

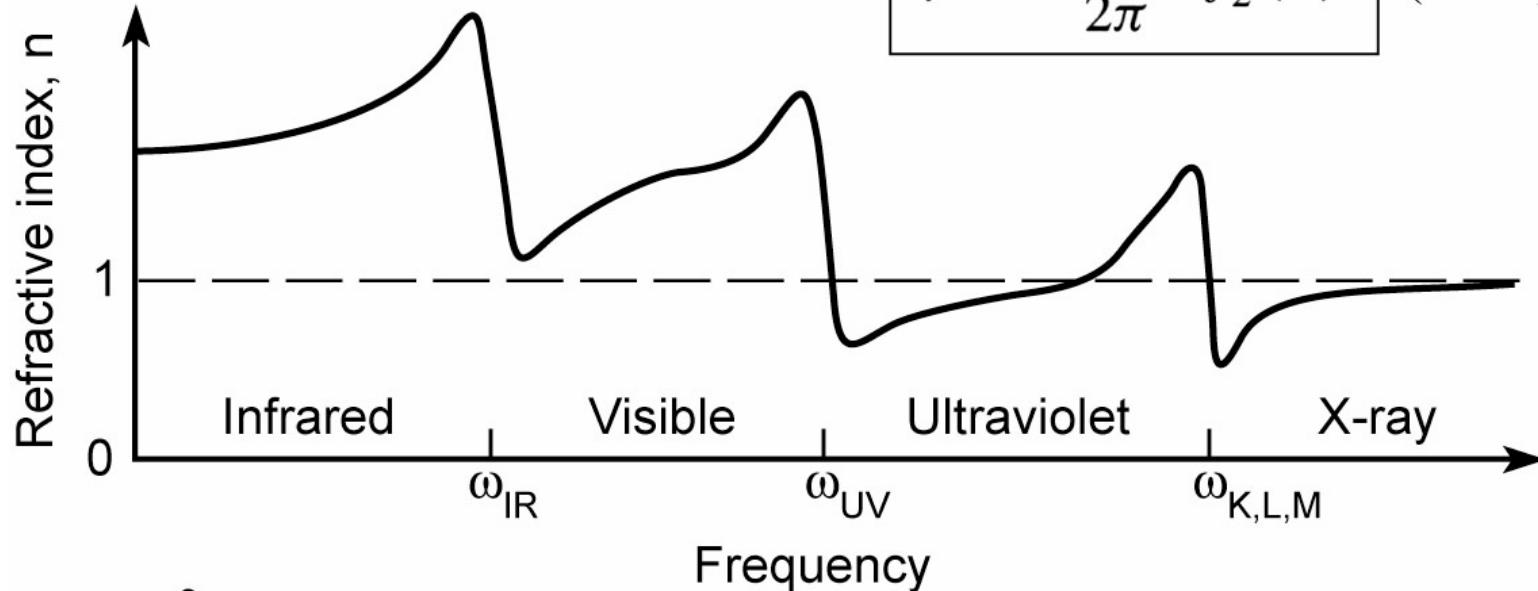
Refractive index from the IR to the x-ray region of the electromagnetic spectrum



$$n(\omega) = 1 - \delta + i\beta \quad (3.12)$$

$$\delta = \frac{n_a r_e \lambda^2}{2\pi} f_1^0(\omega) \quad (3.13a)$$

$$\beta = \frac{n_a r_e \lambda^2}{2\pi} f_2^0(\omega) \quad (3.13b)$$



- λ^2 behavior
- $\delta & \beta \ll 1$
- δ -crossover

Ch03_RefrcIdxIR_XR_Jan2009.ai



Reflection and refraction of EUV/soft x-ray radiation

The refractive index, $n(\omega)$, is complex because EUV/soft x-ray radiation is absorbed appreciably by all atoms. This is reflected in the semi-classical model

$$n(\omega) = 1 - \frac{1}{2} \frac{e^2 n_a}{\epsilon_0 m} \sum_s \frac{g_s}{(\omega^2 - \omega_s^2) + i\gamma\omega} \quad (3.8)$$

where again $\sum_s g_s = Z$ (2.73), or by its quantum mechanical equivalent $\sum_{k,n} g_{kn} = Z$. (2.74)

The convention is to express scattering and refractive index in terms of a complex scattering factor, $f^0(\omega)$ specific to each element

$$f^0(\omega) = f_1^0(\omega) - i f_2^0(\omega) = \sum_s \frac{g_s \omega^2}{\omega^2 - \omega_s^2 + i\gamma\omega}$$

where the scattering factor arises from consideration of the scattered electric field due to an atom, relative to that of a free electron, a topic we will discuss again in a later lecture. Introducing the classical electron radius

$$r_e = \frac{e^2}{4\pi\epsilon_0 mc^2} \quad (2.44)$$

The refractive index can be written as

$$n(\omega) = 1 - \frac{n_a r_e \lambda^2}{2\pi} [f_1^0(\omega) - i f_2^0(\omega)] \quad (3.9)$$

or in simpler notation

$$n(\omega) = 1 - \delta + i\beta \quad (3.12)$$

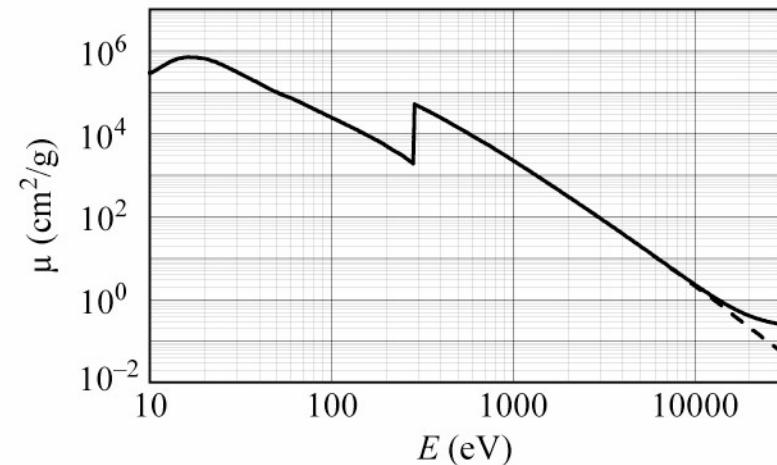
Atomic scattering factors for Carbon (Z = 6)



$$\sigma_a(\text{barns/atom}) = \mu(\text{cm}^2/\text{g}) \times 19.95$$

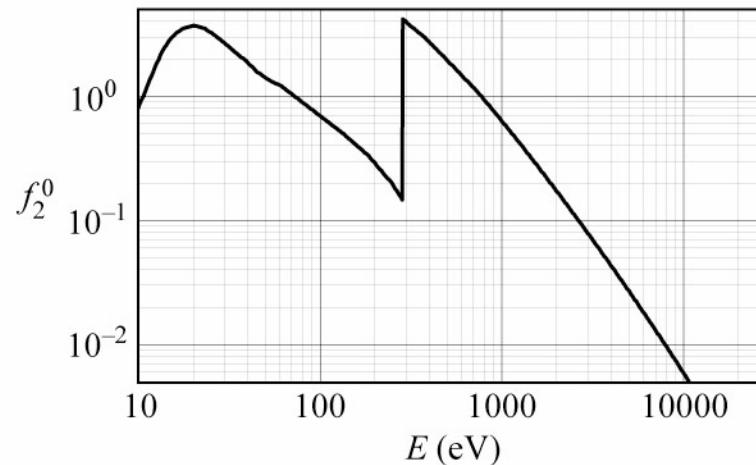
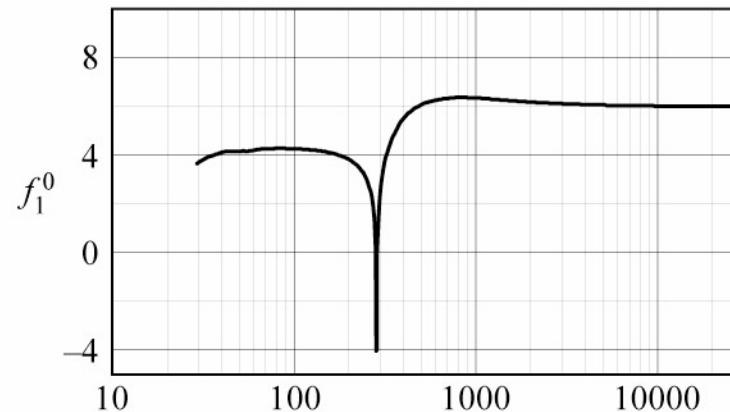
$$E(\text{keV})\mu(\text{cm}^2/\text{g}) = f_2^0 \times 3503.31$$

