Atomic (and nuclear) physics with highly-charged heavy ions at the Gamma Factory

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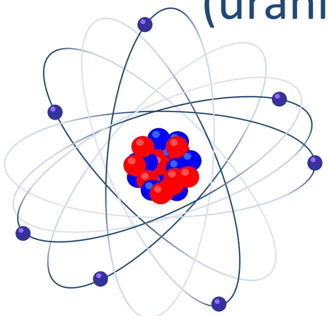
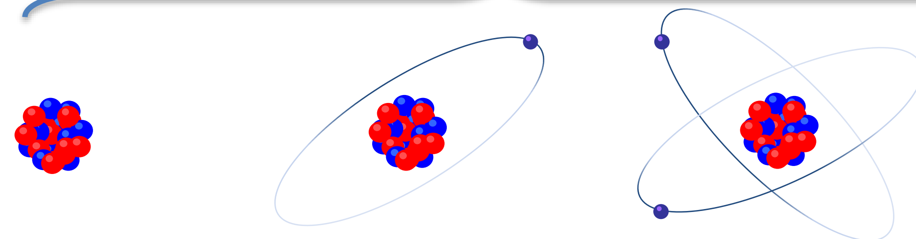
Highly-charged ions

Heavy atom
(uranium, for example)

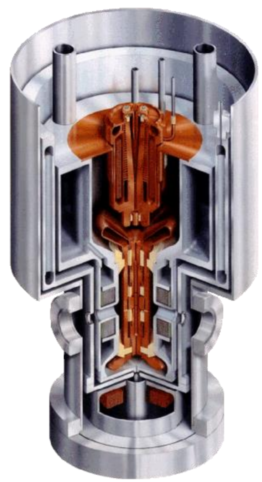


Highly-charged, heavy ions



bare | hydrogen-like | helium-like

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 highly-charged, heavy ions.

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Heavy multiply-charged ions

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

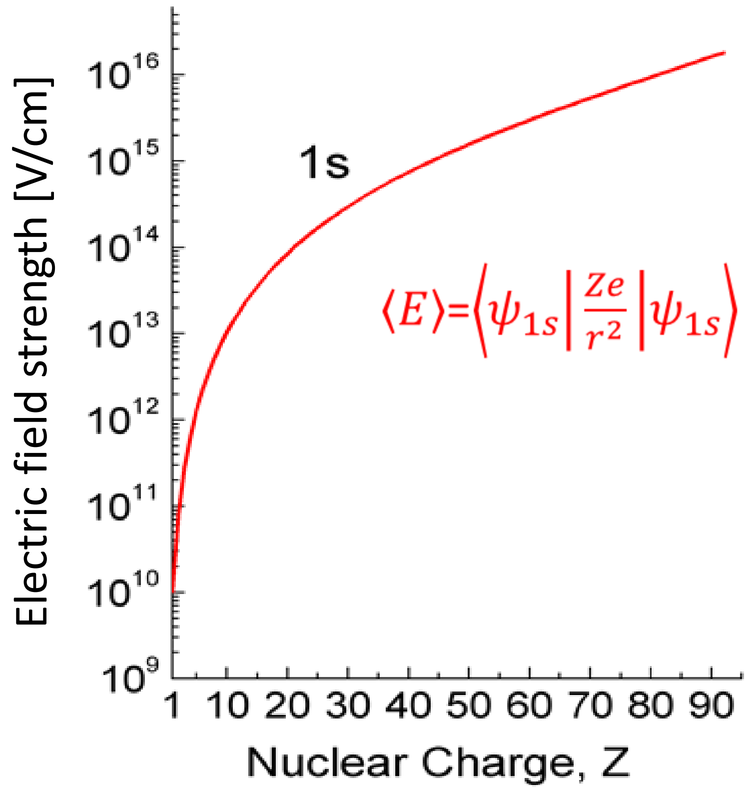
Energies of transitions in highly-charged ions are much higher comparing to those in neutral atoms.

$\Delta E_{\text{fs}} \propto Z^4$ → ~ keV

$\Delta E_{\text{hfs}} \propto Z^3$ → ~ eV

$\Delta E_{\text{QED}} \propto Z^4$ → ~ 10-100 eV

Binding energies are up to 100 keV



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

These ions are natural "laboratories" for studying simple atomic systems under critical conditions.

Structure and dynamics studies

The studies of the structure and dynamics of highly-charged ions are currently under intense studies both in theory and experiment (EBIT & storage rings). What Gamma Factory can offer to this field?

Electronic structure: relativistic, QED, many-body effects

- Spectroscopy of Li- and B-like heavy ions

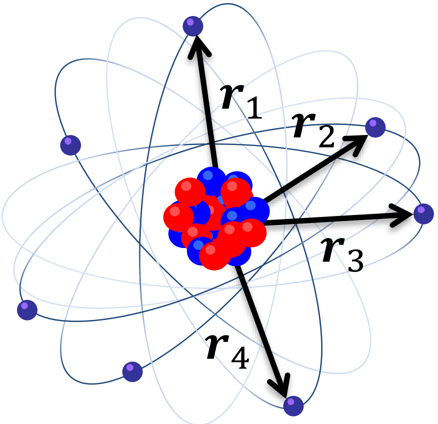
P- and CP-violation studies

- Atomic parity violation in H- and He-like ions
- Polarized ions beams and search for EDM

Relativistic collisions

- Elastic scattering of x-rays by ions
- Pair production in laser field and ion-atom collisions

Theory of many-electron systems



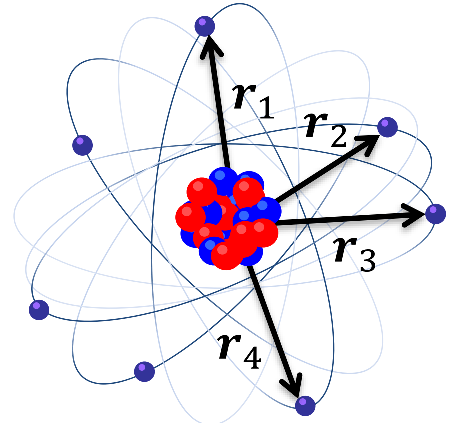
In quantum theory, states of an atom are described by their energy values and by wave-functions:

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

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

Theory of many-electron systems

Many electron methods (CI, MCDF) are based on large-scale expansions of the wave-function into basis sets:



$$\Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3, \dots, \boldsymbol{r}_N) = \sum_r c_r \sum_s d_s \begin{vmatrix} \varphi_1(r_1) & \dots & \varphi_N(r_1) \\ \vdots & \ddots & \vdots \\ \varphi_1(r_N) & \dots & \varphi_N(r_N) \end{vmatrix}$$

Summation over configurations

Configuration state-function (CSF)
State of particular symmetry

and based on this approach we still need to account for:

- Nuclear effects (field shift, nuclear recoil, hyperfine)
- Relativistic corrections to e-e interactions (Breit term)
- QED corrections

These effects are especially „uncovered“ for highly-charged ions!

