PHYSICAL REVIEW VOLUME 135, NUMBER 3B 10 AUGUST 1964

Modulation of Heavy Nuclei in the Primary Cosmic Radiation*

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(Received 23 March 1964)

The intensities of the primary cosmic-ray heavy nuclei, $Z \geqslant 3$, have been studied during several Forbush decreases. Fifteen values of the intensity were measured using nuclear emulsion detectors flown during a balloon cosmic-ray monitoring program. These values are those observed before, during, or after four of the largest Forbush decreases that occurred in the last solar cycle. Examination of these data, together with those previously available in the literature, suggests that the heavy nuclei are modulated in a similar manner to the α particles and protons of the primary radiation, showing that the modulation process is not a strongly charge-dependent one.

INTRODUCTION

SINCE the beginning of the IGY, the University of Minnesota has made several hundred balloon flights to monitor the primary cosmic radiation. Typically these balloons have carried ion chambers, geiger counters, and small stacks of nuclear emulsions to altitudes of around 100 000 feet, corresponding to a residual pressure of about 10 mbar. Analyses of the data obtained from these flights have been reported extensively in the literature,[1–3] with particular emphasis on the behavior of the singly and doubly charged particles observed during geophysically disturbed times. In the work reported here, attention is directed toward the heavier $Z \geqslant 3$ nuclei of the primary cosmic radiation observed in nuclear emuslions and, in particular, toward the variations in the intensity of these nuclei during disturbed times. These nuclei have been chosen for study since they are easily detected in nuclear emulsions and, due to the relatively high air cutoff energies imposed by the residual atmosphere in these exposures, are seldom, if ever, contaminated by solar-produced nuclei. Except at times when large intensities of slow solar α particles are recorded in the emulsions, these heavy nuclei may be rather easily distinguished from the other particles present.

Biswas[4] has used this experimental material to make a preliminary study of the changes in intensity of these nuclei during the Forbush decreases of 12 May and 12 July 1959, finding intensity decreases of $53 \pm 9\%$ and $43 \pm 9\%$, respectively. These intensity decreases were somewhat greater than those predicted for α particles with $E > 200$ MeV/nucleon in the same events of 35 and 33%, respectively, which was particularly significant since these α particles should presumably be more sensitive to modulation effects than the somewhat higher energy heavy nuclei. These results have been amplified by the improvement of the statistical accuracy of the earlier data and by the examination of additional data. In addition, the Forbush decreases of 16 July 1959 and 12 July 1961 have been studied in a similar manner. Altogether, 15 independent values of the intensity of the $Z \geqslant 3$ nuclei have been determined at times associated with Forbush decreases. In addition, intensities of $Z \geqslant 3$ nuclei and α particles have been measured at a number of other times. The results have been analyzed by comparing them with the data available in the literature on the intensities of α particles and heavy nuclei, and studying the regression curves between these intensities and the sea level cosmic-ray intensity as recorded by neutron monitors.

INTENSITY MEASUREMENTS

The typical monitoring emulsion stack consisted of 24 4-in.×4-in. 600 μ stripped Ilford G5 emulsions. The processed emulsions were scanned along a line either 5 or 10 mm below the top edge for tracks heavier than six or seven times minimum ionization. In general, the tracks accepted had to be longer than 4 mm per plate and have a zenith angle less than 50°. In order to reduce effects due to possible scanning losses, only those tracks longer than 4.5 mm and with zenith angles less than 45° were used in calculations of the intensity. In addition, some 15–20% of the total area scanned in each stack was rescanned to guard against random scanning losses. Those tracks which were not obviously produced by heavy nuclei were further studied by following through the stack, δ-ray counting and/or grain counting, and by making multiple scattering measurements. As a consequence, the light nuclei were uniquely separated from the slow α particles with which they could be confused. The density of $Z \geqslant 3$ nuclei at the top of the atmosphere was calculated by separating the tracks into 10° intervals of zenith angle and correcting each group to the top of the emulsions using an absorption mean free path of 13 cm of emulsion, and to the top of the atmosphere using an absorption mean free path of 45 g/cm² of air. The intensity was then determined by calculating the effective time spent at the assumed ceiling altitude. In this calculation the correction for the ascent portion of the flight was made by considering 10-min intervals at the appropriate mean depth. The

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* This work was supported in part by the U. S. Office of Naval Research under Contract No. Nonr-710(19).

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flight characteristics, selection criteria, intensities, and other pertinent data are shown in Table I. Columns give the following:

(1) τ—time balloon took to rise from 200 to 20 mb, in minutes,

(2) dx/dt—rate of ascent in feet per minute,

(3) x—average amount of vertical overlying atmosphere and packing material, in g/cm^2,

(4) Δx—maximum fluctuation in x during floating phase of flight,

(5) t'—exposure time at ceiling in seconds,

(6) T—total exposure time at ceiling including correction for ascent in seconds, calculated assuming $Z \geqslant 3$ nuclei are absorbed with a mean free path of 45 g/cm^2,

