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THE PROTON AND HELIUM RIGIDITY SPECTRA FROM 10 TO 100 GV

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A magnet spectrometer flown from Palestine, Texas, in September 1976 and May 1976 under ~6 g cm^{-2} has produced measurements on 7×10^5 protons and 5×10^4 helium nuclei of rigidity greater than ~4 GV. In the interval 9-100 GV, the proton and helium nuclei can be well represented by a power law in rigidity, $J(R)=AR^{-\gamma}$, with an index, γ, of 2.78 ± 0.03 and 2.80 ± 0.03 respectively. From analysis of the α/p ratio, which has the virtue of removing common instrumental biases, one finds that $(\gamma_{He} - \gamma_p)$ is 0.02 ± 0.02 and this ratio has the numerical value of $0.150\pm.002$ at the top of the detector. We have also placed an upper limit of 10% on the $^2H/p$ at ≈35 GeV/n.

1. Introduction. Proton and helium nuclei are the two dominant cosmic ray components. It is therefore of basic importance to study their spectral shape and relative abundance. Though numerous experiments have been performed in the past to study these components, there are, perhaps, only six[1-6] in which direct measurements significantly greater than 10 GV have been made. In these experiments, Anand et al.[1] and Badhwar et al.[2] used the variation of geomagnetic cut-off with zenith angle, Webber et al.[3] employed a gas Cerenkov counter and the geomagnetic cut-off, Verma et al.[4] used a permanent magnet with an emulsion stack, Ryan et al.[5] used an ionization calorimeter and Smith et al.[6] used a superconducting magnet spectrometer. There is, however, considerable disagreement among the spectral indices determined by the various experiments. In the two experiments of Ryan et al.[5] and Smith et al.[6] with the highest statistical accuracy, the spectral indices of helium nuclei above ~20 GV are respectively 2.77 ± 0.05 and 2.47 ± 0.03. The measurements of Verma et al.[4] and Anand et al.[1] are in agreement with a steeper index of 2.7 - 2.8. As for the proton component, it seems from the measurements made so far[5] that in the rigidity range of 10-50 GV the spectrum is somewhat flatter than that of 2.75 now generally accepted for rigidities between 50 and 1000 GV[5]. In the present paper, we describe an experiment with a superconducting magnet spectrometer to determine the spectral shapes of protons and helium nuclei in the rigidity interval of 10-100 GV.

2. Experimental Details. The magnet spectrometer which is described in detail elsewhere[7] is shown in Figure 1. It consists of: (i) a gas Cerenkov counter, G, having a threshold, $\gamma_c=40$; (ii) scintillators S1 and S2 each of 0.625 cm thick Pilot Y; (iii) a stack of multiwire proportional chambers, MWPC, with a spatial resolution in the cathode coordinate of ≈200μm[8], and (iv) scintillators P1-P7 each of 0.625 cm thick Pilot Y and each separated by ≈1.2 radiation lengths of lead forming a shallow shower counter of ≈7 radiation length. The signals from S1, S2, P1-P7 and G are all pulse height analyzed. The magnet was operated at a current of 120 amps producing a magnetic field of ≈40KGauss at the center of the coil.

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Only events satisfying the trigger S1 P1 P7 were accepted for analysis. This mode has a useful geometry factor of ≈ 315 cm^{2}sr. Events were selected by requiring that (a) they represent a single particle traversal through all MWPC, (b) the particles have a downward direction of motion as determined by the time of flight between S1 and P1, (c) the charge determined by S1, S2 and P1 is consistent with Z=1 or Z=2.

