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Final Technical Report

Contract NAS 5-9090

Imp F/G(4,5)

The University of Chicago

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by

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I. Introduction

Contract NAS 5-9090 was initiated on 30 December 1964 in response to a proposal by the University of Chicago for a Solid State Cosmic Ray Telescope Experiment to be included in the IMP F/G mission payloads.

The contract called for the provision of a flight quality prototype instrument, two flight units, two sets of ground support equipment and experiment stimulii, field support as required, and the reduction and analysis of flight data.

The spacecraft were launched in May 1967 and June 1969. The University of Chicago Cosmic Ray Experiments aboard the two satellites remained fully operational and in calibration during the entire mission lifetimes and have proven to be highly productive of scientific information, as attested by the publications and papers which have resulted (See the report on "Scientific Results of the University of Chicago IMP 4 and IMP 5 Satellit Experiments," dated 3 January 1973).

This report is being submitted in partial fulfillment of the requirements of contract NAS 5-9090 as Item 8, Appendix A. It sets forth a technical description of the flight instrumentation and the hardware effort.

II. Flight Instrument Design

The charged particle telescopes are shown in cross-section in Figure 1. In the first generation of instruments built at this laboratory it was necessary to design each instrument to yield either high charge resolution or large dynamic range in charge and flux levels. The second generation IMP-4 and IMP-5 instruments evolved from the solid state telescope developments proven successful in the University of Chicago IMP-1, 2, and 3, and OGO-1 and 3 satellite experiments. It was possible not only to achieve higher charge resolution than the IMP-3 experiment, but also to cover a large dynamic range in flux levels and energy than the OGO-1 and 3 experiments. These advances were made possible by a number of factors including (1) highly stable Li-drifted Si detectors fabricated at this laboratory, (2) The addition of almost total anticoincidence protection (e.g., D6 in Figure 1), (3) low power amplifiers and pulse height analyzers with long-term stability and large dynamic range, and (4) spacecraft encoder technology.

In Figure 1 particles are analyzed which enter the telescope acceptance cones defined by the D1 detector and the anticoincidence scintillator (D6). The D6 scintillator also serves to protect against background caused by nuclear interactions in the telescope. The relatively small geometrical factors of the telescopes are offset by long collection times achievable with a stable spacecraft experiment.

These telescopes identify particle types and incident kinetic energy by making use of the fact that when the energy loss (i.e. - dE/dx) of a particle passing through a thin detector such as D1 is plotted against residual energy of the particle deposited in a second detector, such as D2 or D4, the resulting matrix of all analyzed particles contains particle "tracks" which separate different elements according to nuclear charge number Z or isotopes. The incident energy of the particle is determined from its position on the track. The relative populations of analyzed events along the tracks are <u>directly</u> proportional to the incident differential energy spectra for nuclear species expressed in kinetic energy per nucleon (i.e., per atomic mass unit).

The instrument flown on IMP 5 had modifications from that used in the IMP 4 mission. The modifications related to the incorporation of a Cerenkov detector in the form of a sapphire faced photomultiplier tube replacing the plastic scintillator and photomultiplier in the IMP 4 instrument. The D_5 function was retained by substituting a CsI (T1) scintillator and associated photodiode assembly for the plastic (See Figure 1).

The electronics subsystem was modified to accommodate these changes in the logic and by providing a means of sharing the Pulse Height Analyzer between the D_1 and CK in such a way that if the signal level in the CK detector were above threshold, the PHA was automatically switched. Thus the switching function was internally dependent upon the incident particle energy.

For the high energy analysis the IMP 5 Cerenkov detector (CK) is used to separate different particle tracks by a charge-velocity measurement, while the two - dE/dx measurements in D2 and D4 are evaluated using the Vavilov distribution to determine the particle energy.

Table 1 describes the detectors in the telescopes. D1, D2 and D3 are large-area Li-drifted Si detectors. D4 is a CsI (T1) scintillator viewed by two Au-Si photodiodes optically coupled to the CsI (T1) using a technique developed at this laboratory. We have found that the photodiode-viewed CsI detector, unlike photomultiplier-viewed CsI detectors, remains stable in its calibration even after exposure to intense radiation in the Earth's radiation belts. Furthermore, the solid-state detectors have a linear response to nuclear charge from at least $1 \leq Z \leq 26$. The D5 detector is of different design in the two instruments (Figure 1 and Table 1), but this is not important in the analysis here since it serves only as a "yes-no" detector which tags the analysis of particles energetic enough to penetrate the D4 detector ($\gtrsim$ 95 MeV for protons). The Cerenkov detector (IMP-5 only) allows the determination of differential spectra up to the relativistic region ($\sim$ 1000 MeV per nucleon). Integral fluxes of nuclear species are measured for $\gtrsim$ 1000 MeV per nucleon. Figure 2 is a schematic block diagram of the logic and principal electronic functions for the IMP-5 version of this experiment.