(7) date of flight,

(8) time at ceiling, UT,

(9) x_{em}—distance of scan line below top edge of emulsion, in cm,

(10) $l_{\min}$—minimum length of track used in calculation, in mm,

(11) $\theta_{\max}$—maximum zenith angle of tracks used in calculation,

(12) n—number of heavy nuclei found in each stack,

(13) J_{Δ^0}—intensity at top of atmosphere in nuclei/m^2 sr sec,

(14) ΔJ—correction necessary to J_{Δ^0} to find intensity that would have been obtained if x had been $=10$ g/cm^2 and x_{em} had been $=1$ cm. Changing x and x_{em} results in differing air cutoff energies for various nuclei, and some allowances must be made for this. Under these conditions the air cutoff energies of the three separate groups of nuclei, L, $3 \geqslant Z \geqslant 5$, M, $6 \geqslant Z \geqslant 9$, and H, $Z \geqslant 10$, which are combined here, are 190 MeV/nucleon, 280 MeV/nucleon, and 390 MeV/nucleon, respectively. For a flight over Minneapolis, the geomagnetic threshold is 1.2 BV, corresponding to a threshold energy of 180 MeV/nucleon. Consequently, it has been generally assumed that the air cutoff is dominant.

(15) J_{Δ^0}(corr)—intensity obtained from $J_{\Delta^0} + \Delta J$.

(16) N—the average hourly counting rate of the Ottawa neutron monitor[5] during the flight, corrected to Epoch 1956—1960.

The variations of the corrected intensities during the several Forbush decreases considered are shown in Figs. 1 and 2. Here, the Ottawa hourly neutron monitor rate is plotted for the times of interest, together with an indication of the times of exposure of each stack and the intensity observed. From these figures it can be seen that the J_{Δ^0}(corr) values show some correlation with N, but that the correspondence is far from perfect. In 1959 the correlation was good until flight XI, when the largest single neutron monitor *decrease* is associated with an intensity *increase*. In 1961 the correlation was less marked, due to flight XIV.

TABLE I. Intensities of heavy nuclei during Forbush decreases.

Name		1 τ (min)	2 dx/dt (ft/min)	3 x (g/cm^2)	4 Δx (g/cm^2)	5 t' (10^4 sec)	6 T (10^4 sec)	7 Date	8 Time (UT)	9 x_{em} (cm)	10 $l_{\min}$ (mm)	11 $\theta_{\max}$ (deg)	12 n	13 J_{Δ^0} (nuclei/m^2 sr sec)	14 ΔJ (nuclei/m^2 sr sec)	15 J_{Δ^0}(corr) (nuclei/m^2 sr sec)	16 Ottawa[b] (N. M. 1956–1960)
IGC7	I	48	1010	13	$^{-4}_{+3}$	5.33	5.55	6 May 1959	0550–2105	0.5	5.0	45°	86	20.5±2.2	+0.40	20.9±2.2[a]	2834
BP473	II	50	965	13.5	±0.5	1.53	1.72	12 May 1959	0915–1335	0.5	4.5	45°	51	10.0±1.4	+0.10	10.1±1.4[a]	2578
BP475	III	48	1010	12	±1	1.50	1.69		1335–1750								
IGC9	IV	52	930	10	±1	5.22	5.48	13 May 1959	0830–2300	1.0	4.5	45°	127	11.9±1.1	0	11.9±1.1	2629
IGC-C	V	130	270	5.5	±0.5	2.40	2.98	16 May 1959	1700–2340	1.0	4.5	45°	68	11.8±1.4	−0.56	11.2±1.4	2677
IGC-E	VI	47	1030	5.5	±0.5	3.50	3.71	2 June 1959	1200–2145	1.0	4.5	45°	107	17.1±1.7	−1.12	16.0±1.7	2850
IGC-10	VII	55	880	9.0	±1	6.34	6.62	12 June 1959	0410–2150	1.0	4.5	45°	98	16.3±1.6	−0.23	16.1±1.6	2785
IGC-12	VIII	54	890	10.5	±0.5	4.50	4.67	10 July 1959	0845–2130	0.5	5.0	45°	107	17.4±1.7	−0.23	17.2±1.7[a]	2819
IGC-13	IX	65	730	13	±3	5.19	5.36	11 July 1959	0500–1925	0.5	5.0	45°	39	18.3±2.9	+0.39	18.7±2.9[a]	2823
M2	X	53	930	6	±1	4.15±0.45	4.33±0.45	12 July 1959	0700–1815	0.5	5.0	45°	32	10.0±1.9	−0.68	9.3±1.9[a]	2599
IGC-15	XI	63	770	10	±4	4.69	4.95	16 July 1959	0400–1730	1.0	4.5	45°	72	12.2±1.4	0	12.2±1.4	2322
M250	XII	55	880	12	±2	2.34	2.63	11 July 1961	0400–1040	1.0	4.5	45°	74	17.2±2.0	+0.50	17.7±2.0	2932
M252	XIII	52	930	10	±3	2.59	2.77	12 July 1961	1850–0210	1.0	4.5	45°	87	20.5±2.2	0	20.5±2.2	2955
553N	XIV	92	530	3.3	±0.5	3.06	3.78	17 July 1961	1400–2350	1.0	4.5	55°	82	23.2±2.5	−1.5	21.7±2.5	2812
M269	XV	50	970	8.0	±2	3.75	3.94	29 July 1961	0440–1500	1.0	4.5	45°	105	14.1±1.4	−0.35	13.8±1.4	2770

[a] Also measured by Biswas (Ref. 4) although with generally lower statistical weight.
[b] See Ref. 5.

