OSU PHYSICS DEPARTMENT COMPREHENSIVE EXAMINATION #77

April 1 and 2, 1996

Comprehensive Examination for Spring 1996

PART I

General Instructions

This Comprehensive Examination for Spring 1996 (#77) consists of eight problems of equal weight (20 points each). It has four parts. The first part (Problems 1-2) is handed out at 9:00 am on Monday, April 1, 1996, and lasts three hours. The second part (Problems 3-4) will be handed out on the same day, at 1:30 pm, and also lasts three hours. The third and fourth parts will be administrated in the same way on Tuesday, April 2, 1996.

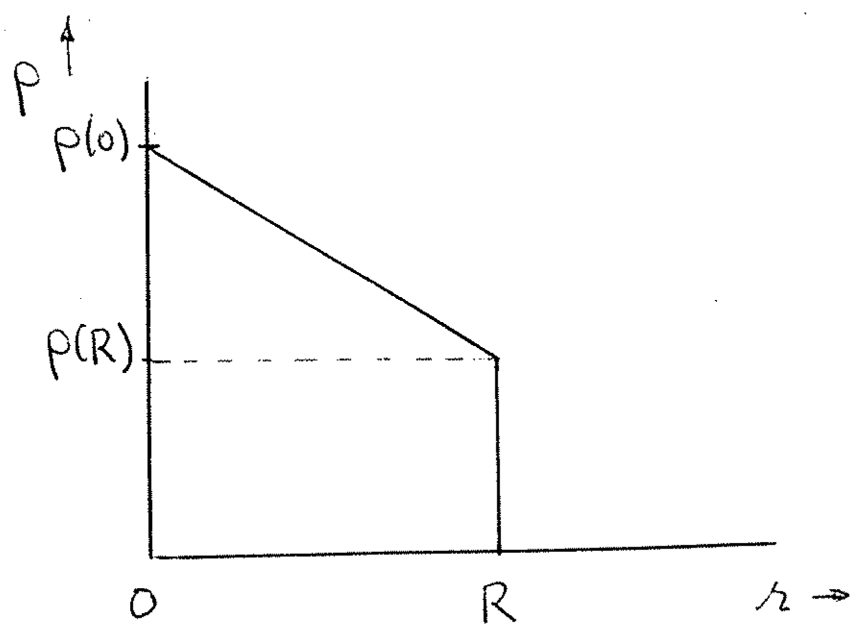
Work carefully, indicate your reasoning, and display your work clearly.. Even if you do not complete a problem, it might be possible to obtain partial credit - especially if your understanding is manifest. Use no scratch paper; do all work in the bluebooks, work each problem in its own numbered bluebook, and be certain that your chosen student letter (but not your name) is inside the back cover of every booklet. Be sure to make note of your student letter for use in the remaining parts of the examination.

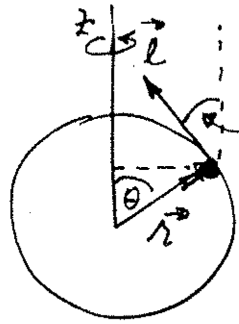
If something is omitted from the statement of the problem or you feel there are ambiguities, please get up and ask your question quietly and privately, so as not to disturb the others. Put all materials, books, and papers on the floor, except the exam, bluebooks and the collection of formulae and data distributed with the exam. Calculators are not allowed. Please return all bluebooks and formula sheets at the end of the exam.

Use the last pages of your bluebooks for "scratch" work separated by at least one page from your solutions. "Scratch" work will not be graded.

OSU Physics Depart. Comp. Exam #77. April 1-2, 1996 **PROB 1**

Starting with the expression $\vec{l} = \vec{r} \times \vec{p}$, for the angular momentum of a point mass, m, having linear momentum, $\vec{p}$, determine an expression for the angular momentum of a sphere of mass, M, and radius, R, whose mass density varies as shown below. The sphere should be considered to be rotating about its diameter.





$$d\vec{l} = \vec{r} \times d\vec{p}$$
$$= \vec{r} \times \vec{v}\, dm$$

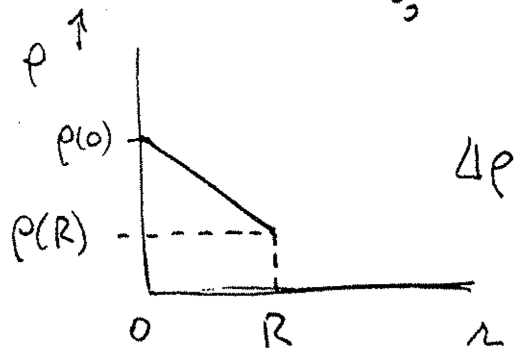
where $dm = \rho\, r^2 \sin\theta \, d\theta \, d\varphi \, dr$

