

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

10/23/2025

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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/>]

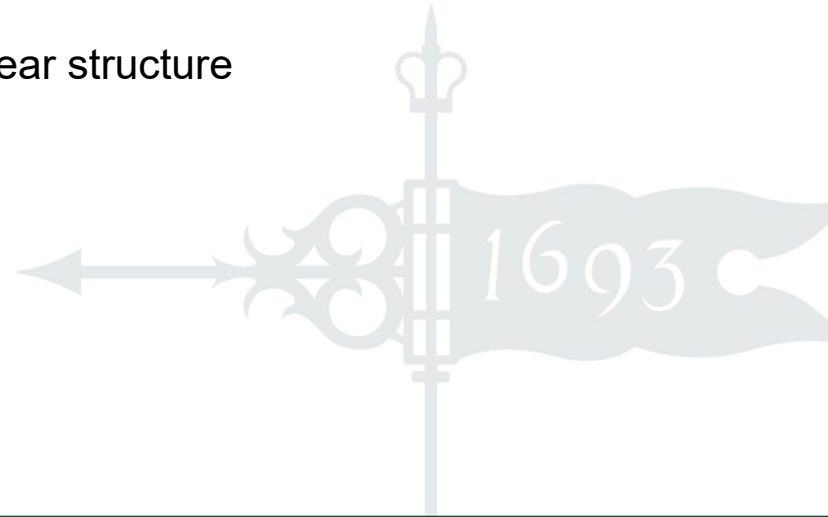


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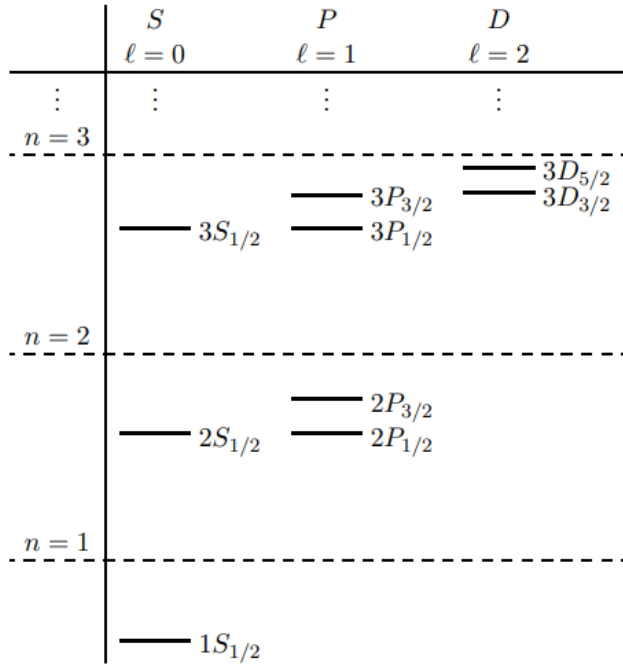
Overview

- 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

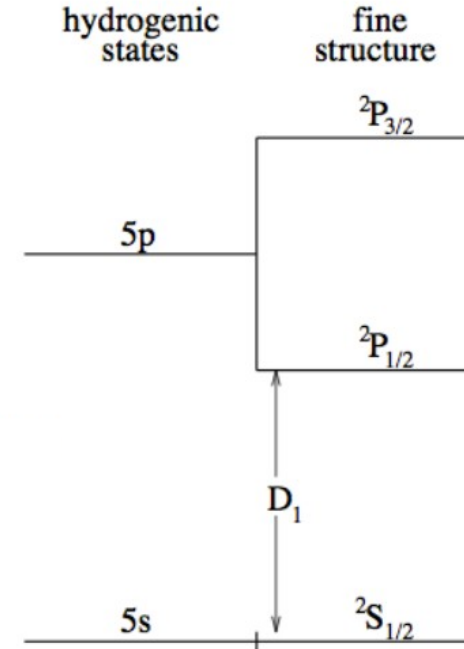


Fine structure splitting ($J=S+L$)

