Physics 471 - Introduction to Modern Atomic Physics
Time: MW 9:00 AM - 10:20 AM
Location: KPTC 105

Lecturer: Cheng Chin
Office: GCIS E107
Office hour: TuTh 11am to noon
Email: cchin@uchicago.edu

Online discussion on Piazza
Sign up: https://piazza.com/uchicago/winter2024/physics47100
Access code: 47100
Physics 471 - Introduction to Modern Atomic Physics

Where do I find class information?
Winter 2024 P471

Physics 47100 Introduction to Atomic Physics

Day/Time: MW 9:00 - 10:20 am
Location: KPTC 105
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Office: GCIS 107
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Class outline: 17 Lectures, 2 presentation sessions

Single Atom
Wk1 01/03 M 9:00~10:20 Atomic structure
Wk2 01/08 M 9:00~10:20 Atom-field interaction HW1
Wk2 01/10 W 9:00~10:20 Application 1: Laser cooling and trapping
Wk3 01/15 M 9:00~10:20 Application 2: Atomic interferometry HW2
Wk3 01/17 W 9:00~10:20 Application 3: Single qubit rotation

Two Atoms
Wk4 01/21 M 9:00~10:20 Atom-atom interactions HW3
Wk4 01/23 W 9:00~10:20 Low energy scattering
Wk5 01/29 M 9:00~10:20 Feshbach resonance HW4
Wk5 01/31 W 9:00~10:20 Application 1: Ultracold molecules
Wk6 02/05 M 9:00~10:20 Application 2: Quantum logic gates HW5

Many Atoms
Wk6 02/07 W 9:00~10:20 Second quantization
Wk7 02/12 M 9:00~10:20 Bose-Einstein condensation HW6
Wk7 02/14 W 9:00~10:20 Degenerate Fermi gas
Wk8 02/19 M 9:00~10:20 Application 1: Hubbard model HW7
Wk8 02/21 W 9:00~10:20 Application 2: Dynamical instability

Special topics
Wk9 02/26 M 9:00~10:20 Topic 1: HW8
Wk9 02/28 W 9:00~10:20 Topic 2:

Evaluation Problem sets and presentation/term paper

Recommended Textbooks
Atomic Physics, D. Budker, D. F. Kimball and D. P. DeMille
Bose-Einstein Condensation in Dilute Gases, C.J. Pethick and H. Smith
Evaluation and Textbooks

**Evaluation**
- Problem sets
- Presentation or term paper

**Recommended Textbooks**
- Atomic Physics, D. Budker, D. F. Kimball, D. P. DeMille 2010
- Bose-Einstein Condensation in Dilute Gases, C.J. Pethnick and H. Smith
<table>
<thead>
<tr>
<th>Period</th>
<th>Group</th>
<th>Element</th>
<th>Atomic Number</th>
<th>Mass Number</th>
<th>Electron Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Hydrogen</td>
<td>1</td>
<td>1</td>
<td>1s^1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Helium</td>
<td>2</td>
<td>4</td>
<td>1s^2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Lithium</td>
<td>3</td>
<td>6</td>
<td>1s^2 2s^1</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Beryllium</td>
<td>4</td>
<td>8</td>
<td>1s^2 2s^2</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Boron</td>
<td>5</td>
<td>10</td>
<td>1s^2 2s^2 2p^1</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>Carbon</td>
<td>6</td>
<td>12</td>
<td>1s^2 2s^2 2p^2</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>Nitrogen</td>
<td>7</td>
<td>14</td>
<td>1s^2 2s^2 2p^3</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>Oxygen</td>
<td>8</td>
<td>16</td>
<td>1s^2 2s^2 2p^4</td>
</tr>
</tbody>
</table>

**Notes**

- s blocks: light yellow
- p blocks: orange
- d blocks: blue
- f blocks: red

**Periodic Table of the Elements**

Atomic number $Z = \#$ of protons
Mass number $A = Z + N = \#$ of protons + neutrons
Proton number $Z$  
Neutron number $N$  

$N = 1.5Z$  

The heaviest stable element is $^{82}\text{Pb}$.  
The lightest unstable atom is $^{43}\text{Tc}$.  

Isotopes of rubidium ($^{37}\text{Rb}$)  

<table>
<thead>
<tr>
<th>Main isotopes</th>
<th>Decay mode</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{82}\text{Rb}$ synth 1.2575 m</td>
<td>$\beta^+$</td>
<td>$^{82}\text{Kr}$</td>
</tr>
<tr>
<td>$^{83}\text{Rb}$ synth 86.2 d</td>
<td>$\varepsilon$</td>
<td>$^{83}\text{Kr}$</td>
</tr>
<tr>
<td>$^{84}\text{Rb}$ synth 32.9 d</td>
<td>$\beta^+$</td>
<td>$^{84}\text{Kr}$</td>
</tr>
<tr>
<td>$^{85}\text{Rb}$ synth</td>
<td>$\gamma$</td>
<td>-</td>
</tr>
<tr>
<td>$^{86}\text{Rb}$ synth 18.7 d</td>
<td>$\beta^-$</td>
<td>$^{86}\text{Sr}$</td>
</tr>
<tr>
<td>$^{87}\text{Rb}$</td>
<td>$\gamma$</td>
<td>-</td>
</tr>
</tbody>
</table>

