Today's Outline - February 19, 2015

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- Homework #2 solutions

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Homework Assignment #03:
Chapter 3: 1, 3, 4, 6, 8
due Thursday, February 26, 2015

Homework 02 - Problem 1

Knowing that the photoelectric absorption of an element scales as the inverse of the energy cubed, calculate

(a) The absorption coefficient at 10keV for copper when the value at 5keV is 1698.3 cm^{-1}.

(b) The actual absorption coefficient of copper at 10keV is 1942.1 cm^{-1}, why is this so different than your calculated value?

Homework 02 - Problem 1

Knowing that the photoelectric absorption of an element scales as the inverse of the energy cubed, calculate

(a) The absorption coefficient at 10keV for copper when the value at 5keV is 1698.3 cm^{-1}.

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(a) We are given the energy dependence of the absorption coefficient and its value at 5 keV.

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$$\frac{\mu_{10keV}}{\mu_{5kev}} = \frac{1/10^3}{1/5^3}$$

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$$\frac{\mu_{10keV}}{\mu_{5kev}} = \frac{1/10^3}{1/5^3}$$

$$\mu_{10keV} = \mu_{5keV}\left(\frac{5}{10}\right)^3$$

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$$= 1698.3\,\text{cm}^{-1}\left(\frac{1}{8}\right)$$

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(a) We are given the energy dependence of the absorption coefficient and its value at 5 keV.

(b) The calculation does not take into account the Cu K absorption edge at 8.98 keV.

$$\frac{\mu_{10keV}}{\mu_{5kev}} = \frac{1/10^3}{1/5^3}$$

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A 30 cm long, ionization chamber, filled with 80% helium and 20% nitrogen gases at 1 atmosphere, is being used to measure the photon rate (photons/sec) in a synchrotron beamline at 12 keV. If a current of $i = 10$ nA is measured, what is the photon flux entering the ionization chamber?

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A 30 cm long, ionization chamber, filled with 80% helium and 20% nitrogen gases at 1 atmosphere, is being used to measure the photon rate (photons/sec) in a synchrotron beamline at 12 keV. If a current of i =10 nA is measured, what is the photon flux entering the ionization chamber?

The number of free electrons per second generated in the ion chamber by the beam is given by

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The total absorption coefficient μ is a weighted sum of the absorption of the substance in the ion chamber. Where the quantity μ_i can be computed from the absorption cross section of each component ($\sigma_{a,i}$), its mass density ($\rho_{m,i}$), molar mass (M_i), and Avogadro's number (N_A).

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These values can be computed or looked up in the orange book or on the MuCal online calculator for the energy desired. For $E = 12\,\text{keV}$, the *photoelectric* cross-section is

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$$\mu_{He} = 2.0 \times 10^{-6}\,\text{cm}^{-1}$$

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$$\mu = 0.8\mu_{He} + 0.2\mu_{N_2}$$

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$$\mu_{He} = 2.0 \times 10^{-6}\,\text{cm}^{-1} \qquad \mu_{N_2} = 2.29 \times 10^{-3}$$

$$\mu = 0.8\mu_{He} + 0.2\mu_{N_2} = 0.8 \cdot 2.0 \times 10^{-6} + 0.2 \cdot 2.29 \times 10^{-3}$$

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$$\mu_{He} = 2.0 \times 10^{-6}\,\text{cm}^{-1} \qquad \mu_{N_2} = 2.29 \times 10^{-3}$$

$$\mu = 0.8\mu_{He} + 0.2\mu_{N_2} = 0.8 \cdot 2.0 \times 10^{-6} + 0.2 \cdot 2.29 \times 10^{-3}$$
$$= 4.60 \times 10^{-4}\,\text{cm}^{-1}$$

Homework 02 - Problem 2 (cont.)

Now we use this to calculate the fraction of photons absorbed in the chamber

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$$\mu = 4.60 \times 10^{-4}\,\mathrm{cm}^{-1}$$

$$f(E) = 1 - e^{-\mu L} = 1 - e^{-4.60\times^{-4}\cdot 30}$$

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Now we use this to calculate the fraction of photons absorbed in the chamber

$$\mu = 4.60 \times 10^{-4}\,\text{cm}^{-1}$$

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$$= 0.0136 = 1.36\%$$

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$$\frac{dN}{dt} = \frac{i}{e}$$

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The number of electrons per second can be computed directly from the measured current

$$\frac{dN}{dt} = \frac{i}{e} = \frac{10 \times 10^{-9}}{1.602 \times 10^{-19}}$$

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The number of electrons per second can be computed directly from the measured current

$$\frac{dN}{dt} = \frac{i}{e} = \frac{10 \times 10^{-9}}{1.602 \times 10^{-19}}$$
$$= 6.24 \times 10^{10}\,\text{s}^{-1}$$

Homework 02 - Problem 2 (cont.)

