PROPORTIONAL COUNTERS

Introduction

1. Principles of Operation
   - Charge Creation
   - Charge Collection
2. Proportional Counter Data
   - Spectral Response
   - Background
3. The Proportional Counter System
   - Gas
   - Window
   - Collimator
   - NOT discussed: Vehicle, Electronics, Gas Supply
4. Configurations
   - Counters
   - Low Resolution Spectrometry
   - One dimensional resolution: All-sky monitors
   - Imaging counters: Telescope focal planes

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20 August 2002

INTRODUCTION

Why Are We Discussing Proportional Counters?

1. Had been the historical Workhorse of X-ray Astronomy
    - *Chandra* and *XMM/Newton* the first missions in which they play no role!
2. Basic General principles of interaction, measurement of a distribution of pulse heights, background, apply to more modern detectors.
3. They still play a key role in ground calibration!
4. They can be extended to very large areas:
    - Needed at higher energies, or without telescopes.
5. They can 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. You may think of something clever to do with them!

GENERAL PRINCIPLES

Rossi, B. & Staub, H. 1948, “Ionization Chambers and Counters,” (New York: McGraw-Hill); 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.

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.

Executive Summary:

An X-ray interacts with an atom of the prop counter gas.

Charge is generated; (i.e., electrons and positive ions separated).

The charge multiplies, proportional to the incident X-ray energy.

The charge is collected, measured, digitized, and telemetered.

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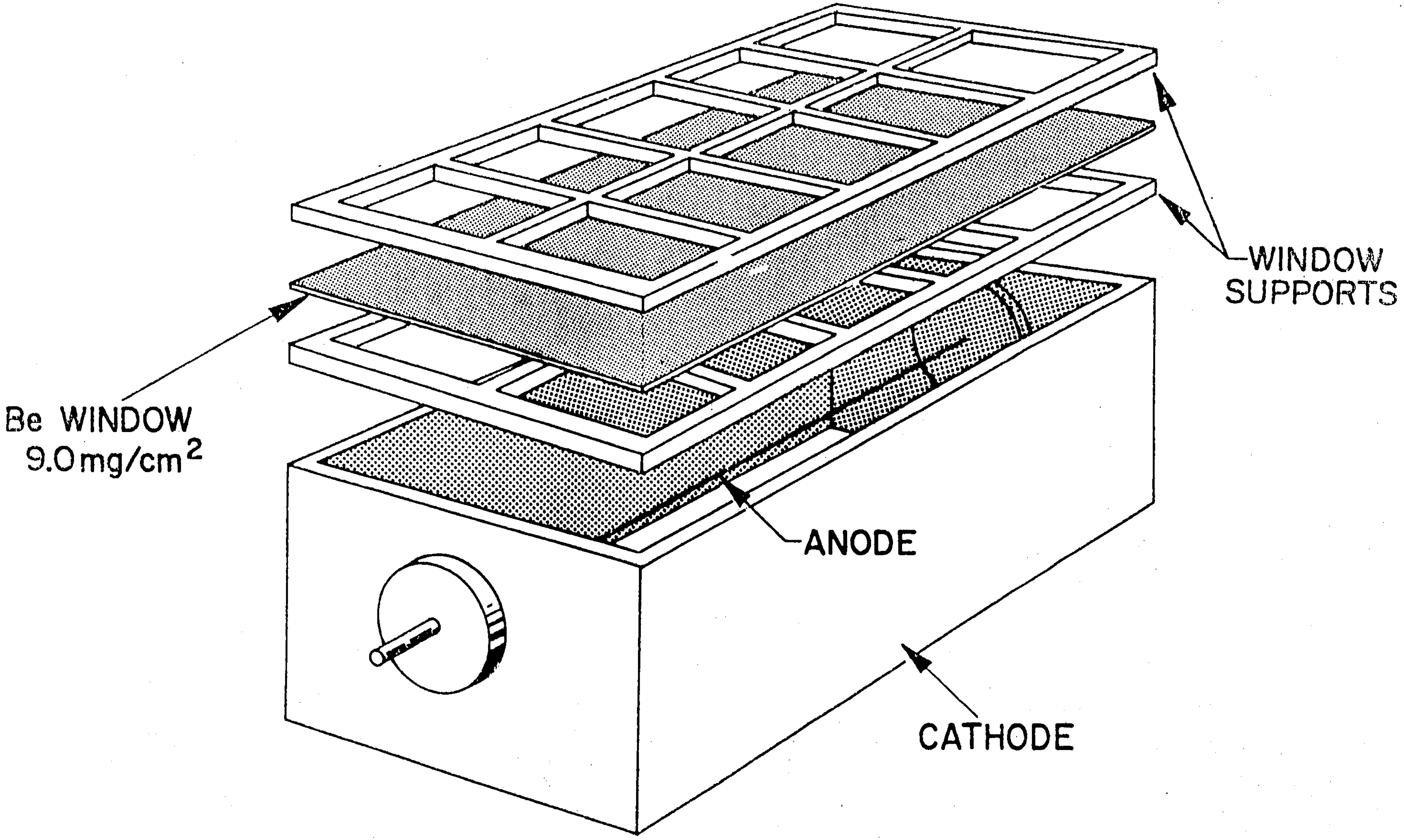
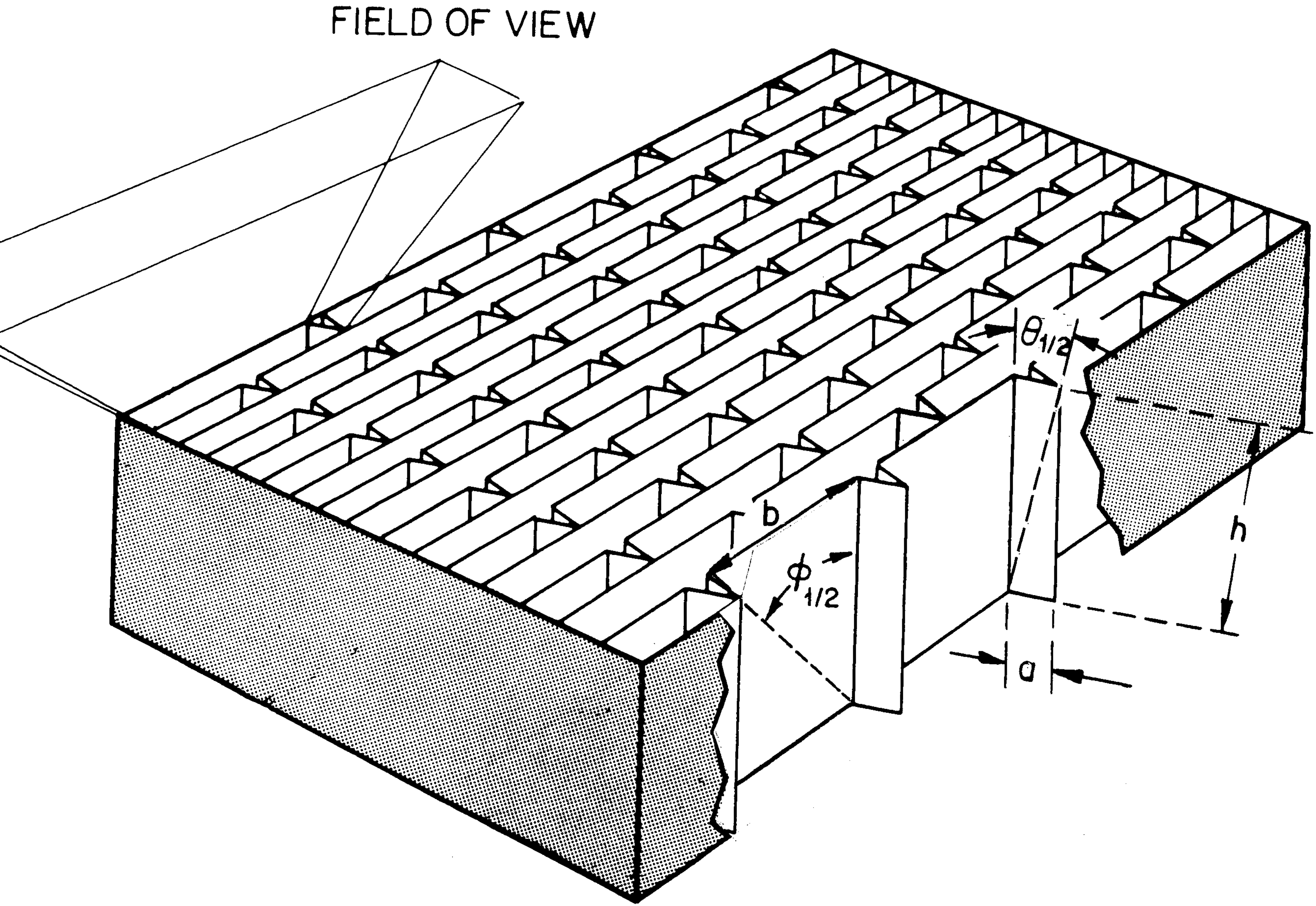


WINDOW SUPPORTS
Be WINDOW 9.0mg/cm^2
ANODE
CATHODE


FIELD OF VIEW
$\theta_{1/2}$
b
$\phi_{1/2}$
h
a

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 gas *after* having penetrated the window is

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

where we have used j to index the gas. (More generally, we would have $\Sigma_{j=1}^{n}\rho_j\,\mu_j(E)$ in the exponent, for a mixture of n counter gases.)

