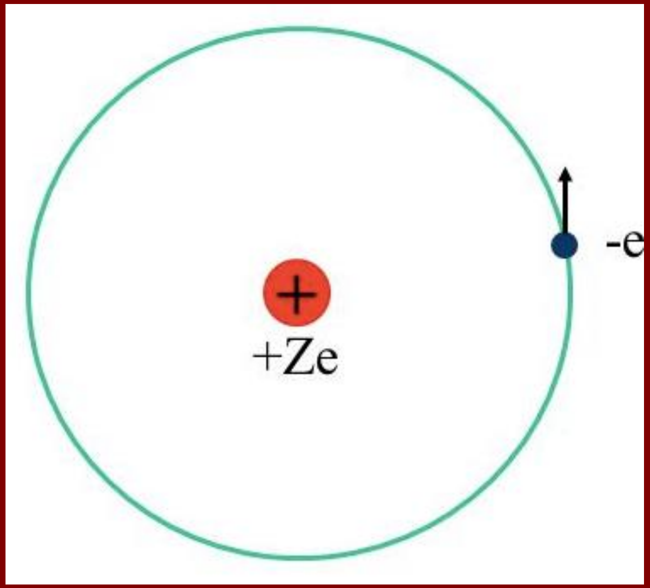
Atomic Physics with Partially Stripped Ions



