Generation of Twisted Gamma-Rays via Two-Photon Transition

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公募研究「イオンビームを用いた高エネルギー光渦生成の基礎的研究」

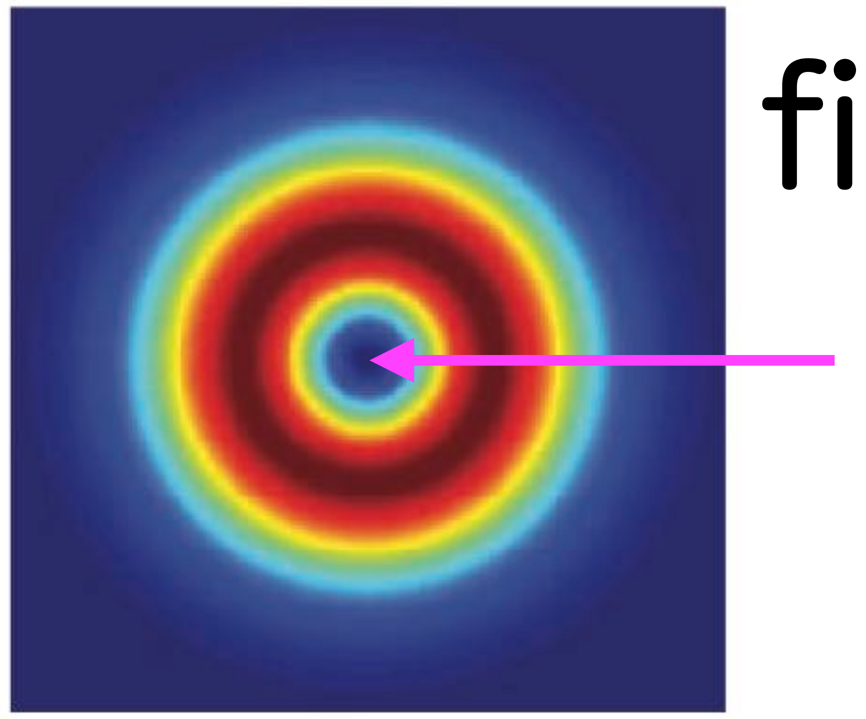
「量子ビーム応用」領域研究会 2022/05/20

Twisted photon(捩光子), optical vortex(光渦)

