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Parity Nonconservation in Hydrogen: Revisited

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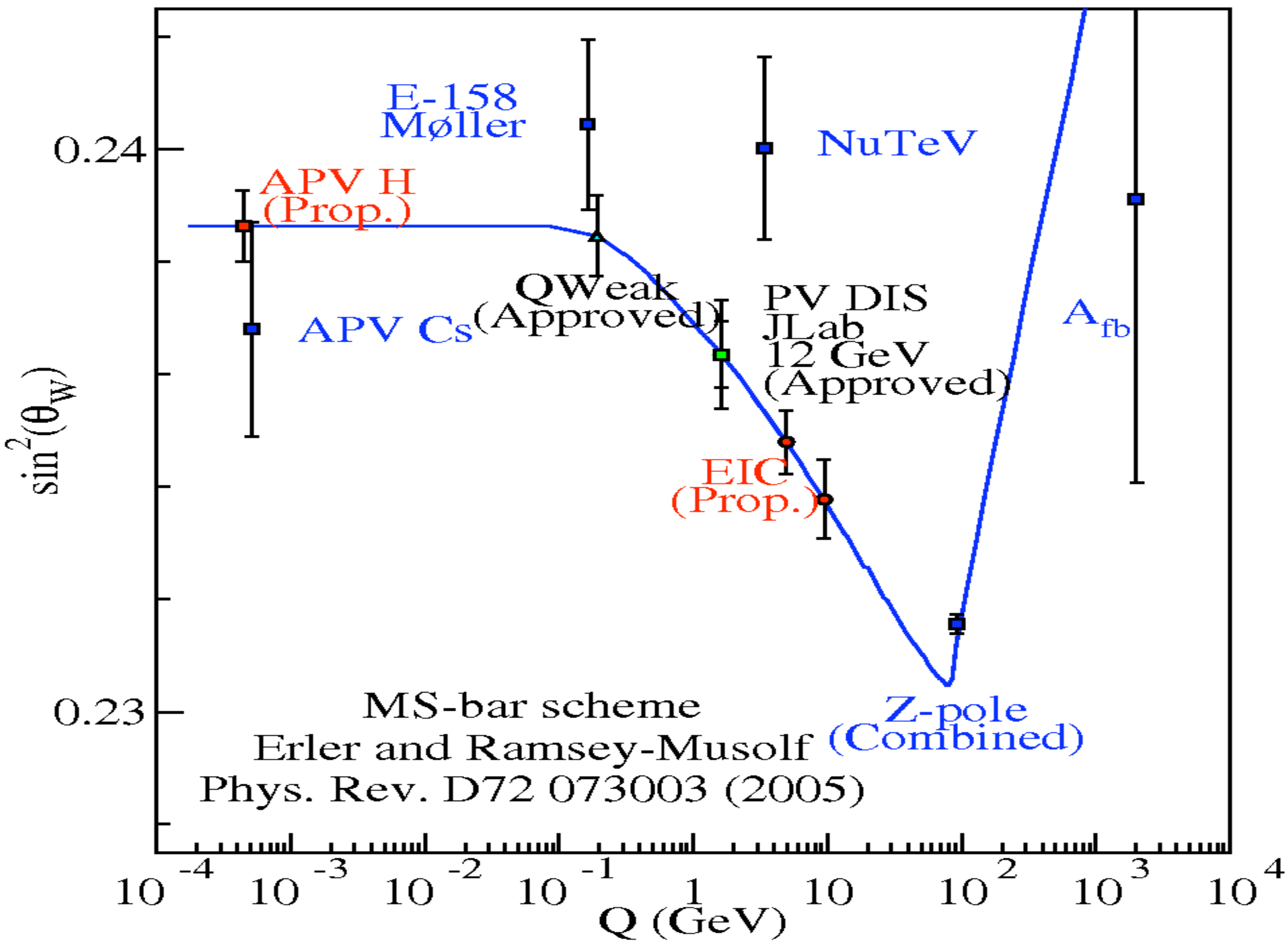
Questions:

How well does PV in H need to be measured to make a useful contribution?

What experimental parameters are needed to achieve the required precision?

Outline

- ***Motivation***
- ***Review of Former H APV Experiments***
- ***Sensitivity and Systematic Errors for Future***
- ***Production of Metastable Beams***



From Paul Reimer, ANL

Why Hydrogen?

- Close lying states of opposite parity

  $2S_{1/2}$ - $2P_{1/2}$ Separated by the Lamb shift

- Calculability

- Determination of four weak interaction coupling constants

Hydrogen	Deuterium		
C1p	C1p + C1n	nuclear spin independent	$(A_e V_N)$
C2p	C2p + C2n	nuclear spin dependent	$(V_e A_N)$

- Accessibility of the $2S_{1/2}$ - $2P_{1/2}$ level crossings

Table 1. Parity violating weak neutral current couplings for H and D.

Coupling	From model-independent fit[1]	Standard Model
C_{1p}	0.082 ± 0.034	0.0355
C_{1D}	-0.441 ± 0.012	-0.4587
C_{2p}	-0.16 ± 0.26	0.043
C_{2D}	-0.32 ± 0.4	0.007

