NPRE 447 & 521
Interaction of Radiation with Matter
Homework Assignments

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March 12, 2019
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 breadth 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
Griffiths's Quantum Mechanics: Page 14, Problem 1.5. (30 Calories)

1.2

1.3
Griffiths's Quantum Mechanics: Page 22, Problem 1.15. (30 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 \( \Psi(r,t) = e^{i(k \cdot r - \omega t)}/r \). (10 Calories)

2.2
The Hamiltonian of a 1-dimensional quantum harmonic oscillator is
\[ H = \frac{p^2}{2m} + \frac{1}{2} m \omega^2 x^2 \]
1. Solve the stationary 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 Let’s reconsider the 1-dimensional quantum harmonic oscillator

\[ H = T + V = \frac{p^2}{2m} + \frac{1}{2}m\omega^2x^2 \]

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 \([a, a^\dagger], [N, a], [N, a^\dagger]\), 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)
3.2

In atomic and nuclear physics, many systems can be described by pseudo-potentials, such as the Fermi pseudo-potential \( V(r) = \frac{2\pi\hbar^2}{m} b\delta(r) \) 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 \( \psi_i(x) = Ae^{ikx} \) \((E > 0, \text{scattering state})\). (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)
4 Homework 4

Readings:

4.1
Griffiths’s Quantum Mechanics: Page 123, Problem 3.22. (20 Calories)

4.2
Griffiths’s Quantum Mechanics: Page 124, Problem 3.26. (20 Calories)

4.3
Griffiths’s Quantum Mechanics: Page 128, Problem 3.37. (20 Calories)

4.4
Consider a two-state system (e.g. 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. What are the eigen states and their corresponding eigen energies. Note that \( |\uparrow\rangle \) and \( |\downarrow\rangle \) are not the energy eigen states of this system. (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
Griffiths’s Quantum Mechanics: Page 112, Problem 3.13. (30 Calories)

5.2
Griffiths’s Quantum Mechanics: Page 125, Problem 3.27. (30 Calories)

5.3
Griffiths’s Quantum Mechanics: Page 129, Problem 3.38. (30 Calories)

5.4
1. Produce pseudo-color plots of the spherical harmonics $Y_{l}^{m}(\theta, \phi)$ on a sphere for $l \leq 3$ and all the allowed $m$. The color should be mapped to the values of $Y_{l}^{m}(\theta, \phi)$. Attach your code. (20 Calories)

2. Produce surface plots of the real, imaginary, and absolute values of the spherical harmonics $Y_{l}^{m}(\theta, \phi)$ for $n \leq 3$ and all the allowed $l$ and $m$. The distance of the surface from the origin should indicate the values of $Y_{l}^{m}(\theta, \phi)$. 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)