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AMES COLLABORATIVE STUDY OF COSMIC-RAY NEUTRONS. II: LOW- AND MID-LATITUDE FLIGHTS

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"The untented kosmos my abode
Ipass, a wilful stranger;
My mistress still the open road
And the bright eyes of danger."

—from Youth and Love
Robert Louis Stevenson
1850-1894

1. INTRODUCTION

The collaborative study to more precisely define the properties of the cosmic ray produced neutron spectrum have been previously described in detail [He76] and preliminary results obtained from three flights at northern mid-geomagnetic latitudes (30°N $\leqslant \lambda \leqslant$ 48°N) published [He78].

In this second report of experimental data, the data obtained from six flights made in the period August - October 1975 are described and discussed. All data were taken aboard the NASA Airborne Observatory, a C-141 aircraft, based at the Ames Research Center.

2. SUMMARY OF FLIGHT PATHS

Four flights (flights numbered 4 through 7) originated from Hickam Field, Hawaii, and the flight paths are shown on Fig. 1. These flights, which were made primarily to facilitate astronomical observations, happened to follow flight paths of almost constant geomagnetic latitude, in the range 17°N $\leqslant \lambda \leqslant$ 21°N, which was very convenient for the measurement of cosmic ray radiation. Altitude during the flights varied from 12.5 km to 13.7 km (41,000 ft to 45,000 ft).

Following the four flights from Hawaii, which took place in August 1975, two flights originating from Moffett Field were utilized to calibrate the instruments flown from Hickham Field. The flight paths of these latter flights (#8 and #9) are shown in Fig. 2. With the exception of one leg on Flight #9, there was a large variation in geomagnetic latitude on these two flights.

