Fundamental characteristics of elementary particles and spectroscopy of light exotic atoms

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  magnetic moment of the antiproton, known to 0.3%

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  charge radius of the proton – Lamb shift exp.

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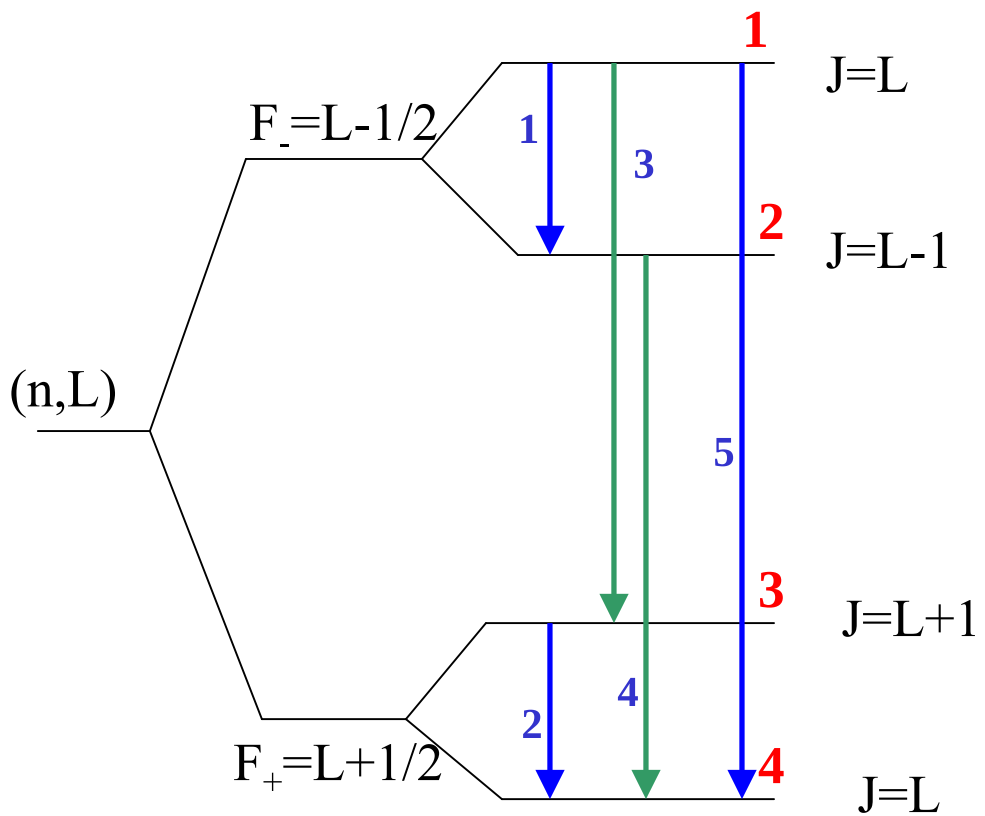
Difficult spectroscopy: very weak M1-transitions,

→ much power required

Other difficulties:

HF transitions in antiprotonic ^{4}He



- 5(+1) allowed M1-transitions:

  1: $\nu_{s_-} = (E_1 - E_2)/h$

  2: $\nu_{s_+} = (E_3 - E_4)/h$

  3: $\nu_{m_-} = (E_1 - E_3)/h$

  4: $\nu_{m_+} = (E_2 - E_4)/h$

  5: $\nu_{so} = (E_1 - E_4)/h$

  6: $\nu_X = \nu_{m_-} - \nu_{m_+}$

HF transitions in antiprotonic ^{4}He

Sensitivity S to variations of μ_p in (35,1)

$E_1 = 6.6113$ GHz; $\delta E_1/\delta\mu_p = 28.2$ MHz

$E_2 = 6.4784$ GHz; $\delta E_2/\delta\mu_p = -30.2$ MHz

$E_3 = -6.2846$ GHz; $\delta E_3/\delta\mu_p = 36.2$ MHz

$E_4 = -6.4456$ GHz; $\delta E_4/\delta\mu_p = -32.5$ MHz

	Intensity
$\nu_{S_-} = 132.94$ MHz; $\delta\nu_{S_-}/\delta\mu_p = -58.5$ MHz,	$\sim 2.10^{-4}$
$\nu_{S_+} = 160.93$ MHz; $\delta\nu_{S_+}/\delta\mu_p = -68.5$ MHz,	$\sim 2.10^{-4}$
$\nu_{m_-} = 12923.96$ MHz; $\delta\nu_{m_-}/\delta\mu_p = -8.0$ MHz	
$\nu_{m_+} = 12895.98$ MHz; $\delta\nu_{m_+}/\delta\mu_p = 2.0$ MHz	
$\nu_{S_\circ} = 13056.90$ MHz; $\delta\nu_{S_\circ}/\delta\mu_p = -66.5$ MHz,	$\sim 4.10^{-4}$

HF structure of antiprotonic ^{4}He

Effective spin Hamiltonian of $^4\mathrm{He}\bar{p}$

$$H^{eff} = H_1(\vec{s}_e.\vec{J}) + H_2(\vec{s}_{\bar{p}}.\vec{J}) + H_3(\vec{s}_{\bar{p}}.\vec{s}_e)$$
$$+ H_4\left(3(\vec{s}_{\bar{p}}.\vec{J})(\vec{s}_e.\vec{J}) - J(J+1)(\vec{s}_{\bar{p}}.\vec{s}_e)\right)$$

Analysis of the theoretical uncertainty and the sensitivity of the transition frequencies to μ_p required.

HF transitions in antiprotonic ^{4}He

At present, $\Delta_q H_i \sim 10^{-4}$ (where $\Delta x = \delta x / x$)

Response $R = \Delta_q \nu / \Delta_q H_i$, of the transition frequencies to variations of H_i: $\Delta\nu = \max R.|\Delta H|$