Dmitry Budker
Helmholtz Institute
JGU Mainz
UC Berkeley Physics
NSD LBNL

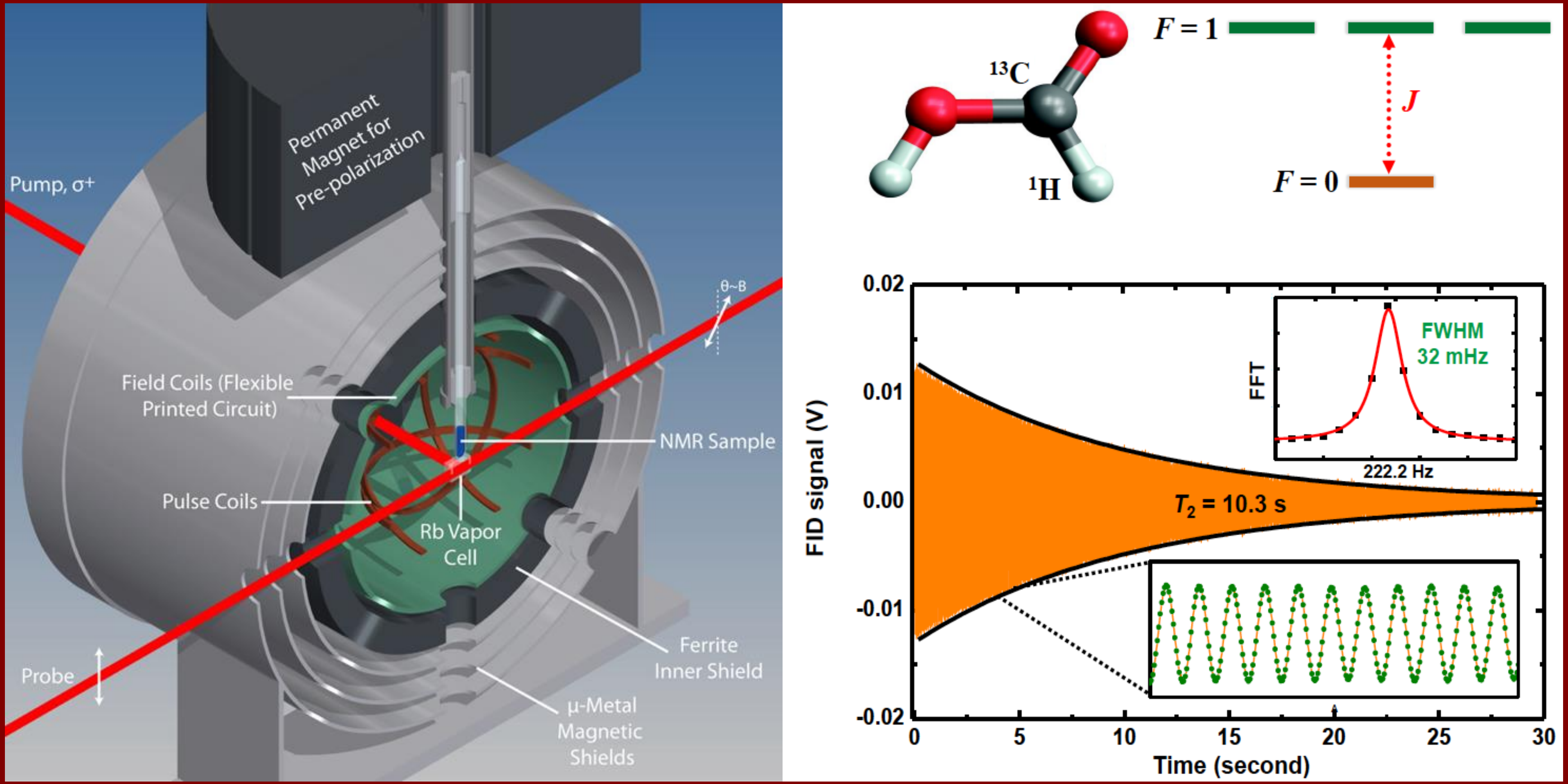
Padova, November 28, 2017

Global Network of Optical Magnetometers for Exotic