By symmetry, only z-components of the $d\vec{l}$ contributions will survive the integration:

$$L_z = \int dl_z = \iiint r v \cos\left(\frac{\pi}{2} - \theta\right) \rho\, r^2 \sin\theta \, d\theta \, d\varphi \, dr$$

Rigid body allows $v = \omega r \sin\theta$

$$\therefore \quad L_z = \omega \int_0^{2\pi} d\varphi \int_0^{\pi} \sin^3\theta \, d\theta \int_0^R \rho\, r^4 \, dr.$$



$$\Delta\rho = \rho(0) - \rho(R)$$

$$L_z = 2\pi\omega \frac{4}{3} \left\{ \frac{\rho(0) R^5}{5} - \frac{\Delta\rho}{6} R^5 \right\}$$

But $M = 4\pi R^3 \left\{ \frac{\rho(0)}{3} - \frac{\Delta\rho}{4} \right\}$

$$\therefore \quad L_z = \frac{2}{3} \left\{ \frac{\rho(0)/5 - \Delta\rho/6}{\rho(0)/3 - \Delta\rho/4} \right\} M R^2 \omega$$

OSU Physics Depart. Comp. Exam #77. April 1-2, 1996 **PROB 2**

A solid is in equilibrium with an ideal monatomic vapor. The energy required per atom to separate the solid into atoms is ϕ. Consider the solid to be described by the Einstein model for the vibrations in a solid, that is, assume that each atom is represented by a three-dimensional harmonic oscillator of frequency, ω. Find the vapor pressure as a function of temperature.

$$Z_{solid} = e^{N_s \varphi/kT}\left[\sum_{n=0}^{\infty} e^{-(n+\frac{1}{2})\hbar\omega/kT}\right]^{3N_s}$$

$$= e^{N_s\varphi/kT}\left[2\sinh\left(\frac{\hbar\omega}{2kT}\right)\right]^{-3N_s} \equiv \left[\frac{\alpha}{\gamma^3}\right]^{N_s}$$

$$Z_{gas} = \frac{1}{N_g!}\left(\frac{2\pi mkT}{h^2}\right)^{3N_g/2} V^{N_g} = \frac{1}{N_g!}(\Omega V)^{N_g}$$

Constraint: $N_s + N_g = N$, a constant

$$F = -kT\ln Z = -kT\ln Z_s Z_g$$

maximize $\ln Z_s Z_g$ WRT N_g using $N_s = N - N_g$

$$\ln Z_s Z_g = (N-N_g)\ln \alpha/\gamma^3 - N_g\ln N_g + N_g + N_g\ln \Omega V$$

$$\frac{\partial \ln Z_s Z_g}{\partial N_g} = 0 \Rightarrow -\ln\frac{\alpha}{\gamma^3} - \ln N_g - 1 + 1 + \ln \Omega V = 0$$

or $\ln \dfrac{\Omega V}{N_g \alpha/\gamma^3} = 0 \Rightarrow \dfrac{\Omega V}{N_g \alpha/\gamma^3} = 1 \Rightarrow N_g = \dfrac{\Omega V}{\alpha/\gamma^3}$

Now use ideal gas e.q. state $P = N_g kT/V$

$$\text{so } P = \left(\frac{2\pi mkT}{h^2}\right)^{3/2}\left(\frac{2\sinh(\hbar\omega/2kT)}{e^{\varphi/kT}}\right)^3 kT$$

If we could make a quantum-mechanical solenoid that was infinitely long with zero radius it would produce a magnetic vector potential

$$\boldsymbol{A} = \frac{\Phi}{2\pi\rho}\boldsymbol{\varphi},$$

where Φ is a constant. (This is sometimes called the Aharanov-Bohm potential.) You are asked to investigate the solutions of Schrodinger's equation with this potential.

(a) Use the principle of minimal electromagnetic coupling to write the Hamiltonian for this problem.

(b) Solve the time-independent Schrodinger equation using separation of variables $\psi(\rho, \varphi, z) = R(\rho)Q(\varphi)Z(z)$. What is $Z(z)$?