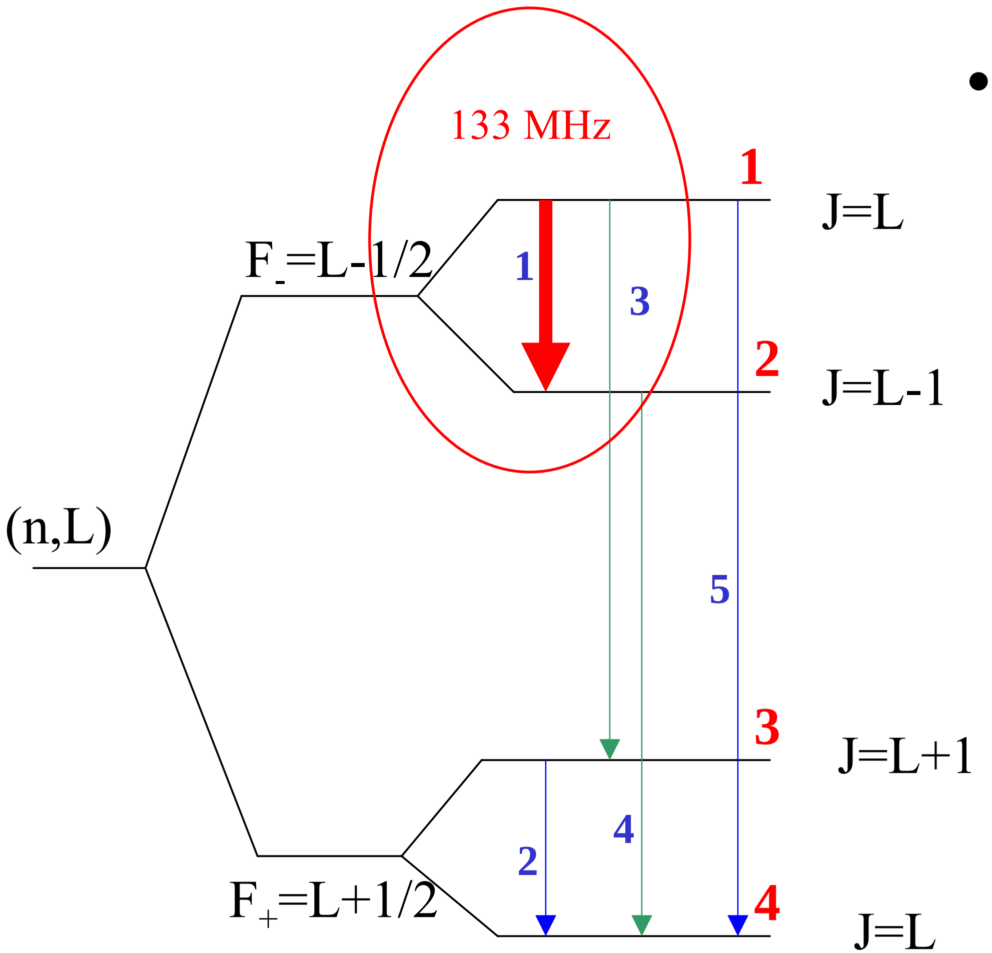
i	s^-	s_+	m_-	m_+	m_0	X
1	-0.031	-0.025	0.995	1.000	0.988	0.000
2	1.125	0.929	0.000	0.000	0.011	0.000
3	1.141	-0.903	-0.011	0.012	0.000	-10.61
4	-1.235	0.999	0.013	-0.012	0.000	11.61

HF transitions in antiprotonic ^{4}He

Most appropriate HF lines in (33,1)[a] and (35,3)[b]

HF transition	s_-	s_+	m_-	m_+	m_0	X
Upper limit on the experimental error (a)	0.90	0.72	0.06	0.12	0.84	0.18
accuracy gain in μ_p	35.3	36.9	0.0	0.1	0.6	5.0
experimental error (b)	0.27	0.54	0.16	0.11	0.42	0.27
accuracy gain	40.6	34.4	0.1	0.1	0.1	8.9

HF transitions in antiprotonic ^{4}He



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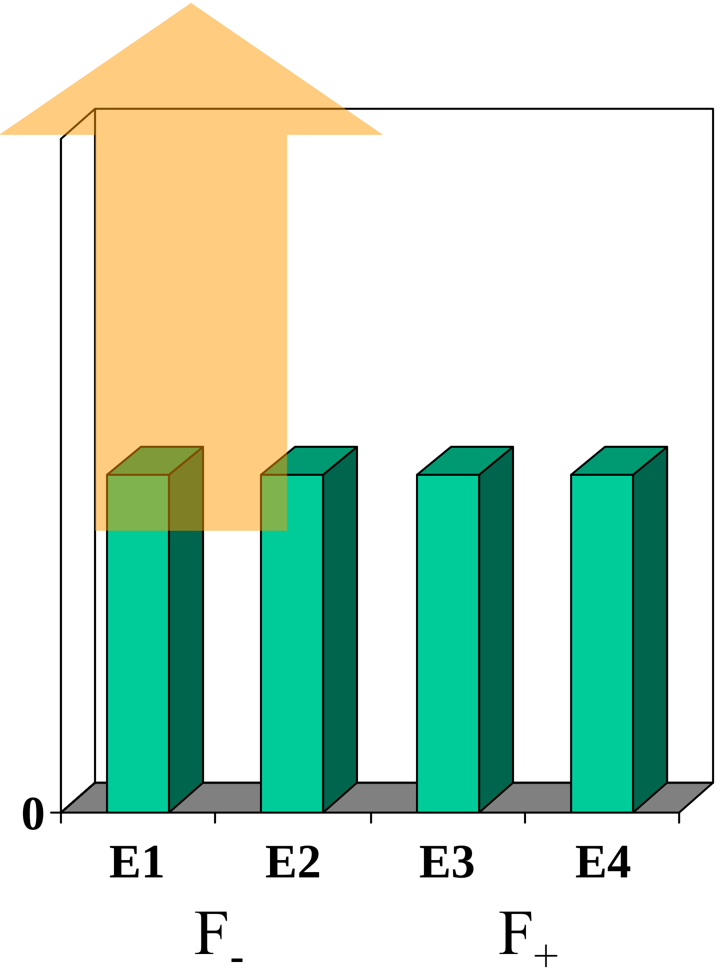
6: $\nu_X = \nu_{m_-} - \nu_{m_+}$

Measuring the HF splitting?

Tripple laser-VHF-laser resonance

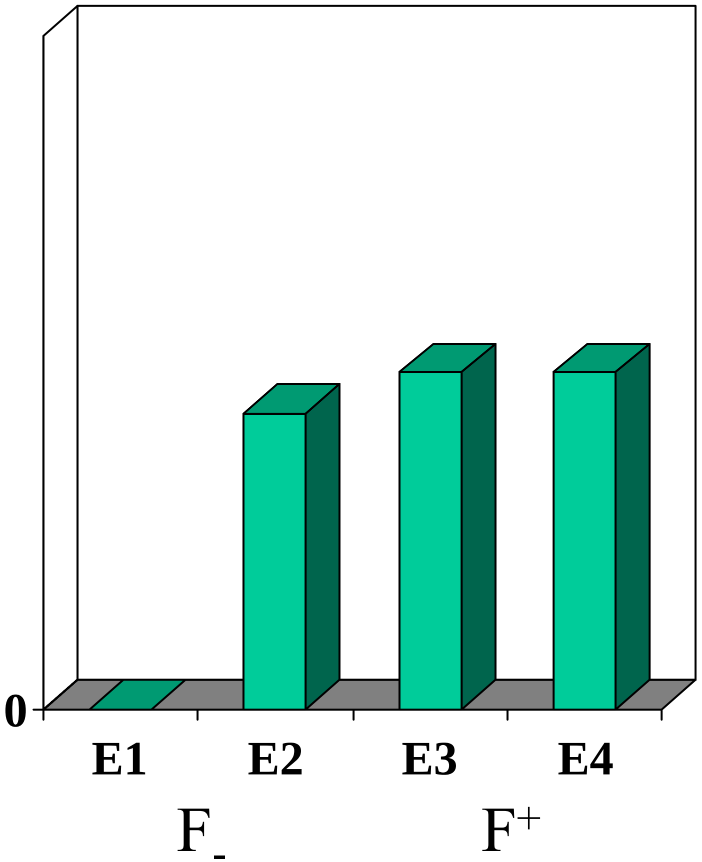
- First laser pulse with λ=726 nm and width 100 MHz. The laser is detuned from the center of F_- and depopulates predominantly E1



