Overview of Atomic Physics at the Gamma Factory

Andrey Surzhykov

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Technische Universität Braunschweig

Many thanks to colleagues

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FEATURE ARTICLE

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Atomic Physics Studies at the Gamma Factory at CERN

Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, and Max Zolotorev*

The Gamma Factory initiative proposes to develop novel research tools at CERN by producing, accelerating, and storing highly relativistic, partially stripped ion beams in the SPS and LHC storage rings. By exciting the electronic degrees of freedom of the stored ions with lasers, high-energy narrow-band photon beams will be produced by properly collimating the secondary radiation that is peaked in the direction of ions' propagation. Their intensities, up to 10^{17} photons per second, will be several orders of magnitude higher than those of the presently operating light sources in the particularly interesting γ–ray energy domain reaching up to 400 MeV. This article reviews opportunities that may be afforded by utilizing the primary beams for spectroscopy of partially stripped ions circulating in the storage ring, as well as the atomic-physics opportunities made possible by the use of the secondary high-energy photon beams. The Gamma Factory will enable ground-breaking experiments in spectroscopy and novel ways of testing fundamental symmetries of nature.

1. Introduction

The Gamma Factory (GF) is an ambitious proposal, currently explored within the CERN Physics Beyond Colliders program.[1] The proposal aims at developing a source of narrow-band photons with energies up to ≈ 400 MeV, with photon fluxes up to ≈ 10^{17} photons per second, exceeding those of the currently available γ–ray sources (**Table 1**) by many orders of magnitude. In this paper, we briefly survey some of the new opportunities that may be afforded by the GF in atomic physics and related fields.

The GF is based on circulating partially stripped ions (PSI), that is, nuclei with a few bound electrons rather than bare nuclei, in a high-energy storage ring. The electrons intrinsic to the PSI open new experimental possibilities for

As well as on the discussions/idea exchange with Julian Berengut, Stephan Fritzsche, Adriana Palffy, Vladimir Shabaev, Valery Serbo, Thomas Stöhlker, Andrey Volotka, and on the experience gained by SPARC (GSI) collaboration

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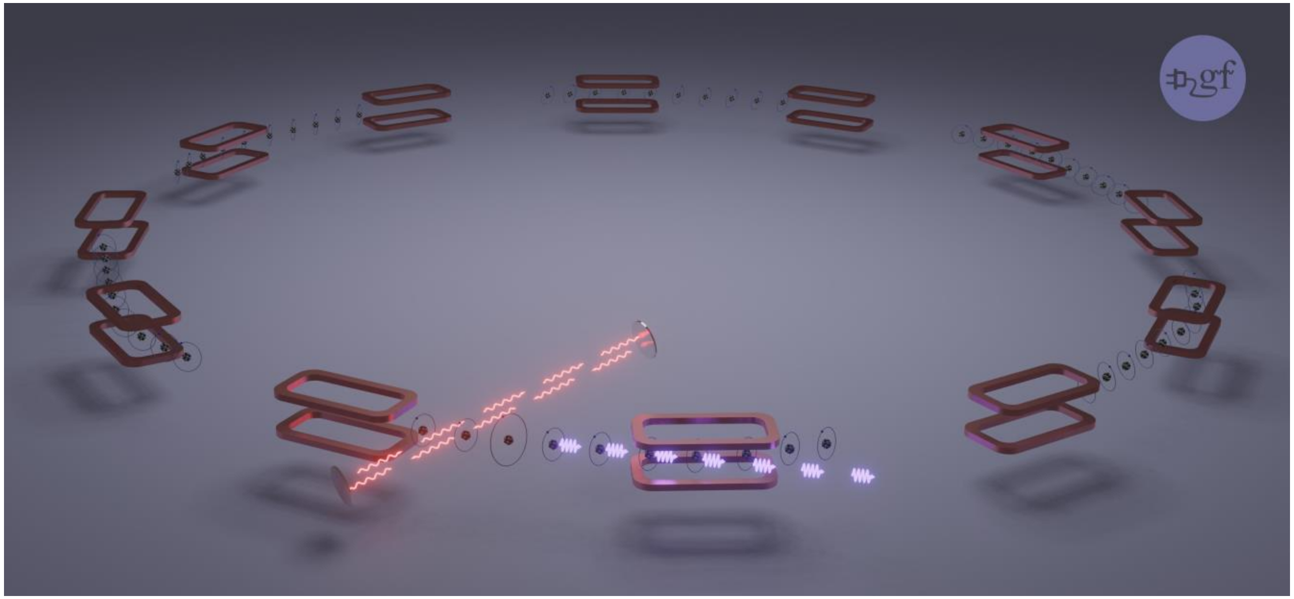
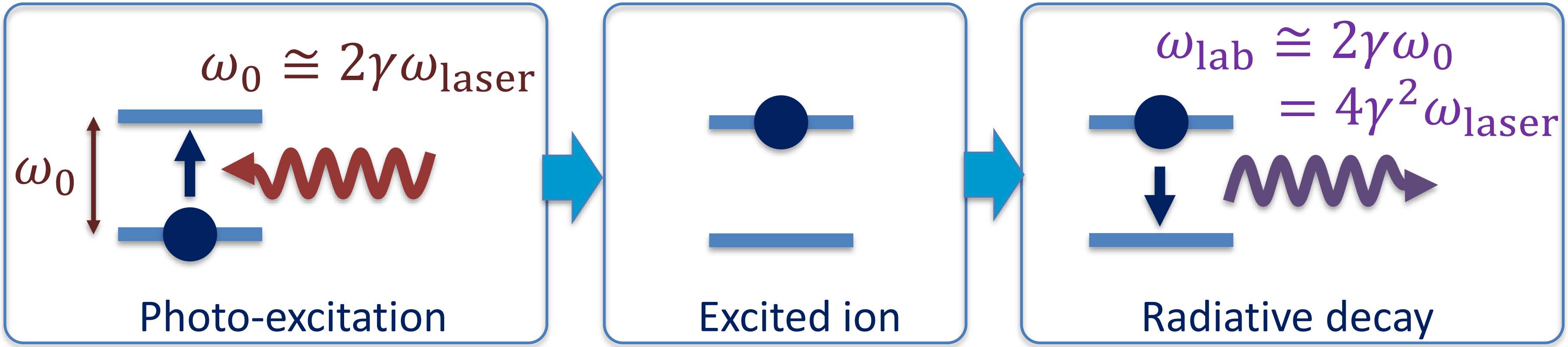
Gamma Factory: Basic scheme



Picture: Alexey Petrenko

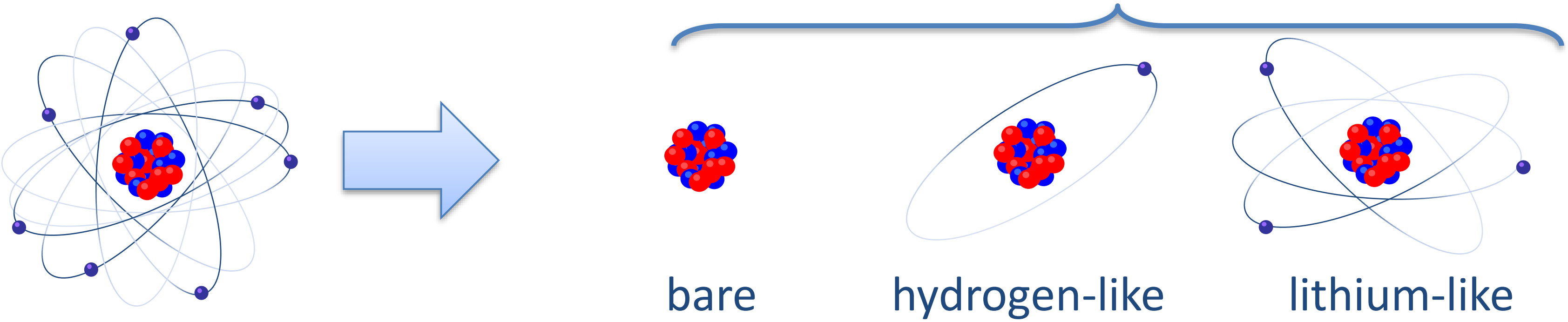
Atomic physics at Gamma Factory



We focus today on the "first step" of the GF operation: absorption of primary- and emission of secondary photons. Why this *absorption-and-emission* is important for atomic physics studies?

