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Measurements of the energy spectrum of nuclei with $Z \geqslant 3$ in the primary radiation using a balloon borne Cerenkov-scintillation counter †

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Abstract. The spectra of the so called L, M and H nuclei have been measured on eleven balloon flights at seven geomagnetic latitudes during the period 1963-65. The instrument used is a modified version of the Cerenkov scintillation counter. These spectra have been measured over the range 1.5 to 16 GV. The flights attained depths of 2-6 g cm^{-2} which, coupled with the detector's large geometrical factor (~50 sterad cm^2), has enabled details of the absorption of the L, M and H components to be studied in the upper atmosphere. The large geometrical factor has allowed identification of over 10 000 nuclei with $Z \geqslant 3$, over 2000 being observed on a single flight. A total of about 150 VH nuclei have been observed and the spectrum of these nuclei has been found to be similar to that of M and LH nuclei above about 2 GV. The spectrum of the L nuclei is found to be significantly different from that of the M and H nuclei, with the exponent on a power law energy spectrum being 0.3 ± 0.1 larger. The M and LH nuclei spectra are also different from the He nuclei spectra above 3 GV: the exponent on a power law spectrum being 0.1 ± 0.03 larger with the integral spectrum being given by an average exponent of −1.6 ± 0.03 over the range 3-16 GV. The solar modulation of these nuclei is found to be similar to that of the He nuclei.

In this paper we wish to discuss the energy spectra and modulation of the heavy nuclei, essentially those with $3 \leqslant Z \leqslant 26$ as measured by the Cerenkov-scintillator system discussed in Chap. 4, SPEC 29. The study of these nuclei presents a number of special problems with which we would like to concern ourselves before the actual presentation of the data.

First of all, the identification of these nuclei is relatively simple and although the intensity is not great it is possible to get meaningful absorption curves of the different components (the L, M and LH groups) as the balloon rises to altitude. These may then be used to compare with fragmentation-diffusion theory and to extrapolate the intensities of the different components to the top of the atmosphere.

During a typical four-hour duration of a high latitude flight approximately 2000 nuclei with $Z \geqslant 3$ are observed. This permits breakdown into the usual L, M, LH and VH charge groups. The spectrum of the M nuclei can be determined with an accuracy formerly associated with the helium nuclei and the spectra of L and LH nuclei are each based on about 300 counts.

The identification of the different nuclei passing through the detector is controlled by two factors. First the background of unwanted counts is virtually zero for particles of all energy with $Z \geqslant 5$. Second, the charge resolution is good enough to enable the counts due to individual charges to show up as distinct groups over the range $5 \leqslant Z \leqslant 14$ in a flight at latitudes less than 50° and a series of successive lines at high latitudes where non-relativistic particles are entering and the energy spectrum is being measured. For values of $Z > 15$ it is difficult to make individual charge identification, a distinct grouping at a $Z \sim 26$ being the dominant feature of this part of the charge distribution. Because of the print-out in 64 × 64 arrays it is difficult to show a complete charge spectrum at the highest resolution. However, figure 1 shows an array covering boron, carbon, and nitrogen for the Fayetteville flight where all the particles are relativistic. The system linearity is calibrated by a light pulser system before each flight. In addition, the proton and helium peaks provide in-flight calibration. The ability to identify each charge peak up to $Z = 14$ then provides a continuous measure of the linearity of response of the system to particles of different charge and energy loss. As a result it is possible to measure the non-linearities of energy loss in the plastic scintillator and Cerenkov-scintillator up to a charge of about 26. The results are shown in figure 2. Our results show that the saturation effect in the scintillator becomes logarithmic at high rates of energy loss. This is in some ways an advantage since it converts a normal Z^2 charge dependence into an approximate Z dependence giving effectively a logarithmic system and allowing us to extend our charge measurement out to $Z = 26$. This charge calibration has been established for several flights.

The energy spectra of the heavy nuclei are then determined in a straightforward way. An additional check is possible on the energy calibration for non-relativistic heavy nuclei by observing the location of the minimum on the S + C output curve (as well as the slope of the (S, S) (C = 0) output). Detailed study of these features shows that the non-linearity is independent of charge and depends only on dE/dx in the range of energies that do not end in the scintillator.

It is to be noted that at energies somewhat below the Cerenkov threshold (< 250 MeV/nucleon) it becomes impossible to resolve individual charges. In the range 100-250 MeV/nucleon it is still possible to get the differential intensity of particles of a given charge group, however. The complete charge breakdown for all flights analysed to date is shown in the table.

