Physics 430 / 631: Quantum Optics & Atomics: Hyperfine structure

10/23/2025

Dr. Adam Vernon

avernon@wm.edu

Launched in 1977, both Voyager spacecraft carry a unique 'time capsule' along with them into interstellar space [https://science.nasa.gov/mission/voyager/voyager-golden-record-overview/]

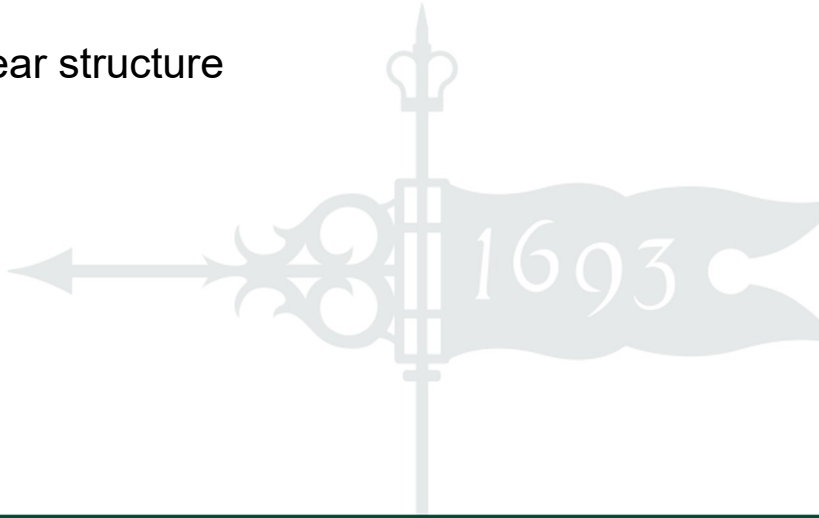
WILLIAM & MARY

CHARTERED 1693

Overview

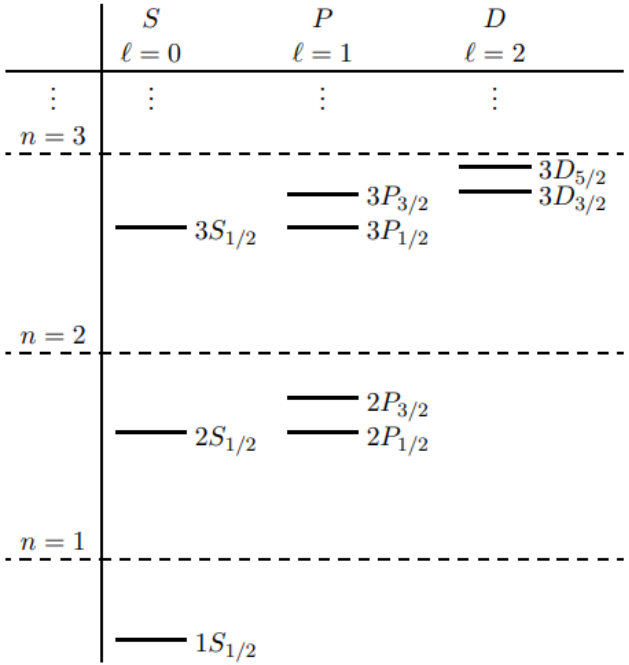
- Fine structure Hydrogen from P.T. reminder
- Hyperfine structure from P.T.
- Hyperfine structure of Hydrogen: 0 field
- Hyperfine structure parameters (many-electron, many-nucleon)
- Zeeman splitting: Weak- and Strong- field
- Hyperfine structure in atoms and molecules → nuclear structure

- Optional HW: line isotope shift



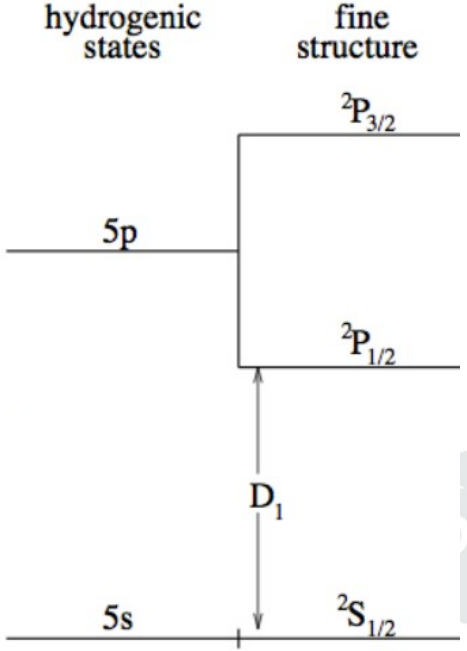
Fine structure splitting (J=S+L)