(c) Find $Q(\varphi)$.

(d) What is the differential equation for $R(\rho)$? Expand the general solution to $\psi(\rho, \varphi, z)$ in terms of the (famous) solutions to this equation.

(e) What are the constants of motion?

Note that

$$\boldsymbol{\nabla} = \boldsymbol{\rho}\frac{\partial}{\partial\rho} + \boldsymbol{\varphi}\frac{1}{\rho}\frac{\partial}{\partial\varphi} + \boldsymbol{z}\frac{\partial}{\partial z}$$

$$\nabla^2 = \frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\right) + \frac{1}{\rho^2}\frac{\partial^2}{\partial\phi^2} + \frac{\partial^2}{\partial z^2}$$

Minimal Substitution means replace

$$\vec{p} \Rightarrow \vec{p} - e\vec{A}$$

$$-i\hbar\vec{\nabla} \Rightarrow -i\hbar\vec{\nabla} \quad e\vec{A}$$

$$\vec{p}^{\,2} \Rightarrow \left(-i\hbar\vec{\nabla} - e\vec{A}\right)^2 \qquad \text{Since } \vec{\nabla}\cdot\vec{A} = 0$$

$$= -\hbar^2\nabla^2 + 2i\hbar e\,\vec{A}\cdot\vec{\nabla} + e^2A^2$$

$$= -\hbar^2\left\{\frac{\partial^2}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial^2}{\partial\phi^2} + \frac{\partial^2}{\partial z^2}\right.$$

$$\left. - \frac{2ie}{2\pi\hbar\rho^2}\frac{\partial}{\partial\phi} - \frac{e^2\Phi^2}{(\hbar 2\pi\rho)^2}\right\}$$

Let $\alpha = -e\Phi/2\pi\hbar$

$$= -\hbar^2\left\{\frac{\partial^2}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial}{\partial\rho} + \frac{1}{\rho^2}\left(\frac{\partial}{\partial\phi} + i\alpha\right)^2 + \frac{\partial^2}{\partial z^2}\right\}$$

Then $\quad H\psi = E\psi$

(a) $$\frac{-\hbar^2}{2m}\Big\{\quad\Big\}\psi = E\psi$$

Now do Separation of variables: $\psi = R(\rho)\Phi(\phi)Z(z)$

$$-\frac{\hbar^2}{2m}\left\{\frac{R''}{R} + \frac{1}{\rho}\frac{R'}{R} + \frac{1}{\Phi\rho^2}\left(\Phi'' + 2i\alpha\Phi' - \alpha^2\Phi\right) + Z''/Z\right\} = E$$

c) Let $\Phi \sim e^{im\phi}$ $\quad Z \sim e^{iK_z z}$

d) $$\frac{R''}{R} + \frac{1}{\rho}\frac{R'}{R} + \frac{1}{\rho^2}\left(-m^2 - 2im\alpha - \alpha^2\right)$$

$$- K_z^2 = \frac{-2mE}{\hbar^2}$$

Let $\frac{2mE}{\hbar^2} - K_z^2 = K^2 - K_z^2 = \bar{K}^2$

$$-m^2 - 2im\alpha - \alpha^2 = -\beta^2$$

Then we have

$$R'' + \frac{1}{\rho} R' + \left(\bar{K}^2 - \frac{\beta^2}{\rho^2}\right) R = 0$$

This is Bessel's eqn. if we let $R = R(\bar{K}\rho)$

$$\frac{d^2R}{dx^2} + \frac{1}{x}\frac{dR}{dx} + \left(1 - \frac{\beta^2}{x^2}\right) R = 0$$

where $x \equiv \bar{K}\rho$

The general soln is an expansion in Bessel fn.

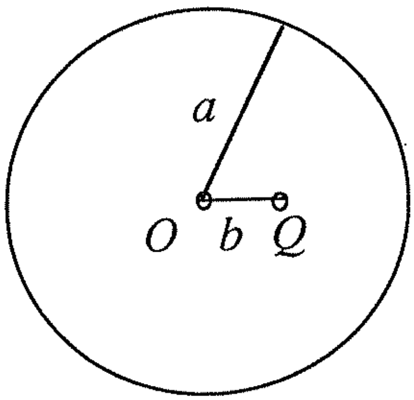
$$\psi = e^{iK_z z} \sum_{m=-\infty}^{+\infty} A_\beta J_\beta(\bar{K}\rho)\, e^{im\phi}$$

β is not an integer in general and J_β must include all independent B fn that are regular at $\rho \to \infty$.

