Probing nuclear properties with multiply-charged ions

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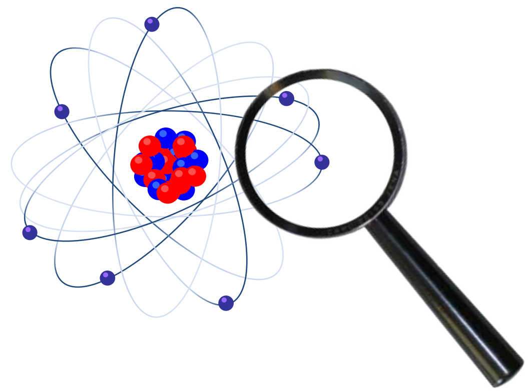
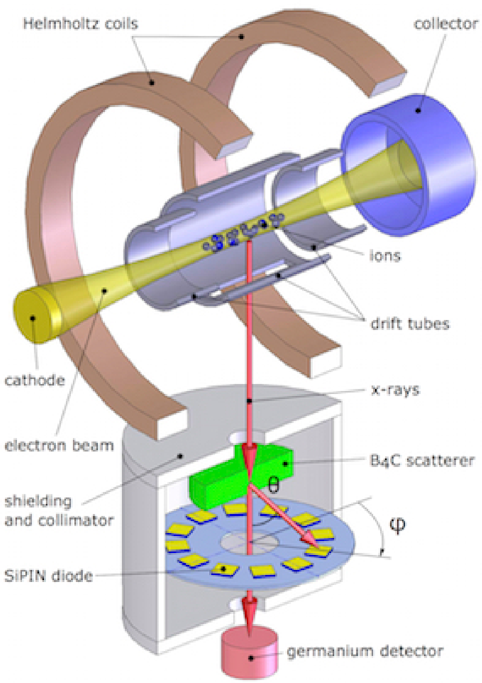
Modern atomic physics: Experiment and theory

During the last decades, a significant progress has been achieved in experimental and theoretical atomic physics.

- In **theory**, advanced methods have been developed that allow high-precision calculations of atomic structure and dynamics.





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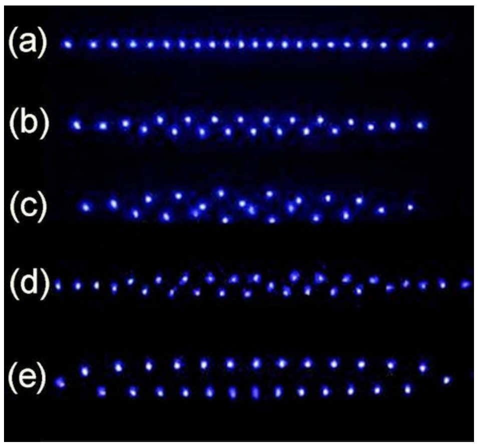
- In **experiment**, one can produce, store and operate with atoms and ions in any required charge state. Moreover, experiments with single atoms (ions) became possible.



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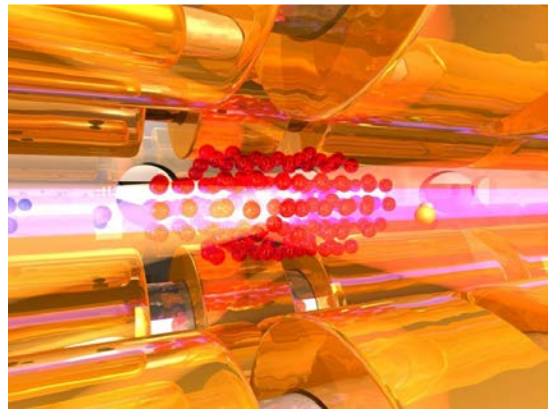

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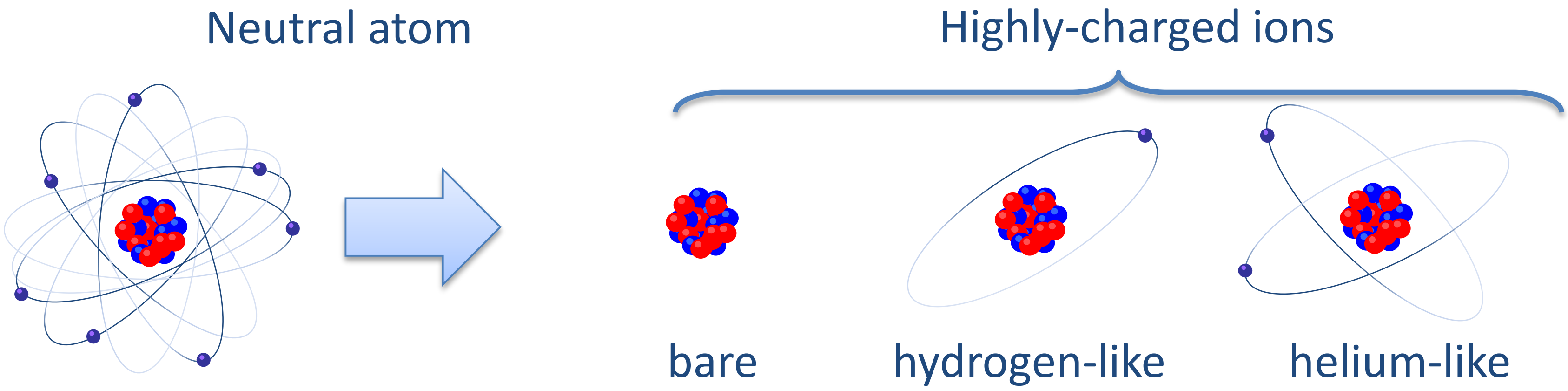
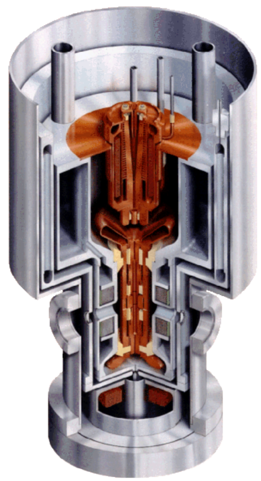
Multiply- and highly-charged ions



Advanced particle acceleration facilities (e.g. GSI and FAIR, DESY)

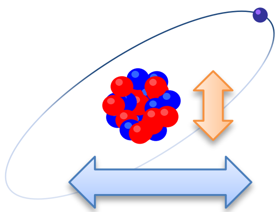


Electron beam ion traps (EBITs) (e.g. MPI-K, Livermore)

During the last decades, a number of experimental facilities have been built (or designed) that are capable of producing and storing ions in any charge state.

Heavy ions: Structure

- What is so special about multiply-charged, heavy ions?



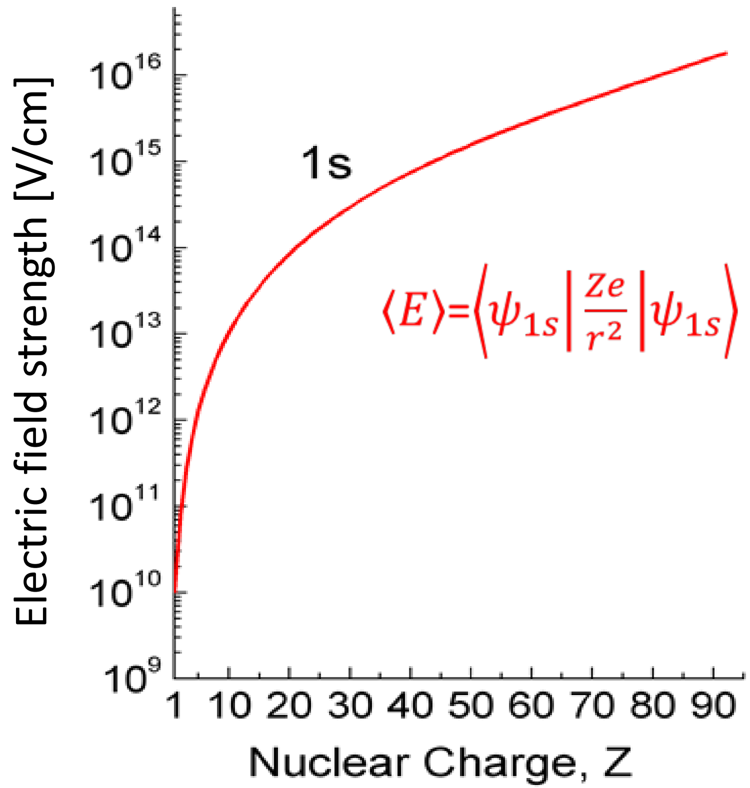
(nuclear size)
$R \sim 10^{-14}$ m

(electron orbit)
$r \sim 10^{-13} - 10^{-12}$ m

One can estimate the electron "velocity" in the ground state:

$$v_{el} \approx \alpha Z c \quad \Rightarrow \quad v_{el} \approx 0.7c$$

(for U^{91+})

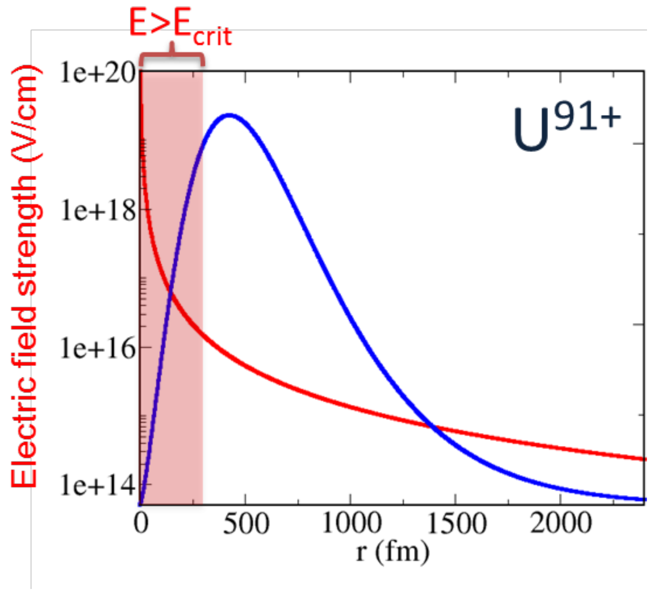


Electron is exposed to huge fields (of microscopic) dimensions.