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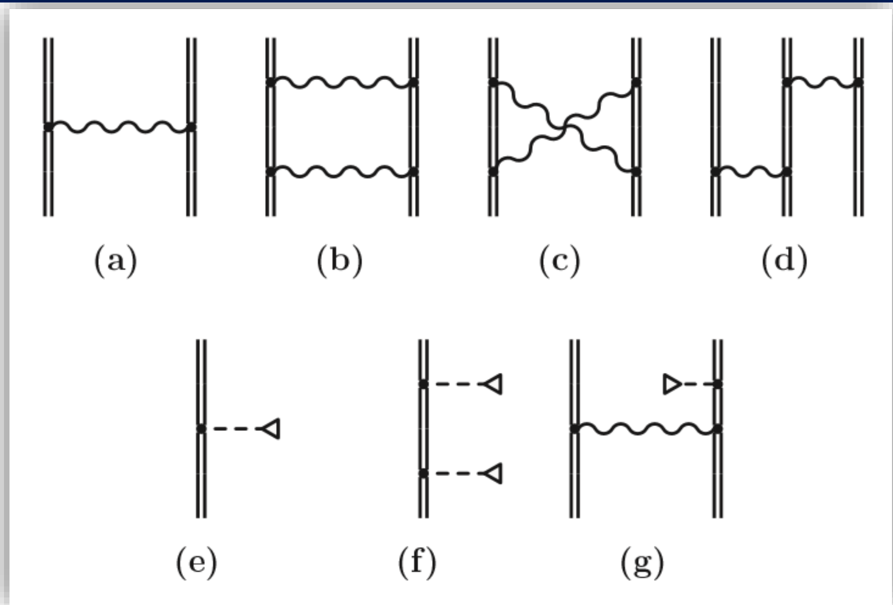
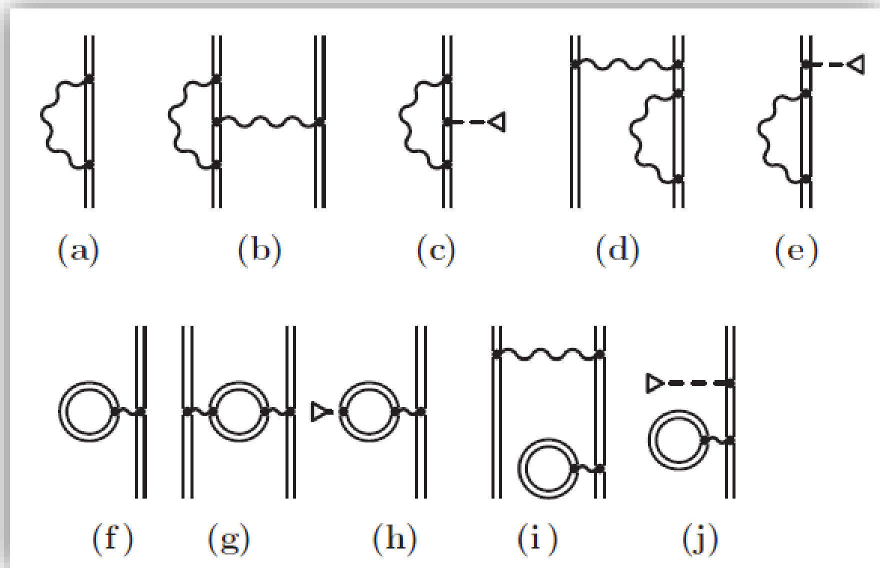
ab initio QED calculations



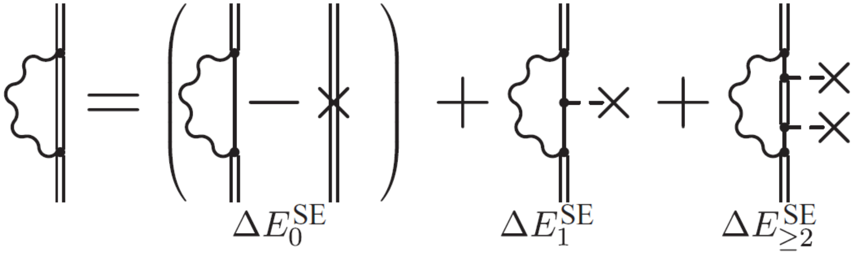


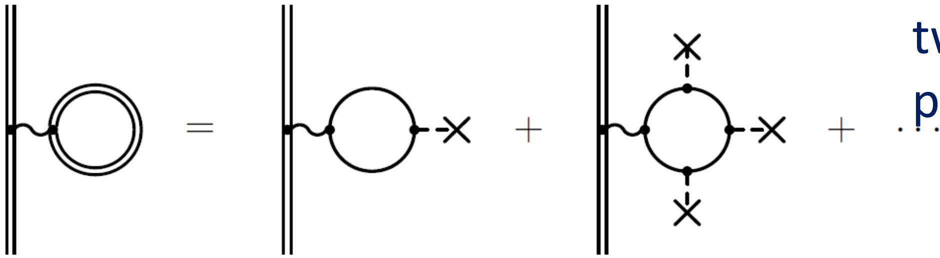
Calculations can conveniently be performed in a few separate steps. First, we calculate those parts that correspond to the Feynman diagrams *without* any photon or electron loops.

Apart of “pure” e-e interaction diagrams one has to evaluate also QED corrections.

A. Artemyev *et al.*, PRA **88**, 032518 (2013)

QED effects in highly-charged ions

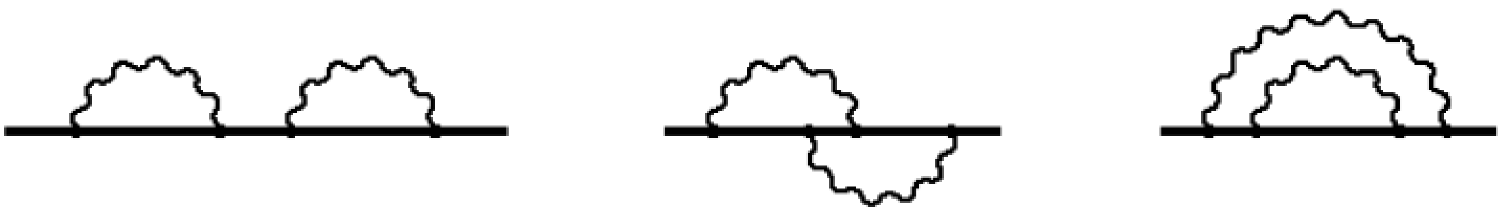




There are well-developed approaches to calculate one-loop self-energy and vacuum polarization corrections.

The accurate evaluation of (some of) two-loop corrections is still an open problem.

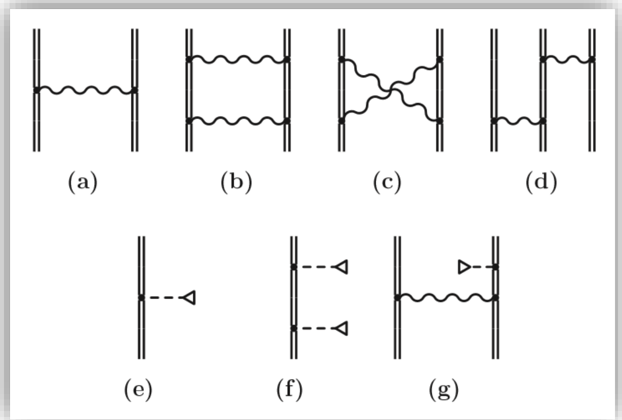
Two-loop self-energy yields the dominant theoretical uncertainty for the Lamb shift in hydrogen and light hydrogen-like ions.

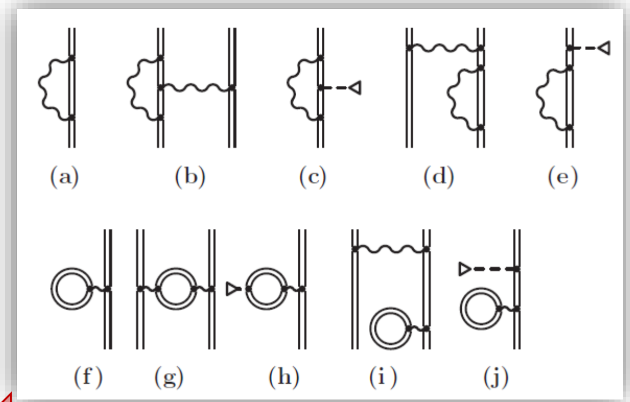


Li-like ions: QED calculations

TABLE III. Various contributions to the $2p_{1/2}$-$2s$ transition in Li-like uranium, in eV.

