

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA 91109

FINAL REPORT

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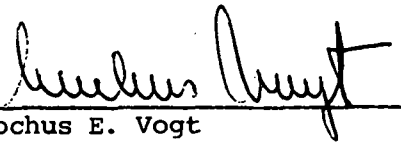
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Rochus E. Vogt
Professor of Physics
Principal Investigator

TABLE OF CONTENTS

	Page
Introduction	1
I. Outer Planets Missions (OPM) Definition Studies	1
II. Development and Investigation of Particle Detectors and Detector Systems	2
1) Triple-grooved LID Solid State Devices	3
A. Electrical Characteristics	4
B. Charge Collection Efficiency	5
C. Charged Particle Response	5
D. Surface Effects	6
2) Development of an Electron Telescope (TET)	6
A. Scientific Rationale	7
B. Experimental Approach and Performance	8
Figure Captions	10
Figures	

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NASA Grant NGR 05-002-225
California Institute of Technology
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This report covers the studies performed by the Space Radiation Laboratory at the California Institute of Technology under NASA Grant NGR 05-002-225 in support of the mission definition phase of the Outer Planets Missions.

The activities may be divided into two major categories:

- I. Participation in the study activities of the NASA-formed Energetic Particles Team and of the Science Steering Group for the OPM-project of the Caltech Jet Propulsion Laboratory (JPL) during mission definition.
- II. Development and laboratory investigations of new particle detectors and detector systems for the Outer Planets Missions

I. Outer-Planets-Missions (OPM) Definition Studies.

For the OPM definition studies, NASA formed an Energetic Particles Team (EPT), consisting of:

W. I. Axford, University of California - San Diego
S. M. Krimigis, Johns Hopkins Applied Physics Laboratory
F. B. McDonald, Goddard Space Flight Center
P. Meyer, University of Chicago
J. H. Trainor, Goddard Space Flight Center
J. A. Van Allen, University of Iowa
R. E. Vogt, California Institute of Technology

R. E. Vogt served as Team Leader, and S. M. Krimigis as Deputy Team Leader of the Energetic Particles Team.

The EPT's primary responsibility was the development of a scientific and technical rationale for the use of Energetic-Particle investigations in the exploration of the outer solar system and to assist the JPL project office in the design of the OPM spacecraft and mission objectives.

The Outer Planets Missions open up the outer solar system to intensive investigation. They provide a first opportunity to make quantitative comparative studies of the magnetospheres and radiation environments of the outer planets. They allow extensive exploration of the unknown outer regions of the interplanetary medium and of the heliospheric boundary, and they provide excellent opportunities to penetrate into the interstellar medium and to study cosmic rays, the most energetic component of the galaxy, beyond the influence of the solar wind.

The Energetic Particles Team met periodically during the OPM definition phase to develop science objectives, mission rationale, and to assist the JPL project office in the solution of technical problems. Parts of this work are reflected in the following reports generated by the EPT:

1. "Energetic Particle Measurements on the Outer Planets Missions" (9 July 1971)
2. "Energetic Particles Measurements on the Outer Planets Missions, Investigation Summary" (16 July 1971)
3. "Energetic Particles Measurements on Minimum Science Payload OPGT Missions" (29 September 1971)
4. "Energetic Particles Measurements on the Outer Planets Missions" (31 January 1972)
5. "Energetic Particles Measurements on Outer-Solar-System Missions" (30 April 1972)

In addition, R. Vogt participated in a study, conducted by the Space Science Board of the NRC/National Academy of Sciences, on "Outer Planets Exploration," 8-14 August 1971, at Woods Hole, Mass. (see NRC/NAS report, "Outer Planets Exploration 1972-1985," National Academy of Sciences, Washington, D. C. 1971).

R. Vogt also gave presentations on science objectives of Energetic-Particles investigations on OP Missions to various NASA evaluation panels.

After completion of its objectives, the Energetic Particles Team dissolved in June 1972, and its individual members, in collaboration with other scientists, submitted separate proposals for participation in the Outer Planets Missions.

II. Development and Investigation of Particle Detectors and Detector Systems.

The Caltech Space Radiation Laboratory (SRL) under direction of E. C. Stone and R. E. Vogt, considered the investigation and development of mission-unique solid-state-detector devices and cosmic-ray telescopes an important objective for the ultimate success of the Outer Planets Missions. The results of these investigations allow a realistic appraisal of the technical feasibility and the reliability of cosmic-ray and trapped-particle detector systems designed to accommodate the unique constraints and opportunities of the Outer Planets Missions.

In addition to the usual environmental conditions of space missions (e.g., vacuum, thermal environment, power restrictions, mechanical and acoustical strains, etc.) the Outer Planets Missions present other and new constraints in the performance of high-quality cosmic-ray observations. Among these are:

Extended mission lifetime - requiring extended reliability and stability of components.

Intense radiation environments, affecting the charge collection properties and survival rate of solid state devices.

Intense radiation background due to the Radioisotope Thermo-electric Generators (RTG's), causing both continuous real time interference and lattice defects.

A non-spinning spacecraft and considerable weight restrictions on the payload, demanding design of minimum-weight telescopes.

The Caltech Space Radiation Laboratory (and colleagues from the Goddard Space Flight Center and the University of New Hampshire, who have formed an investigator team for the OP missions) considers the use of all-solid-state particle telescopes of prime importance for the accomplishment of the fundamental scientific objectives. The choice of all-solid-state telescopes, with novel solid-state anticoincidence guards instead of the usual scintillator-photomultiplier guard counters, is dictated by considerations of stability, sensitivity, reliability, and weight and high-voltage requirements. In addition, the crucially important measurements of potentially small anisotropies of cosmic-ray fluxes from a 3-axis stabilized spacecraft require rotation devices for the particle telescopes, both for scanning and intercalibration. Such rotation devices¹ can be built economically and reliably (within realistic S/C constraints) only for small, light-weight telescopes, i.e. of all-solid-state construction.

In the pursuit of these investigations, the Caltech SRL concentrated upon triple groove silicon devices (center active element + ring active element + active guard electrode),² shown in Figures 1 and 2, while the GSFC investigated double-groove devices (outer active element + ring active element, without guard). These two independent approaches were considered essential in view of the time constraints of the program. The double-groove devices are clearly simpler and therefore preferable. However, it was not certain whether they would have the necessary energy resolution, stability and ease of manufacturability, whereas, the more complex triple-groove devices appeared more promising on purely theoretical grounds. In the final analysis, both types of devices proved to be satisfactory; however, only after experience with triple-groove devices provided essential technical feedback for double-groove devices to the design engineers of the manufacturer.

1) Triple-groove LID Solid-State Detectors

The solid-state detectors were developed and manufactured by the Nuclear Physics Division of KEVEX Corporation, Burlingame, California under close supervision and technical consultation of Caltech and GSFC personnel.

The configuration of the LID detectors which were tested by Caltech's SRL is shown in Figure 2. This configuration can be referred to as a triple-groove detector, since the n-type contact is cut by 3 concentric grooves so that the area of the single wafer of silicon is divided into 3 electrically separate areas.

¹A working rotation device has been built and fully tested at GSFC and is incorporated in our MJS proposal.

²The results of the GSFC investigations appear in separate GSFC reports. GSFC has also undertaken a full radiation testing program of these detectors for the effects of intense particle fluxes and fluences.

The central circular area A of the detector is the primary detector of the three. The adjacent ring B is designed to serve as an anti-coincidence detector, so that particles which penetrate area A and exit through area B can be rejected without further analysis. The second ring (C) is a guard ring which provides a separate path for the larger leakage currents often associated with the edges of the silicon wafer. The particle detection characteristics of the guard ring C were also investigated.

The triple groove detectors were subjected to the standard detector tests which have been developed in the Caltech Space Radiation Laboratory in support of solid-state-detector telescopes which have been launched on OGO-2, OGO-4, OGO-6, and IMP-H/J. Eight examples of these tests are listed in Table I and summarized below.

