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High-Altitude Cosmic-Ray Neutron Density at the Geomagnetic Pole*

H. A. C. Neuburg, R. K. Soberman, M. J. Swetnick,† and S. A. Korff
New York University, University Heights, New York, New York

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Two successful balloon flights were launched near the geomagnetic North Pole, bearing low-energy cosmic-ray neutron detectors. The neutron maximum was found to occur at 75±5 mb. A value of 161 mb was found for the mean absorption depth, L.

INTRODUCTION

A MEASUREMENT of the neutron density as a function of altitude has been made by means of high-altitude balloon-borne equipment launched near the geomagnetic North Pole from a Coast Guard icebreaker. This is a continuation of the work of several investigators[1,2] to determine the latitude effect on cosmic-ray neutrons. The theory of the origin and vertical distribution of cosmic-ray neutrons has been developed by such investigators as Bethe, Korff, and Placzek,[3] Flügge,[4] and Davis.[2] Present results again indicate an exponential increase in neutron intensity as a function of altitude from sea level to about 200 millibars and a slower rise to a maximum somewhat above 100 millibars. Of major interest is the variation of the absorption coefficient and position of the maximum with geomagnetic latitude. Experiments are still in progress which, it is hoped, will yield a complete picture of the cosmic-ray neutron intensity dependence on altitude and latitude.

APPARATUS AND METHODS OF MEASUREMENT

The main features of the apparatus were the same as those used by Staker[1] and Davis.[2] A comprehensive description thereof is given by Pavalow, Davis, and Staker.[5] Essentially, two geometrically identical proportional BF_3 counters were employed. One was filled to an S.T. pressure of 23.3 cm Hg with B^{10}-enriched BF_3 gas,[6] the other to the same pressure with regular commercial unenriched BF_3. This arrangement afforded a means of determining the expected neutron counting rate for a counter containing 100 percent B^{10} isotope and also the background (due mainly to giant showers, stars, slow protons, and natural contamination alpha particles). The two brass-walled counters in each frame were carefully matched with respect to efficiencies and plateaus[7] and operated at approximately 2300 volts. Counter dimensions were: active length, 30 cm; inner diameter, 49.2 mm; diameter of central wire, 0.05 mm (0.002 in.); and wall thickness, 1 mm.

As in previous experiments, the counters, high-voltage batteries, and connecting cables were kept at atmospheric pressure to avoid spurious counts from corona discharge at altitudes above 40 000 ft. A 20-gauge galvanized iron stovepipe, with brass endcaps and brazed seams, served as a pressure chamber in which the counters were mounted with axes in line and separated by the high-voltage batteries. This geometrical arrangement afforded symmetry, provided a minimum contribution from neutrons produced in the batteries, and resulted in one counter subtending a negligibly small solid angle at the other. The counter pulses were fed into identical trains of circuitry com-

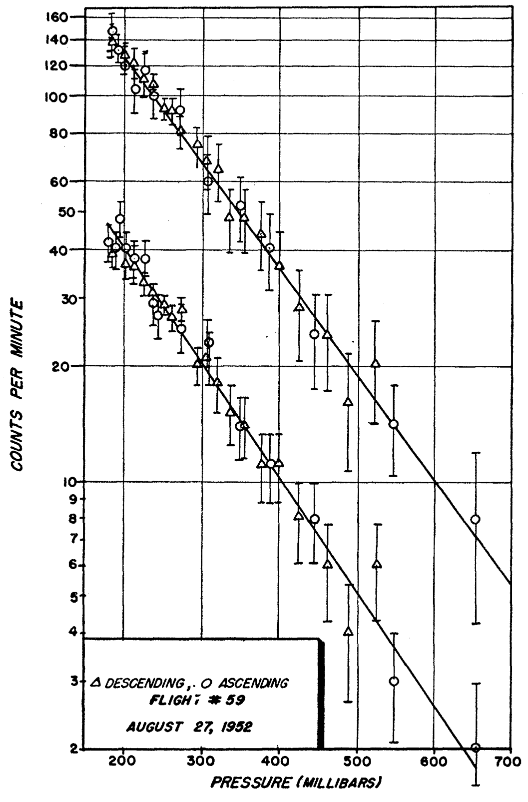

FIG. 1. Individual counting rates *vs* pressure. Flight No. 59. The upper curve represents the data for the enriched BF_3 counter, and the lower curve the data for the unenriched BF_3 counter.

