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ANOMALY IN THE QUIET-TIME HELIUM SPECTRUM AT 1 MeV PER NUCLEON

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ABSTRACT

An unusual spectral feature and anomalously large abundance of helium between 0.6 and ∿2 MeV per nucleon observed during the most quiet time periods in 1974-75 indicate the presence of low energy helium of an unknown origin. Alphas below 0.6 MeV per nucleon and protons below 1.5 MeV have an $E^{-1.8}$ spectrum and the proton to alpha ratio is about 30. These $\lesssim 1$ MeV particles are found to be emitted continuously by the Sun even during its most inactive periods.

Subject headings: Cosmic rays-solar system-abundance, cosmic ray

I. INTRODUCTION

Despite extensive investigation of low energy protons and alpha particles during solar quiet periods (times when the intensity of particles in a given energy interval reaches its minimum value) it has not been possible to establish whether these particles are predominantly of solar or galactic origin or have been accelerated to the observed energies in the heliosphere (Fan et al., 1968, 1970; Kinsey, 1970; Simpson and Tuzzolino, 1973; Krimigis et al., 1973; Zamov, 1975). In this paper we report our observations of quiet-time protons and helium nuclei with energies as low as 300 keV per nucleon. We find that during quiet times the spectrum of helium between $\sim$1 and 3 MeV per nucleon has an unexpected hump and that the proton to alpha ratio is less than 5. The origin of this component of helium is at present unknown.

On the other hand, low energy protons ($\lesssim$ 1.5 MeV) and helium nuclei below $\sim$0.6 MeV per nucleon have differential energy spectra of the form $E^{-1.8}$, and the proton to helium ratio is about 30. Since, in addition, the most probable arrival direction is measured to be along the interplanetary magnetic field away from the Sun, we conclude that these low energy particles are continuously emitted by the Sun even during its most inactive periods.

II. INSTRUMENTATION

Our measurements are made using the ULET sensor of the University of Maryland/Max-Planck Institut Experiment on the earthorbiting IMP-8 satellite. IMP-8 is a spinning spacecraft (spin period ∿2.6 sec, spin axis perpendicular to the ecliptic plane) in a nearly circular orbit with perigee of ≳ 23 earth radii and a period of about 12 days. ULET is a three element dE/dx vs E telescope which is pointing approximately perpendicular to the satellite spin axis, has a geometrical factor of 0.53 $cm^2 sr$ and an opening cone full angle of 50^o (Hovestadt and Vollmer, 1971). The detector system consists of detectors D1, a 130 $\mu g/cm^2$ thick flow-through proportional counter; D2, a conventional circular Au-Si surface barrier detector; and A2, a plastic scintillator anti-coincidence cup detector. This design enables us to obtain two-parameter pulse-height analysis and separately identify protons, helium isotopes and individual heavier elements having energies far below 2 MeV per nucleon, the low energy limit of most conventional dE/dx vs E telescopes using thin ΔE solid state detectors. In addition to the pulse-height analysis information the D1D2 ⟨A2⟩ counting rate (corresponding primarily to protons between 0.43 and 1.5 MeV and alpha particles in the range 0.26 to 6.6 MeV per nucleon) is sectored into four 90^o quadrants and is read out once every 20 seconds.

III. RESULTS

The coincidence counting rate D1D2 ⟨A2⟩, averaged over three hours and all four sectors is plotted in Figure 1 for an eighty-four day period in 1973 and 1974. Although no solar flares of importance 2 or above have been observed during this time period there is an unmistakable presence of low energy particles at all times (the ULET background is far below 5×10^{-4} counts per second --see caption of Figure 3). Their intensities vary slowly by factors of 10^2 to 10^3 over 10 to 20 day periods indicating in general a non-impulsive, quasi-steady emission by the Sun of less than $\sim$1 MeV protons and alpha particles. It is interesting to note that the earth's magnetosphere has little influence on the intensity of the low energy solar particles we observe. This is evident when one examines the behavior of the rate plotted in Figure 1 at the bowshock crossings of the satellite (boundaries of shaded regions) or when IMP-8 is inside the bowshock (shaded regions). No obvious discontinuities in the rate are seen near the bowshock crossings nor is there a systematic difference between the intensity inside and outside the magnetosphere.