TABLE I: Tests of Solid-State Detectors

- A. Electrical characteristics
 - 1. Leakage current as a function of bias voltage.
 - 2. Leakage current as a function of temperature.
- B. Charge Collection Efficiency
- C. Charged Particle Response
 - 1. Energy resolution for alpha particles.
 - 2. Anticoincidence efficiency for penetrating particles.
 - 3. Alpha-particle size scan.
 - 4. Penetrating-electron size scan.
- D. Surface Effects

A. Electrical Characteristics

- 1. Leakage current as a function of bias voltage

The reverse bias current-voltage characteristics of each detector diode is carefully measured in order to determine the stable operating range. Figure 3 shows the results for each of three sensitive areas for two different detectors. The current-voltage characteristic of the central area and the anticoincidence ring are similar in both cases, while the guard ring exhibits a much higher leakage current. In all cases, however, stable operation was possible with up to at least 500 V applied bias.

2. Leakage current as a function of temperature.

On the basis of the room temperature test, a bias voltage of 491 V was applied to the three sensitive areas of each detector and the leakage current was measured as a function of temperature. Results for two of the detectors are shown in Figure 4. The devices functioned properly over the temperature range up to 45° C.

B. Charge Collection Efficiency

The operating bias voltage of a detector must be high enough to ensure almost complete charge collection efficiency, so that the measured signal is directly relatable to the energy loss of the incident particle. To determine the minimum operating voltage, the detectors were exposed to a beam of 8.785-MeV alpha particles incident on the p-contact (see Fig. 2). The charge signal was measured as a function of the applied bias voltage. The results for one detector are shown in Figure 5. An operating bias as low as 250 V would satisfy the requirement of full charge collection for alpha particles.

C. Charged Particle Response

1. Energy resolution for alpha particles

Each detector was exposed to 8.785-MeV alpha particles in order to determine its resolution characteristics. A fixed bias voltage of 491 V was applied to all 3 sensitive areas of each detector, and the alpha resolution was measured for each of the areas. Results for detector #1590 are shown in Figure 6. All three areas exhibit acceptable alpha-particle-resolution, although the guard ring has somewhat lower resolution than the center and anticoincidence ring. Thus in many instances the guard ring could serve as an anticoincidence and the separate anticoincidence ring could be eliminated.

2. Anticoincidence efficiency for penetrating particles

Since the triple groove detectors are designed to measure not only stopping particles but also penetrating particles, each detector was tested with a beam of 1.8 MeV electrons from a β -spectrometer. The results of one penetrating-particle test of particular interest are shown in Figure 7, where two measured energy-loss distributions for 1.8 MeV β -particles are compared. In both cases, the electrons were incident near one edge of the center area, so that edge effects such as the scattering of some electrons out of the collection region of the center area produce some energy-losses which are too small. The distribution with circles clearly shows the edge effect by the large number of counts below 600 keV. The distribution with solid dots, however, is

much freer of edge effects. This second distribution was obtained by rejecting for analysis all events which produced a measurable signal in the adjacent anticoincidence ring. This marked reduction in edge effects is an especially important feature of the integral anticoincidence ring.

3. Alpha-particle size scans

The size and location of each of the 3 sensitive areas on each detector were determined by measuring the alpha-particle counting rate due to a source which was scanned along a detector diameter. One such alpha scan is shown in Figure 8. For comparison, a cross-section diagram of the detector shows the physical location of the 3 concentric grooves which define the 3 sensitive areas.

4. Penetrating electron size scans

The size and location of each sensitive region was also determined by scanning along a detector diameter with a 1.8 MeV electron beam. The measured counting rate as a function of beam position is shown for one detector in Figure 9. Because the electrons scatter significantly on penetrating the detector, the edges of each region are diffuse and the response curves of adjacent regions overlap. This overlap is greatly reduced by placing adjacent areas in anticoincidence, so that only particles remaining within a single area are counted or analyzed.

D. Surface Effects

The n-type contact is a relatively thick layer of low resistivity material from which no signal is collected. The thickness of this dead layer was measured with alpha particles and was found to be between 48 ± 1 and 52 ± 1 μm of silicon for the various detectors. The p-type contact has a much thinner dead layer which was measured to be 0.3 ± 0.2 μm of silicon equivalent. These dead layers were within specification.

2) Development of an Electron Telescope (TET)

During the OPM definition studies it became clear that the spacecraft and payload constraints of the Outer Planets Missions would make it unlikely that a full and ideal complement of cosmic-ray detectors could be accommodated. When requested to investigate and discuss "Minimum Science Payloads," the Energetic-Particles Team consistently emphasized the priority of investigations of the charge, mass, and energy spectra of cosmic-ray nuclei below energies of about 500 MeV/nucleon. It was impossible, realistically, to accommodate a standard electron telescope (which weighs typically about 10 pounds). On the other hand, the EPT, the SSG and various other scientific advisory groups continued to emphasize the extreme scientific importance of electron studies, particularly in the low energy

region, where no information on galactic phenomena can be deduced from observations near Earth.

A. Scientific Rationale

The measurement of the galactic intensity of electrons, specifically below ≈ 100 MeV, will have a profound effect on our understanding of the role of these electrons in producing the diffuse x- and γ -ray background in the galactic disk, in understanding the dynamics of the galactic disk-halo magnetic-field relationship, as well as understanding the method of escape of these electrons from known source regions such as the Crab Nebula.

Above a few hundred MeV, the electron spectrum near the Earth is reasonably well known, and, although less well understood, the broad features of the solar modulation have also been extensively measured and can be adequately determined at the orbit of Earth. The understanding of the modulation at rigidities >100 MV, to be gained from the study of nuclei on the MJS missions, makes it possible to determine the galactic spectrum of electrons >100 MeV outside of the solar cavity. Furthermore, using estimates of galactic radio emissivity obtained from measurements of non-thermal radio emission, under the assumption that this radio emission is caused by synchrotron radiation by energetic electrons in galactic magnetic fields, it is also possible to deduce the interstellar electron spectrum. A comparison of the galactic electron spectra obtained from these two approaches may be used to examine the spatial distribution of electrons and magnetic fields in the galaxy.

It should be noted that the radio measurements extend down to only ~ 1 MHz, which corresponds to a few hundred MeV electron energy in the galactic magnetic fields. Below a few hundred MeV, we can only speculate on the interstellar electron spectrum. For example, the low-energy galactic radio spectrum is observed to turn over and decrease below 1 MHz. It is usually assumed that this is due to free-free absorption by interstellar hydrogen. But it is possible that the electron spectrum itself turns over as well at the equivalent energies. Obviously, the correct interpretation of this feature is of fundamental importance in understanding the conditions in the interstellar medium (e.g., the presence of cold gas clouds and the temperature of the intercloud medium) and for the understanding of the origin of these electrons and their importance in galactic dynamics.

If one extends the interstellar electron spectrum above 300 MeV, as deduced from radio background measurements, down to below 20 MeV, then this spectrum exceeds that observed at Earth by a factor of >1000 ! Yet the spectrum observed at Earth is roughly consistent with an interstellar knock-on origin for these electrons without invoking an additional, perhaps primary, source. Is this difference due to extremely large solar modulation effects or is the interstellar spectrum at low energies really not much different than at Earth? Some of the rich possibilities for the behavior of the low-energy electron spectrum in interstellar space are illustrated in Figure 10. The resolution of this problem requires measurements of electrons specifically below 100 MeV.

B. Experimental Approach

The Caltech Space Radiation Laboratory therefore concentrated on the possibility of developing a small, lightweight electron telescope (design goal: ~ 1 lb.) which could be added to the MJS payload and cover the crucial energy range for electrons between ~ 5 - 150 MeV, which range cannot be covered by the nuclei-detector systems of energetic-particle experiments.

We have been able to design, test, and calibrate a relatively simple, small, and light-weight electron energy spectrometer in the 5-110 MeV energy range. The use of novel integral detector-guarding devices (see Sec. B-1) allows an all-solid-state detector design with adequate energy resolution and background rejection so that meaningful spectra can be measured even at the relatively low electron intensities near Earth. The response of the electron telescope, including the effects of background, have been verified by accelerator calibrations (with support from the GSFC group) of a prototype model and by Monte-Carlo calculations.

Figure 11 represents a schematic cross-section of the principal features of a prototype electron-telescope developed by the SRL for the MJS missions. It consists of an array of solid-state detectors and absorbers in a cylindrical geometry, surrounded by a grid of solid-state guard detectors. In the prototype model shown, electrons and their energies are identified by a double- dE/dx measurement in detectors D_1 and D_2 and by a simultaneous measurement of their range, as determined by the penetration of detectors D_3 through D_7 . The use of range spectroscopy, while providing satisfactory energy resolution and background rejection (see below), has the additional virtue of being insensitive to electronic gain drifts which may arise in MJS-type long-term missions.

