

# PHY293 Abridged

Aman Bhargava

September 2019

# Contents

0.1	Introduction . . . . .	3
<b>1</b>	<b>Simple Harmonic Oscillators (SHO's)</b>	<b>4</b>
1.1	Set Up . . . . .	4
1.2	ODE and Solution . . . . .	4
<b>2</b>	<b>Dampened Harmonic Oscillators (DHO's)</b>	<b>5</b>
2.1	Set Up . . . . .	5
2.2	ODE and Solutions . . . . .	5
2.2.1	General Solution . . . . .	5
2.2.2	Regieme 1: Underdampened . . . . .	6
2.2.3	Regieme 2: Heavily Dampened . . . . .	6
2.2.4	Regieme 3: Critically Dampened . . . . .	7
2.3	Energy . . . . .	7
2.3.1	Underdampened Energy . . . . .	7
2.3.2	Critical and Overdampened Energy . . . . .	7
2.4	Q-Factor . . . . .	7
<b>3</b>	<b>Forced Oscillators</b>	<b>9</b>
3.1	Equation of Motion ODE . . . . .	9
3.2	Solution: Undamped Forced Oscillator . . . . .	9
3.2.1	$\omega = \omega_0$ . . . . .	9
3.3	Solution: Forced Damped Oscillators . . . . .	9
3.4	Transient Response . . . . .	10
3.5	Power in FDHO's . . . . .	10
3.5.1	Average Power Per Cycle . . . . .	10
3.5.2	Power vs. $\omega$ . . . . .	11
<b>4</b>	<b>Coupled Oscillators</b>	<b>12</b>
4.0.1	How to Solve Coupled Systems . . . . .	12
4.0.2	Review: Results from Linear Algebra . . . . .	13

<b>5</b>	<b>Standing Waves</b>	<b>14</b>
5.1	Expectations and Takeaways . . . . .	14
5.2	The Taut String . . . . .	15
5.3	Solution to Wave Equation . . . . .	15
5.3.1	Boundary Conditions . . . . .	15
5.3.2	Final Solution . . . . .	16
5.3.3	Surrounding Math . . . . .	16
5.3.4	Energy Considerations . . . . .	16
<b>6</b>	<b>Travelling Waves</b>	<b>17</b>
6.1	Energy Considerations . . . . .	17
6.2	Power Considerations . . . . .	18
6.3	Reflection and Transmission . . . . .	18
6.4	travelling Waves in Multiple Dimensions . . . . .	19
<b>7</b>	<b>Dispersion</b>	<b>20</b>
7.1	Example of Dispersive Waves . . . . .	20
<b>8</b>	<b>Special Relativity</b>	<b>21</b>
8.1	Introduction . . . . .	21
8.2	Formulae . . . . .	21
8.2.1	Time Dilation . . . . .	21
8.2.2	Length Contraction . . . . .	22
8.2.3	Relativistic Events: Location and Time . . . . .	22
8.2.4	Relativistic Energy and Momentum . . . . .	22
8.2.5	4-Vectors . . . . .	22
<b>9</b>	<b>Quantum</b>	<b>24</b>
9.1	Particle Energy, Wave Energy . . . . .	24
9.2	Compton Scattering . . . . .	24
9.3	Photoelectric Effect . . . . .	24
9.4	Hydrogen Model . . . . .	24
9.5	De Broglie Waves . . . . .	24
9.6	Wave-Particle Duality . . . . .	24
9.6.1	Uncertainty Principle . . . . .	24
9.6.2	Double Slit Experiment . . . . .	24
9.7	Black Body Radiation . . . . .	24
<b>10</b>	<b>Matter Waves and The Schrödinger Equation</b>	<b>25</b>
10.1	Normalization and Probability . . . . .	25
10.2	Energy Considerations . . . . .	25

10.3	Infinite Well . . . . .	26
10.3.1	Superposition . . . . .	26
10.4	Expectation Values . . . . .	27
10.5	Operators . . . . .	27
10.6	Schrödinger's For Free Particle . . . . .	27

## 0.1 Introduction

Prof. Grisouard has put up some pretty solid notes written in jupyter notebooks. Those offer a great comprehensive guide for the course contents. The goal here is to give a very concise overview of the things you need to know (NTK) to answer exam questions. Unlike some of our other courses, you don't need to be very intimately familiar with the derivations of everything in order to solve the problems (though it certainly doesn't hurt). Think of this as a really good cheat sheet.

