OG 4.1-2

COSMIC RAY PROTON & HELIUM SPECTRA FROM 5 - 200 GV MEASURED WITH A MAGNETIC SPECTROMETER

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ABSTRACT

We have measured the cosmic ray proton and Helium spectra in 1976 and again in 1979, between the geomagnetic cut-off of 5 GV and a rigidity ∿ 200 GV using a magnetic spectrometer. Above ∿ 10 GV the rigidity spectra of both of these components are almost identical and have an average exponent = 2.70 ± 0.05. The difference in the exponent of the rigidity spectra for protons and Helium nuclei can be no greater than ∿ ± 0.03. The ratio of the two rigidity spectra R(P/He) is found to be = 7.0 ± 0.2 throughout the rigidity range from 5 - 200 GV. The implications of these measurements with regard to the type of source spectra for protons and Helium are briefly discussed.

1. Introduction.

The measurement of the absolute rigidity or energy spectra of protons and Helium nuclei has become particularly important in recent years. On one hand, there has been a great improvement in our knowledge of the spectra of heavier nuclei with $Z \geq 6$ from HEAO-3 measurements (eg. Koch et.al., 1981). Also, new measurements of proton and Helium secondaries, ^{2}H and ^{3}He, (Webber and Yusak, 1983, Beatty, 1986) have made it essential to know very precisely the interstellar spectra of protons and Helium. And finally, there is the question of the method of acceleration of the particles themselves. Recent theories of cosmic ray acceleration in the galaxy have focused on first order Fermi acceleration in strong shocks, occurring in the shells of supernova or in the surrounding interstellar medium (eg. Blandford and Ostriker, 1978). These models generally lead to rigidity spectra of the form $dj/dp \sim P^{-q}$ where $q = -(2 + \varepsilon)$, P is rigidity, and ε is determined by the characteristics of the shock and is between 0.1 and 0.3. This spectrum is expected to apply over a wide range of rigidities from perhaps ∿ 1 GV to 10^{3} - 10^{4} GV. At lower rigidities the spectrum will be modified by details of the injection process and escape from the sources, while at high rigidities the scale size of the acceleration region will eventually modify the spectrum. Specific models have examined this acceleration process together with subsequent galactic propagation to predict the spectra of particles arriving at the solar system in considerable detail. (Blandford and Ostriker, 1980, Kota and Owens, 1981, Ip and Axford, 1985). These models appear to lead to identical rigidity spectra at the sources for protons, Helium and heavier nuclei as well as electrons. These spectra may be modified by galactic propagation so that the spectra of particles with different A/Z observed at earth will not be identical. However, if the propagation effects can be well described, then it may be possible to directly infer the injection-acceleration spectrum - for example to distinguish between rigidity and momentum or energy/nucleon type spectra which can be quite different for particles of different A/Z.

In this paper we present an analysis of the New Mexico State University magnetic spectrometer data from balloon flights made in 1976 and 1979. This analysis uses the full precision of this spectrometer, giving a maximum detectable momentum > 100 GV/c, thus enabling proton and Helium nuclei spectra to be derived from the geomagnetic cut-off ∿ 5 GV/c to ∿ 200 GV/c - a factor ∿ 40 in rigidity, a rigidity range in which no previous measurements of comparable accuracy exist.

2. Data Analysis.

The magnet spectrometer used in these studies and the data analysis procedures have been described in several publications (Golden et.al., 1984). Basically, one derives deflection distributions for each charge species as shown in Figure 1 for the 1979 flight. These deflection distributions are then converted to intensity versus rigidity distributions by deconvolution with the rigidity resolution function of the instrument and the appropriate geometry, live time, and selection criteria factors. These rigidity spectra, multiplied by $P^{2.5}$, are shown in Figure 2 for protons and Helium nuclei for both the 1976 and 1979 flights. The error bars on the individual points are those due to statistical and deconvolution errors only. In addition, there are errors in absolute intensity, believed to be $\sim$ 5-10%, that may move the spectrum from each year up or down relative to one another, but should not effect the slope of the spectrum. The 1979 flight appeared to exhibit somewhat better rigidity resolution than the 1976 flight ($\sigma \sim 120$ c/GV versus 90 c/GV) so the 1979 flight was analyzed in finer rigidity bins (0.005 GV/c versus 0.010 GV/C), thus enabling the rigidity spectrum to be obtained up to 200 GV/c versus 100 GV/c. In the highest rigidity intervals, the uncertainties due to the resolution function as well as the zero deflection offset both introduce uncertainties comparable to the statistical errors. However, the choice of these two parameters must lead to consistency between the differential and integral spectra that are derived since at the maximum rigidity, P_o, the integral flux, J_o, that is determined must be related to the differential flux, j_o, at the same rigidity by

$$j_o = \frac{(\gamma - 1)J_o}{P_o},$$

where the value of γ, the spectral index, is such that j is continuous at P_o.

