History and Significance of the "Spin-Statistics Connection" (the subject of our conference)

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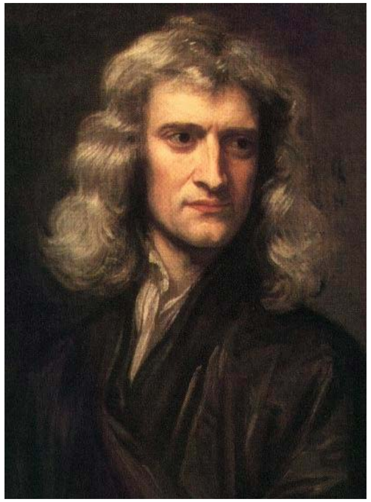
Supported by the National Science Foundation, the Howard Hughes Medical Institute, and the University of Texas at Dallas

Outline

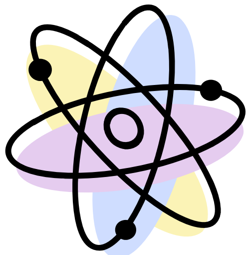
- Basic science issues :
  - Identical particles
  - Fermions and bosons
  - Behavior of groups of fermions and bosons = “statistics”
- Some history of these issues
- Important consequences
- Take-home messages

Identical Particles – same mass, electrical charge, ...

- Newtonian Physics – identity is of no consequence



- Quantum Physics – very important!



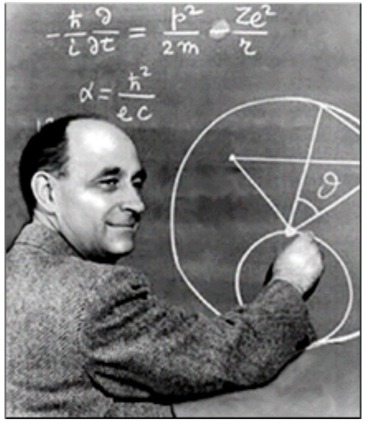
Identical Particles

- Example: all electrons have the same mass, electrical charge, magnetic properties... Therefore, we cannot distinguish one electron from another.
- Quantum theory then restricts the kinds of states for electrons
- Both theoretical and practical importance (Example: electrons in semiconductors).

Two Families of Fundamental Particles

- Fermions

Enrico Fermi
1901-1954



- Bosons

Satyendranath Bose
1894-1974

Fermions

- electrons, neutrinos, protons, quarks…
- At most one particle per quantum state

"statistics"

Bosons

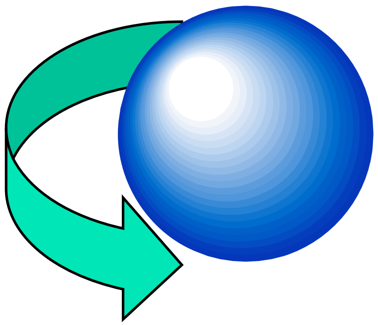
- **photons, W, Z bosons, gluons, ^{4}He (nucleus and atom), ^{16}O (nucleus), ^{85}Rb (atom),...**

- **Possibly many particles in the same quantum state**

"statistics"

What distinguishes Fermions from Bosons?

- Spin (angular momentum)



Fermions versus Bosons

- Quantum theory tells us that angular momentum (amount of spin) = n (h/2)

Experimental fact:

- Fermions have n = 1, 3, 5, ...

- Bosons have n = 0, 2, 4, ...

Fermions versus Bosons?

- Why spin?

- Richard Feynman

  1918-1988

Library of Congress (AP photo)

Feynman quote
(Feynman Lectures Vol. III, Chapter 4)