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[5] We are indebted to Dr. D. C. Rose for providing the data from the Ottawa neutron monitor.

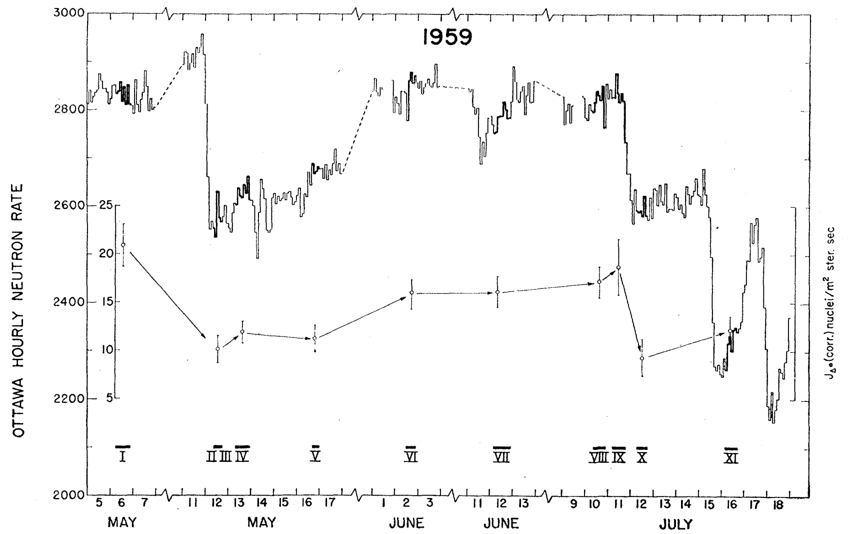

FIG. 1. The variation in the Ottawa neutron monitor rates and in J_{Δ^0}(corr) observed during three large Forbush decreases that occurred in 1959. Details of the flights I to XI are given in Table I.

ANALYSIS

It is clearly of fundamental interest to theories of the modulation process to attempt to explain these relations between the intensities of the heavy nuclei and the neutron monitor. In attempting to do this it is necessary to examine not only the data obtained in this experiment, but also that relevant data obtained previously. In particular, it is necessary to consider the available α-particle and heavy-nuclei intensity measurements which can be related to the counting rate of a single neutron monitor, in this case that one located at Ottawa.[5] Table II shows the values of the heavy nuclei,[6–12] J_{Δ^0}, as determined by a number of workers, and of J_{Δ^0}(corr), the values obtained after correction to the standard air cutoff values used in this experiment. These data are not entirely self-consistent, as slightly different estimates have been made by the various authors for the effects of the residual atmosphere, but wherever possible, this has been taken into account.

The α-particle intensities J_{α^0} measured at energy cutoffs of 300 MeV/nucleon or less, are listed in Table III.[13–23] These values include a number made in this laboratory which will be discussed in detail in a later publication. Also shown is $J_{\alpha^0}(>200$ MeV/nucleon) the value that would have been observed if the cutoff energy had been 200 MeV/nucleon. This correction, like that on the heavy nuclei, was made using the α-particle differential energy spectra typical of solar

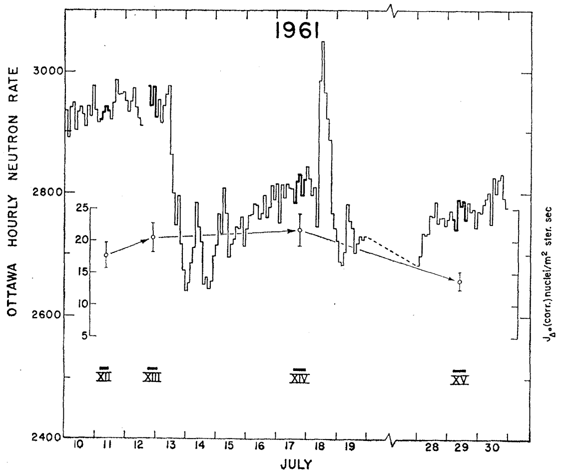

FIG. 2. The variations in the Ottawa neutron monitor rate and in J_{Δ^0}(corr) observed during a large Forbush decrease that occurred in 1961. Details of the flights XII to XV are given in Table I.

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Table II. Intensities of heavy nuclei.

