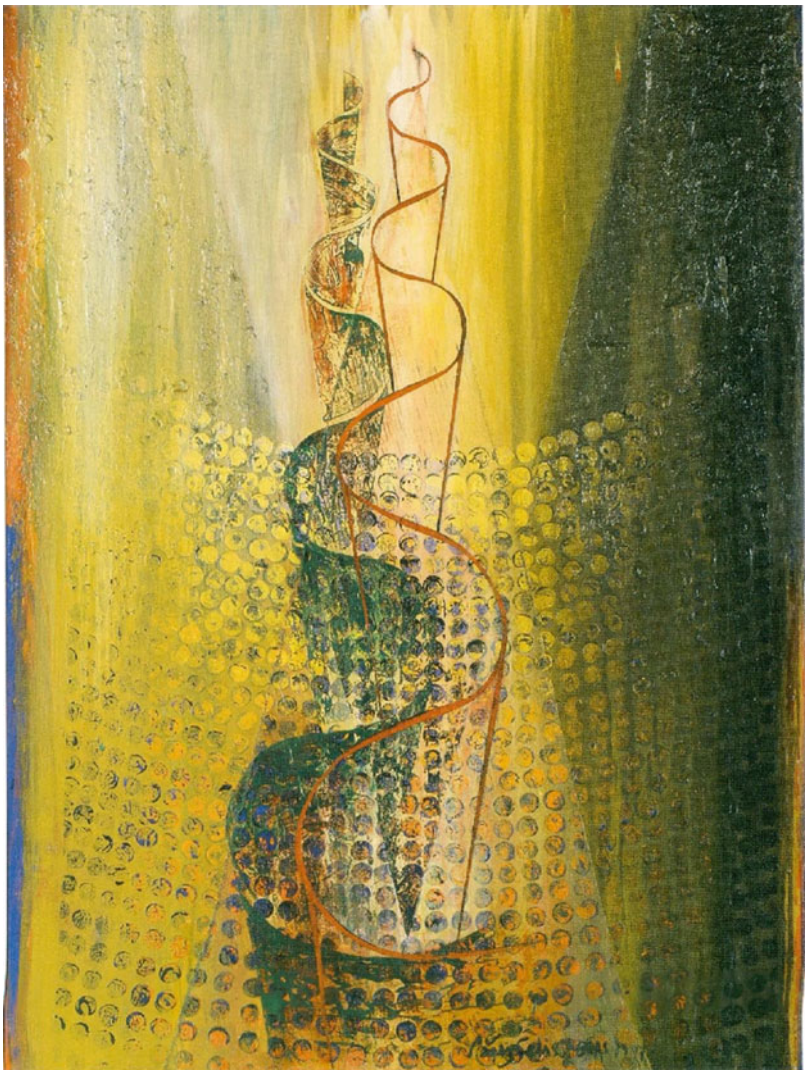

An Evanescent Particle (1997). Pérez Celis, Argentine painter (1939–2008). Starting from the *bottom*, this beautiful picture conveys the image of the linear combination (2.29), representing a particle exiting from the intermediate screen in a two-slit experiment (Fig. 2.5). Both *green* and *brown* components display a definite wave length, as befits a plane wave. Environment effects become effective after traveling some distance, resulting in a classical, decohered, single component. This picture belongs to the collection of Banco de la Nación Argentina, and is reproduced with authorization from this institution and from Pérez Celis' family

Appendix A
Solutions to Problems and Physical Constants

Solutions to Problems

Chapter 2

Problem 1. (1) $\Psi = \dfrac{c_1}{\sqrt{|c_1|^2 + |c_2|^2}}\Psi_1 + \dfrac{c_2}{\sqrt{|c_1|^2 + |c_2|^2}}\Psi_2$.
(2) $\dfrac{|c_1|^2}{|c_1|^2 + |c_2|^2}$.

Problem 2. (1) $\Psi_3 = -\dfrac{c}{\sqrt{1-|c|^2}}\Psi_1 + \dfrac{1}{\sqrt{1-|c|^2}}\Psi_2$.
(2) $\Psi = \dfrac{(c_1 + cc_2)\Psi_1 + c_2\sqrt{1-|c|^2}\Psi_3}{\sqrt{|c_1|^2 + |c_2|^2 + c_1c^*c_2^* + c_1^*cc_2}}$.

Problem 5. $-\mathrm{i}\dfrac{\hbar\hat{p}}{M}$.

Problem 6. (1) $-\mathrm{i}\hbar n\,\hat{p}^{n-1}$. (2) $-\mathrm{i}\hbar\dfrac{\mathrm{d}f}{\mathrm{d}\hat{p}}$.

Problem 8. (1) $\hat{R}\Psi = \Psi$. (2) $\hat{R}\Psi = 0$.

Problem 9. $\dfrac{\langle i|p|j\rangle}{\langle i|x|j\rangle} = \dfrac{\mathrm{i}M(E_i - E_j)}{\hbar}$.