We therefore have the probability for interaction in the counter:

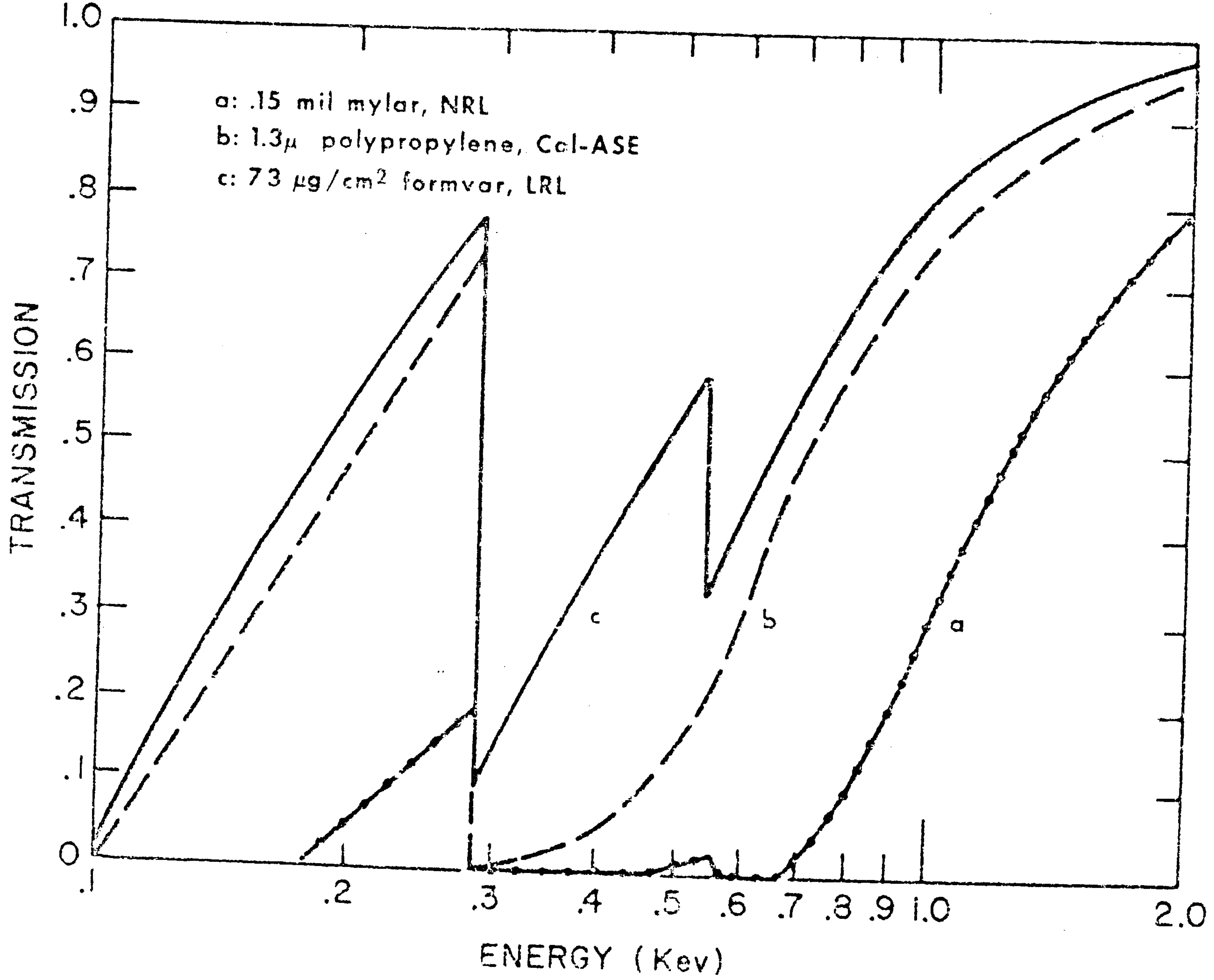
$$e^{-t_i\,\rho_i\,\mu_i(E)}\left(1\text{-}e^{-t_j\,\rho_j\,\mu_j(E)}\right)$$

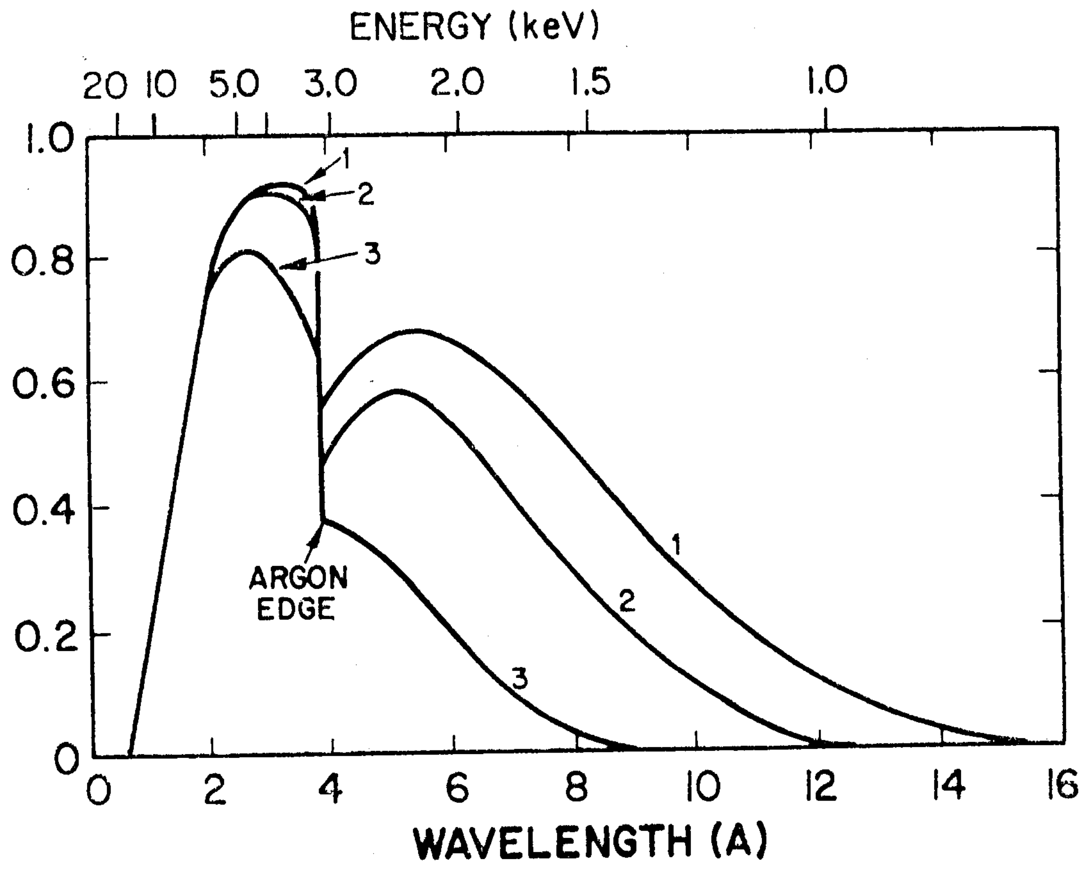
Note that this probability is NOT the "Quantum Efficiency," which should be defined for a photon of energy E as "The probability that such an isolated photon, incident to the instrument, gives rise to a detected X-ray event."

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!

TRANSMISSION OF COUNTER WINDOWS





[illegible] IN TER ACTION

1" Argon, 1.2 atm
1) 1 mil mylar
2) 2 mil Be
3) 5 mil Be

[illegible] 37

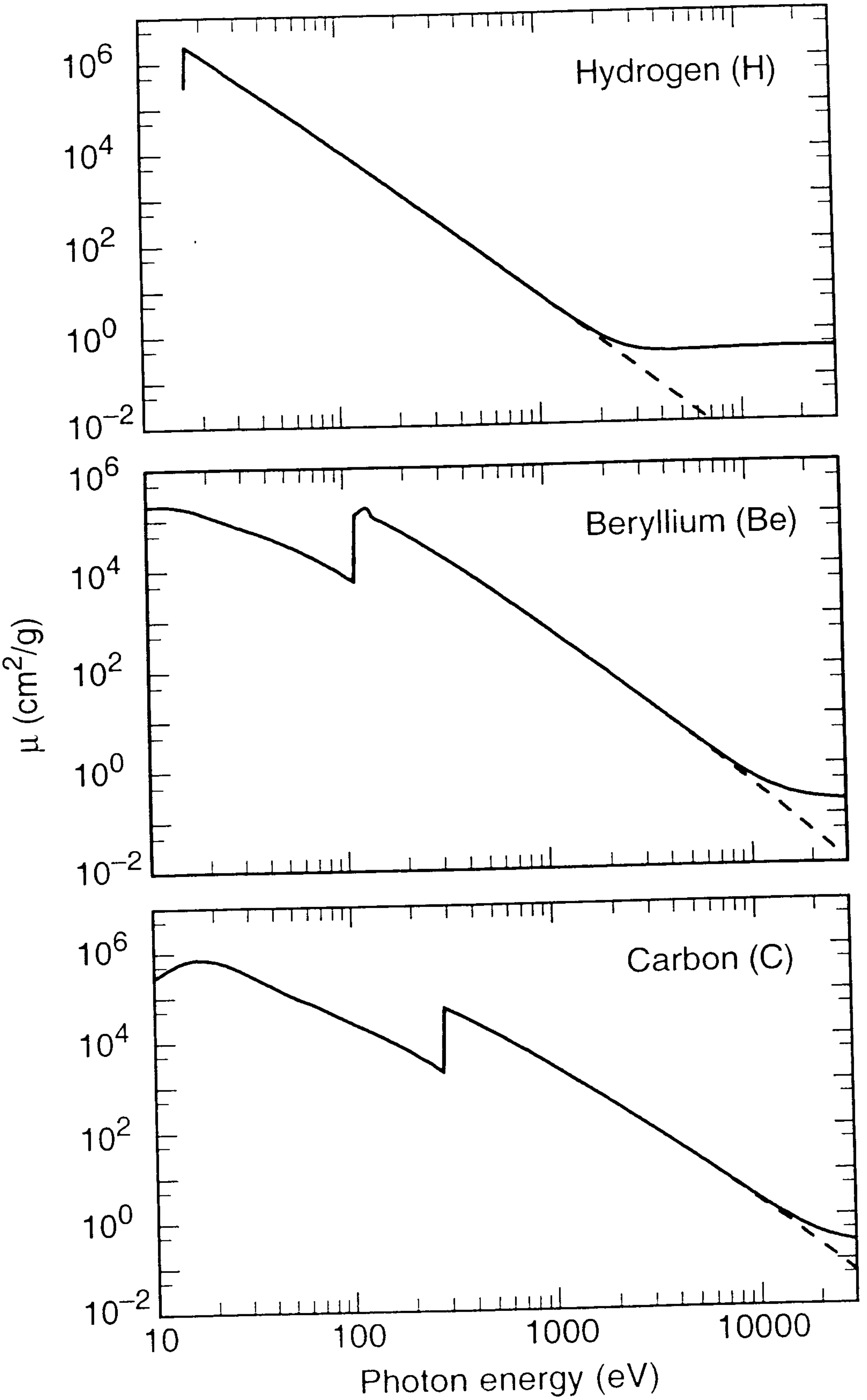


Fig. 1-5. Plots of mass absorption coefficients for several elements in their natural forms. For H, Be, C, N, and O, the photoabsorption cross section is shown as a dashed curve.