Distribution of particles of different charge at balloon altitudes

Charge	Counts			
	Total		> 12 GV	
Li	390	1, 226	14	36
Be	214		5	
B	622		17	
C	1, 390	3, 142	65	124
N	530		15	
O	1, 132		44	
F	90		0	
Ne	301	764	17	37
Na	110		3	
Mg	167		10	
Al	65		0	
Si	121		7	
$15 \leqslant Z \leqslant 19$	103		1	
$Z \geqslant 20$	204		8	
$Z \sim 40$	2		0	

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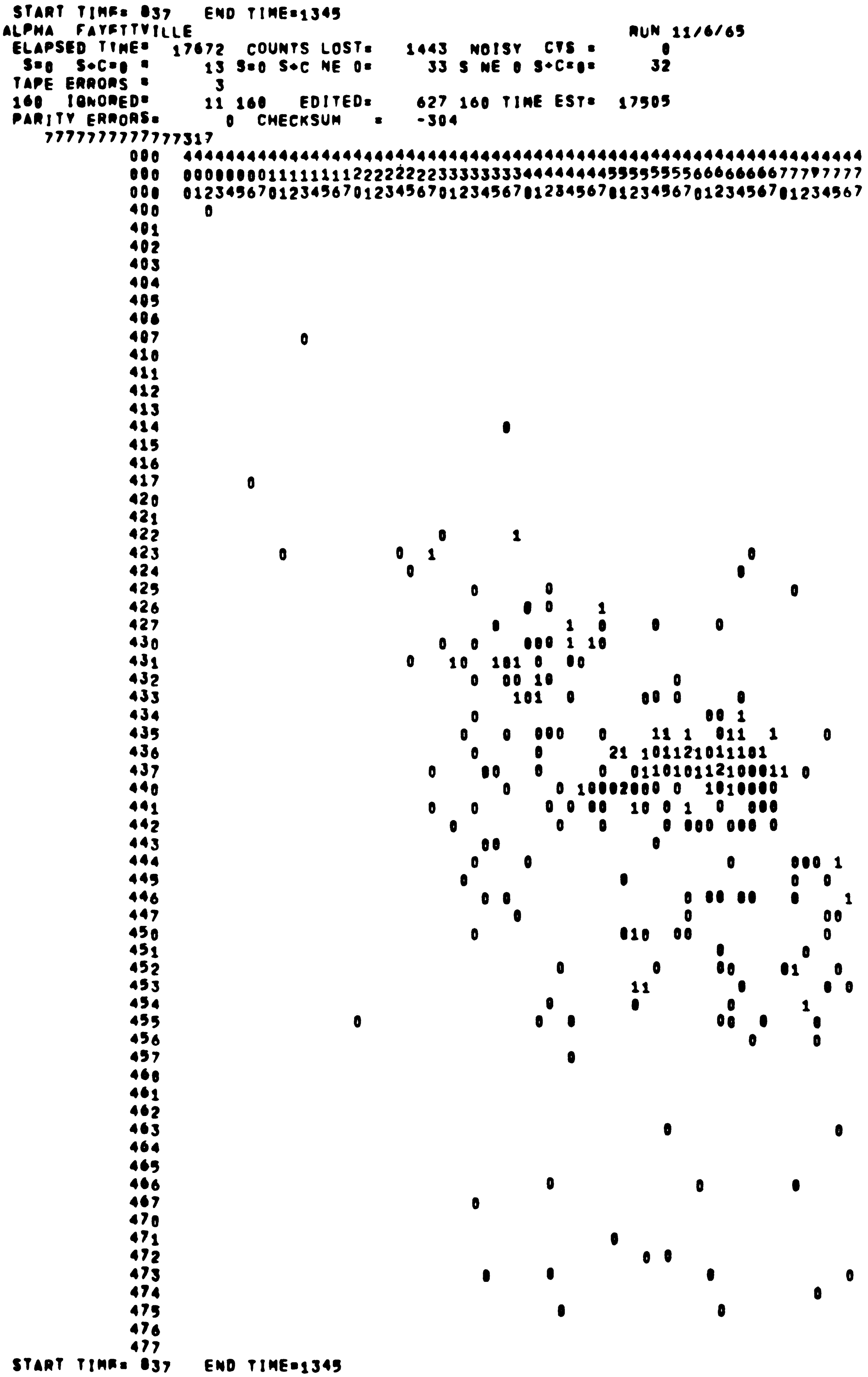

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Fig. 1 64 × 64 array showing a part of the pulse height distribution containing boron, carbon (the large group right centre) and nitrogen. S output along vertical axis, S + C output along horizontal. The geomagnetic cut-off of approximately 900 MeV/nucleon means that the distributions should be slightly skewed in the direction of smaller S + C outputs and this is clearly evident from the figure.