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Finally, we look up in the orange book the energy required to make a free electron by inoization for each gas and take a weighted average

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$$W_{He} = 41\,\text{eV} \qquad W_{N_2} = 36\,\text{eV}$$

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$$W_{He} = 41\,\text{eV} \qquad W_{N_2} = 36\,\text{eV}$$
$$W = 0.8 \cdot 41 + 0.2 \cdot 36$$

Homework 02 - Problem 2 (cont.)

Now we use this to calculate the fraction of photons absorbed in the chamber

$$\mu = 4.60 \times 10^{-4}\,\text{cm}^{-1}$$

$$f(E) = 1 - e^{-\mu L} = 1 - e^{-4.60\times^{-4}\cdot 30}$$
$$= 0.0136 = 1.36\%$$

$$\frac{dN}{dt} = \frac{i}{e} = \frac{10 \times 10^{-9}}{1.602 \times 10^{-19}}$$
$$= 6.24 \times 10^{10}\,\text{s}^{-1}$$

The number of electrons per second can be computed directly from the measured current

Finally, we look up in the orange book the energy required to make a free electron by inoization for each gas and take a weighted average

$$W_{He} = 41\,\text{eV} \qquad W_{N_2} = 36\,\text{eV}$$
$$W = 0.8 \cdot 41 + 0.2 \cdot 36 = 40\,\text{eV}$$

Homework 02 - Problem 2 (cont.)

Now we use this to calculate the fraction of photons absorbed in the chamber

$$\mu = 4.60 \times 10^{-4}\,\text{cm}^{-1}$$

$$f(E) = 1 - e^{-\mu L} = 1 - e^{-4.60\times^{-4}\cdot 30}$$
$$= 0.0136 = 1.36\%$$

The number of electrons per second can be computed directly from the measured current

$$\frac{dN}{dt} = \frac{i}{e} = \frac{10 \times 10^{-9}}{1.602 \times 10^{-19}}$$
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$$W = 0.8 \cdot 41 + 0.2 \cdot 36 = 40\,\text{eV}$$

Putting it all together

Homework 02 - Problem 2 (cont.)

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$$W_{He} = 41\,\text{eV} \qquad W_{N_2} = 36\,\text{eV}$$
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Putting it all together

$$\Phi = \frac{dN}{dt}\frac{W}{f(E)E}$$

Homework 02 - Problem 2 (cont.)

Now we use this to calculate the fraction of photons absorbed in the chamber

$$\mu = 4.60 \times 10^{-4}\,\text{cm}^{-1}$$

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Putting it all together

$$\Phi = \frac{dN}{dt}\frac{W}{f(E)E} = \frac{(6.24 \times^{10}\ \text{s}^{-1})(40\,\text{eV})}{(0.0136)(12 \times 10^{3}\,\text{eV/photon})}$$

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Putting it all together

$$\Phi = \frac{dN}{dt}\frac{W}{f(E)E} = \frac{(6.24 \times^{10}\ \mathrm{s}^{-1})(40\,\mathrm{eV})}{(0.0136)(12 \times 10^3\,\mathrm{eV/photon})} = 1.53 \times 10^{10}\,\mathrm{photon/s}$$

Homework 02 - Problem 3

A 5 cm deep ionization chamber is used to measure the fluorescence from a sample containing arsenic (As). Using any noble gases or nitrogen, determine a gas fill (at 1 atmosphere) for this chamber which absorbs at least 60% of the incident photons. How does this change if you are measuring the fluorescence from ruthenium (Ru)?

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The energy of the arsenic fluorescence line can be obtained from MuCal or from Hephaestus and is 10.54 keV. We would like to have at least 60% absorption in the 5 cm chamber. This can give us the desired value of μ.

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$$-\mu L = \ln[1 - f(E)]$$

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$$f(E) = 1 - e^{-\mu L}$$
$$e^{-\mu L} = [1 - f(E)]$$
$$-\mu L = \ln[1 - f(E)]$$
$$\mu = \frac{-\ln[1 - F(E)]}{L}$$

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$$
\begin{aligned}
f(E) &= 1 - e^{-\mu L} \\
e^{-\mu L} &= [1 - f(E)] \\
-\mu L &= \ln[1 - f(E)] \\
\mu &= \frac{-\ln[1 - F(E)]}{L} \\
&= \frac{-\ln[1 - 0.6]}{5\,\text{cm}}
\end{aligned}
$$

Homework 02 - Problem 3

A 5 cm deep ionization chamber is used to measure the fluorescence from a sample containing arsenic (As). Using any noble gases or nitrogen, determine a gas fill (at 1 atmosphere) for this chamber which absorbs at least 60% of the incident photons. How does this change if you are measuring the fluorescence from ruthenium (Ru)?

The energy of the arsenic fluorescence line can be obtained from MuCal or from Hephaestus and is 10.54 keV. We would like to have at least 60% absorption in the 5 cm chamber. This can give us the desired value of μ.

