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Abstract

Sustained emission of low energy solar particles with a composition richer in iron than oxygen is observed in the time period 1974 May 7 to 17. Between 0.7 and 4 MeV/nucleon the relative abundances of C:O:Fe are 0.24:1:1.35. We suggest that these observations provide indication for effects of heavy ion enrichment in the lower corona of the sun.

Overabundance of heavy nuclei is frequently observed in the composition of low energy particles accelerated at the sun (Price et al. 1971; Lanzerotti et al. 1972; Mogro-Compero and Simpson, 1972; Fleischer and Hart 1973; Hovestadt et al. 1973a; Crawford et al. 1975). No satisfactory explanation exists as yet to account for these enhancements, and specifically for Fe/O ratios reported to be as high as 0.1 to 0.6 (Crawford et al. 1975). In this letter we describe a 10 day period of sustained emission of solar particles having a highly unusual composition. In this "event" iron is more abundant than oxygen and the composition of nuclei heavier than helium is enriched by a factor of about 20.

Our data are obtained using the ULET sensor of the University of Maryland/Max Planck Institute Experiment aboard the IMP 8 earth orbiting satellite. IMP 8 is in a low eccentricity orbit with perigee of $\gtrsim$ 23 earth radii and a period of $\sim$ 12 days. ULET is a dE/dx vs E three detector telescope with a geometrical factor of 0.53 $cm^2 sr$, a 330 $\mu g/cm^2$ flow through proportional counter as the "ΔE" element, D1, a conventional surface barrier Au-Si "E" detector, D2, and a plastic scintillator anti-coincidence cup, A (Hovestadt and Vollmer, 1971). This design allows two parameter pulse height analysis and unique identification of heavy particles with energies far below 1 MeV/nucleon as indicated in Table 1. Every three hours the experiment is automatically switched between a low and a high threshold mode of operation where either all chemical elements or only nuclei heavier than helium are counted and analyzed respectively.

The coincidence counting rates of the D1D2$\bar{A}$ detector combination for the low threshold (protons, alpha particles and heavier elements) and the high threshold (nuclei heavier than helium) modes are plotted in Fig. 1(a) for the time period 1974 May 5 to 20. The first day and the last four days represent the typical behavior of low energy particle fluxes during "relatively quiet" time periods. In particular, the ratio $R(\frac{Z>1}{Z>2})$ plotted in Fig. 1(b) is about 2-3 x 10^2 and remains relatively constant. However, beginning about May 7 the ratio R decreases by about a factor of 20 and remains relatively constant for the next ten days at about 10 to 20 despite large time variations in both rates during this period (for example, on May 14 both rates increase by a factor of about 10^3). On May 16-17 the $Z > 2$ rate drops by about a factor of 10 without a corresponding decrease in the fluxes of proton and alpha particles.

Analysis of the D1 vs D2 pulse height data allows us to establish in detail the relative composition and energy spectra of heavy nuclei during the period of enrichment. In Fig. 2 we display the ΔE by E matrix for ULET for data summed from May 7, 12:00 to May 17, 0:00. The curves labeled C, O and Fe are the tracks of carbon, oxygen and iron group nuclei obtained from inflight calibration and calibrations with heavy ions from accelerators. There is an unmistakable clustering of points near the tracks, especially for iron and oxygen, indicating the predominance of these nuclei. The points in the region between O and Fe correspond to Ne-Ca nuclei, which are also abnormally overabundant. The abundance of carbon is visibly below that of oxygen.

In table 2 we compare the relative abundances of protons, helium, and heavier particles between 0.7 and 4 MeV/nucleon derived for this iron rich event from the high threshold ΔE vs E matrix to similar ratios for high energy solar flare particles, the solar wind, solar corona and galactic cosmic rays. One can immediately notice the large enhancement of nuclei heavier than oxygen for the iron enriched particle event.

The differential energy spectra of iron and oxygen derived from the high threshold pulse height data summed from 1974 May 7 to 17 are shown in Fig. 3. In the energy interval 0.65 to $\sim$ 1.3 MeV/nucleon the flux of iron exceeds that of oxygen by about a factor of two, while at lower energies the iron enrichment is even larger. Between 2.3 and 7.5 MeV/nucleon the flux of oxygen is consistent with the anomalous oxygen hump discovered by Hovestadt et al. (1973b). Below 0.7 MeV/nucleon the iron spectrum includes contributions from Ne-Ca nuclei for which no correction has been made for this preliminary report. These corrections would tend, however, to lower data points labeled (a) and make the turn-over of the spectrum already noticeable even more pronounced. The oxygen point labeled (b) has been corrected for contributions from low energy iron nuclei. In the insert we show the anisotropy of heavy nuclei above 0.7 MeV/nucleon for the 10 day time period. The arrow indicates the most probable arrival direction (corrected for the Compton-Getting effect) which is roughly along the average garden hose direction of the interplanetary magnetic field.

