Quantum Physics

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Johns Hopkins University

Johns Hopkins University QuarkNet Physics Workshop
Spin = Intrinsic angular momentum of a particle (system)

Classically: \[ \vec{L} = \vec{r} \times \vec{p} \]
\[ L = m r v \]

Magnetic moment = current (I) x loop areas (A)

\[ \vec{\mu} = I \times \vec{A} \]
\[ \mu = \frac{q v}{2 \pi r} \pi r^2 = q r v \frac{1}{2} \]

\[ \mu = g \times \frac{q}{2m} S \]

\[ g \neq 1 \] in QM
Quantum Physics: Stern–Gerlach experiment

1922 (100 years!)

Atom, outer electron interaction energy:

\[ E = -\vec{\mu} \cdot \vec{B} \]

\[ F_z = \frac{\partial}{\partial z} (\vec{\mu} \cdot \vec{B}) = \mu_z \frac{\partial B_z}{\partial z} \]

\[ \mu_z = g \times \frac{q}{2m} S_z \quad \Rightarrow \quad S_z = \pm \frac{\hbar}{2} \quad \text{electron} \]
Quantum Physics: Spin of Electron

\[ S_z = \pm \frac{\hbar}{2} \]

Planck’s constant
\[ \hbar = \frac{h}{2\pi} = 6.5821 \times 10^{-16} \text{ eV} \cdot \text{s} \]

electron’s spin
\[ S = \frac{\hbar}{2} \]

spin projection on axis \( z \)
\[ S_z = \pm \frac{\hbar}{2} \]

Foundation of Quantum Physics!
Spin of Elementary Particles

- Until recently, all elementary particles were of two types:

\[ S = \frac{\hbar}{2} \]

Fermions (half-integer spin)
- occupy space (Fermi statistics: exclusion princ.)
- constitute matter (quarks, leptons)

\[ S = 1\hbar \]

Bosons (integer spin)
- carry interactions (\( \gamma \) photons, \( g \) gluons, \( W^\pm, Z \))

- One can create compose particles of any spin \( S = \frac{N\hbar}{2} \), \( N = 0,1,2,... \)
  - for example \( \pi^0 \) meson made of \( q\bar{q} \) has \( S = 0 \)
  - but there was no elementary particle with no spin, until 2012…
Spin of the Higgs boson?

• Spin = 0

2012 (10 years!)

• The only known elementary particle with no spin!
  — how do we know it has no spin?
Spin of the Higgs boson?

- Spin = 0 from observing H decay:

- $m_H = 125$ GeV
- $m_{Z^*} < 35$ GeV
- $m_Z = 91$ GeV
- $\sim 62.5$ GeV
- $\sim 7000$ GeV
Spin of elementary particles

- Spin = 0  
  \( \frac{\hbar}{2} \)  
  \( H \) boson  (excitation of the vacuum field)

- Spin = \( \frac{\hbar}{2} \)  
  \( e^\pm, \mu^\pm, \tau^\pm, \nu_e, \nu_\mu, \nu_\tau \), quarks…  matter

- Spin = \( \hbar \)  
  \( \gamma, Z, W^+, W^-, g_1, g_2, g_3, g_4, g_5, g_6, g_7, g_8 \)  interactions

- Spin = \( \frac{3\hbar}{2} \)  
  Not known  
  (may be supersymmetric particle, e.g. gravitino)

- Spin = \( 2\hbar \)  
  Not discovered, expect graviton

- Arguments for higher Spin to be composite particles…
Two events in July

• July 4, 2022 Symposium at CERN to celebrate 10 years of H boson
  — local JHU article on the topic
Two events in July

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  — local JHU article on the topic

June 14, 2012, CERN  July 4, 2022, CERN
Two events in July
Two events in July

- July, 2022 Community Summer Study in Seattle (“Snowmass”)

- Big questions and big facilities
  - next Higgs factory ???

- Followup to Snowmass 2001
  Snowmass 2013…
Back to Quantum Physics: Time Evolution

Non-relativistic energy expression:

\[ E = \frac{\vec{p}^2}{2m} + V \]

Quantum prescription:

\[ E \rightarrow i\hbar \frac{\partial}{\partial t} \]

\[ \vec{p} \rightarrow -i\hbar \vec{\nabla} = -i\hbar \left( \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right) \]