(c) The solutions (without the sum) are eigenfunctions of K_z, L_z, and H. The corresponding eigenvalues are K_z, m, E.

A hollow conducting sphere of radius a contains a point charge Q at the radius b.

Calculate the force of attraction between the point charge and the sphere.



Use method of images: place charge Q' outside sphere at radius D ,
choose Q' and D so sphere is equipotential.
Symmetry $\Rightarrow$ image charge on same axis as original charge

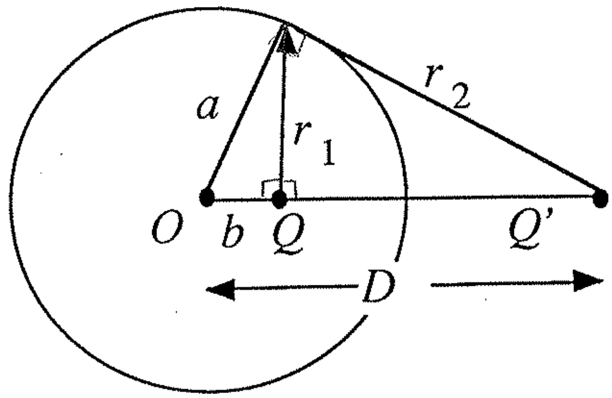
First find the distances from the geometry:

look at triangles formed by the center O,

the point on the surface ($r=a$, θ, ϕ), and either:

Q : then $r_1^2 = a^2 + b^2 - 2ab\cos\theta$;

or Q' : then $r_2^2 = a^2 + D^2 - 2aD\cos\theta$



when $D = a^2/b$, then $r_2^2 = a^2 + a^4/b^2 - 2a^3/b\cos\theta = \frac{a^2}{b^2} r_1^2$, so $r_2 = \frac{a}{b} r_1$

total potential $V(r=a, \theta, \phi) = \frac{Q}{4\pi\varepsilon_0 r_1} + \frac{Q'}{4\pi\varepsilon_0 r_2} = \frac{Q}{4\pi\varepsilon_0 r_1}\left(1 + \frac{Q'}{Q}\frac{r_1}{r_2}\right) = 0$ when $\frac{Q'}{Q} = -\frac{a}{b}$

The electric field at Q due to the surface charges is the same as that due to Q',

and so is the force on Q: $|F| = \frac{|QQ'|}{4\pi\varepsilon_0 (D-b)^2}$ directed radially outward

OSU Physics Depart. Comp. Exam #77. April 1-2, 1996 **PROB 5**

When compressed, a gas exhibits a change in temperature given by $T = \left(V / V_o \right)^{\eta} T_o$, where V_0 and T_0 are the initial volume and temperature, and η is a constant. The gas is ideal, and the process is quasi-static.

a. Find the work W done on the gas.

b. Find the change in energy ΔU of the gas.

c. Find the heat Q transferred to the gas through the walls by using the results of (a) and (b).

d. Find the heat Q transferred by integrating $dQ = TdS$.

e. From the results of (c) and (d), for what value of η is $Q = 0$? Show that for this value of η the path followed in the compression process is that of an adiabat.

$$T = \left(\frac{V}{V_0}\right)^n T_0$$ for quasi-static compression to $V < V_0$

a) $dW_{on} = -PdV \Rightarrow W_{on} = -\int PdV = -NR\int_{V_0}^{V} \frac{T\,dV}{V}$

$$W_{on} = -NR\int_{V_0}^{V} \frac{T_0}{V_0^n} V^{n-1}dV = -\frac{NRT_0}{V_0^n}\frac{1}{n}\left[V^n - V_0^n\right]$$

b) $\Delta U = \frac{3}{2}NR(T-T_0) = \frac{3}{2}NRT_0\left(\left(\frac{V}{V_0}\right)^n - 1\right)$

c) $\Delta U = Q + \Delta W_{on} \Rightarrow Q = \Delta U - \Delta W_{on}$

$$Q = NRT_0\left\{\frac{3}{2}\left(\left(\frac{V}{V_0}\right)^n - 1\right) + \left(\frac{1}{nV_0^n}\right)\left[V^n - V_0^n\right]\right]$$