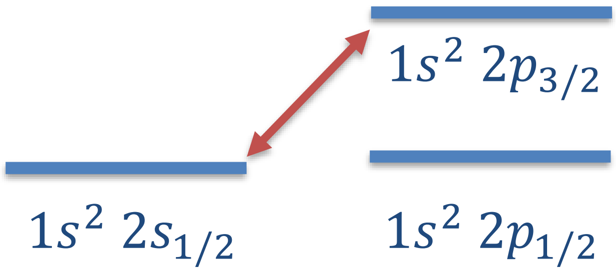
Correction	Value	Reference
One-electron extended nucleus	−33.35(6)	Yerokhin *et al.* [4]
One-photon exchange	368.83	Yerokhin *et al.* [4]
First-order self-energy	−55.87	Mohr and Soff [22]
First-order vacuum polarization	12.94	Persson *et al.* [23]
Two-photon exchange	−13.37	This work
Three- and more photon exchange	0.14(7)	This work
Two-electron self-energy	1.52	Yerokhin *et al.* [4]
Two-electron vacuum polarization	−0.36	Artemyev *et al.* [3]
Nuclear recoil	−0.07	Artemyev *et al.* [24]
Nuclear polarization	0.03(1)	Plunien *et al.* [25] Nefiodov *et al.* [26]
One-electron second-order QED	±0.20	Not yet calculated
Total theory	280.44(20)	
Experiment	280.59(9)	Schweppe *et al.* [1]

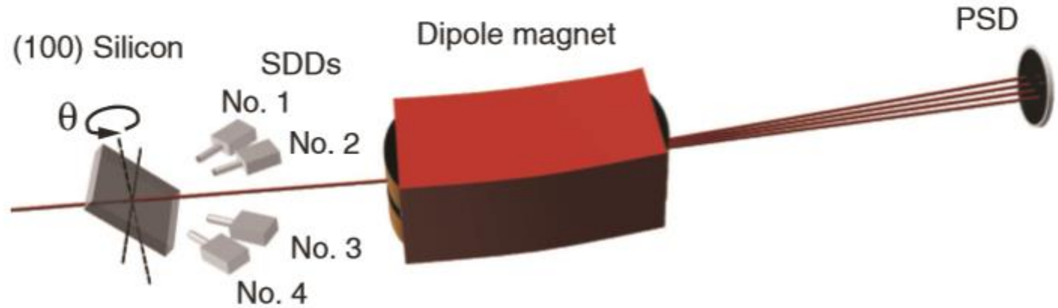




V. Yerokhin *et al*, PRL **85**, 04699 (2000)

Lithium-like ions: $2\ ^2S_{1/2} - 2\ ^2P_{3/2}$





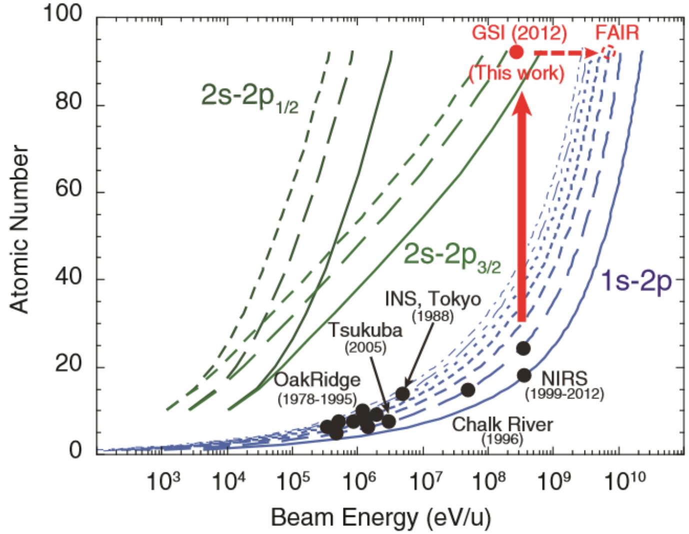


FIG. 1. (Color) Relationship between beam energy and atomic number required to observe the RCE process. The lines are calculated for the $1s$-$2p$ transition in H-like ions, and the $2s$-$2p_{1/2}$ and $2s$-$2p_{3/2}$ transitions in Li-like ions. The dots show experimental data reported to date.

The $2\ ^2S_{1/2} - 2\ ^2P_{3/2}$ transition in high-Z ions is in the keV range that is inaccessible with conventional lasers. Recently, the excitation of the $2\ ^2P_{3/2}$ state of uranium U^{89+} ions was observed through a resonant coherent excitation (RCE) process, in which U^{89+} ions move in the periodic field of a crystal.

$$E = 4460.9 \pm 0.1\ \pm 2.2\ \text{eV}$$

Y. Nakano *et al*, PRA **87**, 060501(R) (2013)

Boron-like ions

$1s^2\ 2s^2\ 2p_{3/2}$

$1s^2\ 2s^2\ 2p_{1/2}$

The $^2P_{1/2} - {}^2P_{3/2}$ transition provides a perfect testing ground for the relativistic and QED effects in few-electron systems. The relativistic and QED corrections are not masked in this case by the (often overwhelming) non-relativistic contributions.

TABLE IV. Individual contributions to the $2p_{3/2}$-$2p_{1/2}$ transition energy in boronlike ions. Results (in eV) are shown for four selected ions and four screening potentials as described in Sec. III A. See text for details.

Ion		V_{CH}	V_{DF}	V_{PZ}	V_{SI}
Cl^{12+}	E_{Dirac}	2.3276	2.4226	2.3805	2.5460
	E^1_{Breit}	−0.1011	−0.2099	−0.1560	−0.3531
	E^2_{Breit}	−0.1410	−0.1188	−0.1082	−0.0952
	$E^{\geqslant 3}_{Breit}$	0.0686	0.0603	0.0378	0.0563
	E^1_{QED}	0.0052	0.0053	0.0053	0.0057
	E^2_{QED}	0.0003	−0.0000	0.0001	−0.0004
	E^{2l}_{QED}	−0.0000	−0.0000	−0.0000	−0.0000
	E_{rec}	−0.0001	−0.0001	−0.0001	−0.0001
	E_{total}	2.1595	2.1593	2.1594	2.1592