What mechanisms could produce such enormous enrichments of heavy nuclei? What causes the enhancement to appear, persist for about ten days (despite large intensity variations for both $Z \geq 1$ and $Z > 2$ particles) and then disappear? In an attempt to answer the second question, first we find that the only correlation with the onset of the iron enrichment is a sudden Forbush decrease at $\sim$ 2-5 hours on May 7. During this same day solar wind data recorded by the Los Alamos Experiment on IMP 8 indicated presence of a high speed stream and fluctuating densities, but no abnormal proton to helium abundance (Bame, private communication). This leads us to propose that on May 7 the IMP 8 satellite entered a corotating region filled with energetic particles having a composition superenriched in iron and remained in this region for about 9 to 10 days. This region is presumably associated with McMath 12906, which also produced the two small solar flare particle events on May 9-10 and May 14-15 respectively. We note with interest that the first of these events was He^3 rich as Mewaldt and Stone (private communication) pointed out to us and we also observed with our ULET sensor, indicating an additional anomaly in particle composition.

Although other explanations undoubtedly exist, we suggest that the particles observed in the 9-10 day period originated and were accelerated in regions of the lower solar corona where density enhancements of heavy ions are likely to exist. Chapman (1958) first pointed out and subsequently Jokipii (1965, 1966), Nakada (1969), Geiss (1972) and others (Delache, 1967) have discussed the basic mechanism of ion separation due to velocity difference of various species which are caused by combined effects of a strong temperature gradient between the photosphere and the corona and gravitational settling. These authors indeed find large enrichments of heavy ions in the lower corona of the sun.

Finally we note that the magnitude of this particle event was very modest. The time averaged intensity of iron at 1 MeV/nucleon was only $2 \times 10^{-3}/(cm^2 sr\ sec\ MeV/nucleon)$ and much smaller than the average for solar flare events summarized by Crawford _et al_. (1975). Perhaps subflare particle events such as this will indicate the extent of the inhomogeneity in the composition of the solar atmosphere and provide new insights on dynamical processes on the sun.

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TABLE 1. ENERGY RANGE OF ULET RESPONSE TO VARIOUS NUCLEI

Chemical Element	Energy Range (MeV/nucleon)	Threshold Mode
Protons	0.43 - 1.49	Low Threshold
He	0.31 - 6.6	
C	0.19 - 19	
O	0.17 - 21	High Threshold
Fe	0.075 - 35	

TABLE 2. RELATIVE ABUNDANCES OF PROTONS AND HEAVY PARTICLES NORMALIZED TO OXYGEN

Chemical Element	Iron Rich Event[a] (0.7 - 4 MeV/n)	Solar Flare Particles[b] ($\geq$ 15 MeV/n)	Solar Wind[d]	Solar Corona[b]	Galactic Cosmic Rays[f] ($\sim$ 100 MeV/n)
Protons	$(3.20 \pm 0.15) \times 10^4$	-	5×10^5	1.4×10^5	1.8×10^4[g]
He	2470 ± 320	8400[c]	1.5×10^4	8300	4500[g]
C	65 ± 11	50 ± 4	-	60	100
O	$\equiv 100$	$\equiv 100$	$\equiv 100$	$\equiv 100$	$\equiv 100$
Ne-Ca	140 ± 22	39 ± 5	31[e]	27	63
Fe	135 ± 21	8 ± 2	17	6	7

(a) present work
(b) from data compiled by Crawford *et al*. (1975)
(c) variable
(d) Bame (1972)
(e) includes only Ne and Si
(f) Garcia-Munoz (1973)
(g) Fan *et al*. (1968)

