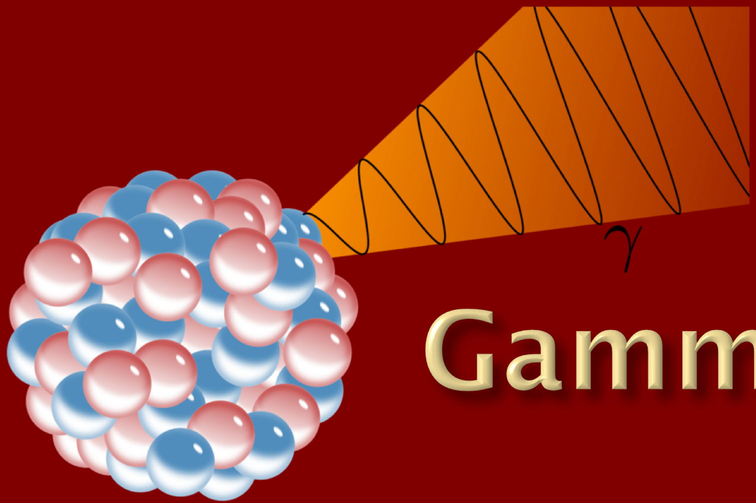
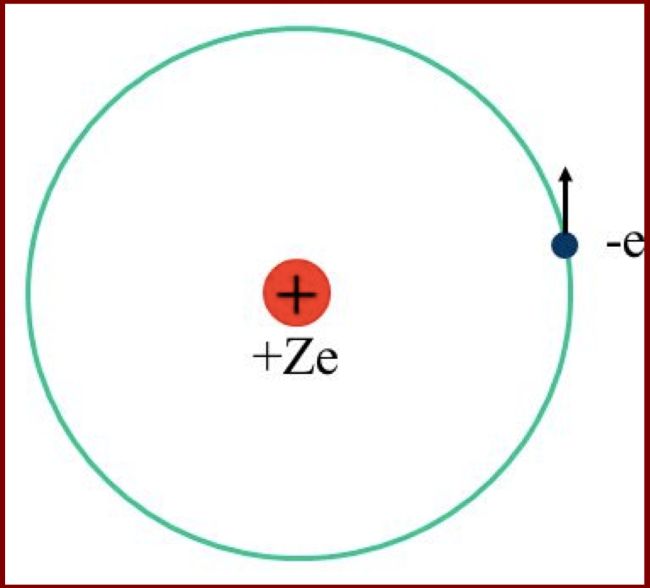



# Gamma-Ray Sources with Partially Stripped Ions

*basics*





**Dmitry Budker**

Helmholtz Institute
JGU Mainz

UC Berkeley Physics
NSD LBNL


CERN, 27 March 28, 2019

# My Qualifications to give this talk

1. I am a GF enthusiast:

**My** **is gamma factory!**

2. Co-authored: ***Atomic physics with highly-charged heavy ions and atomic-physics inspired nuclear physics at the Gamma Factory*** with A. Derevianko, M. Zolotorev, V. Flambaum, S. Pustelny, and A. Surzhykov
3. Provided critique of the draft of the Bessonov *et al* paper
4. Co-authored a related paper 22 years ago!

VOLUME 78, NUMBER 25 PHYSICAL REVIEW LETTERS 23 JUNE 1997

# Parity Nonconservation in Relativistic Hydrogenic Ions

M. Zolotorev and D. Budker

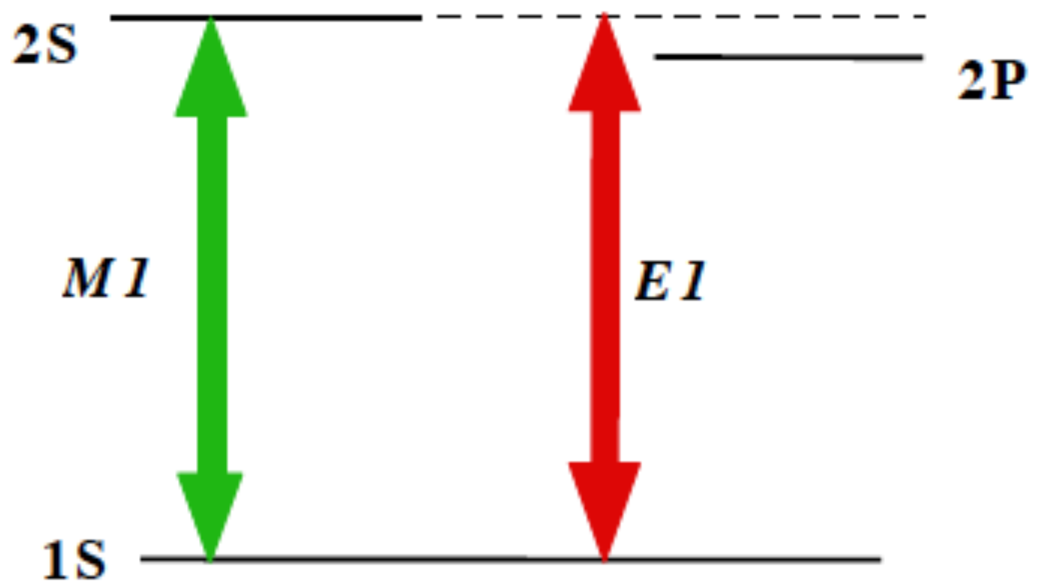



Fig. 1. The 1S→2S transition in a hydrogenic system.