Schrödinger equation, for a wave function \( \psi(t, x, y, z) \)

\[ E\psi = \frac{\vec{p}^2}{2m}\psi + V\psi \]

\[ i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi + V\psi \]
Quantum Physics: Hydrogen Atom

\[i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi + V\psi\]

special case:

\[V(x, y, z, t) = V(r) = -\frac{e^2}{4\pi\varepsilon_0 r}\]

solve in spherical coordinates:

\[\left(-\frac{\hbar^2}{2\mu} \nabla^2 - \frac{e^2}{4\pi\varepsilon_0 r}\right) \psi(r, \theta, \varphi) = E\psi(r, \theta, \varphi)\]
Quantum Physics: Hydrogen Atom

\[ -\frac{\hbar^2}{2\mu} \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial \psi}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial \psi}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 \psi}{\partial \phi^2} \right] - \frac{e^2}{4\pi\varepsilon_0 r} \psi = E\psi \]

\[ \psi(r, \theta, \phi) = R(r) \Theta(\theta) \Phi(\phi) \]

Quantum numbers: \( n, \ell, m \)

\[ \psi_{n,\ell,m}(r, \theta, \phi) \propto R_{n,\ell}(r) Y_{\ell,m}(\theta, \phi) \]

principal quantum number: \( n = 1,2,3,\ldots \)

orbital angular momentum: \( \ell = 0,1,2,3,\ldots < n \)

projection of angular momentum: \( m = -\ell, (-\ell + 1), \ldots, 0, \ldots, (\ell - 1), \ell \)
Quantum Physics: Hydrogen Atom

\[ \psi_{n,\ell,m}(r, \theta, \varphi) \propto R_{n,\ell}(r) Y_{\ell,m}(\theta, \varphi) \]

\[ |m| \leq \ell = 0,1,2,3,... < n \]

Probability to find electron in \((r, \theta, \varphi)\)

\[ \left| \psi_{n,\ell,m}(r, \theta, \varphi) \right|^2 \]

\[ E_n = -\frac{\hbar^2}{2ma_0} \frac{1}{n^2} \]

\[ n = 1,2,3,... \]

\[ R_{1,0}(r) \propto e^{-r/a_0} \]

\[ Y_0^0(\theta, \varphi) = \frac{1}{2} \sqrt{\frac{1}{\pi}} \]
\[ Y_1^{-1}(\theta, \varphi) = \frac{1}{2} \sqrt{\frac{3}{2\pi}} \sin \theta e^{-i\varphi} \]
\[ Y_1^0(\theta, \varphi) = \frac{1}{2} \sqrt{\frac{3}{\pi}} \cos \theta \]
\[ Y_1^1(\theta, \varphi) = -\frac{1}{2} \sqrt{\frac{3}{2\pi}} \sin \theta e^{i\varphi} \]
\[ Y_2^{-2}(\theta, \varphi) = \frac{1}{4} \sqrt{\frac{15}{2\pi}} \sin^2 \theta e^{-2i\varphi} \]
\[ Y_2^{-1}(\theta, \varphi) = \frac{1}{2} \sqrt{\frac{15}{2\pi}} \sin \theta \cos \theta e^{-i\varphi} \]
\[ Y_2^0(\theta, \varphi) = \frac{1}{4} \sqrt{\frac{5}{\pi}} (3 \cos^2 \theta - 1) \]
\[ Y_2^1(\theta, \varphi) = -\frac{1}{2} \sqrt{\frac{15}{2\pi}} \sin \theta \cos \theta e^{i\varphi} \]
\[ Y_2^2(\theta, \varphi) = \frac{1}{4} \sqrt{\frac{15}{2\pi}} \sin^2 \theta e^{2i\varphi} \]
Atomic Physics
Andrei Gritsan, JHU

Quantum Physics: Atoms

- Particles (electrons) occupy the lowest energy states

- No two identical particles (electrons) may have the same set of quantum numbers \((n, \ell, m, s_z)\)

(Pauli exclusion principle)

\[
| m | \leq \ell = 0,1,2,3,... < n
\]

\[
s_z = \pm \frac{\hbar}{2}
\]

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Quantum Physics: Atoms

Periodic Table of Elements Showing Electron Shells

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Key:
- Alkali Metals
- Alkaline Earth Metals
- Transition Metals
- Non-metals
- Metalloids
- Halogens
- Noble Gases
- Lanthanides
- Actinides

The primary determinant of an element’s chemical properties is the electron configuration, particularly of the outermost electrons (those in the valence shell).

In the periodic table, a period is represented by a row. The number of electron shells an atom has determines what period it belongs to.