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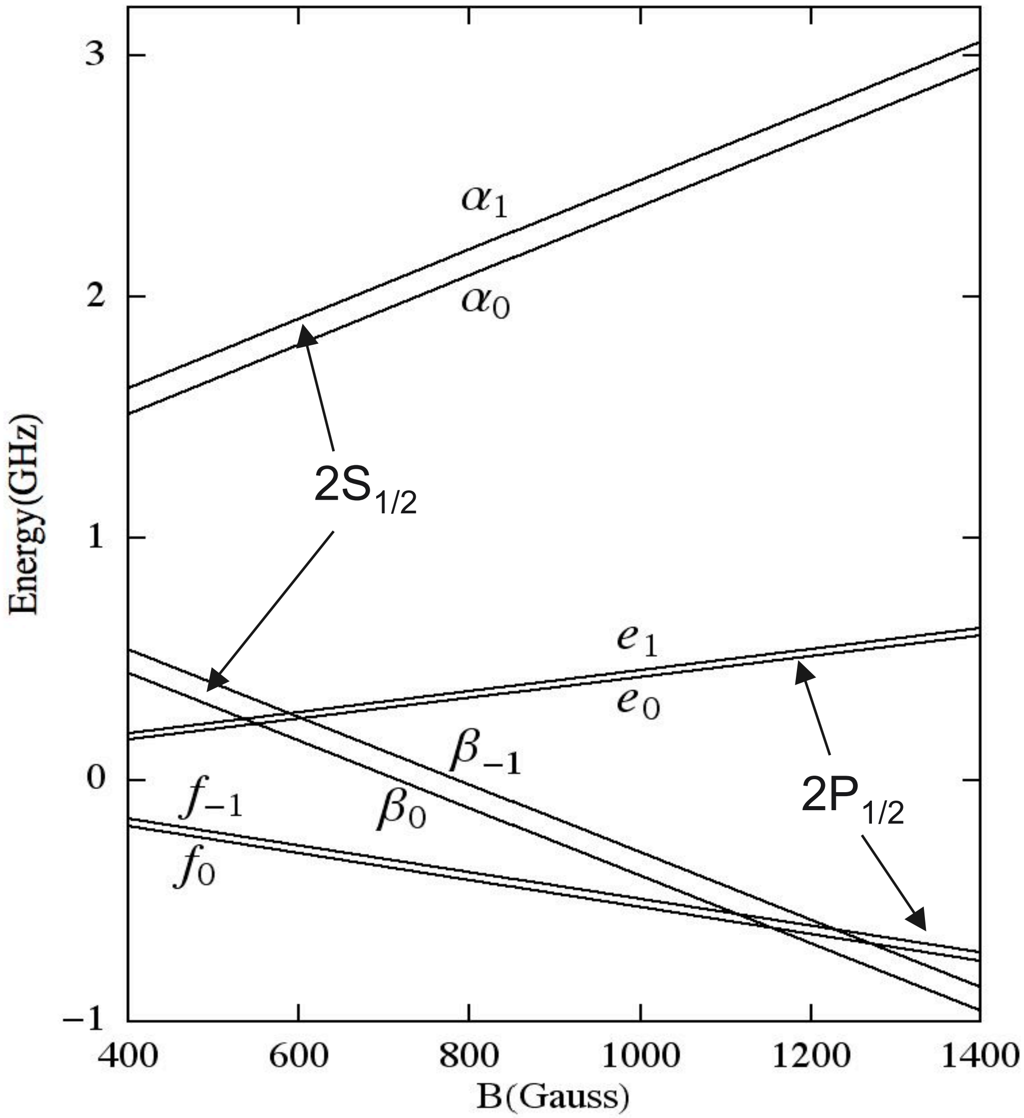
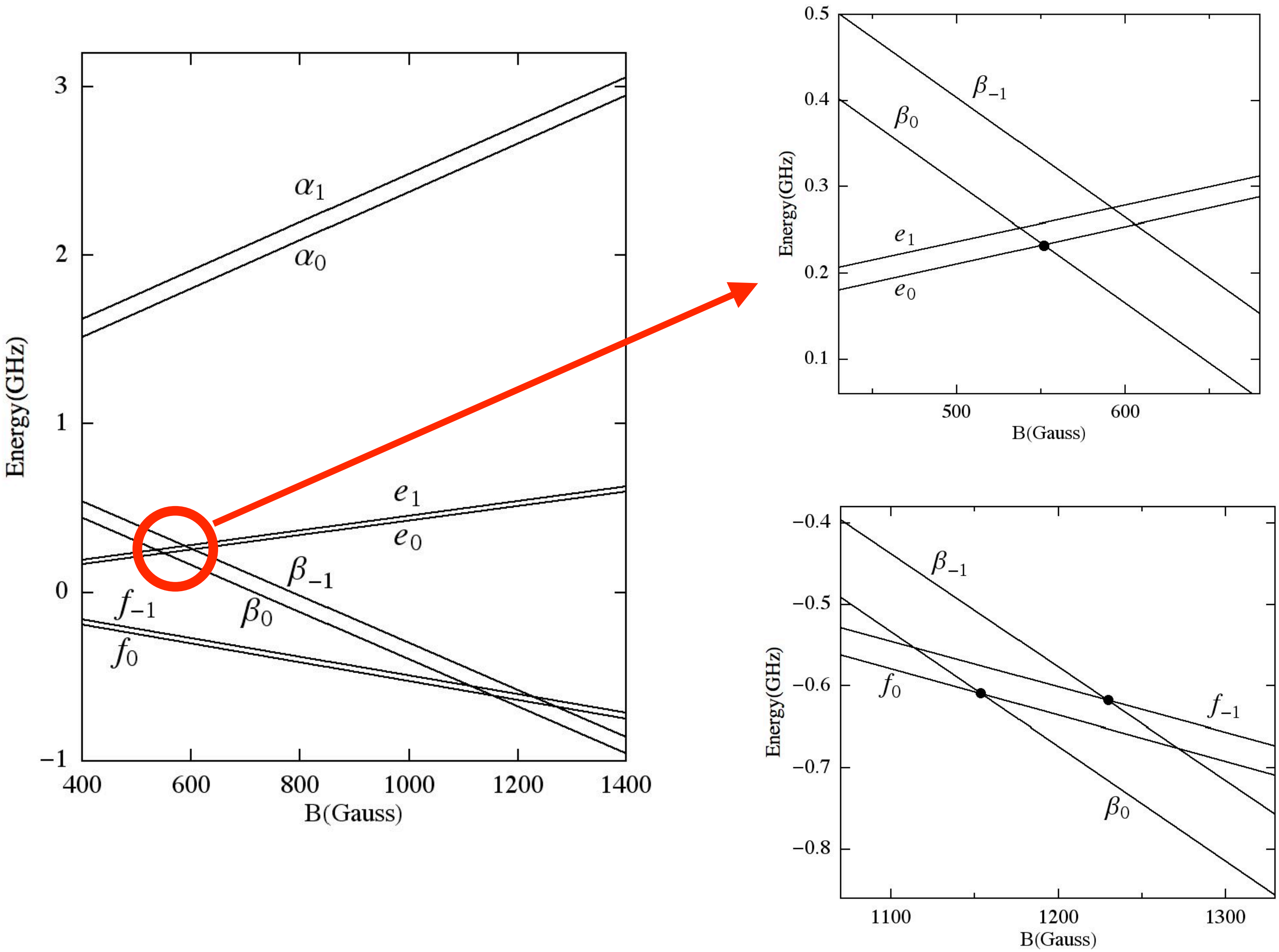
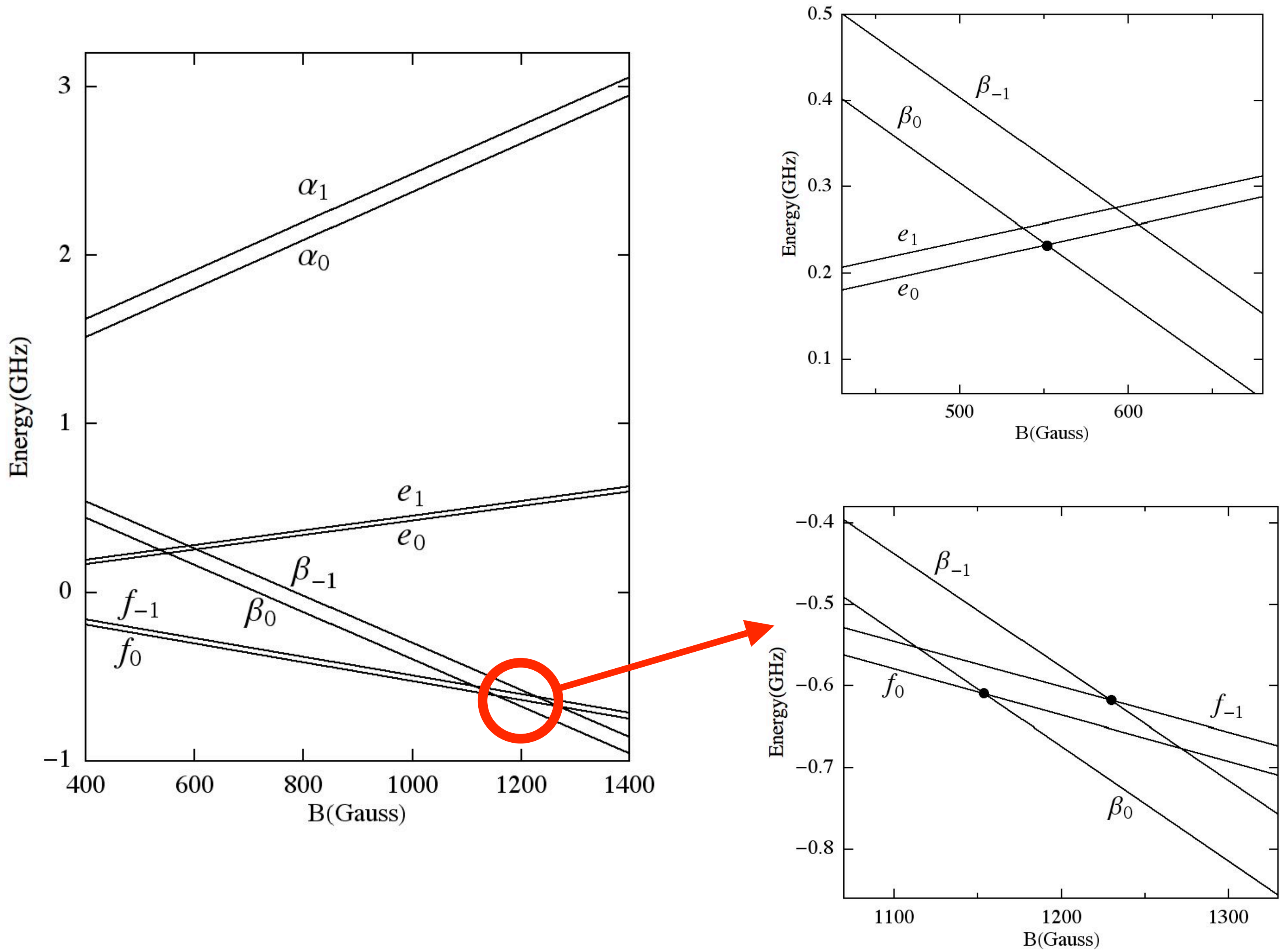


Level Crossings In Hydrogen n=2

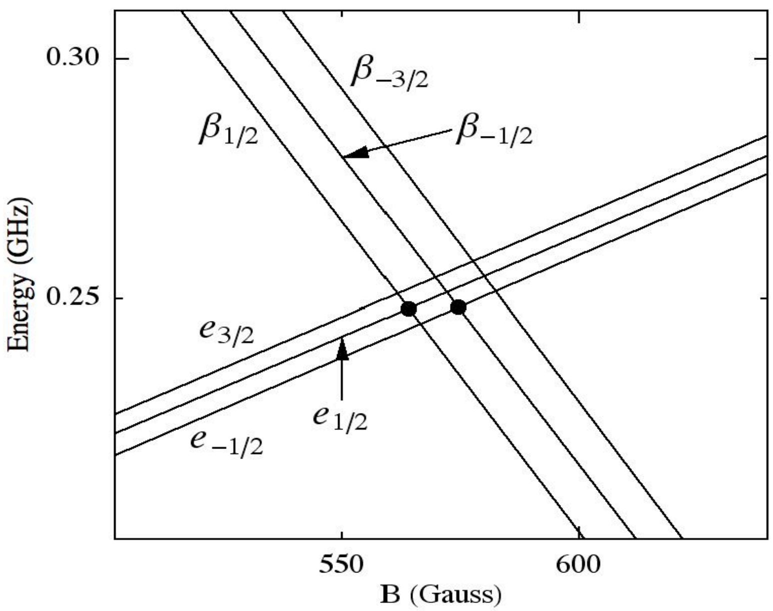
Subscripts are m_F


3
2
1
0
−1
400
600
800
1000
1200
1400
Energy(GHz)
B(Gauss)
α_1
α_0
e_1
e_0
β_{-1}
β_0
f_{-1}
f_0
0.5
0.4
0.3
0.2
0.1
500
600
−0.4
−0.5
−0.6
−0.7
−0.8
1100
1200
1300



