MEASUREMENTS OF THE NEUTRON INTENSITY IN SPACE

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FINAL REPORT

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I. INTRODUCTION

The emphasis under this contract has been upon the following specific tasks:

1. Measurements of the fast-neutron flux and energy spectrum near the top of and above the atmosphere;

2. Measurements of the gamma-ray (γ-ray) flux and energy spectrum in the energy interval 0.5-10 Mev simultaneously on the same flights;

3. Extend the energy range of the neutron and gamma-ray detectors;

4. Complete a rocket flight to measure the fluxes of neutrons, γ-rays, X-rays (0.1-2.0 Å range) and low-energy charged particles above the atmosphere.

2. THE ENERGY SPECTRA AND FLUXES OF FAST NEUTRONS AND GAMMA RAYS IN THE ATMOSPHERE

A series of balloon flights have been made carrying a UNH-designed payload to measure the fast-neutron energy spectrum and flux at the top of the atmosphere. The dates and locations were as follows:

1. April 22, 1969, Palestine, Texas

2. April 3, 1970, Palestine, Texas

3. July 5, 1970, Ft. Churchill, Canada

4. October 22, 1970, and November 18, 1970, Parana, Argentina.

In all the above flights, except at Parana, extensive data were obtained on the fast neutron and gamma-ray fluxes. In the Ft. Churchill and Argentina flights the total neutron flux from about 10^{-3} to 10 Mev was measured with a moderated He^3 proportional counter similar to that flown previously on rocket flights (Lockwood and Friling, 1968). This He^3 detector is also a prototype of the UNH OGO-6 detector (Lockwood et al., 1969). The balloon flights carrying the He^3 detector, although not simultaneous with the satellite detector, do provide comparisons of the neutron flux at ~5 g cm^{-2} and the neutron leakage flux. The results of the first flight have been analyzed provisionally. The final analysis of all the flights will be completed when the fast neutron detector has been calibrated, probably at the Lowell Technological Institute accelerator, later this summer. In these analyses considerable effort will be made to deduce a γ-ray spectrum in the energy interval 1-10 Mev. Since our detecting system separates the electrons from protons and alphas, we can discuss a γ-flux and spectrum without any contributions from these background efforts.

The data from the April 22, 1969, flight were included with those of an earlier flight (September 7, 1968) and analyzed (Lockwood et al., 1970). In the neutron energy range (3-17 Mev) at 42^{o}N (P_c = 4.4 Gv) and at an altitude 5.5 g cm^{-2}, the slope of the differential neutron energy spectrum given by $dN/dE = BE^{-\beta(E)}$ was 2.0 ± 0.15 between 3.5 - 7.0 Mev and 1.0 ± 0.15 in the range 7-17 Mev. The details of these measurements are presented in Appendix A.

3. ROCKET FLIGHT MEASUREMENTS

A new rocket payload was prepared in 1969 for launch in the summer of 1970. The layout of the payload is shown schematically in Figure 1. The following experiments were originally included:

1. Neutron-γ detector (Lockwood);
2. Moderated He^3 counter to measure the neutron flux from 10^{-3} to 10 Mev (Lockwood);
3. Solar X-ray measurements (Houston);
4. Electron density measurements (Houston);
5. Low energy electron detectors (Arnoldy);
6. Low energy X-ray measurements (Webber).

The experiments included are briefly described as follows:

1. Neutron-γ Detector

The neutron-γ ray detector was designed to measure the flux and energy spectrum of the two neutron radiations in the energy range 3-17 Mev and 1-10 Mev. The n-γ detector and surrounding charged-particle anticoincidence shield were similar to those flown on balloon flights (St. Onge and Lockwood, 1969; St. Onge and Lockwood, 1969). The purposes of the measurements are discussed in Appendix A and in Lockwood et al. (1970).