The prototypes calibrated on accelerators over an energy range of ~1 MeV to ~1 GeV did not contain the solid-state guardring devices (unavailable within the restricted budget of this study) but rather conventional solid-state detectors available in our laboratories. However, the guard devices had no intrinsic bearing on the range-energy calibrations performed. They mainly affected the Monte-Carlo calculations for detection efficiency and background rejection, where they were fully considered. The energy-response data derived from accelerator calibrations showed an equivalent energy resolution comparable in quality to those of conventional (and much heavier) total-energy-absorption devices. The response curves form the basis of a conversion matrix which is used to unfold energy spectra from range distributions, as illustrated in Figure 13 and Table II. The three energy spectra used for illustration purposes represent realistic estimates for the MJS missions. The interstellar electron spectrum shown is based upon the galactic non-thermal radio spectrum for energies above several hundred MeV and represents a power-law extrapolation at lower energies. The spectra shown for 5 AU and 1 AU have been derived from the interstellar spectrum by use of numerical solutions of the cosmic-ray transport equation using accepted values for the solar wind velocity and the cosmic-ray diffusion coefficients. In addition, the calculated electron spectrum at 1 AU agrees with observational results. The 1 AU spectrum shown may be considered typical for the expected electron fluxes at the beginning of the MJS '77 missions.

TABLE II: Telescope Range Distributions and Maximum Background Levels for Three Typical Cosmic-Ray Electron Spectra Shown in Figure 13.

Range (Di's triggered)	Geometry Factor (cm ² -sr)	Counts/Month			
		1 AU	5 AU	Interstellar	Max Background
D ₁ D ₂ D ₃	1.8	1.8x10 ³	3.4x10 ⁴	1.6x10 ⁶	3.9x10 ²
D ₁ ...D ₄	1.4	1.6x10 ³	1.6x10 ⁴	5.2x10 ⁵	5.2x10 ²
D ₁ ...D ₅	1.0	1.4x10 ³	8.6x10 ³	1.7x10 ⁵	5.2x10 ²
D ₁ ...D ₆	0.8	1.4x10 ³	6.0x10 ³	7.3x10 ⁴	5.2x10 ²
D ₁ ...D ₇	0.6	1.4x10 ³	4.9x10 ³	4.2x10 ⁴	7.8x10 ²

As an example, we show in Table II the expected range distributions (determined from the calibrated detector response) for the three typical electron energy spectra shown in Figure 13. The application of a simple unfolding technique to these data results in the very satisfactory reproduction of the input spectra shown by the data points in Figure 8. The dashed areas in Figure 13 indicate conservative estimates of maximum background levels during the mission which are caused by the spacecraft RTG's (below .2.5 MeV) or by interacting high-energy protons in the detector stack. The RTG background levels are obtained from direct calibrations of the GSFC/UNH Pioneer 10 telescope. The basic D₁D₂D₃ coincidence requirement, which includes the absorber A₁, makes the electron telescope insensitive to RTG-background. The proton induced background (above .2.5 MeV) has been calculated by Monte-Carlo techniques for the maximum flux levels of primary cosmic rays during the MJS missions. The Monte-Carlo programs and the nuclear cross sections used in the calculations have been successfully applied by the Caltech laboratory to other cosmic-ray telescopes with extensive verifications on particle accelerators and in nature. Definitive electron energy spectra can be measured for all phases of the MJS missions without significant background interference.

FIGURE CAPTIONS

- Figure 1 Photograph of a "triple-groove" LID detector.
- Figure 2 Schematic diagram of the triple-groove detector.
- Figure 3 Detector leakage currents versus applied bias at room temperature.
- Figure 4 Detector leakage currents versus temperature at 491 V applied bias.
- Figure 5 Measured alpha-particle energy versus applied bias voltage. The incident alpha-particle energy was 8.785-MeV and was incident on the p-contact of the detector (see Figure 2).
- Figure 6 Energy resolution for 8.785-MeV alpha particles incident on the p-contact for each of the 3 sensitive areas of detector #1590.
- Figure 7 Energy-loss spectra of penetrating electrons incident on one edge of the central sensitive area. The spectrum with open circles was accumulated without regard for any response in the anticoincidence ring. The spectrum with closed circles illustrates the effect of analyzing only those events which are not accompanied by a signal from the anticoincidence ring.
- Figure 8 Alpha-particle counting rate as a function of source position on detector #1601. The counting rate is measured as a function of position of the source as the source is moved along a detector diameter. The response in each of the 3 sensitive areas is indicated, as are the physical locations of the 3 concentric grooves.
- Figure 9 Penetrating-electron counting rate as a function of the position of the incident beam. Due to the scattering of electrons, the edges of the 3 sensitive areas are more diffuse for electrons than for alpha particles. For comparison, the physical location of the 3 sensitive areas is also indicated.
- Figure 10 Electron spectra observed at Earth and limits on possible spectra for the MJS missions.
- Figure 11 Schematic cross section of a SRL prototype MJS electron telescope.
- Figure 12 Typical electron spectra (solid lines) for heliocentric radii of 1 AU, 5 AU, and the interstellar medium. Data points show the response and resolving power of the prototype electron telescope to these spectra.

