SNO-STR-93-032

A Gd PROPORTIONAL COUNTER SYSTEM FOR USE AS A NEUTRAL CURRENT DETECTOR IN SNO

C. K. Hargrove and Ira Blevis, CRPP, David Paterson, Carleton University, E. Davis Earle, CRL

ABSTRACT

The default method of detecting neutral current (NC) neutrons in the Sudbury Neutrino Observatory (SNO) uses neutron capture on the Cl of dissolved salt by detection of the resulting capture gamma rays. It has been well established that discrete neutron counters would enhance the detection of these neutrons. A discrete counter system using ^{3}He counters has been proposed (Ref 4). In this document we describe an alternative to the ^{3}He discrete counter method based on neutron capture on Gadolinium.

We have designed a system using Gadolinium in proportional counters (PCs) for the detection of the NC neutrons in SNO. Neutrons produced by the NC disintegration of the deuteron are captured in Gd producing 8 Mev of capture gamma rays. Following the neutron capture there is a high probability of producing conversion electrons. One can use the coincidence between these electrons, detected in a PC, and the capture gamma rays, detected by the SNO photomultipliers (PMT), to register the neutron capture event. This coincidence measurement makes the system independent of random noise and backgrounds from the PCs and the PMTs. In a preliminary design we require 830-1 m long by 6 cm diameter counters on a 90 cm lattice. We predict a net neutron detection efficiency of 31% for neutrons in coincidence. The total efficiency for neutron detection is 48% when the non-coincident neutron captures are included. The photon losses for the charged current photons are 20%. The estimated cost for production of the required PCs is about 1 million dollars.

I INTRODUCTION

Discrete counters for the detection of NC neutrons have fundamental advantages:

- NC and Charged Current (CC) events are distinguished event by event and recorded separately giving a significant statistical and systematic advantage.
- The effective CC rates are doubled and the NC rates quadrupled in comparison with the dissolved salt method.
- Time variations in the neutrino flux could be followed simultaneously in the NC and CC channels on a time scale of milliseconds to years.
- All signals and backgrounds can be determined at the same time, and there is no need to compare and subtract data taken at different times and under different conditions.
- The duty factor for full efficiency NC detection rises from 50% to 100% and the possibility of missing NC data from a supernova or other interesting events is correspondingly diminished.

Gadolinium has a number of properties that make it an interesting element for use as a neutral current detector in SNO (Ref 2 & 3). For this discussion the important properties are:

- The cross section for natural Gd is 49000 b which corresponds to a mean free path of 6.75 microns in the Gd metal.
- The de-excitation of Gd nuclei after neutron capture is primarily via their first excited states.
- These states have high electron conversion coefficients. Thus electrons with energies up to about 90 keV are produced with high probability following neutron capture.
- The Cherenkov light from conversion of the gamma rays is easily detected by the SNO PMT's.

These properties combine in the following way to make Gd useful in detecting the NC neutrons in SNO.

- The large neutron capture cross section makes the neutron capture fraction high for the neutrons produced in SNO with only a small amount of material.
- The high electron conversion coefficient of the first excited state combined with the large fraction of neutron captures going through this state makes it possible to detect a large fraction of the neutron captures through the detection of the conversion electrons in relatively simple PCs.
- The coincidence between the counters and the SNO photomultipliers makes it possible to eliminate the background from random noise and radioactivity in the materials of the counters.
- The small amount of materials required in the counters makes it possible to reduce the neutron background in the D_20 caused by high energy gamma rays originating in the counter material to acceptable levels.

II MONTE CARLO DETERMINATION OF NEUTRON CAPTURE EFFICIENCY

A Monte Carlo (MC) program (ref 1) was written to determine the amount and distribution of additives to the D_2O of SNO needed to capture a significant number of the neutrons. The neutron capture efficiency as a function of the mass of ^{157}Gd is shown in Fig 1a and Fig 1b. Fig 1a is for Gd counters taken out to full radius of the D_2O at 600 cm while 1b is for them taken out to a radius of 550 cm. Included in these graphs are the fraction of the Cherenkov photons which would be lost due to the installation of these counters.

It was also determined that the distribution of the counters which optimized the neutron capture for a fixed amount of Gd was a uniform distribution with a maximum outer radius of 550 cm. The neutron capture probability as a function of the outer radius of the distribution for the case of discrete counters is shown in Fig 2. The outer 50 cm make up 27% of the voume of SNO. Therefore omitting this region of the volume reduces the total number of counters by that amount with little loss in the number of neutrons detected.

The calculations shown in Fig 1a and 1b indicate that we can obtain a neutron capture efficiency of > 50% for reasonable geometries with photon losses < 20%.

III NEUTRON CAPTURE DETECTION EFFICIENCY IN A Gd PROPORTIONAL COUNTER

In order to determine the overall efficiency of the method it is necessary to know the probability of observing a conversion electron in a proportional counter following neutron capture in Gd. We have determined this efficiency experimentally. In addition we have simulated the escape of the electrons from a Gd foil using the EGS IV MC program (ref. 5) and compared the calculation with the experiment.

Measurements were carried out in the monoenergetic neutron beam at Chalk River Nuclear Laboratories. The experimental set up is shown in Fig 3. Four foils of nominal thicknesses 0.0008, 0.0016, 0.004, and 0.008 gm/cm2 were measured. The foils were produced at Chalk River Nuclear Laboratories by the method of rolling.

The efficiency for detecting conversion electrons is plotted against the foil thickness in microns in Fig 4. The zero thickness efficiency is about 85%. A 4 micron foil would give a neutron detection efficiency of 64%.

The electron detection efficiency in the PCs was modelled using the EGS IV program as developed for low energies by the IRS section of the NRC, (ref 5). The results are shown as the crosses in Fig 4.

IV THE COINCIDENCE OPTION

The detection of the coincidences between the Gd conversion electrons in the PC and the Cherenkov light produced in SNO by the associated neutron capture gamma rays is the major advantage to this technique. It is possible to operate the NC counters and the PMTs in coincidence with their normal and expected singles rates.

The random coincidence background can be estimated from the expected PMT and PC rates. This simple calculation shows that the coincidence requirements (100nsec, $2m^3$) will essentially remove any random backgrounds and/or most rate related technical problems with the PCs.

R(PMTs)	= 6.3×10^{-3} Hz (200,000 counts per year above 3 MeV)
R(PCs)	= 100 Hz
Resolving Time	= 1×10^{-7} Sec.
Spatial resolution	= 2 m^3
Random rate	= .01/day
NC rate	= ~3/day

In Fig. 5 the top curve is a Monte Carlo calculation of the neutron capture gamma-ray spectrum in coincidence with the PCs. It shows the real advantage of this system. This spectrum and the rate calculated from it are clean and free from non-neutron background above about 4 MeV.

V TH/U BACKGROUNDS AND THE CAPTURE GAMMA RAY EFFICIENCY

The main non-random contribution to the NC background will come from the decays of the high energy beta branches in the Th and U chains which can simulate the Gd capture gamma-ray signals. The SNO response to the ^{208}Tl (total energy, gamma plus beta, is 5 MeV) beta decay spectrum and the Gd capture gamma-ray spectrum were modelled by MC and the efficiency for separating the Th produced background and the neutron produced Gd signal were examined.