2. Moderated He^3 Neutron Detector

A moderated He^3 neutron detector was included to compare with previous flights (Lockwood and Friling, 1968) and with the UNH OGO-6 detector (Lockwood et al., 1969). The details of the detecting system are described fully in the references cited. This provided a direct comparison of the 1-10 Mev ("fast") neutron leakage flux with the total neutron leakage flux.

3. Solar X-ray Measurements

The X-ray detector will be used primarily to measure the solar X-ray in the upper "D" layer (85-95km) and the "E" layer (95-120 km). X-ray flux measurements will be taken simultaneously with measurements of the electron-density (Faraday rotation) and a Lyman α-flux. The solar X-ray flux throughout the whole flight will be monitored; and, in addition, the detector will scan a large portion of the sky. This detector subtends a total solid angle of $\pi/40$ ster. with the azimuthal resolution equalling 36°. The X-ray energy range to be covered is from 0.08 to 6 keV to be divided into three bands: 0.08-0.3 keV, 0.3-1 keV, and 1-6 keV. The detector will be time-shared between these three bands in the time ratios of about 6:1:1 respectively. Energy resolution from 0.08-0.30 keV will average about 50% or better (depending upon statistics), while there will be no energy resolution in the other bands. The large dynamic range of fluxes will be covered by splitting the range ($0 \rightarrow 10^9$ photons/cm^2/sec) up into pulse-counting and analogue (current) ranges.

The detector consists of a rotating (0.3 Rev/sec) absorber-photocathode combination mounted concentrically on a wheel, with the photoelectrons detected by an electron multiplier (Channeltron). The absorber is a constantly varying aluminum layer deposited on 1000 Å of Formvar and 2000 Å of carbon. The photocathode is uniform MgF_2 (3000Å). The combination gives a swept high-pass filter characteristic. The geometry of the photocathode, and the 2000 Å carbon layer (and Aℓ) give extremely high rejection of the ultraviolet light. A pair of deflection plates provide low-energy, charged particle rejection, while protection against arcing is provided by feedback circuitry which disengages the high voltage for 5 sec should arcing occur.

4. Electron density measurements

This is a radio propagation experiment at 1.6 MHz to determine the electron distributions in the lower ionosphere. Faraday rotation data obtained from the rocket telemetry signal and the appropriate linearly polarized ground transmission are used to determine the difference in the ordinary and extraordinary indices of refraction. In addition, measurements of the 1217 Å and 1450 Å radiation flux are made.

5. Low Energy Electron Detectors

One double electrostatic analyzer identical to that being built at UNH for the NASA ATS-F satellite will be flown. It will be operated in the electron mode on both sides. Fifty point spectral measurements will be made each second from a few eV to 175 eV and a few eV to 15 keV energy by the analyzers. Bendix Channeltron electron multipliers will be used as the electron sensors. The data will be handled by a digital encoder with a bit rate of 2000 BPS transmitting on subcarrier 17 of the FM-FM payload telemetry.

The experiment objectives are both scientific and developmental. Scientifically, we wish to explore the suprathermal electrons observed by low altitude satellites at low L values. The sources of these particles is postulated to be the inner Van Allen belt from which the particles are convected down by the dynamo electric field. The instrumental objective is to study the ultraviolet immunity of the electrostatic analyzer. As mentioned above, similar analyzers will be flown on the ATS-F mission and will be exposed at certain parts of its orbit to strong solar ultraviolet radiation. It is believed that the design of the analyzer is adequate to operate normally during this exposure, but we welcome this opportunity to evaluate the analyzer under flight conditions.

6. Low Energy X-ray Measurements

The X-ray experiment was designed to survey the background radiation and to look at known sources in the 1.5 to 15 keV energy range using two back-to-back proportional counters with thin Beryllium windows. The counters have large areas (206 cm^2 each) and narrow collimation. One counter viewed the sky through a 3^o hexagonal collimator and covered the 1.5 to 6.0 keV energy range in two intervals. Both counters were filled with one atmosphere of a Xenon-CO_2 mixture and operated in anticoincidence to greatly reduce the charged particle background.