A. Artemyev *et al.*, PRA **88**, 032518 (2013)

Boron-like ions

Ion	E_{theo}	Ref. [31]	Experiment	Reference
Cl^{12+}	2.1593(4)	2.1604	2.1583(25)	[32]
Ar^{13+}	2.8091(4)	2.8107	2.8090279(6)	[1]
K^{14+}	3.5976(5)	3.5983	3.5963(31)	[32]
Ca^{15+}	4.5411(5)	4.5417	4.5397(37)	[32]
Sc^{16+}	5.6602(8)	5.6603	5.6583(4)	[33]
Ti^{17+}	6.9756(11)	6.9754	6.9732(4)	[34]
V^{18+}	8.5100(15)	8.5089	8.5061(50)	[32]
Cr^{19+}	10.2867(19)	10.285	10.2815(17)	[34]
Mn^{20+}	12.3308(23)	12.327	12.3100(12)	[32]
Fe^{21+}	14.6686(27)	14.663	14.6640(35)	[34]
Co^{22+}	17.3278(27)	17.321		
Ni^{23+}	20.3379(27)	20.330	20.3286(68)	[34]
Cu^{24+}	23.7300(28)	23.720	23.7154(93)	[34]
Zn^{25+}	27.5364(30)	27.525		
Ge^{27+}	36.5304(41)	36.513		
Kr^{31+}	61.0920(62)	61.061		
Zr^{35+}	96.6835(84)	96.632		
Mo^{37+}	119.5750(98)	119.511		
Ag^{42+}	195.249(13)	195.145		
Sn^{45+}	255.855(15)	255.722		
Xe^{49+}	358.487(19)	358.303		
Nd^{55+}	570.473(28)	570.197		
Eu^{58+}	708.494(31)	708.168		
Yb^{65+}	1136.590(52)	1136.117		
W^{69+}	1463.342(69)	1462.762		
Au^{74+}	1977.87(12)	1977.134		
Hg^{75+}	2097.13(13)	2096.356		
Bi^{78+}	2492.20(17)	2491.339		
Th^{85+}	3671.44(34)	3670.227		
U^{87+}	4087.59(41)	4086.394		
Fm^{95+}	6214.2(1.0)	6212.580		

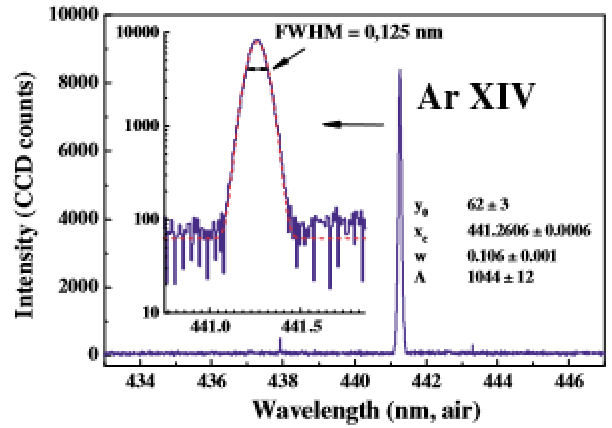


FIG. 1 (color online). A typical spectrum (single exposure) of the Ar XIV forbidden transition. The inset shows in logarithmic scale the data and the results of a Gaussian fit (dashed line).

The $^2P_{1/2}$ – $^2P_{3/2}$ has been experimentally studied at EBIT facilities. But only for low- and medium-Z ions.

Structure and dynamics studies

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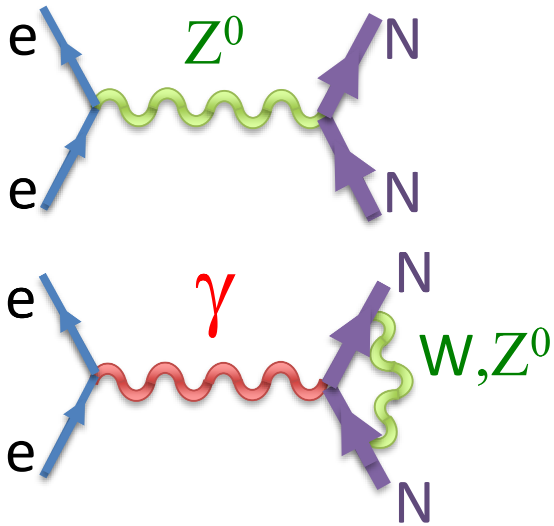
Atomic parity violation studies



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

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

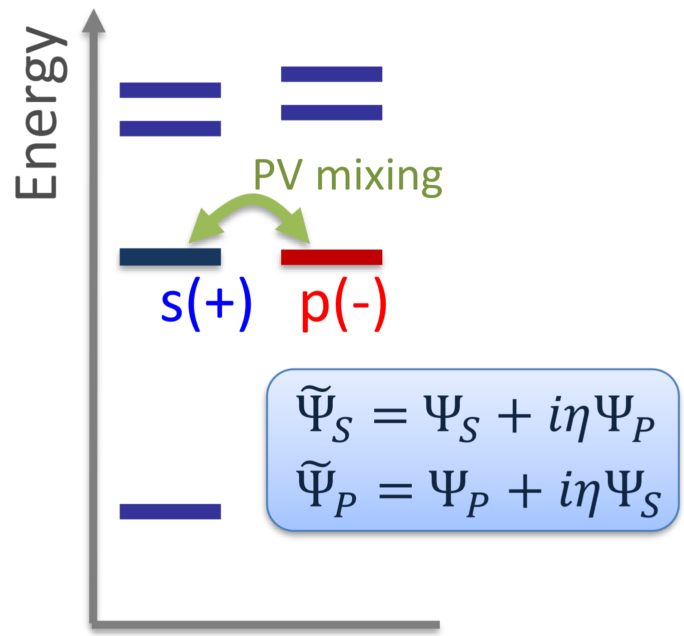
Nuclear spin-independent interaction (NSI)

Nuclear spin-dependent interaction (NSD)

The parity-violating interactions lead to the mixing of atomic levels with opposite parity

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

Energy splitting should be small!