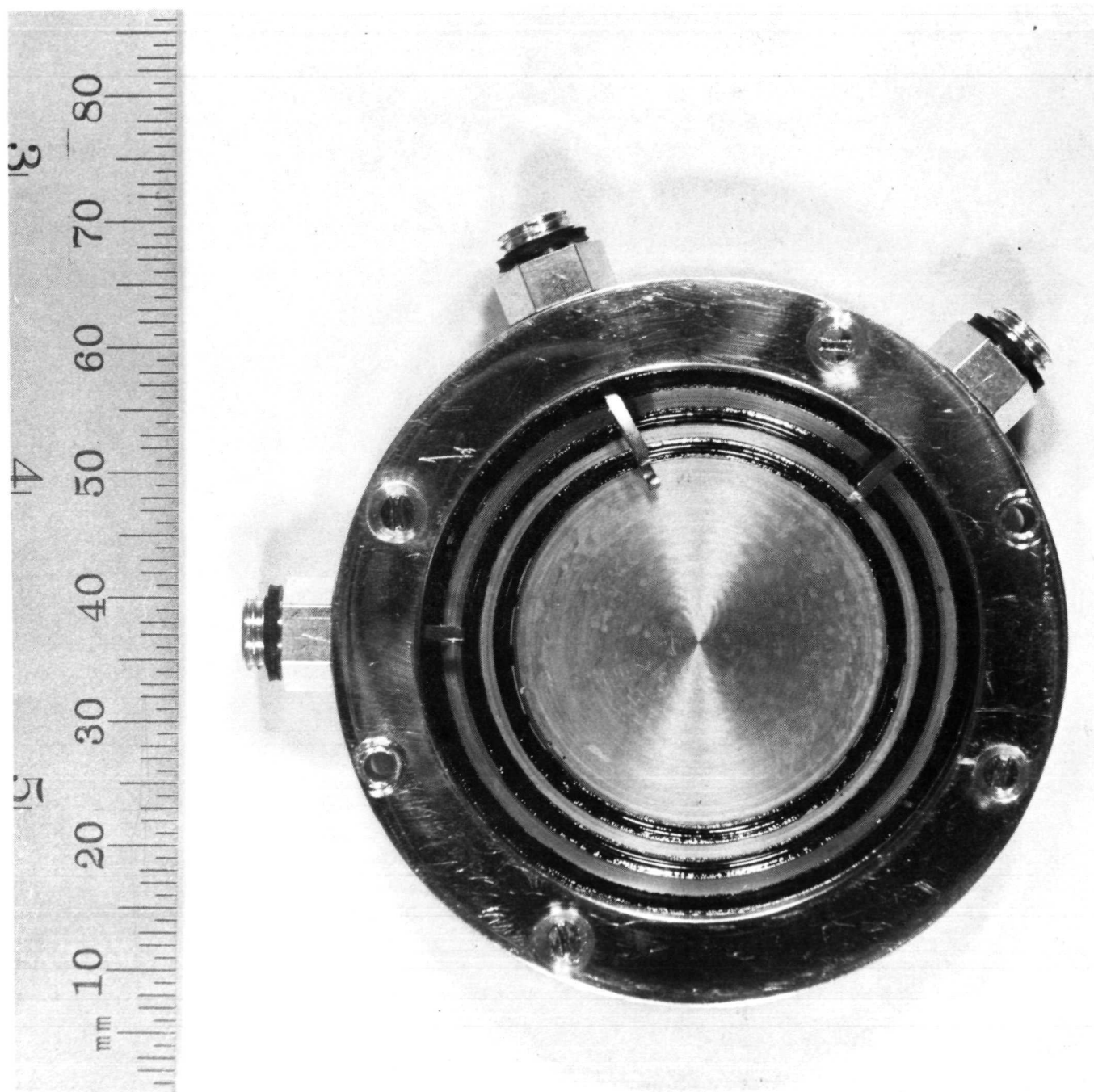
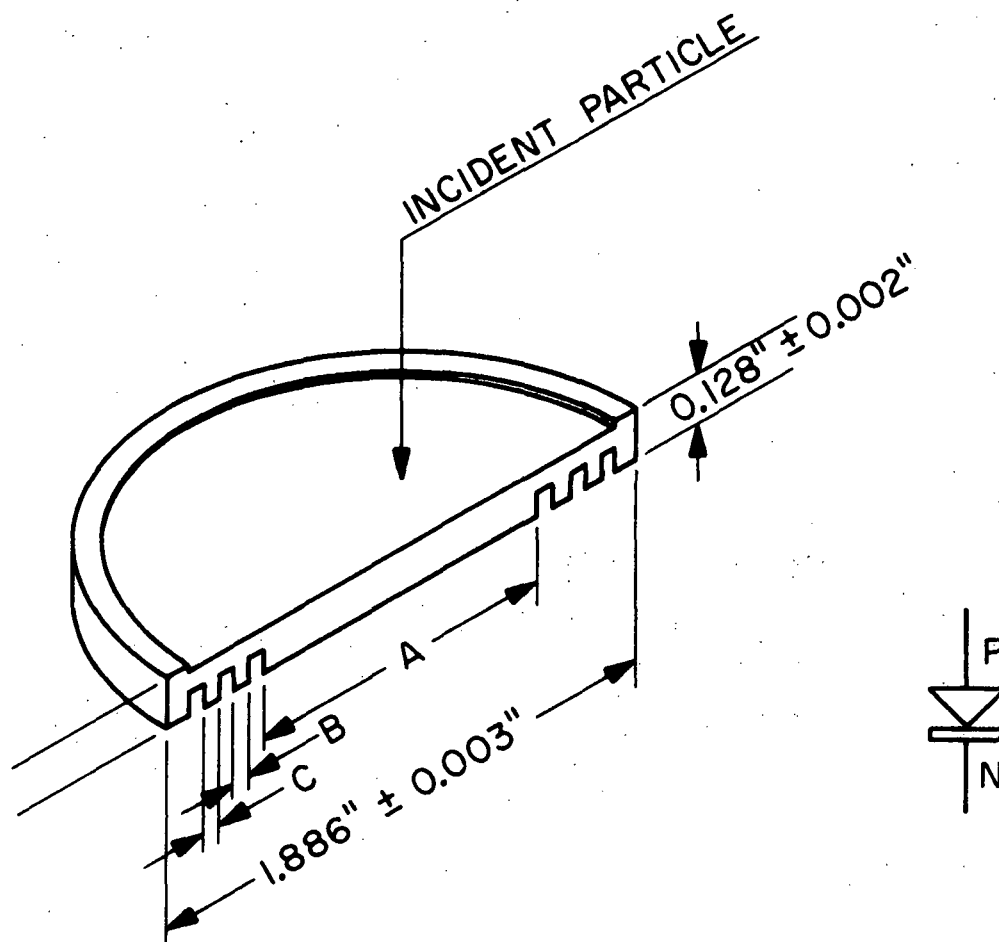


