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Neutron Physics Division

SOLAR NEUTRON TRANSPORT IN THE EARTH'S ATMOSPHERE

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Abstract

The neutron flux per unit energy induced in the earth's atmosphere by solar neutrons has been calculated as a function of atmospheric depth for depths of less than 300 g/cm^2 ($\sim$30,000 ft). The calculated flux is compared with estimates of the cosmic-ray neutron flux per unit energy, and it is found that for many flares the solar neutron flux per unit energy is sufficiently above the cosmic-ray neutron flux per unit energy to produce a measurable effect at both balloon and aircraft altitudes.

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1. *Introduction.* It has often been suggested that the high-energy protons emitted from the sun during solar flares will interact with the solar photosphere and produce high-energy neutrons. In a series of papers, hereinafter referred to as 1, *Lingenfelter et al.* [1965] have estimated the intensity and energy spectra of solar neutrons which might exist in the vicinity of the earth following a solar flare. In 1, it is estimated that following a major flare high-energy neutrons should be observable in the vicinity of the earth for times of the order of one hour after the flare. It is furthermore estimated that these neutrons produce no observable effect on the surface of the earth, and it is suggested that the search for solar neutrons be "conducted with a satellite in equatorial orbit or a balloon at high altitude and low latitude carrying a neutron counter sensitive above 10 Mev."

In this paper, the alternate possibility of observing solar neutrons by neutron spectral measurements at aircraft altitudes is considered. When high-energy neutrons enter the atmosphere, they interact with the atmospheric nuclei to produce a nuclear cascade in much the same manner as do the incident cosmic-ray protons and alpha particles. The question considered here is the magnitude of the neutron flux per unit energy at various depths in the atmosphere due to incident solar-flare neutrons compared to that due to incident cosmic rays. Throughout the paper, consideration is restricted to latitudes where the earth's magnetic field shields the atmosphere from solar-flare protons, and thus neutrons induced in the atmosphere by such protons need not be considered.

Using the estimate of the solar-neutron flux given in 1, high-energy neutron transport calculations have been carried out, and the neutron flux per unit energy at various depths in the atmosphere has been obtained. Since in 1 it is estimated that the solar neutrons reaching the earth's atmosphere are essentially monoenergetic with the energy varying as a function of time, the calculations have been carried out for incident energies of 50, 100, 200, 300, 400, and 500 Mev. Calculated results are given at balloon altitudes as well as at greater atmospheric depths. The calculated neutron flux is compared with estimates of the cosmic-ray neutron-flux background and is found to be sufficiently above this background, at least under some circumstances, to make measurements of the solar neutrons at balloon and airplane altitudes quite feasible.

In section 2 the details of the calculations are given. In section 3 the results are presented and discussed.

2. *Calculational Details.* The geometry considered throughout this paper is that of a normally incident neutron flux on a half-space of air. The air is assumed to be composed of 79% nitrogen and 21% oxygen. An explicit assumption about the density variation in the upper atmosphere is not required since it can be shown from the transport equations that if the depth is measured in g/cm^2 the calculated results are independent of the density variation.

The transport calculations were carried out using the nucleon transport code NTC [*Kinney,* 1964]. Since the operation of this code has been described in detail by *Kinney,* only a brief description of the physical processes will be given here. The interactions of the incident neutrons with the nuclei of the atmosphere initiate a complex avalanche of secondary neutrons and protons which proceed through the atmosphere increasing in number and decreasing in energy. In general, the first nuclear interactions of the incident high-energy neutrons produce several nucleons having energies ranging from a few Mev to the source energy and quite complex angular distributions. The higher energy secondary neutrons and protons collide with other atmospheric nuclei thus producing additional particles and expanding the cascade. The protons continually lose energy between their nuclear collisions. The low-energy neutrons undergo elastic nuclear collisions which degrade their energy and change their direction of travel. In the calculations presented here, Monte Carlo methods are employed, and all of these various processes are taken into account. The nonelastic cross section for nucleon-nucleus collisions and the energy and angular distributions of the secondary nucleons from such collisions when the incident particle energy is greater than 25 Mev are taken from the calculations of *Bertini* [1966, 1967]. Elastic nucleon-nucleus collisions at energies of greater than 25 Mev are neglected. Protons of energy less than 25 Mev are assumed to slow down and stop without undergoing nuclear collision. Elastic neutron collisions below 25 Mev are treated using primarily experimental data[2] and nonelastic neutron collisions below 25 Mev are treated using the evaporation calculations of *Dresner* [1961].

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[2]The master cross-section tape compiled by *D. C. Irving* for use in the neutron transport code, together with references to all the data used, is available on request from the Radiation Shielding Information Center of the Oak Ridge National Laboratory.

3. *Results and Conclusions.* Calculations have been carried out for monoenergetic incident neutrons of 50, 100, 200, 300, 400, and 500 Mev. At each of these energies, the normally incident flux (neutrons/cm^2/sec) was taken to correspond to the estimate of the incident solar-neutron flux given in 1 for a proton flare spectrum with a characteristic rigidity of 125 Mv and a time-integrated proton flux in the vicinity of the earth of 1.4×10^9 protons/cm^2 with energy greater than 30 Mev. The incident flux and the approximate time after the flare when neutrons of this energy will be incident on the atmosphere are shown in Table 1. A time-integrated proton flux of 1.4×10^9 protons/cm^2 with energy greater than 30 Mev corresponds to a very large flare which can not be expected to occur very often. The values in Table 1 and consequently all of the calculated results are, however, directly proportional to the assumed proton flux, so the results may easily be scaled to correspond to a smaller flare. The values in Table 1 are also dependent on the characteristic rigidity of the flare used. The scaling factors that must be applied to the results to make them correspond to flare spectra of other characteristic rigidities may be obtained from 1 (page 4090).

