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Differential Energy Spectra of Low-Energy (<8.5 MeV per Nucleon) Heavy Cosmic Rays during Solar Quiet Times*

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(Received 19 June 1973)

Carbon, oxygen, and heavier nuclei have been observed below 8 MeV per nucleon during solar quiet times. We find that the C/O abundance ratio is 0.8 ± 0.4, the N/O ratio is 0.4 ± 0.25, and the differential energy spectra below 1 MeV per nucleon have the form $KE^{-4.9 \pm 0.3}$. We infer from this spectral form that most of these particles are likely to be of solar origin. The large errors on the abundance ratio do not allow a decisive answer to the likely origin.

Although extensive satellite and balloon measurements[1-5] have provided abundant information over most of the present solar cycle about the modulated galactic cosmic rays above roughly 15 MeV per nucleon, the extension of observations during solar quiet times below this energy has been limited to protons and α particles.[6,7] The continuous presence of low-energy protons and helium nuclei during solar quiet times was first established by Fan and co-workers[6,8] who also found unexpected upturns in the spectra below about 20 MeV and surprisingly little variation in the flux or spectral shapes during quiet periods from 1964 to 1967. Kinsey's[7] careful analysis of data from the Goddard dE/dx-versus-E experiments on IMP-3 and IMP-4, while revealing a continuous presence of protons and α particles down to 5 MeV per nucleon, showed substantial variability of these low-energy components over the period from May 1967 to August 1968. He concluded that during most of the time period particles below about 10 MeV per nucleon were substantially of solar origin.

In this Letter we present for the first time measurements of low-energy (<8 MeV per nucleon) heavy cosmic rays in interplanetary space during relatively quiet time periods. The data were obtained in October 1972 using a newly designed ultralow energy telescope (ULET) on board the IMP-7 (Explorer 47) satellite which was launched on 22 September 1972 into a nearly circular, 240 000-km apogee orbit. ULET operated successfully until 19 November 1972 when the thin window of the proportional counter ruptured. Because of this only a limited amount of quiet-time data could be collected. In this Letter we restrict ourselves to particles with a nuclear charge $Z \geq 6$.

The detector system[9] makes use of the dE/dx-versus-E method for particle identification and energy determination. To extend to 200 keV per nucleon the energy range over which two-parameter analysis can be made, we use a thin-window proportional counter (D_1) for the "dE/dx" measurement and a conventional, fully depleted, 700-μm-thick surface-barrier silicon detector (D_2) for the "E" determination. A plastic scintillator cylindrical cup anticoincidence detector S, which surrounds D_1 and D_2, is used to reject background and penetrating particles. The *total* thickness of material in front of the solid-state detector is 330 $\mu g/cm^2$, 140 $\mu g/cm^2$ of which is due to the isobutane counter gas. The geometrical factor of the telescope is 1.0 cm^2 sr. To obtain preferential analysis of heavy particle we set the energy threshold at 450 keV for the proportional counter which sets a limit on the upper energy for analysis of carbon and oxygen at 3.5 and 8 MeV per nucleon, respectively. We should note that the ULET telescope scans in the ecliptic plane, thus allowing us to obtain angular-distribution measurements.

Analysis of an event takes place only when the proportional counter D_1 is triggered in coincidence with the solid-state detector D_2 in absence of pulses from the anticoincidence scintillator S. The pulse heights of the D_1 and D_2 signals, together with the value of the azimuth angle of the telescope with respect to the sun-satellite line, are transmitted at a maximum rate of 11.7 events per minute. In addition, we record the counting rate $D_1D_2\bar{S}$, corresponding to the true rate of all events which satisfy the coincidence logic.

Only data accumulated during two time periods when $D_1D_2\bar{S}$ was at its lowest level (0.0013 counts/sec) were used in the present analysis (1 to 11 and 19 to 22 October 1972). In addition, we examined the 120–160 keV proton rate of the University of Maryland experiment[10] on the same spacecraft and excluded times when this rate was significantly above background. The satellite was outside the bow shock for all but 60 of 315 h of the quiet-time periods; hence, these measurements are representative of conditions in interplanetary space. As a further indication of solar quiet conditions we note that the K_p index was generally substantially less than 3 and never exceeded 4.

The counting rate $D_1D_2\bar{S}$ remained constant in each period and had the same average value, within statistical error, in both periods indicating that during these quiet-time periods the particle flux remained steady.

