Proc. Int. Conf. Cosmic Rays 1965

Measurements of the primary proton and helium spectra and their modulations using a balloon-borne Cerenkov-scintillation counter*

J. F. ORMES and W. R. WEBBER

School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota, U.S.A.

Abstract. During the years 1963-65 the spectra of protons and helium nuclei have been studied on eleven flights at seven geomagnetic latitudes using a modified version of the Cerenkov-scintillation counter. The flights attained depths of 2-6 g cm^{-2} which coupled with the detector's large geometry factor (~50 sterad cm^2) enabled details of the helium intensity, and the different contributions, primary and secondary, to the singly charged distribution, to be evaluated as a function of atmospheric depth. These results demonstrate that it is necessary to know in detail the contribution of all non-primary components, particularly at the lower energies, before a spectrum of primary protons can be determined. The spectra of primary protons and helium nuclei measured on these flights are presented. These spectra cover the range from about 0.6-16 GV rigidity. Our results indicate that the lowest energy protons have increased by more than 50% between 1963 and 1965. The proton spectrum is almost flat down to 0.5 GV in 1965, but the helium spectrum is falling sharply at the corresponding rigidities. A study of the modulation of these two components during this period reveals that (1) the modulation depends approximately on $1/\beta$ for $0.45 \leqslant \beta \leqslant 0.85$ for both components, and (2) at the same velocity, the modulation for protons is at least twice that for helium nuclei.

During the past two years eleven balloon flights have been made with a Cerenkov-scintillation telescope by the University of Minnesota group. The detector measures the energy spectrum of the individual nuclei from $Z = 1$ to $Z = 26$ over an energy range from 40-1000 MeV/nucleon. Relevant data pertaining to these flights are shown in the table.

The four flights at Churchill were made by outside contractors using very large plastic balloons, the remaining seven by the Minnesota group itself using 300 K or 600 K cubic ft balloons to carry the total payload of 50 pounds to altitudes ranging from 4-6 g cm^{-2}. Our instrument is different from the usual Cerenkov-scintillation counter and although it has been described previously (Ormes and Webber 1965) we would like briefly to review some of its salient features here. First, the so-called Cerenkov detector is actually a combination Lucite Cerenkov counter and plastic scintillation counter with the integrated light from both processes being viewed by a single 7 in. photomultiplier tube. The degree of separation of the different charge components and the ability to measure the low energy particles of different charges is determined essentially by the ratio of scintillator (S) light o Cerenkov (C) light —the so-called S/C ratio. We have used a ratio of 0.6 in all standard flights. Discrimination against multiple events is carried out by studying the pulse height distributions themselves rather than with an active anticoincidence system. We believe that this approach has many advantages for a telescope as large as ours where one can apply statistical methods to the analysis of the data. Furthermore, the material in and around the telescope is kept to a minimum.

Perhaps the most important feature of the detector is, however, its large geometry factor of ~50 sterad cm^2. This is a factor of 10-100 times that of comparable detectors flown in balloons. This large geometry factor is achieved without loss in resolution by a careful selection of components.

Data pertaining to balloon flights of Cerenkov-scintillation counter

Location	P_c	Date	Alt. (g cm^{-2})	Mt. Wash. bi-hourly rate	Inst.
Churchill	0.2	1 Aug. 1963	4.0	2297	S
Churchill	0.2	11 Jul. 1965	1.9	2425	S
Churchill	0.2	28 Jun. 1965	3.2	2445	MS
Churchill	0.2	2 Jul. 1965	4.3	2440	LAS
Ely, Minn.	0.7	23 May 1964	4.1	2418	S
Devils Lake, N. D.	1.0	11 Nov. 1963	6.8	2325	S
Minneapolis, Minn.	1.2	4 Jul. 1963	6.5	2320	S
Fayetteville, Ark.	3.2	26 Mar. 1964	6.5	2378	S
Kerrville, Texas	5.6	29 Mar. 1965	5.5	2450	MS
Tucuman, Argentina	12.1	1 Aug. 1964	5.5	2407	S
Tucuman, Argentina	12.1	9 Aug. 1964	5.0	2410	RS

S = standard detector; MS = modified 3 element detector to measure additionally the low energy electron spectrum; LAS = large area version of standard detector with geometry factor = 1000 sterad cm^2; RS = standard detector pointing at 60° to the vertical and rotating in azimuth once every 15 minutes.

