NPREE 447 & 521

INTERACTION OF RADIATION WITH MATTER

Homework Assignments

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1 Homework 1

Attention:

1. Write down your UIN instead of your name if you worry about privacy when turning in homework. Also write down the course number next to your UIN clearly.

2. Explanation of the score: our brains typically consume about 0.2 Calories per minute. When actively thinking, our brains can kick it up to burning about 1 Calorie per minute. So instead of assigning each question with points, I will assign with Calories. For example, if a problem is given 10 Calories, it means you will need to burn about 10 Calories to solve the problem and the estimated time to solve the problem is about 10 minutes.

3. Because of the breath and depth of the content of the course, it is only possible to cover the essence during the lectures. One must read the relevant chapters in the textbooks to learn the details and gain deeper understandings.

Readings:

1.1
Review the Homework 1 to 3 of NPRE 446 from last semester (no credits). Redo Griffiths and Schroeter: Page 22, Problem 1.16. (30 Calories)

1.2
Consider a particle in a one dimensional infinite square well potential:

\[ V(x) = \begin{cases} 
0, & 0 \leq x \leq a \\
\infty, & \text{otherwise} 
\end{cases} \]

1. Compute the eigen energies and the eigen state wave functions. (20 Calories)

2. Compute \( \langle x \rangle, \langle x^2 \rangle, \sigma_x, \langle p \rangle, \langle p^2 \rangle, \sigma_p \) for the \( n \)-th eigen state. Compute the uncertainty relation quantity \( \sigma_x \sigma_p \). Check whether the uncertainty relation is satisfied. Which state is closest to the uncertainty limit? (20 Calories)

3. If the initial wave function is

\[ \Psi(x,0) = \begin{cases} 
Ax, & 0 \leq x \leq \frac{a}{2} \\
A(a - x), & \frac{a}{2} \leq x \leq a \\
0, & \text{otherwise} 
\end{cases} \]

for some constant \( A \).

(a) Sketch \( \Psi(x,0) \). Determine the constant \( A \). (10 Calories)
(b) Compute $\Psi(x,t)$. (20 Calories)

(c) If we perform a measurement of the energy, what values may we get and with what probabilities? What's the expectation value? (10 Calories)

1.3
Griffiths and Schroeter: Page 76, Problem 2.36. (30 Calories)

1.4
Griffiths and Schroeter: Page 23, Problem 1.17. (30 Calories)

1.5
In atomic and nuclear physics, many systems can be described by pseudo-potentials, such as the Fermi pseudo-potential $V(r) = \frac{2\pi\hbar^2 b}{m}\delta(r)$ used in describing neutron scattering processes, where $b$ is the bound scattering length. Let's consider a particle with mass $m$ in the 1-dimensional $\delta$-potential

$$V(x) = -\alpha\delta(x)$$

where $\alpha > 0$ is the strength of the potential with the dimension of [EL].

1. Compute the bound state ($E < 0$) wave function and the corresponding eigen energy level(s). (30 Calories)

2. Compute the probability current of the wave function in Part 1. Explain the physical meaning of the result. (5 Calories)

3. Compute the transmitted and reflected wave functions of an incoming plane wave $\psi_i(x) = Ae^{ikx}$ ($E > 0$, scattering state). (30 Calories)

4. Compute the probability current on both sides of the potential in Part 3. Explain the physical meaning of the result. (10 Calories)

5. Compute the transmission coefficient $T$ and reflection coefficient $R$ in Part 3. (10 Calories)

6. Perform dimensional analysis on the eigen energy computed in Part 1, and the transmission and reflection coefficients computed in Part 5. (10 Calories)

7. What's the asymptotic behavior of $T$ and $R$ if the potential is very deep, i.e. $\alpha \to \infty$? Explain the physical meaning. (5 Calories)

8. If we flip the potential, i.e. let $\alpha < 0$, do we still have bound states? How about the scattering state? (10 Calories)
2 Homework 2

Readings:

2.1
1. From the continuity equation
   \[ \frac{\partial \rho}{\partial t} + \nabla \cdot J = 0 \]
   derive the probability current
   \[ J = \frac{i\hbar}{2m}(\Psi \nabla \Psi^* - \Psi^* \nabla \Psi) = \frac{\hbar}{m} \text{Im}\{\Psi^* \nabla \Psi}\] (10 Calories)
2. Compute the probability current for the plain wave \( \Psi(x,t) = e^{i(kx-\omega t)} \). (10 Calories)
3. Compute the probability current for the spherical wave \( \Psi(r,t) = e^{i(kr-\omega t)}/r \). (10 Calories)

2.2
Griffiths and Schroeter: Page 75, Problem 2.33. (30 Calories)

2.3
The Hamiltonian of a 1-dimensional quantum harmonic oscillator is
\[ H = \frac{p^2}{2m} + \frac{1}{2}m\omega^2x^2 \]
1. Solve the time-independent Schrödinger equation to show the eigen state wave functions \( \psi_n(x) \) and the corresponding eigen energy \( E_n \) are
   \[ \psi_n(x) = \frac{1}{\sqrt{2^n n!}} \left( \frac{\lambda}{\pi} \right)^{1/4} \exp\left(-\frac{1}{2}\lambda x^2\right)H_n\left(\sqrt{\lambda}x\right) \]
   \[ E_n = \left(n + \frac{1}{2}\right)\hbar\omega \]
   where \( \lambda = m\omega/\hbar \), \( H_n(x) = (-1)^n e^{x^2} \frac{d^n}{dx^n} e^{-x^2} \) are the Hermite polynomials. (30 Calories)
2. For \( n = 0, 1, 2 \), write down \( \psi_n(x) \) explicitly, produce computer plots of the wave functions \( \psi_n(x) \) and the square of the wave functions \( |\psi_n(x)|^2 \) on top of the potential. Attach your code. (15 Calories)
3. For \( n = 0, 1, 2 \), check the orthogonality of \( \psi_n(x) \) by explicit integrations. (15 Calories)
4. For \( n = 0, 1, 2 \), compute \( \langle x \rangle \), \( \langle x^2 \rangle \), \( \sigma_x \), \( \langle p \rangle \), \( \langle p^2 \rangle \), \( \sigma_p \). Compute the uncertainty relation quantity \( \sigma_x \sigma_p \). Check whether the uncertainty relation is satisfied. Which state is closest to the uncertainty limit? (15 Calories)

5. For \( n = 0, 1, 2 \), compute the expectation values of the kinetic energy \( \langle T \rangle \) and the potential energy \( \langle V \rangle \) by explicit integrations. (15 Calories)

6. If the particle starts out in the initial state

\[
\Psi(x, 0) = A [3\psi_0(x) + 4\psi_1(x)]
\]

what is \( A \)? what is \( \Psi(x, t) \)? If we measure the energy of this particle, what values may we get and with what probabilities? What’s the expectation value of \( \langle H \rangle \)? (20 Calories)
3 Homework 3

Readings:

3.1
Griffiths and Schroeter: Page 54, Problem 2.14. (20 Calories)

3.2
Let’s reconsider the 1-dimensional quantum harmonic oscillator
\[ H = T + V = \frac{p^2}{2m} + \frac{1}{2}m\omega^2 x^2 \]

using the ladder operators
\[ a = \sqrt{\frac{m\omega}{2\hbar}}(x + \frac{ip}{m\omega}) \]
\[ a^\dagger = \sqrt{\frac{m\omega}{2\hbar}}(x - \frac{ip}{m\omega}) \]

1. Solve \( x \) and \( p \) in terms of \( a \) and \( a^\dagger \). Show that the Hamiltonian operator can be written in terms of the ladder operators \( H = (N + \frac{1}{2})\hbar \omega \), where \( N = a^\dagger a \). (10 Calories)

2. Compute \([a, a^\dagger]\), \([N, a]\), and \([N, a^\dagger]\), where \( N = a^\dagger a \). (15 Calories)

3. Show that the energy eigenstates are \( |n\rangle = \frac{1}{\sqrt{n!}}(a^\dagger)^n|0\rangle \) and the energy eigenvalues are \( E_n = (n + \frac{1}{2})\hbar \omega \). (20 Calories)

4. Sketch the wave functions of the first three eigen states (\( n = 0, 1, \) and 2) in a harmonic potential. (5 Calories)