Fig. 1



		AREA IN MM ²
A	CENTER DETECTOR	850 MM ²
B	ANTI COINC.	200 MM ²
C	GUARD RING	200 MM ²

Fig. 2

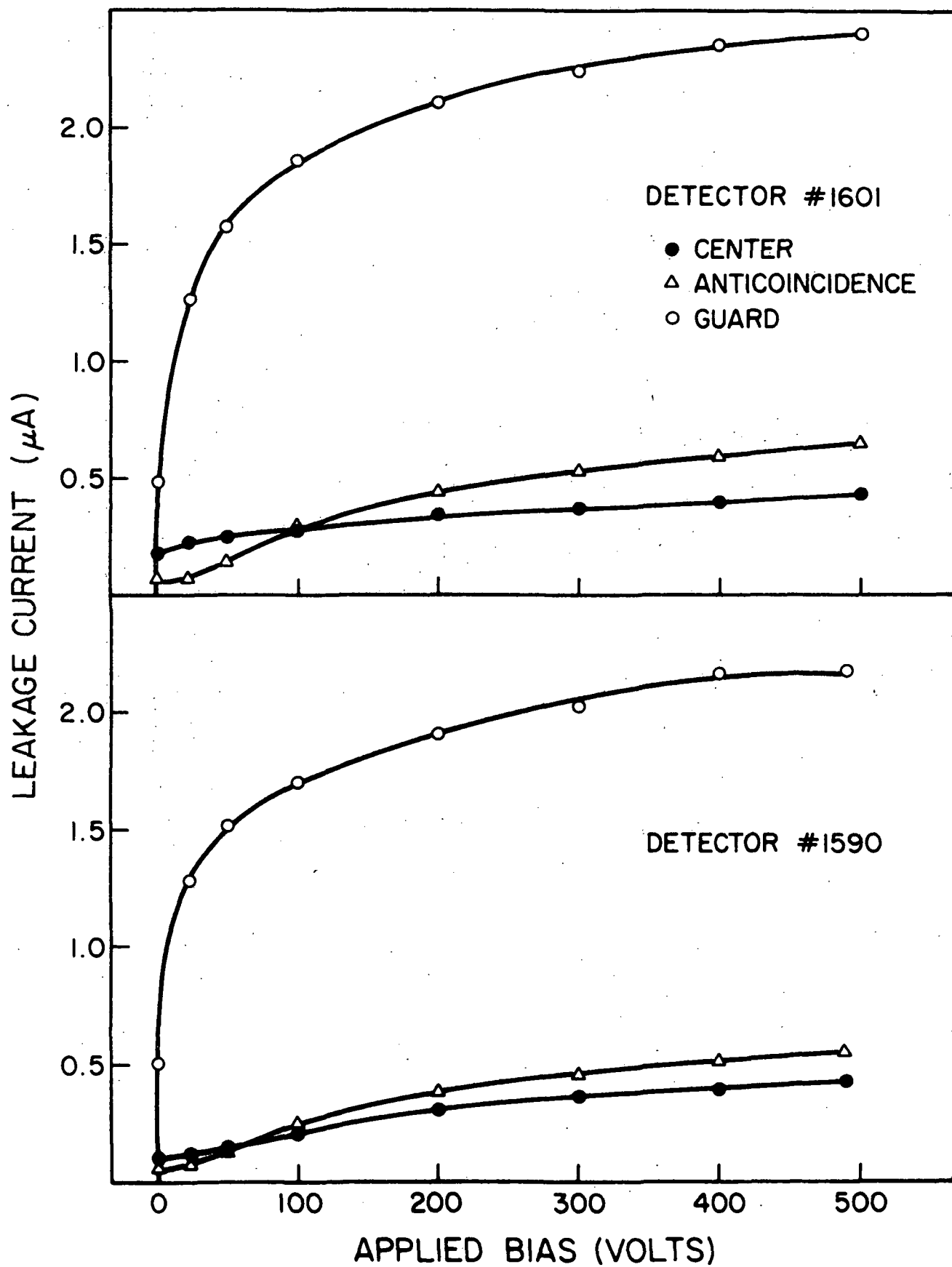


Fig. 3