Energy(GHz)
B(Gauss)
α_1
α_0
e_1
e_0
β_{-1}
β_0
f_{-1}
f_0
3
2
1
0
−1
400
600
800
1000
1200
1400
0.5
0.4
0.3
0.2
0.1
500
600
−0.4
−0.5
−0.6
−0.7
−0.8
1100
1200
1300

Crossings in Deuterium



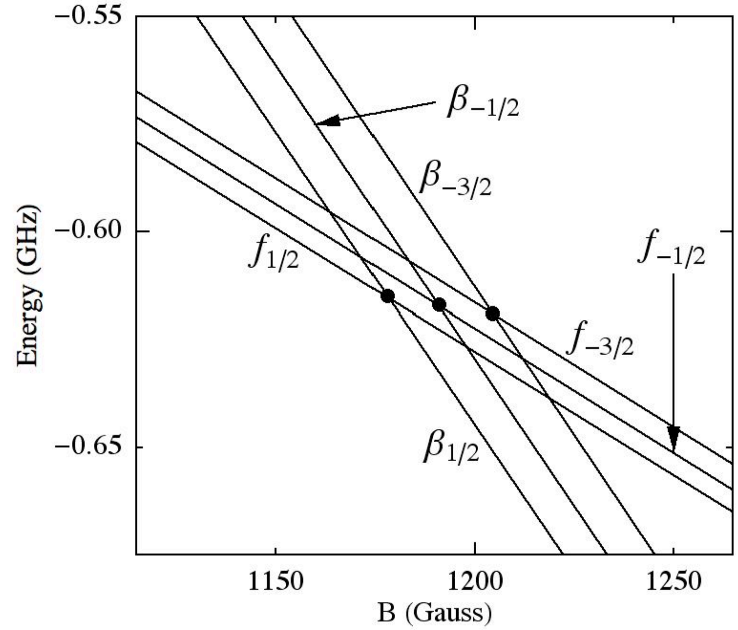


Table 2. Matrix elements for parity-violating, weak-neutral-current couplings for hydrogen and deuterium at the level crossings. In units of $i\bar{\mathcal{V}}_w \approx 2\pi \times 0.013\ s^{-1}$. $C_{1D} \equiv C_{1p} + C_{1n}$ and $C_{2D} \equiv C_{2p} + C_{2n}$.

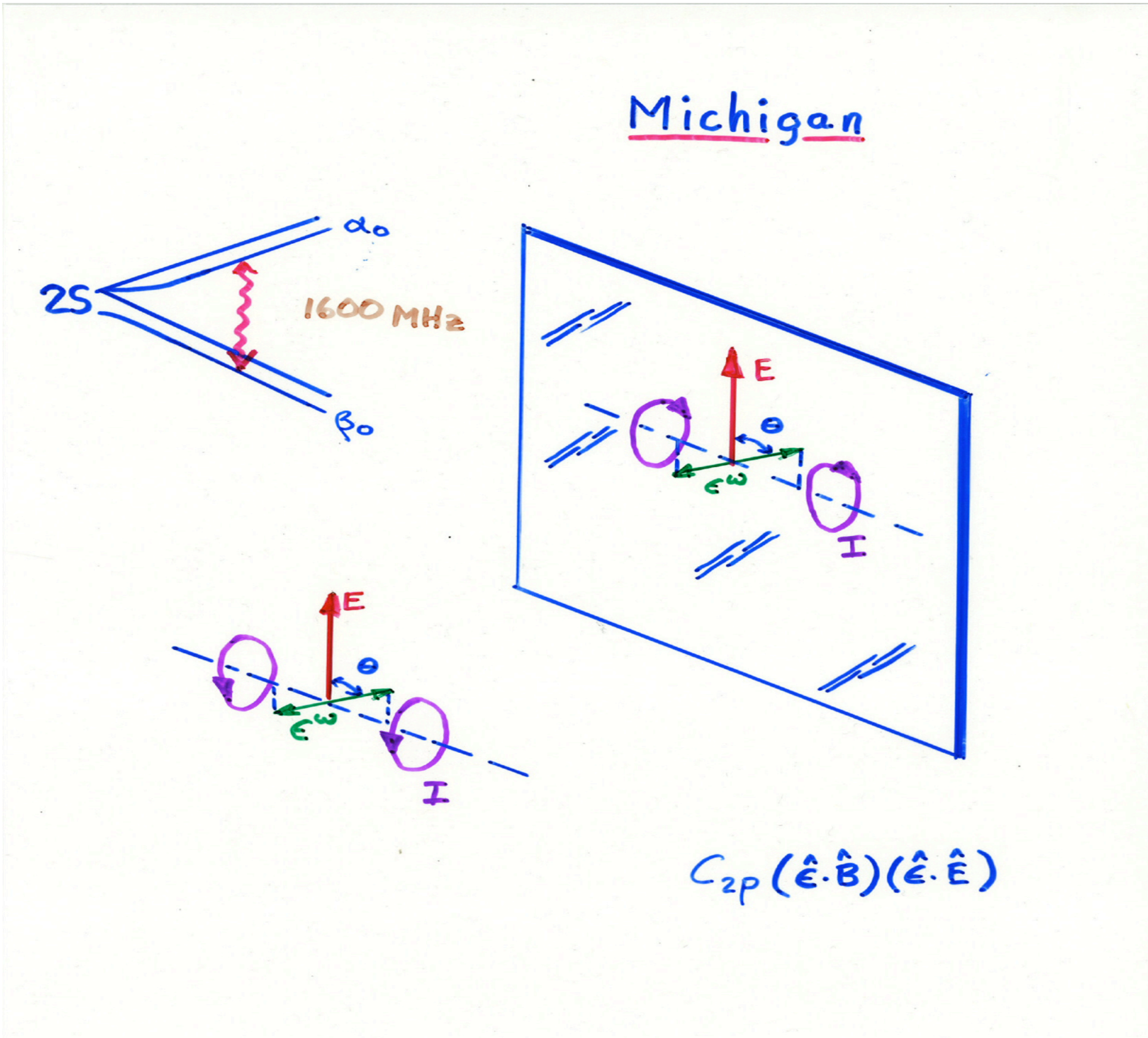
Matrix Element	Value	Standard Model
Hydrogen		
$\langle e_0 \vert V \vert \beta_0 \rangle$	$-2C_{2p}$	-0.086
$\langle f_0 \vert V \vert \beta_0 \rangle$	$C_{1p} + 1.1C_{2p}$	0.083
$\langle f_{-1} \vert V \vert \beta_{-1} \rangle$	$C_{1p} - C_{2p}$	-0.007
Deuterium		
$\langle e_{1/2} \vert V \vert \beta_{1/2} \rangle$	$-\sqrt{2}C_{2D}$	-0.010
$\langle e_{-1/2} \vert V \vert \beta_{-1/2} \rangle$	$-\sqrt{2}C_{2D}$	-0.010
$\langle f_{1/2} \vert V \vert \beta_{1/2} \rangle$	$C_{1D} + C_{2D}$	-0.452
$\langle f_{-1/2} \vert V \vert \beta_{-1/2} \rangle$	C_{1D}	-0.459
$\langle f_{-3/2} \vert V \vert \beta_{-3/2} \rangle$	$C_{1D} - C_{2D}$	-0.466

Hydrogen PNC Groups

- Michigan (Ann Arbor)
  R. R. Lewis and W. L. Williams [Phys. Lett. B59, 70 (1975)].
  E. Fry, T. Clegg, C. Wieman, R. W. Dunford, L. Lévy, D. Smith,
  C. Fehrenbach (Thesis, 1993)

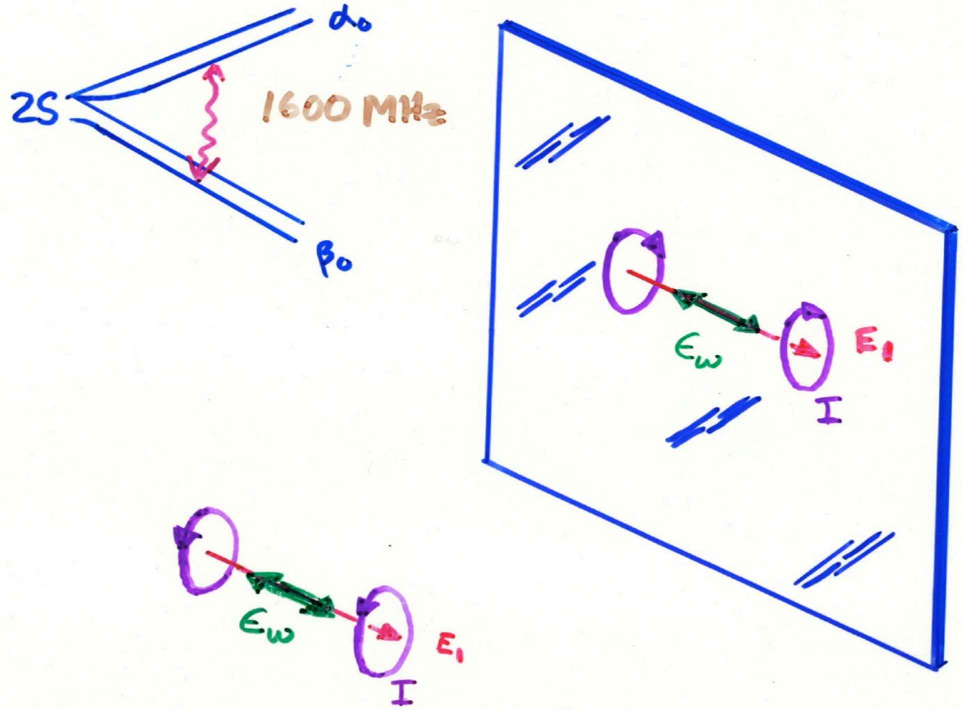
- Yale
  E. A. Hinds and V. W. Hughes [Phys. Lett. B67 487 (1977)] .
  J. W. Edwards, G. L. Greene, J. M. Hettema (Thesis,1990)

- Washington (Seattle)
  E. G. Adelberger, E. N. Fortson, T. A. Trainor [NIM, 179, 181 (1981)].
  T. E. Chupp, D. W. Holmgren, M. Z. Iqbal, H. E. Swanson,
  P. W. Wong (Thesis, 1990).



