STUDIES ON INNER BREMSSTRAHLUNG OF ^{113}Sn
and
THE RADIOACTIVITY OF NATURAL ROCKS
with
LITHIUM DRIFTED GERMANIUM DETECTORS

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by
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To

Dr. and Mrs. K.I.Roulston

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ABSTRACT

Lithium drifted germanium detectors have extensively been used for spectroscopic studies of ^{113}Sn as well as some rock samples that contain traces of natural radioactive elements Th, U, and K.

The ground state to ground state transition energy of ^{113}In, due to electron capture decay of ^{113}Sn, was determined by measuring the inner bremsstrahlung end-point energy. This was carried out by inner bremsstrahlung X-ray coincidence experiment, using two Ge(Li) detectors. The relative intensity of the 255 keV gamma ray relative to the 393 keV gamma ray, was found to be $(2.9\pm0.3)\times10^{-2}$. The inner bremsstrahlung end-point energy was determined to be 604 keV, giving a ground state to ground state transition energy of 1026±150 keV.

Solid state detectors were used for the first time to investigate the concentration of "trace elements" (Thorium, Uranium, and Potassium) in surface crystalline Canadian rocks. This spectroscopic method provides a non-destructive means of determining the concentrations, and gives much better accuracy than similar work done using NaI crystals. The concentration of the trace elements was inferred by comparision with standard sources prepared in the Earth Science Department of this University, by mixing known amounts of Th, U, and K. The mean concentrations of these trace elements are presented.

CHAPTER I

Ge(Li) DETECTORS

I.1 INTRODUCTION

Spectroscopic investigations of the nucleus began as early as 1911 and up to today the physicists devoted themselves to the laborious task of gathering data, and the field of nuclear spectroscopy grew rapidly. During the "forties" a tremendous effort was put into the development of better instruments and techniques in order that data of higher quality might be obtained.

Lithium drifted germanium gamma-ray detectors were used extensively in the experiments described in this work. When using germanium detectors for gamma-ray spectroscopy, one is concerned primarily with three parameters: energy resolution, time resolution, and counting rate per channel. These are not completely independent parameters, and it is not possible to optimize all three. Generally, the energy resolution is worse with higher counting rates. On the other hand, time resolution is limited by the spread in time required for sufficient charge collection. The total charge released will depend on the total energy expended in ionization. Hence it will depend on both the gamma-ray energy and the mode of gamma-ray interaction. (See page 8).

The following sections are devoted to a brief discussion of Ge(Li) detectors.

I.2 Ge(Li) SPECTROMETERS

The lithium drift process was first introduced by Pell(1) in order to produce large sensitive volume silicon detectors and was first applied to germanium by Freck and Wakefield(2).