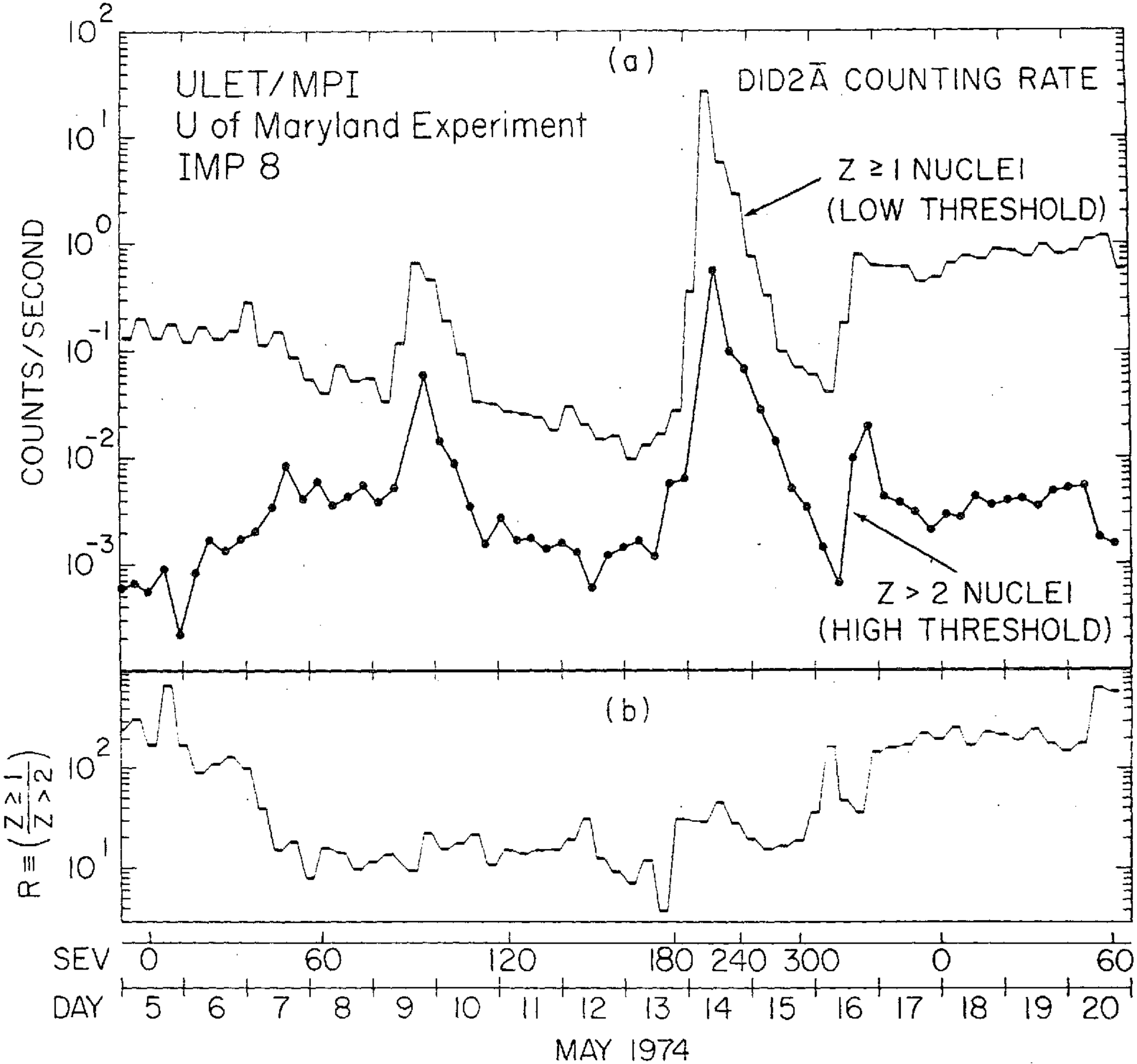
Figure Captions

Fig. 1 (a) Counting rates of $Z \geq 1$ nuclei (primarily protons and alpha particles) and $Z > 2$ nuclei for the 1974 May 5-20 time period.

(b) Time dependence of the ratio of proton plus alpha to $Z > 2$ particles. Note that this ratio is small and remarkably constant from May 7 to 16 despite large intensity variations in the counting rates. SEV gives the angle between the earth-sun and the earth-satellite vectors and shows that between the onset and disappearance of the iron enrichment the IMP 8 satellite was in interplanetary space.