During three rather short time periods (marked by solid bars in Figure 1) the particle intensity dips to the <u>same</u> average minimum value of about 5×10^{-3} counts per second which corresponds to a proton flux of about 10^{-2} protons per (cm^2sec sr MeV). We have used data accumulated during these three periods and four similar time intervals (not shown) for our quiet time analysis. To exclude low energy particles accelerated in the earth's magnetosphere we have eliminated from our data set periods during which the 10 minute averaged D1D2 $\langle A2 \rangle$ counting rate showed "spike" structures and required that variations between consecutive 10 minute averages be consistent with statistical fluctuations.

In Figure 2 we show five polar plots of the angular distribution in the ecliptic plane of protons and alphas derived from the D1D2 ⟨A2⟩ sectored counting rates averaged over several days during the quiet-time periods. For reference we have indicated the respective locations of a model bowshock and magnetopause. The average interplanetary magnetic field direction, measured during identical time intervals by the Goddard magnetometer on IMP-8 (King, 1975) is indicated in polar diagrams on the left hand side of the figure.

It is evident from Figure 2(b) that the strongest unidirectional anisotropy is seen when the satellite is in the dusk side and farthest away from the bowshock in a region where the interplanetary magnetic field is least likely to connect with the magnetosphere. The anisotropy data [lower polar plot of Figure 2(b)] indicate that the particles are moving along the magnetic field from the solar direction. We note that when the satellite is near the bowshock (within about 10 earth radii) and particularly in the dawn side [Figure 2(a)] or near the subsolar point upstream from the bowshock [Figure 2(c)], the particle anisotropy is significantly modified. This shows the influence of the magnetosphere on low energy solar particles, especially where the field lines are likely to connect with the bowshock. We emphasize that due to our selection criterion there is no substantial contribution of >430 keV protons escaping from the magnetosphere as is evident from the nearly constant sector averaged rates (dashed circles in Figure 2). The fact that quiet-time particles are also seen in the tail [Figure 2(c)] is interesting in itself and implies a relatively easy access of low energy solar particles into this region of the magnetosphere.

Detailed spectral information is obtained from two-parameter pulse-height data summed during the quiet-time periods between October 1973 and March 1975. The ΔE vs E matrix for ULET, showing the proton and alpha data, is displayed in Figure 3. One should note the relative absence of events in the low energy region (D2 channel number $\lesssim$ 60) of the helium track and a clustering of data points around D2 channel number 80 corresponding to an energy of $\sim$ 1.5 MeV per nucleon.

The differential energy spectra for protons and helium nuclei derived from the pulse-height data accumulated during quiet times are shown in Figure 4. The spectra represented by open and solid symbols correspond to the requirements that the average D1D2 $\langle A2 \rangle$ rate be less than 6×10^{-3} and 4×10^{-3} counts per second, respectively. Thus, the proton spectrum represented by solid triangles corresponds to conditions during the least active periods in the quiet-time intervals. While the proton spectrum is consistent with a power law of the form $E^{-1.8}$, the helium spectrum shows a hump around 1 MeV per nucleon. The proton to alpha ratio is about 20 to 30 below ∿0.6 MeV per nucleon but drops to only 4 to 5 in the energy region of the hump. Furthermore, a more stringent selection of quiet-time intervals shows no spectral changes for protons, but a drop by about a factor of two in the intensity of helium at the hump.

IV. DISCUSSION

Where do the low energy particles we observe during the most quiet-time periods originate? Two cases are distinguished and discussed separately.

(a) Origin of Protons and Helium Nuclei Below ∿1 MeV per Nucleon

For protons between 0.43 and 1.5 MeV and alpha particles below ∿0.6 per nucleon the simplest explanation consistent with our observations is that these energetic particles are continuously emitted by the Sun. In support of this conclusion we note that not only does the anisotropy data show them to be coming from the Sun [lower polar diagram of Figure 2(b)] but, in addition, the observed proton to alpha ratio of 30 is similar to the average value for solar flare particles and the solar wind. We rule out the possibility that protons of magnetospheric origin (Krimigis *et al.*, 1974) contribute significantly to our measurements above 0.43 MeV, because the energy spectra of particles accelerated in the magnetosphere are considerably steeper (Fan *et al.*, 1975) than observed here. Furthermore, the anisotropy data of Figure 2(b) do not support a predominantly magnetospheric origin hypothesis above ∿0.5 MeV. On the other hand, we cannot as yet exclude the possibility that these low energy particles are accelerated in interplanetary space by, for example, second order Fermi processes (Murray et al., 1971; Jokipii, 1971). Wibberenz and Beuermann (1972) indeed estimate that such acceleration could be important near the Sun for $\lesssim$ 1 MeV per nucleon particles.