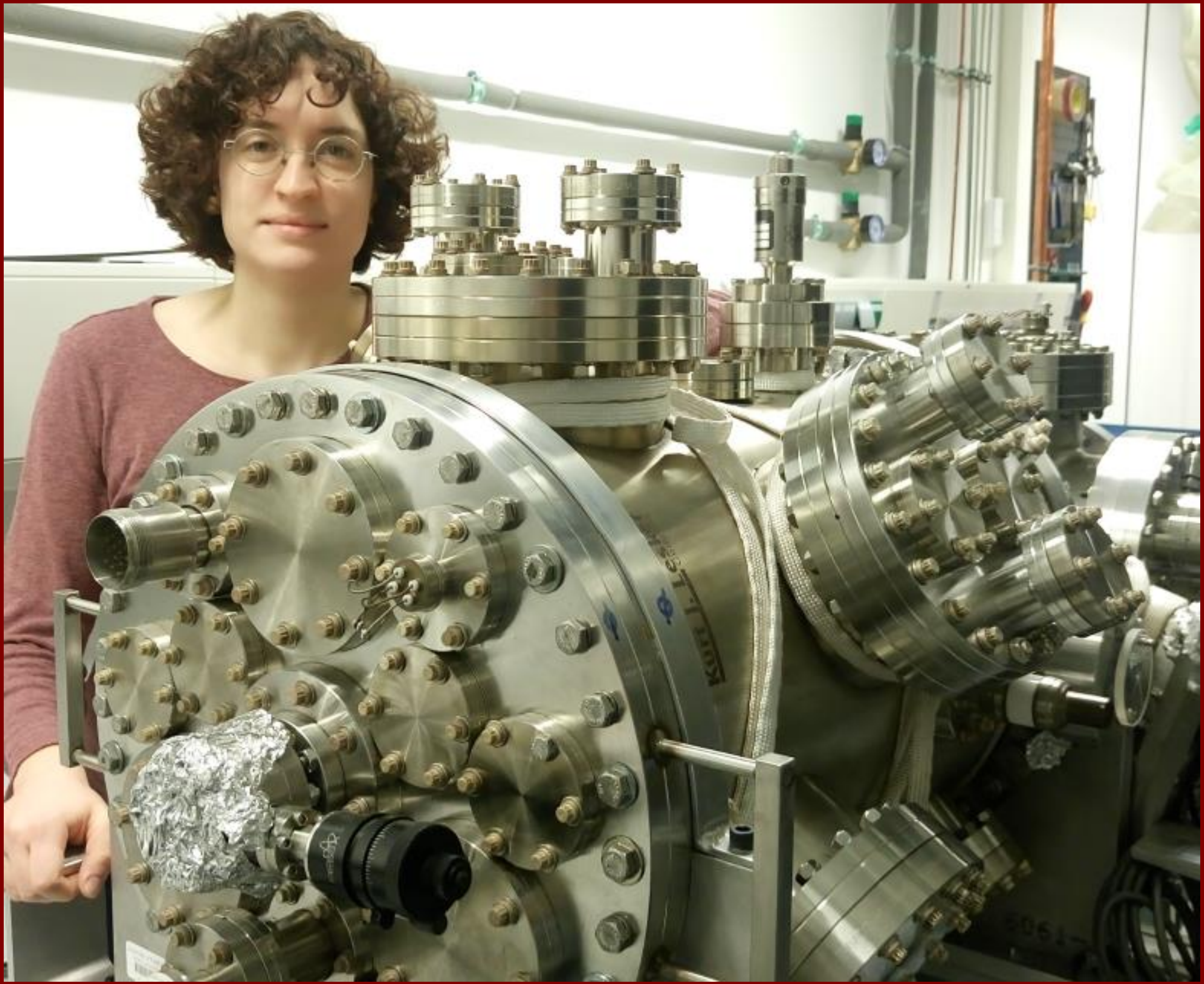
Idea and proof-of-concept:
Annalen der Physik **525**(8-9), 659–70 (2013);
Phys. Rev. Lett. **110**, 021803 (2013)