Hydrogen (Z=1) fine structure spectrum



[https://ocw.mit.edu/courses/8-06-quantum-physics-iii-spring-2018/]

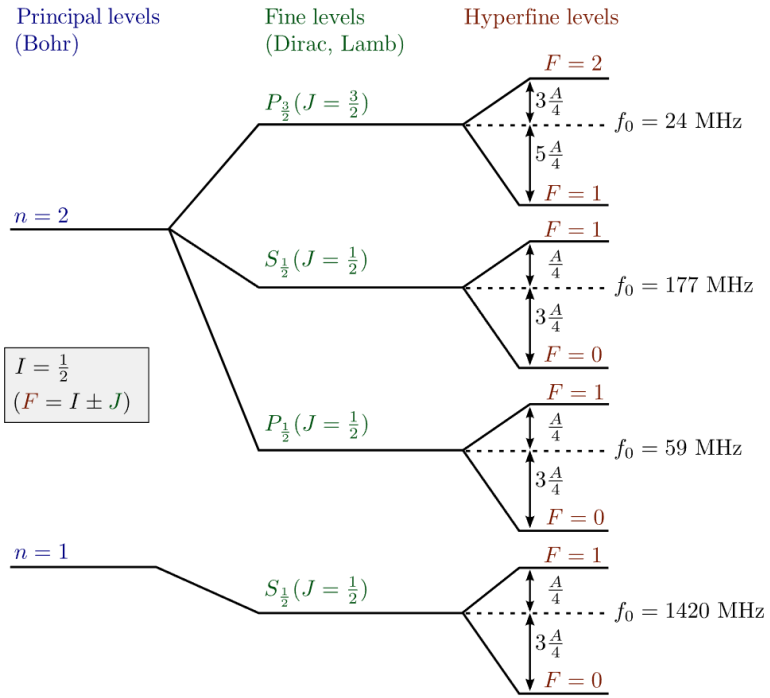
Rubidium (Z=37) fine structure spectrum



[https://physics.bu.edu/~sulak/AdLab/EXPERIMENT%20DOCUMENTATION/OpticalPumping_Lab.pdf]

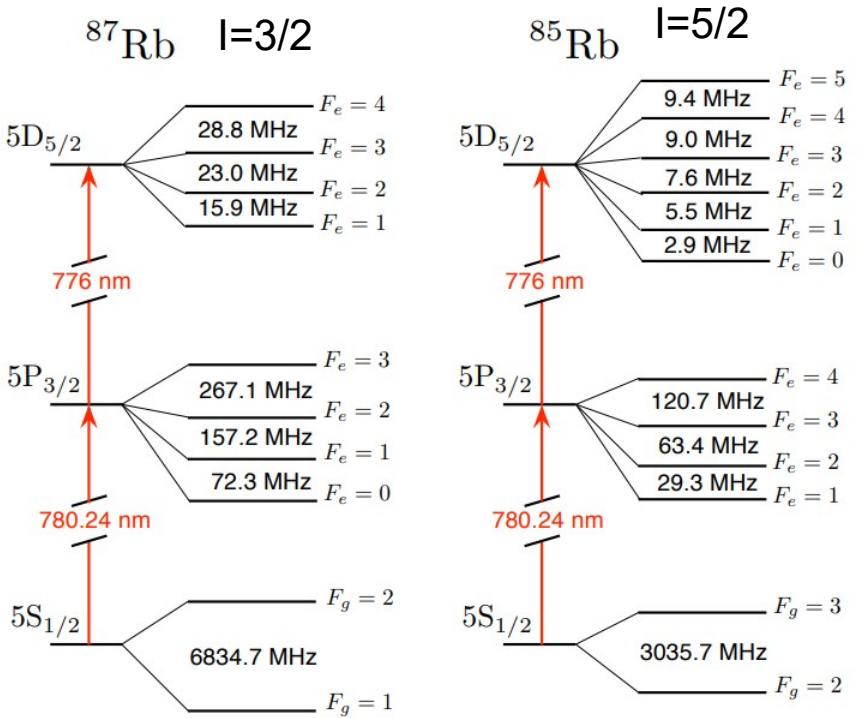
Hyperfine structure splitting (F= I+J)