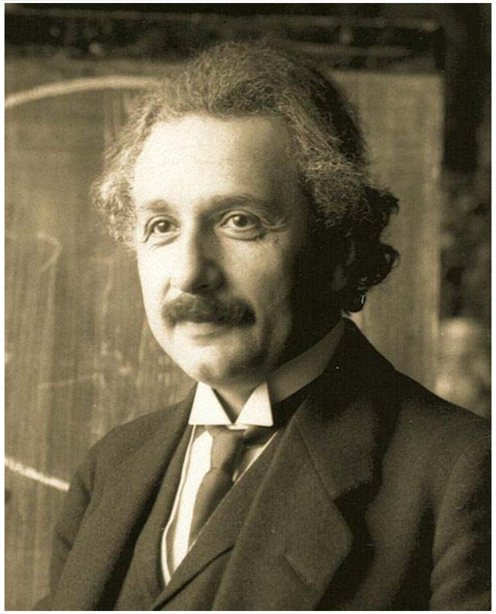
An explanation has been worked out by (Wolfgang) Pauli from complicated arguments of Quantum Field Theory and relativity...but we haven't found a way of reproducing his arguments on an elementary level...this probably means that we do not have a complete understanding of the fundamental principle involved...

Outline of the History

- 1924-25 Exclusion Principle for electrons, Bose-Einstein behavior for photons (1920 Bose, 1924 Einstein
- 1925 Spin: intrinsic angular momentum
- 1926 Identical Particles in Quantum Theory
- 1926-29 Nuclei have spin angular momentum
- 1929-30 The Connection: established through molecular spectroscopy

Photons are Bosons
1924

Satyendranath Bose
1894 - 1974



Albert Einstein
1879-1955

Many photons can be in the same quantum state.
But they said nothing about spin angular momentum.

Wolfgang Pauli

1925 Exclusion Principle explains atomic structure

principio di esclusione di Pauli

Pauli-Fermi Principle

Two electrons <u>cannot</u> be in the same quantum state.

Today, we would say "Electrons are fermions."

Electron Spin

Ralph Kronig
1904-1995

➢ Kronig was first to suggest that electrons have spin angular momentum.

Pauli especially ridiculed the idea of spin, saying that "it is indeed very clever but of course has nothing to do with reality."

Heisenberg and Dirac 1926-27 – Identical Particles

Werner Heisenberg – 1901-1976 Paul Dirac – 1902-1984

Quantum states with identical particles are either symmetric or anti-symmetric if the “coordinates” of the particles are interchanged.