Energy (eV)	f_1^0	f_2^0	$\mu (\text{cm}^2/\text{g})$
30	3.692	2.664E+00	3.111E+05
70	4.249	1.039E+00	5.201E+04
100	4.253	6.960E-01	2.438E+04
300	2.703	3.923E+00	4.581E+04
700	6.316	1.174E+00	5.878E+03
1000	6.332	6.328E-01	2.217E+03
3000	6.097	7.745E-02	9.044E+01
7000	6.025	1.306E-02	6.536E+00
10000	6.013	5.892E-03	2.064E+00
30000	6.000	4.425E-04	5.168E-02



Edge Energies: K 284.2 eV

Carbon (C)
Z = 6
Atomic weight = 12.011



(Henke and Gullikson; www-cxro.LBL.gov)

Ch02_F13VG.ai

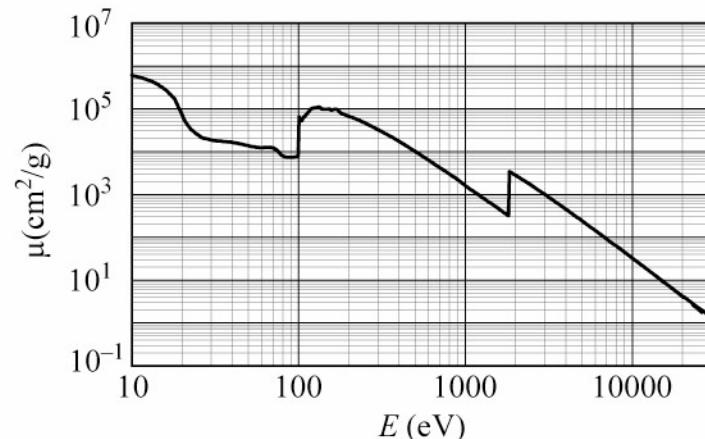
Atomic scattering factors for Silicon (Z = 14)



$$\sigma_a(\text{barns/atom}) = \mu(\text{cm}^2/\text{g}) \times 46.64$$

$$E(\text{keV})\mu(\text{cm}^2/\text{g}) = f_2^0 \times 1498.22$$

Energy (eV)	f_1^0	f_2^0	$\mu(\text{cm}^2/\text{g})$
30	3.799	3.734E-01	1.865E+04
70	2.448	5.701E-01	1.220E+04
100	-5.657	4.580E+00	6.862E+04
300	12.00	6.439E+00	3.216E+04
700	13.31	1.951E+00	4.175E+03
1000	13.00	1.070E+00	1.602E+03
3000	14.23	1.961E+00	9.792E+02
7000	14.33	4.240E-01	9.075E+01
10000	14.28	2.135E-01	3.199E+01
30000	14.02	2.285E-02	1.141E+00



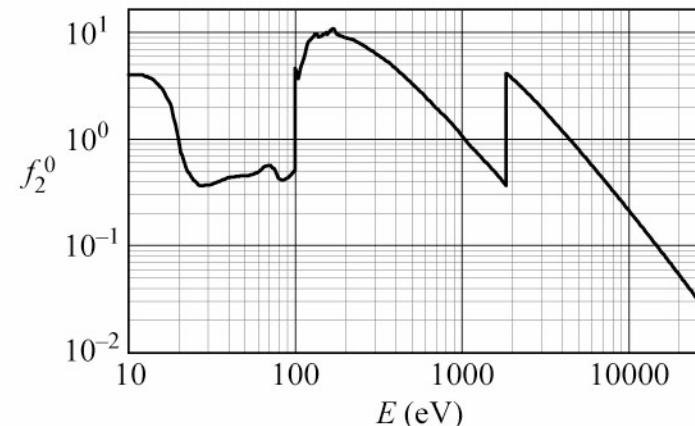
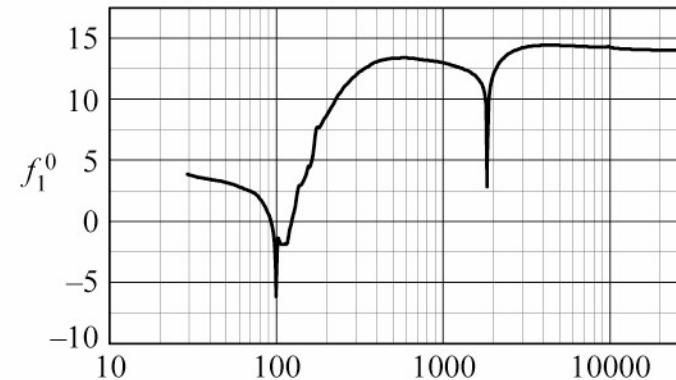
Edge Energies: K 1838.9 eV L₁ 149.7 eV
 L₂ 99.8 eV
 L₃ 99.2 eV

(Henke and Gullikson; www-cxro.LBL.gov)

Silicon (Si)

Z = 14

Atomic weight = 28.086



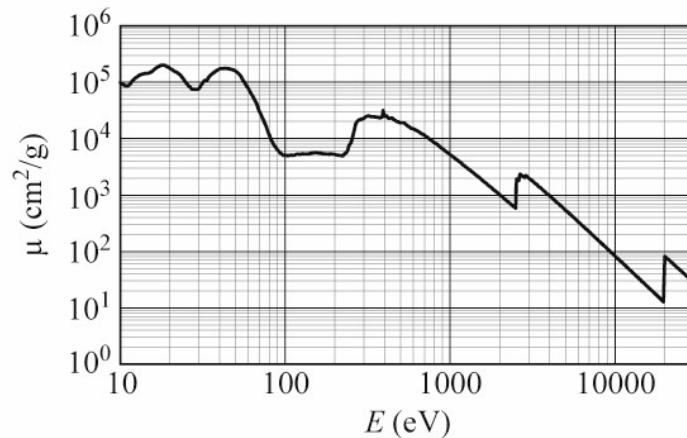
Atomic scattering factors for Molybdenum (Z = 42)