The MWPC chamber alignment is made using a multiparameter minimizing routine to obtain best straight lines to tracks of a large number of sea-level muons which trigger the gas Cerenkov counter when the magnet is off. We define magnetic deflection, D, as the inverse of a particle's rigidity. Since D is proportional to the measured spatial deflection, it is an appropriate parameter for use with magnetic spectrometers. The deflection distribution for the magnet-off muons gives the error distribution due to position measurement and Coulomb scattering errors. It is important to note that because the $\int \underline{B \times dl}$ varies by a factor of ten in the spectrometer, the error function is not a Gaussian. Ideally, one would like to obtain this error function in flight with the magnet off; however, due to premature termination in both flights, this was not possible. In order to check that the ground level error function is applicable to the flight data, we determined the deflection distribution of helium nuclei which triggered the gas Cerenkov (cut-off rigidity $\sim$80 GV). By folding (i) the experimentally determined gas counter efficiency as a function of momentum of sea-level muons, (ii) the error function determined using sea-level muons and (iii) assuming that the helium nuclei have a power law rigidity spectrum $R^{-2.8}$ above 80 GV, we computed the expected deflection distribution of these high rigidity helium nuclei. A comparison of the expected and observed distribution is given in Figure 2 for the

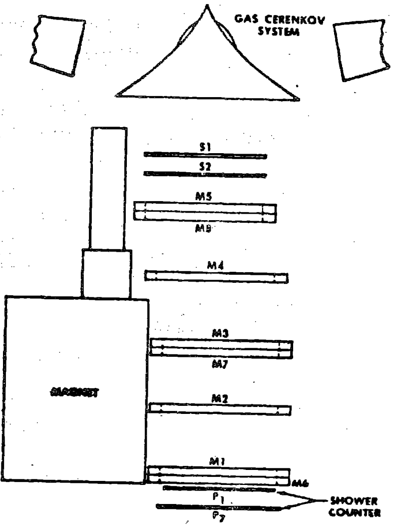

Figure 1 - Magnet Spectrometer detector array.

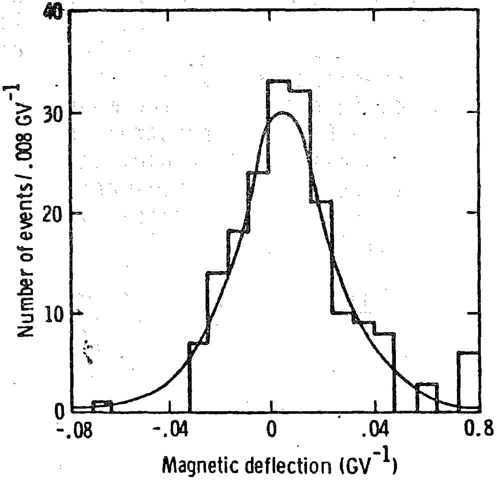

Figure 2 - Calibration data, May 1976 flight.

May 1976 flight. The offset between the two distributions is -0.001±0.002. In the September 1975 flight, this offset was 0.008±0.003.

3. Results

3.1 The Proton Component.

The deflection distribution for Z=1 events is shown in Figure 3 for the May 1976 flight. The deflection distribution in the interval 0.11 to 0.01 GV^{-1} has been fitted to a power law in deflection of the form $J(D) = AD^{\gamma-2}$. In the fitting process, the experimentally determined error function and offset were convoluted with the power law. The best fit power law has an index of 2.74±0.05 (September 75) and 2.83±0.04 (May 76). The fits have a χ^2 of less than 0.9 per degree of freedom. The errors here include the error in determining the flight offset. Since the two flights give the same spectral index within errors the result can be combined to yield a spectral index of 2.78±0.03. This spectral index is steeper than the index of 2.63±0.08 obtained by Smith et al.[6] but agrees with the index of 2.75±0.03 obtained by Ryan et al.[5] in the 50-1000 GV range.

