(solitons) and breathers (paired solitons with periodic behavior) superposed on a decaying background of oscillatory structure. The latter corresponds to the continuous spectrum.

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*Work supported by National Science Foundation Grants No. GP32829X and No. GA27727A1.

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# Energy Spectrum of Nuclei with $Z \geqslant 60$ as Evidence for a New Source of Cosmic Rays*

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(Received 23 April 1973)

We have found the energy spectrum of cosmic rays with $Z \geqslant 60$ to be much steeper in the neighborhood of 1 GeV/amu than measured spectra of less massive cosmic rays. The data analysis includes effects due to solar modulation. This low-energy enhancement of high-$Z$ primaries implies sources which either are strongly enriched in very heavy elements or have a $Z$-dependent acceleration mechanism.

In September of 1970, we carried out a balloon flight of a 22-m$^2$ passive detector array in order to study trans-iron cosmic rays. Included in the array were one layer of 200-$\mu$m G-5 nuclear emulsion, one layer of fast-film Cherenkov detectors, and forty sheets of Lexan plastic track detectors. The effective exposure for extremely heavy primaries was $\sim 60$ h at a mean atmospheric depth of $\sim 3.7$ g/cm$^2$. A detailed description of the flight and data analysis has been presented elsewhere.[1]

One of the principal goals of the experiment was to determine for the first time an energy spectrum for cosmic rays with $Z \geqslant 60$. The realization of this goal revealed a spectrum much steeper than those of lighter nucleonic cosmic rays. We consider this feature to be very significant in terms of implications for cosmic-ray sources. All of our 35 events with $Z \geqslant 60$ were found by scanning 17.8 m$^2$ of the emulsion with stereomicroscopes. The nature of the spectrum dictated that we eliminate insofar as possible any uncertainties associated with scanning efficiency. To this end, the entire area was completely rescanned by different observers with the result that no new events were found. In addition, an ammonia scan of every fourth sheet of Lexan produced only one event (slowing $Z \sim 56$, nearly vertical track) that was missed in the original emulsion scan. As a final check, we have compared our integral flux above 1 GeV/amu at the top of the atmosphere with a similar flux derived from a compilation of data from earlier flights at higher geomagnetic cutoff. These two fluxes are completely consistent when solar modulation of the very steep spectrum is taken into account.

The detector stack was thick enough so that a change in etch rate from top to bottom of the contiguous Lexan could be measured for all but four of our events. This allowed the determination of both energy and charge for 31 events and the determination of charge plus an energy lower limit for the remaining four events. The fast-film Cherenkov detectors[2] gave independent, confirming measurements of velocity in four cases. In order to arrive at an energy spectrum at the top of the atmosphere, we have considered the following corrections to our data: (1) energy loss in the residual atmosphere; (2) nuclei with $Z$, $\beta$, and zenith angle such that they pass through the Lexan without producing etchable tracks; (3) the variation with zenith angle of the fraction of nuclei that survive to detector level; (4) the zenith-angle dependence of the detector geometrical factor; and (5) geomagnetic cutoff effects. Application of all of these in appropriate energy bins results in a corrected event total of 48.8 outside of the magnetosphere. These corrected data are shown as integral energy spectrum points in Fig. 1. We have also examined the spectrum for only those particles with $Z > 70$, and, within the poorer statistics, found it to be similar.