# Chapter 1

## Simple Harmonic Oscillators (SHO's)

### 1.1 Set Up

Pretty much the same as covered last year.

$$F_{restorative} = -kx$$

$$F_{net} = ma$$

$$ma + kx = 0$$

We let  $\omega_0^2 = k/m$  and rename  $a$  to  $\ddot{x}$

### 1.2 ODE and Solution

ODE:

$$\ddot{x} + \omega_0^2 x = 0$$

Solution:

$$x(t) = a \cos(\omega_0 t + \theta)$$

Solve for 2 unknowns (usually  $a$  and  $\theta$ ) based on two initial conditions.

## Chapter 2

# Dampened Harmonic Oscillators (DHO's)

### 2.1 Set Up

We have all the same forces from last time plus the force of friction.

$$F_{friction} = F_f = -bv$$

### 2.2 ODE and Solutions

**ODE** We let  $\gamma = b/m$  so that:

$$\ddot{x} + \gamma\dot{x} + \omega_0^2 x = 0$$

#### 2.2.1 General Solution

And for underdampened and over dampened, the overall solution looks like:

$$x(t) = ae^{rt}$$

Where  $a, r \in \mathbb{C}$ , remembering that

$$e^{i\theta} = i\sin(\theta) + \cos(\theta)$$

This is actually really cool, because the existence of a complex component in  $r$  is what enables oscillation.

If we populate the initial ODE with the derivatives of our  $x(t)$ , we get:

$$ar^2e^{rt} + \gamma are^{rt} + \omega_0^2 ae^{rt} = 0$$

$$r^2 + \gamma r + \omega_0^2 = 0$$

This results in a simple quadratic for which you can solve for  $r$  using the quadratic formula.

$$x = \frac{b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$r = \frac{\gamma \pm \sqrt{\gamma^2 - 4\omega_0^2}}{2}$$

There will be up to 2  $r$  values. Since the solution space is a 2-D vector space, any linear combination of vectors (i.e. values of  $r$ ) is still a valid vector.

You might be wondering how  $a$  figures into this whole thing. That's just based on initial conditions, really.

### 2.2.2 Regime 1: Underdamped

If the dampening is weak enough, there will still be **some** oscillation before the oscillator comes to rest. In this case, the general solution is:

$$x(t) = A_0 e^{-\gamma t/2} \cos(w_d t + \phi)$$

Where  $w_d^2 = w_{damped}^2 = \omega_0^2 - \frac{\gamma^2}{4}$

You get this by solving for  $r$  with the quadratic formula, plugging the two imaginary roots in, then taking just the real components because you know that  $x(t)$  is real.

#### Logarithmic Decrement

This quantity is the  $\ln$  of the ratio of 1 peak to the next.

$$\frac{\gamma T_d}{2}$$

Where  $T_d$  is the period based on  $w_d$ .

### 2.2.3 Regime 2: Heavily Damped

In this case both roots are real. This occurs when  $\gamma^2 - 4\omega_0^2 > 0$

Let  $r_p, r_m$  be the two real roots. Then the solution is:

$$x(t) = a_p e^{r_p t} + a_m e^{r_m t}$$

You can solve for the  $a$  values at leisure with two initial conditions.

### 2.2.4 Regime 3: Critically Dampened

When the discriminant of the quadratic is zero (i.e.  $\gamma^2 = 4\omega_0^2$ ), you get an overconstrained problem because you have fewer unknowns than you have constraints. Therefore, the new solution for this exact case is:

$$x(t) = (A + Bt)e^{-\gamma t/2}$$

And it decays the fastest and is pretty cool. Yay.

