

## 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  $\pm 1$ . 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

**RM Cervero**



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