EFFICIENT LIGHT-ATOM INTERACTION FOR GENERATION OF HUNDREDS MeV RADIATION WITH THE GAMMA FACTORY

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Physics Beyond Colliders

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OUTLINE

INTRODUCTION

SPECTROSCOPY OF HIGHLY CHARGED IONS

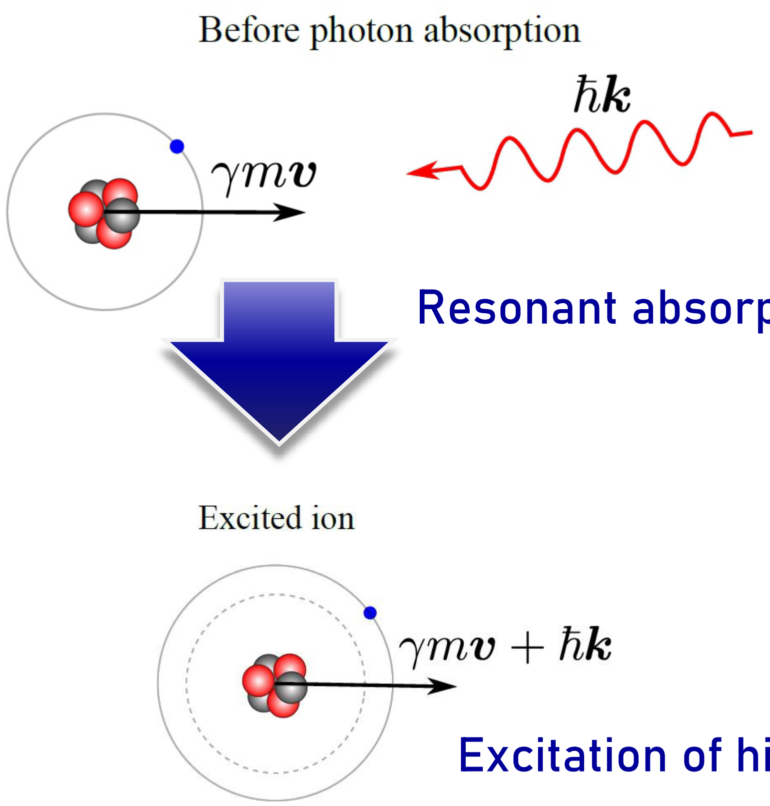
THEORETICAL DESCRIPTION OF LIGHT-ATOM INTERACTION IN THE GAMMA FACTORY

REPRESENTATIVE ATOMIC-PHYSIC STUDY AT THE GAMMA FACTORY

SUMMARY

INTRODUCTION

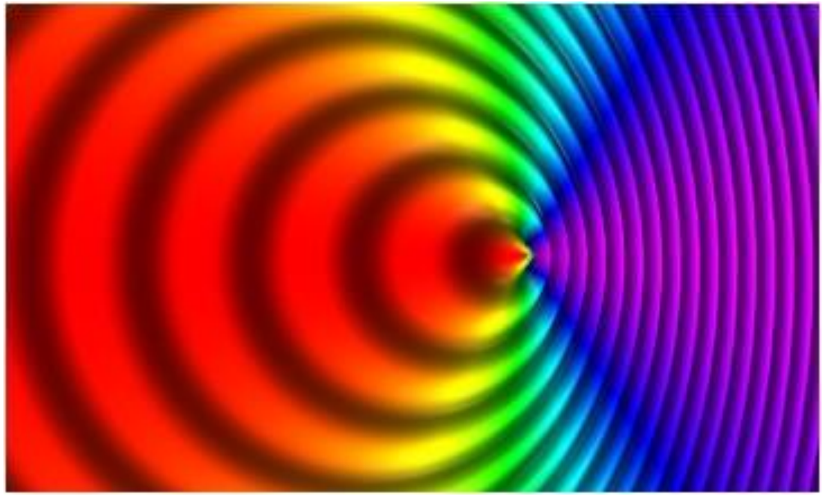
SPECTROSCOPY OF ULTRARELATIVISTIC ATOMS



Resonant absorption

Excitation of high-energy transition with optical photons

DOPPLER EFFECT

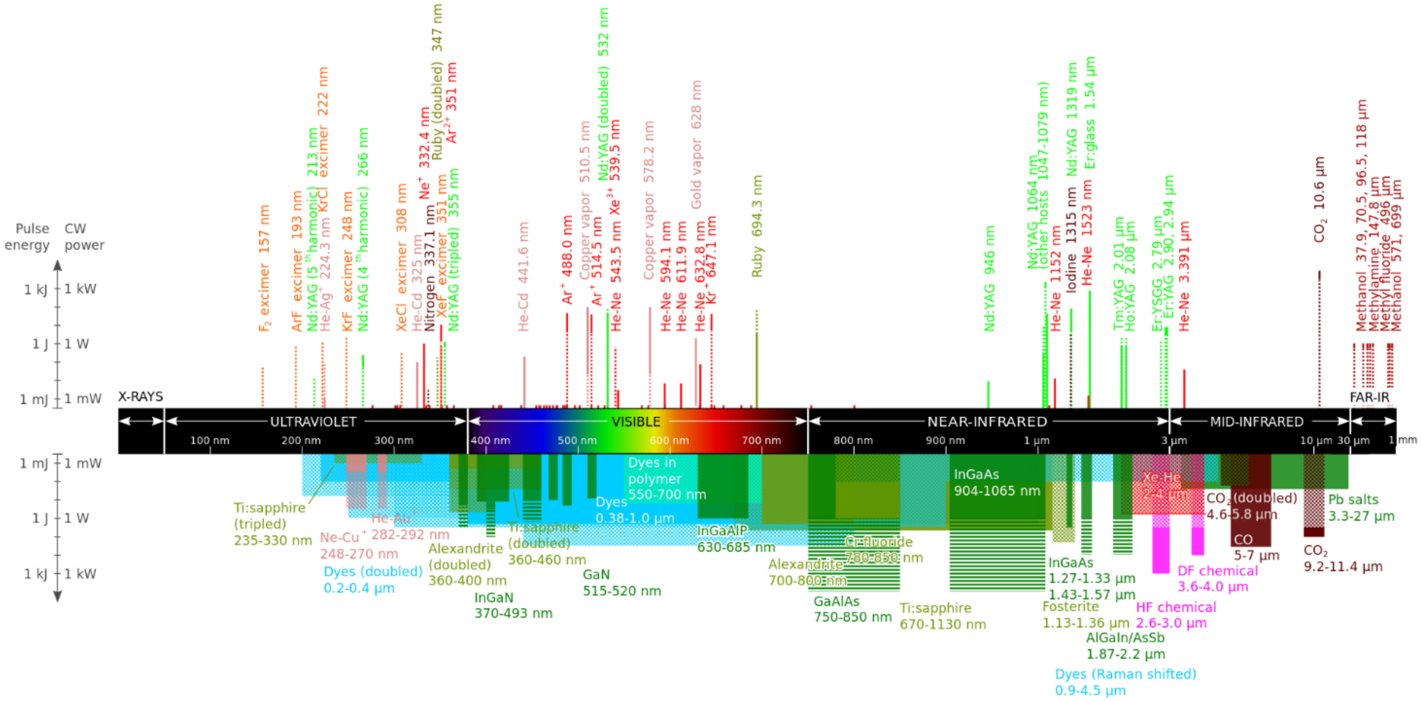


RELATIVISTIC CASE

$$\nu_p = (1+\beta)\gamma_L \nu_l \approx 2\gamma_L \nu_l$$

$\gamma_L = \frac{1}{\sqrt{1-\beta^2}}$ - the Lorentz factor with $\beta = \frac{v}{c}$

