et al.*, PRL 102, 062503
$^{11}$Ne – W. Geithner *et al.*, PRL 101, 252502 (2008)

G. Ewald *et al*., Phys. Rev. Lett. 93, 113002 (2004)
G. Ewald *et al*., Phys. Rev. Lett. 94, 039901 (2005)
R. Sanchez *et al*., Phys. Rev. Lett. 96, 033002 (2006)
C. Forssén *et al*., Phys. Rev. C 79, 021303 (2009)
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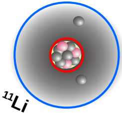


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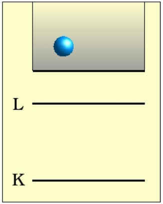
nuclear reactions

# Electron recombination processes - DR

RR




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

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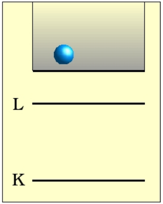


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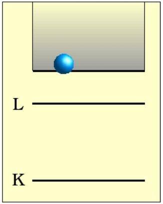


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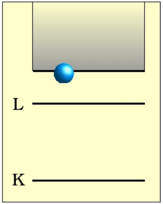


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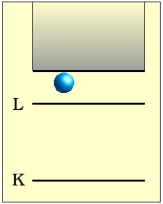


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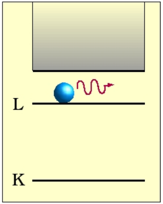


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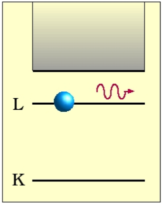


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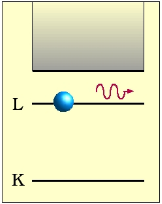


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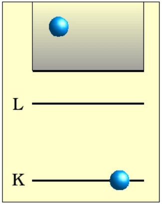


- resonant process
- Coulomb interaction
- Breit interaction

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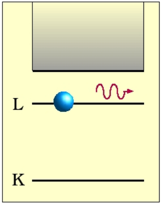


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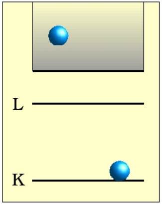


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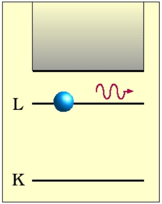


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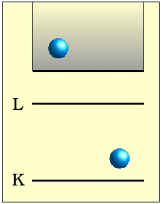


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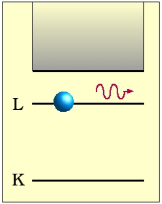


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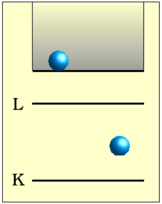


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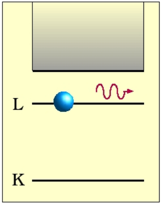


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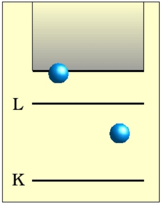


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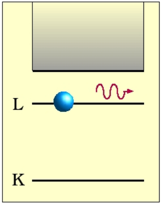


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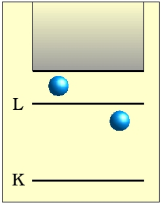
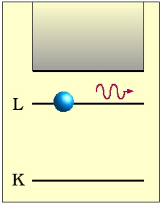
## DR



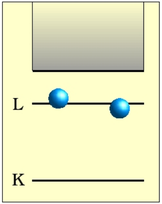

- resonant process
- Coulomb interaction
- Breit interaction

# Electron recombination processes - DR

RR




DR

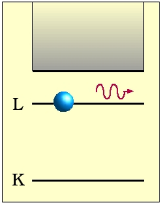



- direct process
- any electron energy
- electron-radiation field

- resonant process
- Coulomb interaction
- Breit interaction

# Electron recombination processes - DR

RR

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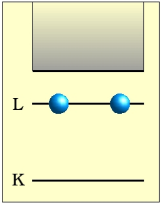
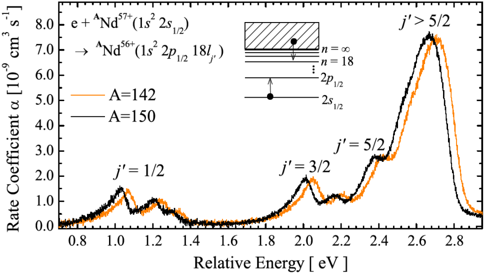
DR