Figure 5 gives a comparison of the absolute flux x $R^{+2.75}$ for the May 1976 flight with the data of Smith et al.[6] and Ryan et al.[5] There are systematic uncertainties in the selection efficiency, dead time and geometry factor; these systematic errors are no greater than 15%. Figure 5 clearly shows that our result is in better agreement with that of Ryan et al.[5] than with Smith et al.[6] The resulting absolute differential rigidity spectrum is $J(R) = (1.91 \pm .28)\ 10^4 \times R^{-2.78\pm0.04}$ $(m^2\ sec\ sr\ GV)^{-1}$ for rigidities above 9 GV. We find the integral flux above 10 GV is 178±27 $(m^2\ sec\ sr\ GV)^{-1}$. This can be compared with the value of 203±40 $(m^2\ sec\ sr\ GV)^{-1}$ by Ryan et al.[5], 203±10 $(m^2\ sec\ sr\ GV)^{-1}$ by Von Rosenvinge et al.[3] and of 140±14 $(m^2\ sec\ sr\ GV)^{-1}$ by Smith et al.[6]

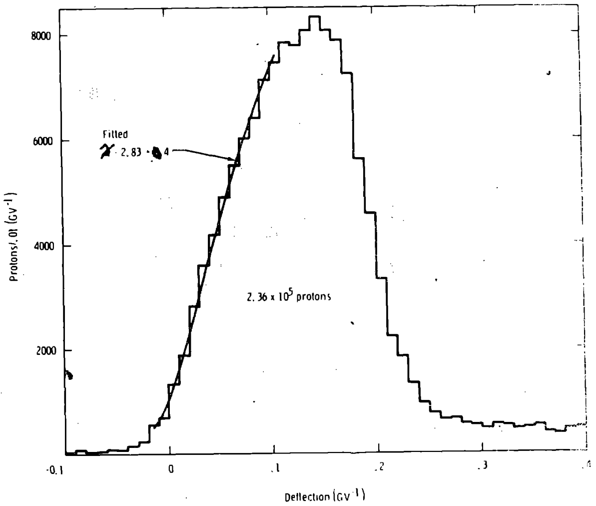

Figure 3 - Observed deflection distribution of Z=1 particles from the May 1976 flight.

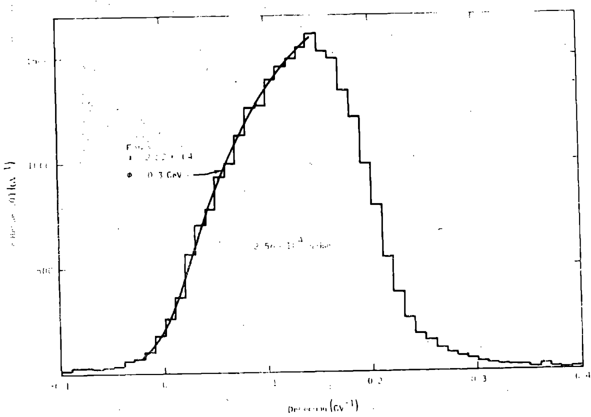

Figure 4 - Observed deflection distribution of Z=2 particles from the May 1976 flight.

