

## LAMPIRAN 1

### PENJABARAN HUBUNGAN KOMUTATOR KOMPONEN-KOMPONEN MOMENTUM SUDUT $\hat{L}_x$ , $\hat{L}_y$ , DAN $\hat{L}_z$

Operator momentum sudut  $\hat{L}$  dalam mekanika kuantum dinyatakan sebagai:

$$\hat{L} = \hat{\mathbf{r}} \times \hat{\mathbf{p}} = \hat{\mathbf{r}} \times (-i\hbar \nabla) \quad (\text{L.1-1}),$$

dengan operator jarak  $\hat{\mathbf{r}}$  dan operator momentum linier  $\hat{\mathbf{p}}$  dinyatakan sebagai:

$$\hat{\mathbf{r}} = x\hat{\mathbf{i}} + y\hat{\mathbf{j}} + z\hat{\mathbf{k}} \quad (\text{L.1-2})$$

$$\hat{\mathbf{p}} = p_x\hat{\mathbf{i}} + p_y\hat{\mathbf{j}} + p_z\hat{\mathbf{k}} \quad (\text{L.1-3}).$$

Maka:

$$\hat{\mathbf{r}} \times \hat{\mathbf{p}} = (yp_z - zp_y)\hat{\mathbf{i}} + (zp_x - xp_z)\hat{\mathbf{j}} + (xp_y - yp_x)\hat{\mathbf{k}} \quad (\text{L.1-4}),$$

sehingga komponen-komponen momentum sudut orbital adalah:

$$L_x = yp_z - zp_y$$

$$L_y = zp_x - xp_z \quad (\text{L.1-5}),$$

$$L_z = xp_y - yp_x$$

yang dalam bentuk operator dinyatakan sebagai:

$$\begin{aligned}\hat{L}_x &= i\hbar \left( z \frac{\partial}{\partial y} - y \frac{\partial}{\partial z} \right) \\ \hat{L}_y &= i\hbar \left( x \frac{\partial}{\partial z} - z \frac{\partial}{\partial x} \right) \\ \hat{L}_z &= i\hbar \left( y \frac{\partial}{\partial x} - x \frac{\partial}{\partial y} \right)\end{aligned}\quad (\text{L.1-6}).$$

Maka hubungan komutator  $\hat{L}_x$  dan  $\hat{L}_y$  dinyatakan sebagai:

$$[\hat{L}_x, \hat{L}_y] = \hat{L}_x \hat{L}_y - \hat{L}_y \hat{L}_x \quad (\text{L.1-7}),$$

dengan:

$$\hat{L}_x \hat{L}_y = -\hbar^2 \left( zx \frac{\partial^2}{\partial y \partial z} - z^2 \frac{\partial^2}{\partial y \partial x} - yx \frac{\partial^2}{\partial z \partial x} + yz \frac{\partial^2}{\partial z \partial x} + y \frac{\partial}{\partial x} \right) \quad (\text{L.1-8a})$$

$$\hat{L}_y \hat{L}_x = -\hbar^2 \left( zx \frac{\partial^2}{\partial y \partial z} + x \frac{\partial}{\partial y} - yx \frac{\partial^2}{\partial z \partial x} - z^2 \frac{\partial^2}{\partial y \partial x} + yz \frac{\partial^2}{\partial z \partial x} \right) \quad (\text{L.1-8b}).$$

Pers. (L.1-8a) dan (L.1-8b) disubstitusikan ke pers. (L.1-7), serta dari bentuk pers. (L.1-6) maka diperoleh:

$$\begin{aligned}[\hat{L}_x, \hat{L}_y] &= -\hbar^2 \left( y \frac{\partial}{\partial x} - x \frac{\partial}{\partial y} \right) \\ \Leftrightarrow [\hat{L}_x, \hat{L}_y] &= i\hbar \hat{L}_z\end{aligned}\quad (\text{L.1-9}).$$

Analogi pers. (L.1-9), maka hubungan komutator komponen momentum sudut orbital yang lain adalah:

$$[\hat{L}_y, \hat{L}_z] = i\hbar \hat{L}_x \quad (\text{L.1-10})$$

dan

$$[\hat{L}_z, \hat{L}_x] = i\hbar \hat{L}_y \quad (\text{L.1-11}).$$

Atau secara umum dapat dituliskan sebagai:

$$[\hat{L}_i, \hat{L}_j] = i\hbar \hat{L}_k \quad (\text{L.1-12}).$$



## LAMPIRAN 2

### KOEFISIEN EINSTEIN ( $A_{ji}$ , $B_{ji}$ , $B_{ij}$ ) DAN NILAI $f$

#### L.1.1. Koefisien Einstein

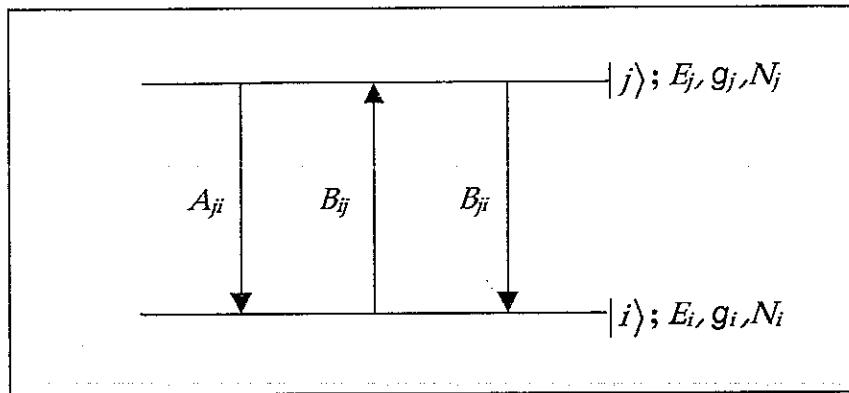
Koefisien Einstein berkaitan erat dengan interaksi radiasi dengan materi. Untuk penyederhanaan, ditinjau dua tingkat energi atomik  $E_j$  dan  $E_i$  dengan frekuensi radiasi emisi atau absorpsi  $\nu$ , sehingga beda energi antara kedua aras adalah:

$$\hbar\nu = \hbar\omega = E_j - E_i \quad (\text{L.2-1}).$$

Diasumsikan populasi pada aras  $|i\rangle$  dan  $|j\rangle$  pada saat t adalah  $N_i$  dan  $N_j$  per satuan volume. Dipostulatkan terdapat tiga proses radiasi, yaitu: *emisi spontan*, dengan angka perubahan  $N_j$  tergantung pada populasi  $N_i$  pada aras yang lebih tinggi  $|j\rangle$ ; *emisi terinduksi*, dengan angka perubahan  $N_j$  tergantung pada  $N_i$  dan kerapatan energi per satuan frekuensi radiasi  $\rho(\omega)$ ; dan *absorpsi*, dengan angka perubahan  $N_j$  tergantung pada populasi  $N_i$  pada aras yang lebih rendah  $|i\rangle$  dan  $\rho(\omega)$  (lihat gb. L.2-1). Angka perubahan  $N_j$  dan  $N_i$  dengan menyertakan koefisien Einstein  $A_{ji}$ ,  $B_{ji}$ , dan  $B_{ij}$  untuk kebolehjadian emisi spontan, emisi terinduksi, dan absorpsi dinyatakan

sebagai:

$$\frac{dN_j}{dt} = -\frac{dN_i}{dt} = -A_{ji}N_j - B_{ji}\rho(\omega)N_j + B_{ij}\rho(\omega)N_i \quad (\text{L.2-2}).$$



