Basic Detector Processes

X-Ray Astronomy School III

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How do we measure the position, energy, and arrival time of an X-ray photon?

No animals were harmed in the preparation of this talk

Detection of X-rays

1. X-ray Interactions
   - Photoelectric Absorption
2. Charge Creation
   - Atomic Emission
   - Secondary ionization: The Fano Factor
3. Charge Multiplication
   - Proportional Counter
   - Microchannel Plates
4. Charge Measurement
   - Spectral Response
   - Background

INTRODUCTION

I will emphasize Proportional Counters (PC) and MicroChannel Plate (MCP) arrays

1. **They are the historical Workhorse of X-ray Astronomy**
2. **Basic principles of interaction, measurement of a distribution of pulse heights, background, apply to CCD and Calorimeters**
3. **They play a key role in ground calibration!**
4. **They can be extended to very large areas:**
   - **Needed at higher energies, or without telescopes.**
5. **PC have a high detection efficiency over a broad energy range.**
6. **They can give high time resolution, to a few μsec, in combination with all of the above.**
7. **CCD and Calorimeters each covered in detail on Thursday**

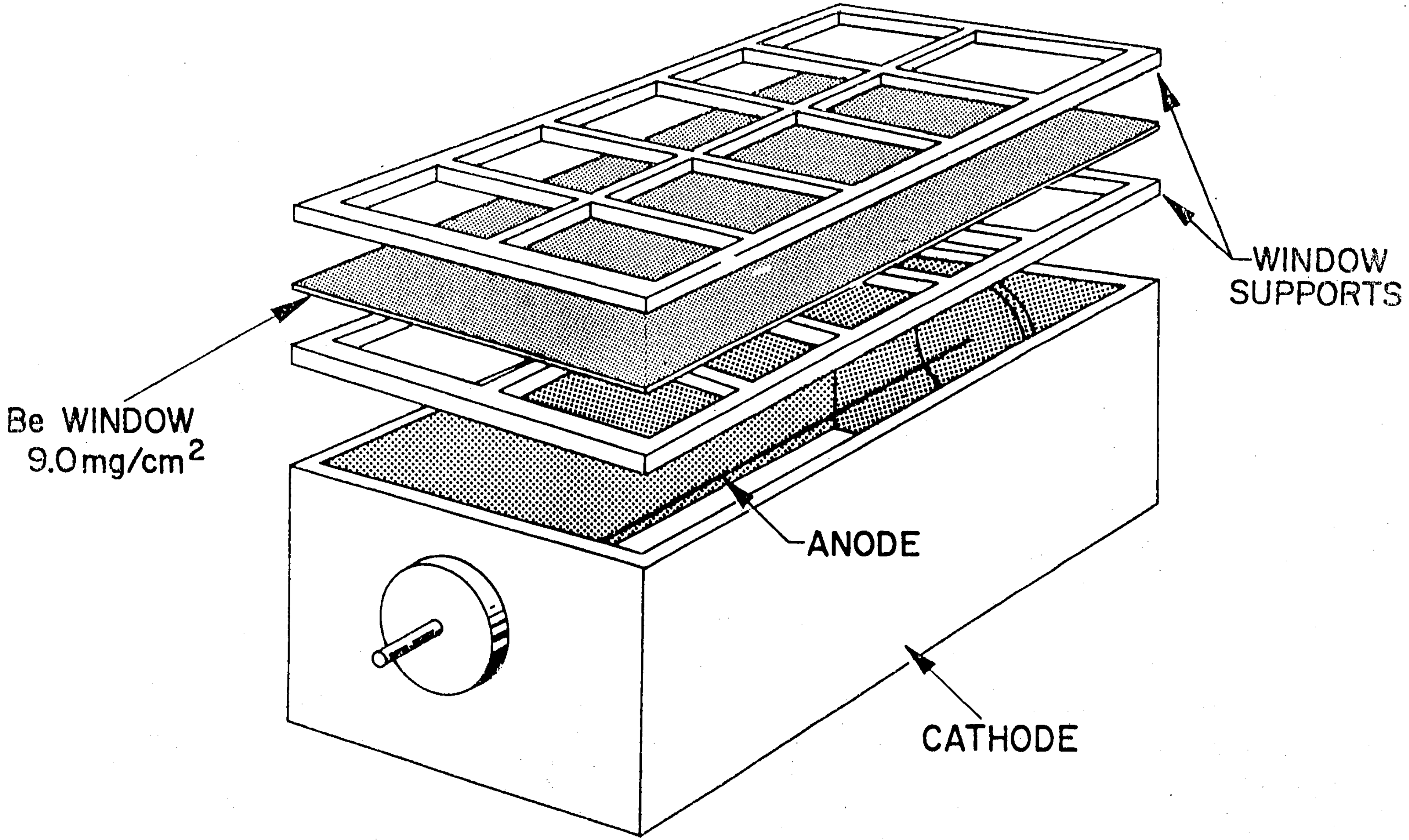
GENERAL PRINCIPLES

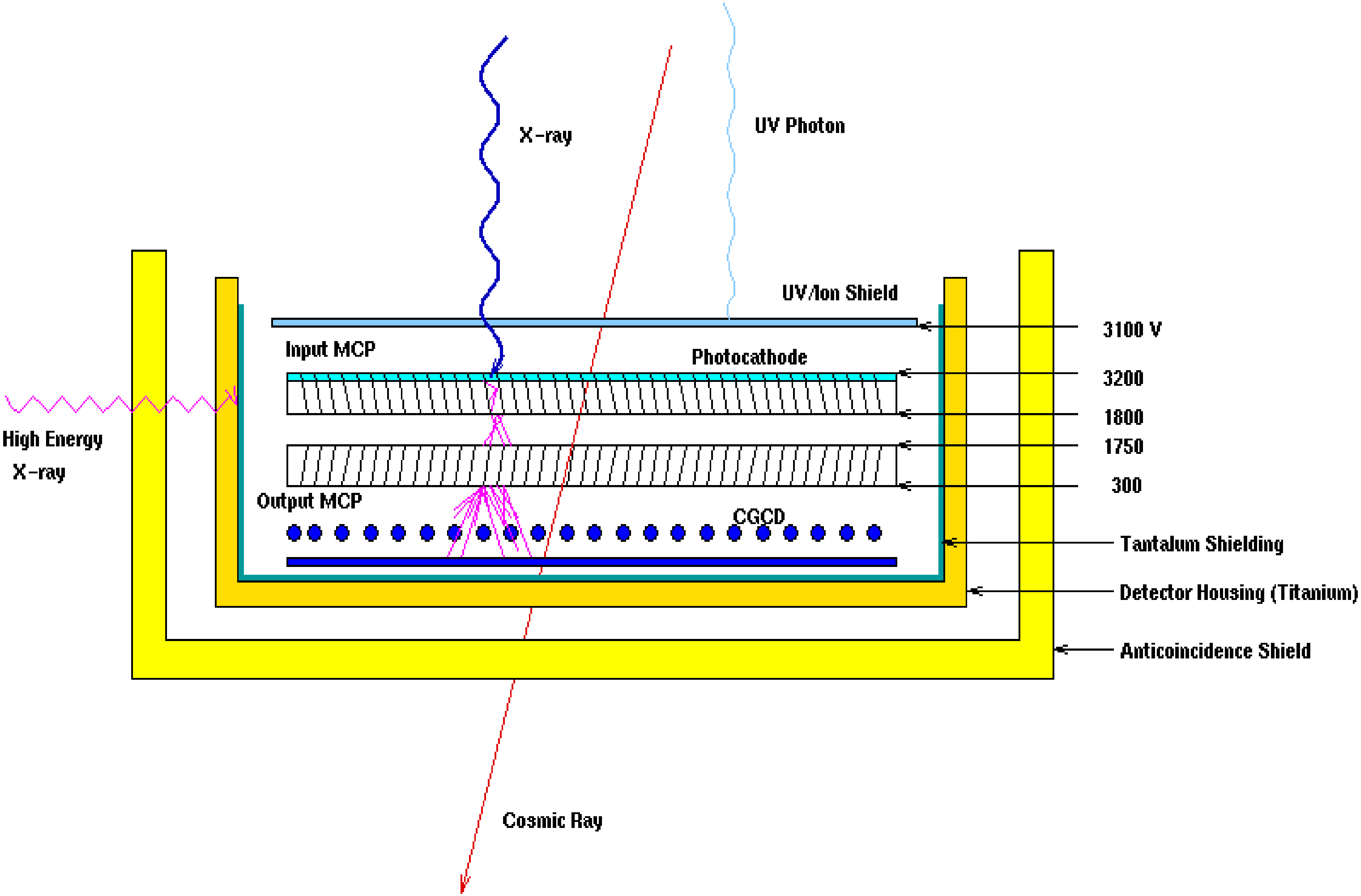
Preamble:

X-ray Photons are of such high energy that it is practical to detect an individual interaction.
Furthermore, in general (for at least 10^{21}-1000 sources) the fluxes are so low that one *must* detect them singly.
We want to measure one or more of the Energy of the photon, the Time it arrived, and the 3-dimensional Position.