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\begin{aligned}
f(E) &= 1 - e^{-\mu L} \\
e^{-\mu L} &= [1 - f(E)] \\
-\mu L &= \ln[1 - f(E)] \\
\mu &= \frac{-\ln[1 - F(E)]}{L} \\
&= \frac{-\ln[1 - 0.6]}{5\,\text{cm}} = 0.183\,\text{cm}^{-1}
\end{aligned}
$$

Homework 02 - Problem 3

A 5 cm deep ionization chamber is used to measure the fluorescence from a sample containing arsenic (As). Using any noble gases or nitrogen, determine a gas fill (at 1 atmosphere) for this chamber which absorbs at least 60% of the incident photons. How does this change if you are measuring the fluorescence from ruthenium (Ru)?

The energy of the arsenic fluorescence line can be obtained from MuCal or from Hephaestus and is 10.54 keV. We would like to have at least 60% absorption in the 5 cm chamber. This can give us the desired value of μ.

This is the minimum value of the absorption that we require.

$$
\begin{aligned}
f(E) &= 1 - e^{-\mu L} \\
e^{-\mu L} &= [1 - f(E)] \\
-\mu L &= \ln[1 - f(E)] \\
\mu &= \frac{-\ln[1 - F(E)]}{L} \\
&= \frac{-\ln[1 - 0.6]}{5\,\text{cm}} = 0.183\,\text{cm}^{-1}
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Homework 02 - Problem 3 (cont.)

Looking at tabulated values of the absorption coefficient for various gases at this energy (from MuCal, *total* cross-section):

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$\mu_{He} = 4.2 \times 10^{-5}\,\text{cm}^{-1}$

Homework 02 - Problem 3 (cont.)

Looking at tabulated values of the absorption coefficient for various gases at this energy (from MuCal, *total* cross-section):

$\mu_{He} = 4.2 \times 10^{-5}\,\text{cm}^{-1} \quad \mu_{N_2} = 3.9 \times 10^{-3}\,\text{cm}^{-1}$

Homework 02 - Problem 3 (cont.)

Looking at tabulated values of the absorption coefficient for various gases at this energy (from MuCal, *total* cross-section):

$\mu_{He} = 4.2 \times 10^{-5}\,\text{cm}^{-1} \quad \mu_{N_2} = 3.9 \times 10^{-3}\,\text{cm}^{-1} \quad \mu_{Ne} = 8.8 \times 10^{-3}\,\text{cm}^{-1}$

Homework 02 - Problem 3 (cont.)

Looking at tabulated values of the absorption coefficient for various gases at this energy (from MuCal, *total* cross-section):

$\mu_{He} = 4.2 \times 10^{-5}\,\text{cm}^{-1} \quad \mu_{N_2} = 3.9 \times 10^{-3}\,\text{cm}^{-1} \quad \mu_{Ne} = 8.8 \times 10^{-3}\,\text{cm}^{-1}$

$\mu_{Ar} = 0.098\,\text{cm}^{-1}$

Homework 02 - Problem 3 (cont.)

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$\mu_{He} = 4.2 \times 10^{-5}\,\text{cm}^{-1} \quad \mu_{N_2} = 3.9 \times 10^{-3}\,\text{cm}^{-1} \quad \mu_{Ne} = 8.8 \times 10^{-3}\,\text{cm}^{-1}$

$\mu_{Ar} = 0.098\,\text{cm}^{-1} \quad \mu_{Kr} = 0.17\,\text{cm}^{-1}$

Homework 02 - Problem 3 (cont.)

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$\mu_{Ar} = 0.098\,\text{cm}^{-1} \quad \mu_{Kr} = 0.17\,\text{cm}^{-1} \quad \mu_{Xe} = 0.89\,\text{cm}^{-1}$

Homework 02 - Problem 3 (cont.)

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$\mu_{He} = 4.2 \times 10^{-5}\,\text{cm}^{-1} \quad \mu_{N_2} = 3.9 \times 10^{-3}\,\text{cm}^{-1} \quad \mu_{Ne} = 8.8 \times 10^{-3}\,\text{cm}^{-1}$

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$$f(E)_{Kr} = 1 - e^{-(0.17)(5)}$$

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Thus for the most likely candidates we have

$$f(E)_{Kr} = 1 - e^{-(0.17)(5)} = 1 - 0.43 = 57\%$$

Homework 02 - Problem 3 (cont.)

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For the Ru K-edge at 19.28 keV, we have

Homework 02 - Problem 3 (cont.)

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For the Ru K-edge at 19.28 keV, we have

$\mu_{Ar} = 0.017\,\text{cm}^{-1}$

Homework 02 - Problem 3 (cont.)

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For the Ru K-edge at 19.28 keV, we have

$\mu_{Ar} = 0.017\,\text{cm}^{-1} \quad \mu_{Kr} = 0.23\,\text{cm}^{-1}$

Homework 02 - Problem 3 (cont.)

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$$f(E)_{Kr} = 1 - e^{-(0.23)(5)} = 1 - 0.32 = 68\%$$

Homework 02 - Problem 3 (cont.)