Gambar L.2-1: Skema Proses emisi dan absorpsi

Didefinisikan secara umum kebolehjadian emisi dan kebolehjadian absorpsi per atom per satuan waktu  $P_{ji}$  dan  $P_{ij}$  berupa (Woodgate, 1980):

$$-\frac{dN_j}{dt} = P_{ji}N_j - P_{ij}N_i \quad (\text{L.2-3}),$$

dengan  $P_{ji} = A_{ji} + B_{ji}\rho(\omega)$  (L.2-4)

dan  $P_{ij} = B_{ij}\rho(\omega)$  (L.2-5).

Dalam keadaan kesetimbangan (steady state), didefinisikan:

$$\frac{dN_j}{dt} = 0 \quad (\text{L.2-6}),$$

sehingga persamaan (L.2-2) menjadi:  $P_{ji}N_j - P_{ij}N_i = 0$  (L.2-7).

Maka dengan mensubstitusikan pers. (L.2-4) dan pers. (L.2-5) pada pers. (L.2-7) diperoleh perbandingan:

$$\frac{P_{ij}}{P_{ji}} = \frac{N_j}{N_i} = \frac{B_{ij}\rho(\omega)}{A_{ji} + B_{ji}\rho(\omega)} \quad (\text{L.2-8}).$$

Pada kesetimbangan termal (*thermal equilibrium*) dengan suhu mutlak  $T$ , didefinisikan (Woodgate, 1980):

$$\frac{N_j}{N_i} = \frac{g_j}{g_i} \exp\left(-\frac{\hbar\omega_{jj}}{kT}\right) \quad (\text{L.2-9})$$

dan diberikan persamaan radiasi Planck:

$$\rho(\omega_{jj}) = \frac{\omega_{jj}^2}{\pi^2 c^3} \hbar\omega_{jj} \left\{ \exp\left(\frac{\hbar\omega_{jj}}{kT}\right) - 1 \right\}^{-1} \quad (\text{L.2-10}),$$

serta dengan mengambil:  $g_j B_{ji} = g_i B_{jj}$  (L.2-11),

kemudian pers. (L.2-9), pers. (L.2-10), dan pers. (L.2-11) disubstitusikan ke pers. (L.2-8):

$$\begin{aligned} & \frac{B_{jj} \omega_{jj}^2 \hbar\omega_{jj}}{A_{jj} \pi^2 c^3 \left\{ \exp\left(\frac{\hbar\omega_{jj}}{kT}\right) - 1 \right\} + B_{ji} \omega_{jj}^2 \hbar\omega_{jj}} = \frac{g_j}{g_i} \left\{ \exp\left(\frac{\hbar\omega_{jj}}{kT}\right) \right\}^{-1} \\ \Leftrightarrow & \frac{B_{jj} \omega_{jj}^2 \hbar\omega_{jj}}{A_{jj} \pi^2 c^3 \left\{ \exp\left(\frac{\hbar\omega_{jj}}{kT}\right) - 1 \right\} + B_{ji} \omega_{jj}^2 \hbar\omega_{jj}} = \frac{B_{jj}}{B_{ji}} \left\{ \exp\left(\frac{\hbar\omega_{jj}}{kT}\right) \right\}^{-1} \\ \Leftrightarrow & \frac{B_{ji} \omega_{jj}^2 \hbar\omega_{jj}}{A_{jj} \pi^2 c^3 \left\{ \exp\left(\frac{\hbar\omega_{jj}}{kT}\right) - 1 \right\} + B_{ji} \omega_{jj}^2 \hbar\omega_{jj}} = \frac{1}{\exp\left(\frac{\hbar\omega_{jj}}{kT}\right)} \\ \Leftrightarrow & B_{ji} \omega_{jj}^2 \hbar\omega_{jj} \left\{ \exp\left(\frac{\hbar\omega_{jj}}{kT}\right) - 1 \right\} = A_{jj} \pi^2 c^3 \left\{ \exp\left(\frac{\hbar\omega_{jj}}{kT}\right) - 1 \right\} \quad (\text{L.2-12}) \end{aligned}$$

sehingga diperoleh hubungan :

$$A_{ji} = \frac{\omega_{jj}^2}{\pi^2 c^3} \hbar\omega_{jj} B_{ji} = \frac{\omega_{jj}^2}{\pi^2 c^3} \hbar\omega_{jj} \frac{g_j}{g_i} B_{jj} \quad (\text{L.2-13}).$$

Adanya argumen kesetimbangan termal adalah untuk memastikan hubungan koefisien  $A_{ji}$ ,  $B_{ji}$ , dan  $B_{jj}$ . Hubungan ini dipostulatkan benar untuk atom yang tidak dipengaruhi (*irrespective*) baik oleh keadaan kesetimbangan termal ataupun tidak.

### L.1.2. *Oscillator Strength (Nilai $\gamma$ )*

Persamaan Schrödinger gayut waktu untuk sistem satu elektron non-relativistik adalah:

$$H \Psi = i\hbar \frac{\partial \Psi}{\partial t} \quad (\text{L.2-14}).$$

Hamiltonian  $H$  sistem satu elektron dimodifikasi untuk mengetahui interaksi antara muatan elektron dan medan radiasi. Medan radiasi digambarkan secara umum dengan potensial skalar  $\Omega$  dan potensial vektor  $\mathbf{A}$  yang berhubungan dengan amplitudo medan listrik  $\mathbf{E}$  dan medan magnet  $\mathbf{B}$ , dengan (Woodgate, 1980):

$$\mathbf{E} = -\nabla\Omega - \frac{\partial \mathbf{A}}{\partial t} \quad (\text{L.2-15})$$

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (\text{L.2-16}),$$

sehingga Hamiltonian termodifikasi berupa:

$$H = \frac{1}{2m_e} (\mathbf{p} + e\mathbf{A})^2 - e\Omega + V \quad (\text{L.2-17}),$$

yang dapat ditulis berupa:

$$H = H_0 + H' \quad (\text{L.2-18})$$

dengan:

$$H_0 = \frac{\mathbf{p}^2}{2m_e} + V \quad (\text{L.2-19})$$

$$\text{dan } H' = \frac{1}{2m_e} (\mathbf{p} \cdot \mathbf{A} + \mathbf{A} \cdot \mathbf{p})^2 + \frac{e^2}{2m_e} \mathbf{A}^2 - e\Omega \quad (\text{L.2-20}).$$

Dengan menganggap  $\Omega = 0$  dan  $\mathbf{A} = \mathbf{A}_0 e^{i(\omega t - \mathbf{k} \cdot \mathbf{r})} + \mathbf{A}_0 e^{-i(\omega t - \mathbf{k} \cdot \mathbf{r})}$  disubstitusikan ke pers. (L.2-15) dan pers. (L.2-16), diperoleh:

$$\mathbf{E} = 2\omega \mathbf{A}_0 \sin(\omega t - \mathbf{k} \cdot \mathbf{r}) \quad (\text{L.2-21})$$

$$\mathbf{E} = 2(\mathbf{k} \times \mathbf{A}_0) \sin(\omega t - \mathbf{k} \cdot \mathbf{r}) \quad (\text{L.2-22}),$$

dengan  $\mathbf{A}_0$  merupakan amplitudo medan listrik.