Hydrogen hyperfine spectrum (0 field)



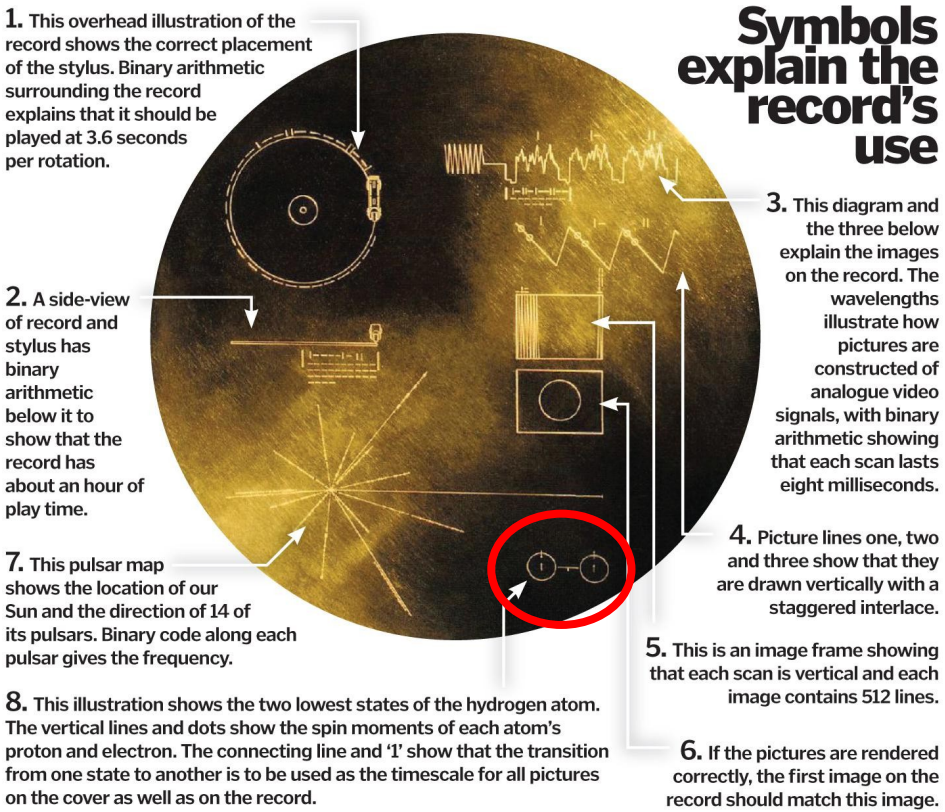
[https://commons.wikimedia.org/wiki/File:Hydrogen-Fine-Hyperfine-Levels-en.svg]

Rubidium hyperfine spectrum (0 field)



[https://doi.org/10.1088/0143-0807/30/5/001]

The Hydrogen hyperfine structure 21 cm line

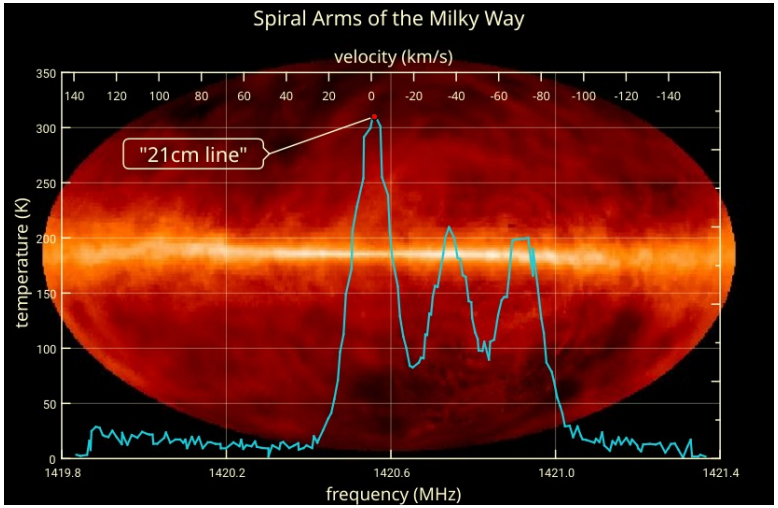


[https://science.nasa.gov/mission/voyager/voyager-golden-record-overview/]

