7. Hydrogen Atoms, 4.5

8. Atomic Physics, 1

lecture 28, November 3, 2017

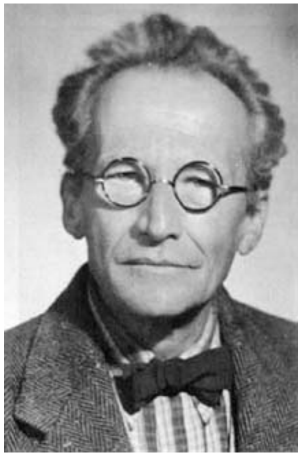
housekeeping

Homework

- I'm going to add a few more chapter 7 problems in the next set of chapter 8 problems

today

Hydrogen atom, more

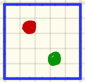


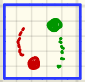
ATOMIC STRUCTURE

HYDROGEN WAS EASY ☺ → closed form mathematics... clean story

now... Helium

Classical red & green balls

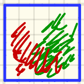




I know — and can track — where the red one is and the green one

I can LABEL them.

Quantum mechanical objects?



wavefunctions overlap

regions exist where one cannot be distinguished from the other

Remember the "definition" of an electron:

$m = 0.511\ \mathrm{MeV}/c^2$

$q = -e$

$s = 1/2$

absolutely identical.

a mish-mesh of electron-ness

which is which??

PLACE is problematic

quantum mechanics must deal with indistinguishability.

S.E. for 2 electrons

ψ_T wavefunction for SYSTEM of 2 electrons $\psi_T(x_1 y_1 z_1 x_2 y_2 z_2)$

V_T potential of system

E_T total energy of system

$$-\frac{\hbar^2}{2m}\left(\frac{\partial^2\psi_T}{\partial x_1^2}+\frac{\partial^2\psi_T}{\partial y_1^2}+\frac{\partial^2\psi_T}{\partial z_1^2}\right)-\left(\frac{\partial^2\psi_T}{\partial x_2^2}+\cdots\right)$$

$$+V_T(x_1 y_1 z_1 x_2 y_2 z_2)\psi_T = E_T\psi_T$$

Separate them:

$$\psi_T(x_1 y_1 z_1 x_2 y_2 z_2) = \phi(x_1 y_1 z_1)\,\eta(x_2 y_2 z_2) = \phi(1)\,\eta(2)$$

particle 1 wavefunction

particle 2 wavefunction

1 $\psi_T = \phi(1)\eta(2)$ particle 1 in state ϕ
particle 2 in state η

If particle 1 was in state η & particle 2 in state ϕ?

2 $\psi_T = \phi(2)\eta(1)$

1 & 2 are different.

Measurables $\longrightarrow$ $|\psi_T|^2$, right?

1 $\psi_T^* \psi_T = \phi^*(1)\eta^*(2)\,\phi(1)\eta(2)$

2 $\psi_T^* \psi_T = \phi^*(2)\eta^*(1)\,\phi(2)\eta(1)$

THE question: if p1 and p2 are indistinguishable ... then $\psi_T^* \psi_T$ should not be different just by switching labels!

BUT:

$$\phi^*(1)\,\eta^*(2)\,\phi(1)\,\eta(2) \xrightarrow[\substack{1\to 2\\ 2\to 1}]{} \phi^*(2)\,\eta^*(1)\,\phi(2)\,\eta(1)$$

not the same ... eg. $\phi(1)$ is a particular function evaluated at $x_1 y_1 z_1$

while $\phi(2)$ is a particular function evaluated at $x_2 y_2 z_2$

WE MUST:

construct wavefunctions that behave properly under particle exchange

HOW ABOUT:

$$\psi_S \equiv \frac{1}{\sqrt{2}} \left[\phi(1)\eta(2) + \phi(2)\eta(1) \right]$$ symmetric

$$\psi_A = \frac{1}{\sqrt{2}} \left[\phi(1)\eta(2) - \phi(2)\eta(1) \right]$$ antisymmetric

these, ψ_S or ψ_A, dont give different E_T than ψ_T

NOTICE:

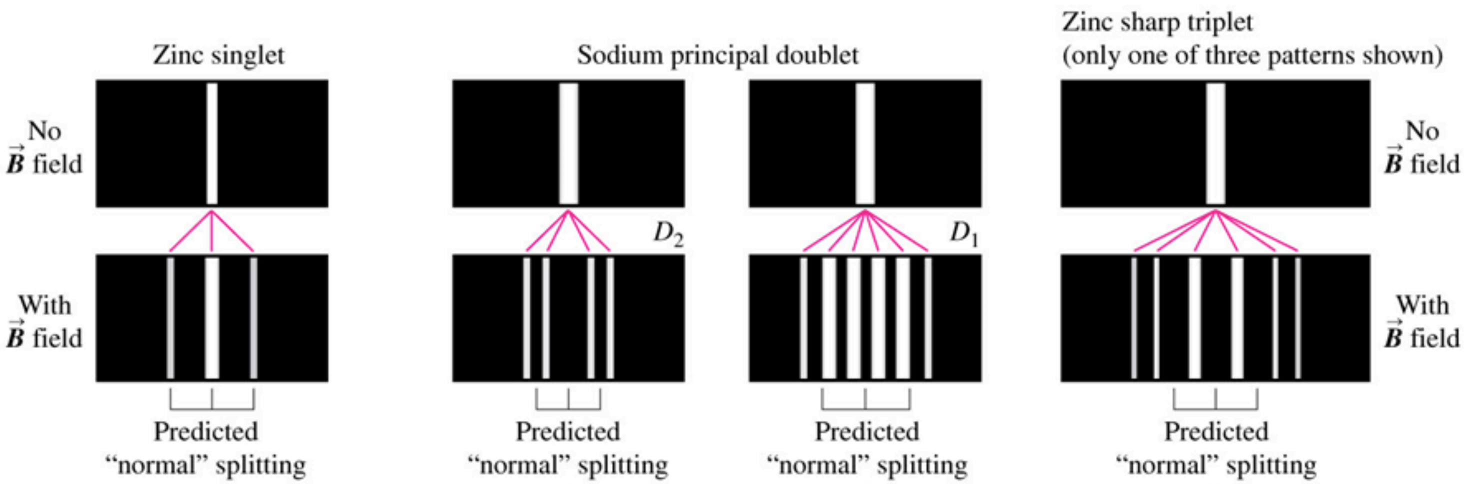
$$\psi_S \xrightarrow[2\to 1]{1\to 2} \psi_S \quad \text{so} \quad \psi_S^* \psi_S \xrightarrow[2\to 1]{1\to 2} \psi_S^* \psi_S$$

$$\psi_A \xrightarrow[2\to 1]{1\to 2} -\psi_A \quad \text{and} \quad \psi_A^* \psi_A \xrightarrow[2\to 1]{1\to 2} (-1)^2 \psi_A^* \psi_A$$

WOLFGANG PAULI

Anomalous Zeeman Effect

more likely than the Normal Zeeman Effect



A colleague who met me strolling rather aimlessly in the beautiful streets of Copenhagen said to me in a friendly manner, "You look very unhappy"; whereupon I answered fiercely, "**How can one look happy when he is thinking about the anomalous Zeeman effect?**".

Wolfgang Pauli

Wolfgang Pauli 1900-1958

Early life in Vienna in heyday

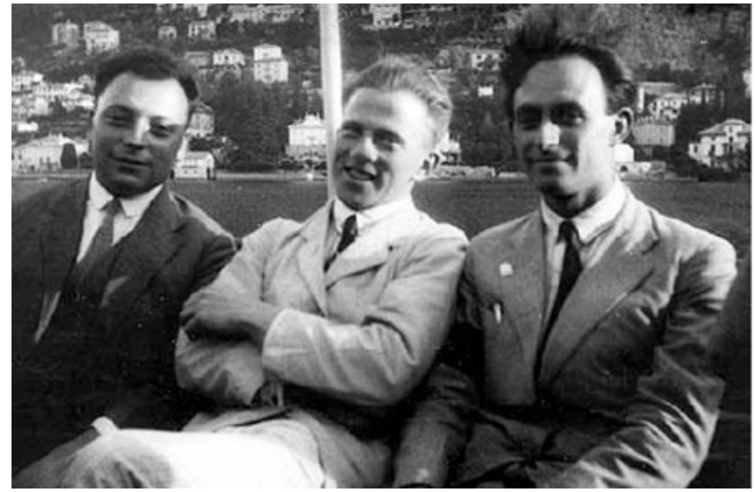
- high school: wrote his first paper on Special Relativity
- University of Munich PhD @21, wrote the definitive review of Special & General Relativity
  - known for mathematical rigor and a…personality from the beginning
  - 1921-1924: Gottingen, Hamburg, Copenhagen
  - 1928: *Eidgenössische Technische Hochschule* (ETH)

