Basic Detector Processes

X-Ray Astronomy School IV

16 August 2005

Richard Edgar

SAO/CXC

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

Based on Dan Schwartz' lecture at X-Ray Astronomy School III

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 covered in detail on Monday**

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:

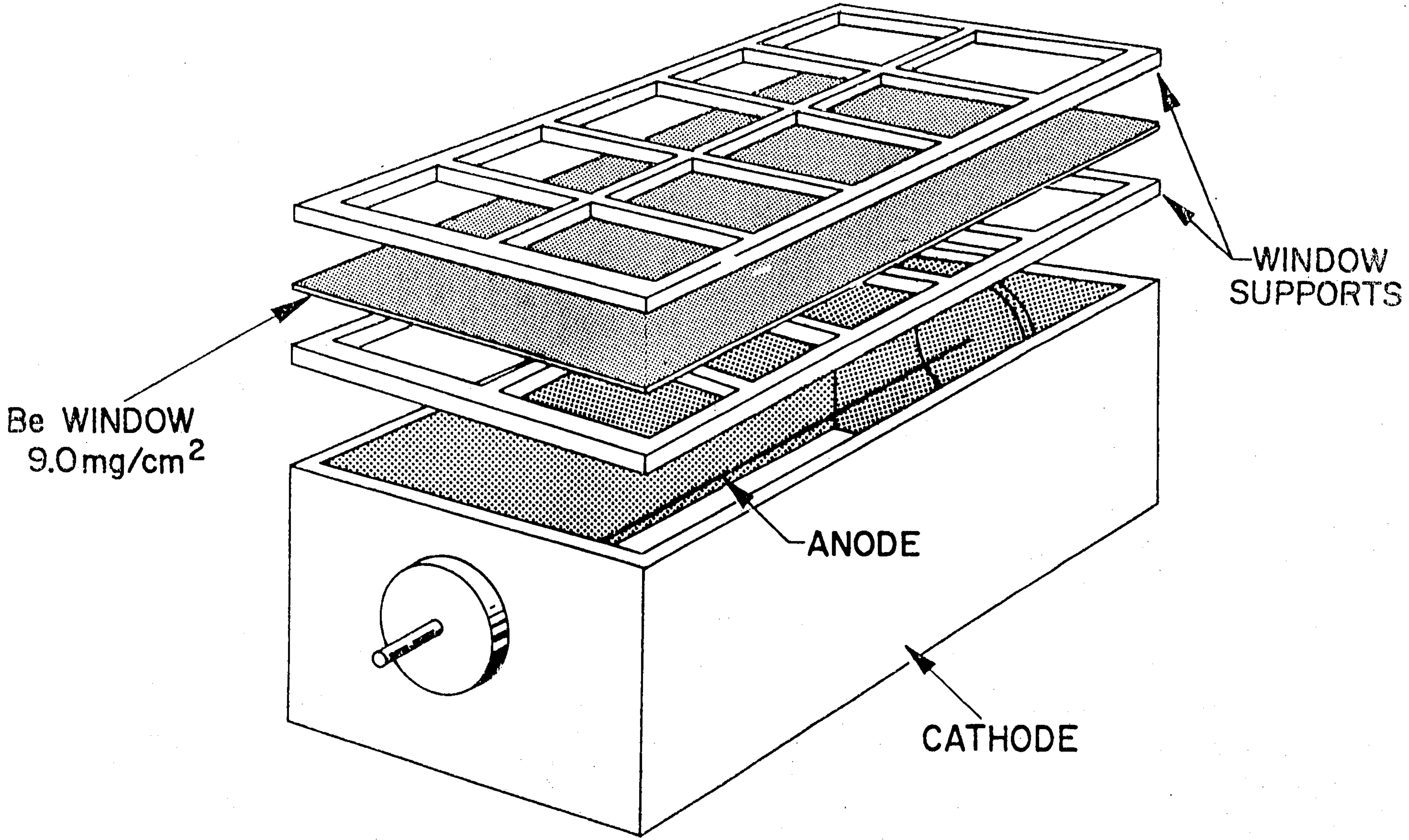
Fraser, G. W. 1989, "X-ray Detectors in Astronomy," (Cambridge: Cambridge University Press)

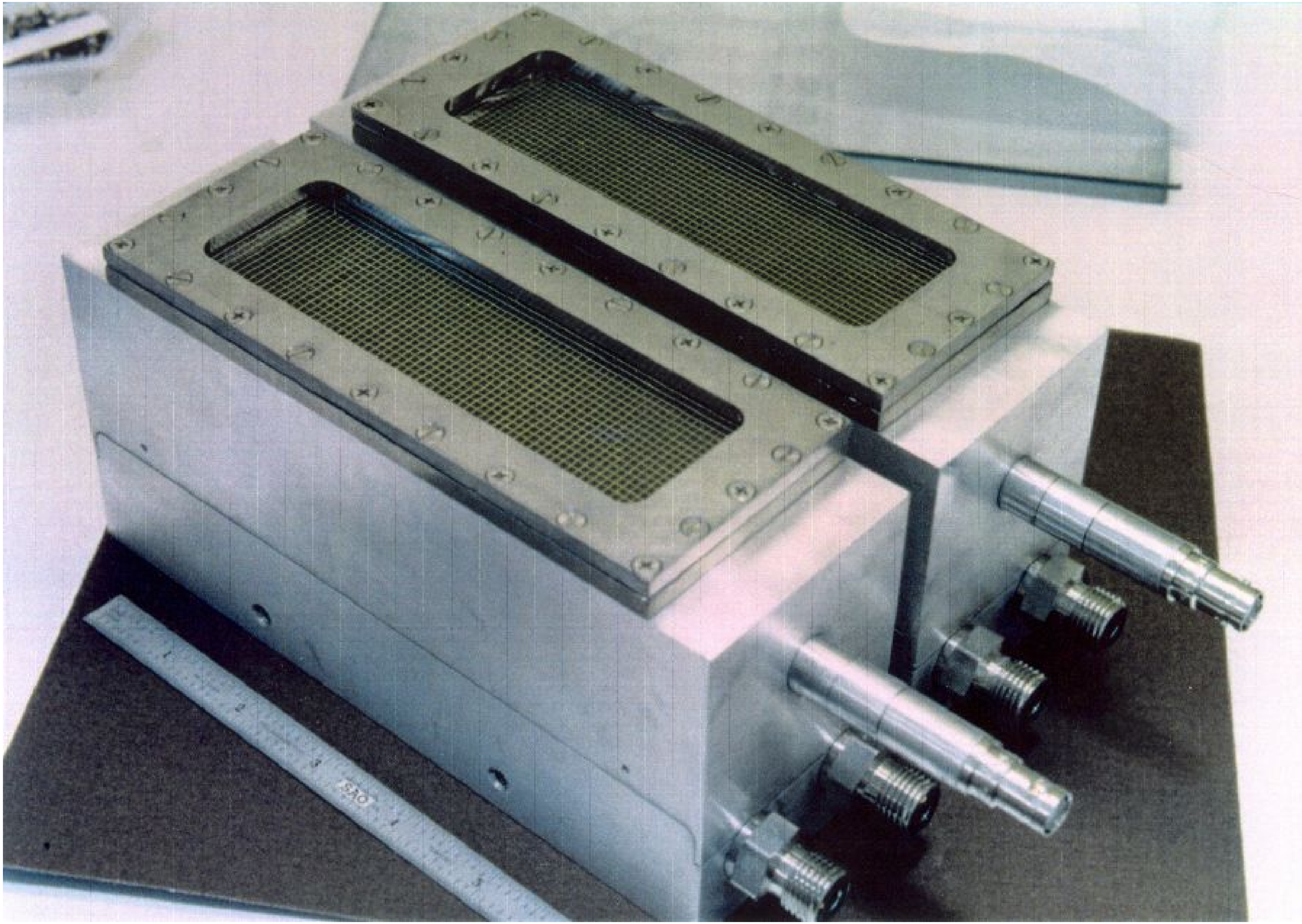
Gursky, H., & Schwartz, D. 1974, in "X-Ray Astronomy," R. Giacconi & H. Gursky eds., (Boston: D. Reidel) Chapter 2, pp 44-52;