The output of detectors D1, D2, D4 and CK is pulse-height-analyzed. In addition to pulse-height-analysis (PHA) information, each analyzed particle is tagged with a range identification (range ID) which specifies the depth of particle penetration into the detector stack. Table 2 shows the pulse-height matrices used for each range ID, and Figure 2 shows the relation between the range ID and incident kinetic energy per nucleon for different particle types. The telescope PHA and logic output data are comprised of subsets of - dE/dx vs. dE/dx-range, -dE/dx vs. E and - dE/dx vs. velocity measurements, allowing the differential analysis of cosmic ray spectra over three decades of kinetic energy per nucleon within a single telescope. The redundant - dE/dx measurements for particles of range ID $\geq$ 4 are included to provide a means of identifying those background events which lie on a particle track in a single matrix. By requiring that the two - dE/dx measurements for each event be mutually consistent, background in the instrument can be determined quantitatively without relying on assumptions about background levels under the pulse height distribution for particles of a given charge number. Details of this type of background subtraction in the IMP 4 and IMP 5 telescopes have been published elsewhere.

The IMP 4 and IMP 5 spacecrafts were launched into highly eccentric polar orbits from the Western Test Range at Vandenberg A.F.B., California.

The in-flight performance of both instruments was monitored by means of a calibration mode which takes place for 45 minutes every 2 days, allowing a precise monitoring of possible detector instabilities or gain shifts in the system. Detector stability is monitored by disabling the counting rate coincidences and counting the background events from the individual detectors. The IMP 4 detectors remained stable throughtout the 23-month mission, except for an increase in the background counting rate of the D3 detector after the sixth month. The IMP 5 detectors remained stable throughout their 42-month mission except during the fifth and sixth months when the D2 detector background increased. These increases in background counting rates of the D3 on IMP 4 and the D2 on IMP 5 did not interfere significantly with the analysis of data.

The pulse-height-analyzer calibrations were checked during a calibration mode by means of a series of pulses sent by an on-board electronic pulser of high stability. Except for some electronic degradation of the D4 channel in IMP 4 after the first year of the mission, gain shifts of all the detectors monitored in both instruments were less than the half-width of any particle track.

The combination of low background and high resolution achieved by the instruments in orbit was such that even the rare isotopes ^{2}H and ^{3}H were separated from the proton and ^{4}He components.

Figure 3 is a simplified block diagram showing the linear and logic circuit elements in the IMP 5 experiment. It is seen that the instrument output consists of two principal kinds of outputs: pulse-height analysis (PHA) information and counting rate information. The output of the analyzed detectors D1, D2, D4 and CK goes to an amplifier chain with a high gain region which smoothly merges with a low gain region in order to achieve a large dynamic range while avoiding the problems of switching between different amplifier sets. The D1 and CK share the same analyzer, with CK always having priority over D1. For each analyzed event, the telemetered information is: D1 (or CK), D2, and D4 PHA channel number, the range of penetration into the telescope, and the octant in the ecliptic plane viewed by the telescope when the event occurred. A priority system is included in the experiment to prevent abundant low energy particles or protons energetic enough to penetrate the telescope from dominating the analysis of particles with other ranges by assigning such events low priority. Other particles (i.e. those penetrating D1 but stopping in the telescope as well as penetrating particles of charge ≥ 2) are given high priority. A high priority event will erase any low priority event awaiting readout. After analysis a switch is set to inhibit further instrument analysis until the event has been read out.

Because the PHA information is read out every ~ 5 seconds, this channel only samples the incident particle spectra. In order to determine the sampling percentage, all particles entering the telescope are counted according to their depth of penetration into the telescope, using accumulators in the spacecraft encoder. Through the use of special accumulators, and automatic prescaling of counting rates in our instrument when flux levels are high, counting rates up to $\sim 10^5$ counts/second can be measured. The overall counting rate resolution of the instrument is ~ 5 micro-seconds.

Figure 4 shows the post-launch calibration history of the IMP 5 experiment as measured with an on-board electronic pulser which was activated every ~ 2 days throughout the mission. The shifts shown are smaller than the inherent resolution of the instrument for particle data. Note that most of the calibration changes occurred during the electronics "burn-in" during the first months of the mission. The periodice changes in the CK calibration are a reflection of the spacecraft temperature history, since the CK analyzers were specially compensated to balance out small temperature dependent gain changes in the photo-multiplier tube viewing the CK crystal. The periodic exposure of the instruments to the radiation belts had no measurable effect on instrument calibration or performance.

