

Homework 2 solutions

Question 3

(a)

$$\vec{x} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}, \quad \vec{p} = \begin{pmatrix} p_1 \\ p_2 \\ p_3 \end{pmatrix} \quad (1)$$

$$\hat{\vec{L}} = \hat{\vec{x}} \times \hat{\vec{p}} = \dots \quad (2)$$

$$[\hat{L}_1, \hat{L}_2] = [x_2 p_3 - x_3 p_2, x_3 p_1 - x_1 p_3] \quad (3)$$

$$[A + B, C + D] = [A + B, C] + [A + B, D] \quad (4)$$

$$= [A, C] + [B, C] + [A, D] + [B, D] \quad (5)$$

$$\Rightarrow [L_1, L_2] = \underbrace{[x_2 p_3, x_3 p_1]}_{\text{I}} - \underbrace{[x_3 p_2, x_3 p_1]}_{\text{II}} - \underbrace{[x_2 p_3, x_1 p_3]}_{\text{III}} + \underbrace{[x_3 p_2, x_1 p_3]}_{\text{IV}} \quad (6)$$

$$[A, BC] = B[A, C] + [A, B]C \quad (7)$$

$$[AB, C] = A[B, C] + [A, C]B \quad (8)$$

$$[x_i, p_j] = i\hbar\delta_{ij}, \quad [p_i, x_j] = -i\hbar\delta_{ij} \quad (9)$$

$$[x_i, x_j] = [p_i, p_j] = 0 \quad (10)$$

$$\text{I} = [x_2 p_3, x_3] p_1 + x_3 [x_2 p_2, p_1] \quad (11)$$

$$= [x_2, x_3] p_3 p_1 + x_2 [p_3, x_3] p_1 + x_3 [x_2, p_1] p_3 + x_2 x_3 [p_3, p_1] \quad (12)$$

$$= -i\hbar x_2 p_1 \quad (13)$$

$$\text{II} = [x_3 p_2, x_3] p_1 + x_3 [x_3 p_2, p_1] \quad (14)$$

$$= x_3 [p_2, x_3] p_1 + [x_3, x_3] p_1 p_2 + x_3 x_3 [p_2, p_1] + x_3 [x_3, p_1] p_2 \quad (15)$$

$$= 0 \quad (16)$$

$$\text{III} = [x_2 p_3, x_1] p_3 + x_1 [x_2 p_3, p_3] = 0 \quad (17)$$

$$\text{IV} = [x_3 p_2, x_1] p_3 + x_1 [x_3 p_2, p_3] \quad (18)$$

$$= [x_3, x_1] p_2 p_3 + x_3 [p_2, x_1] p_3 + x_1 [x_3, p_3] p_2 + x_1 x_3 [p_2, p_3] \quad (19)$$

$$= i\hbar x_1 p_2 \quad (20)$$

$$[L_1, L_2] = i\hbar(x_1 p_2 - x_2 p_1) = i\hbar L_3 \quad (21)$$

$$[L_i, L_j] = \varepsilon_{ijk} i\hbar L_k \quad (22)$$

(b)

$$[\hat{\tilde{L}}_1^2, \hat{L}_1] \quad (23)$$

$$\hat{\tilde{L}}^2 = \hat{L}_1^2 + \hat{L}_2^2 + \hat{L}_3^2 \quad (24)$$

$$= [L_1^2 + L_2^2 + L_3^2, L_1] = 0 \quad (25)$$

$$= [L_2^2, L_1] + [L_3^2, L_1] \quad (26)$$

$$= L_2[L_2, L_1] + [L_2, L_1]L_2 + L_3[L_3, L_1] + [L_3, L_1]L_3 \quad (27)$$

$$= -i\hbar L_2 L_3 - i\hbar L_3 L_2 + i\hbar L_3 L_2 + i\hbar L_2 L_3 \quad (28)$$

$$= -i\hbar(L_2 L_3 + L_3 L_2) + i\hbar(L_3 L_2 + L_2 L_3) = 0 \quad (29)$$

(c)

$$\vec{L} \times \vec{L} = \begin{bmatrix} x_2 p_3 - x_3 p_2 \\ x_3 p_1 - x_1 p_3 \\ x_1 p_2 - x_2 p_1 \end{bmatrix} \times \begin{bmatrix} x_2 p_3 - x_3 p_2 \\ x_3 p_1 - x_1 p_3 \\ x_1 p_2 - x_2 p_1 \end{bmatrix} \quad (30)$$

$$= \begin{bmatrix} (x_3 p_1 - x_1 p_3)(x_1 p_2 - x_2 p_1) - (x_1 p_2 - x_2 p_1)(x_3 p_1 - x_1 p_3) \\ (x_1 p_2 - x_2 p_1)(x_2 p_3 - x_3 p_2) - (x_2 p_3 - x_3 p_2)(x_1 p_2 - x_2 p_1) \\ (x_2 p_3 - x_3 p_2)(x_3 p_1 - x_1 p_3) - (x_3 p_1 - x_1 p_3)(x_2 p_3 - x_3 p_2) \end{bmatrix} \quad (31)$$