The rocket flight was launched 0830 EDT July 30, 1970, after what was assumed to be thorough preflight tests. Break-up of the payload was concluded to occur at T+18 sec. An extensive review was made, both at GSFC and UNH, of this failure. As a result, a more comprehensive Flight Loads, Moments and Deflections Program has been made to check bending and stability. The payload scheduled for flight on August 1, 1971, has been modified slightly to come within the allowable tolerances for bending and stability.

4. NEW NEUTRON-GAMMA DETECTING SYSTEM

The neutron-gamma ray detecting system previously flown on several balloon flights at different latitudes has been redesigned. The first flight of a part of this system will be made this fall.

The primary neutron-gamma detector consists of a 5 x 5 inch diameter liquid scintillator cell (NE213), the light output from which is pulse-shaped discriminated. (Ultimately an 8 x 8 inch diameter cell will be used to increase the gamma-ray efficiency). The pulse-shape discriminating circuit has been improved and is based upon a type used by St. Onge (private communication, 1970). With the new PSD circuit, M values of 4-5 for 2 x 2 inch diameter cells are obtained. For 5 x 5 inch diameter cells M $\sim$ 2 is obtained. The output display on a conventional, two parameter PHA can be varied to achieve a wider dynamic energy range without sacrificing pulse separation. The necessary circuitry to achieve this is shown schematically in Figure 2. As shown, the system utilizes Ortec or Canberra modules. Some portions of the system have been replaced with our own circuits. We are including with this system a new 1024 channel PHA (Kish, private communication, 1971).

The above n-γ detector will ultimately include a directional anticoincident shield so that one or more of these detectors can be used to detect gamma rays from extra-terrestrial sources. Since the scintillator is relatively inexpensive and the associated electronics relatively simple, it should be a reliable gamma-ray detector in the 0.5-15 Mev energy range. The final design of the shield will be made after flights in collaboration with Professor W. R. Webber's 12-2000 keV X-ray detector.

Since it is possible to pulse-shape discriminate large NE213 cells (5 x 5 inch diameter or greater), two cells can be flown, separated by 30-75 cm to provide directionality to the neutron measurements. The pulse height data from both detectors will be separately identified, as well as coincidence events within 50 ms in the two detectors. The necessary fast-timing circuits are now being developed. (These circuits are quite conventional because, for a separation of 20-75 cm, the time of flight of 20 Mev neutrons is about 4-12 ns. Of course, since the number of second scattering events is low even with 5 x 5 inch NE213 cells, the pulses will be merely identified and the time of the flight distribution read out by the scaler. Clearly, the resolution is poor, but neutrons moving upwards and downwards can be definitely separated. In special solar events this crude time-of-flight analysis is useful in assigning an upper limit to the neutron flux.