In Fig. 1 we show the D_1-versus-D_2 pulse-height distribution for the 78 events recorded during 315 h. The dashed curves represent the locations of respective tracks for C, O, and Ne which were obtained from an in-flight calibration provided by solar particles during the 29 October 1972 flare.[11,12]

The angular distribution in the ecliptic plane of all events of Fig. 1 is presented in Fig. 2(a). The polar plot, which shows the number of particles in each of eight angular sectors, indicates a maximum in a direction roughly 20° west of the sun-Earth line. From these data we find an anisotropy of $(25 \pm 8)\%$ with the flow of particles directed away from and 22° west of the sun.

The differential energy spectra for carbon and oxygen derived from data of Fig. 1 are given in Fig. 2(b). Error bars are 1 standard deviation limits resulting from counting statistics. We note that the low-energy portions of the C and O spectra have steep negative slopes and may be represented by a dependence on kinetic energy E of the form $dJ/dE = KE^{-4.9\pm0.3}$, and that the oxygen spectrum has a significant hump between 2 and 8 MeV per nucleon. Whether or not a similar feature exists in the carbon spectrum cannot be determined at this time because we do not analyze carbon above 3.5 MeV per nucleon. At energies between 0.35 and 1 MeV per nucleon the average C/O and N/O abundance ratios are 0.8 $\pm$ 0.4 and 0.4 $\pm$ 0.25, respectively. Because particles heavier than oxygen cannot be uniquely identified[11] below 500 keV per nucleon, the flux points labeled "silicon" and "iron" in Fig. 2(b) were computed under the respective assumptions that events above the oxygen track in Fig. 1 are all either silicon or all iron nuclei.

Our data clearly indicate that during solar quiet times a steady flux of very low-energy heavy particles is present in interplanetary space, and that the observed differential energy spectra are qualitatively similar to the quiet-time spectra of protons and helium nuclei reported by Fan

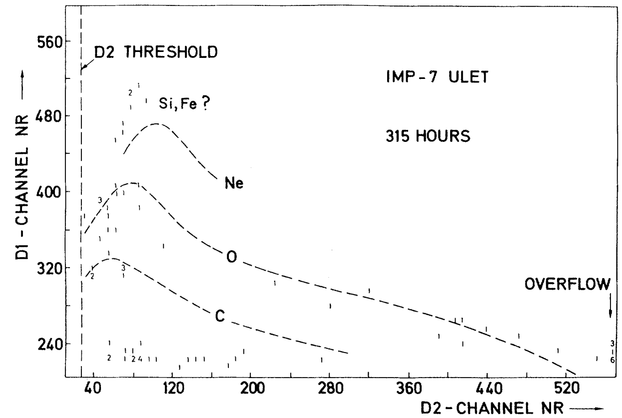

FIG. 1. Two-dimensional dE/dx-versus-E pulse-height–analysis data matrix showing the distribution of events recorded in proportional counter D_1 and solid-state detector D_2 during solar quiet times in October 1972. Dashed curves, track positions for C, O, and Ne derived from solar-particle data of 29 October 1972. Note that below D_2 channel 100 (800 keV per nucleon) one sees an accumulation of C, O, and possibly N as well as particles heavier than oxygen, possibly Si and/or Fe. Around the oxygen track there is a significant reduction of particles between D_2 channels 100 and 380 with a more abundant population starting above channel 380 of 4 MeV per nucleon.

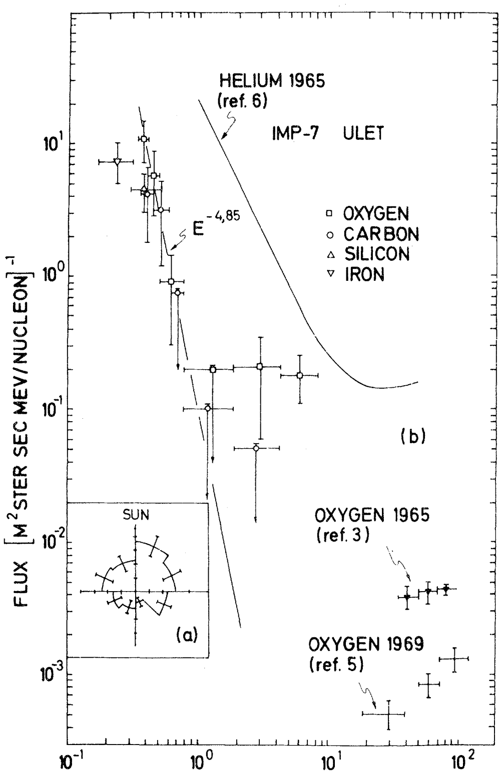

FIG. 2. (a) Polar plot of the pulse-height–analysis data from Fig. 1 representing the angular distribution of the arrival direction of particles in the ecliptic plane. (b) Differential energy spectra of oxygen and carbon nuclei derived from data shown in Fig. 1. Also shown are the flux values for nuclei heavier than oxygen computed under the assumption that (i) all these nuclei are silicon or (ii) all these particles are iron. For comparison we show the low-energy helium spectrum (Ref. 6) as well as the galactic oxygen spectrum during solar minimum in 1965 (Ref. 3) and during 1968 (Ref. 5). Note that the C and O spectra are considerably steeper at low energies than the helium spectrum and that the low-energy upturn for oxygen is at around 1 MeV as opposed to about 20 MeV for helium.