- Network of shielded, GPS-synchronized magnetometers + clocks, interferometers,...
- Sensitive to **topological Dark Matter**: domain walls, axion (ALP) stars, …
- Multi-messenger astronomy (e.g., look for ALPs from sources of gravitational waves)
- Sensor-correlation techniques resembling those of LIGO/Virgo
- Status: Science Run 1 complete, results to be announced; Run 2: Nov/Dec 2017

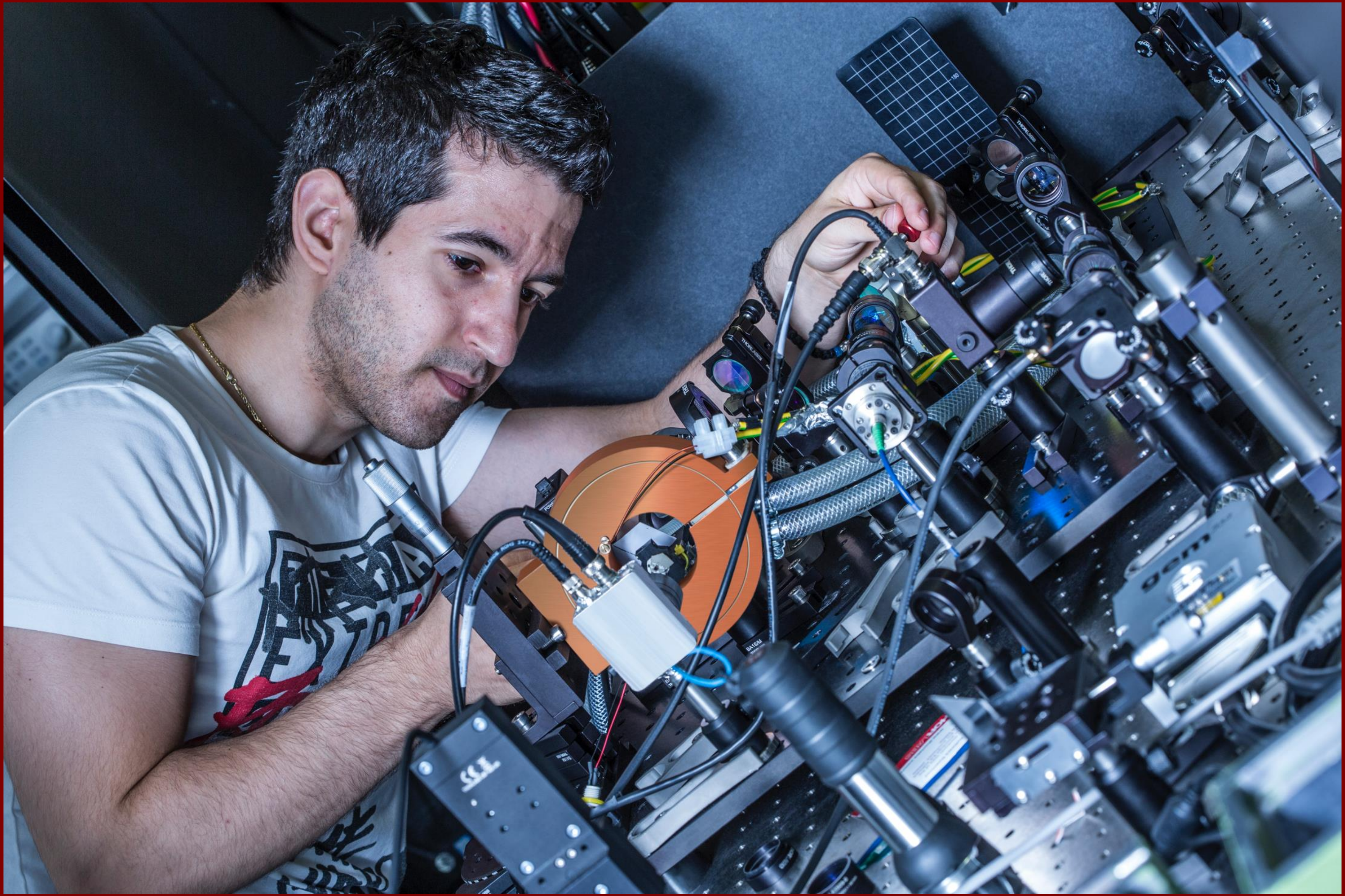
CASPEr-NOW with ZULF NMR



- Zero- and Ultralow-Field Nuclear Magnetic Resonance
- Tool for chemistry, quantum control, and fundamental physics
- A novel scheme to search for ultralight dark matter



Graduate student Ann Fabricant and the Dy parity-violation setup



Graduate student Georgios Chatzidrosos adjusting an NV-diamond magnetometer

Magnetometer…in the sky!