Fig. 5 shows the reconstructed energy distribution for both the Th background and the Gd signal after one year of running assuming 0.1 micrograms of Th total in the Gd foils (about 2×10^{-11} gm Th/gm Gd) and 25% efficiency for detecting the neutrons in the PCs. Fig. 6 shows the integral spectra for the same two cases. Fig. 7 shows the effect of increasing the Th content by an order of magnitude. The result is that the threshold has to be raised to from 3.0 MeV to about 3.7 MeV and the neutron count is decreased from 900 to about 650 neutrons per year. This requires further purification of the Gadolinium which has a Th contamination currently measured at 4×10^{-9}.

Another non-random background comes from photodisintegration of the deuterons by high energy gammas originating in the Th impurities. 0.1 microgram of Th would produce ~10/day of the 2.6 MeV gamma rays (from ^{208}Pb) which would be stopped in the D_2O. This would result in .02 neutrons per day in SNO which can be neglected. Also the alpha spectrum is not a problem because the alphas have no high energy beta or gammas in coincidence with them.

VI THE PROPORTIONAL COUNTER DESIGN

The proposed design would use alternating layers of Gd foil cathodes and anode wire planes. A number of foils can thus be placed in a single tube, increasing the effective surface area of Gd. A cross sectional drawing of such a counter is shown in Fig 8a and the effective foil width as a function of counter diameter is shown in Fig 8b.

A prototype counter with 6 micron aluminum coated mylar foils as cathodes instead of the Gd foils has been constructed and used for preliminary tests. A drawing of this counter is shown in Fig 9. The counter was tested in the neutron beam at AECL with a small 5 micron Gd test foil placed on one of the cathodes. An efficiency of > 50% was measured. This is the result expected from the PC measurements described above. Further, a 55Fe source spectrum was recorded on a Pulse Height analyzer and is shown in Fig 10. The counter used Ar(90%)/CH4(10%) and was operated at 1200 V. It worked reliably during a 1 week test under these conditions. The specifications of a counter for SNO are given in Table I.

TABLE I

COUNTER PARAMETERS

Lattice spacing	90 cm
Counter system outer radius	550 cm
Tube diameter	6.0 cm
Counter body	Acrylic
Foils per counter	6
Counter length	1 m
Total length/no. of counters	830 m
Photon losses	19 %
Natural Gadolinium mass	6763 grams
Foil thickness	4 microns
Foil area	214 mxm
foil width (effective)	24 cm
HV	1200 V
Pressure	1 Atm.
Gas (continuous flow)	Ar (90)/CH4 (10) (P10)
Threshold	0.5 keV (40 electrons)
Preamps	1/counter
Discriminator	1/counter
Register	1 bit/counter
Coincidence system	.1 microsec. resolving time

VII THE TOTAL NEUTRON EFFICIENCY

There are three processes which lead to neutron signals in SNO if one uses the Gd PCs. These are: the coincidence between the PCs and the PMTs, the Gd capture gamma rays which are not registered in the PCs and the deuterium capture gamma rays. The efficiency for detection of these three processes is estimated in Table II.

TABLE II

NEUTRON DETECTION EFFICIENCY IN SNO

Neutron capture (Gd)	.54
Neutron capture (D2)	.14
PC Gd conversion electron efficiency	.64
PMT efficiency, (Gd Capture gamma rays coincident)	.90
PMT efficiency, (Gd Capture gamma rays non-coincident)	.50*
PMT efficiency, (D2 Capture Gamma)	.50*
Total Gd detection efficiency (coincident)	.31
Total Gd detection efficiency (non-coincident)	.10
Total D2 detection efficiency	.07
Total neutron detection efficiency	.48

* These numbers are only rough estimates

The coincidence efficiency (31%) will have the best statistical accuracy and the minimum background. The overall efficiency of 48% is very high but will require considerable analysis to be useful.

VIII COST ESTIMATE

A cost estimate for the construction of 700 counters similar to the test counters was made. Total materials are \$316K and labour is \$659K. The total cost is therefore about \$1.0M. To this must be added the cost of the Gd foil construction, the electronics and the HV and gas handling systems and the mechanical mounting and installation systems. No estimate has been made of these costs for this document.

IX CONCLUSIONS

The use of Gd as a neutron converter in a PC system for SNO has been shown to be an interesting technique for a NC detector for SNO. It has the following properties:

1. The coincidence capability is the biggest advantage. An acceptable event requires both a PC signal and the SNO PMT signal. Therefore the neutron detection efficiency and rate are insensitive to the random singles rates or their fluctuations in either detector.

2. The coincidence allows one to select out the Gd capture gamma ray spectrum well below the background wall in SNO at 5 MeV thereby increasing the overall efficiency. It also allows one to measure and monitor the Gd capture gamma ray spectrum on line in real time and use this calibration to measure the non-coincident gamma-ray spectrum.

3. The counter materials are mainly acrylic. This material is easy to work with and is known to be free of Th/U radioactive contaminants.

4. The counter construction is relatively simple being multiwire proportional chambers which are standard items of construction in our shops and in most high energy physics laboratories.

5. The counters are operated at atmospheric pressure with relatively low voltage (1200 V) and standard counter gas. The gas will be flowed continuously guaranteeing that the conditions in the counters will not be deteriorated by gas contamination over long periods.

6. The electronics is simple requiring only a preamplifier and discriminator. It is quite possible that these components could be installed on the deck giving easy access to them for service and repair.

7. A relatively small number of counters is required: about 830-1m long.

8. The amount of neutron capture material can be kept small : 6.8kg.

9. The cost is relatively low.

ACKNOWLEDGEMENTS

We wish to thank E. Bonvin for his careful reading of this document and support of the project. Art McDonald provided funds which have allowed us to make some of the measurements. Also we wish to express our appreciation for the help of Don Tennant in the running of the Gd efficiency measurements and Peter Dimtrenko for the manufacture of the foils. Peter Skensved ran the MC simulation of the $^{208}Tl \rightarrow ^{208}Pb$ background and Gd capture gamma ray response in SNO.

Figure captions

Fig 1 a) The efficiency of neutron capture in SNO for Gd counters with a maximum outer radius of 600 cm. The upper curve in each figure is for the case of Gd dissolved in the D2O. The lower curves show the results for strips of widths: 0.5, 1.0, 5.0, 10.0, and 15.0 cm on lattices of: 50, 75, and 100 cm. Lines of constant lattice spacing are drawn as solid lines while lines of constant strip width are drawn as dotted lines. The corresponding photon losses are plotted at the bottom.

b) The same for an outer radius of 550 cm.

Fig 2 The efficiency for fixed masses of Gd as a function of the outer radius of the Gd.