The omnidirectional neutron flux per unit energy, that is, the angular neutron flux integrated over all angles, for each of the incident energies considered is shown at atmospheric depths of 5, 10, 25, 50, 100, 200, and 300 g/cm^2 in Figures 1-7, respectively. The neutron flux at energies of less than 0.1 Mev is not shown, but values are given in Table 2. The proton flux, integrated over rather large energy intervals because of the relatively large statistical error associated with this small flux, is given in Table 3. There is no calculated flux of protons with energy less than

TABLE 1. Incident Neutron Flux at Each Energy Used in the Calculations

Energy (Mev)	Time (sec)	Incident Neutron Flux (Neutrons/cm^2/sec)
50	1590	23
100	1160	42
200	880	34
300	763	25.4
400	698	15.9
500	657	7.5

TABLE 2. Neutron Flux Per Unit Energy as a Function of Depth in Atmosphere (Averaged over the energy interval 0 to 0.1 Mev)

Incident Neutron Energy	Neutrons/Mev/cm^2/sec						
(Mev)	5 g/cm^2	10 g/cm^2	25 g/cm^2	50 g/cm^2	100 g/cm^2	200 g/cm^2	300 g/cm^2
50	5.43	8.95	19.53	24.51	19.55	5.68	1.40
100	5.92	11.29	20.27	28.92	28.00	14.01	5.25
200	7.07	10.90	22.31	31.88	35.22	21.40	10.19
300	8.43	11.69	25.75	40.51	40.23	29.80	16.07
400	7.12	13.07	26.50	40.52	49.89	39.52	22.01
500	9.02	17.10	27.20	47.42	56.66	45.10	37.7

TABLE 3. Proton Flux as a Function of Atmospheric Depth

Incident Neutron Energy	10^{-2} Protons/cm^2/sec						
(Mev)	5 g/cm^2	10 g/cm^2	25 g/cm^2	50 g/cm^2	100 g/cm^2	200 g/cm^2	300 g/cm^2
	(Integrated Over Energy Interval 25 to 100 Mev)						
50	0.19	0.27	0.08	0.13	0.10	0.0	0.0
100	1.74	1.04	1.13	0.76	1.12	0.26	0.05
200	3.34	2.28	3.63	4.91	3.04	2.02	0.29
300	2.47	3.29	2.95	6.76	2.34	3.17	2.04
400	1.84	1.45	4.42	4.89	10.2	2.92	3.06
500	3.65	7.99	8.25	8.69	7.69	5.81	3.72
	(Integrated Over Energy Interval 100 Mev to Initial Energy)						
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200	1.44	1.77	2.09	1.79	1.08	0.52	0.14
300	1.96	2.98	5.85	7.15	2.79	1.35	1.44
400	1.83	4.95	6.97	8.77	9.05	4.15	1.39
500	4.50	5.47	11.4	13.7	14.1	5.58	3.27

