1. What did Einstein assume fundamentally about vibrating C atoms?

Einstein assumed that the vibrating C atoms had discrete energies, they were quantized.

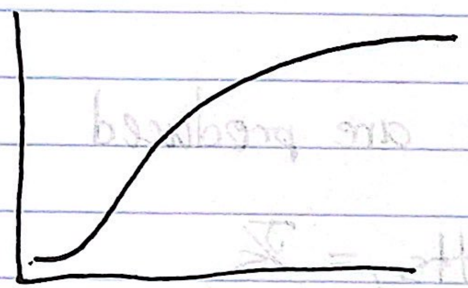
2. Plot the Einstein model from 0 - 1500 K

$\nu = 2.75 \times 10^{13} \, s^{-1}$

gas constant

$$C_V = R \left(\frac{h\nu}{kT}\right)^2 \frac{e^{h\nu/kT}}{(e^{h\nu/kT} - 1)^2}$$

Plotted in python.



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3. Probability for a C atom to have n=1 quanta vs. n=0 at 1500 K? At 150 K?

$$\beta = \frac{1}{k_B T}$$

$$P(n) = e^{-\beta h\nu n} \cdot (1 - e^{-\beta h\nu})$$

	150 K	1500 K
P(0)	0.9998	0.59
P(1)	0.0002	0.24

calculated values with python

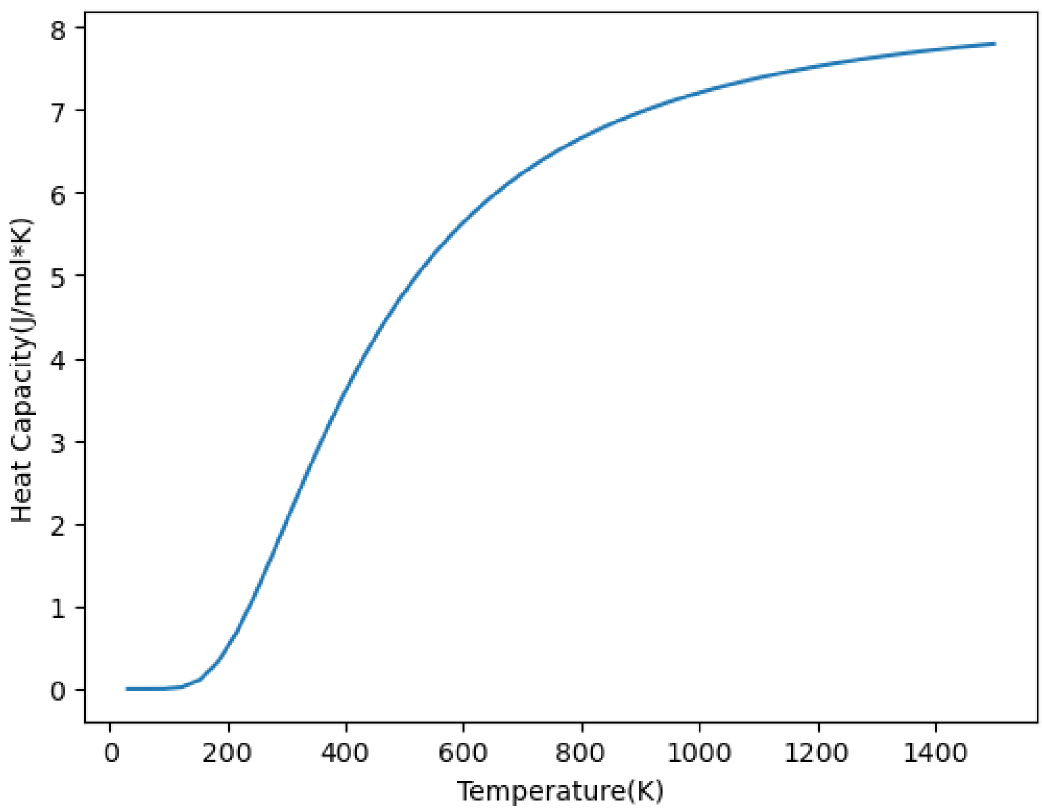
[2]:
```
import numpy
import matplotlib.pyplot as plt
import warnings
warnings.filterwarnings('ignore') #Graph throws warnings for the small values of␣
 ↪T close to 0
```