5. For the \( n^{th} \) energy eigenstate \( |n\rangle \), compute the expectation values of \( \langle n|x|n\rangle \), \( \langle n|x^2|n\rangle \), \( \langle n|p|n\rangle \), \( \langle n|p^2|n\rangle \), and the uncertainty relation quantity \( \sigma_x \sigma_p \). (10 Calories)

6. For the \( n^{th} \) energy eigenstate \( |n\rangle \), compute the expectation values of the kinetic energy \( \langle n|T|n\rangle \) and the potential energy \( \langle n|V|n\rangle \). (10 Calories)

7. If the particle starts out in the initial state
\[ |\Psi(t = 0)\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle \]
what is its state at time \( t \)? If we perform measurements of the total energy of the system at time \( t \), what do we get? Do they depend on time? (10 Calories)

8. Give one physical example of such quantum harmonic oscillators. Hint: one of such examples is a nuclear material. (10 Calories)
3.3
Griffiths and Schroeter: Page 60, Problem 2.17. (10 Calories)

3.4
Griffiths and Schroeter: Page 60, Problem 2.20. (40 Calories)

3.5
Griffiths and Schroeter: Page 69, Problem 2.22. (30 Calories)
4 Homework 4

Readings:

4.1
Griffiths and Schroeter: Page 120, Problem 3.25. (30 Calories)

4.2
Griffiths and Schroeter: Page 120, Problem 3.26. (30 Calories)

4.3
Griffiths and Schroeter: Page 128, Problem 3.44. (30 Calories)

4.4
Consider a two-state system (e.g. a neutron or a proton with spin 1/2) with the following Hamiltonian

\[ H = \epsilon_1 (|\uparrow\rangle \langle \uparrow| + |\downarrow\rangle \langle \downarrow|) + \epsilon_2 (|\uparrow\rangle \langle \downarrow| + |\downarrow\rangle \langle \uparrow|) \]

1. What is the matrix representation of \(H\) in the \(|\uparrow\rangle\) and \(|\downarrow\rangle\) basis? (10 Calories)
2. Are \(|\uparrow\rangle\) and \(|\downarrow\rangle\) the eigen states of this system? If not, what are the eigen states and their corresponding eigen energies? (10 Calories)
3. If the system starts out in state \(|\Psi(0)\rangle = A(3|\uparrow\rangle + 4|\downarrow\rangle)\) for some constant \(A\),
   (a) Determine the constant \(A\)? (10 Calories)
   (b) What is the time-dependent solution \(|\Psi(t)\rangle\)? (10 Calories)
   (c) If we perform a measurement of the energy of the particle, what values may we get and with what probabilities? What’s the expectation value \(\langle H \rangle\)? (10 Calories)

4.5
*Macroscopic Quantum World:* The Planck constant (reduced) \(\hbar \approx 1 \times 10^{-34} \, J \cdot s\) plays a fundamental role in quantum mechanics. Imagine that one day you are teletransported to another universe, where the reduced Planck constant is \(10^{34}\) times larger, i.e. \(\hbar \approx 1 \, J \cdot s\). Let’s picture what strange phenomena you would expect.

1. First, derive the uncertainty principle

\[ \sigma_A \sigma_B \geq \frac{1}{2} |\langle [A, B] \rangle| \]

and state its the significance. (10 Calories)
2. Suppose you have a jar of candies in this quantum world. When you open the jar, estimate the escape velocities of the candies. Do you need to be careful when opening the jar? (A typical weight of a candy is 1 gram. A typical size of a jar is 10 cm.) (10 Calories)

3. Use your imagination, describe another two strange phenomena you would expect in this quantum world. Be as quantitative as possible. (20 Calories)
5 Homework 5

Readings:

5.1

5.2
Griffiths and Schroeter: Page 124, Problem 3.33. (30 Calories)

5.3
Griffiths and Schroeter: Page 124, Problem 3.34. (30 Calories)

5.4
Read Chapter 4.1, 4.2, and 4.3 of Griffiths and Schroeter carefully and study how to solve the eigenstates of hydrogen atom. Summarize the solutions of the eigen wavefunctions, energy, and angular momentum. Explain their physical meanings. (No need to solve the equations.) (30 Calories)