## Parity Violation

☞ level-mixing

$$|2S\rangle \Rightarrow |2S\rangle + i\eta|2P\rangle, \qquad i\eta = \frac{\langle 2P|\hat{H}_w|2S\rangle}{E_{2S} - E_{2P}}$$

☞ circular dichroism

Table 2. Parameters of relativistic ion storage rings.

| Parameter | RHIC | SPS | LHC |
|---|---|---|---|
| $\gamma_{max}$ for protons[a] | 250 | 450 | 7000 |
| Number of ions/ring[b] | $\sim 5\cdot 10^{11}$ | $\sim 2\cdot 10^{11}$ | $\sim 5\cdot 10^{10}$ |
| Number of bunches/ring | 57 | 128 | 500-800 |
| R.m.s bunch length | 84 cm | 13 cm | 7.5 cm |
| Circumference | 3.8 km | 6.9 km | 26.7 km |
| Energy spread w/o laser cooling | $2\cdot 10^{-4}$ | $4.5\cdot 10^{-4}$ | $2\cdot 10^{-4}$ |
| Normalized Emittance (N.E.) | $\approx 4\ \pi\cdot\mu m\cdot rad$ | $\approx 4\ \pi\cdot\mu m\cdot rad$ | $\approx 4\ \pi\cdot\mu m\cdot rad$ |
| Dipole field | 3.5 T | 1.5 T | 8.4 T |
| Vacuum, cold | $<10^{-11}$ Torr ($H_2$, He) | - | $<10^{-11}$ Torr ($H_2$, He) |

[a] For hydrogenic ions, $\gamma_{max}^{ions} = \gamma_{max}^{p} \cdot Z-1/A$

[b] Estimated from proton and heavy ion data.

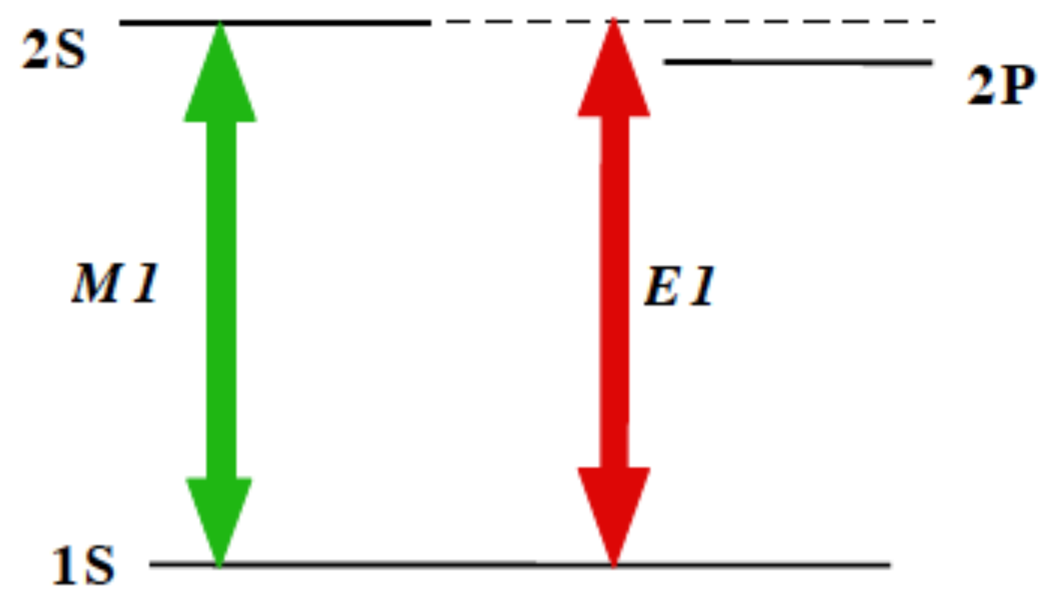


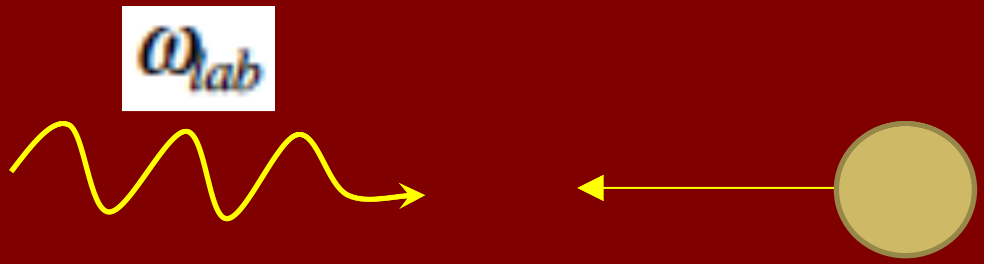
Fig. 1. The 1S→2S transition in a hydrogenic system.