THE ABILITY TO BOOST LASER FREQUENCY BY $2\gamma_L$



CURRENTLY AVAILABLE LASER SOURCES

8th harmonic of YAG laser

$\lambda = 165\ \mathrm{nm}$
$E = 7.5\ \mathrm{eV}$

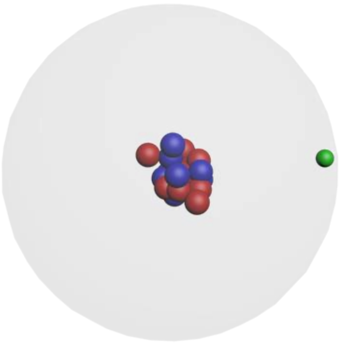
$\gamma_L = 3000$

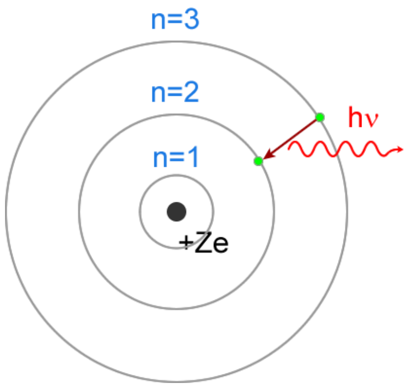
$\lambda_p = 20\ \mathrm{pm}$
$E_p = 45\ \mathrm{keV}$

Features:

- High energy in the ion frame
- The ability to tune light through the control over γ_L
- Selectivity in excitation

WHY HIGHLY CHARGED IONS?



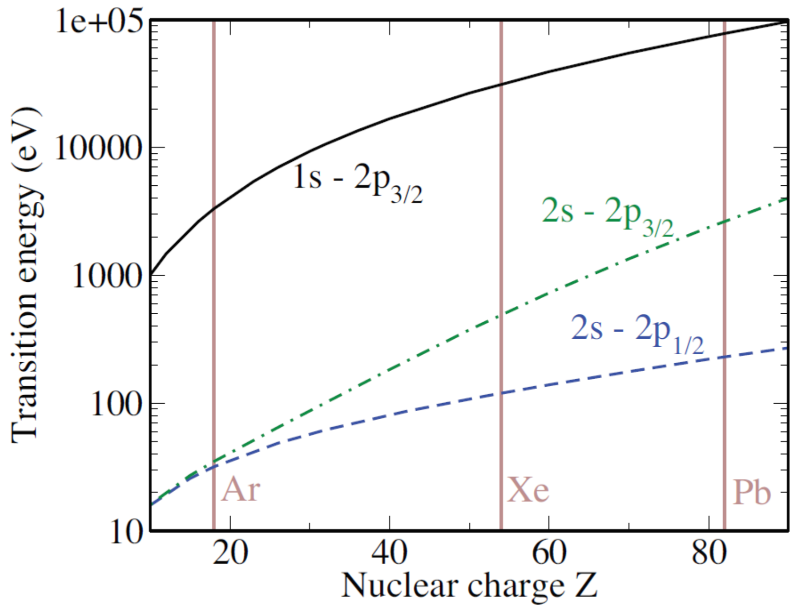


HIGHLY CHARGED IONS (HCIs)

$$E_n = \frac{m_e \mathbf{Z^2} e^4}{2(4\pi\varepsilon_0)^2\hbar^2}\frac{1}{n^2}$$

Z – atomic number

- The lower the electronic level the more energetic transitions between successive levels
- The larger the atomic number Z the closer the electron is to a nucleus

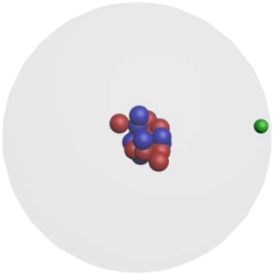


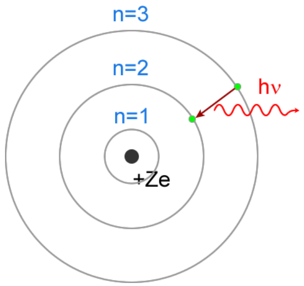
Transition energy between $n \rightarrow n'$ levels $\Delta E_{nn'}$

Ion	Transition	Energy (keV)	Wavelength (pm)	Ion type
$^{208}Pb^{+79}$	$1S_{1/2} \rightarrow 2P_{3/2}$	77	16	Lithium-like
$^{238}U^{+91}$	$1S_{1/2} \rightarrow 2P_{3/2}$	102	12	Hydrogen-like
$^{238}U^{+90}$	$1S_{1/2} \rightarrow 2P_{3/2}$	101	12	Helium-like