Problem 10.

result	probability	result	probability
g_1, f_1	16/25	g_1, f_2	4/25
g_2, f_1	1/25	g_2, f_2	4/25

D. Bes, *Quantum Mechanics*, Graduate Texts in Physics,
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Problem 11. (1) $P(4K_p) = \dfrac{1}{6}$ $P(K_p) = \dfrac{5}{6}$. (2) $\langle |K| \rangle = \dfrac{3}{2} K_p$ $\Delta K = \dfrac{\sqrt{5}}{2} K_p$. (3) $\dfrac{1}{\sqrt{5}} \varphi_2 + \dfrac{2}{\sqrt{5}} \varphi_3$.

Problem 12. $\Delta x \approx 10^{-19}\,\mathrm{m}$, $\Delta v \approx 10^{-19}\ \mathrm{m}\,s^{-1}$.

Problem 13. (1) $\Delta E_{\mathrm{H}} / \Delta E = O(10^{-25})$. (2) $x = O(10^{10})\,\mathrm{m}$.

Chapter 3

Problem 1. (1) $0,\ \pm\sqrt{2}$. (2) $\varphi_{\pm\sqrt{2}} = \dfrac{1}{2} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \pm \dfrac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} + \dfrac{1}{2} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$,

$$\varphi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} - \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} , \qquad \mathcal{U} = \frac{1}{2} \begin{pmatrix} 1 & \sqrt{2} & 1 \\ \sqrt{2} & 0 & -\sqrt{2} \\ 1 & -\sqrt{2} & 1 \end{pmatrix} .$$

Problem 2. (1) $\Delta_\pm = \pm\sqrt{a^2 + c^2}$. (2) $\Delta_\pm = \pm|a| \left(1 + \dfrac{c^2}{2a^2} + \cdots \right)$.
(3) $\Delta_\pm = \pm|c| \left(1 + \dfrac{a^2}{2c^2} + \cdots \right)$.

Problem 3. $\langle 1|2 \rangle = \langle 1|3 \rangle = \langle 2|4 \rangle = \langle 3|4 \rangle = 0$.

Problem 4. (1) $\Delta_Q = (0.5, 0.5, -1)$, $\Delta_R = (0.5, -0.5, 1)$.
(2) $[\hat{Q}, \hat{R}] = 0$. (3) $\begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \\ 0 \end{pmatrix}$, $\begin{pmatrix} 1/\sqrt{2} \\ -1/\sqrt{2} \\ 0 \end{pmatrix}$, $\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$.

Problem 5. (1) $\pm\dfrac{\hbar}{2}$. (3) $\varphi_{\beta\uparrow} = \cos\dfrac{\beta}{2} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \sin\dfrac{\beta}{2} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$,
$\varphi_{\beta\downarrow} = -\sin\dfrac{\beta}{2} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \cos\dfrac{\beta}{2} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$.

Problem 7. (1) $E = V_0 + \dfrac{7\hbar}{2} \sqrt{\dfrac{c}{M}}$. (2) $E = -\dfrac{b^2}{2c} + \hbar \sqrt{\dfrac{c}{M}} \left(n + \dfrac{1}{2} \right)$.

Problem 8. (1) $x_{\mathrm{c}} = \sqrt{\hbar} / (Mc)^{1/4}$. (2) $3\hbar\omega$.

Problem 9. (1) $\dfrac{2M\omega}{\hbar} \langle n+2|x^2|n \rangle = -\dfrac{2}{\hbar M\omega} \langle n+2|p^2|n \rangle =$
$\sqrt{(n+1)(n+2)}$, and 0 otherwise. (3) $\dfrac{\langle n|K|n \rangle}{\langle n|V|n \rangle} = -\dfrac{\langle n \pm 2|K|n \rangle}{\langle n \pm 2|V|n \rangle} = 1$.

Problem 10. Zero.

Problem 11. (1) $\Psi = \frac{1}{\sqrt{2}}\varphi_0 + \frac{1}{\sqrt{2}}\varphi_1$. (2) $\langle\Psi|x|\Psi\rangle = \frac{1}{\sqrt{2}}x_c$, $\langle\Psi|p|\Psi\rangle = \langle\Psi|\Pi|\Psi\rangle = 0$.

Problem 13. $c^{\pm}_{an} = \mp \mathrm{i} c^{\pm}_{b(n+1)} = \frac{1}{\sqrt{2}}$.

Chapter 4

Problem 2. (1) $\varphi_n = \sqrt{\frac{2}{a}}\sin(k_n x)$ $(0 \le x \le a)$ and $\varphi_n = 0$ otherwise. $k_n = n\pi/a$, $E_n = \hbar^2 k_n^2/2M$. (3) No.

Problem 3. $E \approx (\hbar\Delta p)^2/2M \ge \hbar^2/8Ma^2$.

Problem 4. $\mathrm{i}\kappa \coth\frac{\kappa a}{2} = k\cot\frac{ka}{2}$, $\kappa = \sqrt{2M(V_0 - E)}/\hbar$, $k = \sqrt{2ME}/\hbar$.

Problem 5. $\sum_k E_k - \frac{a}{2\pi}\int E_k \mathrm{d}k \approx E_{k_{\max}} = \hbar^2 k_{\max}^2/2M$.

Problem 6. (1) $\rho(E) = \frac{a}{\pi\hbar}\sqrt{\frac{M}{2E}}$. (2) $0.81\ 10^7$ eV.

Problem 7. (1) $-\cot\frac{ka}{2} = \frac{\kappa}{k}$.

