Washington Science Olympiad (Division C)

*50 minutes — Two students per team — **Written by Rowan V.***

Algebra, trig, linear algebra, complex numbers, basic statistics only. No calculus.

Name(s)	
Team #	
School	

Instructions:

- Sections are printed on separate pages and may be torn apart.
- **Free-response questions**: use the blank space provided.
- **Multiple-choice questions**: clearly mark one letter.
- At the end of each section, provide optional feedback about which questions you felt most and least confident about.

Event Parameters:

- One 3-ring binder of notes (any content). Pages may be removed.
- Two stand-alone calculators per team.
- A constants sheet is provided on the next page.

Section 1	______ / 28 pts
Section 2	______ / 29 pts
Section 3	______ / 29 pts
Section 4	______ / 29 pts
Final Score	______ / 115 pts

Constants Sheet (Reference Only)

Fundamental Constants

Speed of light, c	2.998×10^{8} m/s
Planck constant, h	6.626×10^{-34} J·s
Reduced Planck constant, $\hbar = h/2\pi$	1.055×10^{-34} J·s
Elementary charge, e	1.602×10^{-19} C
Electron mass, m_e	9.11×10^{-31} kg
Proton mass, m_p	1.67×10^{-27} kg
Neutron mass, m_n	1.675×10^{-27} kg
Avogadro's number, N_A	6.022×10^{23} mol^{-1}
Boltzmann constant, k_B	1.381×10^{-23} J/K
Gas constant, R	8.314 J/(mol·K)
Stefan–Boltzmann constant, σ	5.670×10^{-8} W/(m^{2}K^4)
Gravitational constant, G	6.674×10^{-11} N·m^2/kg^2

Wave/Photon Relations

Photon energy $E = hf = \dfrac{hc}{\lambda}$

Momentum (photon) $p = \dfrac{h}{\lambda}$

de Broglie wavelength $\lambda = \dfrac{h}{p}$

These constants are provided for convenience. Calculators are allowed unless otherwise stated.

I. Quantum Physics: Fundamentals & History [*28 pts*]

1. The Heisenberg uncertainty principle for position and momentum is: [*1 pts*]
(a) $\Delta x \, \Delta p \geq \hbar$
(b) $\Delta x \, \Delta p \geq \frac{\hbar}{2}$
(c) $\Delta x \, \Delta p \leq \frac{\hbar}{2}$

Answer: _______

2. In bra–ket notation, write the expectation value of an observable $\hat{A}$ in state $|\psi\rangle$, and state (in one sentence) what it represents physically. [*2 pts*]

3. In a double-slit experiment with fixed slit separation d and screen distance L, if the wavelength λ increases, the fringe spacing on the screen: [*2 pts*]
(a) increases
(b) decreases
(c) stays the same

Answer: _______

4. Match each Pauli operator to its matrix representation. [*2 pts*]
Operators: $1 = \sigma_x$, $2 = \sigma_y$, $3 = \sigma_z$.
Options: (a) $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, (b) $\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$, (c) $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

Answer: 1→_____, 2→_____, 3→_____

5. Which experiment provided direct evidence of matter-wave diffraction for electrons? [*1 pts*]
(a) Davisson–Germer
(b) Stern–Gerlach
(c) Millikan oil drop
(d) Rutherford gold foil

Answer: _______

6. The Einstein–Podolsky–Rosen (EPR) argument was designed to challenge which idea? [*2 pts*]
(a) That quantum mechanics predicts discrete energy levels
(b) That the wavefunction provides a complete description of physical reality
(c) That light comes in quanta

Answer: _______

7. Two states $|\psi\rangle$ and $|\phi\rangle$ are orthogonal if: [*1 pts*]
(a) $\langle\psi|\phi\rangle = 0$
(b) $\langle\psi|\phi\rangle = 1$
(c) $|\psi\rangle = |\phi\rangle$

Answer: _______

8. **[Tiebreaker]** State the no-cloning theorem in words and give a short reason (one or two sentences) why an unknown quantum state cannot be copied perfectly. [*3 pts*]

9. A Mach–Zehnder interferometer has two equal beam splitters. If a relative phase φ is introduced in one arm, the probability to detect the photon at the "bright" output is $P = \cos^2(\varphi/2)$. For $\varphi = \pi/2$, P equals: [*2 pts*]
(a) 0
(b) 1/2
(c) 1

Answer: _______

10. A measurement projects a state onto an eigenstate of the measured observable. Explain (briefly) why measuring in a different basis can change which outcomes are possible. [*2 pts*]

11. A *relative* phase between amplitudes can affect interference, but a global phase cannot. In one sentence, explain the difference. [*1 pts*]

12. **Long Answer:** Describe the historical path from early quantum ideas to modern quantum mechanics: include Planck (blackbody radiation), Einstein (photoelectric effect), Bohr (atomic spectra), de Broglie (matter waves), and the development of matrix/wave mechanics. Explain how each step addressed a specific experimental puzzle. [*8 pts*]