III. Instrument Fabrication Techniques

Fabrication of the flight instrumentation was accomplished through use of techniques which have evolved at the University since the beginning of the Space program. A substantial portion of the electronics were assembled in a soldered, cordwood modular style which utilizes a plugin interconnect system developed at the University for the IMP A series of instruments. An example of this type of construction is illustrated in Figure 5. This form of construction and the associated information on the drawing make possible the assembly of circuits by commercial organizations within the Chicago area. All electrical components to be used in University of Chicago flight instrumentation are purchased and screened by the Quality assurance group and subsequently kitted for assembly. The components are submitted together with the appropriate print to the assembly vendor. All the assembly information is contained on the print. After Assembly, the Modules are returned to the University for QA inspection and test prior to assembly at the next level on the plugin "mother" board. An example of this level of assembly is shown in Figure 5. This approach to electronics system buildup has greatly simplified the detailed design effort for flight instruments, since each module represents a functional circuit design which may be used in building-block fashion for the design of the next experiment. As new functional elements are required, they may be added in the same fashion to the library of building blocks.

IV. Mechanical Construction

The instruments flown on IMP 4/5 were designed to fit within the standard Goddard Space Flight Center IMP potting frame which was constructed of black anodized aluminum sheet. Except for the addition of aluminum sheet metal housings for shielding of individual amplifier assemblies, the remainder of the instrument telescope system was fabricated from magnesium alloy AZ31B which was processed with a surface conversion coating of Dow 7.