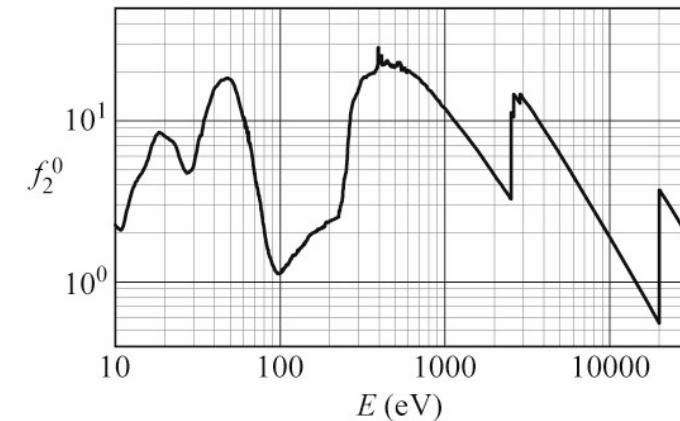
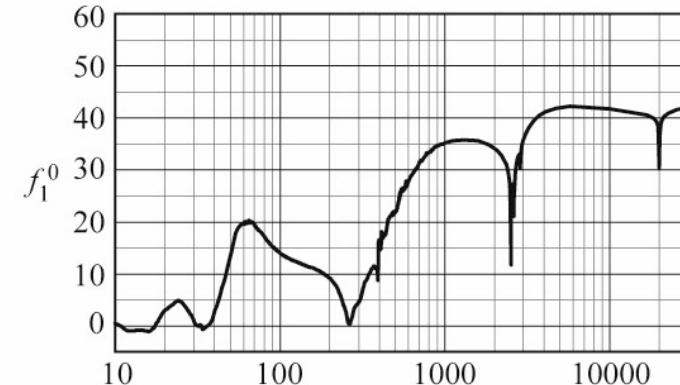
$$\sigma_a(\text{barns/atom}) = \mu(\text{cm}^2/\text{g}) \times 159.31$$

$$E(\text{keV})\mu(\text{cm}^2/\text{g}) = f_2^0 \times 438.59$$

Energy (eV)	f_1^0	f_2^0	μ (cm^2/g)
30	1.071	5.292E+00	7.736E+04
70	19.38	4.732E+00	2.965E+04
100	14.02	1.124E+00	4.931E+03
300	4.609	1.568E+01	2.292E+04
700	31.41	1.819E+01	1.140E+04
1000	35.15	1.188E+01	5.210E+03
3000	35.88	1.366E+01	1.997E+03
7000	42.11	3.493E+00	2.189E+02
10000	41.67	1.881E+00	8.248E+01
30000	42.04	1.894E+00	2.769E+01



Molybdenum (Mo)
Z = 42
Atomic weight = 95.940



Edge Energies:	K	19999.5 eV	L ₁	2865.5 eV	M ₁	506.3 eV	N ₁	63.2 eV
	L ₂	2625.1 eV	M ₂	411.6 eV	N ₂	37.6 eV		
	L ₃	2520.2 eV	M ₃	394.0 eV	N ₃	35.5 eV		
			M ₄	231.1 eV				
			M ₅	227.9 eV				

(Henke and Gullikson; www-cxro.LBL.gov)

Ch02_ApC_Tb1_F12_June2008.ai



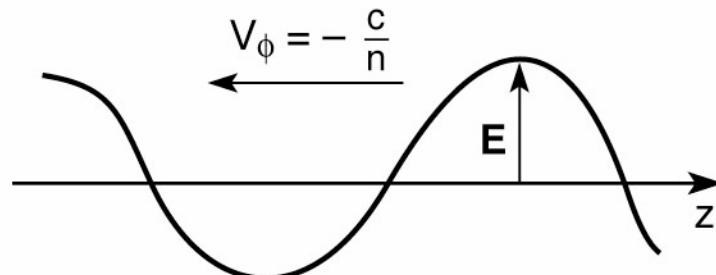
Phase velocity and refractive index

The wave equation can be written as

$$\left(\frac{\partial}{\partial t} - \frac{c}{n(\omega)} \nabla \right) \left(\frac{\partial}{\partial t} + \frac{c}{n(\omega)} \nabla \right) \mathbf{E}_T(\mathbf{r}, t) = 0 \quad (3.10)$$

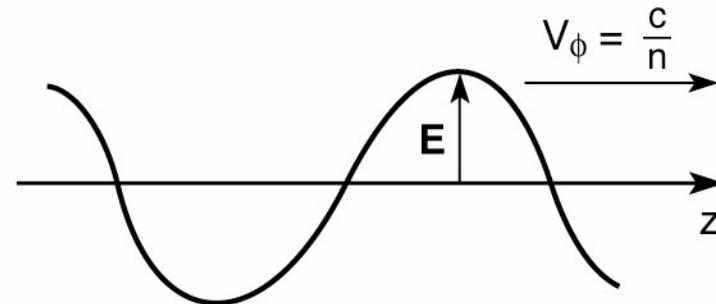
The two bracketed operators represent left and right-running waves

$$\left(\frac{\partial}{\partial t} - \frac{c}{n} \frac{\partial}{\partial z} \right) E_x = 0$$



Left-running wave

$$\left(\frac{\partial}{\partial t} + \frac{c}{n} \frac{\partial}{\partial z} \right) E_x = 0$$



Right-running wave

where the phase velocity, the speed with which crests of fixed phase move, is not equal to c as in vacuum, but rather is

$$v_\phi = \frac{c}{n(\omega)} \quad (3.11)$$

Phase velocity and refractive index (continued)



Recall the wave equation

$$\left(\frac{\partial}{\partial t} - \frac{c}{n(\omega)} \nabla \right) \left(\frac{\partial}{\partial t} + \frac{c}{n(\omega)} \nabla \right) \mathbf{E}_T(\mathbf{r}, t) = 0 \quad (3.10)$$

Examining one of these factors, for a space-time dependence

$$\mathbf{E}_T = \mathbf{E}_0 \exp[-i(\omega t - kz)]$$

$$-i \left(\omega - \frac{ck}{n} \right) = 0$$

Solving for ω/k we have the phase velocity

$$V_\phi = \frac{\omega}{k} = \frac{c}{n}$$

Ch03_PhasVelo_Refrc2.ai

Phase variation and absorption of propagating waves



For a plane wave $\mathbf{E}(\mathbf{r}, t) = \mathbf{E}_0 e^{-i(\omega t - \mathbf{k} \cdot \mathbf{r})}$ (3.14)

in a material of refractive index n , the complex dispersion relation is

$$\frac{\omega}{k} = \frac{c}{n} = \frac{c}{1 - \delta + i\beta} \quad (3.15)$$

Solving for k

$$k = \frac{\omega}{c} (1 - \delta + i\beta) \quad (3.16)$$

Substituting this into (3.14), in the propagation direction defined by $\mathbf{k} \cdot \mathbf{r} = kr$

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{E}_0 e^{-i[\omega t - (\omega/c)(1 - \delta + i\beta)r]}$$

or

$$\mathbf{E}(\mathbf{r}, t) = \underbrace{\mathbf{E}_0 e^{-i\omega(t-r/c)}}_{\text{vacuum propagation}} \underbrace{e^{-i(2\pi\delta/\lambda)r}}_{\phi\text{-shift}} \underbrace{e^{-(2\pi\beta/\lambda)r}}_{\text{decay}} \quad (3.17)$$

where the first exponential factor represents the phase advance had the wave been propagating in vacuum, the second factor (containing $2\pi\delta r/\lambda$) represents the modified phase shift due to the medium, and the factor containing $2\pi\beta r/\lambda$ represents decay of the wave amplitude.

