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SAMPLE EXAM 3

Time — 170 minutes

100 questions

Directions: Each of the questions or incomplete statements below is followed by five suggested answers or completions. Select the one that is best in each case and then fill in the corresponding space on the answer sheet.

TABLE OF INFORMATION

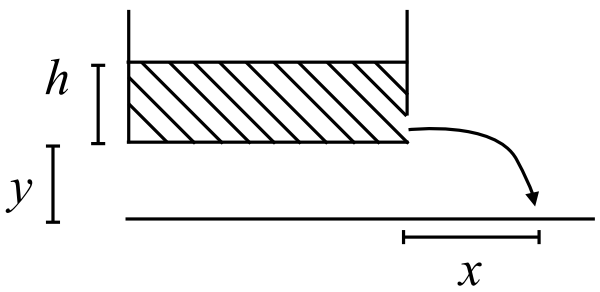
Rest mass of the electron	m_e	=	9.11×10^{-31} kg
Magnitude of the electron charge	e	=	1.60×10^{-19} C
Avogadro's number	N_A	=	6.02×10^{23}
Universal gas constant	R	=	8.31 J/mol $\cdot$ K
Boltzmann's constant	k	=	1.38×10^{-23} J/K
Speed of light	c	=	3.00×10^{8} m/s
Planck's constant	h	=	6.63×10^{-34}J $\cdot$ s $= 4.14 \times 10^{-15}$ eV $\cdot$ s
	$\hbar$	=	$h/2\pi$
	hc	=	1240 eV $\cdot$ nm
Vacuum permittivity	ϵ_0	=	8.85×10^{-12} C^2/(N $\cdot$ m^2)
Vacuum permeability	μ_0	=	$4\,\pi \times 10^{-7}$ T $\cdot$ m/A
Universal gravitational constant	G	=	6.67×10^{-11} m^3/(kg $\cdot$ s^2)
Acceleration due to gravity	g	=	9.80 m/s^2
1 atmosphere pressure	1 atm	=	1.0×10^5 N/m^2 $= 1.0 \times 10^5$ Pa
1 angstrom	1 Å	=	1×10^{-10} m $= 0.1$ nm

Prefixes for Powers of 10

10^{-15}	femto	f
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{-2}	centi	c
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P

Moments of inertia about center of mass

Rod	$\frac{1}{12}M\ell^2$
Disc	$\frac{1}{2}MR^2$
Sphere	$\frac{2}{5}MR^2$



1. A bath of water has hole in the bottom of one side, as shown in the figure. At what horizontal distance x from the edge of the bath does the draining water land? Neglect effects due to viscosity and surface tension.

   (A) $\sqrt{2hy}$
   (B) $\frac{\sqrt{hy}}{2}$
   (C) $2\sqrt{hy}$
   (D) $\frac{h}{2}$
   (E) $\frac{2h^2}{y}$

2. Suppose that light linearly polarized at 45° and with wavelength λ enters a birefringent medium with indices of refraction n_x and n_y ($n_y < n_x$). What is the minimum thickness of material needed for the light to be circularly polarized when it leaves the medium?

   (A) $\frac{\lambda}{4(n_x - n_y)}$
   (B) $\frac{\lambda}{2(n_x - n_y)}$
   (C) $\frac{\lambda n_x n_y}{4(n_x - n_y)}$
   (D) $\frac{\lambda n_x n_y}{2(n_x - n_y)}$
   (E) $\frac{\lambda n_x n_y}{n_x - n_y}$

3. Two objects in the sky have angular separation 1 arcminute, and emit a broad spectrum of radiation. A telescope with aperture diameter 1 cm could resolve the objects by observing which of the following kinds of radiation?

   I. Radio
   II. Visible
   III. X-ray

   (A) I only
   (B) II only
   (C) III only
   (D) I and II
   (E) II and III

4. A block slides frictionlessly on ice at a constant velocity of 10 m/s. The block suddenly encounters a rough patch where its coefficient of kinetic friction suddenly increases from 0 to 0.5. How far does the block slide before stopping?

   (A) 5 m
   (B) 10 m
   (C) 15 m
   (D) 20 m
   (E) 100 m

5. The Euler-Lagrange equations are valid for systems with which of the following properties?

   I. Systems with time-dependent potentials
   II. Systems without rotational symmetry
   III. Systems acted on by only conservative forces

   (A) II
   (B) III
   (C) I and II
   (D) I and III
   (E) I, II and III

6. Order the following corrections to the Bohr energies of hydrogen from smallest to largest.

   I. Fine structure

   II. Hyperfine splitting

   III. Lamb shift

   (A) I, II, III

   (B) I, III, II

   (C) II, III, I

   (D) III, II, I

   (E) III, I, II

7. What is the difference in energy between the $n = 5$ and the $n = 1$ states of the 1D quantized harmonic oscillator?

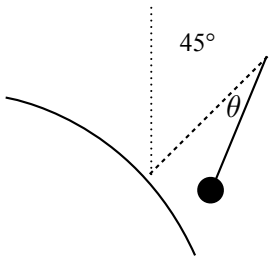
   (A) $\hbar\omega$

   (B) $2\hbar\omega$

   (C) $4\hbar\omega$

   (D) $8\hbar\omega$

   (E) $16\hbar\omega$



8. A mass m hangs from a string of length L at 45° latitude on the Earth. If the Earth has radius R and an angular velocity of Ω about its axis, what is the angular displacement θ of the string from perfect vertical? You may assume θ is small compared to the latitude.

   (A) $\dfrac{\Omega^2 R}{2g + \Omega^2 R}$

   (B) $\dfrac{\Omega^2 R}{2g - \Omega^2 R}$

   (C) $\dfrac{\Omega^2 R}{g - \Omega^2 R}$

   (D) $\dfrac{\Omega^2 R}{g}$

   (E) 0

9. Two parameters x and y were measured with uncertainties Δx and Δy. What is the uncertainty of the quantity $z = x^2/y$?