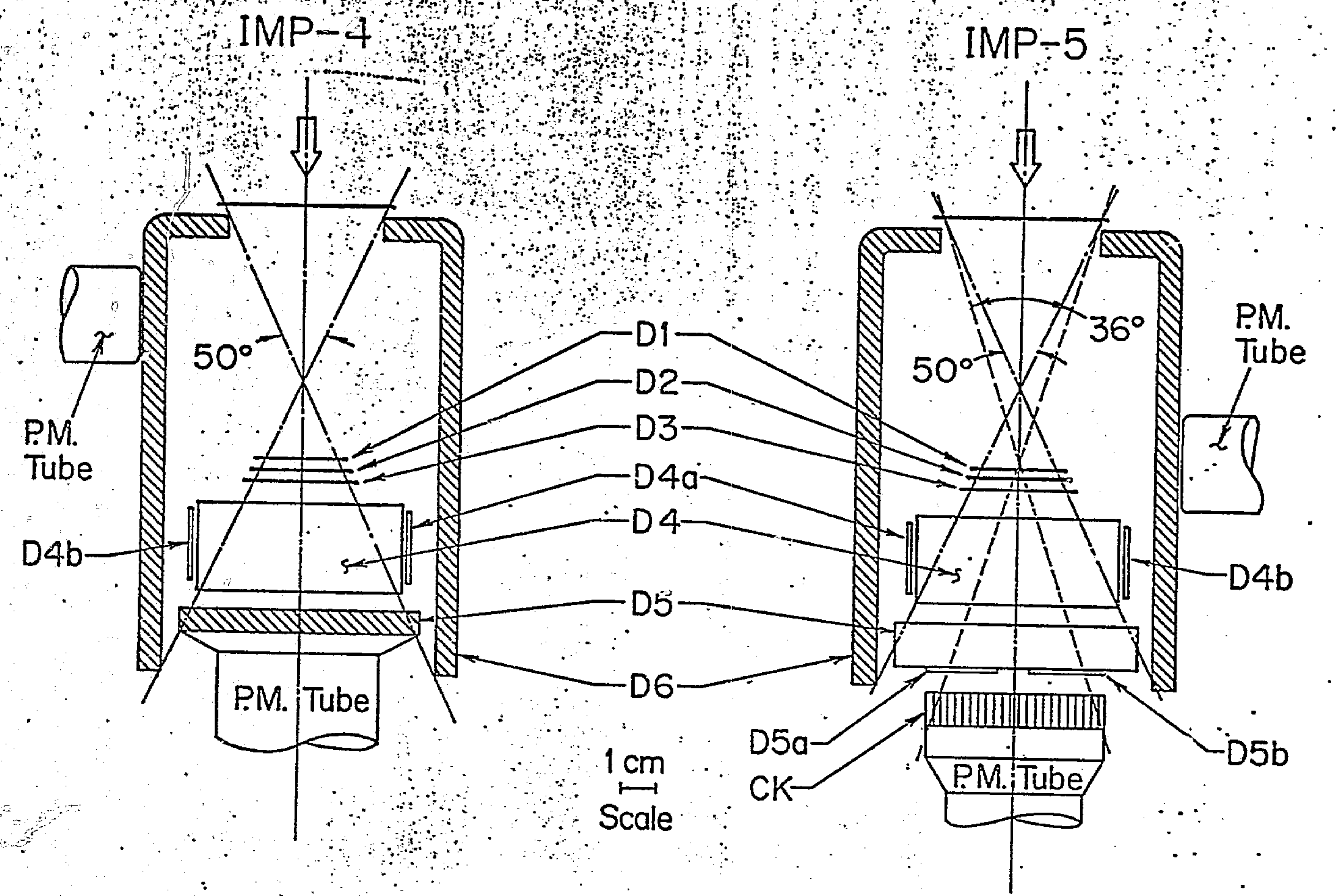
V. Problems Encountered

The most significant problem encountered in the hardware fabrication and test program centered on the use of a hybrid complementary binary circuit developed for the University by General Instruments Company. Samples of these devices, which suffered a high rate of failure, were submitted to GSFC for failure analysis. The analysis revealed that the failures resulted from the encapsulation process in which the materials used exhibited excessive thermal coefficient of expansion. Consequently, during thermal cycling, internal lead and component breakage occurred.

The devices were subsequently repackaged in ceramic cases and have proven to be comparatively reliable when assembled with due caution.