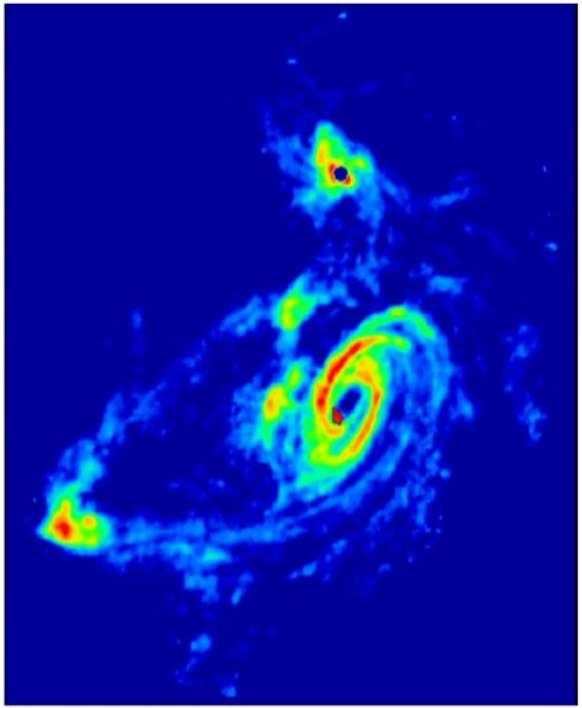
The Hydrogen hyperfine structure 21 cm line

- 90% of matter is Hydrogen
- 21 cm line lies in the radio spectrum and passes easily through insterstellar dust and the Earth's atmosphere

  → stellar probe



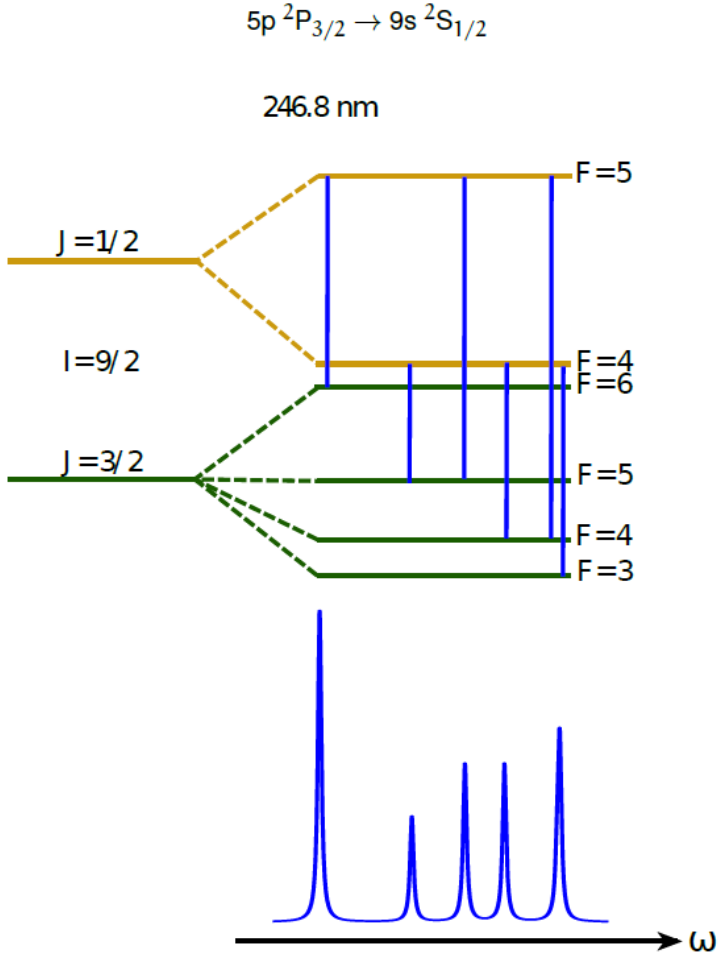
[https://labplot.org/2020/12/28/the-universe-full-of-hydrogen-and-a-new-feature-in-labplot/]