Identical Particles in Quantum Theory

- Symmetric states - bosons
- Anti-symmetric states - fermions

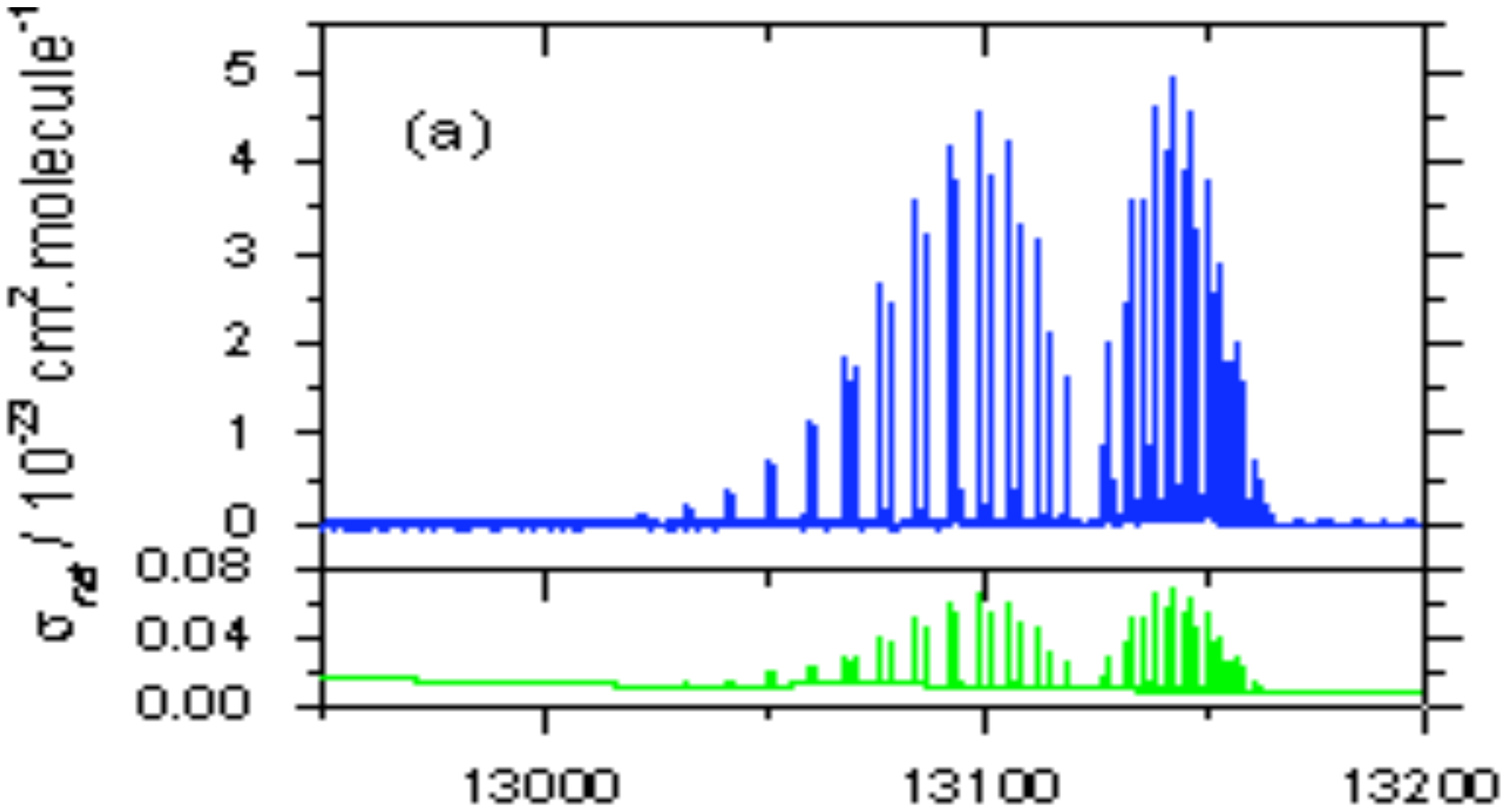
Quantum theory restricts the kinds of states for identical particles.

Anti-symmetric states: at most one particle per state.

Molecular Spectroscopy

- 1925 Some molecules show alternating intensities (or missing lines) in rotationally resolved spectra
- 1925 R. Mecke: these are always homo-nuclear molecules (identical nuclei)
- 1929-30 F. Rasetti, Raman spectroscopy of H_2, N_2, O_2

O_2 Spectrum near 762 nm



Fredrich Hund (1896-1997)

1927 – molecular spectroscopy – Hund associated alternating intensities with the spin angular momentum of nuclei in the molecules

Franco Rasetti (1901-2001)

- In Fermi’s group in Roma
- In 1929 went to the California Institute of Technology to work with Robert A. Millikan
- Carried out Raman spectroscopy at CalTech (a newly discovered technique)

Franco Rasetti

From his Raman spectroscopy on H_2, O_2, and N_2:

He recognized the connection between the alternating intensities and the spin angular momentum of the nuclei in the diatomic molecule and the symmetry and anti-symmetry of the states.

The facts – a review

- Quantum theory tells us that angular momentum (amount of spin) = n (h/2)