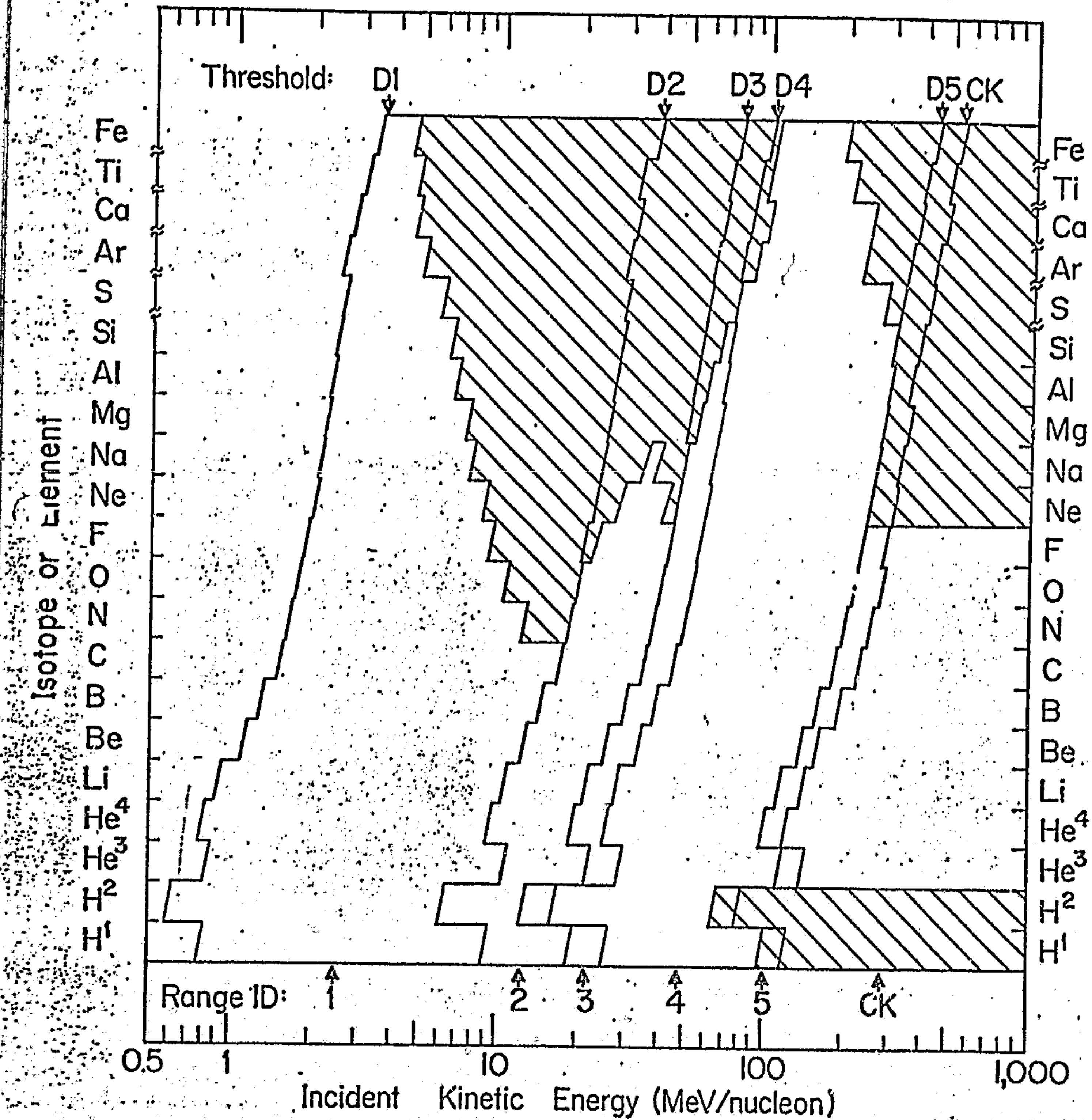
VI. Conclusion

The University of Chicago experiments flown on the IMP 4 and 5 spacecraft have proven to be quite successful and highly productive from a scientific point of view. The instrumentation design concepts evolved from earlier experiments conducted by University Investigators and have since served as a base for the design of instruments of further increased resolution and general overall performance.



IMP-4
IMP-5
50°
36°
50°
P.M. Tube
P.M. Tube
D1
D2
D3
D4a
D4
D5
D6
D4b
D4b
P.M. Tube
P.M. Tube
D5a
CK
D5b
1 cm
Scale

Figure 1



Threshold:
D1
D2
D3
D4
D5
CK
Fe
Ti
Ca
Ar
S
Si
Al
Mg
Na
Ne
F
O
N
C
B
Be
Li
He⁴
He³
H²
H¹
Isotope or Element
Range ID:
1
2
3
4
5
CK
0.5
1
10
100
1,000
Incident Kinetic Energy (MeV/nucleon)