X-ray Interaction (cont.)

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

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 theoretical 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 of the gas, 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 accompanying creation of an electron ion pair.

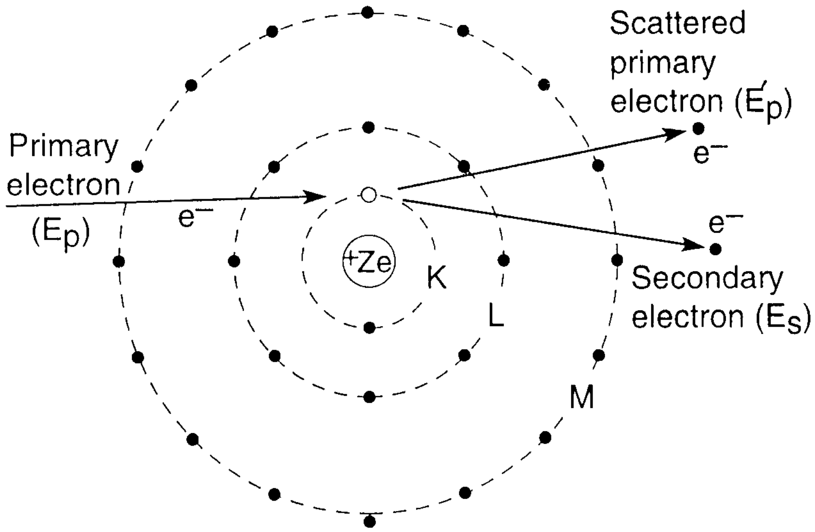
For common gases, $W \sim 30$eV while $W_0 \sim 12$ to 16 eV.

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.

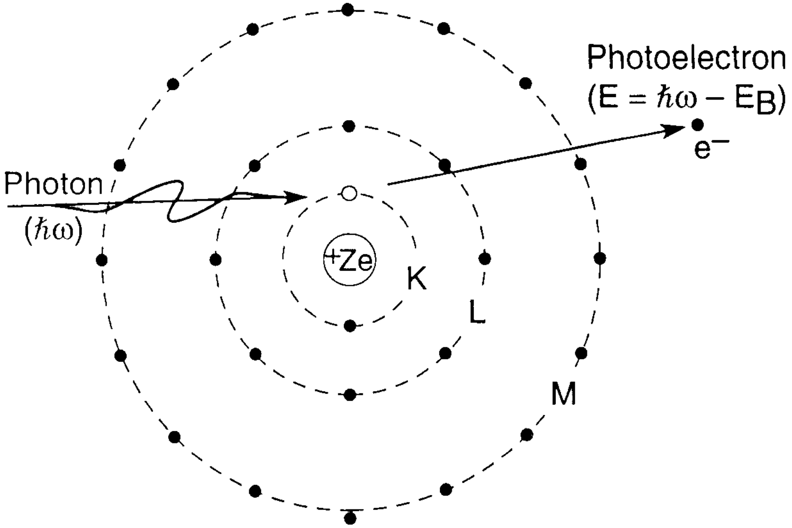
There is one subtlety: A fluorescent X-ray no longer has sufficient energy to liberate an electron from the same shell, so it will have a longer mean free path in the detector than the original X-ray. This gives it some probability for totally escaping the counter, so that the energy ultimately measured for the event is $E-E_K$.

Basic Ionization and Emission Processes in Isolated Atoms

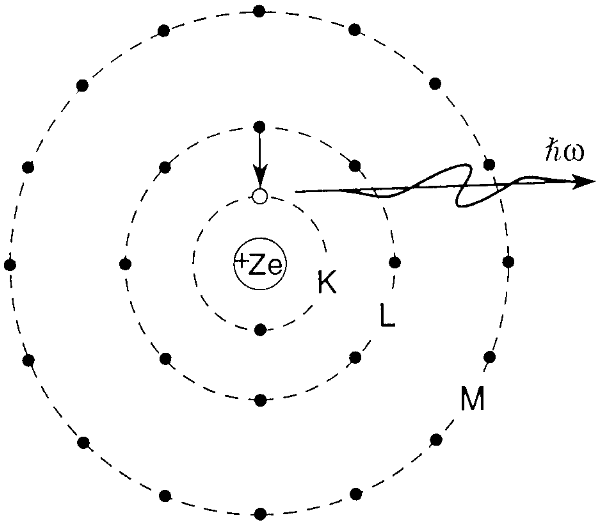
(a) Electron collision induced ionization



