[8] A. J. Dessler, J. Geophys. Res. 69, 3913 (1964).

[9] F. C. Michel, Planet. Space Sci. 13, 753 (1965).

[10] F. C. Michel and A. J. Dessler, J. Geophys. Res. 70, 4305 (1965).

[11] F. C. Michel and A. J. Dessler, to be published.

[12] H. I. West, Jr., J. H. Wujeck, J. H. McQuaid, N. C. Jensen, R. G. D'Arcy, Jr., R. W. Hill, and K. M. Bogdanowicz, Lawrence Radiation Laboratory Report No. UCRL-50572, 1969 (unpublished).

[13] A. L. Vampola, to be published.

[14] Sol.-Geophys. Data No. 298, 111 (1969).

[15] Sol.-Geophys. Data No. 302, Part II, 49 (1969).

[16] A. L. Vampola, J. Geophys. Res. 74, 1254 (1969).

[17] G. A. Paulikas, J. B. Blake, and A. L. Vampola, in *Particles and Fields in the Magnetosphere,* edited by B. M. McCormac (D. Reidel Publishing Company, Dordrecht, The Netherlands, 1969), p. 141.

[18] R. P. Lin and K. A. Anderson, Solar Phys. 1, 446 (1967).

[19] S. T. Lindgren, Solar Phys. 5, 382 (1968).

[20] Provided through the courtesy of C. P. Sonett, D. S. Colburn, and J. M. Wilcox.

[21] W. F. G. Swann, Phys. Rev. 44, 224 (1933).

[22] S. M. Krimigis, J. Geophys. Res. 70, 2943 (1965).

[23] R. P. Lin, S. W. Kahler, and E. C. Roelof, Solar Phys. 4, 338 (1968).

[24] J. A. Van Allen and N. F. Ness, J. Geophys. Res. 74, 71 (1969).

[25] J. A. Van Allen, in *Particles and Fields in the Magnetosphere,* edited by B. M. McCormac (D. Reidel Publishing Company, Dordrecht, The Netherlands, 1969), p. 111.

[26] J. A. Van Allen, J. Geophys. Res. 75, 29 (1970).

[27] K. A. Anderson and R. P. Lin, J. Geophys. Res. 74, 3953 (1969).

[28] K. A. Anderson, in *Particles and Fields in the Magnetosphere,* edited by B. M. McCormac (D. Reidel Publishing Company, Dordrecht, The Netherlands, 1969), p. 3.

[29] H. E. Taylor, Trans. Amer. Geophys. Union 51, No. 4, 393 (1970).

[30] M. D. Montgomery and S. Singer, J. Geophys. Res. 74, 2869 (1969).

[31] N. F. Ness, K. W. Behannon, C. S. Cantaro, and C. S. Scearce, J. Geophys. Res. 72, 927 (1967).

[32] F. Mariani and N. F. Ness, J. Geophys. Res. 74, 5633 (1969).

[33] N. F. Ness, C. S. Scearce, and S. C. Cantaro, J. Geophys. Res. 72, 3769 (1967).

[34] D. H. Fairfield, J. Geophys. Res. 73, 6179 (1968).

High-Resolution Measurements of Slowing Cosmic Rays from Fe to U[†]

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We have identified cosmic rays with $Z=40$, 44, 52, 71, 77, 78, and 92 slowing in a balloon-borne stack. The values of Z assigned by both Lexan plastic detectors and nuclear emulsions were the same to within two units. Both low- and high-energy heavy cosmic rays are synthesized in the rapid neutron-capture process.

We have found that nuclei with Z up to 92 are present in the low-energy cosmic radiation. Their abundance relative to Fe is similar to that previously observed at energies above ~1 GeV/amu.[1,2] From their large rate of change of ionization as they slow down in a detector, their atomic number and energy can be much better determined than if they were relativistic. These observations are important as a basis for understanding the origin and propagation of the cosmic rays and as a standard of comparison with results obtained from the analysis of tracks of ancient cosmic rays left in meteorites[3] and moon rocks.[4]