Figure 2

IMP 5 University of Chicago Experiment

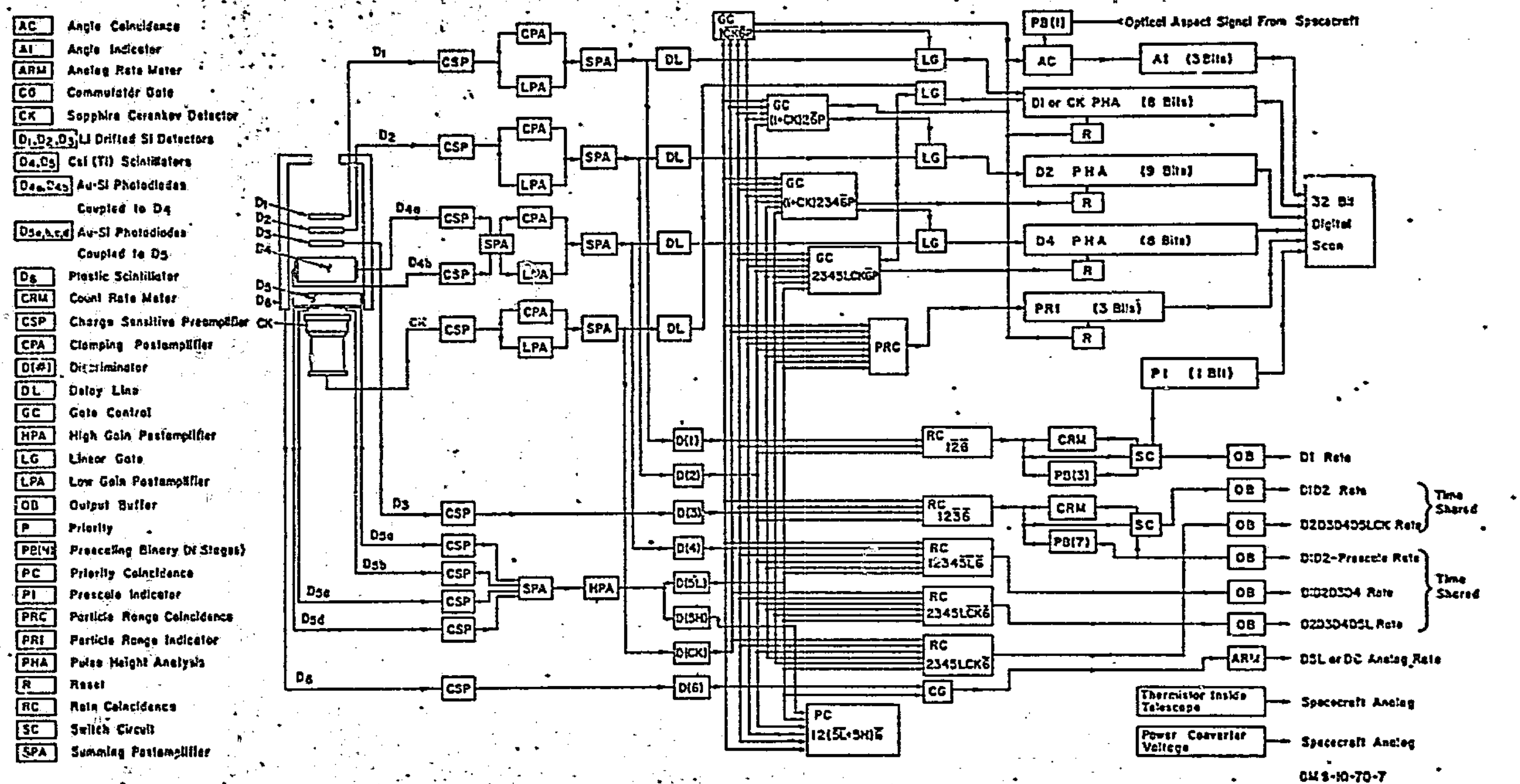


Figure 8.3

IMP-5 The University of Chicago