---

* Supported under NASA Research Grant NsG 281-62.

```
 START TIME= 837   END TIME=1345
ALPHA  FAYFTTVILLE                                          RUN 11/6/65
 ELAPSED TIME=  17505  COUNTS LOST=   1433  NOISY  CTS =      0
  S=0  S+C=0 =      13 S=0 S+C NE 0=     33 S NE 0 S+C=0=     32
 TAPE ERRORS =      3
 160  IGNORED=      11 160   EDITED=    627 160 TIME EST=  17505
 PARITY ERRORS=       0  CHECKSUM   =-118008
    7777777777431407
            000  0000000000000000000000000000000000000000000000000000000000000000
            000  0000000011111111222222223333333344444444555555556666666677777777
            000  0123456701234567012345670123456701234567012345670123456701234567
            000
            001  0 0011 111122001001  1                        0  0 01
            002   100011122332001   0 0    0                                    0
            003   13444445555444332331 00   10 1 011 0   101100    1  00 1   0
            004  0 577766677776655554443444332223132231223132212200122211 1000
            005    4666666676665553344333423332212221012211 00210111   1 11 211
            006  00466666666766554443434323220222211121011101110001 02121020100
            007    46666656776655544333323332222101221121010102010 101100021 1
            010  115677667788876655543444233222212122100112211211012110011 110
            011  00578877899998876665545444423322121102211021202 1221222001211
            012   15888889AAA998776665544444333333222223322212121201221 111110
            013  116899999AAAA988776665554444433333323122222122102213112111011
            014  016899899AAAAA98777666555544444333333222233331 23212  211211110
            015    5899889AAA9887766655554443333223232221112112220122122011200
            016  115888889999998776655544444433233222222212122222 0022111 1101 0
            017  015788888999887766554444343433221232211112210221121110011 1010
            020  0057777788888776655444334332232211220201021102111111 1   0 111
            021    56777778887765554433343323211212 02111 1 11110021020 2110100
            022  0 4677777777777655444433233211321111 121 201110010100 1 00 0011
            023  104677777777766544433333322222211212010001 11211 0 110111 0000
            024  00366777777776655534333332222112122121 001  210120 1  01001210
            025    36767676676654443332333332220002120100   12111 010100 00 121
            026   03567666666665544343334223321121 1 11 100   01111201001     0
            027    356676666665553333333331212222111012100 11 1 0000110 1  0 001
            030   0355666666665554443333322333221202811 1101 01000010 001001 10
            031    15666666665544433223232322 22 00 1000012  0 11 0011 110 0
            032    35666666665554332232332211220110 120 110001 012111 0  1 0 0
            033    1455666665554333332333222211 000001 1    20 1 1  0 1  0  01
            034    24556555554444433323222122 21 010 0100 10 00011201020010101
            035    254555656554443322221222213121111  10 0 1  0 000  0 1
            036    145455555555443222212222 221020 0101    111  01 1 11  01002
            037     354555655444332222112110112000 0 00 1100 00     101000 000
            040    14445555555443323020 1 11220 1 100 1 10  00 100 0 120 0 1 000
            041    134445555554432321122201201110 1 1  1 02 002 1110 2   10 0 0
            042    04444455554533322120211 1 01000 0 10 100001 011200111   01011
            043    23444455555443322211011121 0210 00022001  1110112 220200 001
            044    1444334555554333222310110101 0111   01 1   1010021   0  001
            045     34434445553432121110121  11 102 01 10 0111101 1 1012 00 0 1
            046    13334444544444231211110100000  00 011100200212221222121022 2
            047    144433444554443233221200211 1 12011 00111 221222322222 12 0111
            050    024434444454433222313202111 2011 11  1121112223323222132222 11
            051    1333434444444433332132222020110100 202211222233333322323222222
            052    1233243444444443332202220 1 10101221 021232213422333334332232?
            053    134334444434443333232222221201111201211222233434444333332332332
            054     33433444445343443232222212201221110221333323333334444332233223
            055    02344444433444433422120121 2211222122223333344444443334333 3222
            056    034443343444344443232223002221130022223333443445444434332323
            057    0334343433443332323223221222121221332333344344444444343323232
            060    13333444434443334333322211111021223323333343444334444343432233
            061    134444444443343342332132222121122120233333443433444342322232
            062    12324444444333333433332322212022112222233333343434433233332111
            063    12334433333433233333323211202 0122223232223343343324433333212
            064    133344333333332323333323221221212222321333333333443334331321223
            065    1344443344223333333232321 01211221332233333333332433223223210
            066   013343343434332222233323122 0111122313431332334433233233322210
            067    12333333333322222232332212221 0 211131232322223333332212012111
            070     23333343332233232333222111100108221333222322333332321211011
            071    0243233323232321222222211221100221111112122312212232112201201
            072    13333223223333100223220302111220222 2211322212321232202 2 0 1
            073    033332234332331222322222111121010201131213223121212310 1012
            074     233333233331222122222212213102102120120220211220200002 010
            075    02332133322222122223222222232200 1110122201222121113111120 0
            076    02331223233222313022223321122020 111100111 211101122  100 11
            077
 START TIME= 837   END TIME=1345
```