We assessed the effects of modulation by applying the results of Gleeson and co-workers.[3] Assumed forms (derived in the case of electrons) for the interstellar differential number densities and an analytic approximation, called the force-field solution, furnish a convenient and accurate means of parametrizing the 1965–1970 modulated near-earth spectra of electrons, protrons, and He with kinetic energies greater than 150 MeV or MeV/amu. Our data are to be compared with the He solution since the $Z/A$ ratios are similar. The appropriate interstellar differential number density is $U \sim (T + 0.5m)^{-\nu}$, where $T$ is kinetic energy per amu, $m$ is 1 amu, and $\nu = 2.5$ for He. The quoted value of $\nu$ and the factor of 0.5 which occurs in $U$ were determined by Gleeson and co-workers to furnish a best fit to the He data available to them. By varying $\nu$, we obtained a maximum-likelihood fit to our $Z \geq 60$ data (in the interval 0.5–2.0 GeV/amu) of the force-field solution and the above form of $U$. The result is $\nu = 4.5^{+1.1}_{-1.0}$ (68% confidence limits). The integral spectrum which follows from this fit and normalization of the associated differential spectrum to the data in the interval 0.5–2.0 GeV/amu is included in Fig. 1 as the curve labeled $\nu = 4.5$. This curve is slightly below the data points because the spectral form predicts fewer events (difference is not statistically significant) above 2.0 GeV/amu than the data indicate. The integral spectrum which corresponds to $\nu = 2.5$ and normalization of the differential spectrum for this smaller index to our data between 0.5 and 2.0 GeV/amu is also shown in Fig. 1. The latter spectrum predicts that the corrected number of events above 2.0 GeV/amu should be 27.4. The corresponding experimental number is $8^{+6.4}_{-4.0}$. This three-standard-deviation ($3\sigma$) difference, in combination with the statistically independent $2\sigma$ difference between our maximum-likelihood value of $\nu(Z \geq 60)$ and $\nu$(He), implies an overall con-

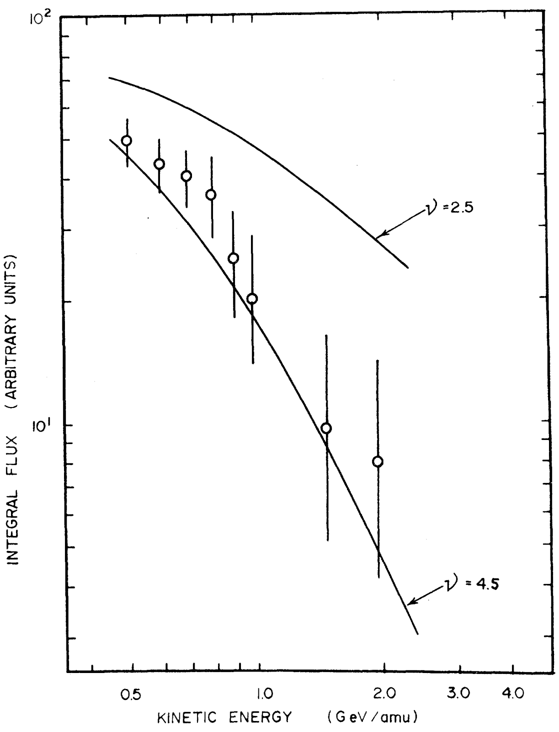

FIG. 1. Integral energy spectrum for cosmic rays with $Z \geq 60$ at the top of the atmosphere. The curves labeled 4.5 and 2.5 refer to interstellar differential number densities and normalizations defined in the text. The latter curve corresponds to He.

fidence level of 99.99% for the existence of a real effect. We believe this is strong evidence that the interstellar energy spectrum for cosmic rays with $Z \geq 60$ and energies below a few GeV/amu is much steeper than spectra of the sub-iron cosmic rays. (Information now available shows no difference in galactic spectra of the elements from He through Fe for energies below ~3 GeV/amu.)

The above conclusion is supported by the results of a Monte Carlo simulation of the experiment. Our program first selected isotropically directed nuclei with $Z \geq 60$ from an r-process charge spectrum and the interstellar differential number density for a given $\nu$. Nuclei so selected were traced from outside the solar system through the modulation process and the atmosphere to detector level, or to loss from the sample if that occurred first. Possible loss mechanisms included (1) modulation, (2) geomagnetic cutoff, (3) interaction in the atmosphere, (4) energy loss in the atmosphere, (5) passage through the Lexan without etchable tracks, and (6) zenith-angle dependence of the effective detector area. Geomagnetic cutoff was computed as a function of both zenith angle and azimuthal angle according to the prescription of Durgaprasad *et al.*[4] Interaction did not imply loss if an eventual interaction product with $Z \geq 60$ reached detector level. We used the modified Rudstam[5] cross sections in these calculations, and included the possibility of multiple interactions before a product reached detector level. We explored the effects of excursions of the altitude profile from our best estimate. Since the balloon was aloft for two weeks we paid particular attention to the assumption that the detectors spent long periods of time at 5–10 g/cm$^2$. This assumption produces apparent spectra flatter than the input spectrum when the samples are treated in exactly the same way (maximum-likelihood calculation) as the experimental data. We also compared Monte Carlo and experimental scatter plots of energy versus zenith angle for etchable events with various charge cuts. In no case did we observe a significant difference during these comparisons. Taken *in toto*, the Monte Carlo results show that the spectrum outside the solar system is, if anything, slightly steeper than indicated by the maximum-likelihood method.