and co-workers[6,8] and Kinsey.[7]

It is not easy from these observations alone to decide on the likely origin of the steady flux of low-energy particles. For energies below about 1 MeV per nucleon we favor a solar origin primarily because of the similarity between the steep spectra reported here and commonly observed spectra of solar flare particles.[11,13] The abundance ratios reported here are consistent within errors with either a galactic or solar origin for these particles.[14] The anisotropy we observe suggests that these nuclei come from the sun. We note, however, that low-energy galactic particles under special conditions can also exhibit anisotropies directed away from the sun.[15]

A surprising feature of our measurements is the increased oxygen flux between 2 and 8.5 MeV per nucleon which is a factor of 40 larger than the maximum galactic cosmic ray flux at 35 MeV per nucleon observed in 1965.[3] We find it difficult to interpret this feature of the spectrum but note that it may be related to similar anomalies found recently in the quiet-time helium spectrum.[16] Further and more extensive observations during quiet times in this energy range will be required before we understand more fully the nature of the observed steady flux of low-energy particles.

We are grateful to the staff of the Department of Physics and Astronomy of the University of Maryland, especially E. Tums, J. Cain, M. Pairel, and R. Sciambi, and to the Max-Planck-Institut für extraterrestrische Physik personnel, in particular P. Laeverenz, E. Künneth, H. Arbinger, F. Eberl, E. Seidenschwang, and H. Waldleben, for their contributions to the management, design, and testing of the IMP-7 instrument. We thank J. Dalton for the development of the computer programs used in data reduction and analysis. We especially acknowledge the efforts of the IMP project staff in integrating our experiment with the IMP-7 satellite and its launching. We have benefited by discussions with J. J. O'Gallagher and L. A. Fisk.

*Research supported in part by the National Aeronautics and Space Administration under Contract No. NAS5-11063, Grant No. NGR 21-002-224, and by the German Government.

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Di-pion System in the Reaction $\pi^- p \to n\pi^0\pi^0$ at 1.6 to 2.4 GeV/c*

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(Received 7 June 1973)

We report results from a high-statistics study of the reaction $\pi^- p \to n\pi^0\pi^0$ between 1.6 and 2.4 GeV/c, in which *all* the final-state particles were detected. The $2\pi^0$ mass spectrum exhibits a marked enhancement in the region of 800 MeV, which is narrower in width than predicted by the recently reported "down-down" solution for $I=0$, S-wave, π-π phase shifts.

In principle, the study of the isoscalar ($I=0$) dipion system below 1-GeV $\pi\pi$ mass is simplified by analyzing the $2\pi^0$ system, from which the effects of the $I=1$ $\rho(765)$ are excluded.[1] However, because of the complexity of detecting and measuring the kinematics of neutral particles, experiments which study reactions such as

$$\pi^- p \to n\pi^0\pi^0 \tag{1}$$

have yielded inconsistent results.[2,3]

We report results from a high-statistics experiment, performed at the Berkeley Bevatron, to study Reaction (1) at beam momenta of 1.59 to 2.39 GeV/c in 0.20-GeV/c intervals.[4] The prominent features of the experiment which minimized the systematic biases are the following:

(1) Identification of the final state by detecting the neutron and *all* the γ rays from the π^0 decays. The kinematic variables of *each* of the particles were measured and an overconstrained (6-constraint, 3-vertex) kinematic fit was made to each event, using a modified version of the Lawrence Berkeley Laboratory bubble-chamber program SQUAW.[5]

(2) A high γ-ray detection efficiency over more than 90% of the entire 4π-sr lab solid angle.

(3) An empirical check of systematic effects by comparing the differential cross sections for the two-body final states, $n\pi^0$ and $n\eta$, measured with and without the neutron detector in the triggering logic.

The experimental setup is the same as described in a previous paper,[6] except for the addition of the neutron detector.[7] This detector consisted of twenty cylindrical plastic scintillation counters, each 8 in. in diameter and 8 in. long, located 15 ft from the target and subtending polar lab angles (θ_n) from 12 to 72 deg with respect to the central beam ray. Each neutron counter had an additional counter mounted in front of it to veto charged particles. The neutron trigger was set to accept neutrons of velocity (β) in the re-