Problem 8. 1 eps, 1 eps + 1 ops, 2 eps + 1 ops, 2 eps + 2 ops.

Problem 9. $R = 0.030$, $T = 0.97$.

Problem 10. (1) $x_d \approx 1/\kappa = 1.13$ Å. (2) $T = 1.7 \times 10^{-15}$.

Problem 11. $\lim_{\kappa a \ll 1} T = \frac{2E/V_0}{2E/V_0 + MV_0a^2/\hbar^2}$,

$\lim_{\kappa a \gg 1} T = \frac{16E}{V_0}\left(1 - \frac{E}{V_0}\right)\exp\left[-\frac{2a}{\hbar}\sqrt{2M(V_0 - E)}\right]$.

Problem 12. $3\ 10^{-3}$ Å.

Problem 13. (2) The lattice exerts forces on the electron.
(3) $\langle k|p|k\rangle = \hbar k\int |u_k|^2 \mathrm{d}x - \mathrm{i}\hbar\int u_k^* \frac{\mathrm{d}u_k}{\mathrm{d}x}\mathrm{d}x$.

Problem 14. $\dfrac{1}{M_{eff}} = \dfrac{1}{M} \mp \dfrac{d^2}{\hbar^2(\mathrm{d}f/\mathrm{d}E)_{E=E_0}}$, where $f(E_0) = \pm 1$.

Problem 15. (1) $\eta = \left(\dfrac{2\hbar\sqrt{2\pi}}{a\alpha}\right)^{1/2}$. (2) $|\Psi|^2 = \dfrac{\alpha}{\hbar\sqrt{2\pi}} \exp[-x^2\alpha^2/2\hbar^2]$
(3) $0, \hbar^2/\alpha^2$. (4) $0, \alpha^2/4$.

Chapter 5

Problem 1. $O\left(10^{31}\right)$.

Problem 2. $\dfrac{\hbar}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \longrightarrow \hbar \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$.

Problem 4. $\mathrm{i}\hbar \boldsymbol{J}$.

Problem 5. (1) $\langle 00|Y_{20}|00\rangle = \langle 11|Y_{21}|21\rangle = \langle 00|Y_{11}|11\rangle = \langle 00|\Pi|10\rangle = 0$.
(2) $\langle 10|Y_{20}|10\rangle = 0.25$, $\langle 00|Y_{11}|1(-1)\rangle = -0.28$, $\langle 00|\Pi|00\rangle = -\langle 11|\Pi|11\rangle = 1$.

Problem 7. (1) $\varphi_{s_x=\pm\frac{1}{2}} = \dfrac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm 1 \end{pmatrix}$, $\varphi_{s_y=\pm\frac{1}{2}} = \dfrac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm \mathrm{i} \end{pmatrix}$.
(2) $\pm\dfrac{\hbar}{2}$, $\dfrac{1}{2}$. (3) $\hat{S}_x = \dfrac{\hbar}{2} \begin{pmatrix} 0 & \mathrm{i} \\ -\mathrm{i} & 0 \end{pmatrix}$.
(4) $\varphi_{s_x=\pm\frac{1}{2}} = \dfrac{1 \pm \mathrm{i}}{2}\varphi_{s_y=\frac{1}{2}} + \dfrac{1 \mp \mathrm{i}}{2}\varphi_{s_y=-\frac{1}{2}}$.

Problem 8. (1) $\dfrac{1}{2}(a+b)^2$. (2) $\dfrac{1}{2}(a^2+b^2)$. (3) a^2.

Problem 9. (1) $\dfrac{\hbar}{2}, \cos^2\dfrac{\beta}{2}$, $-\dfrac{\hbar}{2}, \sin^2\dfrac{\beta}{2}$. (2) $\dfrac{\hbar}{2}\cos\beta$.

Problem 10. (1) $\varphi_{\frac{3}{2}\frac{1}{2}} = -\sqrt{\dfrac{2}{5}}Y_{20} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \sqrt{\dfrac{3}{5}}Y_{21} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$,
$\varphi_{\frac{5}{2}\frac{1}{2}} = \sqrt{\dfrac{3}{5}}Y_{20} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \sqrt{\dfrac{2}{5}}Y_{21} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$. (3) $Y_{ll} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$, 1.

Problem 11. Equation (7.12).

Problem 12. $\sum_{m_1 m_2} c(j_1 m_1, j_2 m_2, jm) c(j_1 m_1, j_2 m_2, j'm') = \delta_{jj'}\delta_{mm'}$,
$\sum_{jm} c(j_1 m_1, j_2 m_2, jm) c(j_1 m_1', j_2 m_2', jm) = \delta_{m_1 m_1'}\delta_{m_2 m_2'}$.

Problem 13. $\varphi_{\frac{1}{2} ljm} = (-1)^{\frac{1}{2}+l-j}\, \varphi_{l\frac{1}{2}jm}$.

Chapter 6

Problem 1. 2.5×10^{-3} eV.