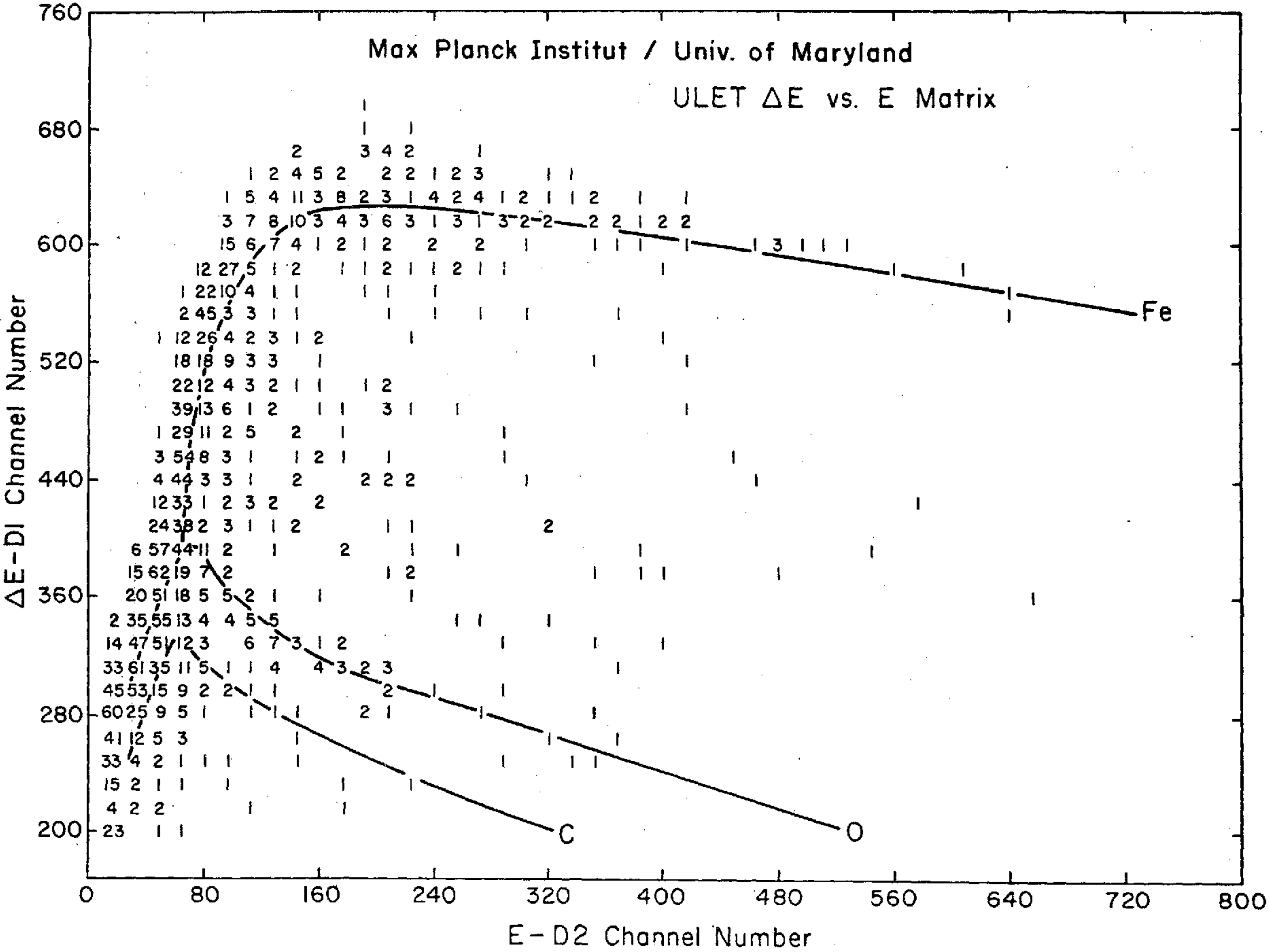
Fig. 2 The ΔE vs E pulseheight analysis matrix for the 1974 May 7 to 17 time period showing the enormous enrichment of iron nuclei.

Fig. 3 Time averaged differential energy spectra for iron and oxygen during 1974 May 7 to 17. The energy dependent enrichment of iron over oxygen is evident, with the iron flux exceeding oxygen. Points labeled (a) include contributions from low energy Ne to Ca nuclei. Point (b) has been corrected for relatively large contributions from $Z > 8$ nuclei below $\sim$ 0.2 MeV/nucleon. The insert shows the relative number of heavy particles above 0.7 MeV/nucleon in each of four 90^{o} sectors in the ecliptic plane. The most probable arrival direction is along the average garden hose angle of the interplanetary magnetic field.