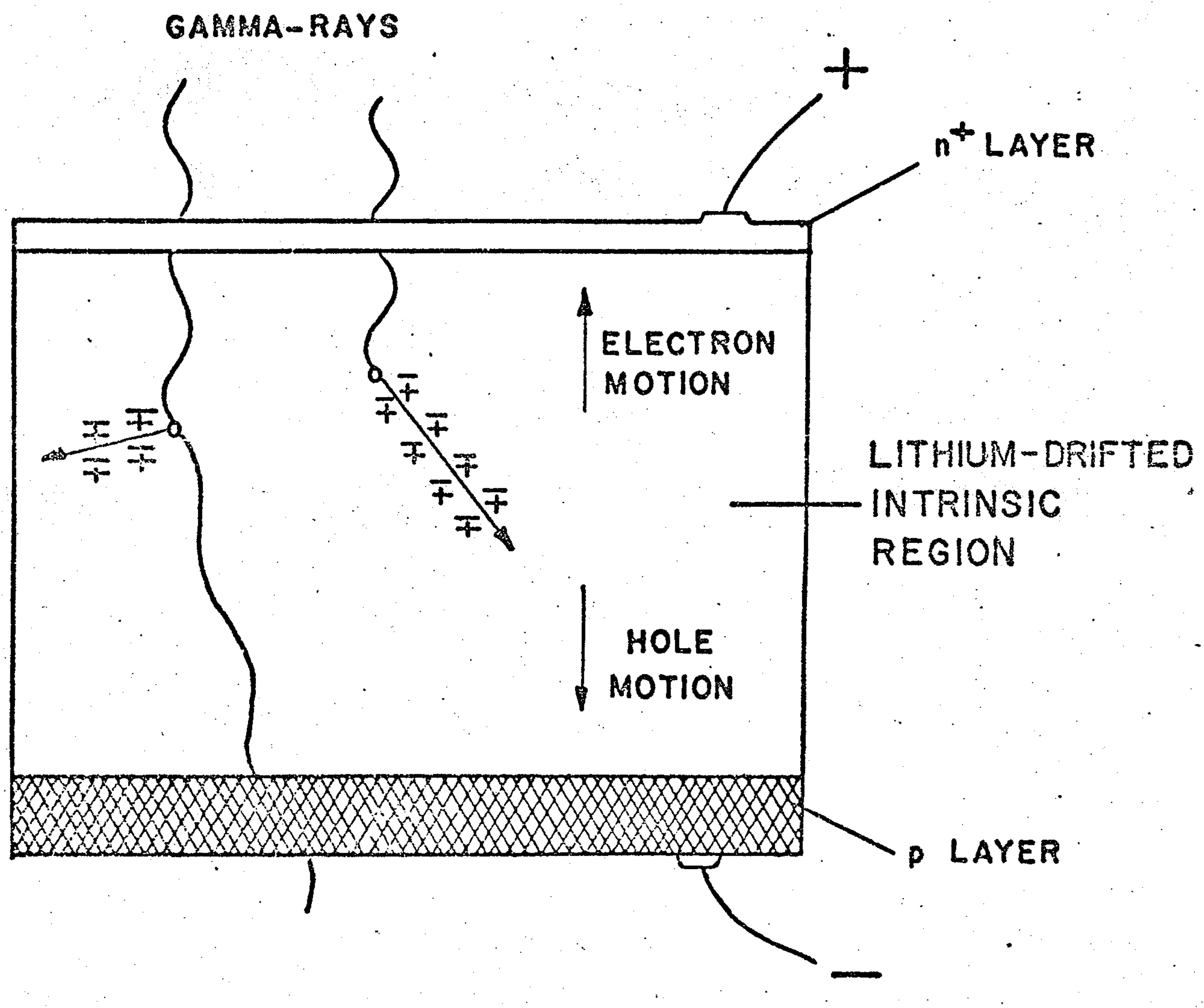
A lithium drifted germanium detector is a solid state ionization device, technically termed a p-i-n structure. (See Fig.I-1). The process consists of evaporating a layer of lithium onto a p-doped germanium crystal and then diffusing it into the crystal to produce an n^+ layer from 100 to 200 μ deep. An electric field is then applied across the p-n junction such that it is reverse biased. The Li^+ ions, which are donors and migrate easily in germanium, are drifted under the influence of this field so that they almost perfectly compensate the acceptors in the p-type material. Thus "intrinsic" layers are produced by compensation and depths of up to 16 mm have been obtained.

At room temperature the leakage current due to thermal agitation of carriers across the band gap (0.67 eV in germanium) prohibits the use of these drifted crystals as spectrometers. Also, at room temperature, the mobility of Li^+ ions is extremely

Figure I-1

Lithium Drifted p-i-n Junction Structure

LITHIUM-DRIFTED p-i-n JUNCTION STRUCTURE



high and unless crystals are cooled, a loss of composition is observed. For these reasons, and the fact that liquid nitrogen is readily obtainable, the detectors are operated at liquid nitrogen temperatures (77^{o}K) where leakage currents of 10^{-10} and 10^{-11} amperes are not uncommon.

Absorption or scattering of gamma-rays within the intrinsic region produces high speed electrons which lose their energy by creating free charge carriers (electron-hole pairs). These carriers are collected by applying a voltage gradient of the order of 50-100 volt/mm across the intrinsic region and integrating and applying the resultant current. The observed charge spectrum consists of a continuum and one or more narrow peaks from which one can infer the energy spectrum of the incident gamma-ray flux. The area under the peak is a function of the detector size, the shape, and the position of the source with respect to the detector, and the incident photon energy. The mode of the interaction between a gamma ray and the atom within the detector are three:

1) PHOTOELECTRIC INTERACTION: The gamma ray interacts with a K-electron ejecting it from the K shell with energy $E_{\gamma} - E_{K}$, where E_{K} is the binding energy of the K-electron. This electron subsequently loses energy by the production of free charge carriers. The X-rays produced by the rearrangement of the orbital electrons filling the K shell vacancy are also absorbed

by the detector, giving a total pulse corresponding to the full energy E_γ. The cross-section for the photoelectric process is proportional to Z^5 and increases rapidly with decreasing photon energy.