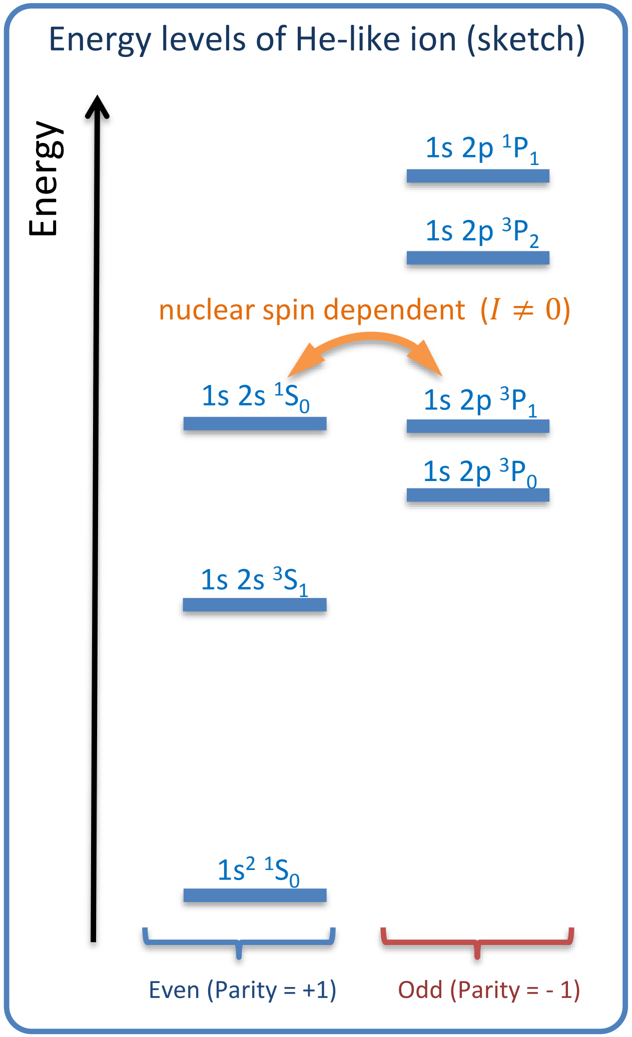
PV experiments with neutral atoms

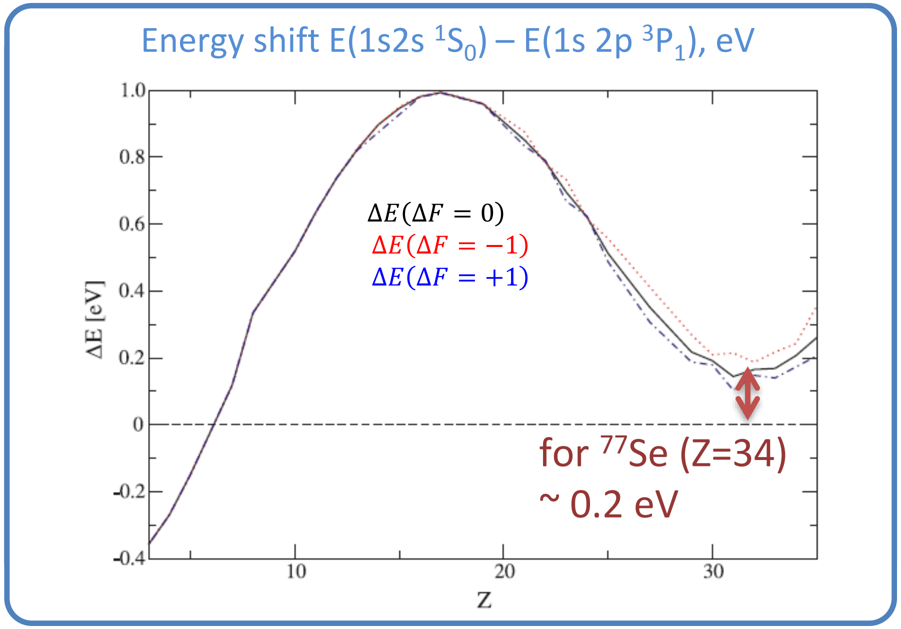
PV experiments with neutral atoms have provided us with valuable information on the weak interaction.

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





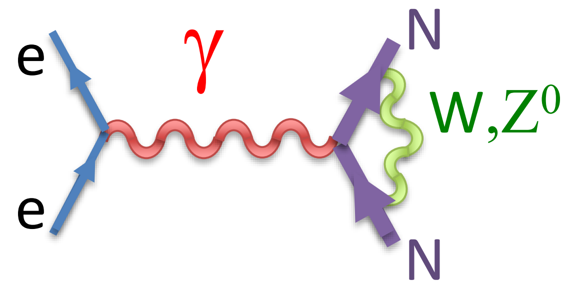
Owing to the (spin-dependent) part of PV Hamiltonian, the 2^1S_0 atomic state in He-like ions with nuclear spin $I \neq 0$ can be described as:

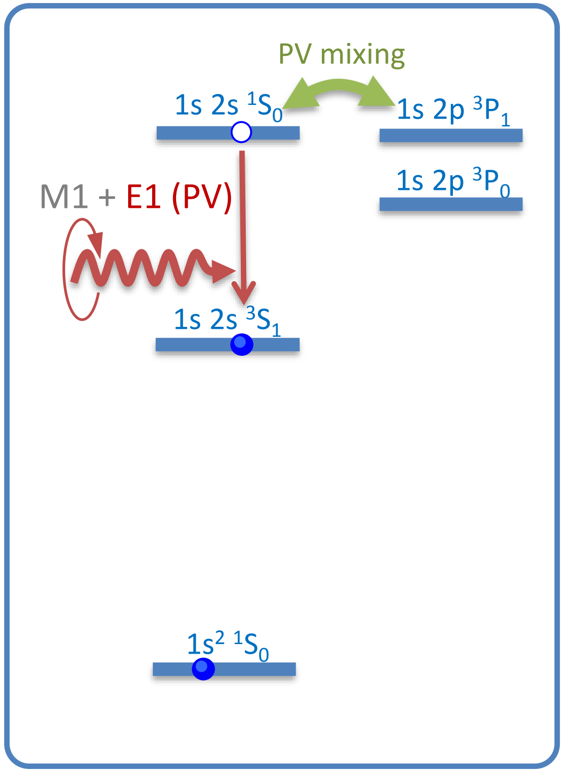
$$|1s\,2s\,^1S_0, F = I\rangle + \mathrm{i}\eta|1s\,2p\,^3P_1, F = I\rangle$$

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 $A \propto 10^{-7}$!

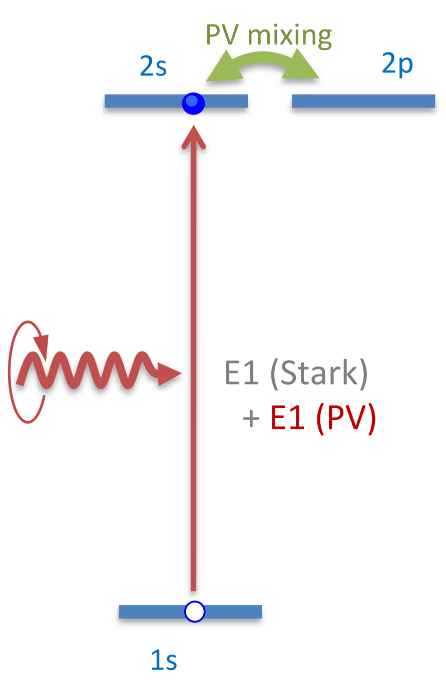
F. Ferro, A. S., and Th. Stöhlker, Phys. Rev. A **83** (2011) 052518

In this and many other scenarious we need to „compete" with spontaneous decay!

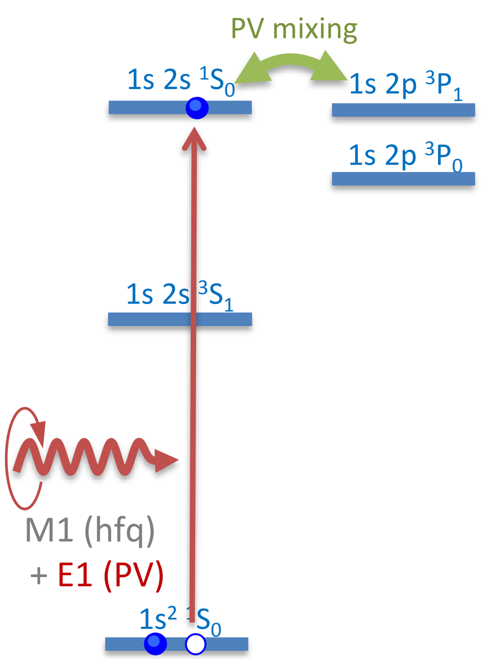
Parity-violation studies at Gamma Factory

At the Gamma Factory we can excite the levels of interest directly from the ground state! It will resolve the problem of short-lived excited states.

H-like ions



He-like ions



M. Zolotorev and D. Budker, Phys. Rev. Lett. **78**, 4717 (1997).

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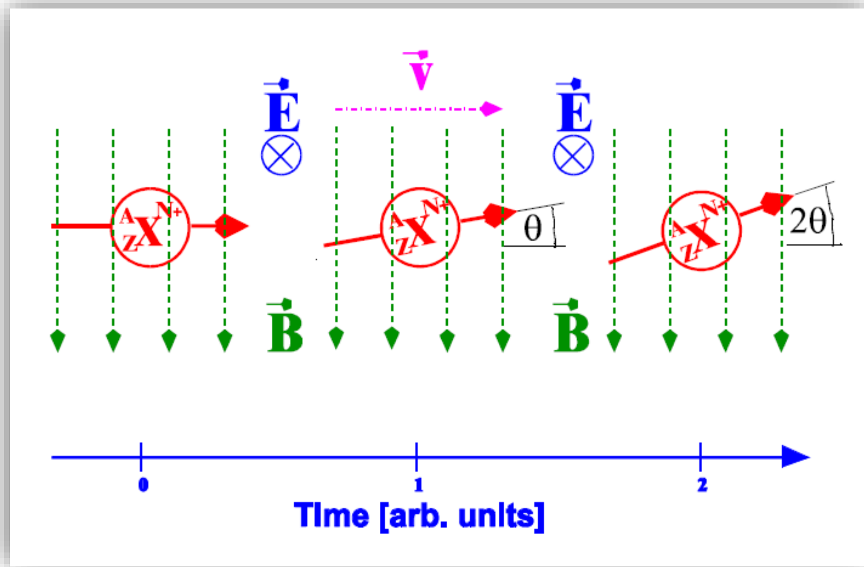
Permanent EDM and CP-violation