Fig 3 The experimental set up for the conversion electron efficiency measurement. Two PCs containing the Gd foil samples to be measured were placed in a monoenergetic thermal neutron beam. The difference between the counts in a downstream ^{3}He monitor counter with the foil in and with the foil out gave a measure of the number of neutrons absorbed by the foil. The number of counts recorded with the foil in the counter minus the no foil background counts in the PC gave the number of captured neutrons that produced a detectable conversion electron. The ratio of the PC neutron counts to the difference in the ^{3}He counter gives the PC efficiency.

Fig 4 Gives typical results of the measurement of the efficiency for detecting conversion electrons produced in the Gd foils in a PC. The crosses in Fig 4 are the results of a calculation using the EGS Monte Carlo program. The calculation was carried out for 1, 2, and 5 micron foil thicknesses.

Fig 5 MC simulation of the differential spectrum of Gd capture gamma rays for one year of running in SNO assuming 25% efficiency for detecting neutron capture in Gd PCs and the Th background spectrum for 0.1 microgram of Th contamination in the Gd.

Fig 6 MC simulation of the integral spectrum of Gd capture gamma rays for one year of running in SNO and the Th background spectrum for 0.1 microgram of Th contamination in the Gd.

Fig 7 MC simulation of the integral spectrum of Gd capture gamma rays for one year of running in SNO and the Th background spectrum for 1.0 microgram of Th contamination in the Gd.

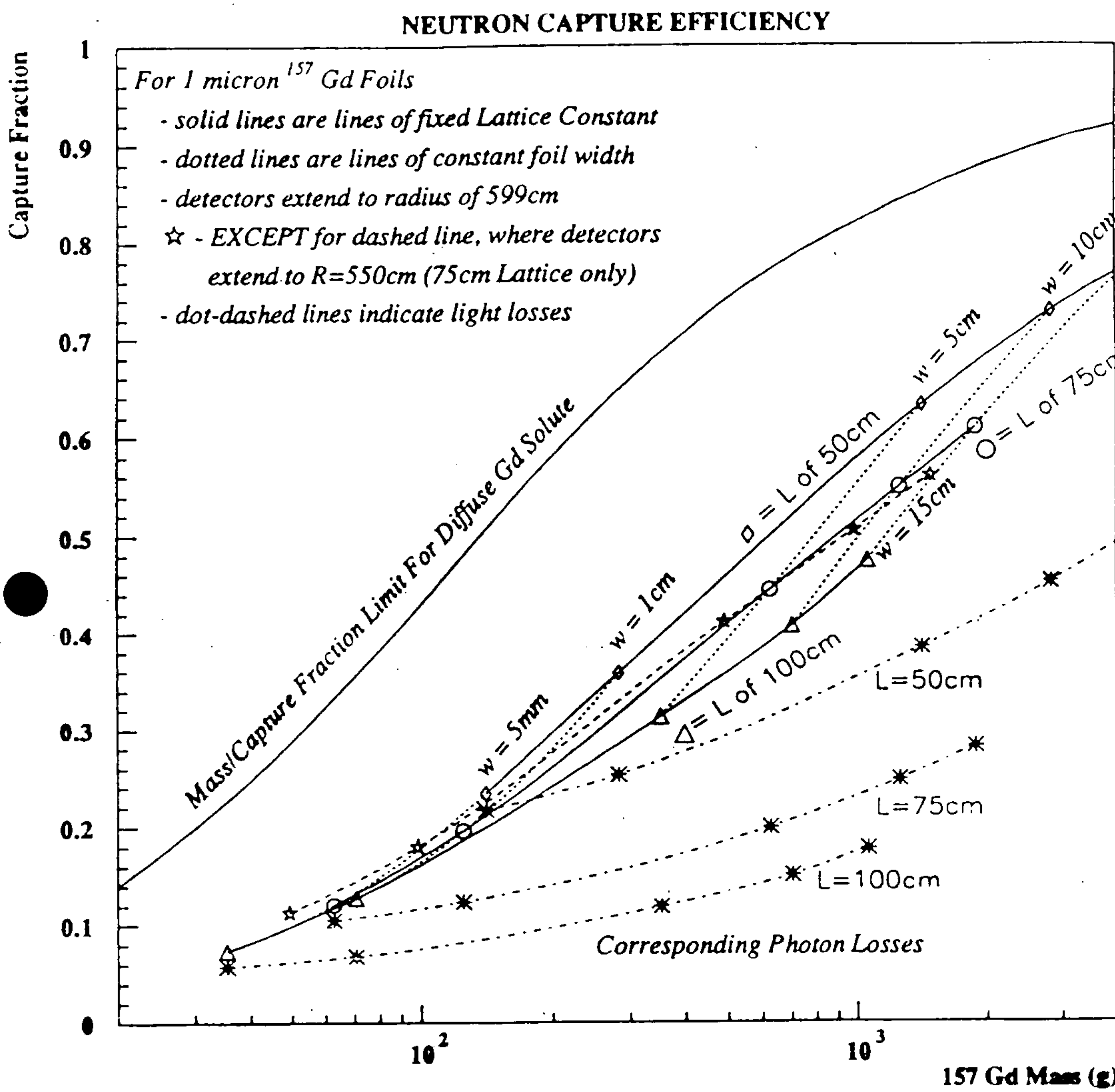
Fig 8 a) Cross sectional drawing of a possible Gd neutral current PC.
b) Width of foil vs counter radius

Fig 9 Line drawing of the prototype counter

Fig 10 55Fe Spectrum in the prototype counter

REFERENCES

1. C. K. Hargrove and D. J. Paterson, Can J Phys. 69,1309(1991)
2. Greenwood et al Nucl. Phys. A304,327(1978).
3. A. Backlin et al Nucl. Phys. A380, 189(1982).
4. T. J. Bowles et al., LASL # FIN-94-ER-E324
5. Private Communication D. Rogers, IRS section of NRC, Ottawa



NEUTRON CAPTURE EFFICIENCY
Capture Fraction
For 1 micron 157 Gd Foils
- solid lines are lines of fixed Lattice Constant
- dotted lines are lines of constant foil width
- detectors extend to radius of 599cm
☆ - EXCEPT for dashed line, where detectors extend to R=550cm (75cm Lattice only)
- dot-dashed lines indicate light losses
Mass/Capture Fraction Limit For Diffuse Gd Solute
w = 5mm
w = 1cm
w = 5cm
w = 10cm
w = 15cm
◇ = L of 50cm
○ = L of 75cm
△ = L of 100cm
L=50cm
L=75cm
L=100cm
Corresponding Photon Losses
157 Gd Mass (g)