Measuring the HF splitting

Tripple laser-VHF-laser resonance

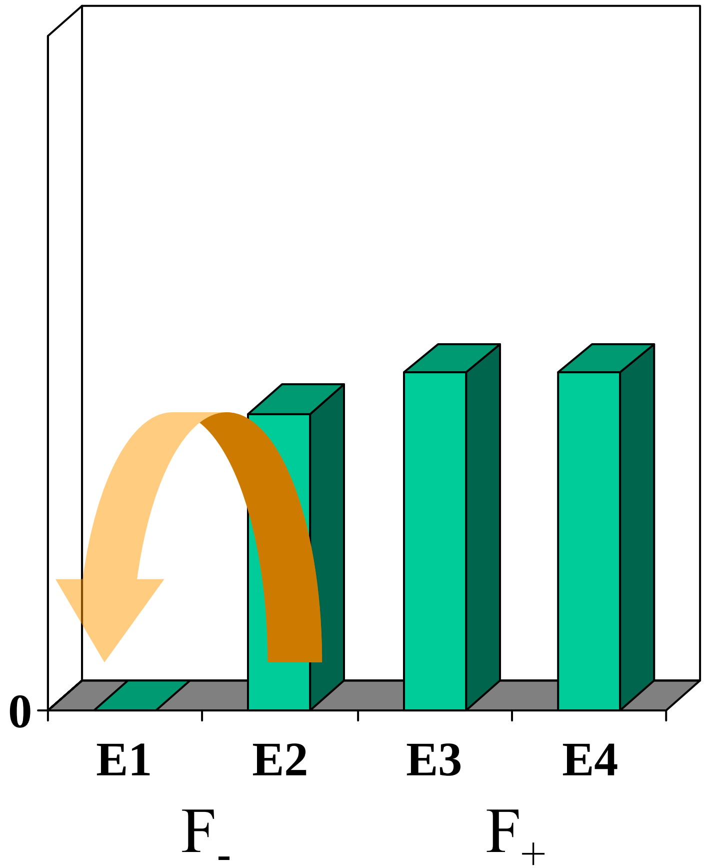
- Level E1 of the doublet F_- is depopulated.



Measuring the HF splitting

Tripple laser-VHF-laser resonance

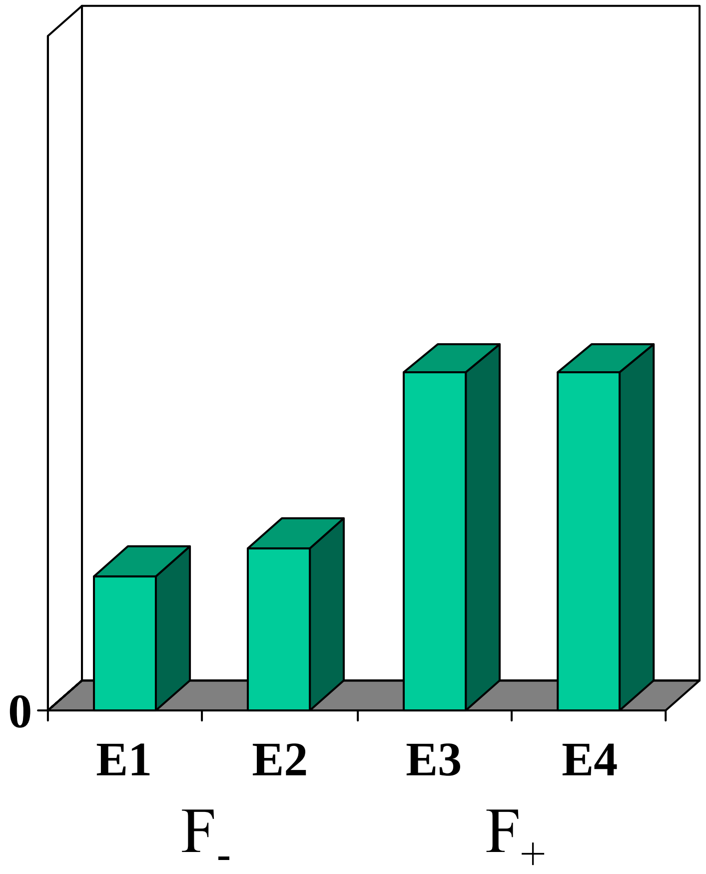
- VHF-stimulated M1 transitions of frequency ν_{s-} fill E1 from E2 for 160 ns.



Measuring the HF splitting

Tripple laser-VHF-laser resonance

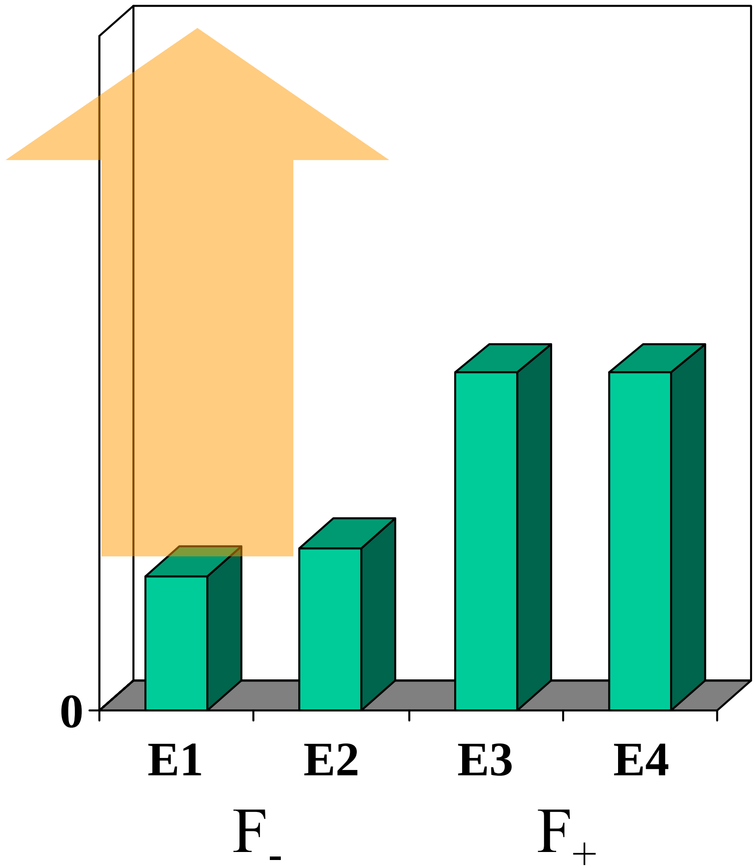
- E1 is partially refilled, while E2 is partially depopulated