(b) Origin of the Anomalous Helium Nuclei Between 0.6 and ∿3 MeV per Nucleon

For helium nuclei above 0.6 MeV per nucleon no simple explanation comes to mind. We consider two alternatives.

Solar Origin. The observed correlation between the intensity of alpha particles between ∿0.6 and 2 MeV per nucleon and that of low energy protons (compare spectra represented by open and solid symbols in Figure 4) suggests that helium in this energy range may also come from the Sun. The hump could then be viewed as a flattening in the helium spectrum similar to that observed for C + O at lower energies and explained by coronal propagation and storage of these ions (Gloeckler et al., 1975a). Applying these ideas to the present case we can imagine the existence of regions in the Sun (different from those emitting <1.5 MeV protons and alphas below 0.6 MeV per nucleon) where particles, after being accelerated, are, on the average, stored for long time periods before being released.

For example, starting with an initial spectrum of helium of the form $j(E) \sim E^{-4}$, storage in the lower corona (at 1.6 $R_\odot$) at a temperature of $\sim 1.2 \times 10^6$ °K for 5×10^4 sec and followed by adiabatic deceleration in interplanetary space by a factor of two will result in an alpha particle spectrum shown as the solid curve in Figure 4. Increasing the storage time t[illegible] [illegible].5 $\times 10^4$ sec without changing any of the other parameters will give the spectrum shown by the dotted curve. It should be recognized that this process would flatten the proton spectrum in a similar fashion (Gloeckler et al., 1975a) which is not observed. Therefore, the intensity of protons produced by this mechanism must be comparable or lower than that of the α-particles and we are left with explaining the unusually large abundance of helium (or the absence of protons) in these source regions. Although it is difficult to find a simple explanation for helium to be so enriched, we note that anomalous compositions have been observed in He^3-rich events (Garrard et al., 1973; Anglin, 1974) and, more recently, in iron-rich emissions from the Sun (Gloeckler et al., 1975b).

Non-Solar Origin. Arguments in favor of a non-solar origin for helium above 0.6 MeV per nucleon may be based on the similarity in the spectral feature (hump) of helium and the anomalous oxygen below $\sim$10 MeV per nucleon (Hovestadt et al., 1973, Klecker et al., 1975) which is believed to be non-solar in origin. In addition, the low proton to α-particle ratio above 2 MeV per nucleon (only about 2 to 5, see Figure 5), and studies of the 11-year variation in the flux of 6 MeV per nucleon quiet-time helium nuclei (Fan et al., 1970; Zamov, 1975) suggest a non-solar origin. Acceleration in the interplanetary medium of interstellar gas ionized within the heliosphere (Fisk et al., 1974) could qualitatively account for the observed features in the helium spectrum. One should bear in mind, however, that quiet-time helium already has an unusual spectral feature between ∿5 and 70 MeV per nucleon (Garcia-Munoz et al., 1973; Van Hollebeke et al, 1973) and that, unlike for the case of oxygen, the hump we find at lower energies is an additional anomaly which must be accounted for by any non-solar origin models (see Figure 5).

VI. SUMMARY AND CONCLUSIONS

Low energy (0.43 to 1.5 MeV) protons are observed to be continuously present during quiet-time periods between October 1973 and March 1975. We find that in general the earth's magnetosphere has little influence on the intensity of these particles and that, in particular, they have easy access to the outer regions of the magnetosphere. The spectrum of protons between 0.43 and 1.5 MeV has the form $E^{-1.8}$ and while the absolute intensity is somewhat variable during quiet-time periods, the spectral shape remains unchanged within the errors of our measurements. On the basis of the measured anisotropies, spectra and abundances we conclude that these low energy quiet-time protons are very likely of solar origin.

