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SOLAR MODULATION OF THE GALACTIC HELIUM SPECTRUM
ABOVE 30 MEV PER NUCLEON

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Solar Modulation of the Galactic Helium Spectrum Above 30 Mev per Nucleon

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Abstract. Time variations in the differential energy spectrum and flux of primary helium nuclei in the energy range 30 to 90 Mev per nucleon have been studied over the time period from December 1963 to January 1965. Continuous measurements over most of the one-year period were made using dE/dx vs. E type solid-state, charged particle telescopes which were flown on two satellites IMP-I and IMP-II which had highly eccentric orbits. The helium spectra obtained are well represented by a power dependence of the type $\propto E^{+\gamma}$ where E is the particle total kinetic energy. The exponent γ changed from 1.75 to 1.3 in the one-year period while the flux of helium increased by about 75 percent in the same time interval. Since in addition to this observed modulation, the helium nuclei were continuously present and since the spectrum extends smoothly into the higher energy spectrum measured on balloons, we are convinced that we are observing the low energy extension of the modulated local galactic helium spectrum. From the measured fractional helium intensity increases with time we are able to deduce that the modulation depends predominantly on the particle velocity.

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I. Introduction

The understanding of the nature of the eleven-year modulation of galactic cosmic radiation is important for at least two reasons. First, one may be able to deduce the low energy local galactic energy spectra of cosmic rays, which is needed to answer questions on origin, acceleration and propagation of galactic nuclei. Second, the electrodynamical structure of the interplanetary region which is responsible for the modulation may then be better understood. The best opportunity to study the modulation is to observe time changes in the low energy components of the primary cosmic rays, since most models predict strong time variation at low particle energies. Further, one would like to make these studies near the minimum of the 11-year solar cycle, at which time the low energy galactic particles will appear near their maximum intensity at Earth.

In this paper we present measurements of the primary helium spectrum above 7 Mev per nucleon as obtained from two satellites, IMP-I and IMP-II. These satellites, because of their highly eccentric orbits (apogees at 200,000 and 95,000 km respectively) provided the opportunity to make "clean" measurements of primary radiation over extended time periods in interplanetary space. The measurements were made in two continuous time intervals, 27 Nov. 1963-15 May 1964 (IMP-I) and 4 October 1964 - 31 Dec. 1964 (IMP-II).

II. Time Variation in the Helium Flux and Spectra

The instruments used on board the IMP-I and II satellites were dE/dx vs. E type cosmic ray telescopes details of which were already published (Fan, Gloeckler and Simpson, 1965). For reference we show in Figure 1 the cross section of the four-element telescope which employs solid-state Au-Si surface barrier detectors. The mass, charge and energy of a particle stopped in detector D_3 can, in principle, be determined by a simultaneous recording of the pulse heights in the dE/dx detector D_1 and the total residual energy detector D_3. With this cosmic ray telescope we are able to determine with good precision the energy spectra of nuclei with charge $Z \leq 6$ below ~90 Mev/nucleon. We report here, in particular, the detailed analysis of the energy spectrum and fluxes of helium nuclei in the energy range 7 to 90 Mev/nucleon.

In Figure 2 we show how the differential energy spectrum of helium in the energy interval 30 to 90 Mev per nucleon has changed with time over a period of one year. Four spectra were obtained which are shown in a chronological time sequence. The rise in the helium energy spectrum with time is evident and furthermore the lower energy helium is seen to show a larger percentage increase than the higher energy helium flux. The lines through each of the four sets of data points represent power spectra with the exponent ranging from +1.7 to +1.3 and were calculated on the assumption that the modulation mechanism depends on the velocity of the particle only, and in accordance with the model proposed by Parker (1963). Below ~ 25 Mev/nucleon (100 Mev total kinetic energy) a sharp increase in the spectrum is observed (Oct. - Dec. 1964 average), details of which are being reported elsewhere in this conference (Fan, Gloeckler and Simpson 1965). We should emphasize that the helium measurements reported here were taken only during those time periods which contained no solar associated events (i.e. no flares, 27-day recurrent events) and therefore are representative of a quasi-stationary component of the primary cosmic radiation.