References:

Fraser, G. W. 1989, "X-ray Detectors in Astronomy," (Cambridge: Cambridge University Press)
Gursky, H., & Schwartz, D. 1974, in "X-Ray Astronomy," R. Giacconi & H. Gursky eds., (Boston: D. Reidel) Chapter 2, pp 44-52;
Jahoda, K., & McCammon, D. 1988, Nuc. Instr. & Meth. A272, 800.
Rossi, B. & Staub, H. 1948, "Ionization Chambers and Counters," (New York: McGraw-Hill);
Thompson, A. C. in "X-ray Data Booklet," Section 4.5 "X-ray Detectors," at http://xdb.lbl.gov/


WINDOW
SUPPORTS
Be WINDOW
9.0mg/cm2
ANODE
CATHODE


X-ray
UV Photon
UV/Ion Shield
Input MCP
Photocathode
3100 V
3200
1800
1750
300
High Energy
X-ray
Output MCP
CGCD
Tantalum Shielding
Detector Housing (Titanium)
Anticoincidence Shield
Cosmic Ray

X-ray Interaction

Photoelectric absorption is the dominant interaction in the 0.1 to 10 keV range.

To be detected, a photon of energy E must penetrate the counter window, for which the probability is

$$e^{-t_i \rho_i \mu_i(E)}$$

where ρ_i is the density of the window material *i*,
t_i is the thickness of the window, and
$\mu_i(E)$ is the total mass absorption coefficient of the window at energy E.
The probability of interaction in the counter *after* having penetrated the window is

$$1 - e^{-t_j \rho_j \mu_j(E)}$$

where we have used *j* to index the counter material.

X-ray Interaction

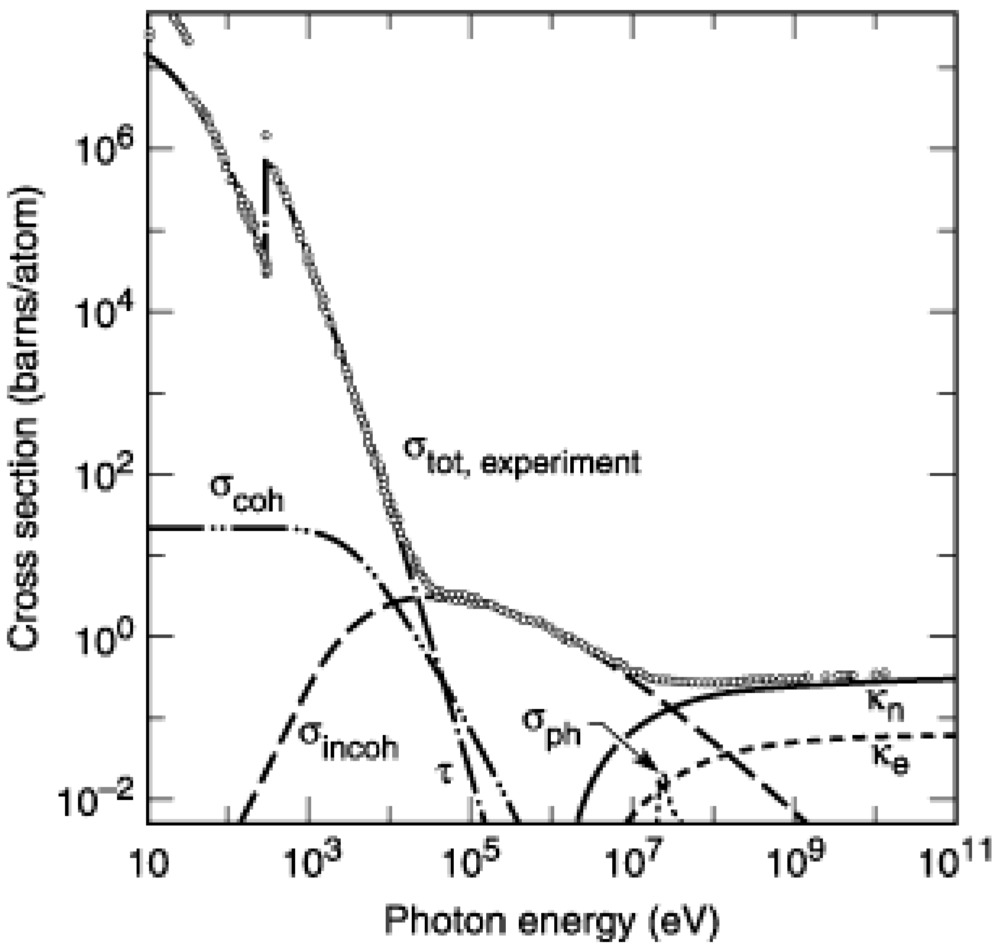
We therefore have the probability for interaction in the counter:

$$e^{-t_i \rho_i \mu_i(E)} \left(1 - e^{-t_j \rho_j \mu_j(E)}\right)$$

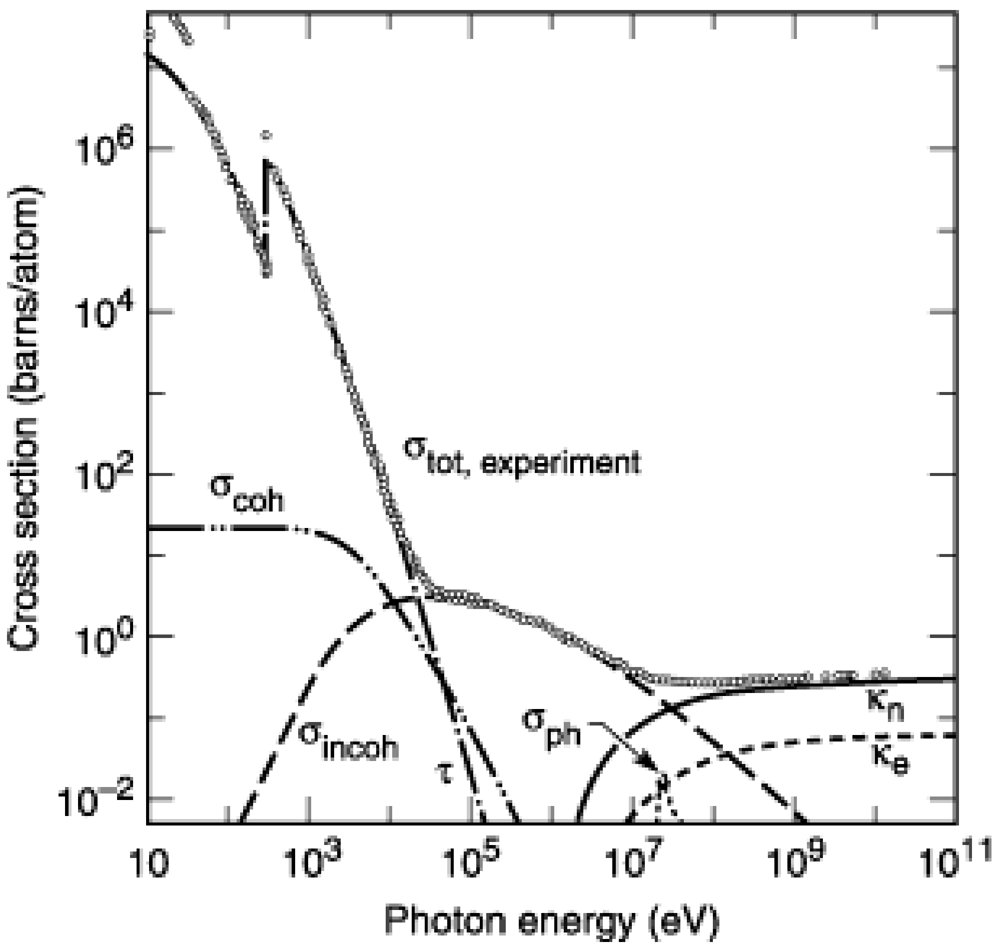
Note that this probability is NOT the "Quantum Efficiency," which should be defined for a photon of energy E as "The probability that such an isolated photon, incident to the instrument, gives rise to a detected X-ray event."