$$Q = \frac{NRT_0}{V_0^n n}\left(\frac{3}{2}n+1\right)\left[V^n - V_0^n\right]$$

d) $dQ = TdS$ where $dS = \frac{1}{T}dU + \frac{P}{T}dV = \frac{3}{2}NR\frac{dT}{T} + \frac{NR}{V}dV$

but $dT = \frac{nT_0}{V_0^n}V^{n-1}dV$, so $\frac{3}{2}NR\frac{dT}{T} = \frac{3}{2}NR\frac{1}{T_0}\left(\frac{V_0}{V}\right)^n \frac{nT_0V^{n-1}}{V_0^n}dV$

and $dS = \frac{3}{2}NRn\frac{dV}{V} + NR\frac{dV}{V} = NR\left(\frac{3}{2}n+1\right)\frac{dV}{V}$

$$\Delta S = NR\left(\frac{3}{2}n+1\right)\ln\frac{V}{V_0}$$

And $dQ = NR\left(\frac{3}{2}n+1\right)\frac{1}{V}\left(\frac{V}{V_0}\right)^n T_0\,dV = NRT_0\left(\frac{3}{2}n+1\right)\frac{1}{V_0^n}V^{n-1}dV$

So $Q = \frac{NRT_0\left(\frac{3}{2}n+1\right)}{V_0^n}\frac{1}{n}\left(V^n - V_0^n\right)$

e) $Q = 0 \Rightarrow n = -2/3$

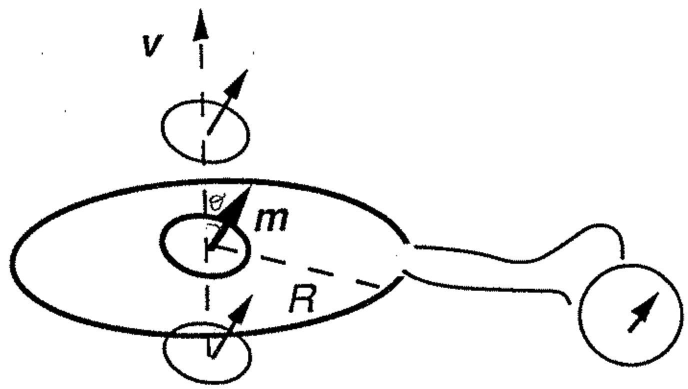
For an ideal gas (monatomic) compressed adiabatically (   ) $\frac{V}{V_0} = \left(\frac{T_0}{T}\right)^{3/2}$

or $\left(\frac{V}{V_0}\right)^{2/3} = \frac{T_0}{T}$ or $T = T_0\left(\frac{V}{V_0}\right)^{-2/3} = T_0\left(\frac{V}{V_0}\right)^n$ as originally declared

A small current loop of dipole moment $\boldsymbol{m}$ moves with velocity v along the axis of a large circular conducting loop of radius R. The centers of the loops coincide at $t = 0$.

The angle between $\boldsymbol{m}$ and v is θ.

If you must, assume $v \ll c$ for partial credit.



(a) (10 pts) Prove that the total magnetic flux through the *plane* of the large loop is zero.

(b) (10 pts) Find the emf induced in the large loop, as a function of time t, for the case $\theta = 0$.

possible hint: for a dipole at rest, $\boldsymbol{B}(r) = \dfrac{\mu_0 m}{4\pi r^3}\,(\hat{r}\ 2\cos\theta + \hat{\theta}\sin\theta)$

(a) Actually the total magnetic flux through any closed surface is zero, which follows from integrating $\nabla \cdot \boldsymbol{B}$ over a volume enclosed by the surface (there are no magnetic charges).

The plane under discussion is not a closed surface, but we can make it one by adding a hemisphere at infinity. Since the dipole field falls off faster than $1/r^2$, its integral over the surface at infinity vanishes, so we are left with the integral over the plane which has to be zero too.

Simpler argument, not rigorous, part credit: Every flux line that passes through the plane comes back again, so its contributions to the flux cancel.