[3]:
```
#Problem 2
Temp = numpy.linspace(0,1500)
h = 6.62607e-34 #J*s
nu = 2.75e13 #s^-1
k = 1.38065e-23 #J/K
R = 8.314472 #J/K*mol

const = (h*nu)/(k*Temp)
Cap = R*((const)**2)*(numpy.exp(const)/((numpy.exp(const)-1)**2))

plt.plot(Temp,Cap)
plt.xlabel('Temperature(K)')
plt.ylabel('Heat Capacity(J/mol*K)')
```

[3]:
```
Text(0, 0.5, 'Heat Capacity(J/mol*K)')
```



[10]:

```
#Problem 3

def P(n,T):
    return numpy.exp((-n*h*nu)/(k*T))*(1-numpy.exp((-h*nu)/(k*T)))

print(P(1,1500),'n=1 at 1500 K')
print(P(0,1500),'n=0 at 1500 K')
print(P(1,150),'n=1 at 150 K')
print(P(0,150),'n=0 at 150 K')
```

```
0.24274790174502242 n=1 at 1500 K
0.5851592523157498 n=0 at 1500 K
0.00015092060049755725 n=1 at 150 K
0.9998490566155972 n=0 at 150 K
```

0.1 Blackbody radiators.

By treating the sun as a blackbody radiator, Joseph Stefan derived the first reliable estimate of the temperature of the sun's surface.

0.1.1 4. Stefan estimated that the power per unit area radiated from the surface of the sun was 43.5 times greater than that of a metal bar heated to 1950 C. What is the temperature of the sun?

```
[ ]: T_metal = 1950+273 # K
     n = 43.5

     #Then we use Stefan-Boltzmann law to calculate the Temperature of the sun
     T_sun = (n*T_metal**4)**0.25 # K, Stefan-Boltzmann Law
     print("The temperature of the sun is {:.3f} K.".format(T_sun))
```

```
The temperature of the sun is 5709.023 K.
```

0.1.2 5. Based on this temperature, what wavelength λ of light does the sun emit most intensely, in nm? What frequency of light, in s$\breve{}^{1}$? What color does this correspond to?

```
[ ]: W_cons = 2897768 # nm*k, Wien's Law
     lam_max = W_cons/T_sun # nm
     c = 2.99792e8 # m/s
     nu = c/(lam_max*1e-9) # s^-1
     print('The wavelength of light that the sun emits most intensely is {0:.3f} nm,␣
      ↪the frequency is {1:0.3E} s^-1.'.format(lam_max,nu))
     print('This is green light.')
```

```
The wavelength of light that the sun emits most intensely is 507.577 nm, the
frequency is 5.906E+14 s^-1.
This is green light.
```

0.1.3 6. What is the ultraviolet catastrophe, and what did Planck have to assume to circumvent it?

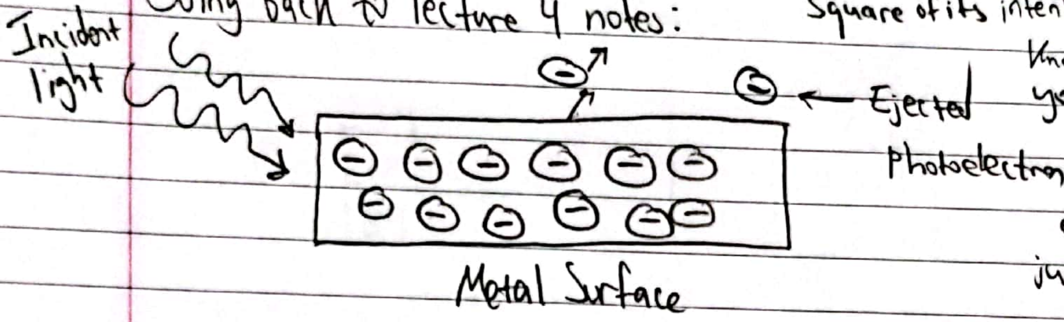
The classical physics theory regarding blackbody radiation predicted that an infinite amount of energy is emitted at small wavelengths, which makes no sense from the perspective of energy conservation. Because small wavelengths correspond to the ultraviolet end of the spectrum, this puzzle was known as the ultraviolet catastrophe. Planck assumed that energy is quantized, which means electromagnetic radiation can only be emitted or absorbed in discrete energy in units of hv = hc/lambda