M.S. Yun, et al., "A New Observational and Numerical Study of Tidal Interactions in M81-M82-NGC3077 System," in *NASA Ames Research Center, The evolution of galaxies and their environment, p 253-254 (1993).*

Hyperfine structure parameters

Dynamic Python plot demonstration



Hyperfine structure parameters

$$K = F(F+1) - I(I+1) - J(J+1)$$

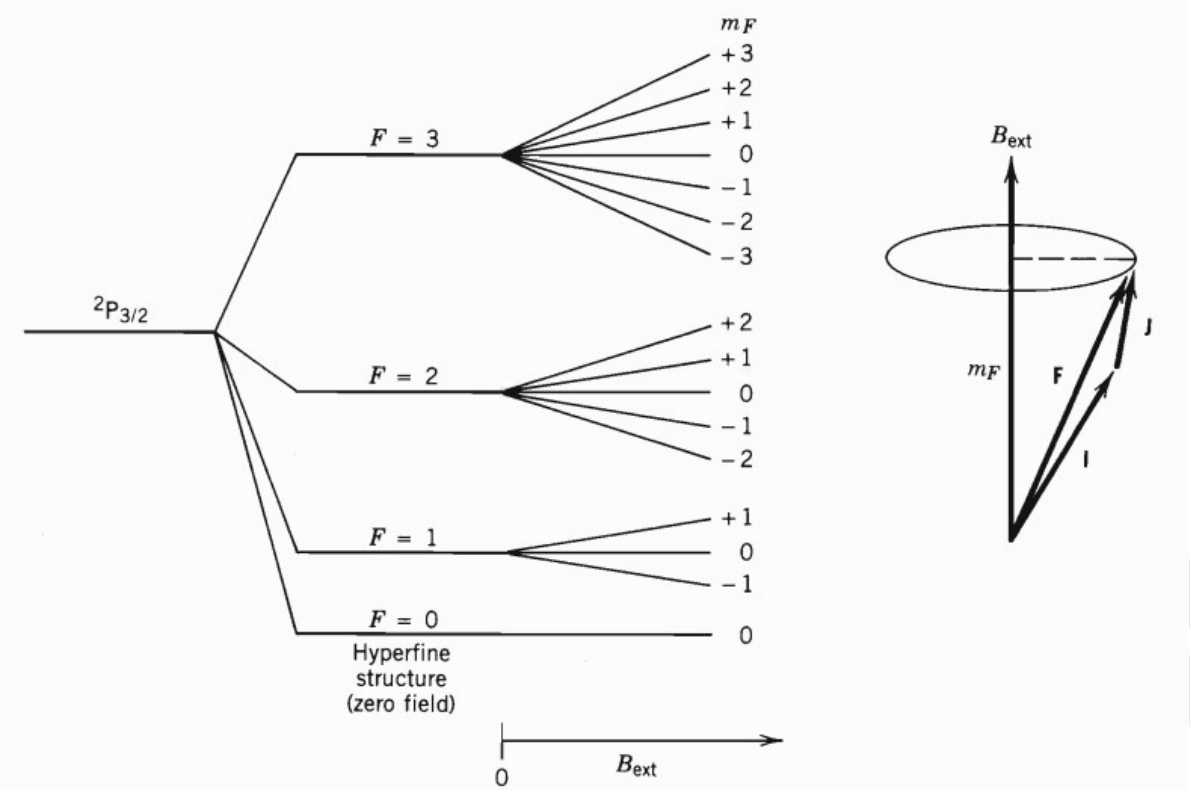
$$E_F^{(1)} = \frac{AK}{2} + \frac{3B}{4}\frac{K(K+1) - I(I+1)J(J+1)}{(2I(2I-1)J(2J-1))} + \frac{5C}{4}\frac{K^3 + 4K^2 + \frac{4}{5}K(-3I(I+1)J(J+1) + I(I+1) + J(J+1) + 3) - 4I(I+1)J(J+1)}{I(I-1)(2I-1)J(J-1)(2J-1))}$$

+ ...