Looking at tabulated values of the absorption coefficient for various gases at this energy (from MuCal, *total* cross-section):

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$$f(E)_{Kr} = 1 - e^{-(0.23)(5)} = 1 - 0.32 = 68\%$$

$$f(E)_{Xe} = 1 - e^{-(0.17)(5)}$$

Homework 02 - Problem 3 (cont.)

Looking at tabulated values of the absorption coefficient for various gases at this energy (from MuCal, *total* cross-section):

$\mu_{He} = 4.2 \times 10^{-5}\,\text{cm}^{-1}$ $\mu_{N_2} = 3.9 \times 10^{-3}\,\text{cm}^{-1}$ $\mu_{Ne} = 8.8 \times 10^{-3}\,\text{cm}^{-1}$

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$$f(E)_{Kr} = 1 - e^{-(0.23)(5)} = 1 - 0.32 = 68\%$$

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Homework 02 - Problem 3 (cont.)

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Homework 02 - Problem 4

Calculate the characteristic angle of reflection of 10keV and 30keV x-rays for:

(a) A slab of glass (SiO_2)

(b) A thick chromium mirror;

(c) A thick platinum mirror.

(d) If the incident x-ray beam is 2mm high, what length of mirror is required to reflect the entire beam for each material?

Homework 02 - Problem 4

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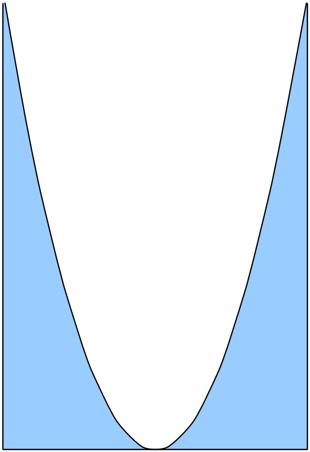
Homework 02 - Problem 5

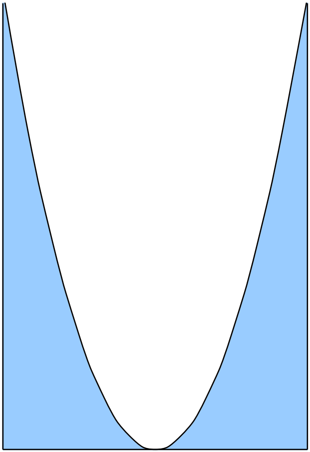
Calculate the fraction of silver (Ag) fluorescence x-rays which are absorbed in a 1 mm thick silicon (Si) detector and the charge pulse expected for each absorbed photon. Repeat the calculation for a 1 mm thick germanium (Ge) detector.

How to make a Fresnel lens



The ideal refracting lens has a parabolic shape (actually elliptical) but this is impractical to make.

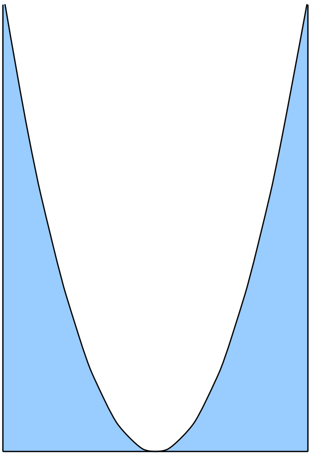
How to make a Fresnel lens



The ideal refracting lens has a parabolic shape (actually elliptical) but this is impractical to make.

$$h(x) = \Lambda \left(\frac{x}{\sqrt{2\lambda_o f}} \right)^2$$

How to make a Fresnel lens



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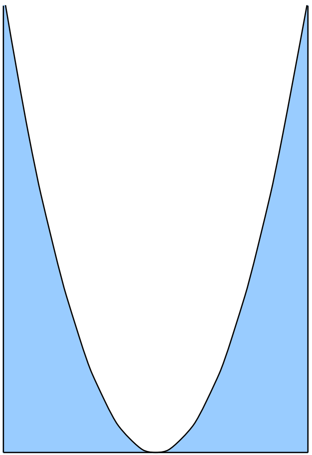
when $h(x) = 100\Lambda \sim 1000\mu$m

How to make a Fresnel lens



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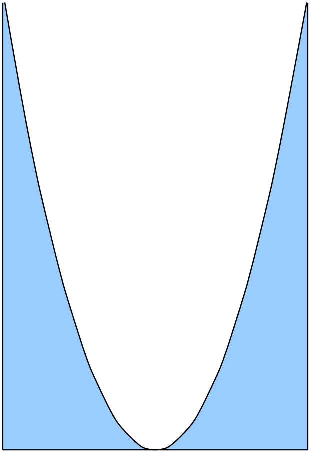
when $h(x) = 100\Lambda \sim 1000\mu\text{m}$

$$x = 10\sqrt{2\lambda_o f} \sim 100\mu\text{m}$$

How to make a Fresnel lens



The ideal refracting lens has a parabolic shape (actually elliptical) but this is impractical to make.