Jika dipilih kondisi (Woodgate, 1998):

$$\nabla \cdot \mathbf{A} = 0 \quad (\text{L.2-23}),$$

serta sifat  $\mathbf{p}$  komut dengan  $\mathbf{A}$ , sehingga  $\mathbf{p} \cdot \mathbf{A} + \mathbf{A} \cdot \mathbf{p} = 2\mathbf{A} \cdot \mathbf{p}$ ; dan diasumsikan bahwa interaksi radiasi dan materi lemah sehingga faktor kuadratik  $\mathbf{A}$  dapat diabaikan, maka Hamiltonian gangguan pers. (L.2-20) dapat dituliskan sebagai:

$$\begin{aligned} H' &= \frac{e}{2m_e} (2\mathbf{A} \cdot \mathbf{p}) + \frac{e^2}{2m_e} \mathbf{A}^2 \\ &= \frac{e}{m_e} \mathbf{A} \cdot \mathbf{p} \end{aligned} \quad (\text{L.2-24}).$$

Fungsi gelombang gayut waktu  $\Psi$  diberikan oleh:

$$\Psi = \sum_n c_n \psi_n e^{-iE_n t / \hbar} \quad (\text{L.2-25}),$$

$\psi_n$  merupakan fungsi gelombang gayut ruang yang memenuhi bentuk:

$$H_0 \psi_n = E_n \psi_n \quad (\text{L.2-26}).$$

Diasumsikan sistem non-degenerasi dan  $c_n$  adalah koefisien normalisasi gayut waktu dengan interpretasi bahwa atom berada pada aras  $|i\rangle$  pada saat  $t=0$  { yaitu  $c_i(0)=1$  dan  $c_{n\neq i}(0)=0$ }, maka dengan kebolehjadian  $|c_j(t)|^2$  pada saat  $t$  atom tersebut berada pada aras  $|j\rangle$ .

Dengan mensubstitusikan pers. (L.2-25) dan pers. (L.2-26) ke pers. (L.2-14), maka diperoleh bentuk persamaan differensial dalam  $c_n$  berupa:

$$\sum_n (i\hbar \dot{c}_n + E_n c_n) \psi_n e^{-iE_n t/\hbar} = (H_0 + H') \sum_n c_n \psi_n e^{-iE_n t/\hbar} \quad (\text{L.2-27}).$$

Karena  $\psi_n$  merupakan fungsi pribadi  $H_0$  dengan nilai pribadi  $E_n$ , maka pers. (L.2-27) dapat dituliskan berupa:

$$\sum_n i\hbar \dot{c}_n \psi_n e^{-iE_n t/\hbar} = \sum_n c_n H' \psi_n e^{-iE_n t/\hbar} \quad (\text{L.2-28}).$$

Dengan mengasumsikan gangguan pada  $H'$  sangat kecil sehingga  $c_n$  tidak banyak berubah terhadap waktu, maka sebagai pendekatan digunakan nilai awal (*initial value*)  $c_n$  pada aras  $|i\rangle$  {  $c_i(0)=1$ } pada ruas kanan pers. (L.2-28),

sehingga pers. (L.2-28) dapat dituliskan berupa:

$$\sum_n i\hbar \dot{c}_n \psi_n e^{-iE_n t/\hbar} = H' \psi_i e^{-iE_i t/\hbar} \quad (\text{L.2-29}).$$

Dengan mengalikan pers. (L.2-29) dari kiri terhadap  $\psi_j^*$  dan diintegrasikan, maka diperoleh:

$$i\hbar \dot{c}_n = \langle \psi_j | H' | \psi_i \rangle e^{-i(E_j - E_i)t/\hbar} \quad (\text{L.2-30}).$$

Jika diperkenalkan vektor satuan (*unit vector*)  $\hat{\mathbf{e}}$  yang menyatakan arah polarisasi radiasi sehingga  $\mathbf{A}_0 = A_0 \hat{\mathbf{e}}$ , dan  $(E_j - E_i)/\hbar = \omega_{ji}$ , maka Hamiltonian gangguan pers. (L.1-24) dapat dituliskan berupa:

$$H' = \frac{e}{m_e} A_0 \hat{\mathbf{e}} \cdot \mathbf{p} \left\{ e^{i(\omega t + \mathbf{k} \cdot \mathbf{r})} + e^{-i(\omega t + \mathbf{k} \cdot \mathbf{r})} \right\} \quad (\text{L.2-31}).$$

Dengan mensubstitusikan pers. (L.2-31) pada pers. (L.2-30) maka diperoleh:

$$\begin{aligned} i\hbar \dot{c}_n &= \left\langle \psi_j \left| \frac{e}{m_e} \hat{\mathbf{e}} \cdot \mathbf{p} e^{-i\mathbf{k} \cdot \mathbf{r}} \right| \psi_i \right\rangle A_0 e^{i(\omega_{ji} + \omega)t} \\ &\quad + \left\langle \psi_j \left| \frac{e}{m_e} \hat{\mathbf{e}} \cdot \mathbf{p} e^{i\mathbf{k} \cdot \mathbf{r}} \right| \psi_i \right\rangle A_0 e^{i(\omega_{ji} - \omega)t} \end{aligned} \quad (\text{L.2-32}).$$

Dengan mengintegrasikan pers. (L.2-32) terhadap  $dt$ :

$$\begin{aligned} c_n &= \frac{1}{i\hbar} \int_0^t \left\{ \left\langle \psi_j \left| \frac{e}{m_e} \hat{\mathbf{e}} \cdot \mathbf{p} e^{-i\mathbf{k} \cdot \mathbf{r}} \right| \psi_i \right\rangle A_0 e^{i(\omega_{ji} + \omega)t} \right. \\ &\quad \left. + \left\langle \psi_j \left| \frac{e}{m_e} \hat{\mathbf{e}} \cdot \mathbf{p} e^{i\mathbf{k} \cdot \mathbf{r}} \right| \psi_i \right\rangle A_0 e^{i(\omega_{ji} - \omega)t} \right\} dt \\ &= \left\langle \psi_j \left| \frac{e}{m_e} \hat{\mathbf{e}} \cdot \mathbf{p} e^{-i\mathbf{k} \cdot \mathbf{r}} \right| \psi_i \right\rangle A_0 \left\{ \frac{1 - e^{i(\omega_{ji} + \omega)t}}{\hbar (\omega_{ji} + \omega)} \right\} \\ &\quad + \left\langle \psi_j \left| \frac{e}{m_e} \hat{\mathbf{e}} \cdot \mathbf{p} e^{i\mathbf{k} \cdot \mathbf{r}} \right| \psi_i \right\rangle A_0 \left\{ \frac{1 - e^{i(\omega_{ji} - \omega)t}}{\hbar (\omega_{ji} - \omega)} \right\} \end{aligned} \quad (\text{L.2-33}).$$