Table 1: *Z*-dependence of atomic characteristics for hydrogenic ions. In the given expressions, $\alpha$ is the fine structure constant, $\hbar$=c=1, $m_e$ is the electron mass, $G_F$ is the Fermi constant, $\theta_w$ is the Weinberg angle, and *A* is the ion mass number.

| Parameter | Symbol | Approximate Expression |
|---|---|---|
| Transition Energy | $\Delta E_{n-n'}$ | $\frac{1}{2}\left(\frac{1}{n^2}-\frac{1}{n'^2}\right)\alpha^2 m_e \cdot Z^2$ |
| Lamb Shift | $\Delta E_{2S-2P}$ | $\frac{1}{6\pi}\alpha^5 m_e \cdot Z^4 \cdot F(Z)^a$ |
| Weak Interaction Hamiltonian | $\hat{H}_w$ | $i\sqrt{\frac{3}{2}}\cdot\frac{G_F m_e^3\alpha^4}{64\pi}\cdot\left\{(1-4\sin^2\theta_w)-\frac{(A-Z)}{Z}\right\}\cdot Z^5$ |
| Electric Dipole Amplitude (2S→2P$_{1/2}$) | $E1_{2S\to 2P}$ | $\sqrt{\frac{3}{\alpha}}\cdot m_e^{-1}\cdot Z^{-1}$ |
| Electric Dipole Amplitude (1S→2P$_{1/2}$) | $E1$ | $\frac{2^7}{3^5}\sqrt{\frac{2}{3\alpha}}\cdot m_e^{-1}\cdot Z^{-1}$ |
| Forbidden Magn. Dipole Ampl. (1S→2S) | $M1$ | $\frac{2^{5/2}\alpha^{5/2}}{3^4}\cdot m_e^{-1}\cdot Z^2$ |
| Radiative Width | $\Gamma_{2P}$ | $\left(\frac{2}{3}\right)^8\alpha^5 m_e\cdot Z^4$ |

[a] The function *F(Z)* is tabulated in Ref. 12. Some representative values are: *F*(1)=7.7; *F*(5)=4.8, *F*(10)=3.8; *F*(40)=1.5 .