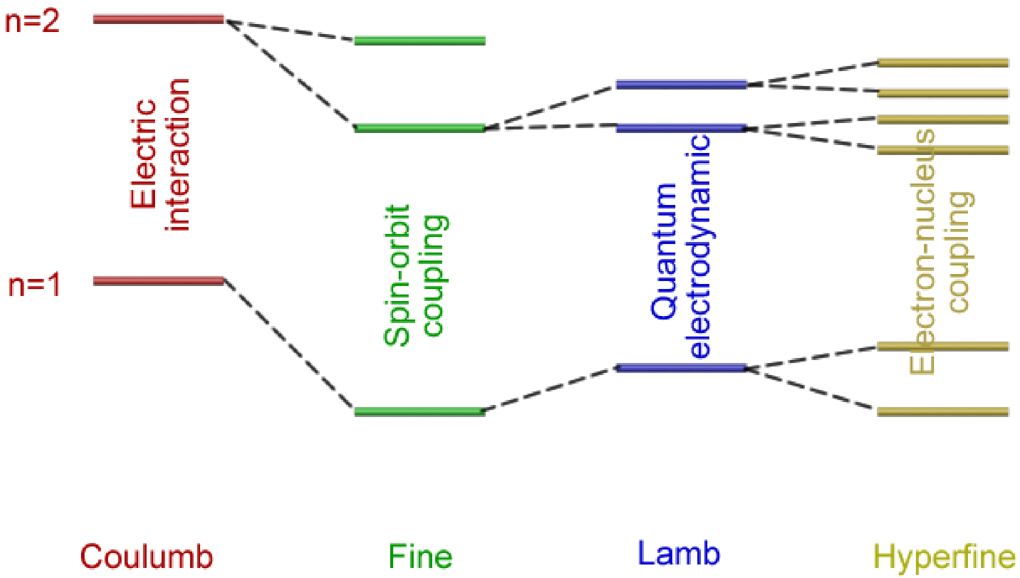
THE ABILITY TO FULLY EXPLORE THE LORENTZ BOOST

INTRAATOMIC AND VACUUM INTERACTIONS



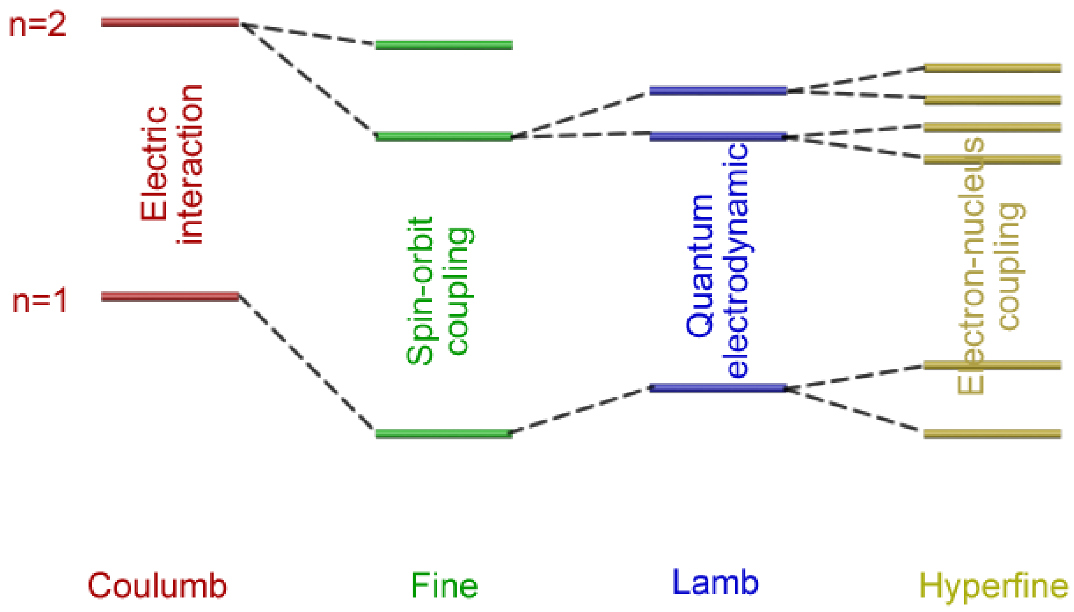


Bohr model is the zeroth approximation of the atom



- **Spin-orbit coupling**
  Coupling of electrons' angular momentum with electrons' spins
- **QED correction**
  Interaction of atom's electrons with quantum-vacuum electrons
- **Electron-nucleus coupling**
  Interaction of electron total angular momentum (spin+orbital) with orbital angular momentum

INTRAATOMIC AND VACUUM INTERACTIONS



DEPENDENCE OF VARIOUS CONTRIBUTIONS ON Z

Transition Energy $\Delta E_{nn'}$	$\propto (Z\alpha)^2$
Fine structure splitting ΔE_{fs}	$\propto (Z\alpha)^4$
Lamb shift	$\propto (Z\alpha)^4$
Hyperfine structure splitting ΔE_{hfs}	$\propto (Z\alpha)^3 \frac{m_e}{m_p}$

TESTING THE THEORIES WITH UNPRECEDENTED PRECISION

SPECTROSCOPY OF HIGHLY CHARGED IONS

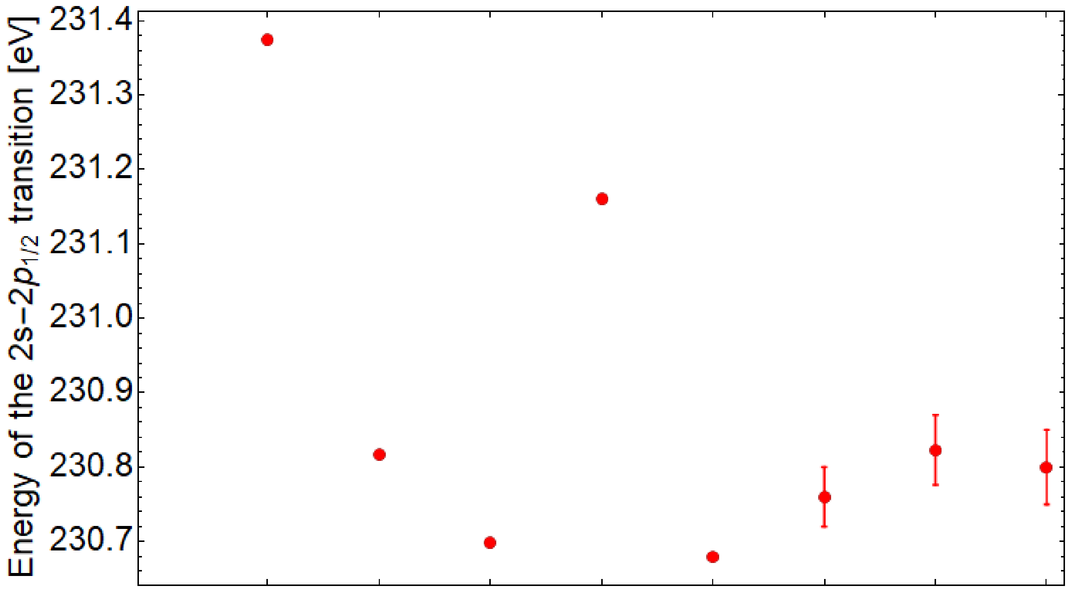
WHERE ARE THE LEVELS?

CALCULATIONS OF TRANSITION ENERGIES

Different calculation contributions:

- electrostatic interaction,
- spin-orbit interaction
- hyperfine coupling
- quantum electrodynamics (QED)
- two-loop QED
- relativistic contribution
- ....

RESULTS OF CALCULATION FOR Pb^{79+}



NECESSITY OF TUNING THE LASER

PARAMETERS OF SPECIFIC TRANSITIONS

Ion	Transition	Energy (eV)	Lifetime (ps)	Ion type
$^{208}Pb^{79+}$	$2S_{1/2} \rightarrow 2P_{1/2}$	~230	77	Lithium-like
$^{40}Ca^{17+}$	$2S_{1/2} \rightarrow 3P_{1/2}$	~662	0.43	Lithium-like
$^{208}Pb^{81+}$	$1S_{1/2} \rightarrow 2P_{1/2}$	~75280	$3.4*10^{-5}$	Hydrogen-like
$^{40}Ca^{+18}$	$1S_0 \rightarrow 2^1P_1$	~3900	$6*10^{-3}$	Helium-like

Zero nuclear spins → NO DARK GROUND STATES

JACEK BIEROŃ

THEORETICAL DESCRIPTION OF LIGHT-ATOM INTERACTION IN THE GAMMA FACTORY

QUANTUM-MECHANICAL DESCRIPTION

STATE DESCRIPTION – DENSITY MATRIX

DENSITY MATRIX

$$\rho = \sum_i p_i |i\rangle\langle i|$$

$$\rho = \begin{pmatrix} \rho_{gg} & \cdots & \rho_{ge'} \\ \vdots & \ddots & \vdots \\ \rho_{e'g} & \cdots & \rho_{e'e'} \end{pmatrix}$$

ρ_{gg} - population of state *ground state*

$\rho_{gg'}$ - Zeeman coherence (between ground-state sublevels)

ρ_{ge} - optical coherence (between ground and excited states)