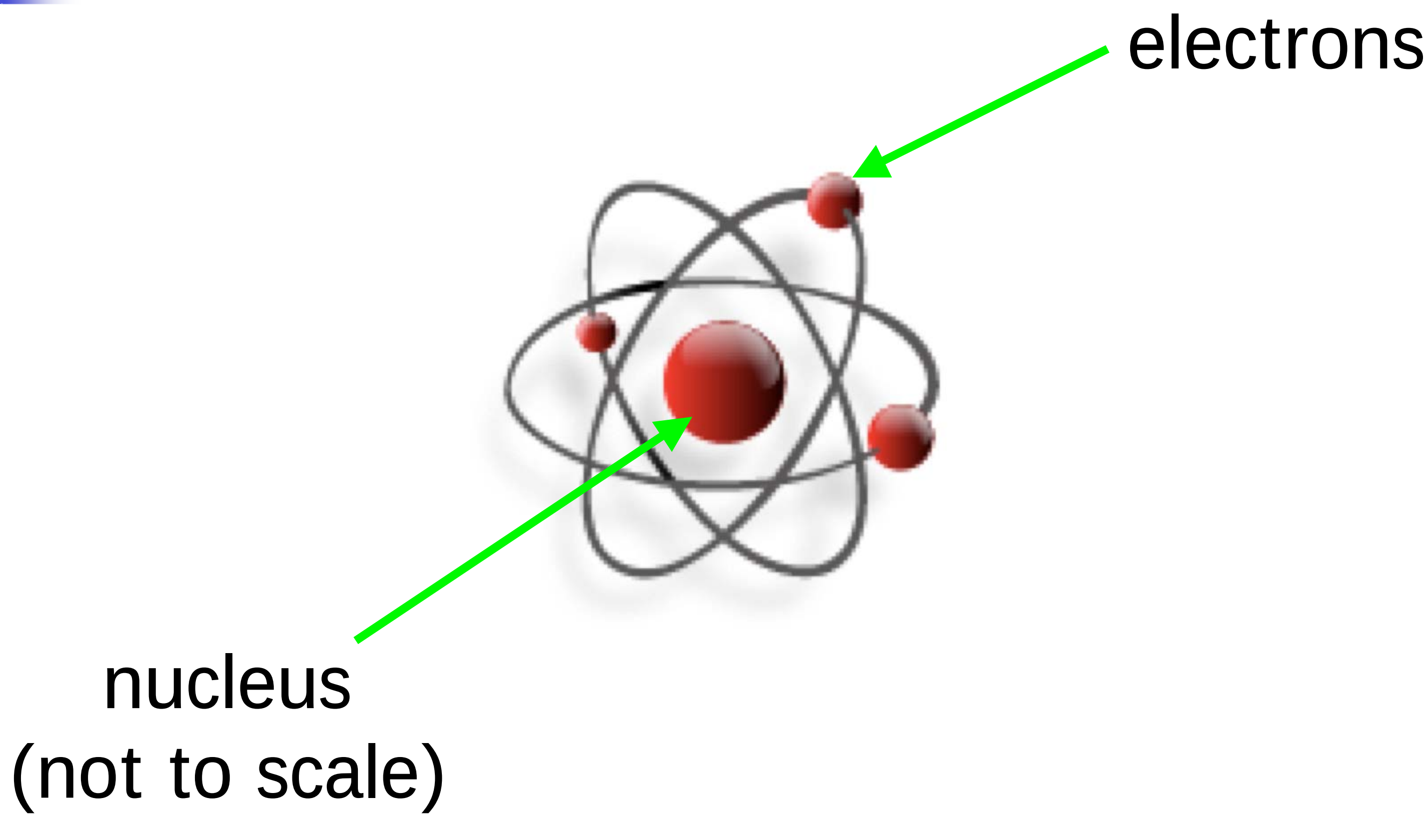
- Fermions have n = 1, 3, 5, ...
  (anti-symmetric states)

- Bosons have n = 0, 2, 4, ...
  (symmetric states)