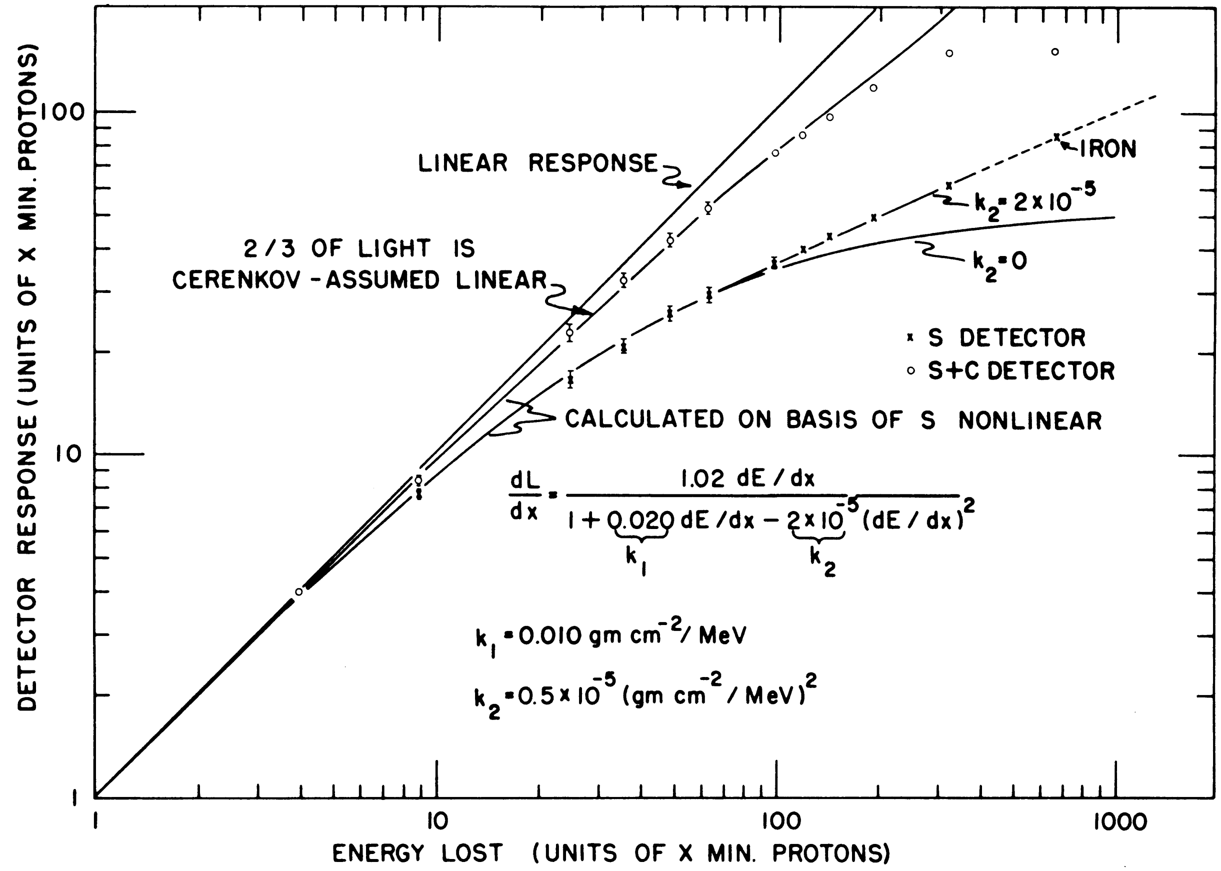

Fig. 2 The relation between energy loss dE/dx and light output dL/dx for relativistic particles of various charge in the plastic scintillator NE 102 and S + C detector.

The integral spectra of the various charge groups are shown in figure 3. The points at 3.2, 5.6 and 12.1 GV are evaluated in the same way as the helium nuclei, that is by extrapolating the growth curves of the individual components to the top of the atmosphere. The remaining points are obtained from the differential spectra measured in the telescope itself. These differential spectra are shown in figure 4 along with a point determined from the differences of the 3.2 and 5.6 GV integral measurements. The effects of the solar modulation are clearly evident in the spectra of the M nuclei and less conspicuously for the L and LH nuclei. As near as can be determined, the solar modulation affects these nuclei (except possibly for the L nuclei) in a manner identical to the helium nuclei.