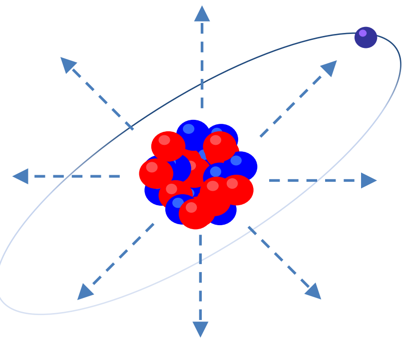
Studies with multiply-charged ions

The strong nuclear fields affect electronic shell structure of heavy ions and make it possible to study the relativistic, QED and nuclear phenomena.

During the last decades a number of experimental and theoretical studies have been focused on:



- Probe of QED under extreme conditions
  - Lamb shift in highly-charged ions
  - QED effects in super-critical fields
  - Electron correlations in strong fields
- Nuclear and "magnetic" sector of QED
  - Hyperfine shifts of ionic and atomic levels
  - Hyperfine-induced transitions
  - Interplay between nuclear and atomic processes
  - Search for PNC effects in nuclei



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Studies of nuclear properties

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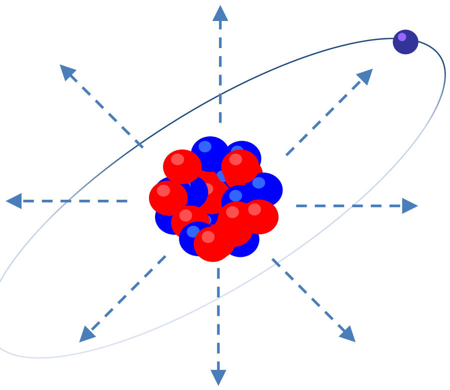

- Isotope-shift in singly-ionized Ca^+ ions
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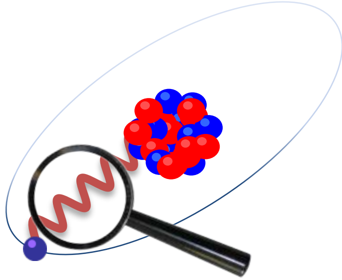
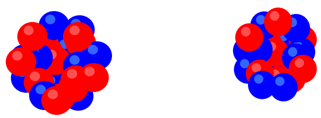
Isotope shift and hyperfine effects



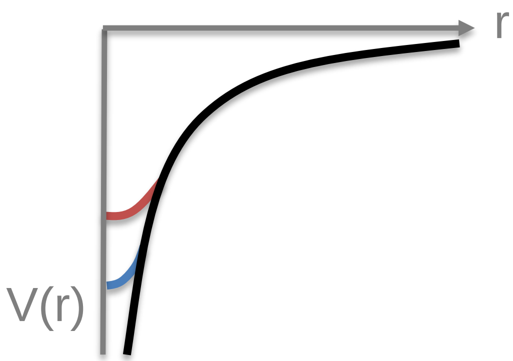
Is the electron-nucleus interaction just an interaction of two point-like charges, one of which (nucleus) is infinitely heavy?

$$V(r) = -\frac{Ze^2}{r}$$

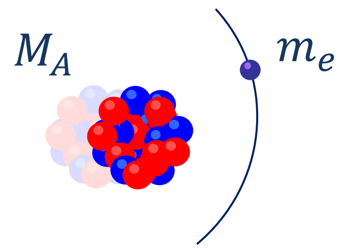
Field shift
due to different charge radii



$\langle r^2 \rangle_A > \langle r^2 \rangle_{A'}$



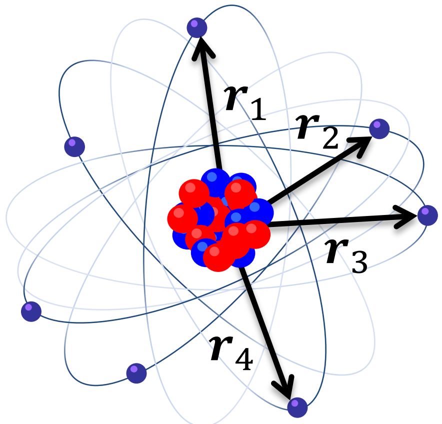
Mass shift
due to finite nuclear mass



The difference in the transition frequency for two isotopes with masses M_A and $M_{A'}$ and (mean square) nuclear radii:

$$\nu_A - \nu_{A'} = K\,\frac{M_A - M_{A'}}{M_A M_{A'}} + F\delta\langle r^2 \rangle_{AA'}$$

How to describe theoretically an atom?



In quantum theory, states of an atom are described by their energy values and by wave-functions:

$$E_n \,, \;\; \Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3, \dots, \boldsymbol{r}_N)$$

The wave function is a function of 3N coordinates, where N is the number of electrons! How to deal with this huge dimension?

We usually construct many-electron wave functions as expansion in terms of anti-symmetrized product of single-electron wave function:

$$\Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3, \dots, \boldsymbol{r}_N) = \underbrace{\textstyle\sum_r c_r}_{\text{Summation over configurations}} \; \underbrace{\textstyle\sum_s d_s \begin{vmatrix} \varphi_1(r_1) & \dots & \varphi_N(r_1) \\ \vdots & \ddots & \vdots \\ \varphi_1(r_N) & \dots & \varphi_N(r_N) \end{vmatrix}}_{\substack{\text{Configuration state-function (CSF)} \\ \text{State of particular symmetry}}}$$

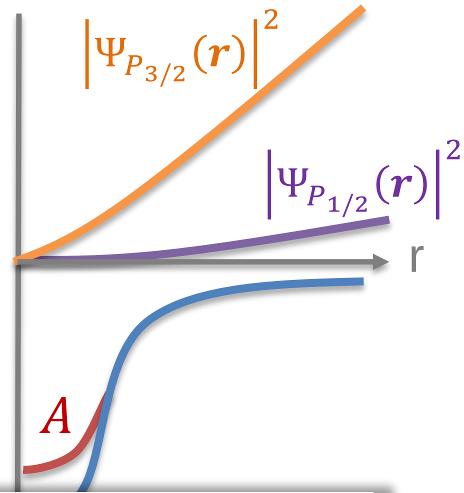
Summation over configurations

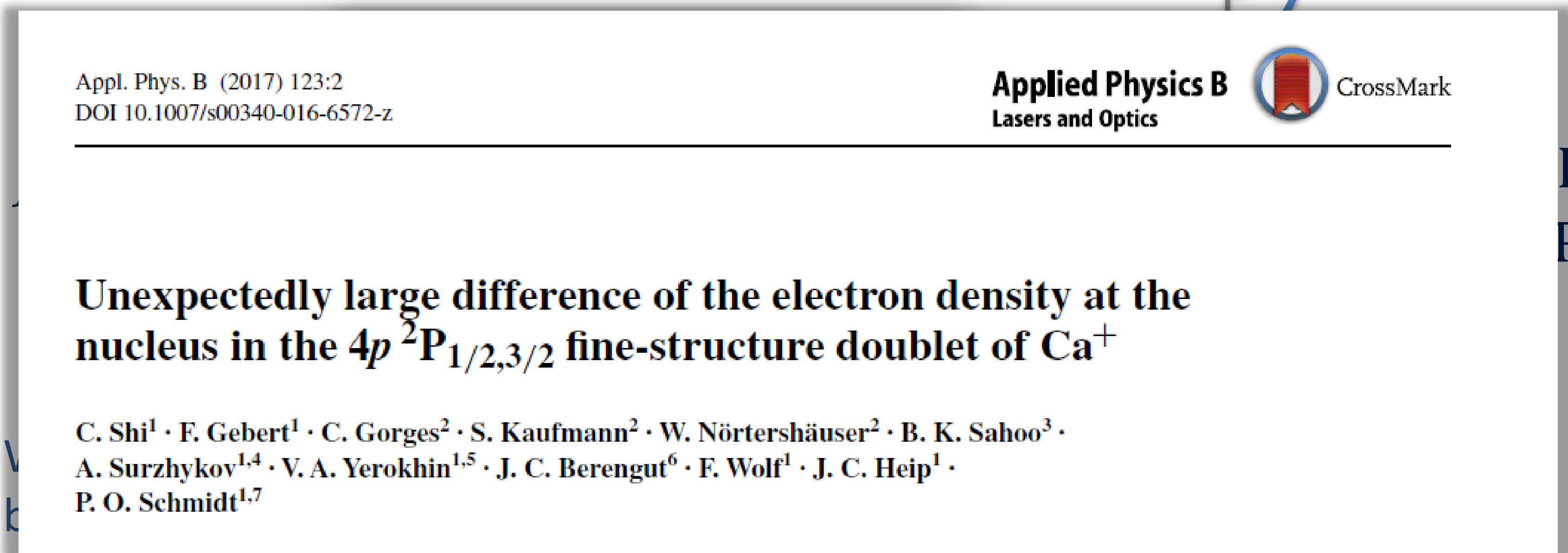
Configuration state-function (CSF)
State of particular symmetry

Isotope shift and hyperfine effects

Recently, high-precision measurements have been performed at the QUEST institute to compare isotope shifts for the $S_{1/2} \rightarrow P_{1/2}$ and $S_{1/2} \rightarrow P_{3/2}$ transitions in Ca^+ ion.

These transitions exhibit different behavior with respect to the field shift.





Appl. Phys. B (2017) 123:2
DOI 10.1007/s00340-016-6572-z
Applied Physics B
Lasers and Optics
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Unexpectedly large difference of the electron density at the nucleus in the $4p\ ^2P_{1/2,3/2}$ fine-structure doublet of Ca^+

C. Shi[1] · F. Gebert[1] · C. Gorges[2] · S. Kaufmann[2] · W. Nörtershäuser[2] · B. K. Sahoo[3] · A. Surzhykov[1,4] · V. A. Yerokhin[1,5] · J. C. Berengut[6] · F. Wolf[1] · J. C. Heip[1] · P. O. Schmidt[1,7]

$P_{3/2}$

$P_{1/2}$

nuclear effects? QED?