## 2.3 Energy

$$\begin{aligned} E &= K + U \\ E &= \frac{1}{2}mv^2 + \frac{1}{2}kx^2 \\ \frac{dE}{dt} &= -bv^2 \end{aligned}$$

### 2.3.1 Underdampened Energy

The equations get really messy so we assume that  $\omega_0 \gg \gamma/2$  and  $\omega_0 = \omega_d$ . After you sub everything in and use the pythagorean identity to cancel out the squared sine/cosine, you get:

$$E = \frac{1}{2}kA_0^2 e^{-\gamma t}$$

### 2.3.2 Critical and Overdampened Energy

These ones are really easy, they just decay and that's it. Just remember the equations for energy and solve for the velocity equation.

## 2.4 Q-Factor

$Q$  is a measure of the tendency to oscillate divided by the tendency to dampen.

$$Q = \frac{\omega_0}{\gamma}$$

Let  $\tau = \frac{1}{\text{gamma}}$  be proportional to the lifetime of the oscillator. Then  $n = \frac{\tau}{T_0}$  is the number of cycles in a lifetime.

$$Q = 2\pi n$$



$Q$  is also proportional to the rate at which dampening removes energy from the system. Then

$$E_n = E_0 e^{-\gamma t}$$

Represents the amount of mechanical energy in the system at time  $t$ .

$$\frac{E_n - E_{n+1}}{E_n} = \dots = \frac{2\pi}{Q}$$

Therefore  $Q$  is the energy in oscillator divided by the amount of energy lost at the following **radian**.

# Chapter 3

## Forced Oscillators

### 3.1 Equation of Motion ODE

$$\ddot{x} + \omega_0^2 x = F'_0 \cos(\omega t)$$

Where  $\omega_0^2 = k/m$ ,  $F'_0 = F_0/m$ ,  $\omega$  is the driving frequency.

### 3.2 Solution: Undamped Forced Oscillator

$$x(t) = A(\omega) \cos(\omega t - \delta(\omega))$$

Where

$$\delta(\omega_0) = 0 \text{ if } \omega < \omega_0, \text{ else } \pi$$

If you shake it too fast, it'll vibrate in exactly opposite phase.

$$A(\omega) = \left| \frac{\omega_0^2}{\omega_0^2 - \omega^2} A_f \right|$$

#### 3.2.1 $\omega = \omega_0$

Perfect resonance makes amplitude tend toward infinity.

$$x(t) = \frac{A_f \omega_0}{\sqrt{2}} t \cos(\omega_0 t - \frac{\pi}{4})$$

### 3.3 Solution: Forced Damped Oscillators

Equation of Motion:  $\ddot{x} + \gamma \dot{x} + \omega_0^2 x = A_f \omega_0^2 \cos(\omega t)$

**General Solution:** Same as before

$$x(t) = A(\omega)\cos(\omega t - \delta(\omega))$$

**Updates to  $A$  and  $\delta(\omega)$ :**

$$A(\omega) = \frac{\omega_0^2}{\sqrt{\gamma^2\omega^2 + (\omega_0^2 - \omega)^2}} A_f$$

$$\tan[\delta(\omega)] = \frac{\gamma\omega}{\omega_0^2 - \omega^2}$$

**Maximum  $A(\omega)$**  occurs when  $\omega = \omega_0^2 - \frac{\gamma^2}{2}$ . In other words,

$$\omega_{max} = \omega_0^2 \left[1 - \frac{1}{2Q^2}\right]$$

$$\therefore A_{max} = \frac{Q}{\sqrt{1 - \frac{1}{4Q^2}}} A_f$$

### 3.4 Transient Response

When you suddenly start a damped, forced oscillator, you have one mode that is the long-term response and one that is the transient response (as if there is no forcing).

$$x_{free} = A_{free}e^{-\gamma t/2}\cos(\omega_d t + \phi)$$

$$x_{forced} = A(\omega)\cos(\omega t - \delta(\omega))$$

$x_{free}$  tend toward zero and only exists for the beginning, so it is the transient response.

### 3.5 Power in FDHO's

$$\therefore -\dot{E}(w, t) = P(w, t) = bv^2 = bV^2(w)\sin^2(\omega t - \delta)$$

Where  $V$  is the amplitude of the velocity.