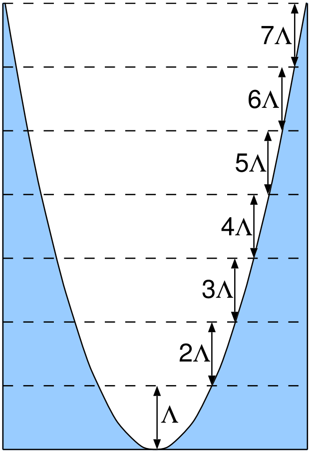
$$h(x) = \Lambda \left(\frac{x}{\sqrt{2\lambda_o f}} \right)^2$$

when $h(x) = 100\Lambda \sim 1000\mu m$

$$x = 10\sqrt{2\lambda_o f} \sim 100\mu m$$

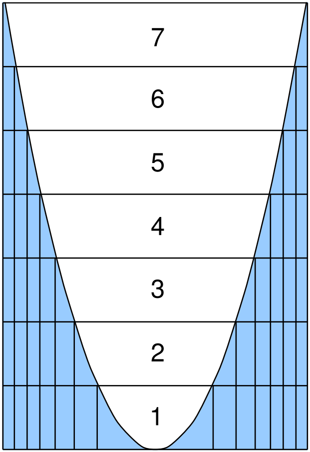
aspect ratio too large for a stable structure and absorption would be too large!

How to make a Fresnel lens



Mark off the longitudinal zones (of thickness Λ) where the waves inside and outside the material are in phase.

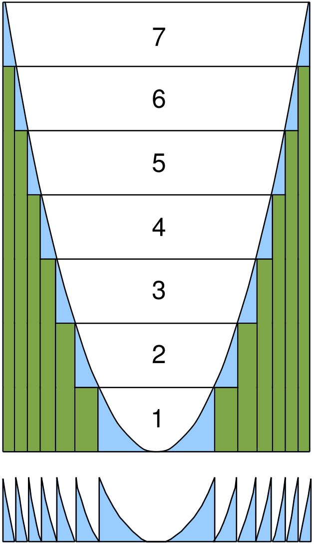
How to make a Fresnel lens



Mark off the longitudinal zones (of thickness Λ) where the waves inside and outside the material are in phase.

Each block of thickness Λ serves no purpose for refraction but only attenuates the wave.

How to make a Fresnel lens

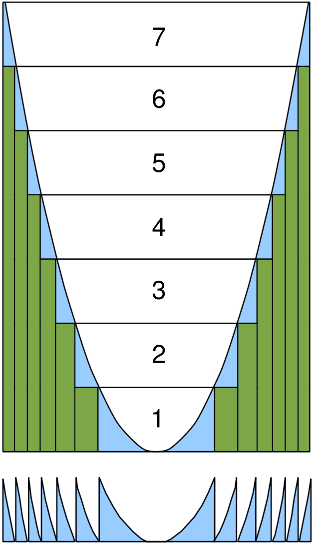


Mark off the longitudinal zones (of thickness Λ) where the waves inside and outside the material are in phase.

Each block of thickness Λ serves no purpose for refraction but only attenuates the wave.

This material can be removed and the remaining material collapsed to produce a Fresnel lens which has the same optical properties as the parabolic lens as long as $f \gg N\Lambda$ where N is the number of zones.

Fresnel lens dimensions



The outermost zones become very small and thus limit the overall aperture of the zone plate. The dimensions of outermost zone, N can be calculated by first defining a scaled height and lateral dimension

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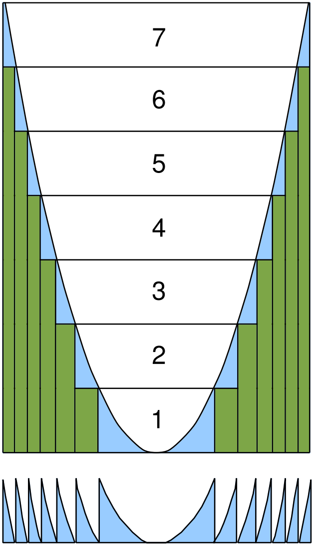

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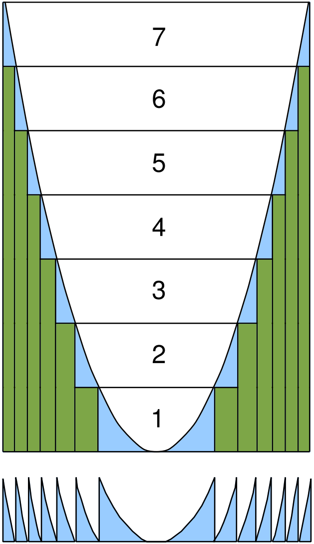
$$\nu = \frac{h(x)}{\Lambda}$$