Untuk proses absorpsi, transisi terjadi dari aras  $|i\rangle$  ke aras  $|j\rangle$  dengan  $E_j > E_i$ . Suku pertama pada penjumlahan pers. (L.2-33) dapat diabaikan karena  $\omega_{ji} + \omega$  bernilai sangat besar dalam daerah frekuensi  $\omega_{ji} \approx \omega$ , yang disebut (Woodgate, 1980) dengan Pendekatan Gelombang Rotasi (*Rotating Wave Approximation = RWA*). Dengan mengkuadratkan  $c_i(t)$ , diperoleh:

$$|c_j(t)|^2 = \left| \langle \psi_j | \frac{e}{m_e} \hat{\mathbf{e}} \cdot \mathbf{p} e^{i\mathbf{k} \cdot \mathbf{r}} | \psi_i \rangle \right|^2 A_0^2 \frac{\sin^2 \left\{ \frac{(\omega_{ji} - \omega)/2}{\hbar} t \right\}}{\hbar^2 \left\{ \frac{(\omega_{ji} - \omega)^2}{2} \right\}} \quad (\text{L.2-34}).$$

Menurut Woodgate (1980), kebolehjadian transisi per satuan waktu suatu atom mengalami transisi dari aras  $|i\rangle$  ke aras  $|j\rangle$  melalui absorpsi radiasi  $P_{ij}$

pada pers. (L.2-5) sama dengan nilai  $\frac{|c_j(t)|^2}{t}$ , maka:

$$\frac{|c_j(t)|^2}{t} = B_{ij} \rho(\omega_{ji}) \quad (\text{L.2-35}),$$

sehingga (Hibbert, 1996):

$$B_{ij} = \frac{2\pi}{3} \frac{c^2}{h^2 v_{ji}^2} \left| \left\langle \psi_j \left| \frac{e}{m_e c} \mathbf{p} e^{i\mathbf{k} \cdot \mathbf{r}} \right| \psi_i \right\rangle \right|^2 \quad (\text{L.2-36}).$$

Jika diekspansikan  $e^{i\mathbf{k} \cdot \mathbf{r}} = 1 + i\mathbf{k} \cdot \mathbf{r} + \dots$ , dengan  $\mathbf{r}$  dalam orde beberapa Å, λ dalam beberapa ribu Å, maka  $\mathbf{k} \cdot \mathbf{r} \ll 1$ . Untuk pendekatan yang baik, dapat

diambil  $e^{ikr} \approx 1$ , yang dikenal sebagai pendekatan dwikutub. Dengan mensubstitusikan pers. (2-40) pada pers. (L.2-36), maka diperoleh nilai  $f$ .

$$f_{ij} = \frac{2m_e c^2}{3e^2} \frac{1}{\hbar v_{ji}} \left| \left\langle \psi_j \left| \frac{e}{m_e c} \mathbf{p} \right| \psi_i \right\rangle \right|^2 \quad (\text{L.2-38}).$$



## LAMPIRAN 3

### PENJABARAN NILAI HARAP HAMILTONIAN INTERPRETASI HARTREE-FOCK

Hamiltonian  $H$  sistem berelektron banyak yang disajikan dalam pers.

(2-28) diperkenalkan sebagai hasil penjumlahan koordinat satu elektron  $F_1$  dan koordinat interaksi  $F_2$  antara elektron ke- $i$  dan ke- $j$ , dalam bentuk:

$$\hat{H} = F_1 + F_2 = \sum_i f_i + \sum_{i < j} g_{ij} \quad (\text{L.3-1}),$$

dengan operator satu elektron:  $\hat{f}_i = -\frac{\hbar^2}{2m_e} \nabla^2 - Z \frac{e^2}{r_{ij}}$  (L.3.-2)

dan operator interaksi antara elektron ke- $i$  dan ke- $j$ :  $\hat{g}_{ij} = \frac{e^2}{r_{ij}}$  (L.3-3).

Maka nilai harap (expected value) untuk masing-masing  $F_1$  dan  $F_2$  adalah:

$$\langle F_1 \rangle = \sum_i \langle i | f | i \rangle \quad (\text{L.3-4a})$$

$$\langle F_2 \rangle = \sum_{i < j} [\langle ij | g | ij \rangle - \langle ij | g | ji \rangle] \quad (\text{L.3-4b}).$$

Dengan mensubstitusikan pers. (L.3-2) dan (L.3-3) ke Pers. (L.3-4a) dan pers. (L.3-4b), maka nilai harap  $F_1$  dan  $F_2$  secara eksplisit dinyatakan sebagai:

$$\langle F_1 \rangle = \sum_i \int u_i^*(r_i) \left( -\frac{\hbar^2}{2m_e} \nabla^2 - Z \frac{e^2}{r_i} \right) u_i(r_i) dr_i \quad (\text{L.3-5a})$$

$$\begin{aligned} \langle F_2 \rangle = & \sum_{i<j} \left[ \sum_{\sigma_i \sigma_j} \int \int u_i^*(r_i) u_j^*(r_j) \left( \frac{e^2}{r_{ij}} \right) u_i(r_i) u_j(r_j) dr_i dr_j \times |\chi_i(\sigma_i)|^2 |\chi_j(\sigma_j)|^2 \right. \\ & \left. - \sum_{\sigma_i \sigma_j} \int \int u_i^*(r_i) u_j^*(r_j) \left( \frac{e^2}{r_{ij}} \right) u_i(r_j) u_j(r_i) dr_i dr_j \times \chi_i^*(\sigma_i) \chi_j^*(\sigma_j) \chi_i(\sigma_j) \chi_j(\sigma_i) \right] \end{aligned} \quad (\text{L.3-5b})$$

Dengan memperkenalkan bahwa  $\sum_{\sigma} \chi_i^*(\sigma) \chi_j(\sigma) = \delta(m_{si}, m_{sj})$  yang merupakan fungsi delta dirac (Bethe and Jackiw, 1986), maka diperoleh nilai harap Hamiltonian (L.3-1) secara eksplisit dinyatakan sebagai:

$$\langle H \rangle = \sum_i \int u_i^* \left( -\frac{\hbar^2}{2m_e} \nabla^2 - Z \frac{e^2}{r_i} \right) u_i dr + \sum_{i<j} \left[ \int \int |u_i|^2 |u_j|^2 \frac{e^2}{r_{ij}} dr_i dr_j - \delta(m_{si}, m_{sj}) \int \int u_i^* u_j^* \frac{e^2}{r_{ij}} u_j u_i dr_i dr_j \right] \quad (\text{L.3-6}).$$