Problem 2. (1) $1s_{\frac{1}{2}}$, $2s_{\frac{1}{2}}$, $2p_{\frac{1}{2}}$, $2p_{\frac{3}{2}}$, $3s_{\frac{1}{2}}$, $3p_{\frac{1}{2}}$, $3p_{\frac{3}{2}}$, $3d_{\frac{3}{2}}$, $3d_{\frac{5}{2}}$.
(2) $0s_{\frac{1}{2}}$, $1p_{\frac{1}{2}}$, $1p_{\frac{3}{2}}$, $2s_{\frac{1}{2}}$, $2d_{\frac{3}{2}}$, $2d_{\frac{5}{2}}$, $3p_{\frac{1}{2}}$, $3p_{\frac{3}{2}}$, $3f_{\frac{5}{2}}$, $3f_{\frac{7}{2}}$.

Problem 3. (1) $(N+1)(N+2)$. (2) $\dfrac{\hbar^2}{2} N(N+3)$.
(3) $E_{Nlj} = \hbar\omega \left(\dfrac{\alpha_{Nlj}}{16} + \dfrac{3}{2} \right)$, where $\alpha_{Nlj} = 0(0s_{\frac{1}{2}})$, $10(1p_{\frac{3}{2}})$, $20(1p_{\frac{1}{2}})$,
$27(2d_{\frac{5}{2}})$, $37(2d_{\frac{3}{2}})$, $37(2s_{\frac{1}{2}})$, $39(3f_{\frac{7}{2}})$, $53(3f_{\frac{5}{2}})$, $53(3p_{\frac{3}{2}})$, $59(3f_{\frac{1}{2}})$.
(4) $l = N$, $\quad j = N + \dfrac{1}{2}$.

Problem 4. $\varphi_n = \dfrac{1}{\sqrt{2\pi a}} \dfrac{1}{r} \sin \dfrac{n\pi r}{a}$, $\quad E_n = \dfrac{1}{2M} \left(\dfrac{\hbar n \pi}{a} \right)^2$.

Problem 5. $r_{\max}^{(n_r=1, l=0)} = 5.2a_0$, $\langle 200|r|200\rangle = 6a_0$, $r_{\max}^{(n_r=0, l=1)} = 4a_0$,
$\langle 21m_l|r|21m_l\rangle = 5a_0$.

Problem 7. (1) $\dfrac{R}{\langle 100|r|100\rangle} = 1.5 \times 10^{-5}$ (H) ,
$\dfrac{R}{\langle 100|r|100\rangle} = 7.3 \times 10^{-3}$ (Pb) . (2) $\dfrac{R}{\langle 100|r|100\rangle} = 3.1 \times 10^{-3}$ (H) ,
$\dfrac{R}{\langle 100|r|100\rangle} = 1.5$ (Pb) .

Problem 8. $r^2 \to s$, $\varphi(r^2) \to s^{1/4}\phi(s)$, $l(l+1) \to \dfrac{1}{4} l(l+1) - \dfrac{3}{16}$,
$\dfrac{1}{4} E \to e^2/4\pi\epsilon_0$, $\dfrac{1}{8} M\omega^2 \to -E$.

Problem 9. $E_{s=0} = -\dfrac{3}{4} a\hbar^2$, $E_{s=1} = \dfrac{1}{4} a\hbar^2$.

Problem 10. (1) $\mu_B B_z$. (2) $\dfrac{3}{2} \nu_{\rm so} \hbar^2$. (3) $\dfrac{1}{2} \nu_{\rm so} \hbar^2 (9 + 2q + q^2)^{1/2}$.

Problem 11. $j_r = |A|^2\hbar k/r^2 M$, $\text{flux}(\mathrm{d}\Omega) = |A|^2\hbar k\mathrm{d}\Omega/M$.

Problem 12. (1) $\beta_- = -1 + ak_-\cot ak_-$; $k_- = \frac{1}{\hbar}\sqrt{2MV_0}$.
(2) $\beta_+ = \sin\delta_0/(ak\cos\delta_0 + \sin\delta_0)$; $k = \frac{1}{\hbar}\sqrt{2ME}$.
(3) $\tan\delta_0 = ka\ (1 - \tan ak_-/ak_-)$. (4) $\sigma(\theta) = a^2\ (1 - \tan ak_-/ak_-)^2$.
(5) $\sigma = 4\pi a^2\ (1 - \tan ak_-/ak_-)^2$.

Problem 13. (1) $V = V(\rho)$, $\rho \equiv \sqrt{x^2 + y^2}$, $\phi \equiv \tan^{-1}(y/x)$.
(2) $\dfrac{1}{2M}\left(\hat{p}_x^2 + \hat{p}_y^2\right) = -\dfrac{\hbar^2}{2M}\left(\dfrac{\partial^2}{\partial\rho^2} + \dfrac{1}{\rho}\dfrac{\partial}{\partial\rho} + \dfrac{1}{\rho^2}\dfrac{\partial^2}{\partial\phi^2}\right)$, $E_{m_l} = E_{-m_l}$.
(3) $E_n = \hbar\omega(n+1)$, $n+1$, $n = 0, 1, 2, \ldots$.

Problem 14. (1) $\omega_{\text{ph}} = \omega_{\text{cl}} = \hbar/Ma_0^2 n^3$.
(2) Bohr correspondence principle (Sect. 15.3.2).