- resonant process
- Coulomb interaction
- Breit interaction

# Isotope shifts in DR




**energy shifts**

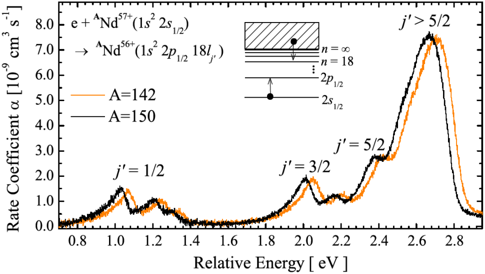
$\delta E^{142,150}(2p_{1/2})$=40.2(3)(6) meV
$\delta E^{142,150}(2p_{3/2})$=42.3(12)(20) meV

**mean-square charge radius**

$^{142,150}\delta\langle r^2\rangle$ = -1.36(1)(3) fm$^2$

C. Brandau, C. Kozhuharov, Z. Harman *et al.*, PRL **100**, 073201 (2008)

# Isotope shifts in DR

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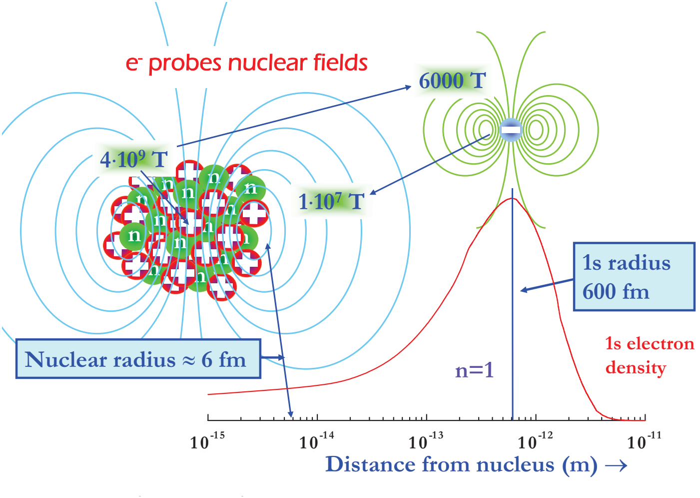
nuclear deformation: Kozhedub *et al.*, PRA **77**, 032501 (2008)

# HFS

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

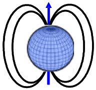


# HFS

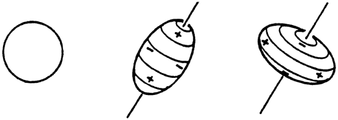
Splittings or shifts of fine structure levels due to the interaction of nuclear multipole moments with the electromagnetic field created by the electrons at the nucleus

- magnetic dipole moment associated to spin

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



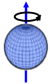
- electric quadrupole moment - deviation from spherical charge distribution



Q=0 Q>0 Q<0

# HFS

***splitting of fine structure levels** due to coupling of electron spin and nuclear multipole moments*



**F = I + J**

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

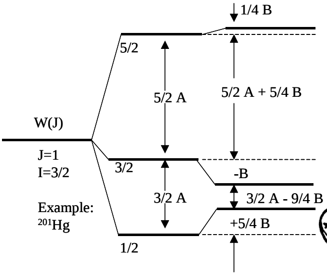
where $K=F(F+1)-I(I+1)-J(J+1)$

Constant A:- magnetic dipole coupling

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

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

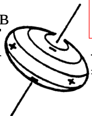
- access to nuclear parameters I (number of lines) and $\mu_I$ (size of splitting)