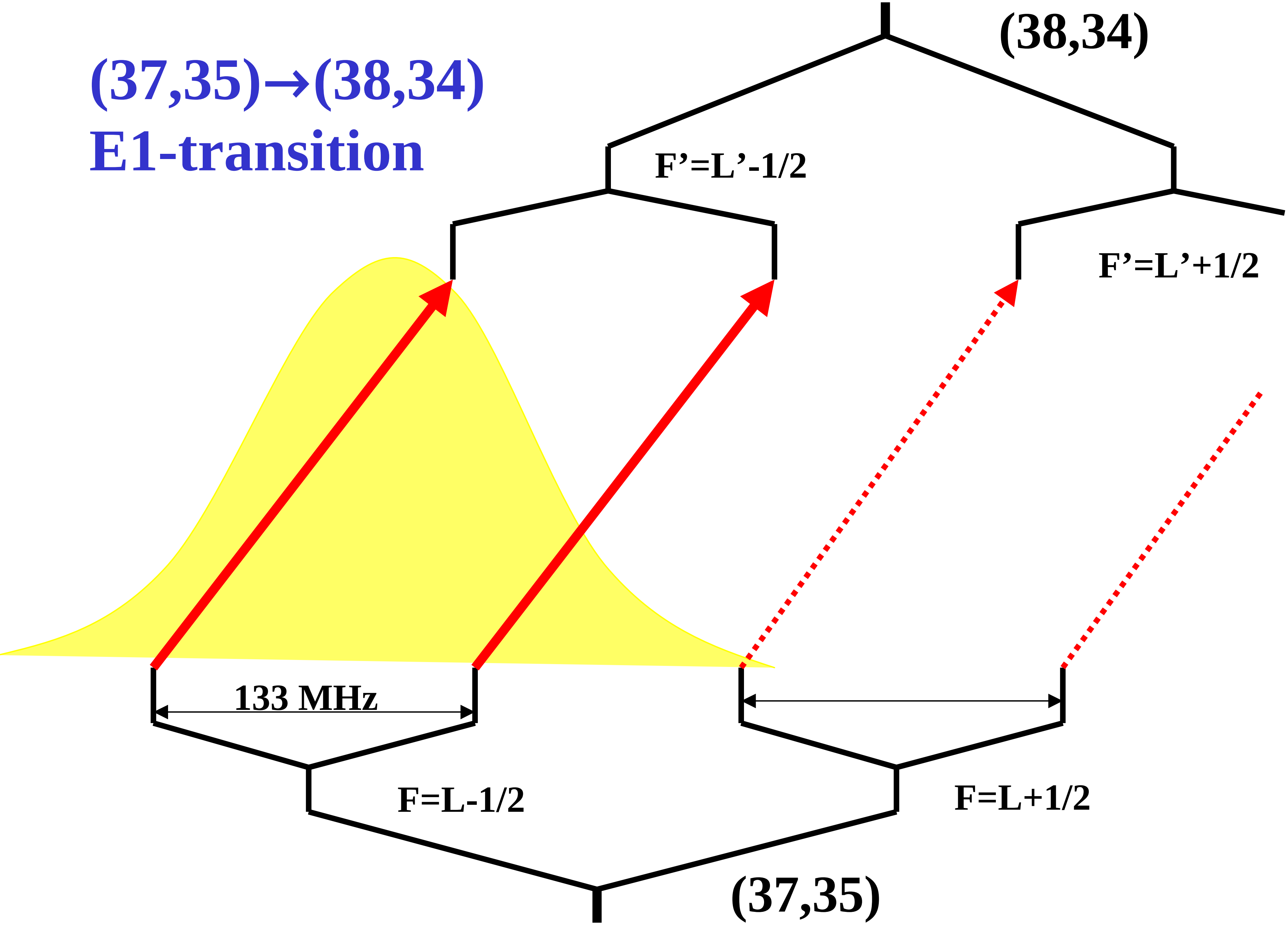
Measuring the HF splitting

Tripple laser-VHF-laser resonance

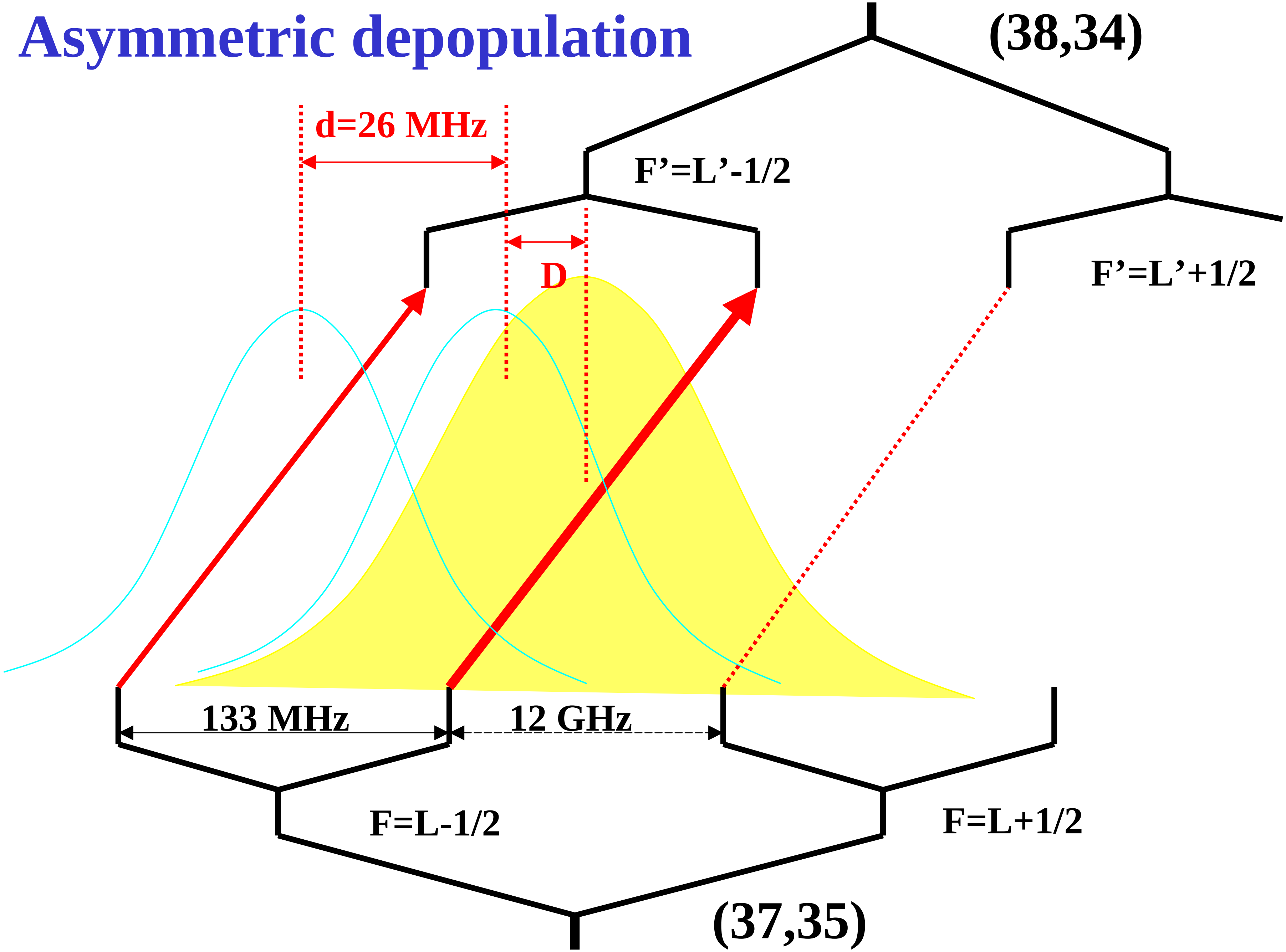
- Second laser pulse with λ=726 nm and width 100 MHz. The annihilation rate depends on the rate of refilling E1