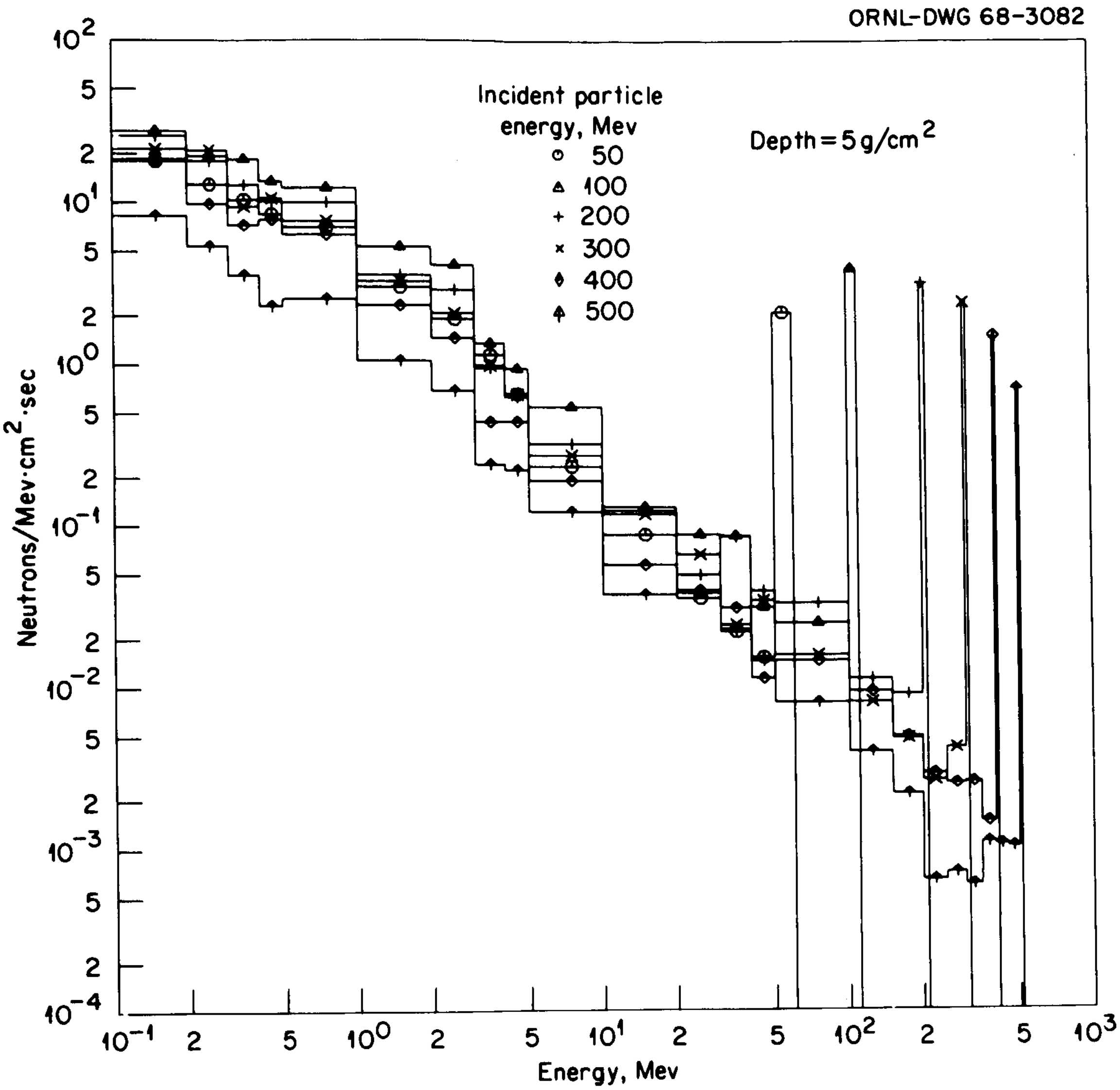

Fig. 1. Neutron Flux Per Unit Energy vs Energy at an Atmospheric Depth of 5 g/cm^2.

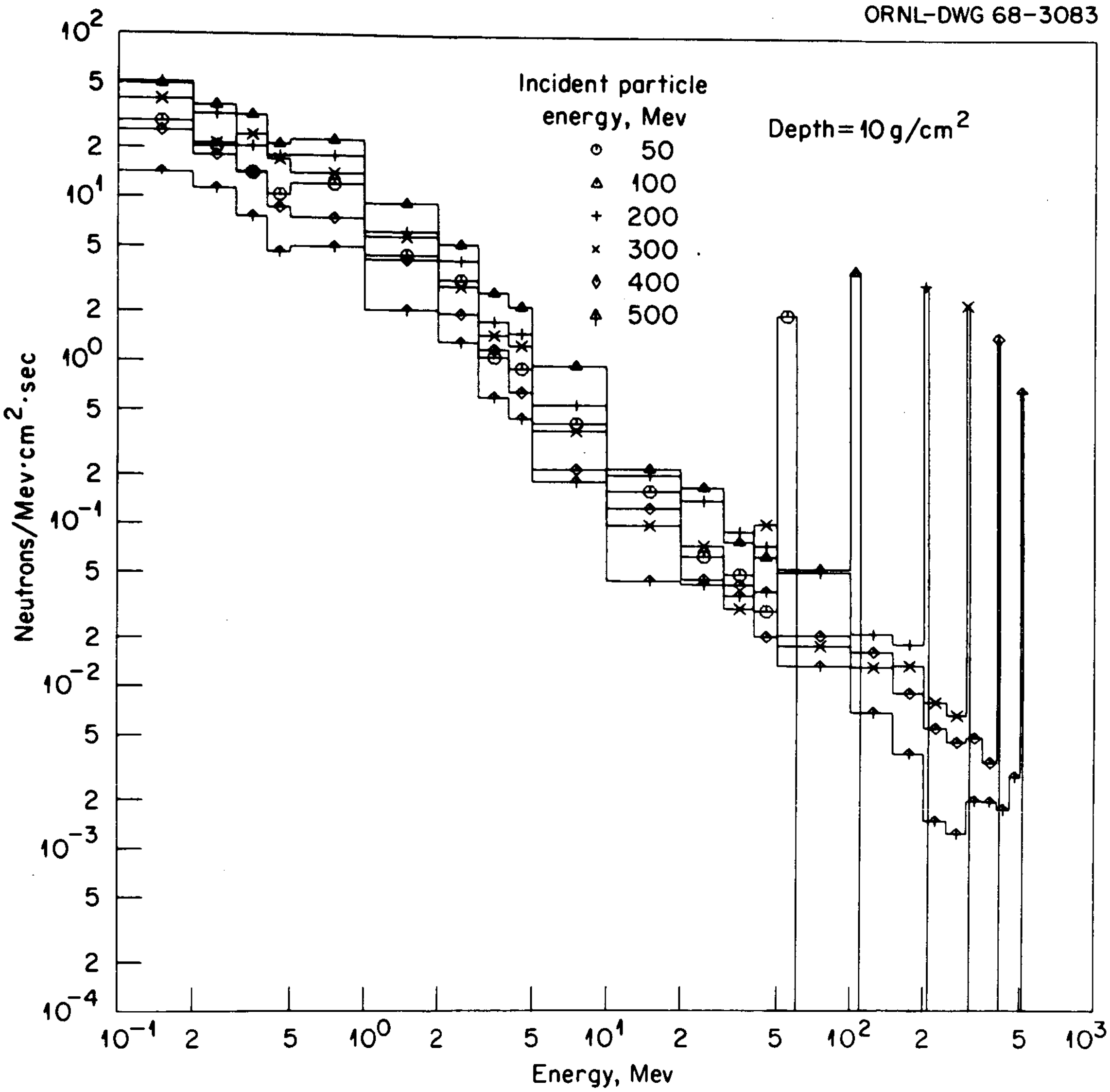

Fig. 2. Neutron Flux Per Unit Energy vs Energy at an Atmospheric Depth of 10 g/cm^2.