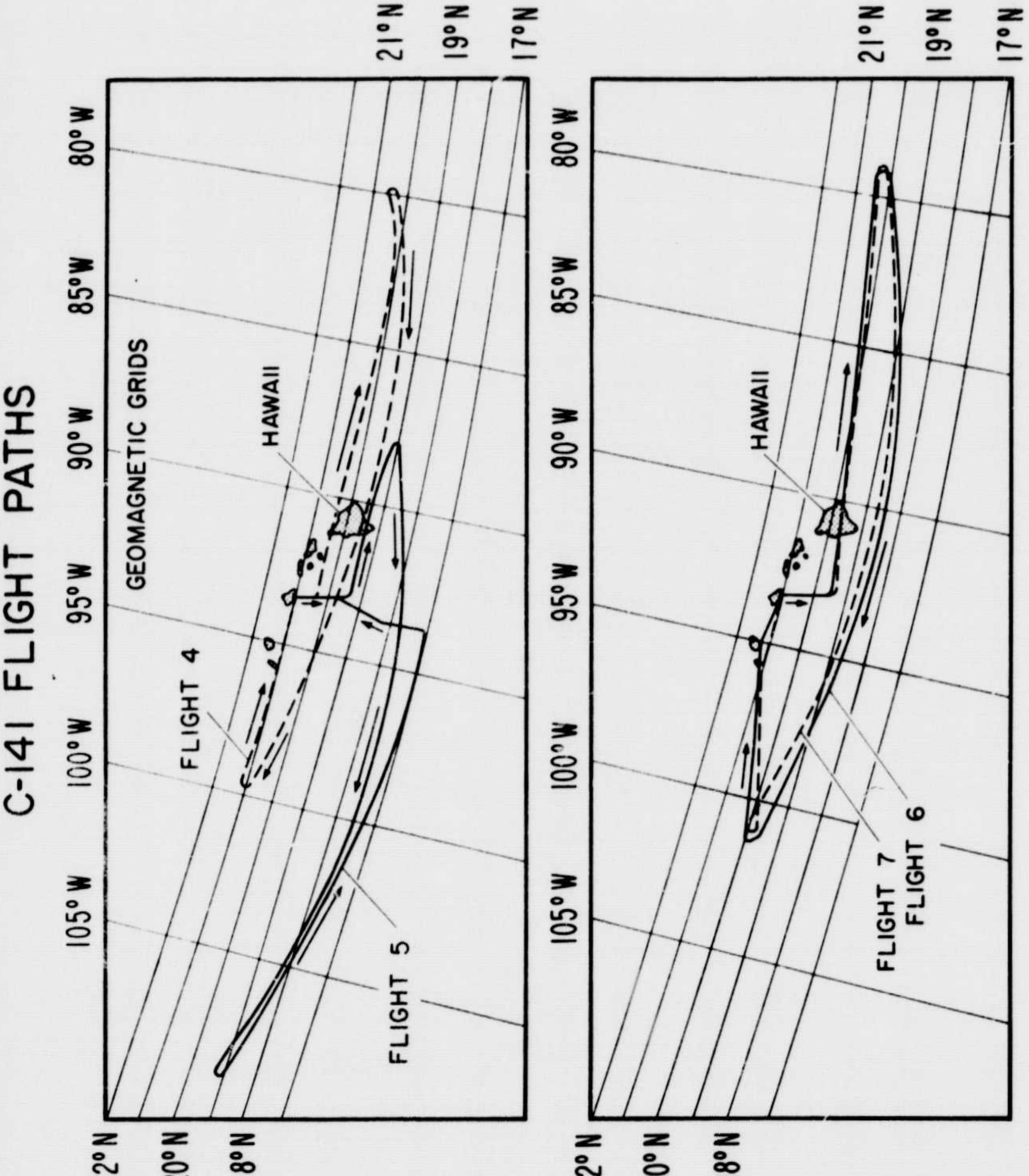

Fig. 1. Flight paths of the four flights (Flights #4-#7), originating from Hawaii (August 1975).