SYSTEM'S EVOLUTION

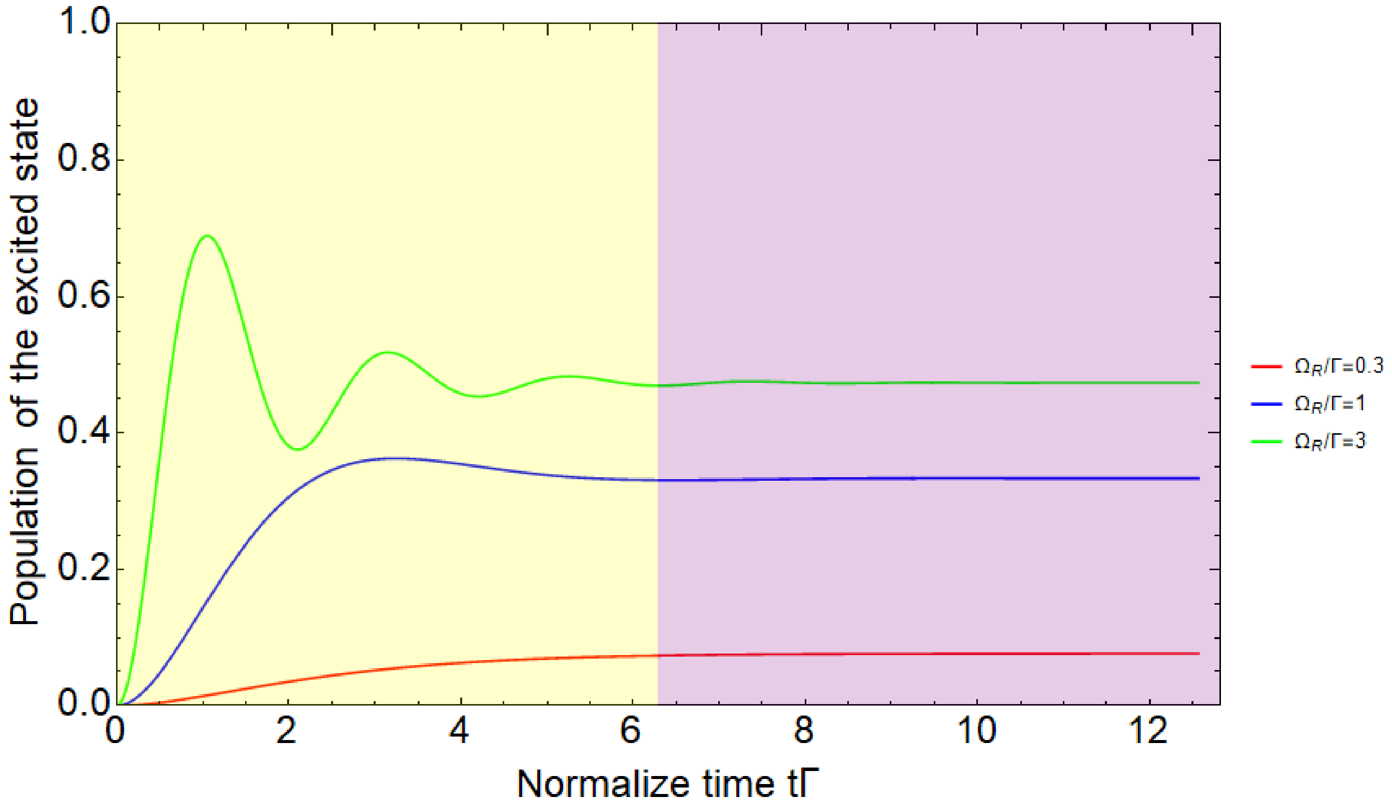
$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] + \Gamma(\rho)$$

H - interaction Hamiltonian

$\Gamma(\rho)$ - relaxation operators

DENSITY-MATRIX APPROACH ENABLES TO DETERMINE EVOLUTION DUE TO COHERENT (INTERACTION) AND INCOHERENT (RELAXATION) PROCESSES

TEMPORAT EVOLUTION OF THE EXCITED STATE



REGIMES

- **DYNAMIC REGIME** $t \leq \frac{1}{\gamma_e}$
  Damped oscillations
- **STEADY-STATE REGIME** $t \gg \frac{1}{\gamma_e}$
  Constant value

INTERACTION REGIME DETRMINED BY THE RELATION BETWEEN PULSE LENGTH AND RELAXATION TIME

STEADY-STATE = NO EVOLUTION OF THE DENISTY MATRIX

$$\dot{\rho} = 0 \quad \Rightarrow \quad \rho_{ee} = \frac{\Omega_R^2/4}{\Delta\omega^2 + \gamma_e^2/4 + \Omega_R^2/2} = \frac{\kappa_1/2}{1 + 4\Delta\tilde{\omega}^2 + \kappa_1}$$

$$\kappa_1 = \frac{\Omega_R^2}{\gamma_e^2}$$ saturation parameter

Form similar of that of the absorption cross section

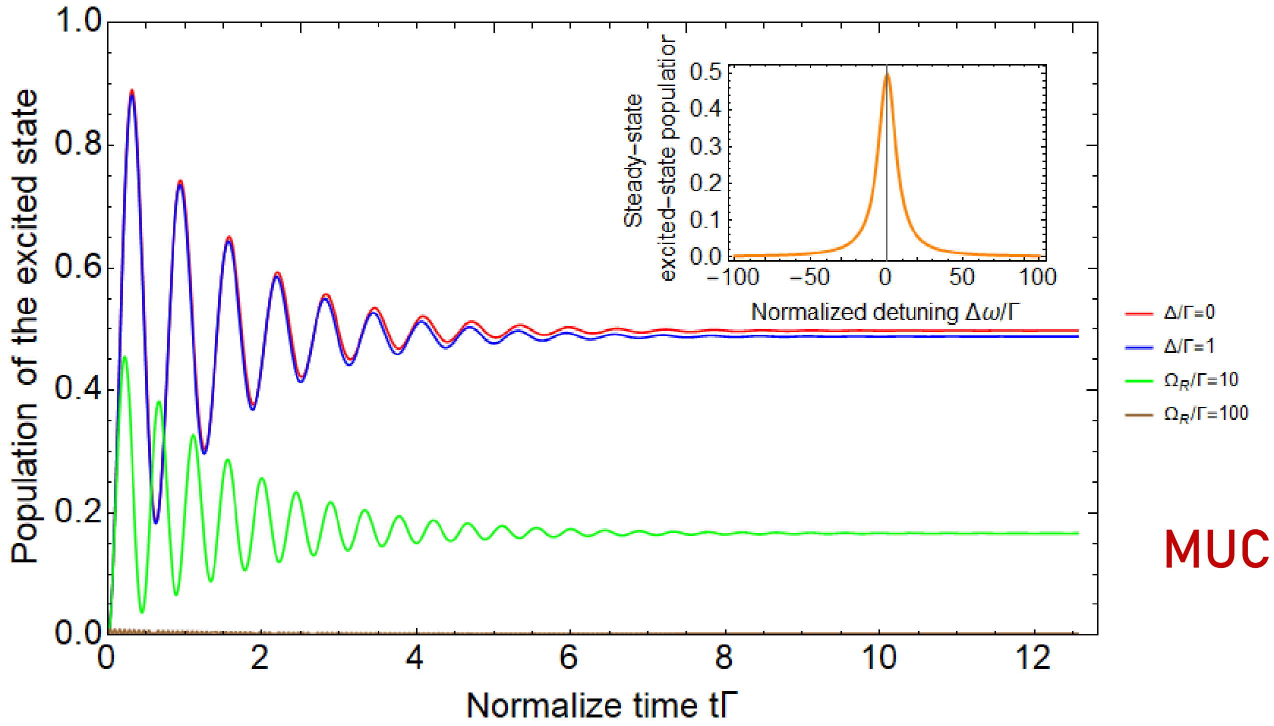
$$\sigma = \frac{\sigma_0}{1 + 4\Delta\omega^2/\gamma_e^2 + 2\Omega_R^2/\gamma_e^2} = \frac{\sigma_0}{1 + 4\Delta\omega^2/\gamma_t^2}$$

CLASSICAL CROSS-SECTION APPROACH WORKS FOR $t \gg \frac{1}{\gamma_e}$

POPULATION/FLUORESCENCE SATURATES AT $\kappa_1 \approx 1$

POPULATION AT DIFFERENT DETUNINGS

It is difficult to saturate with detuned light



- Oscillation frequency increases with detuning
- Oscillation amplitude drops with detuning