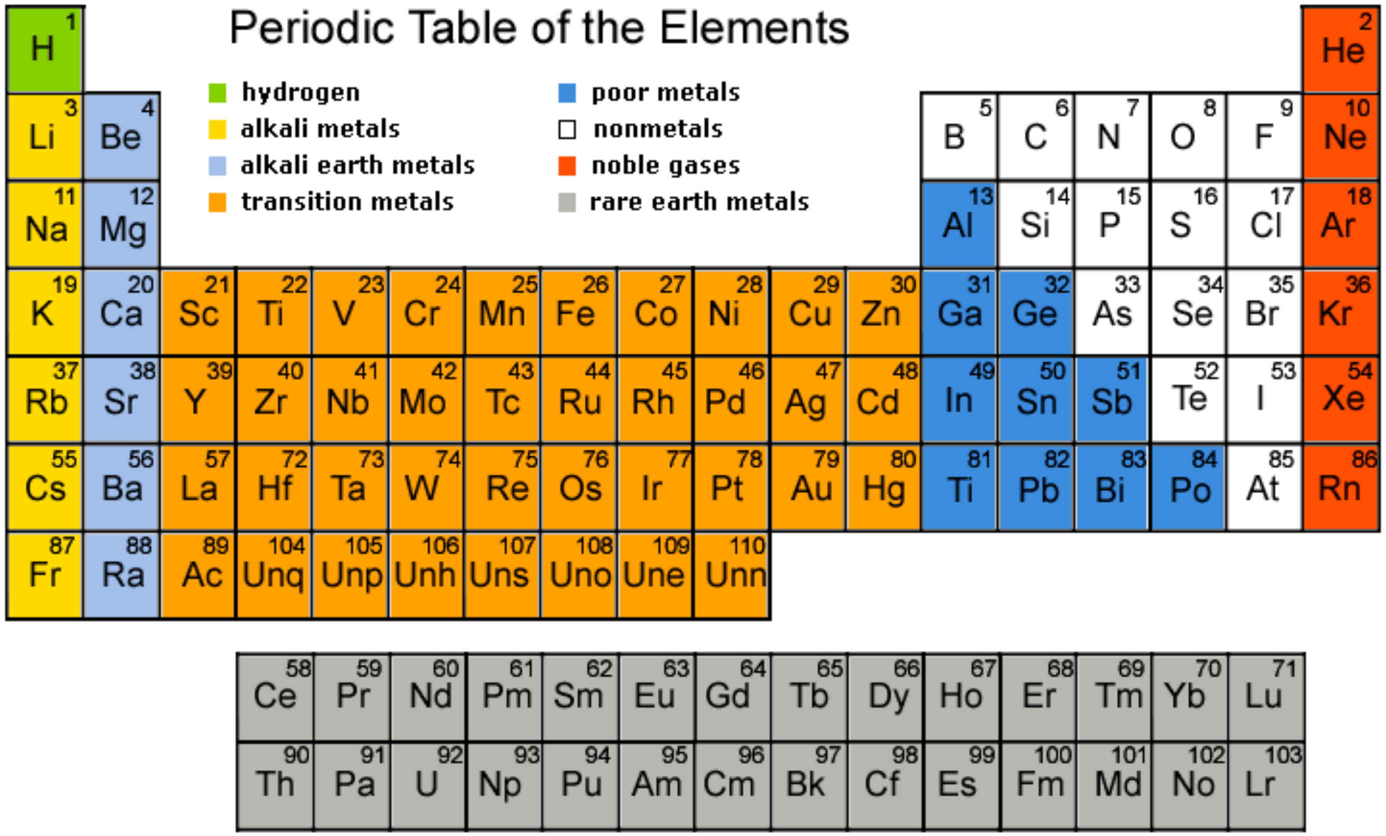
But why spin?

- Pauli 1940 – “proof” using Quantum Field Theory (quantum theory plus Einstein’s theory of relativity).
- Many other scientists…..
- ……
- This conference…..

Consequences: I. Atomic structure and chemistry



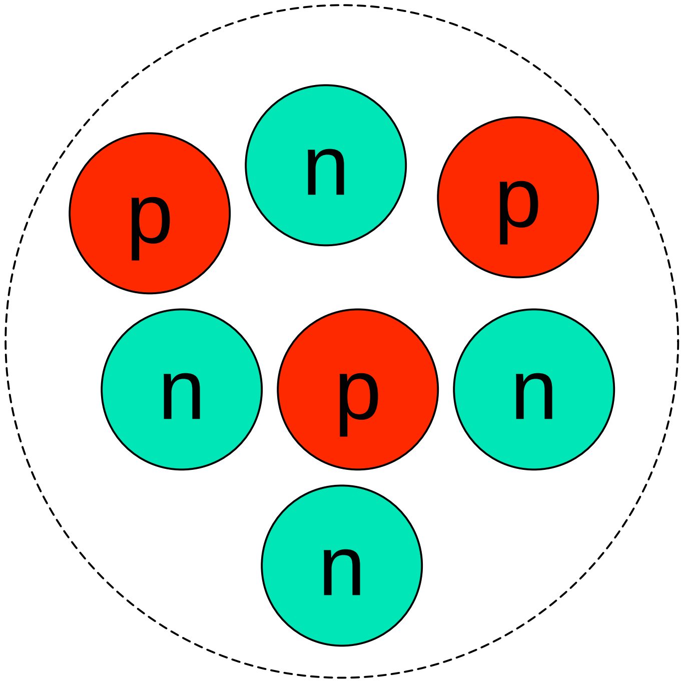
Periodic Table of the Elements



Consequences:
II. Stability of matter

- Matter doesn't collapse – The Pauli Exclusion Principle is important to understand why.