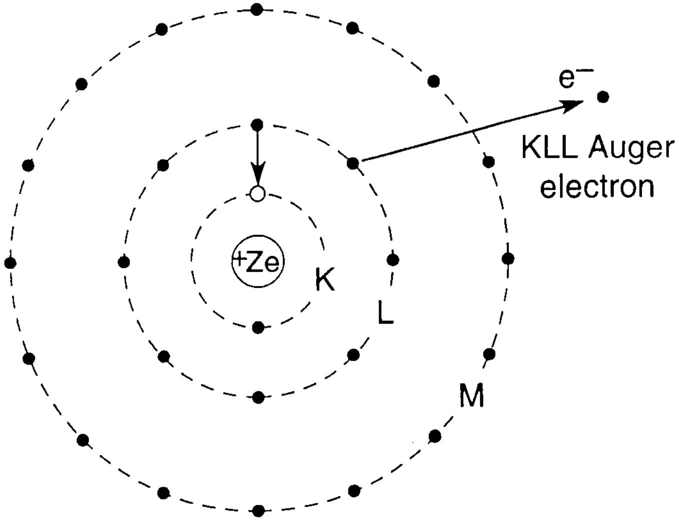
(b) Photoionization

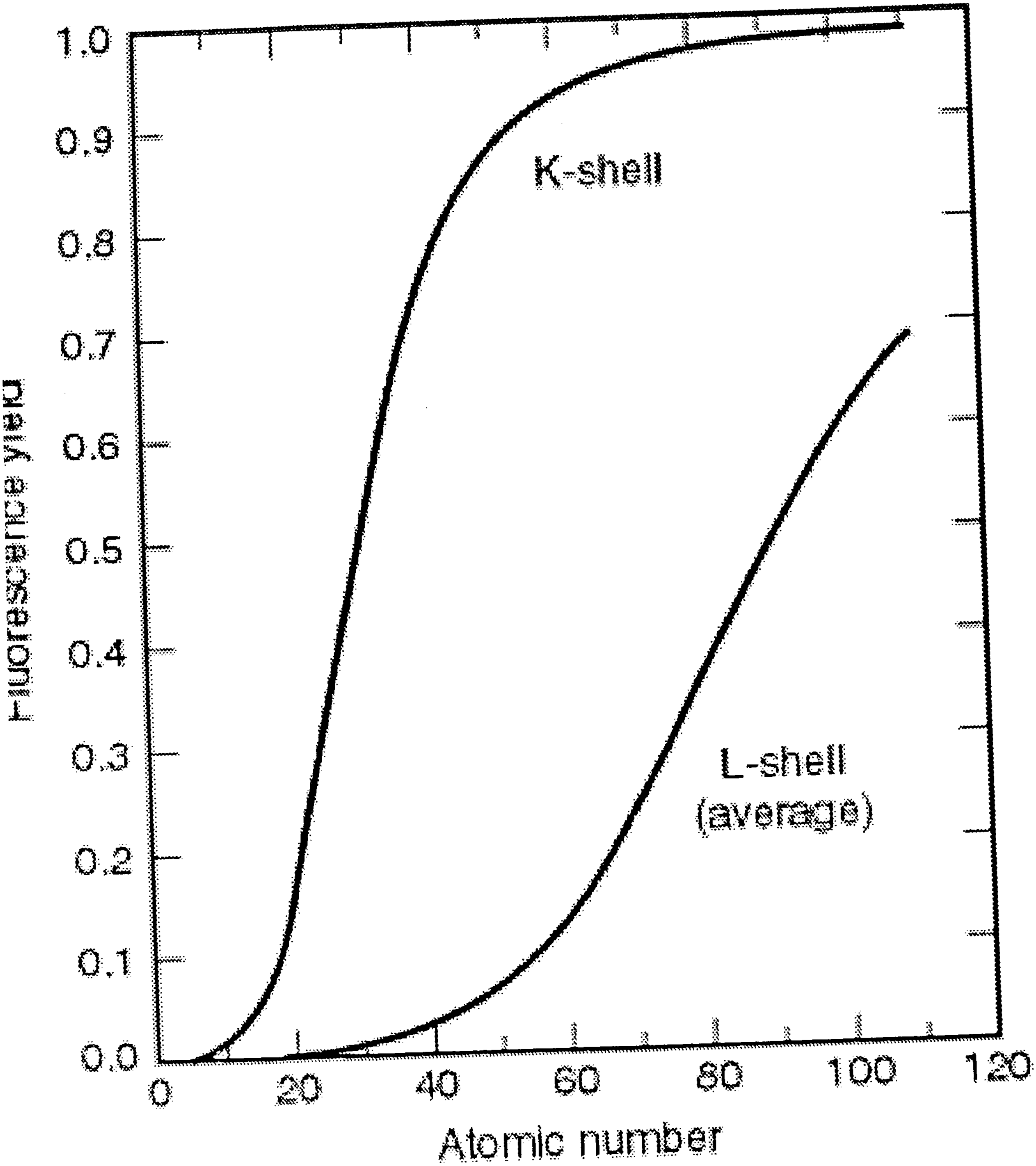


(c) Fluorescent emission of characteristic radiation

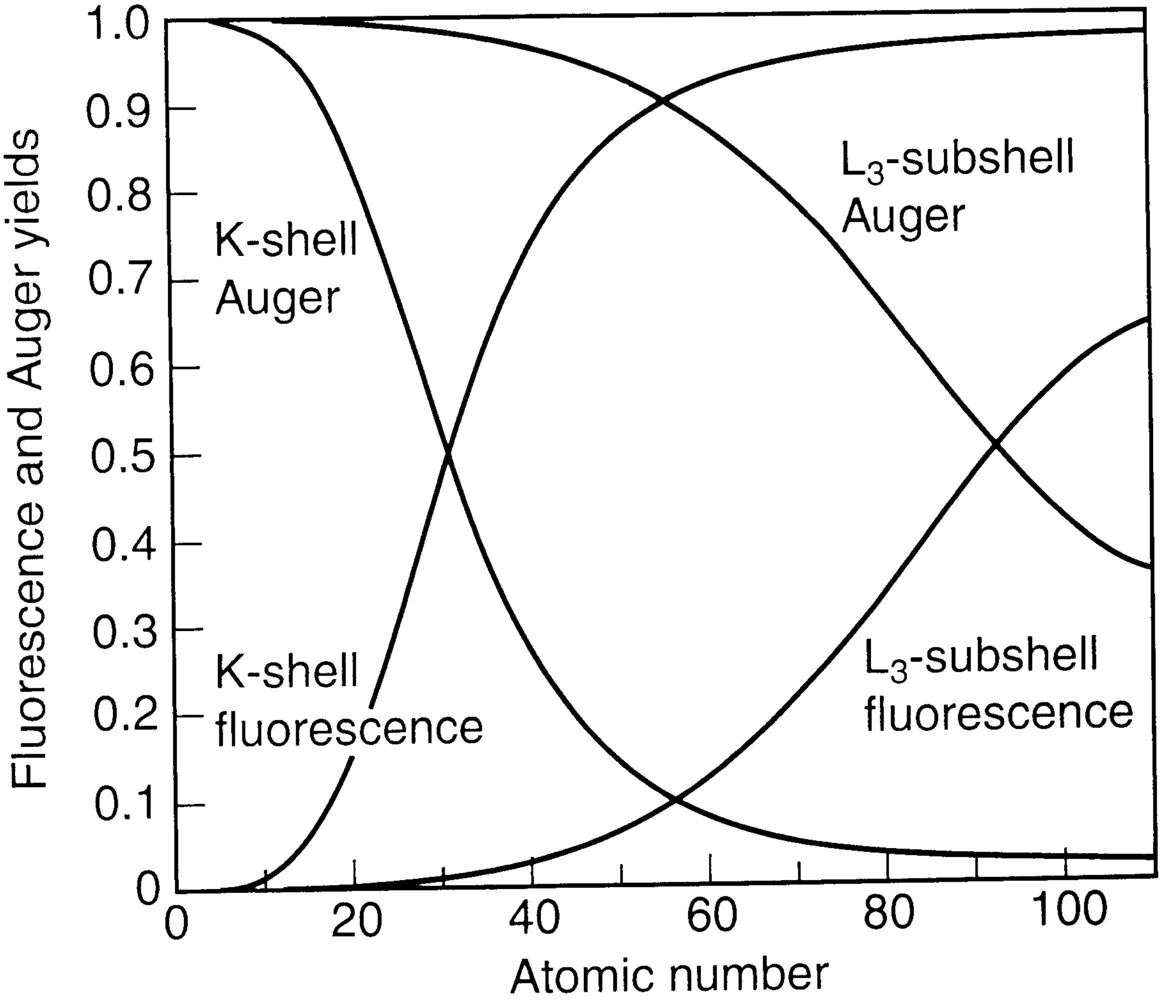


(d) Non-radiative Auger process




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

Fluorescence and Auger Emission Yields



(Courtesy of M. Krause, Oak Ridge)

CHARGE COLLECTION

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

An expected number $N=E_e/W$ of electrons will approach the vicinity of the anode. One might expect 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).

[illegible]

The electric field depends inversely on the distance from the anode, whose radius is typically of order 25μm. Anode voltages may be of order 2000V. Thus when an electron is within a fraction of a cm 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 which may typically multiply the numbers of electrons by 10^4 to 10^5.

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.

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 $\hat{N} = \Sigma_{i=1}^{k} \hat{n}_i$, and $E = \Sigma_{i=1}^{k} \hat{e}_i$, 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:

$\mathrm{var}(\hat{N}) = k <(\hat{n}_i - \hat{e}_i/W)^2> = \frac{E}{W\overline{n}} <(\hat{n}_i - \hat{e}_i/W)^2> = F\ (E/W)$, so that the desired Fano factor is

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

We can make an "eyeball" estimate of $F \sim 3/8$.

Actual typical values are 0.12 to 0.16.

CHARGE COLLECTION (cont.)

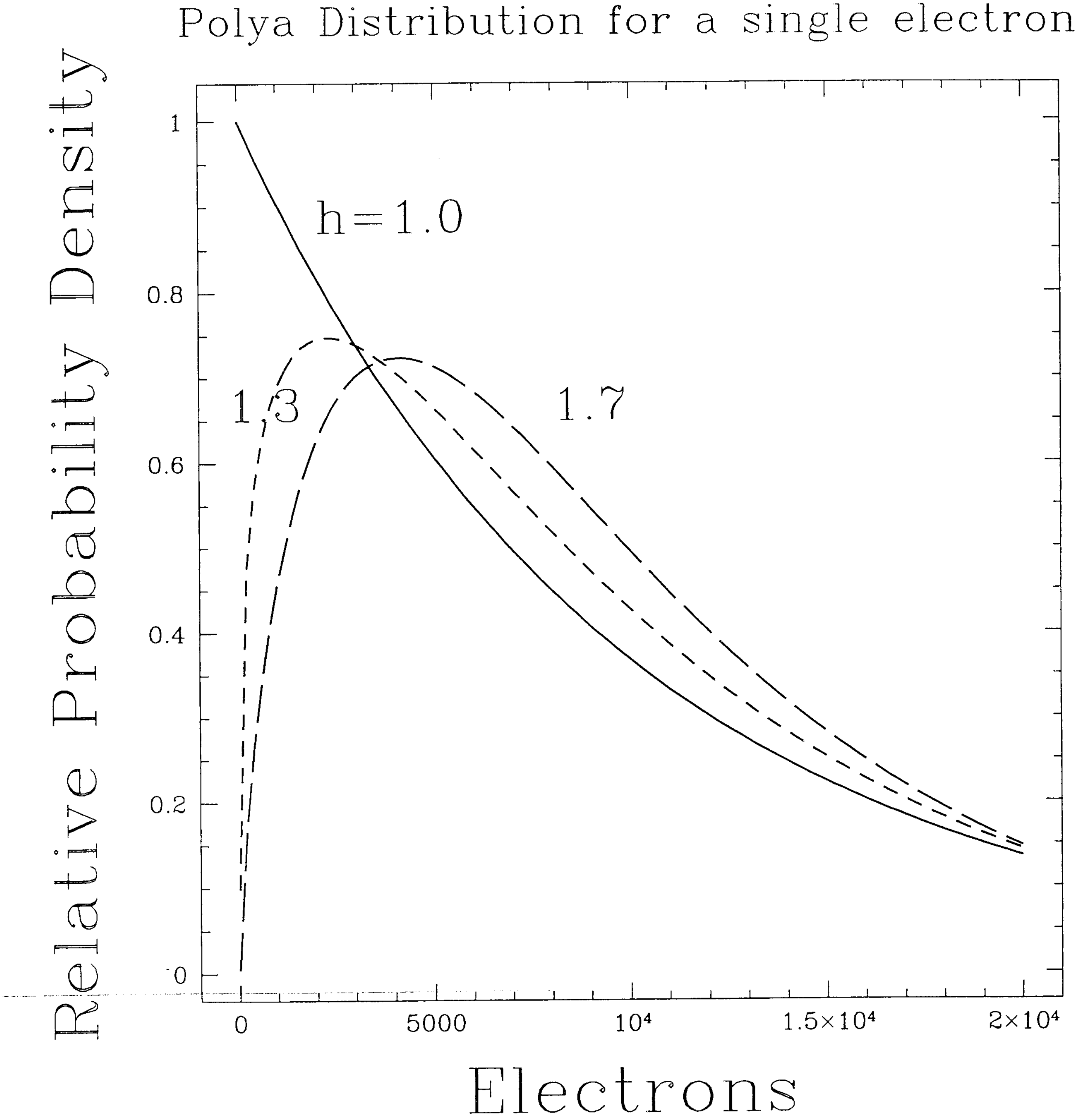
A purely random multiplication process would result in an exponential distribution of total charge resulting from each initial electron. However, just as in the case of creating the initial electron-ion pairs, many more interactions are really taking place, with much of the energy going into ionization potential energy, and resulting 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:

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

This is a Polya function with parameter h, also called a Pearson Type III. It becomes an exponential for h=1, and a δ-function (no variance) for h→ ∞.

The mean is m, the variance m^2/h so 1/h is the relative variance. For a sum of N electrons, the Polya function has the property that the distribution is another Polya function with mean Nm and parameter h→Nh, so the relative variance in the final number of electrons in the charge cloud is 1/(Nh). Empirical values of h range 1.2 to 1.7. Note that for these values the avalanche statistics dominate the original ion-electron pair creation statistics: $1/(Nh)\sim 0.7/N$.

As the electron cloud approaches the anode it *induces* a localized positive charge on the conductor, resulting in a negative charge pulse propagating through the wire, whence it can be measured by a charge sensitive preamp before recombining in the power source.



Polya Distribution for a single electron

SPECTRAL RESPONSE OF A PROPORTIONAL COUNTER

For a monoenergetic photon input we will observe

1. Most photons will be in a "photo-peak," a Gaussian-like distribution representing the fluctuations following complete colletion of the photon energy.
2. A secondary peak due to K-shell X-ray escape will be at an energy lower than primary by the K-shell X-ray energy.
3. A low level, fairly flat continuum due to background, and to losses by some of the secondary electrons into the windows, wires or other structure internal to the counter.
4. At very high counting rates, where a second X-ray may interact and not be distinguished from the first, there may be a lower level peak at an energy corresonding to twice the primary peak.