There are three observations which convince us that we are primarily observing the modulation of the low energy galactic helium. First, the spectra measured on the IMP satellites and shown in Figure 2 connect smoothly with balloon measurements made at higher energies. Second, the helium nuclei are continuously present even in the absence of solar associated events. And third, the helium spectrum is being modulated, this being already evident from Figure 2. To show this last aspect in a more convincing way, we have displayed in Figure 3 the time variations in both the helium flux (30 to 90 Mev per nucleon) and the Climax neutron monitor intensity. Both intensities were averaged in time periods of ~ one month for each data point and all times during which solar associated events were present were excluded in these averages. The very pronounced long-term increase in the helium flux from 0.02 to 0.043 He/M^2 -sec-sr-Mev over the one-year period (Dec. 1963 -

Dec. 1964) is seen to be correlated with a similar but smaller rise in the intensity of the neutron monitor. In particular one should note the sharp increase in both intensities from Nov. to Dec. 1964. The fact that the helium flux so well correlates with the neutron monitor intensities is indeed convincing evidence for the galactic origin of the helium we are observing.

III. Modulation of Low Energy Helium Nuclei

We shall argue that the observed long term time variation in the galactic helium reported above is consistent with a velocity dependent modulation and excludes most types of rigidity dependences. We will make no assumption about the nature of the local galactic helium spectrum, but will suppose that the cosmic ray differential intensity at Earth $\mu_o(\epsilon)$ is related to the corresponding local galactic cosmic ray intensity $\mu_\infty(\epsilon)$ by

$$\mu_o(\epsilon) = \mu_\infty(\epsilon) \exp[-g(\epsilon) L(t)] \qquad (1)$$

where $g(\epsilon)$ is only a function of ϵ, the particle kinetic energy measured in units of its rest energy and $L(t)$ is a parameter depending only on time and has no energy dependence (see Parker 1963, Dorman 1963). For small percentage changes in $L(t)$ with time we can relate the fractional changes in the observed cosmic ray intensity at a given energy $\Delta\mu/\mu_o$ to the corresponding change in the modulating parameter, $\Delta L(t)$ both taken over a specified time interval Δt.

$$\frac{\Delta\mu}{\mu_o}(\epsilon) = -g(\epsilon)\,\Delta L(t) \qquad (2)$$

Plotting $\Delta\mu/\mu$ as a function of ϵ as is done in Figure 4 enables us to determine the explicit dependence of $g(\epsilon)$ on the particle energy ϵ. The parameter $\Delta L(t)$ may also be found by this method. For $\Delta\mu/\mu$ we used two sets of data. The points connected by the solid curve labeled "a" were computed from helium flux measurements on IMP-I and represent the fractional intensity increases over a time period, Δt, of ~ 3 months. The point at ϵ = ~0.3 was calculated from balloon measurements made in 1963 and 1964 (Durgaprasad and Guss, 1965). The value of $\Delta\mu/\mu$ at $\epsilon = 0.4$ (~400 Mev/nucleon) was also measured on IMP-I by a simultaneous analysis of D_1 and D_3 for particles completely penetrating the telescope (Gloeckler, 1965). The second set of data points, which are connected by a dashed curve labeled "b" represents the fractional increase in the helium flux which had occurred over the period of about one year from Jan. to Dec. 1964 and involves both IMP-I and IMP-II measurements. Values for $\Delta\mu/\mu$ at $\epsilon \sim 0.4$ could not be obtained due to a modification in the logic of the IMP-II instrument. The solid and dashed lines represent a v^{-1} dependence of $g(\epsilon)$, while the dash-dotted and dotted lines represent a rigidity dependence of $v^{-1}R^{-2}$ for $g(\epsilon)$ as discussed by Parker (1963). Here v is the particle velocity and R the particle rigidity. Certainly a v^{-1} dependence for $g(\epsilon)$ represents a reasonable fit for both sets of data, and in particular for set "a".

At the same time a rigidity dependence such as $v^{-1} R^{-2}$ can be excluded from these measurements, especially by data in group "a". Therefore, we conclude that below 500 Mev/nucleon our results indicate a predominantly velocity dependent modulation for the galactic cosmic radiation.