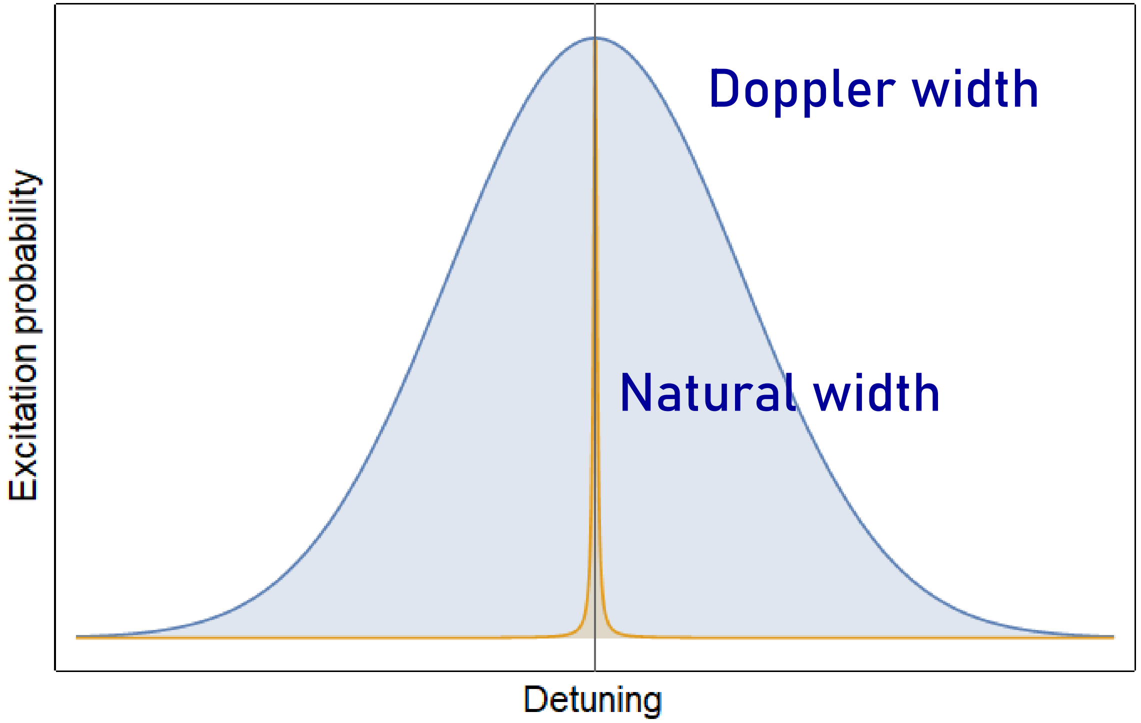
MUCH HARDER TO SATURATE DETUNED TRANSITION

$$\kappa_\Delta \propto \frac{\Delta\omega^2}{{\gamma_e}^2}\kappa_1$$

LIGHT-ATOM INTERACTION – DOPPLER EFFECT

Ions in the bunch have momentum dispersion

$$\frac{\Delta p}{p} \approx 2 \times 10^{-4}$$



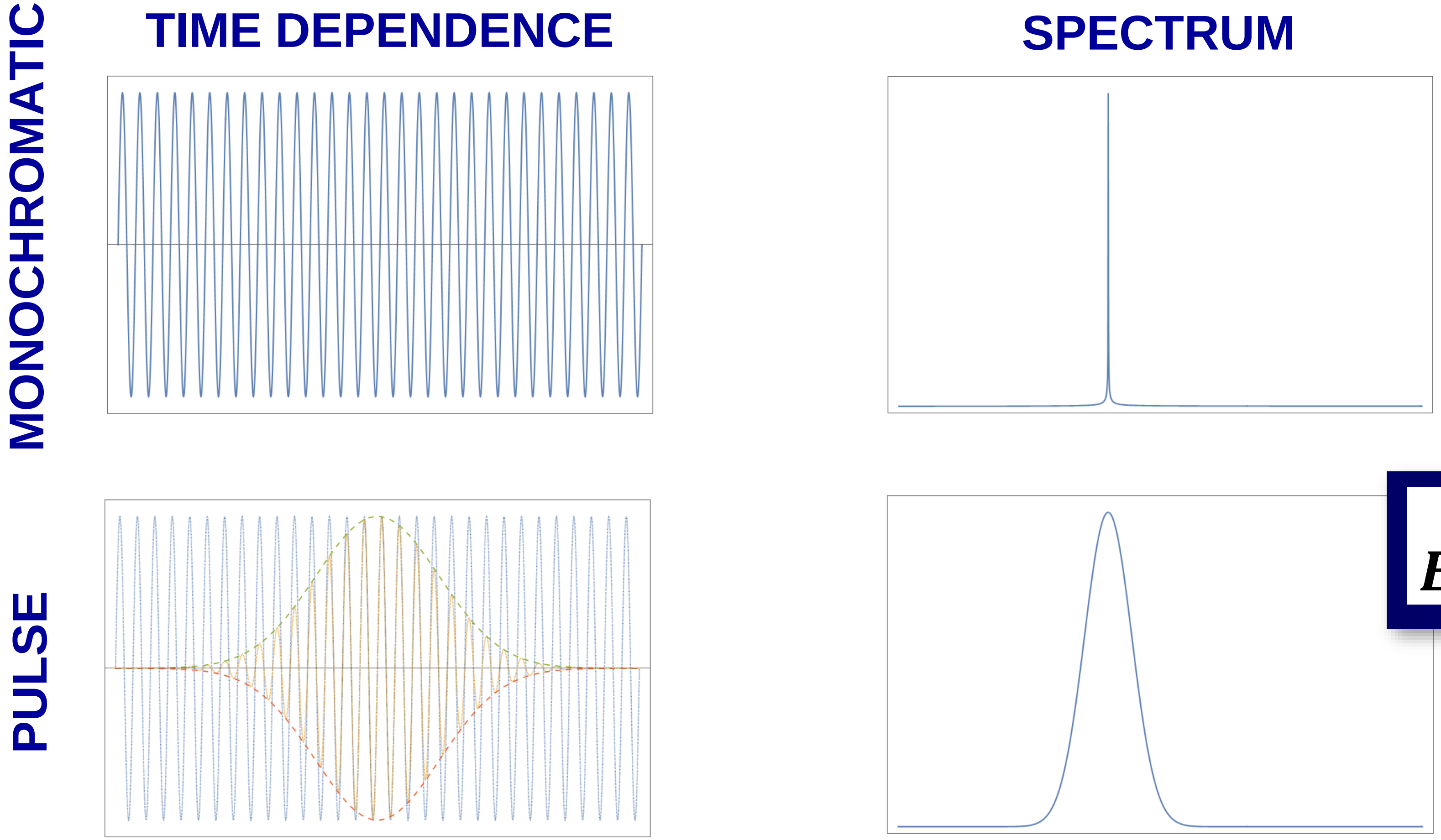
Doppler broadening on the transition

Doppler width much larger than the transition width

Extremely difficult to saturate the transition