The measured quiet-time helium spectrum is more difficult to explain. We argue that below $\sim$0.6 MeV per nucleon helium nuclei come from the Sun from presumably the same source regions which produce the protons. Between 0.6 and $\sim$3 MeV per nucleon we find that the spectrum has an unexpected hump with the helium abundance increasing and remaining enhanced up to about 70 MeV per nucleon (see Figure 5). We speculate on the origin of this anomalous low energy helium but cannot decide at present whether these nuclei are of solar origin, have been accelerated in the heliosphere or are of galactic origin. Additional observations of low energy quiet-time particles extending over a large portion of the eleven-year solar cycle and over a large range of heliocentric distances are essential before one can distinguish between these alternatives.

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to emphasize the measurement of low energy ions and nuclei. This work has been supported by NASA under contract NAS 5-11063, grant NGR-21-002-224 and NGR-21-002-316, and by the German Government.

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FIGURE CAPTIONS

Fig. 1--Time variations in the intensity of 0.43 to 1.5 MeV protons. Each dot represents the mean value of the D1D2 ⟨A2⟩ counting rate, averaged over all four sectors, during a three hour period. The six shaded regions indicate the time periods during which the satellite is inside the earth's bowshock. The intensity reached the same average minimum level ($\sim 10^{-2}$ counts per sec) during the three time intervals marked by the three solid bars (days 10-11, 37-40 and 77 respectively).

Fig. 2--Polar plots of the angular distributions of the D1D2 ⟨A2⟩ counting rate ($\sim$80% protons and 20% alphas) in the ecliptic plane. The left-hand side of the figure is towards the Sun and the orientation for all five polar diagrams is identical. Data for a given polar plot were averaged over the indicated segments of the IMP orbit. The scales are marked in units of ten earth radii. The coordinate system used had its origin at earth with the XSE-axis pointing towards the Sun, the YSE-axis towards the north ecliptic pole and the YSE-axis completing a right-handed system. (a) anisotropy measurements in the dawn side, (b) anisotropy measurements in the dusk side, and (c) anisotropy measurements in the subsolar point and tail of the magnetosphere, respectively.

Fig. 3--Frequency distribution of the (D1,D2) pulse-height-channel-number pairs displayed as a ΔE vs E matrix. The curve labeled "Helium" is derived from flight data accumulated during the September 1974 solar flare particle event. The residual

background (i.e., events below the protons and between the proton and helium tracks) is very low and amounts to at most a few per cent of the particle fluxes.

Fig. 4--Differential energy spectra for protons and helium nuclei during quiet times. The most outstanding feature is the hump in the helium spectrum around 1 MeV per nucleon.

Fig. 5--Differential energy spectra for quiet-time protons and helium nuclei. The solid and dashed curves are shown for reference. The data are from: ▲ (protons) ● (helium), this work; ◇ (protons) ⊖ (helium), Garcia-Munoz 1973; △ (protons) ○ (helium), Garcia-Munoz *et al*., 1975).