Orbital angular momentum (OAM) of light

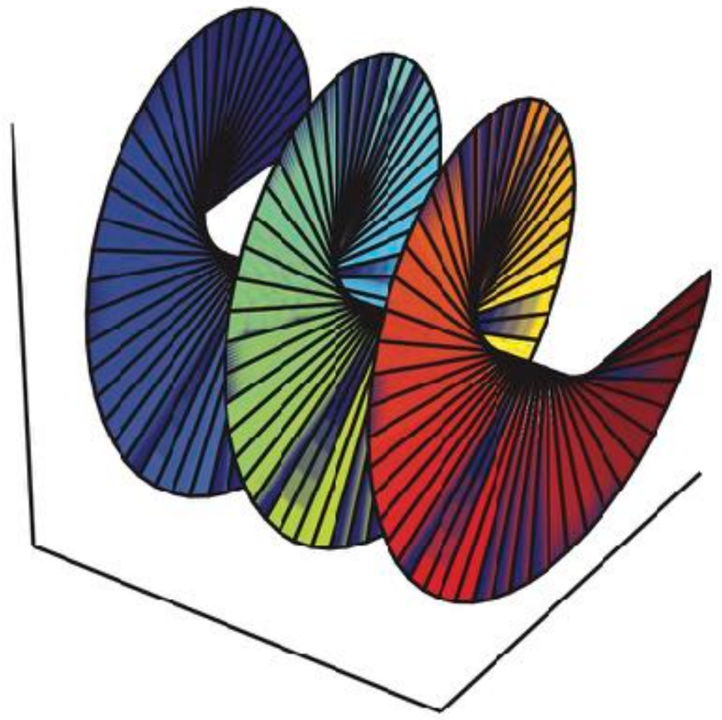
winding field phase ~ $e^{im\varphi}$

G. Molina-Terriza et al.
Nat. Phys. 3, 305 (2007)



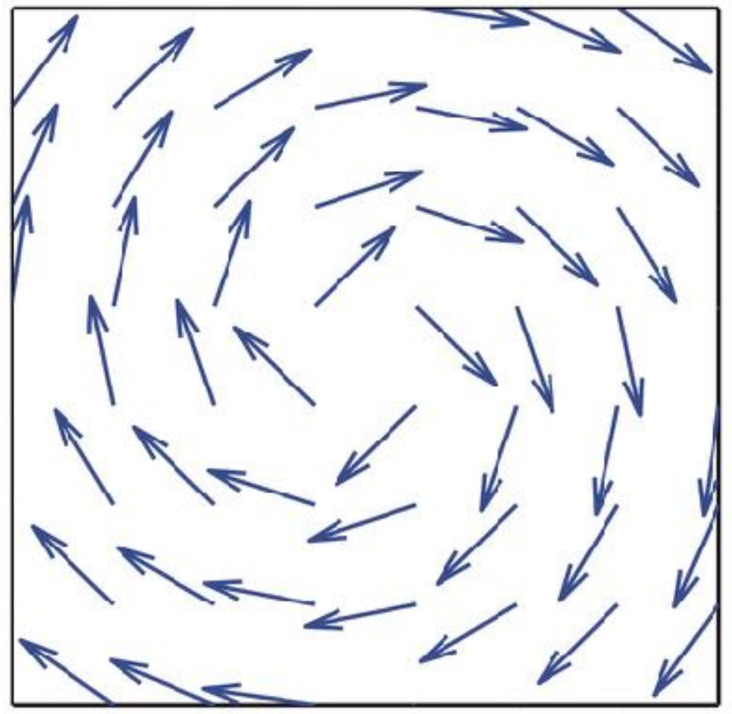
field intensity

phase
singularity

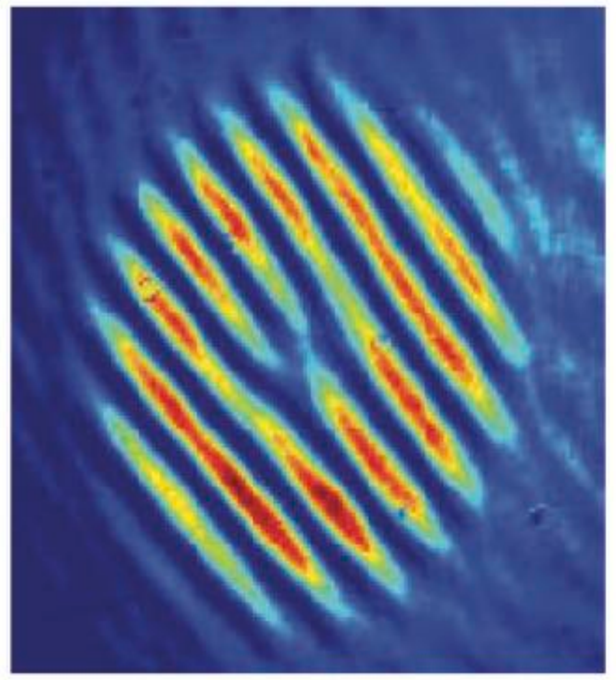


wave front

helicoid



transvers
Poynting vector



Interference patter
with plane wave

computer-generated hologram

Generation (and use) of twisted photons

Optical region

Y. Shen et al., Light: Sci. & App. 8, 90 (2019)

fork hologram, lens-based mode converter, etc.

(micro manipulation, imaging, data transmission, etc.)

X-ray region

S. Sasaki, I. McNulty, PRL 100, 124801 (2008)

E. Hemsing et al. Nat. Phys. 9, 549 (2013)

helical undulator, FEL

Gamma-ray region (proposals)

backward Compton scattering

$$e + \gamma_{\rm tw} \to e + \gamma_{\rm tw}$$

U.D. Jentschura, V.G. Serbo, PRL 106, 013001 (2011)

nonlinear Thomson scattering

$$e + \gamma_{\rm pw/tw} + \gamma_{\rm pw/tw} + \cdots \to e + \gamma_{\rm tw} + \cdots$$

Y. Taira, T. Hayakawa, M. Katoh, Sci. Rep. 7, 5018 (2017)

Y.-Y. Chen et al., Phys. Rev. Lett. 121, 074801 (2018)

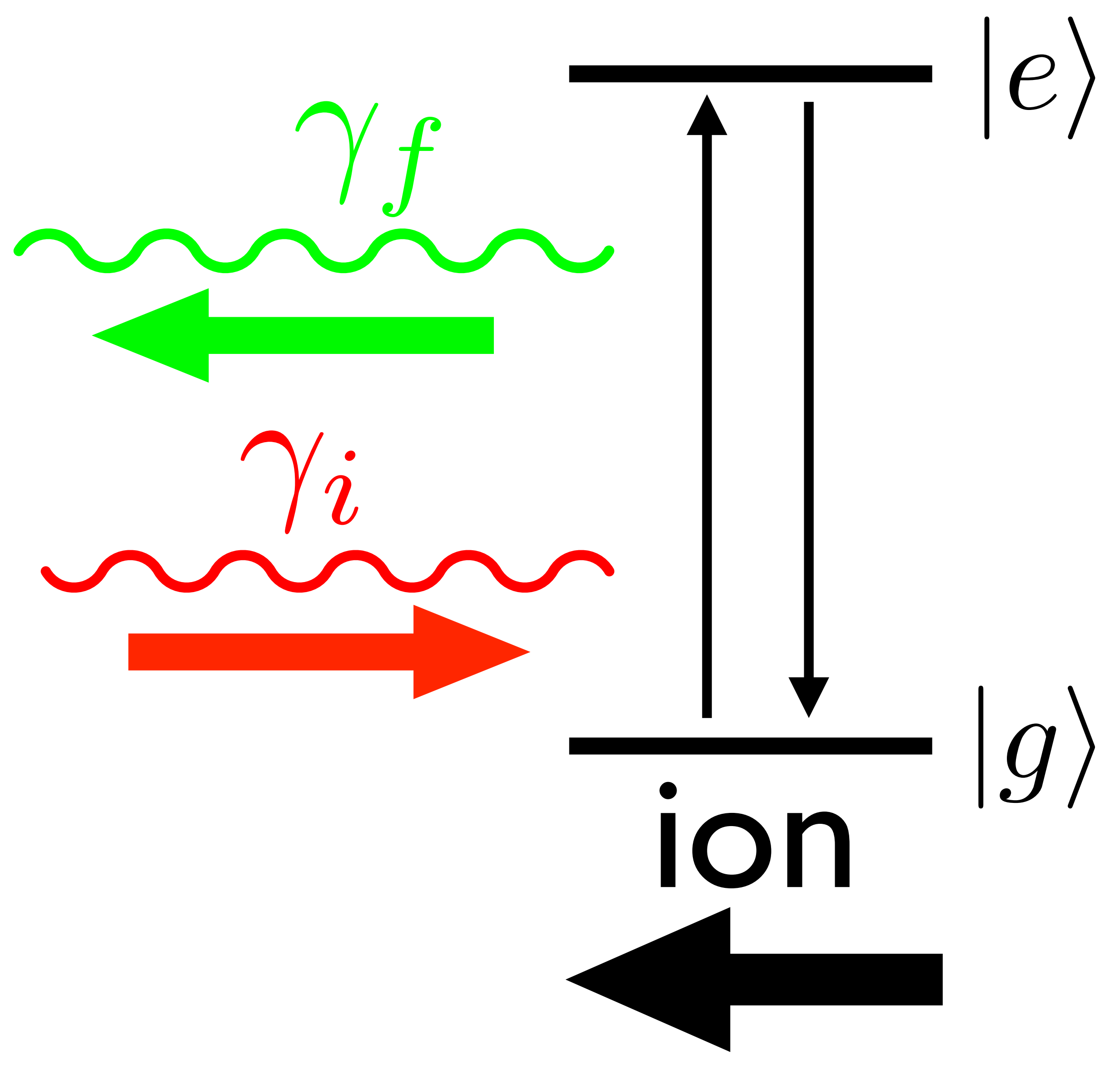
Y.-Y. Liu et al., Opt. Lett. 48, 395 (2020)