Pb^{79+}: $I \approx 5\,\frac{\mathrm{GW}}{\mathrm{cm}^2}$

POPULATION AT DIFFERENT DETUNINGS

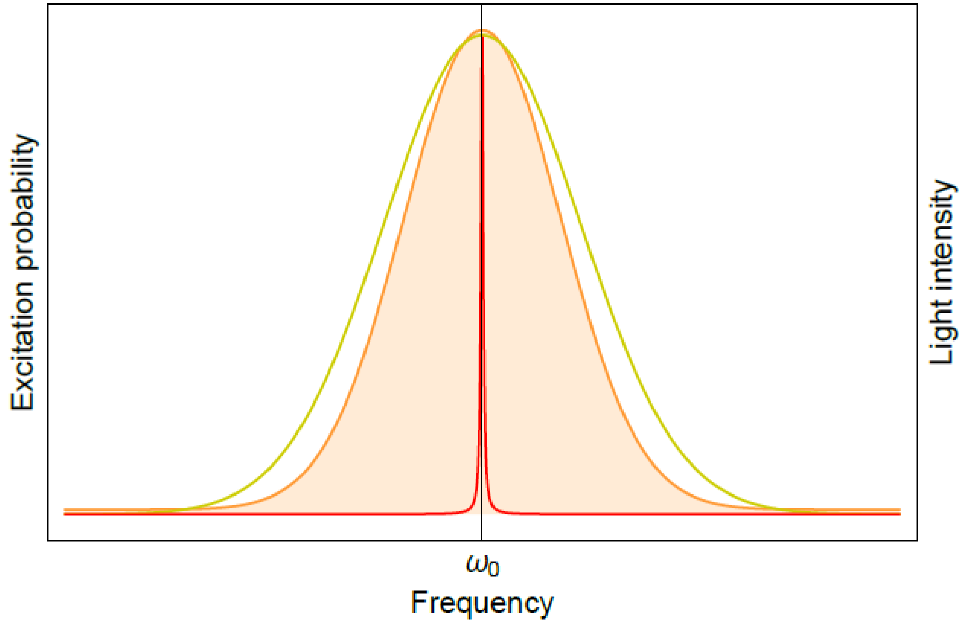


- Finite interaction time broadens spectrum of light

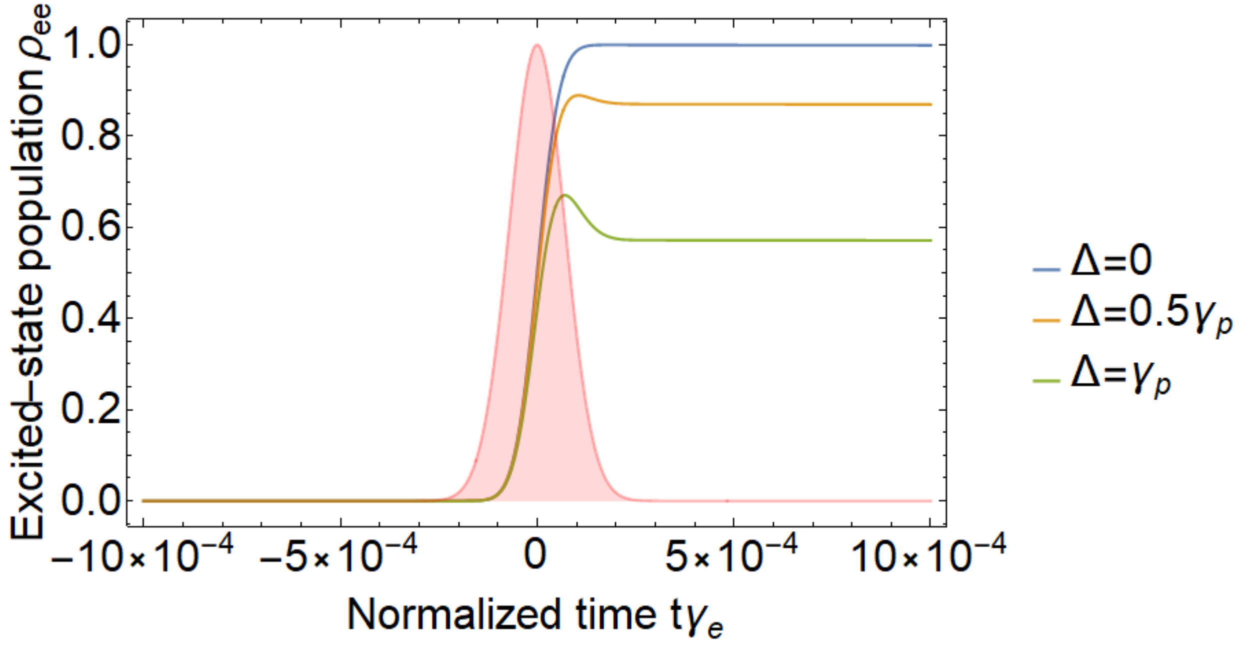
$$\boldsymbol{E}(t,\boldsymbol{r}) = \boldsymbol{e}_{\boldsymbol{\varepsilon}} E_0 e^{i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r})} e^{-\frac{t^2}{\tau^2}}$$

LIGHT-ATOM INTERACTION – PULSE EXCITATION

Using spectrally broad light (pulse)