HW # 3

1.3 Photoelectric effect.

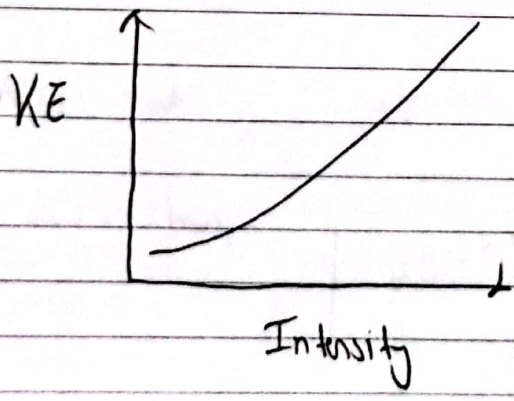
You setup an experiment in which you shine light of varying intensity and constant frequency at a metal surface and measure the maximum kinetic energy of the emitted electrons. As an accomplished student of classical physics, you know that the energy contained in a wave is proportional to the square of its intensity. Based on this knowledge, sketch how you expect the kinetic energy of the electrons to vary in the experiment. Briefly justify your answer.

1.3.1 Going back to lecture 4 notes:



Now let's set up an experiment in which we shine light of varying intensity and constant frequency at a metal surface and measure the maximum kinetic energy of the emitted electrons.

$E_{wave} \propto \text{Intensity}^2$ classical physics



Plot in jupyter notebook with code.

Not finding a result that you like, you set up another experiment in which you vary the frequency of light at constant intensity. Below is the data you collect. Use graphical analysis to determine the work function of the metal, in eV, and to estimate Planck's constant.

1.3.2

Light Wavelength (nm)	Electron Kinetic Energy (eV)
263	0.13
250	0.33
234	0.68
218	1.08
184	2.13

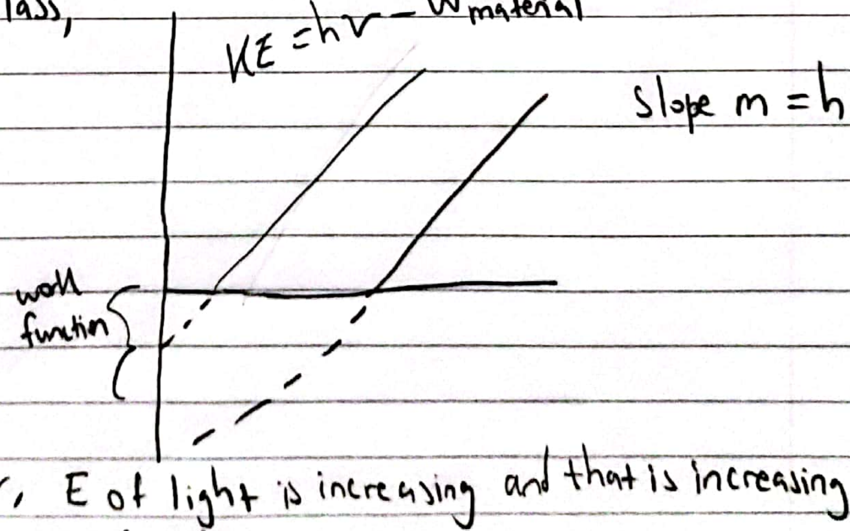
Speed of light: $c = 2.99792 \times 10^{8}$ m/s

$\underbrace{\lambda}_{\text{wavelength}} \underbrace{\nu}_{\text{frequency}} = c$; $\underbrace{E}_{\text{energy}} = \underbrace{h}_{\text{Planck's constant}} \nu = \frac{hc}{\lambda}$

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

Einstein model says photon has energy + momentum

As we saw in class,



As you vary ν, E of light is increasing and that is increasing the Kinetic Energy (KE).

Plot in jupyter notebook.

$$KE = h\nu - W$$

The workfunction of the metal is 4.598 eV
Planck's constant (h) is 4.127E-15 eV·s

1.3.3

What is the metal? Hint: It is a coinage metal.

According to the solution before, the workfunction of the metal is 4.598 eV.

Looking up a table of work function of elements, it seems it is in the range of silver and copper.

Ag 4.26-4.74 eV
Cu 4.53-5.10 eV

Table can be found if you google "tabulation of work functions metals" and click on "Work function - Wikipedia".