## LAMPIRAN 4

### TRANSISI-TRANSISI PADA ATOM HELIUM

Ground State

$1s^2 \ ^1S_0$

Ionization Potential

$24.580 \text{ eV} = 198305 \text{ cm}^{-1}$

#### Allowed Transitions

List of tabulated lines:

Wavelength [Å]	No.	Wavelength [Å]	No.	Wavelength [Å]	No.
506.200	11	4387.93	29	19543	105
506.570	10	4437.55	23	20425	113
507.058	9	4471.5	86	20581.3	12
507.718	8	4713.2	80	21120	97
508.643	7	4921.93	28	21132.0	39
509.998	6	5015.68	13	21494	116
512.098	5	5047.74	22	21608	126
515.617	4	5875.7	85	21617	67
522.213	3	6678.15	27	21841	60
537.030	2	7065.19	79	22284	57
584.334	1	7065.71	79	23063	54
2677.1	78	7281.35	21	24727	120
2696.1	77	8361.77	96	26113	63
2723.2	76	9463.57	95	26185	125
2763.8	75	9603.42	38	26198	66
2829.07	74	9702.66	100	26248	69
2945.10	73	10311	104	26251	128
3187.74	72	10667.6	99	26531	59
3231.27	20	10829.1	70	26671	122
3258.28	19	10830.2	70	26881	115
3296.77	18	10830.3	70	27600	56
3354.55	17	10902.2	48	28542	112
3447.59	16	10912.9	110	33299	53
3554.4	92	10917.0	51	37026	119
3562.95	84	10996.6	107	40053	62
3587.3	91	11013.1	37	40365	124
3613.64	15	11045.0	44	40396	65
3634.2	90	11225.9	41	40536	68
3652.0	83	11969.1	103	40550	127
3705.0	89	12528	94	41216	58
3819.6	88	12755.7	47	42430	121
3833.55	34	12785	109	42497	93
3867.5	82	12790.3	50	46053	55
3871.79	33	12846	98	46936	114
3888.65	71	12968.4	43	74351	35
3926.53	32	12985	106	108800	111
3935.91	26	13411.8	40	180950	52
3964.73	14	15083.7	36	186200	101
4009.27	31	17002	102	439440	118
4023.97	25	18555.6	46	957600	45
4026.2	87	18686	108	$2.16 \times 10^6$	61
4120.8	81	18696.9	49	$1.39 \times 10^7$	123
4143.76	30	19063	117	$1.82 \times 10^7$	64
4168.97	24	19089.4	42		

### He I. Allowed Transitions

Transition Array	Multiplet	$\lambda(\text{\AA})$	$E(\text{cm}^{-1})$	$E_k(\text{cm}^{-1})$	$g_i$	$g_k$	$A_{ki}(10^8 \text{ sec}^{-1})$	$f_{ik}$	S(at.u.)	$\log gf$	Accuracy	Source
1s <sup>2</sup> - 1s2p	'S - 'P <sup>o</sup> (2 uv)	584.334	0	171135	1	3	17.99	0.2762	0.5313	-0.5588	AA	1
1s <sup>2</sup> - 1s3p	'S - 'P <sup>o</sup> (3 uv)	537.030	0	186210	1	3	5.66	0.0734	0.1298	-1.1343	AA	1
1s <sup>2</sup> - 1s4p	'S - 'P <sup>o</sup> (4 uv)	522.213	0	191493	1	3	2.46	0.0302	0.0519	-1.520	A	2
1s <sup>2</sup> - 1s5p	'S - 'P <sup>o</sup> (5 uv)	515.617	0	193943	1	3	1.28	0.0153	0.0260	-1.815	B+	3
1s <sup>2</sup> - 1s6p	'S - 'P <sup>o</sup> (6 uv)	512.098	0	195275	1	3	0.719	0.00848	0.0143	-2.072	B+	3, 4
1s <sup>2</sup> - 1s7p	'S - 'P <sup>o</sup> (7 uv)	509.998	0	196079	1	3	0.507	0.00593	0.00995	-2.227	B	5, 6
1s <sup>2</sup> - 1s8p	'S - 'P <sup>o</sup> (8 uv)	508.643	0	196602	1	3	0.343	0.00399	0.00668	-2.399	B	5, 6
1s <sup>2</sup> - 1s9p	'S - 'P <sup>o</sup> (9 uv)	507.718	0	196960	1	3	0.237	0.00275	0.00459	-2.561	B	5, 6
1s <sup>2</sup> - 1s10p	'S - 'P <sup>o</sup> (10 uv)	507.058	0	197216	1	3	0.181	0.00209	0.00349	-2.680	B	5, 6
1s <sup>2</sup> - 1s11p	'S - 'P <sup>o</sup>	506.570	0	197406	1	3	0.130	0.00150	0.00250	-2.824	B	6
1s <sup>2</sup> - 1s12p	'S - 'P <sup>o</sup>	506.200	0	197550	1	3	0.104	0.00119	0.00199	-2.923	B	6
1s2s - 1s2p	'S - 'P <sup>o</sup>	20581.3	166278	171135	1	3	0.01976	0.3764	25.50	-0.4244	AA	1
1s2s - 1s3p	'S - 'P <sup>o</sup> (4)	5015.68	166278	186210	1	3	0.1338	0.1514	2.500	-0.8199	AA	1
1s2s - 1s4p	'S - 'P <sup>o</sup> (5)	3964.73	166278	191493	1	3	0.0717	0.0507	0.662	-1.295	A	2
1s2s - 1s5p	'S - 'P <sup>o</sup> (6)	3613.64	166278	193943	1	3	0.0376	0.0221	0.263	-1.656	B	7
1s2s - 1s6p	'S - 'P <sup>o</sup> (7)	3447.59	166278	195275	1	3	0.0239	0.0128	0.145	-1.894	A	4
1s2s - 1s7p	'S - 'P <sup>o</sup> (8)	3354.55	166278	196079	1	3	0.0130	0.00660	0.0729	-2.180	B	7
1s2s - 1s8p	'S - 'P <sup>o</sup> (9)	3296.77	166278	196602	1	3	0.00901	0.00440	0.0478	-2.356	B	7
1s2s - 1s9p	'S - 'P <sup>o</sup>	3258.28	166278	196960	1	3	0.00650	0.00310	0.0333	-2.508	B	7
1s2s - 1s10p	'S - 'P <sup>o</sup>	3231.27	166278	197216	1	3	0.00490	0.00230	0.0245	-2.638	B	7
1s2p - 1s3s	'P <sup>o</sup> - 'S (45)	7281.35	171135	184865	3	1	0.181	0.0480	3.45	-0.842	A	2
1s2p - 1s4s	'P <sup>o</sup> - 'S (47)	5047.74	171135	190940	3	1	0.0655	0.00834	0.416	-1.602	A	4
1s2p - 1s5s	'P <sup>o</sup> - 'S (50)	4437.55	171135	193663	3	1	0.0313	0.00308	0.135	-2.034	B	ca
1s2p - 1s6s	'P <sup>o</sup> - 'S (52)	4168.97	171135	195115	3	1	0.0176	0.00153	0.0630	-2.338	A	4