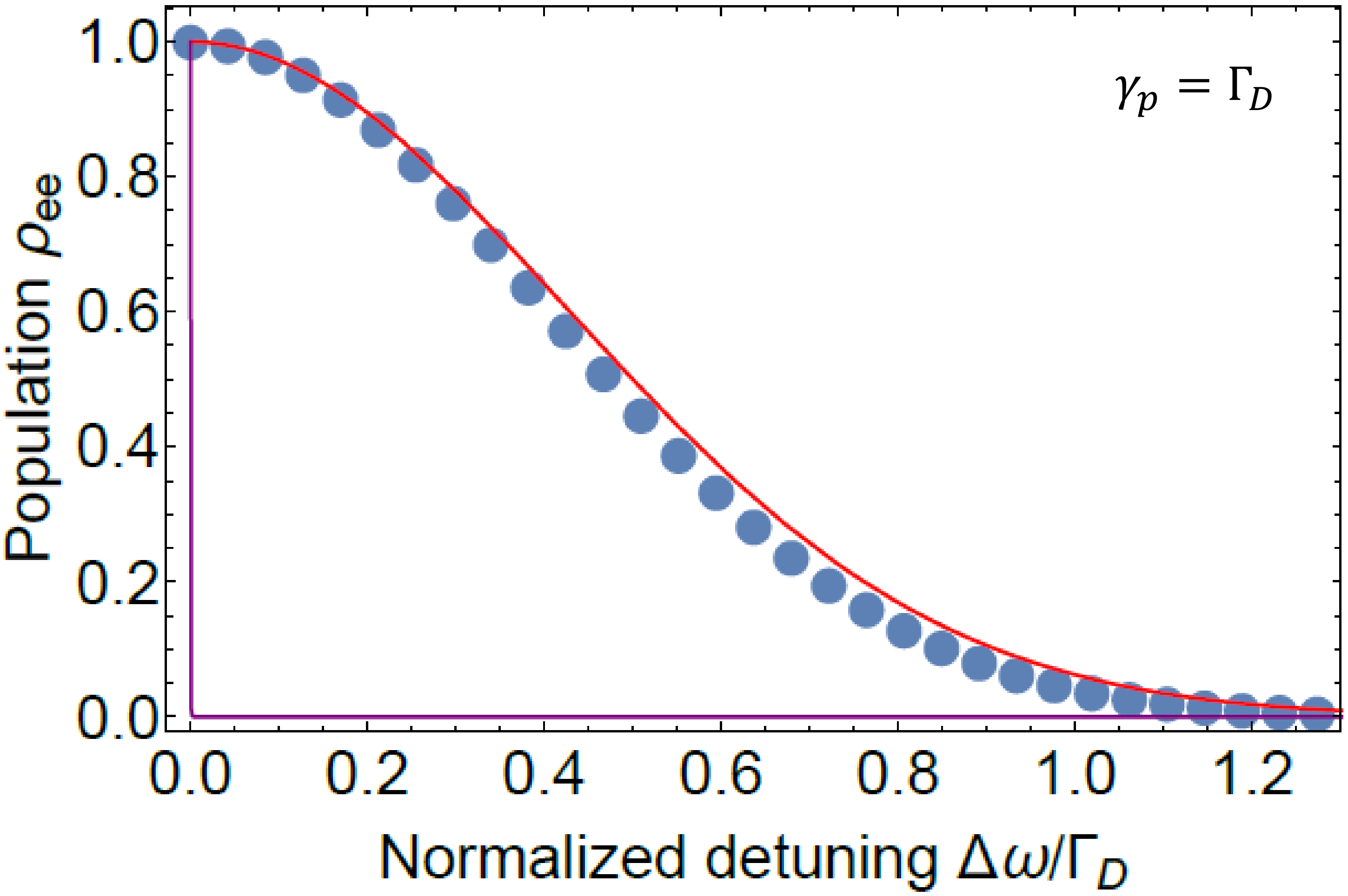
Population for different detunings



FINAL POPULATION DETERMINED A CUMULATED RABI PHASE

$$\rho_{ee} = \sin^2\left(\int_0^{t_1} \Omega_R(t)dt\right)$$

LIGHT-ATOM INTERACTION – PULSE EXCITATION



EFFICIENT EXCITATION OF ATOMS

RESULTS OF THEORETICAL SIMULATIONS

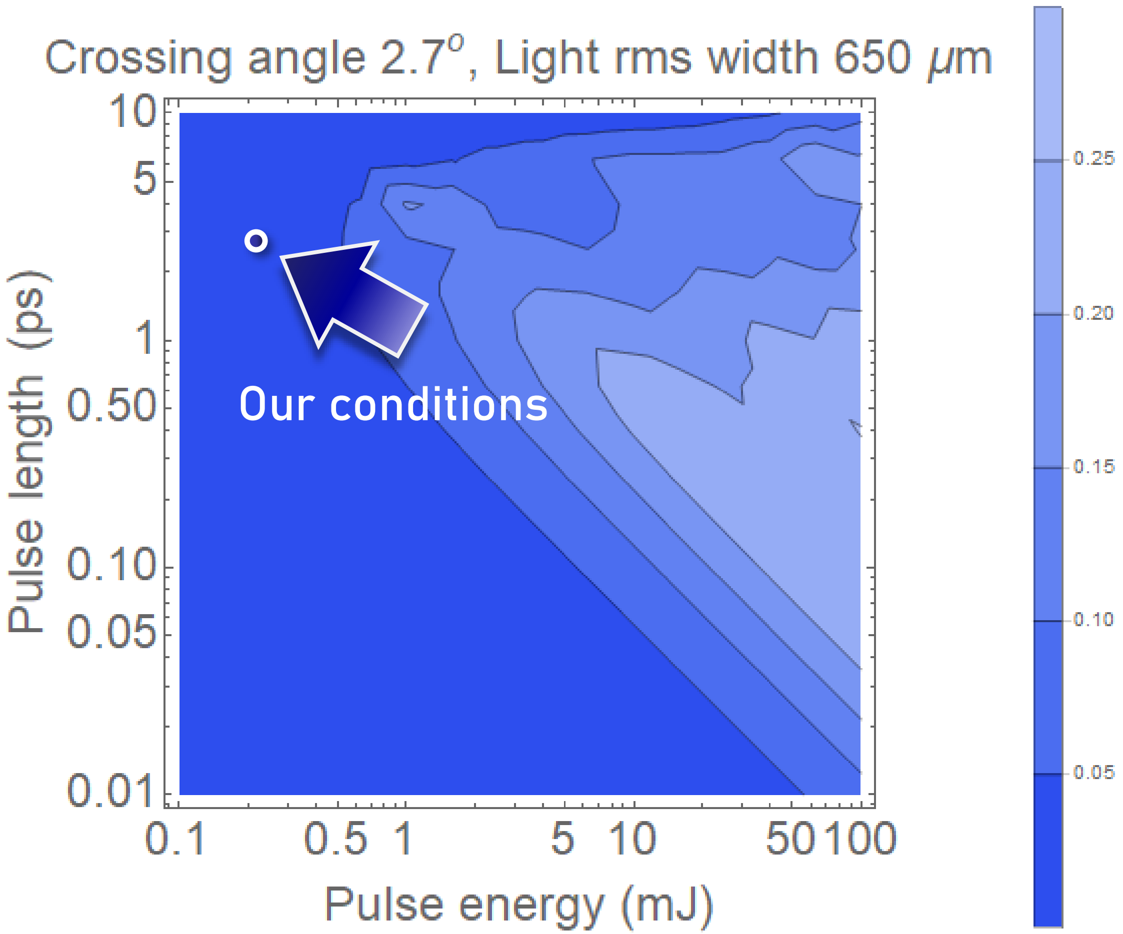
TWO REGIMES

	DYNAMIC REGIME	STEADY-STATE REGIME	
	Inaccesible to absorption-cross-section-based approach	Corresponding to steady-state approach	
	Li-like Pb^{+79}	H-like Pb^{+81}	Absorption cross section
Transition	$2s \rightarrow 2p_{1/2}$	$1s \rightarrow 2p_{1/2}$	
Transition energy	230 eV	75280 eV	
Transition width	1.3×10^{10} 1/s	3.0×10^{16} 1/s	
Doppler width	1.6×10^{14} 1/s	5.4×10^{16} 1/s	
Lorentz factor	96	2989	
Pulse energy	0.2 mJ	5 mJ	
Pulse length	2.8 ps	500 ps	
EFFICIENCY OF PUMPING	**2%**	**≈ 440%**	**≈ 250%**