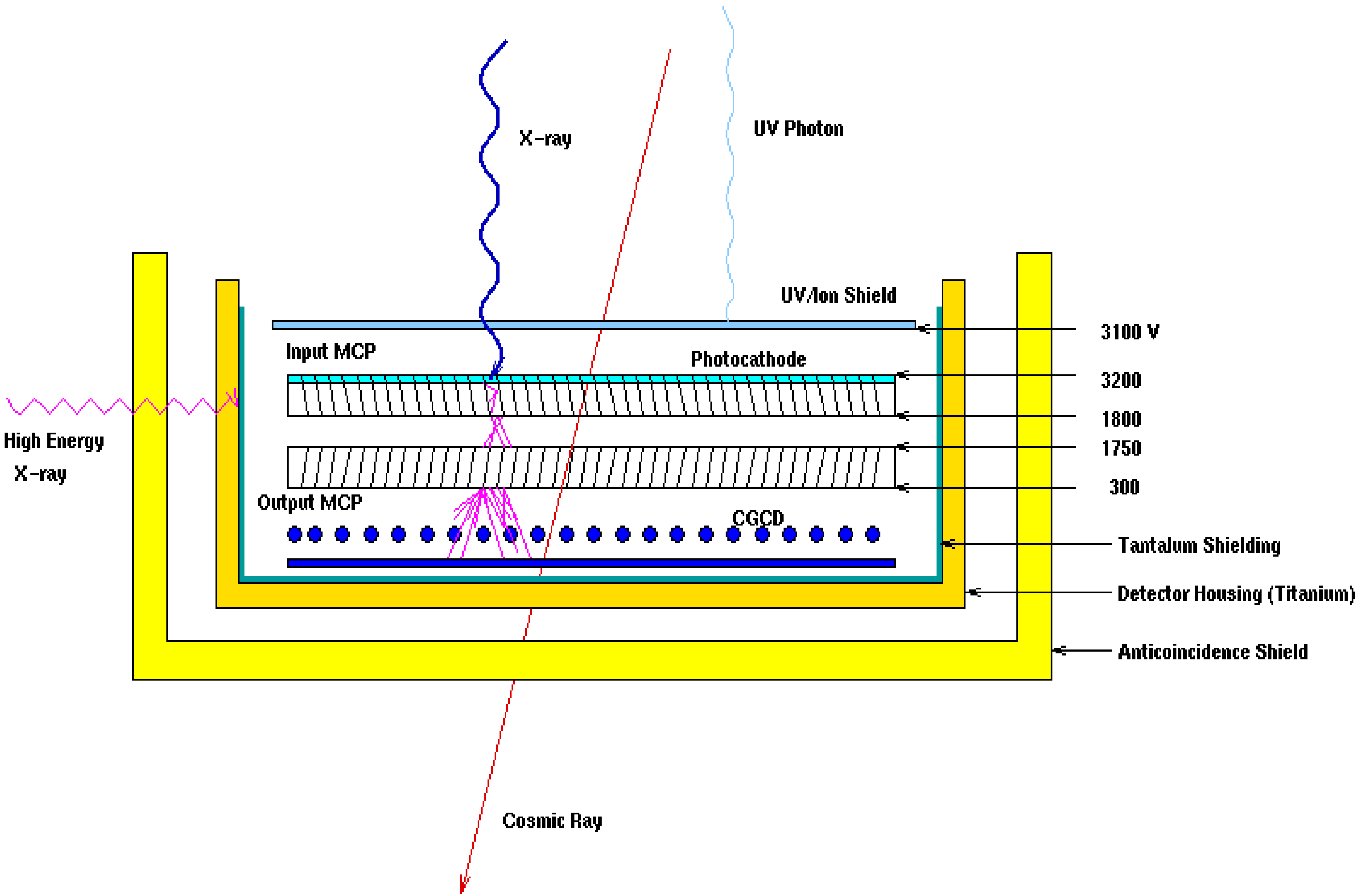
Jahoda, K., & McCammon, D. 1988, Nuc. Instr. & Meth. A272, 800.

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
3100 V
Input MCP
Photocathode
3200
1800
High Energy
X-ray
1750
300
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

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

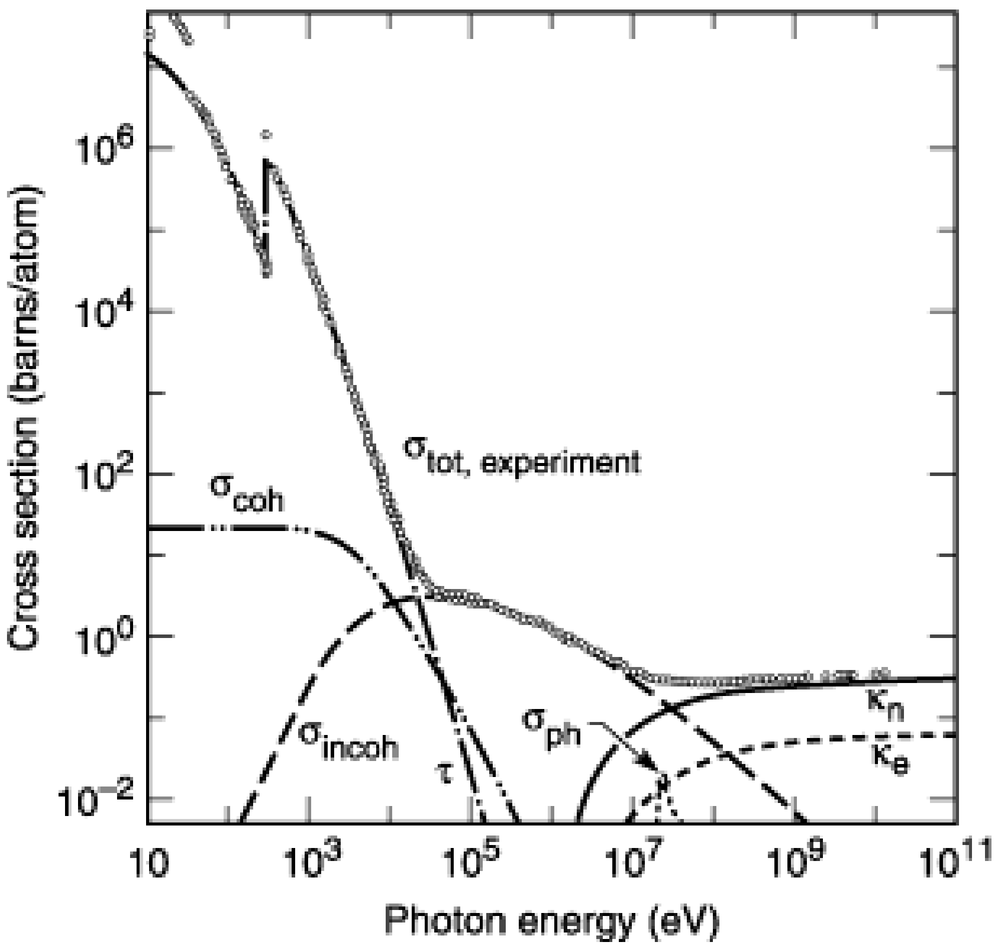
where we have used *j* to index the counter material.

X-ray Interaction

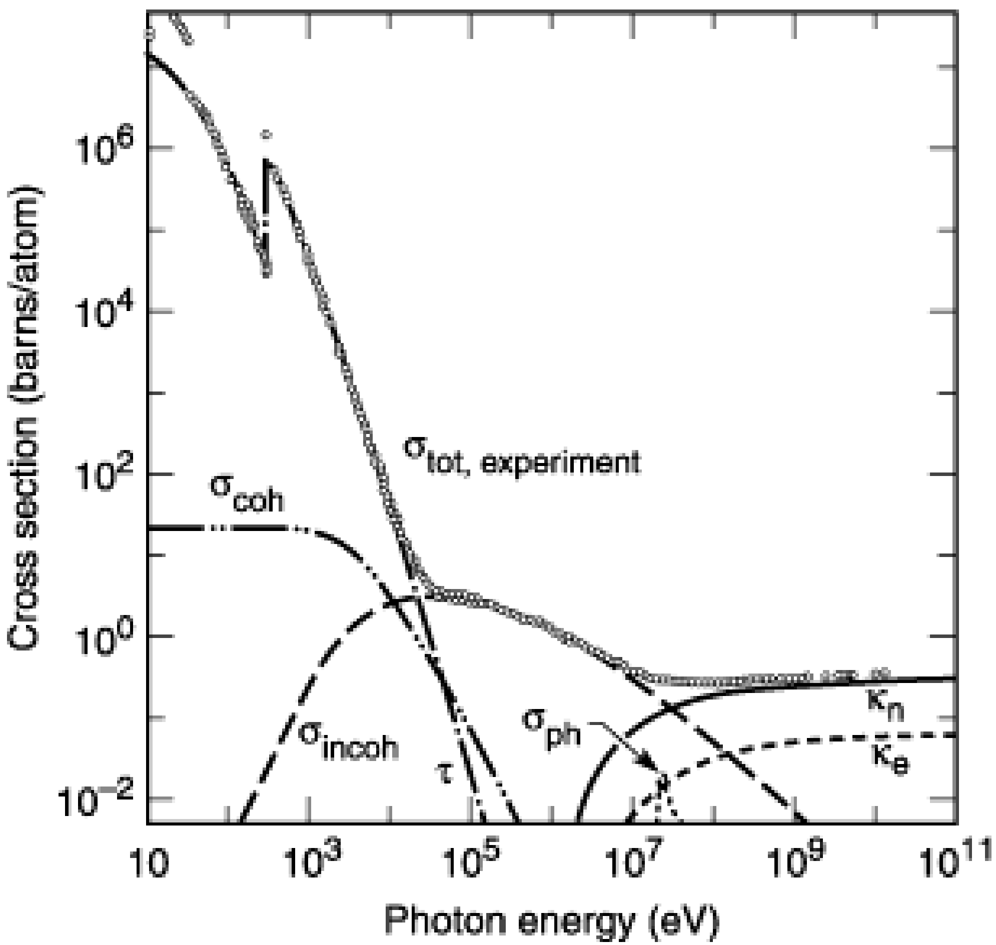
We therefore have the probability for interaction in the counter:

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

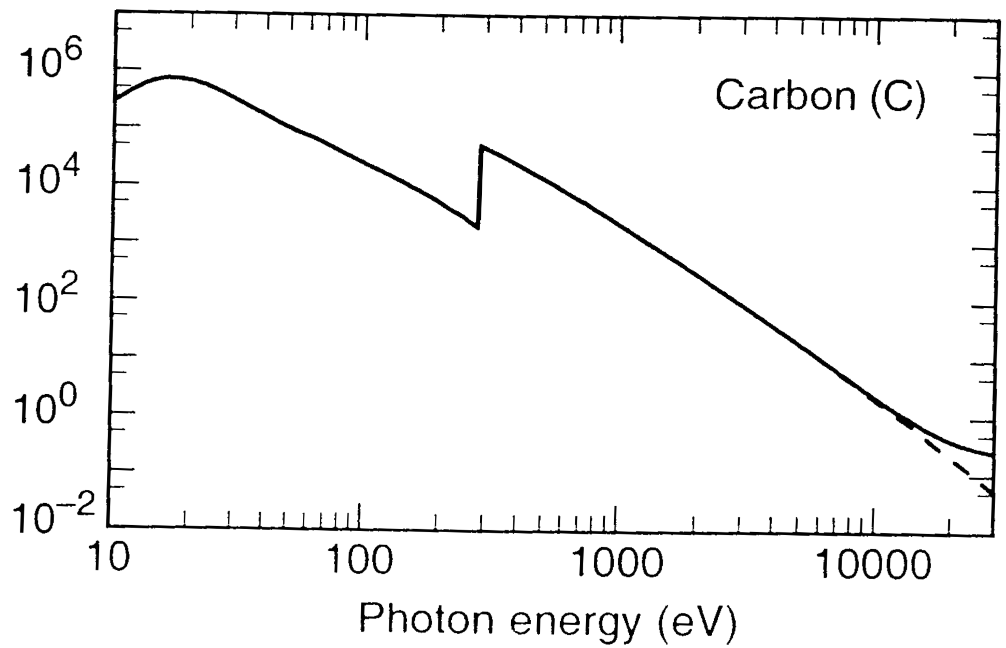
Note that this probability is NOT the "Quantum Efficiency," which should be defined for a photon of energy E as "The probability that such an isolated photon, incident to the instrument, gives rise to a detected X-ray event."
The distinction of QE from interaction probability involves the collection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

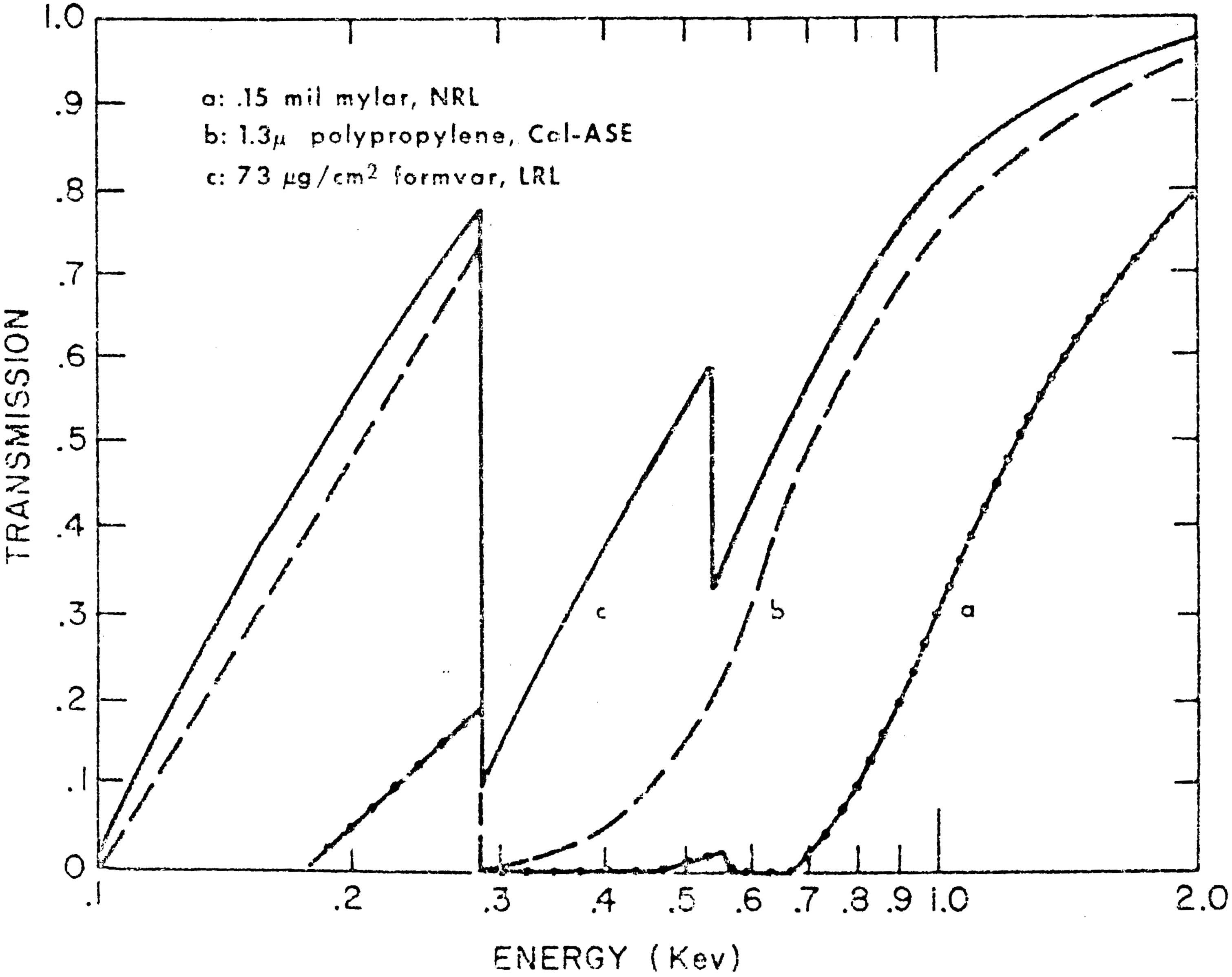


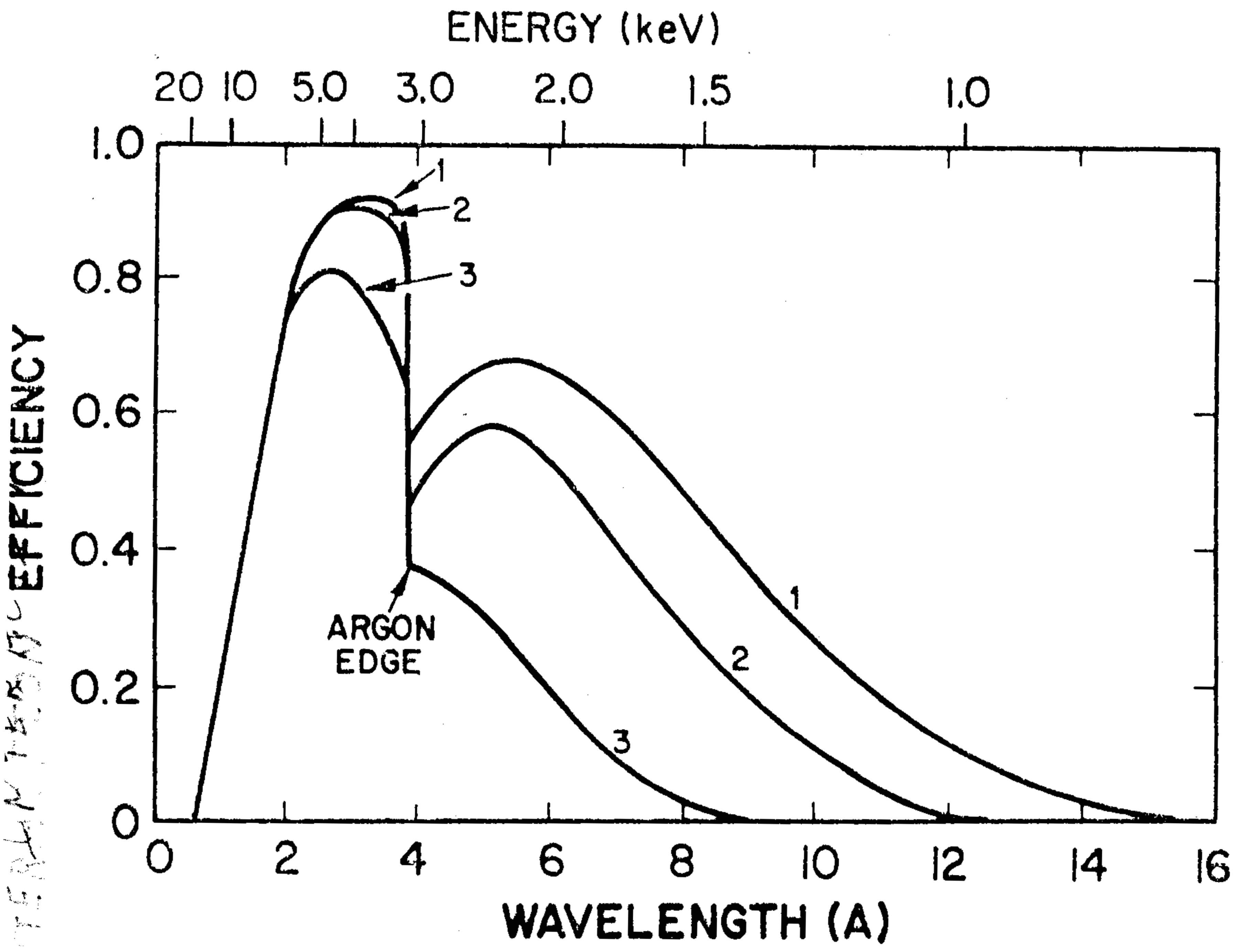
Cross section (barns/atom)
10^6
10^4
10^2
10^0
10^{-2}
$\sigma_{tot, experiment}$
σ_{coh}
σ_{incoh}
τ
σ_{ph}
κ_n
κ_e
10
10^3
10^5
10^7
10^9
10^{11}
Photon energy (eV)