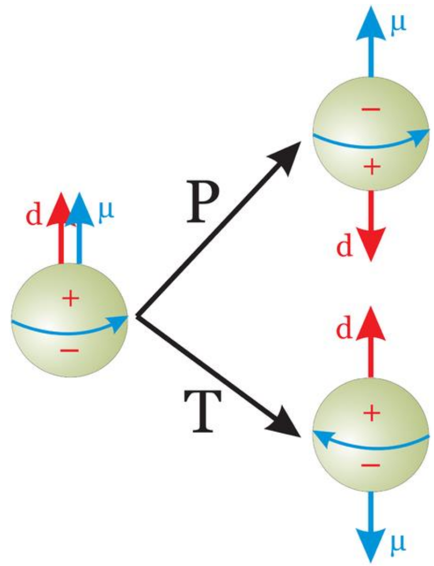
A permanent electric dipole moment of a fundamental particle violates both parity (P) and time reversal symmetry (T).

A number of experiments with multiply-charged ions are proposed to measure EDM of proton and heavier nuclei.

Idea: EDM causes a spin precession in an electric field!



But! We need spin-polarized ions (nuclei)!



Under T-reversal, the spin direction reverses while the EDM direction remains the same, thus a particle that possesses both an EDM and a spin is converted into a different kind of particle, and T-symmetry is violated.

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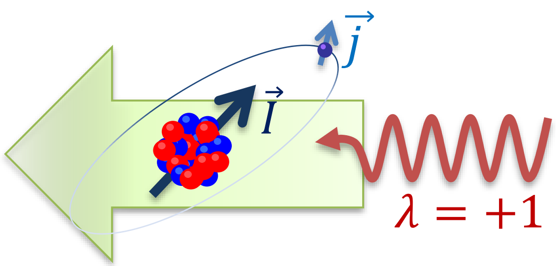
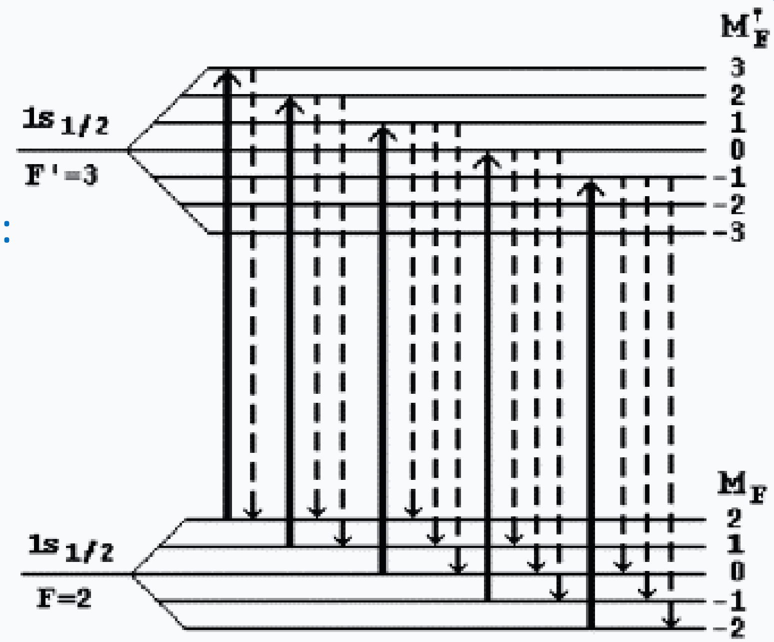
Polarization of highly-charged ions

Theoretical proposal: Optical pumping of hyperfine levels of the hydrogen-like heavy ions with non zero nuclear spin.



Example of Eu^{62+} ion:

- I=5/2, j=1/2
- F=2,3
- $\Delta E \approx 1\ eV$



One has to apply about 40 laser pulses in order to get dominant population of the ground state level $1s_{1/2}\ F = 2$.

A. Prozorov *et al.*, Phys. Lett. B **574** (2003) 180

Polarization of highly-charged ions

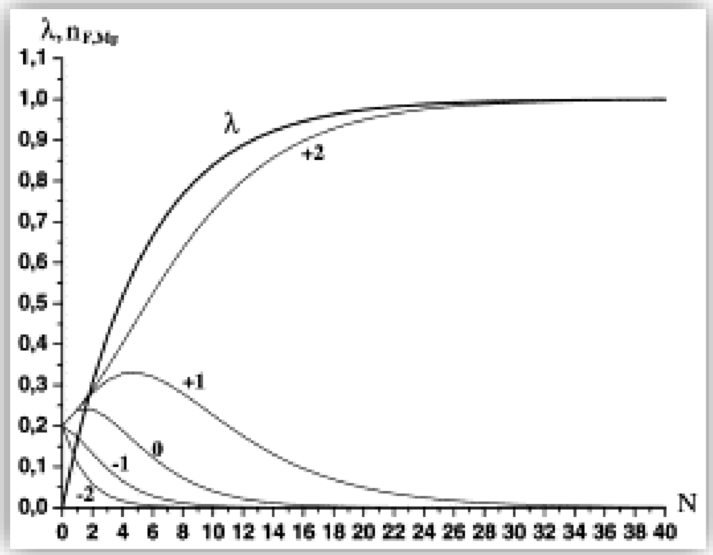
Degree of ion polarization is described by the parameter:

$$\lambda_F = \frac{1}{F} \sum_{M_F} n_{M_F} M_F$$

where n_{M_F} is the sublevel population.

Based on the angular momentum algebra, we can always find the degree of nuclear polarization:

$$\lambda_F = 1 \quad \Rightarrow \quad \lambda_I = \frac{1}{I} \sum_{M_I} n_{M_I} M_I = 0.93$$



Two important problems to be solved:

- How to control (measure) ion polarization?
- Whether polarization is preserved in bending magnets?