PROPORTIONAL COUNTER GAS

Use a noble gas

- Higher ionization potential
- Molecular vibrational and rotational states absent
- Results in lower W, the energy lost per ionization, and higher number E/W of ion-pairs created

Also need a polyatomic quench gas; e.g., CO_2, CH_4

- Absorb the UV photons to which the noble gas is transparent
- Collisionally de-excite metastable states of the noble gas

PROPORTIONAL COUNTER BACKGROUND

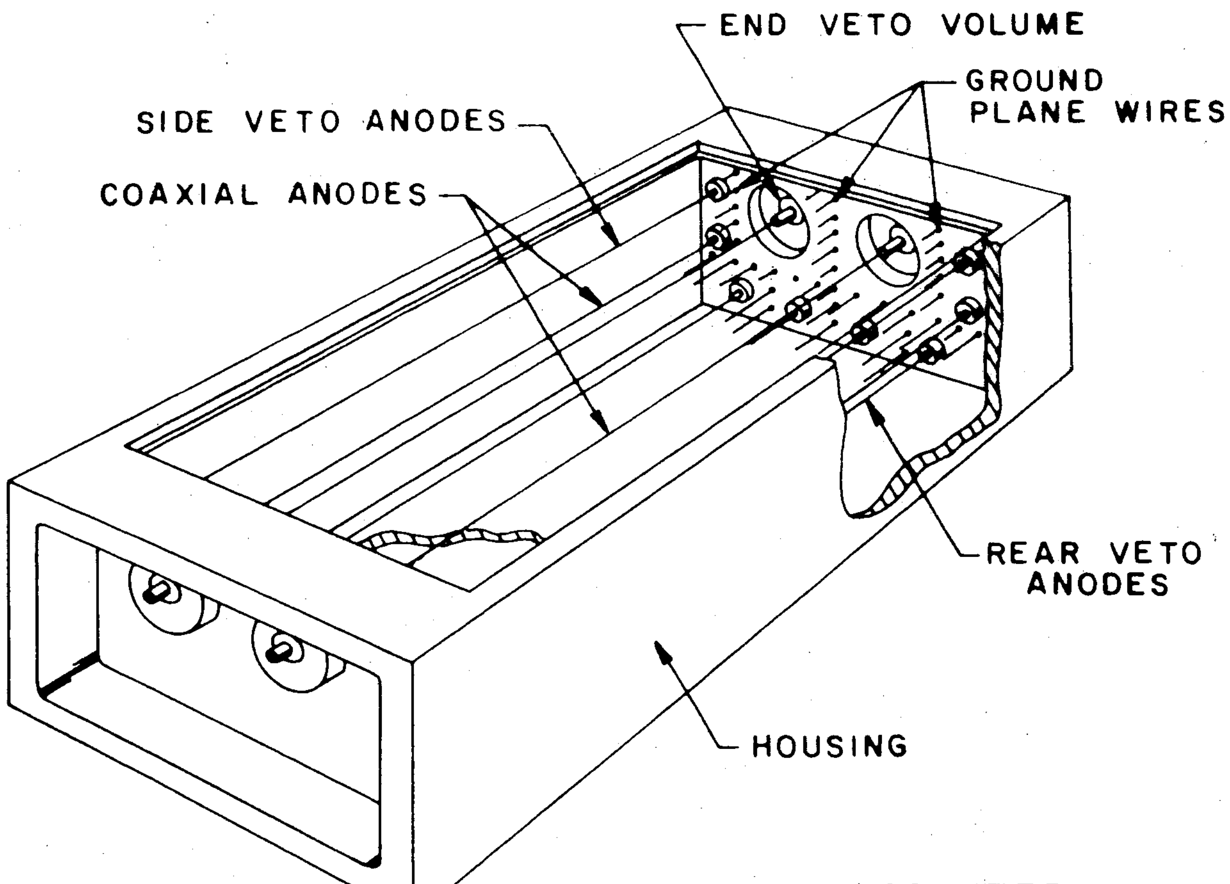
Charged Particles

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

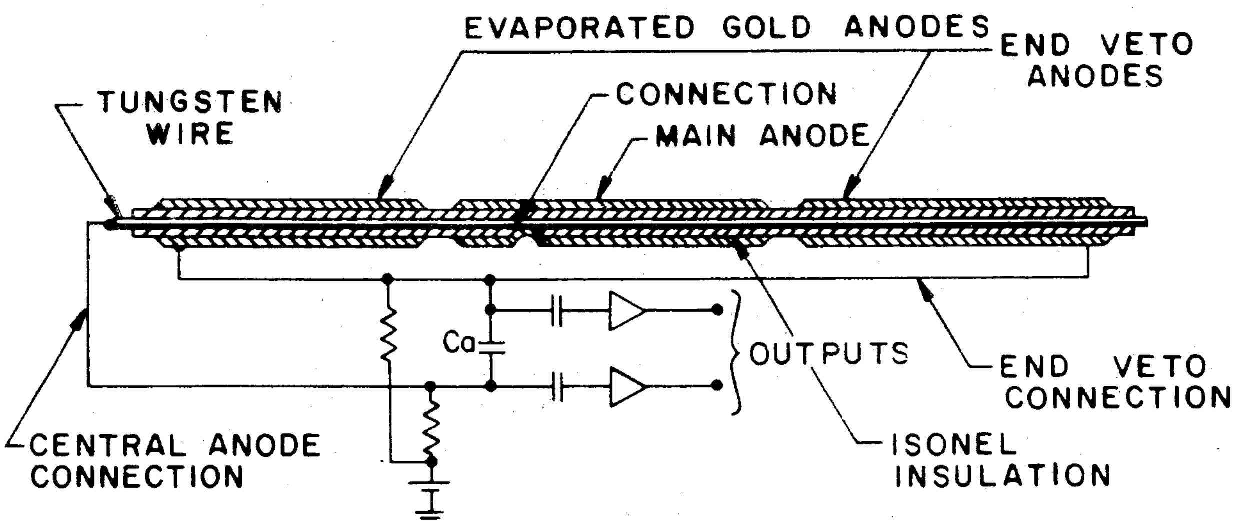
Photon induced

- Forward Compton scattering of gamma rays in the gas can deposit 0.1 to 10 keV of energy.
- X- or gamma-rays created by cosmic ray interactions in the counter walls.
- Fluorescent X-rays may be produced in the mechanical collimator, detector housing, or other structure with a large view factor to the counter entrance window.