   (A) $\sqrt{(\Delta x/x)^2 + (\Delta y/y)^2}$

   (B) $\sqrt{4(\Delta x/x)^2 + (\Delta y/y)^2}$

   (C) $z\sqrt{(\Delta x/x)^2 + (\Delta y/y)^2}$

   (D) $z\sqrt{4(\Delta x/x)^2 + (\Delta y/y)^2}$

   (E) $z\sqrt{8(\Delta x/x)^2 + (\Delta y/y)^2}$

10. A circuit made only of which of the following circuit elements may function as a bandpass filter?

    (A) One resistor, one inductor, and one capacitor

    (B) One resistor and one inductor

    (C) One resistor and one capacitor

    (D) Two resistors

    (E) Two capacitors

11. Consider a planet of mass m that orbits a star of mass $M \gg m$. For a fixed orbital angular momentum L, what is the relationship between the energies of the three possible orbit shapes: circular (E_{cir}), elliptical (E_{ell}), or hyperbolic (E_{hyp})?

    (A) $E_{cir} < E_{ell} < E_{hyp}$

    (B) $E_{ell} < E_{hyp} < E_{cir}$

    (C) $E_{hyp} < E_{cir} < E_{ell}$

    (D) $E_{cir} < E_{hyp} < E_{ell}$

    (E) $E_{ell} < E_{cir} < E_{hyp}$

12. For a system of electrons at zero temperature, the energy of the highest occupied quantum state is called the

    (A) zero-point energy

    (B) Einstein energy

    (C) Fermi energy

    (D) Bose energy

    (E) binding energy

13. A beam is comprised of particles that have a lifetime of 10^{-8} s. If the beam travels at 0.8c, at what location down the beamline is there only a fraction $1/e$ of the particles remaining?

    (A) 6.19 m

    (B) 4.00 m

    (C) 3.59 m

    (D) 2.70 m

    (E) 2.46 m

14. A 100 keV photon scatters off an electron at 60°. Approximately how much energy is transferred to the electron? Recall that for photons scattering on electrons

$$\Delta\lambda = \frac{h}{mc}(1 - \cos\theta).$$

    (A) 1 keV

    (B) 9 keV

    (C) 50 keV

    (D) 91 keV

    (E) 99 keV

15. Which of the following nuclei were produced during big bang nucleosynthesis?

    I. ^{3}He

    II. ^{7}Li

    III. ^{55}Fe

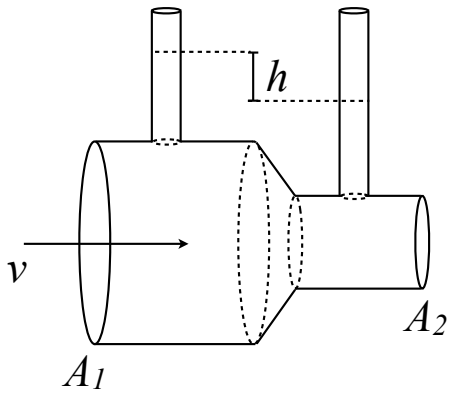
    (A) I

    (B) III

    (C) I and II

    (D) I and III

    (E) I, II, and III



16. Venturi tubes consist of horizontal tube with a wide section of cross-sectional area A_1 and a narrow section with cross-sectional area A_2, as shown in the diagram. Two vertical tubes rise from each section of the horizontal tube and are exposed to air. If a incompressible fluid of density ρ moves with velocity v through the wide part of the horizontal tube, what is the difference in height h of the fluids in the vertical tubes?

(A) $\frac{v}{2A_1}\left(\frac{A_1^2}{A_2^2}-1\right)$

(B) $\frac{v^2}{2g}\left(\frac{A_1^2}{A_2^2}-1\right)$

(C) $\frac{v}{2A_1}\left(\frac{A_2^2}{A_1^2}-1\right)$

(D) $\frac{v^2}{2g}\left(\frac{A_2^2}{A_1^2}-1\right)$

(E) $\frac{v^2}{4g}\left(\frac{A_2^2}{A_1^2}-1\right)$

17. A car accelerates from rest at 5 m/s^2. How fast is it traveling after 40 m?

(A) 9.7 m/s

(B) 15 m/s

(C) 20 m/s

(D) 30 m/s

(E) 54.2 m/s

18. A bullet of mass m is fired at velocity v into a block of mass M on a table, where it stops and is embedded. If there is a coefficient of friction μ between the block and the table, how much time does it take for the block to come to rest?

(A) $\frac{Mv}{\mu g(m+M)}$

(B) $\frac{\mu mv}{g(m+M)}$

(C) $\frac{mv}{2\mu g(m+M)}$

(D) $\frac{mv}{\mu gM}$

(E) $\frac{mv}{\mu g(m+M)}$

19. Thermal fluctuations produce voltage fluctuations in all resistors. Which of the following is the spectral density (units of V Hz$^{-1/2}$) of voltage fluctuations in a resistor at temperature T and of resistance R?

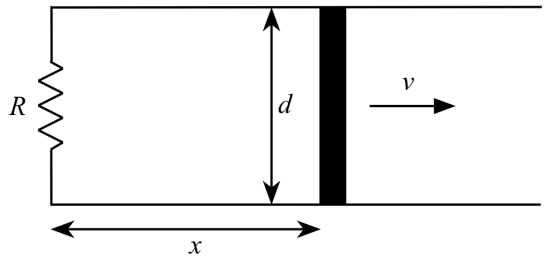
(A) $\sqrt{4kT/R}$

(B) $\sqrt{4kR/T}$

(C) $\sqrt{4kTR}$

(D) $\sqrt{kT}$

(E) $\sqrt{4R}$



20. A metal bar is pulled at constant velocity $v\hat{\mathbf{x}}$ along two metal rails a distance d apart connected by a resistor of resistance R, as shown in the diagram. There is a magnetic field, pointing into the page, of magnitude $B = Cx$, where $x = 0$ is the initial position of the bar. At time T, how much energy has been dissipated in the resistor thus far, as a function of T?

(A) $\dfrac{C^2v^2d^2}{R}$

(B) $\dfrac{C^2v^2d^4T}{R}$

(C) $\dfrac{C^2v^2d^2T}{R}$

(D) $\dfrac{C^2v^4d^2T^2}{3R}$

(E) $\dfrac{4C^2v^4d^2T^3}{3R}$

21. The coexistence curve at temperature $T = 500$ K for a material at a phase transition has a slope of $dP/dT = 10$ MPa/K. If the latent heat for the phase transition is $L = 10^5$ J/kg, what is the change in volume per unit mass due to the phase transition?