Figure 1a

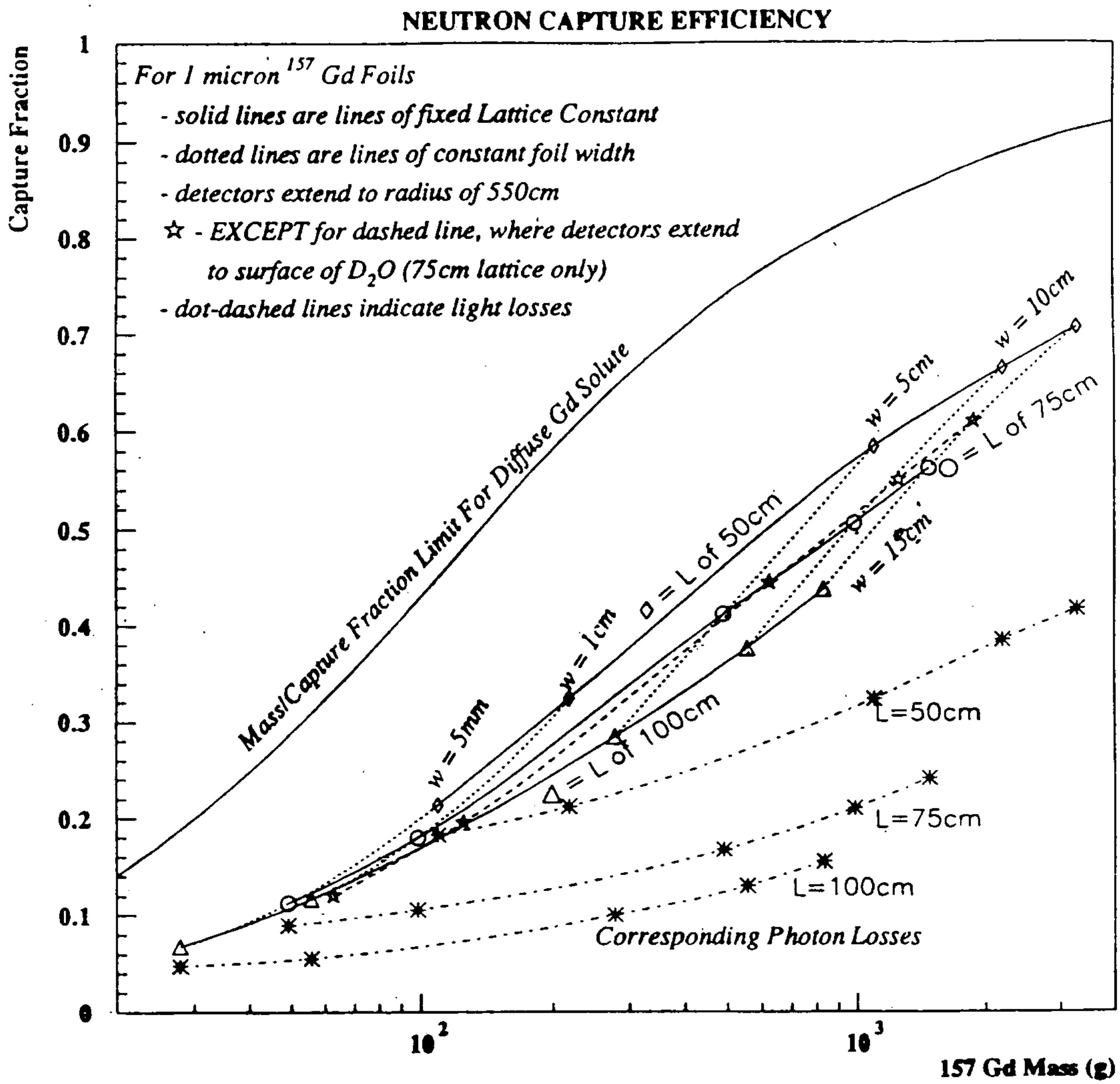

NEUTRON CAPTURE EFFICIENCY
Capture Fraction
For 1 micron 157 Gd Foils
- solid lines are lines of fixed Lattice Constant
- dotted lines are lines of constant foil width
- detectors extend to radius of 550cm
☆ - EXCEPT for dashed line, where detectors extend
to surface of D2O (75cm lattice only)
- dot-dashed lines indicate light losses
Mass/Capture Fraction Limit For Diffuse Gd Solute
w = 5mm
w = 1cm
w = 5cm
w = 10cm
w = 15cm
□ = L of 50cm
○ = L of 75cm
△ = L of 100cm
L=50cm
L=75cm
L=100cm
Corresponding Photon Losses
157 Gd Mass (g)