Constant B: - electric quadrupole coupling

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

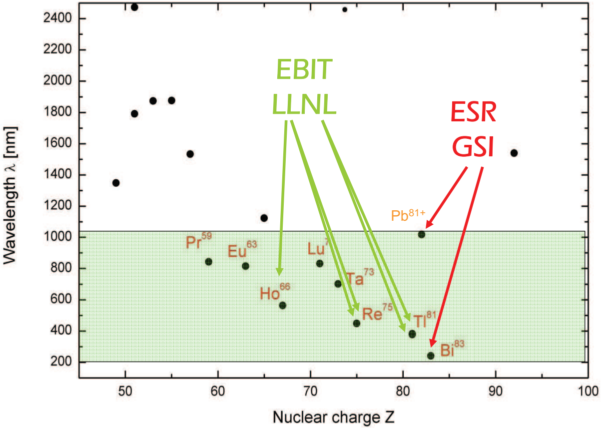
$\varphi_{jj}(0)=$ electric field gradient at the site of the nucleus



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

# 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)

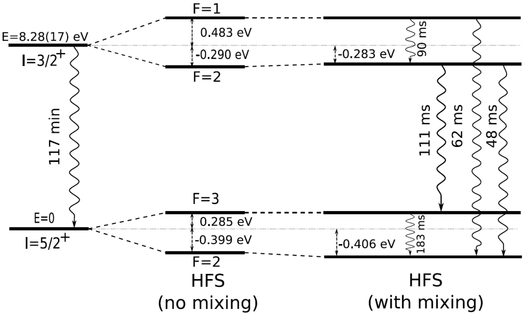
  TRICKS: low-energy electron and Rydberg state!

- hyperfine induced transitions: $2s2p\,^3P_0 \rightarrow 2s^2\,^1S_0$ 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



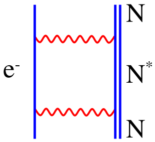

In $^{229}Th^{89+}$ the very strong 28 MT magnetic field of the unpaired electron mixes $F = 2$ states

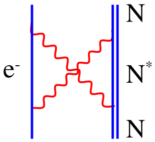
V. M. Shabaev *et al.*, arXiv:2109.01642 [physics.atom-ph]

# Nuclear polarization

# What does this mean?

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

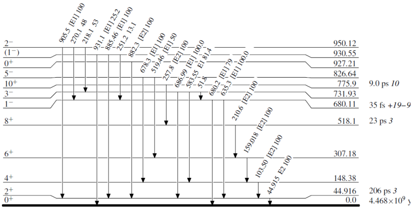


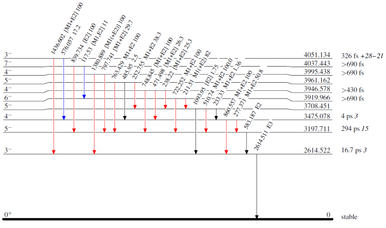

$$\Delta E \sim (E_n - E_a)^{-1}$$

Main theoretical challenge for high-precision tests of QED!

# Nuclear level schemes



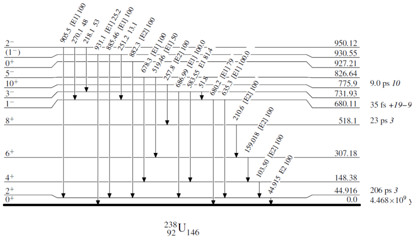

$^{238}_{92}U_{146}$

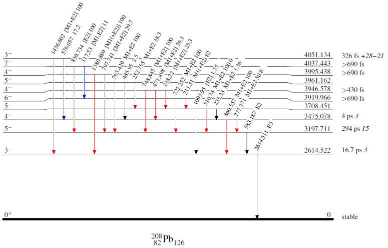



$^{208}_{82}Pb_{126}$

200 meV for K-shell electron

# Nuclear level schemes




200 meV for K-shell electron

three orders of magnitude smaller!

# Conclusions for today

mass shift
field shift

nuclear spin

laser
spectroscopy

Isotope shifts

laser
spectroscopy

X-ray
spectroscopy

DR

DR

EBIT

ESR

HFS

halo nuclei

nuclear
properties

HCI

Rydberg
states

astrophysics

Atomic physics
experiments

NEEC

IC

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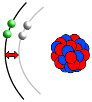

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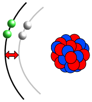

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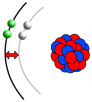

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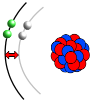

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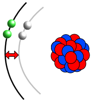

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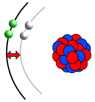

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