In the periodic table, a group is represented by a vertical column. The number of electrons in the outermost shell determines the group.
## Atomic / Nuclear Physics

### Periodic Table of the Elements

#### 1. Hydrogen
- Atomic number: 1
- Symbol: H
- Mass number: 1.00794

#### 2. Lithium
- Atomic number: 3
- Symbol: Li
- Mass number: 6.941

#### 3. Sodium
- Atomic number: 11
- Symbol: Na
- Mass number: 22.989

#### 4. Potassium
- Atomic number: 19
- Symbol: K
- Mass number: 39

#### 5. Rubidium
- Atomic number: 85
- Symbol: Rb
- Mass number: 85.467

#### 6. Caesium
- Atomic number: 55
- Symbol: Cs
- Mass number: 132.905

#### 7. Actinium
- Atomic number: 89
- Symbol: Ac
- Mass number: 227.027

#### 8. Thorium
- Atomic number: 92
- Symbol: Th
- Mass number: 232.034

#### 9. Uranium
- Atomic number: 92
- Symbol: U
- Mass number: 238.028

#### 10. Nitrogen
- Atomic number: 7
- Symbol: N
- Mass number: 14.007

#### 11. Oxygen
- Atomic number: 8
- Symbol: O
- Mass number: 15.999

#### 12. Fluorine
- Atomic number: 9
- Symbol: F
- Mass number: 18.998

#### 13. Neon
- Atomic number: 10
- Symbol: Ne
- Mass number: 20.18

### Lanthanide series
- Elements: La (138.905), Ce (140.116), Pr (144.242), Nd (144.924), Pm (150.36), Sm (151.962), Eu (157.25), Gd (158.925), Tb (162.50), Dy (162.933), Ho (164.933), Er (167.25), Tm (173.054), Lu (174.966)

### Actinide series
- Elements: Ac (227.027), Th (232.034), Pa (231.038), U (238.028), Np (237.041), Pu (244.062), Am (243.061), Cm (247.070), Bk (247.070), Cf (251.079), Es (252.08), Fm (257.095), Md (258.098), No (259.101), Lr (262.106)

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**July 25, 2022**

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m = -\ell, (-\ell + 1), \ldots, 0, \ldots, (\ell - 1), \ell
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Nuclear Physics
Nuclear binding energy

\[ B(A, Z) = [Z(M_p + m_e) + (A - Z)M_n - M(A, Z)] \cdot c^2 \]
Abundance of the chemical elements on Earth

- Rock-forming elements
  - Si, O, Al, Fe, Mg
- Major industrial metals in red
  - Fe, Ni, Cu, Zn
- Precious metals in purple
  - Au, Pt, Pd
- Rare-earth elements in blue
  - La, Ce, Nd, Sm
- Rarest "metals"
  - Ir, Re, Os, Ru, Rh

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Stable nuclide (nuclear species)

Stable isotopes (do not decay)

Type of Decay
- $\beta^+$
- $\beta^-$
- $\alpha$
- Fission
- Proton
- Neutron
- Stable Nuclide
- Unknown

(Number of Neutrons) $N$

(Number of Protons) $Z$
Types of decay (weak force)

Weak interactions:

- too many neutrons: 
  \[ n \rightarrow p + e^- + \bar{\nu}_e \]
  including double-\( \beta \) decay

- too many protons: 
  \[ p \rightarrow n + e^+ + \nu_e \]
  including double-\( \beta \) decay

\[ {}^{106}_{48}\text{Cd} \rightarrow {}^{106}_{46}\text{Pd} + 2e^+ + 2\nu_e \]

also electron capture 
\[ p + e^- \rightarrow n + \nu_e \]
Types of decay (strong force)

- Too many nucleons: fission (more next)
- Too many nucleons: eject α particle (2n2p)
  - Parent nucleus: uranium-238
  - α particle
  - Daughter nucleus: thorium-234
- Too many protons: eject proton
- Too many neutrons: eject neutron

Strong interactions:

- Eject proton
- Eject neutron

(Number of Protons) (Number of Neutrons)
Types of decay

Radioactive isotopes: 

- $\beta^+$
- $\beta^-$
- $\alpha$
- Fission
- Proton
- Neutron
- Stable Nuclide
- Unknown

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Fission

Type of Decay
- $\beta^+$
- $\beta^-$
- $\alpha$
- Fission
- Proton
- Neutron
- Stable Nuclide
- Unknown

too many nucleons: fission

induced nuclear fission

$\gamma$ rays (energy)

neutrons

$^{235}\text{U}$

$^{236}\text{U}$

$^{92}\text{Kr}$

$^{141}\text{Ba}$
Fission

Chain reaction

$^{235}_{92}\text{U} + ^0_1\text{n} \rightarrow ^{140}_{56}\text{Ba} + ^{93}_{36}\text{Kr} + 3 ^0_1\text{n}$

(a) $^{235}_{92}\text{U} + ^0_1\text{n} \rightarrow ^{96}_{37}\text{Rb} + ^{137}_{55}\text{Cs} + 3 ^0_1\text{n}$

(b) $^{235}_{92}\text{U} + ^0_1\text{n} \rightarrow ^{90}_{38}\text{Sr} + ^{144}_{54}\text{Xe} + 2 ^0_1\text{n}$