Hydrogen ($Z=1$) fine structure spectrum

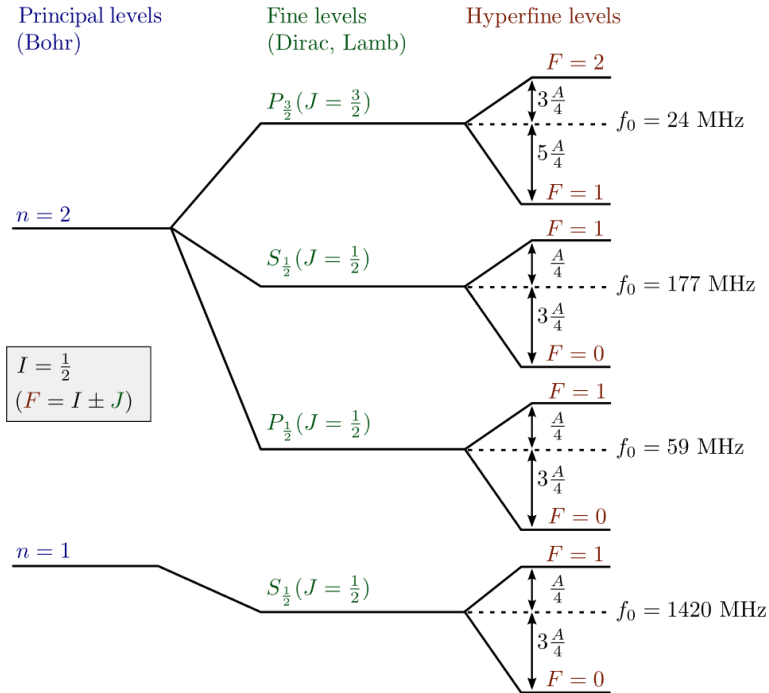


Rubidium ($Z=37$) fine structure spectrum

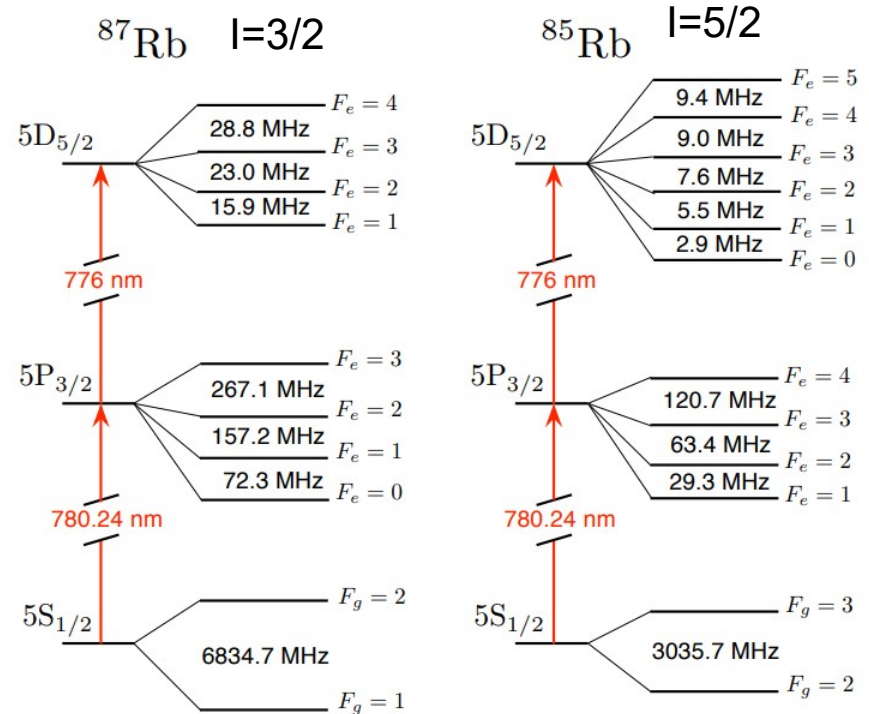


Hyperfine structure splitting ($F = I + J$)

Hydrogen hyperfine spectrum (0 field)



Rubidium hyperfine spectrum (0 field)



The Hydrogen hyperfine structure 21 cm line

1. This overhead illustration of the record shows the correct placement of the stylus. Binary arithmetic surrounding the record explains that it should be played at 3.6 seconds per rotation.