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* Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

† Now at Anton Laboratories, Brooklyn, New York.

[1] W. P. Staker, Phys. Rev. **80**, 52 (1950).

[2] W. O. Davis, Phys. Rev. **80**, 150 (1950).

[3] Bethe, Korff, and Placzek, Phys. Rev. **57**, 573 (1940).

[4] S. Flügge in *Cosmic Radiation*, edited by W. Heisenberg (Dover Publications, New York, 1946), Chap. 14.

[5] Pavalow, Davis, and Staker, Rev. Sci. Instr. **21**, 529 (1950).

[6] Obtained from the U. S. Atomic Energy Commission, Oak Ridge, Tennessee.

[7] Because of the difficulty in obtaining a source with a neutron energy spectrum comparable to that of neutrons in the atmosphere, an absolute calibration of the counters was not practicable.

posed of a preamplifier, amplifier, scalers, and a pulse lengthener. Both channels were continuously telemetered to the "ground" station. The pulses from the enriched counter, occurring between four and five times as frequently as those from the regular counter, were scaled down by a factor of 1:16 before being transmitted as a pulse of 0.2-second length. The pulses from the regular counter were scaled down by 1:4 and transmitted with a 0.4-second length. This different length permitted easy differentiation between enriched and regular counts, even in cases of overlapping.

A previously calibrated Olland cycle modulator sent data as to the atmospheric pressure at which the balloon floated, at one-minute intervals throughout each flight. The enriched and regular pulses as well as the pressure readings were broadcast at 3135 kilocycles by a three-watt AM crystal-controlled transmitter developed by Hillman.[8] Recording took place at the "ground" station on board the icebreaker by means of a shortwave receiver and a Brush oscillograph recorder system.

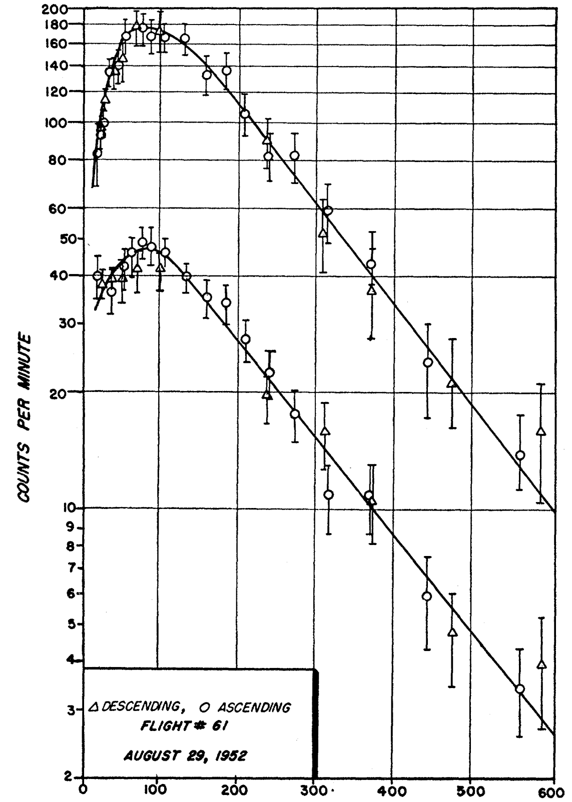

FIG. 2. Individual counting rates *vs* pressure. Flight No. 61. The upper curve represents the data for the enriched BF_3 counter, and the lower curve the data for the unenriched BF_3 counter.