(37,35)→(38,34)
E1-transition



Asymmetric depopulation



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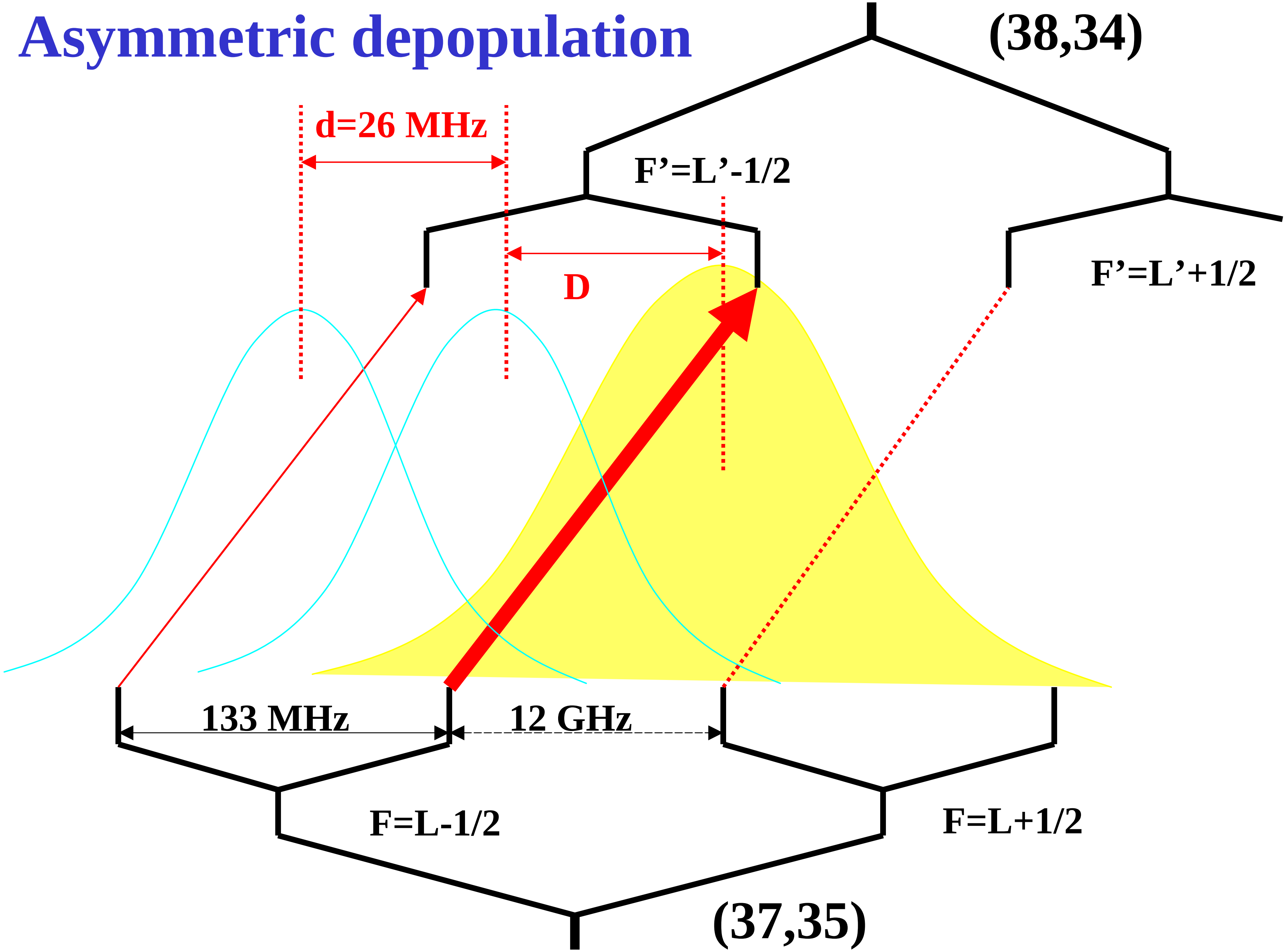
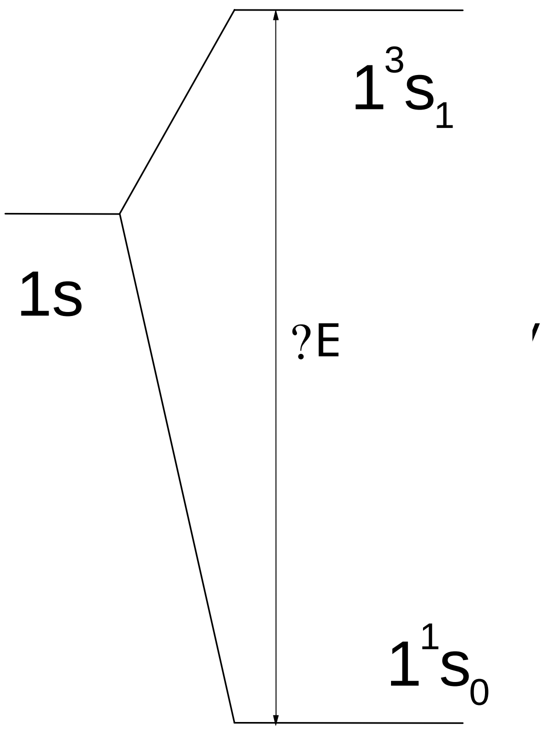


Measuring the HF splitting

Asymmetric depopulation rate ratio q:						120%		150%	
(L,v)→(L′,v′)	λ	Γ_c	Γ_d	d	q_x	D	f	D	f
(34,2)→(33,2)	470	24	499	57	1.6	136	.84	359	.29
(33,1)→(32,1)	372	9	630	75	1.9	146	.87	375	.39
(35,1)→(34.3)	726	75	323	26	1.2	247	.40		