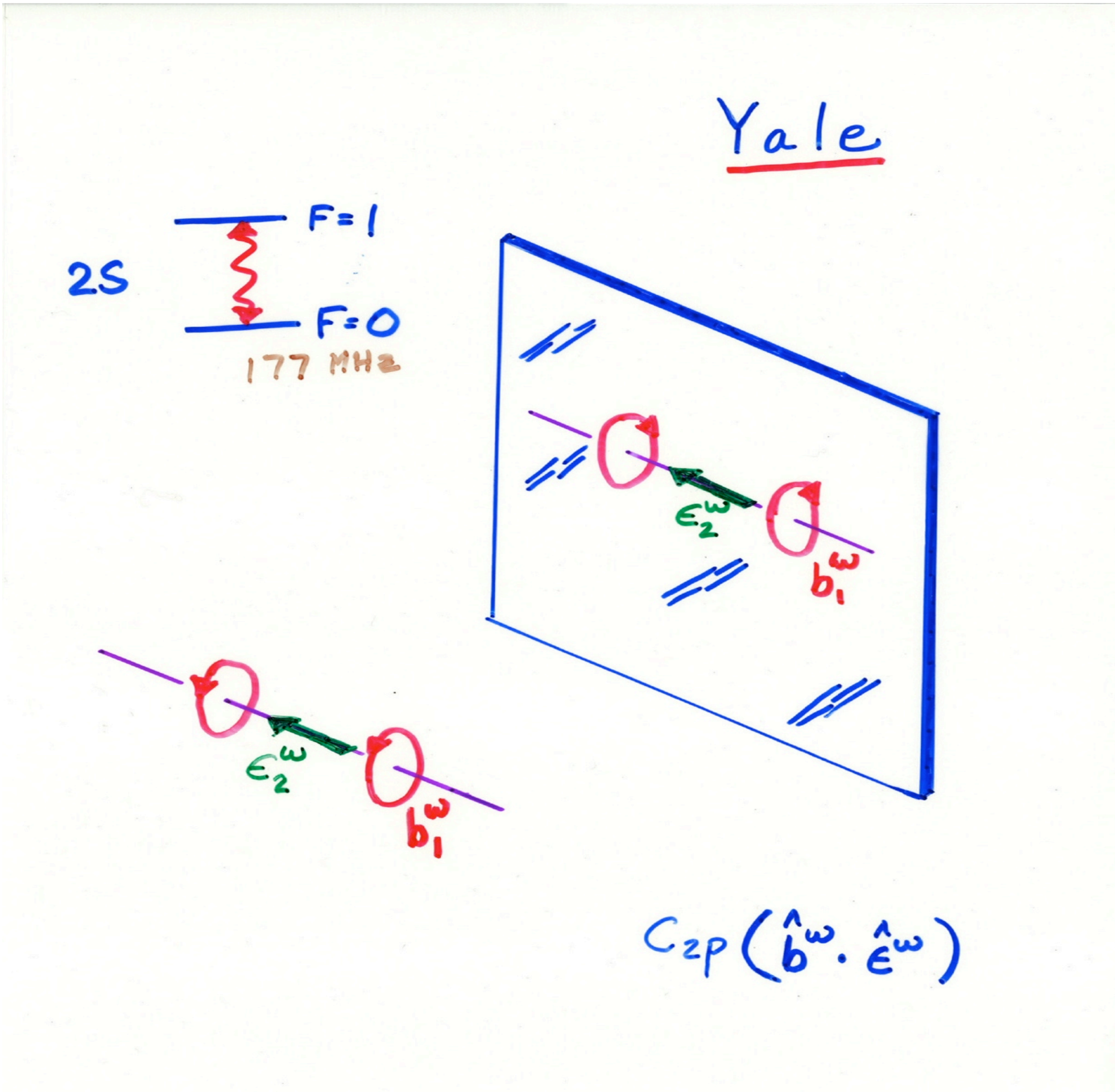
Michigan
α_0
2S
1600 MHz
β_0
E
θ
ϵ^ω
I
E
θ
ϵ^ω
I
$C_{2p}(\hat{\epsilon}\cdot\hat{B})(\hat{\epsilon}\cdot\hat{E})$

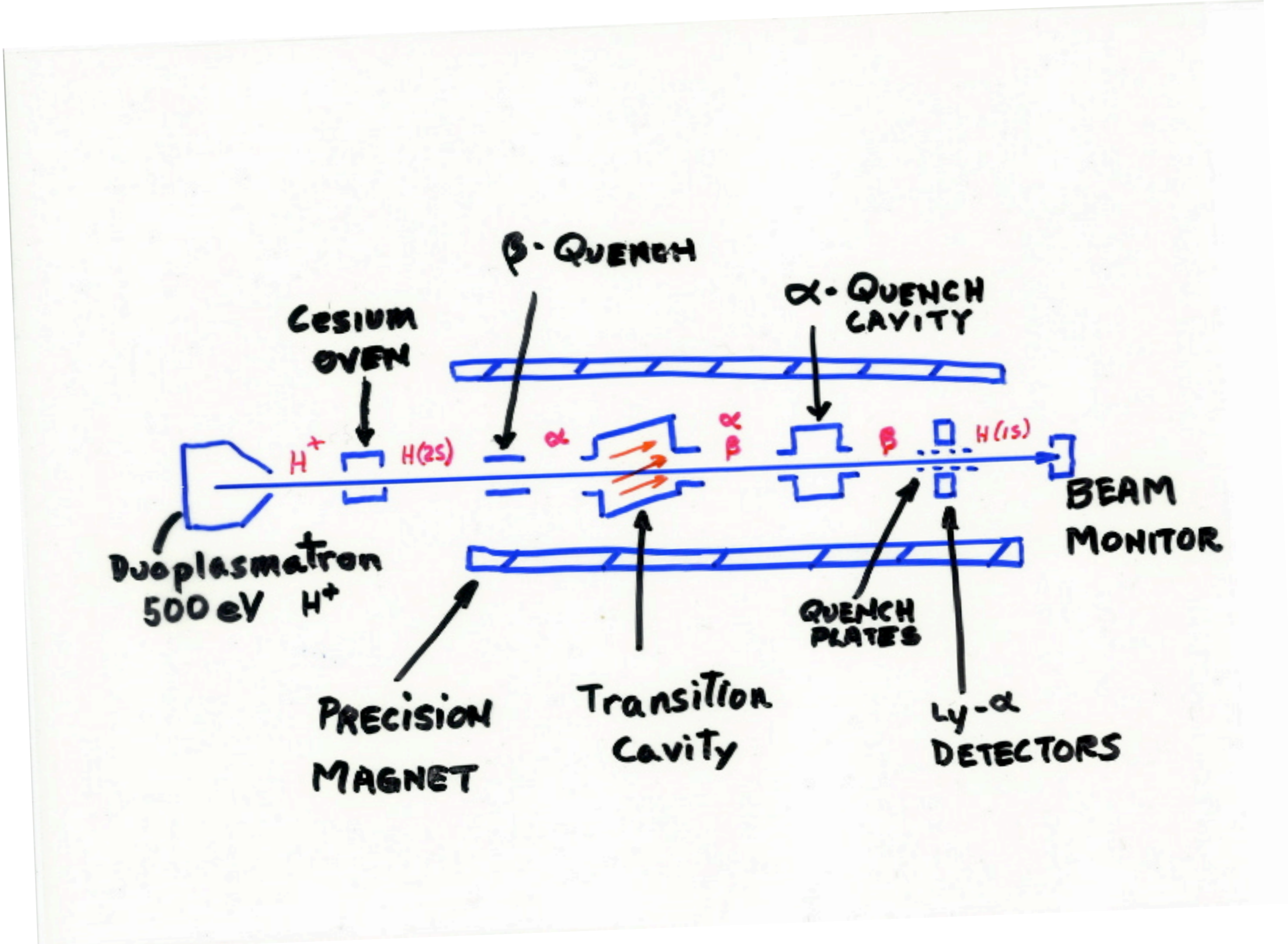
Washington H Parity Experiment



$C_{2p}\epsilon^2(\hat{E}\cdot\hat{B})$

Two Cavities


Yale
2S
F=1
F=0
177 MHz
ϵ_2^ω
b_1^ω
ϵ_2^ω
b_1^ω
$C_{2p}(\hat{b}^\omega \cdot \hat{\epsilon}^\omega)$