Feedback (optional):
Which question in this section did you feel most confident about? ________

II. Atomic & Statistical Physics [*29 pts*]

13. In the photoelectric effect with f above threshold, increasing the light intensity (keeping f fixed) primarily increases the: [*1 pts*]
(a) stopping potential
(b) maximum kinetic energy of ejected electrons
(c) photocurrent (rate of emitted electrons)

Answer: _______

14. If the stopping potential is V_s, write the photoelectric relationship between V_s, the work function ϕ, and the light frequency f. [*2 pts*]

15. A hydrogen atom transitions from $n = 3$ to $n = 2$. Using $E_n = -13.6\,\mathrm{eV}/n^2$ and $hc = 1240\,\mathrm{eV{\cdot}nm}$, find the emitted photon wavelength (in nm). [*2 pts*]

16. For Compton scattering at $\theta = 90°$, what is the wavelength shift $\Delta\lambda$ in terms of λ_C? Use $\Delta\lambda = \lambda_C(1 - \cos\theta)$. [*2 pts*]

17. For a fixed barrier height, tunneling probability generally increases when the particle's kinetic energy: [*1 pts*]
(a) decreases
(b) increases
(c) stays the same

Answer: _______

18. Match each hydrogen spectral series to the typical region of the EM spectrum. [*1 pts*]
Lyman, Balmer, Paschen vs (a) ultraviolet, (b) visible, (c) infrared.

Answer: Lyman→_____, Balmer→_____, Paschen→_____

19. State the second law of thermodynamics for an isolated system. [*1 pts*]

20. Write the Boltzmann probability p_i of occupying energy level E_i in a canonical ensemble. Define β. [*2 pts*]

21. Quantum (FD/BE) statistics become important when the thermal de Broglie wavelength is comparable to the interparticle spacing. This typically occurs at: [*2 pts*]

(a) high T and low density
(b) low T and/or high density
(c) any temperature if particles are charged

Answer: _______

22. Find the photon momentum for $\lambda = 400\,\text{nm}$ using $p = h/\lambda$. [*1 pts*]

23. Define *stimulated emission* and explain why it is essential for laser coherence/amplification. [*2 pts*]

24. For a two-level system with degeneracies g_0 (ground) and g_ϵ (excited) separated by energy ϵ, write N_ϵ/N_0 at temperature T. [*1 pts*]

25. [**Tiebreaker**] At $T = 0$, compare the occupation of energy states for an ideal Fermi gas and an ideal Bose gas in one paragraph. Mention the Fermi energy and the possibility of Bose–Einstein condensation. [*3 pts*]

26. Long Answer: Compare the photoelectric effect and Compton scattering as evidence for the photon concept. Include what each effect predicts about (i) the role of intensity vs frequency and (ii) momentum/energy transfer, and explain why classical wave theory fails for at least one key observation. [*8 pts*]

Feedback (optional):
Which question in this section did you feel most confident about? ________

III. Solid-State Materials & Quantum Instruments [*29 pts*]

27. Compared to metals, intrinsic semiconductors generally become *more* conductive as temperature increases because: [*2 pts*]
(a) the band gap widens with temperature
(b) more carriers are thermally excited across the band gap
(c) the lattice stops vibrating

Answer: ________

28. Doping silicon with *acceptor* impurities (e.g. boron) produces: [*1 pts*]
(a) n-type material with electron majority carriers
(b) p-type material with hole majority carriers
(c) an insulator

Answer: ________

29. For an *intrinsic* semiconductor, sketch or describe the qualitative behavior of resistivity vs. temperature. [*2 pts*]

30. Define a *critical magnetic field* (or critical current) for a superconductor, and state what happens when it is exceeded. [*2 pts*]

31. In NMR, the Larmor *frequency* (not angular frequency) for protons is $f = (\gamma/2\pi)B_0$ with $\gamma/2\pi \approx 42.58\,\mathrm{MHz/T}$. For $B_0 = 3\,\mathrm{T}$, f is closest to: [*1 pts*]
(a) $14\,\mathrm{MHz}$
(b) $128\,\mathrm{MHz}$
(c) $425\,\mathrm{MHz}$

Answer: ________

32. Many quantum sensors improve sensitivity by averaging repeated measurements. If the noise is uncorrelated (white), explain why the uncertainty typically scales like $1/\sqrt{N}$ with the number of averages N. [*2 pts*]

