Relative Abundance of the Helium Isotopes ^{3}He and ^{4}He in the Cosmic Radiation

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The geomagnetic field near the equator is used to measure the abundance ratio of ^{3}He/^{4}He near 6 GeV/nucleon. This ratio is found to be 0.24 ± 0.05, under the assumption that the helium rigidity spectrum has the form $dI/dR \sim R^{-2.65}$. If all ^{3}He is of secondary origin this implies an interstellar mean escape path length of ≈ 15 g/cm^2, a value considerably larger than that determined from observations of heavier elements, but compatible with measurements of the helium isotopic ratio at lower energies.

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Much effort has been made over the past years to determine the relative abundance of the two stable isotopes of the element helium in the cosmic radiation since their abundance ratio is important to understand the propagation of cosmic rays in the interstellar medium. These two isotopes are assumed to have separate origins. The ^{3}He abundance in astronomical objects and in the interstellar medium amounts to about 10^{-4} that of ^{4}He, while cosmic-ray measurements give $> 10^{-1}$ for that fraction. This large flux in ^{3}He is interpreted as being due to the spallation products ^{3}H and ^{3}He originating in collisions of ^{4}He and, to a small degree, of heavier cosmic rays with nuclei in the interstellar gas. Since ^{3}H has a short half-life, it rapidly converts to ^{3}He. The fraction of ^{3}He in the He flux provides a measure for the amount of matter traversed by He during its life in the galaxy.

Most experiments that determine the ^{3}He/^{4}He abundance ratio were limited to measurements at energies of less than a few hundred megaelectronvolts per nucleon,[1-6] and required major corrections to take solar modulation into account. Only one experiment[7] was carried out at high energy, actually employing a method similar to the one used in this work. The authors found a high flux of ^{3}He, but with large errors.

Our experiment, which measures the ^{3}He/^{4}He ratio, $\Gamma_E(3/4)$, at three energy intervals around 6 GeV/nucleon, finds a value for $\Gamma_E(3/4)$ of 0.24 ± 0.05, under the assumption that at the rigidity corresponding to this energy the spectrum of He near Earth has the form $dI/dR \sim R^{-2.65}$. This isotopic ratio is compatible with earlier low-energy results, if modulation is accounted for. It leads to an average escape mean free path for He of about 15 g/cm^2, a value considerably larger than that deduced from measurements of the flux of heavier secondary nuclei.

The only practical method available at this time to measure the abundance ratio of the two He isotopes at energies > 5 GeV/nucleon (rigidity > 11 GV) is the use of the geomagnetic field as a rigidity spectrometer.[8] This requires measurements near the geomagnetic equator, where the cutoff is highest, and where it is also predicted to be sharp. Within the resolution of our instrument, we could demonstrate that the cutoff is indeed sharp and has a numerical value within 2% of that predicted from calculations using the computer code of Shea, Smart, and Carmichael.[9]

Our instrument was flown from the Hawaiian island of Kauai on 7 April 1981 and spent 12 h under 5 g/cm^2 of residual atmosphere. It consists of two scintillation counters, two large gas Cherenkov counters, and four multiwire proportional counters, each determining x and y coordinates of the particle trajectory. Charge resolution for helium is 0.1 charge units. The multiwire proportional chamber grid provides an angular resolution of 1.5°, and the orientation of the instrument was monitored by two triaxial magnetometers. The accuracy of the isotope separation depends on the resolution of the gas Cherenkov counters. They were both filled wth 20 atm of ethylene, yielding an index of refraction of 1.021 (threhsold 3.7 GeV/nucleon). Their resolution is dominated by statistical fluctuations in the ≈ 240 photoelectrons generated by a relativistic He nucleus. Details of the instrument and the data analysis are described in separate papers.[10,11]

The cutoff rigidity is a function of the direction of incidence of the particle. To investigate particles above a particular rigidity requires restrictions to certain sky directions. Figure 1 shows a map in azimuth and zenith angle of the sky over the launch site in Kauai on which are entered several cutoff rigidities in gigavolts. It turns out that certain crescent shape contiguous areas contain a narrow range

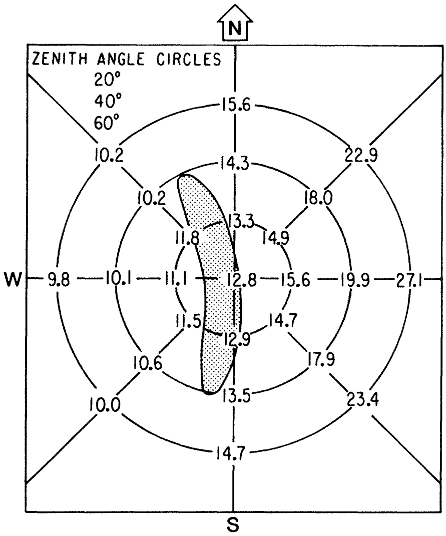

FIG. 1. The calculated cutoff rigidity (GV) vs zenith and azimuth for a location 35 km above Kauai, Hawaii. Cutoff values were determined by tracing particle trajectories through a model of the Earth's field. The shading indicates a region of the sky where similar cutoffs are found and is typical of those used in the analysis.

of cutoff rigidities. The shaded area covers the cutoff range from 11.9 to 12.9 GV, similar to the intervals chosen for analysis. Since the balloon drifted less than 50 miles from the launch site, no correction for change of its location had to be made.