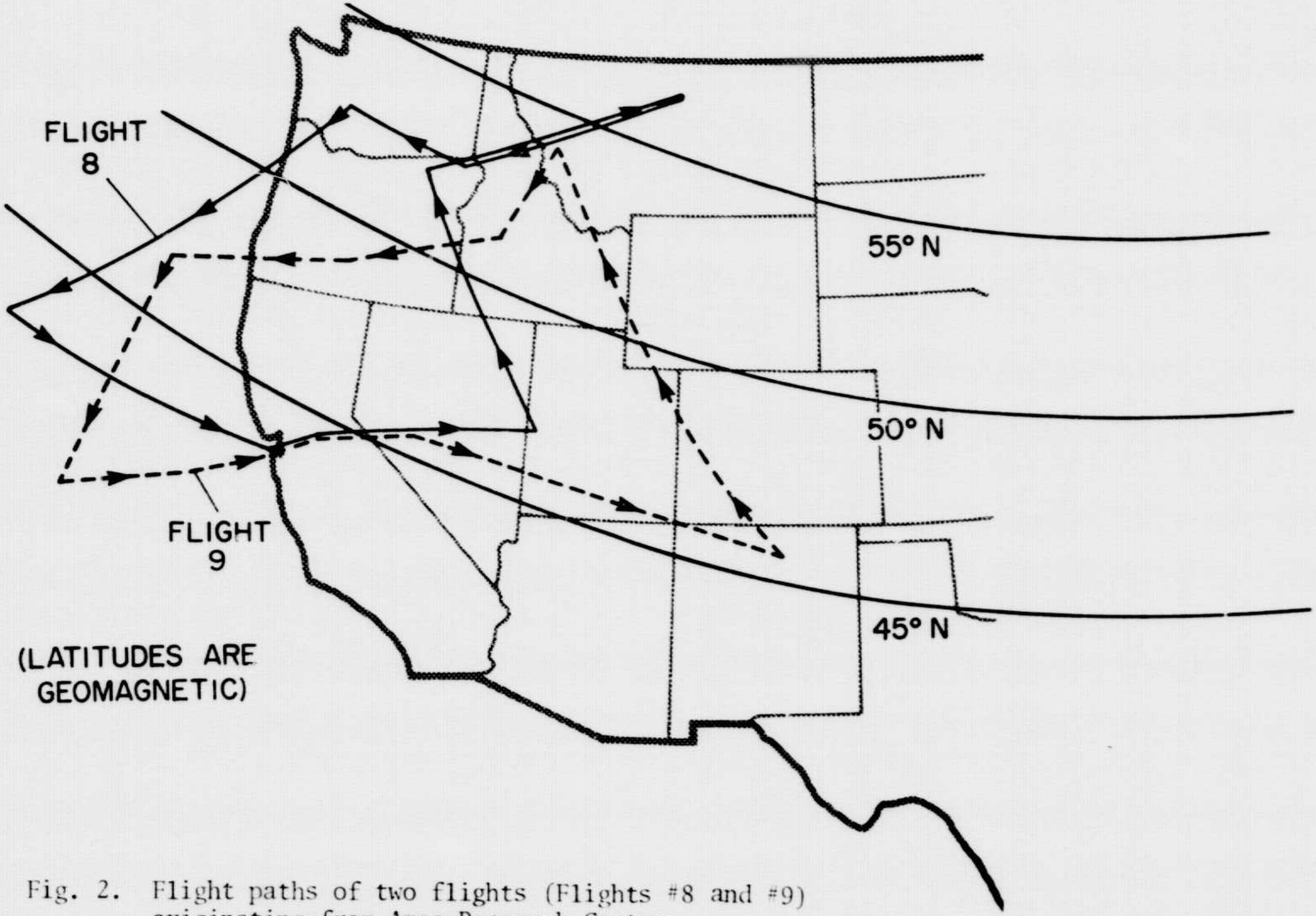

Fig. 2. Flight paths of two flights (Flights #8 and #9) originating from Ames Research Center (29 and 30 October 1975).

3. INSTRUMENTATION

Hewitt et al [He76, He78] have described the radiation detectors that may be routinely flown aboard the C-141 aircraft.

A Reuter-Stokes ionization chamber and a Bonner sphere neutron spectrometer obtained data during the Hawaii based flights. In addition, the operation of a recoil proton scintillation counter spectrometer [He76] and a large area bismuth fission chamber [Mc65] were tested during flight conditions.

The dimensions of the moderators of the Bonner sphere neutron spectrometer are summarized in Table 1.

TABLE 1. Bonner sphere spectrometer moderators (flights #4 - #9)

Moderator size	Moderator material
5.1 cm (2 in.)	CH_2
7.6 cm (3 in.)	CH_2
12.7 cm (5 in.)	CH_2
20.3 cm (8 in.)	H_2O
25.4 cm (10 in.)	H_2O
30.5 cm (12 in.)	H_2O
45.7 cm (18 in.)	H_2O

The smaller moderators (5 inch diameter and less) were of polyethylene, while the larger moderators consisted of water-filled aluminum shells. Interpretation of the data taken in Hawaii is made difficult because these mixed moderators were used and also because a LiI crystal 8 mm dia. × 4 mm high was used to detect thermal neutrons, rather than the standard 12.7 mm dia. × 12.7 mm high (0.5 in. × 0.5 in.) crystal for which response functions have been calculated.

The experimental data taken with the smaller crystal were later normalized to that which would have been observed had a standard-size crystal detector been used. These normalization factors were obtained during Flights #8 and #9 at higher geomagnetic latitudes (44°N to 56°N). During the flights originating from Ames Research Center (Flights #8 and #9) aluminum activation detectors were flown in addition to the Bonner sphere spectrometer.

4. EXPERIMENTAL DATA AND ANALYSIS

4.1 Ionization Measurements

The high pressure, argon-filled ionization chamber was aboard all flights. Prior to the Hawaiian series of measurements it was calibrated using an instrument which had been calibrated at the standard range of the Health Physics Group, Stanford University. The experimental data obtained are presented in Table 2 in the range of geomagnetic latitude $17°N \leq \lambda \leq 21°N$ and at altitudes between 41,000 ft and 45,000 ft. The exposure rate varied from 200 μR/hr to 230 μR/hr. During flights #8 and #9, at a geomagnetic latitude of 45°N the exposure rates measured were 375 μR/hr and 383 μR/hr respectively

4.2 Neutron Measurements and Spectrum Determination

The average of the counting rates obtained for each sphere during the flights originating from Hawaii are summarized in Table 3. Data were

TABLE 2. Ionization chamber measurements.