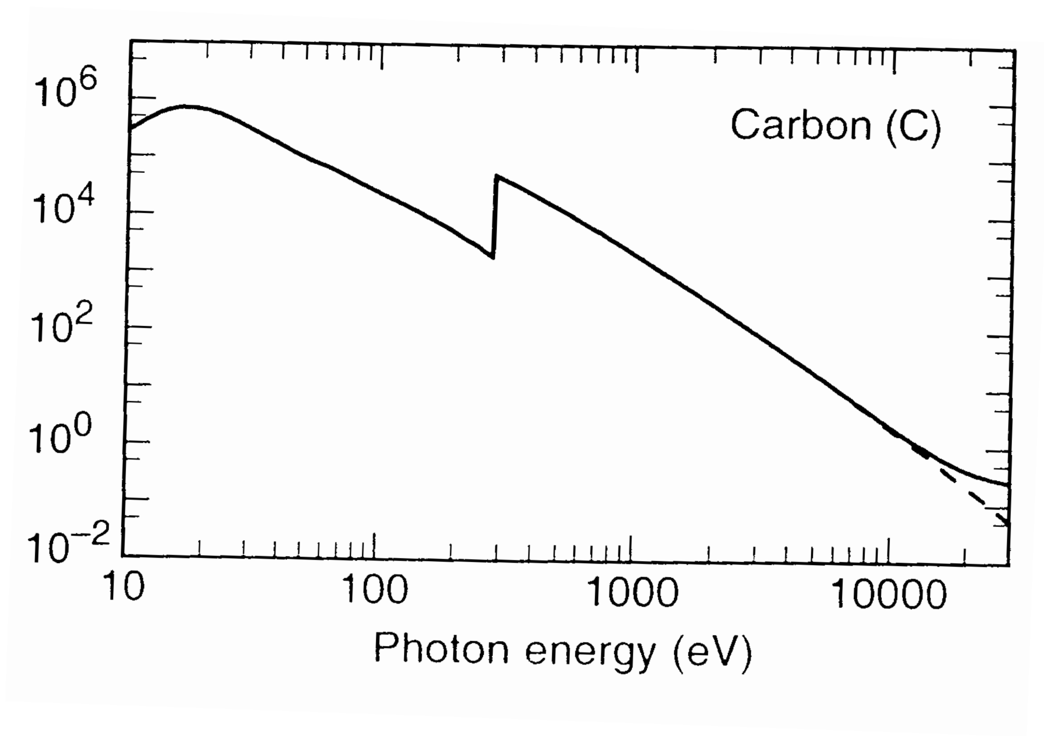
The distinction of QE from interaction probability involves the collection of charge and the recognition as a valid X-ray event. We say "isolated" photon so that variable effects such as deadtime and cosmic ray background are considered separately.

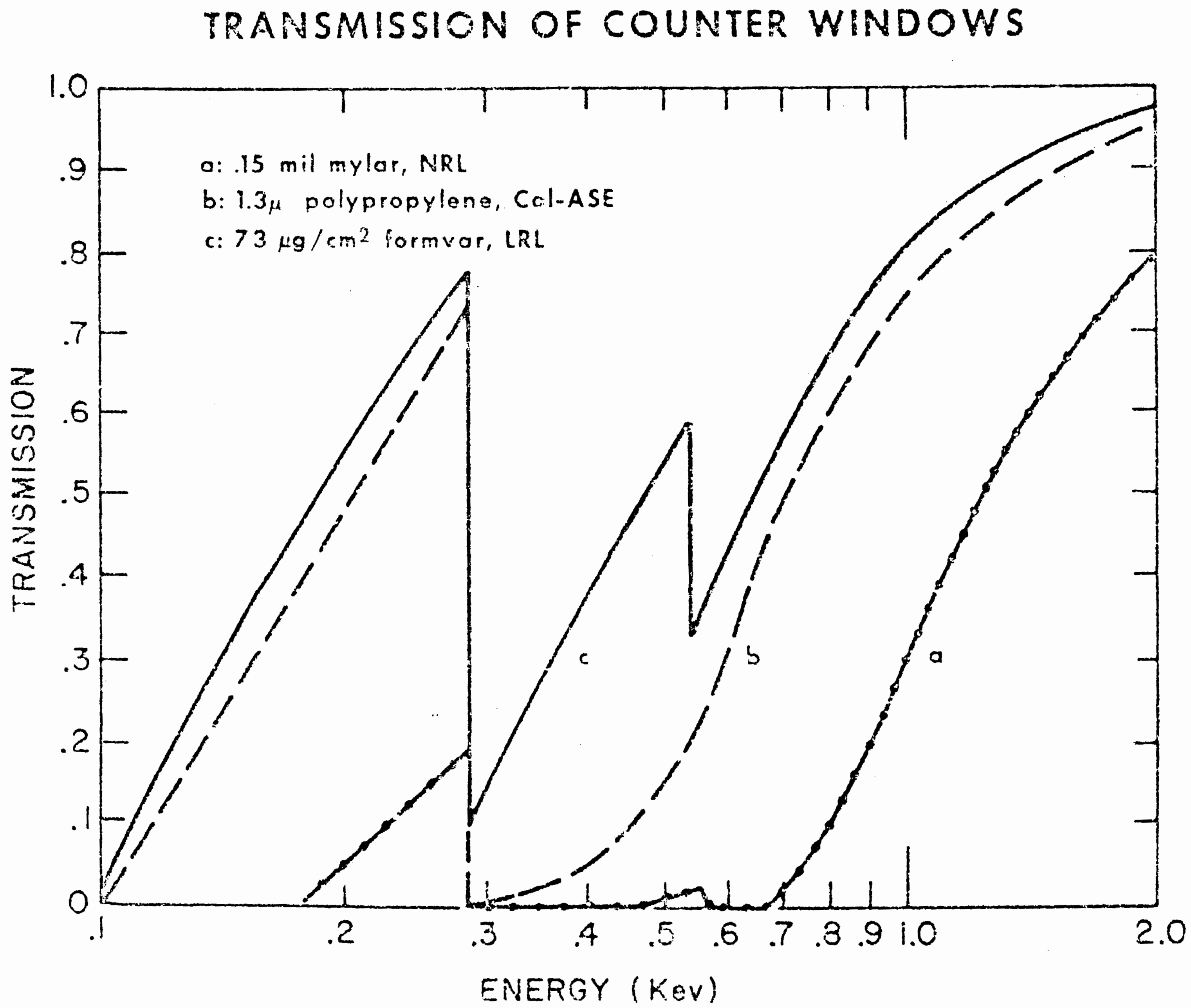
KEY FEATURE: The detected X-ray may have a pulse height very different from that corresponding to energy E!