The results of this experiment are contained in the velocity spectra for three different narrow rigidity-cutoff ranges. An example of a velocity distribution in the form of a signal spectrum in the Cherenkov counter is shown in Fig. 2. The separate contributions of ^{3}He and ^{4}He that have different velocities at the same rigidity can be qualitatively observed. For a quantitative analysis the distribution is modeled, with use of the known parameters of the instrument: index of refraction, counter resolution, delta-ray contribution, Cherenkov signal corresponding to a particle with $\beta = 1$, residual scintillation in the gas, and the point of zero signal. The geomagnetic cutoff is sharp, and the shape of the ^{4}He rigidity spectrum is obtained from other experiments. Unfortunately widely diverging results for the power-law index of the helium rigidity spectrum have been published.[12-17] These results were weighted, compared to the best fit with our distribution, and a spectrum $dI/dR \sim R^{-2.65}$ was chosen for the rigidity range where we observe. The solid line shown with the data of Fig. 2 represents this fit. With the assumption that both the ^{3}He and ^{4}He spectra follow this power law, and with use of three independent measurements for the cutoff ranges 10.8–11.5, 11.6–12.6, and 12.6–13.6 GV, we derive the fraction at constant rigidity $\Gamma_R(3/4) = 0.15 \pm 0.03$. While this result is sensitive to the choice of the ^{4}He spectrum it is not very sensitive to the shape of the ^{3}He spectrum. For comparison with other results it can be translated into a fraction at constant energy: $\Gamma_E(3/4) = 0.24 \pm 0.05$.

Figure 3 shows our result in comparison with ear-

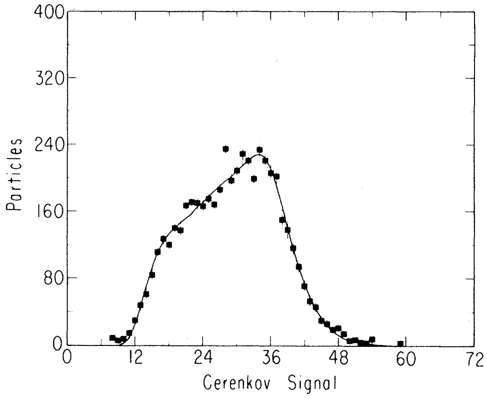

FIG. 2. Cherenkov signal distribution observed for helium events incident from a skybin with 10.8- to 11.5-GV cutoff over Kauai. The solid line is a fit to the data with the instrument model.

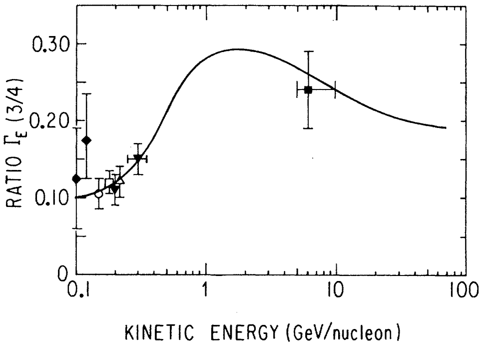

FIG. 3. Measurements of the helium isotopic ratio at different energies. The solid curve is a prediction based on the propagation and modulation models discussed in text. The data points are due to, solid square, this work; lozenge, Hofmann and Winckler (Ref. 2); open circle, Badhwar *et al.* (Ref. 3); open triangle, Webber and Schofield (Ref. 4); inverted triangle, Webber and Yushak (Ref. 5); open square, Leech and O'Gallagher (Ref. 6).

lier determinations at lower energy, all of which have smaller values since they are subject to considerably more solar modulation. The observed abundances at low energy alone can be viewed as arising from 3–7 g/cm^2 of interstellar material if a modulation model is chosen appropriately. However, using the modulation parameters recently derived from the evaluation of long-term intensity changes of protons, electrons, and alpha particles by Evenson *et al.*,[18] and the propagation model of Meyer[19] which includes the energy-dependent cross sections for ^{3}He production and destruction, one obtains the solid curve of Fig. 3 for the expected energy dependence of $\Gamma_E(3/4)$ at Earth. This value of Γ_E leads to an escape mean free path for He nuclei of ≈ 15 g/cm^2, more than twice that measured from observation of secondary nuclear particles of higher charge, a result incompatible with the model describing the galaxy as a simple leaky box. It may be significant that similar conclusions are reached from observation of the flux of other secondary components of low charge: antiprotons,[20] and possibly positrons,[21] and deutrons.[22] The flux of all of these other components is very small, and their measurement more difficult than for the He isotopes.

The results of this work therefore require a modification of the simple leaky-box model of the galaxy. The need for such a modification is not surprising. It may take the form of a closed galaxy model as proposed by Peters and Westergaard,[23] or a model that invokes a fraction of the particle sources embedded in dense interstellar or circumstellar material,[24] devised to explain the high flux of antiprotons. One should keep an open mind though for the possibility that not all ^{3}He need be of secondary origin. The surprising experience with ^{3}He-rich solar-particle events, which occasionally show ^{3}He abundances that exceed the abundance of ^{4}He, has taught us that, at least on the Sun, preferential acceleration of ^{3}He must take place. It is not know whether other flaring stars exhibit the same phenomenon, or may serve as injectors for cosmic-ray particles.

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