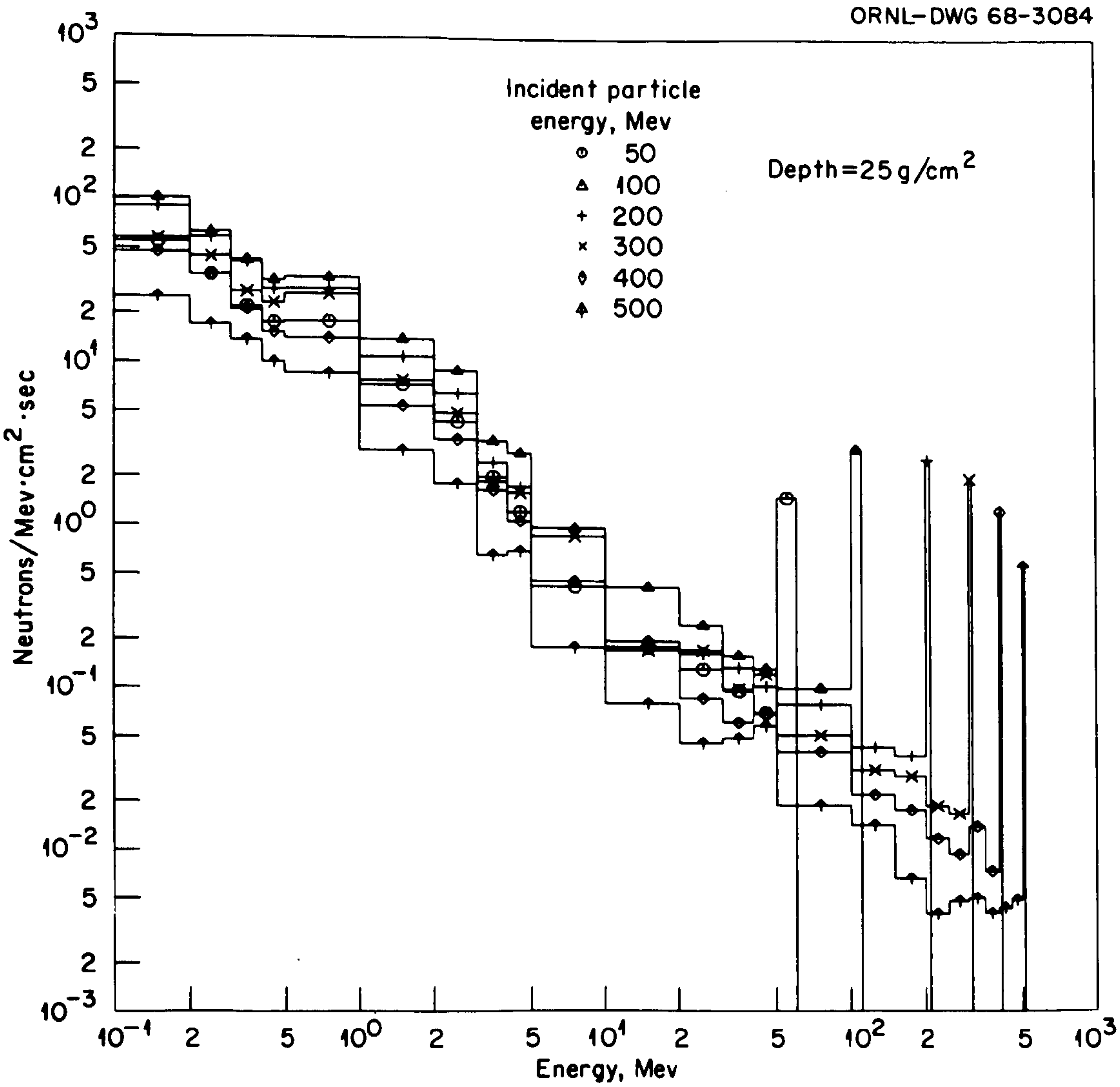

Fig. 3. Neutron Flux Per Unit Energy vs Energy at an Atmospheric Depth of 25 g/cm^2.