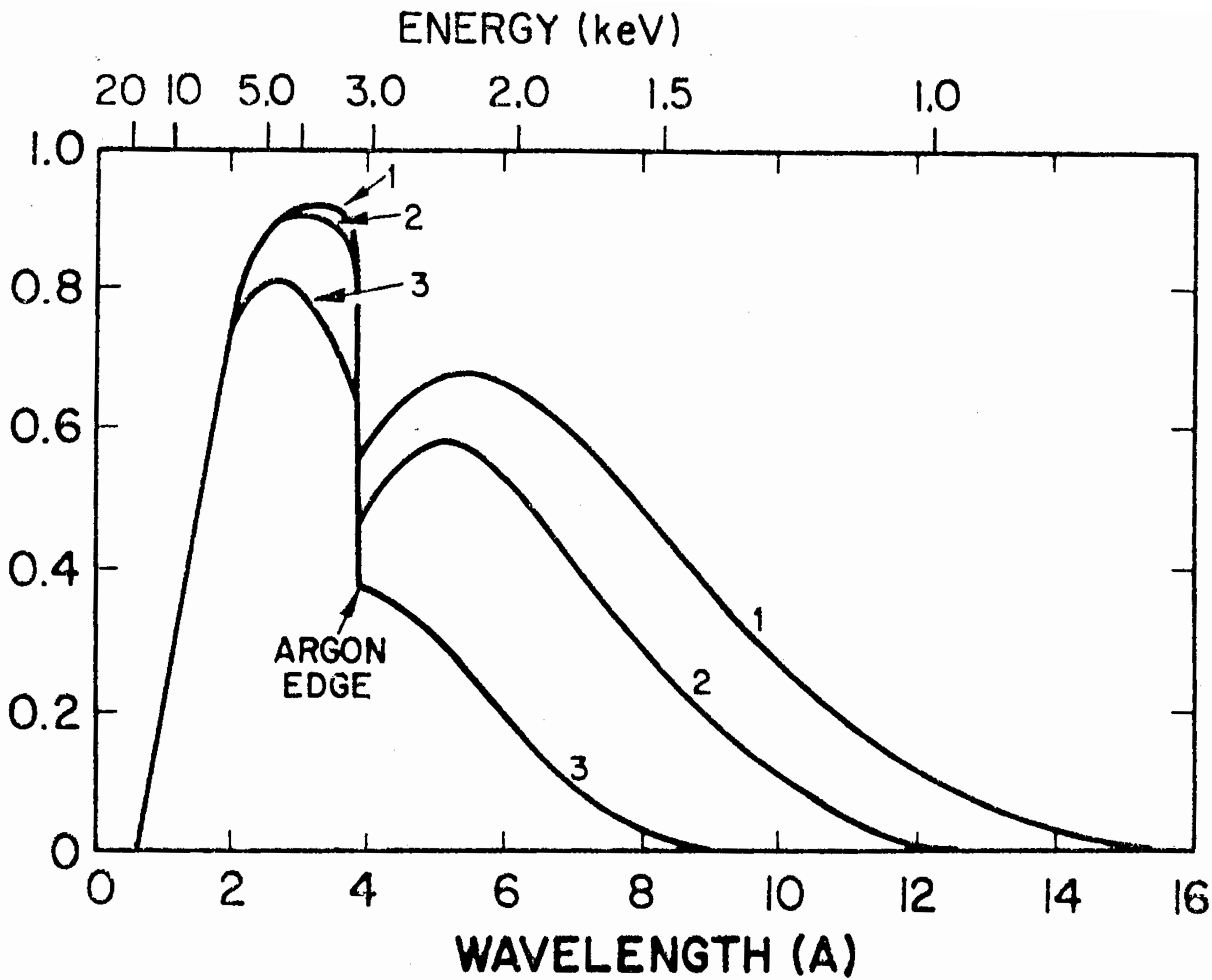
Cross section (barns/atom)
10^6
10^4
10^2
10^0
10^{-2}
$\sigma_{tot, experiment}$
σ_{coh}
σ_{incoh}
τ
σ_{ph}
κ_n
κ_e
10
10^3
10^5
10^7
10^9
10^{11}
Photon energy (eV)


Cross section (barns/atom)
Photon energy (eV)
σtot, experiment
σcoh
σincoh
τ
σph
κn
κe
10
10^3
10^5
10^7
10^9
10^11
10^6
10^4
10^2
10^0
10^−2


Carbon (C)
Photon energy (eV)
10
100
1000
10000
10^6
10^4
10^2
10^0
10^−2



TRANSMISSION OF COUNTER WINDOWS
a: .15 mil mylar, NRL
b: 1.3μ polypropylene, Cal-ASE
c: 73 μg/cm2 formvar, LRL
TRANSMISSION
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
c
b
a
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
2.0
ENERGY (Kev)


ENERGY (keV)
20 10 5.0 3.0 2.0 1.5 1.0
EFFICIENCY
1.0 0.8 0.6 0.4 0.2 0
1
2
3
ARGON EDGE
1
2
3
0 2 4 6 8 10 12 14 16
WAVELENGTH (A)

Charge Creation

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Following absorption in the counter gas, we have

1. **An energetic electron, with kinetic energy E_e equal to the X-ray energy minus the electron binding energy**
2. **A positive ion of the counter gas, with potential energy equal to the binding energy**

Charge Creation (cont.)

1. The electron will ionize more atoms, but will also lose energy via non-ionizing collisions which just give up momentum to the atoms. Thus while the maximum number, N_{max} of electron ion pairs which could be created is

$$N_{max} = E_e/W_0$$

where W_0 is the ionization potential, the actual number *expected* to be created is $N=E_e/W$, where $W > W_0$ is an empirical mean total energy loss of the electron per creation of an electron ion pair.

For common gases, $W \sim 30$eV while $W_0 \sim$ 12 to 16 eV

For Si (e.g., CCD) $W \sim 3.65$eV while $W_0 \sim$ 1.14 eV (band gap)

For scintillators, $W \sim 300$eV

For calorimeters, $W \sim 10^{-4}$eV ! (phonon energy)

Charge Creation (cont.)

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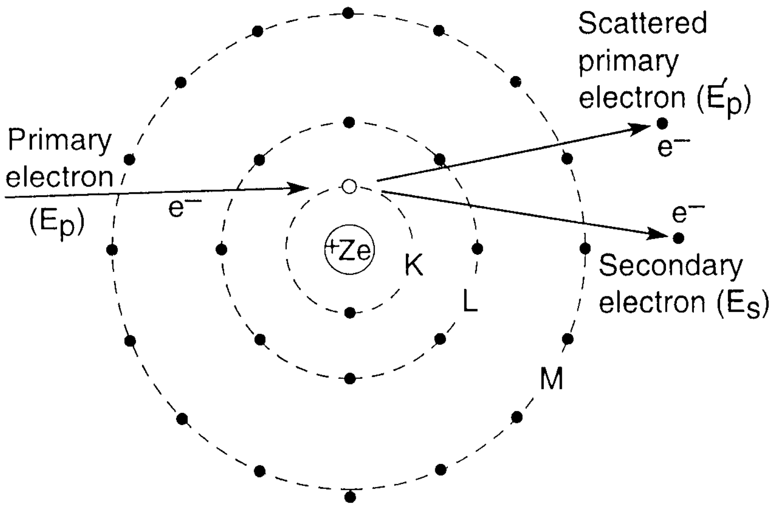
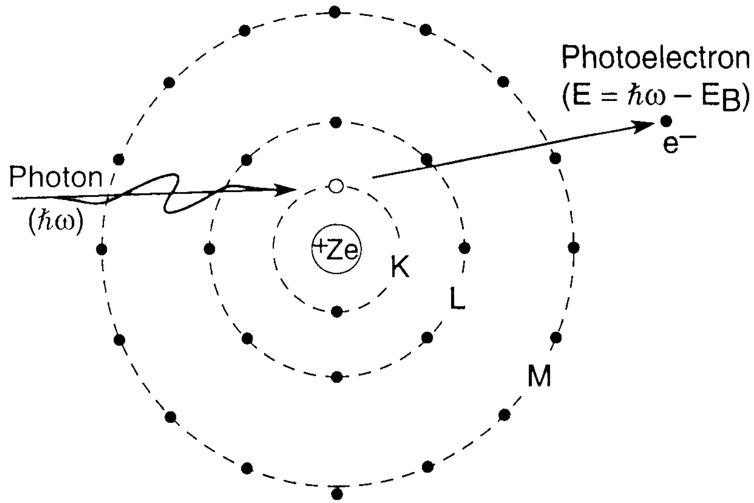
This gives it some probability for totally escaping the counter, so that the energy ultimately measured for the event is $E\text{-}E_K$.