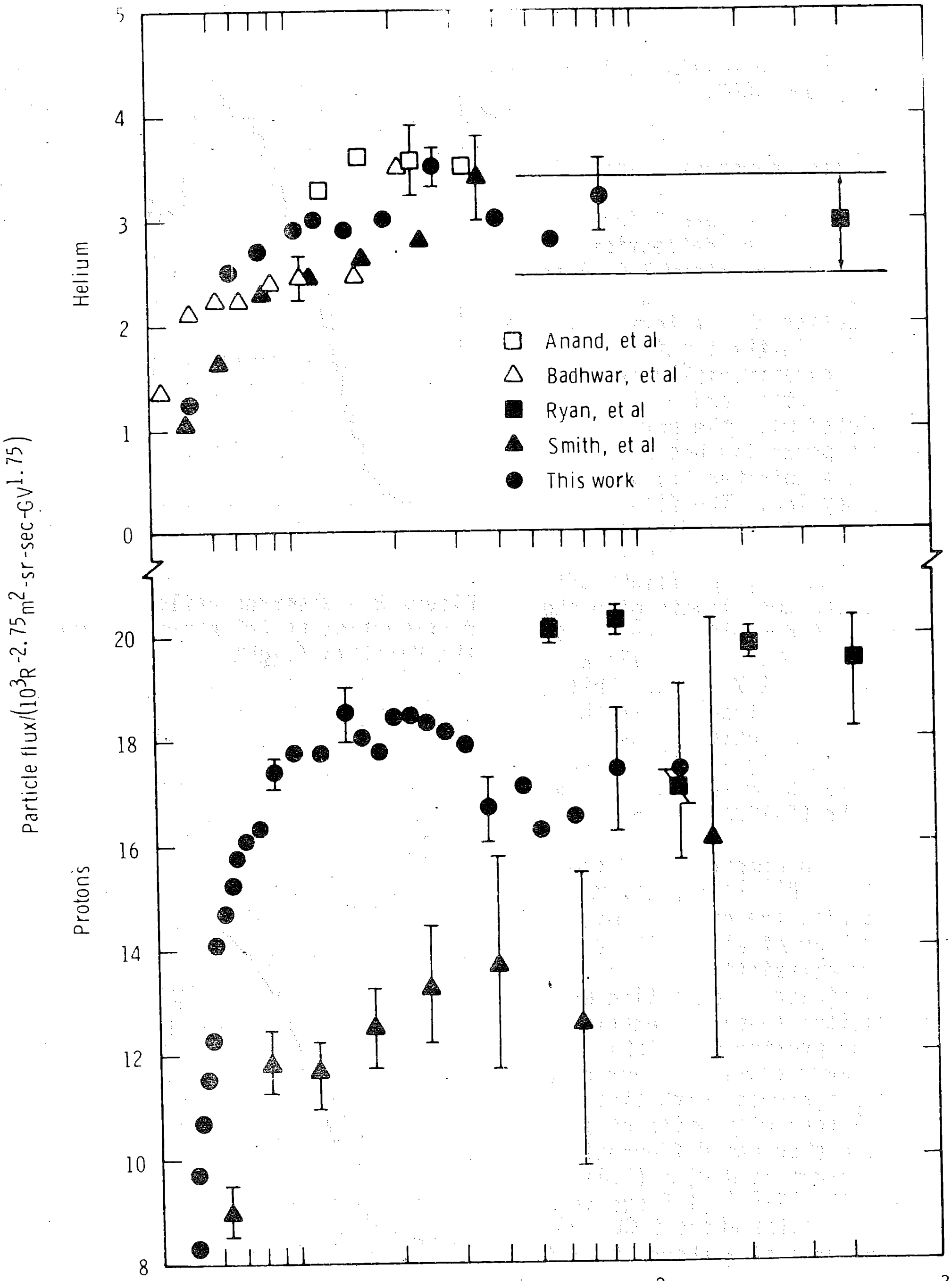

Figure 5 - Particle fluxes vs rigidity. Note the Z=2 data of Ryan et al.[5] have not been shown in detail. Their data falls in the band illustrated in the upper figure.

3.2 Helium Nuclei. The deflection distribution of Z=2 events is shown in Figure 4. The solid curve is the fitted spectrum with an index of 2.82±.04 (where the error includes the error on the offset). In September 1975, we find that γ=2.78±0.05. The combined result gives γ=2.80±0.03. The absolute differential spectrum is given by $J(R)=(3.43\pm0.5)10^3 \times R^{-2.80\pm0.03}$ (m^2 sec sr GV)$^{-1}$. Figure 5 shows the comparision of various measurements. Note the general good agreement between all of the measurements. Table I is a comparison of the integral flux above 8.3 GV and the spectral index obtained by various groups.

Table I

	Anand et al.[1]	Badhwar et al.[2]	Ryan et al.[5]	Smith et al.[6]	Verma et al.[4]	Present (MAY 76
γ	2.74±.15	2.54±.08	2.77±.05	2.47±.03	2.8±.15	2 2.8~~0~~±.0~~3~~ 4
Rigidity Range in GV	12-40	8-26	20-800	8.3-100	22-150	9.0-100
Integral Flux >8.3 (m^2 sr sec)$^{-1}$	40±2	41±1		38.6±2		6. 42±~~.4~~

We also note the integral flux of Von Rosenvinge et al.[3] of 40±1 (m^2 sr sec GV)$^{-1}$ is also in agreement with these observations. We also find that the helium spectral index of 2.82 can be continued down to 6.25 GV if a solar modulation corresponding to a deceleration of Φ = .3 GeV/n for May 1976 is assumed. This fit has a χ^2 of 0.7 per degree of freedom. Note that the χ^2 for the fit of Smith et al.[6] was 1.4 per degree of freedom.