Gamma factory

E.G.Bessonov, NIMB 309, 92 (2013)
M.W. Krasny, CERN-SPSC-2019-031; SPSC-I-253

Rayleigh scattering by boosted ion

$$\gamma_i + |g\rangle \to |e\rangle \to |g\rangle + \gamma_f$$



Lorentz boost $E = \gamma M$

e.g. $\gamma \sim 10^3$ @LHC

Level splitting: E_{eg}

binding energy of H-like ion $= (Z^2/n^2) 13.6 \text{ eV}$

Resonance condition: $2\gamma\omega_i \simeq E_{eg}$ $\quad \omega_i \sim$ 1-10 eV

$\longrightarrow$ $Z^2/2\gamma \sim$ 0.1-1

heavy ion

Up-conversion:

$$\omega_f^{\max} \simeq 2\gamma E_{eg} \simeq 4\gamma^2\omega_i \sim 0.1\text{-}1 \text{ GeV} (2\gamma/10^4)^2$$

昨年度の領域研究会での報告

resonant Rayleigh scattering with boosted ions

$$\gamma_{\rm tw} + I \to I^* \to I + \gamma_{\rm tw}$$

D. Budker et al. Ann. Phys. (Berlin) 532, 2000204 (2020)
MT, N. Sasao, Int. J. Mod. Phys. E 30, 06, 2150040 (2021)

Ion beam

resonant Rayleigh scattering $\sigma \propto \lambda^2 \sim \frac{1}{(Z^2\alpha^2 m_e)^2}$

Electron beam

Thomson/Compton scattering $\sigma \propto r_0^2 = \left(\frac{\alpha}{m_e}\right)^2$