Intensity and absorption in a material of complex refractive index



The average intensity, in units of power per unit area, is

$$\bar{I} = \frac{1}{2} \operatorname{Re}(n) \sqrt{\frac{\epsilon_0}{\mu_0}} |\mathbf{E}|^2 \quad (3.20)$$

$$\bar{I} = \frac{1}{2} \operatorname{Re}(n) \sqrt{\frac{\epsilon_0}{\mu_0}} |\mathbf{E}_0|^2 e^{-2(2\pi\beta/\lambda)r}$$

or

$$\bar{I} = \bar{I}_0 e^{-(4\pi\beta/\lambda)r} \quad (3.21)$$

The wave decays with an exponential decay length

$$l_{\text{abs}} = \frac{\lambda}{4\pi\beta} \quad (3.22)$$

Recalling that $\beta = n_a r_e \lambda^2 f_2^0(\omega) / 2\pi$

$$l_{\text{abs}} = \frac{1}{2n_a r_e \lambda f_2^0(\omega)} \quad (3.23)$$

In Chapter 1 we considered experimentally observed absorption in thin foils, writing

$$\frac{\bar{I}}{\bar{I}_0} = e^{-\rho\mu r} \quad (3.24)$$

where ρ is the mass density, μ is the absorption coefficient, r is the foil thickness, and thus $l_{\text{abs}} = 1/\rho\mu$. Comparing absorption lengths, the macroscopic and atomic descriptions are related by

$$\mu = \frac{2r_e \lambda}{Am_u} f_2^0(\omega) \quad (3.26)$$

where $\rho = m_a n_a = Am_u n_a$, m_u is the atomic mass unit, and A is the number of atomic mass units



Phase shift relative to vacuum propagation

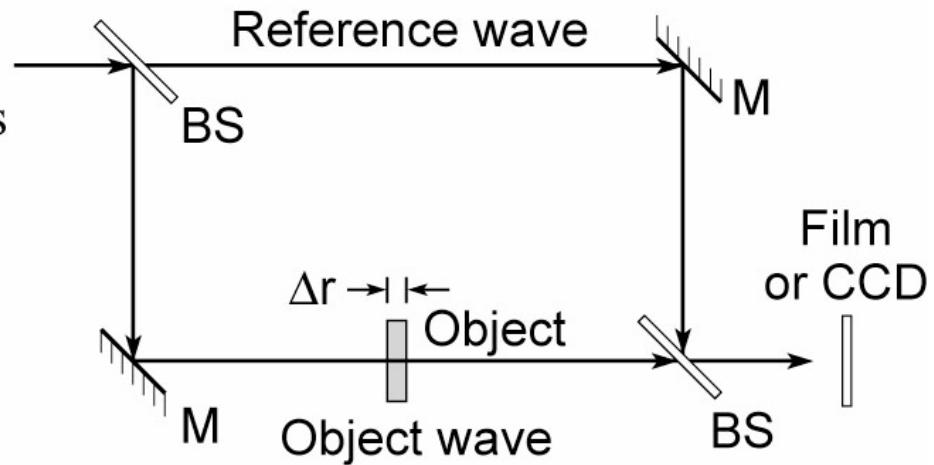
For a wave propagating in a medium of refractive index $n = 1 - \delta + i\beta$

$$\mathbf{E}(\mathbf{r}, t) = \underbrace{\mathbf{E}_0 e^{-i\omega(t-r/c)}}_{\text{vacuum propagation}} \underbrace{e^{-i(2\pi\delta/\lambda)r}}_{\phi\text{-shift}} \underbrace{e^{-(2\pi\beta/\lambda)r}}_{\text{decay}} \quad (3.23)$$

the phase shift $\Delta\phi$ relative to vacuum, due to propagation through a thickness Δr is

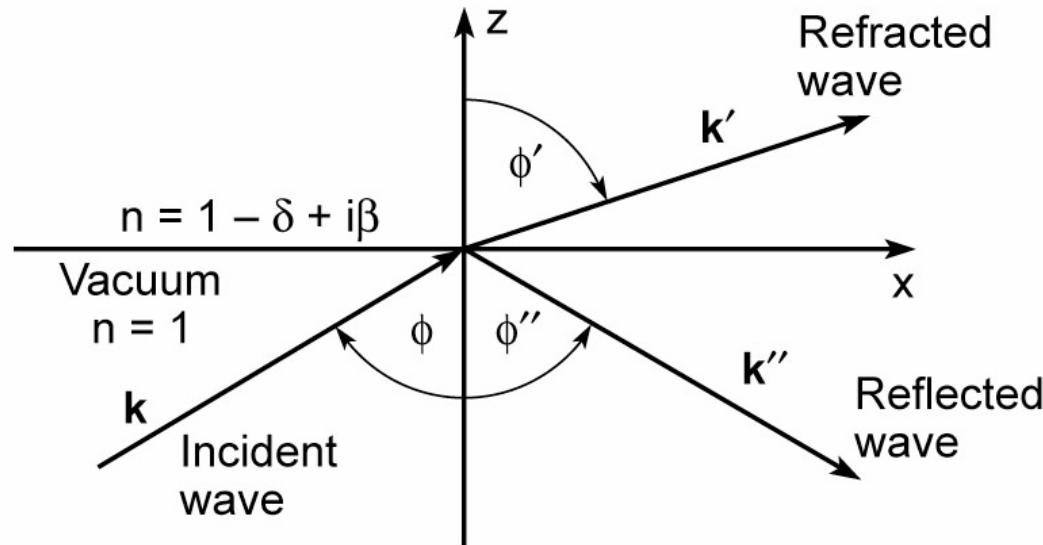
$$\boxed{\Delta\phi = \left(\frac{2\pi\delta}{\lambda}\right) \Delta r} \quad (3.29)$$

- Flat mirrors at short wavelengths
- Transmissive, flat beamsplitters
- Bonse and Hart interferometer
- Diffractive optics for SXR/EUV



Ch03_PhaseShift.ai

Reflection and refraction at an interface



$$\text{incident wave: } \mathbf{E} = \mathbf{E}_0 e^{-i(\omega t - \mathbf{k} \cdot \mathbf{r})} \quad (3.30a)$$

$$\text{refracted wave: } \mathbf{E}' = \mathbf{E}'_0 e^{-i(\omega t - \mathbf{k}' \cdot \mathbf{r})} \quad (3.30b)$$

$$\text{reflected wave: } \mathbf{E}'' = \mathbf{E}''_0 e^{-i(\omega t - \mathbf{k}'' \cdot \mathbf{r})} \quad (3.30c)$$

- (1) All waves have the same frequency, ω , and $|\mathbf{k}| = |\mathbf{k}''| = \frac{\omega}{c}$
- (2) The refracted wave has phase velocity

$$V_\phi = \frac{\omega'}{k'} = \frac{c}{n}, \text{ thus } k' = |\mathbf{k}'| = \frac{\omega}{c} (1 - \delta + i\beta)$$

Ch03_ReflectnRefrctn_Sept05.ai

Boundary conditions at an interface



- **E** and **H** components parallel to the interface must be continuous

$$\mathbf{z}_0 \times (\mathbf{E}_0 + \mathbf{E}'_0) = \mathbf{z}_0 \times \mathbf{E}'_0 \quad (3.32a)$$

$$\mathbf{z}_0 \times (\mathbf{H}_0 + \mathbf{H}''_0) = \mathbf{z}_0 \times \mathbf{H}'_0 \quad (3.32b)$$

- **D** and **B** components perpendicular to the interface must be continuous

$$\mathbf{z}_0 \cdot (\mathbf{D}_0 + \mathbf{D}''_0) = \mathbf{z}_0 \cdot \mathbf{D}'_0 \quad (3.32c)$$

$$\mathbf{z}_0 \cdot (\mathbf{B}_0 + \mathbf{B}''_0) = \mathbf{z}_0 \cdot \mathbf{B}'_0 \quad (3.32d)$$

Ch03_BndryConditns.ai



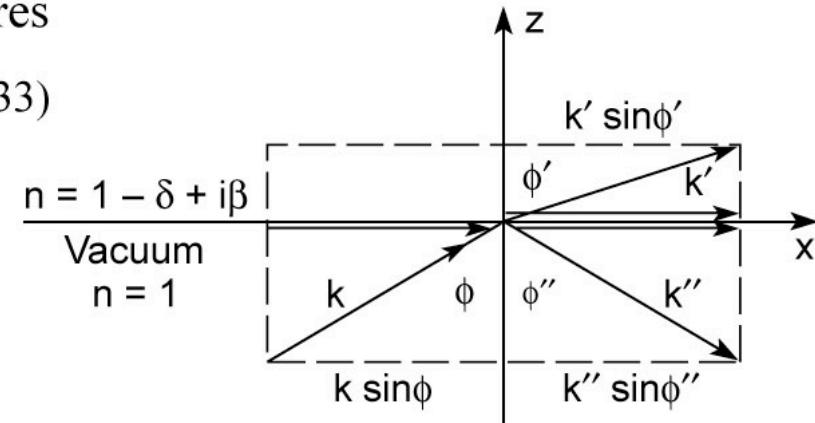
Spatial continuity along the interface

Continuity of parallel field components requires

$$(\mathbf{k} \cdot \mathbf{x}_0 = \mathbf{k}' \cdot \mathbf{x}_0 = \mathbf{k}'' \cdot \mathbf{x}_0) \quad \text{at } z = 0 \quad (3.33)$$

$$k_x = k'_x = k''_x \quad (3.34a)$$

$$k \sin \phi = k' \sin \phi' = k'' \sin \phi'' \quad (3.34b)$$



Conclusions:

Since $k = k''$ (both in vacuum)

$$\sin \phi = \sin \phi'' \quad (3.35a)$$

$$\therefore \boxed{\phi = \phi''} \quad (3.35b)$$

The angle of incidence equals
the angle of reflection

$$k \sin \phi = k' \sin \phi' \quad (3.36)$$

$$k = \frac{\omega}{c} \text{ and } k' = \frac{\omega'}{c/n} = \frac{n\omega}{c}$$

$$\sin \phi = n \sin \phi'$$

$$\boxed{\sin \phi' = \frac{\sin \phi}{n}} \quad (3.38)$$

Snell's Law, which describes
refractive turning, for complex n.

Total external reflection of soft x-ray and EUV radiation



Snell's law for a refractive index of $n \approx 1 - \delta$, assuming that $\beta \rightarrow 0$

$$\sin \phi' = \frac{\sin \phi}{1 - \delta} \quad (3.39)$$

Consider the limit when $\phi' \rightarrow \frac{\pi}{2}$

$$1 = \frac{\sin \phi_c}{1 - \delta}$$

$$\sin \phi_c = 1 - \delta \quad (3.40)$$

$$\sin(90^\circ - \theta_c) = 1 - \delta$$

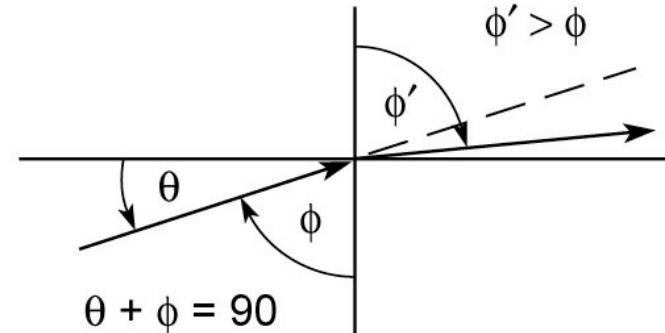
$$\cos \theta_c = 1 - \delta$$

$$1 - \frac{\theta_c^2}{2} + \dots = 1 - \delta$$

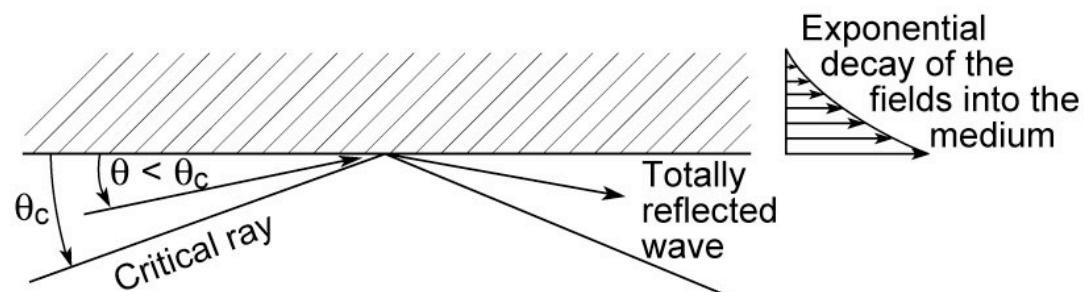
$$\boxed{\theta_c = \sqrt{2\delta}}$$

(3.41)

The critical angle for total external reflection.



Glancing incidence ($\theta < \theta_c$) and total external reflection





Total external reflection (continued)

$$\theta_c = \sqrt{2\delta} \quad (3.41)$$

$$\delta = \frac{n_a r_e \lambda^2 f_1^0(\lambda)}{2\pi}$$

$$\theta_c = \sqrt{2\delta} = \sqrt{\frac{n_a r_e \lambda^2 f_1^0(\lambda)}{\pi}} \quad (3.42a)$$

The atomic density n_a , varies slowly among the natural elements, thus to first order

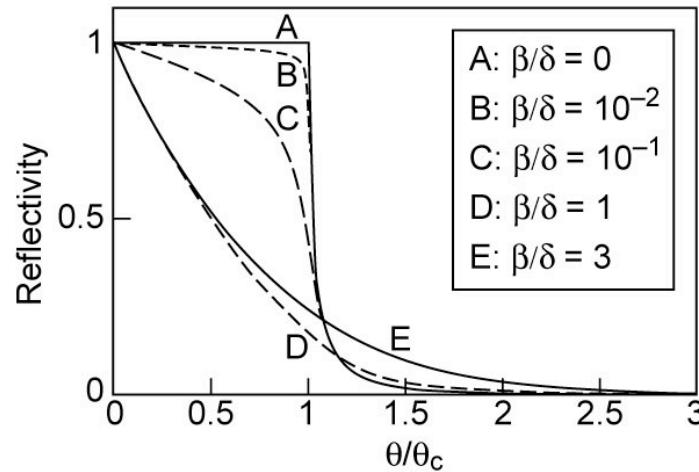
$$\theta_c \propto \lambda \sqrt{Z} \quad (3.42b)$$

where f_1^0 is approximated by Z . Note that f_1^0 is a complicated function of wavelength (photon energy) for each element.



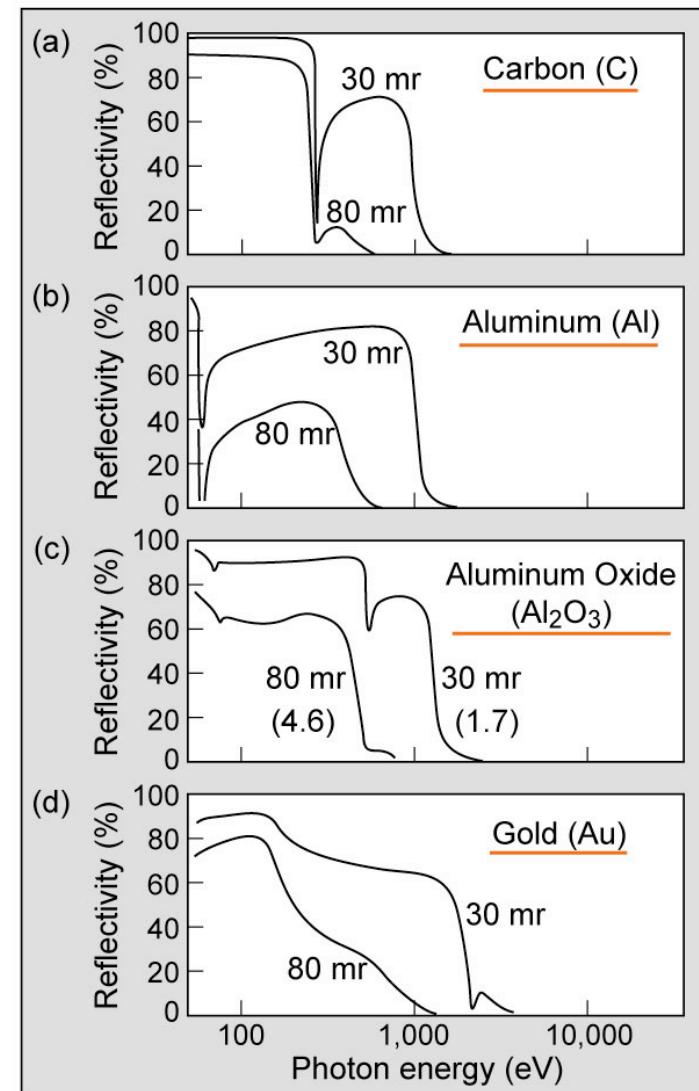
Total external reflection with finite β

Glancing incidence reflection
as a function of β/δ



- finite β/δ rounds the sharp angular dependence
- cutoff angle and absorption edges can enhance the sharpness
- note the effects of oxide layers and surface contamination