Fig. 1 64 × 64 matrix for the Fayetteville flight. S output on vertical axis, S + C on horizontal. Note helium in lower right-hand corner and slow proton distribution (atmospheric secondaries) running diagonally to lower centre of distribution. Numbers give n where each bin has between 2^n and 2^{n+1} counts.

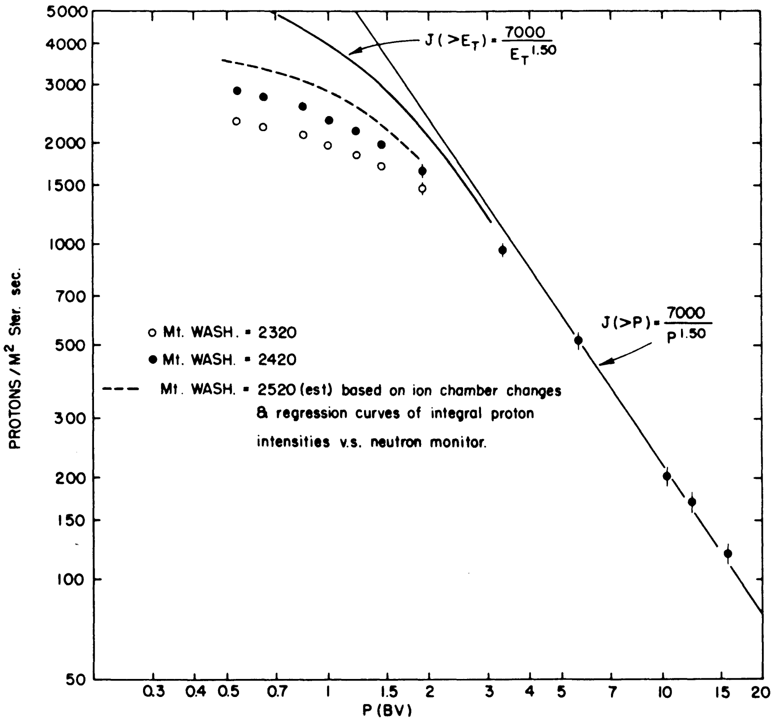

Fig. 2 Integral spectrum of primary protons at two levels of modulation.

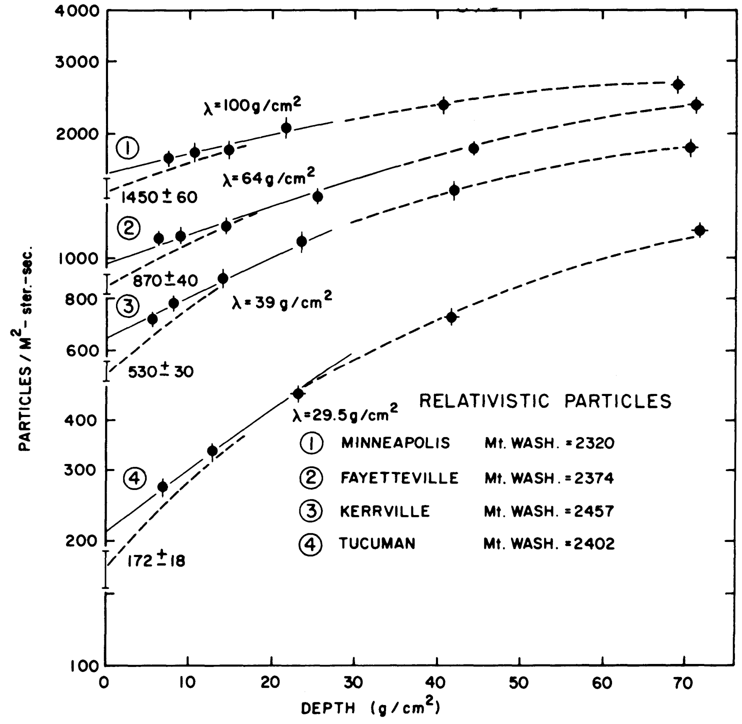

Fig. 3 Growth curves of relativistic particles measured on four flights at different latitudes.