β-QUENCH
α-QUENCH
CAVITY
CESIUM
OVEN
H+
H(2S)
α
β
H(1S)
BEAM
MONITOR
Duoplasmatron
500 eV H+
QUENCH
PLATES
PRECISION
MAGNET
Transition
Cavity
Ly-α
DETECTORS

Limits on C_{2p} from H PNC experiments

- *< 575* — *Nuclear Physics Laboratory Annual Report, U. of Washington, 1983, p50.*
- *< 300* — *E. A. Hinds, in "The Spectrum of Atomic Hydrogen - Advances", pg. 245 (1988).*
- *0 ± 620* — *L. Lévy, W. L. Williams, Phys. Rev. Lett. 48, 607 (1982).*
- *1.5 $+1.5_{statistical}$ $+22_{systematic}$* — *Charles Fehrenbach, Thesis, U. of Michigan, 1993.*

Requirements for 0.3% Measurement of $\sin^2 \theta_W$ in H

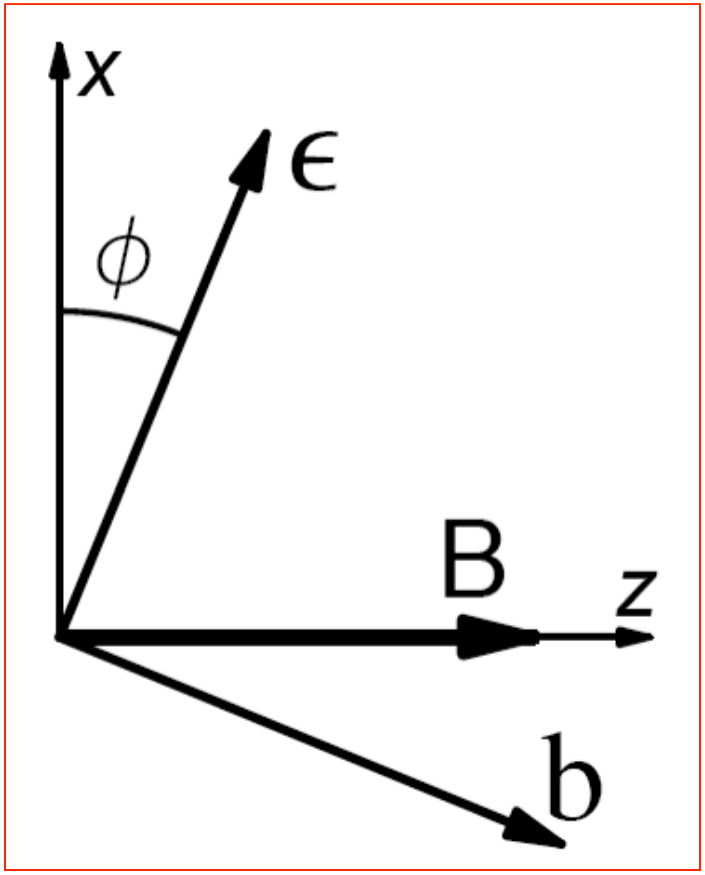
Signal/Noise (S/N) improvement by 2 orders of magnitude

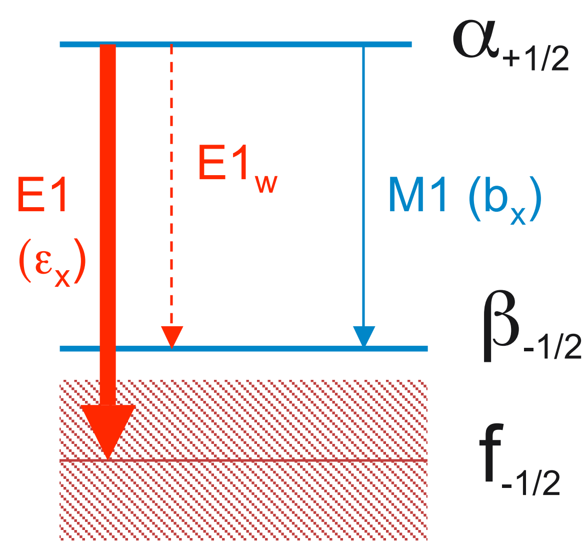
- Increase the transit time τ through the interaction region
- More intense metastable beam
- Slow, Intense H(2S) beam using FEL

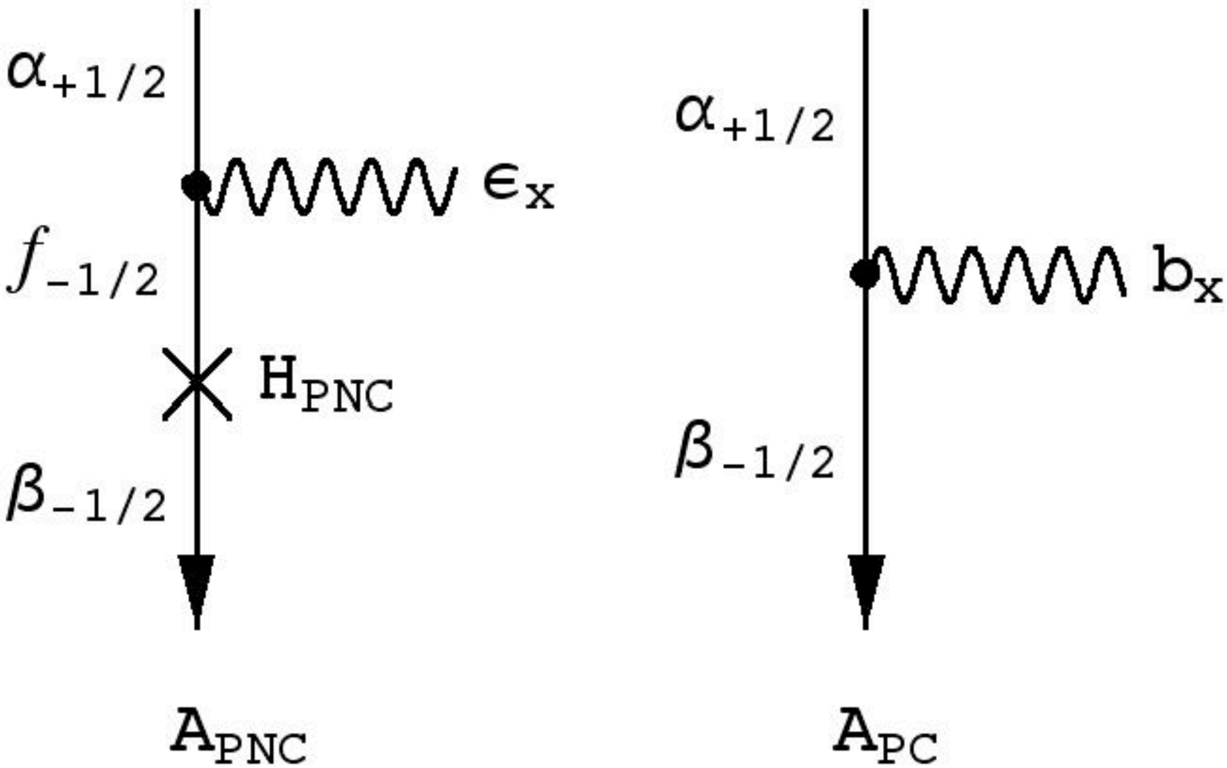
Significantly Reduce Systematic Errors

- Precise control over alignment and applied fields
- Simple configuration
- Slow beam to minimize "motional" fields

RW Dunford and RJ Holt, J. Phys. G 34(2007) 2099


x
ϵ
ϕ
B
z
b


α+1/2
E1
(εx)
E1w
M1 (bx)
β-1/2
f-1/2


$\alpha_{+1/2}$
ϵ_x
$f_{-1/2}$
H_{PNC}
$\beta_{-1/2}$
A_{PNC}
$\alpha_{+1/2}$
b_x
$\beta_{-1/2}$
A_{PC}

Fraction of rate due to APV

$$\approx \frac{-1.1 \times 10^{-7}}{\tan \phi}$$

Signal to Noise at Optimum Microwave Power

Weak Coupling Strength

Counting Time

Transit Time

$$\left(\frac{S}{N}\right)_{opt} = 1.8|\bar{\mathcal{V}}_{\rm w} C_{1D}|(\eta J T \tau / \gamma_{2p})^{1/2}$$

Detection Efficiency

Metastable Atoms/s

2p Decay Rate

Fraction of rate due to APV

$$\approx \frac{-1.1 \times 10^{-7}}{\tan\phi}$$

Signal to Noise at Optimum Microwave Power

$$\left(\frac{S}{N}\right)_{opt} = 1.8|\bar{\mathcal{V}}_{\mathrm{w}} C_{1D}|(\eta J T \tau / \gamma_{2p})^{1/2}$$

Requirement on Magnetic Field Homogeneity

$$\frac{\Delta B}{B} < \frac{\gamma_{\alpha_{+1/2}}}{\omega_{\alpha_{+1/2}\beta_{-1/2}}} \sim \frac{10^{-10} s}{\tau}$$