DYNAMIC CASE – Li-LIKE Pb – OPTIMIZATION

OPTIMIZING PULSE CONDITIONS

LENGTH AND ENERGY OPTIMIZATION



BETTER EFFICIENCY FOR

- MORE ENERGETIC PULSE
- SHORTER (SPECTRALLY BROADER) PULSE

INITIAL CONDITIONS

$P_{excite} \approx 2\%$

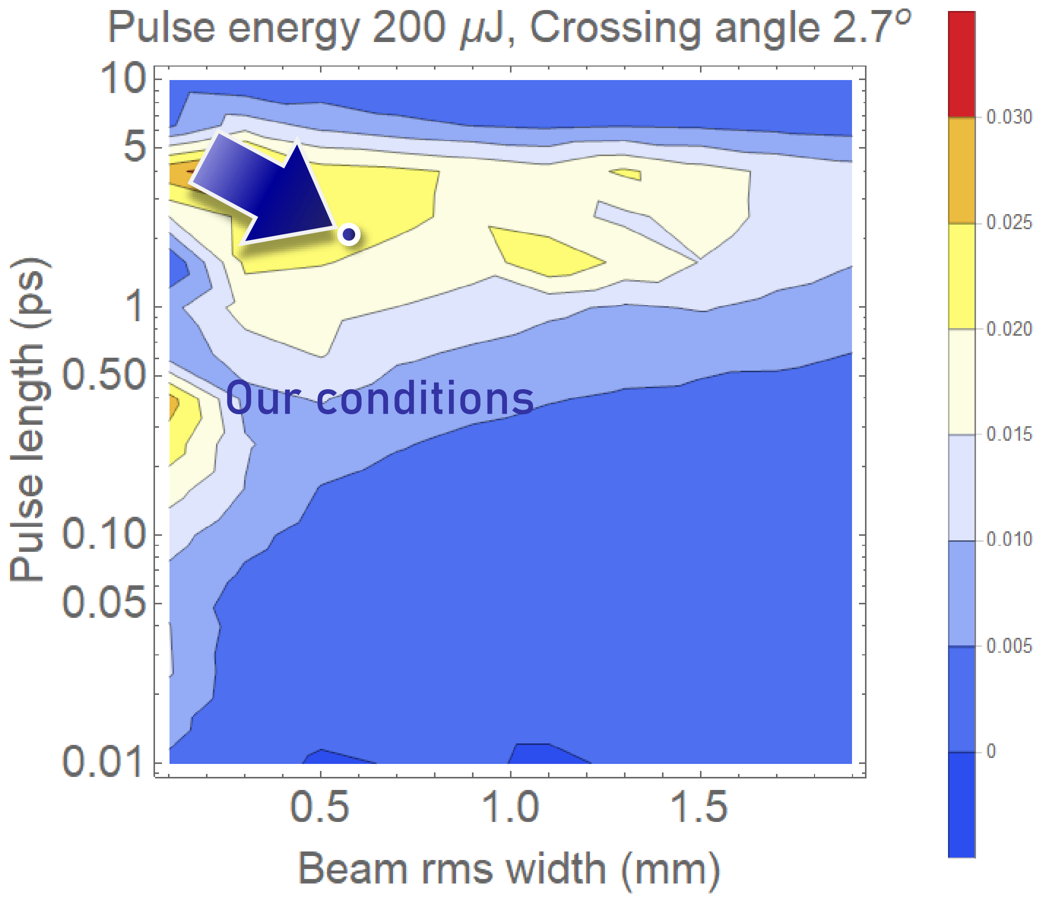
OPTIMIZED CONDITIONS

$P_{excite} \approx 30\%$

DYNAMIC CASE – Li-LIKE Pb – OPTIMIZATION

OPTIMIZING PULSE CONDITIONS

LENGTH AND WIDTH OPTIMIZATION



BETTER EFFICIENCY FOR

- BROADER BEAM
- SHORTER (SPECTRALLY BROADER) PULSE

INITIAL CONDITIONS

$P_{excite} \approx 2\%$

OPTIMIZED CONDITIONS

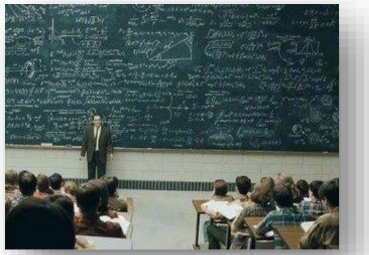
$P_{excite} \approx 4\%$

THE ABILITY TO OPTIMIZE THE EXCITATION

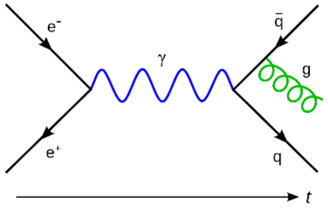
REPRESENTATIVE ATOMIC-PHYSICS STUDY AT THE GAMMA FACTORY

SCALING OF DIFFERENT INTERACTIONS IN HCI

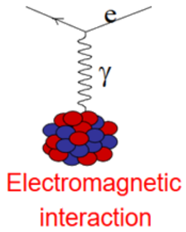
HIGHLY CHARGED IONS (HCIs) OFFER UNIQUE CAPABILITIES

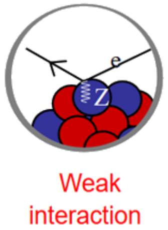


Comparing theoretical calculations with experimental results

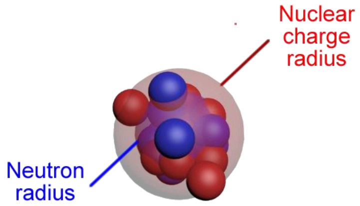


Testing QED at very strong electron-nucleus interaction





Testing parity nonconservation at large nucleus-electron overlap



Determination of nuclear charge and neutron radius

INVESTIGATIONS OF THE EFFECTS CAN BE DONE THROUGH ANALYSIS OF ENERGY-LEVEL STRUCTURE OF HCIs

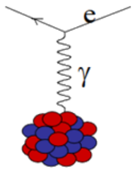
PARITY

PARITY

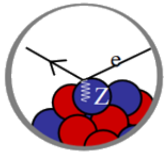
$$\mathbf{P}: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}.$$

Parity assumes that laws of physics are identical in a mirror Universe

PARITY CONSERVATION VS NONCONSERVATION



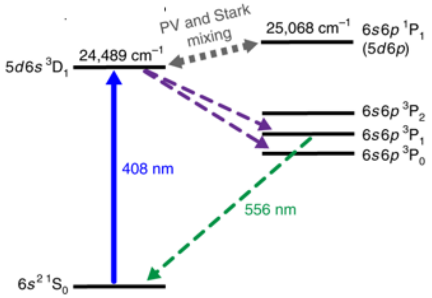
Electromagnetic interaction



Weak interaction

Electromagnetic interaction conserves the parity

Weak interaction does not conserve the parity



A single photon cannot couple states with same parity …

…unless there is an admixture of opposite parity state

PARITY NONCONSERVATION IN IONS

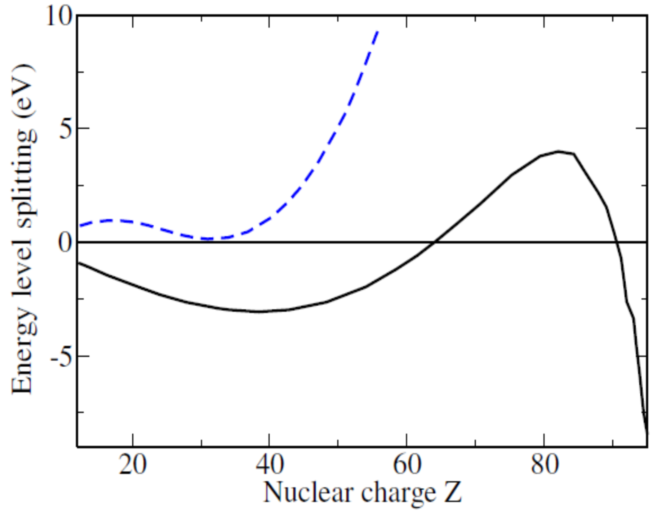
MIXING COEFFICIENT η

$$\eta = \frac{\langle \psi_s | H_w | \psi_p \rangle}{E_s - E_p + \frac{i\Gamma}{2}}$$

$\psi_{s,p}$ – wave functions of opposite parity states, $E_{s,p}$ – energies of the states, Γ – relaxation rate

- Strength of the mixing is inversely proportional to the level splittings
- In HCIs H_w scales as Z^5 (in contrast to atoms where the scaling is Z^3)

Potentially 10^4-fold improvement of the effect



Energy level splittings between $^1S_0$ and $^3P_0$ or $^3P_1$ states in helium-like ions

- Enhancement of the effect
- Comparison of electron and relativistic contribution to the parity nonconservation

SUMMARY… AND WHAT I DID NOT TALK ABOUT

- THE GAMMA FACTORY IS NOVEL RESEARCH PROPOSAL OFFERING UNIQUE CAPPABILITIES
- THE ATOMIC PHYSICS DESCRIPTION SHOWS THAT IONS CAN BE EFFICIENTLY EXCITED
- EFFICIENT EXCITATION OPENS NEW RESEARCH POSSIBILITIES FOR VARIOUS FIELDS OF PHYSICS
- THERE ARE ALSO SECODARY PHOTONS AND MANY OF THEIR INTERESTING APPLICATIONS
- THERE IS HIGH PROBABILITY OF PROJECT IMPLEMENTATION AT SPS

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