Chapter 7

Problem 1. (1) $\dfrac{1}{2x_{\text{c}}\sqrt{2\pi}}\exp\left(-\dfrac{x^2}{2x_{\text{c}}^2}\right)\left(1 + \dfrac{x^2}{x_{\text{c}}^2}\right)$, $x_{\text{c}}\sqrt{2}$, 0.10 .
(2) $\dfrac{1}{x_{\text{c}}\sqrt{2\pi}}\exp\left(-\dfrac{x^2}{2x_{\text{c}}^2}\right)$, x_{c} , 0.16 .
(3) $\dfrac{1}{x_{\text{c}}^3\sqrt{2\pi}}\exp\left(-\dfrac{x^2}{2x_{\text{c}}^2}\right)x^2$, $x_{\text{c}}\sqrt{3}$, 0.0021 .

Problem 2. (1) $\varphi_+ = \dfrac{1}{\sqrt{2}}\left[\varphi_{100}(1)\varphi_{21m_l}(2) + \varphi_{100}(2)\varphi_{21m_l}(1)\right]\chi_{s=0}$,
$\varphi_- = \dfrac{1}{\sqrt{2}}\left[\varphi_{100}(1)\varphi_{21m_l}(2) - \varphi_{100}(2)\varphi_{21m_l}(1)\right]\chi_{s=1,m_s}$. (2) $E_+ > E_-$.

Problem 3. $J = 0, 2, 4$.

Problem 4. (1) s. (2) a. (3) s. (4) a. (5) s.

Problem 5. J even.

Problem 6. (1) $3/2, 1/2$. (2) $1/2$.

Problem 8. $\dfrac{1}{2}+$, $\dfrac{3}{2}-$, $\dfrac{1}{2}-$, $\dfrac{5}{2}+$, $\dfrac{7}{2}-$, $\dfrac{1}{2}-$.

Problem 9. (1) $3.8/-0.26/4.8\ (\mu_{\text{p}})$. (2) $-1.9/0.64/-1.9\ (\mu_{\text{p}})$.

Problem 10. (1) $1\ 10^{-3}$. (2) $2\ 10^{-1}$. (3) $4\ 10^{-3}$.

Problem 11. $n(\epsilon) = \dfrac{M\epsilon}{\pi\hbar^2}$, $C_{\mathrm{V}} = 2n_{\mathrm{F}}k_{\mathrm{B}}\dfrac{T}{T_{\mathrm{F}}}$.

Problem 12. 1/3; 1/2; 3/5.

Problem 13. (1) 5.9×10^3 Å. (2) Red.

Problem 14. (1) $-\frac{\pi^2}{12}\left(k_{\mathrm{B}}T\right)^2/\epsilon_{\mathrm{F}}$. (2) -1.7×10^{-4} eV.

Problem 15. Constant.

Problem 16. $q_{aa} + q_{bb}$, $-q_{ac}$, q_{bc} .

Chapter 8

Problem 1. (1) Equation (8.10).

(2) $c_{p\neq n}^{(2)} = \dfrac{1}{E_n^{(0)} - E_p^{(0)}}\left[\sum_{q\neq n} c_q^{(1)}\langle\varphi_p^{(0)}|V|\varphi_q^{(0)}\rangle - E_n^{(1)}c_p^{(1)}\right]$,

$c_n^{(2)} = -\dfrac{1}{2}\sum_{p\neq n}|c_p^{(1)}|^2$.

Problem 2. (1) $E_1^{(1)} = E_2^{(1)} = 0$, $E_3^{(1)} = 2c$.

(2) $E_1^{(2)} = -E_2^{(2)} = \dfrac{|c|^2}{3}$, $E_3^{(2)} = 0$.

(3) $\varphi_1^{(1)} = \dfrac{c}{3}\varphi_2^{(0)}$, $\varphi_2^{(1)} = -\dfrac{c}{3}\varphi_1^{(0)}$, $\varphi_3^{(1)} = 0$.

(4) $\varphi_1^{(2)} = -\dfrac{|c|^2}{18}\varphi_1^{(0)}$, $\varphi_2^{(2)} = -\dfrac{|c|^2}{18}\varphi_2^{(0)}$, $\varphi_3^{(2)} = 0$.

(5) $E_\pm = \dfrac{7}{2} \pm \dfrac{3}{2}\sqrt{1 + \dfrac{4|c|^2}{9}} \approx \dfrac{7}{2} \pm \dfrac{|c|^2}{3}$, $E_3 = -1 + 2c$.

Problem 3. (1) $E_0^{(1)} = 0$, $E_0^{(2)} = -\dfrac{k^2}{2M\omega^2}$.

(2) $E_0^{(1)} = \dfrac{bx_{\mathrm{c}}^2}{4}$, $E_0^{(2)} = -\dfrac{b^2x_{\mathrm{c}}^2}{16M\omega^2}$.

Problem 4. (1) $E_0^{(1)} = -\dfrac{3}{32M}\left(\dfrac{\hbar\omega}{c}\right)^2$. (2) 10^{-8} .