Required Experimental Parameters

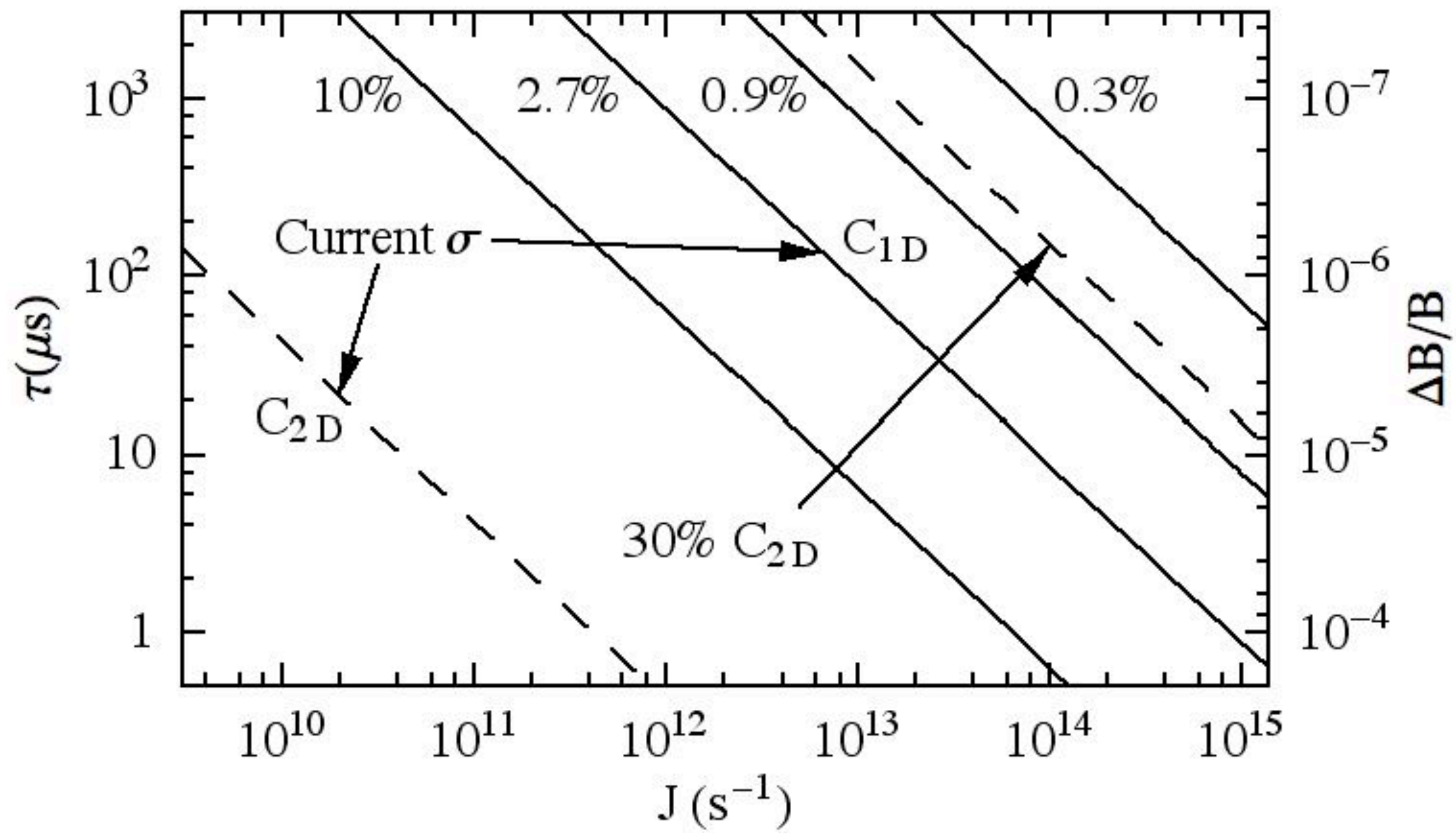
$$\left(\frac{S}{N}\right)_{opt} = 1.8|\bar{\mathcal{V}}_{\rm w} C_{1D}|(\eta J T \tau/\gamma_{2p})^{1/2}$$

$$\frac{\Delta B}{B} < \frac{\gamma_{\alpha_{+1/2}}}{\omega_{\alpha_{+1/2}\beta_{-1/2}}} \sim \frac{10^{-10}s}{\tau}$$

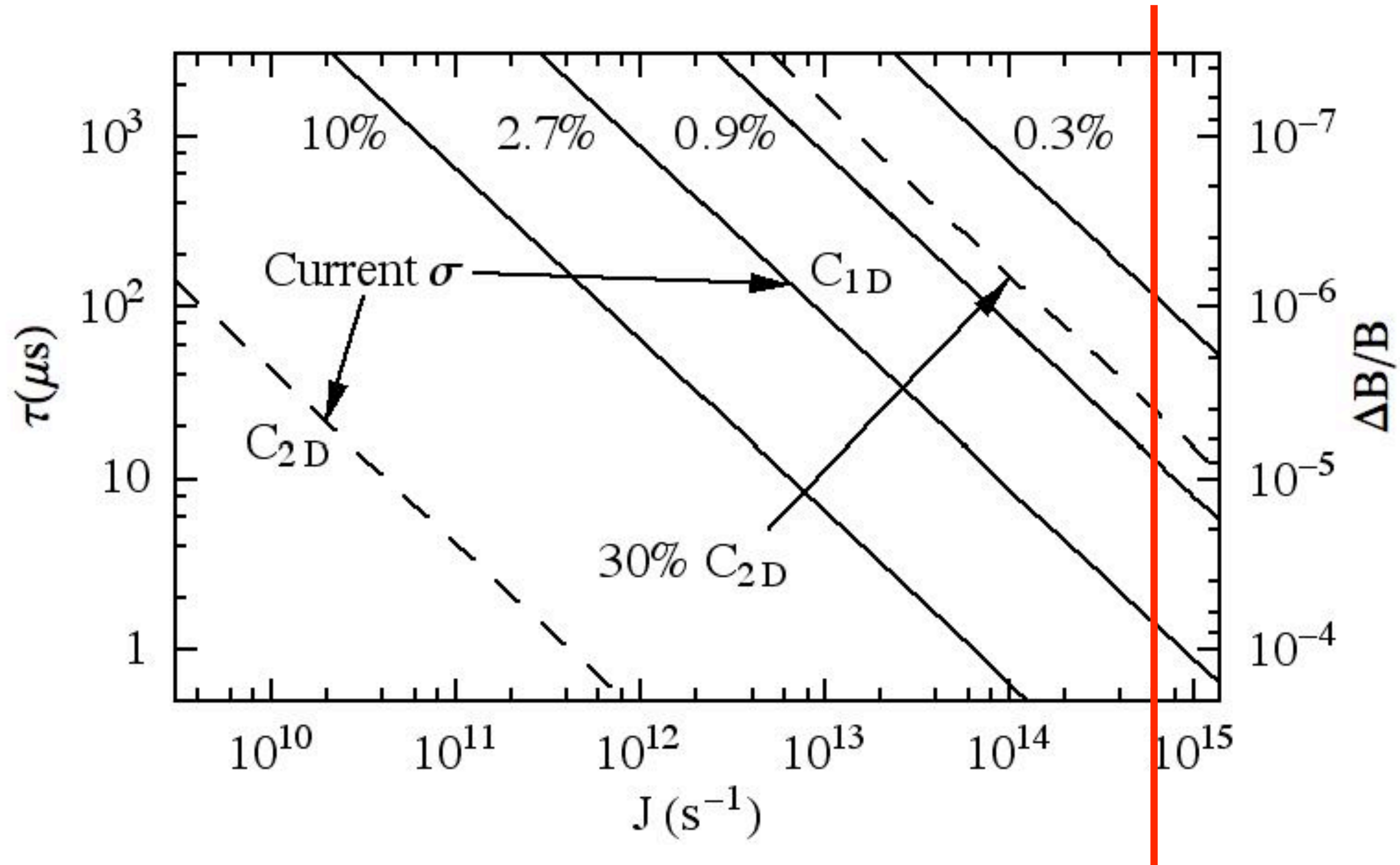
Table 3. Parameters determining the optimized sensitivity (Eq. 22)

Symbol	Meaning	Assumed for Figs. 6 and 7
η	Total detection efficiency	0.5
J	Metastable flux/hyperfine component	–
T	Counting time	5 days
τ	Interaction time	–
$i\bar{\mathcal{V}}_{\rm w}$	H PNC coupling strength (n=2)	$2\pi \times 0.013\ s^{-1}$
γ_{2p}	2p decay rate	$2\pi \times 10^8\ s^{-1}$