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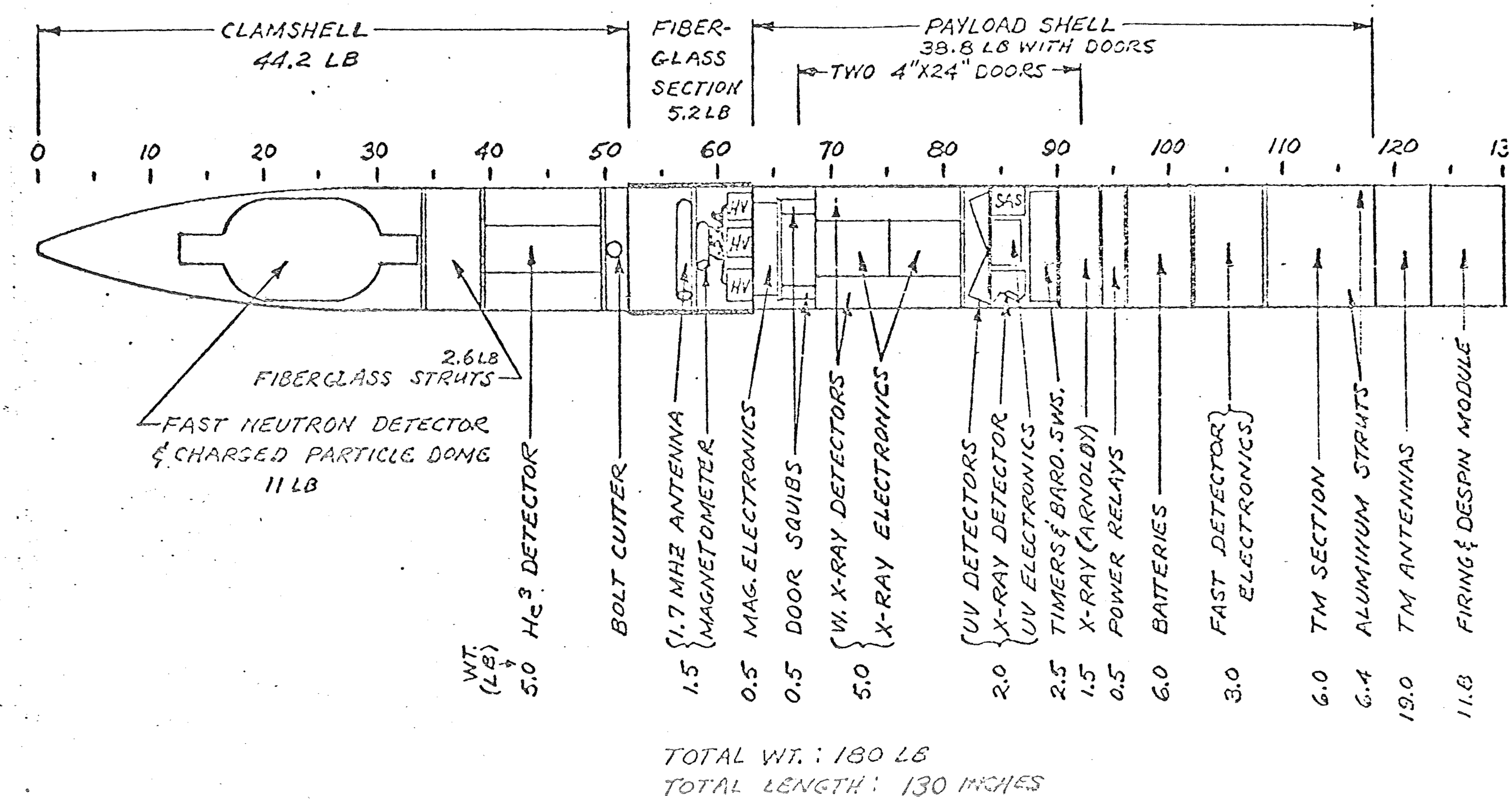
FIGURE CAPTIONS