Problem 5. $\Psi_n = \left[1 - \frac{1}{2}\sum_{p\neq n}\frac{|\langle\varphi_p^{(0)}|V|\varphi_n^{(0)}\rangle|^2}{(E_n^{(0)}-E_p^{(0)})^2}\right]\varphi_n^{(0)}$
$+\sum_{p\neq n}\frac{\langle\varphi_p^{(0)}|V|\varphi_n^{(0)}\rangle}{E_n^{(0)}+\langle\varphi_n^{(0)}|V|\varphi_n^{(0)}\rangle-E_p^{(0)}}\varphi_p^{(0)}+\sum_{p,q(\neq n)}\frac{\langle\varphi_p^{(0)}|V|\varphi_q^{(0)}\rangle\langle\varphi_q^0|V|\varphi_n^{(0)}\rangle}{(E_n^{(0)}-E_p^{(0)})(E_n^{(0)}-E_q^{(0)})}\varphi_p^{(0)}$.

Problem 7.
(1) $\langle H\rangle = \frac{\hbar\omega}{4}\left[\frac{M}{M^*}+\frac{M^*}{M}-\frac{3}{8}\frac{\hbar\omega}{Mc^2}\left(\frac{M^*}{M}\right)^2+\frac{15}{32}\left(\frac{\hbar\omega}{Mc^2}\right)^2\left(\frac{M^*}{M}\right)^3+\cdots\right]$.
(2) $1 = \left(\frac{M^*}{M}\right)^2-\frac{3}{4}\frac{\hbar\omega}{Mc^2}\left(\frac{M^*}{M}\right)^3+\frac{45}{32}\left(\frac{\hbar\omega}{Mc^2}\right)^2\left(\frac{M^*}{M}\right)^4+\cdots$.
(3) $\frac{M^*}{M} = 1+\frac{3}{8}\frac{\hbar\omega}{Mc^2}-\frac{45}{128}\left(\frac{\hbar\omega}{Mc^2}\right)^2+\cdots$.
(4) $\langle H\rangle = \frac{\hbar\omega}{2}\left[1-\frac{3}{16}\frac{\hbar\omega}{Mc^2}+\frac{3}{16}\left(\frac{\hbar\omega}{Mc^2}\right)^2+\cdots\right]$.

Problem 8. $\left\langle 1s2p\pm\left|\frac{e^2}{4\pi\epsilon_0 r}\right|1s2p\pm\right\rangle = -(0.98\pm0.08)E_{\mathrm{H}}$.

Problem 9.

	$\langle H\rangle_Z$	Z^*	$\langle H\rangle_{Z^*}$	exp
He	5.50	1.69	5.69	5.81
Li^+	14.25	2.69	14.44	14.49
Be^{++}	27.00	3.69	27.19	27.21

Problem 10. $\Delta E = \frac{3\hbar\omega}{4}\left(\frac{x_c}{R_0}\right)^4 l(l+1)-\frac{\hbar\omega}{2}\left(\frac{x_c}{R_0}\right)^6 l^2(l+1)^2$.

Problem 11. (1) $\epsilon_0 = -8.75\ 10^{-4}\,\mathrm{eV}$; $R_0 = 2.87\ \mathring{A}$.
(2) $\hbar\omega = 4.0\ 10^{-3}\,\mathrm{eV}$. (3) $\frac{\hbar^2}{2\mu R_0^2} = 1.29\ 10^{-4}\,\mathrm{eV}$.

Problem 12. $E_\pm(m=0) = E_{n=2}^{(0)}\pm 3eE_z a_0$, $E(m=\pm1) = E_{n=2}^{(0)}$.

Problem 13. (1) $H = \frac{1}{2M}\sum_{\mu\eta}\langle\mu|p^2|\eta\rangle a_\mu^+ a_\eta$
$+\frac{g}{2}\sum_{\mu\eta}\langle\mu|x^2|\eta\rangle\sum_\nu a_\mu^+ a_\nu^+ a_\nu a_\eta - \frac{g}{2}\sum_{\mu\nu\eta\zeta}\langle\mu|x|\eta\rangle\langle\nu|x|\zeta\rangle a_\mu^+ a_\nu^+ a_\zeta a_\eta$.
(2) $H_{\mathrm{H}} = \hbar\omega_{\mathrm{H}}\sum_\mu\left(a_\mu^+ a_\mu+\frac{1}{2}\right)$; $V' = -\frac{g}{2}\left(\sum_{\mu\eta}\langle\mu|x|\eta\rangle a_\mu^+ a_\eta\right)^2$;

$\omega_{\mathrm{H}} = \sqrt{\dfrac{Ng}{M}}$. (3) $H_{\mathrm{RPA}} = \hbar\omega_{\mathrm{H}}\gamma^{+}\gamma - \frac{g}{2}\langle N+1|x|N\rangle^{2}(\gamma^{+}+\gamma)^{2}$;
$\gamma^{+} = a^{+}_{N+1}a_{N}$; $\omega_{RPA} = 0$. (4) Translational invariance.

Chapter 9

Problem 1. $0.50 - 0.40\sin(3\pi^{2}\hbar t/2Ma^{2})$.

Problem 2. $\dfrac{\mathrm{d}\langle\Psi|p|\Psi\rangle}{\mathrm{d}t} = -\left\langle\Psi\left|\dfrac{\mathrm{d}V}{\mathrm{d}x}\right|\Psi\right\rangle$.

Problem 3. $c_{y\uparrow} = \dfrac{1-\mathrm{i}}{\sqrt{2}}\cos\left(\dfrac{1}{2}\omega_{\mathrm{L}}t + \dfrac{\pi}{4}\right)$.