[https://doi.org/10.1103/PhysRevA.103.032826]

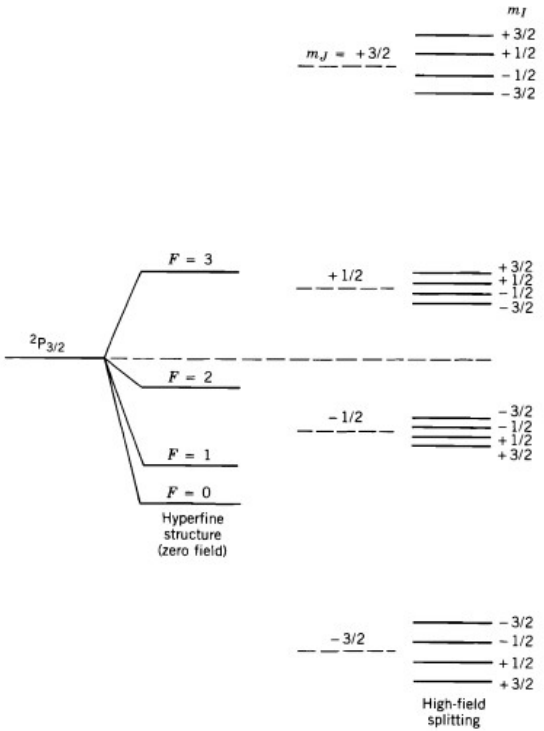
Zeeman effect: weak-field

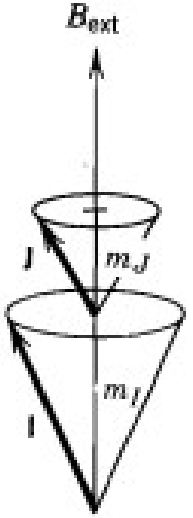
$$g_F = g_J \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)} - g_I' \frac{F(F+1) - J(J+1) + I(I+1)}{2F(F+1)}$$



[K. S. Krane and D. Halliday, Introductory nuclear physics. Wiley, 1988]

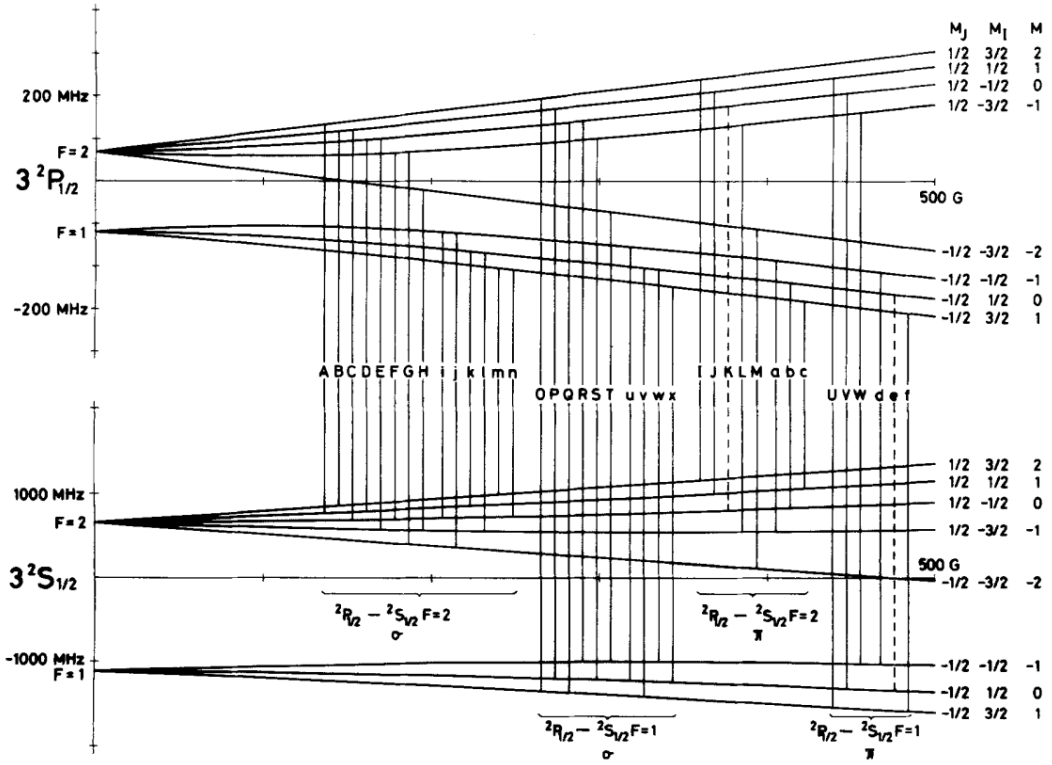
Zeeman effect: strong-field / the Paschen-Bach effect