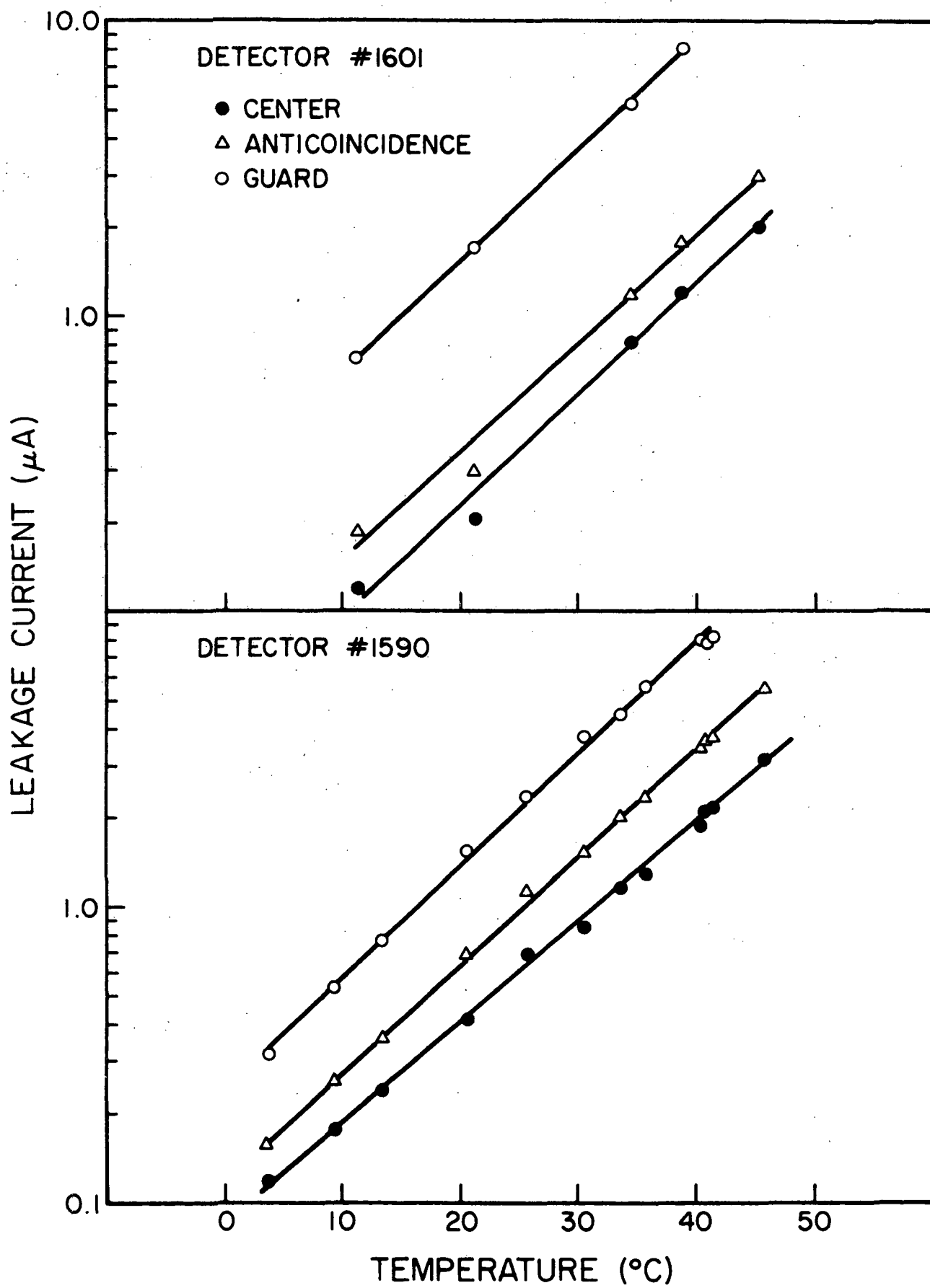


Fig. 4

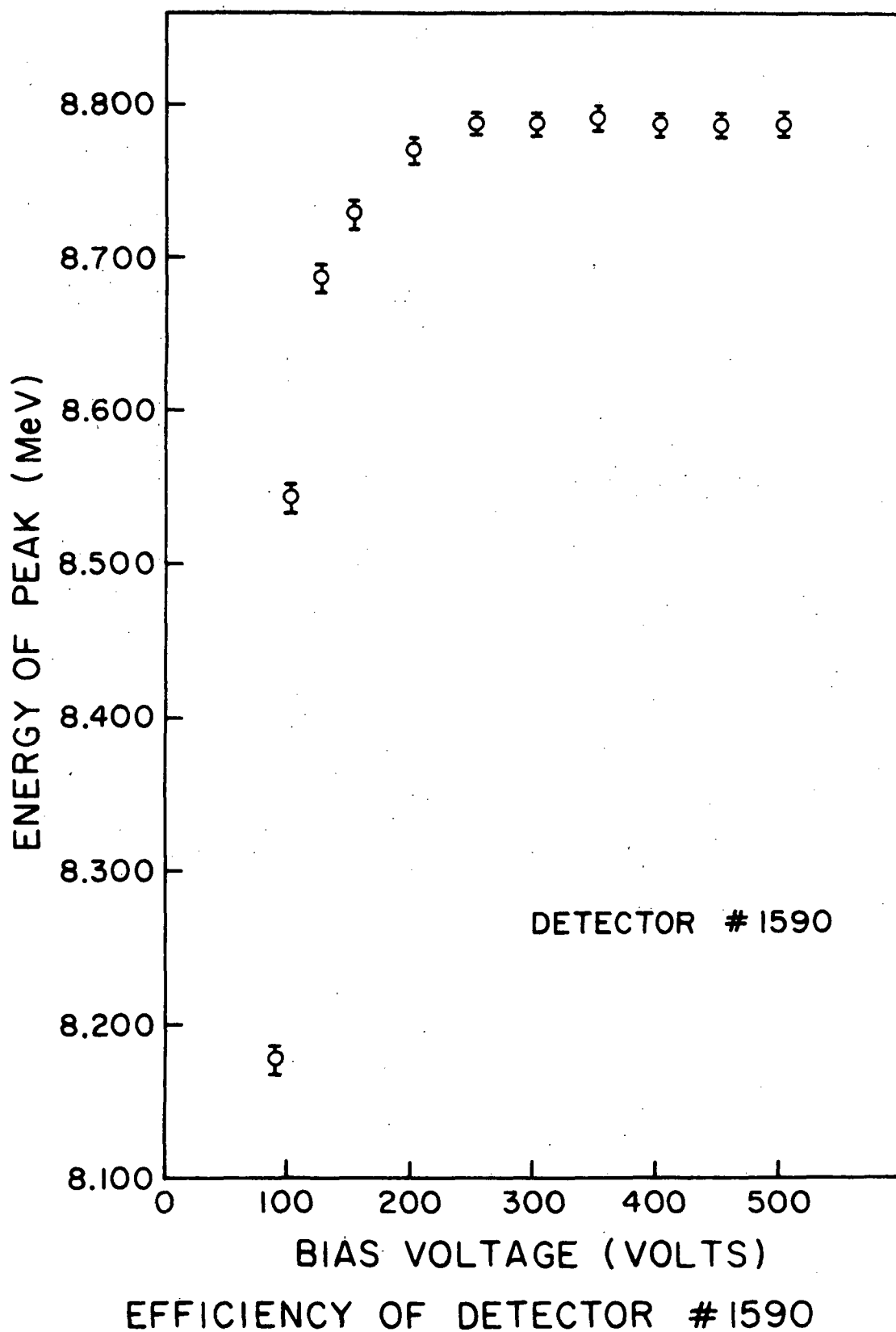


Fig. 5

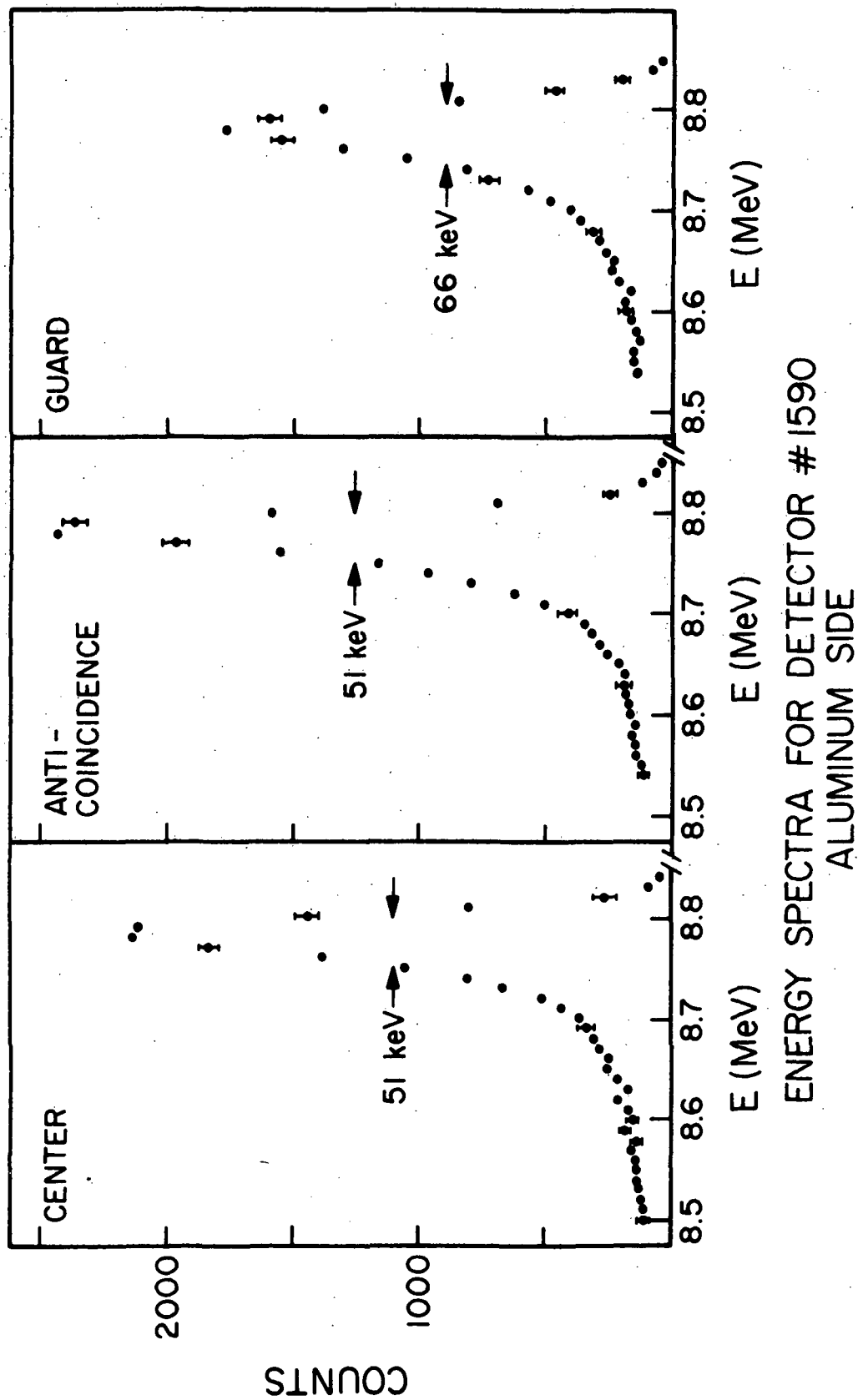


Fig. 6

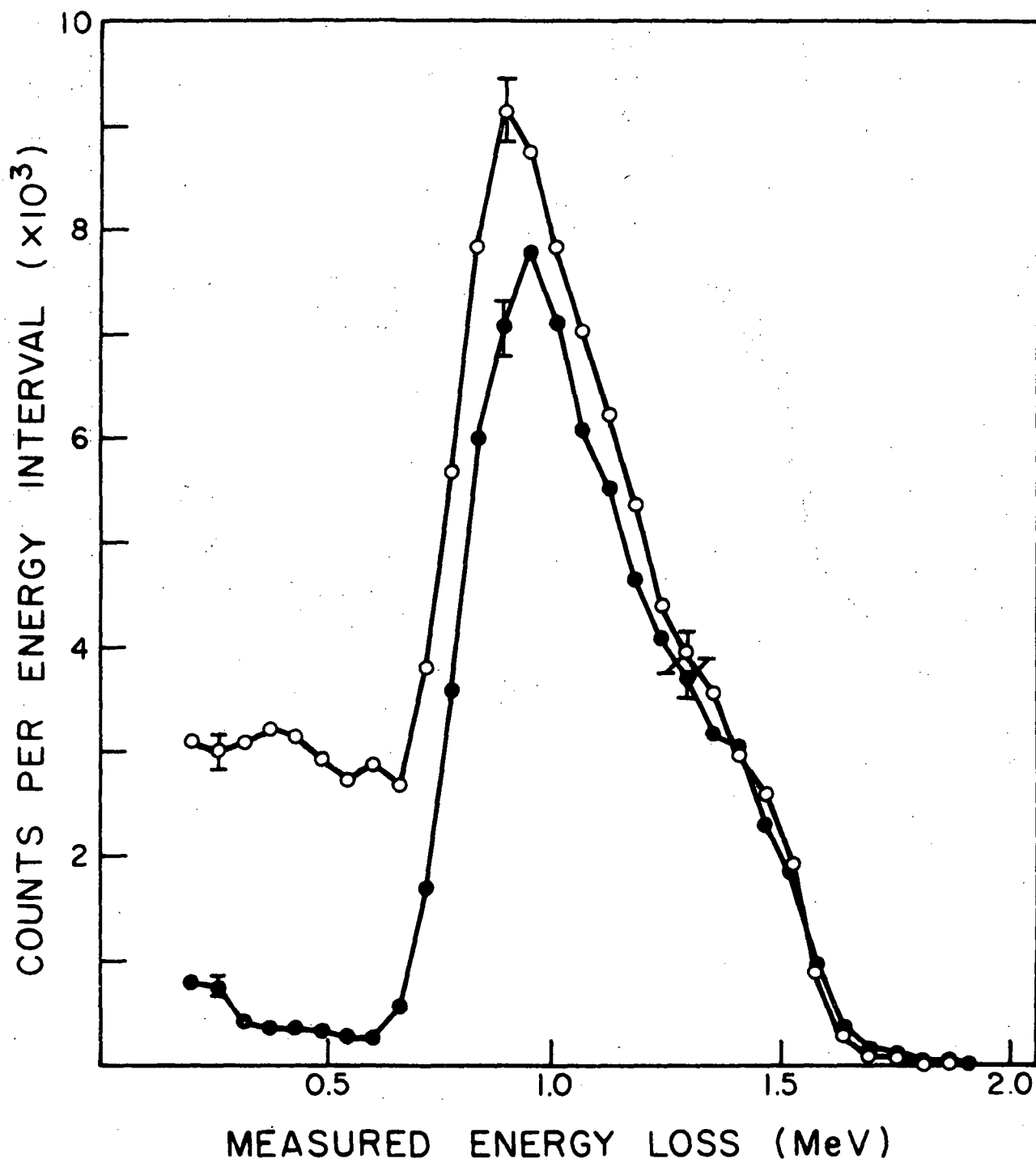