(A) 2×10^{-3} m^3/kg

(B) 5×10^{-4} m^3/kg

(C) 2×10^{-5} m^3/kg

(D) 2×10^{-6} m^3/kg

(E) 5×10^{-7} m^3/kg

22. A circuit consists of a capacitor C in parallel with a series combination of resistor R and inductor L. What is the resonant frequency?

(A) $\sqrt{\dfrac{1}{LC} - \left(\dfrac{R}{2L}\right)^2}$

(B) $\sqrt{\dfrac{1}{LC} - \left(\dfrac{1}{2RC}\right)^2}$

(C) $\sqrt{\dfrac{1}{LC}}$

(D) $\sqrt{\dfrac{1}{LC} - \left(\dfrac{R}{L}\right)^2}$

(E) $\sqrt{\dfrac{1}{LC} - \left(\dfrac{1}{RC}\right)^2}$

23. A pipe with two open ends is 20 cm long. What is the fundamental frequency of the pipe? (You may assume the speed of sound is 343 m/s.)

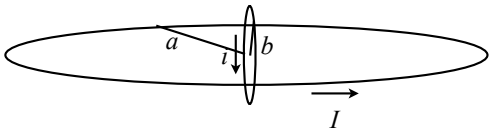
(A) 1715 Hz

(B) 858 Hz

(C) 563 Hz

(D) 429 Hz

(E) 205 Hz



24. A current loop of radius a carrying current I is centered at the origin and lies in the xy-plane. Another loop, carrying current $i \ll I$, and of radius $b \ll a$, is centered at the origin and lies in the xz-plane. What is the torque on the smaller loop about its center?

(A) $\dfrac{\mu_0 \pi i I b^2}{a}$

(B) $\dfrac{\mu_0 \pi i I b^2}{2a}$

(C) $\dfrac{\mu_0 \pi i I b^3}{2a^2}$

(D) $\dfrac{\mu_0 \pi i I b^2}{4a^2}$

(E) $\dfrac{3\mu_0 \pi i I b^2}{2a^2}$

25. A merry-go-round of radius R rotates at an angular velocity of Ω. A ball A is released at radius $R/2$, initially at rest, by a person standing on the merry-go-round. An identical ball B is released at radius R, also at rest. In the non-inertial reference frame of the rotating merry-go-round, what is the ratio of the acceleration experienced by ball A to ball B immediately after they are released?

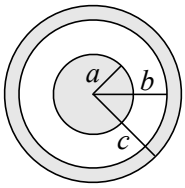
(A) 0

(B) 1/2

(C) 1

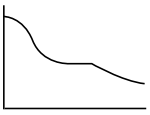
(D) 2

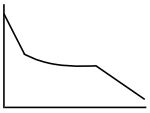
(E) 4

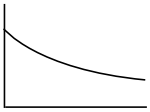


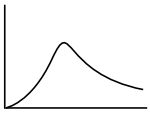
26. A ball of uniform charge density and radius a is surrounded by a conducting shell of inner radius b and outer radius c. Which could be the potential as a function of radius?

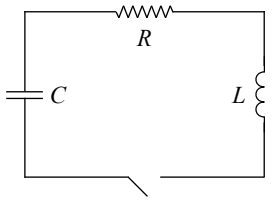
(A) 

(B) 

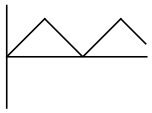
(C) 

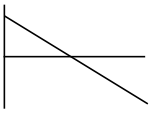
(D) 

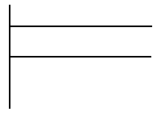
(E) 

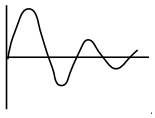


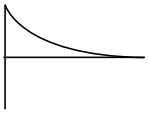
27. A charged capacitor is in series with a resistor and inductor as in the diagram. Which of the following could be a graph of the current when the switch is closed?

(A) 

(B) 

(C) 

(D) 

(E) 

28. A beam of electrons (mass m and charge q) with uniform velocity enters a region of constant magnetic field B perpendicular to the beam direction. Assuming that the electrons are able to follow a circular path completely within the field, how long does it take for the beam to make one complete revolution?

(A) $2\pi m/(qB)$

(B) $\pi m/(qB)$

(C) $m/(2\pi qB)$

(D) $m/(\pi qB)$

(E) $m/(qB)$

29. Photons of wavelength 10 nm are incident on a crystal with interatomic space 80 nm. At what angle is the first order maximum in the diffraction pattern?

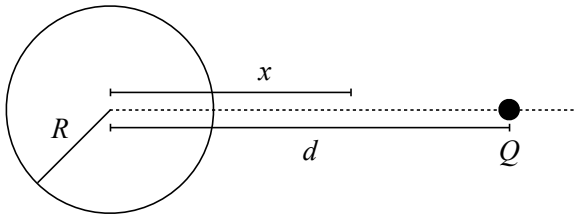
(A) 7.2°

(B) 3.6°

(C) 2.4°

(D) 1.8°

(E) 0.9°



30. A charge Q is brought to a distance d from the center of a grounded conducting sphere of radius R. What is the electric potential at a distance x from the center of the sphere along the axis between the charge and the sphere?

(A) $\frac{Q}{2\pi\epsilon_0}\left(\frac{1}{|x-d|}-\frac{d}{|xd-R^2|}\right)$

(B) $\frac{Q}{4\pi\epsilon_0}\left(\frac{1}{|x-d|}-\frac{R}{d\,|x-R^2/d|}\right)$

(C) $\frac{Q}{4\pi\epsilon_0}\left(\frac{1}{|x-d|}-\frac{1}{|2x-R|}\right)$

(D) $\frac{Q}{4\pi\epsilon_0}\left(\frac{1}{|x-d|}-\frac{1}{|x|}\right)$

(E) 0

31. What type of lattice is the reciprocal lattice to a simple cubic lattice in three dimensions?

(A) face-centered cubic

(B) simple cubic

(C) body-centered cubic

(D) simple hexagonal

(E) none of the above

32. The magnetic vector potential in a region of space is given by

$$\mathbf{A}(x,y,z) = Ay^2\hat{\mathbf{x}} + B\sqrt{z}\hat{\mathbf{y}} + Cx^2\hat{\mathbf{z}}.$$

where A, B, and C are constants. What is the magnetic field in this region?