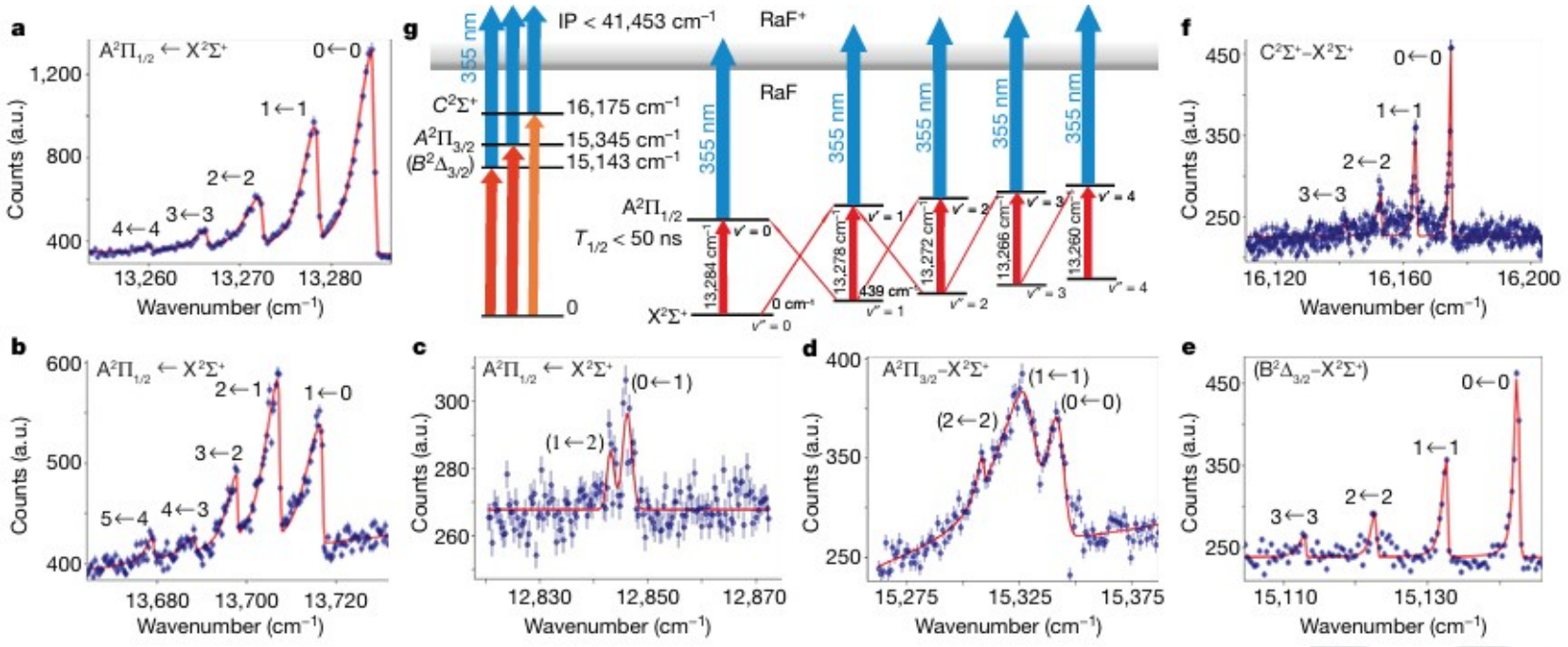
[K. S. Krane and D. Halliday, Introductory nuclear physics. Wiley, 1988]

Zeeman effect: intermediate field...