Larger cross section of ions

→ twisted gamma rays from boosted ions

Twisted gamma rays from boosted H-like ions

$$\gamma_{\rm tw} + I \to I^* \to I + \gamma_{\rm tw}$$

Excitation to states of larger angular momentum

Ex. $1\mathrm{s}_{1/2} \to 3\mathrm{d}_{5/2}(|m| = 5/2)$

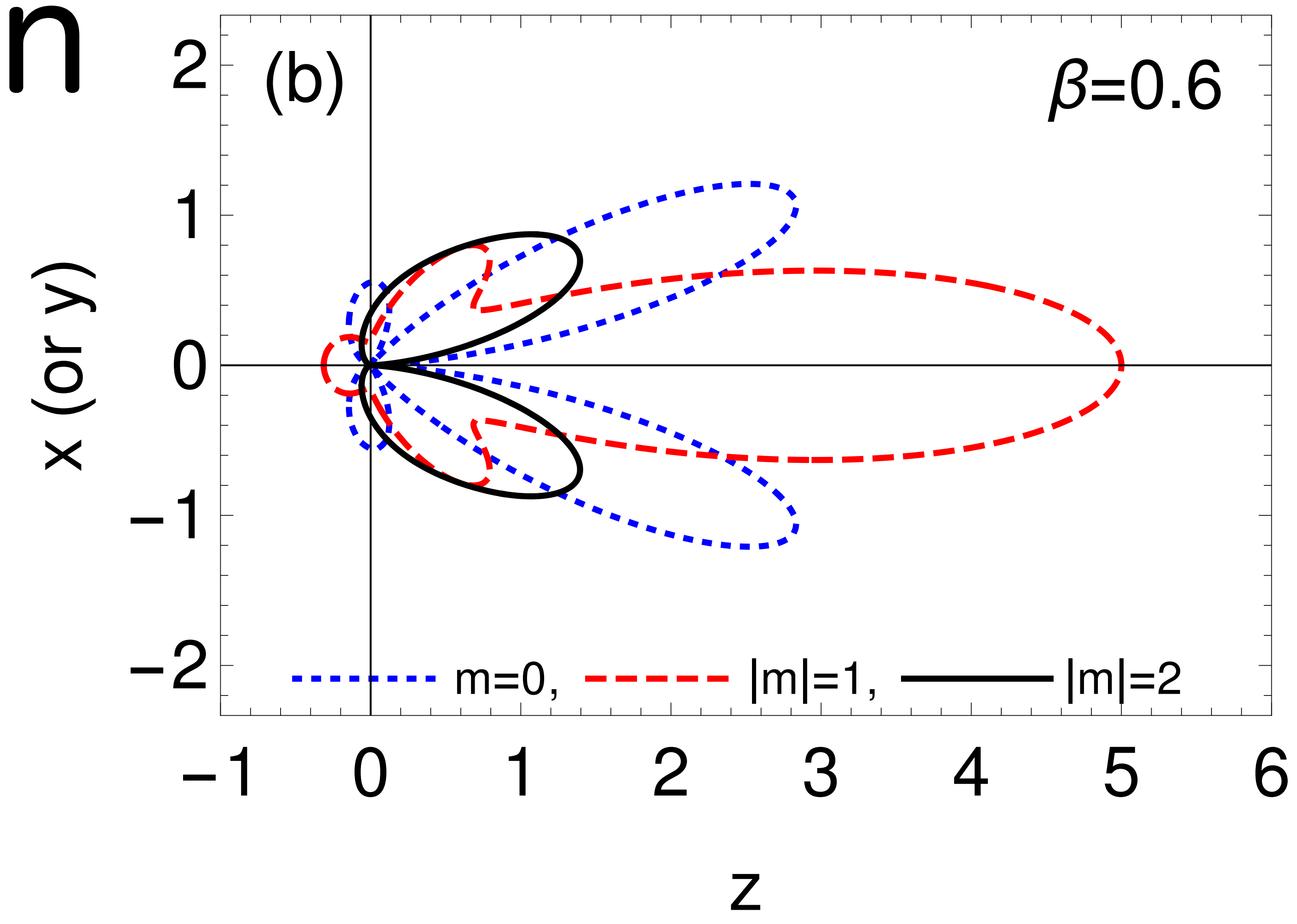
forbidden in single PW photon absorption

allowed in single TW photon absorption

Deexcitation with twisted photon emission

$3\mathrm{d}_{5/2}(|m| = 5/2) \to 1\mathrm{s}_{1/2}$

E2 transition



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問題点: 背景事象 $1\mathrm{s}_{1/2}(m_i = 1/2) \to 3\mathrm{d}_{5/2}(m_f = 3/2)$