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

TRANSMISSION OF COUNTER WINDOWS




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
WAVELENGTH (A)
0
2
4
6
8
10
12
14
16

Charge Creation

The X-ray is most likely to be absorbed by the deepest level electron for which the X-ray energy exceeds the binding energy of the atomic shell.

Charge Creation

The X-ray is most likely to be absorbed by the deepest level electron for which the X-ray energy exceeds the binding energy of the atomic shell.

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

Charge Creation

The X-ray is most likely to be absorbed by the deepest level electron for which the X-ray energy exceeds the binding energy of the atomic shell.

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.)

2. The ion will relax by emitting one or more Auger electrons, or perhaps a fluorescent photon. These will subsequently behave like the original electron and photon, respectively.

Charge Creation (cont.)

2. The ion will relax by emitting one or more Auger electrons, or perhaps a fluorescent photon. These will subsequently behave like the original electron and photon, respectively.

There is one subtlety: A fluorescent X-ray no longer has sufficient energy to liberate an electron from the same shell, so it will have a longer mean free path in the detector than the original X-ray.

Charge Creation (cont.)

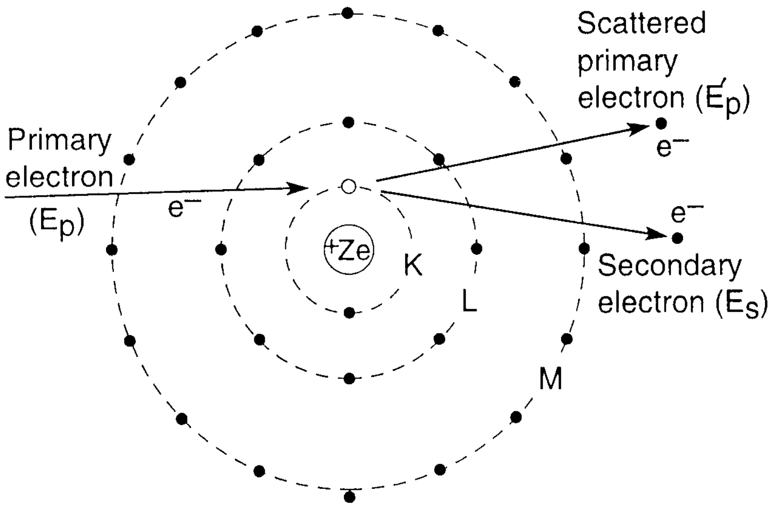
2. The ion will relax by emitting one or more Auger electrons, or perhaps a fluorescent photon. These will subsequently behave like the original electron and photon, respectively.

There is one subtlety: A fluorescent X-ray no longer has sufficient energy to liberate an electron from the same shell, so it will have a longer mean free path in the detector than the original X-ray.

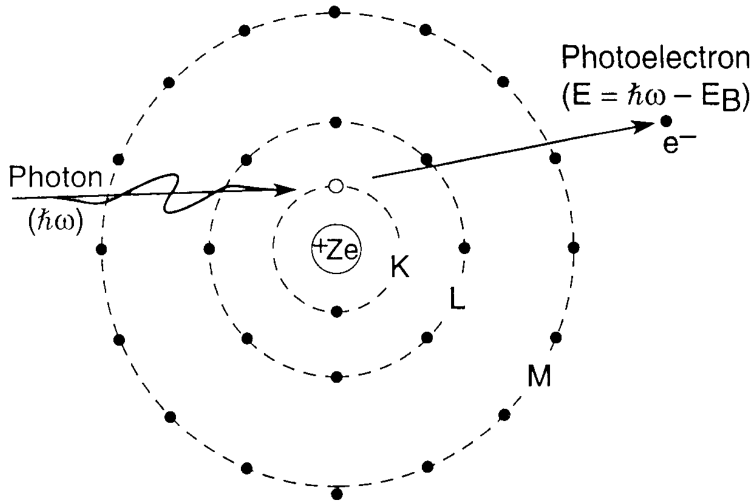
This gives it some probability for totally escaping the counter, so that the energy ultimately measured for the event is $E - E_K$.

Basic Ionization and Emission Processes in Isolated Atoms

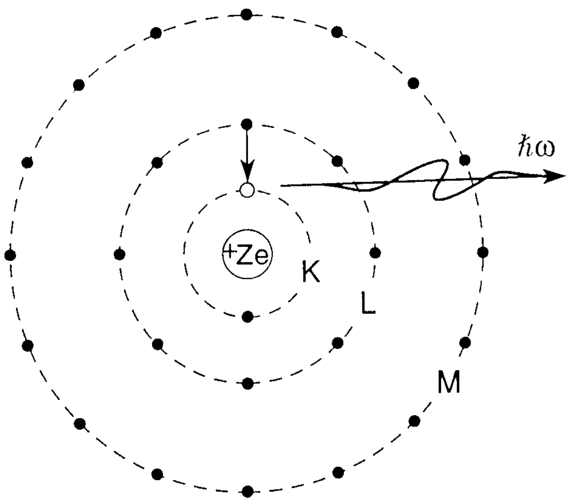
(a) Electron collision induced ionization