(b) We know $\boldsymbol{B}$ for a magnetic dipole at rest at the origin, $\boldsymbol{B}(r) = \frac{\mu_0 m}{4\pi r^3}(\hat{r}\ 2\cos\theta + \theta \sin\theta)$

We need the boosted $\boldsymbol{B}'$ in the frame where the dipole is moving along the z-axis.
First we use the result of part (a) to show that

$$\Phi = \int d\mathcal{A}\cdot\boldsymbol{B}' = \int_0^{2\pi} d\phi' \int_0^R r'\,dr'\ B'_{||} = -\int_0^{2\pi} d\phi' \int_R^\infty r'\,dr'\,B'_{||}$$

Fortunately we only need the parallel component of $\boldsymbol{B}'$, since the motion is perpendicular to the surface. The parallel component of $\boldsymbol{B}$ is independent of the frame.

$$B_{||} = \boldsymbol{B}\cdot\hat{z} = \frac{\mu_0 m}{4\pi r^3}(\hat{r}\cdot\hat{z}\ 2\cos\theta - \theta\cdot\hat{z}\sin\theta) = \frac{\mu_0 m}{4\pi r^3}(2\cos^2\theta - \sin^2\theta) = \frac{\mu_0 m}{4\pi r^5}(2r_{||}^2 - r_\perp^2)$$

$$= \frac{\mu_0 m}{4\pi}\frac{2r_{||}^2 - r_\perp^2}{(r_{||}^2 + r_\perp^2)^{5/2}} = \frac{\mu_0 m}{4\pi}\frac{2\gamma^2(z'-vt')^2 - r'^2_\perp}{(\gamma^2(z'-vt')^2 + r'^2_\perp)^{5/2}} = B'_{||}$$

In the plane, $z' = 0$, $r'^2_\perp = r'^2$, so

$$\Phi = -\int_0^{2\pi} d\phi' \int_R^\infty r'\,dr'\ \frac{\mu_0 m}{4\pi}\frac{2(\gamma v t')^2 - r'^2}{((\gamma v t')^2 + r'^2)^{5/2}} = -\frac{\mu_0 m}{4}\int_{R^2}^\infty d(r'^2)\ \frac{2(\gamma v t')^2 - r'^2}{((\gamma v t')^2 + r'^2)^{5/2}}$$

change variables, $u = (\gamma v t')^2 + r'^2$, $du = d(r'^2)$,

$$\Phi = -\frac{\mu_0 m}{4}\int_{(R^2+\gamma^2 v^2 t'^2)}^\infty du\ \frac{3(\gamma v t')^2 - u}{u^{5/2}} = -\frac{\mu_0 m}{4}\left(2\frac{\gamma^2 v^2 t^2}{(R^2+\gamma^2 v^2 t'^2)^{3/2}} - \frac{2}{(R^2+\gamma^2 v^2 t'^2)^{1/2}}\right)$$

$$= \frac{\mu_0 m}{2}\frac{R^2}{(R^2+\gamma^2 v^2 t'^2)^{3/2}},$$

$$\mathcal{V}_{emf} = -\frac{d\Phi}{dt'} = \frac{3\mu_0 m}{2}\gamma^2 v^2 t'\ \frac{1}{(R^2+\gamma^2 v^2 t'^2)^{5/2}}$$

OSU Physics Depart. Comp. Exam #77. April 1-2, 1996 **PROB 7**

An important case of fluid flow is that known as irrotational flow. In such cases, the velocity vector, $\vec{v}$, can be expressed in terms of the gradient of a potential function, $\Phi(\vec{r},t)$, i.e., $\vec{v} = -\vec{\nabla}\Phi$.

Consider a cylindrical column of length, L, and radius, a, filled with a compressible fluid. The walls of this cylinder are rigid, as are the end faces of it. The situation is illustrated in the figure below.

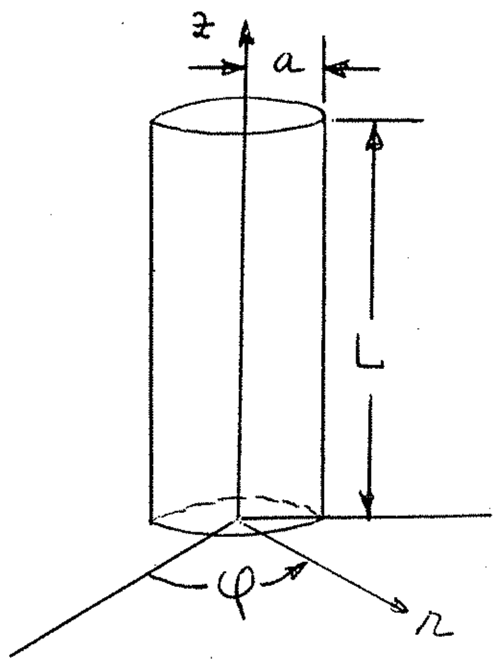
For small-amplitude motion, $\Phi(\vec{r},t)$ satisfies the wave equation, with small oscillations being described by

$$\Phi(\vec{r},t) = \Re e\Phi(\vec{r})e^{-i\omega t}$$

Determine

(a) the form of $\Phi(\vec{r},t)$, and

(b) the eigenfrequencies $\{\omega_{mnp}\}$ of the normal modes available to such a system.