Basic Ionization and Emission Processes in Isolated Atoms

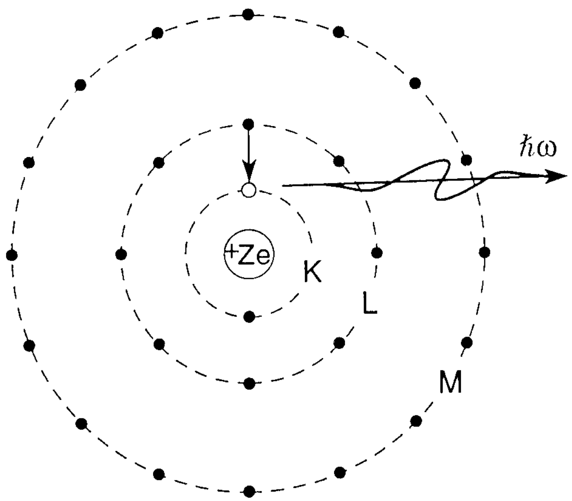
(a) Electron collision induced ionization



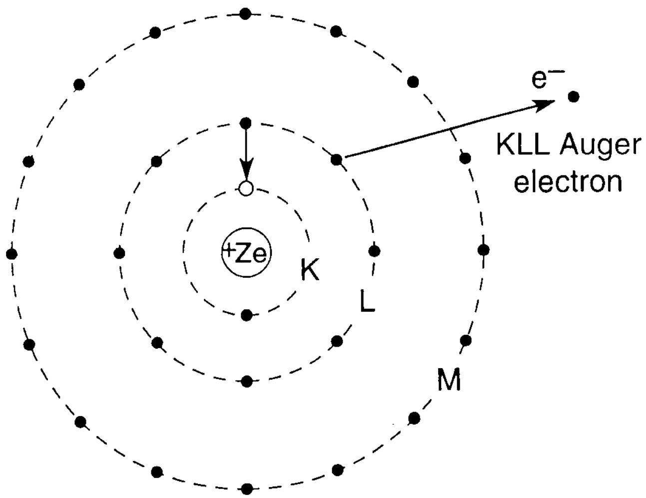
(b) Photoionization

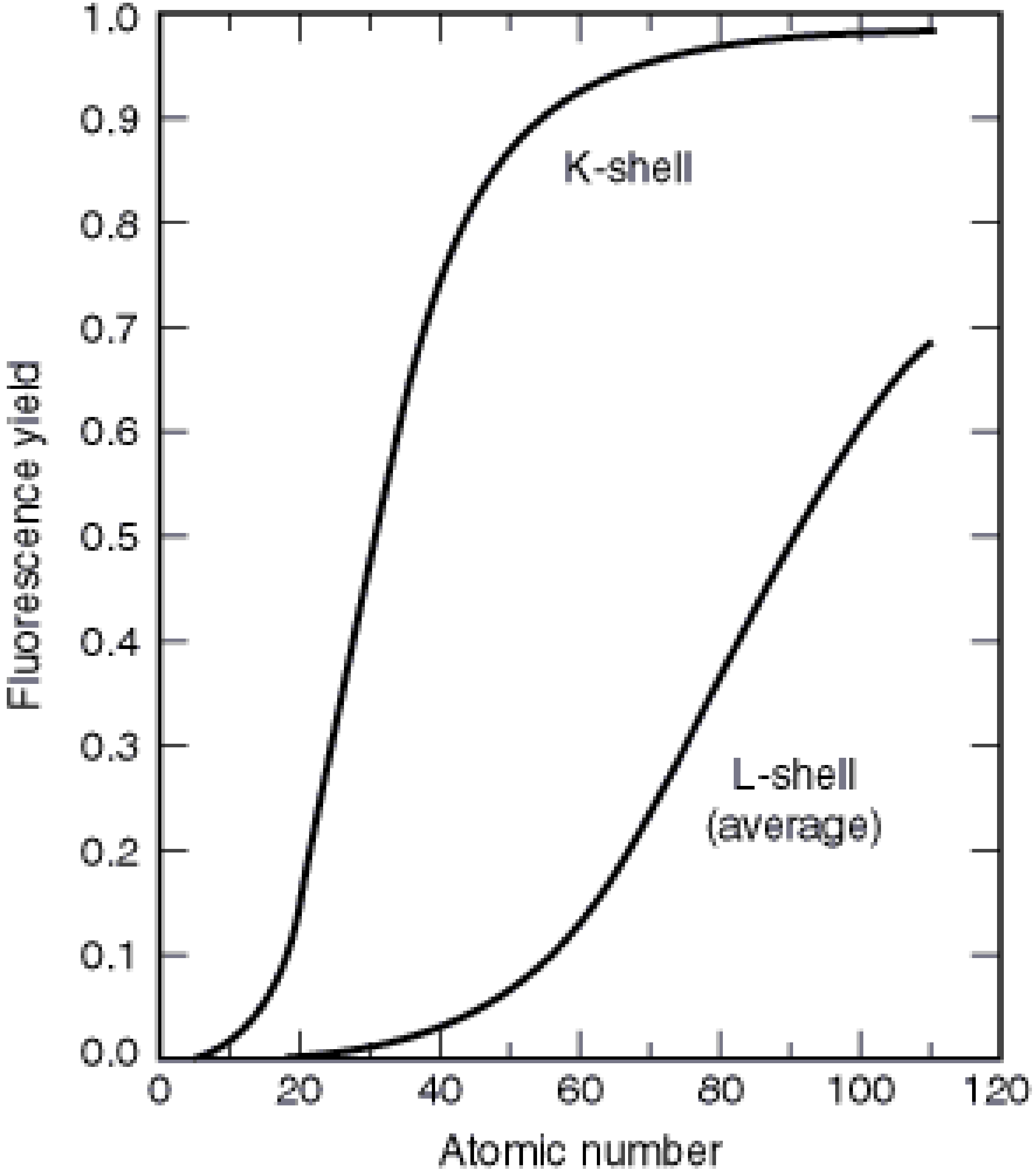


(c) Fluorescent emission of characteristic radiation



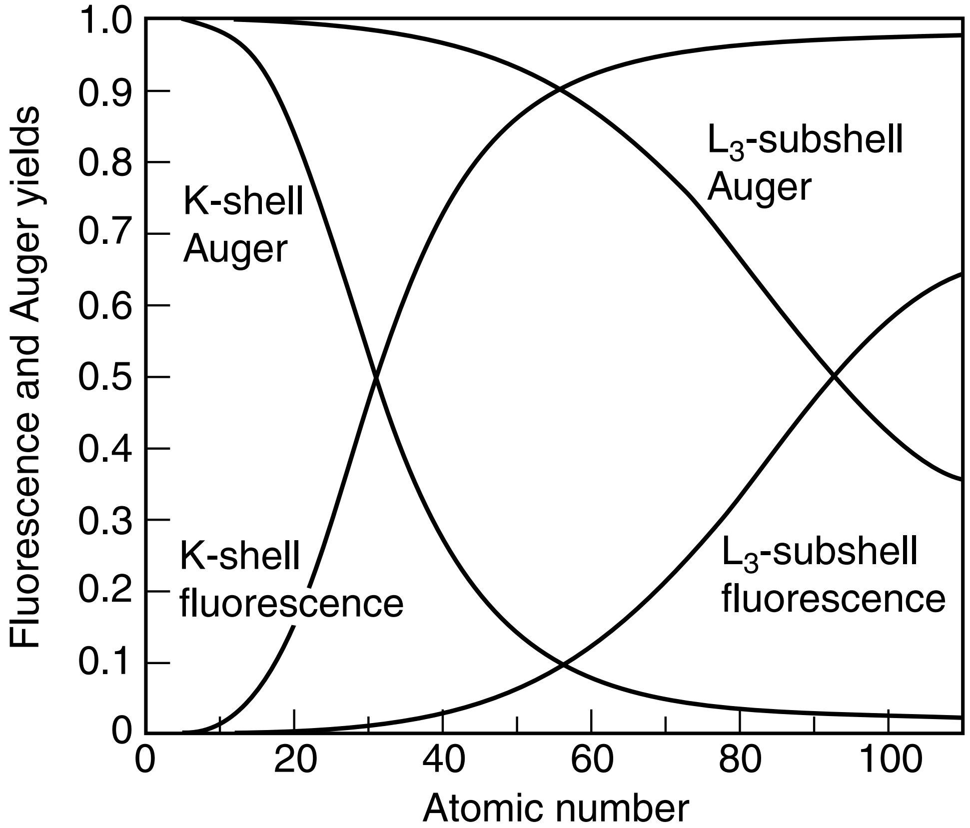
(d) Non-radiative Auger process





1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Fluorescence yield
K-shell
L-shell
(average)
0
20
40
60
80
100
120
Atomic number

Fluorescence and Auger Emission Yields



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(PC) Electrons will drift toward the anode, and the ions will drift, more slowly, toward the cathode.
(CCD) The electrons in the conduction band are held in the pixel by an applied potential, and by the doping structure of the CCD.