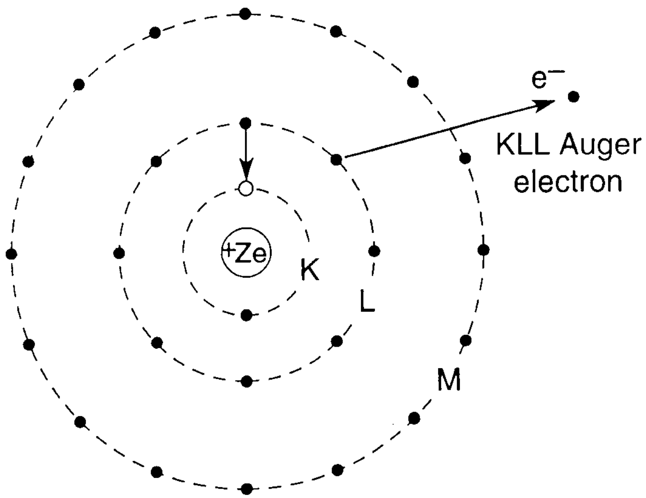
(b) Photoionization

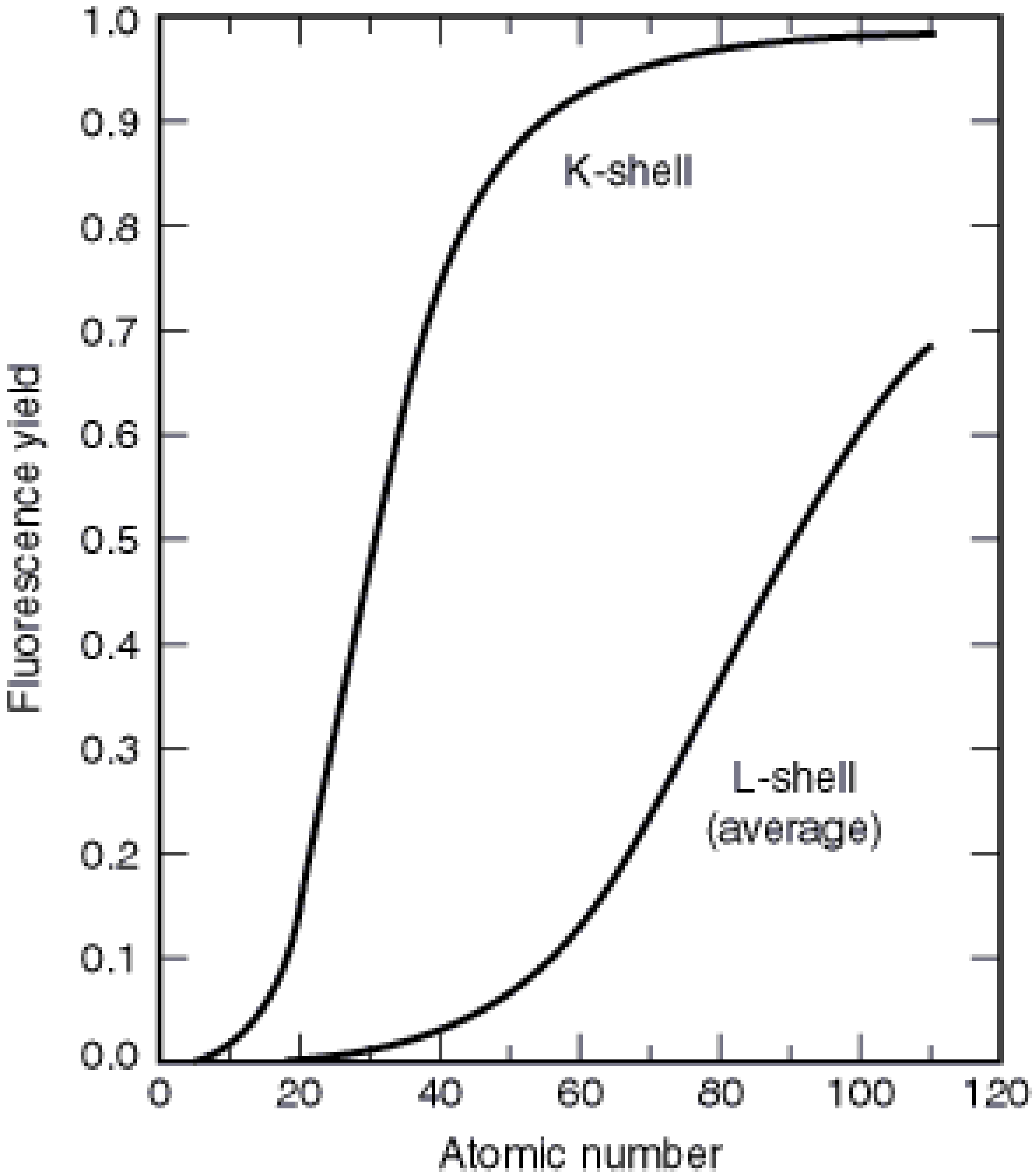


(c) Fluorescent emission of characteristic radiation

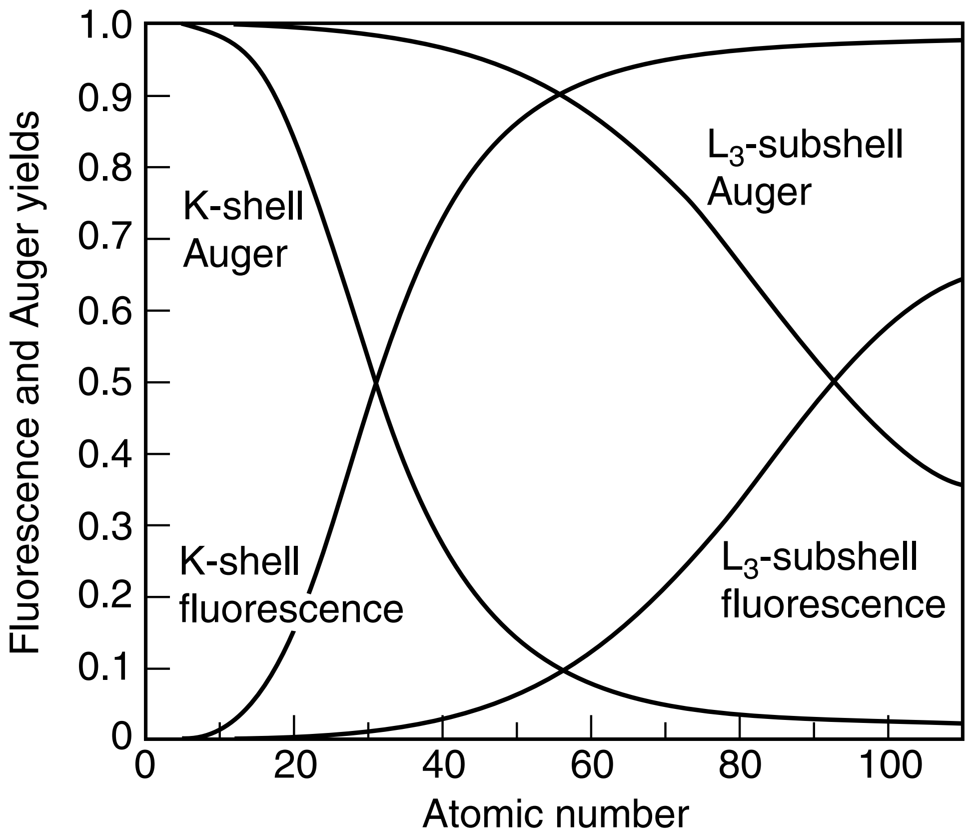


(d) Non-radiative Auger process




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

Fluorescence and Auger Emission Yields



CHARGE CREATION

Prop Counters, CCD

The processes above will iterate, until the electrons do not have sufficient energy to ionize any further atoms.

CHARGE CREATION

Prop Counters, CCD

The processes above will iterate, until the electrons do not have sufficient energy to ionize any further atoms.
(PC) Electrons will drift toward the anode, and the ions will drift, more slowly, toward the cathode.

CHARGE CREATION

Prop Counters, CCD

The processes above will iterate, until the electrons do not have sufficient energy to ionize any further atoms.

(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.

CHARGE CREATION

Prop Counters, CCD

The processes above will iterate, until the electrons do not have sufficient energy to ionize any further atoms.
(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

The variance in the number of ion pairs created is much smaller than E/W because:

1. The total energy deposited must be E

SPECIAL TOPIC: FANO FACTOR

The variance in the number of ion pairs created is much smaller than E/W because:

1. **The total energy deposited must be E**
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.**

SPECIAL TOPIC: FANO FACTOR

The variance in the number of ion pairs created is much smaller than E/W because:

1. The total energy deposited must be E

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:

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

SPECIAL TOPIC: FANO FACTOR (cont.)

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

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

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.

SPECIAL TOPIC: FANO FACTOR (cont.)

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

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

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.

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:

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

SPECIAL TOPIC: FANO FACTOR (cont.)

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

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

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.

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:

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

so that the desired Fano factor is

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

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

Actual typical values are 0.12 to 0.16.

CHARGE MULTIPLICATION

1. Prop Counters. G=10^3 to 10^5. Measurement of X-ray energy.

CHARGE MULTIPLICATION

1. Prop Counters. G=10^3 to 10^5. Measurement of X-ray energy.

2. MCP. G=10^6 to 10^8. Measurement of very precise spatial location.

CHARGE MULTIPLICATION

1. Prop Counters. G=10^3 to 10^5. Measurement of X-ray energy.

2. MCP. G=10^6 to 10^8. Measurement of very precise spatial location.

3. CCD. G$\equiv$ 1. Micron dimensions of integrated circuits give fF capacitance, μV per electron sensitivity.

CHARGE MULTIPLICATION

1. Prop Counters. G=10^3 to 10^5. Measurement of X-ray energy.

2. MCP. G=10^6 to 10^8. Measurement of very precise spatial location.

3. CCD. G$\equiv$ 1. Micron dimensions of integrated circuits give fF capacitance, μV per electron sensitivity.

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

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

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:

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

CHARGE MULTIPLICATION: Statistics

A random multiplication $\Rightarrow$ 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.

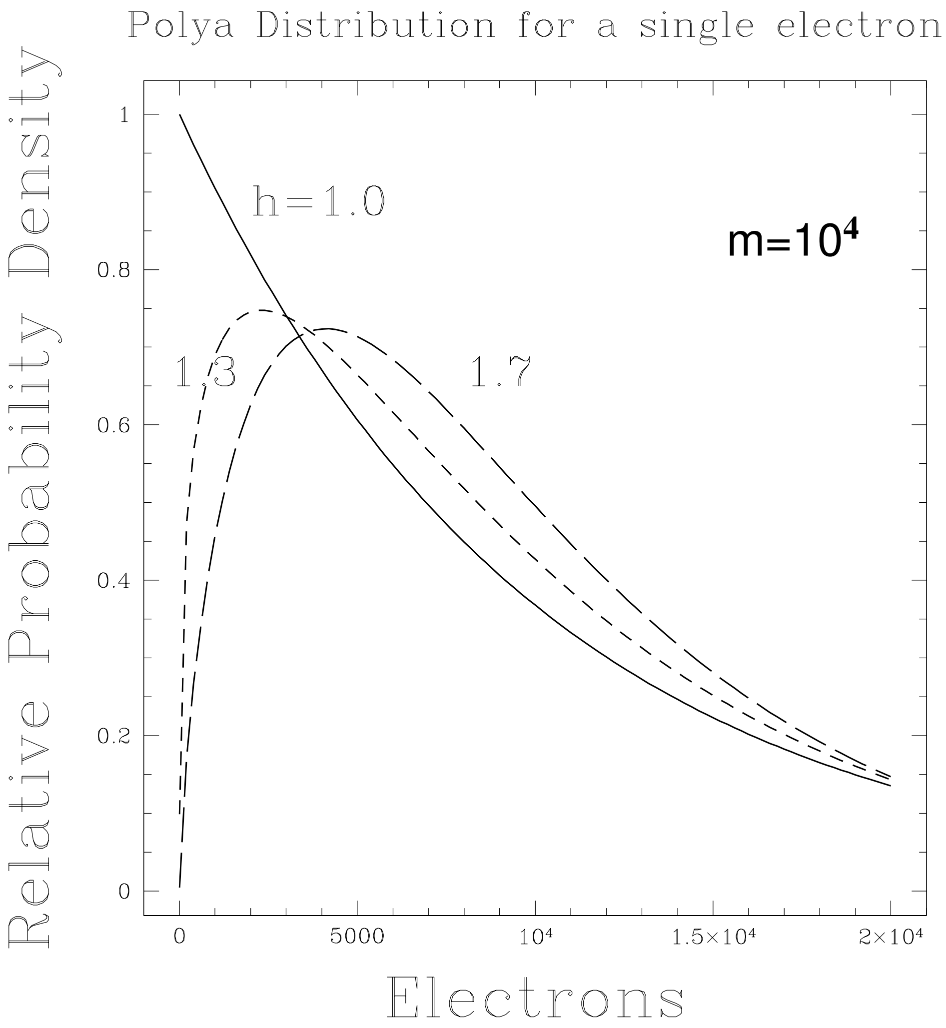
Jahoda and McCammon quote Alkhazov (1970, Nucl. Instr. Meth., 89 155) for the theoretical form of the probability of creating j electrons when m are expected:

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

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 $h \rightarrow \infty$.

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

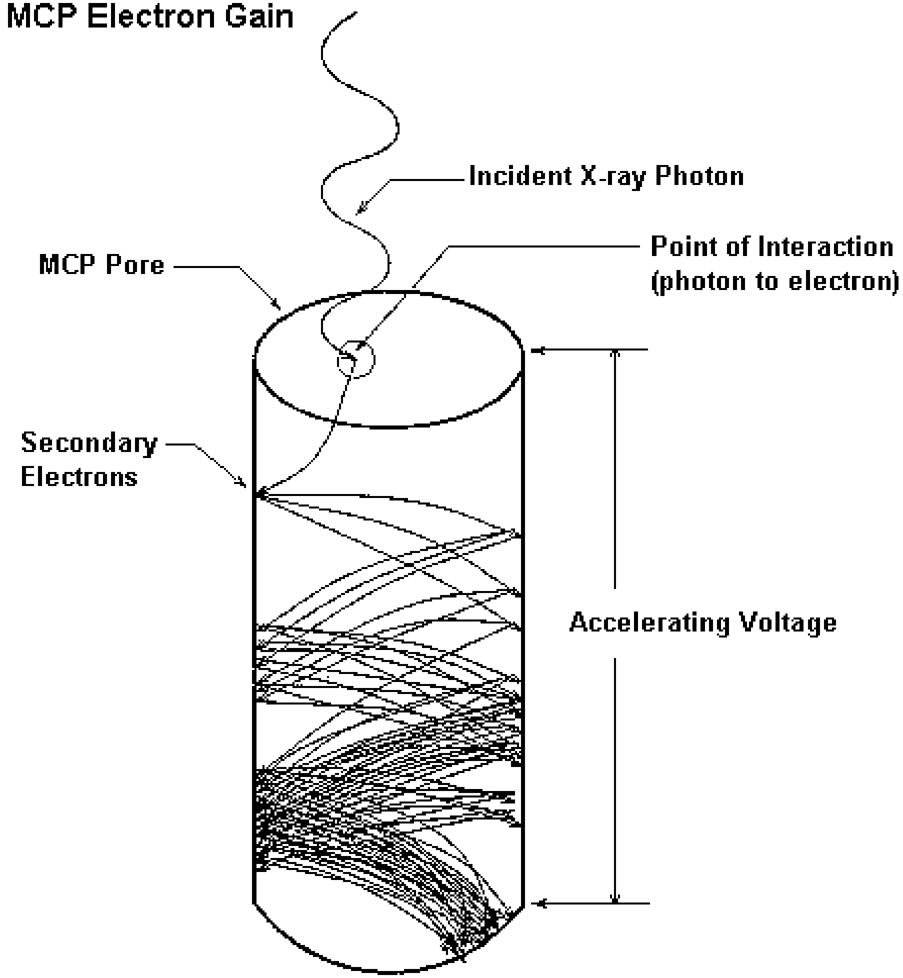


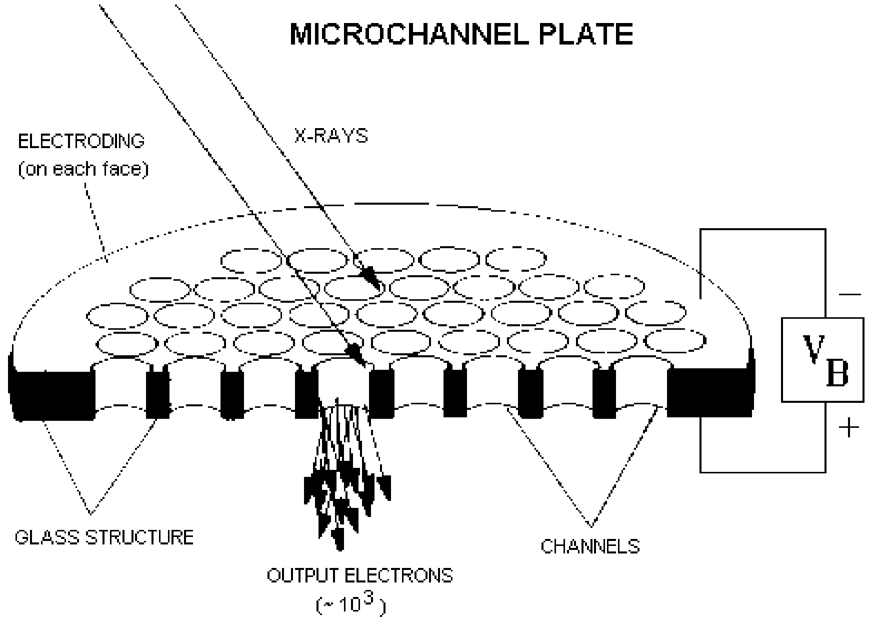
Polya Function:

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

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



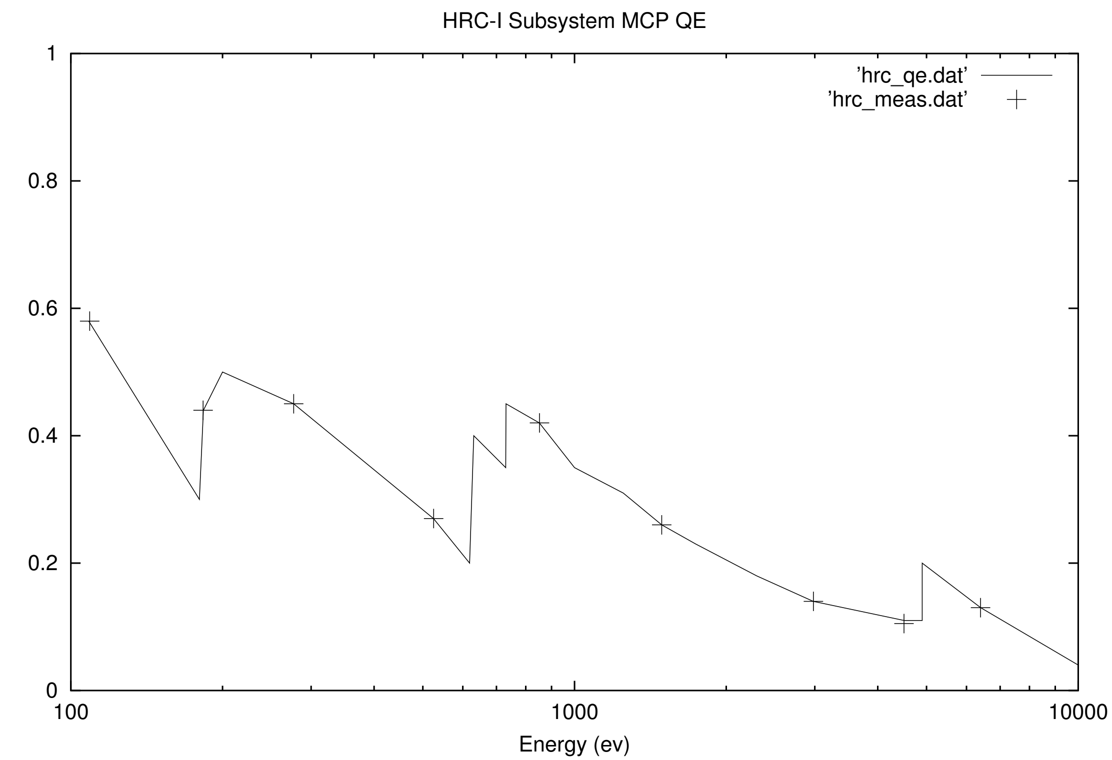


Because electron ranges are so small, at most 1 electron escapes the absorbing material to start a cascade.