1965ICRC....1..349O

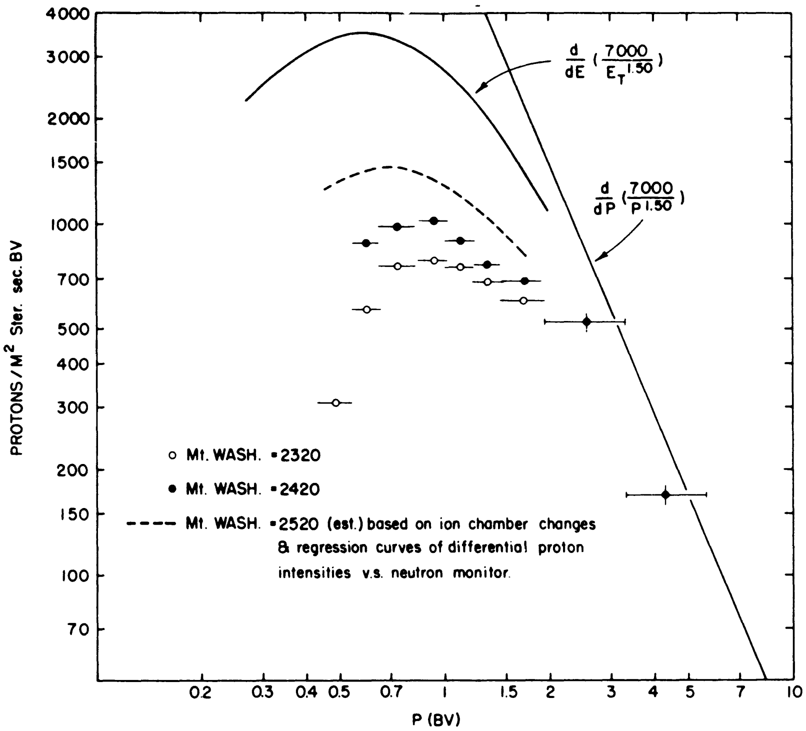

Fig. 4 Differential spectrum of primary protons at two levels of modulation.

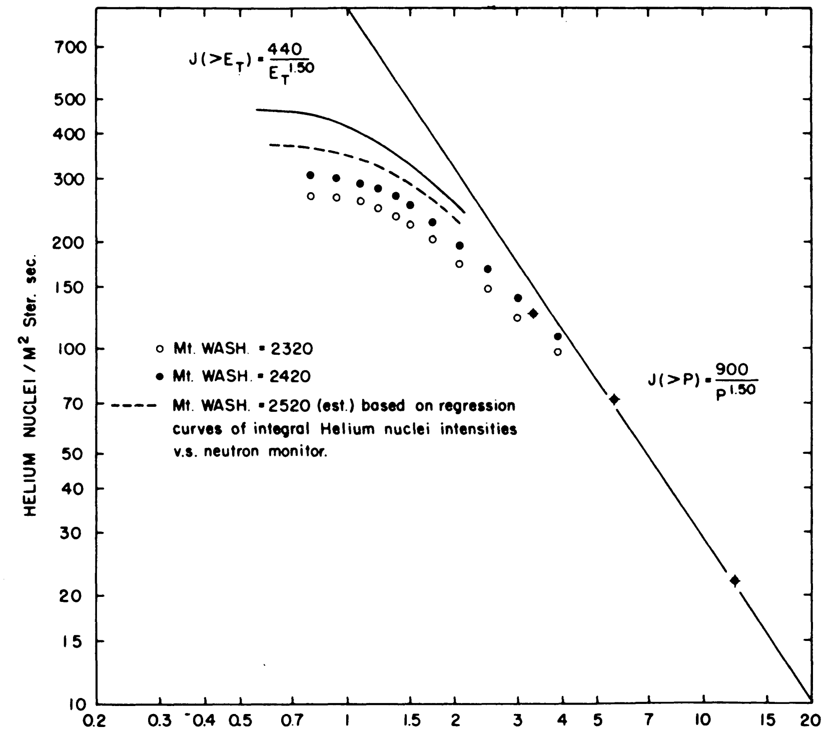

Fig. 5 Integral spectrum of primary helium nuclei at two levels of modulation.