#### 3.5.1 Average Power Per Cycle

$$\bar{P}(w) = \frac{F_0^2}{2m} \frac{\gamma}{\gamma^2 + (\omega_0^2/\omega - \omega)^2}$$

**Maximizing Case:**  $\bar{P}$  is maximized when  $w = w_0$

### **3.5.2 Power vs. $\omega$**

Let us plot  $\bar{P}(w)$  vs.  $\omega/\omega_0$ . The  $\omega_{fullwidthhalfheight} = \omega_{fwhh} = \gamma$

# Chapter 4

## Coupled Oscillators

### Main Takeaways

- Motion of coupled systems is a linear combination of orthogonal forms of motion.
- Motion can be found via 2x2 matrix system
- Each normal mode has a unique frequency common to all elements.
- ‘Eigen’ = ‘normal’.
- **Beating** = when frequencies of modes are very close.

### 4.0.1 How to Solve Coupled Systems

From tutorial note:

#### Determine Equations of Motion

You must give each mass its own coordinate system where deviation in one direction adds to the zero coordinate and deviation to the other subtracts from the zero coordinate.

Implement  $f = ma$  and  $f = kx$  to create equations of motion of each mass depending on its position and the position of its neighbouring masses.

Now we have

$$m\ddot{x}_a = \dots$$

...

$$m\ddot{x}_c = \dots$$

**Assume  $\exists$  a normal mode**

This implies that

$$x_a = A \cos(\omega t)$$

...

$$x_c = C \cos(\omega t)$$

All we need to solve for now is  $\omega$ , and  $A \rightarrow C$ . To do so, we sub our definitions for  $x_a, x_b$ , and  $x_c$  into our initial EoM, which gives us relationships between  $A, B, C, \omega$  (cosines cancel out!)

Now we just have to put everything in a matrix equation of the form:

$$[\dots][A, B, C] = [0, 0, 0]$$

$$[M][A, B, C] = [0, 0, 0]$$

which implies that  $\det(M) = 0$ . This will give us 3 different eigen frequencies (or however many degrees of freedom we have). From there, we just have to solve for the coefficients  $A, B, C$  via initial conditions, remembering that  $x_a = A \cos(\omega t)$  and so on!

#### **4.0.2 Review: Results from Linear Algebra**

- $Av = \lambda v, (A - \lambda I)v = 0$
- We get non-trivial solutions for  $v$  if  $\det(A - \lambda I) = 0$
- A matrix is diagonalizable if  $\exists n$  eigen values  $\lambda$  (sufficient, not necessary)
- Each solution to the initial  $Ax = b$  is unique because the eigen vectors form a basis.

#### **Connecting Eigen Things to Real Things**

- Each  $\lambda_i = \omega_i^2$

# Chapter 5

## Standing Waves

**travelling wave:** a travelling disturbance where no matter travels on average.

**Continuum:** infinite coupled oscillators  $\rightarrow$  infinite modes can arise, characterized by nodes and antinodes.

Boundaries give rise to standing waves (think about boundaries on a plucked guitar string).

### 5.1 Expectations and Takeaways

1. Wave equation is

$$\frac{\partial^2 y}{\partial t^2} = v^2 \frac{\partial^2 y}{\partial x^2}$$

2. Phase speed equation is

$$v = \sqrt{\frac{T}{\mu}}$$

3. **Seperation of variables** is when you
4. Wavenumbers  $k_n$  are basically the number of antinodes in the given mode and angular frequencies  $\omega_n$  are frequency at which mode  $n$  vibrates, wavelengths  $\lambda_n$  are the physical length of each wave in the mode  $n$ .
5. Orthogonality relates how different modes of oscillations in standing waves don't interact.
6. Total energy = sum of energy in each mode of oscillation.

## 5.2 The Taut String

Properties of a taut string:

- $\tan\theta = \frac{dy}{dx} \ll 1$  where  $x$  is along the string and  $y$  is across the string.
- Vibrations occur in only one plane
- **Phase speed** is  $v^2 = T/\mu$  with  $T$  as **tension** and  $\mu$  as **mass per unit length of string**.