An expected number $N=E_e/W$ of electrons will be released. One might suppose the variance of this number to also be N, as for a Poissonian or Gaussian process. Actually, the variance is F N, where F is the Fano factor, and is less than one since the total energy lost must be identically the initial energy (Fano 1947, Phys. Rev., 72, 26).

SPECIAL TOPIC: FANO FACTOR

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2. **The fluctuations need to consider the total number of interactions taking place. These are mostly inelastic collisions with an energy transfer much less than W_0.**

3. **In effect, 2 W_0 is the maximum energy transfer. If it were more, that would just mean that the liberated electron can now create more ion pairs.**

SPECIAL TOPIC: FANO FACTOR (cont.)

Following Fano (1947) (for fun, see also Schwartz 1974, ApJ 194 L139) we want to estimate the variance:

$$\mathrm{var}(\hat{N}) = \langle (\hat{N} - E/W)^2 \rangle$$

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We can consider that $\hat{N} = \sum_{i=1}^{k} \hat{n}_i$, and $E = \sum_{i=1}^{k} \hat{e}_i$, where the random variables $\hat{n}_i$ and $\hat{e}_i$ are the number of ionizations and the amount of energy lost in each of the k interactions.

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Since the set of ($\hat{n}_i - \hat{e}_i/W$) are independent, identically distributed, and of mean zero, we essentially take the root-sum-square:

$$\mathrm{var}(\hat{N}) = k\,\langle(\hat{n}_i - \hat{e}_i/W)^2\rangle = \frac{E}{W\bar{n}}\,\langle(\hat{n}_i - \hat{e}_i/W)^2\rangle = F\,(E/W),$$

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so that the desired Fano factor is

$$F = \langle(\hat{n}_i - \hat{e}_i/W)^2\rangle / \bar{n}.$$

We can make an "eyeball" estimate of F ~ 3/8.

Actual typical values are 0.12 to 0.16.

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4. Calorimeters. G$\equiv$ 1. Huge numbers of phonons; cryogenic temperatures minimize noise

CHARGE MULTIPLICATION: PC

$E = (V_0/r)/\ln(r_C/r_A)$

V_0 is applied voltage, typically of order 2000 volts

r_C, is cathode radius, typically of order25mm

r_A is anode radius, typically of order 25μm

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When an electron is at r$\leq$ mm's of the anode, it can be sufficiently accelerated so that it can ionize another atom.

That liberated electron is also accelerated, and a cascade ensues.

CHARGE MULTIPLICATION: Statistics

A random multiplication ⇒ an exponential distribution of total charge.

BUT, many more interactions are really taking place.

Energy goes into ionization potential energy, and results in *less* variance.

Jahoda and McCammon quote Alkhazov (1970, Nucl. Instr. Meth., 89 155) for the theoretical form of the probability of creating j electrons when m are expected:

$$P(j;m,h)= \frac{1}{m}\frac{h^h}{\Gamma(h)} \exp(\frac{-h\, j}{m})(j/m)^{h-1}$$

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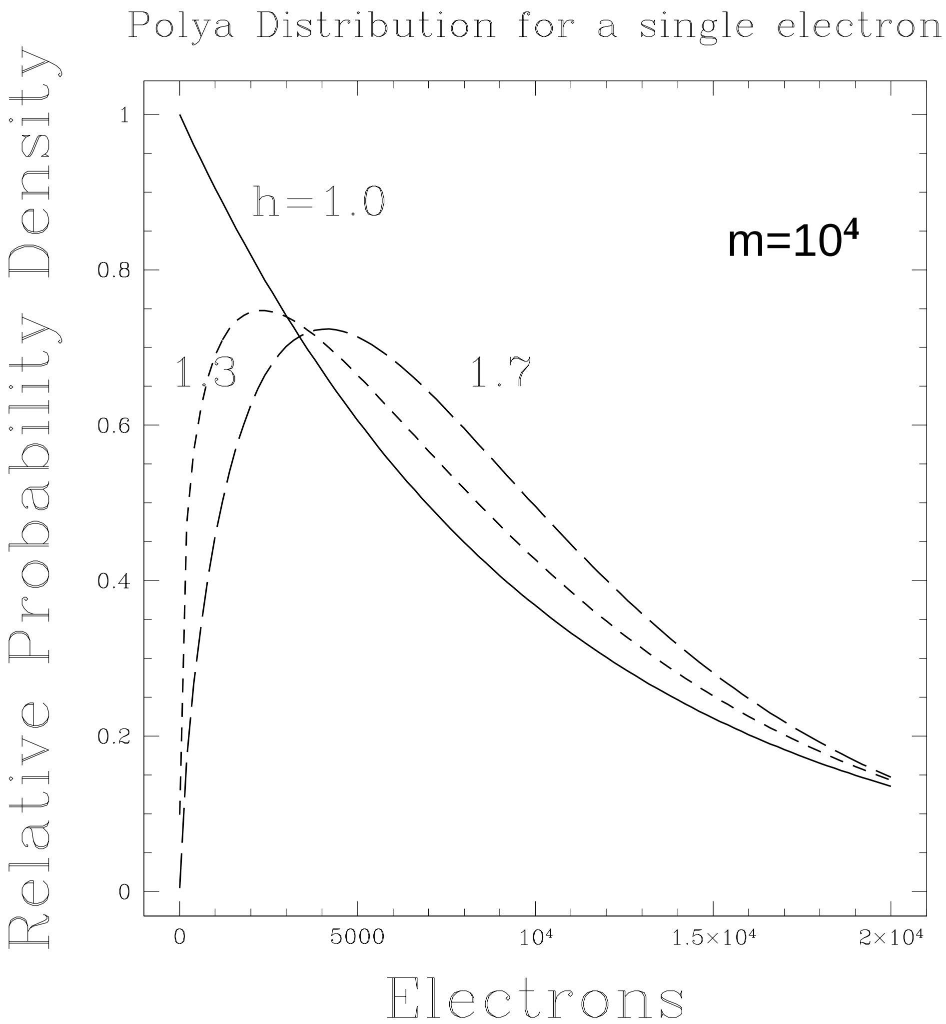
This is a Polya function with parameter h, (also called Pearson Type III).

It becomes exponential for h=1, a δ-function (no variance) as h→ ∞.

Mean is m; variance is m^2/h; relative variance 1/h.