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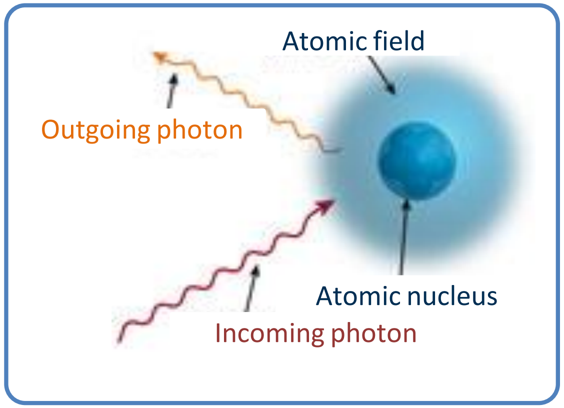
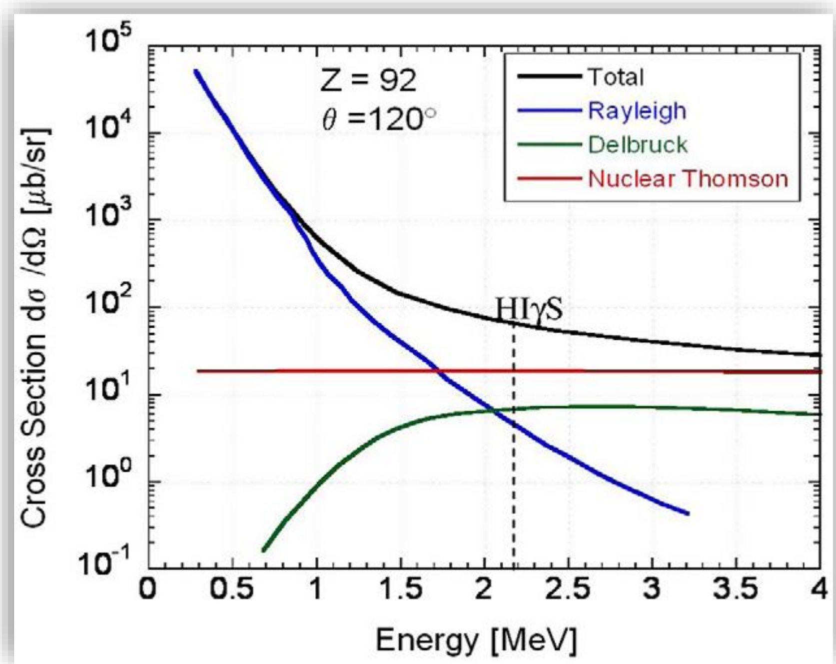
Elastic photon scattering

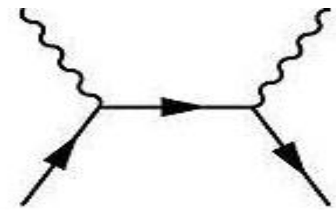
Which processes we refer to when talking about elastic photon scattering?

- Nuclear Thomson scattering (by nucleus)
- **Rayleigh scattering (by bound electrons)**
- **Delbrück scattering (by quantum field)**

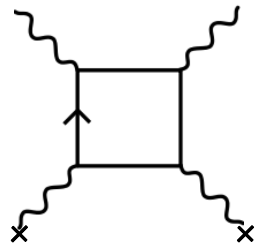




Data from: M.S. Johnson *et al.*, NIMA 285 (2012) 72



Rayleigh scattering



Delbrück scattering

For incident light with energy of few hundreds keV, the elastic $\gamma + A \rightarrow \gamma + A$ process is dominated by the Rayleigh scattering off bound atomic (or ionic) electrons.

PTB
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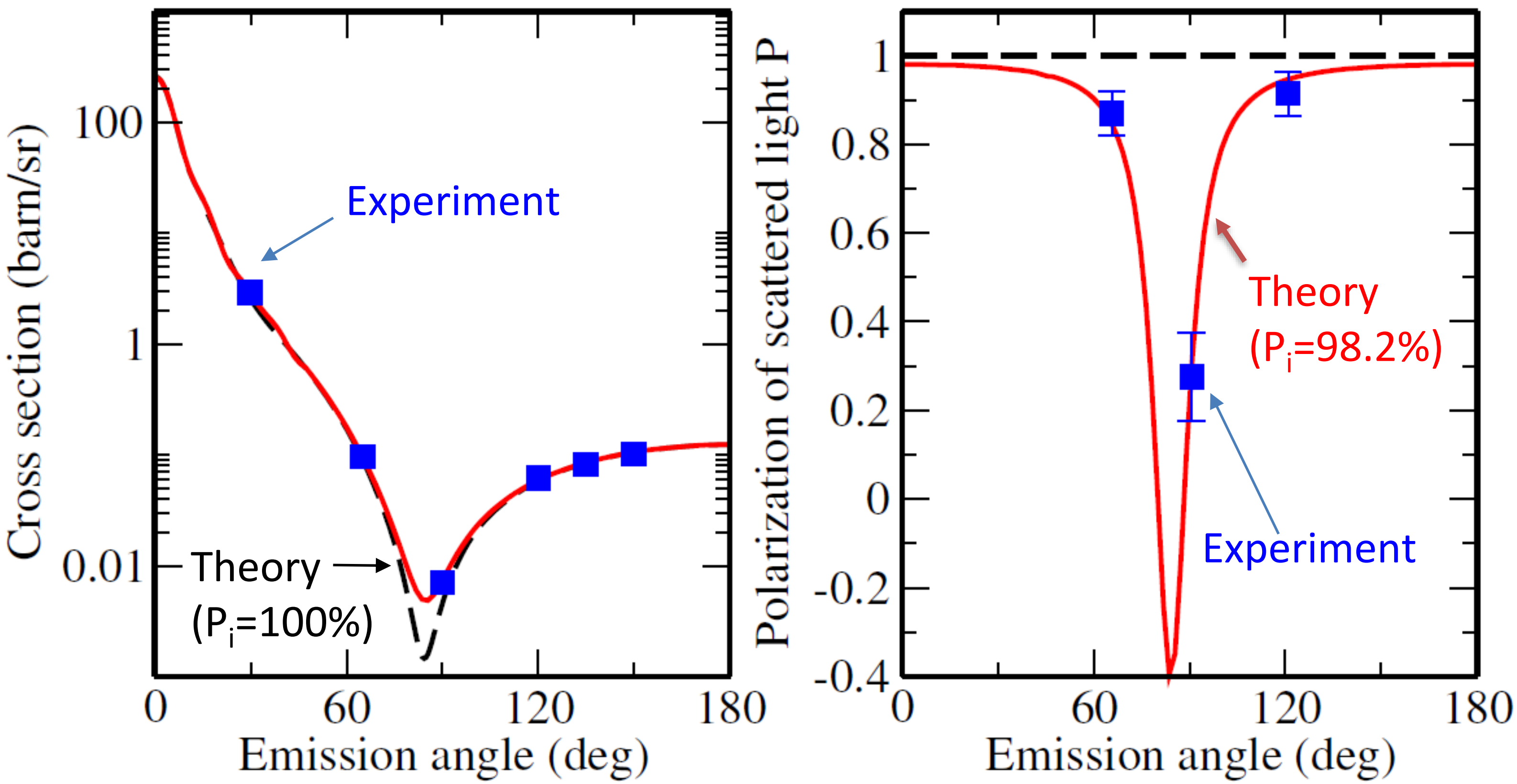
Rayleigh scattering experiment

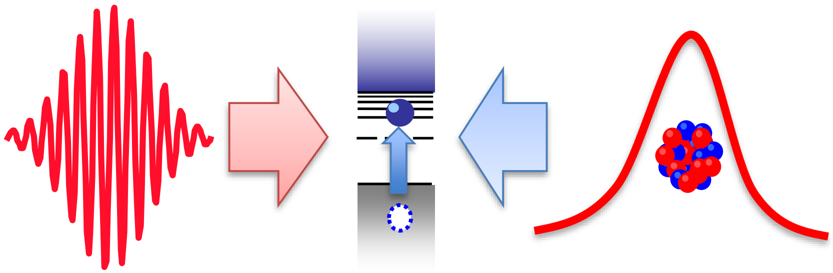
The Rayleigh scattering of 175 keV photons by neutral gold atoms has been measured by the group of Prof. Stöhlker at the PETRA III facility in DESY.