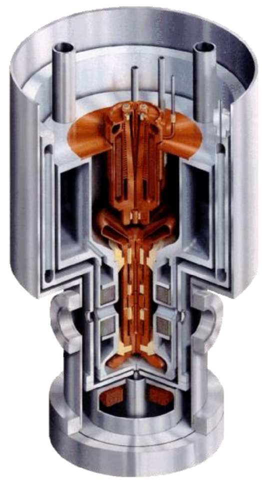
- Spectroscopy of partially stripped ions
- Atomic parity violation studies and EDM search
- Production of spin-polarized ion beams
- Resonant photon scattering

Highly-charged ions = Partially stripped ions



bare hydrogen-like lithium-like

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



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 partially stripped ions.

Partially stripped ions

What is so special about partially stripped heavy ions?

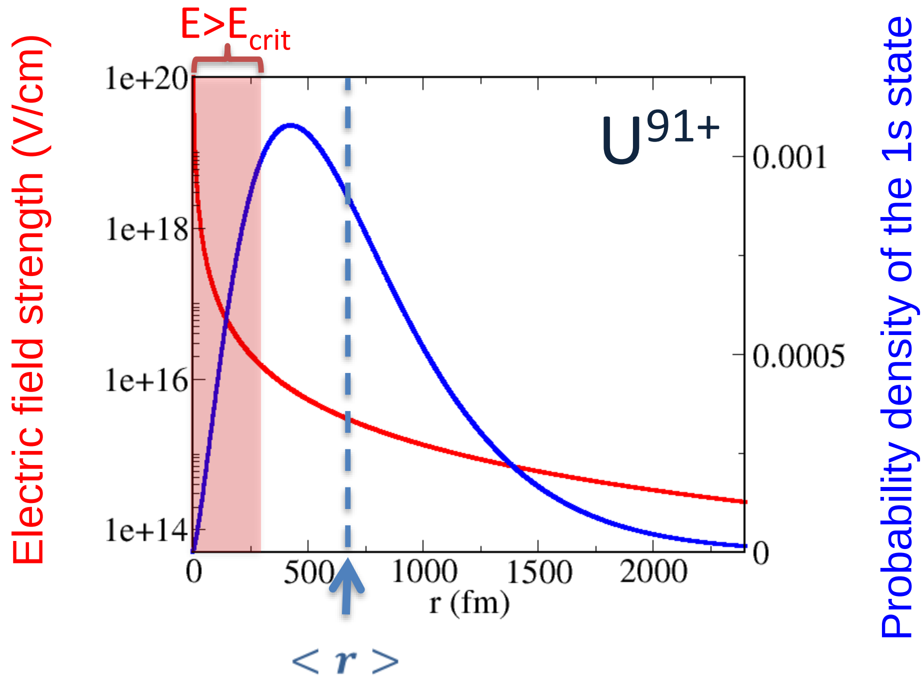
Energies of transitions in PSIs are much higher comparing to those in neutral atoms.

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

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

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

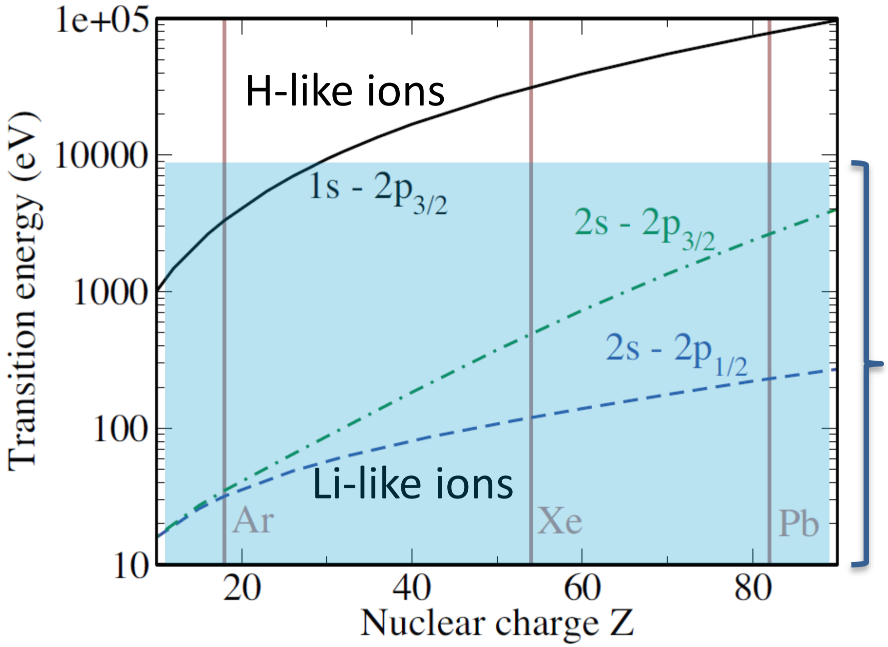
Binding energies are up to 100 keV



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

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

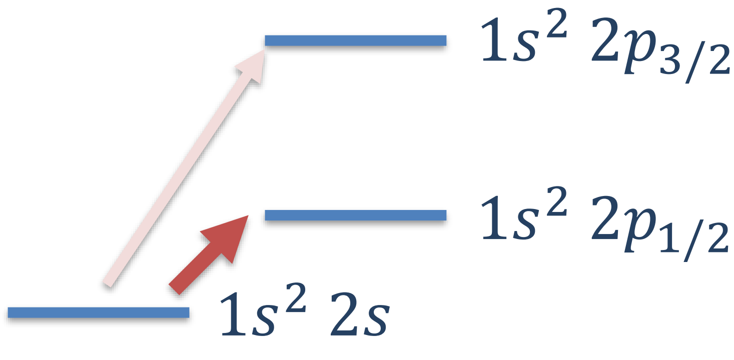
Spectroscopy of heavy partially stripped ions



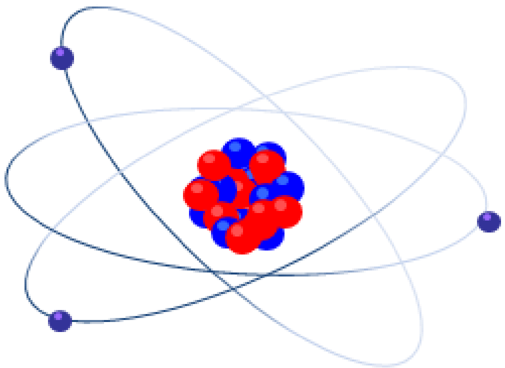
Assuming the ion γ factor up to 2900, the Gamma Factory will allow **direct** photo-excitations with energies up to about $\hbar\omega_0 \cong 8$ keV

Transitions in *all* Li-like ions become available!

Photoexcitation of the ground state into the $1s\ 2p_{1/2}$ excited state of lithium–like Pb^{79+} is proposed as the first proof–of–principle experiment.

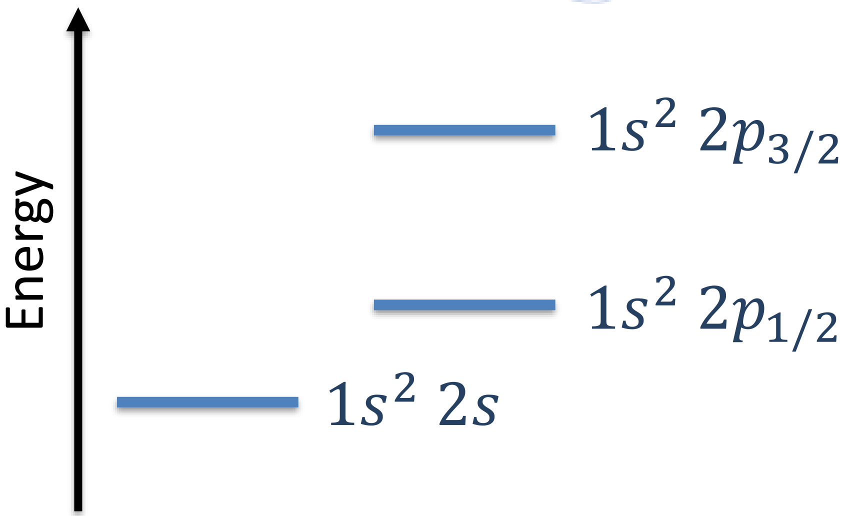


$2s \rightarrow 2p$ transitions in Li-like ions

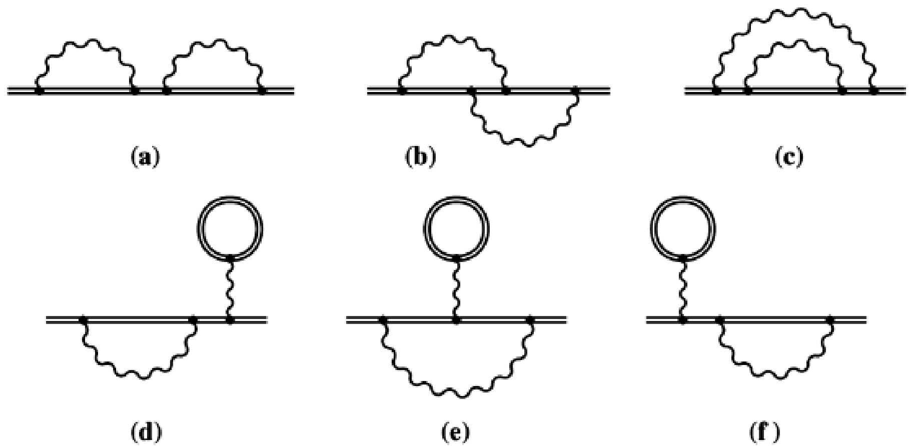


Li-like heavy ions provide a testbed for studying relativistic, many-body, nuclear and QED effects.