In this Letter we report results from ~1 m^2 or $\frac{1}{4}$ of a stack of 10.2 g/cm^2 thickness consisting of 120 Lexan sheets each of 0.03 g/cm^2 thickness, 9 G-5 nuclear emulsions each of 0.11 g/cm^2 thickness, and 56 steel sheets each of ~0.10 g/cm^2 thickness, interleaved so that a number of transiron cosmic rays with velocities β up to at least 0.75 could be brought to rest with a minimum of nuclear interactions. The stack was flown in September 1969 over Sioux Falls, S. D., for ~40 h at 6 g/cm^2 and again for 40 h at 3 g/cm^2. We reserve for a more comprehensive paper a description of our procedures for chemically processing and scanning the stack. The principle of particle identification with Lexan detectors and its application to low-energy cosmic rays with $14 \leq Z \leq 30$ have been previously described.[5]

Figure 1 shows some of the results of measure-

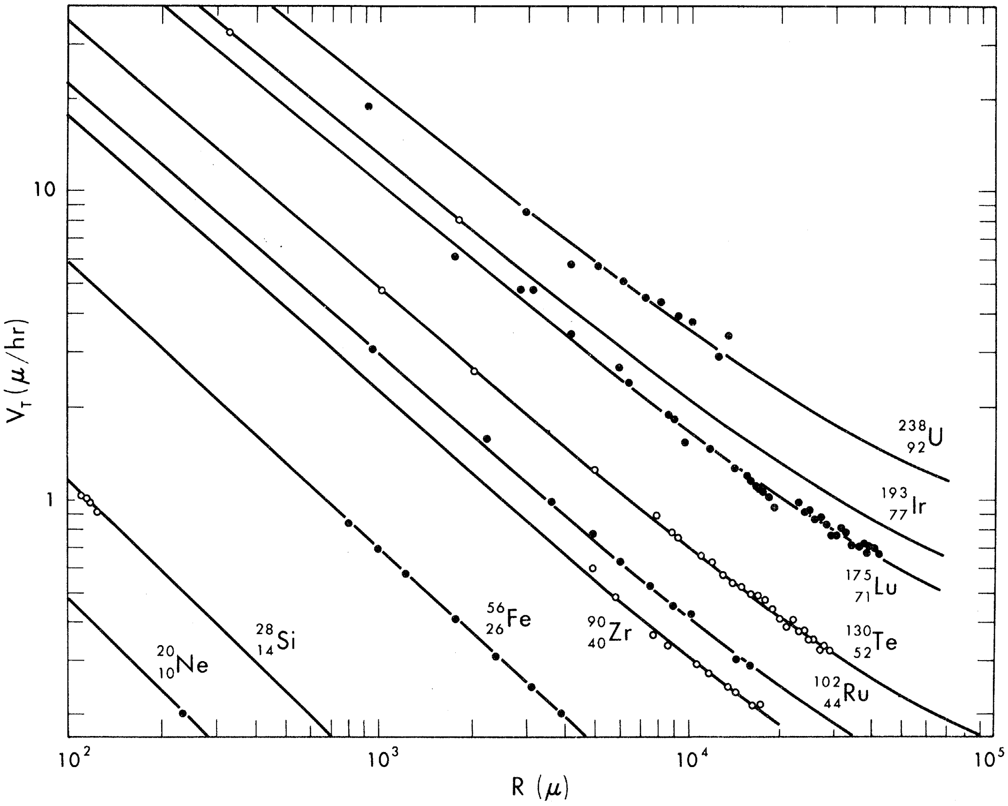

FIG. 1. Track etching rate V_t in Lexan as a function of range R for stopping cosmic rays with charge $Z \geq 26$ and for accelerator ions with $Z = 10$ and 14. The maximum spread in measurements on the Fe tracks is ±5%. The Lexan was etched at (40 ± 0.03)°C in 6.25N NaOH to which 1.8 g/l of blank Lexan had been added as described by Peterson, Ref. 6.

ments in Lexan. Not shown in the figure are data for a highly relativistic nucleus with $Z \approx 78$ that passed through the entire stack without detectable change in ionization rate. In addition to the nuclei with $Z > 28$, we measured about fifty tracks of stopping nuclei in the Fe group, as well as fifteen Si^{28} and ten Ne^{20} tracks obtained by bombarding equivalent Lexan sheets in the Berkeley heavy-ion linear accelerator.