Figure 1b

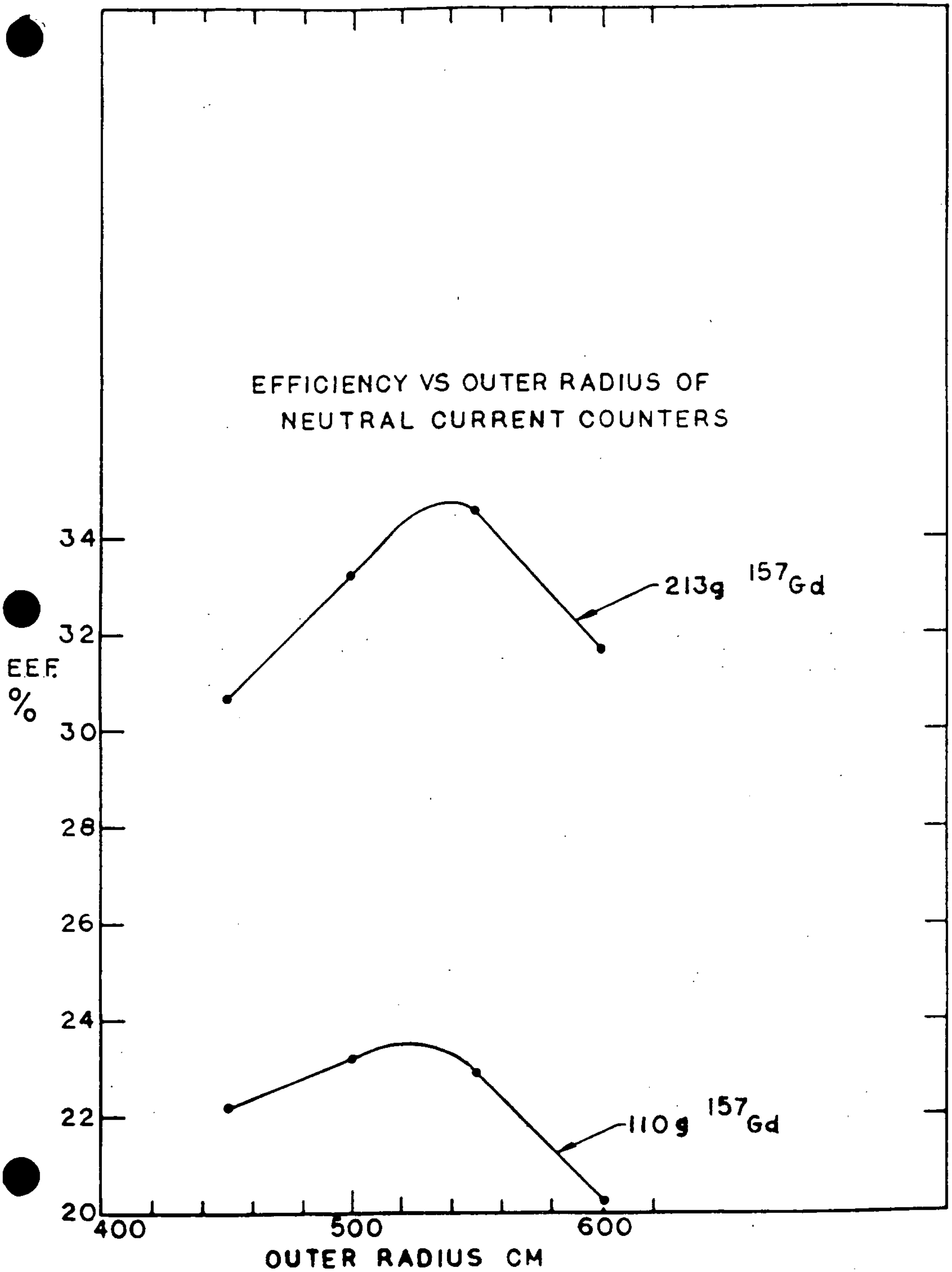
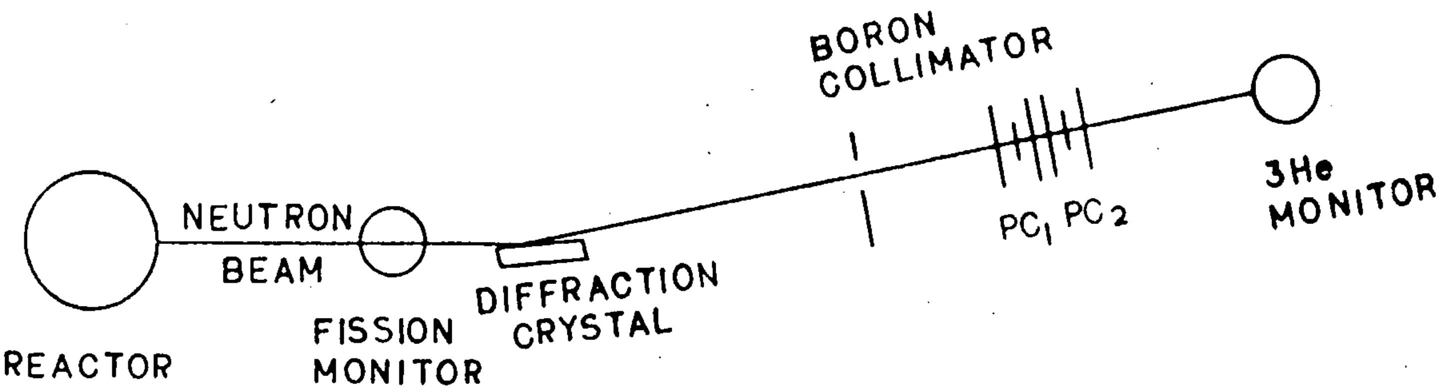
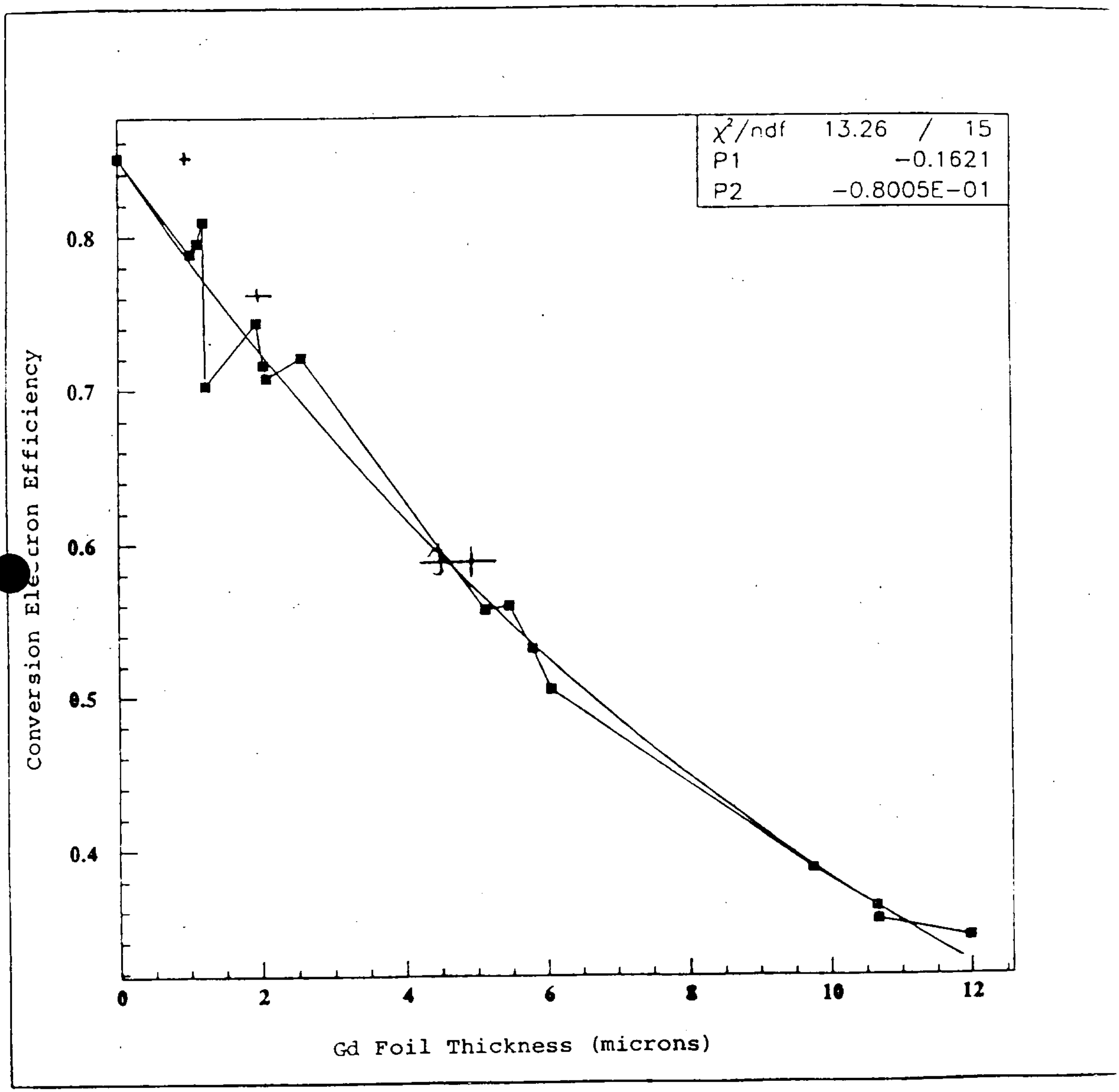

EFFICIENCY VS OUTER RADIUS OF
NEUTRAL CURRENT COUNTERS
213g 157Gd
110g 157Gd
EEF
%
34
32
30
28
26
24
22
20
400
500
600
OUTER RADIUS CM