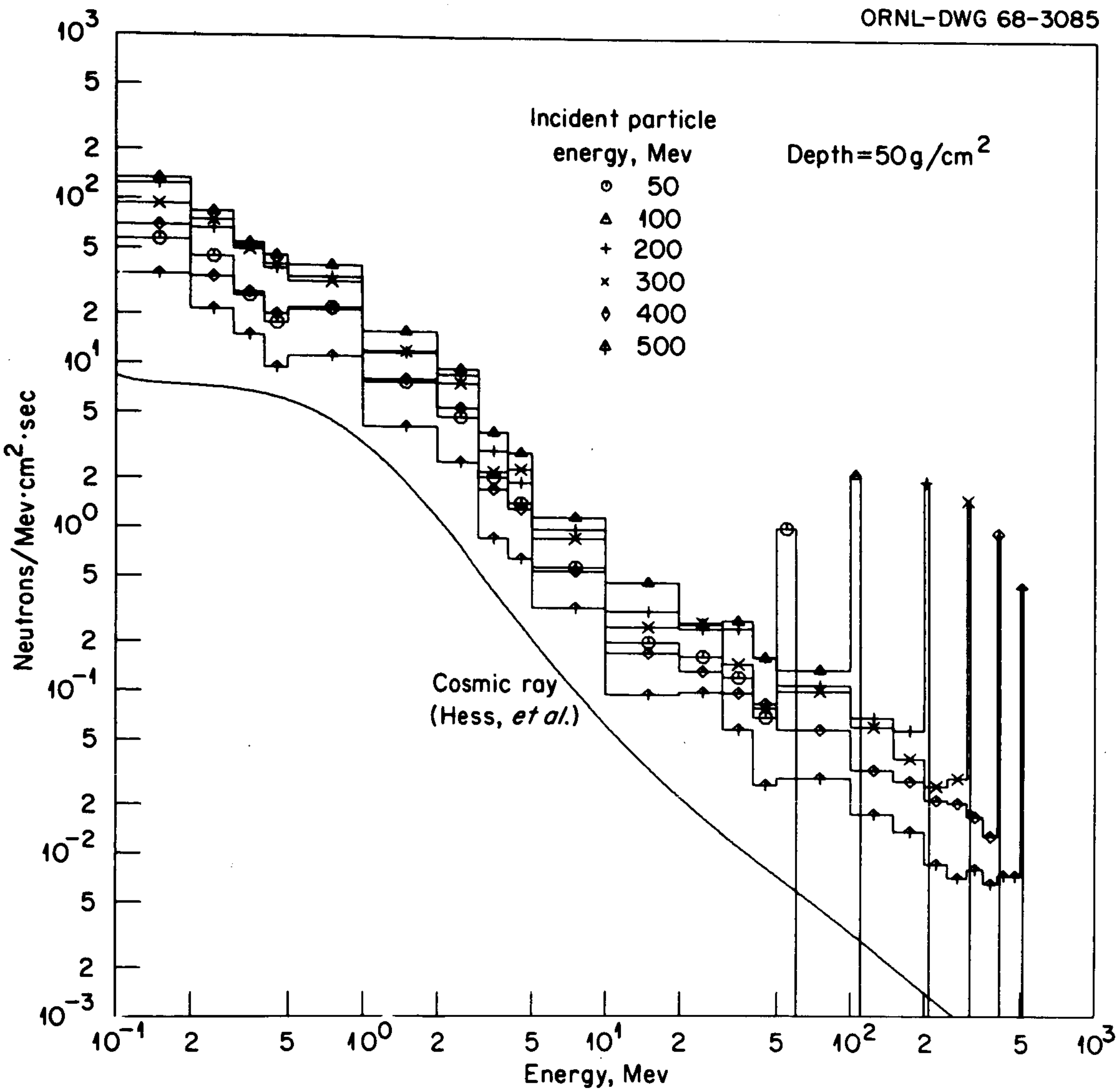

Fig. 4. Neutron Flux Per Unit Energy vs Energy at an Atmospheric Depth of 50 g/cm^2.