Problem 4. $\mathcal{U}_{\mathbf{n}}(t,0) = \cos\dfrac{\omega_{\mathrm{L}}t}{2}\mathcal{I} + \mathrm{i}\sin\dfrac{\omega_{\mathrm{L}}t}{2}\boldsymbol{n}\cdot\boldsymbol{\sigma}$.

Problem 5. 0.36, 0.50, 0.13 .

Problem 6. $P^{(1)}_{\uparrow\to\downarrow} = \dfrac{\omega'^{2}}{(\omega-\omega_{\mathrm{L}})^{2}}\sin^{2}\left[\dfrac{1}{2}t(\omega-\omega_{\mathrm{L}})\right]$.

Problem 7.
(1) $c_{0\to1} = -\dfrac{\mathrm{i}vV_0}{\hbar x_{\mathrm{c}}}\sqrt{\dfrac{2}{\pi}}\exp\left(-\dfrac{\hbar\omega}{4Mv^{2}}\right)\displaystyle\int_{t_1}^{t_2} t\exp\left[-\dfrac{v^{2}}{x_{\mathrm{c}}^{2}}\left(t-\mathrm{i}\dfrac{\hbar\omega}{2Mv^{2}}\right)^{2}\right]\mathrm{d}t$.
(2) $|c_{0\to1}|^{2} = \dfrac{V_0}{2Mv^{4}}\exp\left(-\dfrac{\hbar\omega}{2Mv^{2}}\right)$.

Problem 8.
(1) $\Psi(t) = \cos\theta_0\exp\left[-\dfrac{\mathrm{i}V_0\sin(\omega t)}{4\hbar\omega}\right]\chi_0^{1} + \sin\theta_0\exp\left[\dfrac{\mathrm{i}3V_0\sin(\omega t)}{4\hbar\omega}\right]\chi_0^{0}$.
(2) $\Psi(t) = \exp\left[-\dfrac{\mathrm{i}V_0\sin(\omega t)}{4\hbar\omega}\right]\varphi_{B_0}$.

Problem 9. $P_{0\to1} = 2\left(\dfrac{Kx_{\mathrm{c}}}{\hbar\omega}\right)^{2}\sin^{2}\dfrac{\omega t}{2}$.

Problem 10.
(1) $c_k^{(2)} = \dfrac{1}{\hbar^{2}}\displaystyle\sum_j\langle k|V|j\rangle\langle j|V|i\rangle\left[\dfrac{1}{\omega_{ki}\omega_{kj}} + \dfrac{\exp(\mathrm{i}\omega_{ki}t)}{\omega_{ki}\omega_{ji}} + \dfrac{\exp(\mathrm{i}\omega_{kj}t)}{\omega_{kj}\omega_{ij}}\right]$.
(2) $P_{0\to2} = 2\left(\dfrac{Kx_{\mathrm{c}}}{\hbar\omega}\right)^{4}\sin^{4}\dfrac{\omega t}{2}$.

Problem 11. (1) 0.5 and 0.5×10^{-7}. (2) 2×10^{-2}.

Problem 12. $\left|\dfrac{\langle 210|\boldsymbol{r}|100\rangle}{\langle 310|\boldsymbol{r}|100\rangle}\right|^2 = 6.3\,, \quad \dfrac{P(100 \to 210)}{P(100 \to 310)} = 3.8\,.$

Problem 13. (1) $\dfrac{P(310 \to 200)}{P(310 \to 100)} = 0.13\,.$ (2) 1.1×10^{-8} s. (3) 4×10^{-7} eV.

Problem 14. (1) $\langle n, n-1||Q_1||n-1, n-2\rangle = -a_0\, n^3/\sqrt{2}\,.$

(2) $\tau(n, n-1 \to n-1, n-2) = 6n^4\hbar/\alpha^5 Mc^2\,.$

(3) $\dfrac{\tau(n, n-1 \to n-1, n-2)}{\tau(2, 1 \to 1, 0)} = 7n^4.$

Chapter 10

Problem 1. (1) $j(2j+1) \times j(2j+1)\,.$ (2) $\left(j+\dfrac{1}{2}\right) \times \left(j+\dfrac{1}{2}\right)\,.$

(3) $E_a = -g\left(j+\dfrac{1}{2}\right)\,, \quad E_b = 0\,.$

Problem 2. (1) $\langle 0|H_{tb}|0\rangle_{A_\pi = \frac{\Omega}{2}} = -g\,\dfrac{\Omega^2}{4}\left(1+\dfrac{2}{\Omega}\right).$ (2) $\mathcal{I} = \dfrac{h^2}{2g}.$

(3) $\Delta E_{A_\pi = \frac{\Omega}{2}} = g\,\Omega.$

Problem 3. (1) $E_p = \dfrac{g\Omega}{2}\,; \quad V_p^2 = \dfrac{A_\pi}{\Omega}\,; \quad \Delta = g\sqrt{A_\pi(\Omega - A_\pi)}\,;$

$\mu = g\left(A_\pi - \dfrac{\Omega}{2}\right).$

(2) $\langle 0|H_{tb}|0\rangle_{A_\pi = \frac{\Omega}{2}} = -g\dfrac{\Omega^2}{4}\,; \quad \mathcal{I} = \dfrac{h^2}{2g}\,; \quad \Delta E_{A_\pi = \frac{\Omega}{2}} = g\,\Omega.$

(3) The BCS approximation is only correct to leading order in Ω^{-1}.