Muonic hydrogen atom



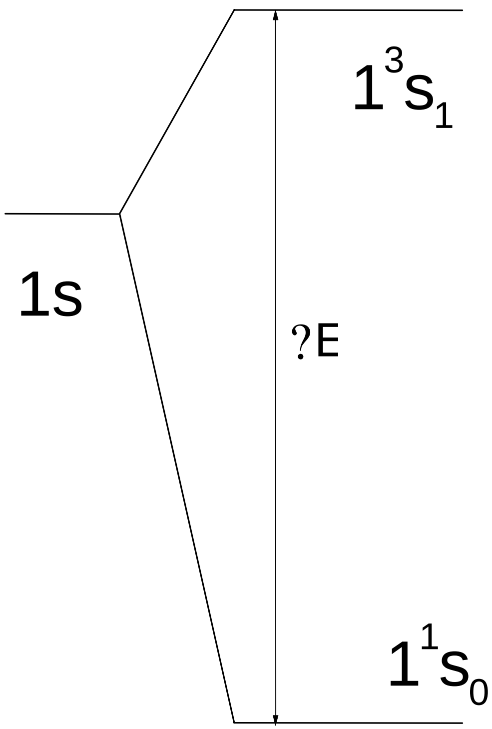
Theory

General expression of the hfs of hydrogenlike atoms

$$\Delta E = \Delta E^{F}(1+\delta^{QED}+\delta^{str})$$

- $\delta^{QED} = a_e + \alpha^2(\ln 2 - 1) + \ldots$
- $\delta^{str} = \delta^{rigid} + \delta^{pol} + \delta^{hvp} + \ldots$
- $\delta^{rigid} = \delta^{Zemach} + \delta^{recoil}$
- $\delta^{Zemach} = -2\alpha m R_p + O(\alpha^2)$

Muonic hydrogen atom



Theory

The quantities in red depend on the proton radius R_p:

$$\Delta E = \Delta E^F (1 + \delta^{QED} + \delta^{str})$$

- $\delta^{QED} = a_e + \alpha^2(\ln 2 - 1) + \ldots$
- $\delta^{str} = \delta^{rigid} + \delta^{pol} + \delta^{hvp} + \ldots$
- $\delta^{rigid} = \delta^{Zemach} + \delta^{recoil}$
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Proton Zemach radius

- First moment of the convolution of the charge and magnetic form factors

$$R_p = -\frac{1}{\pi^2}\int \frac{d^3p}{(p^2+\alpha^2 m^2)^2}\left(\frac{1}{\mu_p} G_E(-p^2) G_M(-p^2) - 1\right)$$

- Depends on both G_E and G_M!

Why muonic hydrogen?

Zemach radius from the HFS of H

R_p= 1.037(16) (Dupays *et al.*- known δ^{pol}, δ^{QED})

R_p= 1.047(19) (Volotka *et al.* - similar δ^{QED})

R_p= 1.013(18) (Brodsky *et al.* – muonium)

R_p= 1.086(12) (Friar & Sick – elastic scattering)

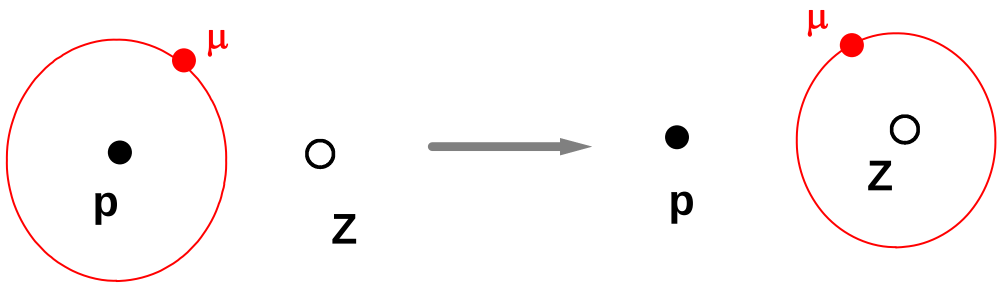
HFS of muonic hydrogen atoms

Comparison of H with $\mu^- p$

	hydrogen		Muonic hydrogen	
E^{Fermi}	1.4 GHz	$\pm 10^{-8}$	0.182 eV	$\pm 10^{-7}$
ΔE^{Zemach}	39×10^{-6}	$\pm 2\times 10^{-6}$	7.5×10^{-3}	$\pm 10^{-4}$
ΔE^{recoil}	6×10^{-6}	$\pm 10^{-8}$	1.7×10^{-3}	$\pm 10^{-6}$ (*)
ΔE^{pol}	1.4×10^{-6}	$\pm .6\times 10^{-6}$	$.46\times 10^{-3}$	$\pm .8\times 10^{-4}$
ΔE^{hvp}	10^{-8}	$\pm 10^{-9}$	2×10^{-5}	$\pm 2\times 10^{-6}$
ΔE^{QED}	1.1×10^{-3}	$\pm 10^{-9}$	$\sim 10^{-3}$	$\pm 10^{-6}$(*)