Parker (1963) obtained an expression for the 11-year modulation of cosmic radiation of the form given in equation (1) with $g(\epsilon) = v^{-1}$ and $L(t) = 3\,Vn$ where V is the solar wind velocity, and n is the effective number of mean free paths between the point of observation (Earth) and the termination of the modulating region. Our results imply that n is independent of particle energy which can arise when the mean free path for scattering is independent of the rigidity of the particle. It is interesting to note that Bryant *et al*, (1965) also concluded that the degree of scattering is independent of the particle rigidity in the measured range of 1.4 to 500 Mev. They based their conclusions on evidence obtained from three solar proton events which had occurred in the time period Sept. 1961 to October 1962.

Two idealized, but physically plausible configurations of the irregularities in the interplanetary magnetic field lead to rigidity independent scattering. The first is a rather smooth magnetic field with sharp bends which are separated by a typical mean distance ℓ_0 . The second type of distribution is continuous in the scale size L and goes as $\propto L^{-1}$ between suitable limits, L_1 and L_0. Here we have taken account of the fact that scattering of a particle by a magnetic irregularity reaches a maximum when the gyroradius of the particles is comparable to the scale size of that irregularity (Parker 1964). In either of the two examples rigidity dependence for the mean free path is not ruled out for higher energy particles which have gyroradii exceeding either ℓ_0 or L_0 as the case may be. The question which type of distribution in L really exists can be answered by analysis of the structure of interplanetary magnetic fields observed on satellites.

IV. Acknowledgments

We are grateful for the assistance given us in the design, fabrication and data reduction on the IMP-I and IMP-II satellites by the staff of our Laboratory for Astrophysics and Space Research.

We thank the staff of the Goddard Space Flight Center, NASA, for preparation of our experiments for flight and for data processing.

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References

Bryant, D. A., Cline, T. L., Desai, U. D. and McDonald, F. B., 1965, Astrophys. J., 141, 478-499.

Dorman, L. I., 1963, Progress in Elementary Particle and Cosmic Ray Physics, Vol. VII, North-Holland Publishing Company.

Durgaprasad, N., and Guss, D. E., 1965, Trans. Am. Geophys. U., 46, No. 1, 120.

Fan, C. Y., Gloeckler, G., and Simpson, J. A., 1965, J. Geophys. Res., 70, 3515-3527.

Fan, C. Y., Gloeckler, G., and Simpson, J. A., 1965, International Conference on Cosmic Radiation, London (Accel. 3, Session I).

Gloeckler, G., 1965, J. Geophys. Res., 70 (to be published).

Parker, E. N., 1963, Interplanetary Dynamical Processes, Interscience Publishers, New York.

Parker, E. N., 1964, J. Geophys. Res., 69, 1755-1758.

Figure Captions

Figure 1. Cross-sectional view of the four detector IMP charged particle telescope.

Figure 2. Time dependent changes in the differential energy spectrum of primary helium. The spectra above 100 Mev total kinetic energy can be represented by the form $E^{+\gamma}$ where the respective values for the exponent γ are + 1.75, +1.6, +1.45 and +1.3 for the curves labeled "a", "b", "c" and "d". Below 100 Mev energy the spectrum turns sharply and the exponent has the value of -1.85.

Figure 3. Time variation of the Climax neutron monitor intensity and the helium flux in the 30 - 90 Mev per nucleon energy range covering the period Dec. 1963 to Jan. 1965. The fractional increase in this time interval is 75 percent for the helium flux and 10 percent for primaries of rigidity greater than $\sim$ 3GV. The sharp increase in both the Climax intensity and the helium flux in Dec. 1964 indicates a sudden relaxation in the eleven-year modulation.

Figure 4. Measured fractional changes in the helium flux at given particle energies. The curves labeled "a" and "b" (solid and dashed) are calculated assuming a velocity dependent modulation. The curves labeled "c" and "d" (dash-dotted and dotted) represent calculations based on rigidity dependent modulation.