Amplifier Calibrations

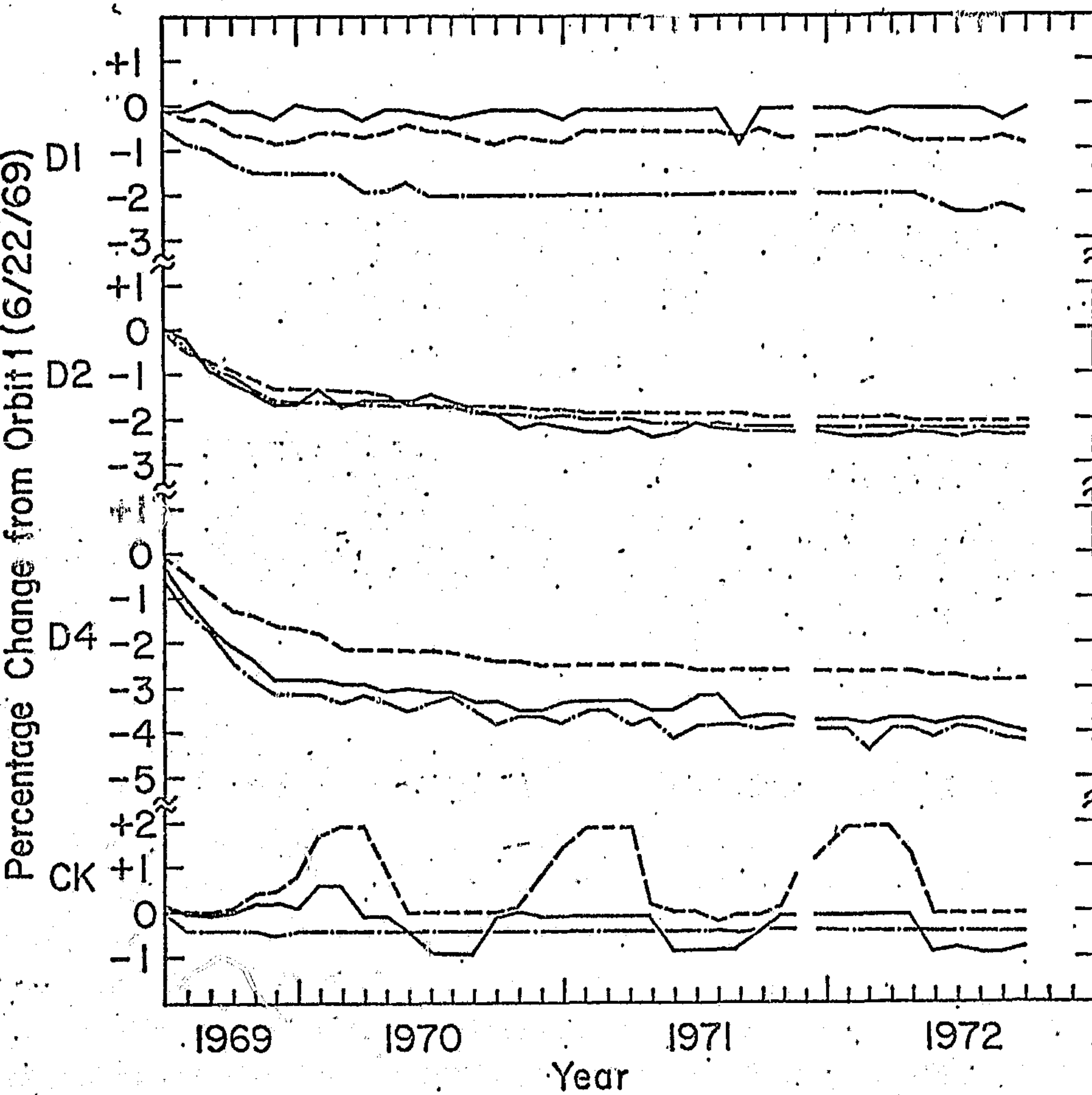
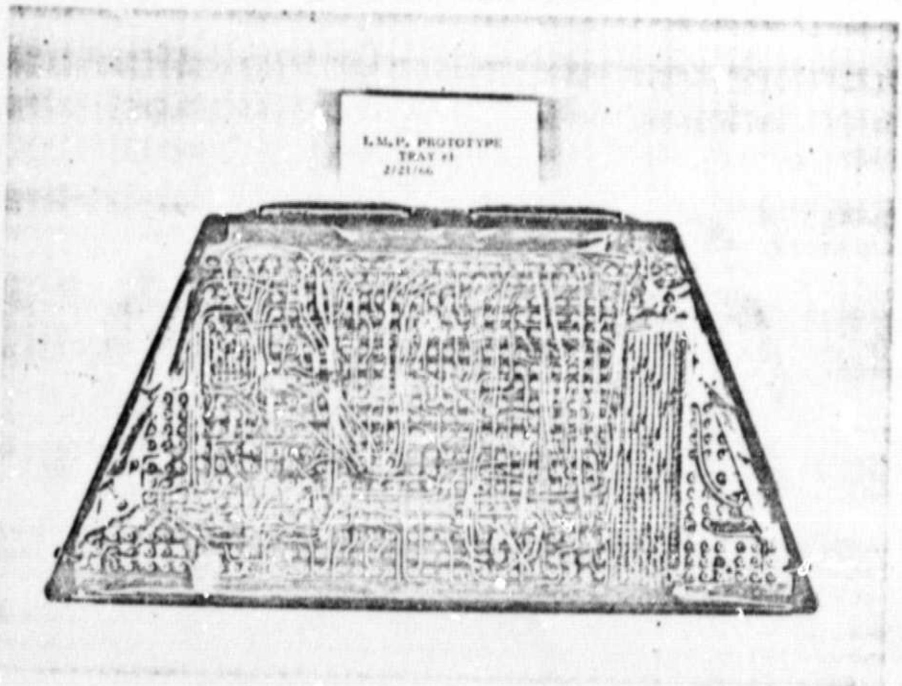