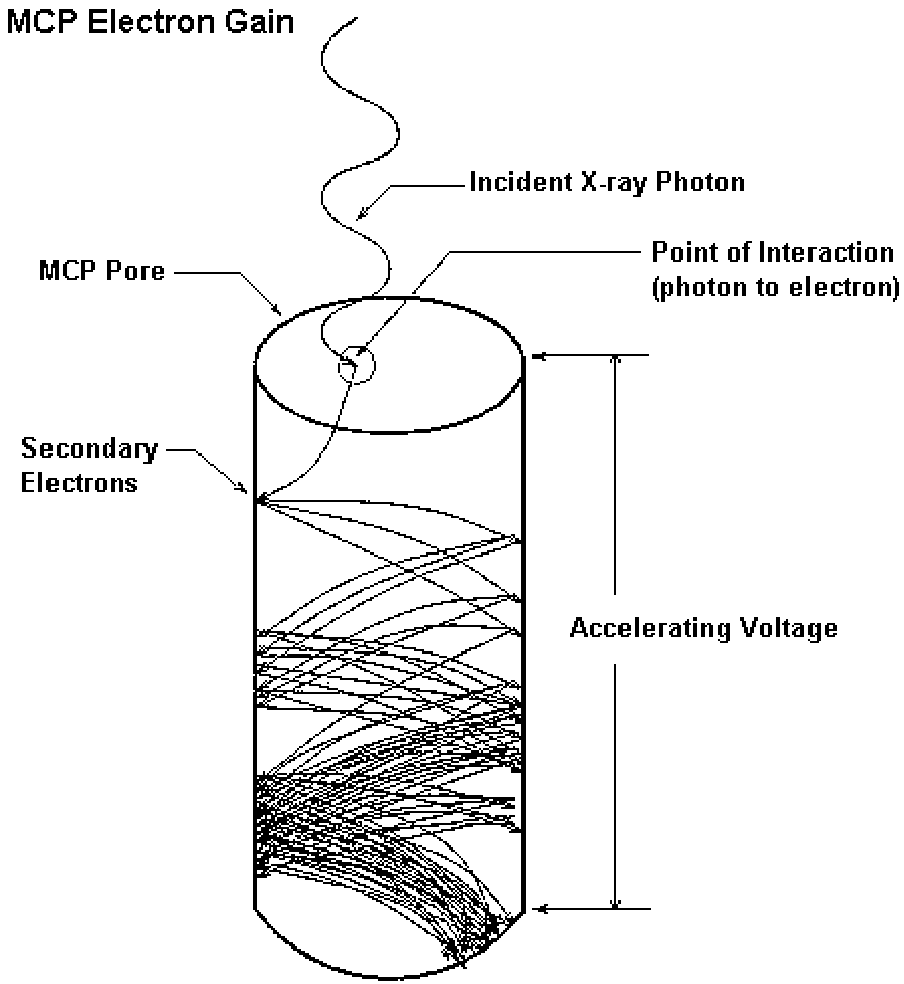


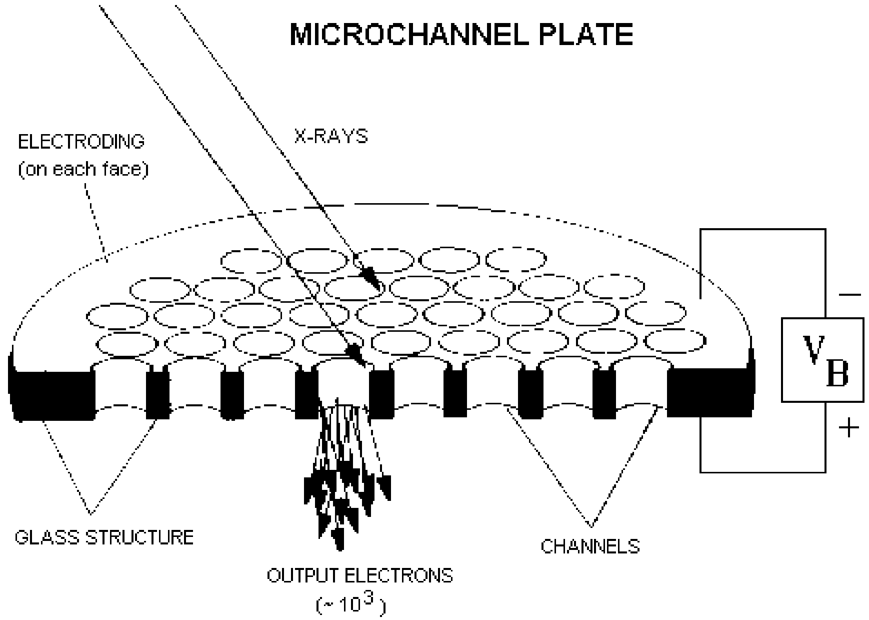
Polya Function:

$$P(j;m,h) = \frac{1}{m}\frac{h^h}{\Gamma(h)}\exp\left(\frac{-h\,j}{m}\right)(j/m)^{h-1}$$

For a sum of N electrons, the distribution is also a Polya function with m→ Nm and parameter h→Nh. Relative variance of number of electrons in charge cloud is 1/(Nh). Empirical values of h range 1.2 to 1.7. For these values the avalanche statistics dominate the original ion-electron pair creation statistics: 1/(Nh) ~ 0.7/N.

Charge Multiplication: MCP



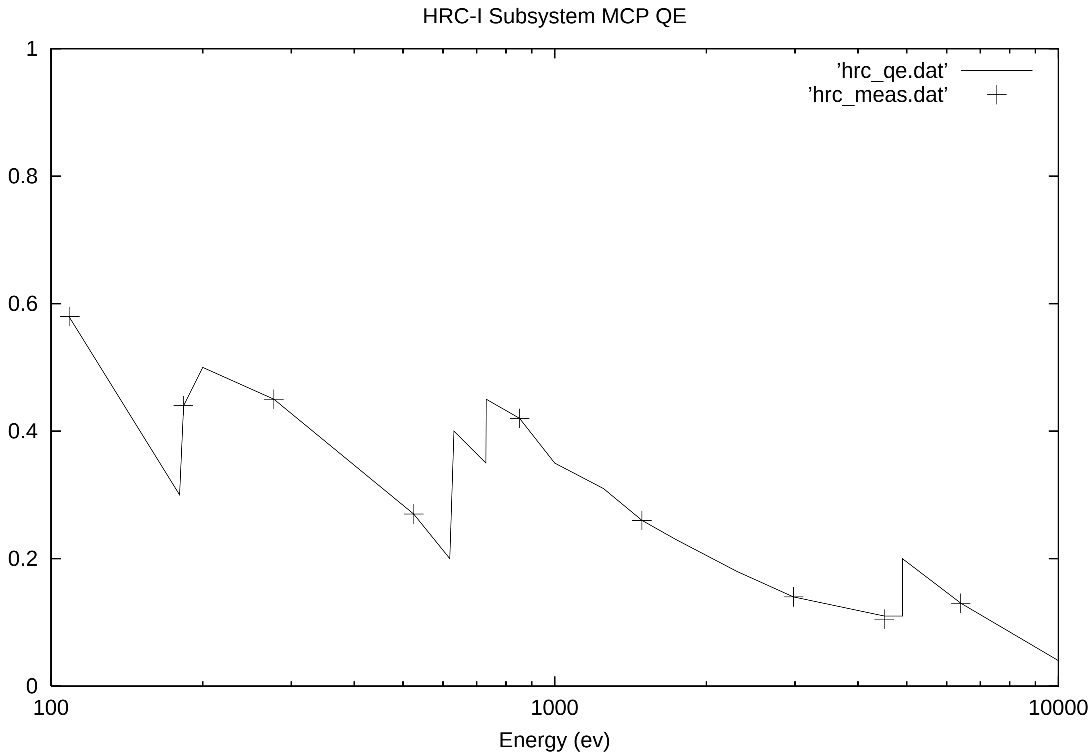


Because electron ranges are so small, at most 1 electron escapes the absorbing material to start a cascade.