Sensitivity for Deuterium APV Experiment

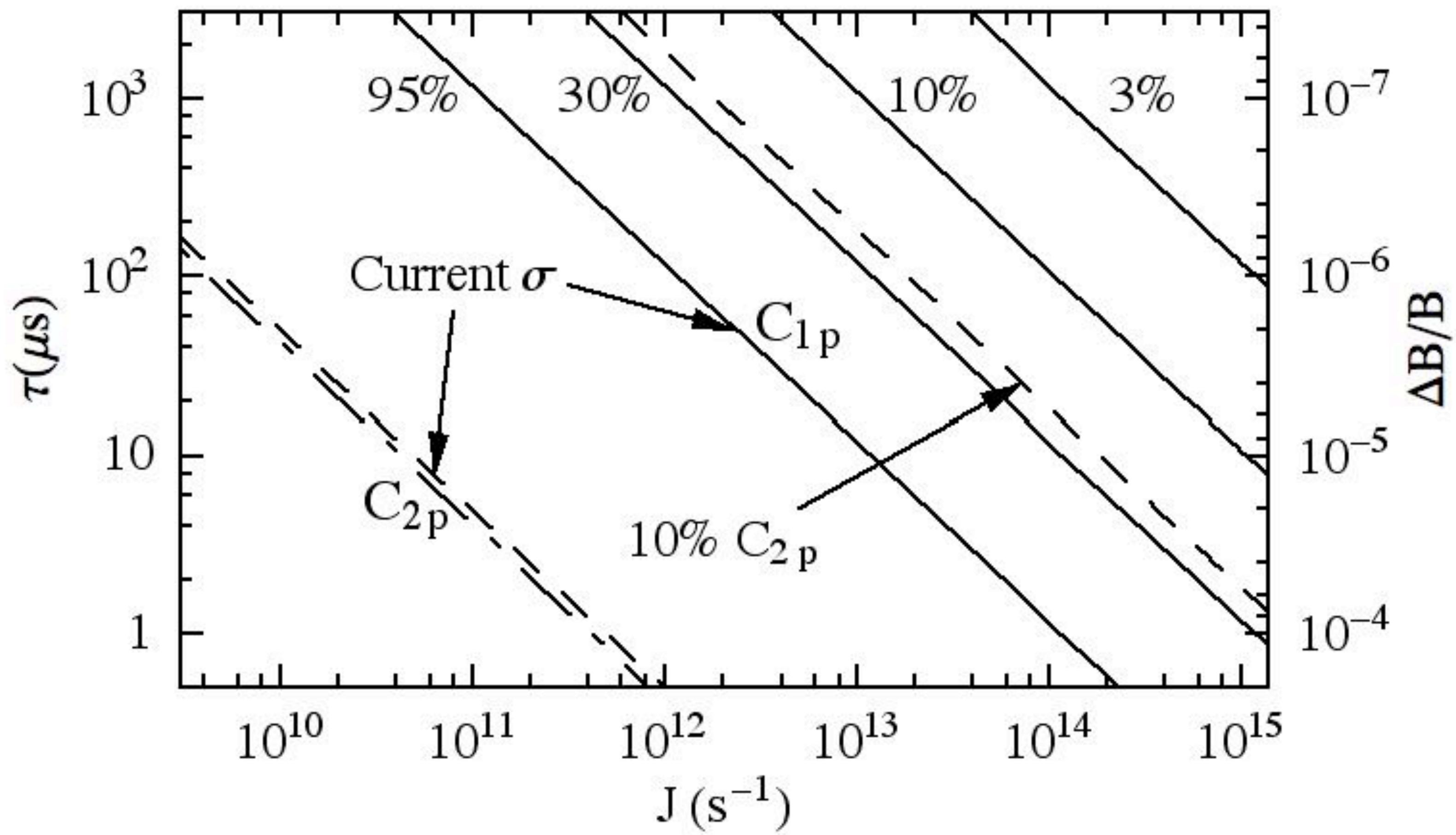


Sensitivity for Deuterium APV Experiment



$\Delta\ \mathrm{Sin}^2\ \theta_w \sim 0.3\%$ $t \sim 100\ \mu s$ $\Delta B/B \sim 10^{-6}$ $J \sim 5 \times 10^{14}\ s^{-1}$

Sensitivity for Hydrogen APV Experiment



Motional electric field systematic effect:

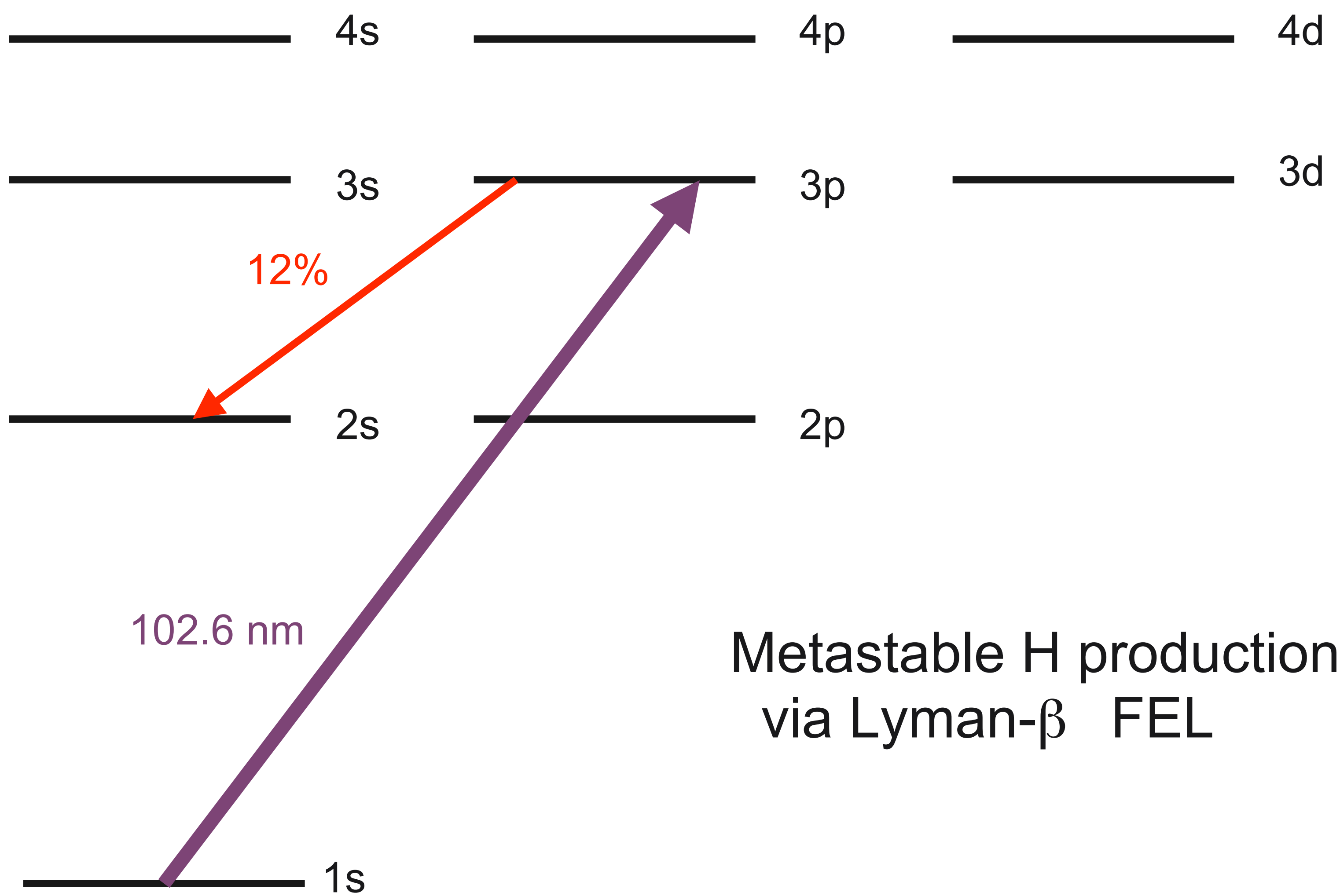
- Slow D beam ~1/300 Suppression compared to Fehrenbach experiment
- High crossing ~1/10 Suppression compared to Fehrenbach experiment
- Ratio of motional field term to the Pseudoscalar

$$R^{mot} = 8 \times 10^5 \frac{\langle E^{mot} \rangle \sin \chi}{C_{1D}}$$

- Proposed experiment with alignment as good as Fehrenbach

$$R^{mot} \approx \frac{0.01}{C_{1D}} \approx 0.02$$

- Monitor electric fields during expt. using the atoms themselves
  Advantage Intense Beam