$27.8\% = 72.2\% e^{-\frac{T}{49.7\text{B yrs}}}$
What do S, P, D, F… mean?
Term symbol: $^{2s+1}L_J$  \( J=L+S \): Total electron angular momentum

Principal levels (Bohr)

Fine levels (Dirac, Lamb)

Hyperfine levels

<table>
<thead>
<tr>
<th>Principal Level</th>
<th>Fine Level</th>
<th>Hyperfine Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n=2 )</td>
<td>( S_{1/2}(J=1/2) )</td>
<td>( P_{1/2}(J=3/2) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( F=1 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( f_0 = 177 \text{ MHz} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( F=0 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( f_0 = 59 \text{ MHz} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( F=1 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( f_0 = 24 \text{ MHz} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( F=1 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( f_0 = 1420 \text{ MHz} )</td>
</tr>
</tbody>
</table>

H

\( I = \frac{1}{2} \)  
\( (F = I \pm J) \)
H and Alkali metals
Fine structure: spin-orbit interaction

\[ H = -\vec{\mu} \cdot \vec{B}_L \sim g_s \mu_B \vec{s} \cdot \vec{L} \sim J(J+1) - l(l+1) - s(s+1) \]
Term symbol: $^2s+1L_J$  
$J=L+S$: Total electron angular momentum

Cs

$7s \ 2S_{1/2}$

$6s \ 2S_{1/2}$

$6p \ 2P_{3/2}$

$6p \ 2P_{1/2}$

1079 nm

1.36 µm

1.47 µm

895 nm

852 nm

Hyperfine structure skipped here
Term symbol: $^2s^1L_J$  $J=\ell+\Sigma$: Total electron angular momentum
H and Alkali metals
Fine structure: spin-orbit interaction

\[ H = -\vec{\mu} \cdot \vec{B}_L \sim g_s \mu_B \vec{s} \cdot \vec{L} \sim J(J+1) - l(l+1) - s(s+1) \]
Hyperfine structure

F = L + s + i

Spin-spin interaction

$^{133}\text{Cs}$

$L = 1$  $s = 1/2$  $i = 7/2$

$^{62}\text{P}_{3/2}$

$L = 0$  $s = 1/2$  $i = 7/2$

$^{62}\text{S}_{1/2}$

$L = 1$  $s = 1/2$  $i = 7/2$
Physics 471 - Introduction to Modern Atomic Physics

Hyperfine structure  \( F = L + s + i \)  
Spin-spin interaction

\(^{133}\text{Cs}\)  
\(6^2\text{P}_{1/2}\)  
\(6^2\text{S}_{1/2}\)
The BNM-LPTF Rubidium fountain

Ramsey fringes in atomic fountain

G. Santarelli et al., PRL 82, 4619 (1999)
Test of fundamental symmetry

Example:
- Electric dipole moment of electrons and ground state atoms
- T-reversal symmetry and CPT invariance
4.2 Astrophysical constraints:
Quasars - probing the universe back to much earlier times

Variation of Fundamental constants
So far we have considered ....

Case 1: \( H = H_0 \) diagonal in \( s \) and \( L \)

Case 2: \( H = H_0 + \varepsilon s \cdot L \) small \( \varepsilon \)

(\textit{spin-orbit})

Case 3: \( H = H_0 + \varepsilon s \cdot L + \delta s \cdot i \) small \( \varepsilon \) very small \( \delta \)

(\textit{spin-orbit + hyperfine})

Next: \( H = H_0 + \varepsilon s \cdot L + \delta s \cdot i + s \cdot B \)

(spín-orbit, hyperfine and Zeeman effect)

Remark:
1. \( \delta \) is typically very small
2. \( s \cdot L \) is not necessarily small compared to \( H_0 \)
Zeeman effect in the ground state

\[ H = A_s \cdot L + B_s \cdot i - \vec{\mu} \cdot \vec{B} \]

\[ \vec{\mu} = -\frac{\mu_B}{\hbar} (g_s S + g_L L + g_i i) \]

\[ L = 0 \]
\[ s = 1/2 \quad g_s = 2.002 \]
\[ i = 1 \quad g_L = 1.000 \]
\[ F = L + s + i \quad g_i = 0.0004 \]
Zeeman effect in the ground state

\[ H = A s \cdot L + B s \cdot i - \vec{\mu} \cdot \vec{B} \]

\[ \vec{\mu} = -\frac{\mu_B}{\hbar} (g_s S + g_L L + g_i i) \]

\[ \begin{align*}
  L &= 1 \\
  s &= 1/2 \\
  i &= 1 \\
  F &= L + s + i
\end{align*} \]

\[ \begin{align*}
  g_s &= 2.002 \\
  g_L &= 1.000 \\
  g_i &= 0.0004
\end{align*} \]