C. Shi *et al.*, Applied Physics B (2017)

Studies of nuclear properties

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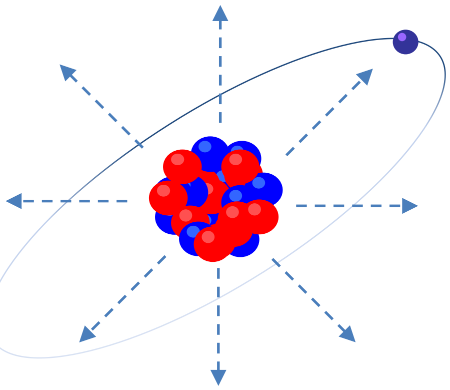

- Isotope-shift in singly-ionized Ca^+ ions
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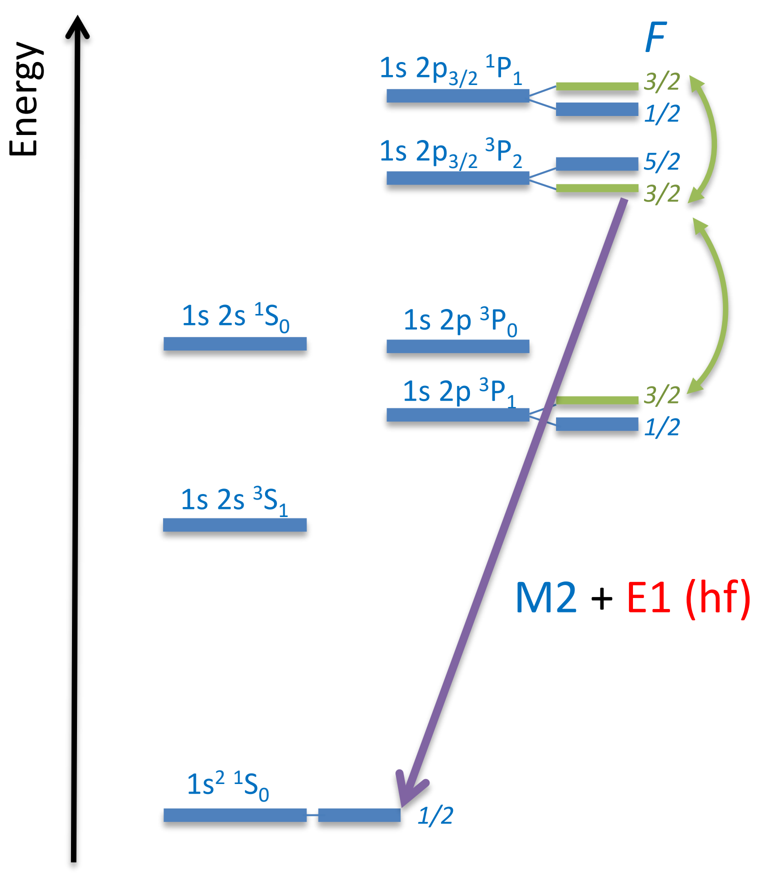
Hyperfine-induced mixing of ionic states



Example: Helium-like ion with the nuclear spin I=1/2

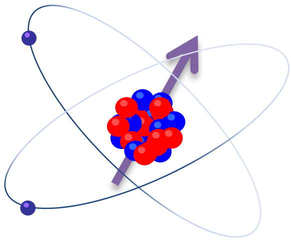
- Hyperfine interaction may affect not only the energy spectrum of highly-charged ions but also the properties of their characteristic emission.

- For example, hyperfine interaction leads to the mixing of $^3P_2$ and $^{1,3}P_1$ states of He-like ions:

$$\left|{}^3P_2\ F\right\rangle \rightarrow C_{^3P_2}\left|{}^3P_2\ F\right\rangle + C_{^3P_1}\left|{}^3P_1\ F\right\rangle + C_{^1P_1}\left|{}^1P_1\ F\right\rangle$$

- As a result, the $^3P_2$ state can decay not only via the magnetic quadrupole (M2) but also the HF-induced electric dipole (E1) transition.

Theoretical background



- Hamiltonian of helium-like ion with non-zero nuclear spin:

$$\hat{H} = \hat{H}_0 + \hat{H}_{hf}$$

$$\hat{H}_0 = \sum_{i=1,2} \hat{h}_i + V(\boldsymbol{r}_1, \boldsymbol{r}_2)$$

Magnetic dipole hyperfine operator

$$\hat{H}_{hf} = \sum_{\lambda} (-1)^{\lambda} \, M^{(1)}_{-\lambda} T^{(1)}_{\lambda}$$

- We can find eigenfunctions of the Hamiltonian $\hat{H}$ by making expansion:

$$|\alpha \; F \; M_F\rangle = \sum_{\beta \; J} C_{\beta J} \sum_{M_I M_J} \langle I \; M_I \; J \; M_J | F \; M_F\rangle \, |I M_I\rangle |J M_J\rangle$$

- Expansion coefficients $C_{\beta J}$ can be then found by diagonalization of Hamiltonian matrix.
- In order to perform such a diagonalization, one needs first to evaluate matrix elements of the magnetic dipole hyperfine operator:

$$\langle \alpha \; F \; M_F | \hat{H}_{hf} | \alpha' \; F \; M_F \rangle \propto \mu_I = g_I \; I \; \mu_N$$

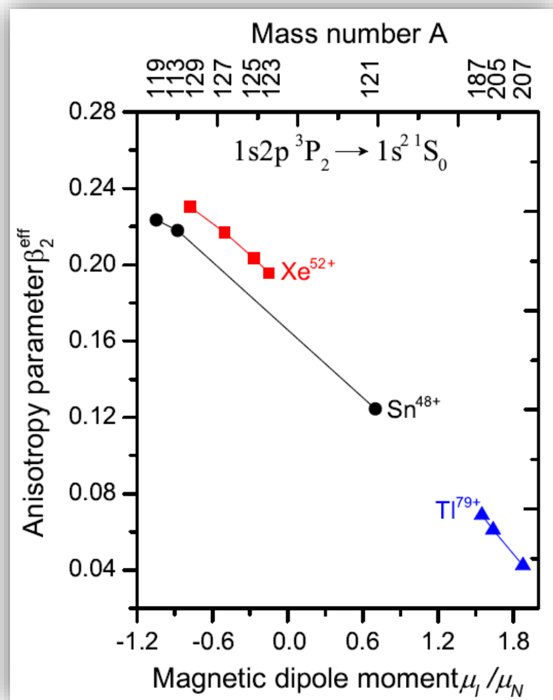
Nuclear magnetic moment

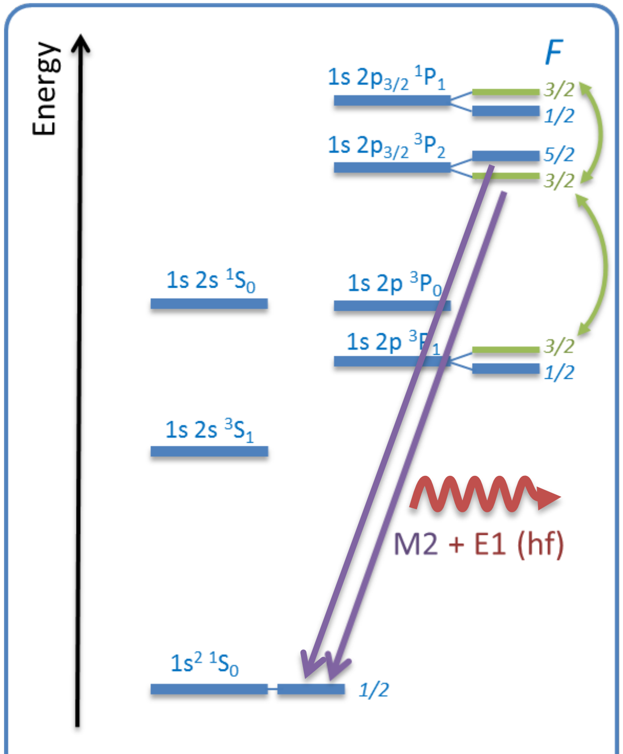
Kα transitions in helium-like ions

- The angular distribution of the hyperfine- as well as fine-structure resolved transitions in helium-like ions:

$$W(\theta) \sim 1 + \beta_2^{eff} P_2(\cos\theta)$$

- Owing to hyperfine-induced mixing between leading M2 and hf-E1 transitions, the Kα emission pattern appears to be very sensitive to the magnetic dipole moment.





Example: Ion with nuclear spin I=1/2

The effect of the nuclear magnetic dipole moment on the angular distribution of characteristic x–rays can still be observed if the hyperfine structure of helium–like ions is not resolved!

Z. W. Wu, A. Surzhykov and S. Fritzsche, Phys. Rev. A **90** (2014) 063422

Studies of nuclear properties

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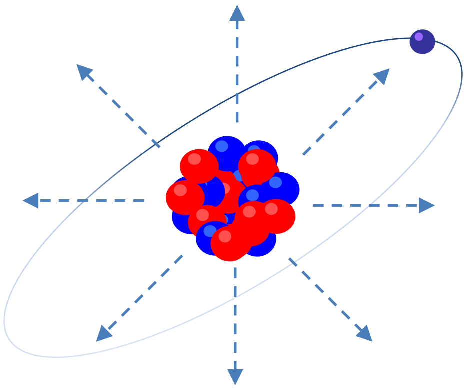