References		Date	x g/cm²	x_{em} cm	$J_{\Delta 0}$	ΔJ (nuclei/m² sr sec)	$J_{\Delta 0}$(Corr)	Ottawa N. M. 1956–1960
Evans (Ref. 6)	α	18 September 1956	7.0	0.6	30.0 ± 2.4	-1.4	28.6 ± 2.4	3133
McDonald and Webber (Ref. 7)	β	20 March 1956	$E>0.43$ BeV/n		17.9 ± 1.3	$+2.8$	20.7 ± 1.7	3088
McDonald and Webber (Ref. 7)	γ	17 August 1956	$E>0.41$ BeV/n		23.7 ± 1.8	$+3.7$	27.4 ± 2.0	3103
McDonald and Webber (Ref. 7)	δ	1 August 1958	$E>0.55$ BeV/n		11.5 ± 0.9	$+2.4$	13.9 ± 1.1	2699
Foster and Debenedetti (Ref. 8)	ϵ	3 August 1958	3.8	3.0	14.9 ± 0.7	-0.3	14.6 ± 0.7	2622
Fichtel (Ref. 9)	ζ	30 July 1957	$E>0.36$ BeV/n		14.3 ± 1.2	$+0.8$	15.1 ± 1.2	2829
Aizu *et al.* (Ref. 10)	η	11 September 1957	7.6	1.0	15.9 ± 0.9	-1.2	14.7 ± 0.9	2675
Koshiba *et al.* (Ref. 11)	θ	4 September 1959	2.0	0.7	14.8 ± 0.5	-0.8	14.0 ± 0.5	2574
Biswas *et al.* (Ref. 12)	ι	13 March 1956	6.1	0.5	18.8 ± 1.4[a]	-0.4	18.4 ± 1.4	3010
Present work	κ	14 June 1958	4.4	1.3	21.8 ± 2.0	-1.0	20.8 ± 2.0	2771
Present work	λ	26 March 1958	10.3	0.2	10.4 ± 1.2	0	10.4 ± 1.2	2517
Present work	μ	21 March 1958	11.0	0.2	12.6 ± 1.5	0	12.6 ± 1.5	2734

[a] Assumes $\Gamma_{LS}(0)=0.21\pm0.05$.

maximum or minimum.[24] The uncertainty in the magnitude of this correction is appreciable, but since in no case does the correction exceed 10% of the total intensity and is typically 5% or less, the error introduced is considerably less than that which would result from neglecting this effect. These intensities were either determined by nuclear emulsion detectors or by a Cerenkov-Scintillator (C-S) array. It is therefore desirable, before using these data, to show that there are no serious systematic differences in the values determined by these two dissimilar techniques. Figure 3 shows the emulsion and counter results plotted as a function of the appropriate neutron monitor rates. Also shown are linear regression lines determined by least squares for the two sets of data. It can be seen that while neither of these is an entirely adequate fit to the data, they are not significantly different. Consequently, the linear regression line for all the data, which has the form

$$(J_{\alpha^0}(>200\ \mathrm{MeV/nucleon})-176)\pm4.7 = (0.262\pm0.022)(N-2854) \quad (1)$$

is also shown. This latter relation will be assumed to represent the variation between the α-particle intensity and the neutron monitor counting rate over the range of values $N=2600$ to 3400, even though clearly the true physical relation must be appreciably more complex. However, the experimental scatter of the values is such that a more complex form hardly appears justified, nor is it essential to the following analysis.

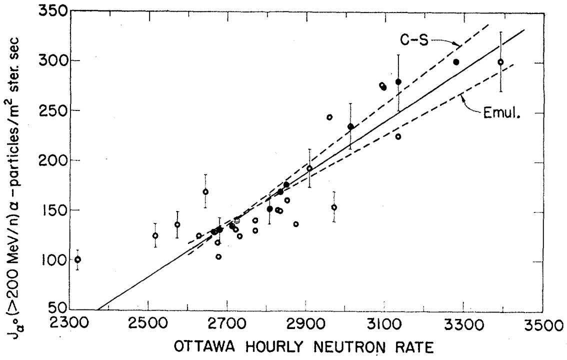

Fig. 3. The variation of $J_{\alpha 0}(>200$ MeV/nucleon) with the Ottawa neutron monitor rate as given in Table III. Points shown by ○ were obtained from emulsions, those by ● from the C-S array. Dashed lines show the least-mean-squares fit to these two groups of data, the solid line the fit to all the data which has $N>2600$. For simplicity, typical error bars are shown only on some of the values.

Under extreme conditions of modulation, represented by $N<2600$, very few α-particle intensities have been measured, but it is clear that the linear relation used above becomes completely inadequate. Apart from the one value obtained in this work, which will be reported elsewhere, the only published values having $N<2500$ are those obtained during a series of measurements by the Chicago group,[25–27] using a variant of the C-S array which imposed an energy cutoff of 560 MeV/nucleon on the observed particles. The relationship between these α-particle intensities and those obtained by the other C-S array and by emulsions has been studied by correcting the intensities to a standard cutoff energy of 500 MeV/nucleon, and then examining the variation with the neutron monitor rate. This cutoff energy was chosen as being approximately intermediate between that applicable to the Chicago data and that applicable to much of the other available data. The available data are listed in Table IV together with the corrections necessary to bring each value to the standard cutoff. Once again, these corrections were made from the differential energy spectra and are rather uncertain, but generally small. Figure 4 shows these data plotted as a function of the neutron monitor rate. It can be seen that the emulsion and McDonald and Webber (C-S) array data are in good agreement, but that the Chicago data are appreciably higher. Regression lines are shown for the two sets of data.

It seems reasonable to assume that the Chicago data have been affected by some systematic error which results in high values of the intensities. Making the comparison between the regression lines at $N=2700$, it appears that the Chicago data are about 25% above the

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TABLE III. α-particle intensities.