Detailed propagation calculations[1,6] which include ionization losses show that the $Z \geq 60$ energy spectrum at the sources should be slightly steeper than it is just outside the solar system. How do we account for this extremely steep spectrum? During flares the sun emits particles with a steep energy spectrum, and at energies below ~10 MeV/amu the flux of heavy elements (through Fe) is strongly enhanced by an amount that increases with $Z$ and decreases with energy.[7] The mean energy of heavy elements in solar flares is only ~1 to 10 MeV/amu, and the power is inadequate for sunlike stars to account for our observations. What we need are sources which can produce the steep spectrum and which are either (a) more powerful than the sun and preferential emitters of heavy elements at energies up to at least 1 GeV/amu or (b) greatly enriched in heavy elements. Flare stars, which comprise at least 10% of all disc stars, are often suggested[8] as contributors to cosmic rays because they flare up much more frequently (~1 to 10 times per day) and emit many orders of magnitude more power in the optical, radio, and x-ray bands than does the sun. Edwards and McQueen[9] have used observations of the x-ray brightness of the galactic disc to derive an upper limit of $f \times 10^{37}$ erg/sec on the cosmic-ray power from flare stars, where $f$ is the ratio of energies in energetic charged particles and in soft x rays ($\simeq 10\%$ for solar flares). Although the total power requirement for all cosmic rays is ~$10^{39}$ to ~$10^{41}$ erg/sec, flare stars might adequately account for the small fraction of the total power concentrated at energies less than 2 GeV/amu in the $Z > 60$ cosmic rays if the heaviest elements are preferentially emitted by as much at energies of ~1 GeV/amu in flare stars as they appear to be at ~1 MeV/amu in solar flares. One of us (E.K.S.) has measured an abundance ratio of $[Z \gtrsim 50]/\mathrm{He}$ in a solar flare that may be as much as $10^3$ times the ratio in the photosphere.

Another possible source of the $Z > 60$ cosmic rays might be peculiar $A$ stars, whose surfaces are known to be extremely enriched in very heavy elements such as the rare earths, Hg, Au, Pb, and U.[10] These stars have surface magnetic fields of ~$10^3$ to ~$10^4$ G, and one of the explanations of their peculiar composition is that the heavy elements are synthesized in nuclear reactions by energetic neutrons and charged particles produced in flares.

Acceleration of ions in supernova remnants[11] is yet a third type of process which might conceivably account for our observations.

The present results suggest that a new kind of source is responsible for generating cosmic rays with $Z > 60$ at energies below ~2 GeV/amu. Even among the well-studied cosmic rays with $Z \leq 28$ whose spectra are indistinguishable at low energies, small differences in spectral index have recently been detected at energies above ~3 GeV/amu.[12] Ramaty, Balasubrahmanyan, and Ormes have suggested that much of the Fe, which has a spectral index of $-2.1$, may originate in sources different from those responsible for the lighter primaries which have a spectral index of $-2.6$.

Future observations of the energy spectra of the elements between Fe and the $Z > 60$ group could establish whether the enhancement of the flux at energies less than 2 GeV/amu systematically increases with $Z$, as has been observed in solar flares at much lower energies, or abruptly increases at $Z \sim 50$ or 60. We might expect such an abrupt increase if the new sources had a composition enriched in the heaviest elements relative to those sources which yield spectral indices near $-2.6$ at energies below 3 GeV/amu.

We are indebted to Otto Winzen and the staff of Winzen Research, Inc., for launching and recovering the experiment, to Dr. D. E. Hagge and Dr. R. J. Kurz for support in initiating and continuing the experiment, and to Professor J. P. Ostriker and Professor R. M. Kulsrud for useful conversations.

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*Work supported by the National Aeronautic and Space Administration, Grants No. NGR-05-003-376 and No. NGL-44-005-041, and by the U. S. Atomic Energy Comission, Contract No. AT(04-3)-34.

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