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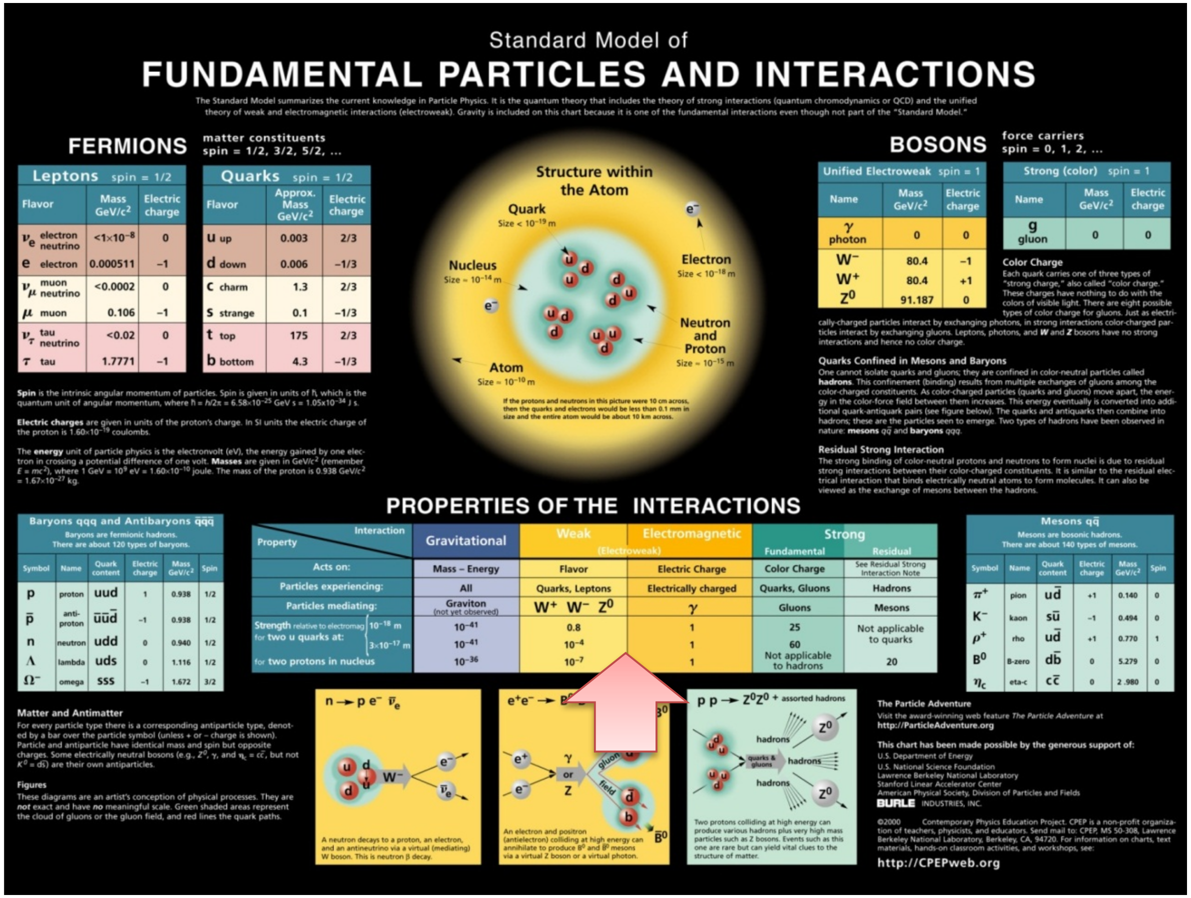
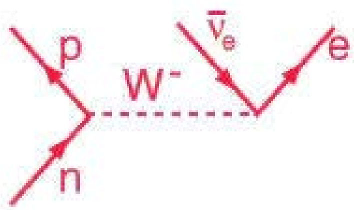
Unified electro-weak interaction



One of the biggest successes of the Standard Model is the unification of the electromagnetic and the weak forces into the so-called electroweak force.

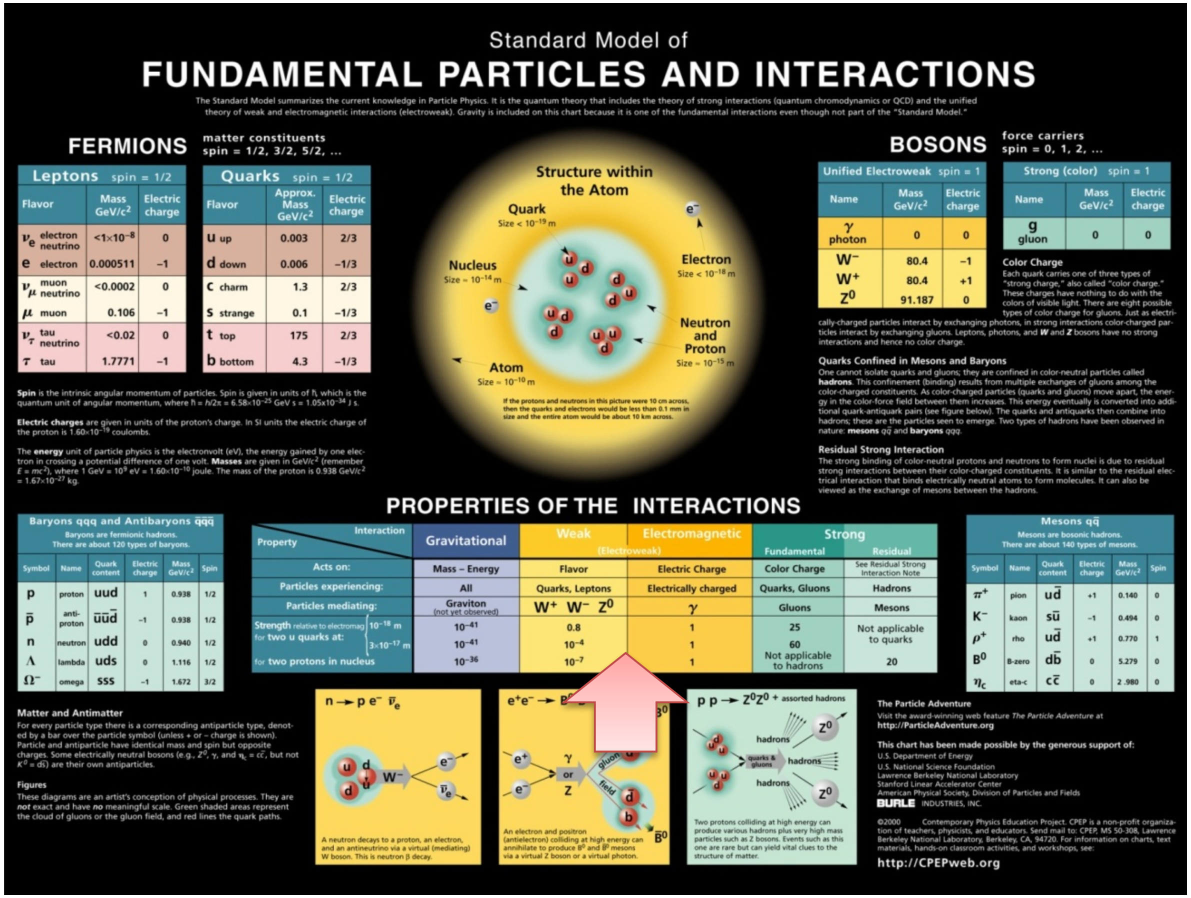
Note that electromagnetic interaction preserves spatial parity while weak interaction – not!

Electromagnetic



Weak

Unified electro-weak interaction



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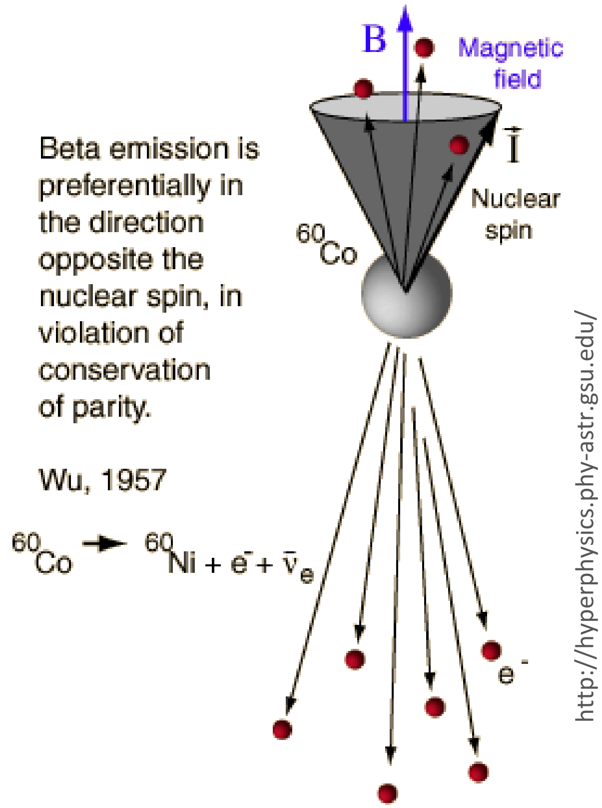
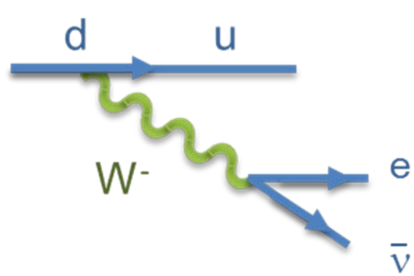


Parity violation (PV) is first time observed in famous Wu experiment (1956) on the beta-decay of cobalt nuclei.

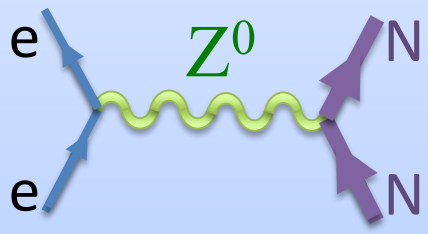


Parity violating interactions

The effective Hamiltonian of the PV electron-nucleus interaction can be cast in the form:

$$H_{PV} = \frac{G_F}{\sqrt{2}}\left(\boxed{-\frac{Q_W}{2}\gamma_5} + \boxed{\frac{\kappa}{I}\boldsymbol{\alpha}\cdot\boldsymbol{I}}\right)\rho(\boldsymbol{r})$$

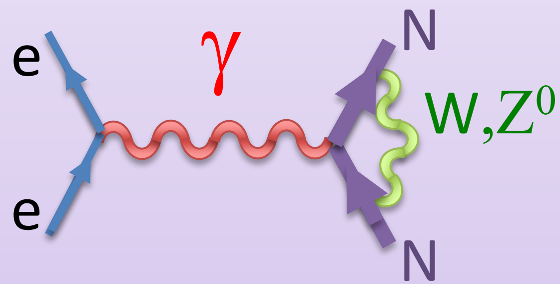
Dominant part is the nuclear-spin-independent (NSI) interaction that arises due to exchange of neutral Z^0 boson between nucleus and electrons.



- Weak charge Q_w characterizes NSI part:

$$Q_W = Z(1 - 4\sin^2\theta_W) - N$$

The nuclear-spin-dependent (NSD) part comes mainly from the electromagnetic interaction with weakly interacting nucleons.



- NSD is characterized by the coupling constant κ:

$$|\kappa| \approx \frac{|Q_W|}{100}$$

How we can observe the parity-violating interactions?