Figure 4

~~Figure 9~~



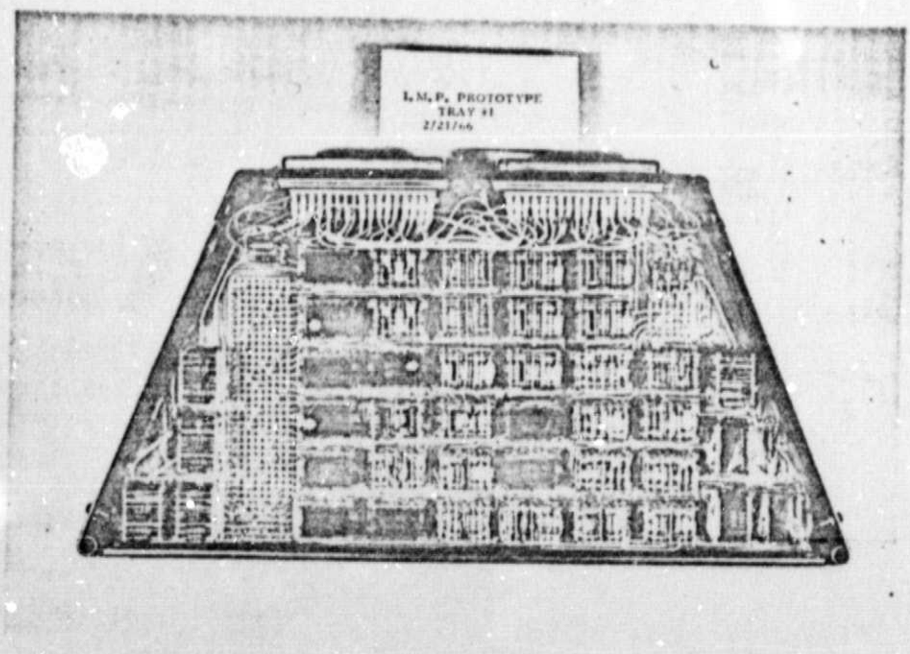


Figure 5

Table 1

COMPOSITION TELESCOPE DETECTORS

Absorber Name+		Material	IMP-4 Thickness ($g\text{-}cm^{-2}$)	IMP-4 Dynamic Range* (MeV)	IMP-5 Thickness ($g\text{-}cm^{-2}$)	IMP-5 Dynamic Range* (MeV)
Mylar Window		Aluminized mylar	1.24×10^{-3}	–	1.24×10^{-3}	–
D1	Sensitive layer	Li-drifted Si	8.81×10^{-2}	0.07 to 290	9.47×10^{-2}	0.17 to 220
	Dead layer		2.26×10^{-2}		7.6×10^{-3}	
D2	Dead layer	Li-drifted Si	3.19×10^{-2}	0.25 to 610	1.33×10^{-2}	0.33 to 740
	Sensitive layer		3.50×10^{-1}		3.62×10^{-1}	
D3	Sensitive layer	Li-drifted Si	1.93×10^{-1}	0.162	1.97×10^{-1}	0.14
	Dead layer		3.98×10^{-2}		1.98×10^{-2}	
D4		CsI (Tl)	1.15×10^{1}	15 to 7000	1.15×10^{1}	18 to 7900
D5	IMP-4	Plastic	6.48×10^{-1}	0.53		
	IMP-5	CsI(Tl)			5.72	4.4
CK		Sapphire	—	—	3.98	16 to Z < 10**

+A thin Ti shield between D1 and D2, and thin Mg housings around D4 and D5 are not included here.

* The first value given is that deposit needed to trigger the detector discriminator of lower threshold (several of the detectors have 2 discriminators). For pulse-height-analyzed detectors, the second value given is the approximate maximum deposit before amplifier saturation sets in.

** Due to scintillation of the sapphire Cerenkov radiator, an energy deposit of 16 MeV is sufficient to trigger the detector. The output of the Cerenkov detector due to scintillation light + Cerenkov light does not saturate the Cerenkov amplifier for particles of charge less than 10.

TABLE 2
COMPOSITION TELESCOPE RANGE INTERVALS

Range Identification (range ID)	IMP-4 Coincidence Requirement*	IMP-4 Counting Rates	IMP-4 Particles Identified by Measurement of: (PHA matrices used)	IMP-5 Coincidence Requirement*	IMP-5 Counting Rates	IMP-5 Particles Identified by Measurement of: (PHA matrices used)
1	$D1\overline{D2D6}$	Yes	Energy vs. range (D1)	$D1\overline{D2D6}$	Yes	Energy vs. range (D1)
2	$D1D2\overline{D3D6}$	Yes	-dE/dx vs. E (D1 vs. D2)	$D1D2\overline{D3D6}$	Yes	-dE/dx vs. E (D1 vs. D2)
3	$D1D2D3\overline{D4D6}$	No	-dE/dx vs. -dE/dx - range (D1 vs. D2)	$D1D2D3\overline{D4D6}$	No	-dE/dx vs. -dE/dx-range (D1 vs. D2
4	$D1D2D3D4\overline{D5_L D6}$	Yes	-dE/dx vs. E (D1 vs. D4; D2 vs. D4)	$D1D2D3D4\overline{D5D6}$	Yes	-dE/dx vs. E (D1 vs. D4; D2 vs. D4)
5	$D1D2D3D4D5_L\overline{D5_H D6}$ +	Yes, with no $D5_H$ requirement	-dE/dx (D1 vs. D4; D2 vs. D4)	$D2D3D4D5\overline{CKD6}$ ‡	Yes	-dE/dx vs. -dE/dx-range (D1 vs. D4; D2 vs. D4)
6 (CK on IMP-5)	$D1D2D3D4D5_L D5_H\overline{D6}$			$D2D3D4D5CK\overline{D6}$ ‡	Yes	-dE/dx vs. charge-velocit (D2 vs. CK; D4 vs. CK)

* Notation: $D1\overline{D2D6}$ reads: D1 fired, D2 and D6 NOT fired.

\+ On IMP-4, threshold $D5_L$ ($L \equiv$ low) is set for minimum ionizing protons, and threshold $D5_H$ ($H \equiv$ high) is set for minimum ionizing He^4 nuclei.

‡ On IMP-5, D1 is not required on range ID5 and ID6 so as to include minimum ionizing protons.