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

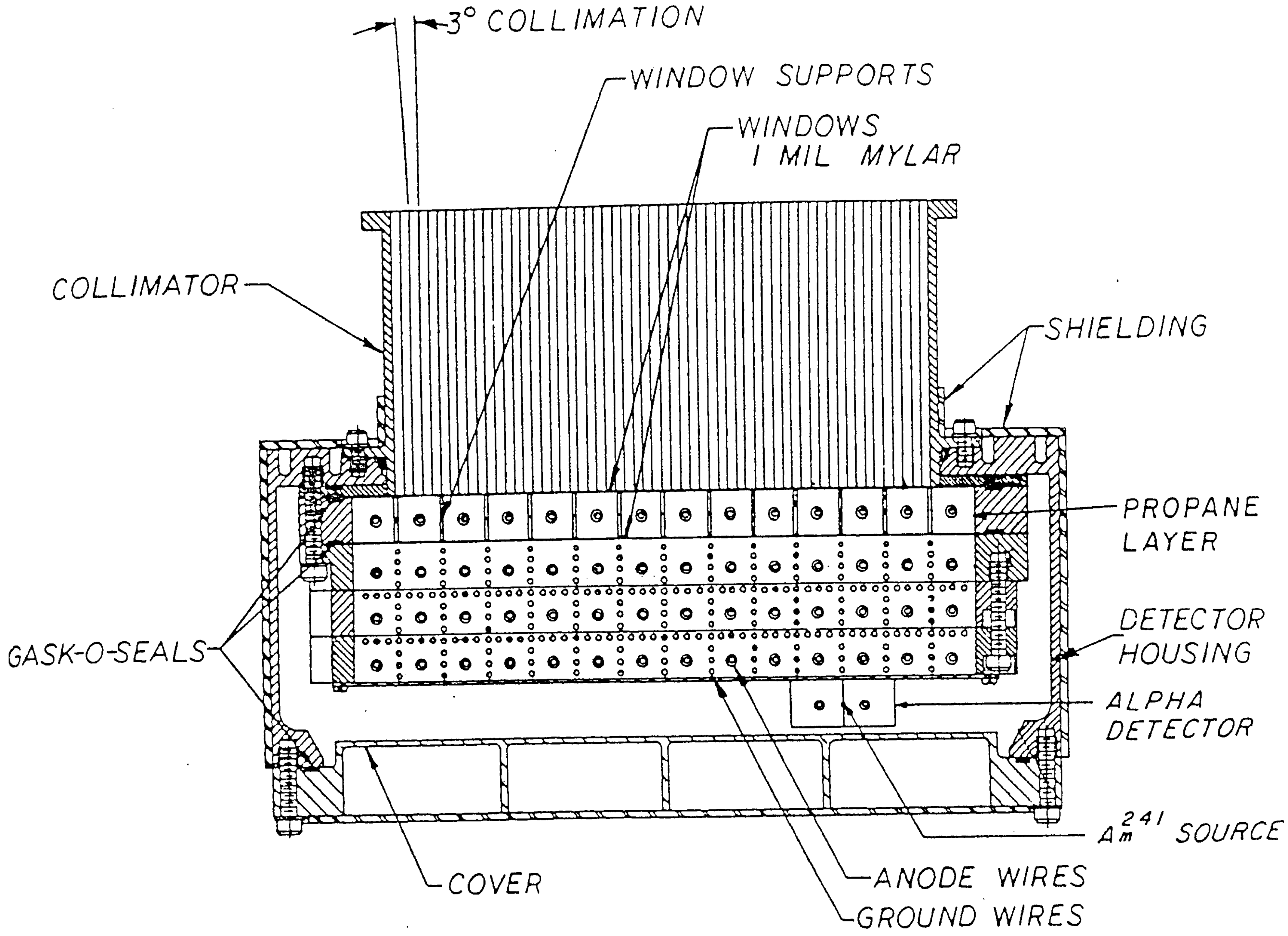


PROPORTIONAL COUNTER

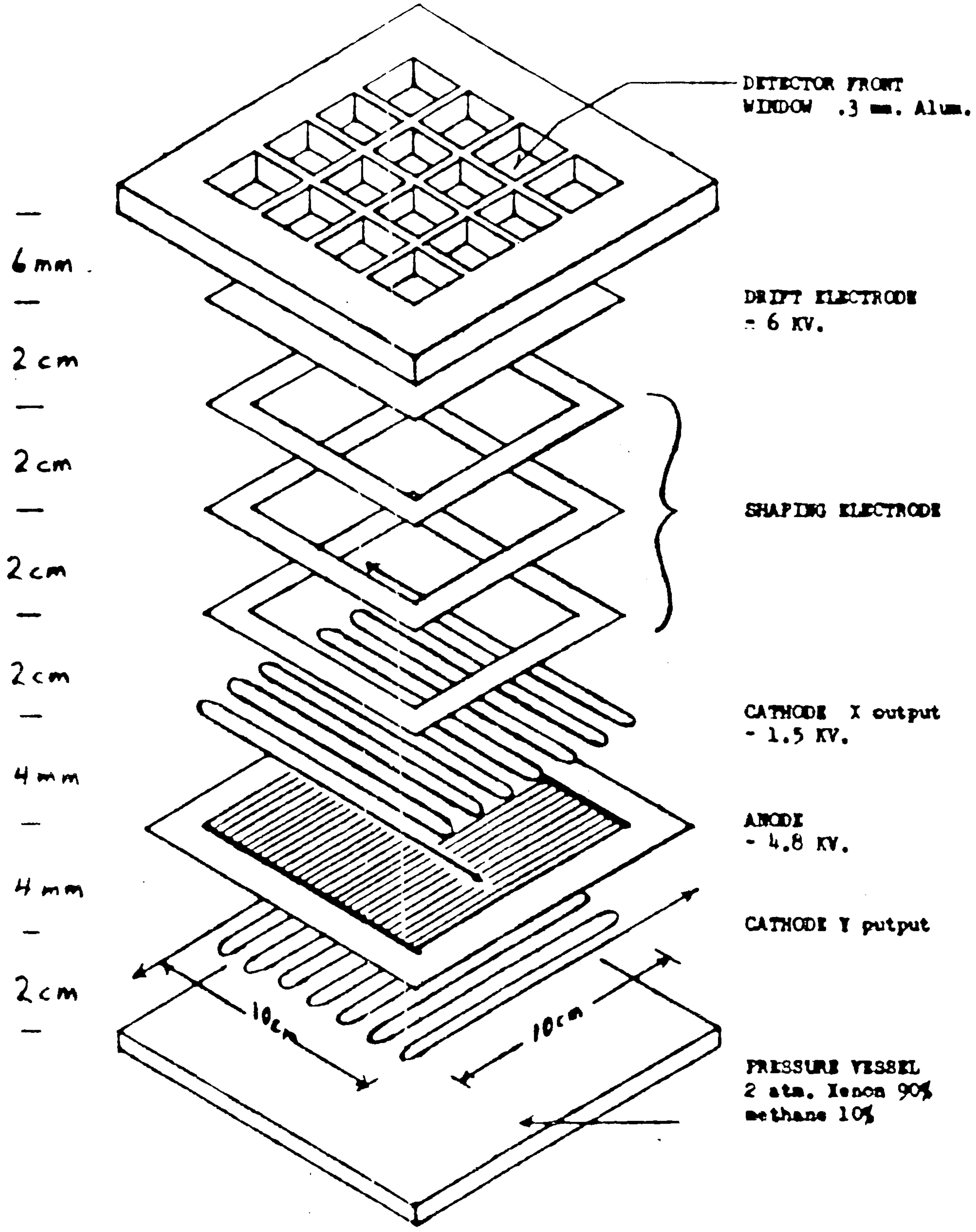


COAXIAL ANODE

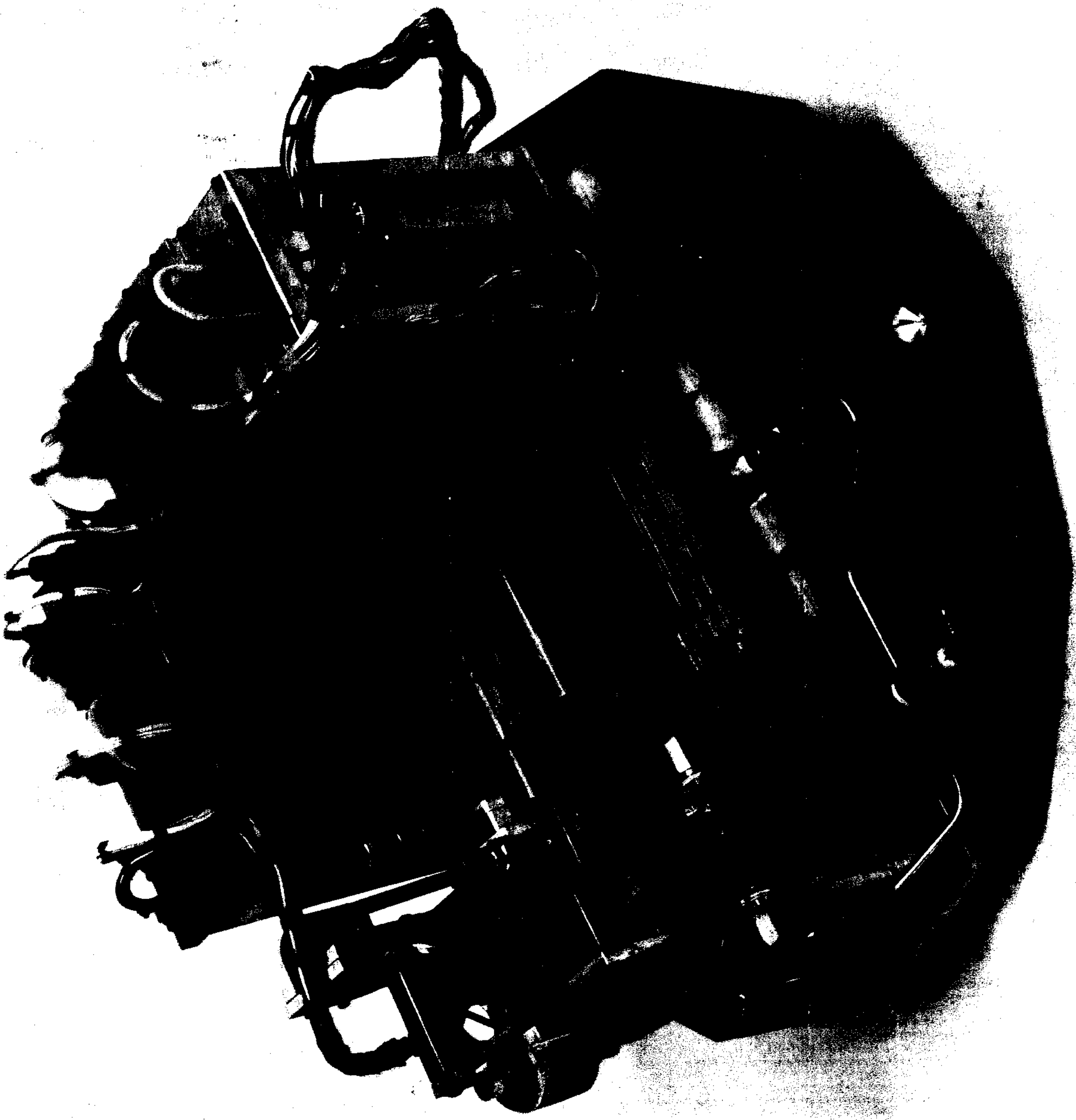
Figure 31

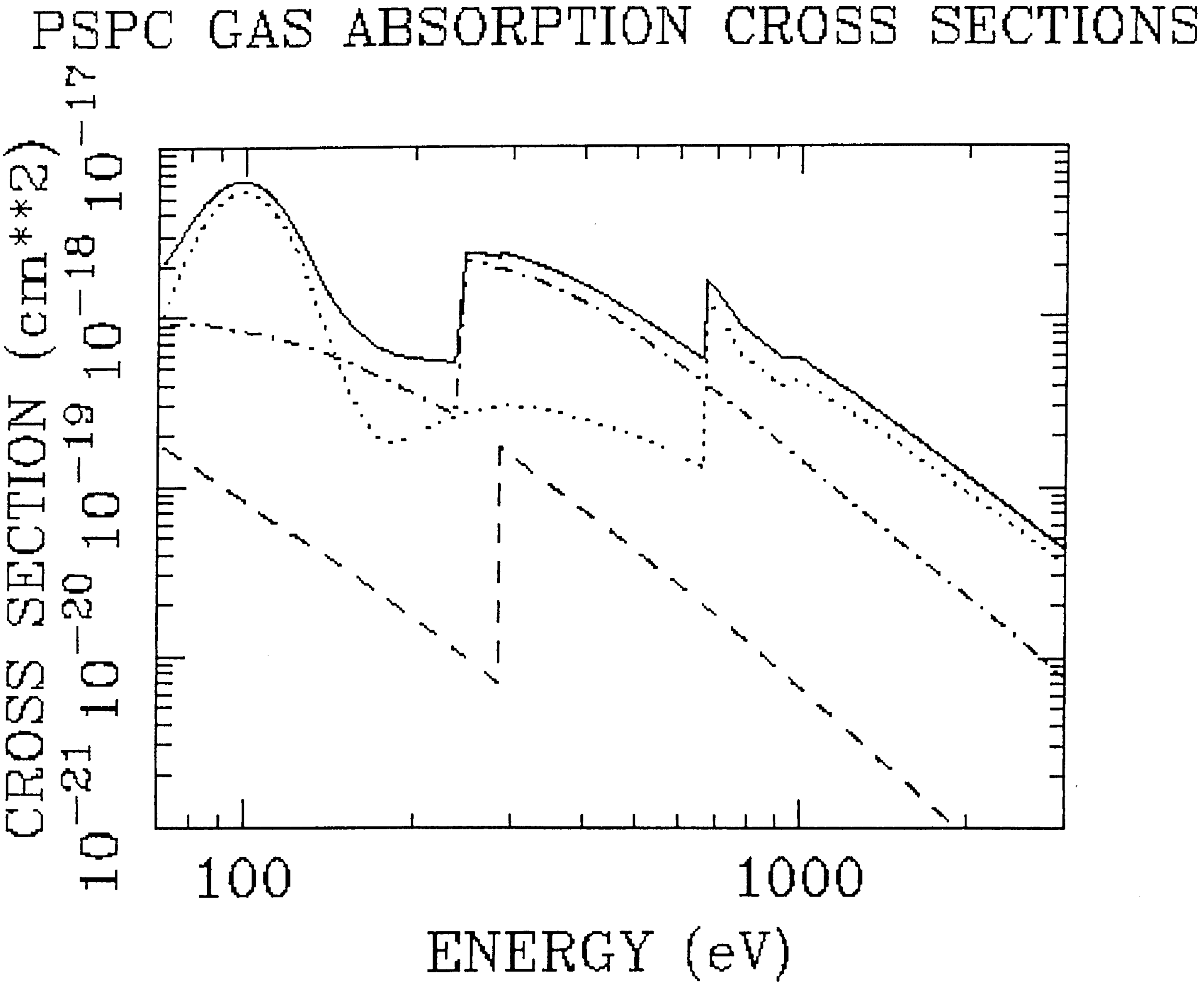

3° COLLIMATION
WINDOW SUPPORTS
WINDOWS
1 MIL MYLAR
COLLIMATOR
SHIELDING
PROPANE
LAYER
GASK-O-SEALS
DETECTOR
HOUSING
ALPHA
DETECTOR
A_m^{241} SOURCE
COVER
ANODE WIRES
GROUND WIRES