Metastable H production
via Lyman-β FEL

K. C. Harvey, JAP **53**(1982)3383

Metastable Beam Production

- Quench Mechanism: Beam Density Requirement

$$H(2s) + H(2s) \rightarrow H(2p) + H(2p) \qquad \sigma^{sp} = 9 \times 10^{-12} cm^2$$

$$\rho_{2s} < \frac{1}{\sigma^{sp} \lambda_{mfp}} \approx 10^9 cm^{-3}$$

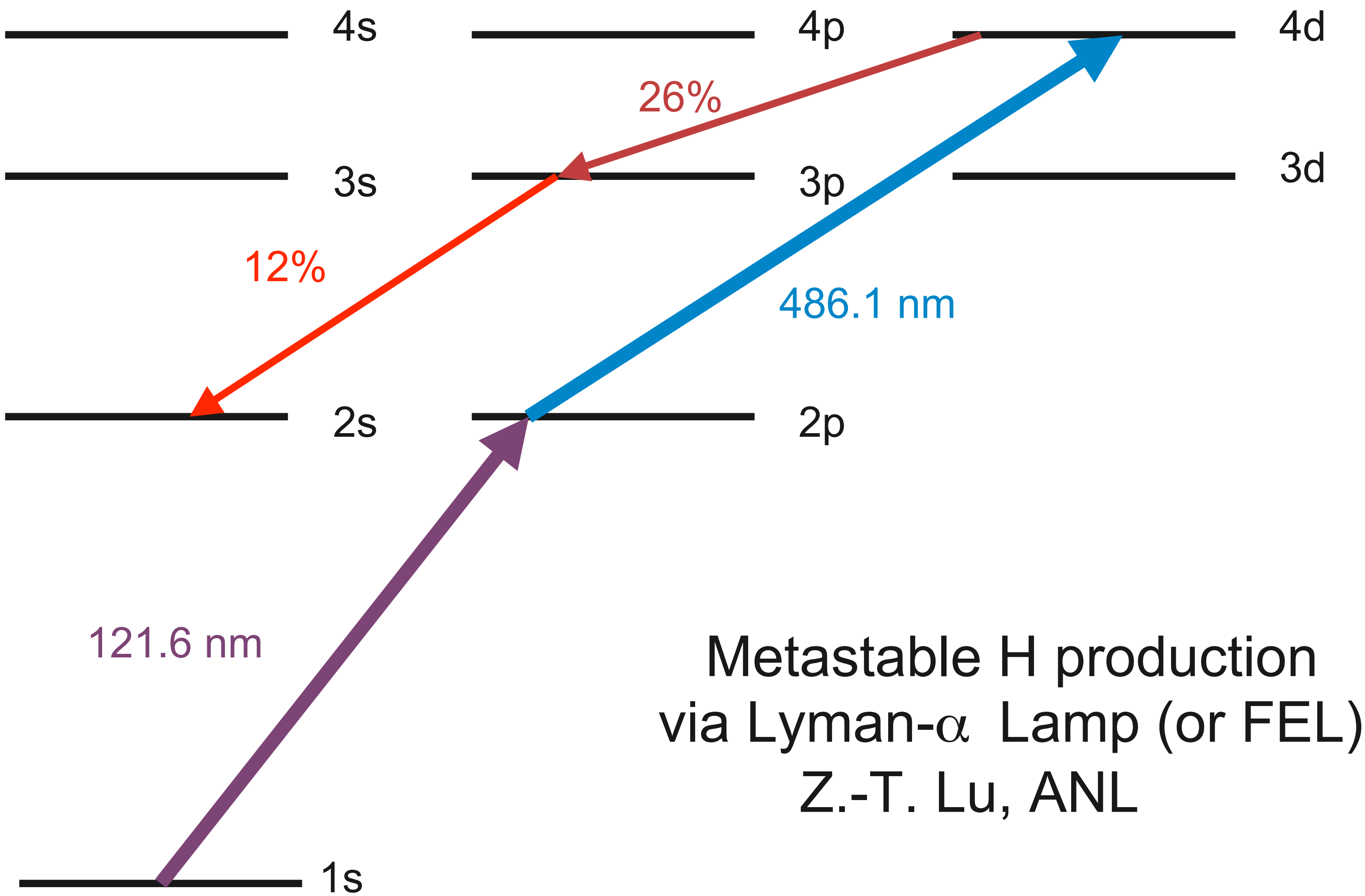
- Pumping 1s → 3p → 2s (12% Branch)

$$\sigma_{1s3p} \approx \frac{1.3 \times 10^{-12}}{\gamma_{\text{line}}(GHz)} \text{cm}^2 \qquad \text{at } 102.6 \text{ nm}$$

- FEL Requirement for 5 x10^{14} D(2s) /s

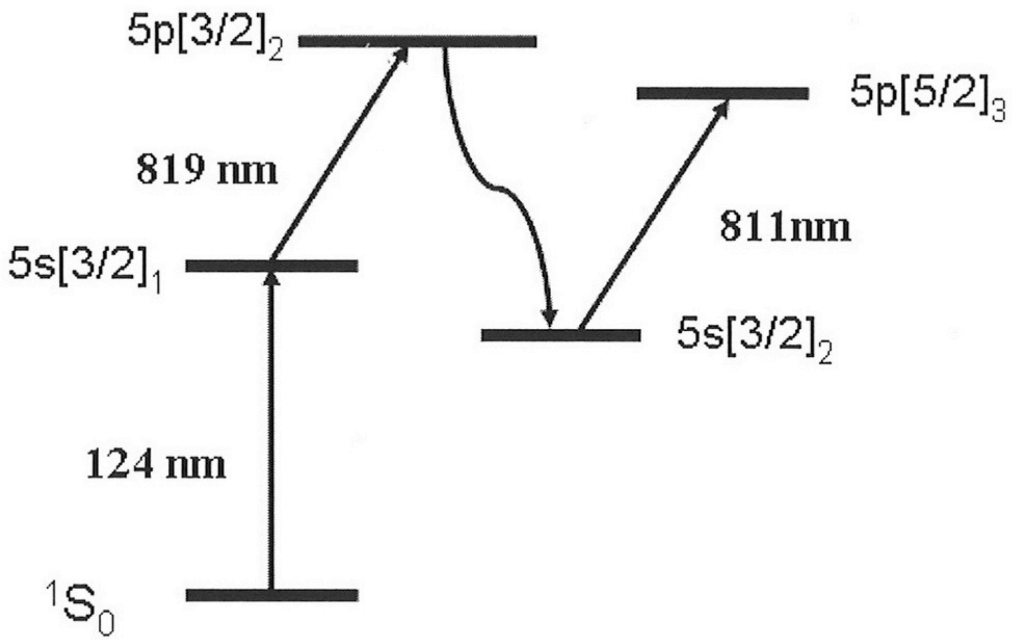
With 2 x 10^{17} D(1s)/s in 2.5 cm diameter

40 mW GHz^{-1}

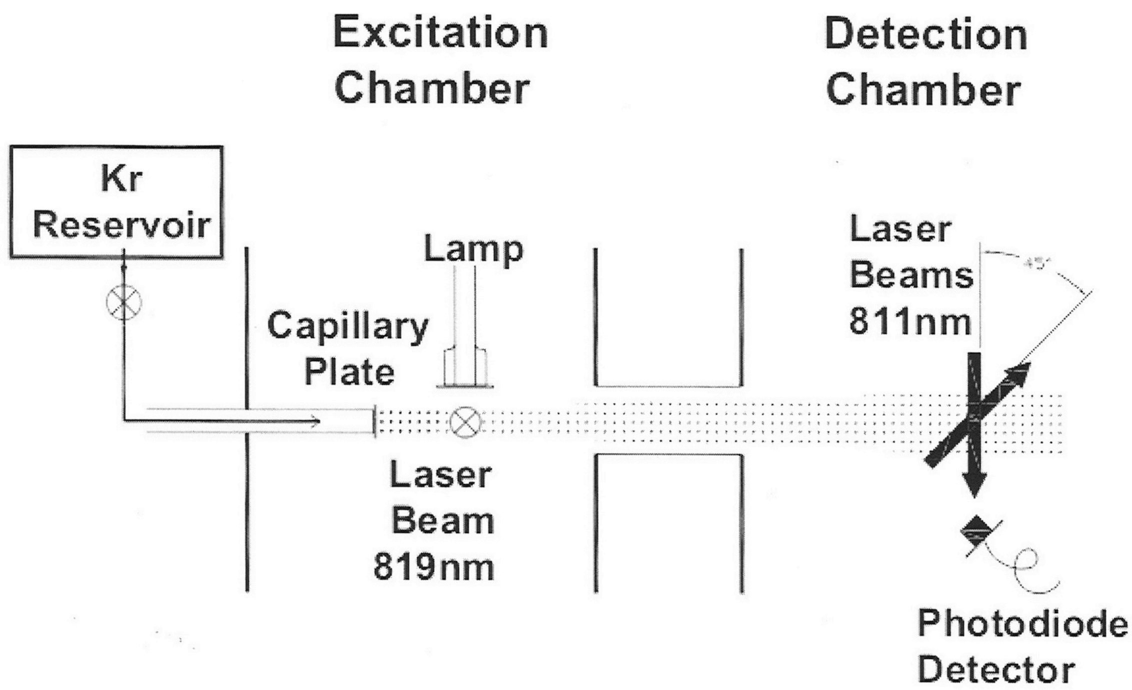


Metastable H production
via Lyman-α Lamp (or FEL)
Z.-T. Lu, ANL

Pumping/Detection in Kr Beam Experiment*



Kr Beam for Atomic Trap Trace Analysis (ATTA)*



Ding, Bailey, Davis, Dunford, Lu, O'Connor, Young, RSI 78 (2007) 023103

Summary:

- Negligible atomic physics uncertainty for H APV experiments compelling
- Goal of 0.3% measurement of C_{1D} - factor of 3 improvement on APV limit on $\mathrm{Sin}^2\,\theta_w$
- Such an experiment requires a minimum of 5×10^{14} slow D(2S) Atoms/s
- requires FEL at 102.6 nm with power/bandwidth 40 mW GHz^{-1}
- Work on optical production of metastable Kr suggests another scheme
  10^{14} Kr*/s achieved in a cell