HW 3

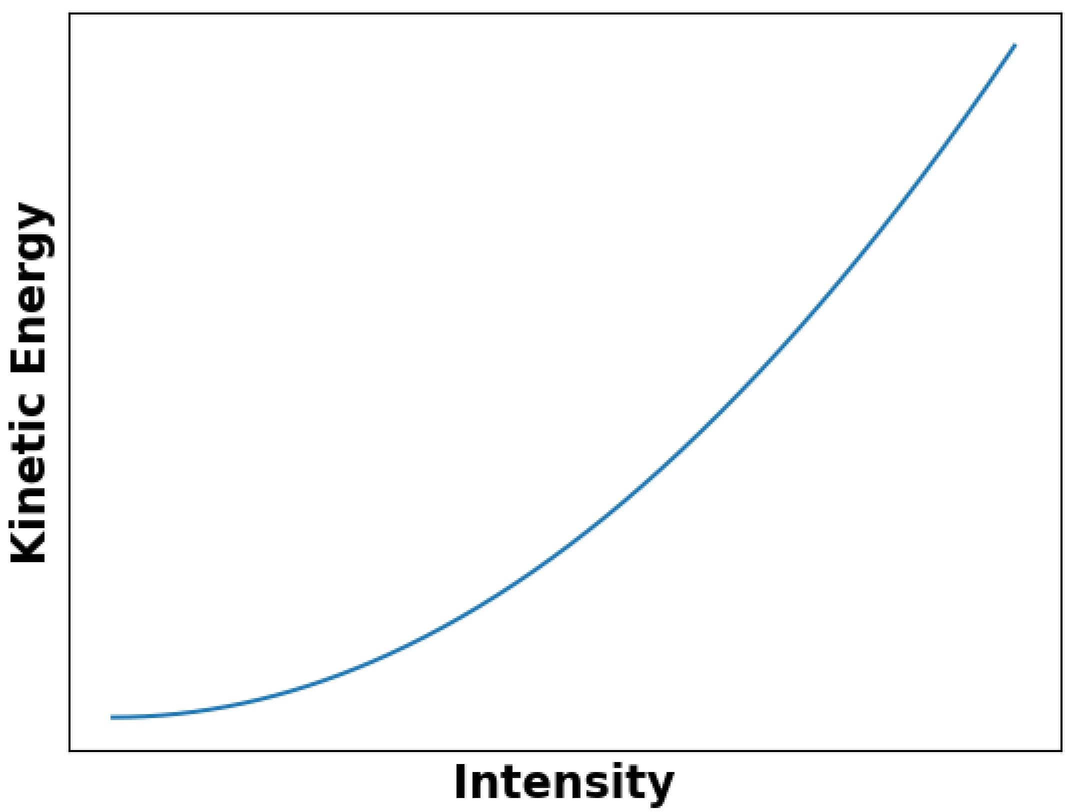
1.3 Photoelectric effect

1.3.1

In [2]:
```
import numpy as np
import matplotlib.pyplot as plt
```

In [32]:
```
intensity = np.linspace(0,500,500) # intensity square
ke = intensity**2 # Kinetic energy = energy of the wave = constant*in
plt.plot(intensity,ke)
plt.xlabel('Intensity',fontsize=16,fontweight='bold')
plt.ylabel('Kinetic Energy',fontsize=16,fontweight='bold')
# Removing numbers on both axes
plt.xticks([])  # Remove numbers on the x-axis
plt.yticks([])  # Remove numbers on the y-axis

plt.show()
```



1.3.2

Gathering data from the problem:

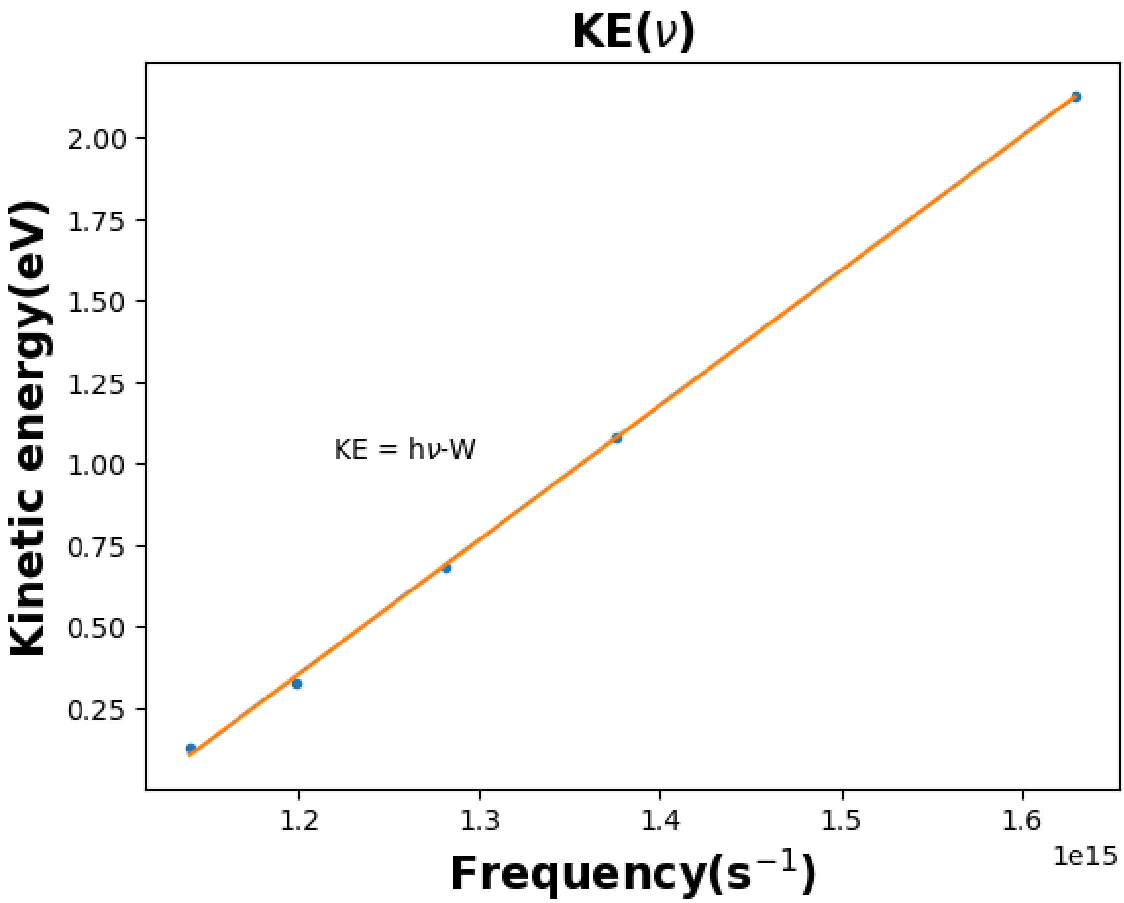
In [14]:
```
c = 2.99792e8 # value speed of light m/s
wavelength = [263,250,234,218,184] # wavelenght in nanometers
KE = [0.13,0.33,0.68,1.08,2.13] # kinetic energies in eV
```

In [33]:
```
frequency = [] # stores frequencies calculated based on the given wav
for i in wavelength: #iterates over each wavelength in the wavelength
    frequency.append(c/(i*1.0e-9)) # s^-1, frequency = c/wavelength;

h, W = np.polyfit(frequency, KE, 1) #linear fitting; slope related to
                                    #work function of metal
```

In [34]:
```
KE_fit = np.poly1d([0,h,W]) # A 1-D polynomial class representing lin
print ('The workfunction of the metal is {0:.3f} eV\nPlanck\'s consta
plt.plot(frequency, KE, '.')
plt.plot(frequency, KE_fit(frequency), '-')
plt.xlabel('Frequency(s$^{-1}$)',fontsize=16,fontweight='bold')
plt.ylabel('Kinetic energy(eV)',fontsize=16,fontweight='bold')
plt.text(1.3e15, 1.0, 'KE = h$\\nu$-W', ha='right', va='bottom')
plt.title('KE($\\nu$)',fontsize=16,fontweight='bold')
plt.show()
```

```
The workfunction of the metal is 4.598 eV
Planck's constant (h) is 4.127E-15 eV*s
```



In [ ]:

10. What is the energy (in eV) of a photon of wavelength 2.9 Å? What part of the electromagnetic spectrum does it correspond to?