(A) $-\frac{B}{2\sqrt{z}}\hat{\mathbf{x}} - 2Cx\hat{\mathbf{y}} - 2Ay\hat{\mathbf{z}}$

(B) $\frac{B}{2\sqrt{z}}\hat{\mathbf{x}} - 2Cx\hat{\mathbf{y}} + 2Ay\hat{\mathbf{z}}$

(C) 0

(D) $-\frac{B}{\sqrt{z}}\hat{\mathbf{x}} - Cx\hat{\mathbf{y}} - Ay\hat{\mathbf{z}}$

(E) $\frac{B}{\sqrt{z}}\hat{\mathbf{x}} + Cx\hat{\mathbf{y}} + Ay\hat{\mathbf{z}}$

33. The CMB has a temperature of 2.7 K and has a peak intensity at a wavelength of approximately 1 mm. If the CMB were at 5 K, what would be the wavelength with the maximal intensity?

(A) 1 mm

(B) 0.54 mm

(C) 0.32 mm

(D) 5.3 mm

(E) 57 mm

34. Which of the following decays is allowed in the standard model?

(A) $\mu^- \to e^- + \nu_e$

(B) $\pi^- \to \gamma$

(C) $\Delta^+ \to p + n$

(D) $\pi^+ \to 2\gamma$

(E) $K^+ \to \mu^+ + \nu_\mu$

35. A nearby star is moving away from the Earth with peculiar velocity $0.1c$. It appears to have an effective blackbody temperature of 10^4 K. What is its true effective blackbody temperature? (Assume a negligible cosmological redshift)

(A) 0.6×10^4 K
(B) 0.9×10^4 K
(C) 10^4 K
(D) 1.1×10^4 K
(E) 1.4×10^4 K

36. A two level system has energies $\pm\epsilon$. What is the entropy as the temperature $T \to \infty$?

(A) ∞
(B) $k(\ln 2 + 2)$
(C) $k(\ln 2 + 1)$
(D) $k \ln 2$
(E) 0

37. An ideal gas is confined to half of a rigid box with volume $2V$. If a valve is opened suddenly, letting the gas suddenly fill the full volume of the box, which of the following is unchanged?

I. internal energy U
II. temperature T
III. entropy S

(A) I
(B) III
(C) I and II
(D) I and III
(E) I, II, and III

38. Suppose a heat engine that transfers heat from a warm bath at temperature T_H to a cold bath at T_C has an efficiency

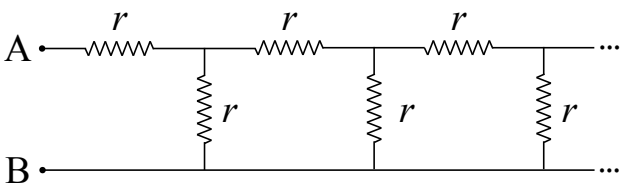
$$e = \frac{T_H + T_C}{T_H + 2T_C}.$$

Which of the following must be violated?

(A) conservation of energy
(B) first law of thermodynamics
(C) second law of thermodynamics
(D) third law of thermodynamics
(E) postulate of equal *a priori* probabilities

39. Two spaceships pass each other. Spaceship A moves relative to a nearby planet at velocity v_1, while spaceship B moves at velocity v_2 relative to the planet. How fast does spaceship A move relative to spaceship B?

(A) $\dfrac{v_1 - v_2}{1 + v_1 v_2/c^2}$
(B) $\dfrac{|v_1 + v_2|}{1 - v_1 v_2/c^2}$
(C) $|v_1 - v_2|$
(D) $\dfrac{v_1 + v_2}{1 + v_1 v_2/c^2}$
(E) $\dfrac{|v_1 - v_2|}{1 - v_1 v_2/c^2}$



40. Consider the infinite ladder of resistors with resistance r, shown in the figure. What is the resistance between terminals A and B?

(A) $(\sqrt{5}+1)r$

(B) $\frac{\sqrt{5}}{2}r$

(C) $\frac{\sqrt{5}+2}{2}r$

(D) 0

(E) $\frac{(\sqrt{5}+1)}{2}r$

41. An ideal monoatomic gas initially at pressure P undergoes adiabatic expansion from a volume V to a volume $2V$. What is the final pressure of the gas?

(A) P

(B) $P/2$

(C) $P/4$

(D) $2^{-5/3}P$

(E) $2^{-7/3}P$

42. What is the expectation value of L_z for the following wavefunction,

$$\psi(\theta,\phi) = \frac{1}{\sqrt{2}}\left(Y_1^{-1}(\theta,\phi) + Y_1^0(\theta,\phi)\right),$$

where $Y_l^m(\theta,\phi)$ are the spherical harmonics?

(A) $-\hbar$

(B) $-\hbar/2$

(C) 0

(D) $\hbar/2$

(E) $\hbar$

43. Which of the following statements is true in general for 1-dimensional spin-0 quantum mechanical systems?

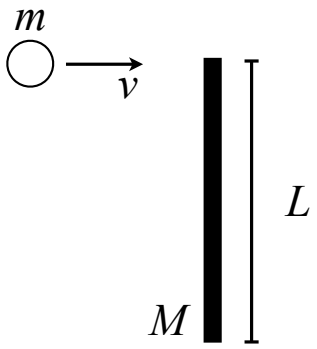
(A) All states are energy eigenstates.

(B) Energies are always quantized.

(C) There are no degenerate bound states.

(D) All states have real-valued wavefunctions in the x basis.

(E) None of the above.



44. A mass m moves at speed v perpendicular to a rod of uniform density, mass M, and length L on a frictionless table. Suppose $m \ll M$. If the mass collides with the end of the rod and sticks to it, at what angular speed does the rod begin to rotate? (You may treat the mass m as a point particle.)

(A) $\frac{3mv}{2ML}$

(B) $\frac{3mv}{ML}$

(C) $\frac{6mv}{ML}$

(D) $\frac{12mv}{ML}$

(E) $\frac{Mv}{2mL}$

45. An electron is in a magnetic field and has a Hamiltonian $H = \alpha \mathbf{S} \cdot \mathbf{B}$. If the electron is aligned with the magnetic field at $t = 0$, what is its time-dependent wavefunction? ($|+\rangle$ represents a spinor aligned with the magnetic field.)