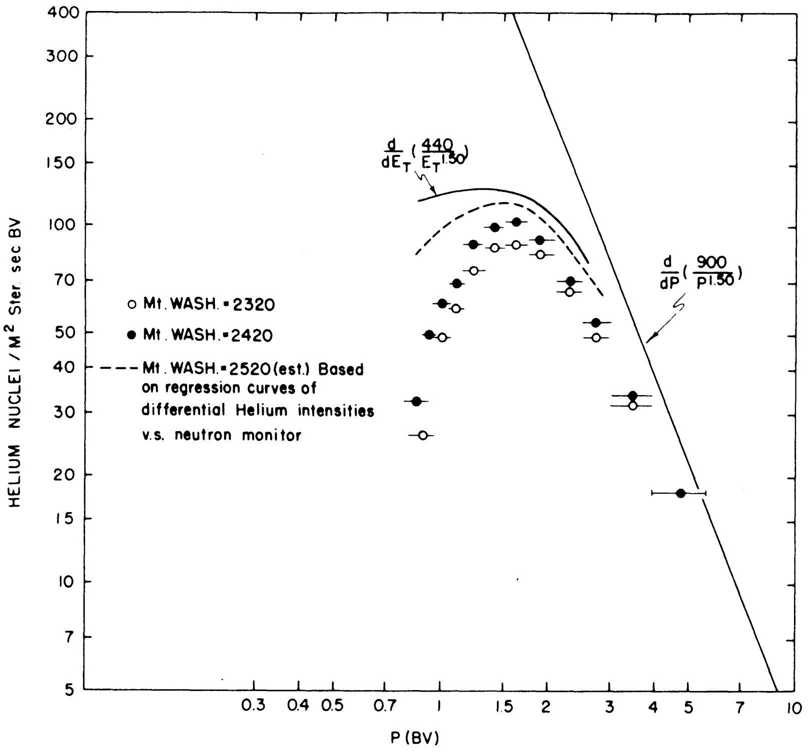

Fig. 6 Differential spectrum of primary helium nuclei at two levels of modulation.

The flight data are divided into 5-10 minute intervals during the ascent and appropriate longer intervals while the balloon is at altitude. This means that the absorption of helium nuclei can be obtained as a function of altitude. The development of low energy protons can also be studied as a function of altitude—a most important input for the separation of low-energy primary and secondary protons at high latitude and high altitude. Although these data are available they will not be presented here.

During the course of a typical four-hour flight at high latitude, a total of approximately 20 000 helium nuclei are observed. Each differential interval for helium nuclei will thus contain about 1000 counts. Unlike other detectors statistical uncertainties are not the most important source of error in the proton and helium differential spectra. For this reason great care has been taken in the standardization of the instrumentation—both with regard to its physical properties and the analysis of the data.

The two largest sources of uncertainty in the analysis of the data are (i) the energy (or charge) calibration and (ii) the identification of 'true' counts as indicated by their being at the location in the pulse height distribution predicted (e.g. the removal of 'background' counts). (i) is discussed in an accompanying paper (Webber 1965, this Conference, Chap. 4, SPEC 12) on the heavier nuclei, where the energy or charge is a much more sensitive function of the known calibration of the instrument. The importance of (ii) depends on the energy and charge being considered. For energies from 600-1200 MeV/nucleon for both protons and helium the pulses lie within the region of scatter of the symmetrical distributions of pulses from particles with energy greater than 1200 MeV/nucleon. Statistical methods are used to obtain the spectrum in this range and the accuracy varies according to how far into the symmetrical minimum ionizing distribution the pulses lie. The errors on the differential proton and helium intensities range from about 5% at the low energy end of this range to about 10% at the high energy end. The background in the proton distribution below 600 MeV runs between 20 and 40% of the true counts. Various subtraction processes and comparison with lower latitude data enable the true counts to be obtained and these counts separated into primary and secondary components. Errors on these differential points range from 3-5%. At the location where the proton and helium distributions cross, the helium nuclei dominate and the proton spectrum cannot be determined in the range 60 ± 15 MeV. The background in the helium distribution below 400 MeV runs between 10 and 25% of the true counts. Again various subtraction processes and comparison with lower latitude data enable the true counts to be obtained to an accuracy approximating to the statistical accuracy. We estimate that the systematic errors on the integral and differential proton and helium intensities are about ±3-6% for the whole series of flights; however, the relative errors when comparing individual flights are ±2% when not limited by statistical errors. As a result the features of the modulation are defined somewhat more accurately than the spectrum itself and indeed we are able to observe statistically significant modulation effects at low energies for a 1% change in neutron monitor intensity.