Flight number	Geomagnetic latitude, λ. (deg. North)	Altitude (ft)	Exposure rate (μR/hr)
4	19.5 - 21	41,000	202
		43,000	215
		45,000	225
5	17 - 19	41,000	200
		45,000	227
6	18.5 - 21	41,000	202
		45,000	230
7	18.5 - 21	41,000	200
		43,000	210
		45,000	230
8	45	41,000	383
9	45	41,000	375

TABLE 3. Average counting rates measured during the Hawaii flights (normalized to a LiI detector 0.5 in dia. × 0.5 in. high, and a geomagnetic latitude of 20°N).

Moderator diameter (inches)	Altitude (ft)	Counting rate (cpm)	Standard deviation (±%)
0	41,000 ft	14.3	22
2	$\lambda = 20°$N	27.5	19
3		38.9	12.8
5		57.9	5.4
8		57.0	4.4
10		50.7	5.5
12		39.4	5.3
18		14.8	13
0	45,000 ft	--	--
2	$\lambda = 20°$N	25.5	10.6
3		38.2	8.0
5		66.6	6.2
8		66.5	5.1
10		55.2	5.3
12		45.2	6.1
18		17.0	11.8

TABLE 4. Northern latitude flights; LiI detector counting rates 0.5 in × 0.5 in.

	Bonner sphere diam (in.)	Altitude (ft)	Counting rate (cpm)	Standard deviation (±%)
October 29, 1975	0	41,000	59.2	3.6
	2		136.8	1.7
	3		223.4	5.4
	5		302.5	1.5
	8		283.17	1.8
	10		224.5	1.2
	12		165.4	1.6
	18		--	--
	8-in. aluminum disc		26.6	3.8%
October 30, 1975	0	41,000	51.3	5.4
	2		108.	2.5
	3		193.	1.4
	5		257.	1.4
	8		236.5	1.4
	10		193.	1.3
	12		143.9	1.2
	18		69.5	2.4
	8-in. aluminum disc		24.1	5.8%

obtained at two altitudes -- 41,000 ft and 45,000 ft. A moderated BF_3 counter was used to monitor the variations in counting rate due to changes in geomagnetic latitude and alitutude and to correct the counting rates observed in the various moderators of the Bonner sphere spectrometer [He78]. The data of Table 3 are normalized to a geomagnetic latitude of 20°N.

In addition to normalization with respect to geomagnetic latitude, the data of Table 3 have been normalized to the counting rate that would have been observed, had a standard 0.5 in diam. × 0.5 in. high LiI crystal been used. As discussed in Section 3, a detector of non-standard size was used. Because the moderator response functions have been calculated for a 0.5 in diam. × 0.5 in. high LiI crystal, it was necessary to determine normalization factors. These factors were obtained during flights #8 and #9. The factors obtained in this way are uncertain to the extent that they vary with neutron spectrum and the cosmic ray neutron spectrum varies with geomagnetic latitude. At the present time, errors introduced by this normalization procedure are judged to be much smaller than errors due to other sources.

Table 4 summarizes the experimental counting rates observed in the calibration flights #8 and #9.

Measurements made with the recoil proton spectrometer were perturbed by aircraft vibration during flight. (This problem has subsequently been mitigated by an improved mounting system.) Because of this vibration the data show a larger statistical spread than had been obtained in previous flights [He76, He78]. The spectrometer was used to determine the neutron flux density in the energy range 3 MeV $\leq E_n \leq$ 13 MeV and the data obtained compared with measurements of the moderated BF_3 counter (which measures neutrons from thermal energies to about 20 MeV) are summarized in Table 5. During operation the proton spectrometer was calibrated with a standard NBS PuB(α,n) neutron source and checked with a ^{252}Cf neutron source.