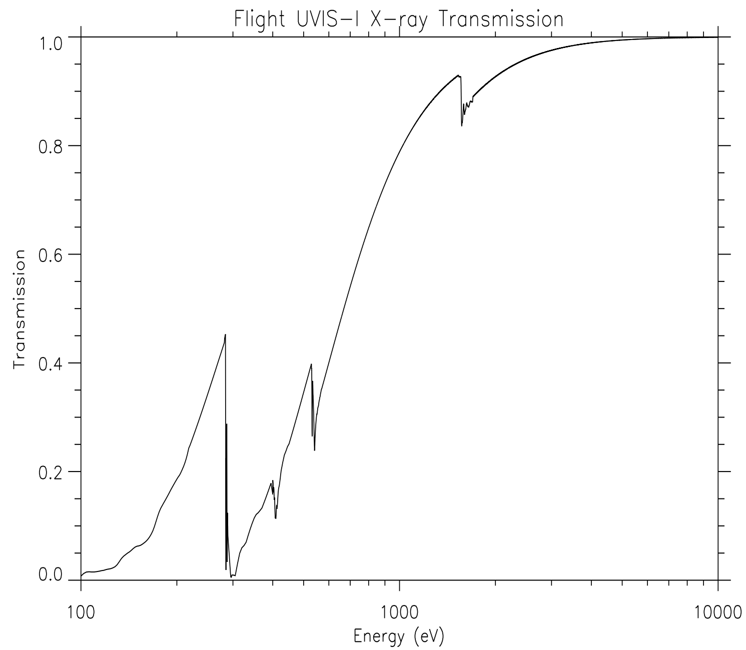
⇒ QE is low

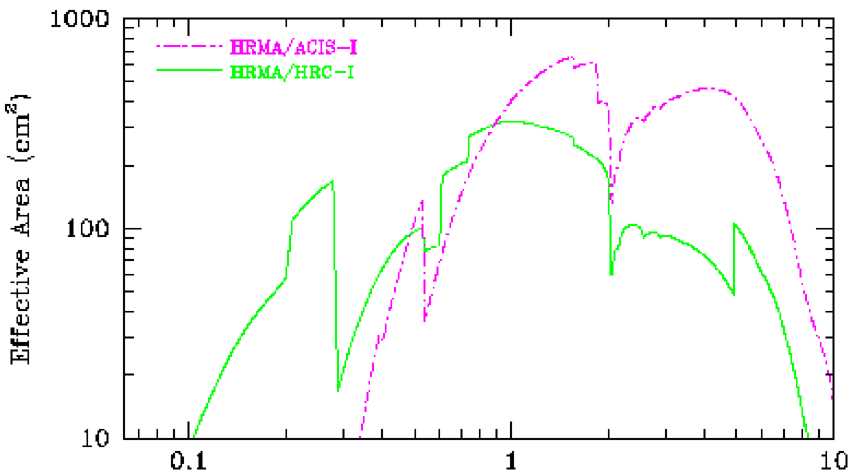
⇒ No energy resolution

Quantum Efficiency: MCP

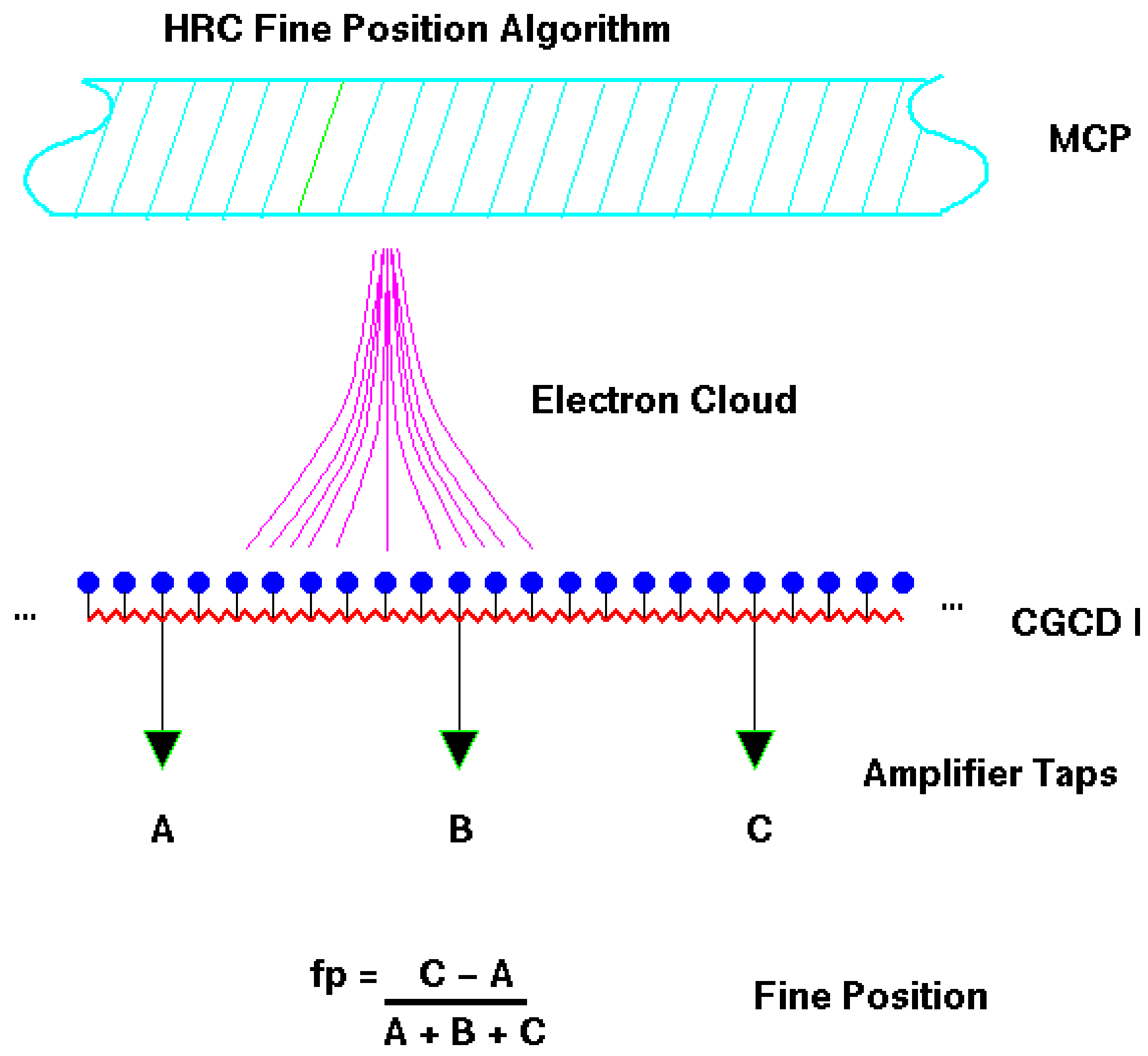


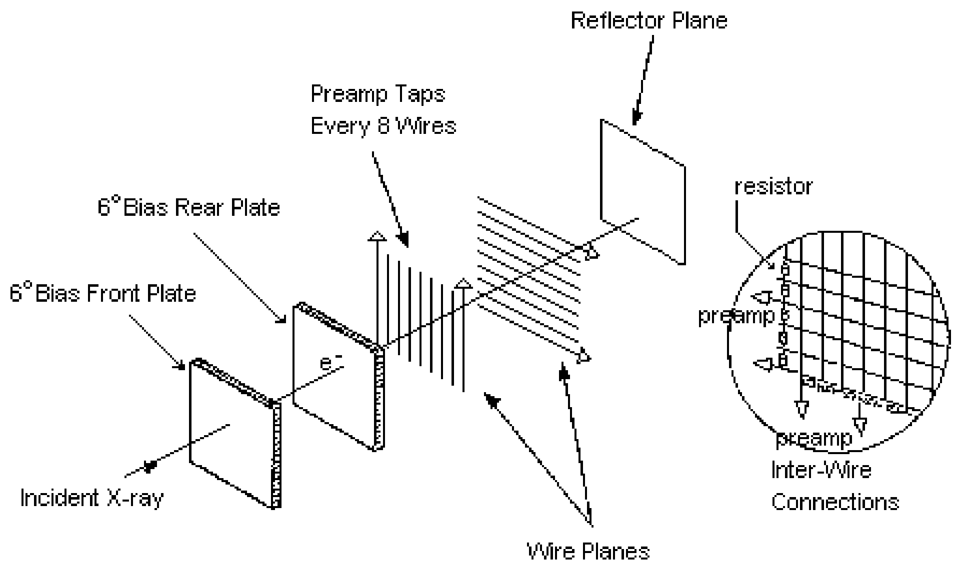
[RC-I quantum efficiency measured at subsystem level at SAO prior to detector housing assembly.