## He I. Allowed Transitions—Continued

Transition Array	Multiplet	$\lambda(\text{\AA})$	$E_i(\text{cm}^{-1})$	$E_k(\text{cm}^{-1})$	$g_i$	$g_k$	$A_{ik}(10^8 \text{ sec}^{-1})$	$f_{ik}$	$S(\text{at.u.})$	$\log gf$	Accuracy	Source
1s2p – 1s7s	${}^1\text{P}^o - {}^1\text{S}$ (54)	4023.97	171135	195979	3	1	0.0109	$8.81 \times 10^{-4}$	0.0350	-2.578	B+	4
1s2p – 1s8s	${}^1\text{P}^o - {}^1\text{S}$ (57)	3935.91	171135	196535	3	1	0.00718	$5.56 \times 10^{-4}$	0.0216	-2.778	B+	4
1s2p – 1s3d	${}^1\text{P}^o - {}^1\text{D}$ (46)	6678.15	171135	186105	3	5	0.638	0.711	46.9	0.329	A	2
1s2p – 1s4d	${}^1\text{P}^o - {}^1\text{D}$ (48)	4921.93	171135	191447	3	5	0.202	0.122	5.95	-0.435	A	4
1s2p – 1s5d	${}^1\text{P}^o - {}^1\text{D}$ (51)	4387.93	171135	193918	3	5	0.0907	0.0436	1.89	-0.883	A	4
1s2p – 1s6d	${}^1\text{P}^o - {}^1\text{D}$ (53)	4143.76	171135	195261	3	5	0.0495	0.0213	0.870	-1.195	B	ca
1s2p – 1s7d	${}^1\text{P}^o - {}^1\text{D}$ (55)	4009.27	171135	196070	3	5	0.0279	0.0112	0.444	-1.473	C+	8
1s2p – 1s8d	${}^1\text{P}^o - {}^1\text{D}$ (58)	3926.53	171135	196596	3	5	0.0195	0.00750	0.291	-1.648	A	4
1s2p – 1s9d	${}^1\text{P}^o - {}^1\text{D}$ (60)	3871.79	171135	196956	3	5	0.0126	0.00471	0.180	-1.850	C+	8
1s2p – 1s10d	${}^1\text{P}^o - {}^1\text{D}$ (62)	3833.55	171135	197213	3	5	0.00971	0.00357	0.135	-1.971	A	4
1s3s – 1s3p	${}^1\text{S} - {}^1\text{P}^o$	[74351]	184865	186210	1	3	0.00253	0.629	154	-0.201	A	2
1s3s – 1s4p	${}^1\text{S} - {}^1\text{P}^o$	15083.7	184865	191493	1	3	0.0137	0.140	6.95	-0.854	B	2
1s3s – 1s5p	${}^1\text{S} - {}^1\text{P}^o$ (70)	11013.1	184865	193943	1	3	0.00956	0.0521	1.89	-1.283	B	ca
1s3s – 1s6p	${}^1\text{S} - {}^1\text{P}^o$ (71)	9603.42	184865	195275	1	3	0.00564	0.0234	0.739	-1.631	B	9
1s3p – 1s4s	${}^1\text{P}^o - {}^1\text{S}$	21132.0	186210	190940	3	1	0.0459	0.103	21.4	-0.512	B	ca
1s3p – 1s5s	${}^1\text{P}^o - {}^1\text{S}$	[13411.8]	186210	193664	3	1	0.0202	0.0182	2.41	-1.263	B	ca
1s3p – 1s6s	${}^1\text{P}^o - {}^1\text{S}$ (87)	11225.9	186210	195115	3	1	0.0110	0.00690	0.765	-1.684	B	ca
1s3p – 1s4d	${}^1\text{P}^o - {}^1\text{D}$	19089.4	186210	191447	3	5	0.0711	0.647	122	0.288	B	ca
1s3p – 1s5d	${}^1\text{P}^o - {}^1\text{D}$	12968.4	186210	193918	3	5	0.0331	0.139	17.8	-0.380	B	ca
1s3p – 1s6d	${}^1\text{P}^o - {}^1\text{D}$ (88)	11045.0	186210	195261	3	5	0.0181	0.0553	6.03	-0.780	B	ca
1s3d – 1s3p	${}^1\text{D} - {}^1\text{P}^o$	[957600]	186105	186210	5	3	$1.68 \times 10^{-6}$	0.0139	219	-1.158	B	2
1s3d – 1s4p	${}^1\text{D} - {}^1\text{P}^o$	18555.6	186105	191447	5	3	0.00277	0.00858	2.62	-1.368	C+	2
1s3d – 1s5p	${}^1\text{D} - {}^1\text{P}^o$	12755.7	186105	193943	5	3	0.00127	0.00186	0.390	-2.032	B	ca
1s3d – 1s6p	${}^1\text{D} - {}^1\text{P}^o$	10902.2	186105	195275	5	3	$9.23 \times 10^{-4}$	$9.86 \times 10^{-4}$	0.177	-2.307	B	9
1s3d – 1s4f	${}^1\text{D} - {}^1\text{F}^o$	18696.9	186105	191452	5	7	0.138	1.01	312	0.705	B	ca
1s3d – 1s5f	${}^1\text{D} - {}^1\text{F}^o$	12790.3	186105	193921	5	7	0.0461	0.158	33.3	-0.102	B	ca
1s3d – 1s6f	${}^1\text{D} - {}^1\text{F}^o$ (84)	10917.0	186105	195263	5	7	0.0212	0.0529	9.51	-0.577	B	ca