TABLE 5. Neutron density measured at two latitudes (altitude 41,000 ft).

Geomagnetic latitudes, λ (deg. N)	Flux density measured by the recoil proton spectrometer (n/cm^2 - sec)	Flux density measured by the moderated BF_3 counter (n/cm^2 - sec)
50.7	0.35 ± 5%	2.28 ± 1.5%
20	0.084 ± 14%	0.437 ± 1.8%
Ratio of the flux density at 50.7°N to that at 20°N:	4.2 ± 15%	5.2 ± 2.4%

4.3 Neutron Differential Energy Spectrum

The experimental data obtained with the Bonner sphere spectrometer have been used to estimate the neutron differential energy spectrum with the computer program LOUHI [Rou69]. The results are shown in Fig. 3.

The LOUHI unfolding routine permits varying constraints to be placed on the rapidity and magnitude of fluctuations in the solutions it generates. This is achieved by the use of a smoothing parameter, γ, which normally is given values between 0 and 1.0. The higher value of γ, the more constrained are fluctuations in the solution generated and the lower the ability to resolve sharp structure in the spectrum. Figure 3 shows

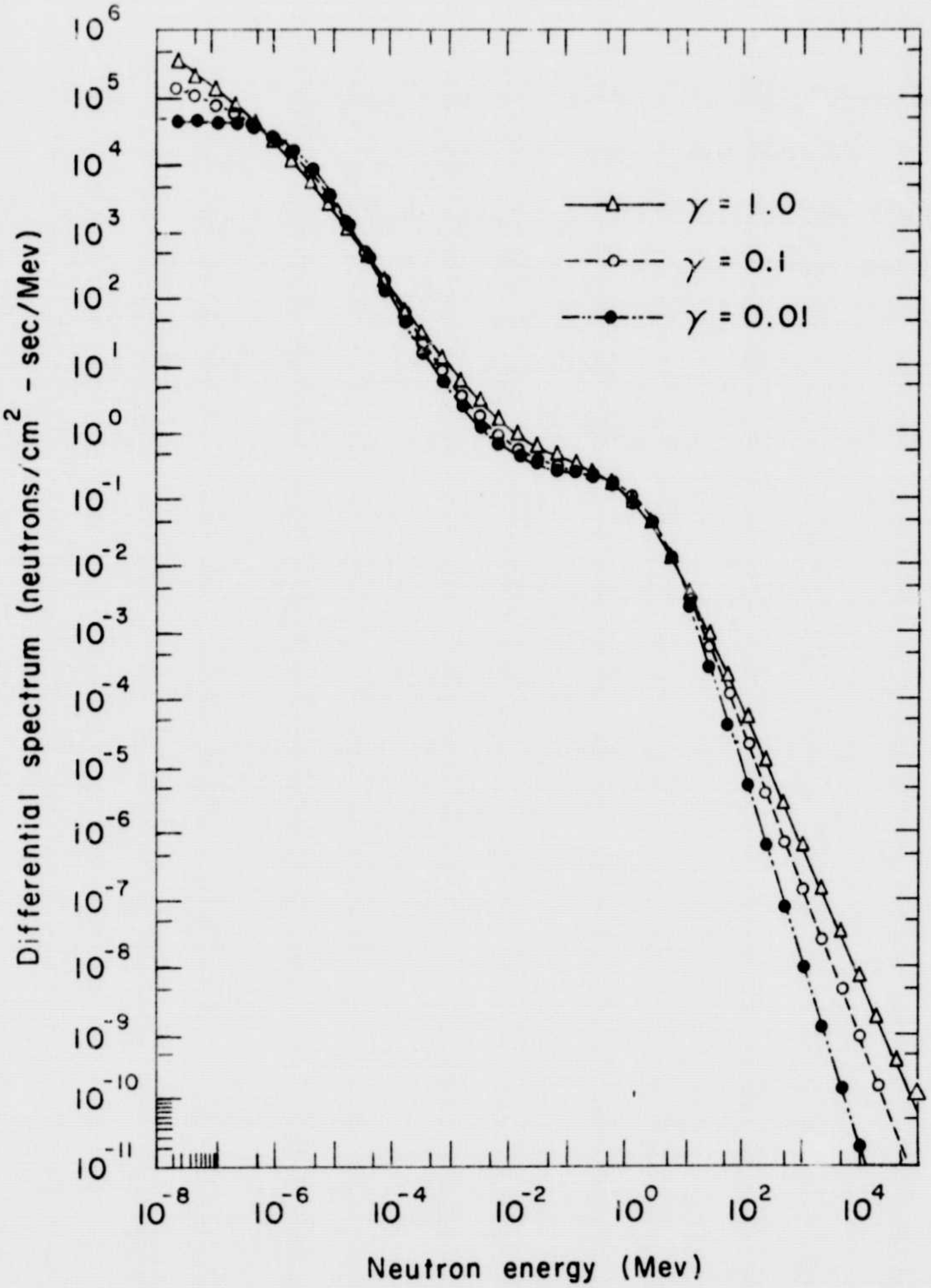

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Fig. 3. Neutron differential energy spectra unfolded from the Hawaii data [41,000 ft; geomagnetic latitude 20°N for different values of the smoothing parameter γ].

solutions for values of $\gamma = 1.0$ (heavily damped), $\gamma = 0.1$ (moderately damped) and $\gamma = 0.01$ (slightly damped). Significant differences in the calculated spectra are evident, but it is not entirely clear whether this inconsistency is due to fluctuations of statistical origin or systematic errors introduced by the use of two detectors of different size and a mixed set of moderators.

Table 6 summarizes data taken during Flight #9 on 30 October 1975 and Fig. 4 shows the differential neutron spectrum calculated by the LOUHI routine. This spectrum is important in that it is obtained from data taken with a complete set of Bonner moderators and from an aluminum activation detector. It represents a significant step forward in our goal to obtain an improved determination of the cosmic ray neutron spectrum.

TABLE 6. Moffett Field Flight #9, 30 October 1975. 0.5 in. diam. × 0.5 in. high LiI and aluminum activation detector counting rates.

Moderator diameter	Counting rate (cpm)
0 in.	51.3
2 in.	108.
3 in.	193.
5 in.	257.
8 in.	236.
10 in.	193.
12 in.	144.
18 in.	69.5
$Al^{27} \rightarrow Na^{24}$	24.1