Figure 2



EXPERIMENTAL SET UP

Figure 3



χ²/ndf 13.26 / 15
P1 -0.1621
P2 -0.8005E-01
Conversion Electron Efficiency
0.8
0.7
0.6
0.5
0.4
0
2
4
6
8
10
12
Gd Foil Thickness (microns)

Figure 4

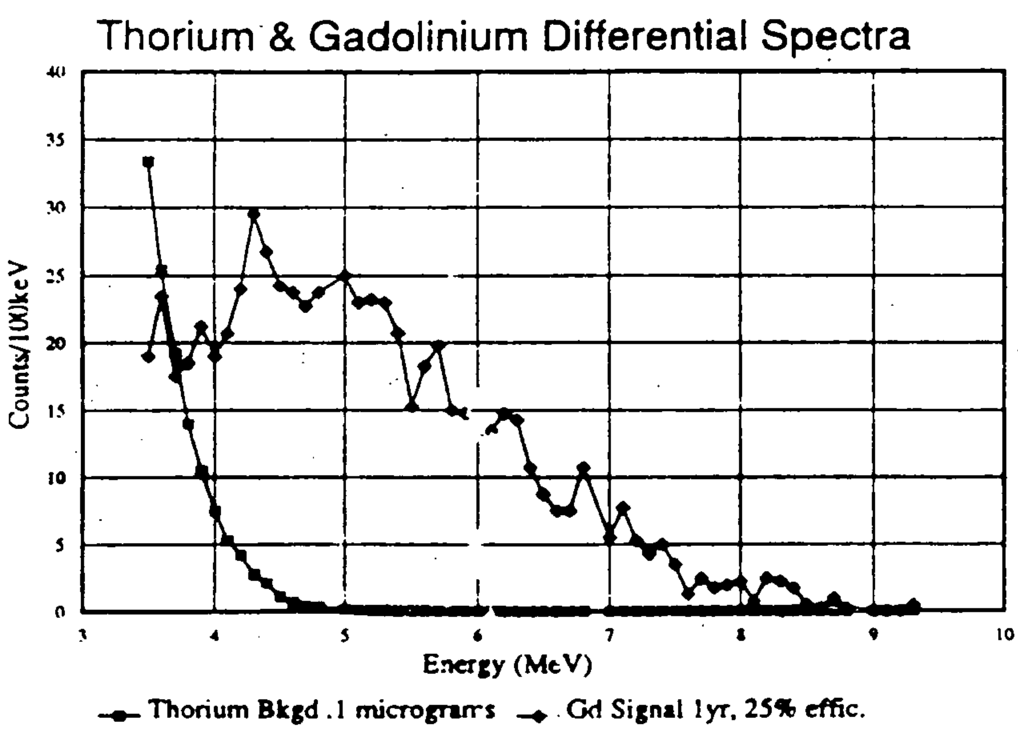

Thorium & Gadolinium Differential Spectra
Counts/100keV
Energy (MeV)
Thorium Bkgd .1 micrograms
Gd Signal 1yr, 25% effic.