3.3 The Ratio α/p. The difference in the proton and helium spectra can be more easily displayed by plotting the α/p ratio as a function of deflection (see Figure 6). There is no evidence of a change in this ratio between 6.25 GeV and 100 GV. The least square fit yields an index of -.01±.01 and 0.036±0.02 in the May 76 and September 75 flights respectively. We note that displaying this effect in terms of a ratio has the virtue of removing all instrumental biases which are common to both Z=1 and Z=2 particles. We conclude that the difference of $\gamma_{He} - \gamma_p$ = 0.02±0.02 and thus within the experimental uncertainty the two components have identical slopes.

3.4 The Ratio $^2H/p$. The fraction of Z=1 particles with rigidity between 50-80 GV agrees well with the fraction predicted from sea-level muon measurements assuming all Z=1 particles are protons. Since ^2H in this rigidity interval would lower the fraction of G triggers, we have deduced an upper limit of 10% on $^2H/p$ at an energy per nucleon of ~35 GeV/n.

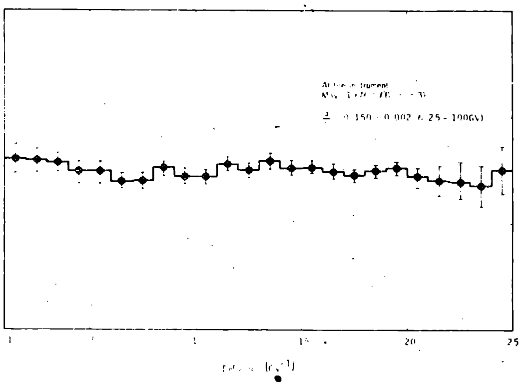

Figure 6 - Helium/proton flux ratio as a function of deflection

Events with $\int B.dl \geq 4$ from the September 75 flight corresponding to a maximum detectable momentum of $\gtrsim$ 200 GV were used. We hope to add the May 76 data soon. This limit is well below that required by Adair[9] to explain the μ^+/μ^- ratio.

4. Conclusion. We have determined the rigidity spectra of protons and helium nuclei in 9 GV to 100 GV range and found them to be the same with an index of ∿2.78. We have also placed an upper limit on $^2H/p$ of 10% at 35 GeV/n.

References

1. K. C. Anand, R. R. Daniel, S. A. Stephens, B. Bhowmik, C. S. Krishna, P. K. Aditya and P, K. Puri, Canadian J. of Physics 46, 5652, 1968.
2. G. D. Badhwar, M. F. Kaplon and D. A. Valentine, J. Geophys. Res. 76, 4224, 1976.
3. T. T. Von Rosenvinge, W. R. Webber and J. F. Ormes, Astrophys. and Spa. Sci. 5,, 342, 1969 and 3, 4, 1969.
4. R. P. Verma, T. N. Rengarajan, S. N. Tandon, S. V. Damle and Yash Pal, Nature 240, 135, 1972.
5. M. J. Ryan, J. F. Ormes and V. K. Balasubrahmanyan, Phys. Rev. Letts. 28, 985, 1972.
6. L. H. Smith, A. Buffington, G. F. Smoot, L. W. Alvarez and W. A. Wahlig, Astrophysical J. 180, 987, 1973.
7. R. L. Golden, G. D. Badhwar, J. Lacy and J. E. Zipse, Nucl. Inst. and Methods, 1977.
8. Chambers M1, M3, M4, M5 were used during the September 75 flight and all chambers M1-M8 were used during the May76 flight.
9. R. K. Adair, Phys. Rev. Letts. 33, 115, 1974.