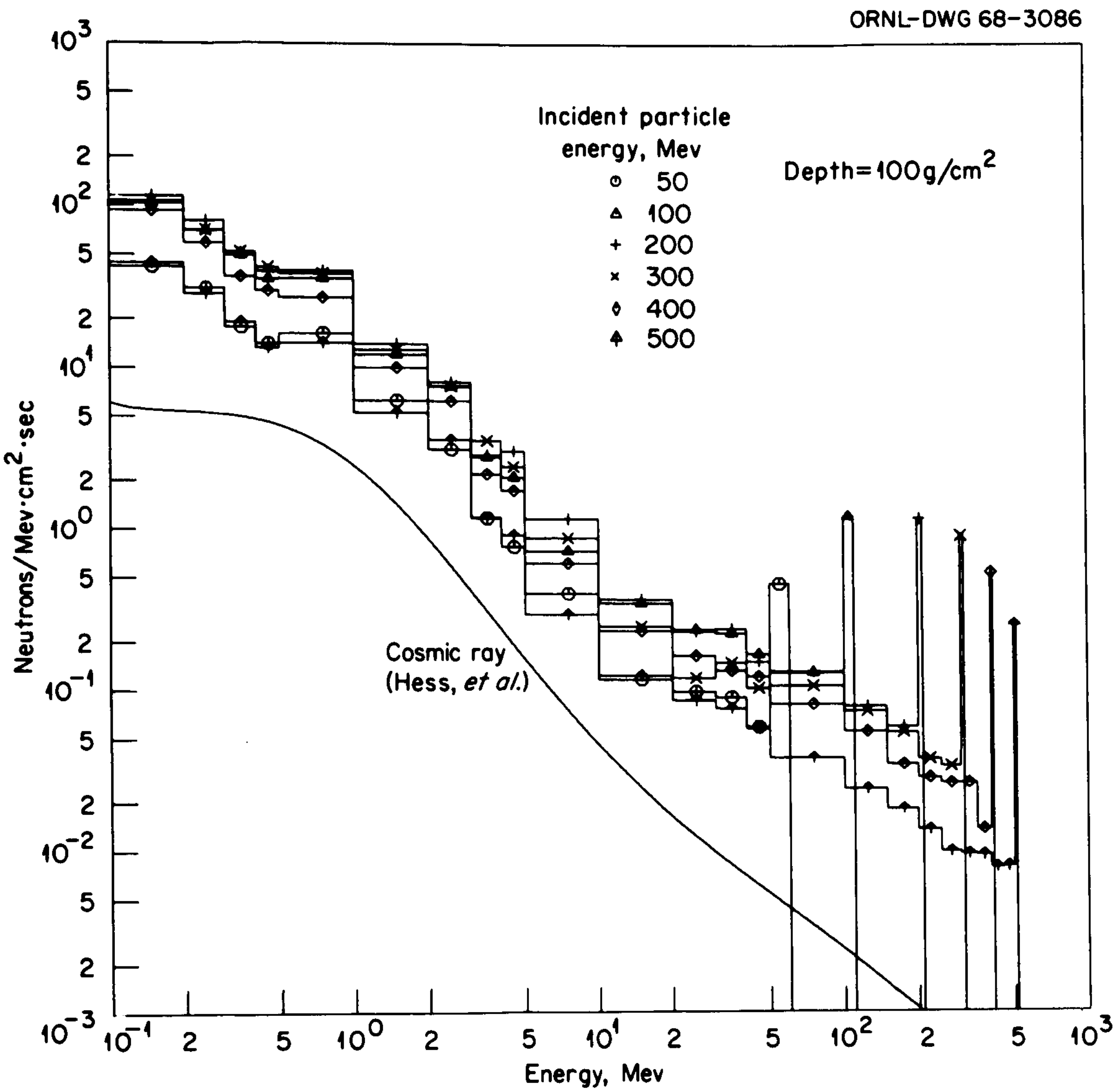

Fig. 5. Neutron Flux Per Unit Energy vs Energy at an Atmospheric Depth of 100 g/cm^2.

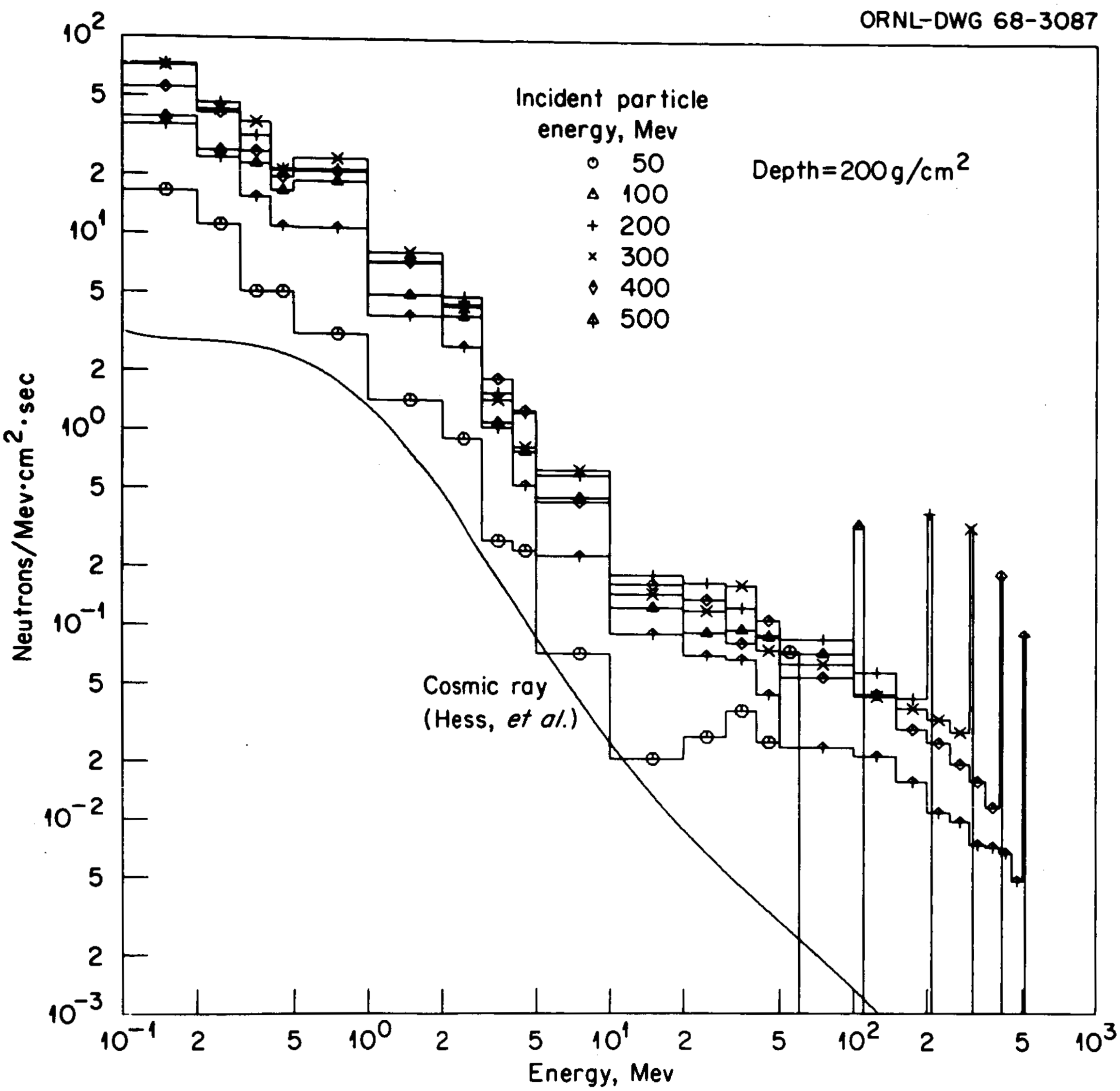

Fig. 6. Neutron Flux Per Unit Energy vs Energy at an Atmospheric Depth of 200 g/cm^2.