Although superficially the spectra of these heavy nuclei are similar, important differences exist, both in the low and high rigidity parts of the spectrum. These differences seem to be best illustrated by taking ratios of the differential intensities of helium nuclei to the various heavy nuclei groups. Three of these ratios are shown in the previous paper (SPEC 29, figure 3) as a function of rigidity. (Energy/nucleon and rigidity are equivalent if we neglect ^{3}He in the helium component). Very little can be said of the He/VH ratio—except that it shows no pronounced changes from 2-12 GV. Even this fact has some important astrophysical implications, as is discussed in SPEC 29. The He/M and He/LH ratios both behave in a similar manner, however. Above about 2.5 GV these ratios slowly increase with increasing rigidity. This increase appears to be continuous and is equivalent to the power law spectra of the M, and LH nuclei having an exponent 0.1 ± 0.03 larger than the helium nuclei. It is important to note that this result is not based on a single equatorial flight but appears in both flights—in which over 200 of these nuclei have been recorded. This trend is also evident in the Kerrville flight at 5.6 GV where a further 400 of these nuclei were recorded. Unless a systematic distortion exists between energies measured by the detector and those deduced from geomagnetic considerations for these charges, we must regard this effect as statistically significant.

Finally, below 2 GV a rapid increase in these ratios occurs—most notable for the M nuclei. The significance of these spectral differences and a discussion of the spectra of L nuclei which shows even more pronounced differences is discussed in SPEC. 29.

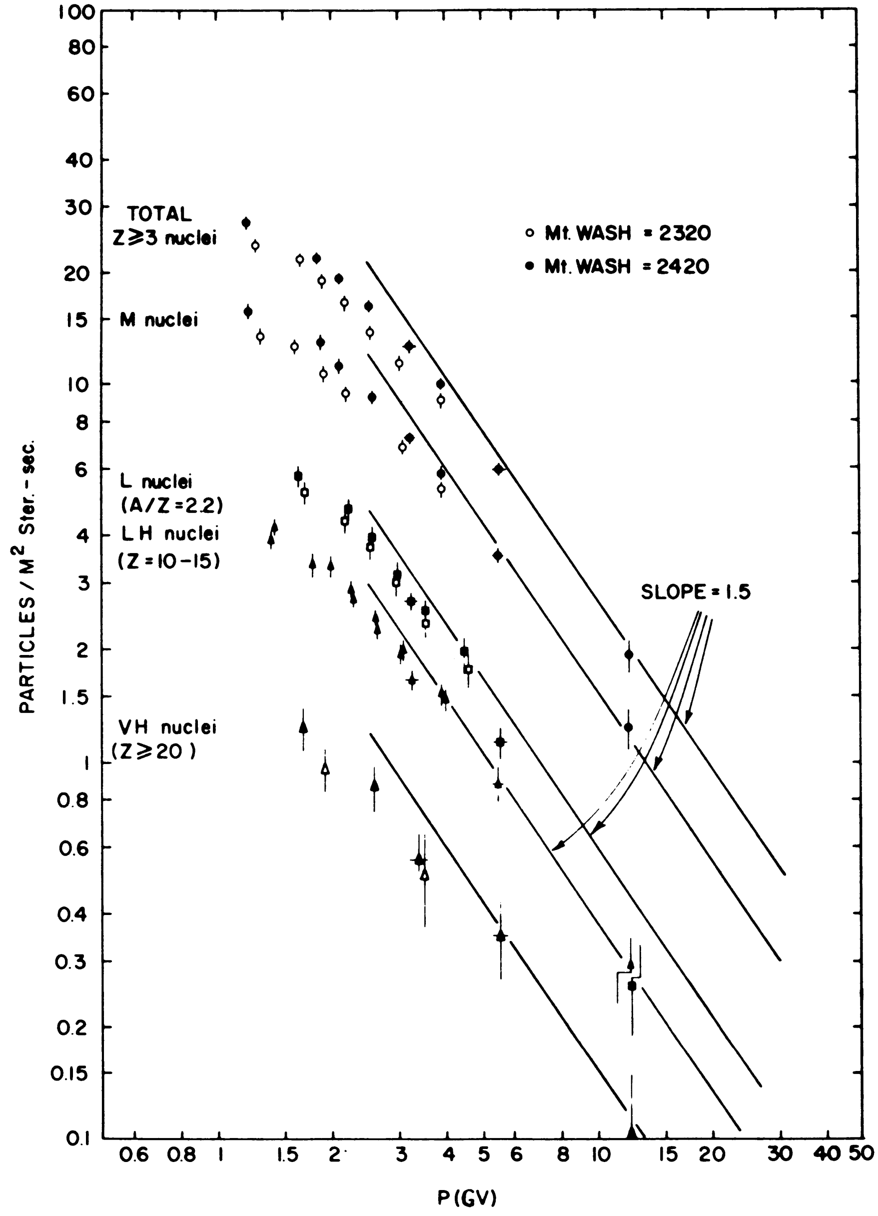

Fig. 3 Integral spectra of the L, M, LH, and VH charge groups. The full lines indicating integral rigidity spectra with exponents −1.5 are shown for guide purposes only.