2) COMPTON INTERACTION; In this process, the photon is scattered by an electron with a partial energy loss dependent on the angle of scattering. The electron kinetic energy lies between zero and an upper energy limit which depends on the photon energy. The scattering gives rise to a continuous electron-energy distribution between these limits. Cross-section for this process is proportional to the Z of the scattering material.

3) PAIR PRODUCTION: In the vicinity of a nucleus, a gamma-ray energy greater than 1022 keV may produce an electron-positron pair. The electron loses energy by creation of more electron hole pairs. The positron also produces electron hole pairs until it comes to rest, after which it annihilates with another electron producing two 511 keV gamma-rays. If both quanta escape a "double escape" peak is observed with energy (E_γ-1022) keV while if one escapes a "single escape" peak with energy (E_γ-511) keV is observed. Figure I-2 shows the cross-sections of the three processes as a function of energy.

I.3 TYPES OF Ge(Li) DETECTORS

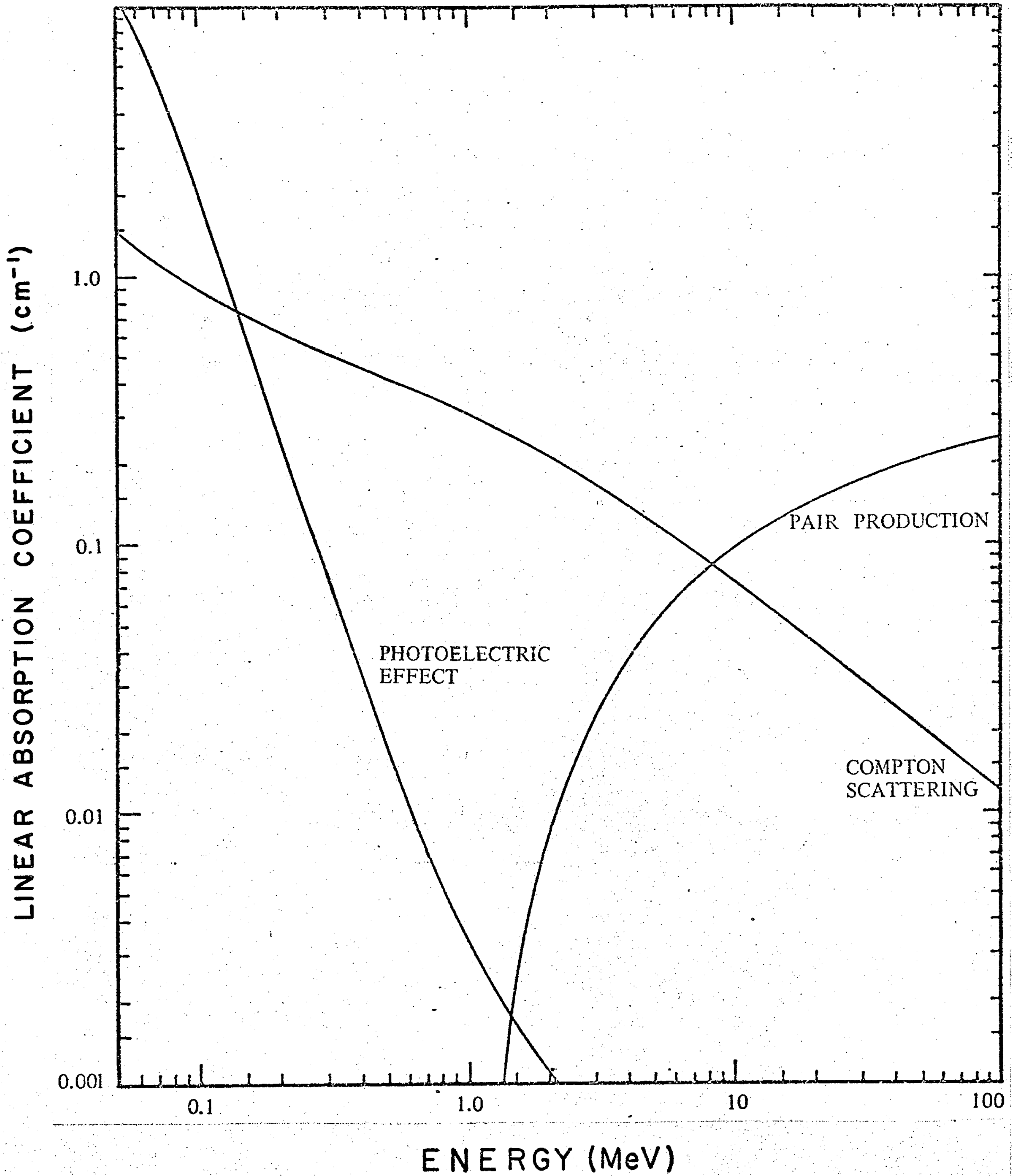
Ge(Li) detectors are of two basic configurations:

Figure I-2

Photoelectric Effect, Compton Scattering

and

Pair Production Cross-Sections in Ge


LINEAR ABSORPTION COEFFICIENT (cm^{-1})
1.0
0.1
0.01
0.001
ENERGY (MeV)
0.1
1.0
10
100
PHOTOELECTRIC EFFECT
PAIR PRODUCTION
COMPTON SCATTERING

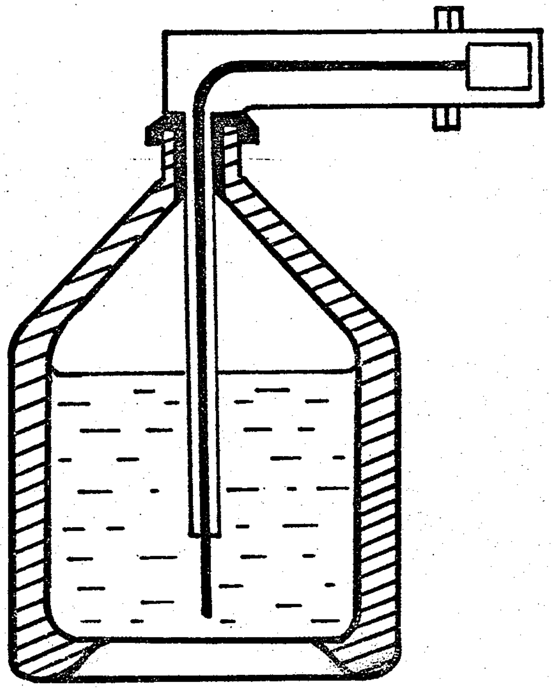
PLANAR for finest energy and timing resolution, and true COAXIAL for increased efficiency with excellent timing properties. The detectors are supplied in any of two cryostat configurations: DIP-STICK type and GRAVITY FEED type. (See Fig. I-3). For the dip-stick type cryostat, cooling is achieved by having a cold finger immersed in liquid nitrogen stored in a large-volume dewar. The vacuum chamber surrounding this cold finger is either straight or with a 90° bend. In the chicken-feeder type cryostat, the detector is mounted on the end of a hollow cold finger which is kept filled by gravity with liquid nitrogen from a reservoir above the vacuum chamber.

As a result of the general limitation to the depletion depth, planar detectors are generally available up to a maximum value of about 15 cc. Cylindrical detectors can be made to about 30 cc, and the closed-ended coaxial detectors are available in volumes up to 40 to 50 cc.

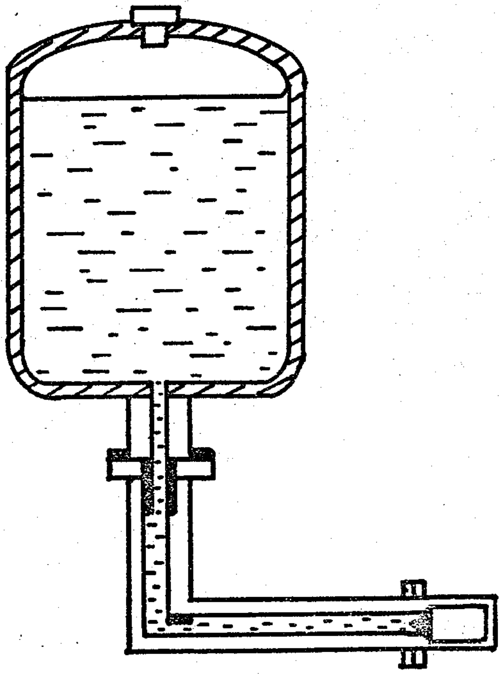
The basic limitation of the energy resolution of a Ge(Li) detector is the statistical fluctuation in the number of ion pairs created for a given energy E. This limit involves the Fano factor. Consider a gamma-ray whose energy E is completely absorbed within the intrinsic region of a Ge(Li) detector.