**WAVE EQUATION:**

$$\frac{\partial^2 y}{\partial t^2} = v^2 \frac{\partial^2 y}{\partial x^2}$$

## 5.3 Solution to Wave Equation

We assume that the solution is of the form

$$y(x, t) = f(x)h(t)$$

so that it is separable and works nicely with the wave equation. When we sub this into the wave equation, we get:

Let

$$\frac{1}{h(t)} \frac{d^2 h(t)}{dt^2} = -w^2 = v^2 \frac{1}{f(x)} \frac{d^2 f(x)}{dx^2}$$

So we can still have a  $w^2$  that fits well into our SHO ODE:

$$h(t) = H \cos(wt + \phi)$$

$$f(x) = A \cos(kx) + B \sin(kx)$$

where  $k = w/v$

### 5.3.1 Boundary Conditions

We know that  $y(t, 0) = y(t, L) = 0$  because the string is secured on either end. This forces the  $A$  term in the equation  $f(x) = A \cos(kx) + B \sin(kx)$  to be zero, so now  $f(x) = B \sin(kx)$ . Now  $f(kL) = 0$  for any natural number  $k$ .

$$k_n = \frac{n\pi}{L}, \quad n \in \mathbb{N}$$

Recall that  $k = w/v$  so now  $w_n = \frac{n\pi v}{L}$ .



### 5.3.2 Final Solution

$$y_n(x, t) = C_n \cos(w_n t + \phi_n) \sin(k_n x)$$

$$y(x, t) = \sum_{n=1}^{\infty} y_n(x, t)$$

### 5.3.3 Surrounding Math

We need some tools to do proofs and reasoning about these standing and travelling waves.

$$f \odot g = \frac{2}{L} \int_0^L f(x)g(x)dx$$

which represents the inner product of the vector space and  $\delta_{mn}$  which is 1 when  $m = n$ .

$$\sin(k_n x) \odot \sin(k_m x) = \delta_{mn}$$

Because they are orthogonal to eachother.

### 5.3.4 Energy Considerations

$$E_n = \frac{1}{4} \mu L w_n^2 A_n^2$$

# Chapter 6

## Travelling Waves

The real general solution to the wave equation:

$$\frac{\partial^2 y}{\partial t^2} = v^2 \frac{\partial^2 y}{\partial x^2}$$

$$y(x, t) = f(x - vt) + g(x + vt)$$

It can be shown via trig sums that this is the same as the standing wave solution when you put it between two boundaries.

**Most common travelling wave function:**

$$y(x, t) = A \sin\left(\frac{2\pi}{\lambda}(x \pm vt)\right)$$

$$= A \sin(k(x \pm vt))$$

$$= A \sin(kx \pm \omega t)$$

- $\lambda$  = wavelength
- $k$  = wavenumber
- $\omega^2 = v^2 k^2$ ,  $k$  is the wave number.
- $\frac{2\pi}{\omega} = \text{period}$

### 6.1 Energy Considerations

$$K = \frac{1}{2} \mu \left( \frac{\partial y}{\partial t} \right)^2$$

$$U = \frac{1}{2}\mu v^2 \left(\frac{\partial y}{\partial x}\right)^2$$

$\langle \rangle$  corresponds to integration over one wavelength, so  $\langle f \rangle = \int_0^\lambda f(x)dx$ .

To find  $\langle E \rangle$  we can apply the above formulae for  $K$  and  $U$  to the general solution  $y(x, t) = A\cos(kx - \omega t)$ .

$$\langle E \rangle = \frac{1}{2}\mu\lambda A^2\omega^2$$

## 6.2 Power Considerations

Since these waves are unbounded travelling entities, it's useful to consider how much energy they transport past a certain point per second.

We start with instantaneous energy  $E = \mu A^2 \omega^2 \sin^2(kx - \omega t)$ . Then

$$\bar{P} = \frac{\omega \langle E \rangle}{2\pi} = \frac{\mu\lambda A^2 \omega^3}{4\pi} = \frac{\mu A^2 \omega^2 v}{2}$$

## 6.3 Reflection and Transmission

When medium changes discontinuously, you get reflection and transmission. The boundary conditions at the discontinuity are

**Boundary Condition 1:** matching frequency, amplitude, and phase.

**Boundary Condition 2:** transverse (across-string) forces must match.

Therefore we know that

$$y_T(x, t) = A_T \cos(\omega t - k_t x)$$

$$y_R = A_R \cos(\omega t + k_r x)$$

have the same  $\omega t$  term, and  $k_R, k_T > 0$  so they propagate in the right directions. The reflected wave is in the same original medium, so its spatial frequency  $k_R = k_I = \omega/v_1$  while  $k_T = \omega/v_2$ .