For the $2s \rightarrow 2p_{1/2}$ transition, the best accuracy of 0.015 eV was attained for U^{89+} at the LLNL's EBIT.



Such accuracy allows one to probe the two-loop QED effects.



See talk by Vladimir Shabaev (Th, 15:20)

$2s \rightarrow 2p$ transitions in Li-like ions

TABLE III. Various contributions to transition energies in Li-like bismuth and uranium, in eV.

	$2p_{3/2}$-$2s$, $Z = 83$	$2p_{1/2}$-$2s$, $Z = 92$
Dirac value	2792.21(3)	−33.27(9)
One-photon exchange	23.82	368.83
Two-photon exchange	−1.61	−13.37
Three-photon exchange	−0.02(2)	0.15(7)
One-loop QED	−27.48	−42.93
Screened QED	1.15(4)	1.16(3)
Two-loop QED	0.12(4)	0.22(6)
Recoil	−0.07	−0.07
Nuclear polarization		0.04(2)
Total theory	2788.12(7)	280.76(14)
Experiment	2788.14(4) [3]	280.645(15) [5]

Li-like heavy ions provide a testbed for studying relativistic, many-body, nuclear and QED effects.

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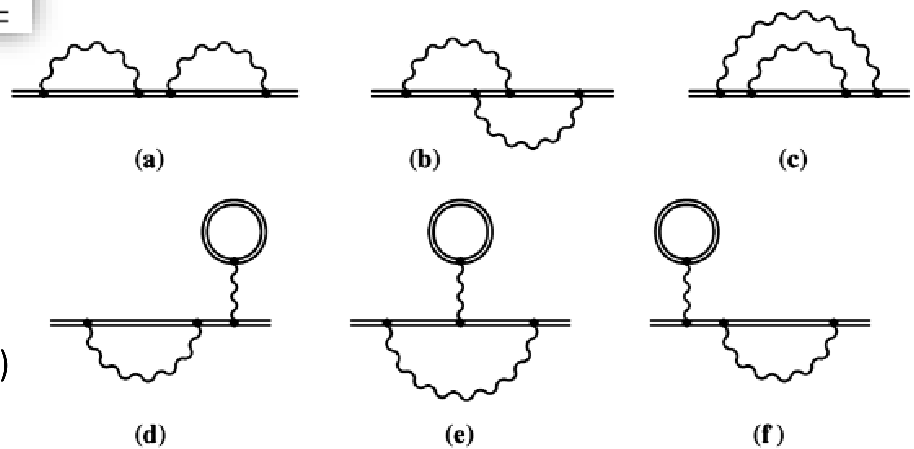
Such accuracy allows one to probe the two-loop QED effects.

Theory (table):
V. A. Yerokhin, P. Indelicato, and V. M. Shabaev, Phys. Rev. Lett. **97**,253004 (2006)



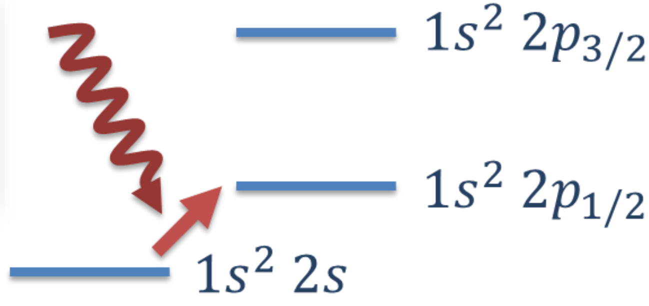
Experiment:

[3] P. Beiersdorfer *et al.*, Phys. Rev. Lett. **80**, 3022 (1998)
[5] P. Beiersdorfer *et al.*, Phys. Rev. Lett. **95**, 233003 (2005)

See talk by Vladimir Shabaev (Th, 15:20)

$2s \rightarrow 2p_{1/2}$ transition in Pb^{79+}

Ion	Transition	Energy [eV]		Reference
Pb^{79+}	$1s^2 2p_{1/2} - 1s^2 2s$	230.823 (47) (4)	theo	[25,97,98]
		230.76 (4)	theo	[23]



A number of theoretical studies have been performed to calculate $2s - 2p_{1/2}$ splitting:

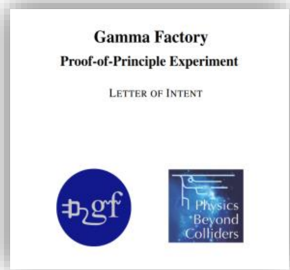
[23] J. Sapirstein, K. T. Cheng, Phys. Rev. A **83**, 012504 (2011)

[25] V. A. Yerokhin, P. Indelicato, V. M. Shabaev, Phys. Rev. Lett. **97**, 253004 (2006)

[97] V. A. Yerokhin, A. Surzhykov, J. Phys. Chem. Ref. Data **47**, 023105 (2018)

[98] Y. S. Kozhedub et al., Phys. Rev. A 81, 042513 (2010)

The PoP GF experiment will be the first observation of the $2s \rightarrow 2p_{1/2}$ transition in Pb^{79+}. Its accuracy is expected to better than one of the theory!



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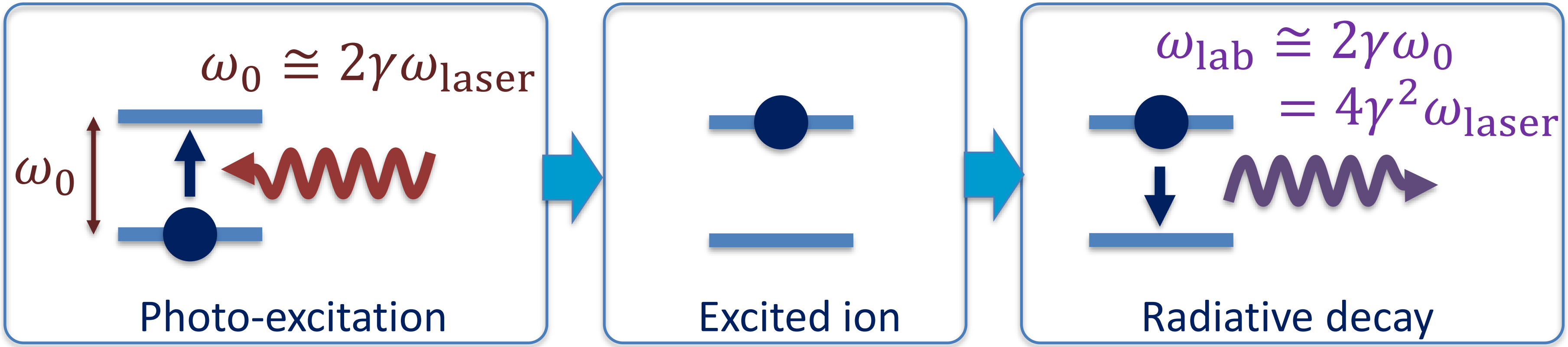
Atomic physics at Gamma Factory