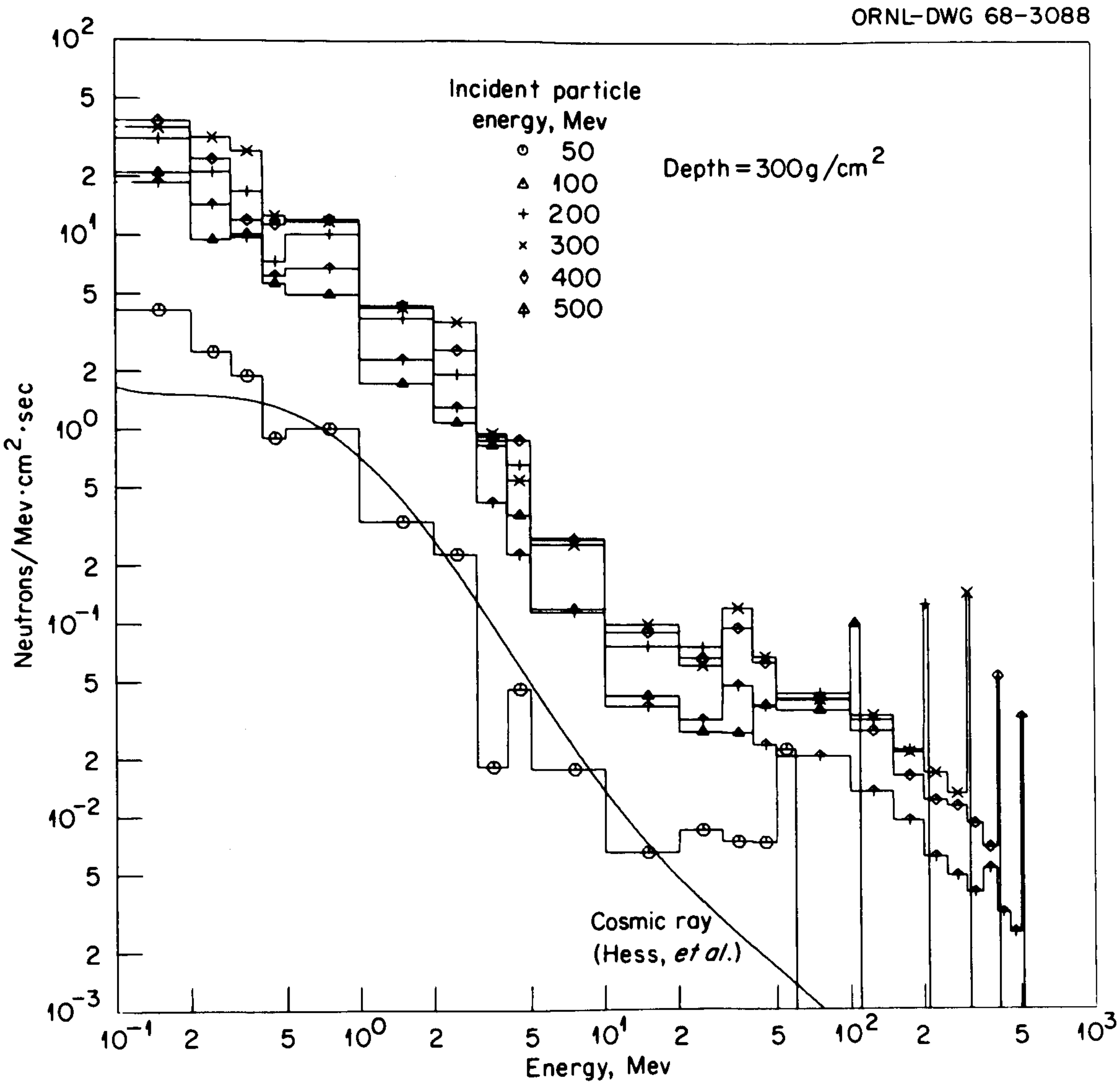

Fig. 7. Neutron Flux Per Unit Energy vs Energy at an Atmospheric Depth of 300 g/cm^2.

25 Mev because these particles are assumed in the calculation to stop where they originate. The large 'spikes' at the right of each curve in the figures represent the uncollided flux. For purposes of plotting, the monoenergetic uncollided particles have arbitrarily been spread over a 10-Mev interval. While detailed results are not given, it is to be understood that the calculated flux at the lower energies has essentially an isotropic angular distribution while the calculated uncollided and high-energy fluxes are highly directional.

The spectral shape of the cosmic-ray neutron spectrum at the top of the atmosphere is not well established. *Boella et al.*[3] [1965] have recently measured the flux of cosmic-ray neutrons with energy less than 20 MeV as a function of atmospheric depth at 42° latitude, and it is possible to compare the calculated results with these measurements. This comparison is shown in Figure 8. For the flare considered and all incident energies considered, the low-energy neutron flux induced in the atmosphere by the solar neutrons is well above the low-energy cosmic-ray neutron spectrum at all depths. The flare proton flux would have to be reduced by one to two orders of magnitude, that is, would have to be of the order of 10^7 to 10^8 protons/cm^2 with energy greater than 30 Mev, before the solar-neutron-induced low-energy neutron flux would become comparable with the low-energy cosmic-ray neutron flux. The comparison in Figure 8 is for 42° latitude where the measurements were made. At equatorial latitudes where the geomagnetic cut-off is higher, the cosmic-ray neutron flux will be smaller. The magnitude

[3]A comprehensive list of references to the earlier measurements of the cosmic-ray neutron flux in the atmosphere and a discussion of the degree of agreement of these measurements are given by *Boella* [1965] and *Haymes* [1965].