解決法: 衝突点付近で磁場を印加

Stark効果でm_f=5/2を選択励起

spin rotatorが必要

2光子遷移による光渦生成

高角運動量状態への励起

2光子吸収 $\gamma_{\rm pw} + \gamma_{\rm pw} + I \to I^*$

ラマン過程 $\gamma_{\rm pw} + I \to I^* + \gamma_{\rm pw}$

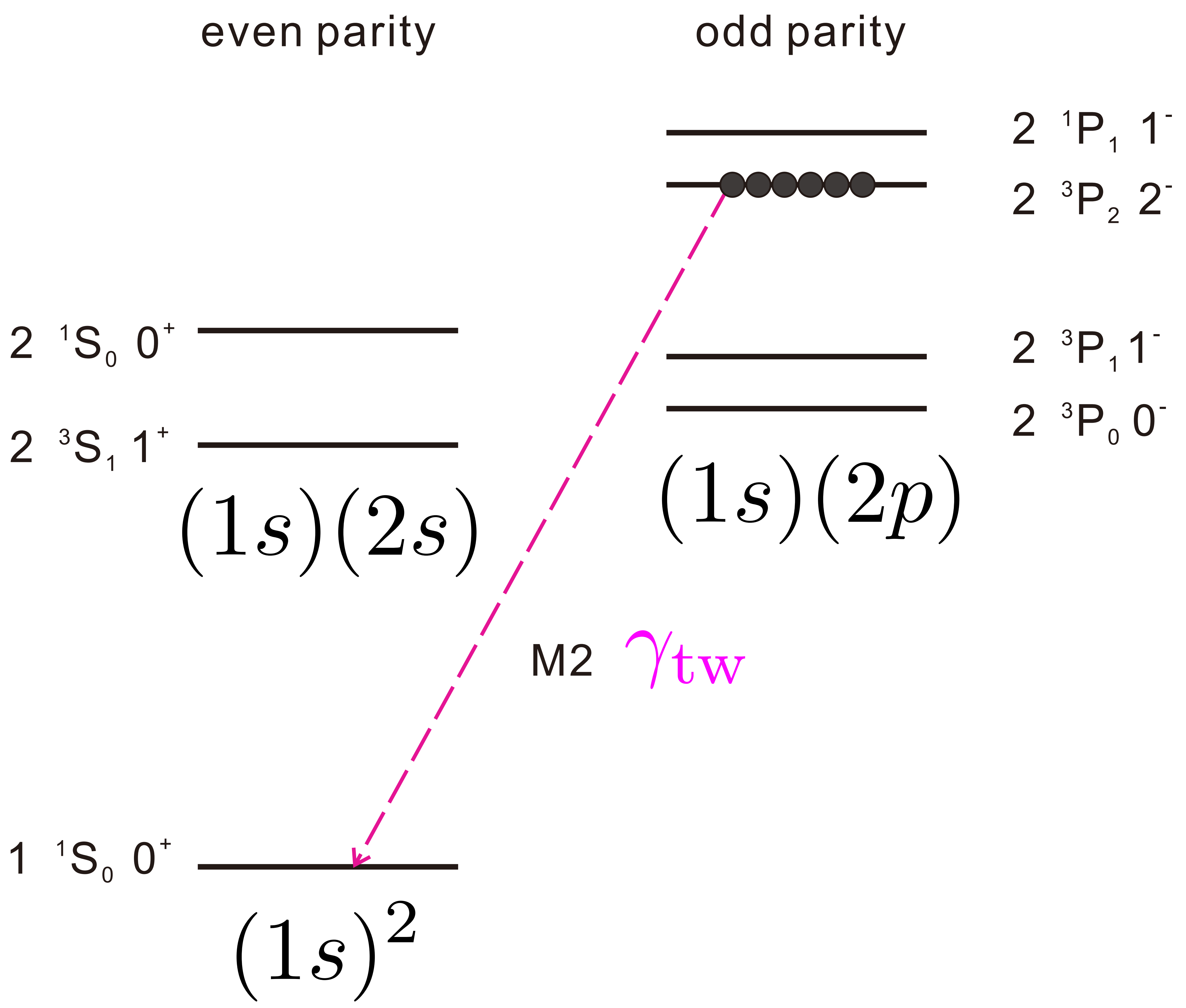
Stimulated Adiabatic Raman Passage (STIRAP)

efficient population transfer

脱励起による光渦生成: $I^* \to I + \gamma_{\rm tw}$

ヘリウム様イオンを想定

Twisted photon from He-like ions



$$(1s)(2p)\,{}^3\mathrm{P}_2 \to (1s)^2\,{}^1\mathrm{S}_0 + \gamma_{\rm tw}$$
$$(m = 2)$$

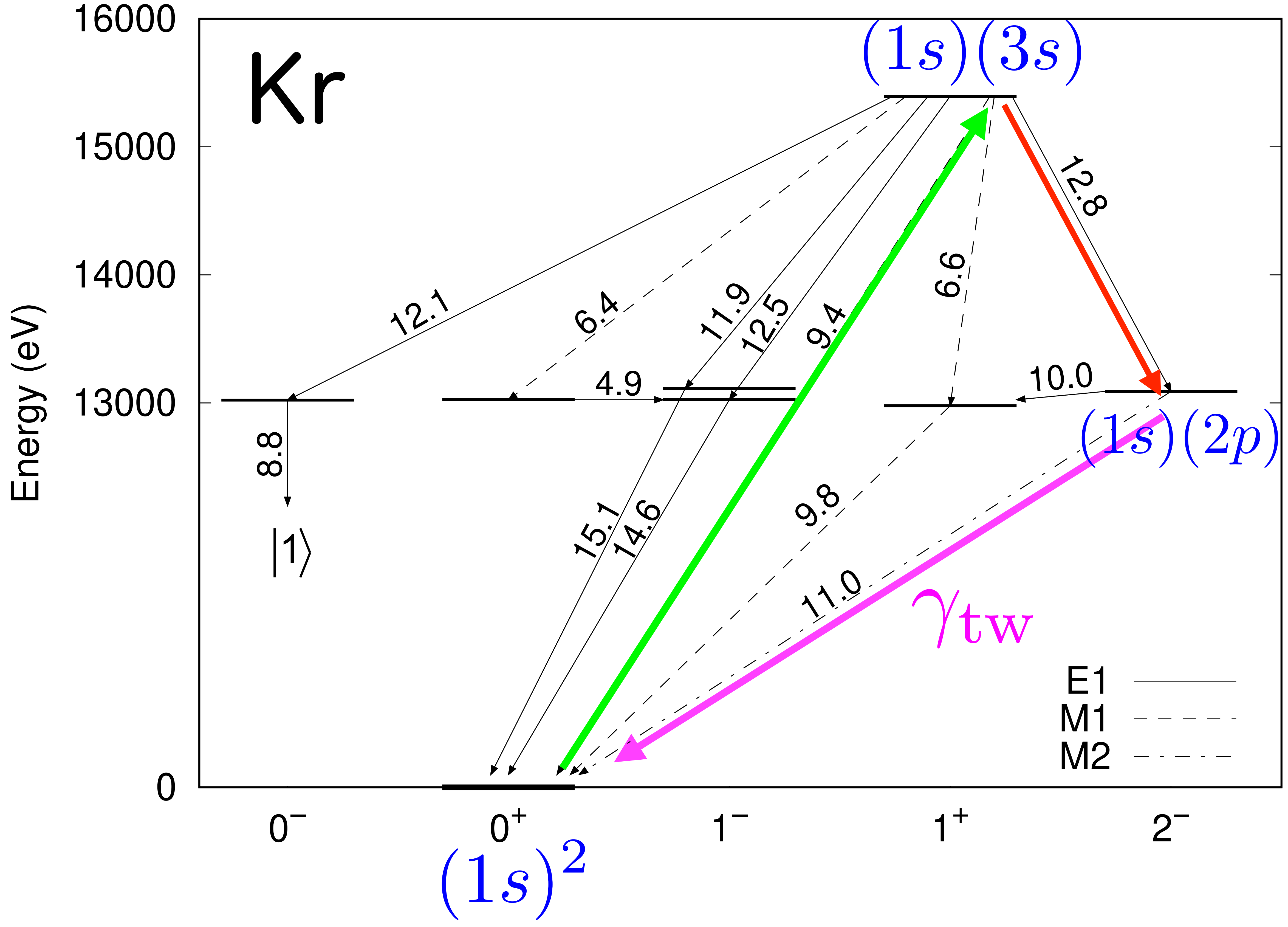
M2 transition dominates.