Fig. 7

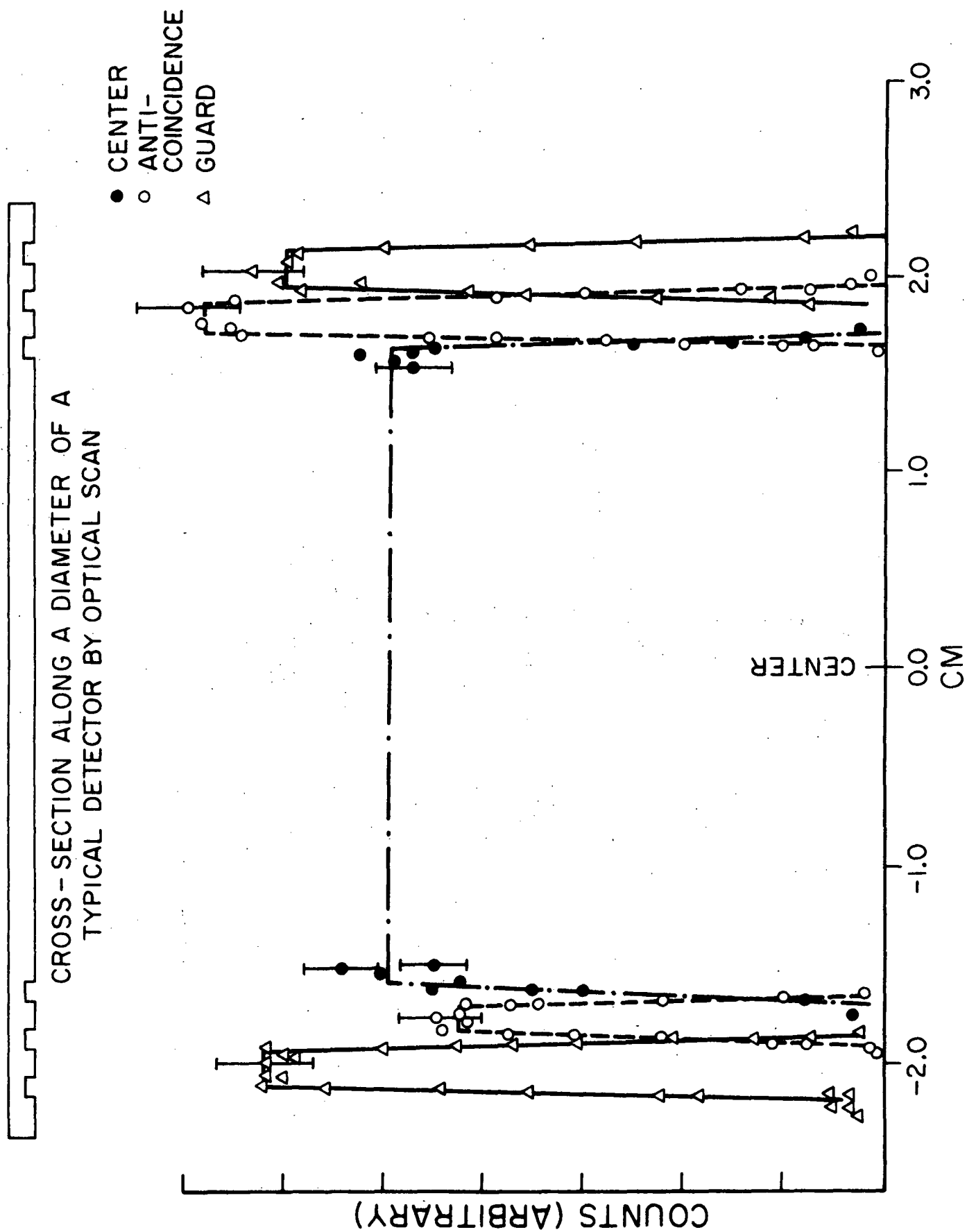


Fig. 8

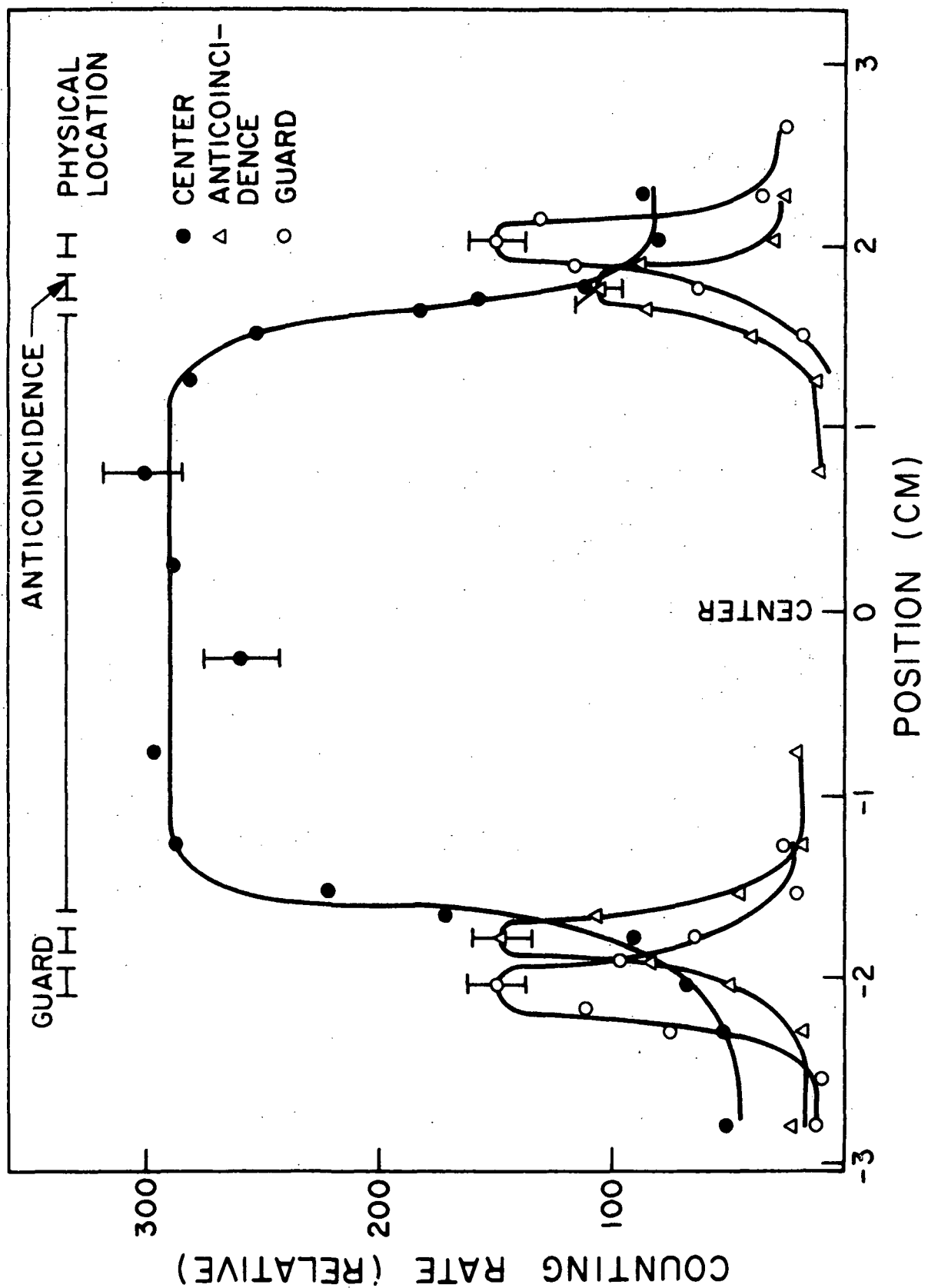


Fig. 9

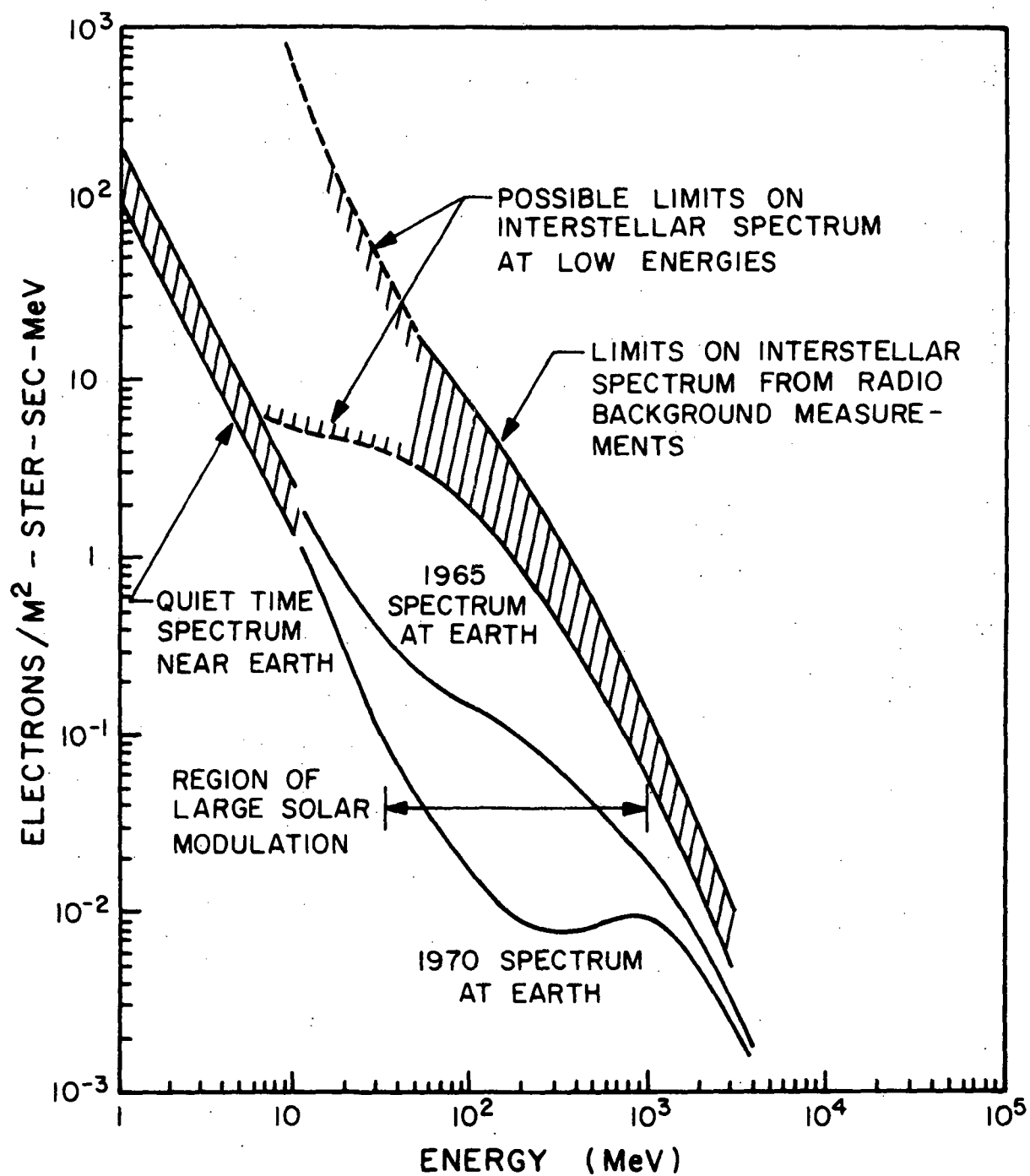