Now the only numbers that aren't known are  $A_R, A_T$ . According to boundary condition 1,  $A_I + A_R = A_T$ . Now we use boundary condition to solve for

$$\frac{A_T}{A_I} = \frac{2k_1}{k_1 + k_2} = \tau_{12} = \frac{2\sqrt{\mu_1}}{\sqrt{\mu_1} + \sqrt{\mu_2}}$$

$$\frac{A_R}{A_I} = \frac{k_1 - k_2}{k_1 + k_2} = \rho_{12} = \frac{\sqrt{\mu_1} - \sqrt{\mu_2}}{\sqrt{\mu_1} + \sqrt{\mu_2}}$$

## 6.4 travelling Waves in Multiple Dimensions

The wave equation become:

$$\frac{\partial^2 f}{\partial t^2} = v^2 \nabla^2 f = v^2 \left[ \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} \right]$$

# Chapter 7

## Dispersion

For non-dispersive waves (the ones we have been talking about up to this point), the following relationship is true for angular frequency, wave number  $k$ , and velocity  $v$ :

$$\omega^2 = k^2 v^2$$

For dispersive waves, you have a non-linear relationship. Therefore different waves disperse at different rates.

Let's think about the phenomenon of beating: when you have similar frequency waves going past each other, you get these "beats" from interference patterns (look up a picture to solidify your understanding!).

Since we have different frequencies going at different rates, the beats now move! Let's have an example:

### 7.1 Example of Dispersive Waves

Let the following relationship hold for angular frequency and speed of a wave ( $g$  is actually just gravity, this is a weird example)

$$\begin{aligned}\omega &= \sqrt{gk} \\ v &= \omega/k = \sqrt{g/k}\end{aligned}$$

The only thing you can really be asked on the exam is to find the group velocity (according to Shayne, at least):

$$v_g = \frac{d\omega}{dk} \approx \frac{\Delta\omega}{\Delta k}$$

Group velocity is just the speed of the little wave packets. It's an absolute speed that a stationary observer would see. If you have two different waves interfering at  $\omega_1$  and  $\omega_2$ , use the  $\Delta$  form to find the speed of the packets!

# Chapter 8

## Special Relativity

### 8.1 Introduction

An intuitive grasp of this stuff is pretty easy. Just watch the minute physics videos about it, they do a great job.

The key points are that light speed is constant no matter your frame of reference. In other words, it looks like  $v_1 + c = v_1$ , regardless of what  $v_1$  is. Therefore, the way you would think to transform a spacetime diagram to be from another person's reference frame is not correct. You use this cool Lorentz transformation thing:

### 8.2 Formulae

**The Lorentz factor** comes up all the time:

$$\gamma(v) = \frac{1}{\sqrt{1 - v^2/c^2}}$$

#### 8.2.1 Time Dilation

Let's say you pass by some dude on a planet at close to the speed of light. Both of you will see the other acting really slowly. In other words, **the moving clock is always observed to be slower than the stationary clock**. Therefore, for this relationship,  $\Delta t'$  is just **the other clock**:

$$\Delta t' = \gamma(v)\Delta t$$

### 8.2.2 Length Contraction

Same thing as above applies with **the moving object is always observed to be scrunched up more than the stationary object**:

$$L = \frac{L_0}{\gamma(v)}$$

### 8.2.3 Relativistic Events: Location and Time

Let's say you're watching a dude running close to the speed of light ( $v$ ) who is about to detonate a cake. If the dude does so at position  $x$  and time  $t$  from his perspective, the position  $x_{new}$  and time  $t_{new}$  that you observe are given by the following equations.

$$t_{new} = \gamma\left(t - \frac{v^2}{c^2}x\right)$$

$$x_{new} = \gamma(x - vt)$$

### 8.2.4 Relativistic Energy and Momentum

$$p = \gamma(v)m_0v$$

$$E = \gamma mc^2$$

$$KE = E - mc^2 = \gamma mc^2 - mc^2 = (\gamma - 1)mc^2$$

**Invariant Energy:**

$$m_0^2 c^4 = E - p^2 c^2$$

Apparently the doppler shift equation (relativistic) is given, so don't worry too much about that.