# Relativistic Doppler Tuning



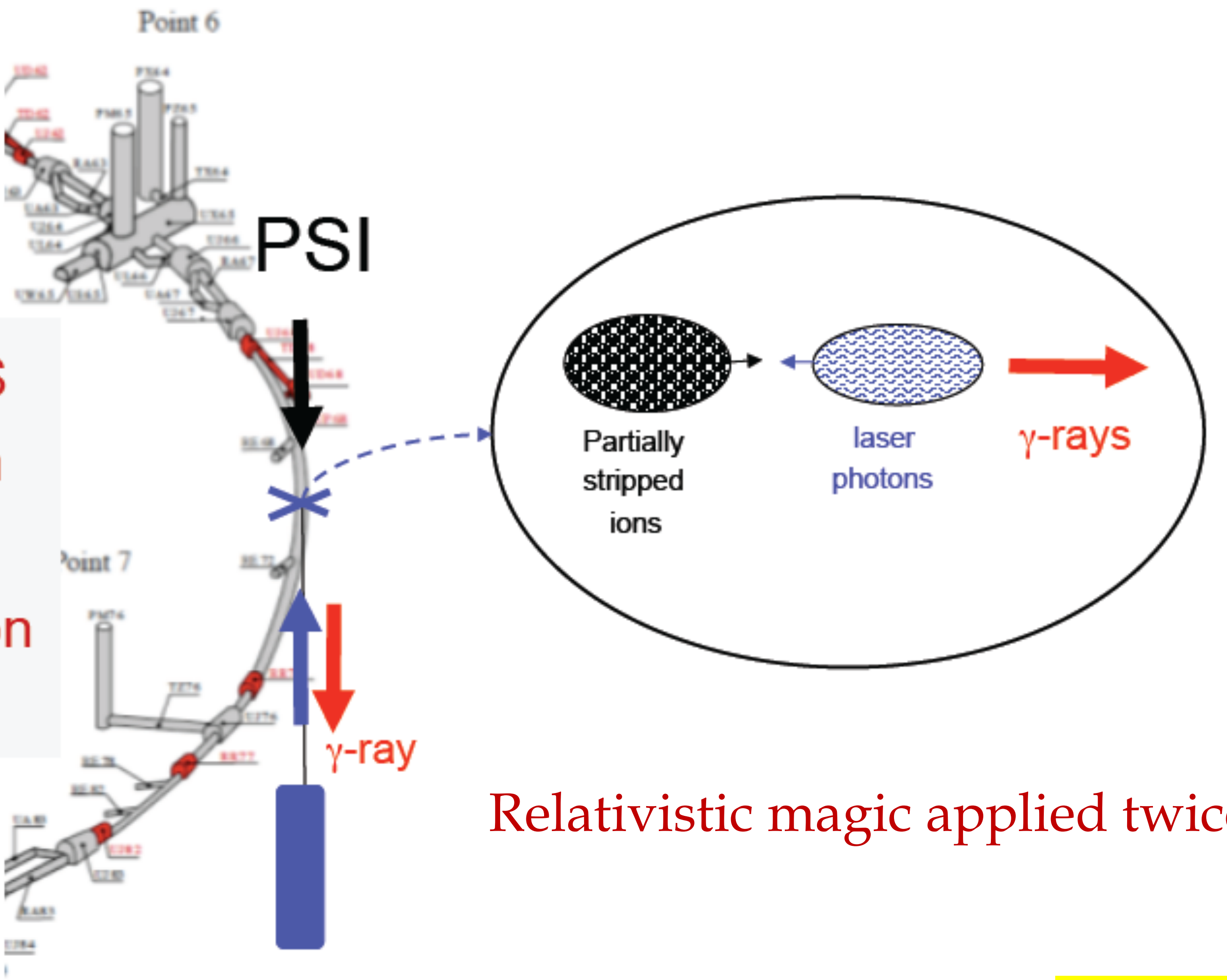

$$\omega_{ion\,frame} = \gamma(1+\beta)\omega_{lab} \approx 2\gamma\omega_{lab}$$

Resonance condition: $\Delta E_{1S-2P} \approx Z^2\, 10.2\ \text{eV} = 2\gamma\hbar\omega_{lab}$

With LHC ($\gamma \approx 3000$): up to Z=48 (Cd)
(for 1s→2p in hydrogenic ion)

# The γ-ray source scheme for CERN

LHC/SPS filled with partially stripped ion bunches




Laser photon

Relativistic magic applied twice!

Witek Krasny

# Gamma Factory @ CERN

Partially Stripped Ion beam as
a light frequency converter

$$\nu^{max} \longrightarrow (4\,\gamma_L^2)\;\nu_i$$

*Tuning of the beam energy, the choice of the ion type, the number of left electrons and of the laser type allows to tune the $\gamma$-ray energy, at CERN, in the energy domain of 100 keV – 400 MeV.*

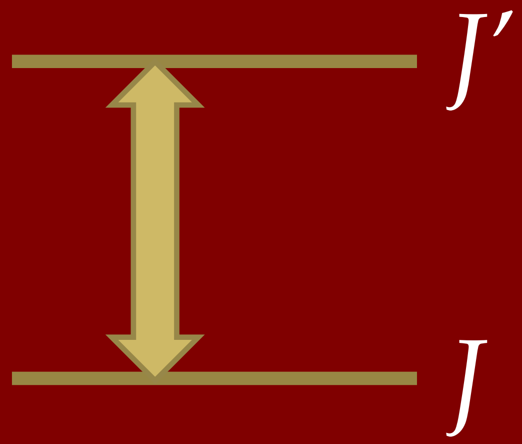
*Example (maximal energy):*

*LHC*, $Pb^{80+}$ *ion*, $\gamma_L = 2887$, n=1→2, $\lambda = 104.4$ nm, $E_\gamma$(max) = 396 MeV

Witek Krasny

# Basics of laser-driven transitions in PSI

- Resonant cross-section:




$$\sigma_{abs} = \frac{\lambda^2}{2\pi} \cdot \frac{2J'+1}{2J+1} \cdot \frac{\Gamma_p}{\Gamma_{tot}}$$

Note: Rabi oscillations picture is equivalent!

$\hbar = 1$

- 1s→2p in PSI: $\lambda \approx 122\ \mathrm{nm}/Z^2$

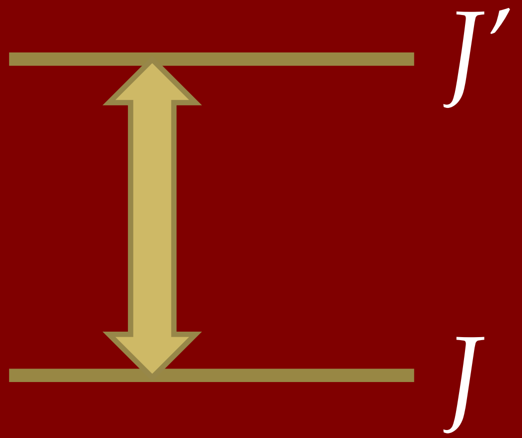
- Transition rate: $\sigma_{abs} \cdot \Phi = \sigma_{abs} \cdot \frac{\dot{N}_{phot}}{\lambda_{laser} \cdot \frac{z_R}{2}} = \frac{d^2 E^2}{\Gamma_p}$

Example: $\lambda_{laser} = 1\ \mu\mathrm{m}$, $z_R = 1\ \mathrm{m} \rightarrow \lambda_{laser} \cdot \frac{z_R}{2} \approx 0.5\ \mathrm{mm}^2$