33. The DC Josephson relation for a junction can be written as: [*1 pts*]

(a) $I = I_c \sin\varphi$

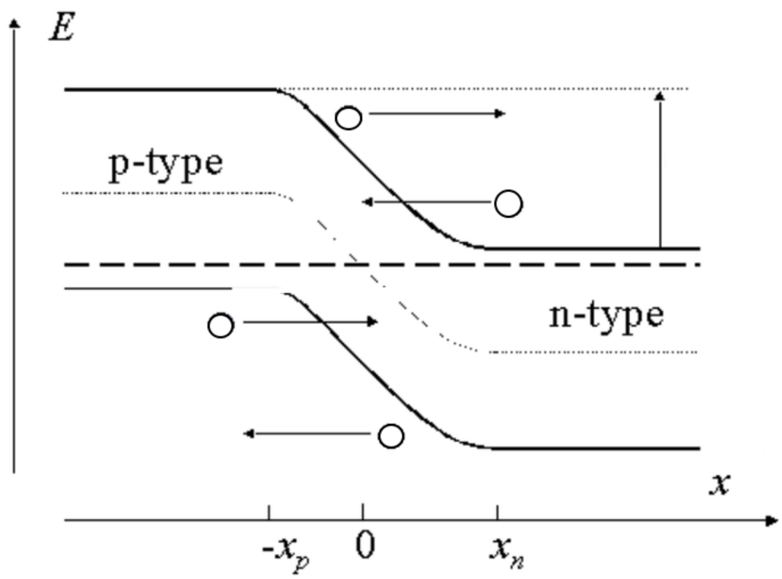
(b) $V = I_c \sin\varphi$

(c) $I = \frac{h}{2e} V$

Answer: _______

34. Give one practical tradeoff between SQUID magnetometers and NV-diamond magnetometers (e.g., sensitivity, spatial resolution, operating temperature). [*2 pts*]

35. Using the band diagram provided, indicate which side is p-type and which side is n-type, and identify the depletion region. [*3 pts*]



36. Thermal (Johnson) noise for a resistor is $V_{\text{rms}} = \sqrt{4k_B T R \Delta f}$. If you double the bandwidth Δf, what happens to V_{rms}? Explain briefly. [*2 pts*]

37. **[Tiebreaker]** Type-II superconductors allow magnetic flux to enter as quantized vortices. Explain (briefly) what a vortex is and give one consequence for superconducting devices or imaging/sensing. [*3 pts*]

38. **Long Answer:** Explain the physics of a p–n junction at equilibrium (depletion region, built-in field/potential, band bending) and how this enables one device (choose: diode, LED, solar cell, or photodiode). Include one realistic noise source or limitation relevant to measuring small signals. [*8 pts*]

Feedback (optional):
Which question in this section did you feel most confident about? ________

IV. Quantum Information Processing *[29 pts]*

39. The Hadamard gate acting on $|1\rangle$ produces: *[1 pts]*
(a) $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$
(b) $\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$
(c) $-|1\rangle$

Answer: _______

40. Give one clear difference between a classical probability mixture over $\{0, 1\}$ and a qubit superposition $\alpha|0\rangle + \beta|1\rangle$. Mention interference. *[2 pts]*

41. A CNOT with control on qubit 1 acts on $|01\rangle$ to produce: *[1 pts]*
(a) $|01\rangle$
(b) $|00\rangle$
(c) $|11\rangle$

Answer: _______

42. Write the matrix for the Pauli-X gate and state what it does to $|0\rangle$ and $|1\rangle$. *[2 pts]*

43. For the Bell state $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, if the first qubit is measured in the X basis and the outcome is $|+\rangle$, the second qubit collapses to: *[1 pts]*
(a) $|+\rangle$
(b) $|-\rangle$
(c) $|0\rangle$

Answer: _______

44. Grover's algorithm finds a marked item among N possibilities in $O(\sqrt{N})$ queries. For $N = 16$, about how many Grover iterations are needed (order-of-magnitude / nearest integer)? *[2 pts]*

45. In the Deutsch–Jozsa algorithm, the ancilla is often prepared in $|-\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$ mainly to: [*1 pts*]
(a) convert the oracle output into a global phase
(b) convert the oracle output into a relative phase on the input register (phase kickback)
(c) reduce gate count by removing Hadamards

Answer: _______

46. A single-qubit state is $|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\varphi}|1\rangle)$. Explain how measuring in the X basis depends on φ. [*2 pts*]

47. Explain why any closed-system quantum gate must be reversible, and relate this to unitarity. [*2 pts*]

48. Bit-flip, phase-flip, and both correspond to which Pauli errors? (Give the mapping.) [*2 pts*]

49. Starting from $|0\rangle$, apply H, then Z, then H. The final state is: [*2 pts*]
(a) $|0\rangle$
(b) $|1\rangle$
(c) $|+\rangle$

Answer: _______

50. **[Tiebreaker]** Some quantum algorithms gain advantage by *interference* rather than just entanglement. In a few sentences, explain why entanglement alone is not automatically a speedup, and how constructive/destructive interference is used in algorithms. [*3 pts*]

51. Long Answer: Discuss decoherence in qubits (distinguish dephasing vs amplitude damping) and outline how a simple repetition-style code can correct either bit-flip or phase-flip errors. Explain how to adapt a bit-flip code to detect phase flips, and why fault-tolerant error correction is needed for long computations. [*8 pts*]

Feedback (optional):
Which question in this section did you feel most confident about? ________