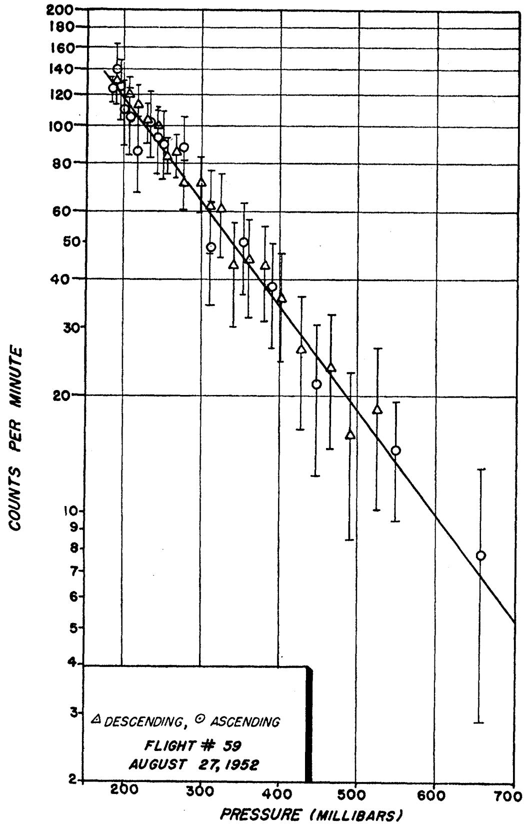

FIG. 3. Neutron counting rates *vs* pressure. Flight No. 59.

EXPERIMENTAL RESULTS

Two successful flights were completed in the vicinity of the geomagnetic North Pole from the rear flight deck of the U.S.C.G.C. Eastwind. Flight No. 59 was launched at 3:52 P.M. GMT on August 27, 1952. The ship's position was 77°45′ North and 72°47′ West in geographic coordinates. The balloon ascended at a decreasing rate of rise to an altitude of 40 800 feet, where it leveled off for about 30 minutes and then began a very gradual descent. This flight lasted a total of 4 hours and 33 minutes and came down at the approximate geographic position: latitude 78°00′ North, longitude 70°50′ West. Although this flight did not reach the altitude region of neutron maximum, the slow rise and descent gave counting rates with good statistical accuracy for the exponential portion of the curves described below.

The second successful flight (No. 61) was launched at 11:42 A.M. GMT on August 29, 1952, from the geographic position of 77°28′ North and 73°37′ West. This flight ascended at a rate of 800 feet per minute to a maximum altitude of 92 000 feet and then slowly descended to an altitude of 72 500 feet. Here the gondola was released by clock-controlled explosive "squibs" and promptly descended by parachute to the ice-filled waters of upper Kane Basin. The approximate geographic position of descent was 77°51′ North and 74°45′ West, and the total horizontal distance traveled was 28 miles. The total elapsed time of the flight was 4 hours and 52 minutes. Good statistical results were

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[8] L. Hillman, Radio-Electronics (December, 1948).

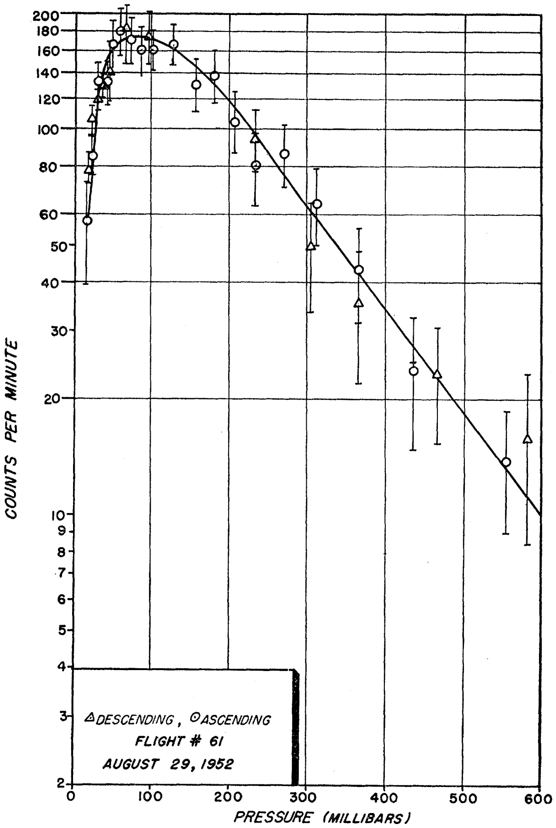

FIG. 4. Neutron counting rates *vs* pressure. Flight No. 61.

obtained from this flight both on the rise and in the vicinity of the maximum.