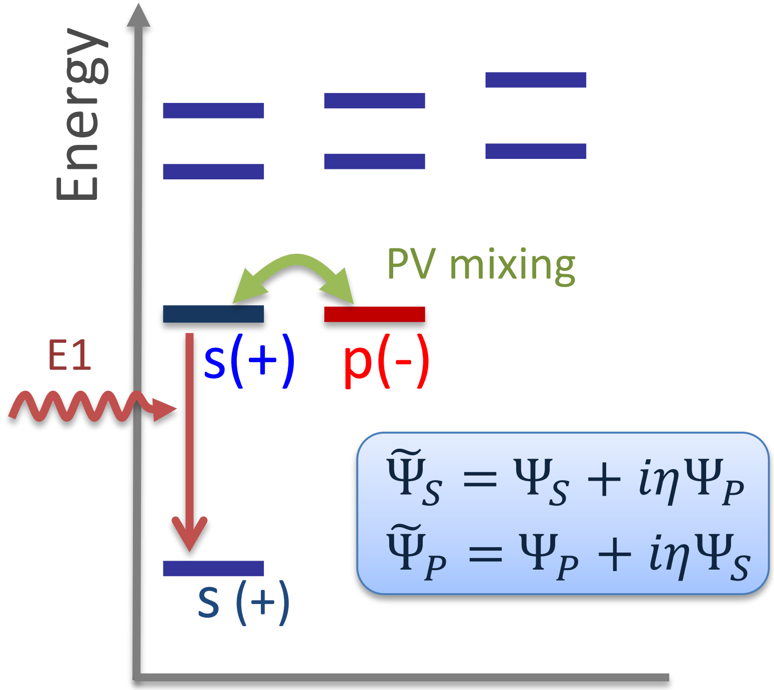
Atomic parity violation

The parity-violating (NSI and NSD) interactions lead to the mixing of atomic levels with opposite parity.

Mixing coefficient is given by:

$$\eta = \frac{\left\langle \Psi_S \left| \frac{G_F}{\sqrt{2}} \left(-\frac{Q_W}{2}\gamma_5 + \frac{\kappa}{I}\boldsymbol{\alpha}\cdot\boldsymbol{I} \right) \rho(\boldsymbol{r}) \right| \Psi_P \right\rangle}{E_S - E_P - i\,\Gamma/2}$$

Energy splitting should be small!



Total angular momenta “selection rules”:

- Nuclear spin independent interaction mixes only states with the same *J’s*
- Nuclear spin dependent interaction can mix levels with different *J’s* but same *F’s*

- If the parity is broken due to the weak interaction this transition becomes possible!

PV experiments with neutral atoms

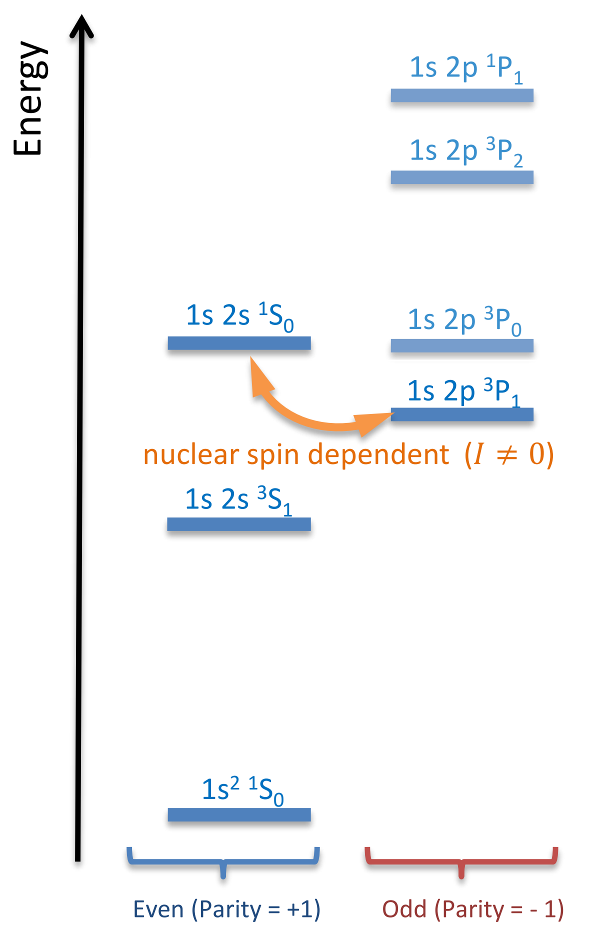
PV experiments with neutral atoms have provided us with valuable information on the weak interaction.

But! Analysis of these experiments is rather difficult task because of "many-electron nature" of systems.

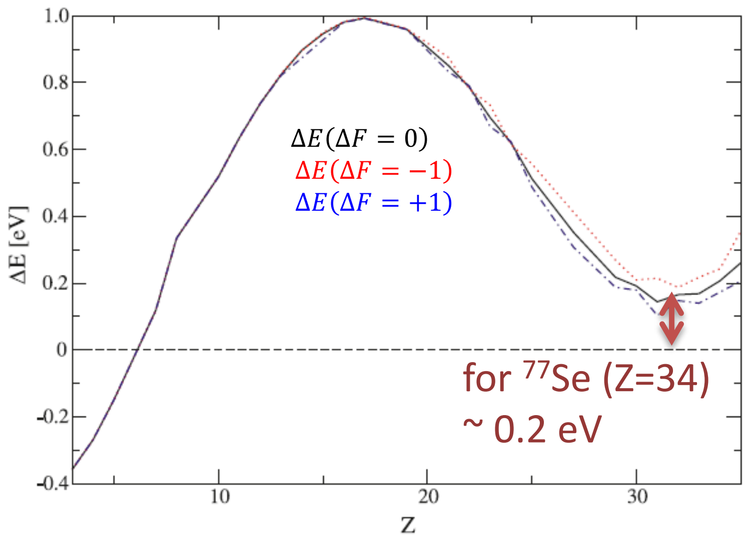
- Alternatively, we may explore APV effects as appear in few-electron ions!
- Few-electron ions may be perfect candidates for PV studies:
  - Relatively simple atomic systems
  - Large electron-nucleus overlap
  - Effect scales as Z^5 (in contrast to Z^3 in neutral systems)
  - Levels with opposite parities might be almost degenerated

Parity-violation in helium-like ions

Energy levels of He-like ion (sketch)



Energy shift $E(1s2s\ {}^1S_0) - E(1s\ 2p\ {}^3P_1)$, eV



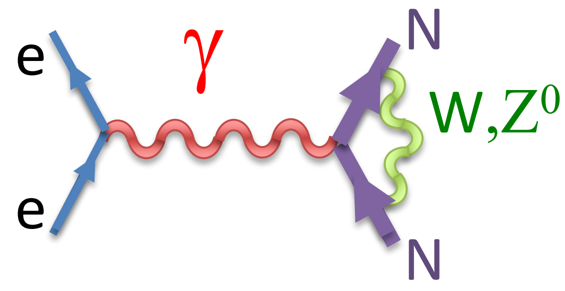
Owing to the (spin-dependent) part of PV Hamiltonian, the 2^1S_0 atomic state in He-like ions with nuclear spin $I \neq 0$ can be described as:

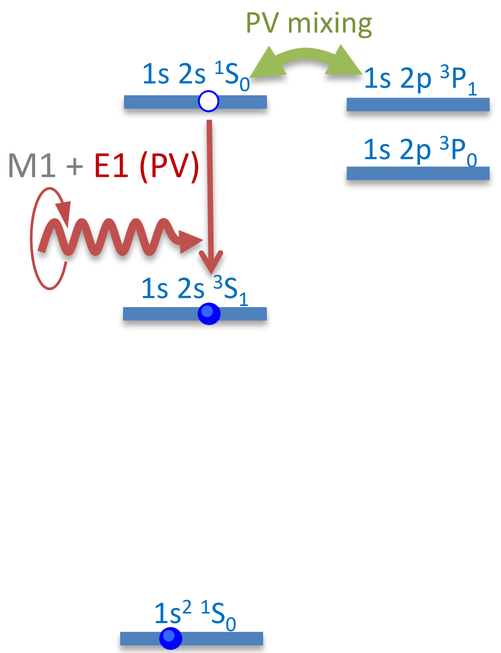
$$|1s\ 2s\ {}^1S_0, F = I\rangle + \mathrm{i}\eta|1s\ 2p\ {}^3P_1, F = I\rangle$$

Mixing coefficient (for ^{77}Se) is $\eta \propto 10^{-9}$.

Towards analysis of nuclear PV effects

Novel schemes for studying the nuclear-spin-dependent part of the atomic parity violation have been also proposed.





Probability of the induced 1s2s $^1S_0 \rightarrow$ 1s 2s $^3S_1$ transition in He-like ions:

$$\Gamma_\lambda(M1 + E1) = (2I + 1) \cdot \Gamma_{M1} \cdot (1 + \lambda A)$$

parity-preserving rate (M1)

photon's helicity

Asymmetry coefficient $A = (\Gamma_+ - \Gamma_-)/(\Gamma_+ + \Gamma_-)$ is directly related to the nuclear-spin dependent mixing parameter: $A \propto \eta/(2I + 1)$

For medium-Z ions the asymmetry reaches $A \propto 10^{-7}$!

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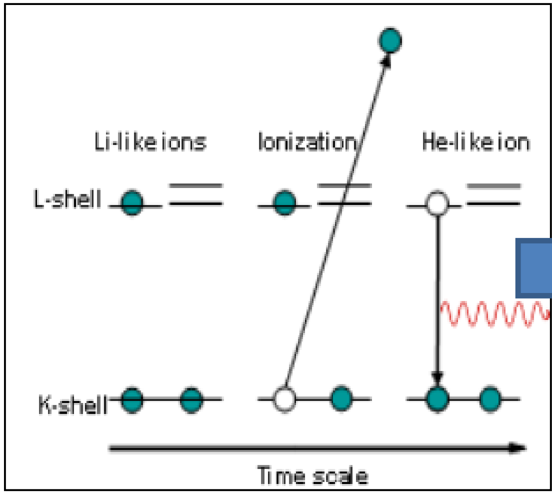
GSI experimental proposal

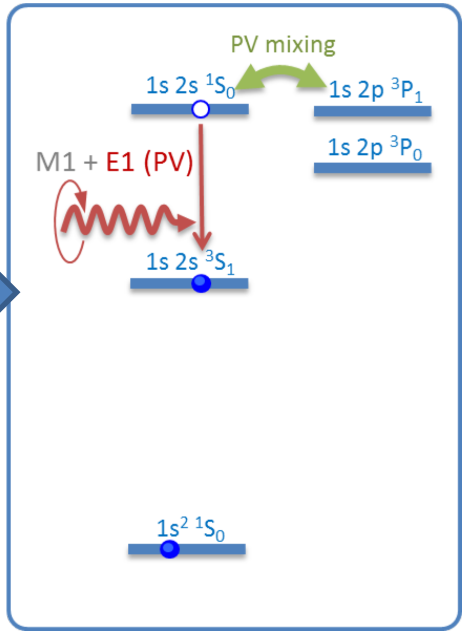
We propose three-step process to study PNC phenomena in He-like ion:

Production of 2^1S_0 state by means of inner-shell ionization (of Li-like ions)

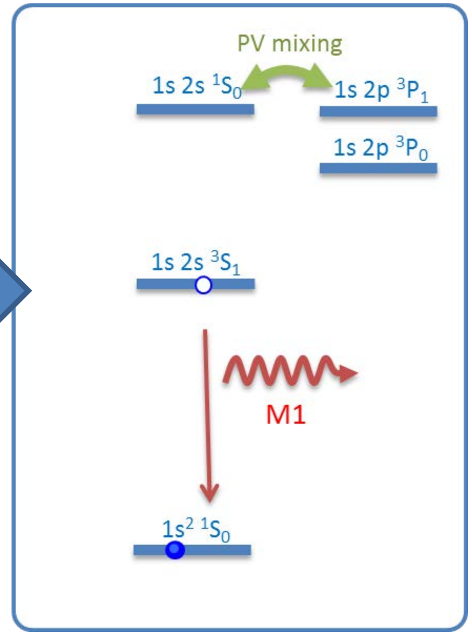


J. Rzadkiewicz et al, PRA **74** (2006) 012511

Inducing by laser M1 + E1(PV) transition



Measurement of the M1 radiative stabilization



Important question: which experimental parameters do we need to make E1(PV) transition “visible”? Some theory predictions are required!

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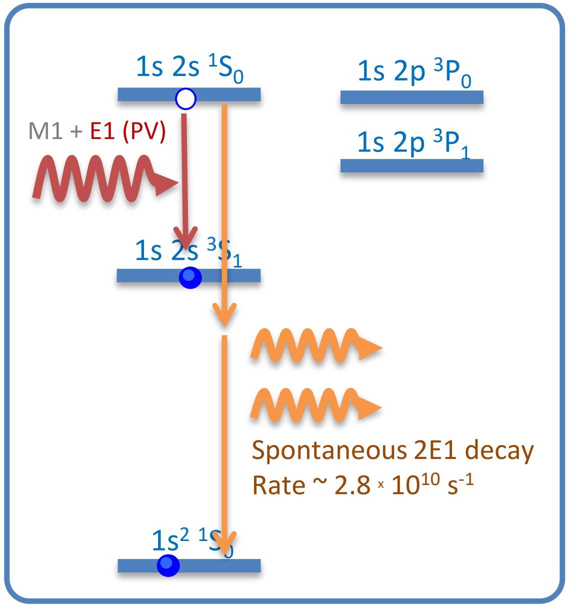
Nuclear PV effects: Estimates

- Based on the predictions of the Standard Model we have estimated the size of the expected asymmetry for several isotopes.

- Stable isotope of ^{77}Se seems to be most convenient for the study.

Ion	$t_{1/2}$	I	μ	$10^{-7}\mathcal{A}$
$^{70}_{33}$As	53 min	4	2.106 100	0.801 74
$^{71}_{33}$As	65.3 h	5/2	1.673 500	1.251 77
$^{72}_{33}$As	26 h	2	−2.156 600	1.278 89
$^{74}_{33}$As	17.78 d	2	−1.597 000	1.335 09
$^{75}_{33}$As	stable	3/2	1.439 475	2.086 91
$^{76}_{33}$As	26.3 h	2	−0.906 000	1.403 86
$^{73}_{34}$Se	7.1 h	9/2	0.8700 000	0.623 39
$^{75}_{34}$Se	118.5 d	5/2	0.6700 000	1.084 38
$^{77}_{34}$Se	stable	1/2	0.535 0422	4.663 09
$^{79}_{34}$Se	65000 yr	7/2	−1.018 0000	0.787 13

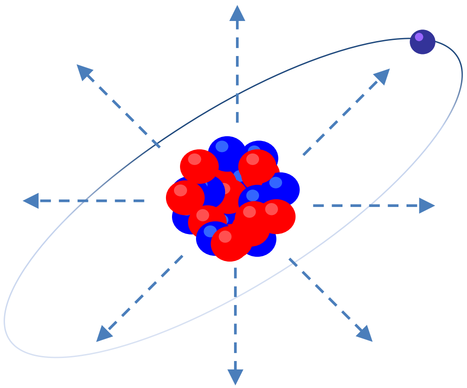


- To induce M1+E1 (PV) transition in He-like Se we need to apply circularly polarized light of:
  - energy 43.85 eV (extreme ultraviolet)
  - intensity $I \propto 10^{12} - 10^{13}$ W/cm^2 (to "compete" with the spontaneous E1E1 decay)

F. Ferro, A. S., and Th. Stöhlker, Phys. Rev. A **83** (2011) 052518

Studies of nuclear properties

The strong nuclear fields affect electronic shell <u>structure</u> of heavy ions and make it possible to study the relativistic, QED and **nuclear phenomena**.



During the last decades a number of experimental and theoretical studies have been focused on:

- Isotope-shift in singly-ionized Ca^+ ions
- Hyperfine-induced effects in angular distributions of characteristic emission
- Parity non-conservation effects in nuclei
- Excitation of atomic nuclei by atomic transitions

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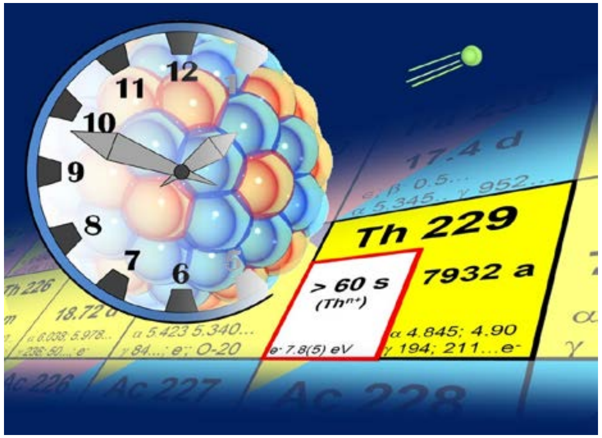
Nuclear clocks and “thorium puzzle”



Observation of nuclear transition in ^{229}Th is important for the development of novel nuclear clocks.

A number of various schemes are proposed to observe this transition. Very promising are atomic processes in which excitation of electronic shell is transferred to a nucleus.

NATURE | ARTICLE

日本語要約

Direct detection of the ^{229}Th nuclear clock transition

Lars von der Wense, Benedict Seiferle, Mustapha Laatiaoui, Jürgen B. Neumayr, Hans-Jörg Maier, Hans-Friedrich Wirth, Christoph Mokry, Jörg Runke, Klaus Eberhardt, Christoph E. Düllmann, Norbert G. Trautmann & Peter G. Thirolf

Affiliations | Contributions | Corresponding author

Nature **533**, 47–51 (05 May 2016) | doi:10.1038/nature17669

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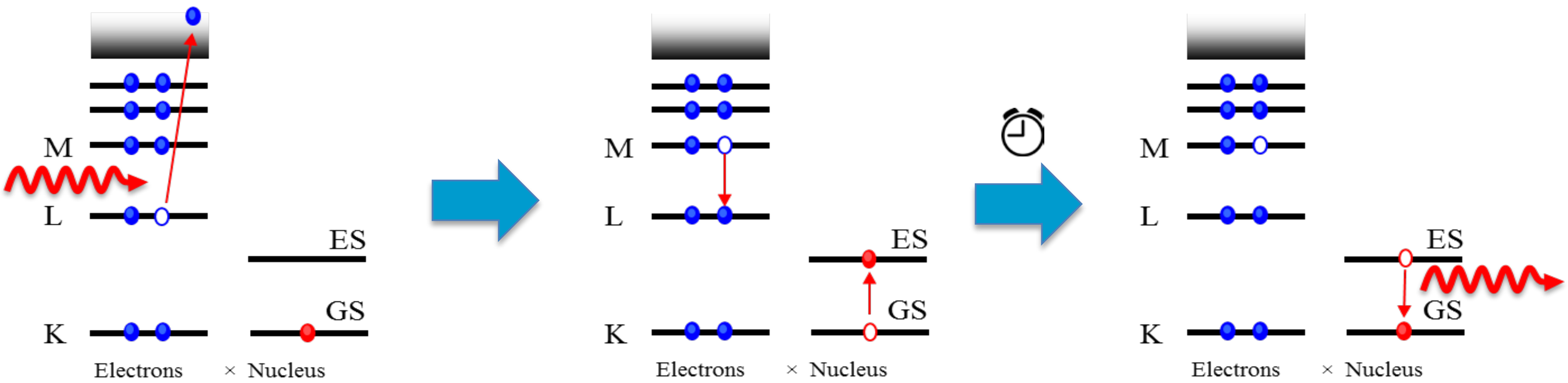
Abstract

Abstract • References • Author information • Extended data figures and tables

Today's most precise time and frequency measurements are performed with optical atomic clocks. However, it has been proposed that they could potentially be outperformed by a nuclear clock, which employs a nuclear transition instead of an atomic shell transition. There is only one known nuclear state that could serve as a nuclear clock using currently available technology, namely, the isomeric first excited state of ^{229}Th (denoted ^{229m}Th). Here we report the direct detection of this nuclear state, which is further confirmation of the existence of the isomer and lays the foundation for precise studies of its decay parameters. On the basis of this direct detection, the isomeric energy is constrained to between 6.3 and 18.3 electronvolts, and the

Nuclear excitation by electron transitions



Nucleus is in its ground state (GS). Atomic shell vacancy is produced.

Bound-electron transition leads to the nuclear excitation.

Radiative nuclear decay by gamma-ray emission.

NEET – nuclear excitation by electron transition. Bound-electron transitions being **energetically very close** to nuclear excitations can directly induce them.

Fine adjustment of atomic and nuclear transition energies is crucial!