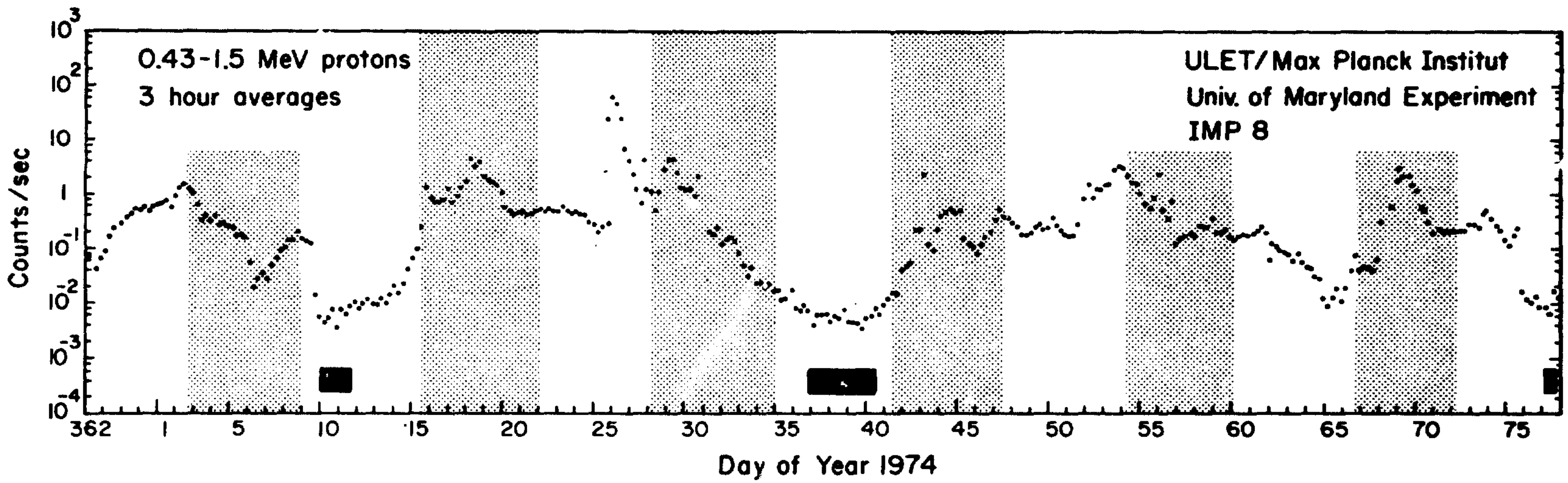

0.43-1.5 MeV protons
3 hour averages
ULET/Max Planck Institut
Univ. of Maryland Experiment
IMP 8
Counts/sec
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
362
1
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
Day of Year 1974