Included in Figure 2 for comparison are proton and Helium measurements of Ryan et.al., 1972, and measurements at lower energies at a time of the most recent minimum modulation in 1977 (Webber and Yusak, 1983). It is seen that both the proton and Helium nuclei exhibit spectra $\sim P^{-2.70}$, with an error not larger than $\sim \pm 0.05$ in the exponent, above 10 GV, up to the highest rigidities measured. Below 10 GV the spectrum flattens, due mainly to solar modulation effects and at lower rigidities by propagation effects.

The proton-Helium intensity ratio as a function of rigidity shown in Figure 3 is remarkably constant at a value of 7.0 ± 0.2 between $\sim$ 2 GV and several hundred GV. This constancy was noted earlier by Webber and Lezniak, 1974, but is determined here to a much greater accuracy. In fact, the constancy of this ratio observed over such a wide rigidity range, means that the source spectra of these two nuclei, with very different A/Z, cannot differ by more than $\sim \pm 0.03$ in the exponent, an important constraint on the acceleration mechanism.

This constancy, while suggestive of similar source rigidity spectra does not immediately prove that this type of spectrum is unique. To examine this question further, we show in Figures 4 and 5, the same data plotted as a function of energy/nuc. The proton-Helium ratio also looks very similar to Figure 5 when converted to momentum/nuc spectra, so essentially most of the statements that apply to the interpretation in terms of energy/nucleon spectra also apply to momentum/nucleon stectra. It is immediately seen that the observed ratio changes in a rather smooth fashion from a value $\sim$ 24 at energies > 10 GeV/nuc to a value < 10 below 1 GeV/nuc.

3. Interpretation of Spectra. To interpret the observed spectra we must make certain assumptions regarding the propagation of cosmic ray protons and helium muclei and also the effects of solar modulation. In addition, we must make assumptions regarding the source spectra. These assumptions apply to the consideration of both energy/nuc and rigidity spectra. We assume that for energy/nuc source spectra the P/He ratio is 24.0 as indicated by the high energy data; for rigidity source spectra we shall assume the P/He ratio is 7.0. For propagation we shall use the latest set of parameters in the leaky box model, which provide an excellent fit to a wide variety of data for $Z \geq 3$ nuclei. The path length, λ, and therefore the lifetime, τ, are described by the functional form $\lambda = 23.8\ \beta P^{-0.6}$ above P = 5.0 GV and $\lambda = 9.64 x \beta$ at lower rigidities. This very distinct change in the rigidity dependence of the path (escape) length at about 5 GV is necessary to fit the variation of secondary to primary ratios - eg. B/C - as a function of energy or rigidity. Note that since this propagation is purly a function of rigidity, it will not effect the

P/He ratio when expressed as a function of rigidity, but will when the ratio is expressed in terms of energy/nucleon or momentum/nucleon because of the different A/Z of protons and Helium nuclei. This will cause the interstellar ratio to decrease to a value ∿ 15 at low energies as indicated in Figure 5. This change takes place over the energy/nucleon range from 1.5 - 4.0 GeV/nuc. Solar modulation effects will also change the P/He ratio observed at earth. If this modulation is described in terms of the force field approximation with the diffusion coefficient ∿ βP, as is generally assumed above 1 GV (eg. Gleeson and Axford, 1968, Palmer, 1983); then solar modulation effects will not appreciably change the P/He ratio when expressed as a function of rigidity, however, the

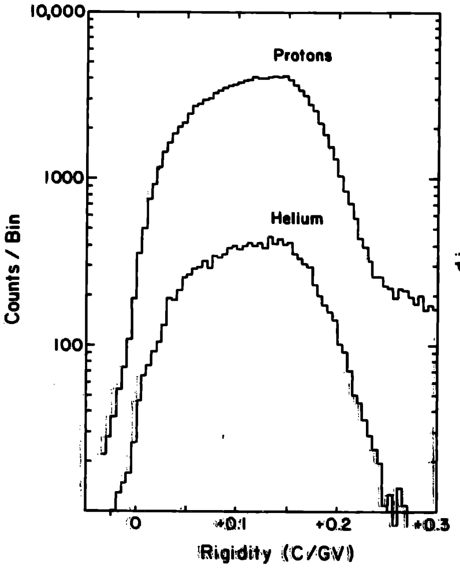

Figure 1. Deflection spectra for H and He nuclei from 1979 flight

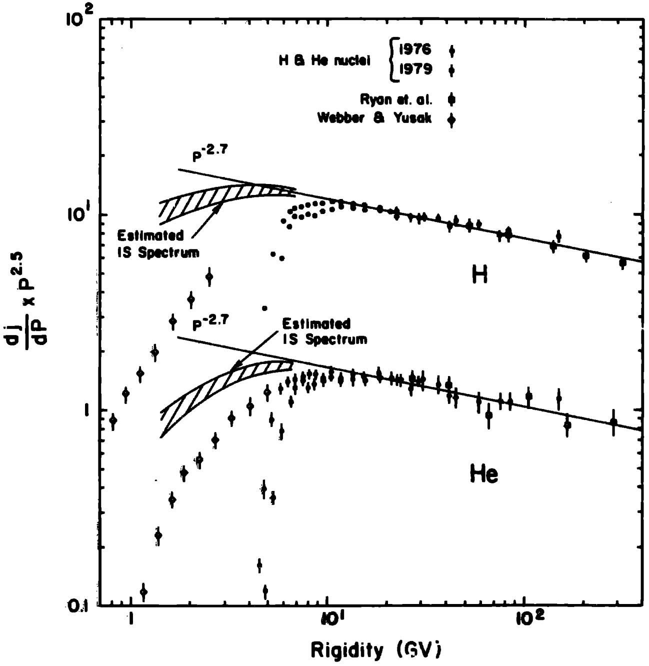

Figure 2. Spectra of H and He nuclei obtained from the 1976 and 1979 data. of Ryan et.al. at high energies and Webber and Yusak at low energies are also shown