2. A side-view of record and stylus has binary arithmetic below it to show that the record has about an hour of play time.

7. This pulsar map shows the location of our Sun and the direction of 14 of its pulsars. Binary code along each pulsar gives the frequency.

8. This illustration shows the two lowest states of the hydrogen atom. The vertical lines and dots show the spin moments of each atom's proton and electron. The connecting line and '1' show that the transition from one state to another is to be used as the timescale for all pictures on the cover as well as on the record.

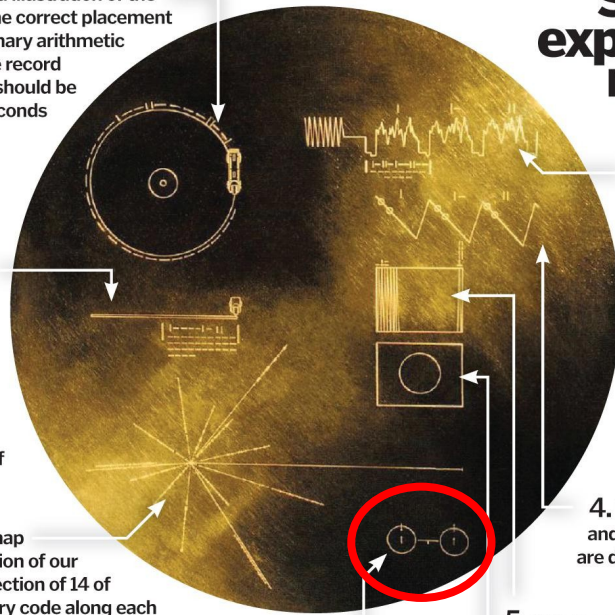
Symbols explain the record's use

3. This diagram and the three below explain the images on the record. The wavelengths illustrate how pictures are constructed of analogue video signals, with binary arithmetic showing that each scan lasts eight milliseconds.

4. Picture lines one, two and three show that they are drawn vertically with a staggered interlace.

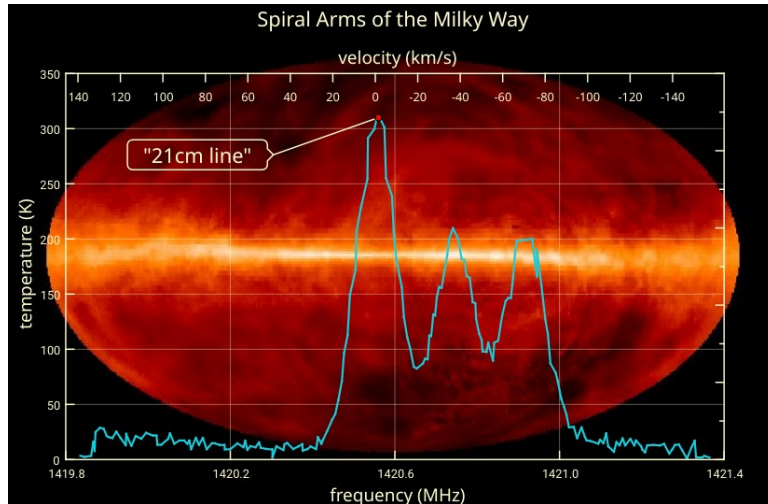
5. This is an image frame showing that each scan is vertical and each image contains 512 lines.