Fresnel lens dimensions



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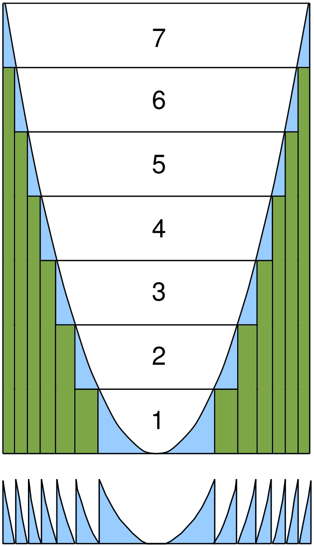

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Since $\nu = \xi^2$, the position of the N^{th} zone is $\xi_N = \sqrt{N}$ and the scaled width of the N^{th} (outermost) zone is

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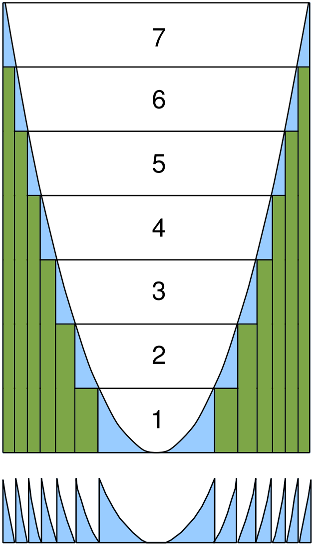

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$$\Delta\xi_N = \xi_N - \xi_{N-1} = \sqrt{N} - \sqrt{N-1}$$

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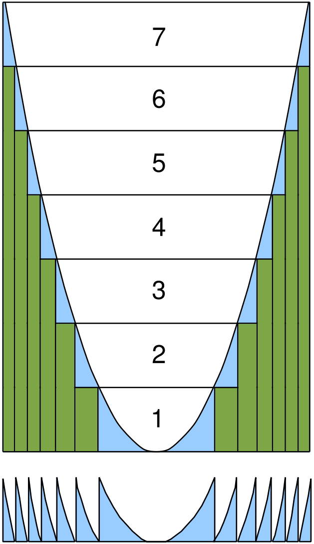

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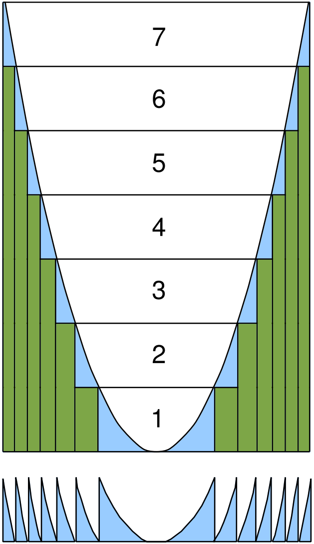
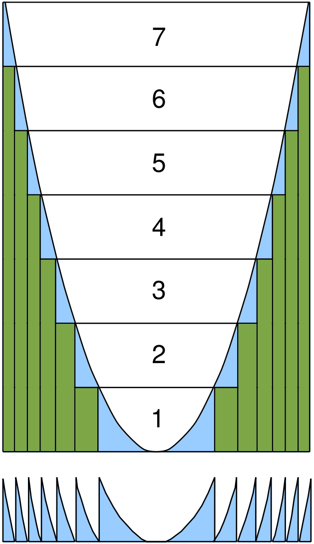


$$\Delta\xi_N = \xi_N - \xi_{N-1} = \sqrt{N} - \sqrt{N-1}$$
$$= \sqrt{N}\left(1 - \sqrt{1 - \frac{1}{N}}\right)$$

Fresnel lens dimensions



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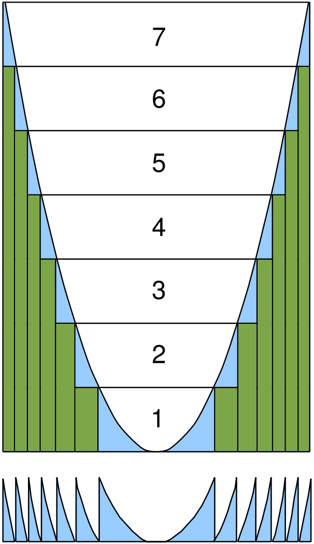

$$
\begin{aligned}
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&\approx \sqrt{N}\left(1 - \left[1 - \frac{1}{2N}\right]\right) \\
\Delta\xi_N &\approx \frac{1}{2\sqrt{N}}
\end{aligned}
$$

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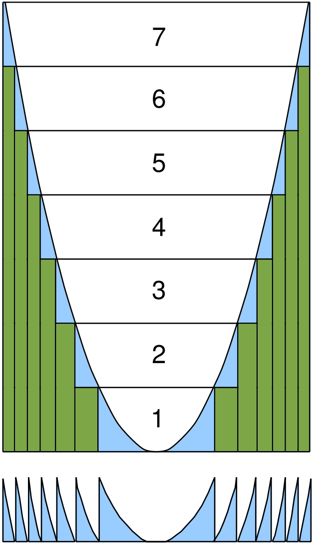