FIGURE 1

University of Maryland/Max Planck Institut Experiment

ULET - IMP 8

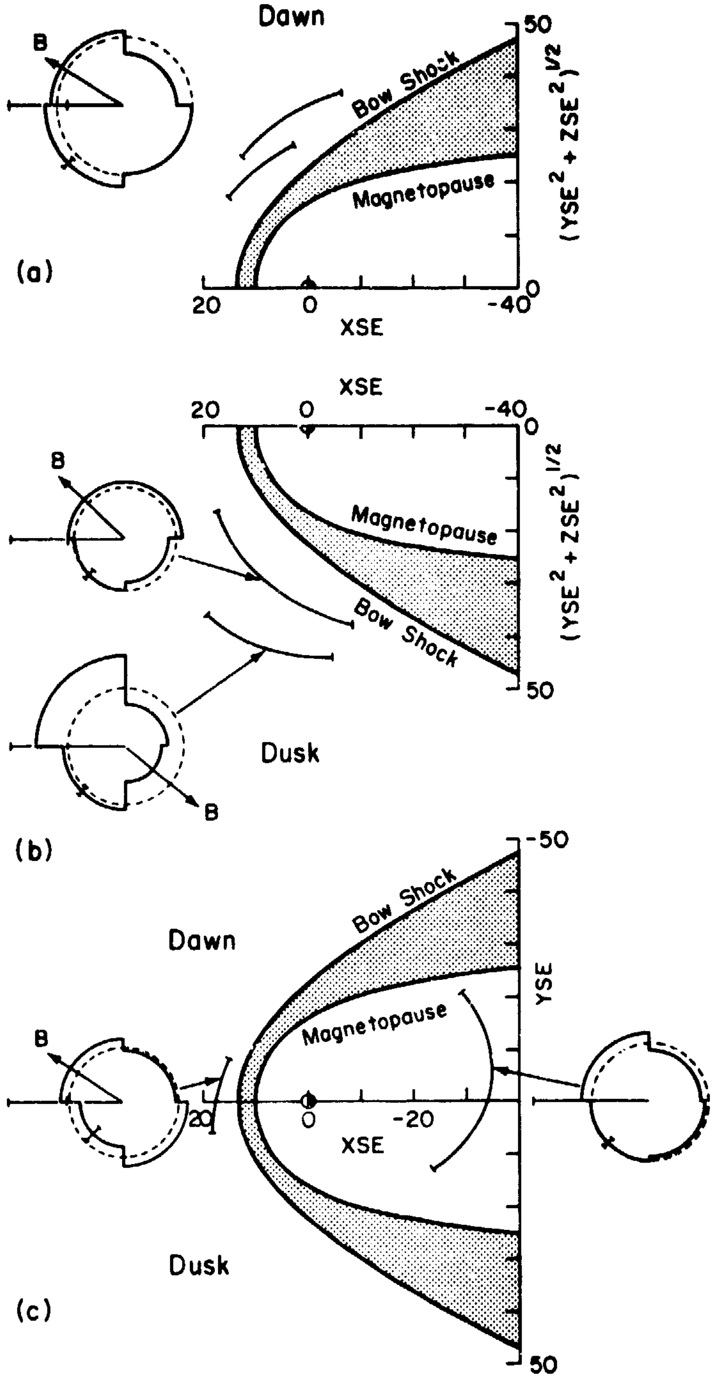