Problem 4. $P^+ = \sum_{p>0}\Big[U_p V_p(1 - \alpha_p\alpha_{-p}) + U_p^2\alpha_p^+\alpha_{-p}^+ - V_p^2\alpha_{-p}\alpha_p\Big].$

Problem 5. $2\Delta.$

Problem 8. (1) $\hat{L}^{(0)} = \sqrt{\frac{\mathcal{I}}{2}}\left(\Gamma_1^+ + \Gamma_0^+ + \Gamma_1 + \Gamma_0\right).$ (2) 0.

Chapter 13

Problem 1.

	φ_{B_0}	φ_{B_1}	φ_{B_2}	φ_{B_3}
$\hat{S}_z(1)\,\hat{S}_z(2)$	1	1	-1	-1
$\hat{S}_x(1)\,\hat{S}_x(2)$	1	-1	1	-1

Problem 2. $1,\ 0,\ \frac{1}{2},\ \frac{3}{8},\ \frac{1}{8},\ \frac{1}{4}.$

Problem 3. $\hat{S}_z\left(\varphi_{B_1}\right)\ ,\quad \hat{S}_x\left(\varphi_{B_2}\right)\ ,\quad \hat{S}_y\left(\varphi_{B_3}\right)\ .$

Problem 4. $\mathcal{U}_{\mathrm{H}}\ .$

Problem 8. Alice's transformations yield a unique Bell state.

Problem 9.

f_i	c_{i0}	c_{i4}	c_{i8}	c_{i12}
1	1	1	1	1
2	1	i	-1	$-$i
4	1	-1	1	-1
8	1	$-$i	-1	i

Chapter 14

Problem 1. $L_\lambda = 0.2\ \mathrm{m}.$

Problem 4.

(1) $\hat{\rho} = \frac{1}{2}\begin{pmatrix} 1+\cos\beta & \exp[-\mathrm{i}\phi]\,\sin\beta \\ \exp[\mathrm{i}\phi]\,\sin\beta & 1-\cos\beta \end{pmatrix}$

(2) $\langle S_x\rangle = \frac{\hbar}{2}\sin\beta\,\cos\phi;\quad \langle S_y\rangle = \frac{\hbar}{2}\sin\beta\,\sin\phi;\quad \langle S_z\rangle = \frac{\hbar}{2}\cos\beta.$

Problem 5.

(1) $\hat{\rho} = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

(2) $\langle S_x\rangle = \langle S_y\rangle = \langle S_z\rangle = 0.$

Problem 6. $\Delta x = \sqrt{\frac{\hbar}{M\omega}\left(\frac{1}{2} + \frac{k_{\mathrm{B}}T}{\hbar\omega}\right)}.$

Physical Units and Constants

Table A.1 Equivalence between physical units and the value of constants used in the text [131]

Quantity	Symbol	Units (m.k.s.)	Atomic scale	Nuclear scale
		1 m	10^{10} Å	10^{15} F
		1 J	0.625×10^{19} eV	0.625×10^{13} MeV
		1 kg	0.56×10^{36} eV c^{-2}	0.56×10^{30} MeV c^{-2}
Bohr magneton	μ_B	0.93×10^{-23} J T^{-1}	0.58×10^{-4} eV T^{-1}	0.58×10^{-10} MeV T^{-1}
Bohr radius	a_0	0.53×10^{-10} m	0.53 Å	0.53×10^{5} F
Boltzmann constant	k_B	1.38×10^{-23} J K^{-1}	0.86×10^{-4} eV K^{-1}	0.86×10^{-10} MeV K^{-1}
Constant in Coulomb law	$e^2/4\pi\epsilon_0$	2.34×10^{-28} J m	14.4 eV Å	1.44 MeV F
Electron charge	e	-1.60×10^{-19} C		
Electron mass	M, M_e	0.91×10^{-30} kg	0.51×10^{6} eV c^{-2}	0.51 MeV c^{-2}
Fine structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	1/137		
Hydrogen atom ground state	E_H	-2.18×10^{-18} J	−13.6 eV	-1.36×10^{-5} MeV
Deuteron nucleus ground state	E_D	-3.57×10^{-13} J	-2.23×10^{6} eV	−2.23 MeV
Nuclear magneton	μ_p	0.51×10^{-26} J T^{-1}	0.32×10^{-7} eV T^{-1}	0.32×10^{-13} MeV T^{-1}
Planck constant/2π	$\hbar$	1.05×10^{-34} J s	0.66×10^{-15} eV s	0.66×10^{-21} MeV s
Proton mass	M_p	1.67×10^{-27} kg	0.94×10^{9} eV c^{-2}	0.94×10^{3} MeV c^{-2}
Rydberg constant	R_H	1.10×10^{7} m^{-1}	1.10×10^{-3} Å^{-1}	1.10×10^{-8} F^{-1}
Speed of light in vacuum	c	3.00×10^{8} m s^{-1}	3.00×10^{18} Å s^{-1}	3.00×10^{23} F s^{-1}

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