6. If the pictures are rendered correctly, the first image on the record should match this image.

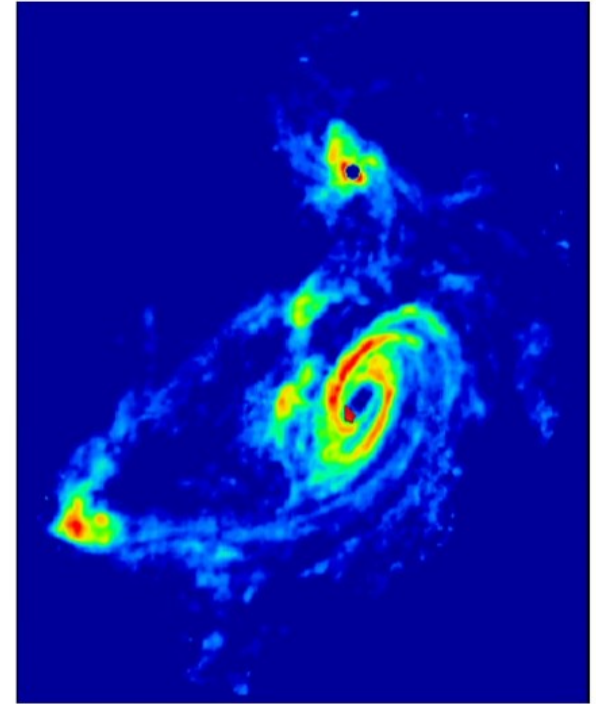


The Hydrogen hyperfine structure 21 cm line

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



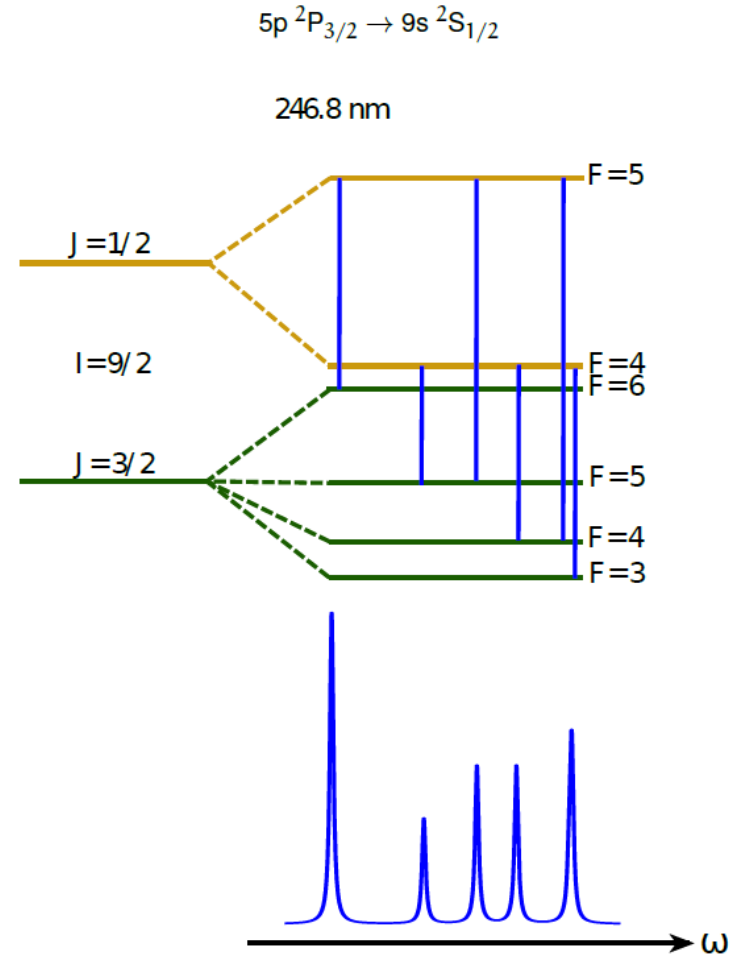
[<https://labplot.org/2020/12/28/the-universe-full-of-hydrogen-and-a-new-feature-in-labplot/>]