The curves for the individual counting rates on the two flights are shown in Figs. 1 and 2. The counting rate is plotted against atmospheric pressure in millibars. (1 millibar$=1.02$ g/cm^2). From the equations derived above, the calculation of N was carried out on the data of each one-minute interval and the curves of neutron counting rate *versus* pressure were plotted so that each point represents the average N over approximately equal pressure ranges. These curves are shown in Figs. 3 and 4. Finally a single composite curve of both flights was drawn. The result is shown in Fig. 5. For the sake of clarity, probable errors were not entered on this curve. It will be noted that there is very good agreement between the points of both flights. Information obtained from Simpson[10] indicated that the sea-level neutron counting rate varied an average of less than one percent during the period in which the two flights mentioned above were flown.

In their description of the neutron distribution in the atmosphere, Bethe, Korff, and Placzek[3] have given the relation $N=N_0e^{-\mu p}$ for the region from sea level to an altitude corresponding to about 200 millibars. Applying this equation to the exponential portions of curves 2, 4, and 5 indicates a mean absorption coefficient μ of 6.2×10^{-3} millibar^{-1}(6.1×10^{-3} cm^2/g). Taking the reciprocal of μ we find the mean absorption thickness L to be 161 millibars (164 g/cm^2). Simpson[11] has reported a figure of 157 g/cm^2 for L at geomagnetic latitudes 53° and 65°. Yuan[12] has also reported an L of 156 g/cm^2 at 51°46′N. geomagnetic latitude. All three of the above positions are north of the knee of the neutron latitude curve. To within experimental accuracy, the present figure at 90° seems to agree with those of Simpson and Yuan despite the fact that Simpson was detecting only those neutrons with energies greater than the cadmium cutoff, and Yuan was interested in those neutrons with energies less than the cadmium cutoff. No discrimination was made in the present experiments.

Above 200 millibars the neutron counting rate curve departs from the exponential and reaches a maximum at 75 ± 5 millibars. The counting rate at the maximum was 177 counts/min for the matched counters with dimensions and characteristics mentioned above. This would result in a neutron counting rate of 1.01 counts/min for a BF$_3$ counter, with a boron component of 100 percent B^{10} at S.T.P., and with a volume of one cubic centimeter. At the highest altitude reached by the balloon of flight 61 (15.5 millibars), the neutron

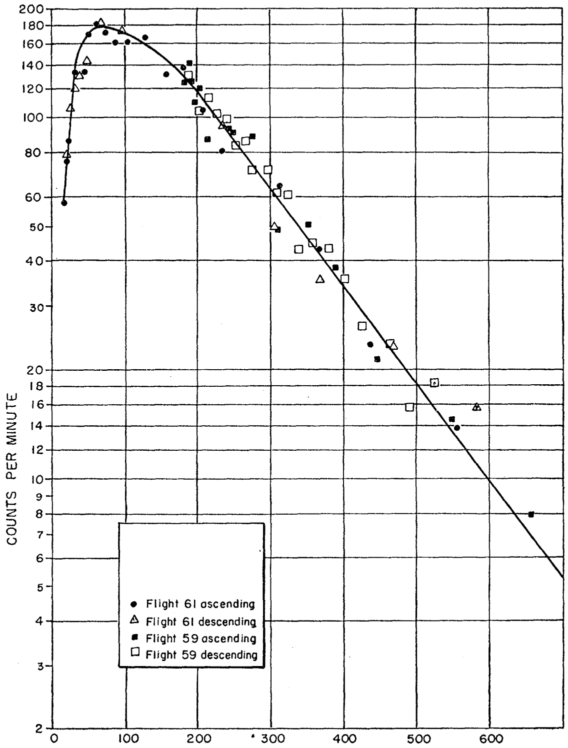

FIG. 5. Composite curve of neutron counting rates *vs* pressure at 90°N geomagnetic latitude.

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[10] J. A. Simpson (private communication).

[11] J. A. Simpson, Phys. Rev. **83**, 1175 (1951).