IMP Cosmic Ray Telescope
University of Chicago

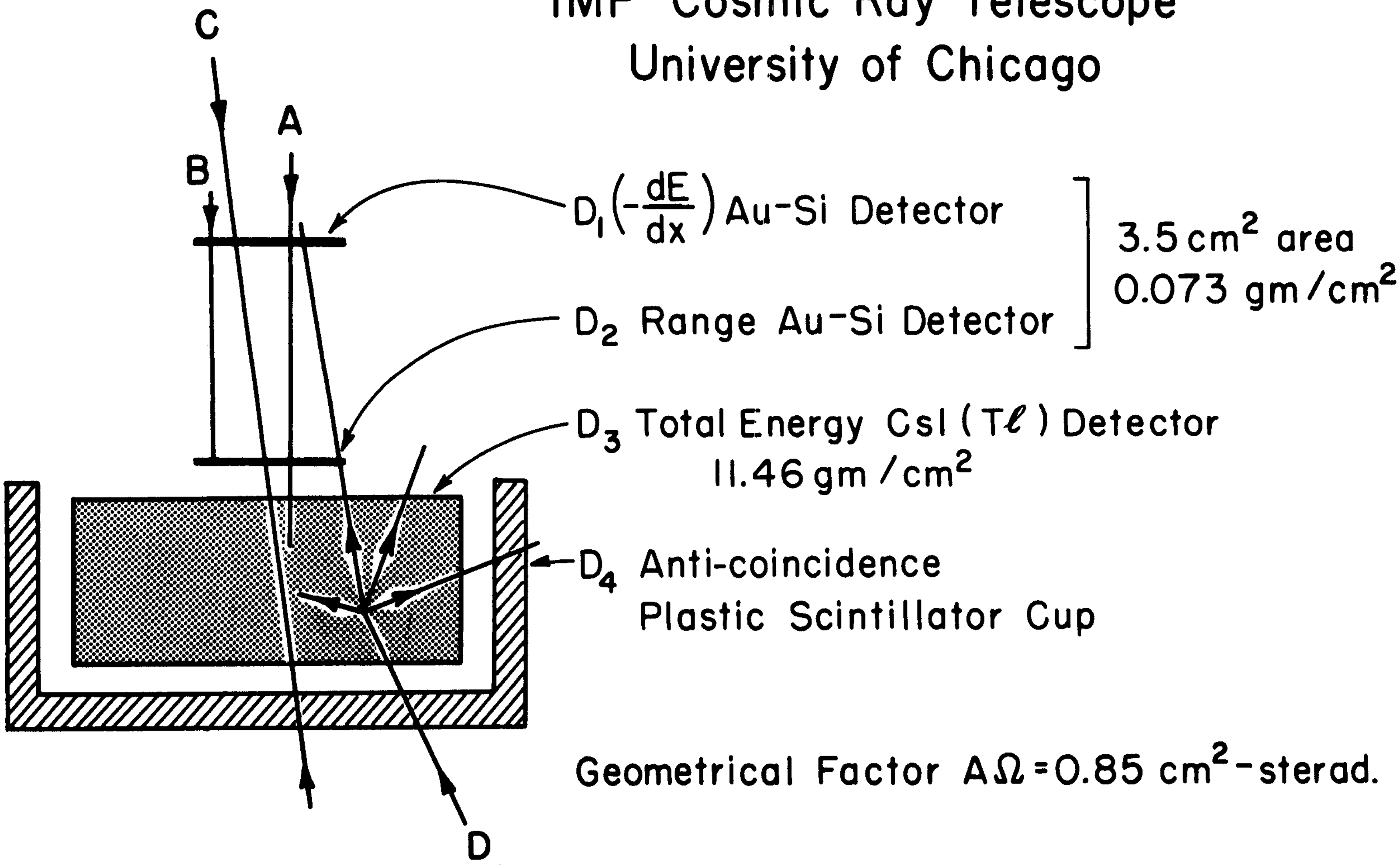
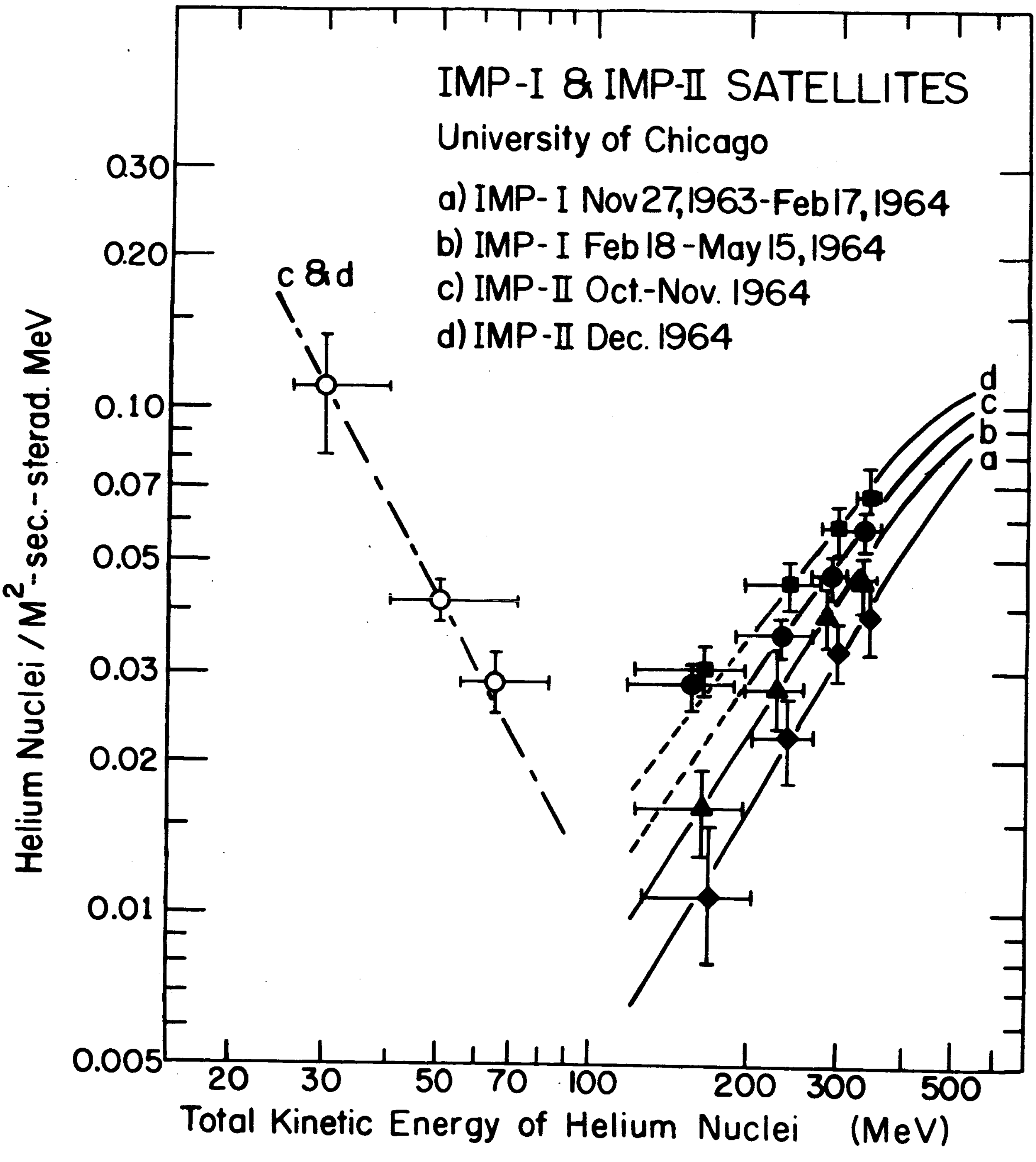