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

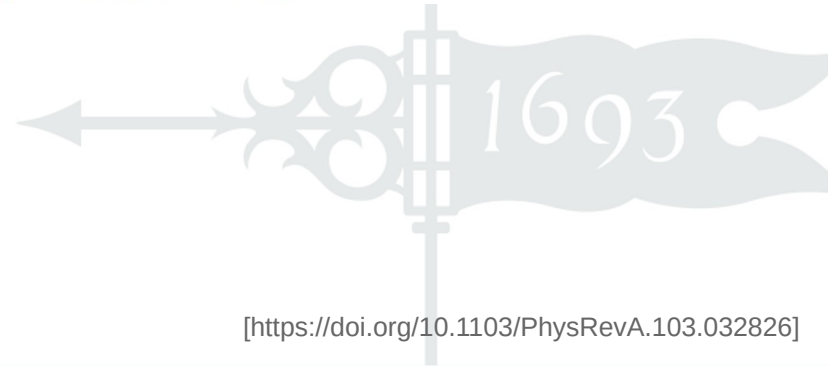
Dynamic Python plot demonstration



Hyperfine structure parameters

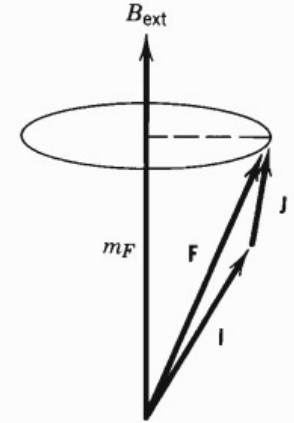
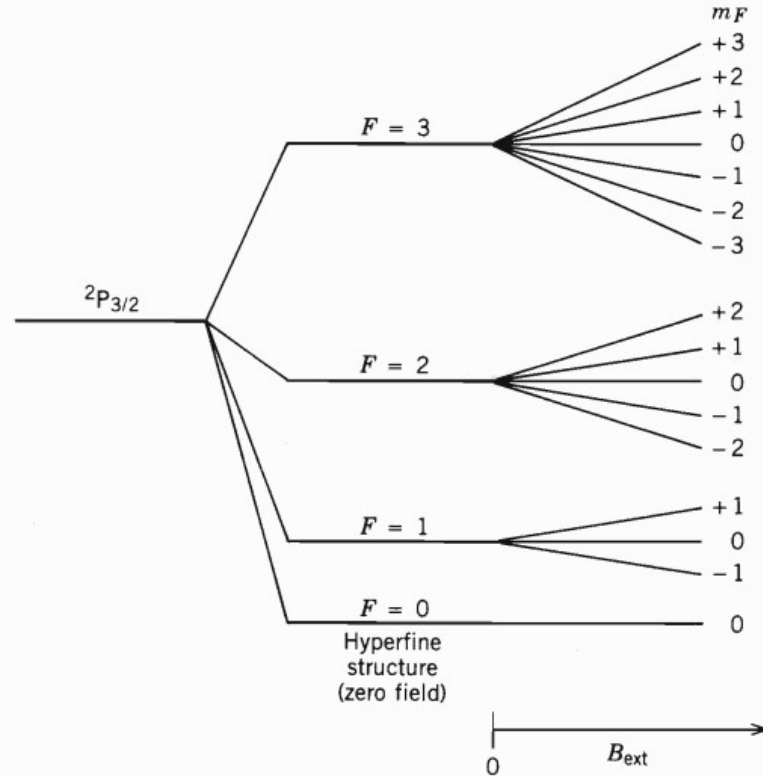
$$K = F(F + 1) - I(I + 1) - J(J + 1)$$