EINSTEIN IPC

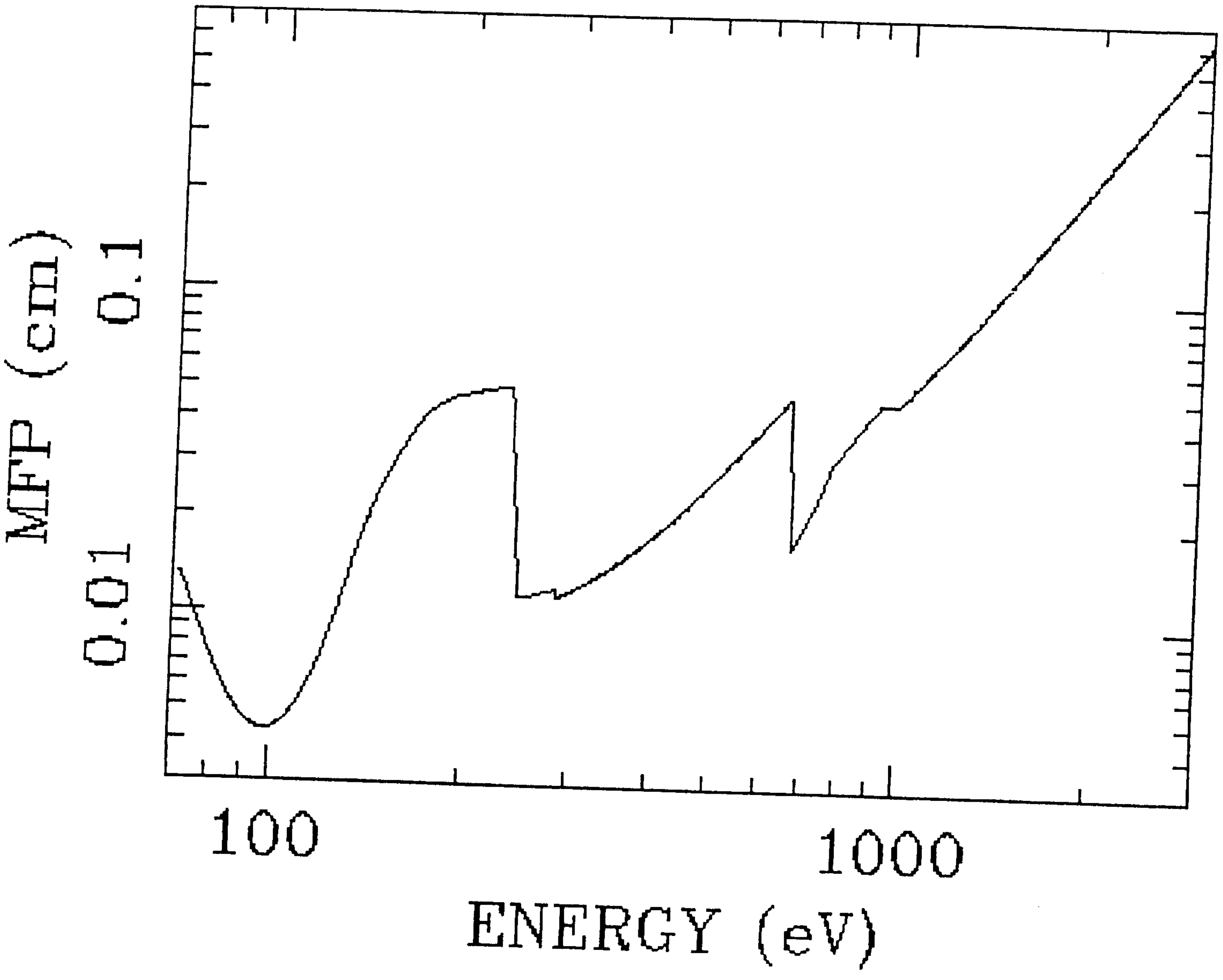


DETECTOR ELECTRODE ASSEMBLY

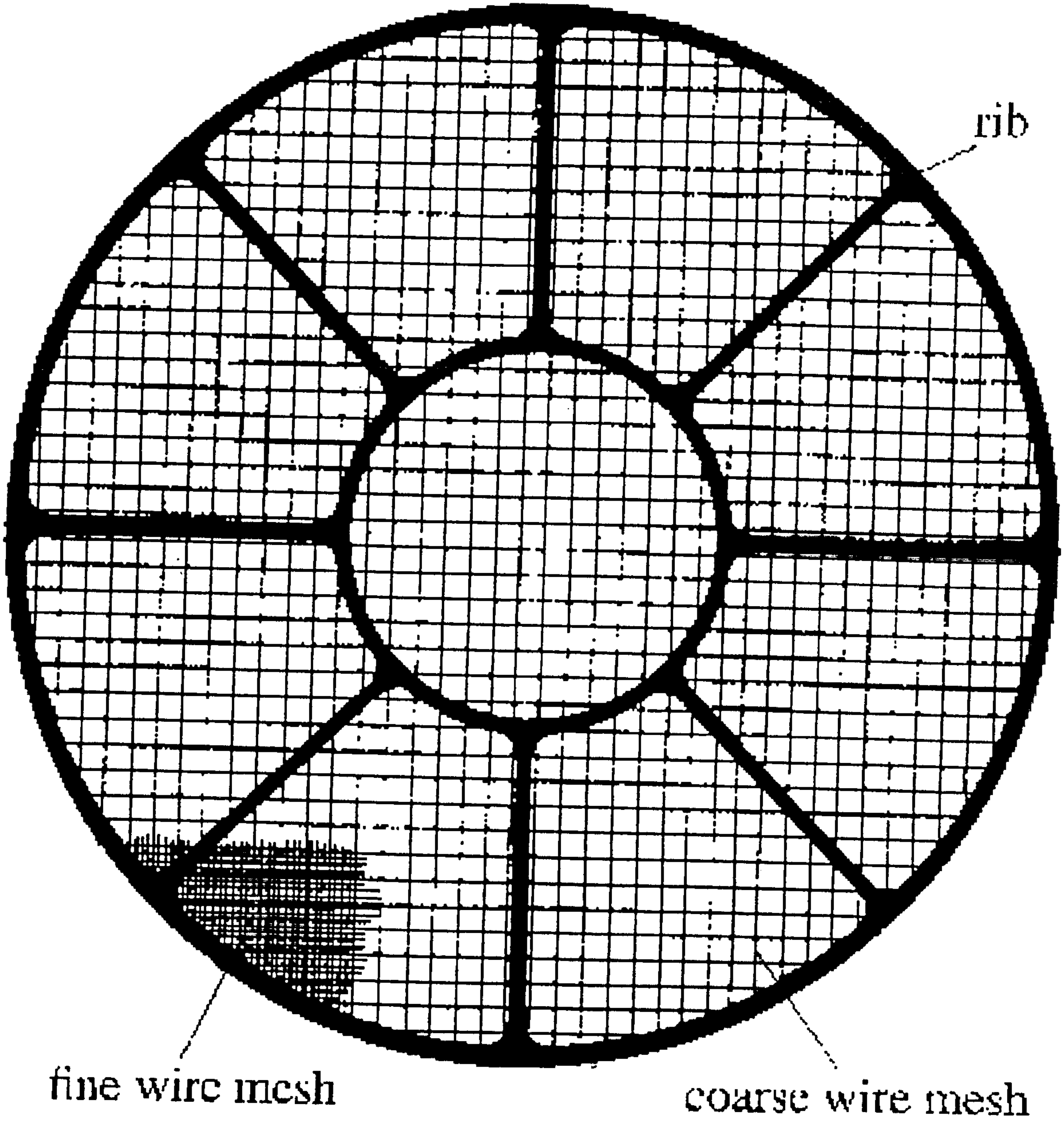



PSPC GAS ABSORPTION CROSS SECTIONS
CROSS SECTION (cm**2)
10^{-21}
10^{-20}
10^{-19}
10^{-18}
10^{-17}
100
1000
ENERGY (eV)