# Basics of laser-driven transitions in PSI

- Doppler broadening: $\Gamma_D = 2\delta\gamma \cdot \omega_{laser} = \frac{\delta\gamma}{\gamma} \cdot (2\gamma\omega_{laser}) = \frac{\delta\gamma}{\gamma} \cdot \omega_0$

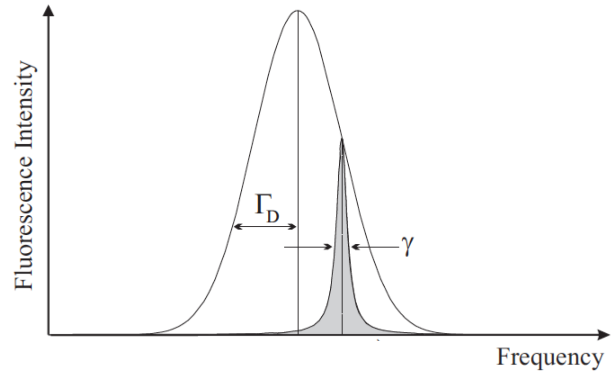
- Fraction of resonant ions: $\Gamma_p / \Gamma_D$ (for $\Gamma_p < \Gamma_D$)




- 1s→2p in PSI: $\frac{\Gamma_p}{\omega_0} \approx 4 \cdot 10^{-8}\, Z^2$

- Resonant-transition rate:

$$\sigma_{abs} \cdot \Phi = \sigma_{abs} \cdot \frac{\dot{N}_{phot}}{\lambda_{laser} \cdot z_R/2}$$



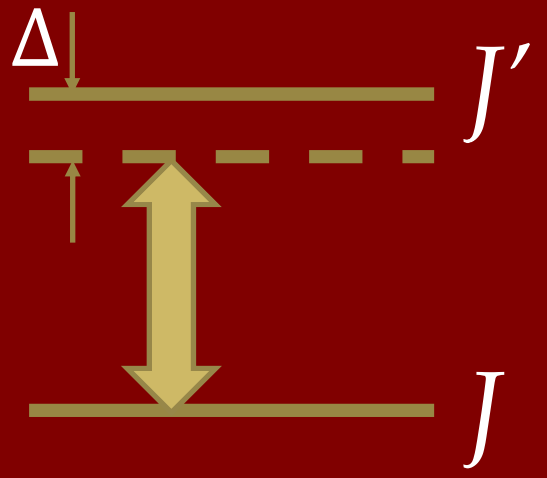

When narrow-band excitation light is tuned to frequency $\omega$ within a Doppler-broadened profile, the fluorescence is due to a particular group of atoms with velocities $\vec{v}$ whose Doppler shifts are $\lesssim \gamma$.

# What happens if light is off resonance?

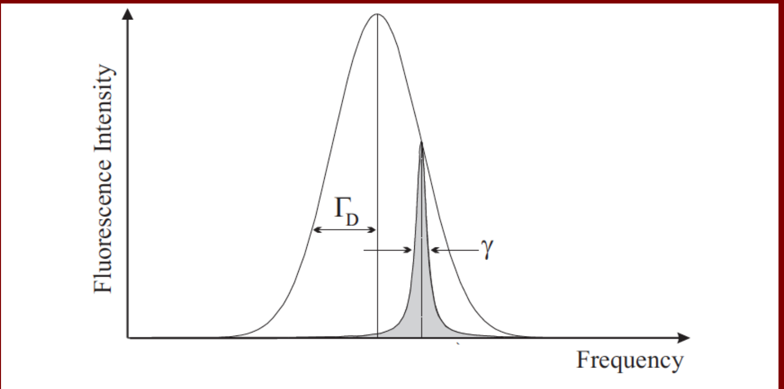
- ⇒ There is still population in upper state:

Off resonance: $\frac{d^2E^2}{4\Delta^2}$ On resonance: $\frac{d^2E^2}{\Gamma_p^2}$

Off resonance: $\frac{d^2E^2}{4\Delta^2}\Gamma_p$ On resonance: $\frac{d^2E^2}{\Gamma_p^2}\Gamma_p$