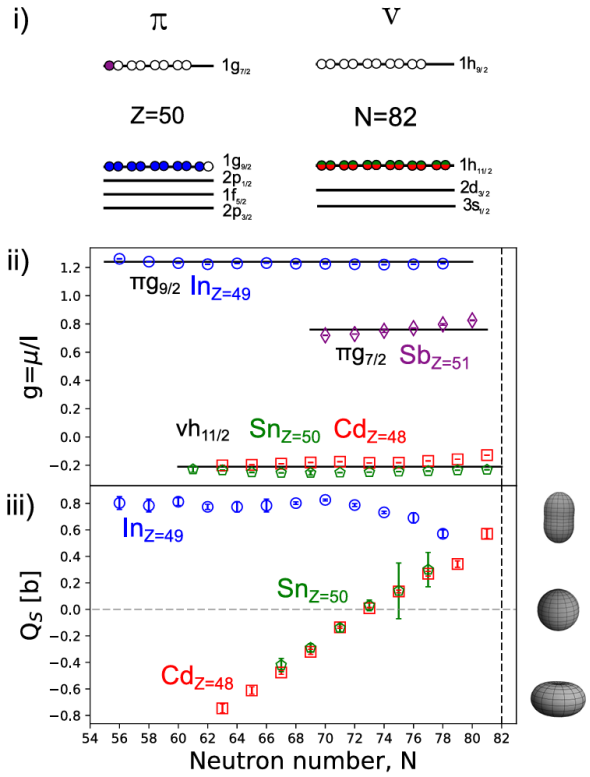
[L. Windholz, “Zeeman-and Paschen-Back-Effect of the Hyperfine Structure of the Sodium D1-Line,” 1985]

Molecules: more complex electronic structure ontop!

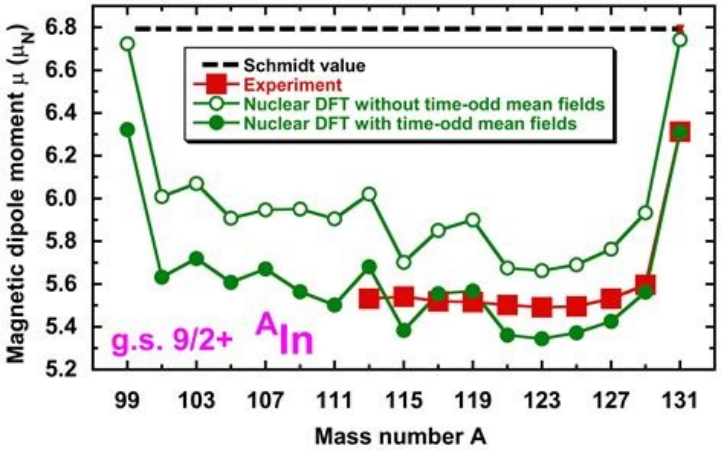


[R. F G; Ruiz ,…, **A. R Vernon** ..., 2020 - https://www.nature.com/articles/s41586-020-2299-4]

Electronic structure ← hyperfine structure → **nuclear structure**



[R. F G; Ruiz, **A. R Vernon**, 2020 - https://doi.org/10.1140/epja/s10050-020-00134-8]



[**A. R Vernon …** , 2022 - https://www.nature.com/articles/s41586-022-04818-7]

Literature

Fine structure notes Seth 2024:

https://saaubi.people.wm.edu/TeachingWebPages/Physics482_690_Spring2024/Week10/Lecture15_2April2024.pdf

Alkali-atom hyperfine structure experimental paper (Seth recc.):

E. Arimondo, M. Inguscio, and P. Violino,1977, doi: 10.1103/RevModPhys.49.31

Angular momentum coupling:

D. M. Brink and G. R. Satchler, Angular Momentum, 1962.

Hydrogen FS and Zeeman P.T. notes:

Chapter 2: Hydrogen Fine Structure - https://ocw.mit.edu/courses/8-06-quantum-physics-iii-spring-2018/

All fine structure terms with P.T.:

Lectures 2,3 – PHYS626 - University of Delaware (M. Safronova) - https://mariannasafronova.com/wp-content/uploads/2023/01/626Lectures2-3.pdf

Isotope shifts (the hyperfine splitting 'center of gravity'):

W. H. King. Isotope Shifts in Atomic Spectra. Plenum,. New York, 1984

Intermediate-field splitting paper:

L. Windholz, "Zeeman-and Paschen-Back-Effect of the Hyperfine Structure of the Sodium D1-Line," 1985.

Hyperfine anomaly in heavy atoms and its role in precision atomic searches for new physics:

https://doi.org/10.1103/PhysRevA.104.022823

Anti-hydrogen hyperfine structure (it's the same as we just did!):

https://cern-courier.web.cern.ch/a/hyperfine-structure-from-hydrogen-to-antihydrogen/

Anonymous feedback on lecture welcome:

QR code