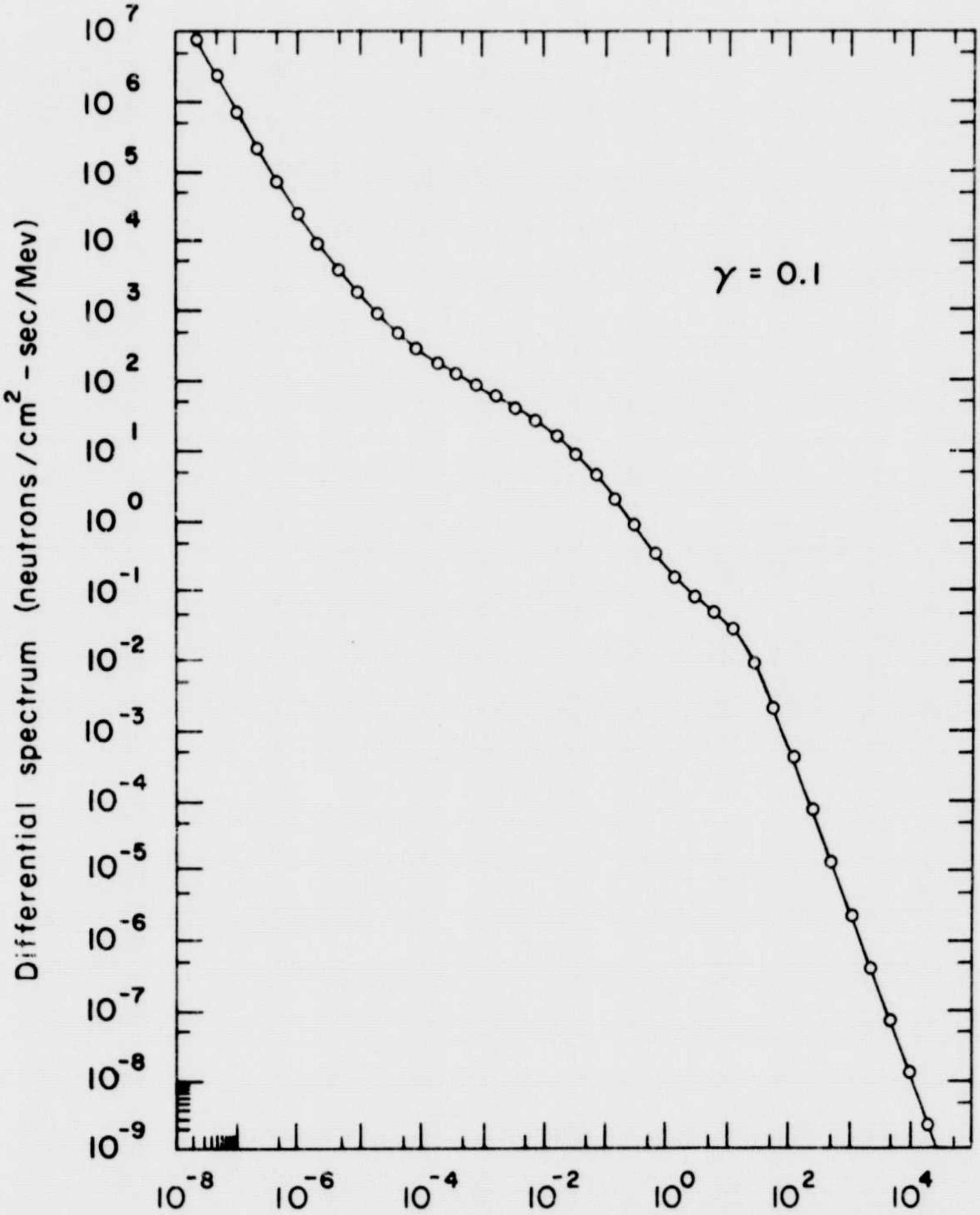

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Fig. 4. Neutron differential energy spectra unfolded from data obtained during Flight #9 originating from Moffett Field. [Altitude 41,000 ft; geomagnetic latitude 45°N; smoothing parameter $\gamma = 0.1$].

Analysis of the data obtained during Flights #4 through #9 have shown that:

a) Data obtained with the Bonner spheres must have a statistical accuracy of about ±1% if the neutron spectrum in the region 0.1 to 10 MeV is to be well defined. (At the present time our data contain statistical errors ranging from ±1% to ±20%.)

b) It will be desirable to obtain a complete set of experimental data with a moderator made of one material.

c) Data should be taken with LiI detectors of the standard dimensions (0.5 in. diam. × 0.5 in. high).

5. CONCLUSIONS

The data taken aboard the six flights described here have enabled significant progress to be made.

First, and most importantly, we now know that Bonner sphere data of accuracy adequate to determine the cosmic ray neutron spectrum may be obtained in flight of duration 4-6 hours. The taking of data simultaneously on all moderators will enable the required statistical precision of ±1% to be obtained and will remove any systematic uncertainties introduced by our present normalization technique.

Second, we know that the moderator response functions calculated by Sanna are internally consistent.

Third, we have been able to combine Bonner sphere data with aluminum activation detector data.

Fourth, we have flow the bismuth fission counter and found it to be stable and reliable in operation during flights at high altitudes.

The ultimate addition of data from this detector is most important to the determination of the high-energy neutron flux density.

Fifth, we have obtained a great deal of insight into the operation of LOUHI.

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