	References	Date	Technique	Cutoff MeV/nucleon	Corr.	$J_{\alpha 0}$ (obs)	$J_{\alpha 0}$ ($\geqslant$200 MeV/nucleon)	Ottawa N. M. 1956–1960	J_{Δ^0}(corr) nuclei/m^2 sr sec	$\Gamma_{\alpha\Delta}$	
					(α particles/m^2 sr sec)						
1	Fowler *et al.* (Ref. 13)	17 May 1956	Em	150	−11	255	244	2959			
2	Duke (Ref. 14)	18 September 1956	Em	130	−15	240	225	3133	$28.6\pm2.4^{\alpha}$	7.9 ± 1.1	
3	Freier *et al.* (Ref. 15)	17 May 1957	Em	225	4	157	161	2852			
4	Engler *et al.* (Ref. 16)	30 July 1957	Em	200	0	151	151	2829	$15.1\pm1.2^{\rho}$	10.0 ± 1.4	
5	Freier *et al.* (Ref. 17)	1 September 1957	Em	200	0	136	136	2573			
6	Present work	14 June 1958	Em	200	0	141	141	2771	$20.8\pm2.0^{\kappa}$	6.8 ± 0.8	
7	Duke (Ref. 14)	14 June 1958	Em	200	0	130	130	2771			
8	Stevenson and Waddington (Ref. 18)	29 July 1959	Em	250	2	167	169	2645			
9	G. Greer (Ref. 19)	6 May 1959	Em	200	0	150	150	2834	$20.9\pm2.2^{\mathrm{I}}$	7.2 ± 0.9	
10	G. Greer (Ref. 19)	13 May 1959	Em	200	0	125	125	2629	$11.9\pm1.1^{\mathrm{IV}}$	10.5 ± 1.4	
11	G. Greer (Ref. 19)	2 June 1959	Em	200	0	137	137	2850	$16.0\pm1.7^{\mathrm{VI}}$	8.6 ± 1.1	See No. 25
12	Present work	21 March 1958	Em	200	0	125	125	2734	12.6 ± 1.5	9.9 ± 1.4	
13	Present work	26 March 1958	Em	200	0	125	125	2517	$10.4\pm1.2^{\lambda}$	12.0 ± 1.7	
14	Aizu *et al.* (Ref. 10)	11 September 1957	Em	100	−4	122	118	2675	$14.7\pm0.9^{\eta}$	8.0 ± 1.2	
15	Engler *et al.* (Ref. 20)	3 August 1958	Em	80	−4	135	131	2722	$14.6\pm0.7^{\epsilon}$	9.0 ± 1.3	
16	Stevenson (Ref. 21)	28 April 1961	Em	250	2	152	154	2972			
17	Fichtel *et al.* (Ref. 22)	8 July 1961	Em	80	−4	197	193	2909			
18	Fowler *et al.* (Ref. 13)	28 September 1956	Em	300	28	249	277	3093			
19	Freier *et al.* (Ref. 15)	18 June 1954	Em	200	0	301	301	3390			
20	Present work	16 July 1959	Em	200	0	100	100	2322	$12.2\pm1.4^{\mathrm{XI}}$	8.2 ± 1.0	
21	McDonald and Webber (Ref. 23)	7 July 1955	C-S	260	15	286	301	3280			
22	McDonald and Webber (Ref. 23)	7 September 1956	C-S	260	15	260	275	3095			
23	McDonald and Webber (Ref. 23)	21 August 1956	C-S	260	15	265	280	3134			
24	McDonald and Webber (Ref. 23)	13 March 1956	C-S	260	15	220	235	3012	18.4 ± 1.4^{i}	12.8 ± 1.5	
25	McDonald and Webber (Ref. 23)	2 June 1959	C-S	260	3	173	176	2850			See No. 11
26	McDonald and Webber (Ref. 23)	1 June 1959	C-S	260	3	166	169	2835			
27	McDonald and Webber (Ref. 23)	12 April 1959	C-S	260	3	149	152	2809			
28	McDonald and Webber (Ref. 23)	16 February 1958	C-S	260	3	131	134	2713			
29	McDonald and Webber (Ref. 23)	2 July 1958	C-S	260	3	126	129	2665			
30	McDonald and Webber (Ref. 23)	16 May 1959	C-S	260	3	128	131	2677			
31	Present work	4 May 1960	Em	200	0	140	140	2725			

TABLE IV. High-energy α-particle intensities.