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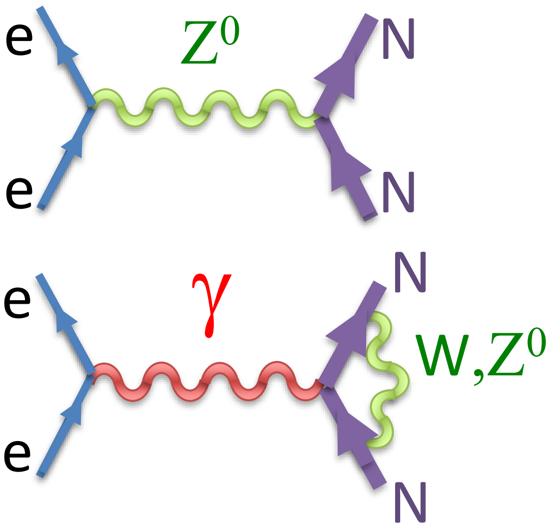
Atomic parity violation studies



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

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

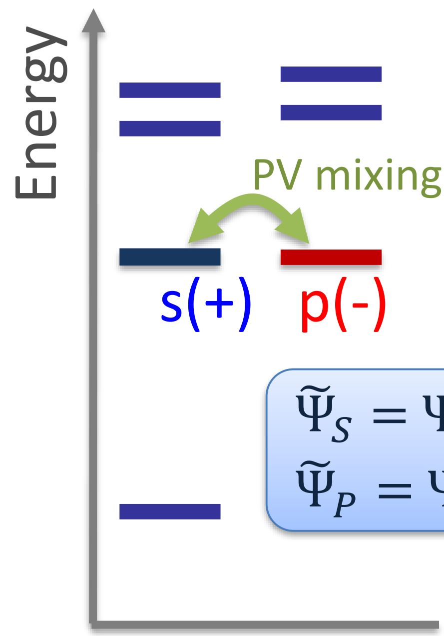
Nuclear spin-independent interaction (NSI)

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!

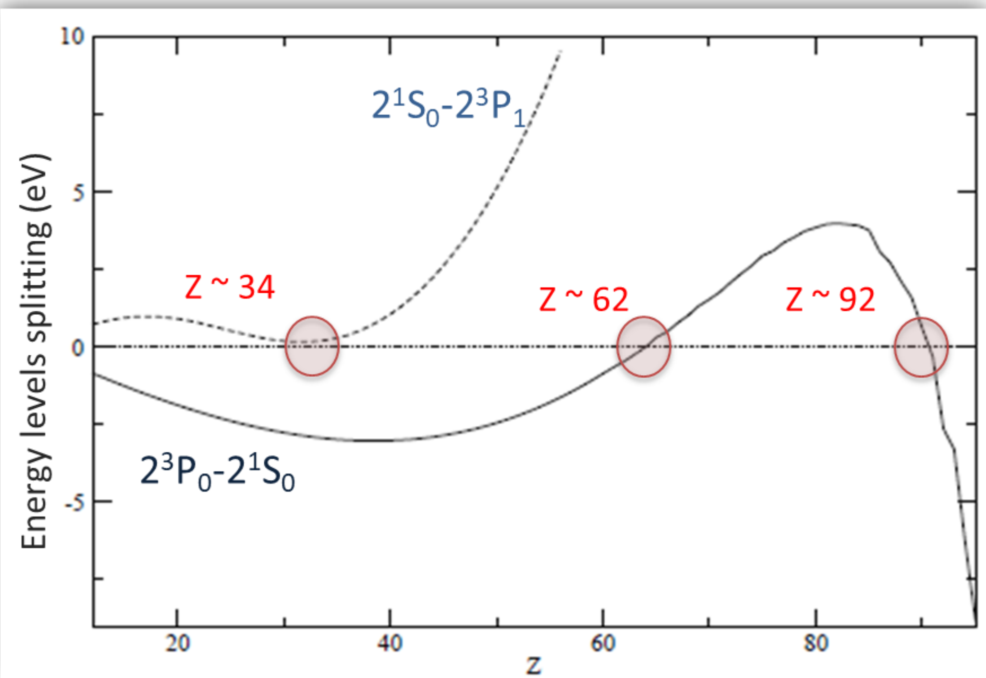


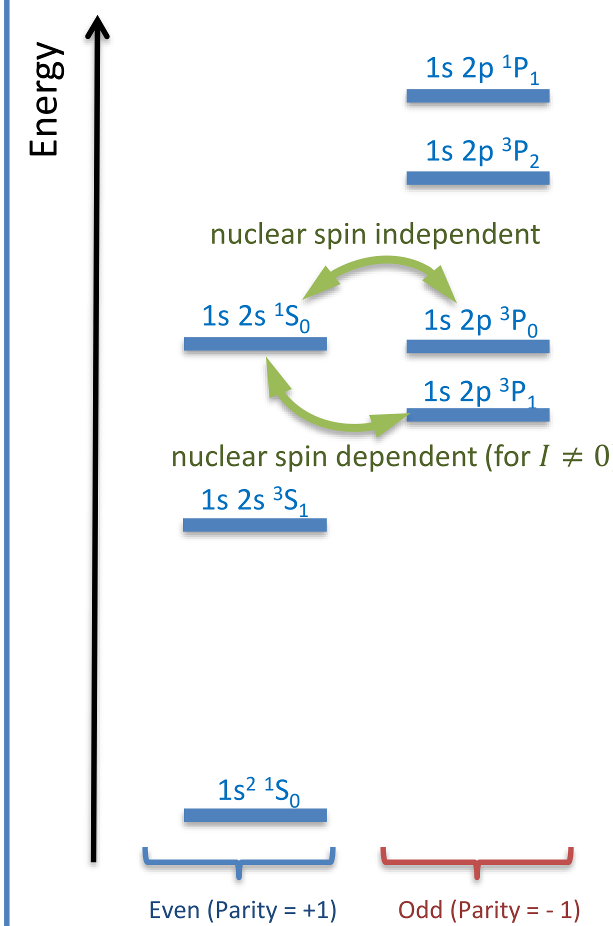
$$\tilde{\Psi}_S = \Psi_S + i\eta\Psi_P$$
$$\tilde{\Psi}_P = \Psi_P + i\eta\Psi_S$$

Parity violation studies with PSI's

Partially stripped ions are considered as very promising candidates for PV studies:

- Relatively simple atomic structure
- Large electron-nucleus overlap
- PV matrix element scales as Z^5
- Degeneracy of ionic levels





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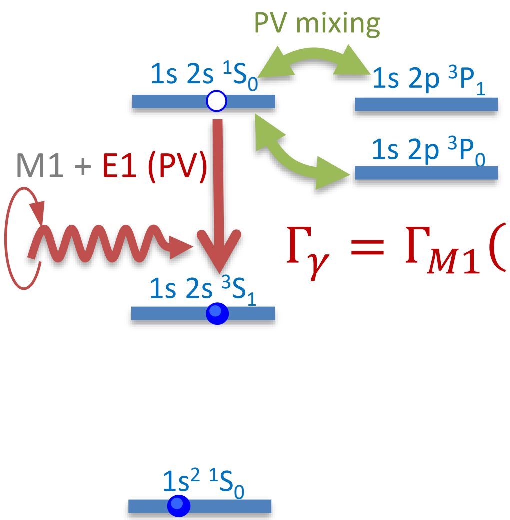
Parity violation studies with PSI's

Various scenarios have been proposed to measure the mixing between 2^1S_0-2^3P_0 and 2^1S_0-2^3P_1 states in helium-like ions.