Emotional life

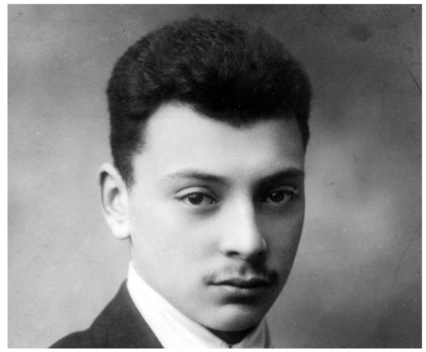
- 1927, mother's suicide; 1930, breakup of first marriage
  - led him to analysis with Carl Jung…life-long relationship

Physics milestones for us

- 1924: "a two-valuedness not describable classically" to explain spectra
  - new quantum number, m_s, 1925, Goudsmit and Uhlenbeck spin
- 1925: "Pauli Matrices" and the "Schroedinger-Pauli Equation"
  - a mathematical basis for spin and the energetics of $V = -\vec{\mu} \cdot \vec{B}$
- 1930: predicted the existence of the neutrino
- 1949: "regularization"…dealing with infinities in field theory
- 1945: Nobel for Exclusion Principle



a character



Reputation was one of

- blistering criticism and ridicule
- but in a nice way

Everyone loved Pauli

- and feared him

After he died, his wife wrote:

- “He was very easily hurt and therefore would let down a curtain. He tried to live without admitting reality. And his unworldliness stemmed precisely from his belief that this was possible.”

"Pauli Effect"

His presence would spontaneously cause things to break

Rudolf Peierls: "This was a kind of spell he was supposed to cast on people or objects in his neighborhood, particularly in physics laboratories, causing accidents of all sorts. Machines would stop running when he arrived in a laboratory, a glass apparatus would suddenly break, a leak would appear in a vacuum system, but none of these accidents would ever hurt or inconvenience Pauli himself."

many stories:

- James Franks' lab at Gottingen, a major piece of equipment blew up

  investigation showed that Pauli had changed trains in the city at that time
- A cyclotron burned at Princeton when he visited
- During the opening of the C.G. Jung Institute in Zurich in 1948, a valuable Chinese vase crashed to the floor when he entered the room
- At Rockefeller University at lunch, Pauli and 3 colleagues discovered that all but him had sat in individual spots of whipped cream
- As a prank, Peierls and friends rigged a chandelier to crash to the floor when Pauli was to walk in…it didn't, thereby proving the Pauli effect for them
- Otto Stern would not allow Pauli into his lab - spoke to him only through the closed door.
- He wasn't allowed to join the Manhattan Project

his criticisms

- This isn’t right, this isn’t even wrong.
- I don’t mind your thinking slowly; I mind your publishing faster than you think.
- If I understand Dirac correctly, his meaning is this: there is no God, and Dirac is his Prophet.
- At the moment physics is again terribly confused…I wish I had been a movie comedian or something of the sort and had never heard of physics
- For quite a while I have set for myself the rule if a theoretician says “universal” it just means pure nonsense
- You know, what Einstein said isn’t so stupid
- I have done a terrible thing, I have postulated a particle that cannot be detected.
- The best that most of us can hope to achieve in physics is simply to misunderstand at a deeper level.
- The setup of the book as far as printing and paper are concerned is splendid.

Comment on Heisenberg's Radio advertisement.

This is to show the world that I can paint like Titian.

Only technical details are missing.

W. Pauli

Pauli Exclusion Principle

In multi-electron atoms there can be no more than 1 electron in the same quantum state.

"State" = wavefunction defined by quantum numbers n, l, m_l, m_s

Insured by requiring that the total wavefunction for electrons is

ψ_A

which for 2 : $\psi_A = \frac{1}{\sqrt{2}}\left[\phi(1)\,\phi(2) - \phi(2)\,\phi(1) \right] = 0$

True for any spin ½ system

quarks in proton / neutron — antisymmetric

neutron star – collapsed to state where every "slot" is full