Reference	Date	E_c (MeV/nucleon)	dJ	$J_{\alpha 0}$ (obs)	$J_{\alpha 0}$ ($\geqslant$500 MeV/nucleon)	-25%	Ottawa	Tech
			⟵	(α particles/m^2 sr sec)		⟶		
1. Meyer (Ref. 26)	16 May 1959	560	+7	132±10	139±10	105	2677	C-S
2. Meyer (Ref. 26)	16 July 1959	560	+7	113±11	120±11	90	2327	C-S
3. Meyer (Ref. 26)	18 July 1959	560	+7	94±11	101±11	76	2236	C-S
4. Meyer (Ref. 26)	27 September 1959	560	+7	163±15	170±15	128	2723	C-S
5. Meyer (Ref. 25)	16 August 1957	560	+7	136±12	143±12	108	2808	C-S
6. Meyer (Ref. 25)	30 August 1957	560	+7	124±11	131±11	98	2520	C-S
7. Meyer (Ref. 25)	16 September 1957	560	+7	154±14	161±14	121	2715	C-S
8. Meyer (Ref. 25)	12 July 1958	560	+7	138±11	145±11	109	2691	C-S
9. Meyer (Ref. 25)	22 July 1958	560	+7	140±11	147±11	110	2656	C-S
10. Yates (Ref. 27)	13 July 1959	560	+7	133±24	140±24	105	2616	C-S
11. Yates (Ref. 27)	19 August 1959	560	+7	143±23	150±24	112	2652	C-S
12. Yates (Ref. 27)	5 May 1960	560	+7	149±19	156±19	117	2732	C-S
13. Yates (Ref. 27)	20 November 1960	560	+7	138±14	145±14	109	2745	C-S
14. McDonald and Webber (Ref. 23)	7 September 1956	430	−18	192±15	174±15		3095	C-S
15. McDonald and Webber (Ref. 23)	2 June 1959	430	−9	152±10	143±10		2850	C-S
16. McDonald and Webber (Ref. 23)	1 June 1959	430	−9	147±10	138±10		2835	C-S
17. McDonald and Webber (Ref. 23)	12 April 1959	430	−9	126±10	117±10		2809	C-S
18. McDonald and Webber (Ref. 23)	16 February 1958	430	−9	118±8	109±8		2713	C-S
19. McDonald and Webber (Ref. 23)	2 July 1958	430	−9	114±8	105±8		2665	C-S
20. McDonald and Webber (Ref. 23)	16 May 1959	430	−9	112±8	103±8		2677	C-S
21. Freier *et al.* (Ref. 17)	18 June 1954	500	0	211±17	211±17		3390	Em
22. Freier *et al.* (Ref. 17)	1 September 1957	500	0	120±6	120±6		2573	Em
23. Freier *et al.* (Ref. 17)	17 May 1957	500	0	127±13	127±13		2852	Em
24. McDonald and Webber (Ref. 23)	20 March 1956	430	−18	176±6	158±6		3088	C-S
25. McDonald and Webber (Ref. 23)	17 August 1956	410	−20	225±10	205±10		3103	C-S
26. McDonald and Webber (Ref. 23)	1 August 1958	550	+6	105±6	111±6		2700	C-S
27. Engler *et al.* (Ref. 20)	30 July 1957	500	0	119±9	119±9		2829	Em
28. Engler *et al.* (Ref. 20)	3 August 1958	500	0	107±8	107±8		2722	Em
29. Greer (Ref. 19)	13 May 1959	500	0	103±10	103±10		2629	Em
30. Greer (Ref. 19)	6 May 1959	500	0	112±11	112±11		2932	Em
31. Greer (Ref. 19)	2 June 1959	500	0	111±11	111±11		2840	Em
32. Present work	4 May 1960	500	0	111±11	111±11		2725	Em

remainder, or, alternatively, approximately 40 particles/m^2 sr sec too high. Whether the error is fractional or additive is not determinable from the data, but a fractional error seems physically more likely. For this reason the Chicago data have been reduced 25% and all the $E \geqslant 500$ MeV/nuclear data replotted in Fig. 5.

The regression lines for all the data, with Chicago corrected this way, and with it corrected for an additive error, are both shown and the difference can be seen to be small. Also shown is the regression line for the $E \geqslant 200$ MeV/nucleon data, Eq. (1). Physically, this last line cannot cross that for the $E \geqslant 500$ MeV/nucleon data and so, from Fig. 5, cannot be linear below $N = 2550$. The convergence of these two lines suggests that for extreme modulation, either all the particles with $E \leqslant 500$ MeV/nucleon are removed, or, alternatively, all those particles with $E \leqslant 500$ MeV/nucleon which can be removed have been removed. Thus, for $N < 2550$, a lower limit to $J_{\alpha^0}(>200$ MeV/nucleon) is provided by the regression line to the $E \geqslant 500$ MeV/nucleon data, which has the form

$$[J_{\alpha^0}(>500\ \text{MeV/nucleon}) - 125] \pm 2.8 = (0.123 \pm 0.012)(N - 2756). \quad (2)$$

If the α particles and heavy nuclei are similarly modulated, then the heavy nuclei intensities should obey relations (1) or (2) after being reduced by the value of the abundance ratio, $\Gamma_{\alpha\Delta}$, of α particles to heavy nuclei.

The most direct way of studying the comparative behavior of the α particles and heavy nuclei is to consider those experiments where the intensities of both components have been determined simultaneously. Figure 6 shows a plot of the α-particle intensity $J_{\alpha^0}(>200$ MeV/nucleon) against the heavy-particle intensity J_{Δ^0}(corr). On a plot with scales proportional to the abundance ratio if both components are modulated equally, the points should lie along a line with a 45°