(A) $\exp(-i\alpha Bt/2)\,|+\rangle$
(B) $\exp(+i\alpha Bt/2)\,|+\rangle$
(C) $\exp(-i\alpha Bt)\,|+\rangle$
(D) $\exp(+i\alpha Bt)\,|+\rangle$
(E) $\exp(-2\pi i\alpha Bt/\hbar)\,|+\rangle$

46. Which of the following is true of observables in quantum mechanics?

I. They are represented by hermitian operators
II. Multiple observables can never be simultaneously measured
III. The operators representing observables must have real eigenvalues

(A) I only
(B) II only
(C) I and II
(D) I and III
(E) I, II, and III

47. A mass attached to a spring has a resonant frequency f. If the mass attached to the spring triples and the spring constant doubles, what is the new resonant frequency of the system?

(A) $(\sqrt{2/3})f$
(B) $(2/3)f$
(C) $(4/9)f$
(D) $(\sqrt{1/2})f$
(E) $(1/2)f$

48. A quantum particle has wavefunction $\psi(x) = \mathcal{N}x^2$ on the interval $[0, 1]$, where $\mathcal{N}$ is a constant. What is the probability that the particle is found at $0 \leq x \leq 1/2$?

(A) 1/2
(B) 1/4
(C) 1/8
(D) 1/16
(E) 1/32

49. A spin-1/2 particle is in a state

$$|\psi\rangle = \sqrt{\frac{2}{3}}\,|m = 1/2\rangle + \sqrt{\frac{1}{3}}\,|m = -1/2\rangle\,.$$

What is the expectation value of the z-component of its spin?

(A) $3\hbar$
(B) $\hbar$
(C) $\hbar/2$
(D) $\hbar/3$
(E) $\hbar/6$

50. Which of the following physical process is responsible for producing the photons from a carbon dioxide laser?

(A) pair annihilation
(B) bremsstrahlung
(C) transitions of nuclear energy levels
(D) transitions between vibrational molecular energy levels
(E) photoelectric effect

51. A car of mass M pulls a trailer of mass m by a cord. The car's engine exerts a force F on the car. Suppose that the trailer has a coefficient of rolling friction μ, but neglect the coefficient of friction of the car. What is the tension in the cord between the car and trailer?

(A) $\dfrac{m(F-\mu Mg)}{M-m}$

(B) $\dfrac{m(F+\mu Mg)}{M+m}$

(C) $\dfrac{m(F-\mu Mg)}{M+m}$

(D) $\dfrac{\mu m(F-Mg)}{M+m}$

(E) $\dfrac{m(F+\mu Mg)}{\mu(M+m)}$

52. A spin-2 particle has orbital angular momentum $l=4$. What is the smallest possible value of its total angular momentum quantum number j?

(A) 6

(B) 5

(C) 4

(D) 3

(E) 2

53. Which of the following is not a ground state electron configuration for an element in the periodic table?

(A) $1s^2 2s^2 2p^6 3s^1$

(B) $1s^2 2s^2 2p^1$

(C) $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$

(D) $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^4$

(E) $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 4p^1$

54. Consider a perturbation to the ground state of the harmonic oscillator given by

$$\delta V(x) = \alpha e^{-\beta x^2}.$$

What is the first-order correction to the ground state energy? Note that

$$\int_{-\infty}^{\infty} e^{-x^2/c^2} = c\sqrt{\pi}.$$

(A) $\alpha\sqrt{\dfrac{\beta\hbar}{m\omega}}$

(B) $\alpha\sqrt{\dfrac{m\omega+\beta\hbar}{m\omega}}$

(C) $\alpha\sqrt{\dfrac{m\omega}{m\omega+\beta\hbar}}$

(D) $\alpha\sqrt{\dfrac{2m\omega+\beta\hbar}{m\omega}}$

(E) $\alpha\sqrt{\dfrac{m\omega}{2m\omega+\beta\hbar}}$

55. Let γ be the path in the xy-plane which traverses the square with vertices $(0,0)$, $(1,0)$, $(1,1)$, and $(0,1)$, in that order. What is the line integral $\oint_\gamma \mathbf{f}\cdot d\mathbf{l}$ of the function $\mathbf{f}(x,y) = y\hat{\mathbf{x}} + x\hat{\mathbf{y}}$?

(A) -2

(B) -1

(C) 0

(D) 1

(E) 2

56. Magnetic flux is quantized in type II superconductors. What is the unit of magnetic flux quanta?

(A) $2eh$

(B) $\dfrac{e}{2h^2}$

(C) $\dfrac{h}{2e}$

(D) $\dfrac{h}{2e^2}$

(E) $\dfrac{e^2}{2h}$

57. Positronium is a bound state of an electron and a positron. Which of the following are true facts about positronium?

I. it obeys Bose-Einstein statistics

II. its binding energy is -6.8 eV

III. it can decay into a single photon

(A) I only

(B) III only

(C) I and II

(D) I and III

(E) I, II, and III

58. A mass m moving at a non-relativistic velocity v collides elastically with a mass M at rest. If m bounces backwards in the opposite direction after the collision, what is the velocity of M after the collision?

(A) $\dfrac{mv}{2M}$

(B) $\dfrac{m^2v}{M^2}$

(C) $\dfrac{2vm}{m+M}$

(D) $\dfrac{vm}{m+M}$

(E) $\dfrac{2vm}{2m+M}$

59. Which of the following transitions of the hydrogen atom is allowed in the electric dipole approximation? (The entries in parentheses are (n, l, m).)

(A) $(2,1,0) \to (1,0,0)$

(B) $(2,0,0) \to (1,0,0)$

(C) $(3,2,0) \to (1,0,0)$

(D) $(3,2,2) \to (2,1,0)$

(E) $(3,0,0) \to (2,0,0)$

60. Suppose that a satellite orbiting the sun can be approximated as a perfect blackbody. Assuming the body is in equilibrium with its surroundings, what is the ratio of its blackbody temperature at radius $2R$ from the sun to the blackbody temperature at radius R from the sun?