Measuring the HFS of $(\mu^{-}p)_{1s}$

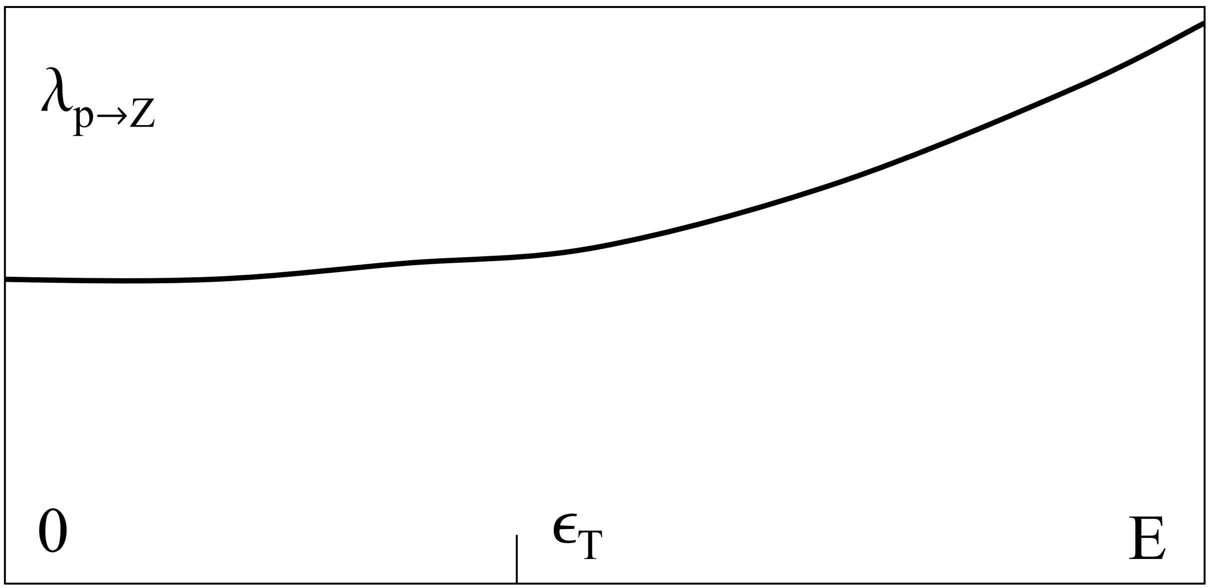
Muon exchange



$(\mu p) + Z \rightarrow p + (\mu Z)$

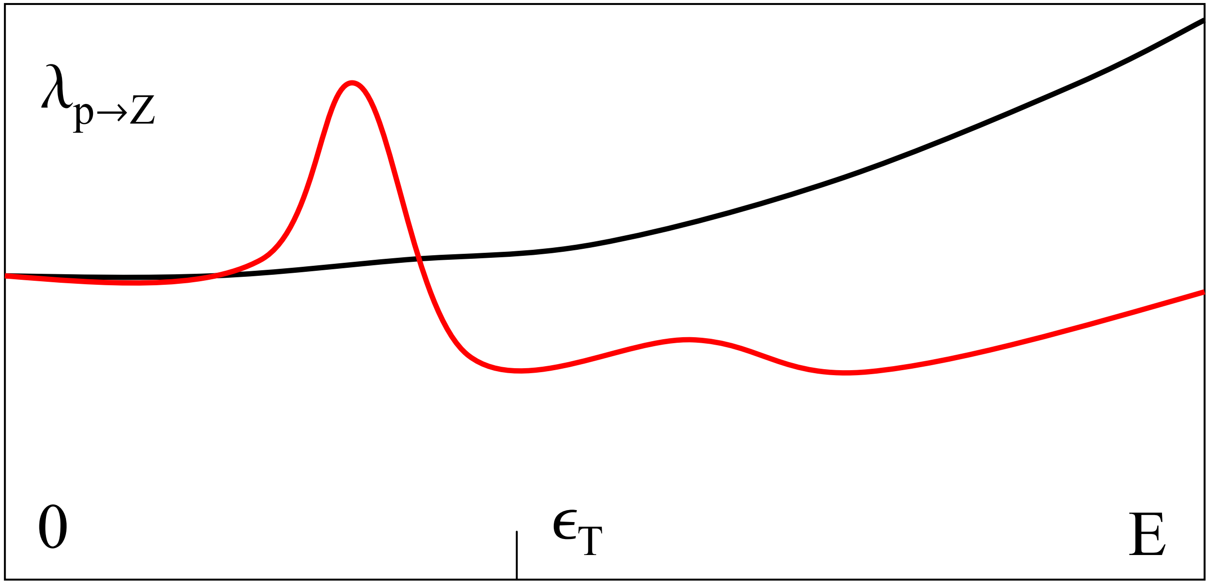
Measuring the HFS of $(\mu^{-}p)_{1s}$

Energy dependence of the muon exchange rate λ (general case)



Measuring the HFS of $(\mu^- p)_{1s}$

Energy dependence of the muon exchange rate λ (resonance case)



Muon exchange rate (theory)

Hyper-radial approach

- Diabatic per sector representation
- No Coriolis terms
- Higher partial waves taken into account

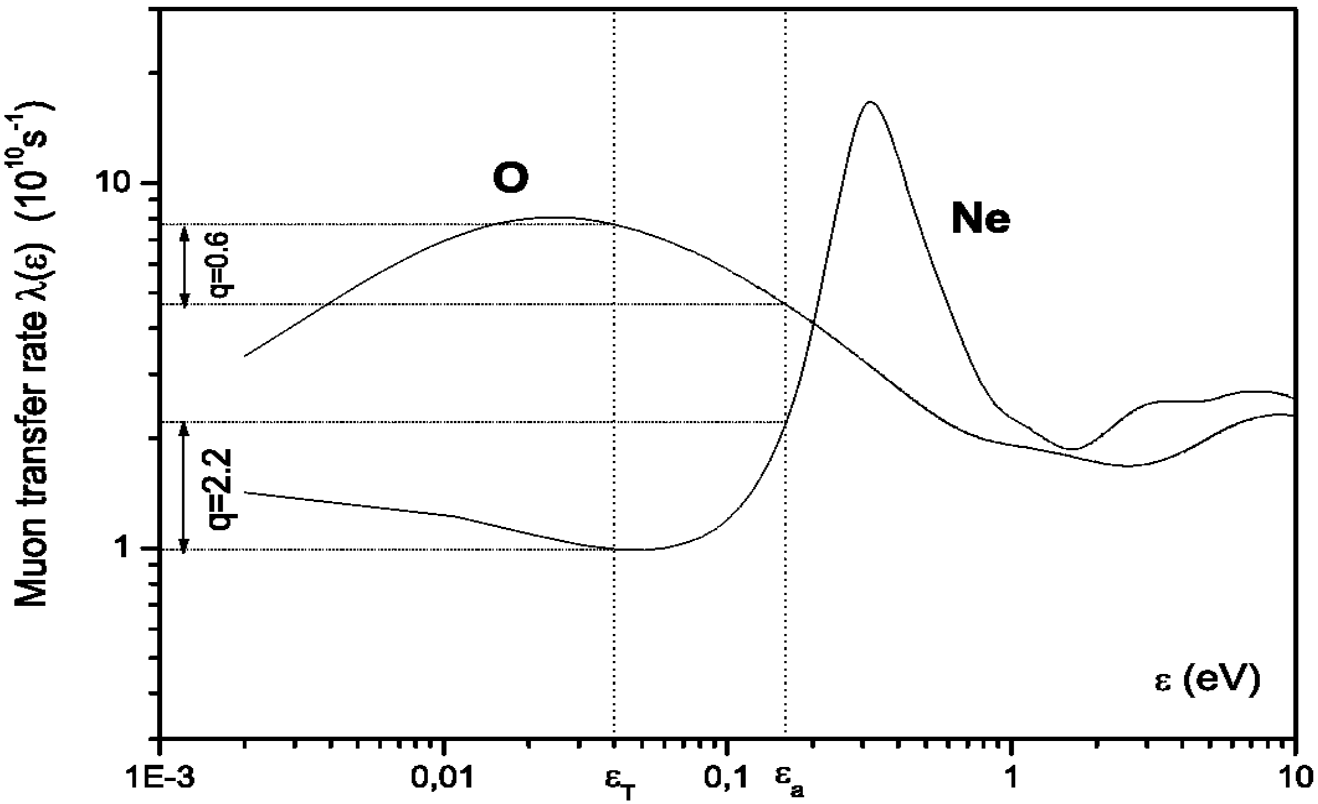
Muon exchange rate (theory)

Hyper-radial approach

- Diabatic per sector representation
- No Coriolis terms
- Higher partial waves taken into account
- Calculated: rates of exchange with O, Ne and C for a broad range of collision energies
- Good agreement with the few experimental points