## He I. Allowed Transitions—Continued

Transition Array	Multiplet	$\lambda(\text{\AA})$	$E_i(\text{cm}^{-1})$	$E_k(\text{cm}^{-1})$	$g_i$	$g_k$	$A_{ki}(10^8 \text{ sec}^{-1})$	$f_{ik}$	S(at.u.)	$\log g_f$	Accuracy	Source
1s4s – 1s4p	$^1S - ^1P^o$	[180950]	190940	191493	1	3	$5.79 \times 10^{-4}$	0.853	508	-0.069	B	ca
1s4s – 1s5p	$^1S - ^1P^o$	[33299]	190940	193943	1	3	0.00302	0.151	16.5	-0.822	B	ca
1s4s – 1s6p	$^1S - ^1P^o$	[23063]	190940	195275	1	3	0.00250	0.0599	4.55	-1.222	B	ca
1s4p – 1s5s	$^1P^o - ^1S$	[46053]	191493	193664	3	1	0.0150	0.159	72.2	-0.322	B	ca
1s4p – 1s6s	$^1P^o - ^1S$	[27600]	191493	195115	3	1	0.00721	0.0274	7.48	-1.085	B	ca
1s4p – 1s7s	$^1P^o - ^1S$	[22284]	191493	195979	3	1	0.00438	0.0109	2.39	-1.487	B	ca
1s4p – 1s5d	$^1P^o - ^1D$	[41216]	191493	193918	3	5	0.0153	0.649	264	0.289	B	ca
1s4p – 1s6d	$^1P^o - ^1D$	[26531]	191493	195261	3	5	0.00861	0.152	39.7	-0.342	B	ca
1s4p – 1s7d	$^1P^o - ^1D$	[21841]	191493	196070	3	5	0.00533	0.0635	13.7	-0.720	B	ca
1s4d – 1s4p	$^1D - ^1P^o$	[ $2.16 \times 10^6$ ]	191447	191493	5	3	$5.70 \times 10^{-7}$	0.0240	856	-0.920	B	ca
1s4d – 1s5p	$^1D - ^1P^o$	[40053]	191447	193943	5	3	0.00166	0.0240	15.8	-0.922	B	ca
1s4d – 1s6p	$^1D - ^1P^o$	[26113]	191447	195275	5	3	$7.85 \times 10^{-4}$	0.00482	2.07	-1.618	B	ca
1s4d – 1s4f	$^1D - ^1F^o$	[ $1.82 \times 10^7$ ]	191447	191452	5	7	$3.63 \times 10^{-10}$	0.00253	757	-1.899	B	ca
1s4d – 1s5f	$^1D - ^1F^o$	[40396]	191447	193921	5	7	0.0259	0.887	590	0.647	B	ca
1s4d – 1s6f	$^1D - ^1F^o$	[26198]	191447	195263	5	7	0.0130	0.187	80.7	-0.029	B	ca
1s4d – 1s7f	$^1D - ^1F^o$	[21617]	191447	196071	5	7	0.00734	0.0719	25.6	-0.444	B	ca
1s4f – 1s5d	$^1F^o - ^1D$	[40536]	191452	193918	7	5	$5.20 \times 10^{-4}$	0.00915	8.55	-1.193	B	ca
1s4f – 1s6d	$^1F^o - ^1D$	[26248]	191452	195261	7	5	$2.49 \times 10^{-4}$	0.00184	1.11	-1.891	B	ca
1s2s – 1s2p	$^3S - ^3P^o$ (1)	10830	159856	169087	3	9	0.1022	0.5391	57.66	0.2088	AA	1
		10830.3	159856	169087	3	5	0.1022	0.2994	32.03	-0.0466	AA	ls
		10830.2	159856	169087	3	3	0.1022	0.1797	19.22	-0.2684	AA	ls
		10829.1	159856	169088	3	1	0.1022	0.05990	6.407	-0.7454	AA	ls
1s2s – 1s3p	$^3S - ^3P^o$ (2)	3888.65	159856	185565	3	9	0.09478	0.06446	2.476	-0.7136	AA	1
1s2s – 1s4p	$^3S - ^3P^o$ (3)	3187.74	159856	191217	3	9	0.0505	0.0231	0.727	-1.159	B	2
1s2s – 1s5p	$^3S - ^3P^o$ (11 uv)	2945.10	159856	193801	3	9	0.0293	0.0114	0.332	-1.465	B	7
1s2s – 1s6p	$^3S - ^3P^o$ (12 uv)	2829.07	159856	195193	3	9	0.0169	0.00608	0.170	-1.739	B	7
1s2s – 1s7p	$^3S - ^3P^o$	2763.8	159856	196027	3	9	0.0111	0.00381	0.104	-1.942	B	7
1s2s – 1s8p	$^3S - ^3P^o$	2723.2	159856	196567	3	9	0.00780	0.00260	0.0700	-2.108	B	7
1s2s – 1s9p	$^3S - ^3P^o$	2696.1	159856	196935	3	9	0.00550	0.00180	0.0479	-2.268	B	7
1s2s – 1s10p	$^3S - ^3P^o$	2677.1	159856	197198	3	9	0.00404	0.00130	0.0344	-2.409	B	7
1s2p – 1s3s	$^3P^o - ^3S$ (10)	7065.3	169087	183237	9	3	0.278	0.0693	14.5	-0.205	A	2
		7065.19	169087	183237	5	3	0.154	0.0693	8.06	-0.460	A	ls
		7065.19	169087	183237	3	3	0.0925	0.0692	4.83	-0.683	A	ls
		7065.71	169088	183237	1	3	0.0308	0.0692	1.61	-1.160	A	ls

## He I. Allowed Transitions—Continued

Transition Array	Multiplet	$\lambda(\text{\AA})$	$E_i(\text{cm}^{-1})$	$E_k(\text{cm}^{-1})$	$g_i$	$g_k$	$A_{ik}(10^8 \text{ sec}^{-1})$	$f_{ik}$	$S(\text{at.u.})$	$\log gf$	Accuracy	Source
$1s2p - 1s4s$	${}^3P^o - {}^3S$ (12)	4713.2	169087	190298	9	3	0.106	0.0118	1.65	-0.973	B	4
$1s2p - 1s5s$	${}^3P^o - {}^3S$ (16)	4120.8	169087	193347	9	3	0.0430	0.00365	0.446	-1.483	B	ca
$1s2p - 1s6s$	${}^3P^o - {}^3S$ (20)	3867.5	169087	194936	9	3	0.0236	0.00176	0.202	-1.800	B	ca
$1s2p - 1s8s$	${}^3P^o - {}^3S$ (27)	3652.0	169087	196461	9	3	0.0108	$7.21 \times 10^{-4}$	0.0780	-2.188	B	4
$1s2p - 1s10s$	${}^3P^o - {}^3S$ (33)	3562.95	169087	197145	9	3	0.00543	$3.45 \times 10^{-4}$	0.0364	-2.508	B	4
$1s2p - 1s3d$	${}^3P^o - {}^3D$ (11)	5875.7	169087	186102	9	15	0.706	0.609	106	0.739	A	2
$1s2p - 1s4d$	${}^3P^o - {}^3D$ (14)	4471.5	169087	191445	9	15	0.251	0.125	16.6	0.052	A	4
$1s2p - 1s5d$	${}^3P^o - {}^3D$ (18)	4026.2	169087	193917	9	15	0.117	0.0474	5.66	-0.370	A	4
$1s2p - 1s6d$	${}^3P^o - {}^3D$ (22)	3819.6	169087	195260	9	15	0.0589	0.0215	2.43	-0.714	B	ca
$1s2p - 1s7d$	${}^3P^o - {}^3D$ (25)	3705.0	169087	196070	9	15	0.0444	0.0152	1.67	-0.864	C+	8
$1s2p - 1s8d$	${}^3P^o - {}^3D$ (28)	3634.2	169087	196595	9	15	0.0261	0.00862	0.928	-1.110	A	4
$1s2p - 1s9d$	${}^3P^o - {}^3D$ (31)	3587.3	169087	196955	9	15	0.0205	0.00660	0.702	-1.226	C+	8
$1s2p - 1s10d$	${}^3P^o - {}^3D$ (34)	3554.4	169087	197213	9	15	0.0131	0.00414	0.436	-1.429	A	4
$1s3s - 1s3p$	${}^3S - {}^3P^o$	[42947]	183237	185565	3	9	0.0108	0.896	380	0.429	A	2
$1s3s - 1s4p$	${}^3S - {}^3P^o$	12528	183237	191217	3	9	0.00608	0.0429	5.31	-0.890	B	2
$1s3s - 1s5p$	${}^3S - {}^3P^o$ (67)	9463.57	183237	193801	3	9	0.00608	0.0245	2.29	-1.134	B	ca
$1s3s - 1s6p$	${}^3S - {}^3P^o$ (68)	8361.77	183237	195193	3	9	$7.16 \times 10^{-4}$	0.00225	0.186	-2.170	B	9
$1s3p - 1s4s$	${}^3P^o - {}^3S$	21120	185565	190298	9	3	0.0652	0.145	91.0	0.117	B	ca
$1s3p - 1s5s$	${}^3P^o - {}^3S$	12846	185565	193347	9	3	0.0269	0.0222	8.45	-0.699	B	ca
$1s3p - 1s6s$	${}^3P^o - {}^3S$ (73)	10667.6	185565	194936	9	3	0.0142	0.00810	2.56	-1.137	B	ca
$1s3p - 1s7s$	${}^3P^o - {}^3S$ (75)	9702.66	185565	195868	9	3	0.00858	0.00404	1.16	-1.440	B	ca
$1s3p - 1s3d$	${}^3P^o - {}^3D$	[186200]	185565	186102	9	15	$1.28 \times 10^{-4}$	0.111	613	0.000	A	2
$1s3p - 1s4d$	${}^3P^o - {}^3D$	17002	185565	191445	9	15	0.0668	0.482	243	0.638	B	ca
$1s3p - 1s5d$	${}^3P^o - {}^3D$ (72)	11969.1	185565	193917	9	15	0.0343	0.123	43.5	0.043	B	ca