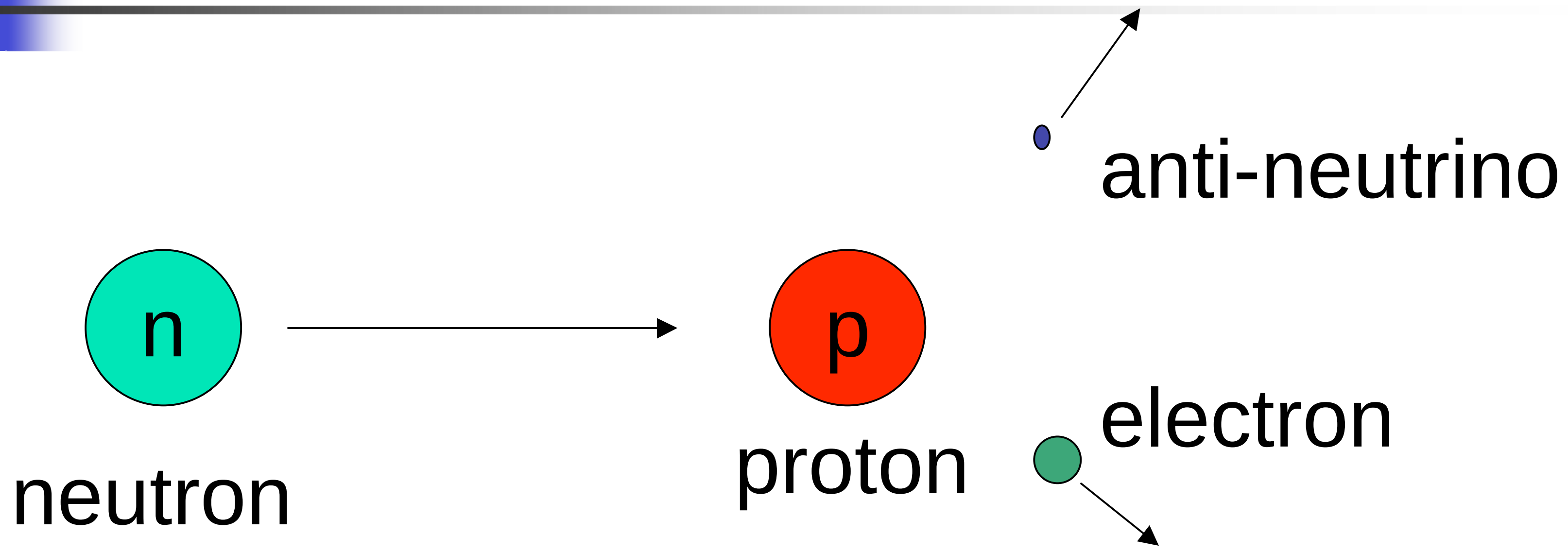
Consequences:
III. Stability of atomic nucleus



^{7}Lithium nucleus

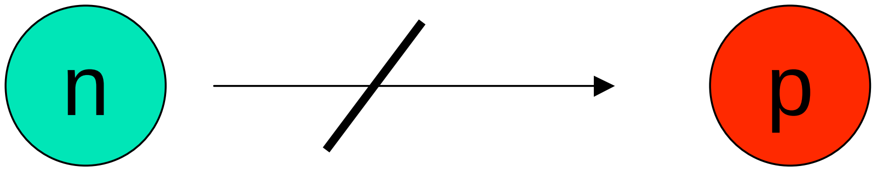
3 protons
4 neutrons

Outside a nucleus: Neutrons are unstable.