$\propto Z^8$ heavy ions

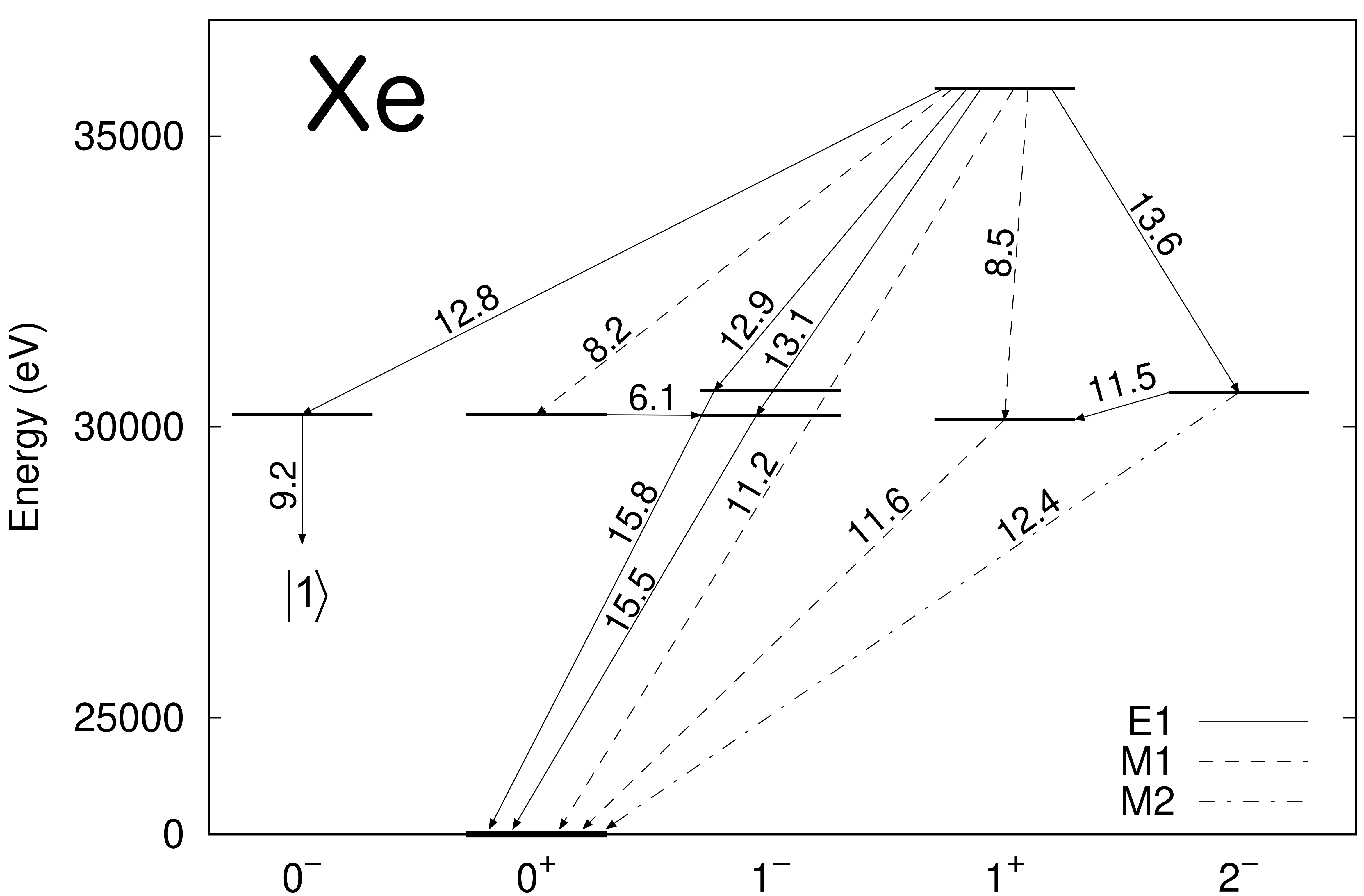
Kr (Z=36), Xe (Z=54) studied

Levels and transitions of He-like ions

Calculation by GRASP2018(MCDHF+RCI)