Figure I-3

Detector Cryostat



Dipstick cryostat (horizontal)



"Chicken-feeder" cryostat (horizontal)

Part of this energy goes into heating the lattice crystal structure. The Fano factor is defined as the ratio of the variance to the yield, as defined below.

The yield is the number of electron-hole pairs produced for a given amount of energy deposition E, while the variance (σ^2) is the mean square variation in the yield. If the average number of electron volts that results in the production of any ion pair in germanium is given by ϵ, then the yield is

$$Y = E/\epsilon$$

and the Fano factor is

$$F = \frac{\sigma^2}{E/\epsilon} \qquad (I,1)$$

To obtain a value for the resolution in keV, (Eq.I.1) is solved for the root mean square variance, σ, and the result converted to electron volts when σ is multiplied by ϵ. This gives

$$\epsilon\,\sigma = \epsilon\sqrt{\frac{FE}{\epsilon}} = \sqrt{\epsilon EF}$$

The full width at half maximum is obtained by multiplying the result by 2.35, (See Appendix I), hence if ϵ is 2.9×10^{-3} keV/ion pair, then ΔE, the F.W.H.M. expressed in keV for radiation of energy E (keV), becomes

$$\Delta E = 2.35\sqrt{0.0029EF} = 0.1286\sqrt{EF}$$ for germanium at $\sim 77^{\circ}$K.

Table I-1 shows the various energy resolutions of the solid state detectors available in this laboratory.

The following is a very brief review of some of the characteristics of planar and coaxial type Ge(Li) detectors.

PLANAR DETECTORS: Planar detectors are right circular cylinders with the lithium diffused along the long axis in a plane parallel to the circular faces, which serves as the entrance window. The lithium drifted (sensitive) region is adjacent to this face and extends over the full area of the detector. These detectors originally have depletion depths of typically 2 or 3 mm, resulting in low photopeak efficiency and large Compton distribution. Since the Compton distribution serves no useful purpose in gamma-ray spectroscopic measurements, it is desirable to reduce it as much as possible relative to the photopeak height. This can be done by increasing the size of depletion region and hence the active volume.

The planar detectors have an n^+ layer whose thickness can be anything from about 100 μ upwards. This dead layer presents serious attenuation problems when dealing

Table I-1

Ge(Li) Detectors

MANUFACTURER	ACTIVE VOLUME	WINDOW	RESOLUTION (Photon Energy).
PRINCETON γ-TECH.	20 cc.	0·020" Al.	5 keV (1333)
ORTEC	35 cc.	0·5 mm. Al.	2·9 keV (1333)
ORTEC X-ray Spec.	0·25 cc.	0·25 mm. Be.	0·430 keV (14·4)

with low-energy gamma rays. In order to remove this dead layer, the lithium can be drifted right through the p-type material and a surface barrier or diffused p^+ layer can be formed at the back surface.

These detector configurations provides superior resolution and the fast, uniform pulse rise time necessary for fast timing experiments.

COAXIAL DETECTORS: True coaxial detectors are right circular cylinders with the lithium doping over the entire cylindrical surface; contacts are provided at both ends. The drifted region extends from the cylindrical surface toward the center of the device. Both this sensitive region and the undrifted "p" type core of the device are symmetric with the surface along the entire length of the detector. This truly coaxial geometry retains the uniform fields and fast, uniform pulse rise times of the planar devices while providing a larger sensitive volume and therefore greater efficiency.

I.4 GAMMA-RAY PEAK SHAPE

The shape of the photoelectric peak in a Ge(Li) detector is roughly Gaussian with a low energy exponential tail(3) due to incomplete charge collection within the detector. Charge collection efficiency can be improved by increasing the detector bias. Another factor which affects the peak shape is the counting rate. In general, high counting