The data are received in terms of a two-dimensional 256 × 256 pulse height matrix with another bit signifying whether the individual pulse height should be multiplied by 8 or not. This gives a total dynamic range of 2048 in each dimension. The limits of computer storage permit the read-out of only a 64 × 64 pulse height matrix, however, so it is necessary to examine the entire distribution by selecting various 64 × 64 matrices. In figure 1 we show a print-out of a matrix containing protons and relativistic helium for a typical flight.

The data we have obtained have been divided into two epochs—one where the average Mount Washington bi-hourly rate is 2320, the other where it is 2420, since a majority of flights were made at approximately these levels. Data from flights made at slightly different levels (mainly low latitude flights) have been corrected to these levels using the observed features of the modulation. The integral spectrum for protons is shown in figure 2. The primary proton intensities at 3.2, 5.6, 10.2, 12.1, and 15.7 GV are determined from extrapolation of the growth curve for relativistic singly charged particles (effectively protons of greater than 1200 MeV) to the top of the atmosphere, correcting for re-entrant albedo (electrons) and using the calculated geomagnetic cut-offs appropriate to the flight locations. These absorption curves are shown in figure 3. Determination of this part of the proton spectrum is most difficult since none of the detectors in use discriminates against either or both of the relativistic secondary mesons and protons produced in the atmosphere above the detector as well as the re-entering electrons. Our results on the intensity of primary protons and on the growth of the relativistic particles are consistent with those measured earlier at similar latitudes by McDonald (1958) and Balasubrahmanyan et al. (1962). A separate study shows that the primary proton intensities at high energies previously deduced from emulsion studies are probably underestimated relative to those obtained using Cerenkov-scintillators. It should be noted that the points at 10.1 and 15.7 GV are obtained from extrapolation of the west and east pointing portions of the rotating flight. The point at 1.9 GV represents the extrapolation of the relativistic particle distributions in the high latitude flights. The points below 1.9 GV are obtained directly from the differential spectrum measured by the detector and corrected for secondary protons. This differential spectrum is shown in figure 4 along with the differential intensities obtained by comparing the 1.9, 3.2 and 5.6 GV integral points.

The integral spectrum for helium nuclei is shown in figure 5. The intensities at 3.2, 5.6 and 12.1 GV are determined from the extrapolation of the exponential growth curve of these nuclei in the atmosphere (mean free path $\sim$ 55 g cm^{-2}). The other points are obtained directly from the differential spectra measured by the detector. These differential intensities are shown in figure 6 along with the differential intensity obtained by comparing the 3.2 and 5.6 GV integral points. In the case of the helium nuclei the differential and integral spectra obtained using the detector itself and the inferred geomagnetic cut-offs overlap, and are in very good agreement.

The comparative spectra and the details of the modulation of protons and helium nuclei as deduced from this study are discussed in an accompanying paper (Webber 1965). We summarize these results here briefly as follows:

Modulation: (i) Depends approximately on $1/\beta$ for $0.45 \leqslant \beta \leqslant 0.85$ for both components and (ii) at the same velocity, the modulation for protons is at least twice that for helium nuclei.

Comparative spectra: (i) Ratio of proton to helium nuclei differential intensities (P/He) remains constant at a value of about 8 as a function of rigidity between 2 and 16 GV. Below 2 GV it increases rapidly. (ii) P/He as a function of energy/nucleon varies continuously from a value of about 5 at 200 MeV/nucleon to about 20 above 6 MeV/nucleon. In addition, this ratio is a function of the amount of modulation.

References

Balasubrahmanyan, V. K., et al., 1962, J. Phys. Soc. Japan (Suppl. A-III), **17**, 8.

McDonald, F. B., 1958, Phys. Rev., **109**, 1367.

Ormes, J. F., and Webber, W. R., 1965, Phys. Rev., **138**, 416.

Webber, W. R., 1965, this Conference, Chap. 4, SPEC 12.

Discussion

J. R. WINCKLER. Is a Fermi process during modulation equivalent to a simple potential difference between the Earth and near galactic space?

W. R. WEBBER. In the sense that the fractional energy loss $\Delta\epsilon/\epsilon$ is constant with energy, I believe that it is. Also the A/Z dependence is equivalent for weak scattering since the particles find themselves being continuously scattered and, hence, continuously losing energy. However, in the Fermi process the net energy loss is a statistical one, depending upon how long the particle is trapped in the expanding field.