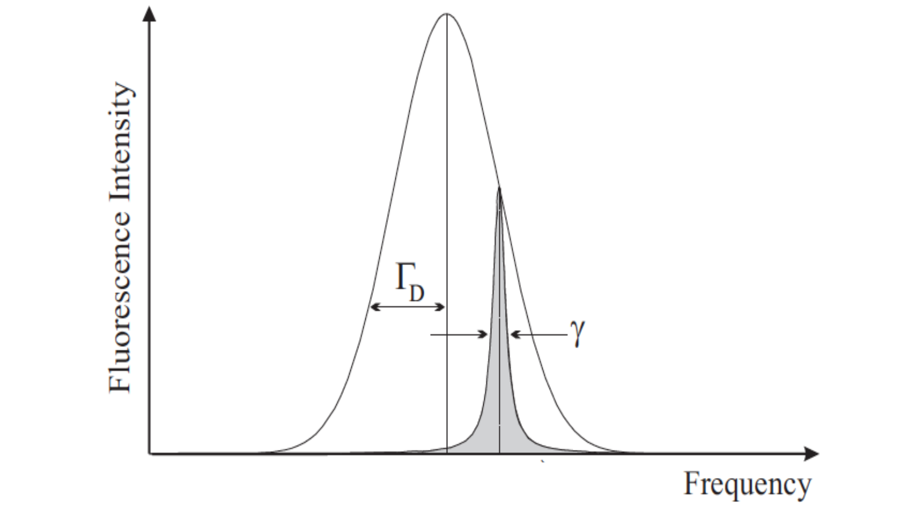

- Homogeneous and inhomogeneous **broadening**




When narrow-band excitation light is tuned to frequency $\omega$ within a Doppler-broadened profile, the fluorescence is due to a particular group of atoms with velocities $\vec{v}$ whose Doppler shifts are $\lesssim \gamma$.

# How to excite a distribution of PSI ?

- With narrow-band light (good)
- With broadband light (better)
- With chirped light (the best)
- This was discussed by Simon Rochester




When narrow-band excitation light is tuned to frequency $\omega$ within a Doppler-broadened profile, the fluorescence is due to a particular group of atoms with velocities $\vec{v}$ whose Doppler shifts are $\lesssim \gamma$.

# Laser cooling of PSI

$\gamma_0 = \Gamma_p$
I am sorry…

- Let us talk about 1D optical molasses first


Photon scattering rate:

$$R_{\pm} = \frac{\kappa\gamma_0}{1 + \left(1 \pm \frac{2\omega}{\gamma_0}\frac{v}{c}\right)^2}$$

Momentum kick:

$$\Delta p_{\pm} = \pm\hbar\frac{\omega}{c}$$

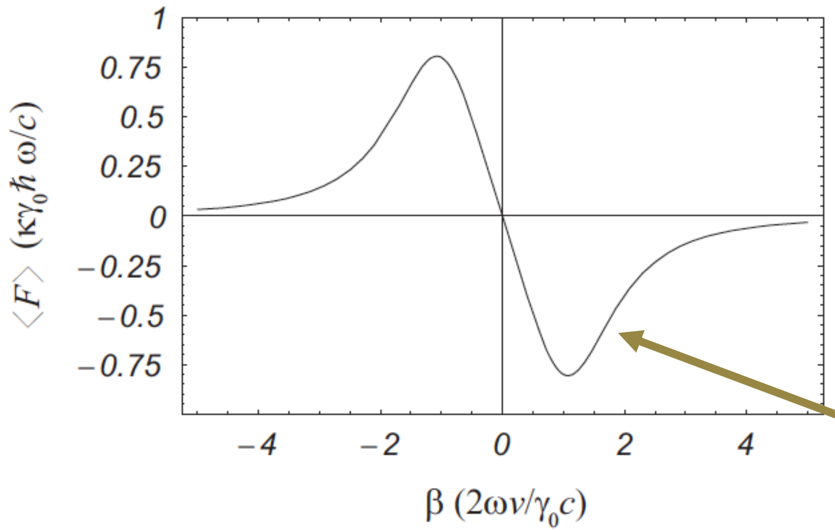



**Fig. 6.2** Velocity-dependent force for a one-dimensional optical molasses in the regime where $\Gamma_D \lesssim \gamma_0$. Note that atoms experience a force which opposes their motion, and in the range $|v| \ll \gamma_0 c/(2\omega)$ it is a linear restoring (spring) force in velocity space.

Average force:

$$\langle F\rangle = \Delta p_+ R_+ + \Delta p_- R_-$$
$$= \frac{\kappa\gamma_0\hbar\omega}{c}\left[\frac{1}{1+(1+\beta)^2} - \frac{1}{1+(1-\beta)^2}\right]$$

- Q: What is the final temperature?

# Q: What is the final temperature?

When $\Gamma_D = \Gamma_p \; (= \gamma_0)$

$$T^* \sim \gamma_0^2 \frac{Mc^2}{2k_B\omega_0^2}\,.$$

But one can go much colder!

# Doppler Limit

- Equilibrium temperature: balance of cooling and heating

$$\bar{v} = \frac{\sqrt{\langle p^2 \rangle}}{M}$$

$$E = \frac{k_B T}{2} = \frac{\langle p^2 \rangle}{2M}$$

$$\frac{\partial}{\partial t}\langle p^2 \rangle\Big|_{\text{heat}} \approx 2\kappa\gamma_0 \frac{\hbar^2\omega^2}{c^2}$$