Position Readout: MCP





Position algorithm necessarily leaves "gaps"

Has non-linearities

SPECTRAL RESPONSE

For a mono-energetic photon input E_0 we will observe

1. Most photons will be in a “photo-peak,” a Gaussian-like distribution from fluctuations centered on E_0.

SPECTRAL RESPONSE

For a mono-energetic photon input E_0 we will observe

1. Most photons will be in a "photo-peak," a Gaussian-like distribution from fluctuations centered on E_0.

2. A secondary peak due to K-shell X-ray escape at an energy $E = E_0 - E_K$.

SPECTRAL RESPONSE

For a mono-energetic photon input E_0 we will observe

1. Most photons will be in a "photo-peak," a Gaussian-like distribution from fluctuations centered on E_0.

2. A secondary peak due to K-shell X-ray escape at an energy $E = E_0 - E_K$.

3. A low level, fairly flat continuum due to background, and to losses by some of the secondary electrons.

SPECTRAL RESPONSE

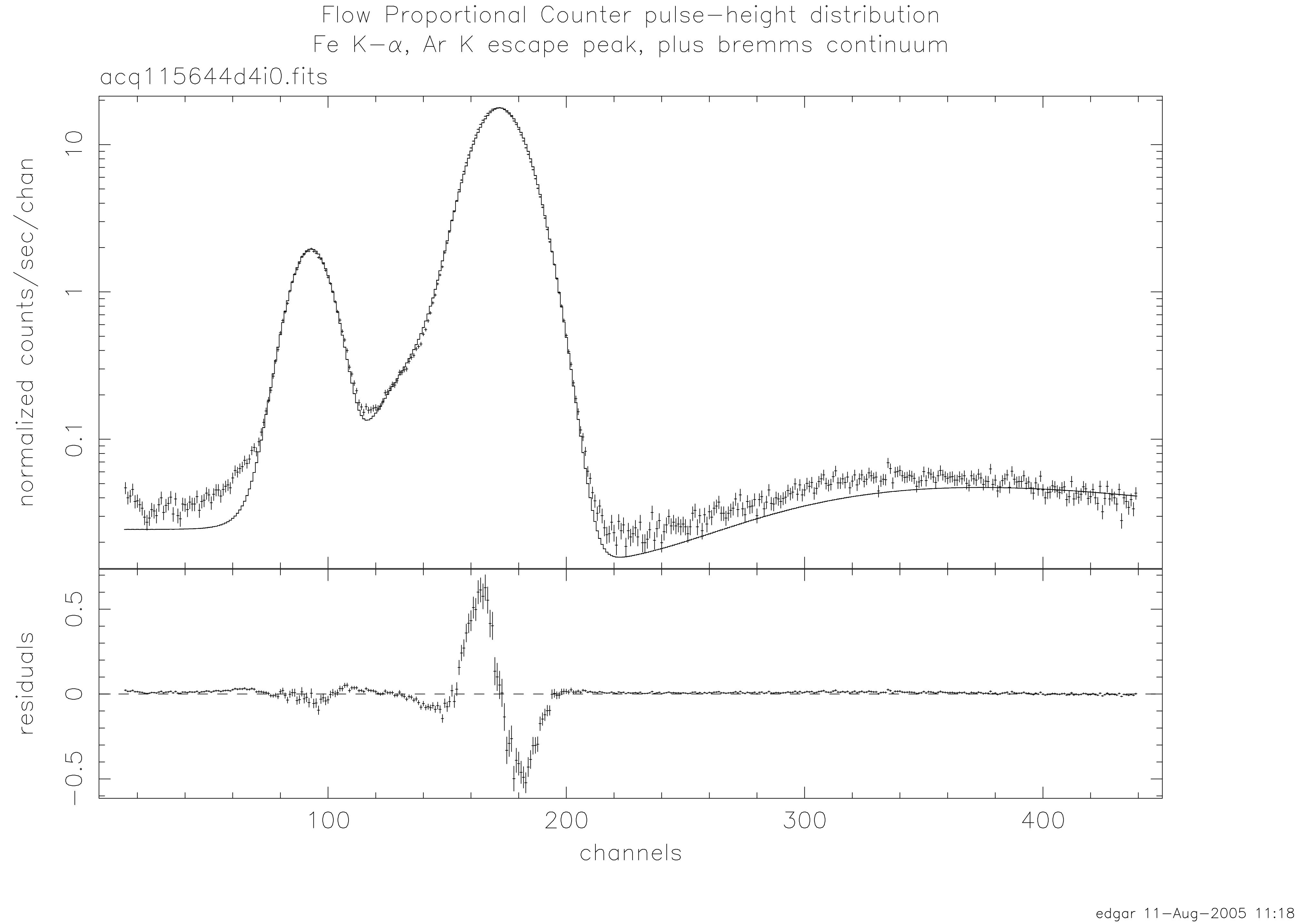
For a mono-energetic photon input E_0 we will observe

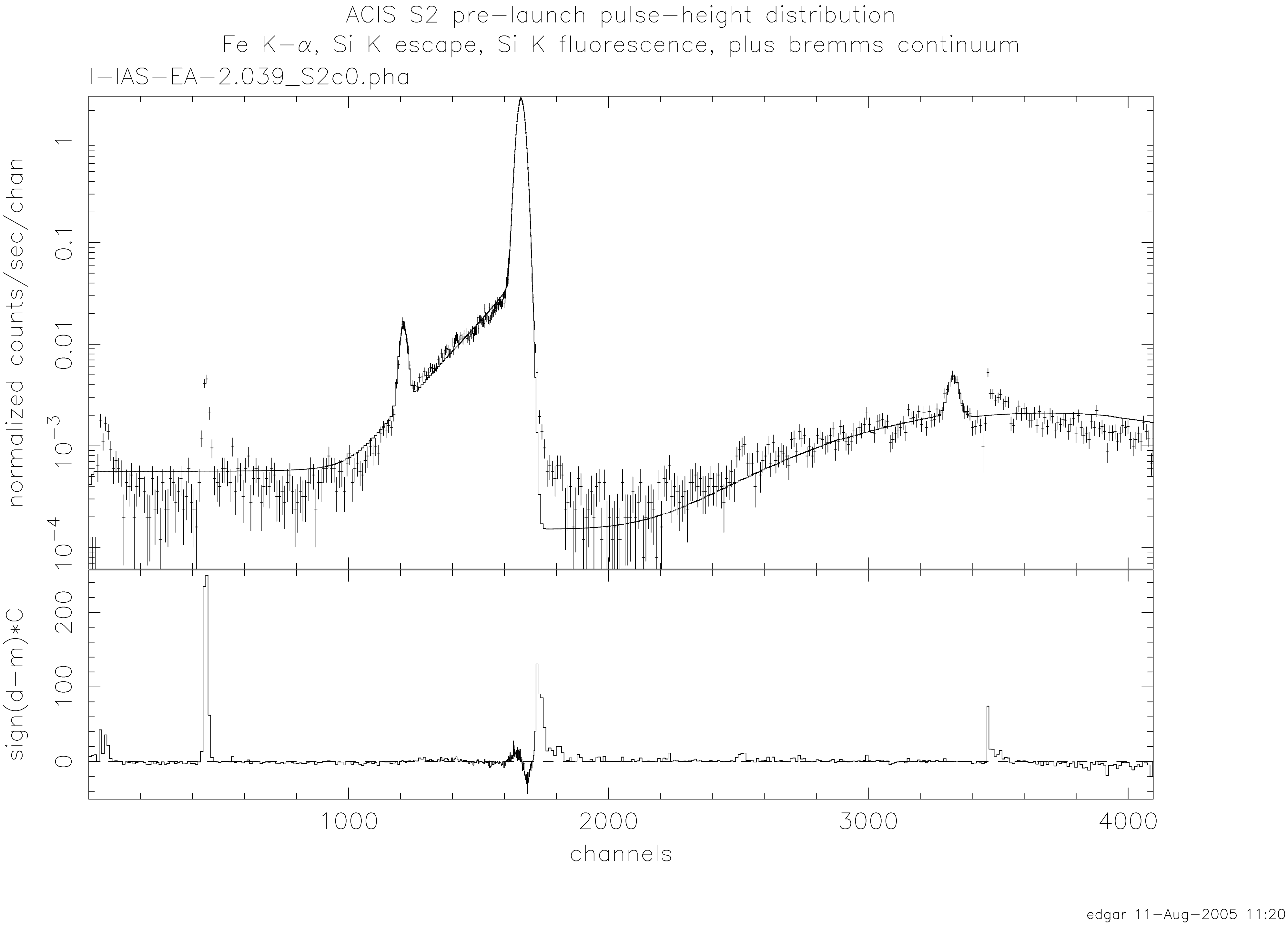
1. Most photons will be in a "photo-peak," a Gaussian-like distribution from fluctuations centered on E_0.

2. A secondary peak due to K-shell X-ray escape at an energy $E = E_0 - E_K$.

3. A low level, fairly flat continuum due to background, and to losses by some of the secondary electrons.

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 $2E_0$.


Flow Proportional Counter pulse−height distribution
Fe K−α, Ar K escape peak, plus bremms continuum
acq115644d4i0.fits
normalized counts/sec/chan
10
1
0.1
residuals
0.5
0
−0.5
100
200
300
400
channels
edgar 11−Aug−2005 11:18


ACIS S2 pre-launch pulse-height distribution
Fe K-α, Si K escape, Si K fluorescence, plus bremms continuum
I-IAS-EA-2.039_S2c0.pha
normalized counts/sec/chan
1
0.1
0.01
10^{-3}
10^{-4}
sign(d-m)*C
200
100
0
1000
2000
3000
4000
channels
edgar 11-Aug-2005 11:20

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.

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.

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