Figure 5

Thorium & Gadolinium integral Spectra

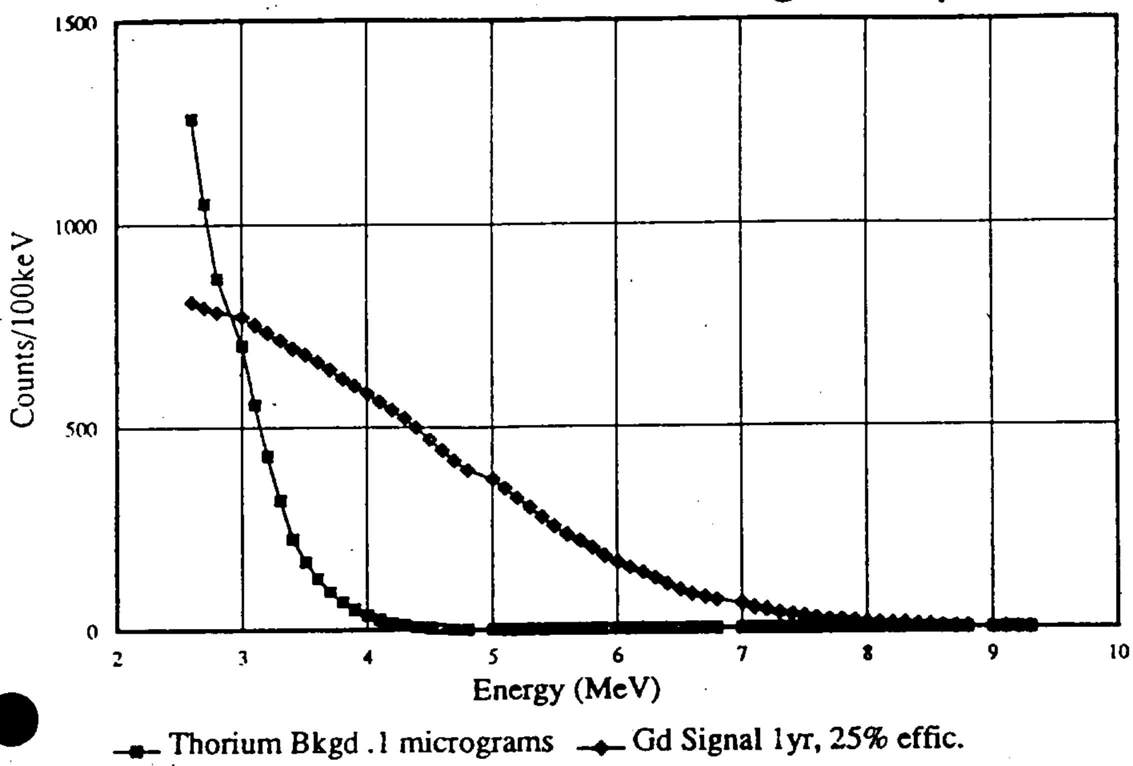


Figure 6

Thorium & Gadolinium Integral Spectra

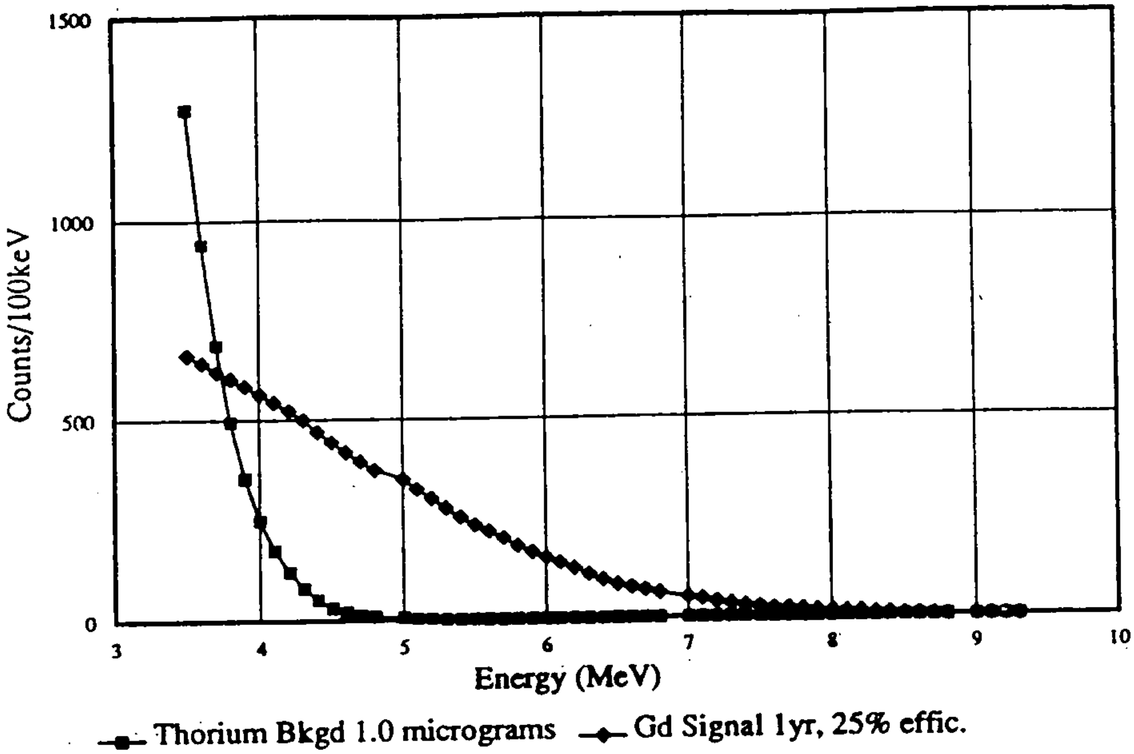


Figure 7

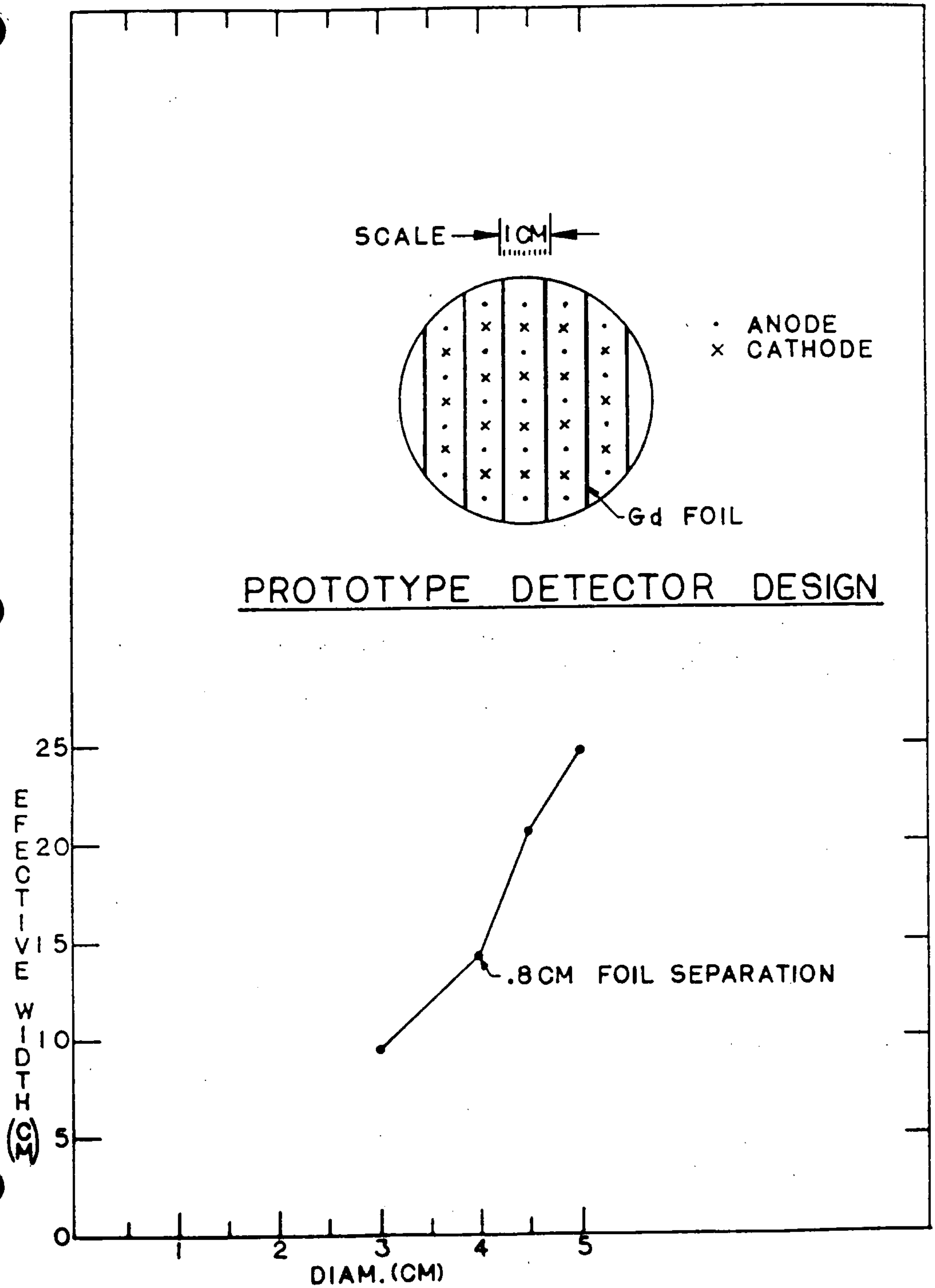

SCALE
1 CM
• ANODE
× CATHODE
Gd FOIL
PROTOTYPE DETECTOR DESIGN
EFFECTIVE WIDTH (CM)
0
5
10
15
20
25
1
2
3
4
5
DIAM. (CM)
.8 CM FOIL SEPARATION