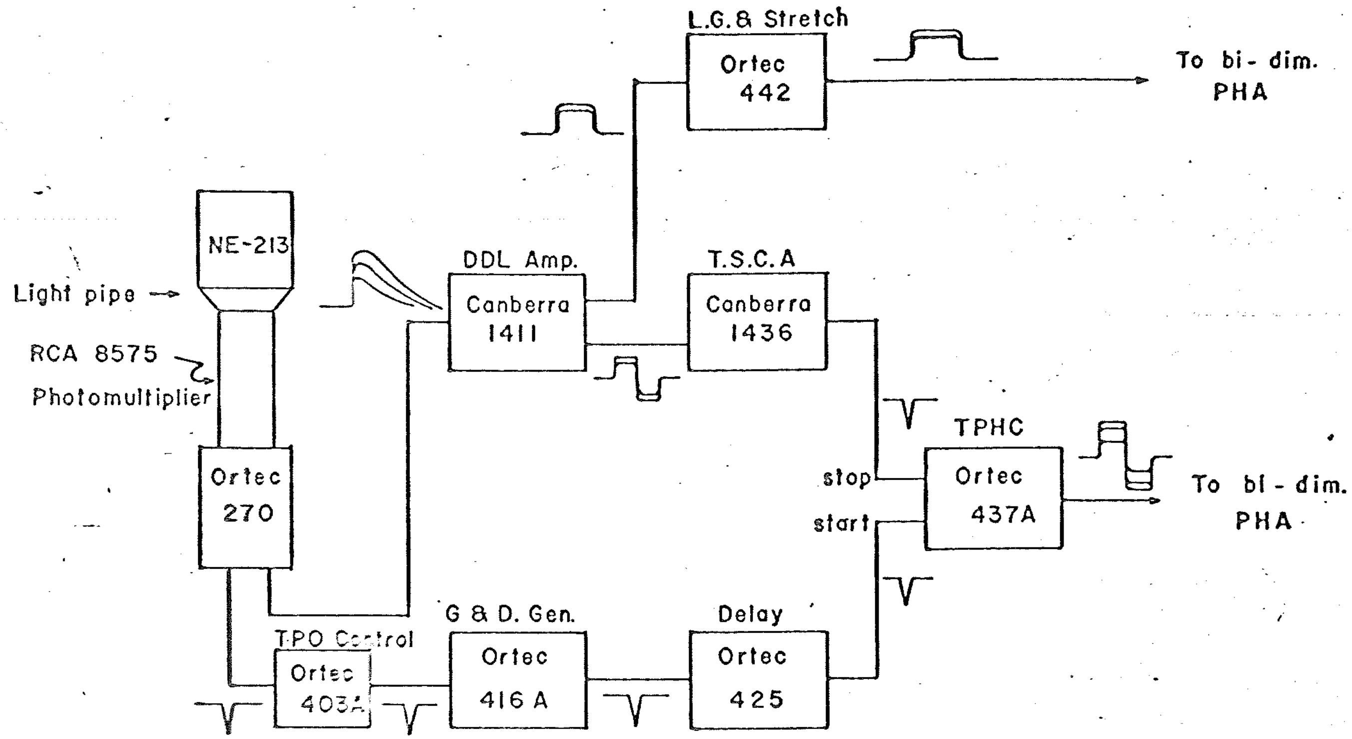
Figure 1 Payload Layout for Flight NASA 18.72 and 18.73 UE

Figure 2 Fast Timing Pulse Shape Discriminator



NASA 18.72 UE PAYLOAD

FIGURE 1



Timing pulse shape discriminator

Univ. of New Hampshire 1 June 1970

APPENDIX I

THE ENERGY SPECTRUM OF FAST NEUTRONS IN THE ATMOSPHERE

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THE ENERGY SPECTRUM OF FAST NEUTRONS IN THE ATMOSPHERE

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The energy spectrum of fast neutrons (3—17 MeV) in the atmosphere was measured at geomagnetic latitude 42°N ($P_c = 4.4$ GV). The n–γ detector, enclosed in an anti-coincidence charged particle shield, was a 5×5 cm diameter cell of organic liquid scintillator (NE213) coupled to a high-resolution, two-parameter, multiparticle pulse-shape discriminator (PSD) with a two-parameter (64×64) logarithmic pulse-height analyzer. At 5.5 g/cm^2 the slope of the differential neutron energy spectrum given by $dN/dE = BE^{-\beta(E)}$ was 2.0 ± 0.15 between 3.5—7.0 MeV and 1.0 ± 0.15 in the range 7—17 MeV.