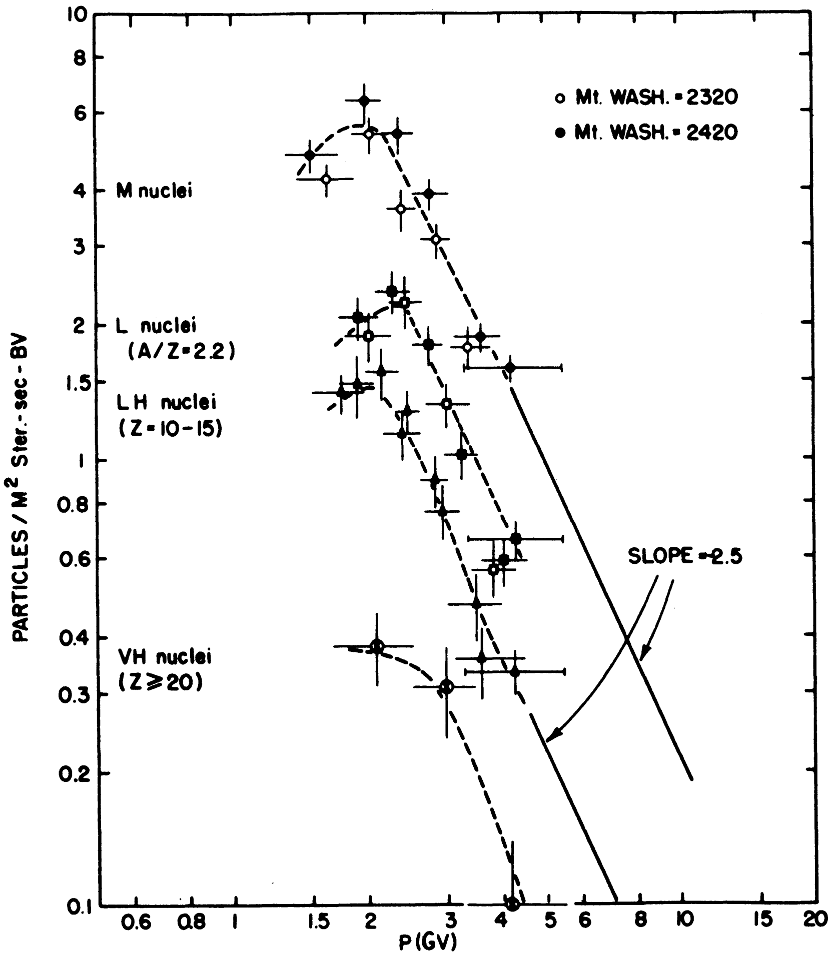

Fig. 4 Differential spectra of the L, M, LH, and VH charge groups. The full lines indicating differential rigidity spectra with exponents —2. 5 are shown for guide purposes only.

Discussion

S. BISWAS. I would like to remark that in comparing our data of the L/M ratio with those of yours, we find good agreement in the increased ratio of L/M at about 150-400 MeV/nucleon; but our data seem to indicate rather rapid decrease in the region 400-600 MeV/nucleon, in contrast to the rather slow decrease seen by you. Now I would like to ask whether your data show an indication of the L/M ratio again being low at energies less than 150 MeV/nucleon.

W. R. WEBBER. Within your rather poorer statistics I think that your data is consistent with ours.

Our data show evidence of a peak in the L/M ratio at 300-400 MeV/nucleon. At this energy the value of this ratio is approximately equal to 0. 5. I should point out that on an energy/nucleon basis this ratio appears to be modulation dependent, however.

C. E. FICHTEL. Can you give the relative abundances of Li, Be and B as a function of energy?

W. R. WEBBER. As far as we can tell they remain essentially constant from about 300 MeV/nucleon to greater than 5 GeV/nucleon. Since the Be/B ratio might be expected to change with the decay of radioactive ^{10}Be this places a limit to the 'age' of these particles at greater than or equal to 10^7 years.