"Half life" about 10 minutes

Inside a nucleus



neutron

proton

Because all of the accessible proton states are already occupied.

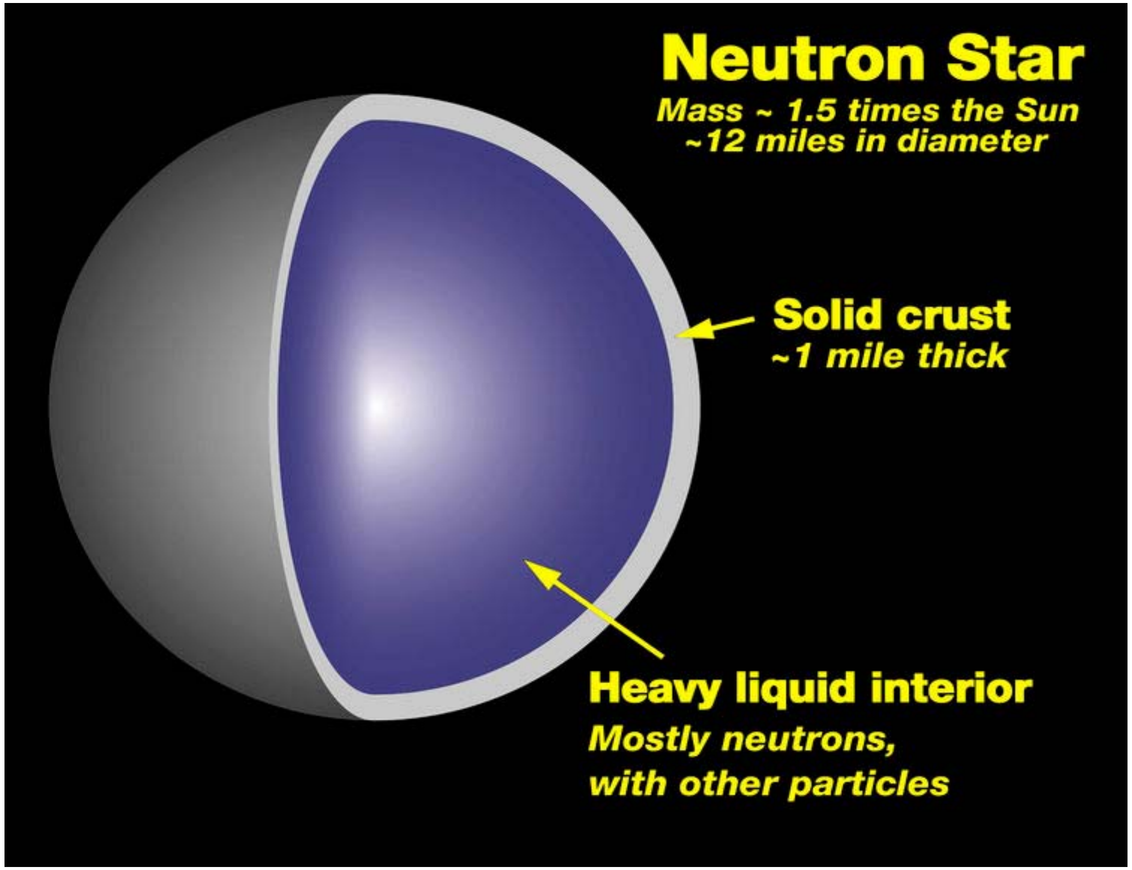
The Pauli Exclusion Principle!

Consequences:
IV. Neutron stars

star

supernova

Neutron star in the
Crab Nebula
1054 AD


Neutron Star
Mass ~ 1.5 times the Sun
~12 miles in diameter
Solid crust
~1 mile thick
Heavy liquid interior
Mostly neutrons,
with other particles

Visible Neutron Star

Conclusions

- Without the Pauli Exclusion Principle, the world would be very different (and we might not be here).

- We should try to understand where the Pauli Exclusion Principle comes from and its limitations.

Take-home Messages

- Even very intelligent scientists can be confused for many years over fundamental principles.

- So, don't give up if you don't understand something immediately. Keep asking questions!

Grazie e Buona Sera!