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

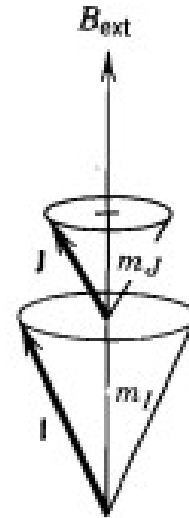
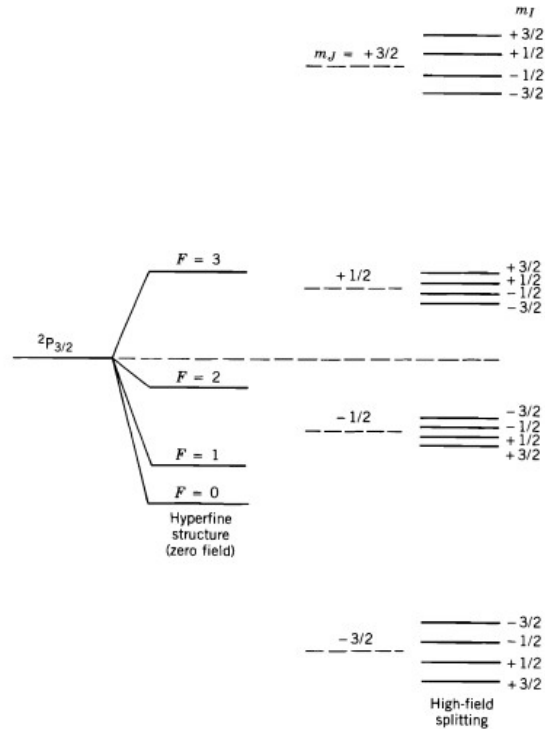


Zeeman effect: weak-field

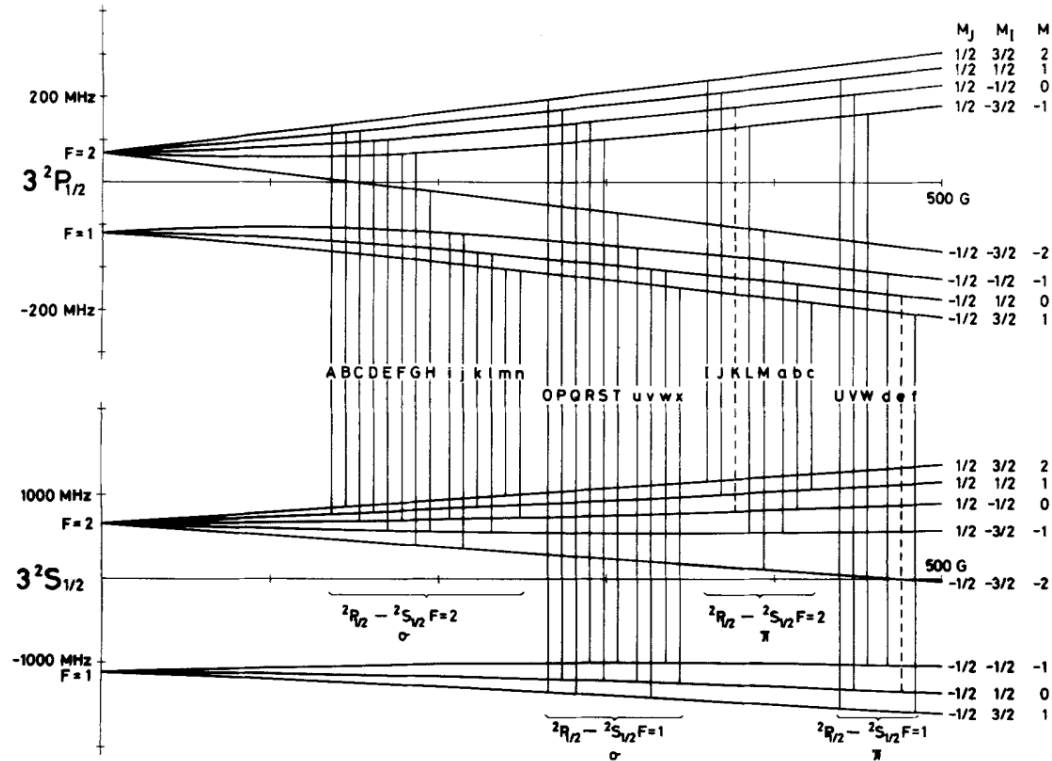
$$g_F = g_J \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)} - g_I' \frac{F(F+1) - J(J+1) + I(I+1)}{2F(F+1)}$$