(A) $2^{-3/2}$

(B) 2^{-1}

(C) $2^{-1/2}$

(D) $2^{-1/3}$

(E) $2^{-1/4}$

61. What is the rms velocity of a gas of diatomic molecules with mass m at temperature T?

(A) $\sqrt{3kT/m}$

(B) $\sqrt{7kT/m}$

(C) $2\sqrt{kT/m}$

(D) $\sqrt{kT/m}$

(E) $\sqrt{5kT/m}$

62. A merry-go-round can be approximated as a disk of uniform density, thickness t, radius r, and mass M. A merry-go-round is spinning at angular velocity ω before a person steps onto it. What is the change in angular velocity after a person of mass m steps onto the edge of the merry-go-round?

(A) $\dfrac{2\omega m}{M+2m}$

(B) $\dfrac{\omega M}{M+2m}$

(C) $\dfrac{2\omega(m+M)}{M+2m}$

(D) $\dfrac{2\omega m}{M+m}$

(E) $\dfrac{\omega m}{M+m}$

63. The He^+ ion experiences an atomic transition from the $n = 2$ state to the $n = 1$ state. What is the energy of the emitted photon?

(A) 10.2 eV

(B) 13.6 eV

(C) 27.2 eV

(D) 31.4 eV

(E) 40.8 eV

64. A string of mass density $\mu = 1$ g cm^{-1} and tension $T = 4 \times 10^3$ N is fixed at both ends. What length must it be in order to have a fundamental frequency of 500 Hz?

(A) 40 cm

(B) 30 cm

(C) 25 cm

(D) 20 cm

(E) 15 cm

65. Four charges $+q$ are placed at the corners of a square of side length a. What is the magnitude of the electric force on one charge due to the other three charges?

(A) $\dfrac{1}{4\pi\epsilon_0}\dfrac{q^2}{4a^2}$

(B) $\dfrac{1}{4\pi\epsilon_0}\dfrac{5q^2}{4a^2}$

(C) $\dfrac{1}{4\pi\epsilon_0}\dfrac{q^2}{a^2}\left(1+\dfrac{\sqrt{2}}{4}\right)$

(D) $\dfrac{1}{4\pi\epsilon_0}\dfrac{q^2}{a^2}\sqrt{2}$

(E) $\dfrac{1}{4\pi\epsilon_0}\dfrac{q^2}{a^2}\left(\dfrac{1}{2}+\sqrt{2}\right)$

66. A spaceship is moving past a planet at a velocity $0.28c$ and transmits a message to a receiver on a planet. When the spaceship transmits the message it is directly overhead and moving tangentially to the planet's surface. If the message is transmitted at 100 MHz in the frame of the spaceship, at what frequency is the message received?

(A) 104 MHz

(B) 100 MHz

(C) 96 MHz

(D) 72 MHz

(E) 28 MHz

67. Unpolarized light is incident on two polarizing filters oriented at 30° to one another. What is the intensity of transmitted light, as a fraction of the incident light intensity?

(A) 1/4

(B) 3/8

(C) 1/2

(D) 3/4

(E) 1/8

68. What is the expectation value of the operator

$$\mathcal{O} = xpxp - xp^2x - px^2p + pxpx$$

for the 2nd excited state of the infinite square well?

(A) $\hbar^2$

(B) $-\hbar^2$

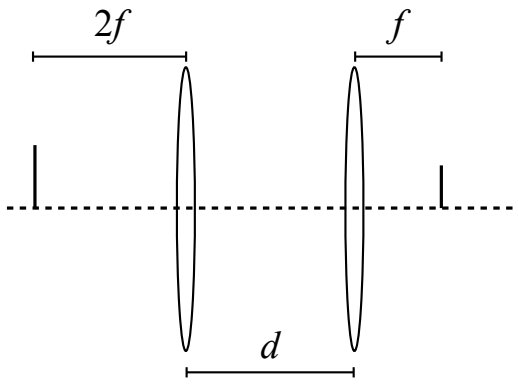
(C) $2\hbar^2$

(D) $-4\hbar^2$

(E) $16\hbar^2$

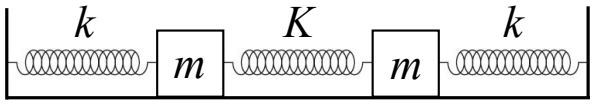
69. What is the inductance of a cylindrical solenoid with n turns, length ℓ, and radius R?

(A) $2\mu_0 n^2 R^2/\ell$
(B) $2\mu_0 n^2 \pi R^2/\ell$
(C) $\mu_0 n \pi R^2/\ell$
(D) $\mu_0 n^2 \pi R^2/\ell$
(E) $\mu_0 n^2 R^2/\ell$



70. Two converging lenses of focal length $f/2$ are placed in series, separated by a distance d. The object is placed a distance $2f$ to the left of the left lens, and the image is located a distance f to the right of the right lens. What is d?

(A) $(2/3)f$
(B) $(5/3)f$
(C) $(7/3)f$
(D) $3f$
(E) $9f$



71. Two masses m are connected by springs with spring constants k and K as shown in the diagram. At what frequency will the system oscillate in the limit of $K \to \infty$?

(A) $\sqrt{3k/m}$
(B) $\sqrt{k/m}$
(C) $\sqrt{2k/m}$
(D) $\sqrt{k/2m}$
(E) $2\sqrt{k/m}$

72. Suppose an atomic transition has a lifetime of 3×10^{-10} sec. The natural line width of this transition is closest to

(A) 10^{-2} eV
(B) 10^{-4} eV
(C) 10^{-6} eV
(D) 10^{-8} eV
(E) 10^{-10} eV

73. Which of the following quantities change under a general gauge transformation in electromagnetism?

I. electric potential
II. electric field
III. magnetic field

(A) I only
(B) II only
(C) I and II
(D) II and III
(E) I, II, and III

74. The degeneracy of the second excited state of the 3-dimensional infinite square well is

(A) 1

(B) 2

(C) 3

(D) 8

(E) 9

75. What is the capacitance of two concentric thin conducting spheres of radii a and $b > a$?

(A) $4\pi\epsilon_0 ab/(b-a)$

(B) $4\pi\epsilon_0 a^2/(b-a)$

(C) $4\pi\epsilon_0 b^2/(b-a)$

(D) $2\pi\epsilon_0 ab/(b-a)$

(E) $4\pi\epsilon_0$

76. How many distinct spin states can be formed by three distinguishable spin-1/2 particles?

(A) 1

(B) 2

(C) 4

(D) 7

(E) 8

77. A thin lens is made of a material with an index of refraction of 1.5. If the radius of curvature of the left side of the lens is 10 cm, and the focal length is 1 m, what is the radius of curvature of the right side of the lens?