5.5
1. Produce pseudo-color plots of the spherical harmonics $Y_{lm}(\theta, \phi)$ on a sphere for $l \leq 3$ and all the allowed $m$. The color should be mapped to the values of $Y_{lm}(\theta, \phi)$. Attach your code. (20 Calories)

2. Produce surface plots of the real, imaginary, and absolute values of the spherical harmonics $Y_{lm}(\theta, \phi)$, namely $r = \text{Re}\{Y_{lm}(\theta, \phi)\}$, $r = \text{Im}\{Y_{lm}(\theta, \phi)\}$, $r = |Y_{lm}(\theta, \phi)|$, for $n \leq 3$ and all the allowed $l$ and $m$. The distance of the surface from the origin should indicate the values of $Y_{lm}(\theta, \phi)$. Attach your code. (20 Calories)

3. Produce pseudo-color plots of the probability density (2D cut along z axis) of the hydrogen atomic orbitals $\psi_{nlm}(r, \theta, \phi)$ for $n \leq 3$ and all the allowed $l$ and $m$. The color should be mapped to the values of the probability density $|\psi_{nlm}(r, \theta, \phi)|^2$. Attach your code. (20 Calories)

4. Produce surface plots of the hydrogen atomic orbitals’ probability density $|\psi_{nlm}(r, \theta, \phi)|^2$ for $n \leq 3$, namely $r = |\psi_{nlm}(r, \theta, \phi)|^2$ for $n \leq 3$, and all the allowed $l$ and $m$. Attach your code. (20 Calories)
6 Homework 6*

*Attention:

This homework is for 521 students only. 447 students will not receive extra credit for solving the problems.

Readings:


6.1

1. Use the ladder operators, prove $L^2|l,m\rangle = \hbar^2 l(l + 1)|l,m\rangle$ and $L_z|l,m\rangle = \hbar m|l,m\rangle$ (20 Calories)

2. Prove $L_\pm|l,m\rangle = \hbar \sqrt{\frac{l \mp m}{l \pm m + 1}}|l,m \pm 1\rangle = \hbar \sqrt{l(l + 1) - m(m + 1)}|l,m \pm 1\rangle$ (20 Calories)

6.2

Write down the angular momentum operator $L$ in spherical coordinates. Show that $L^2 = -\hbar^2 \left[ \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2}{\partial \phi^2} \right]$ and $L_z = -i\hbar \frac{\partial}{\partial \phi}$

Therefore, the eigen equations of them are indeed the angular equations obtained from the separation of variables. (20 Calories)

6.3

Suppose a neutron (or an electron, or a proton) is in the spin state $A \begin{pmatrix} i \\ 1 \end{pmatrix}$.

1. What is the normalization factor $A$? (5 Calories)

2. If we measure $S_x$, what values do we get? What is the probability of each value? (5 Calories)

3. If we measure $S_y$, what values do we get? What is the probability of each value? (5 Calories)

4. If we measure $S_z$, what values do we get? What is the probability of each value? (5 Calories)

5. What are the expectation values of $\langle S_x \rangle$, $\langle S_x^2 \rangle$, $\langle S_y \rangle$, $\langle S_y^2 \rangle$, $\langle S_z \rangle$, and $\langle S_z^2 \rangle$? Verify the uncertainty relations. (20 Calories)
6.4
Consider a neutron in a uniform magnetic field along the z axis $B = B_0 \hat{z}$.

1. If the initial state is $|\psi(0)\rangle = \left(\cos \frac{\alpha}{2}, \sin \frac{\alpha}{2}\right)$, where $\alpha$ is a known constant, what is the time evolution of the state $|\psi(t)\rangle$? (20 Calories)

2. What are the expectation values of $S_x$, $S_y$, and $S_z$? Note that $\omega = \gamma B_0$ is the Larmor frequency, where $\gamma$ is the gyromagnetic ratio. (20 Calories)

6.5
Construct the spin matrices $S_x$, $S_y$, and $S_z$ for a particle with spin 1 (for example, a deuteron). (30 Calories)

6.6
What are singlet and triplet states? (20 Calories)