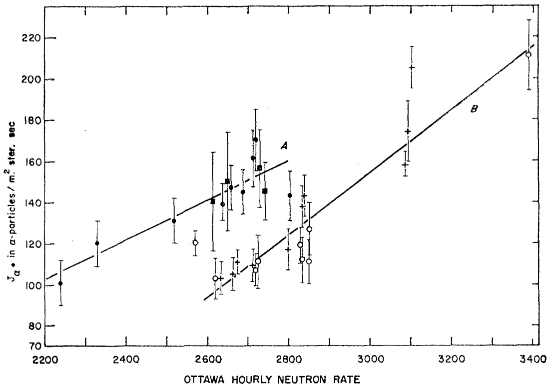

FIG. 4. The variation of $J_{\alpha 0}(>500)$ with the Ottawa neutron monitor rate. Points shown by ● are due to Meyer (Refs. 25 and 26) those by ■ to Yates (Ref. 27). Curve A shows the least mean-squares fit to these data. Points shown by ○ are from emulsion detectors, those by + are from the counter array. Curve B shows the least-mean-squares fit to these data.

slope. Because of the somewhat higher average energy of the heavy nuclei due to their higher air cutoff energy, this slope could be *reduced* slightly if the modulation decreases as the energy increases. Examination of Fig. 6 shows the experimental points are widely scattered, but does suggest that those points obtained during the Forbush decreases could be fitted by a line with a slope much greater than 45°, which would imply differing degrees of modulation for the two components. An alternative presentation of the same data is given in Fig. 7, where the values of $\Gamma_{\alpha\Delta}$ are plotted as a function of the appropriate Ottawa neutron monitor rate. Again there is a wide scattering of the points and an indication that during the Forbush decreases, $\Gamma_{\alpha\Delta}$, increases as the sea-level cosmic-ray intensity decreases,[28] thus implying that the heavy nuclei are appreciably more affected than the α particles.

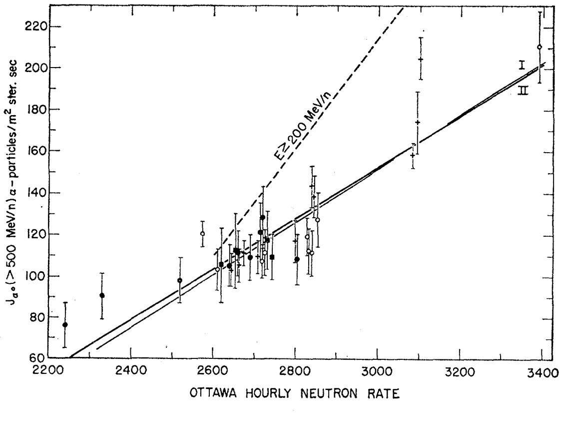

FIG. 5. The variation of $J_{\alpha 0}(>500)$ with the Ottawa neutron monitor rate after the Chicago data is corrected. Curve I shows the least-mean-square fit for a constant correction, curve II shows it for a fractional correction. Data points are represented as in Fig. 4. Also shown is the regression line for $J_{\alpha 0}(>200$ MeV/nucleon), Eq. (1).

This evidence that the α particles and heavy nuclei are affected differently is in conflict with presently accepted theories of possible modulation mechanisms. If verified, this result would suggest that the modulation processes must be charge-dependent with, presumably, ionization energy losses playing an important role. Thus, it is obviously of great importance to investigate this effect further in an attempt to either confirm or rebut the evidence presented above. It may be noted that the effects observed are not of great statistical significance and not entirely self-consistent.

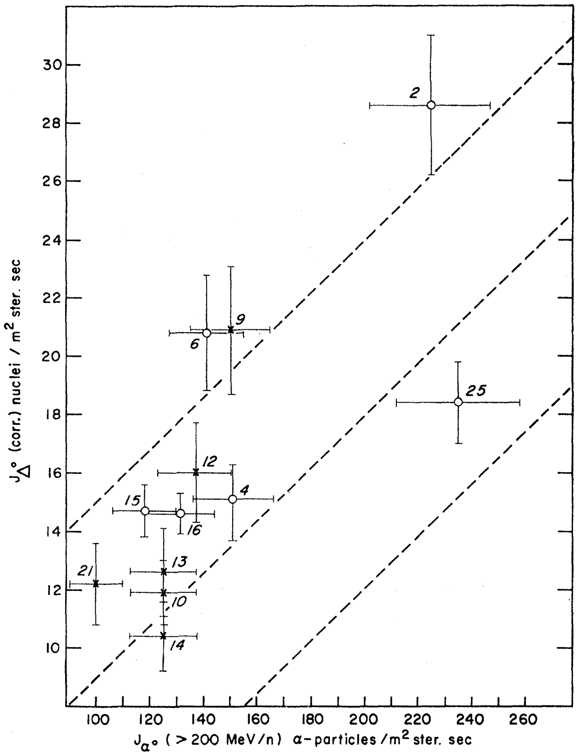

FIG. 6. $J_{\Delta 0}$(corr) plotted against $J_{\alpha 0}(>200$ MeV/nucleon). Here the scale of the abscissa is 9.0 $(=\langle\Gamma_{\alpha\Delta}\rangle)$ times that of the ordinate, so that the points might be expected to lie parallel to one of the arbitrary 45° slope lines shown (see text). Values obtained at times associated with Forbush decreases are shown by ×, others by ○.