(A) 12.5 cm

(B) 6.25 cm

(C) 25 cm

(D) 3.125 cm

(E) 25 cm

78. A car drives through a garage of length l with a front and rear door, at velocity v. The front door is initially open and the rear door is initially closed. In the frame of the garage, the rear door opens when the car is just about to collide with it, and the front door closes at the same time. In the frame of the car, how much time separates the opening of the rear door from the closing of the front door? ($\gamma = 1/\sqrt{1-v^2/c^2}$.)

(A) 0

(B) $\dfrac{\gamma v l}{c^2}$

(C) $\dfrac{vl}{c^2}$

(D) $\dfrac{\gamma c l}{v^2}$

(E) $\dfrac{vl}{\gamma c^2}$

79. Consider the change in entropy of an ideal gas in the following situations:

- ΔS_1: temperature doubles, pressure constant
- ΔS_2: temperature doubles, pressure doubles
- ΔS_3: temperature constant, volume doubles

Which of the following is true?

(A) $\Delta S_1 < \Delta S_2 < \Delta S_3$

(B) $\Delta S_1 < \Delta S_3 < \Delta S_2$

(C) $\Delta S_2 < \Delta S_3 < \Delta S_1$

(D) $\Delta S_3 < \Delta S_1 < \Delta S_2$

(E) $\Delta S_3 < \Delta S_2 < \Delta S_1$

80. A mass m attached to a spring of constant k is driven by a force $F(t) = F_0 \sin(\omega t)$. What is the late-time amplitude of the spring oscillations, assuming friction is small but sufficient to damp out transient oscillations?

(A) $\dfrac{F_0}{k}$

(B) $\dfrac{F_0}{m\omega^2}$

(C) $\dfrac{F_0}{k - 2m\omega^2}$

(D) $\dfrac{F_0}{k - m\omega^2}$

(E) $\dfrac{F_0}{4k - m\omega^2}$

81. An event occurs at $(t, x, y, z) = (0\text{ s}, 5\text{ m}, 10\text{ m}, 0\text{ m})$ in a reference frame S. At what x-position does the event occur in a reference frame that is moving at velocity $0.8c$ along the x-axis, relative to S? You may assume that the origin of coordinates coincides in both reference frames.

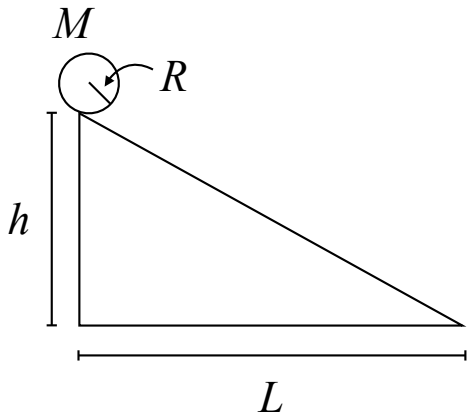
(A) 15.67 m

(B) 11.33 m

(C) 8.33 m

(D) 6.67 m

(E) 4.33 m



82. A dowel of radius R, width w, and mass M rolls without slipping down a ramp of length L and height h. What is its speed at the bottom of the ramp?

(A) $\sqrt{2gh}$

(B) $\sqrt{gh}$

(C) $\sqrt{gL}$

(D) $\sqrt{\dfrac{Rgh}{3w}}$

(E) $2\sqrt{\dfrac{gh}{3}}$

83. A positively-charged particle, initially moving in the $\hat{\mathbf{x}}$ direction, enters a region containing uniform electric and magnetic fields, $\mathbf{E} = E_0(\hat{\mathbf{x}} + 2\hat{\mathbf{y}})$ and $\mathbf{B} = B_0\hat{\mathbf{z}}$. Which of the following is a true statement about the motion of the particle?

(A) The particle moves in a circle.

(B) The particle is confined to the xz-plane.

(C) The particle is confined to the xy-plane.

(D) No work is done on the particle.

(E) The particle moves in a straight line.

84. Which of the following is NOT invariant under Lorentz transformations? Here E is relativistic energy, $\mathbf{p}$ is relativistic momentum, $\mathbf{x}$ is distance, ρ is charge density, $\mathbf{j}$ is current density, m is mass, and $\gamma = 1/\sqrt{1 - v^2/c^2}$.

(A) $E^2 - \mathbf{p}^2c^2$

(B) $m^2c^2 - \mathbf{p}^2$

(C) $c^2t^2 - \mathbf{x}^2$

(D) $c^2\rho^2 - \mathbf{j}^2$

(E) $\gamma^2(c^2 - \mathbf{v}^2)$

85. A Geiger counter measures 1061 events near a radioactive source during 10 seconds, and 421 events during 10 seconds when the source is removed. What is the uncertainty of the rate of events due to the source?

(A) 2.53 Hz

(B) 3.85 Hz

(C) 1.26 Hz

(D) 41.4 Hz

(E) 101 Hz

86. A signal pulse contains a current that has an exponential risetime of 10 msec and an exponential falltime of 100 msec. Approximately what bandwidth should be used to view the pulse in frequency space on a spectrum analyzer?

(A) 0.1 Hz

(B) 1 Hz

(C) 1000 Hz

(D) 10,000 Hz

(E) 1,000,000 Hz

87. A fit of a histogram to a model has a χ^2 statistic of 45.6. Which of the following should be used with the χ^2 to determine whether the model represents the data well?

(A) the number of entries in the histogram

(B) a plot of the data

(C) number of free parameters in the model

(D) number of bins in the histogram

(E) number of degrees of freedom

88. Which of the following is NOT produced in the *pp* cycle of the sun?

(A) ^{2}H

(B) ^{3}He

(C) ^{11}C

(D) ^{8}B

(E) ^{4}He

89. What is the mean energy of a two-state system with energies states 0 and ϵ at temperature T?

(A) $\epsilon/2$

(B) $\epsilon/(1 + e^{-\epsilon/kT})$

(C) $\epsilon/(1 - e^{\epsilon/kT})$

(D) $\epsilon/(1 + e^{\epsilon/kT})$

(E) $\epsilon(1 + e^{\epsilon/kT})$

90. If the Hubble parameter suddenly were increased to twice its present value, which of the following would change?

(A) fundamental particle masses

(B) distance between Earth and distant galaxies

(C) redshift of distant galaxies

(D) cosmological constant

(E) mass of the Earth

91. What is the relation between the phase velocity v_{ph} and the group velocity v_g of a wave on a string with tension T and linear mass density μ?