Fig. 1



IMP-I & IMP-II SATELLITES
University of Chicago
a) IMP-I Nov 27, 1963-Feb 17, 1964
b) IMP-I Feb 18-May 15, 1964
c) IMP-II Oct.-Nov. 1964
d) IMP-II Dec. 1964
c & d
d
c
b
a
0.30
0.20
0.10
0.07
0.05
0.03
0.02
0.01
0.005
20
30
50
70
100
200
300
500
Helium Nuclei / M^2-sec.-sterad. MeV
Total Kinetic Energy of Helium Nuclei (MeV)

Fig. 2

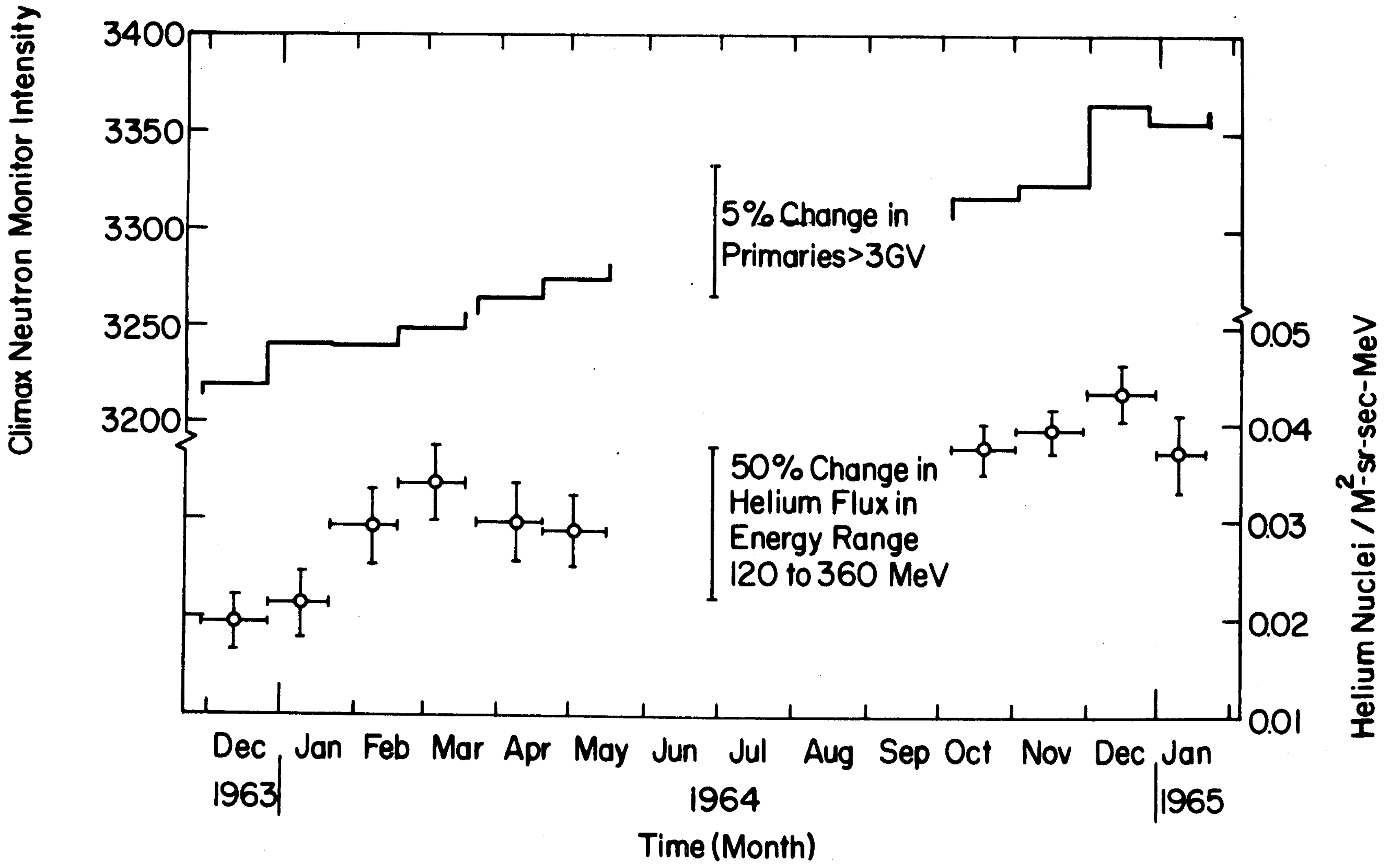

Climax Neutron Monitor Intensity
3400
3350
3300
3250
3200
5% Change in Primaries>3GV
50% Change in Helium Flux in Energy Range 120 to 360 MeV
0.05
0.04
0.03
0.02
0.01
Helium Nuclei / M^2-sr-sec-MeV
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1963
1964
1965
Time (Month)