... for real materials



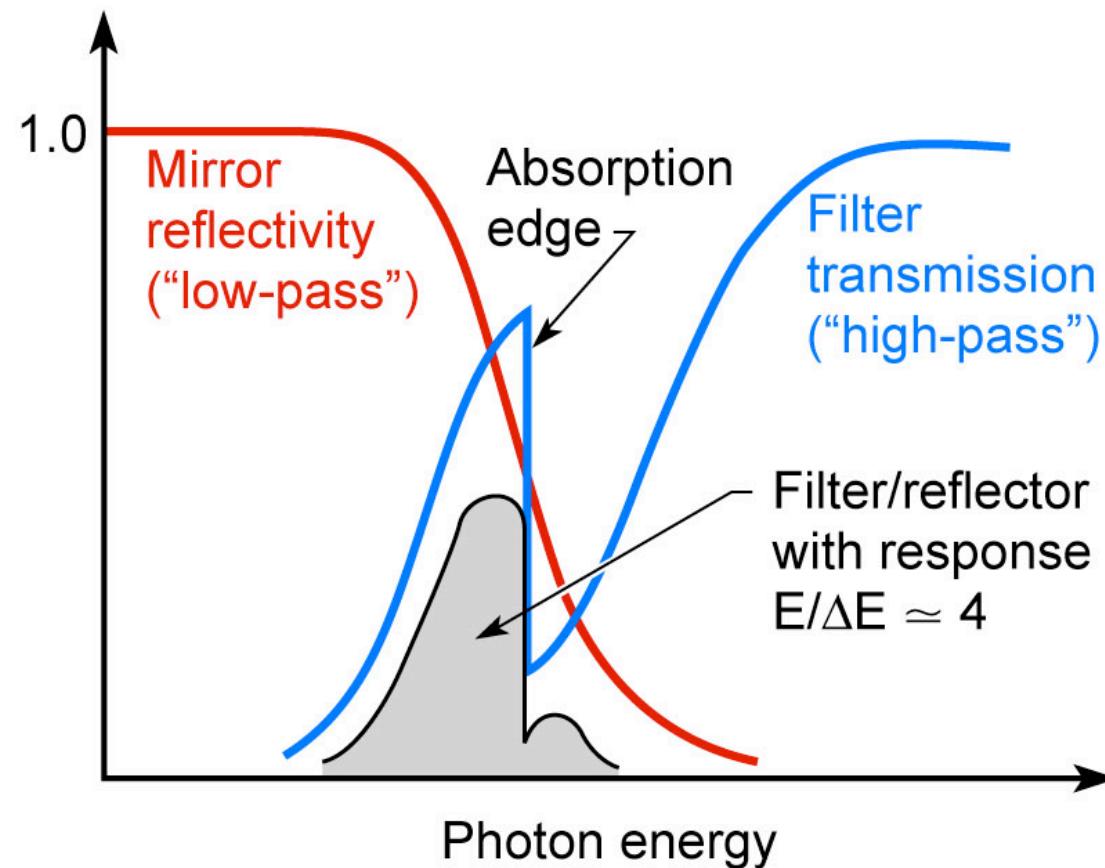
(Henke, Gullikson, Davis)

Ch03_TotalExtrnlReflc3.ai

The Notch Filter



- Combines a glancing incidence mirror and a filter
- Modest resolution, $E/\Delta E \sim 3-5$
- Commonly used



Ch03_NotchFilter.ai



Reflection at an interface

E_0 perpendicular to the plane of incidence (s-polarization)

tangential electric fields continuous

$$E_0 + E_0'' = E'_0 \quad (3.43)$$

tangential magnetic fields continuous

$$H_0 \cos \phi - H_0'' \cos \phi = H'_0 \cos \phi' \quad (3.44)$$

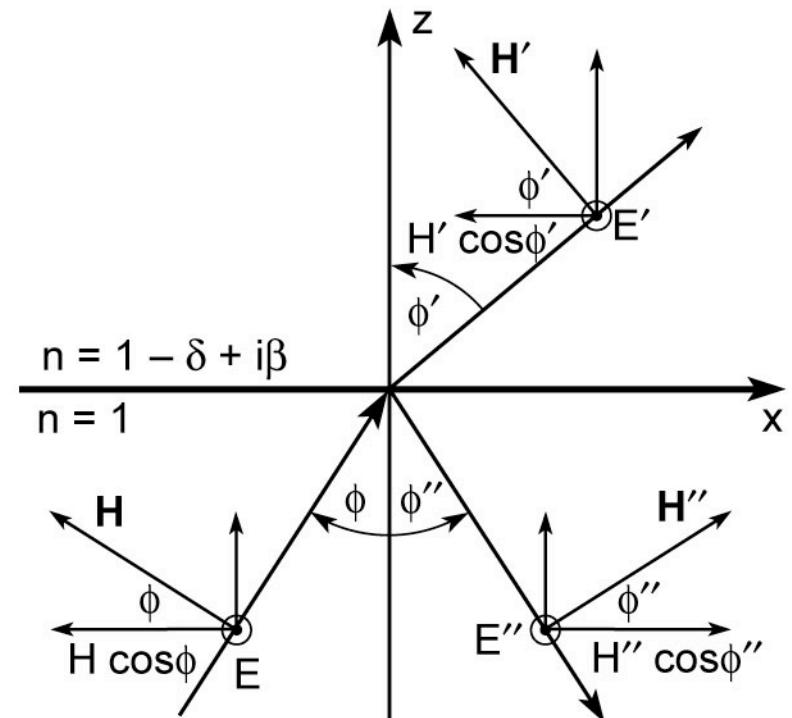
$$\mathbf{H}(\mathbf{r}, t) = n \sqrt{\frac{\epsilon_0}{\mu_0}} \mathbf{k}_0 \times \mathbf{E}(\mathbf{r}, t) \rightarrow H = n \sqrt{\frac{\epsilon_0}{\mu_0}} E$$

$$\sqrt{\frac{\epsilon_0}{\mu_0}} E_0 \cos \phi - \sqrt{\frac{\epsilon_0}{\mu_0}} E_0'' \cos \phi = n \sqrt{\frac{\epsilon_0}{\mu_0}} E'_0 \cos \phi'$$

$$(E_0 - E_0'') \cos \phi = n E'_0 \cos \phi' \quad (3.45)$$

Snell's Law:

$$\sin \phi' = \frac{\sin \phi}{n}$$



Three equations in three unknowns
 (E'_0, E_0'', ϕ') (for given E_0 and ϕ)

Ch03_ReflecInterf1.ai



Reflection at an interface (continued)

E_0 perpendicular to the plane of incidence (s-polarization)

$$\frac{E'_0}{E_0} = \frac{2 \cos \phi}{\cos \phi + \sqrt{n^2 - \sin^2 \phi}} \quad (3.47)$$

$$\frac{E''_0}{E_0} = \frac{\cos \phi - \sqrt{n^2 - \sin^2 \phi}}{\cos \phi + \sqrt{n^2 - \sin^2 \phi}} \quad (3.46)$$