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

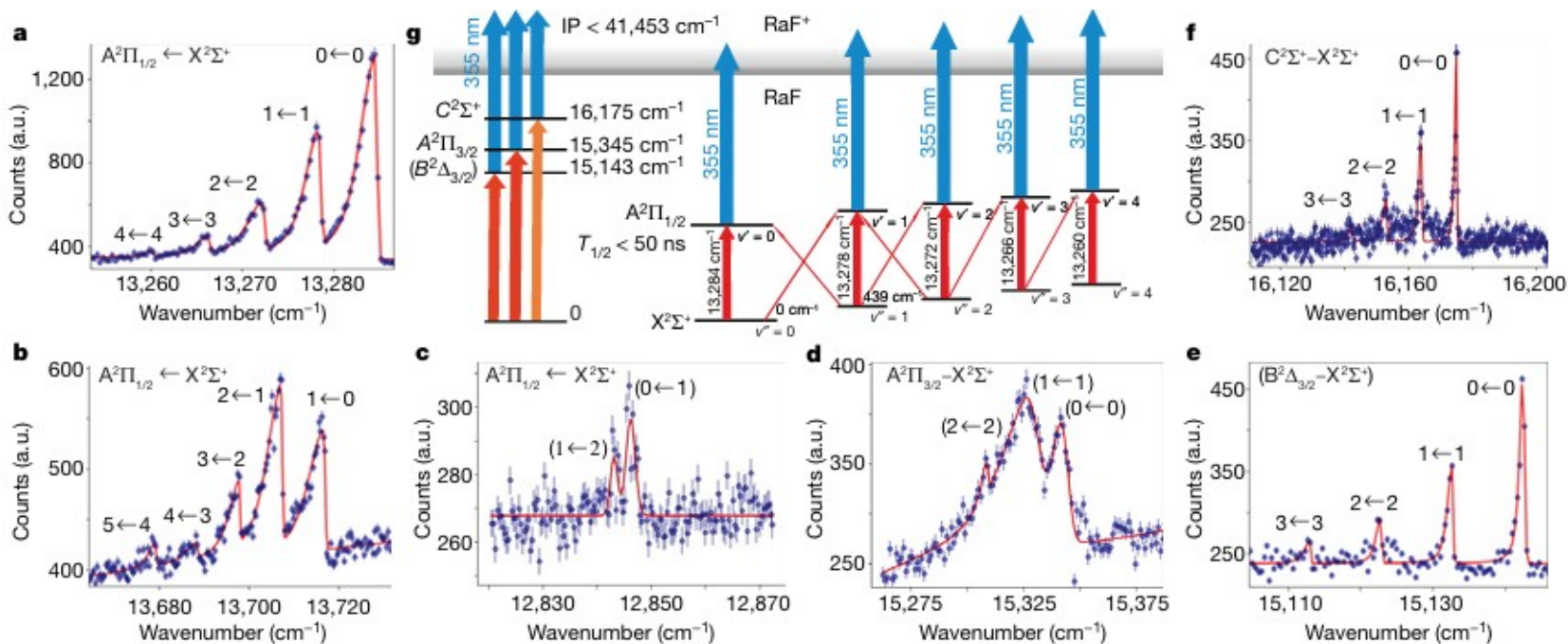


Zeeman effect: intermediate field...