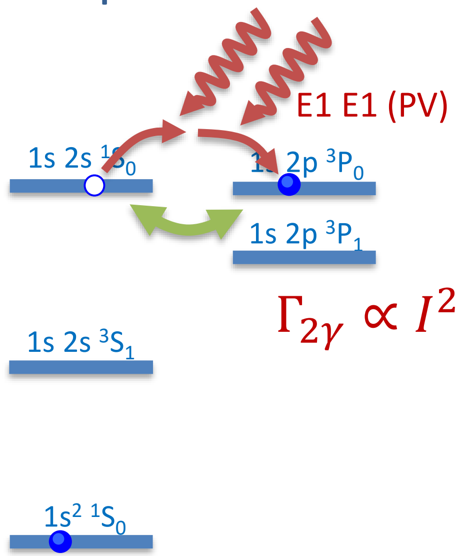
One-photon induced transitions



$$\Gamma_\gamma = \Gamma_{M1}(1 + \lambda\, A_{PV}(\eta))$$

V. M. Shabaev *et al.*, Phys. Rev. A **81** 052102 (2010)
F. Ferro *et al.*, Phys. Rev. A **83** 052518 (2011)

Two-photon induced transitions



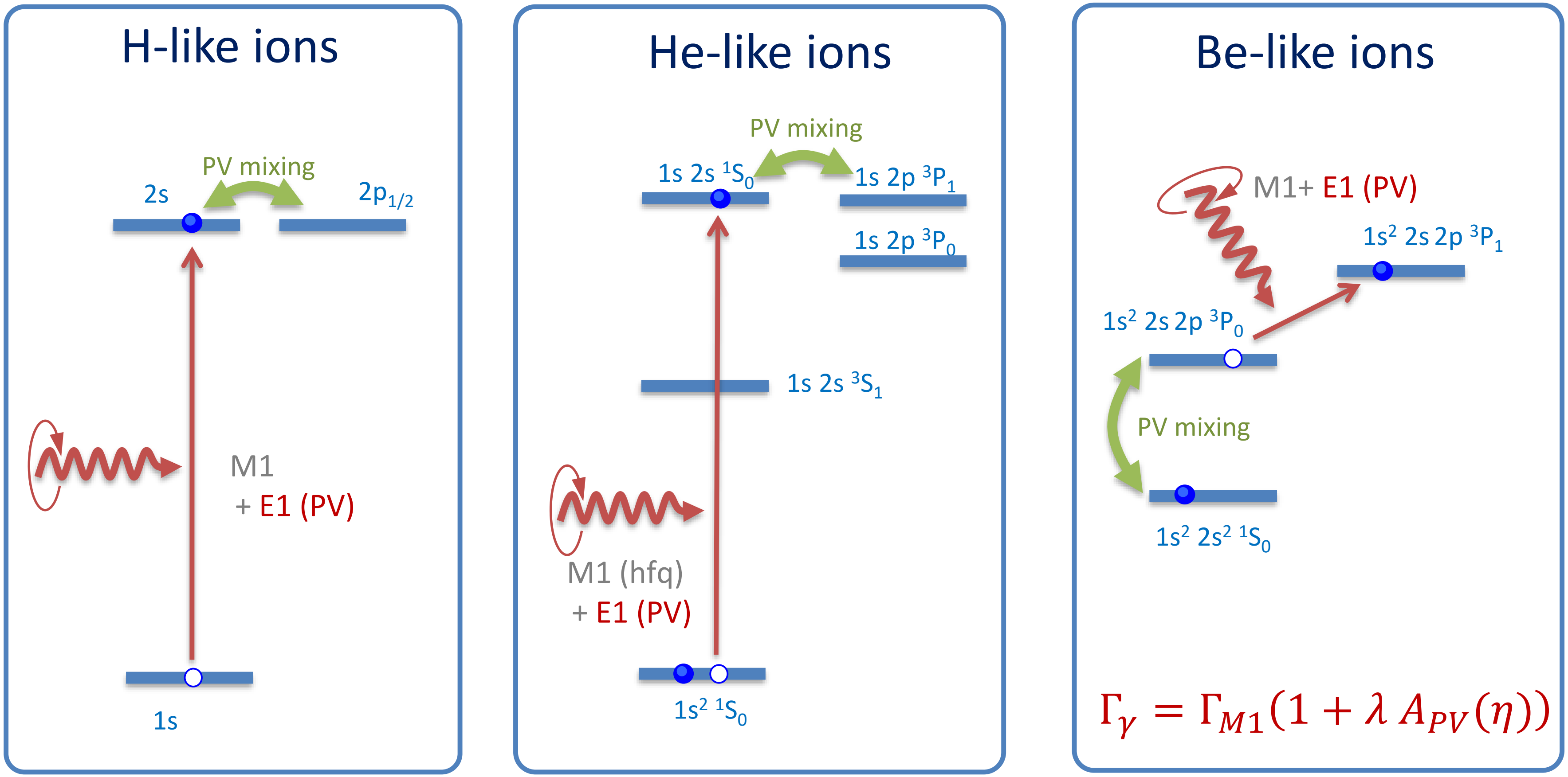
$$\Gamma_{2\gamma} \propto I^2\, \eta^2 (\boldsymbol{\epsilon}_1 \cdot \boldsymbol{\epsilon}_2)^2$$

A. Schafer *et al.*, Phys. Rev. A **40**, 7362 (1989)
A. Surzhykov *et al.*, Phys. Rev. A **84**, 022511 (2011)

Most of these scenarios assume laser-induced transitions from excited states, whose lifetimes are very short.

Parity violation studies at Gamma Factory

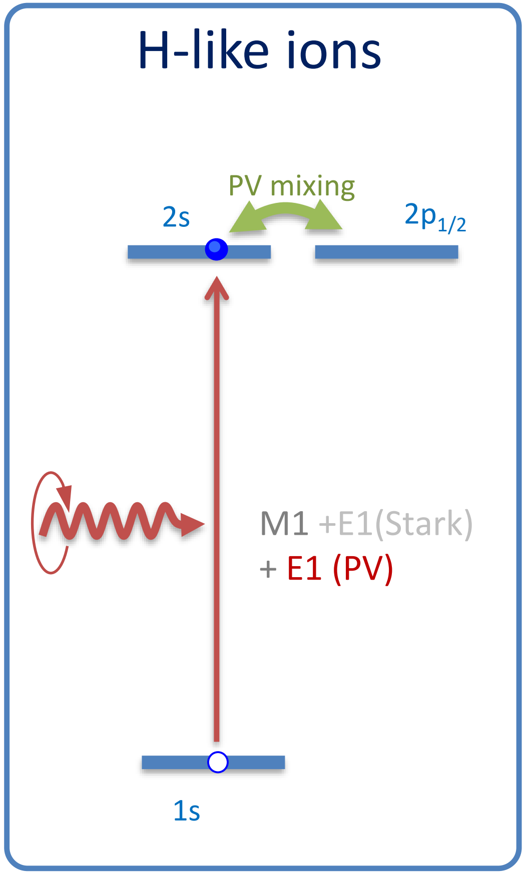
At the Gamma Factory we can excite the levels of interest **directly from the ground state**. It will resolve the problem of short-lived excited states.



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

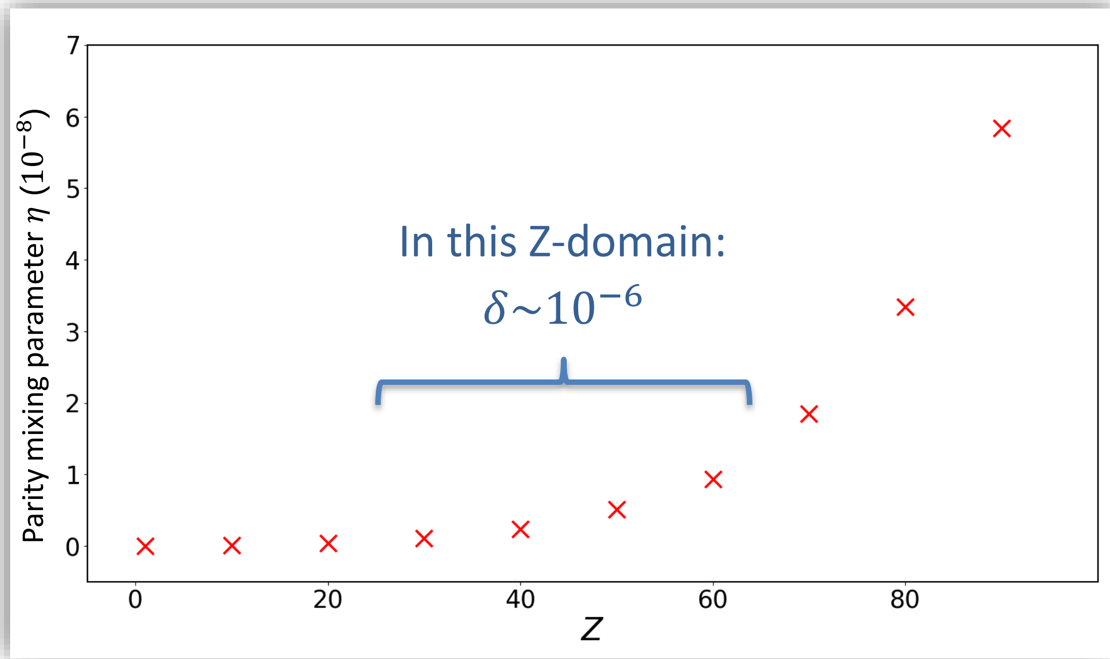
A. Surzhykov *et al.*, Phys. Scr. **T156**, 014027 (2013)

$1s \rightarrow 2s$ transition in H-like ions



One has to measure the photo-excitation rates for left- and right-circularly polarized light and to asymmetry ratio:

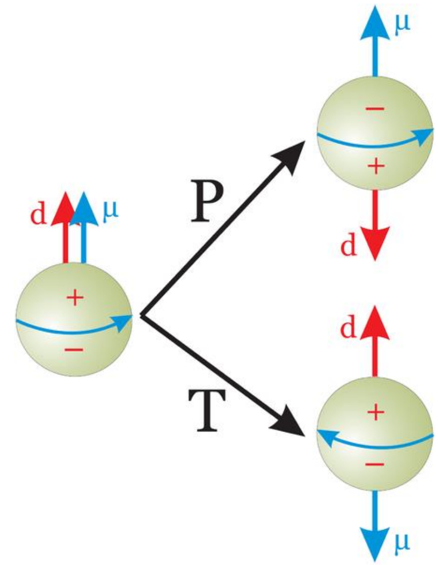
$$\delta = \frac{\Gamma_{+1} - \Gamma_{-1}}{\Gamma_{+1} + \Gamma_{-1}} \cong 2\eta \frac{a_{E1}(2p \rightarrow 1s)}{a_{M1}(2s \rightarrow 1s)}$$

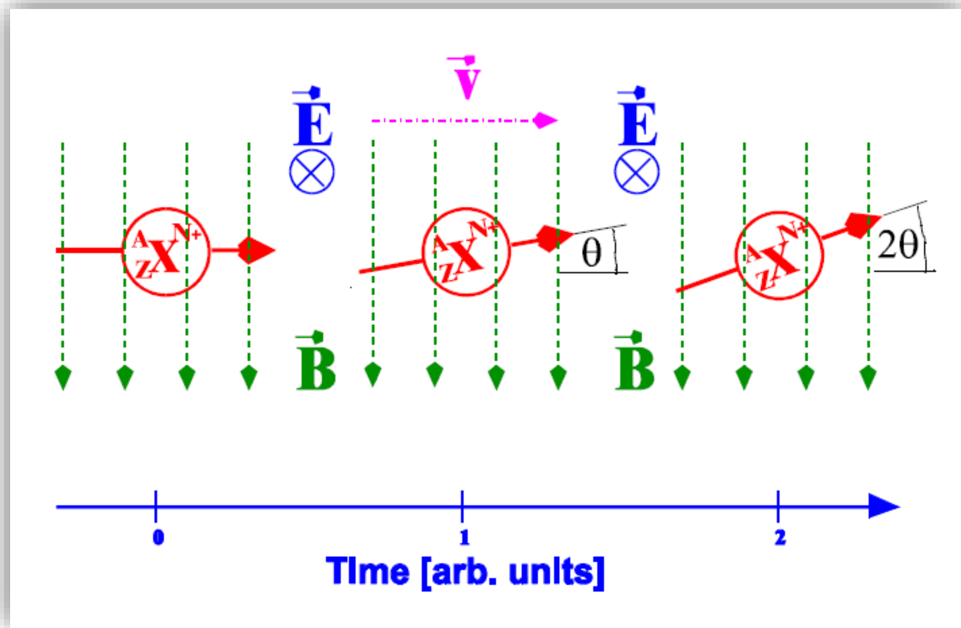


Calculations: Jan Richter (PTB/TU-BS)

Search for a permanent EDM

Several schemes have been recently proposed for the measurements of the electric dipole moment (EDM) of nuclei and electrons in ion storage rings.



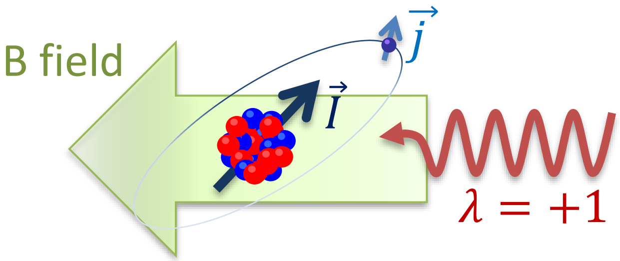


These schemes rely on the spin precession in electric and magnetic fields of a ring.

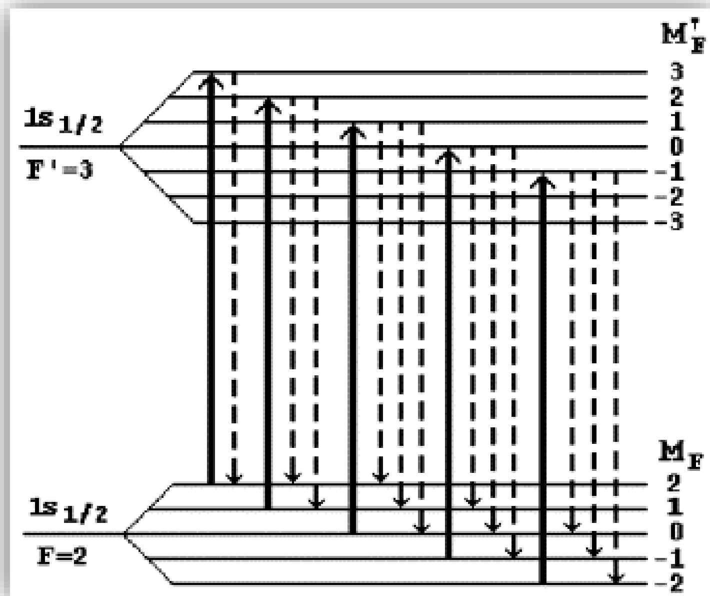
But! This requires the use of polarized ions!

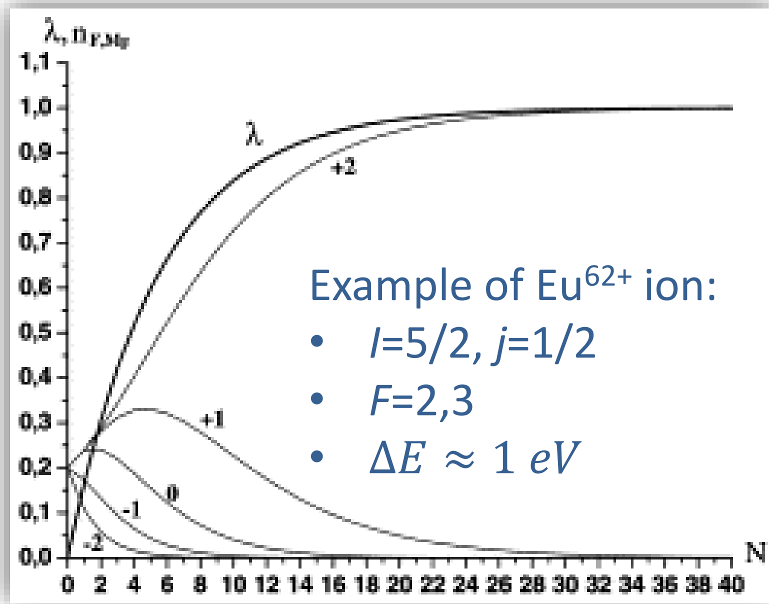
I. B. Khriplovich, Hyperfine Interactions **127**, 365 (2000)
A. Bondarevskaya, A. Prozorov, L. Labzowsky, G. Plunien, D. Liesen, and F. Bosch., Phys. Rep. **507**, 1 (2011)

Optical pumping of hyperfine levels



In the work by Prozorov *et al.* (Phys. Lett. B **574** (2003) 180), the idea of optical pumping of hydrogen-like Eu^{62+} ions has been discussed.