Consider a process in which an electron and a positron are emitted collinearly in the +y and -y direction, respectively. Spins are polarized to lie in the ±z directions. The pair is emitted with zero linear and spin-angular momentum and with total energy $\hbar\omega$. With the electron labeled 1 and the positron labeled 2:

(a) Write down a spin-coordinate, time-dependent product wavefunction for the electron-positron pair which contains these properties.

(b) What is the probability that measurement finds the electron's z component of spin equal to $+\hbar/2$?

(c) Suppose the measurement of the positron's z component of spin finds the value $-\hbar/2$, what is the wavefunction for the pair immediately after this measurement?

(d) What will measurement of the electron's z component of spin now find?

Solutions for $R(r)$: Solution must be bounded at origin and have zero slope at $r = a$. This eliminates $k^2 < 0$.

$\therefore\ k^2 > 0$ and $R(r) = J_m(kr)$

$$J_m'(ka) = 0 \rightarrow k_{mn} = \frac{\alpha'_{m,n}}{a}$$

where $\alpha'_{m,n}$ is the n^{th} root of the eqn

$$J_m'(\alpha'_{m,n}) = 0$$

$\therefore$

(a) $$\Phi(\vec{r},t) = \mathrm{Re}\ \Phi_0\, J_m\!\left(\alpha'_{m,n}\frac{r}{a}\right)\cos\frac{p\pi z}{L}\, e^{im\varphi - i\omega_{mnp}t}$$

where

(b) $$\omega^2_{mnp} = c^2 k^2_{mnp}$$

$$= c^2\left[\left(\frac{\alpha'_{m,n}}{a}\right)^2 + \left(\frac{p\pi}{L}\right)^2\right].$$

2. (a) $\psi = c\left(u_+(1)\,u_-(2) - u_-(1)\,u_+(2)\right) e^{ik(y_1-y_2)}\, e^{-i\hbar\omega t}$

$c = 1/2\pi\sqrt{2}$ $\hbar\omega = 2\left(\frac{\hbar^2 k^2}{2m}\right)$

(b) 50%

(c) $\psi = \left(\frac{1}{2\pi}\right) u_+(1)\, u_-(2)\, e^{ik(y_1-y_2)}\, e^{-i\hbar\omega t}$

(d) $+\hbar/2$

In my notation u_+ means spin up etc.

$u_+ = \begin{pmatrix}1\\0\end{pmatrix}$ $u_- = \begin{pmatrix}0\\1\end{pmatrix}$

$$\nabla^2 \Phi(\vec{r}) + k^2 \Phi(\vec{r}) = 0$$

$$\frac{\partial \Phi}{\partial r} = 0, \quad \text{at } r = a$$

$$\frac{\partial \Phi}{\partial z} = 0, \quad \text{at } z = 0 \text{ and } z = L.$$

$$\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial \Phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \Phi}{\partial \varphi^2} + \frac{\partial^2 \Phi}{\partial z^2} + k^2 \Phi = 0$$

Try $\Phi(r, \varphi, z) = R(r)\, F(\varphi)\, Z(z)$

$$F(\varphi) = e^{\pm i m \varphi} \qquad m = 0, \pm 1, \pm 2, \dots$$

$$Z(z) = e^{\pm i \alpha z}$$

$Z'(0) = 0 \rightarrow \cos \alpha z$, while $Z'(L) = 0$ requires that

$$\alpha = p\frac{\pi}{L}, \quad p = 0, 1, 2, \dots, \infty$$

The radial portion of the DEQ can be put as Bessel's DEQ:

$$\frac{d}{dr}\left(r \frac{dR}{dr}\right) - \frac{m^2}{r} R + ~~\kappa~~ \kappa^2 r R = 0$$

where $\kappa^2 = k^2 - \left(\frac{p\pi}{L}\right)^2$

COMPREHENSIVE EXAMINATIONS

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		Spring 88	Spring 90	Spring 92						

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