Fig 3

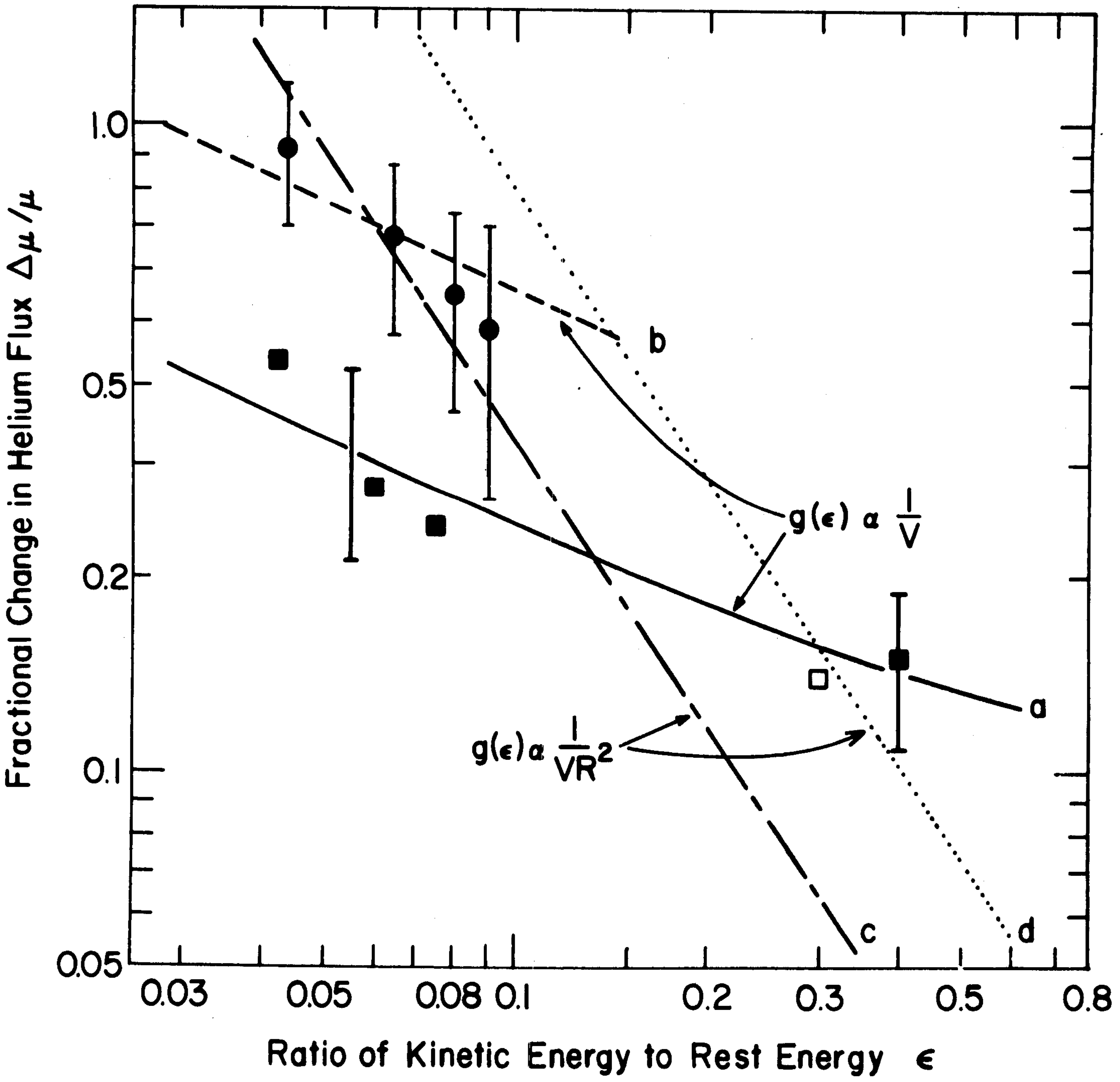
Fractional Change in Helium Flux $\Delta\mu/\mu$
1.0
0.5
0.2
0.1
0.05
0.03
0.05
0.08
0.1
0.2
0.3
0.5
0.8
Ratio of Kinetic Energy to Rest Energy ϵ
a
b
c
d
$g(\epsilon) \propto \frac{1}{V}$
$g(\epsilon) \propto \frac{1}{VR^2}$

Fig. 4