Fig. 2

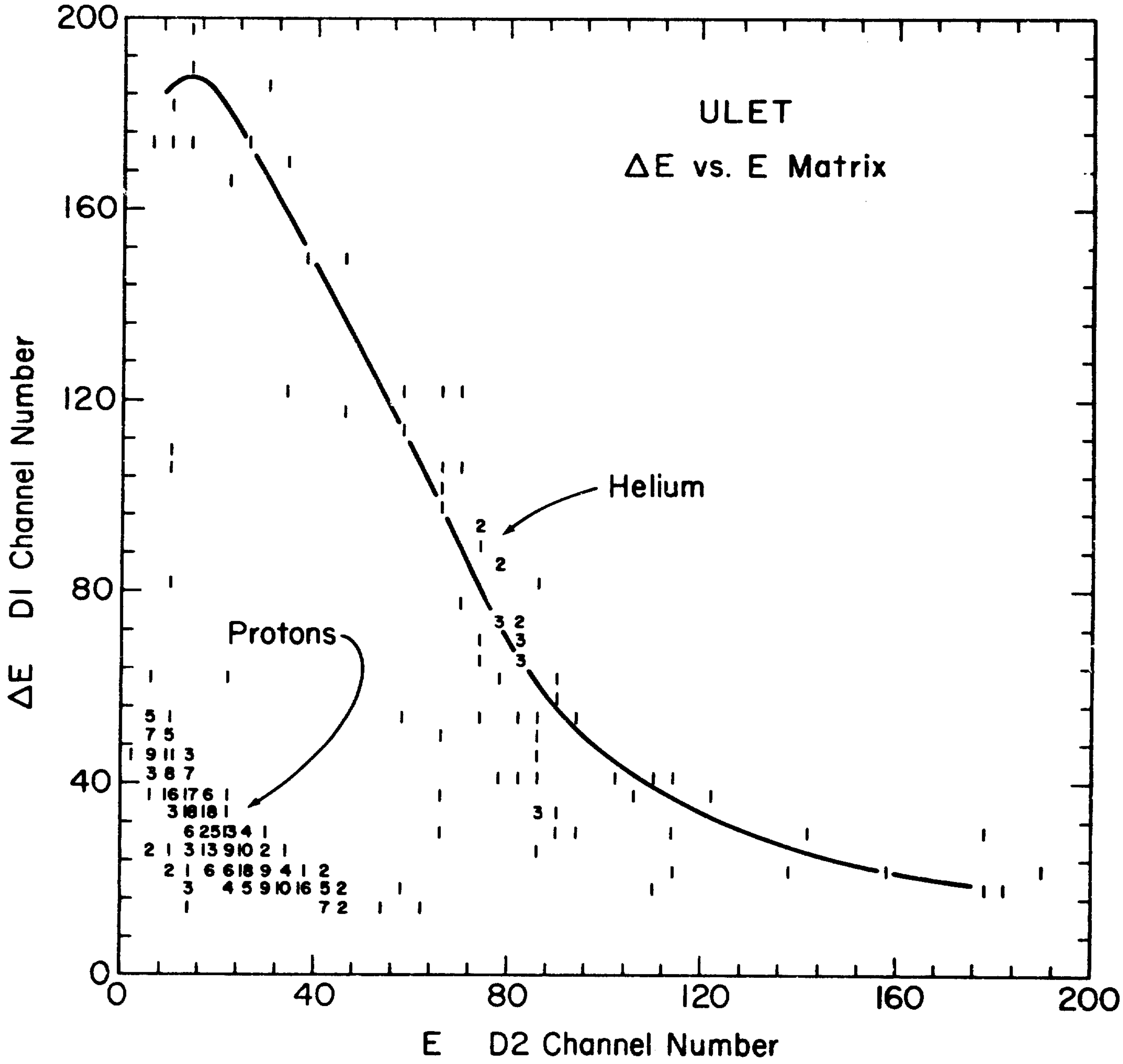
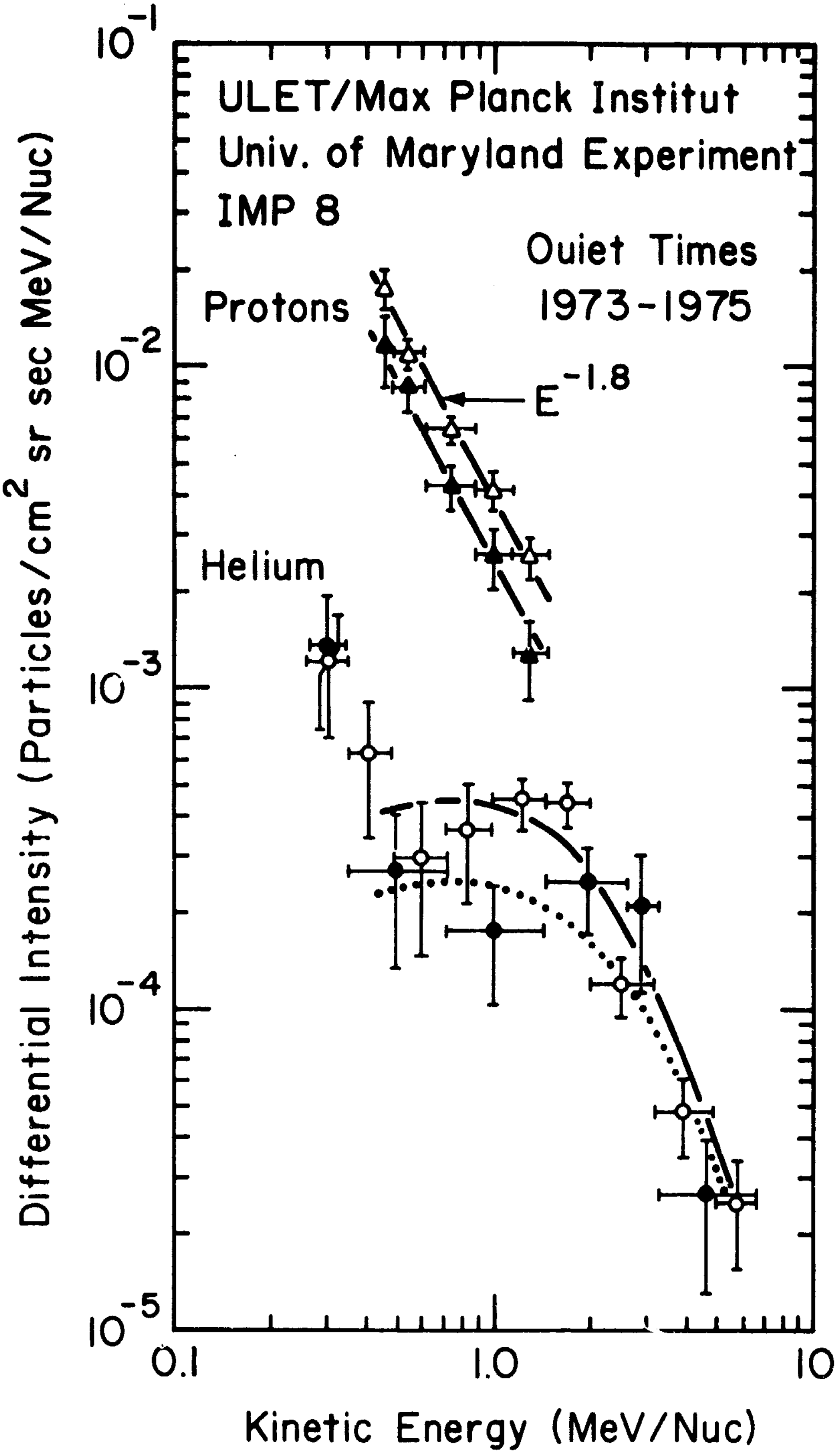