VOLUME 78, NUMBER 25 PHYSICAL REVIEW LETTERS 23 JUNE 1997

Parity Nonconservation in Relativistic Hydrogenic Ions

M. Zolotorev and D. Budker

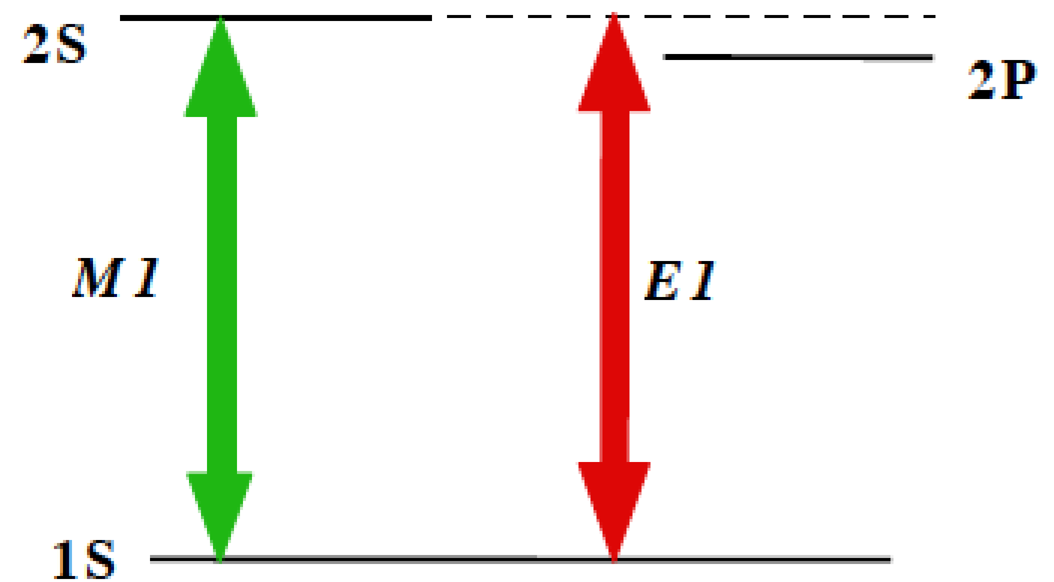


Fig. 1. The 1S→2S transition in a hydrogenic system.

Parity Violation

☞ level-mixing

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

☞ circular dichroism

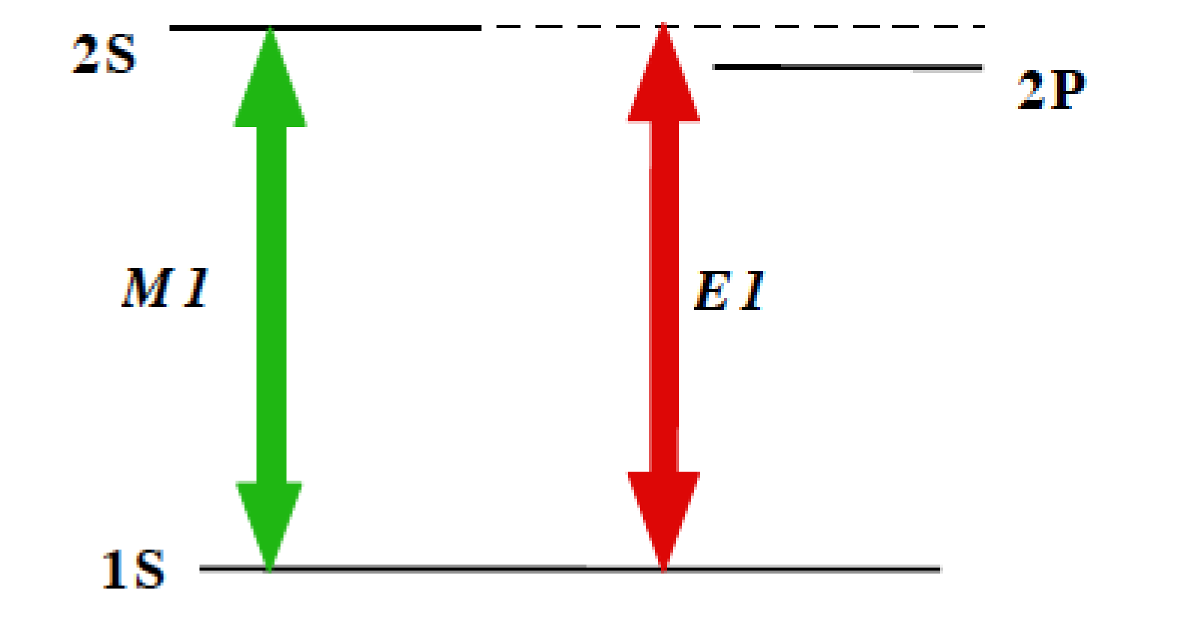


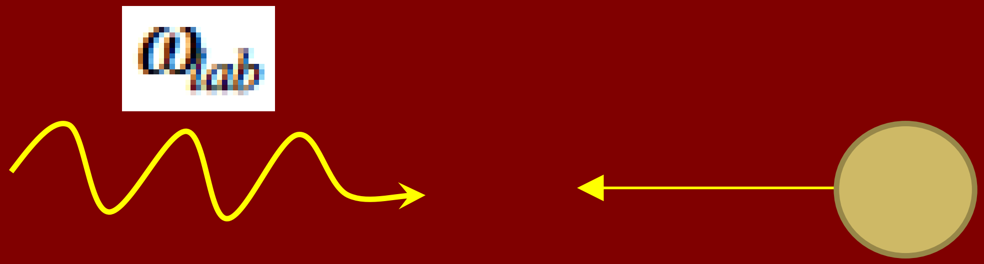
Fig. 1. The 1S→2S transition in a hydrogenic system.