The reflectivity R is then

$$R = \frac{\bar{I}''}{\bar{I}_0} = \frac{|\bar{\mathbf{S}}''|}{|\bar{\mathbf{S}}|} = \frac{\frac{1}{2} \operatorname{Re}(\mathbf{E}_0'' \times \mathbf{H}_0''^*)}{\frac{1}{2} \operatorname{Re}(\mathbf{E}_0 \times \mathbf{H}_0^*)} \quad (3.48)$$

With $n = 1$ for both incident and reflected waves,

$$R = \frac{|E''_0|^2}{|E_0|^2}$$

Which with Eq. (3.46) becomes, for the case of perpendicular (s) polarization

$$R_s = \frac{|\cos \phi - \sqrt{n^2 - \sin^2 \phi}|^2}{|\cos \phi + \sqrt{n^2 - \sin^2 \phi}|^2} \quad (3.49)$$



Normal incidence reflection at an interface

Normal incidence ($\phi = 0$)

$$R_s = \frac{\left| \cos \phi - \sqrt{n^2 - \sin^2 \phi} \right|^2}{\left| \cos \phi + \sqrt{n^2 - \sin^2 \phi} \right|^2} \quad (3.49)$$

$$R_{s,\perp} = \frac{|1-n|^2}{|1+n|^2} = \frac{(1-n)(1-n^*)}{(1+n)(1+n^*)}$$

For $n = 1 - \delta + i\beta$

$$R_{s,\perp} = \frac{(\delta - i\beta)(\delta + i\beta)}{(2 - \delta + i\beta)(2 - \delta - i\beta)} = \frac{\delta^2 + \beta^2}{(2 - \delta)^2 + \beta^2}$$

Which for $\delta \ll 1$ and $\beta \ll 1$ gives the reflectivity for x-ray and EUV radiation at normal incidence ($\phi = 0$) as

$$R_{s,\perp} \simeq \frac{\delta^2 + \beta^2}{4} \quad (3.50)$$

Example: Nickel @ 300 eV (4.13 nm)
From table C.1, p. 433
 $f_1^0 = 17.8$ $f_2^0 = 7.70$ $\delta = 0.0124$ $\beta = 0.00538$ $R_{\perp} = 4.58 \times 10^{-5}$

Ch03_NormIncidReflec.ai

Glancing incidence reflection (s-polarization)



$$R_s = \frac{|\cos \phi - \sqrt{n^2 - \sin^2 \phi}|^2}{|\cos \phi + \sqrt{n^2 - \sin^2 \phi}|^2} \quad (3.49)$$

For $\theta = 90^\circ - \phi \leq \theta_c$

where $\theta_c = \sqrt{2\delta} \ll 1$

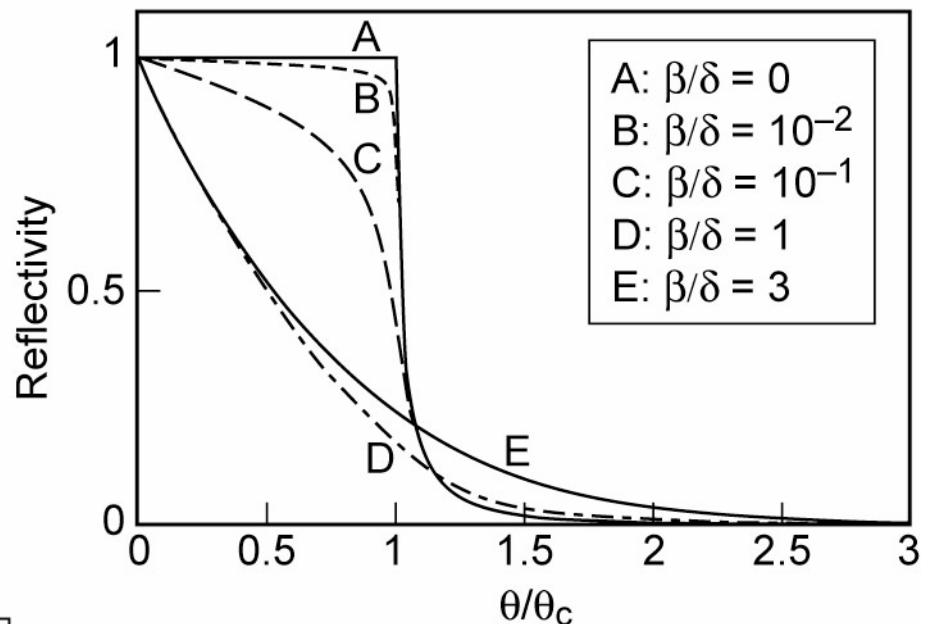
$$\cos \phi = \sin \theta \simeq \theta$$

$$\sin^2 \phi = 1 - \cos^2 \phi = 1 - \sin^2 \theta \simeq 1 - \theta^2$$

For $n = 1 - \delta + i\beta$

$$n^2 = (1 - \delta)^2 + 2i\beta(1 - \delta) - \beta^2$$

$$R_{s,\theta} = \frac{|\theta - \sqrt{(\theta^2 - \theta_c^2) + 2i\beta}|^2}{|\theta + \sqrt{(\theta^2 - \theta_c^2) + 2i\beta}|^2} \quad (\theta \ll 1)$$



E. Nähring, "Die Totalreflexion der Röntgenstrahlen", Physik. Zeitstr. XXXI, 799 (Sept. 1930).



Reflection at an interface

E_0 perpendicular to the plane of incidence (p-polarization)

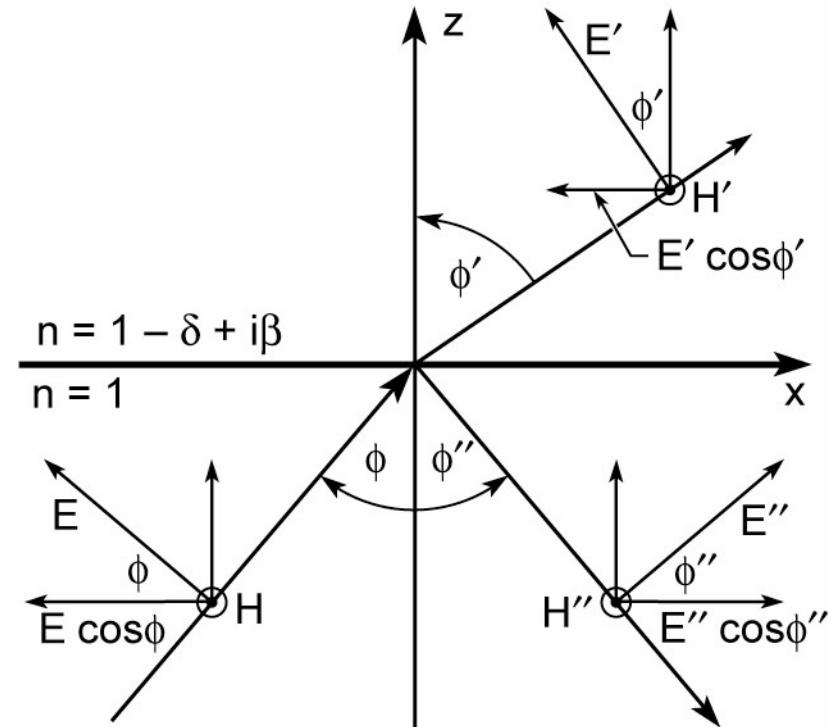
$$\frac{E''_0}{E_0} = \frac{n^2 \cos \phi - \sqrt{n^2 - \sin^2 \phi}}{n^2 \cos \phi + \sqrt{n^2 - \sin^2 \phi}} \quad (3.54)$$

$$\frac{E'_0}{E_0} = \frac{2n \cos \phi}{n^2 \cos \phi + \sqrt{n^2 - \sin^2 \phi}} \quad (3.55)$$

The reflectivity for parallel (p) polarization is

$$R_p = \left| \frac{E''_0}{E_0} \right|^2 = \frac{\left| n^2 \cos \phi - \sqrt{n^2 - \sin^2 \phi} \right|^2}{\left| n^2 \cos \phi + \sqrt{n^2 - \sin^2 \phi} \right|^2} \quad (3.56)$$

which is similar in form but slightly different from that for s-polarization. For $\phi = 0$ (normal incidence) the results are identical.