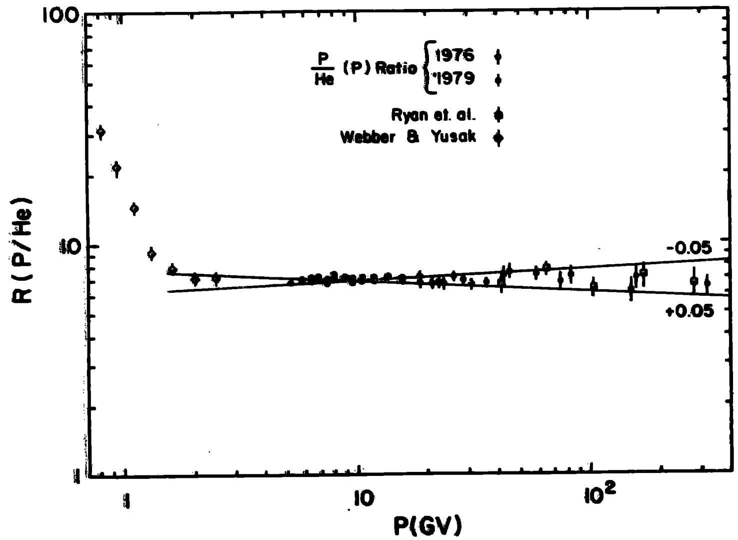

Figure 3. Proton to Helium ratio as a function of rigidity. Symbols the same as Figure 2

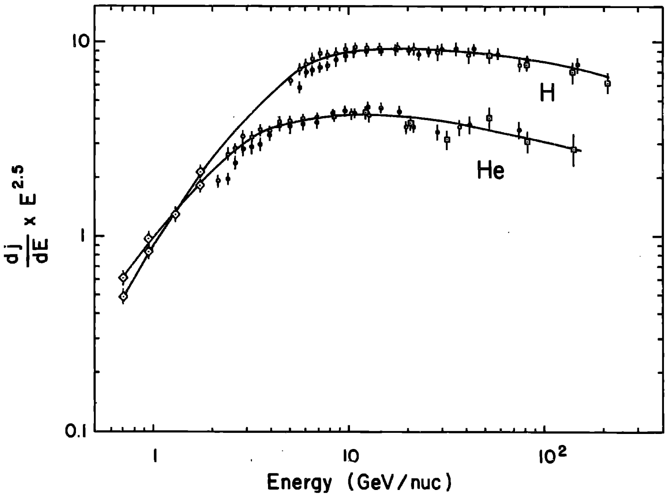

Figure 4. Proton and Helium spectra as a function of energy. Symbols the same as Figure 2

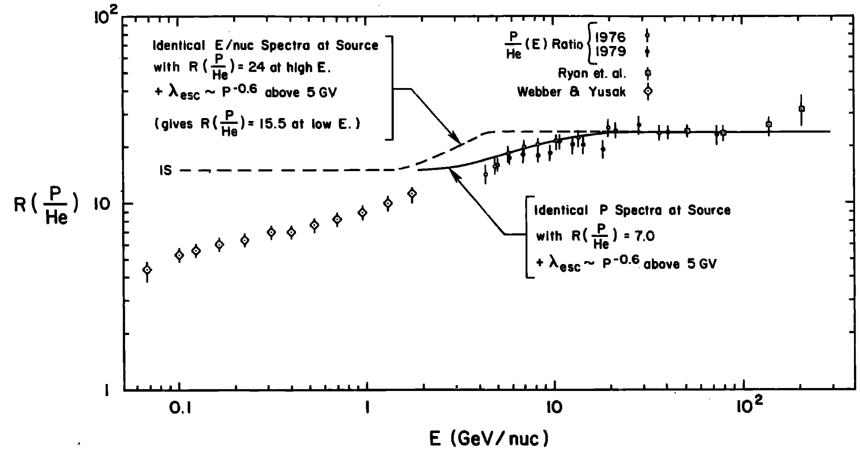

Figure 5. Proton to Helium ratio as a function of energy. Symbols the same as Figure 2

effects due to this modulation are quite large for the P/He ratio expressed as a function of energy/nuc. These modulation effects can produce the decrease in P/He ratio observed at low energies in Figure 5, but are not capable of producing the changing P/He ratio above several GeV/nuc seen in Figure 5. The most reasonable explanation for this changing ratio at energies > several GeV/nuc. is that the source spectra are simply rigidity spectra.

4. Acknowledgements. This work was supported by NASA Grant NGR-30-002-052.

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