

Homework Set #5 – Solutions

1. This problem is essentially Messiah, Chapter 18, Problem 4 (or Sakurai, Chapter 5, Problem 1). Consider a one-dimensional harmonic oscillator perturbed by a constant force

$$H = \frac{p^2}{2m} + \frac{1}{2}m\omega^2 x^2 - Fx$$

- a) Show that the first order perturbation in the energy levels vanishes.

Since we will need to find the second order perturbation in part b), let us consider the general matrix element

$$V_{mn} = -F \langle m^{(0)} | x | n^{(0)} \rangle$$

The operator x is given in terms of creation and annihilation operators by $x = \sqrt{\hbar/(2m\omega)}(a^\dagger + a)$. Thus

$$\begin{aligned} V_{mn} &= -F \sqrt{\frac{\hbar}{2m\omega}} \langle m^{(0)} | (a^\dagger + a) | n^{(0)} \rangle \\ &= -F \sqrt{\frac{\hbar}{2m\omega}} [\sqrt{n+1} \delta_{m,n+1} + \sqrt{n} \delta_{m,n-1}] \end{aligned}$$

This indicates that the x operator changes the oscillator number by ± 1 . In particular, $V_{nn} = 0$, which demonstrates that the first order energy perturbation vanishes.

- b) Now calculate the eigenenergies E_n up to second order in the perturbation.

Using the matrix element calculated above, we find

$$\begin{aligned} E_n^{(2)} &= \sum_{k \neq n} \frac{|V_{kn}|^2}{E_n^{(0)} - E_k^{(0)}} = \frac{|V_{n+1,n}|^2}{E_n^{(0)} - E_{n+1}^{(0)}} + \frac{|V_{n-1,n}|^2}{E_n^{(0)} - E_{n-1}^{(0)}} \\ &= F^2 \frac{\hbar}{2m\omega} \left[\frac{n+1}{-\hbar\omega} + \frac{n}{\hbar\omega} \right] = -\frac{F^2}{2m\omega^2} \end{aligned}$$

Combined with the zeroth order energy, this gives

$$E_n = (n + \frac{1}{2})\hbar\omega - \frac{F^2}{2m\omega^2}$$

- c) Show that the second-order perturbation result gives the exact eigenenergies (which may be obtained by completing the square in H). Explain why this happens.

Sakurai Solutions Chapter 4

**C. V. Nielsen, W. Zhang, L. M. Alves, N.
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Table of Contents Sakurai Solutions Chapter 4

1. Understanding the eBook Sakurai Solutions Chapter 4
 - The Rise of Digital Reading Sakurai Solutions Chapter 4
 - Advantages of eBooks Over Traditional Books
2. Identifying Sakurai Solutions Chapter 4
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Sakurai Solutions Chapter 4
 - User-Friendly Interface
4. Exploring eBook Recommendations from Sakurai Solutions Chapter 4
 - Personalized Recommendations
 - Sakurai Solutions Chapter 4 User Reviews and Ratings
 - Sakurai Solutions Chapter 4 and Bestseller Lists
5. Accessing Sakurai Solutions Chapter 4 Free and Paid eBooks
 - Sakurai Solutions Chapter 4 Public Domain eBooks
 - Sakurai Solutions Chapter 4 eBook Subscription Services
 - Sakurai Solutions Chapter 4 Budget-Friendly Options
6. Navigating Sakurai Solutions Chapter 4 eBook Formats

- ePub, PDF, MOBI, and More
- Sakurai Solutions Chapter 4 Compatibility with Devices
- Sakurai Solutions Chapter 4 Enhanced eBook Features
- 7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Sakurai Solutions Chapter 4
 - Highlighting and Note-Taking Sakurai Solutions Chapter 4
 - Interactive Elements Sakurai Solutions Chapter 4
- 8. Staying Engaged with Sakurai Solutions Chapter 4
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Sakurai Solutions Chapter 4
- 9. Balancing eBooks and Physical Books Sakurai Solutions Chapter 4
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Sakurai Solutions Chapter 4
- 10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
- 11. Cultivating a Reading Routine Sakurai Solutions Chapter 4
 - Setting Reading Goals Sakurai Solutions Chapter 4
 - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Sakurai Solutions Chapter 4
 - Fact-Checking eBook Content of Sakurai Solutions Chapter 4
 - Distinguishing Credible Sources
- 13. Promoting Lifelong Learning
 - Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
- 14. Embracing eBook Trends
 - Integration of Multimedia Elements
 - Interactive and Gamified eBooks

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