### 8.2.5 4-Vectors

In conventional 3-D space, you can have nice invariant properties of objects, like relative distances. In relativistic 4-D space you can have nice invariant 4-vectors that tell you the relative distance of objects and events in 4-D space!

$$\Delta x = (c\Delta t, \Delta x, \Delta y, \Delta z) = (c\Delta t, \mathbf{r})$$

**The Inner Product** (the thing that is actually invariant) is given by:

$$A = (A_0, \mathbf{A}); B = (B_0, \mathbf{B})$$

$$A \cdot B = A_0 B_0 - \mathbf{A} \cdot \mathbf{B}$$

Where the bolded A and B are a vector of the three spatial coordinates, the  $A_0/B_0$  is the the  $c\Delta t$  component of the 4-vector.

The other form of 4-vector is as follows:

...



# Chapter 9

## Quantum

### 9.1 Particle Energy, Wave Energy

Here is a hodge podge of fun properties about waves (and particles, cause they're waves too). Shoutout to De Broglie.

- Energy of particle/wave with angular frequency:  $E = \hbar\omega$
- Momentum of particle/wave with angular frequency:  $p = \hbar\omega/c$ . Now is as good a time as any to tell you that  $k = \omega/c$ , which is really annoying and confusing.

### 9.2 Compton Scattering

When a high energy photon with wavelength  $\lambda_0$  collides with an electron, the photon scatters at angle  $\theta$  with respect to its original direction. The wavelength of the photon changes accordingly to  $\lambda'$

$$\lambda' - \lambda_0 = \frac{R}{mc}(1 - \cos \theta)$$

- $\lambda'$  is the final wavelength of the photon.
- $\lambda_0$  is the initial wavelength of the photon.
- $R$  is some constant we're given.
- $m$  is the mass of the electron.
- $c$  is the speed of light.
- $\theta$  is the angle of deflection of the photon with respect to its initial line of attack.

## 9.3 Photoelectric Effect

If you yeet some photons at a piece of metal, the electrons get ejected if the energy of the light packets is high enough (if the frequency of light is high enough).

$$E_x = \hbar\omega - \phi$$

where  $\omega$  is the frequency of light and  $\phi$  is the binding energy of the electrons.  $E_x$  is the energy of the ejected electrons.

## 9.4 Hydrogen Model

$$\omega_{mn} = 2\pi R_0 c \left( \frac{1}{n^2} - \frac{1}{m^2} \right)$$

## 9.5 De Broglie Waves

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

$$E = \hbar\omega$$

$$p = \hbar k; \quad k = \omega/c$$

## 9.6 Wave-Particle Duality

### 9.6.1 Uncertainty Principle

$$\Delta x \Delta p_x \geq 2\pi\hbar$$

### 9.6.2 Double Slit Experiment

If you shine a laser through two slits (or anything really), the two slits will act as sources of the exact same frequency light and they will interfere with each other to create some diffraction patterns on wall. Difference in path length being an integer multiple of the wavelength makes constructive interference, difference in path length of half makes for destructive.

$$m\lambda = d \sin \theta$$

Where

- $m$  is some integer (0 is the central node, 1 is the next, etc.)
- $\lambda$  is the wavelength of light (or particles) coming through.
- $d$  is the distance between the slits.
- When the equation holds true for integer value of  $m$ , you get constructive point. If it's an integer and a half, it's a destructive point.

## 9.7 Black Body Radiation

A body absorbs and emits radiation with the exact same efficiency for any given frequency. A black body is a perfect absorber and perfect emitter.

$$P = \sigma T^4$$

$P$  is the power per square meter of the emitter surface,  $\sigma$  is the emissivity/absorptivity constant, and  $T$  is the temperature.

$$f_{max} \propto T$$

In other words, the frequency of radiation that is absorbed/emitted most is proportional to temperature.