Measuring the HFS of $(\mu^- p)_{1s}$

Rates of muon exchange with O and Ne, calculated in the hyper-radial approach

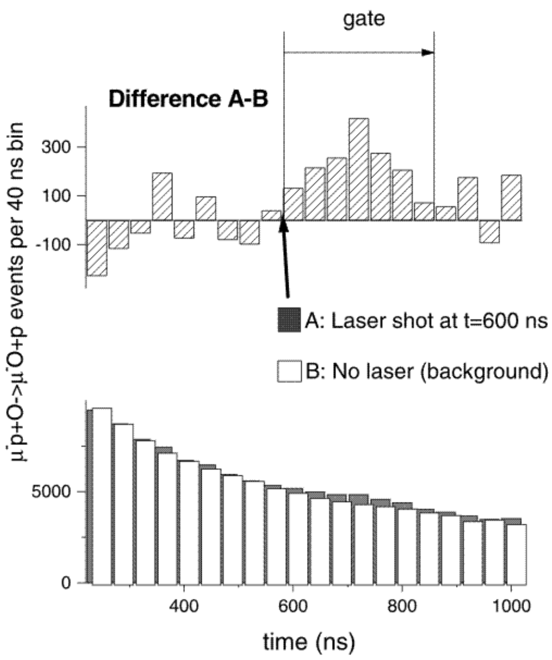


Muon exchange rate (theory)

For O: the step-like behaviour not reproduced!

- Accounting for the molecular excitations in O_2 - in progress
- Accounting for the dominant Fermi spin-spin interaction of the muon with the proton - in preparation
- More gases to be studied

Measuring the HFS of $(\mu^{-}p)_{1s}$

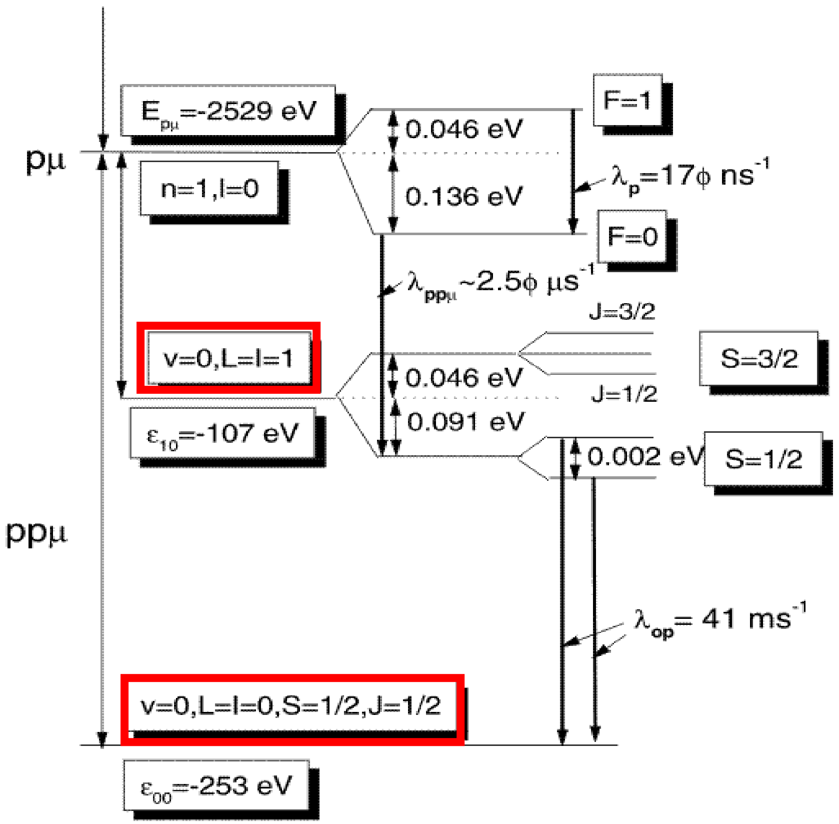


Monte Carlo simmulations of the experiment

- Good efficiency
- Successful optimization

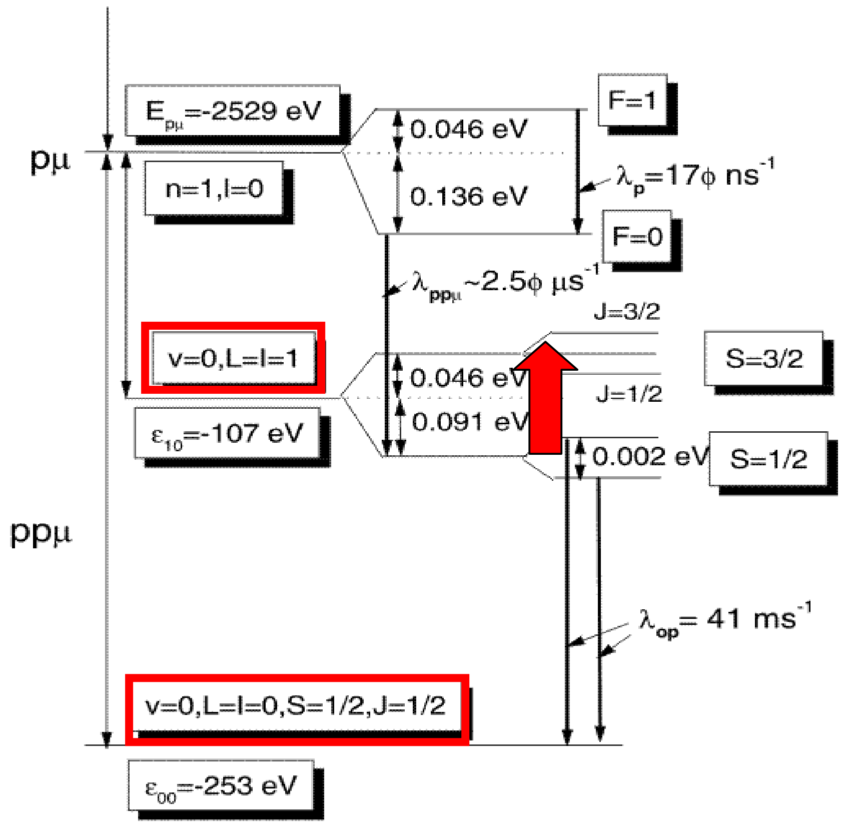
Measuring the HFS of $(p\mu^- p)_{10}$

- Two Coulomb states of ppμ
  ground (para) with L=0,
  excited (ortho) with L=1.
- Formed in L=1.
- Ortho-para transitions in 20% of the molecules, detectable by the X-rays



Measuring the HFS of $(p\mu^{-}p)_{10}$

- Ortho-para from s=1/2 only.
- Laser-stimulated transitions s=1/2 ↔ s=3/2 reduce the observable ortho-para rate.
- Tunable lasers with λ~9μm - available
- High efficieny, low Doppler broadening



Measuring the HFS of $(p\mu^- p)_{10}$?

- More accurate experimental value of ΔE^{hfs} expected compared to $(\mu^- p)$
- Challenge for theory: Accuracy of 10^{-5} or better required