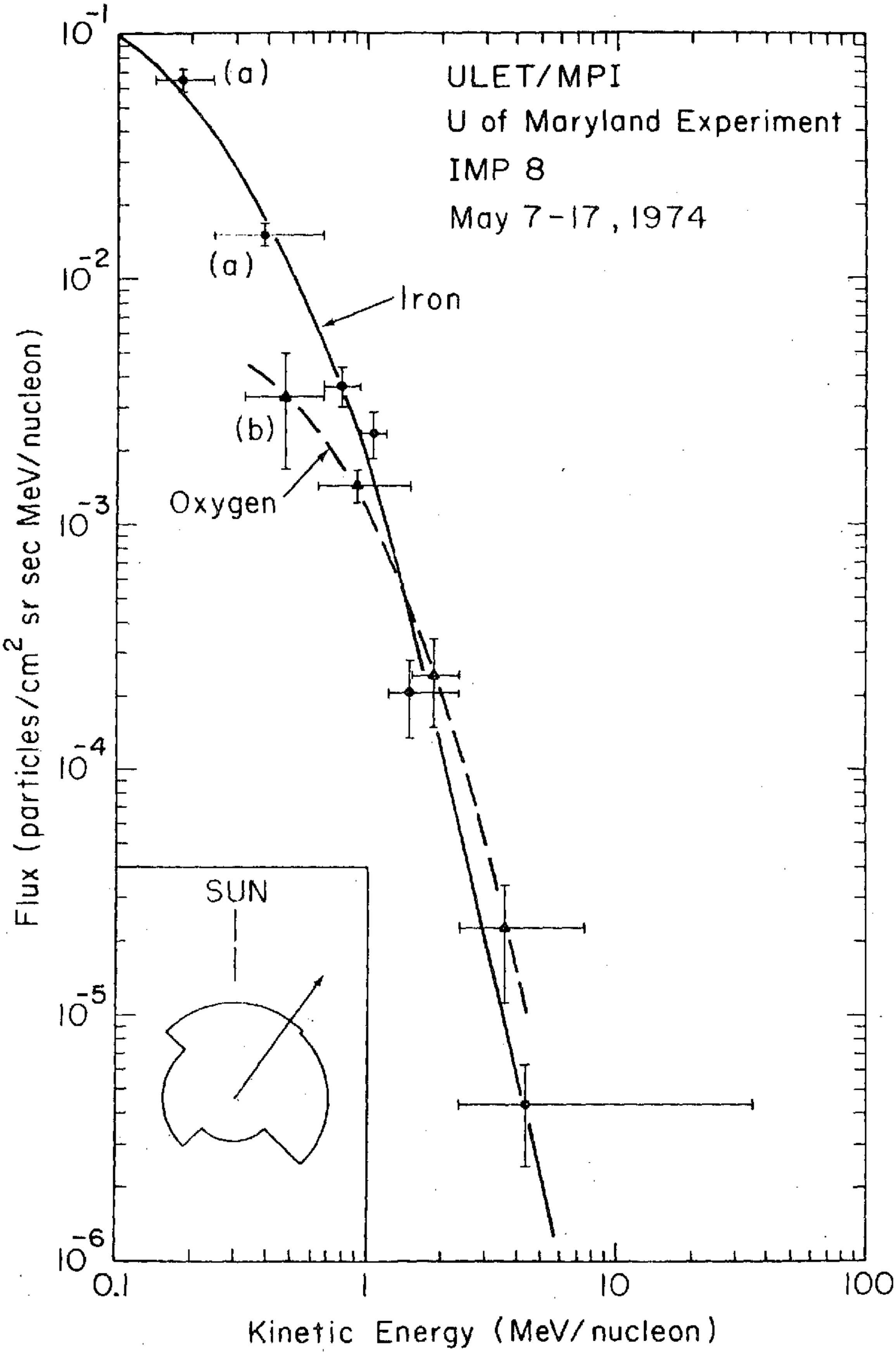
(a)
ULET/MPI
U of Maryland Experiment
IMP 8
DID2Ā COUNTING RATE
Z ≥ 1 NUCLEI
(LOW THRESHOLD)
Z > 2 NUCLEI
(HIGH THRESHOLD)
COUNTS/SECOND
(b)
R ≡ (Z ≥ 1 / Z > 2)
SEV 0 60 120 180 240 300 0 60
DAY 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
MAY 1974

Figure 1



Max Planck Institut / Univ. of Maryland
ULET ΔE vs. E Matrix
ΔE-D1 Channel Number
760
680
600
520
440
360
280
200
E-D2 Channel Number
0
80
160
240
320
400
480
560
640
720
800
Fe
O
C

Figure 2



ULET/MPI
U of Maryland Experiment
IMP 8
May 7-17, 1974
(a)
(a)
Iron
(b)
Oxygen
SUN
Flux (particles/cm2 sr sec MeV/nucleon)
Kinetic Energy (MeV/nucleon)
10-1
10-2
10-3
10-4
10-5
10-6
0.1
1
10
100

Figure 3