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$$= \sqrt{N}\left(1 - \sqrt{1 - \frac{1}{N}}\right)$$
$$\approx \sqrt{N}\left(1 - \left[1 - \frac{1}{2N}\right]\right)$$
$$\Delta\xi_N \approx \frac{1}{2\sqrt{N}}$$

The diameter of the entire lens is thus

$$2\xi_N = 2\sqrt{N} = \frac{1}{\Delta\xi_N}$$

Fresnel lens example

In terms of the unscaled variables

$$\Delta x_N = \Delta\xi_N \sqrt{2\lambda_o f}$$

Fresnel lens example

In terms of the unscaled variables

$$\Delta x_N = \Delta\xi_N \sqrt{2\lambda_o f} = \sqrt{\frac{\lambda_o f}{2N}}$$

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Fresnel lens example

In terms of the unscaled variables

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If we take

$$\lambda_o = 1\text{Å} = 1 \times 10^{-10}\text{m}$$
$$f = 50\text{cm} = 0.5\text{m}$$
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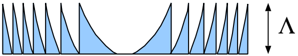
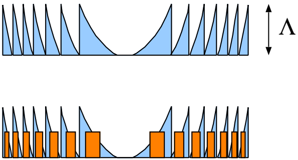
Making a Fresnel zone plate



The specific shape required for a zone plate is difficult to fabricate, consequently, it is convenient to approximate the nearly triangular zones with a rectangular profile.

Making a Fresnel zone plate



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In practice, since the outermost zones are very small, zone plates are generally fabricated as alternating zones (rings for 2D) of materials with a large Z-contrast, such as Au/Si or W/C.

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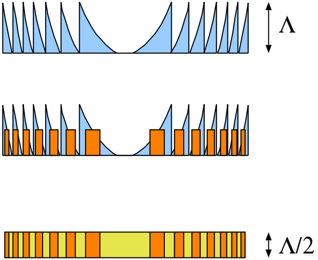

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In practice, since the outermost zones are very small, zone plates are generally fabricated as alternating zones (rings for 2D) of materials with a large Z-contrast, such as Au/Si or W/C.

This kind of zone plate is not as efficient as a true Fresnel lens would be in the x-ray regime. Nevertheless, efficiencies up to 35% have been achieved.

Variable focal length CRL

The compound refractive lenses (CRL) are useful for fixed focus but are difficult to use if a variable focal distance and a long focal length is required.

B. Adams and C. Rose-Petruck, "Hybrid len/mirror x-ray focusing scheme and beam stabilization", *in prepration* (2013).

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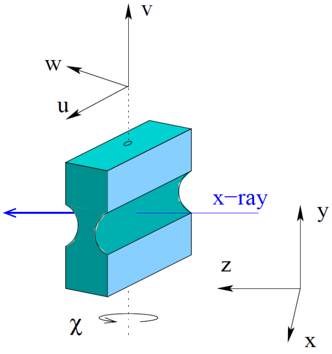
Start with a 2 hole CRL.



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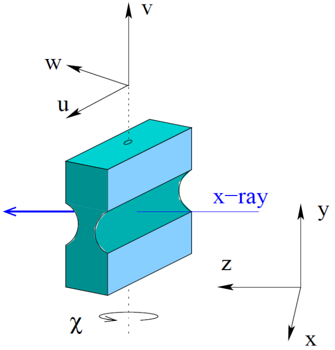
Start with a 2 hole CRL. Rotate by an angle χ about vertical axis



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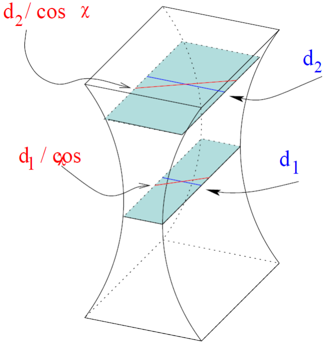
Start with a 2 hole CRL. Rotate by an angle χ about vertical axis giving an effective change in the number of "lenses" by a factor $1/\cos\chi$.



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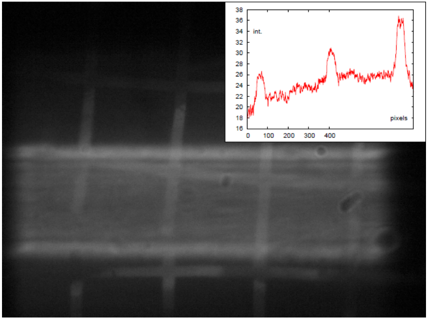
at $E = 5.5$keV and $\chi = 0^\circ$, height is over 120μm