## He I. Allowed Transitions—Continued

Transition Array	Multiplet	$\lambda(\text{\AA})$	$E_i(\text{cm}^{-1})$	$E_k(\text{cm}^{-1})$	$g_i$	$g_k$	$A_{ki}(10^8 \text{ sec}^{-1})$	$f_{ik}$	$S(\text{at.u.})$	$\log g_f$	Accuracy	Source
1s3p – 1s6d	${}^3\text{P}^o - {}^3\text{D}^{(74)}$	10311	185565	195260	9	15	0.0197	0.0524	16.0	-0.327	B	ca
1s3d – 1s4p	${}^3\text{D} - {}^3\text{P}^o$	19543	186102	191217	15	9	0.00597	0.0205	19.8	-0.512	C+	2
1s3d – 1s5p	${}^3\text{D} - {}^3\text{P}^o$	12985	186102	193801	15	9	0.00274	0.00415	2.66	-1.206	B	ca
1s3d – 1s6p	${}^3\text{D} - {}^3\text{P}^o^{(78)}$	10996.6	186102	195193	15	9	$5.67 \times 10^{-4}$	$6.17 \times 10^{-4}$	0.335	-2.034	B	9
1s3d – 1s4f	${}^3\text{D} - {}^3\text{F}^o$	18686	186102	191452	15	21	0.139	1.02	937	1.183	B	ca
1s3d – 1s5f	${}^3\text{D} - {}^3\text{F}^o$	12785	186102	193921	15	21	0.0462	0.158	100	0.376	B	ca
1s3d – 1s6f	${}^3\text{D} - {}^3\text{F}^o^{(79)}$	10912.9	186102	195263	15	21	0.0212	0.0531	28.6	-0.099	B	ca
1s4s – 1s4p	${}^3\text{S} - {}^3\text{P}^o$	[108800]	190298	191217	3	9	0.00227	1.21	1300	0.560	B	ca
1s4s – 1s5p	${}^3\text{S} - {}^3\text{P}^o$	[28542]	190298	193801	3	9	0.00128	0.0468	13.2	-0.852	B	ca
1s4s – 1s6p	${}^3\text{S} - {}^3\text{P}^o$	[20425]	190298	195193	3	9	0.00147	0.0276	5.57	-1.082	B	ca
1s4p – 1s5s	${}^3\text{P}^o - {}^3\text{S}$	[46936]	191217	193347	9	3	0.0202	0.223	310	0.302	B	ca
1s4p – 1s6s	${}^3\text{P}^o - {}^3\text{S}$	[26881]	191217	194936	9	3	0.00925	0.0334	26.6	-0.522	B	ca
1s4p – 1s7s	${}^3\text{P}^o - {}^3\text{S}$	[21494]	191217	195868	9	3	0.00543	0.0125	7.99	-0.947	B	ca
1s4p – 1s8s	${}^3\text{P}^o - {}^3\text{S}$	[19063]	191217	196461	9	3	0.00340	0.00618	3.49	-1.255	B	ca
1s4p – 1s4d	${}^3\text{P}^o - {}^3\text{D}$	[439440]	191217	191445	9	15	$4.15 \times 10^{-5}$	0.200	2610	0.256	B	ca
1s4p – 1s5d	${}^3\text{P}^o - {}^3\text{D}$	[37026]	191217	193917	9	15	0.0129	0.442	485	0.600	B	ca
1s4p – 1s6d	${}^3\text{P}^o - {}^3\text{D}$	[24727]	191217	195260	9	15	0.00795	0.121	89.0	0.039	B	ca
1s4d – 1s5p	${}^3\text{D} - {}^3\text{P}^o$	[42430]	191445	193801	15	9	0.00333	0.0539	113	-0.092	B	ca
1s4d – 1s6p	${}^3\text{D} - {}^3\text{P}^o$	[26671]	191445	195193	15	9	0.00160	0.0102	13.5	-0.813	B	ca
1s4d – 1s4f	${}^3\text{D} - {}^3\text{F}^o$	[ $1.39 \times 10^7$ ]	191445	191452	15	21	$8.15 \times 10^{-10}$	0.00331	2270	-1.305	B	ca
1s4d – 1s5f	${}^3\text{D} - {}^3\text{F}^o$	[40365]	191445	193921	15	21	0.0260	0.888	1770	1.125	B	ca
1s4d – 1s6f	${}^3\text{D} - {}^3\text{F}^o$	[26185]	191445	195263	15	21	0.0130	0.187	242	0.448	B	ca
1s4d – 1s7f	${}^3\text{D} - {}^3\text{F}^o$	[21608]	191445	196071	15	21	0.00734	0.0720	76.8	0.033	B	ca
1s4f – 1s5d	${}^3\text{F}^o - {}^3\text{D}$	[40550]	191452	193917	21	15	$5.25 \times 10^{-4}$	0.00924	25.9	-0.712	B	ca
1s4f – 1s6d	${}^3\text{F}^o - {}^3\text{D}$	[26251]	191452	195260	21	15	$2.51 \times 10^{-4}$	0.00185	3.36	-1.410	B	ca