Introduction

The present experiment is part of a study to evaluate the neutron energy spectrum and flux in the range $1-50$ MeV at the top of and above, the atmosphere. The neutron detector utilized a separate charged-particle rejection scheme and a two-parameter display system for the pulse-shape discriminator (PSD) which separates gamma rays from neutrons. In this paper the neutron energy spectrum and flux in the interval $3-17$ MeV measured during balloon flights on 7 September 1968 and 22 April 1969 are presented with some discussion of the experimental techniques used.

Experimental system

A major difficulty encountered in determining the secondary neutron decay population in the atmosphere is to detect reliably a small flux of fast neutrons in a much larger background flux of gamma rays and charged particles. To accomplish this, the counter logic first separated the particles into two groups: charged and neutral. Second, the neutral particles were separated into their predominant components: gamma rays and neutrons. Experimentally the charged particles were separated from the neutral particles by placing the neutron and gamma-ray detector inside a thin, hollow, 4π-enclosure of plastic scintillator [1], as shown in Fig. 1. The wall thickness of the shield was greater at larger distances from the phototubes to allow particles which enter the shield farther from the photomultipliers to generate a larger scintillation, thus compensating for the light attenuation in the scintillator. For the most effective use of such a 4π shield a parallel sum and coincidence logic scheme were included.

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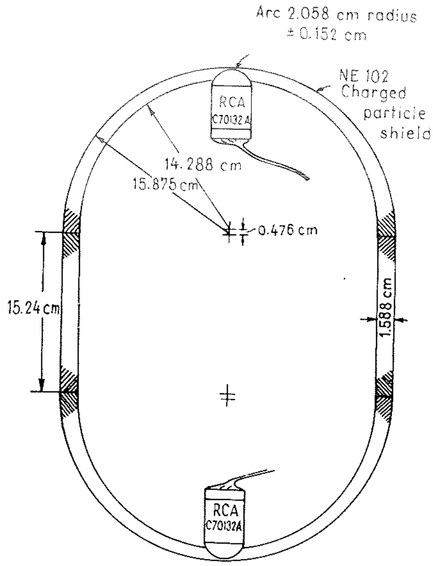

Fig. 1. Charged particle anticoincidence shield design

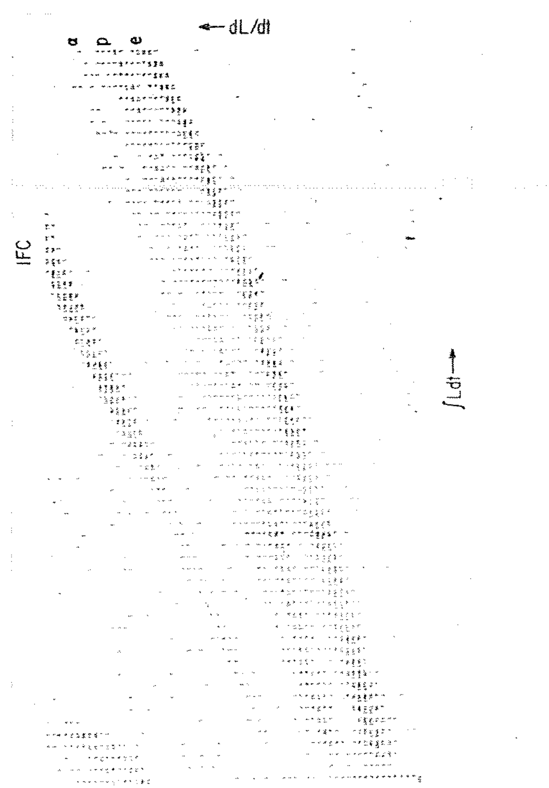

Fig. 2. Two-parameter (∫L dt vs. dL/dt) display of flight data taken from 541 to 62 mbar on 7 September 1968