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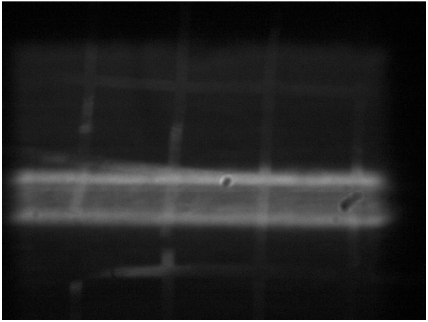

at $E = 5.5\text{keV}$ and $\chi = 0^\circ$, height is over $120\mu\text{m}$

At $\chi = 30^\circ$, it is under $50\mu\text{m}$

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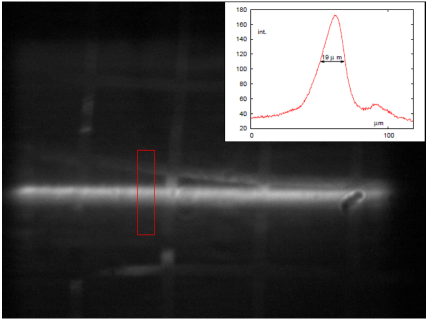
At $\chi = 30^\circ$, it is under 50μm

Optimal focus is 20μm at $\chi = 40^\circ$



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Zone plate fabrication

Making high aspect ratio zone plates is challenging but a new process has been developed to make plates with an aspect ratio as high as 25.

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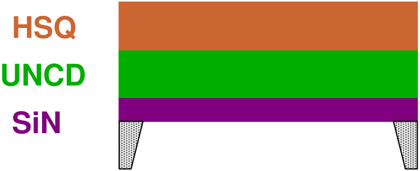

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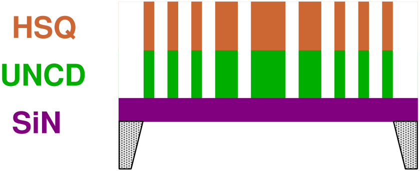
Start with Ultra nano crystalline diamond (UNCD) films on SiN. Coat with hydrogen silsesquioxane (HSQ). Pattern and develop the HSQ layer. Reactive ion etch the UNCD to the substrate.



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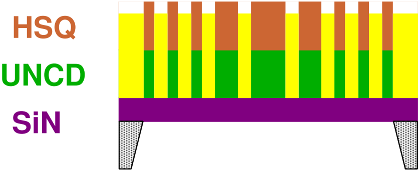

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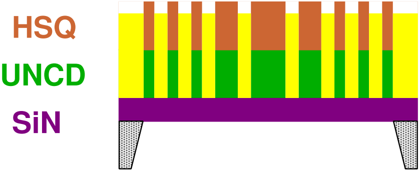
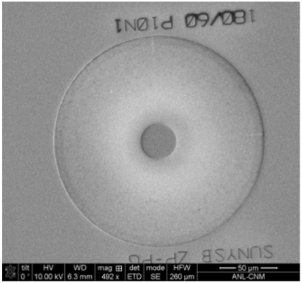


The whole 150nm diameter zone plate



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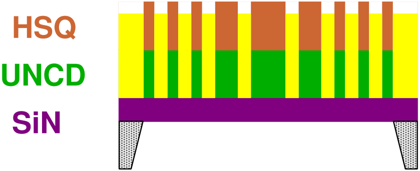

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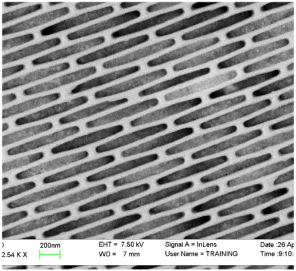
Detail view of outer zones



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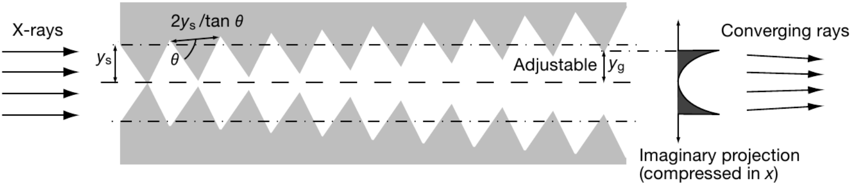
Alligator-type lenses

Perhaps one of the most original x-ray lenses has been made by using old vinyl records in an “alligator” configuration.



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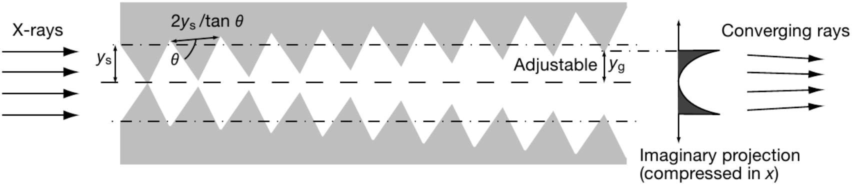

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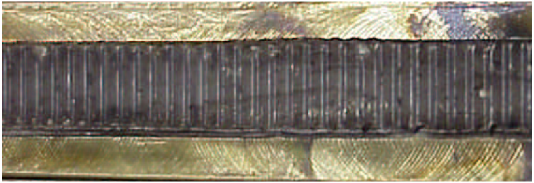

This design has also been used to make lenses out of lithium metal.

E.M. Dufresne et al., “Lithium metal for x-ray refractive optics”, *Appl. Phys. Lett.* **79**, 4085 (2001).