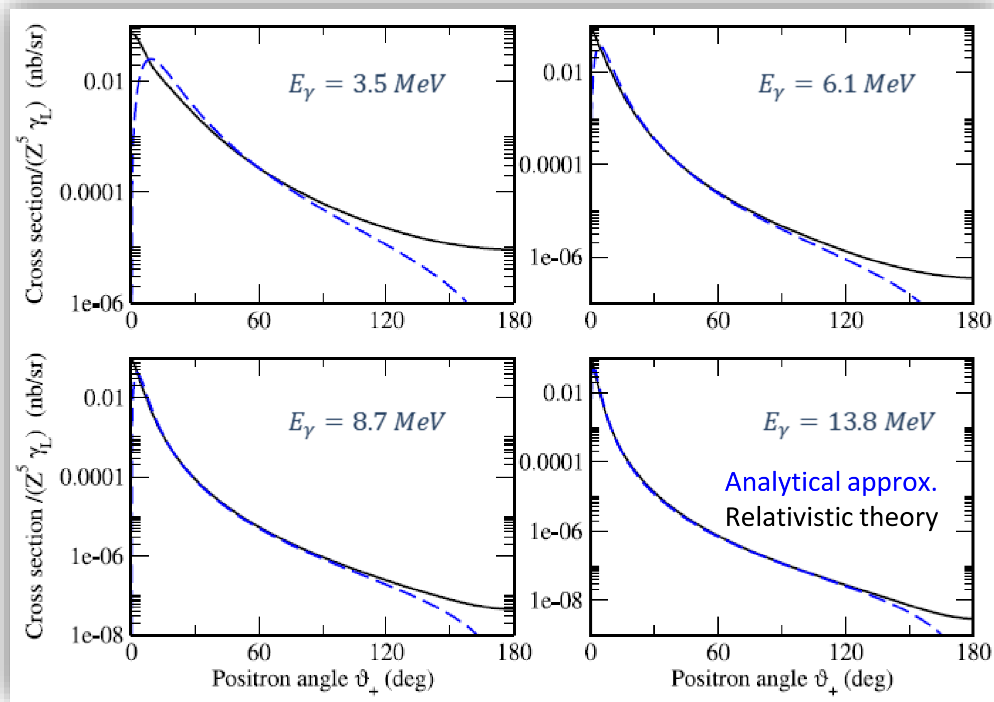
Based on the comparison between experiment and theory we were able to determine polarization of PETRA III beam as 98.24 ± 0.85 %.

K.-H. Blumenhagen *et al.*, New J. Phys. **18** (2016) 103034

Pair production in laser field



$Pb^{82+} + \gamma \rightarrow Pb^{81+}(1s) + e^{+}$



Recent attention is directed toward analysis of angular distributions of emitted positrons.

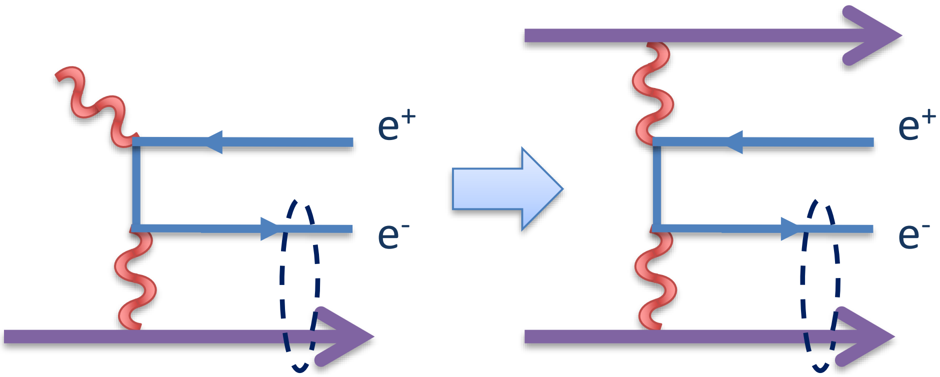
$$\frac{d\sigma_{\gamma Z}}{d\Omega_+} = \frac{4\pi^2\alpha}{k_0} \left| \int \psi_b^*(\boldsymbol{r})\, \boldsymbol{\alpha}\, \boldsymbol{\epsilon}\, e^{i\boldsymbol{k}\boldsymbol{r}}\, \psi_f(\boldsymbol{r}) d\boldsymbol{r} \right|^2 \lambda_C^2$$

Expansion in the parameter αZ for $E_+ \gg mc^2$

$$\frac{d\sigma_{\gamma Z}^{SA}}{d\Omega_+} = \frac{Z^5\alpha^6}{m^2} \frac{v_+ \sin^2\vartheta_+}{(\gamma_L+1)^4(1-v_+\cos\vartheta_+)^4} \times \left[v_+^2(\gamma_L+2)(1-v_+\cos\vartheta_+) - 2\frac{\gamma_L-1}{\gamma_L^3} \right]$$

A. Artemyev, U. Jenschura, V. Serbo, and A. Surzhykov,
Eur. Phys. J. C **72**, 1935 (2012)

Pair production in ion-atom collisions



To calculate the cross section of the pair production we need to "count" number of virtual photons:

$$d\sigma_{ZZ} = dn_T\, d\sigma^T_{\gamma Z} + dn_L\, d\sigma^L_{\gamma Z}$$

Numbers of transversal (T) and longitudinal (L) virtual photons

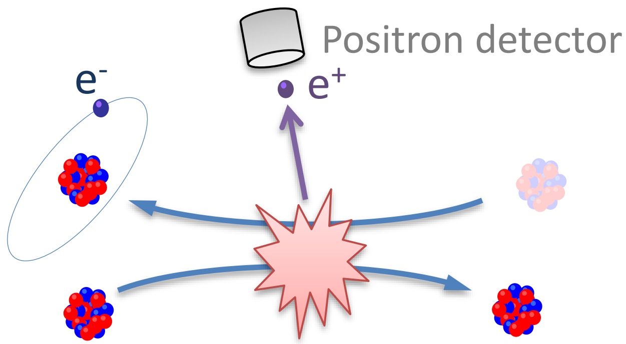
Total cross section: $\sigma_{ZZ} = A \ln\gamma - B$

$A = 5.72\, Z^7\, pb \qquad B = 4.09\, Z^7\, pb$

Angle-differential cross section:

$$\mathrm{d}\sigma^{\mathrm{SA}}_{ZZ} = 16 \frac{(Z\alpha)^7}{m^2} \frac{m}{\omega_L} g\left(\frac{\omega_L R}{\gamma_L}\right) \frac{\mathrm{d}\omega_L}{\omega_L} \frac{m^2 \mathrm{d}p_{+\perp}}{(p_{+\perp})^3}$$

$$g(x) = \int_{x^2}^{\infty} \frac{dy}{y}\left(1 - \frac{x^2}{y}\right) F^2(y/R^2)$$



For the typical LHC (ALICE) parameters: Pb-Pb collisions at $\gamma = 1500$, luminosity $\mathcal{L} = 10^{27}\, \frac{1}{s\ cm^2}$, positron rapidity $y = 1$ and transverse momentum $p_\perp = 1$ GeV/c² observation of positrons unfeasible: 1 event in 67 days.

Structure and dynamics studies

The studies of the structure and dynamics of highly-charged ions are currently under intense studies both in theory and experiment (EBIT & storage rings). What Gamma Factory can offer to this field?

Electronic structure: relativistic, QED, many-body effects

- Spectroscopy of Li- and B-like heavy ions

P- and CP-violation studies

- Atomic parity violation in H- and He-like ions
- Polarized ions beams and search for EDM

Relativistic collisions

- Elastic scattering of x-rays by ions
- Pair production in laser field and ion-atom collisions

And many more ideas!

Outlook: Further studies with HCIs at GF

- Extracting neutron skin from the measurement of parity violation in iso-nuclear sequence of highly-charged ions

- Control of nuclear transitions

- Production of twisted (vortex) gamma-rays by means of back Compton scattering

- Search for exotic spin-dependent interactions