# Chapter 10

## Matter Waves and The Schrödinger Equation

This problem is basically just  $\mathbf{A}\vec{x} = \lambda\vec{x}$  as follows:

$$\left(\frac{p^2}{2m} + V\right)\Psi = E\Psi$$

- $p$  is the momentum
- $m$  is the mass
- $V$  is a conservative field of potential energy..
- $E$  is the energy.

### 10.1 Normalization and Probability

Solve for  $N$  such that

$$\int_{-\infty}^{\infty} |(N\psi(x))^2| dx = 1$$

The probability of the particle being between two points is just the integral between those of  $\int_a^b |\psi(x)|^2 dx$  as long as  $\psi$  is normalized.

### 10.2 Energy Considerations

**Quantum Kinetic and Potential Energy** are given by:

$$U = \frac{\hat{p}^2}{2m}\psi(x)$$

$$K = \frac{\hbar^2}{2m} \nabla^2 \psi(x)$$

Where

- $\hat{p} = -i\hbar \frac{d}{dx}$

## 10.3 Infinite Well

This is a pretty common question to ask. The high level explanation is as follows:

- There is a square well of potential energy with infinitely high side walls.
- The particle is trapped inside. It cannot tunnel out because of the infinitely high walls.
- At the edges of the well and beyond, the wave function must be 0

This is starting to sound a lot like the boundary conditions for standing waves! You can derive this relationship with a bunch of complicated math, but here's the final formula for the energy of each of the possible standing wave pattern that a particle can occupy:

$$E_n = \frac{n^2 \pi^2 \hbar^2}{2mL^2}$$

Where  $n$  is any positive integer,  $m$  is the mass of the particle,  $L$  is the length of the well.

**The actual equation** for the wave is as follows:

$$\Psi(x) = C \sin(Ax)$$

Where  $AL = n\pi$ .

### 10.3.1 Superposition

When you **measure** the particle, there is only one energy level  $n$  that tells you the frequency of the standing wave and, by extension, the energy at that level.

Before you observe the particle, it has a superposition of a bunch of  $n$  values. However, once you observe the particle, it becomes constrained to one  $n$  value. This is why the photoelectric effect still has discrete energy levels!

## 10.4 Expectation Values

Honestly you can get this from our vector calculus course pretty well. We know that the probability distribution is given by  $P = |\psi|^2$ . From vector calculus, we also know how to get the expected values of things from probability distributions. They like to write this with annoying complex conjugates but it's the same thing.

$$\langle x \rangle = \int_{-\infty}^{\infty} \psi^* x \psi dx = \int_{-\infty}^{\infty} |\psi|^2 x dx = \int_{-\infty}^{\infty} P(x) x dx$$

So yeah, nothing really to worry about. Same stuff different variable names.

## 10.5 Operators

Operators are applied to the wave function  $\Psi$  to get physical values out of the wave function. For some reason, those values are called eigenvalues. Whatever. Here are the operators.

1. Position operator  $\hat{x}$ :  $\hat{x}\Psi = x\Psi$ ;  $\hat{r}\Psi = r\Psi$
2. Momentum operator:  $\hat{p}$ :  $\hat{p}_x = -i\hbar \frac{\partial}{\partial x}$
3. Kinetic energy operator:  $\hat{K}$ :  $\hat{K} = -\frac{\hbar^2}{2m} \nabla^2$
4. Total energy operator:  $\hat{H}$ :  $\hat{H} = \hat{K} + \hat{U}$
5. Potential energy is just from any fields of potential energy the particle happens to be riding on.

## 10.6 Schrödinger's For Free Particle

Remember the general traveling wave equation? Yup, it's back baby!

$$\Psi = A \cos(kx - \omega t) + iA \sin(kx - \omega t)$$

And here's how you get all those parameter values:

$$p = \hbar k; \quad K = \frac{1}{2}mv^2; \quad E = \hbar\omega$$

Just remember that  $k$  and  $K$  are different things ( $k$  is the spatial frequency,  $K$  is the kinetic energy of the particle).