ULET
ΔE vs. E Matrix
Helium
Protons
ΔE D1 Channel Number
E D2 Channel Number

Fig. 3



ULET/Max Planck Institut
Univ. of Maryland Experiment
IMP 8
Quiet Times
1973-1975
Protons
$E^{-1.8}$
Helium
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.1
1.0
10
Differential Intensity (Particles/cm^2 sr sec MeV/Nuc)
Kinetic Energy (MeV/Nuc)

Fig. 4

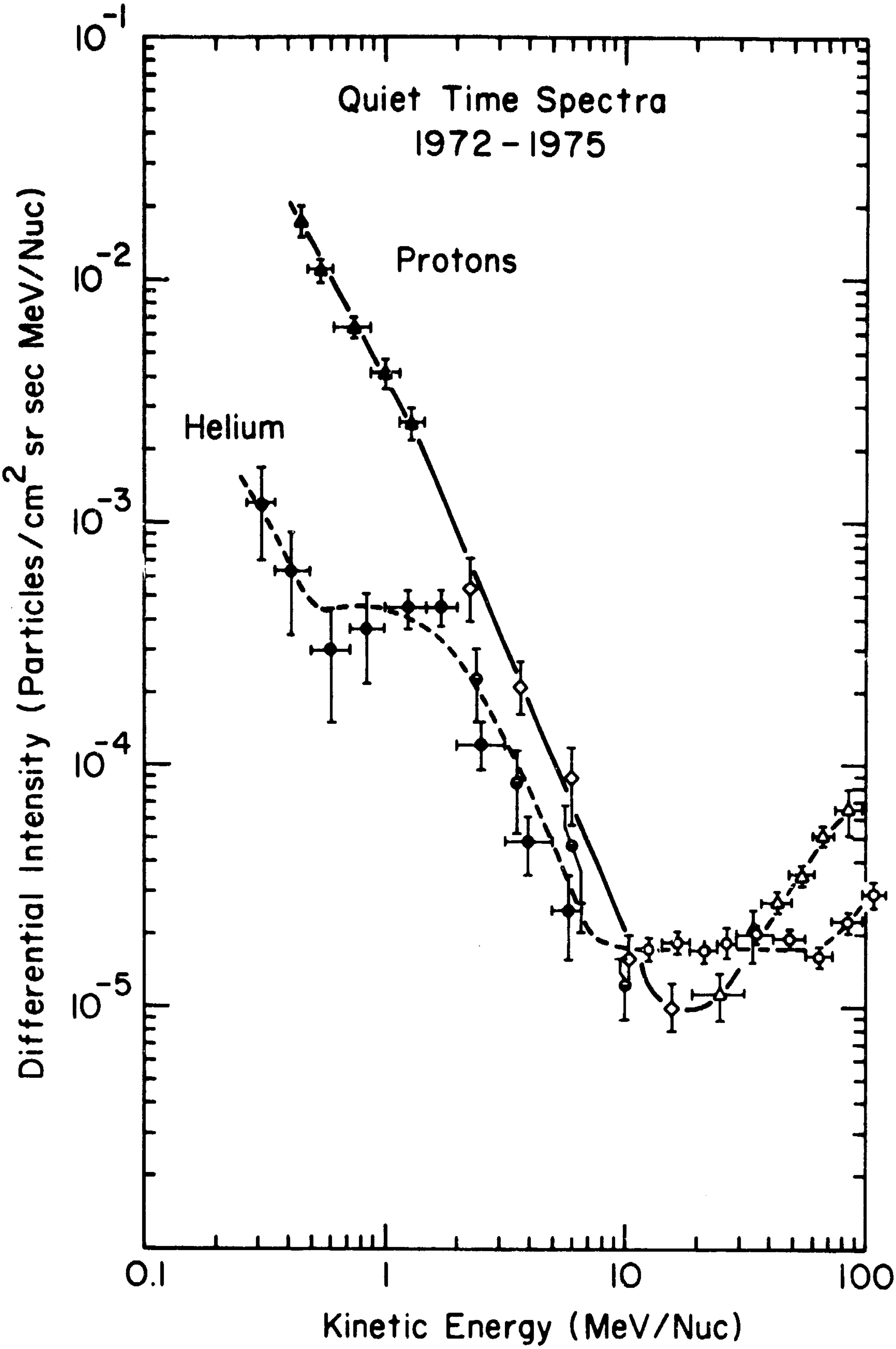

Quiet Time Spectra
1972 - 1975
Protons
Helium
Differential Intensity (Particles/cm^2 sr sec MeV/Nuc)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.1
1
10
100
Kinetic Energy (MeV/Nuc)

Fig. 5