(A) $v_{ph}^2 = 2v_g\sqrt{T/\mu}$

(B) $v_{ph}^2 = v_g\sqrt{T/\mu}$

(C) $v_{ph} = 2v_g$

(D) $2v_{ph} = v_g$

(E) $v_{ph} = v_g$

92. Doping a semiconductor does which of the following to the band structure?

(A) no effect on band structure

(B) eliminates the valence band

(C) increases the gap energy

(D) adds additional states between valence and conduction bands

(E) eliminates the energy gap

93. An infinite conducting cylinder of radius a carries a surface charge density of σ. Assuming that the potential on the surface is 0, what is the potential at a distance $r > a$?

(A) $\dfrac{1}{\epsilon_0}\, a\sigma \ln \dfrac{r}{a}$

(B) $\dfrac{1}{\epsilon_0}\, a\sigma \ln \dfrac{a}{r}$

(C) $\dfrac{1}{2\epsilon_0}\, a\sigma \ln \dfrac{r}{a}$

(D) $\dfrac{1}{2\epsilon_0}\, a\sigma \ln \dfrac{a}{r}$

(E) 0

94. A toy car travels through a vertical loop on a track. If the radius of the loop is 20 cm, what is the minimum initial speed needed by the car at the bottom of the loop to successfully complete it?

(A) 1.4 m/s

(B) 2.8 m/s

(C) 3.2 m/s

(D) 3.8 m/s

(E) 4.6 m/s

95. What is the value of the following commutator?

$$[[S_x S_y, S_y]\,, S_z]$$

(A) $\hbar^2 S_x S_y$

(B) $\hbar^2 S_y S_z$

(C) $\hbar^2 S_y^2$

(D) $\hbar^2 S_z^2$

(E) -$\hbar^2 S_z S_x$

96. A particle undergoes closed orbits in a central potential $U(r)$ and has an energy E such that $V_{\min} < E < 0$, where $V_{\min}$ is the minimum of the effective potential. Which of the following describes the shape of the orbit?

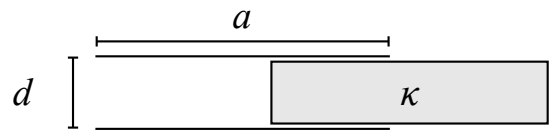
(A) circular

(B) elliptical

(C) parabolic

(D) hyperbolic

(E) The answer cannot be determined from the information given.



97. A square parallel plate capacitor has side lengths a and separation d between the plates. A constant voltage V_0 is applied between the plates. A block of dielectric material of dielectric constant κ and the same area and thickness as the capacitor is slowly inserted into the capacitor. What is the change in energy stored in the capacitor by the time the dielectric is fully inserted?

(A) 0

(B) $\dfrac{(\kappa-1)\epsilon_0 a^2 V_0^2}{4d}$

(C) $\dfrac{(\kappa-1)\epsilon_0 a^2 V_0^2}{d}$

(D) $\dfrac{(\kappa-1)\epsilon_0 a^2 V_0^2}{2d}$

(E) $\dfrac{\kappa\epsilon_0 a^2 V_0^2}{2d}$

98. An object is placed at rest in a potential field $U(x,y,z) = Ax + By^2 - C\cos z$, where A, B, C are constants. What is the force on the object?

(A) $\mathbf{F}(x,y,z) = -A\hat{\mathbf{x}} - 2By\hat{\mathbf{y}} - C\sin z\hat{\mathbf{z}}$

(B) $\mathbf{F}(x,y,z) = Ax\hat{\mathbf{x}} + 2By\hat{\mathbf{y}} - C\cos z\hat{\mathbf{z}}$

(C) $\mathbf{F}(x,y,z) = -Ax\hat{\mathbf{x}} - 2By\hat{\mathbf{y}} + C\cos z\hat{\mathbf{z}}$

(D) $\mathbf{F}(x,y,z) = -A\hat{\mathbf{x}} - 2By\hat{\mathbf{y}} + C\cos z\hat{\mathbf{z}}$

(E) $\mathbf{F}(x,y,z) = A\hat{\mathbf{x}} + 2By\hat{\mathbf{y}} + C\sin z\hat{\mathbf{z}}$

99. Suppose a hydrogen atom is in a uniform external electric field of magnitude E. What is the first order correction to the ground state energy?

(A) eE

(B) $\dfrac{1}{2}eE$

(C) $\dfrac{3}{2}eE$

(D) $\dfrac{16}{5}eE$

(E) 0

100. In Mössbauer spectroscopy, a source of photons of energy E is moved with velocity $v \ll c$ relative to a target material. The absorption of photons by the target material is then measured, with the Doppler shift from the source velocity producing a small variation in the photon energy. If the absorption peaks of two lines correspond to source velocities of 0 and v, what is the energy splitting between the lines to lowest order in v?

(A) Ev^4/c^4

(B) Ev^3/c^3

(C) Ev^2/c^2

(D) Ev/c

(E) $E\sqrt{v/c}$

Answers to Sample Exam 3

1. C
2. A
3. E
4. B
5. E
6. C
7. C
8. A
9. D
10. A
11. A
12. C
13. B
14. B
15. C
16. B
17. C
18. E
19. C
20. D
21. C
22. D
23. B
24. B
25. B
26. B
27. D
28. A
29. B
30. B
31. B
32. A
33. B
34. E
35. D
36. D
37. C
38. C
39. E
40. E
41. D
42. B
43. C
44. C
45. A
46. D
47. A
48. E
49. E
50. D
51. B
52. E
53. E
54. C
55. C
56. C
57. C

58. C
59. A
60. C
61. A
62. A
63. E
64. D
65. E
66. C
67. B
68. B
69. D
70. B
71. B
72. C
73. A
74. C
75. A
76. E
77. A
78. B
79. E
80. D
81. C
82. E
83. C
84. B
85. B
86. C
87. E
88. C
89. D
90. C
91. E
92. D
93. B
94. C
95. E
96. B
97. D
98. A
99. E
100. D