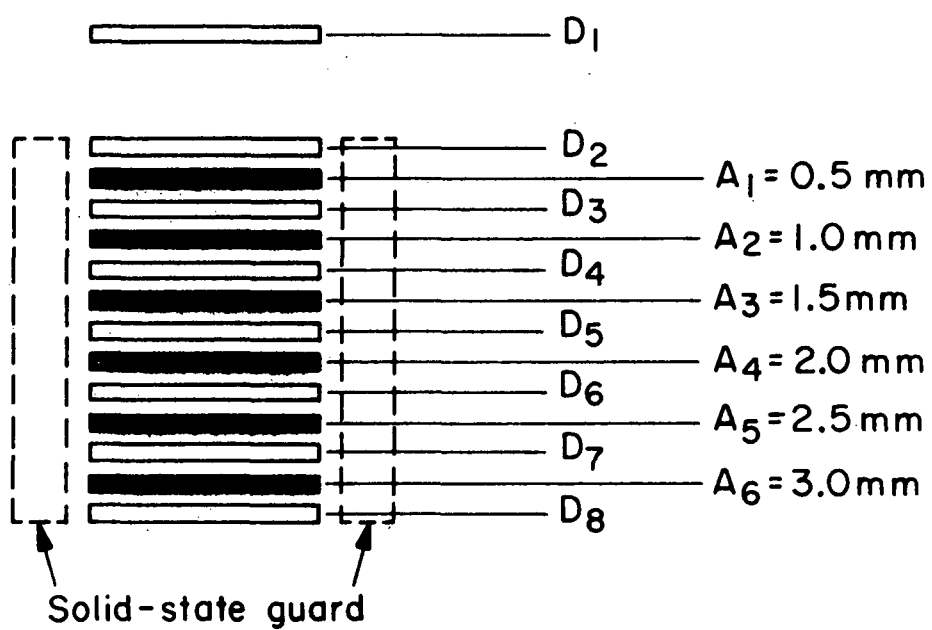


Fig. 10



D_i = 2.5mm LID detectors

A_i = tungsten absorbers

Fig. 11

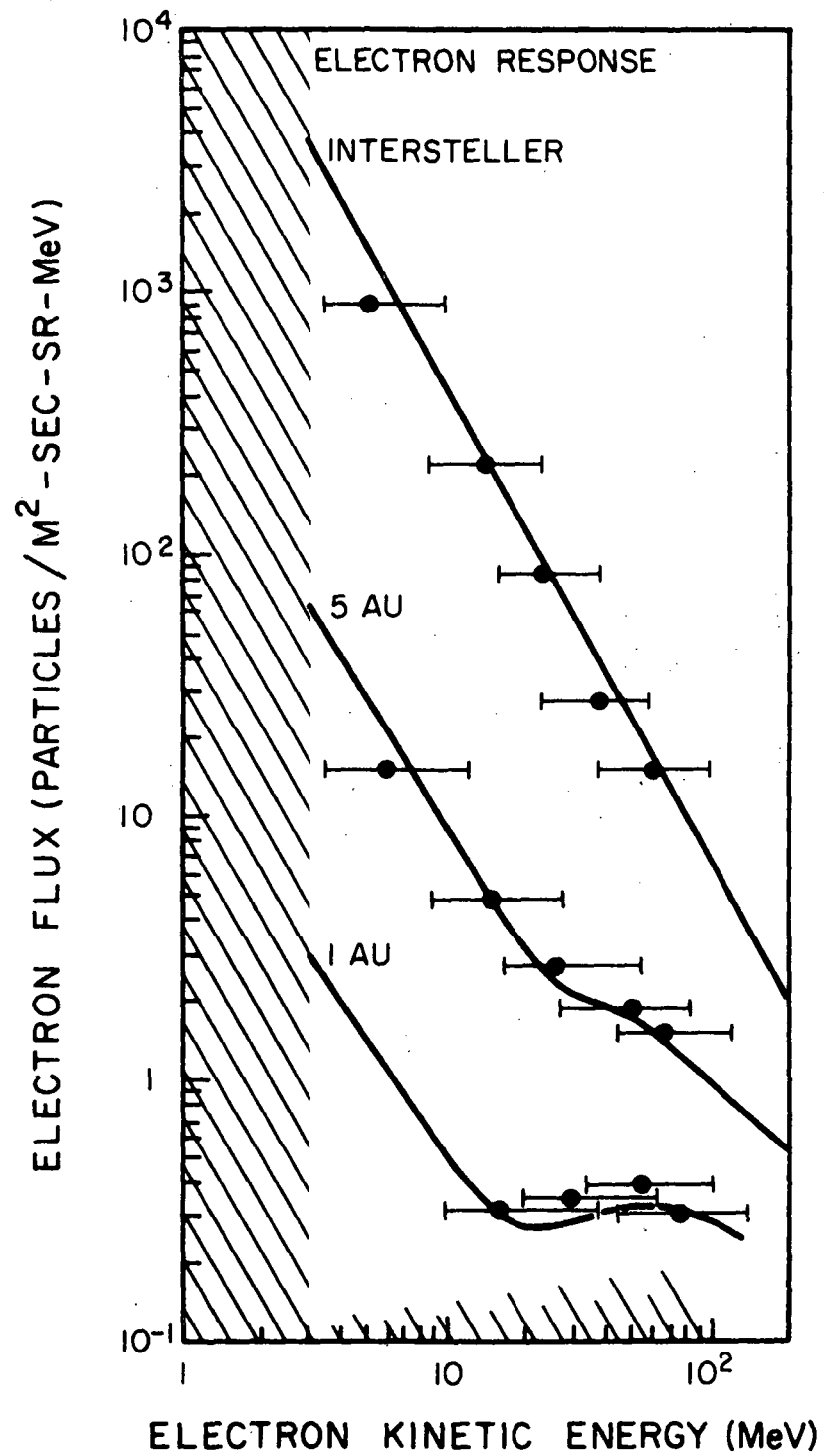


Fig. 12