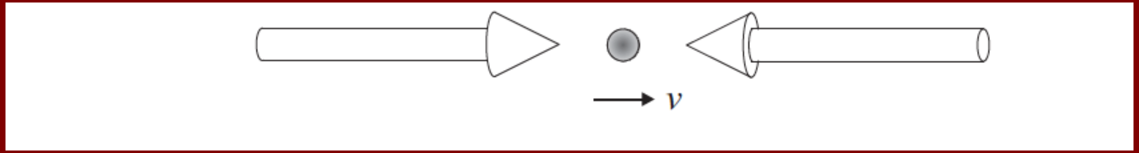
$$\frac{\partial E}{\partial t}\Big|_{\text{cool}} = \langle F \rangle \bar{v} \approx -2\hbar\omega^2 \kappa \frac{\bar{v}^2}{c^2}$$

$$\frac{\partial E}{\partial t}\Big|_{\text{heat}} = \kappa\gamma_0 \frac{\hbar^2\omega^2}{Mc^2}$$

$$\frac{\partial E}{\partial t}\Big|_{\text{cool}} + \frac{\partial E}{\partial t}\Big|_{\text{heat}} = 0 \quad \Rightarrow \quad \frac{1}{2}M\bar{v}^2 = \frac{\hbar\gamma_0}{4}$$

$$T_D = \frac{\hbar\gamma_0}{2k_B},$$

- Doppler limit holds for PSI



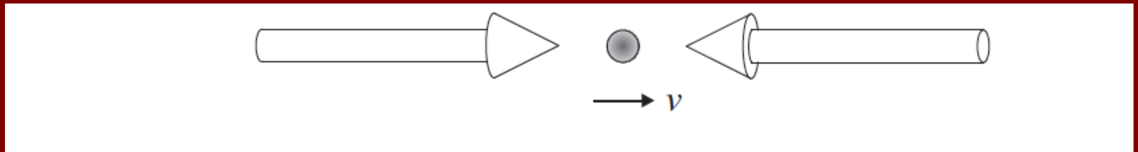
# Single-Photon-Recoil Limit

$$T_\gamma \sim \frac{\hbar^2\omega^2}{2k_B M c^2} ,$$

$$T_D = \frac{\hbar\gamma_0}{2k_B} ,$$

$$T^* \sim \gamma_0^2 \frac{Mc^2}{2k_B\omega_0^2} .$$

$$T_D^2 = T^* T_\gamma .$$



# Cooling PSI

- Only one laser beam

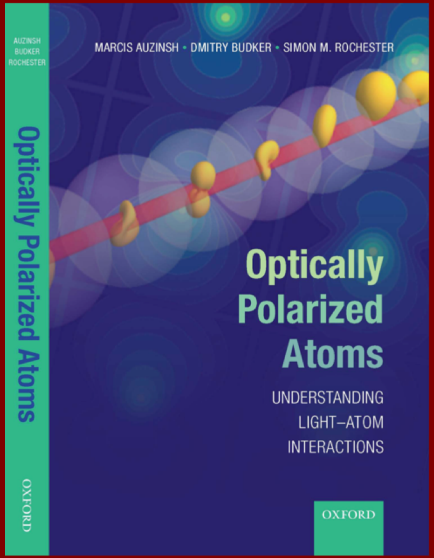
- PSI are not free ⇒ accelerator dynamics important

- It works! since 1990s

- Doppler Limit for PSI: $$\left(\frac{\Delta\gamma}{\gamma}\right)_D = \sqrt{\frac{\Gamma_{2P}}{M_{ion}}}$$
  scales as $Z^{3/2}$

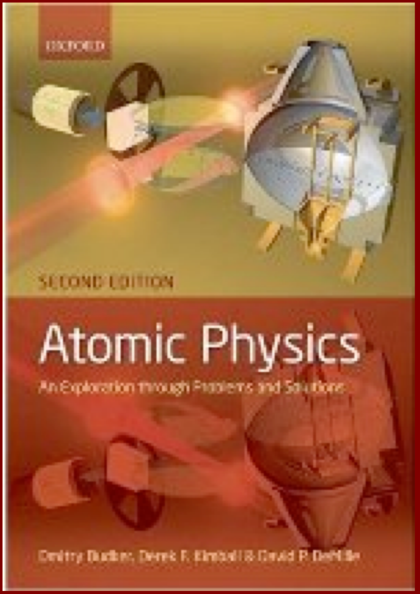
- Cooling dilemma: avoid photoionization but overcome heating due to intrabeam scattering