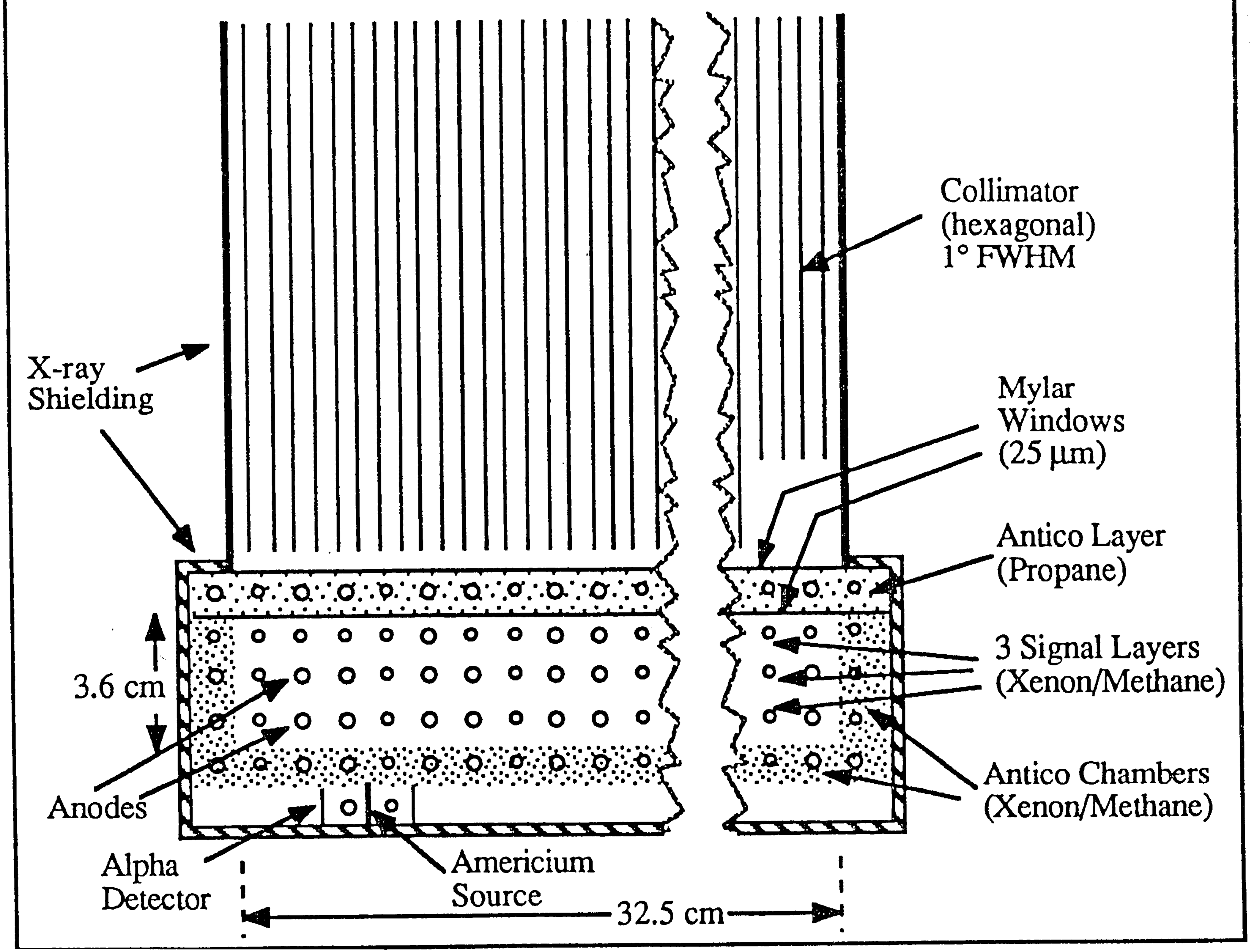
PSPC COUNTER GAS MEAN FREE PATH

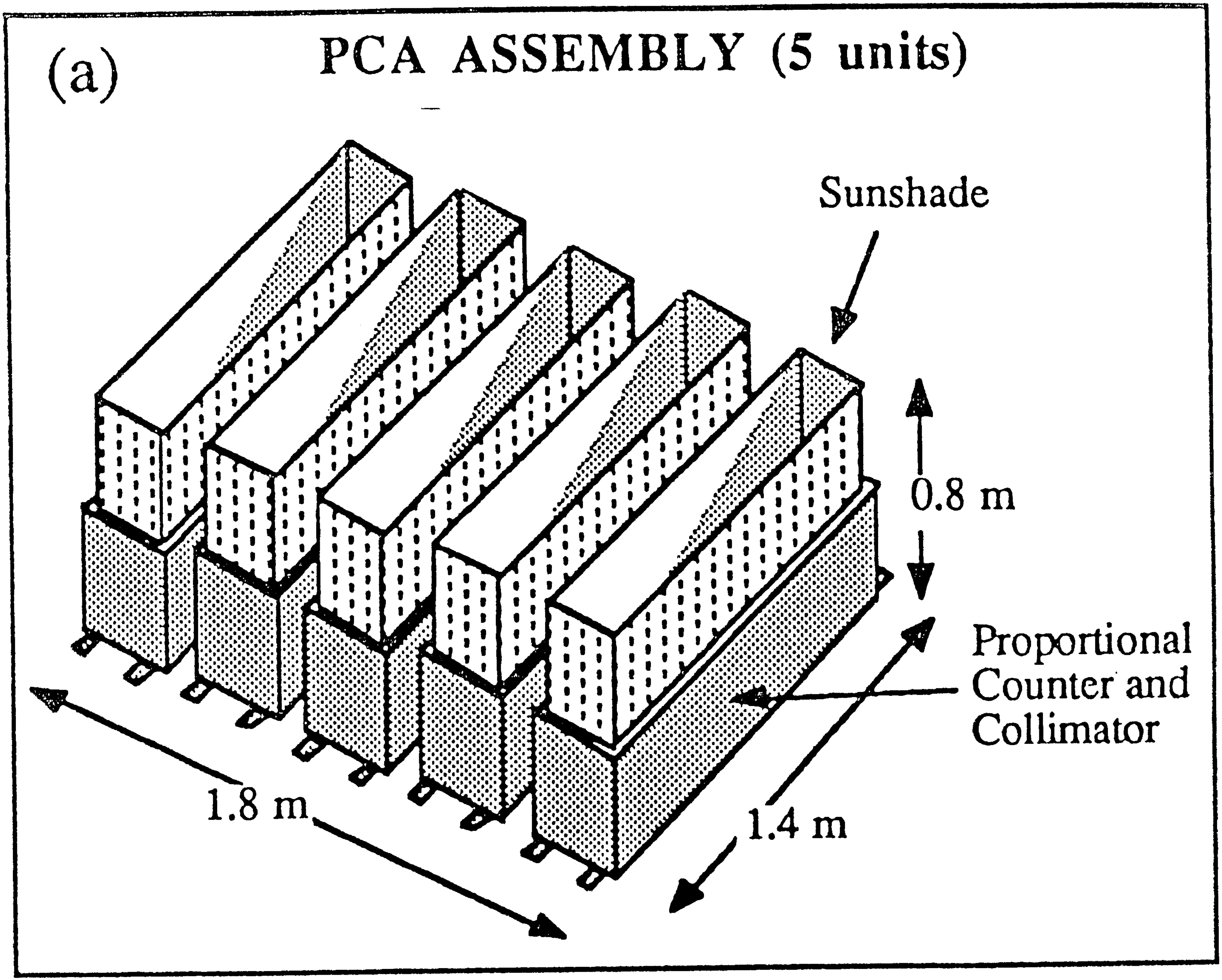


Window Support Structure

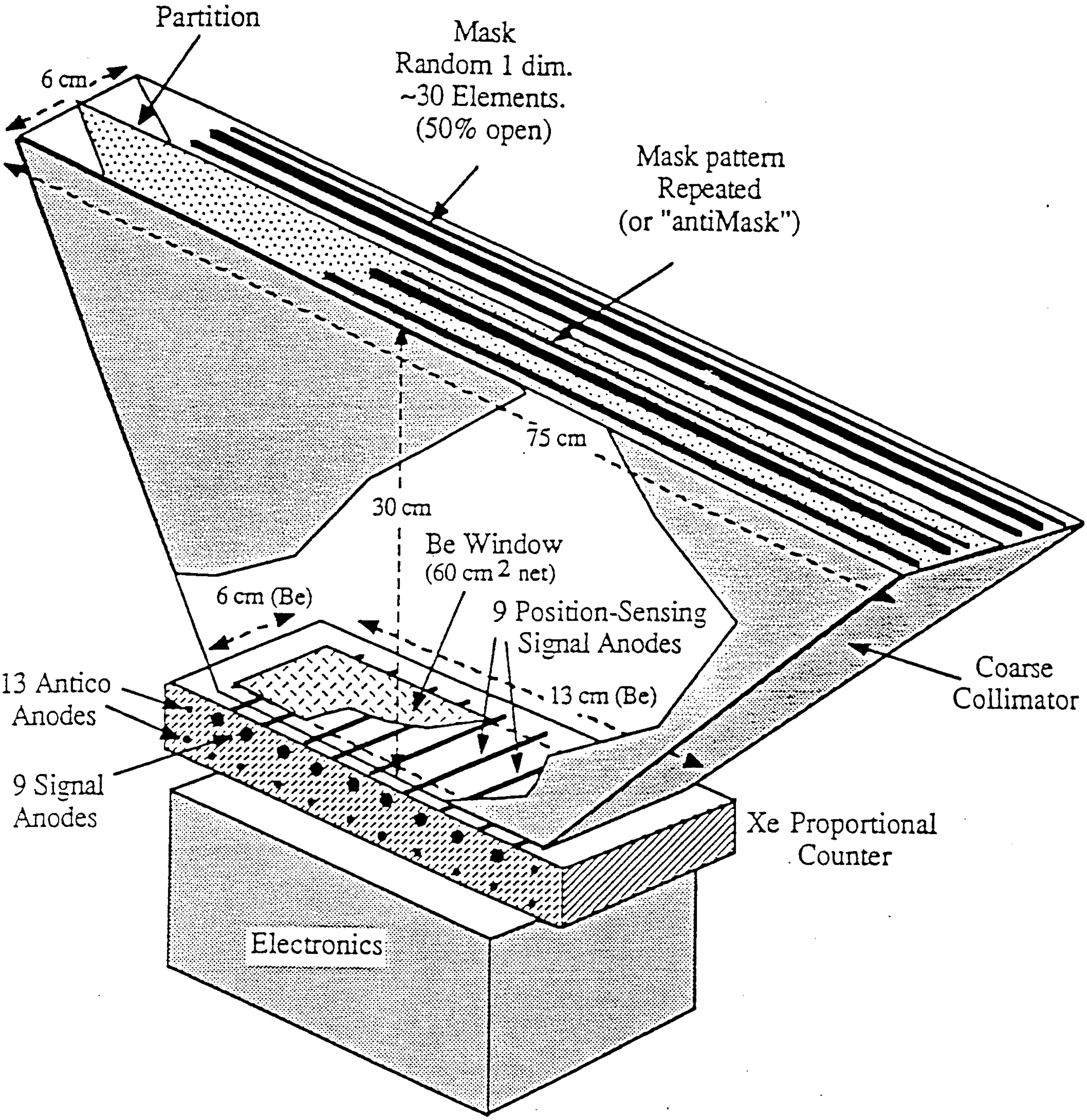


(b) PROPORTIONAL COUNTER (1 unit)




(a)
PCA ASSEMBLY (5 units)
Sunshade
0.8 m
Proportional Counter and Collimator
1.4 m
1.8 m

SHADOW CAMERA (1 of 3)*



*Not to scale; e.g. proportional counter drawn oversize.
Dimensions are approximate.