Ch03_ReflecInterf3.ai



Brewster's angle for x-rays and EUV

For p-polarization

$$R_p = \left| \frac{E_0''}{E_0} \right|^2 = \frac{\left| n^2 \cos \phi - \sqrt{n^2 - \sin^2 \phi} \right|^2}{\left| n^2 \cos \phi + \sqrt{n^2 - \sin^2 \phi} \right|^2} \quad (3.56)$$

There is a minimum in the reflectivity where the numerator satisfies

$$n^2 \cos \phi_B = \sqrt{n^2 - \sin^2 \phi_B} \quad (3.58)$$

Squaring both sides, collecting like terms involving ϕ_B , and factoring, one has

$$n^2(n^2 - 1) = (n^4 - 1) \sin^2 \phi_B$$

or $\sin \phi_B = \frac{n}{\sqrt{n^2 + 1}}$

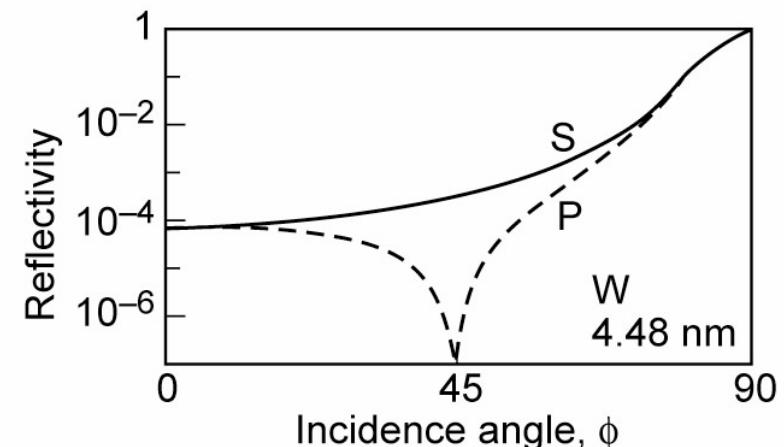
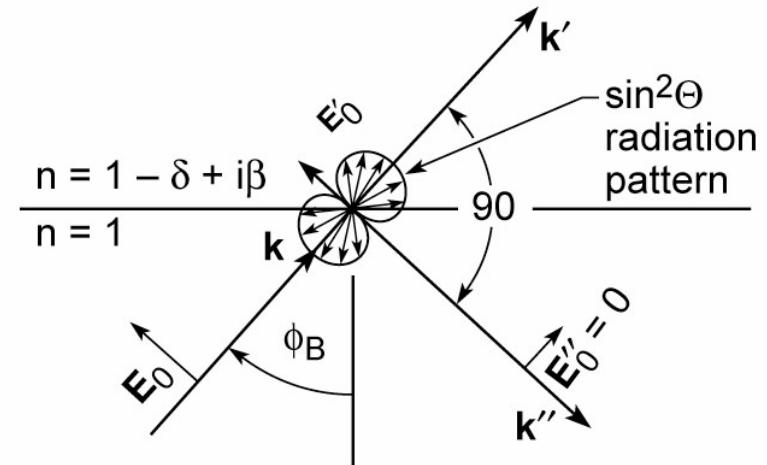
the condition for a minimum in the reflectivity, for parallel polarized radiation, occurs at an angle given by $\tan \phi_B = n$ (3.59)

For complex n , Brewster's minimum occurs at

$$\tan \phi_B = 1 - \delta$$

or

$$\phi_B \simeq \frac{\pi}{4} - \frac{\delta}{2} \quad (3.60)$$

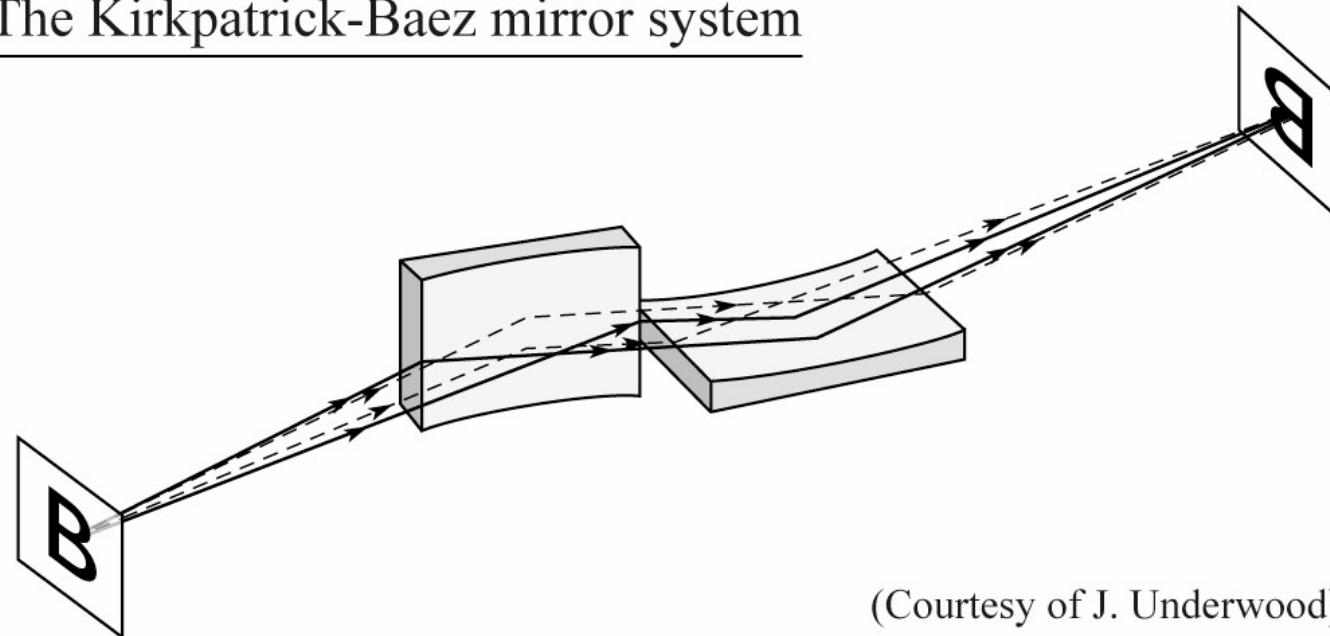


(Courtesy of J. Underwood)

Focusing with curved, glancing incidence optics



The Kirkpatrick-Baez mirror system



(Courtesy of J. Underwood)

- Two crossed cylinders (or spheres)
- Astigmatism cancels
- Fusion diagnostics
- Common use in synchrotron radiation beamlines
- See hard x-ray microprobe, chapter 4, figure 4.14

Ch03_FocusCurv.ai



Determining f_1^0 and f_2^0

- f_2^0 easily measured by absorption
- f_1^0 difficult in SXR/EUV region
- Common to use Kramers-Kronig relations

$$f_1^0(\omega) = Z - \frac{2}{\pi} \mathcal{P}_C \int_0^\infty \frac{uf_2^0(u)}{u^2 - \omega^2} du \quad (3.85a)$$

$$f_2^0 = \frac{2\omega}{\pi} \mathcal{P}_C \int_0^\infty \frac{f_1^0(u) - Z}{u^2 - \omega^2} du \quad (3.85b)$$

as in the Henke & Gullikson tables (pp. 428-436)

- Possible to use reflection from clean surfaces; Soufli & Gullikson
- With diffractive beam splitter can use a phase-shifting interferometer; Chang et al.
- Bi-mirror technique of Joyeux, Polack and Phalippou (Orsay, France)