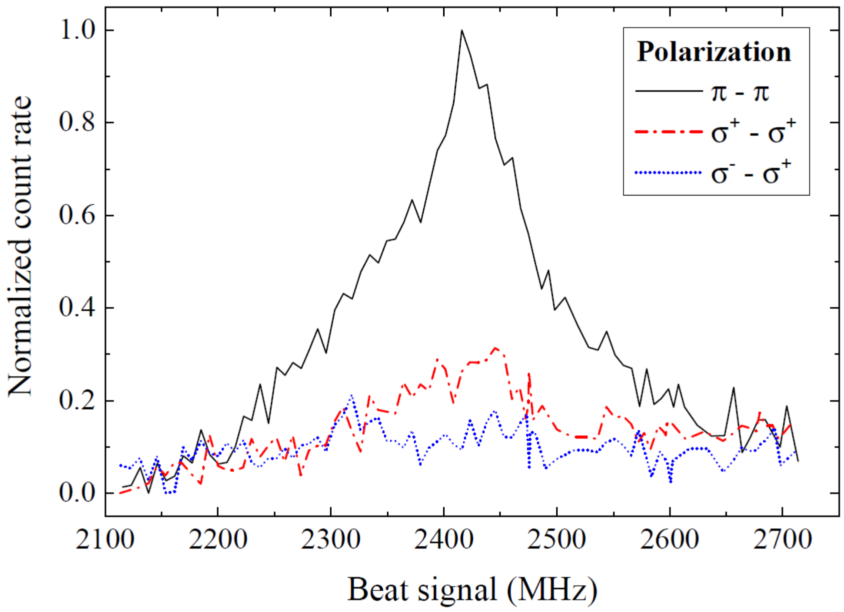
Example of Eu^{62+} ion:

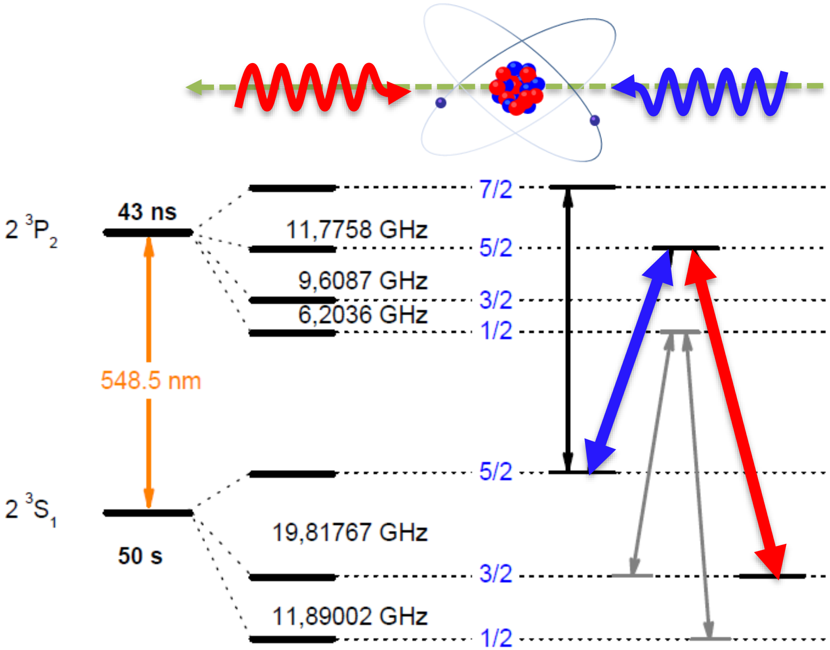
- *I*=5/2, *j*=1/2
- *F*=2,3
- $\Delta E \approx 1\ eV$

By using circularly polarized light, one can produce dominant population of the "dark" levels $1s_{1/2}$: $F = 2\ M_F = \pm 2$. This implies polarization of both nucleus and electron!

Preservation of the ion polarization?

The problem of preservation of polarization of ions in storage rings remains an open and highly debatable issue!

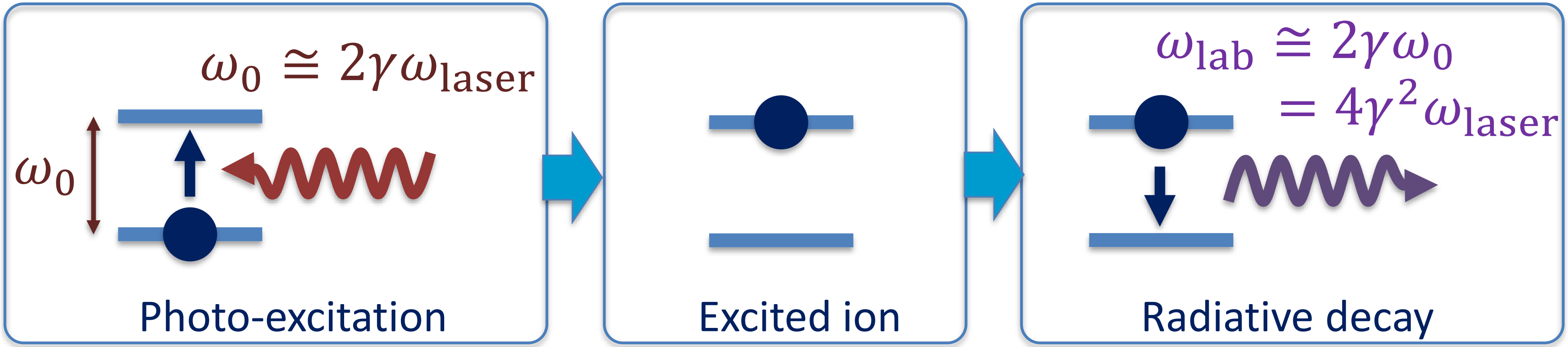




Recent study, performed at the ESR storage ring with Li^+ ions, may be interpreted as a signal: ”yes, ion’s polarization is preserved!”

W. Nörtershäuser et al., arXiv:2011.04435, submitted

Atomic physics at Gamma Factory



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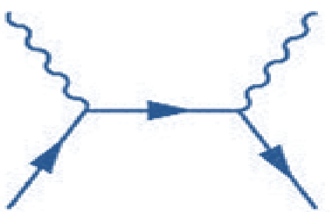
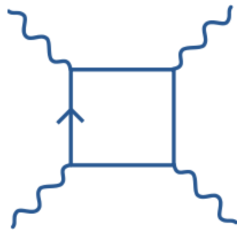
X-ray scattering by partially stripped ions

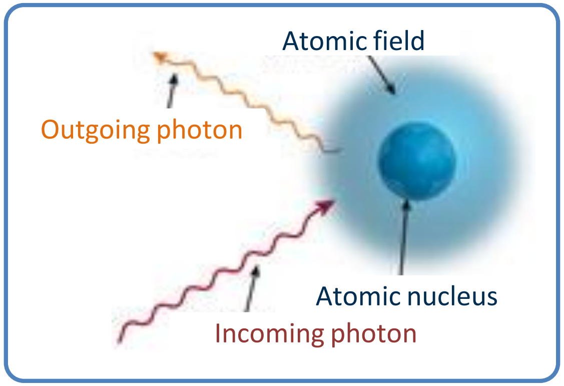
During the last decade, new interest has grown to study elastic scattering of x- and γ-rays by ions.



Rayleigh scattering

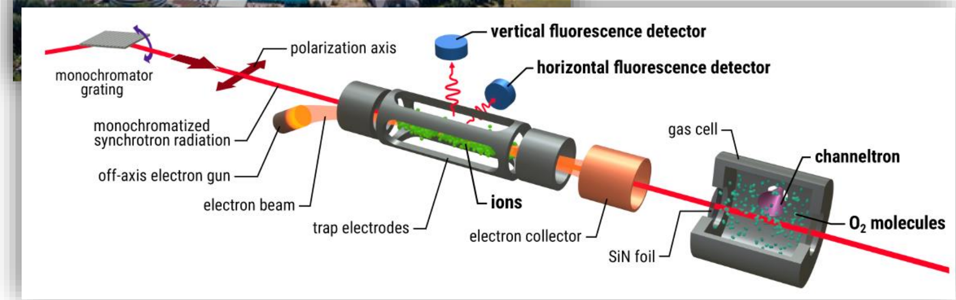


Delbrück scattering



A. Surzhykov *et al.*, J. Phys. B **48**, 144015 (2015)
A. Volotka *et al.*, PRA **93**, 023418 (2016)
D. Samoilenko *et al.*, Atoms **8**, 12 (2020)

Theoretical interest to the photon scattering is caused by recent experiments on non-resonant scattering at PETRA III and resonant scattering studies with EBIT facilities… and by GF plans



K.-H. Blumenhagen *et al.*, New J. Phys. **18**, 103034 (2016)
M. A. Leutenegger *et al.*, arXiv:2003.13838, submitted

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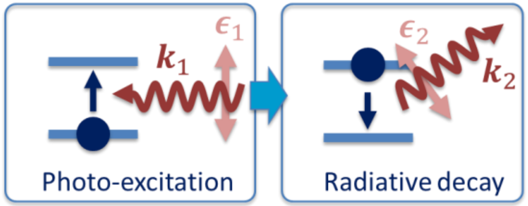
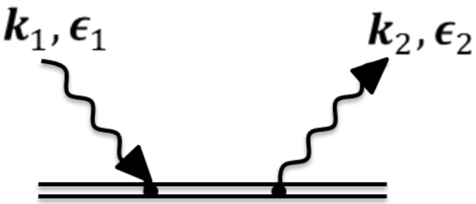
X-ray elastic scattering by Gamma Factory