The neutral particle detector, contained within this closed shell, was gated off whenever a charged particle passed through the shield. The n–γ separation was made by the pulse-shape discrimination [2] of an organic liquid scintillator (NE213) viewed by a fast photomultiplier (RCA 8575). The PSD system compared the integrated scintillation light yield ($\int L\,dt$) with the slow-decay component of the scintillation (dL/dt) in the cylindrical liquid scintillator of 4.60×4.65 cm diameter. The photomultiplier (PM) pulses were fed to a high-resolution, multiparticle PSD and were subsequently analyzed and digitized by a logarithmic, two-parameter (64×64) pulse-height analyzer (PHA). The effectiveness of the PSD for separating gamma rays and neutrons can be seen quantitatively in Fig. 2 where the two-parameter PSD data for the Pfotzer maximum on the 7 September 1968 flight are plotted.

An inflight calibrator (IFC) was incorporated into the neutron detector by optically coupling to the NE213 scintillator a small ($\approx 3 \times 3$ mm diameter) crystal of NaI(Tl) doped with a radioactive salt of the alpha emitter Am^{241}.

Measurements

The PSD system separated four different scintillation pulse shapes as shown in Fig. 2. These correspond to Compton electrons, recoil protons, alpha particles from (n, α) reactions and alpha particles from the IFC.

The individual groups of particles (e, p, α) in Fig. 2 were extracted to obtain pulse-height spectra, which are shown separately in Fig. 3. Then, the pulse-height spectrum for protons (Fig. 3) was converted to the recoil-proton energy spectrum shown in Fig. 4. This conversion involves correcting for the non-linearity of the flight

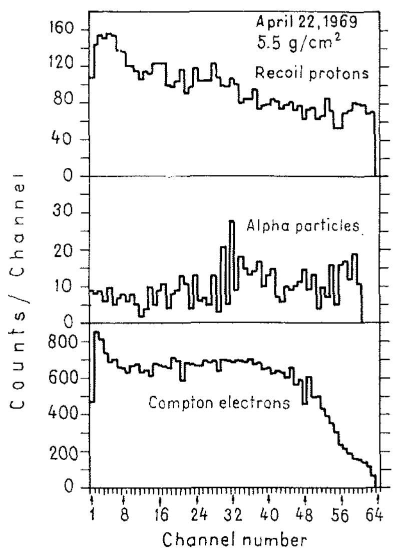

Fig. 3. Recoil proton, alpha particle, and Compton electron histograms from the 22 April 1969 flight taken at 5.5 gm/cm^2

pulse-height analyzer and for the dependence of scintillation light yield upon energy [3]. For example, the channel width of the logarithmic PHA was 0.078 MeV at channel number 10 (3.6 MeV) and 0.463 MeV at channel number 60 (15.3 MeV).

The method of BROEK and ANDERSON [4] was used to obtain the neutron energy spectrum shown in Fig. 5. In this method the derivative $d/dE(dN_p/dE)$ as a function of E_p was evaluated from Fig. 4. Corrections were also made for second scattering and wall effects, and for the neutron flux attenuation in the scintillator.

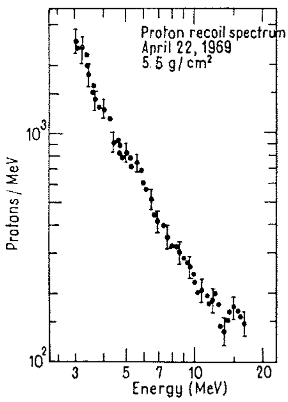

Fig. 4. Recoil proton energy spectrum derived from the data of Fig. 3. The error bars shown are statistical only

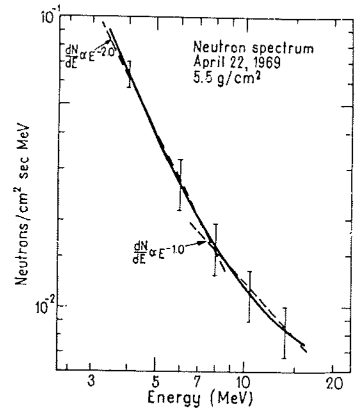

Fig. 5. The differential neutron energy spectrum at 5.5 gm/cm². The error bars shown are the estimated uncertainties in deducing the neutron spectrum from Fig. 4