$$= \begin{bmatrix} [L_2, L_3] \\ [L_3, L_1] \\ [L_1, L_2] \end{bmatrix} = 0 \quad (32)$$

$$(\vec{L} \times \vec{L})_l = \sum_{m,n} \varepsilon_{lmn} L_m L_n = \varepsilon_{lmn} (L_m L_n - L_n L_m) = \varepsilon_{lmn} [L_m, L_n] = i\hbar L_l \quad (33)$$

(d)

$$[\frac{p^2}{2m}, x_i] = \frac{1}{2m} [p^2, x_i] \quad (34)$$

$$= \frac{1}{2m} [p_1^2 + p_2^2 + p_3^2, x_i] \quad (35)$$

$$= \frac{1}{2m} [p_i^2, x_i] \quad (36)$$

$$= \frac{1}{2m} (p_i [p_i, x_i] + [p_i, x_i] p_i) \quad (37)$$

$$= \frac{1}{2m} (p_i (-i\hbar) - i\hbar p_i) \quad (38)$$

$$= \frac{-i\hbar}{m} p_i \quad (39)$$

$$f(x) = \sum_n a_n x^n \quad (40)$$

$$f(\hat{x}) = \sum_n a_n \hat{x}^n \quad (41)$$

therefore,

$$[f(\hat{x}), p_1] = [\sum_n a_n \hat{x}^n, p_1] \quad (42)$$

$$= \sum_n a_n [x_1^n, p_1] \quad (43)$$

$$[x_1, p_1] = i\hbar \quad (44)$$

$$[x_1^2, p_1] = 2i\hbar x_1 \quad (45)$$

$$[x_1^n, p_1] = ni\hbar x_1^{n-1} \quad (46)$$

$$[x_1^{n+1}, p_1] = [x_1 \cdot x_1^n, p_1] = x_1 [x_1^n, p_1] + [x_1, p_1] x_1^n = ni\hbar x_1^n + i\hbar x_1^n = (n+1)i\hbar x_1^n \quad (47)$$

therefore,

$$= \sum_n a_n n i \hbar x_1^{n-1} \quad (48)$$

$$f(\hat{x}_1) = \sum_n a_n \hat{x}_1^n \quad (49)$$

and

$$[\hat{x}_1, f(\hat{x}_1)] = i \hbar f'(\hat{p}_1) \quad (50)$$

$$[f(\hat{x}_1), \hat{p}_1] = i \hbar f'(\hat{x}_1) \quad (51)$$

$$[V(\hat{\vec{r}}), \hat{p}_i] = i \hbar \frac{\partial V}{\partial \hat{x}_i} \quad (52)$$

Question 4

(a)

$$\psi(x, 0) = Ae^{ik_0x} e^{-\frac{x^2}{2b^2}} \quad (53)$$

$$\rho(x, 0) = |\psi(x, 0)|^2 \quad (54)$$

is the density of the wave function

$$\rho(x, 0)dx \quad (55)$$

is the probability to find the particle in $(x, x + dx)$

therefore,

$$1 = \int_{-\infty}^{\infty} \rho(x, 0)dx \quad (56)$$

$$= A^2 \int e^{-\frac{x^2}{2b^2}} dx \quad (57)$$

$$(u = \frac{x}{b}) = A^2 b \int e^{-u^2} du \quad (58)$$

$$= A^2 b \sqrt{\pi} \quad (59)$$

$$\Rightarrow A = \frac{1}{\sqrt{b\sqrt{\pi}}} \quad (60)$$

(b)

$$\psi(x, 0) = \frac{1}{2\pi} \int dk e^{ikx} \tilde{\psi}(k) \quad (61)$$

$$\tilde{\psi}(k) = \int dx e^{-ikx} \psi(x, 0) \quad (62)$$

$$\tilde{\psi}(k) = A \int e^{-ikx - ik_0x} e^{-\frac{x^2}{2b^2}} \quad (63)$$

$$\tilde{\psi}(k) = \sqrt{2b\sqrt{\pi}} e^{-\frac{b^2}{2}(k-k_0)^2} \quad (64)$$

(c) Set potential of e in (b) equal to -1

(d)

$$\psi(x, t) = \frac{\sqrt{b}}{\pi^{\frac{1}{4}}} \frac{e^{-\frac{b^2 k_0^2}{2}} e^{\frac{(b^2 k_0 + ix)^2}{2(b^2 + \frac{i\hbar t}{m})}}}{\sqrt{b^2 + \frac{i\hbar t}{m}}} \quad (65)$$