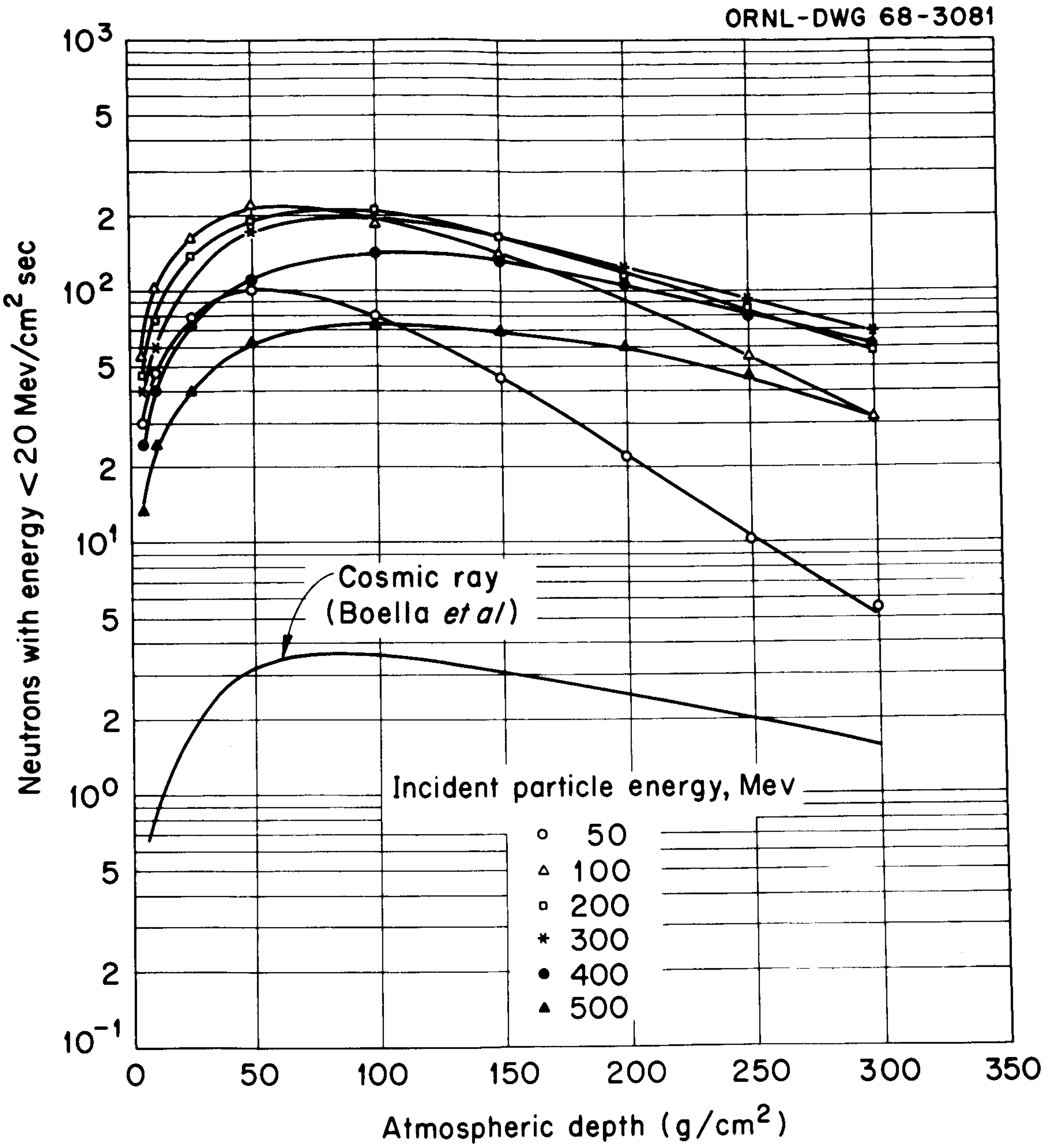

Fig. 8. Flux of Neutrons with Energy of <20 Mev vs Atmospheric Depth.

of this effect is depth dependent and is not well determined, but the existing measurements [*Soberman*, 1956] indicate that the cosmic-ray flux in Figure 8 is a factor of three to five larger than the corresponding flux at the equator.

In Figures 4, 5, 6, and 7, that is, at depths of 50, 100, 200, and 300 g/cm^2, the cosmic-ray neutron flux per unit energy given by *Hess et al.* [1959, 1961] is shown for comparison purposes. At 200 g/cm^2, this flux is the result of measurements while at the other depths it is due to calculations. At the lower energies, there are other measurements and calculations [*Boella et al.*, 1965; *Haymes*, 1965]. The results of *Hess et al.* [1959, 1961] are used here not because they are thought to be more accurate but because in general they are higher than those obtained by other workers, and thus give a more pessimistic comparison for our purposes.

In Figures 4, 5, 6, and 7, the solar-neutron flux per unit energy is in general well above the cosmic-ray neutron flux per unit energy at all secondary energies and at all depths. The major exception to this is in Figure 7 where the flux from 50-Mev incident neutrons is comparable to the cosmic-ray flux. The uncollided solar-neutron flux is well above the cosmic-ray flux at all depths. At the lower energies the reduction in flare magnitude that makes the solar-neutron flux comparable to the cosmic-ray flux is smaller than that determined from Figure 8 because the flux of *Hess et al.* is larger than that of *Boella* [1965]. The comparisons in Figures 4 to 7 are for 44° latitude where the results of *Hess et al.* apply. At equatorial latitudes a reduction in the low-energy cosmic-ray flux due to the higher geomagnetic cutoff, such as that discussed previously, is still to be expected. At higher energies some reduction may also be expected, but the magnitude of this reduction is not known.

In conclusion, it seems that the neutron flux induced in the atmosphere by solar neutrons for a variety of solar flares will be sufficiently above the cosmic-ray flux to produce measurable effects at both balloon and aircraft altitudes. The search for solar neutrons in the atmosphere can, in principle, be carried out by making time-dependent neutron-flux measurements using a counter that is sensitive to either the low-energy secondary neutrons or to the high-energy uncollided incident solar neutrons.

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