$hc = 1239.8 \frac{eV}{nm}$

$E = h\nu = \frac{hc}{\lambda}$ $\lambda = 2.9$ Å $= .29$ nm

$E = 4275$ eV, corresponding to x-rays

~~(This is how x-ray crystallography works, the x-rays can get~~

11. How many photons/s if these photons are produced at a power of 1 μW?

$\text{Power} = \frac{\text{energy}}{\cancel{\Delta} t}$ given in Watts, $= J/s$

$1 J = 6.2415 \times 10^{18}$ eV

$\text{number} (/s) = \frac{P}{E} = 1.460 \times 10^{9}$ photons/s

12. To what speed (in m/s) would an electron need to be accelerated to have the necessary wavelength?

$\cancel{v=hc}$, $\lambda = \frac{h}{p}$, $p = mv$ $\therefore$ $\cancel{v=\frac{hv}{mc}}$ $\lambda = \frac{h}{mv}$

$v = \frac{h}{m\lambda}$ $\lambda = 2.9$ Å $= 2.9 \times 10^{-10}$ m, $m_{e^-} = 9.1094 \times 10^{-31}$ kg

$v = 2.51 \times 10^{6}$ m/s, 0.8% the speed of light

[11]:

```
#Problem 10
lamb = 2.9/10 #Angstrom to nm
hc = 1239.8 #eV/nm

E = (hc)/lamb
print(E,'eV')
```

```
4275.172413793103 eV
```

[24]:

```
#Problem 11
P = 1e-6*6.2415e18 # W=J/s, convert to eV/s

num = P/E
print(num,'photons/s')
```

```
1459941119.535409 photons/s
```

[25]:

```
#Problem 12
m_e= 9.1094e-31 #kg
c = 2.9979e8 #m/s

v = h/(m_e*(lamb/1e9))
print (v,'m/s')
print(v/c)
```

```
2508235.146264223 m/s
0.008366640469209189
```

0.2 The Bohr atom.

Bohr developed the first successful model of the energy spectrum of a hydrogen atom by postulating that electrons can only exist in certain fixed energy "orbits" indexed by the quantum number n. (Recall that the equations describing the Bohr atom are in Table 4 of the course outline.)

0.2.1 13. Would light need to be absorbed or emitted to cause an electron to jump from the $n = 1$ to the $n = 2$ orbit? What wavelength of light does this correspond to?

[ ]:
```
#Energy of a Hydrogen molecule
EH = 27.212 # eV

#Energy at each of the orbital
n1 = 1
n2 = 2
E1 = -EH/2/n1**2 # eV
E2 = -EH/2/n2**2 # eV

#Calculating the wavelength
hc = 1240 # eV*nm
deltaE = E2-E1 # eV
wavelength = hc/deltaE # nm
print ('Light needs to be absorbed to cause an electron to jump from the n=1 to␣
↪n=2 orbit. \nThe wavelength is {:.5f} nm.'.format(wavelength))
```

```
Light needs to be absorbed to cause an electron to jump from the n=1 to n=2
orbit.
The wavelength is 121.51502 nm.
```

0.2.2 14. What is the circumference of the $n = 2$ orbit? What is the de Broglie wavelength of an electron in the $n = 2$ orbit? How do these compare?

[ ]:
```
#First we calculate the circumference using the given constant

a0 = 0.529177e-10 # m, Bohr radius for hydrogen atom

#calculate the r at the second orbital
r2 = a0*n2**2 # m

#using the circumference formula
l = 2*np.pi*r2 # m, circumference

#constants
k = 2.30708e-28 # J*m, k = e^2/(4*pi*epsilon), the value of the constant is in␣
↪the course outline.
me = 9.109e-31 # kg, #mass of electron
h = 6.62607e-34 # J*s
```

```
hbar = 1.05457e-34 #J*s, reduced Planck constant

#calculate the wavelength
p0 = k*me/hbar # kg*m/s
p2 = p0/n2
wavelength_2 = h/p2 # m
print('The circumference of the n=2 orbit is {0:.5E} m. \nThe de Broglie␣
 ↪wavelength of an electron in the n=2 orbit is {1:.5E} m. \nThe relationship is␣
 ↪the circumference={2:.2f}*the de Broglie wavelength.'.format(l,wavelength_2,l/
 ↪wavelength_2))
```

```
The circumference of the n=2 orbit is 1.32997E-09 m.
The de Broglie wavelength of an electron in the n=2 orbit is 6.65010E-10 m.
The relationship is the circumference=2.00*the de Broglie wavelength.
```