Nuclear excitation by electron transitions

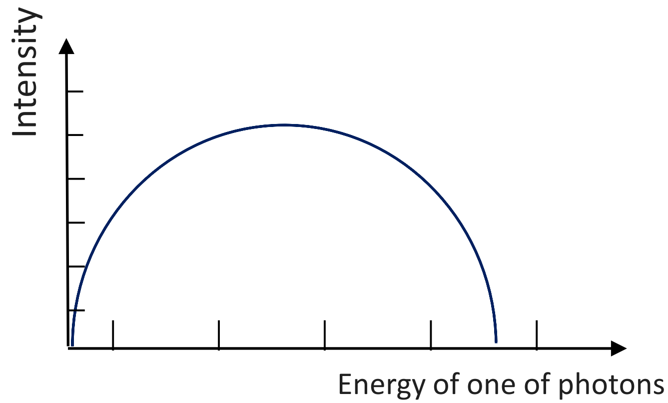
The key parameter is the NEET probability: $P_{NEET} = W_{NEET}/W_{tot}$

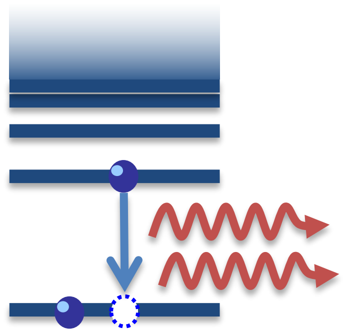
Nucleus	Experiment	References	Theory	References
^{237}Np	$2.1(0.6) \times 10^{-4}$	Saito et al., 1980	1.5×10^{-7} 3.1×10^{-12} 1.9×10^{-9} 2.6×10^{-4} 2.2×10^{-12}	Pisk et al., 1989 Tkalya, 1992 Ho et al., 1993 Ljubicic, 1998 Harston, 2001
^{197}Au	$5.1(3.6) \times 10^{-5}$ $5.0(0.6) \times 10^{-8}$	Shinohara et al., 1995 Kishimoto et al., 2000	3.5×10^{-5} 1.3×10^{-7} 2.4×10^{-7} 2.2×10^{-5} 3.6×10^{-8}	Pisk et al., 1989 Tkalya, 1992 Ho et al., 1993 Ljubicic, 1998 Harston, 2001
^{189}Os	$5.7(1.7) \times 10^{-9}$ $2.0(1.4) \times 10^{-8}$ $<9 \times 10^{-10}$	Shinohara et al., 1987 Lakosi et al., 1995 Ahmad et al., 2000	2.5×10^{-7} 1.1×10^{-10} 2.1×10^{-9} 2.3×10^{-7} 1.1×10^{-10}	Pisk et al., 1989 Tkalya, 1992 Ho et al., 1993 Ljubicic, 1998 Harston, 2001

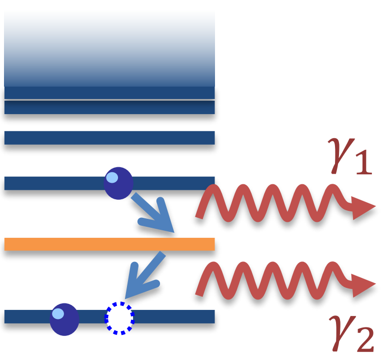
Two-photon transitions with cascades

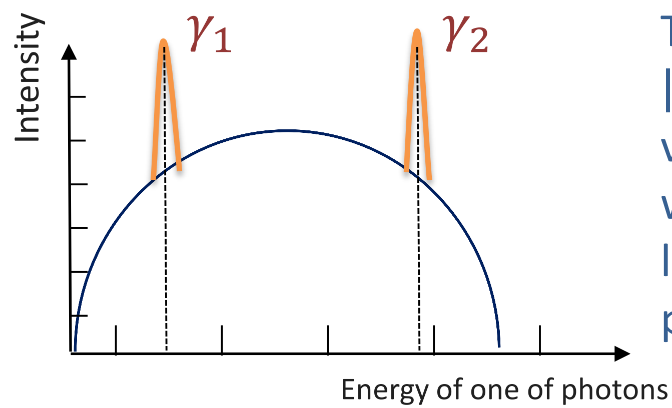
In contrast to single-photon transitions, the two-photon decay has a continuous spectrum. Photon energies just need to satisfy the energy conservation: $E_f - E_i = \hbar\omega_1 + \hbar\omega_2$

If there are no real states between initial and final states, the energy spectrum is smooth.









The peaks arise when transition $|i> \rightarrow |f> + \gamma_1 + \gamma_2$ proceeds via an intermediate state $|\nu>$ with energy $E_i > E_\nu > E_f$, thus leading to two sequential one-photon emissions.

Two-photon transitions with cascades

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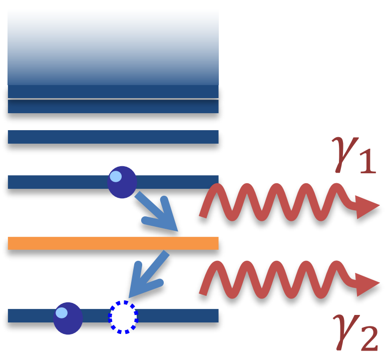

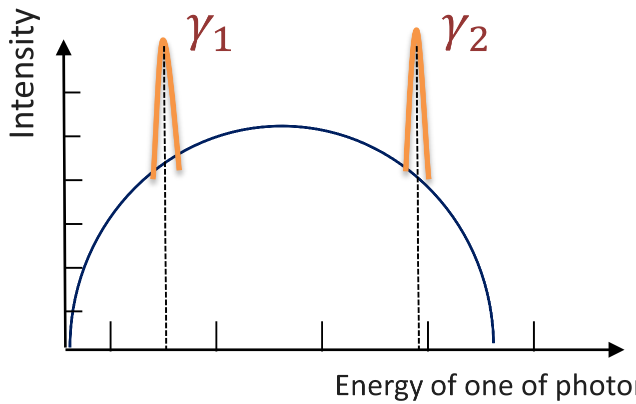

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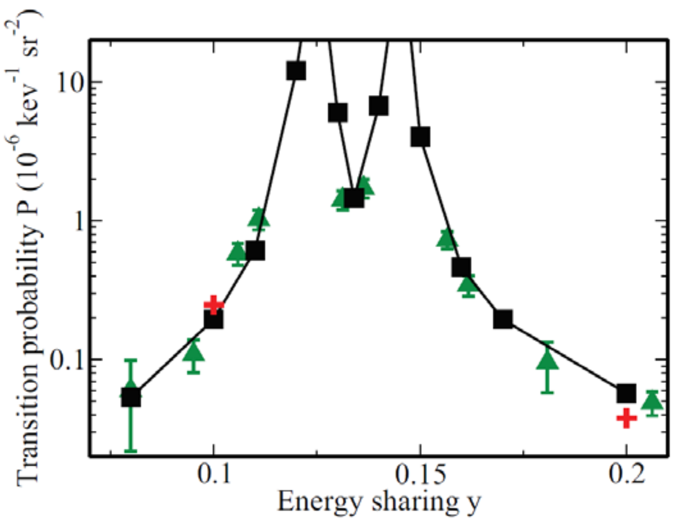

"Resonance" two-photon spectroscopy provides important information about atomic structure.

3d → 1s transition in a gold atom as a function of the energy sharing parameter $y = \hbar\omega_1/(\hbar\omega_1 + \hbar\omega_2)$.

A.S., R. H. Pratt, and S. Fritzsche, Phys. Rev. A **88** (2013) 042512

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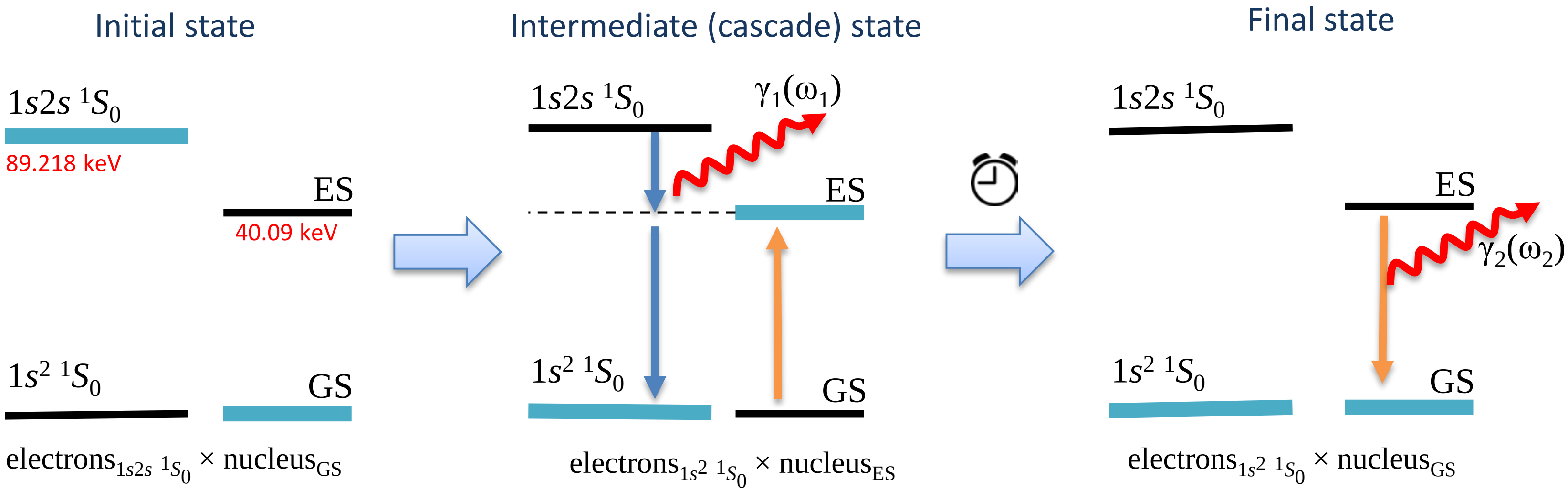
Nuclear excitation by two-photon transition

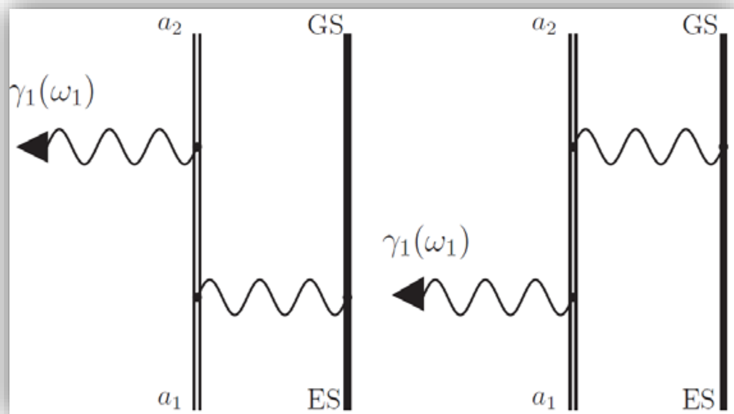
We have considered the two-photon 1s 2s $^1S_0 \rightarrow 1s^2\ ^1S_0$ (2E1) decay in helium-like $^{225}Ac^{87+}$ ion.