The unfolded differential neutron energy spectrum at 5.5 g/cm² shown in Fig. 5 was fitted to a spectral shape of the form:

$$\left(\frac{dN}{dE}\right)_n = BE^{-\beta(E)}.$$

From a simple regression analysis on the values of $\left(\frac{dN}{dE}\right)_n$ between 3.5 and 17 MeV, β was found to be 1.6 ± 0.1 and $B = 0.54$. For the energy range 3–10 MeV the measured neutron flux was 0.23 n/cm² sec.

From Figs. 4 and 5 it appears that the energy spectrum flattens after 7 MeV. An analysis indicated that spectral parameter β decreased from 2.0 ± 0.15 between 3.5–7.0 MeV to 1.0 ± 0.15 in the range 7–17 MeV.

A careful comparison was made of the energy spectrum at 5.5 g/cm² with that at $\approx$100 g/cm² (Pfotzer maximum) on both the 7 September 1968 and the 22 April 1969 flights. There was no difference in β outside the estimated errors.

Discussion of results

In this experiment the largest uncertainties in the proton-recoil spectrum shown in Fig. 4 arise from both systematic and statistical errors, the latter being easily evaluated. The systematic errors, on the other hand, are much more difficult to evaluate. The main contributions come from the conversion of pulse height to energy and from the differential non-linearity of the logarithmic PHA in the lower channels. The latter are comparable to the statistical errors in the lower channels of the flight PHA but less than statistical in the upper channels. The error bars shown in Fig. 4 are, however, only statistical. To obtain the error bars shown in Fig. 5 the uncertainty in the slope of the proton-recoil spectrum was determined at the energies for which error bars are plotted.

The most serious experimental difficulties in atmospheric neutron measurements arise from Compton electrons not being properly identified by the PSD, charged particles "leaking" through the anticoincidence system and thereby being falsely measured as neutrals, and the PSD falsely identifying neutron-produced secondary alpha particles as recoil protons. The first two difficulties are most serious because the electron and proton flight channel spectra (Fig. 3) are different and the ratio of electrons to protons in the detector was >10.

Let us compare the neutron flux and energy spectrum measured here with values obtained in other experiments. At essentially the same geomagnetic latitude HAYMES [5] measured $0.12\,E^{-1.3\pm0.1}$ n/cm^2 sec MeV in the energy range $2-8$ MeV at 4.4 g/cm^2. MENDELL and KORFF [6] and HOLT et al. [7] found $\beta = 1.0 \pm 0.1$. For depths greater than 20 g/cm^2 BAIRD and WILSON [8] obtained $\beta = 1.35 \pm 0.30$ unchanging with height. TAJIMA et al. [9] measured a neutron spectrum with $\beta < 1$ from $2-10$ MeV at depths >200 g/cm^2. These experiments give consistently lower values of β than calculated by LINGENFELTER [10] or observed in this experiment.

Conclusions

The differential neutron energy spectrum at 5.5 g/cm^2 altitude and 42° geomagnetic latitude was $0.54\,E^{-1.6+0.1}$ n/cm^2 sec MeV from $3-17$ MeV and the flux from $3-10$ MeV, corrected to solar minimum was 0.21 n/cm^2 sec. β was observed to change from 2.0 ± 0.15 to 1.0 ± 0.15 over the $3-17$ MeV range. Since the uncertainties are large for $E_n > 10$ MeV, additional data should be obtained at energies to 50 MeV. No change in spectral shape with altitude was observed from Pfotzer maximum (100 g/cm^2) to 5.5 g/cm^2. If the recent results of ZYCH and FRYE [11] are included, the neutron spectrum from $3.5-100$ MeV is independent of altitude from $100-5.0$ g/cm^2.

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