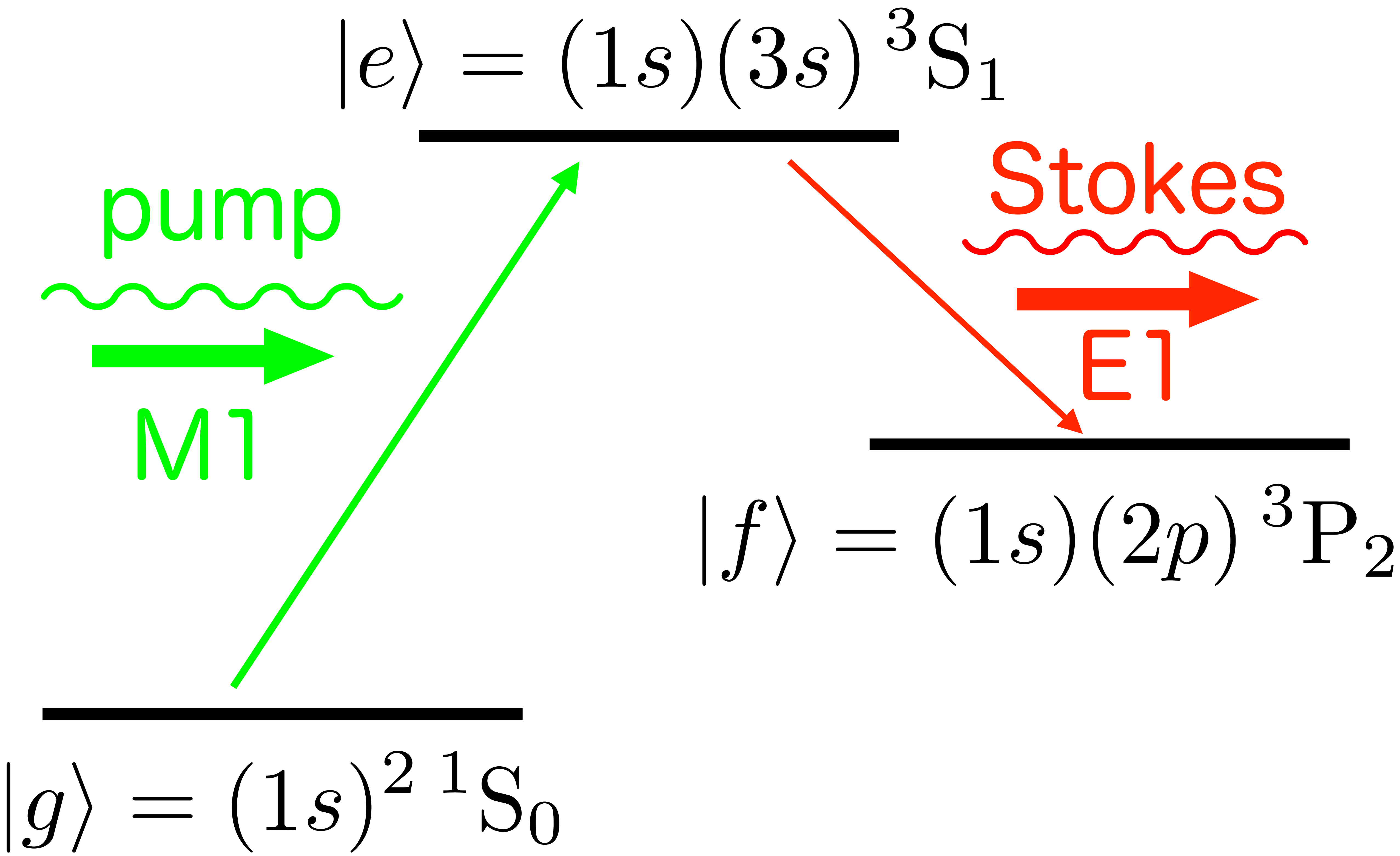


$E_{\gamma_{\rm tw}} = 65.4$ MeV $(\gamma_{\rm ion} = 2500)$



$E_{\gamma_{\rm tw}} = 306$ MeV $(\gamma_{\rm ion} = 5000)$

Excitation scheme by STIRAP



Rabi freq. for 1W/mm^2

Transitions		Type	Kr [s^{-1}]	Xe [s^{-1}]
Ω_p	$\lvert g\rangle \to \lvert e\rangle$	M1	5.570×10^4	1.276×10^5
Ω_s	$\lvert e\rangle \to \lvert f\rangle$	E1	3.935×10^7	2.882×10^7

pulse profile

Kr

pump, Stokes: opposite circular pol.