[12] L. C. L. Yuan, Phys. Rev. **81**, 175 (1951).

counting rate dropped to about $\frac{1}{3}$ that found at the maximum.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to various persons and agencies without whose valued assistance this work would not have been possible. Thanks are due the personnel of the U. S. Office of Naval Research, especially Lieutenant Malcolm Jones for his excellent liason work. We should like to voice our appreciation to Captain Peterson and the Officers and men of the U. S. Coast Guard Cutter Eastwind for their fine cooperation. We are indebted to J. R. Smith and "Bud" Froehlich of General Mills for their superb balloon-launching operations under very difficult conditions. Finally, we should like to thank our colleagues George Timmerman, Arie Borovitch, Israel Schlechter, and Roy Elkind.

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Photoproduction of Neutral Pions in Hydrogen: $p-\gamma$ Coincidences*

R. L. WALKER, D. C. OAKLEY,† AND A. V. TOLLESTRUP
California Institute of Technology, Pasadena, California

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This paper reports measurements of the differential cross section for photoproduction of neutral pions in hydrogen at energies 300, 400, and 450 Mev, at center-of-momentum angles of 70° to 150°. One decay photon from the neutral pion is observed in coincidence with the recoil proton, whose energy and angle are measured to define the photon energy. The results obtained by this method are in good agreement with more accurate measurements obtained recently by the method of observing only the recoil proton.

INTRODUCTION

PROBABLY the most accurate method for measuring the photoproduction of neutral pions in hydrogen is to observe the recoil proton alone. Its energy and angle define uniquely the photon energy as is well known. This method has been used by Goldschmidt-Clermont, Osborne, and Scott[1] and recently in this laboratory by Oakley and Walker.[2] This method makes the assumption (for which there is good evidence) that recoil protons from hydrogen are not produced in competitive numbers by processes other than neutral pion production. In the method of Silverman and Stearns[3] the photoproduction process is identified a little more definitely, by requiring the recoil proton whose energy and angle are observed, to be in coincidence with one of the decay photons from the neutral pion. This method suffers from the disadvantages that the absolute efficiency of the photon counter enters into the cross section, and the counting rates are decreased by the photon coincidence requirement. It has an advantage if solid targets of polyethylene and carbon are used, in reducing considerably the relative background from the carbon. This reduction occurs partly because the angular correlation between neutral pion and recoil proton, which is definite for hydrogen, is destroyed to a significant extent for carbon.

The measurements here described are a continuation of earlier work[4] using the method of Silverman and Stearns. Angular distributions at 300, 400, and 450 Mev are obtained, and compared to the more recent and probably more accurate data of Oakely and Walker[2] which depend on counting the recoil proton only.

APPARATUS

The arrangement of target, counters, and absorbers is shown in Fig. 1. Recoil protons are counted by a counter telescope consisting of two scintillation counters (stilbene crystals $\frac{1}{4}$ inch thick) in coincidence followed by a third one in anticoincidence. The thickness of aluminum absorbers in the telescope determines the range, and thus the energy, of the protons, which are identified by their specific ionization, or pulse height, in the first counter.

The range, ΔT_p, of proton energies accepted by this counter is found from the range interval, ΔR, consisting of the aluminum absorber C plus a thickness of stilbene which depends on the effective biases of counters 2 and 3. This thickness is found by extrapolating the proton counting rate as a function of absorber C thickness to zero counting rate. During this measurement, when C is increased, absorber B is decreased half that amount, in order to keep the mean energy of the observed protons the same.

The photon counter consists of two liquid scintillators of dimensions 4×6×0.5 inches. The first is in

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* This work was supported in part by the U. S. Atomic Energy Commission.

† Now at University of California, Radiation Laboratory, Livermore, California.

[1] Goldschmidt-Clermont, Osborne, and Scott, Phys. Rev. **89**, 329 (1953).

[2] D. C. Oakley and R. L. Walker, following paper [Phys. Rev. **97**, 1283 (1955)].

[3] A. Silverman and M. Stearns, Phys. Rev. **88**, 1225 (1952).

[4] Walker, Oakley, and Tollestrup, Phys. Rev. **89**, 1301 (1953).