Table 1: Z-dependence of atomic characteristics for hydrogenic ions. In the given expressions, α is the fine structure constant, $\hbar$=c=1, m_e is the electron mass, G_F is the Fermi constant, θ_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	ΔE_{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	Γ_{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

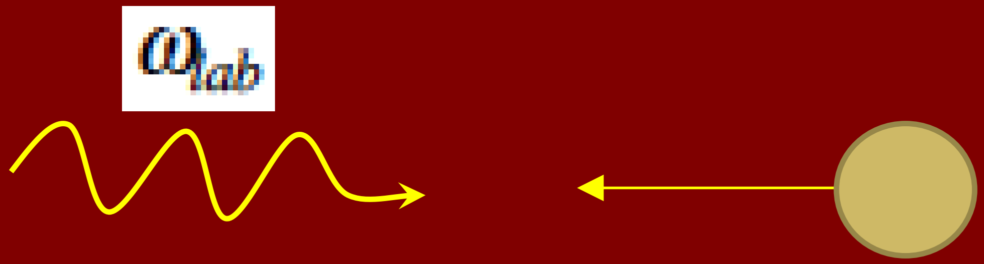


$$\omega_{ion\ frame} = \gamma(1+\beta)\omega_{lab} \approx 2\gamma\omega_{lab}$$

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

With LHC ($\gamma\approx7000$): up to Z=48 (Cd)

Statistical Sensitivity



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

Doppler width:

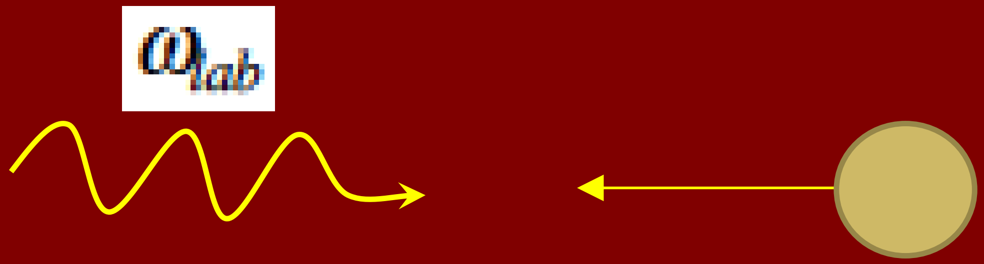
$$\Gamma_D = (\omega \cdot \Delta\beta)_{ion\ frame} \approx \omega_{ion\ frame} \cdot \frac{\Delta\gamma}{\gamma}$$

Fraction of ions excited:

$$\chi_{M1} = (M1 \cdot \tilde{B}\tau)^2 \cdot \frac{1}{\Gamma_D \tau}$$

$\tilde{B} = \tilde{E}$ is the laser field, τ is the ion-laser interaction time

Statistical Sensitivity



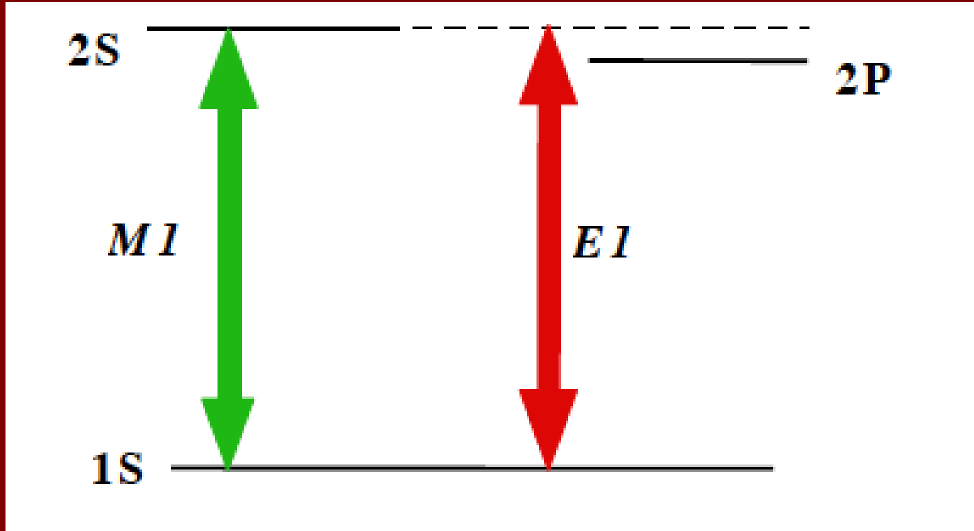


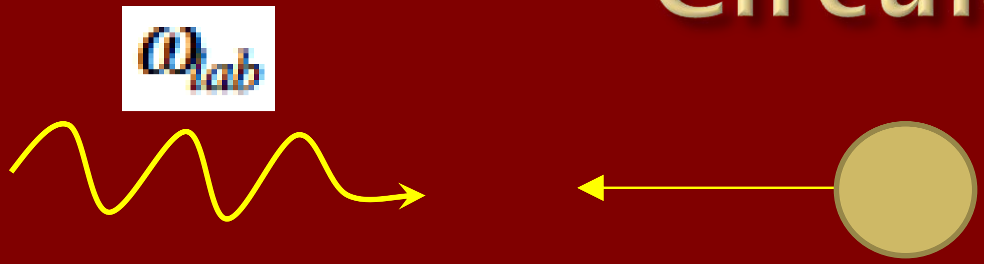
Fig. 1. The 1S→2S transition in a hydrogenic system.

Want **high power** but optical pumping

⇒ Keep saturation parameter

$$\chi_{E1} = \frac{(E1\cdot\tilde{E})^2}{4(\Delta E_{2S-2P})^2}\cdot\Gamma_{2P}\tau \ll 1$$

Circular Dichroism



$$\chi_{M1} = \frac{3^8 \alpha^9 F^2(Z) Z^8}{2^{15} \pi^2 \frac{\Delta\gamma}{\gamma}} \chi_{E1}$$