Considering electrons and nucleus as a "united" system the cascade decay with nuclear excitation in the intermediate state is taken place:

$$|1s\ 2s\ ^1S_0\rangle \times GS \rightarrow |1s^2\ ^1S_0\rangle \times ES + \gamma_1 \rightarrow |1s^2\ ^1S_0\rangle \times GS + \gamma_2$$

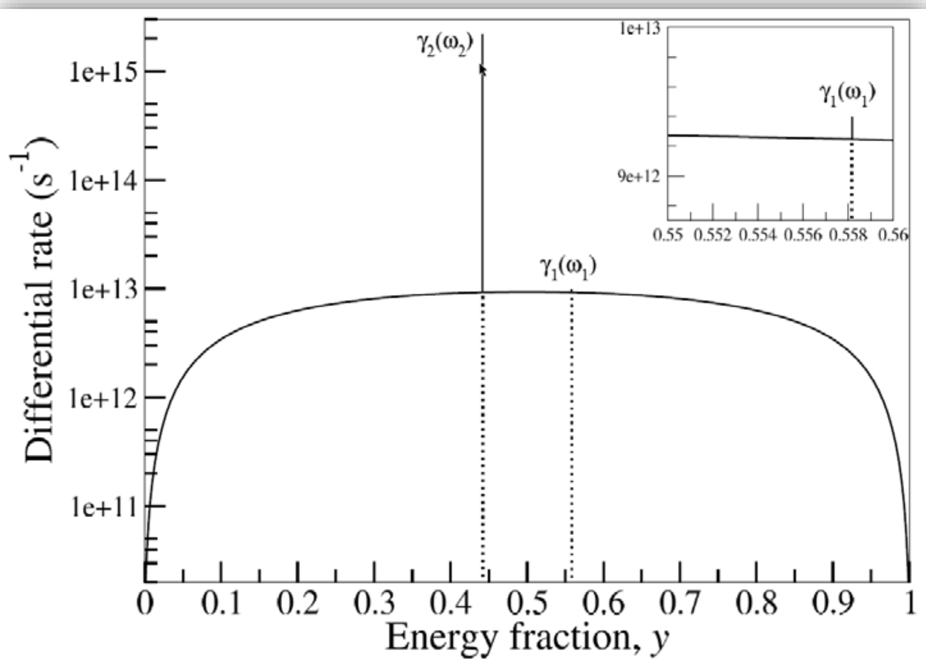
Nuclear excitation by two-photon transition



Based on the relativistic QED approach, we have performed theoretical analysis of the NETP process.

This requires the evaluation of the second order amplitude:

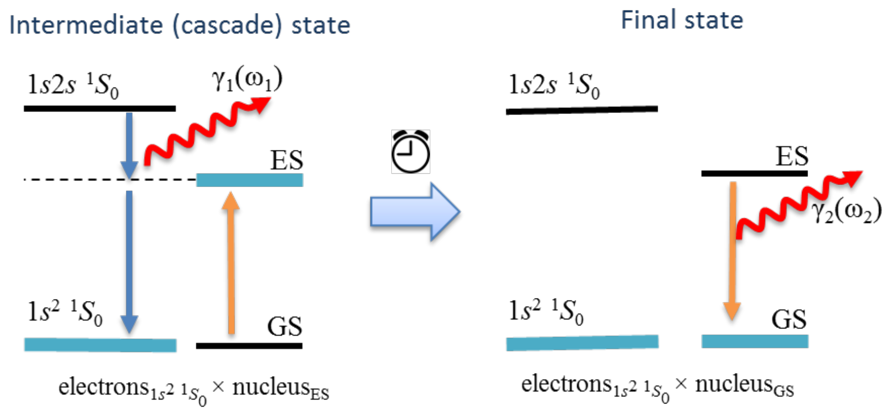
$$
\begin{aligned}
S^{(3)}_{\mathrm{NETP}} = & \frac{1}{\Delta E - \omega_{\mathrm{ES}} - \omega_1 - i(\Gamma_{1s2s\,^1S_0} + \Gamma_{\mathrm{ES}})/2} \\
& \times \frac{e^2}{4\pi} \int d^3r_1 d^3r_2 d^3R\, \overline{\psi}_{a_1}(\mathbf{r}_1) \\
& \times \left\{ \gamma_0 \frac{1}{|\mathbf{r}_1 - \mathbf{R}|} S(\varepsilon_{a_2} - \omega_1, \mathbf{r}_1, \mathbf{r}_2) \gamma^\mu A^*_\mu(\omega_1, \mathbf{r}_2) \right. \\
& + \left. \gamma^\mu A^*_\mu(\omega_1, \mathbf{r}_1) S(\varepsilon_{a_1} + \omega_1, \mathbf{r}_1, \mathbf{r}_2) \gamma_0 \frac{1}{|\mathbf{r}_2 - \mathbf{R}|} \right\} \\
& \times \psi_{a_2}(\mathbf{r}_2)\, \Psi^\dagger_{\mathrm{ES}}(\mathbf{R}) \hat{\rho}_{\mathrm{fluc}}(\mathbf{R}) \Psi_{\mathrm{GS}}(\mathbf{R})
\end{aligned}
$$

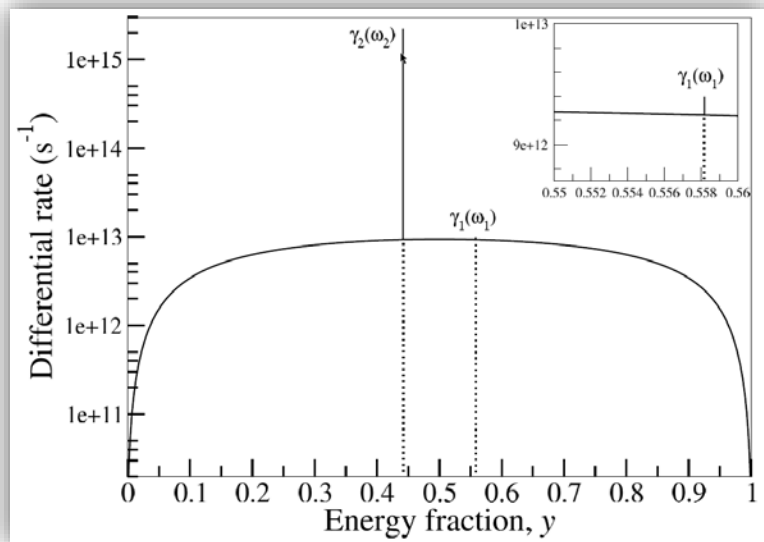


Based on our calculations, we found the NETP probability: $P_{NETP} = 3.5 \times 10^{-9}$!

A. V. Volotka, A. S., S. Trotsenko, G. Plunien, Th. Stohlker, and S. Fritzsche, Phys. Rev. Lett. **117** (2016) 243001

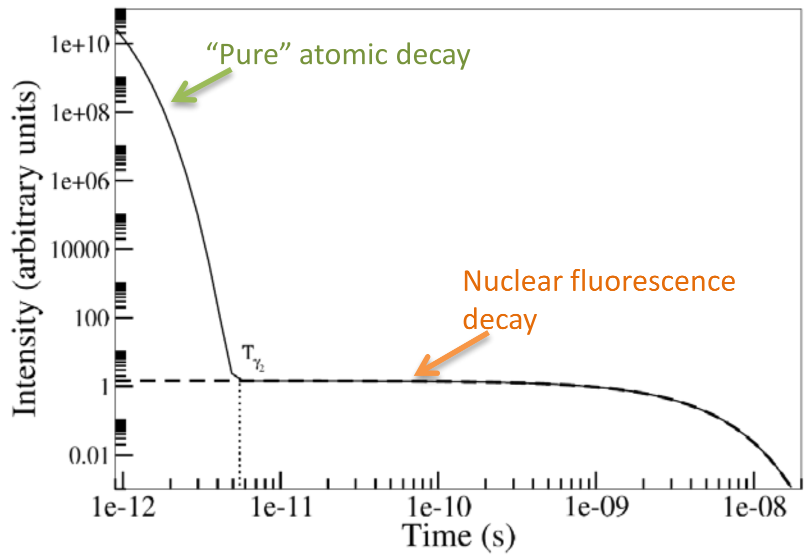
Detection of the NETP process





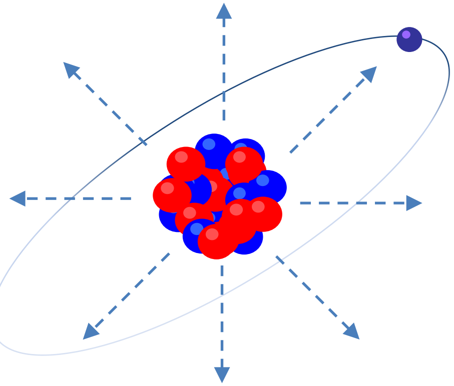
Electron decay photon γ_1 is emitted in a same time scale as the photons from "pure" two-photon decay and its observation requires detectors with high resolution.

Nuclear fluorescence photon γ_2 is emitted with a time delay and can be clearly identified. We need to perform time-delayed spectroscopy!



A. V. Volotka, A. S., S. Trotsenko, G. Plunien, Th. Stohlker, and S. Fritzsche, Phys. Rev. Lett. **117** (2016) 243001

Studies of nuclear properties: Summary



We have discussed several theoretical and experimental studies with multiply-charged ions aiming at deeper understanding of nuclear properties:

- Isotope-shift in singly-ionized Ca^+ ions
  - Large discrepancy between experiment and theory for the field shift
- Hyperfine-induced effects in angular distributions of characteristic emission
  - A new method for studying magnetic moments of nuclei?
- Parity non-conservation effects in nuclei
  - Laser-induced transitions in He-like ions to probe anapole moment
- Excitation of atomic nuclei by atomic transitions
  - Nuclear excitation by two-photon transition (NETP)

Thank you for your attention!

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