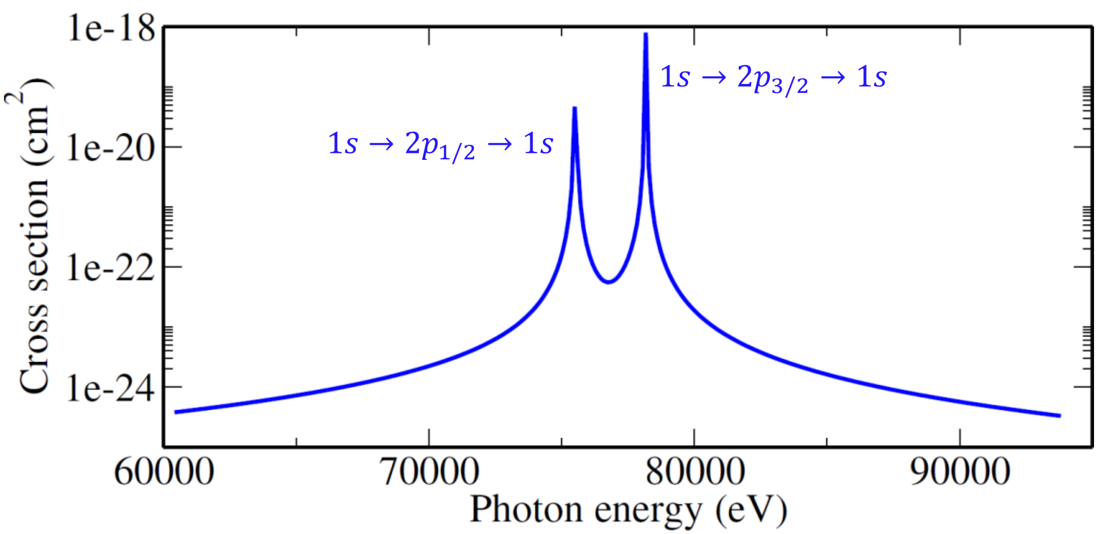


In the heart of Gamma Factory operation principle lays the photon resonant scattering process.

In non-relativistic regime life is easy:

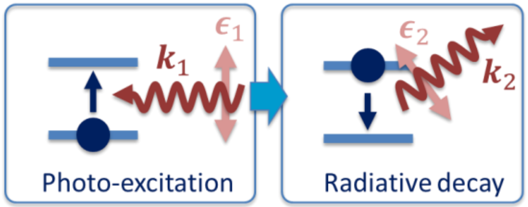


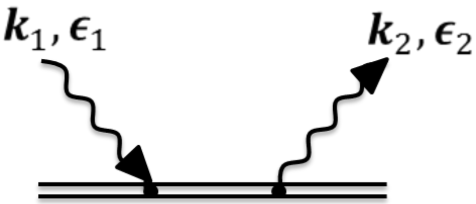
$$\frac{d\sigma}{d\Omega}(\boldsymbol{k}_1, \boldsymbol{\epsilon}_1, \boldsymbol{k}_2, \boldsymbol{\epsilon}_2) = \left(\frac{3\lambda_{if}}{4\pi}\right)^2 (\boldsymbol{\epsilon}_1 \boldsymbol{\epsilon}_2^*)^2$$



Test calculations: elastic x-ray scattering by hydrogen-like Pb^{81+} ions.

X-ray elastic scattering by Gamma Factory





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We are interested in angular, spin- and angular-momentum properties of scattered photons.

The relativistic analysis shows that the amplitude for the $ns \to n'p_j \to ns$ resonant scattering is given by:

$$\mathcal{M}_{if} = (\boldsymbol{\epsilon}_1 \boldsymbol{\epsilon}_2^*) + \sum_{k=1,2} f_k(Z)\, (\boldsymbol{\epsilon}_1 \otimes \boldsymbol{\epsilon}_2^*)_k$$

This implies more complicated angle- and polarization dependence of scattering process. See talk by Andrey Volotka (Th, 16:10)

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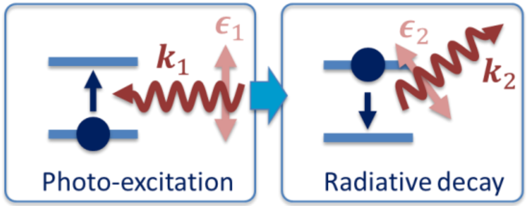
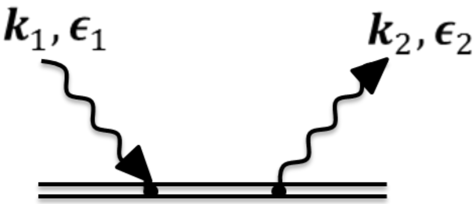
X-ray elastic scattering by Gamma Factory





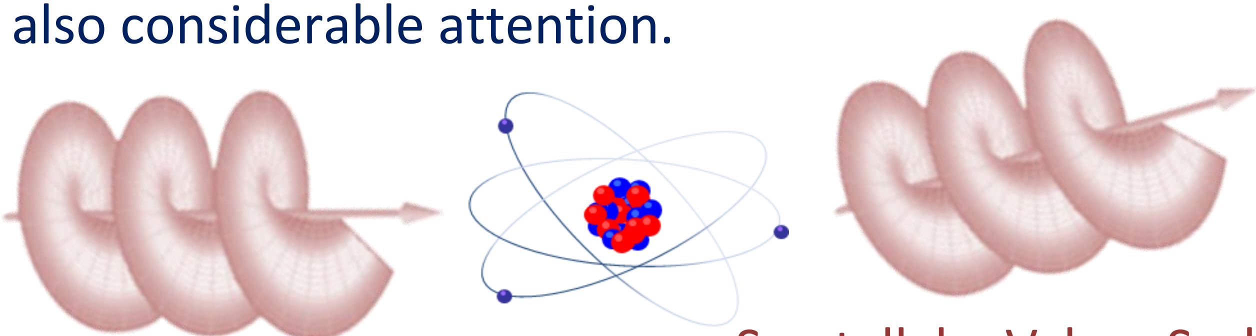
In the heart of Gamma Factory operation principle lays the photon resonant scattering process.

In non-relativistic regime life is easy:

$$\frac{d\sigma}{d\Omega}(\boldsymbol{k}_1, \boldsymbol{\epsilon}_1, \boldsymbol{k}_2, \boldsymbol{\epsilon}_2) = \left(\frac{3\lambda_{if}}{4\pi}\right)^2 (\boldsymbol{\epsilon}_1 \boldsymbol{\epsilon}_2^*)^2$$

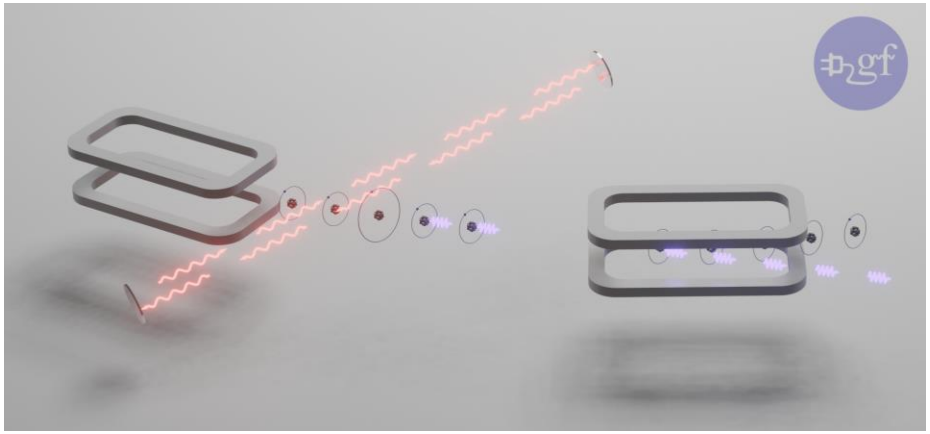
We are interested in angular, spin- and angular-momentum properties of scattered photons.

The scattering of *twisted* photons, that carry orbital angular momentum, attracts also considerable attention.



See talk by Valery Serbo (Th, 14:40).

Summary



Picture: Alexey Petrenko

We briefly discussed the "first step" of the GF operation: absorption of primary- and emission of secondary photons.

- Spectroscopy of partially stripped ions
- Atomic parity violation studies and EDM search
- Production of spin-polarized ion beams
- Resonant photon scattering
- More ideas are discussed in AdP review paper
- And—we hope—even more ideas will be proposed by you!

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