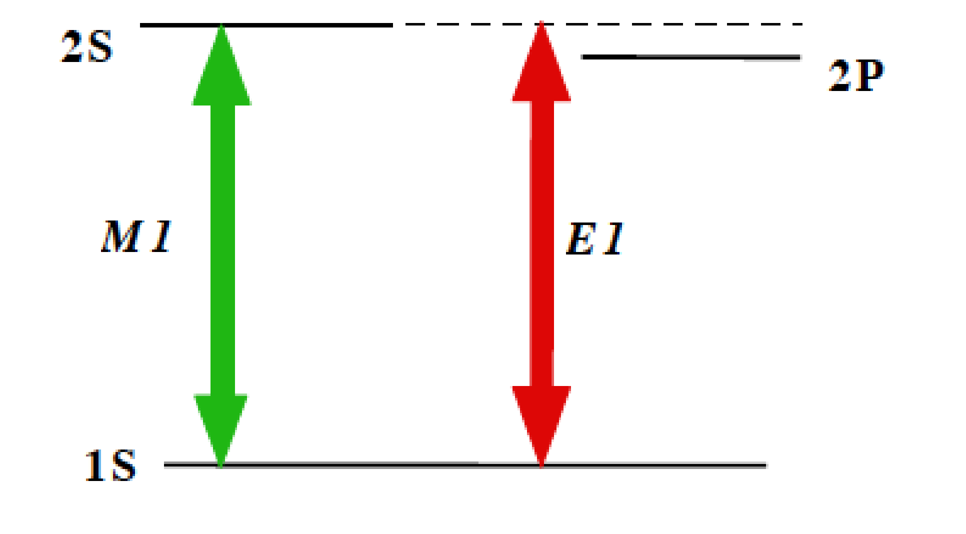


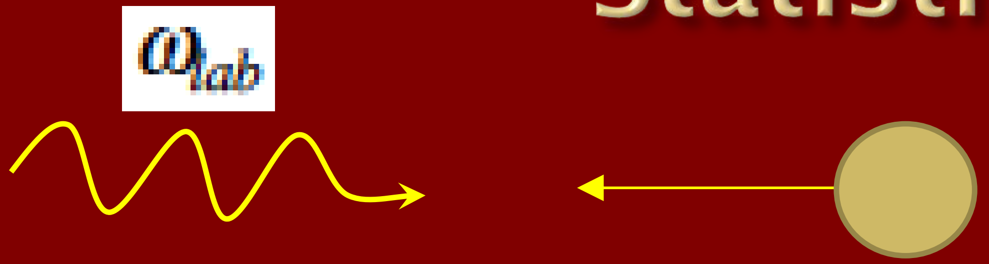
Fig. 1. The 1S→2S transition in a hydrogenic system.

Total number of excited ions in time *T*: $N_{\pm} \approx \chi_{M1} \cdot \dot{N}_{ions} T/2$

PV dichroism: $$P = \frac{N_+ - N_-}{N_+ + N_-} = \frac{2H_w}{\Delta E_{2S-2P}} \cdot \frac{E1}{M1}$$

Statistical uncertainty: $$\delta H_w = \frac{1}{4} \sqrt{\frac{\Gamma_D \Gamma_{2P}}{\dot{N}_{ions} T \chi_{E1}}}$$

Statistical Sensitivity



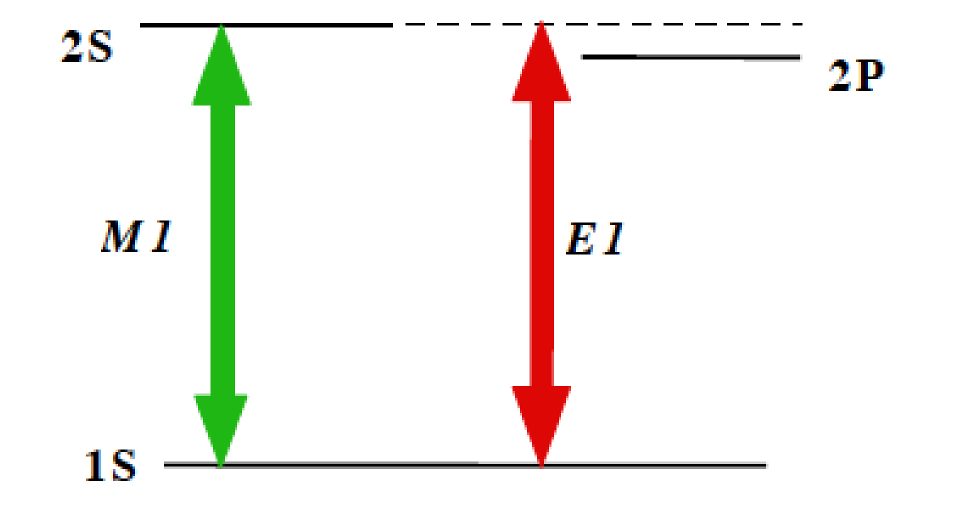


Fig. 1. The 1S→2S transition in a hydrogenic system.

$$Exposure[part.Amp \times year] \geq \frac{\Delta\gamma}{\gamma} \cdot \frac{0.1}{Z^4 \cdot (\delta \sin^2\theta_w)^2 \cdot \chi_{E1}}$$

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 $\frac{\Delta\gamma}{\gamma}$ $\Rightarrow$ 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.

Conclusion

- A lot of cool atomic physics to do with PSI
- Challenging; need laser cooling
- Fundamental symmetry tests may be possible; also Dark-Matter searches

Table 2. Parameters of relativistic ion storage rings.

Parameter	RHIC	SPS	LHC
γ_{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.