Figure 8

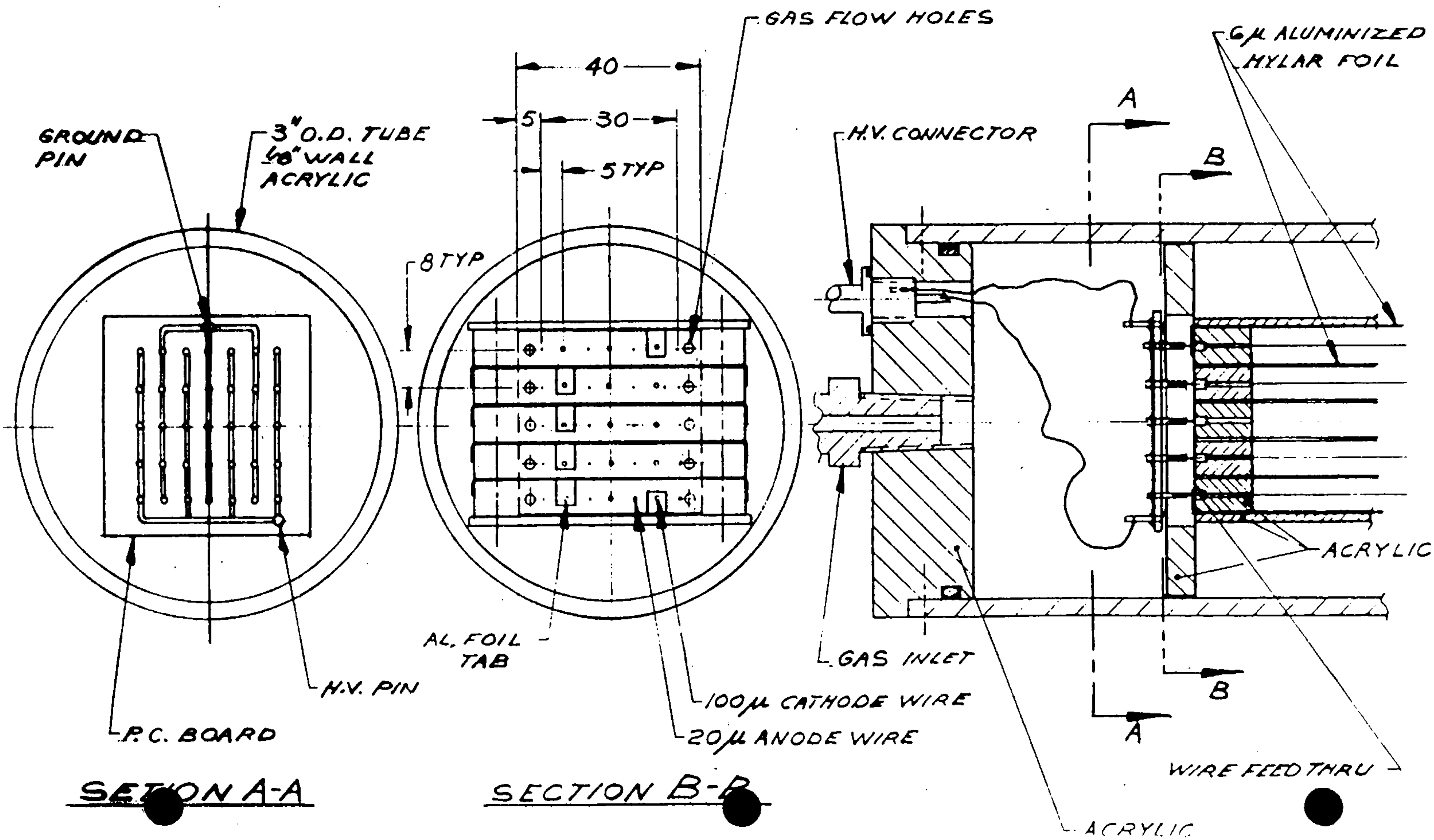

GAS FLOW HOLES
6μ ALUMINIZED MYLAR FOIL
40
5
30
5 TYP
GROUND PIN
3" O.D. TUBE 1/8" WALL ACRYLIC
H.V. CONNECTOR
A
B
8 TYP
ACRYLIC
AL. FOIL TAB
GAS INLET
H.V. PIN
100μ CATHODE WIRE
20μ ANODE WIRE
P.C. BOARD
WIRE FEED THRU
ACRYLIC
SETION A-A
SECTION B-B

Figure 9

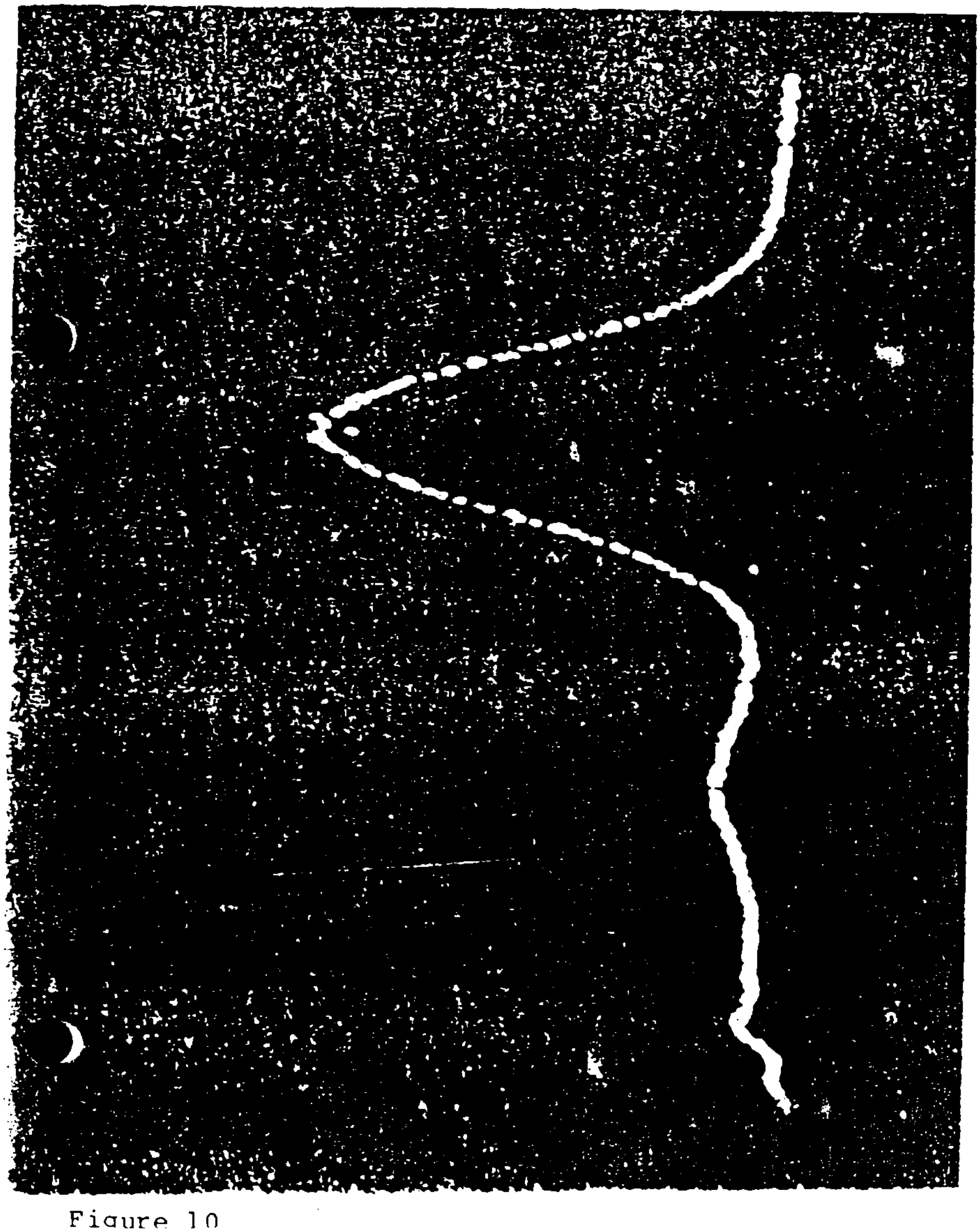


Figure 10