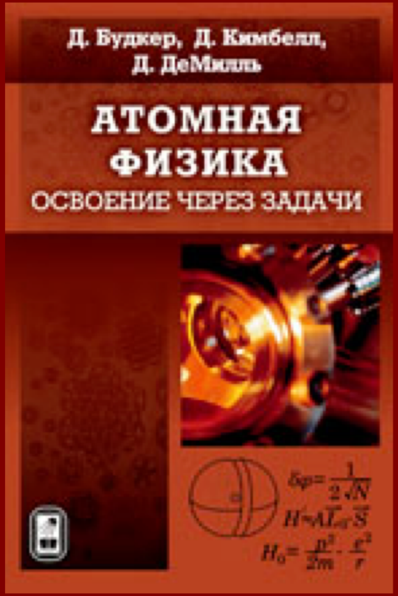
# Further reading on basics



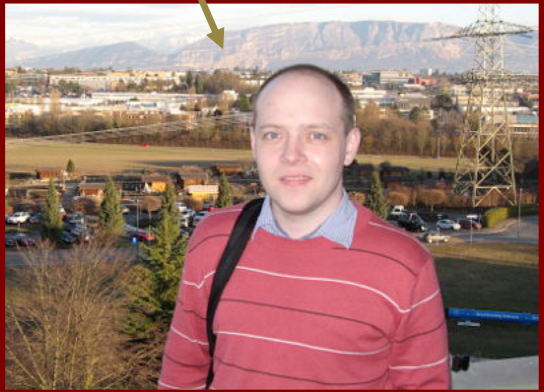

Fundamentals of gamma-ray light sources (Gamma Factory) based on backward resonance scattering of laser photons from relativistic ion beams

E. Bessonov, P. Antsiferov, W. Krasny, A. Petrenko, D. Budker, S. Pustelny







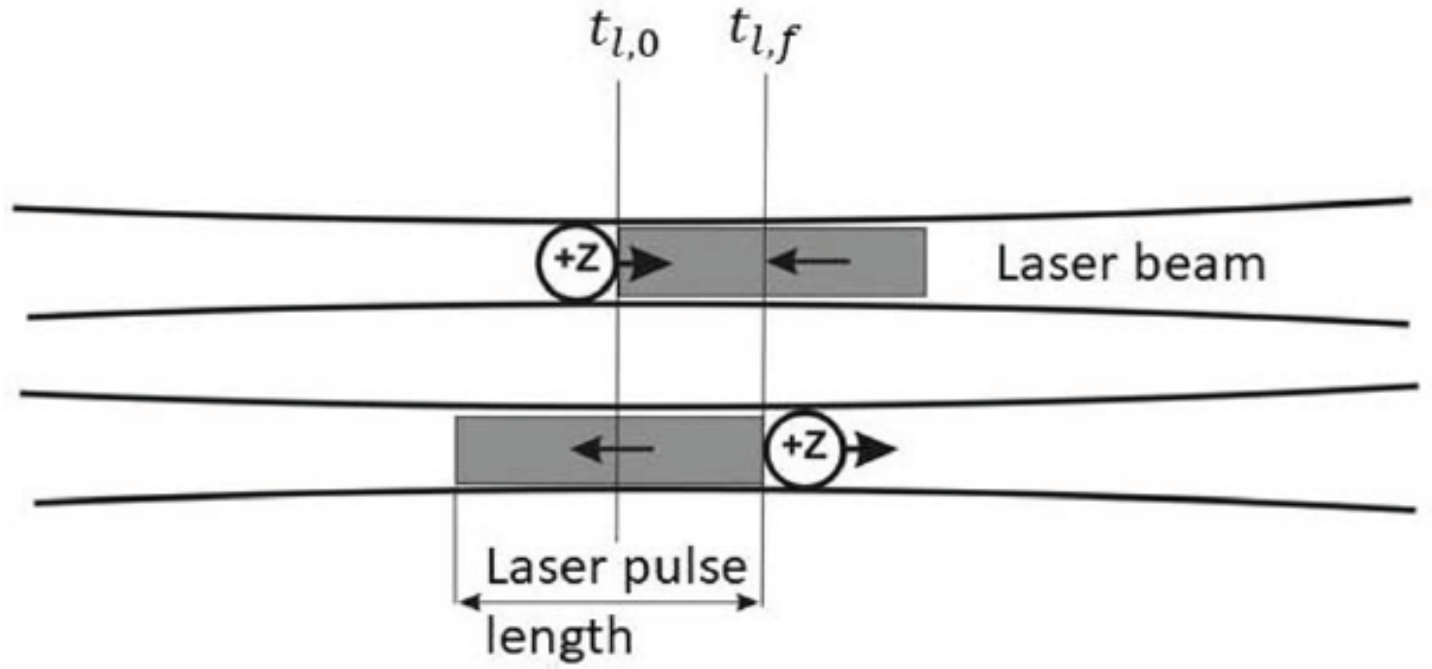



Figure 1: The ion-laser pulse interaction in the laboratory reference frame.

# Things to worry about with PSI

- Ionization on residual gas $\sigma = 4\pi\alpha^2 a_B^2 \frac{Z_a(Z_a+1)}{Z^2}$
- Field ionization $\tau_{f.i.}^{-1} = 4\frac{\alpha c}{a_B} Z^5 \frac{\varepsilon_{at}}{B_D} \exp\left(-\frac{2\varepsilon_{at} Z^3}{3\gamma B_D}\right)$
- Photoionization from 2P (and for Z>40, also 2S)

also

- Need laser cooling to reduce $\frac{\Delta\gamma}{\gamma}$ ⇒ laser cooling
- Is the required laser realistic?

# More things to worry about…

- How to detect the PV transition? Absorption cavity?
- Systematics due to stray *E*-field mixing
- *E*-field due to the ions' space charge
- Laser cooling should be faster than intrabeam scatt.