(c) $^{235}_{92}\text{U} + ^0_1\text{n} \rightarrow ^{87}_{35}\text{Br} + ^{146}_{57}\text{La} + 3 ^0_1\text{n}$
Nature of Nuclear Force

Nuclear binding energy - key in understanding nuclear processes

\[ B(A, Z) = [Z(M_p + m_e) + (A - Z)M_n - M(A, Z)] \cdot c^2 \]

Nuclear force - based on strong force, but works differently than binding force of quarks and baryons

neutron
color-neutral
charge-neutral

proton
color-neutral

no strong or EM force at large distance
Nature of Nuclear Force

Nuclear binding energy - key in understanding nuclear processes

\[ B(A, Z) = [Z(M_p + m_e) + (A - Z)M_n - M(A, Z)] \cdot c^2 \]

strong force attraction and repulsion at shorter distances:

- **deuteron**
  - Isospin=0
  - L=0 (96%)

- **neutron**

- **proton**
Nature of Nuclear Force

Particle Physics perspective:

- **Quark Exchange**
  - Net charge remains constant.
  - Requires exchanges of quarks.

- **Meson Exchange**
  - Color-neutral exchange.
  - Color changes in exchange.

\[ p \left\{ \begin{array}{c} u \\ u \\ d \end{array} \right\} p \rightarrow p \left\{ \begin{array}{c} u \\ u \\ d \end{array} \right\} p \]

\[ n \left\{ \begin{array}{c} d \\ d \\ u \end{array} \right\} n \rightarrow n \left\{ \begin{array}{c} d \\ d \\ u \end{array} \right\} n \]

\[ \pi^0 \rightarrow \text{color-neutral} \]
Nature of Nuclear Force

Yukawa potential at larger distances:

\[ V(r) = g \cdot \frac{e^{-\frac{m_\pi c}{\hbar} r}}{r} \]

range \( d \sim \frac{\hbar}{m_\pi c} \sim 1.4 \text{ fm} \)

\[ \sim 1.4 \times 10^{-15} \text{ m} \]

Compare for \( q\bar{q} \) (colored):

\[ V_{QCD}(r) = -\frac{4\alpha_s}{3r} + kr \]
Nuclear Energy
Energy Sources

- **Fossil fuel** (current $\sim$ 86%)
  
  petroleum, coal, natural gas
  
  - energy from the Sun stored in the past
  - limited supply 40–400 years, environmental concerns

- **Renewable energy** (current $\sim$ 7%)
  
  sunlight, wind, hydro, biomass (&wood, waste),..
  
  - one way or another, mostly convert present Sun energy

- **Nuclear energy** (current $\sim$ 7%)
  
  - uranium-235, plutonium-239 (fission)
  - supply 100’s years (fission), safety concerns
  - there is also fusion, but need technology
Energy Source: Sun as a "Nuclear Reactor"

- Both fossil fuel and renewable energy mostly pass energy from the Sun (past or present).
  - Sun – huge nuclear fusion reactor
    - supply: billions of years, 1 hour flux on Earth = 1 year demand

- Challenge with renewable energy technological:
  - collect enough Sun light
  - effectively convert and store collected energy
  - examples: photosynthesis by green plants; solar power panels
  - beyond the scope of this discussion
Sun as a "Nuclear Reactor"
Stable nuclide (nuclear species)

Nuclear binding energy - key in understanding nuclear processes

\[ B(A, Z) = [Z(M_p + m_e) + (A - Z)M_n - M(A, Z)] \cdot c^2 \]
Sun as a "Nuclear Reactor"

\[ \begin{align*}
\gamma & \quad \text{Gamma Ray} \\
\nu & \quad \text{Neutrino} \\
\nu & \quad \text{Neutrino} \\
\end{align*} \]

- Proton
- Neutron
- Positron

\[ \begin{align*}
p & \quad \text{Proton} \\
n & \quad \text{Neutron} \\
\bar{v}_e & \quad \text{Antineutrino} \\
e^+ & \quad \text{Positron} \\
\end{align*} \]

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Energy Source: Fuel

- combustion
  
  burn fuel (carbon)
  
  \[ CH_4 + 2 O_2 \rightarrow CO_2 + 2 H_2O + \text{energy} \]
  
  (methane) + (oxygen) \rightarrow (carbon dioxide) + (water)

- nuclear fission
  
  \[ n + ^{235}\text{U} \rightarrow ^{92}\text{Kr} + ^{141}\text{Ba} + 3 n + \text{energy} \]

- nuclear fusion
  
  \[ ^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + n + \text{energy} \]

- antimatter annihilation
  
  \[ ^1\text{H}^+ \text{ (matter)} + ^1\text{H}^- \text{ (antimatter)} \rightarrow \text{energy} \]

  science fiction (e.g. see Angels and Demons with Tom Hanks)
Nuclear Energy: Present

- Nuclear fission reactor