While the number of stimultaneous determinations of both the α-particle and the heavy-nuclei intensities is limited, there are quite a large number of individual α-particle intensities and a considerable number of heavy nuclei intensities reported in the literature. If both components are equally affected by the modulation, it should be possible to establish a relation between the α-particle intensities and the neutron monitor rates, and then demonstrate that the same relation, apart from a constant multiplying factor, the ratio of the relative intensities, represents the variation between the heavy-

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[28] This would be particularly true if point 21, which was the last one determined in this study, were omitted.

nuclei intensities and the neutron monitor rates. Since the neutron monitor rate is predominantly determined by the high-energy nucleons in the primary cosmic radiation, such a demonstration would prove that the α particles and heavy nuclei were similarly moderated. If the modulation is similar during the long-term variation, as during Forbush decreases, then all the heavy nuclei intensities, whether taken during such decreases or not, should satisfy the same relation.

From the values of $\Gamma_{\alpha\Delta}$ obtained in this work, $\langle\Gamma_{\alpha\Delta}\rangle = 9.0$. It should be noted that this is *not* the value above a unique energy per nucleon, but only an upper limit to that value.

The values of J_{Δ^0}(corr) are shown as a function of the Ottawa neutron monitor rate in Fig. 8. Also shown in this figure are relations (1) or (2) with J_{α^0}(>200 MeV/nucleon) replaced by J_{α^0}(>200 MeV/nucleon)/$\langle\Gamma_{\alpha\Delta}\rangle$, and the least-mean-square fit to the data. Inspection of this figure suggests that there is still a tendency for the regression curve to the Forbush decrease data to be somewhat steeper than that for the other data. However, this tendency can hardly be statistically significant, and it appears that the heavy nuclei can be represented by a similar regression curve to that observed for the α particles. Consequently, it should be concluded that these nuclei are modulated proportionately to the α particles both during Forbush decreases and during the long term solar cycle variation, and that it is therefore justifiable to assume $\Gamma_{\alpha\Delta}$ is constant at all levels of modulation. It is clear, therefore, that processes such as ionization loss, which might distinguish particles of differing Z, do not seriously influence the solar modulation process. Before this statement can be refined, more accurate and consistent data are needed, particularly at times of sunspot minimum. Similarly, the influence of any charge-dependent effects would be more clearly shown if attention were directed to the heavier nuclei, such as those with $Z \geqslant 10$. Unfortunately, it is difficult to obtain statistically significant samples of these nuclei.

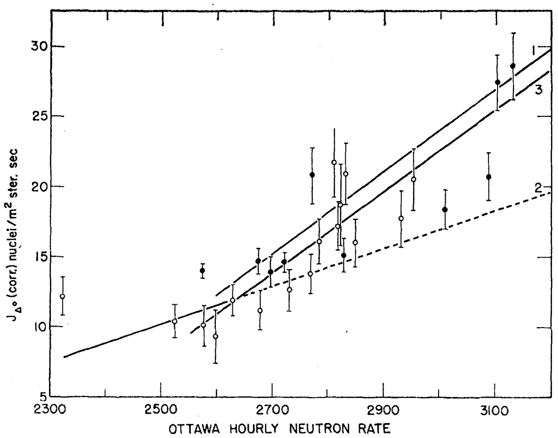

FIG. 8. The variation of J_{Δ^0}(corr) with the Ottawa neutron monitor rate. Curve 1 is derived from Eq. (1) with $J_{\alpha 0}$(>200 MeV/nucleon) divided by $\langle\Gamma_{\alpha\Delta}\rangle$ and similarly curve 2 is derived from Eq. (2) with $J_{\alpha 0}$(>500 MeV/nucleon) divided by $\langle\Gamma_{\alpha\Delta}\rangle$. Curve 3 is the least-mean-square fit to all the data with N>2500. The values obtained in this study are shown by ○, those obtained from the literature by ●.

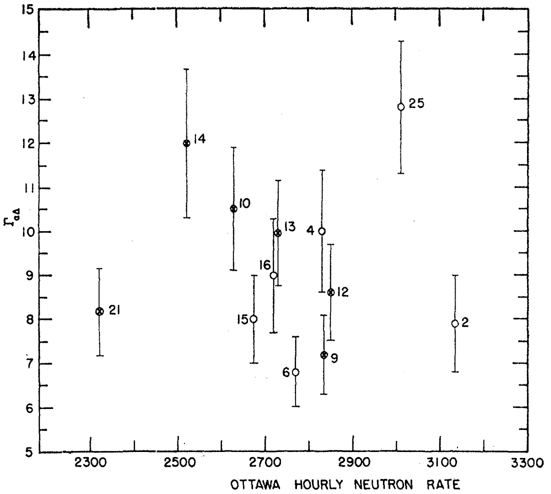

FIG. 7. The variation of the abundance ratio $\Gamma_{\alpha\Delta}$ with the Ottawa neutron monitor rate. Points obtained at times associated with Forbush decreases are shown by ⊗, others by ○.

ACKNOWLEDGMENTS

We are grateful to the many people who have been involved in the balloon launching program and who have remembered to include the small can of emulsion. Sam Brinda has cheerfully and efficiently processed this almost unending stream of emulsions, while the microscope observers mentioned below have carried out the tedious examination of these emulsions: Dulce Chan, Dawn Copeland, Jean Gortner, Audrey Hopkins, Marcie Kluver, Hilde Rahlenbeck, Biruta Sommer, and Nona Spitzner.