Outline of numerical calculation

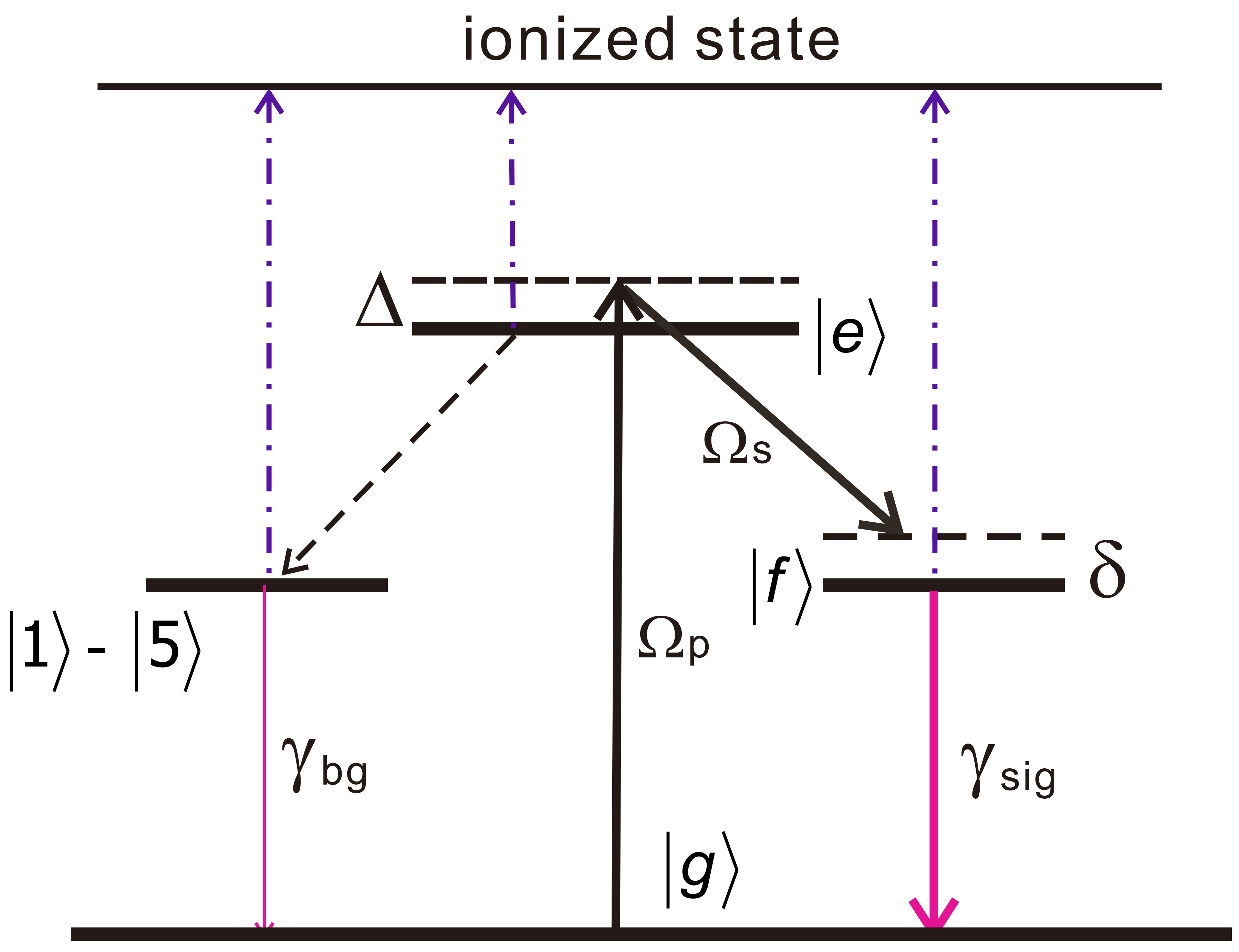
Optical Bloch Equation

$$|g\rangle = (1s)^2\,{}^1\mathrm{S}_0\,,\ |e\rangle = (1s)(3s)\,{}^3\mathrm{S}_1\,,\ |f\rangle = (1s)(2p)\,{}^3\mathrm{P}_2$$

and all other (1s)(2s) and (1s)(2p) states involved

photo-ionization included

Parameter	Symbol	Kr	Xe	units
Lorentz boost factor	γ_{ion}	2500	5000	-
Pump laser wavelength	λ_p	403	346	nm
Pump laser intensity	$I_p(0)$	4×10^5	4×10^5	$\mathrm{W/mm^2}$
Stokes laser wavelength	λ_s	2690	2371	nm
Stokes laser intensity	$I_s(0)$	4×10^5	4×10^5	$\mathrm{W/mm^2}$
Laser pulse width	σ_L	1.0	1.0	nsec
Laser pulse delay	t_d	0.5	0.5	nsec
Pump laser detuning	Δ	5	5	$\Gamma_e^{(tot)}$
Two-photon detuning	δ	0	0	$\Gamma_e^{(tot)}$



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Results (Kr)

Population

Kr

$|f\rangle$

$|e\rangle$

$$|1\rangle = (1s)(2s)\,{}^3\mathrm{S}_1$$

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Signal, background, photo-ionization

Kr

BG photons:
from other 2s, 2p to 1s

B/S=5.6 %

Ion beam lifetime due to photo-ionization~10^5 sec.
(周長30kmのリングを仮定)

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まとめ

- He様イオンの励起と脱励起によるガンマ線光渦の生成

  STIRAP $(1s)^2\,{}^1\mathrm{S}_0 \to (1s)(2p)\,{}^3\mathrm{P}_2\,,$ M2遷移脱励起

- シグナル 65.4(306)MeV for Kr(Xe) of boost 2500(5000)

  10^9 ions/bunch $\to$ $2.3(5.8)\ \times 10^8$ Hz/bunch $\quad C_{\mathrm{ring}} = 30$ km

- バックグラウンド，イオン化ロス

  $B/S = 5.6(19.2)\%\,,$ loss fraction $= 6.9(11) \times 10^{-10}$

- 今後の展望

  Physics applications: nuclear, astro, plasma etc.

  Comparison with electron beam