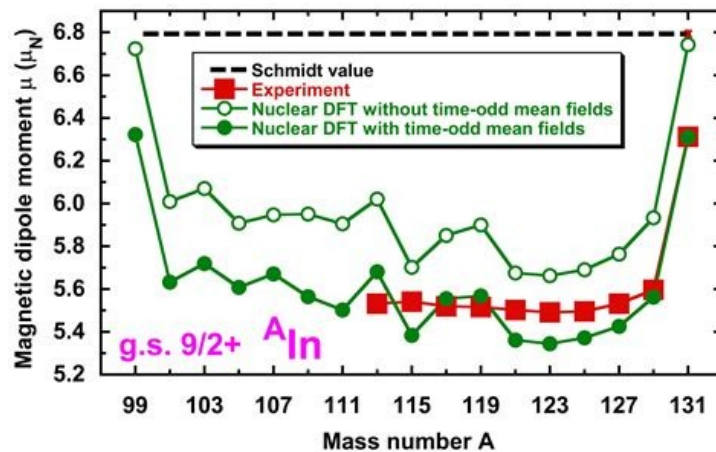
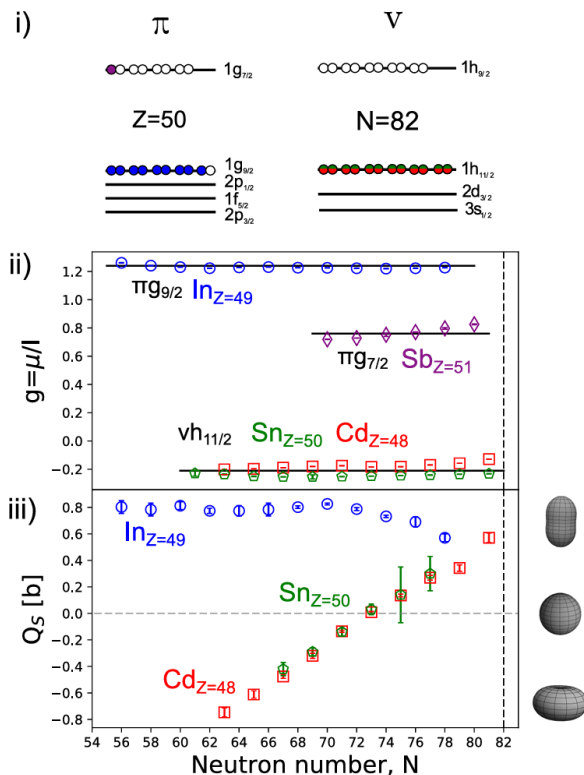
[L. Windholz, "Zeeman-and Paschen-Back-Effect of the Hyperfine Structure of the Sodium D1-Line," 1985]

Molecules: more complex electronic structure on top!



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

Electronic structure ← hyperfine structure → nuclear structure



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:

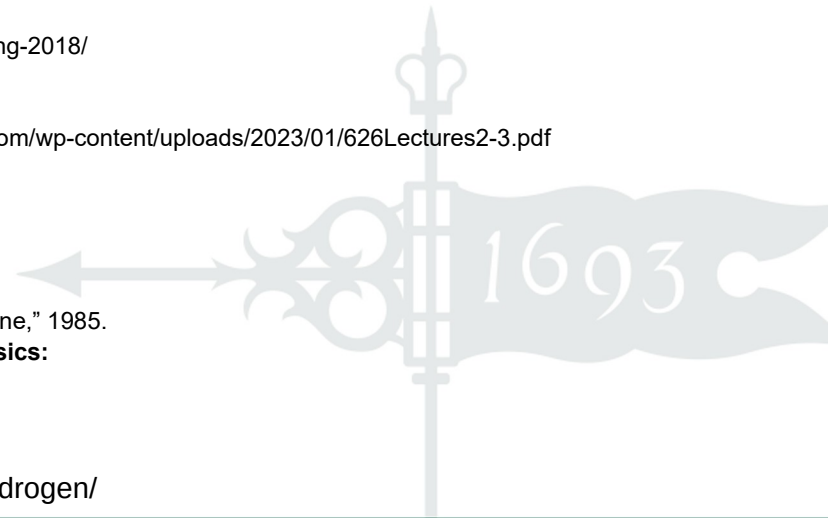
L. Windholz, “Zeeman-and Paschen-Back-Effect of the Hyperfine Structure of the Sodium D1-Line,” 1985.

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