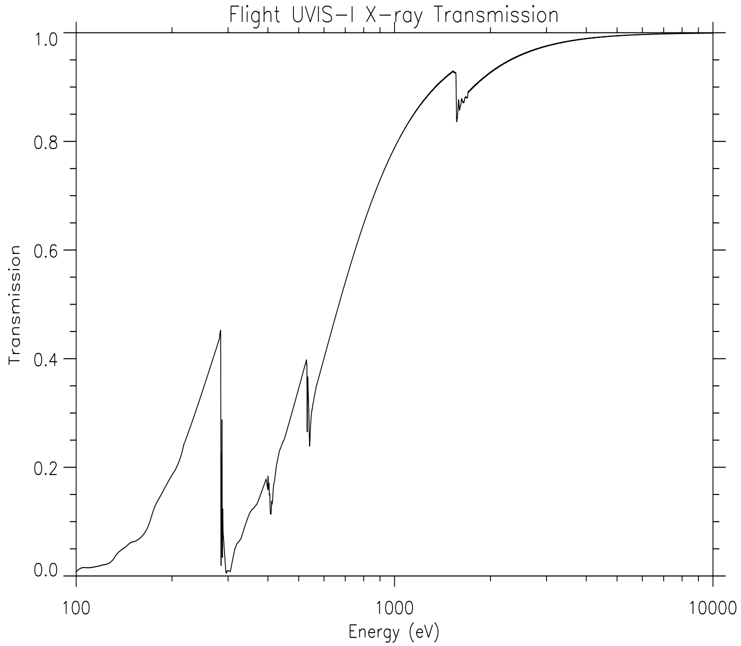
⇒ QE is low

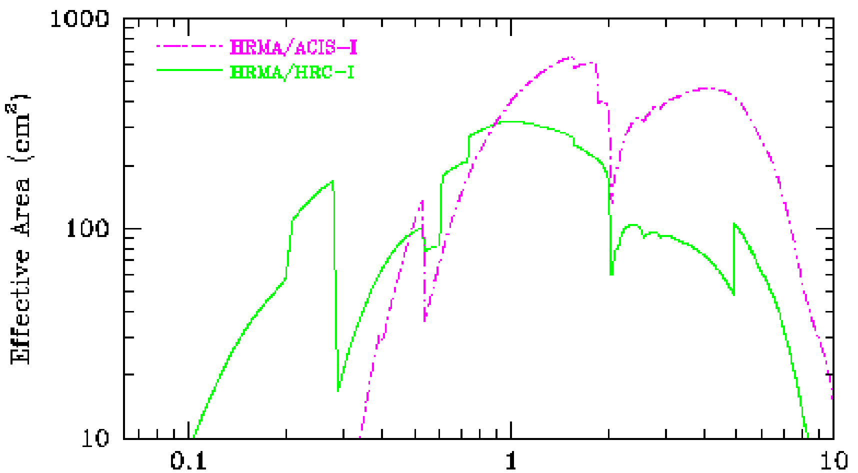
⇒ No energy resolution

Quantum Efficiency: MCP

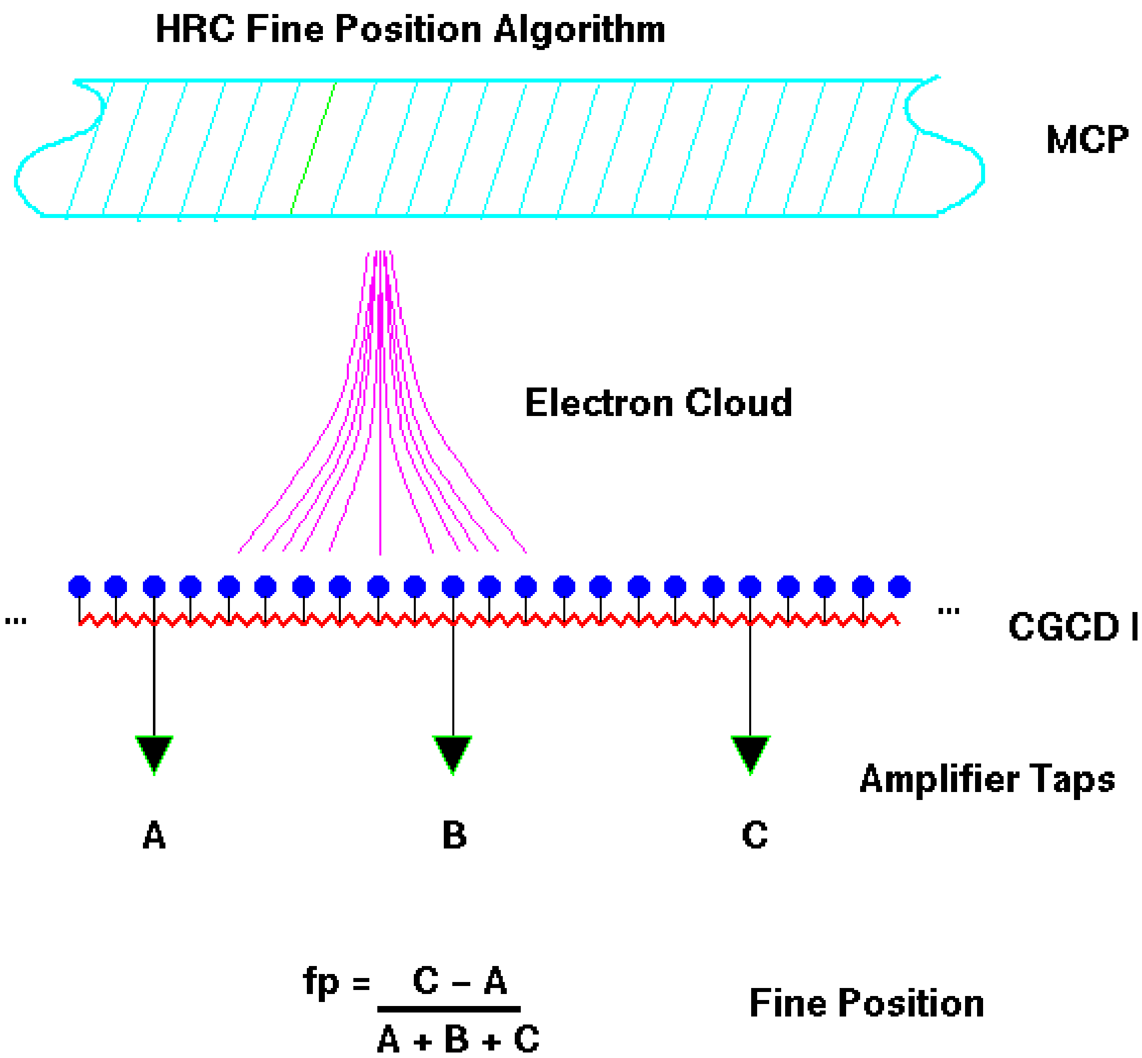


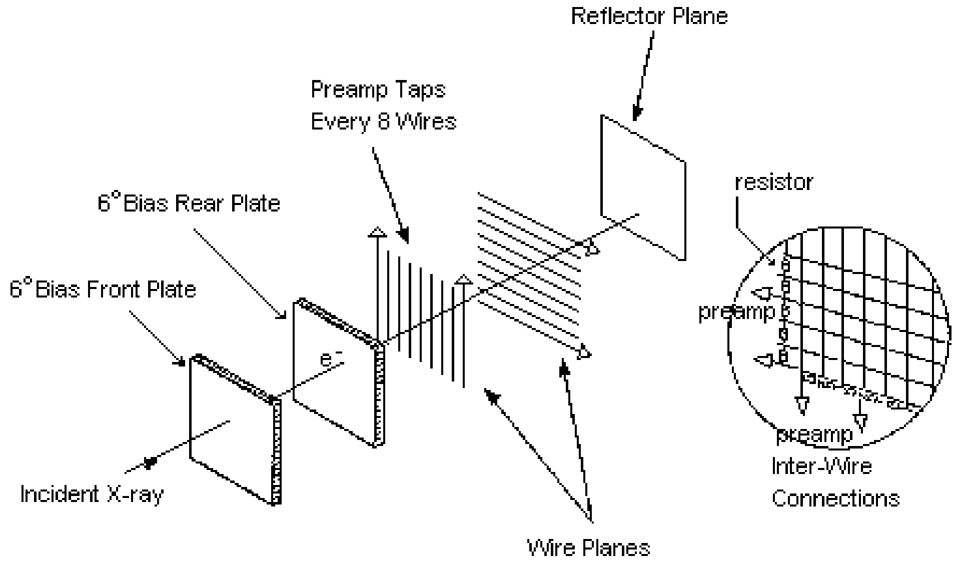
[H]RC-I quantum efficiency measured at subsystem level at SAO prior to detector housing assembly.





Position Readout: MCP





Position algorithm necessarily leaves "gaps"

Has non-linearities

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4. At very high counting rates, a second X-ray may interact and not be distinguished from the first, giving a lower amplitude peak at an energy corresponding to $2E_0$.

DETECTOR BACKGROUND

Charged Particles

- **Minimum ionizing cosmic rays: 2 keV per mg/cm^2**
- **Sub-relativistic electrons: Straggling in windows allows a large initial energy range to enter detector with residual 0.1 to 10 keV.**
- **Particles created by interactions in material of the detector, or in the vehicle in general.**

DETECTOR BACKGROUND (cont.)

Photon induced

- **Forward Compton scattering of gamma rays can deposit 0.1 to 10 keV of energy.**
- **X- or gamma-rays created by cosmic ray interactions in the detector walls.**
- **Fluorescent X-rays may be produced in the mirror, thermal collimator, detector window or housing.**

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Background tends to be relatively flat in equivalent spectral flux density.