The curves in Fig. 1 were calculated on the basis of three assumptions: (1) The track etching rate V_t depends on Z and β only through the relation

$$V_t = B[J(Z, \beta)]^n. \tag{1}$$

(2) The ionization rate is expressible by the function

$$J(Z, \beta) = 10^{-4}(Z^{*2}/\beta^2) \times \{\ln[\beta^2/(1-\beta^2)] + K - \beta^2 - \delta(\beta)\}, \tag{2}$$

where[7]

$$Z^* = Z[1 - \exp(-130\beta/Z^{2/3})],$$

and $\delta(\beta)$ is a parameter that takes into account the polarization of the medium at a relativistic velocity.[8] (3) The most abundant nuclide above Si is Fe^{56}. At low energy, because of the relatively large abundance of other nuclei in the Fe peak,[5] it is essential for the location of Fe that a large number of tracks of stopping nuclei be measured. The parameters B, n, and K were chosen to minimize the square deviations between calculated and measured cone lengths of the Si^{28} and Fe^{56} nuclei. Then the heavier nuclei were identified on the basis of these parameters. The labeled curves in Fig. 1 were computed with $B = 5.45 \times 10^{-4}$ μm/h, $n = 1.8$, and $K = 62$. The mean deviation of all points from the respective curves is ~3%. Since many data points are obtained for nuclei with $Z \gtrsim 14$, it is clearly possible to determine atomic number with very small error.

Charge assignments from the emulsion tracks, like those from the plastic, are dependent on a calibration from tracks of stopping nuclei of the Fe group. Around the heavy tracks in the emulsion, a number of Fe-group tracks were located and their track densities measured. They were

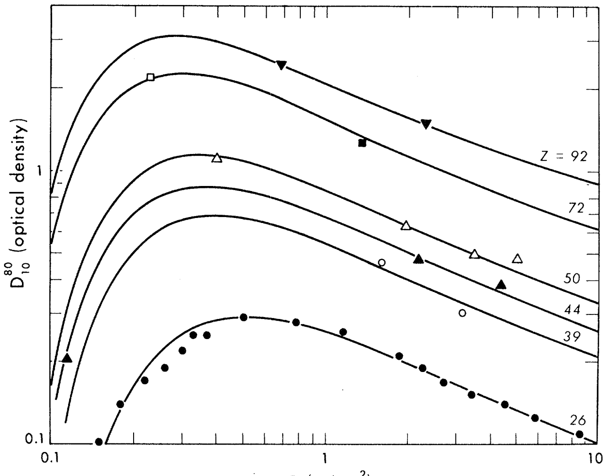

FIG. 2. Optical track density $D_{10}{}^{80}$, in emulsion at 10 μm from the track axis with background taken at 80 μm, as a function of range R for stopping cosmic rays.

then traced through the Lexan sheets and their range and charge determined from the Lexan measurements. The mean difference in charge of an individual nucleus determined by the two methods was ~0.9.

Figure 2 shows the results of emulsion measurements of optical density at 10 μm from the track axis with background taken at 80 μm. Since the sensitivity of each emulsion varies slightly, all measurements were normalized to a standard density.

The curves in Fig. 2 were calculated by combining the density calculations in emulsion at relativistic energies[1] with those valid for lower energies.[9] The resulting expression for a track density D_x at a distance x from the track axis can be expressed as

$$D_x = G(Z^{*2}/x\beta^2)\{1+0.012\ln[\beta^2/(1-\beta^2)]\} \times[1-\Phi(2\sqrt{3}x/R_{\max})]f(Z,\beta,x), \quad (3)$$

where $G=8.23\times10^{-4}$, Φ is the error function, $R_{\max}$ is the range of the δ ray of maximum energy as determined from kinematics, and the function $f(Z,\beta,x)$ represents the ratio of the Mott cross section to the Rutherford cross section for scattering of electrons by point nuclei. The correction $f(Z,\beta,x)$ was kindly supplied to us by Spencer.[10] Although at high energy the correction is small, in the extreme case of a low-energy ($\beta\sim0.2$) U nucleus, f reaches ~1.6.

Table I shows a comparison of the charge assignments in Lexan and emulsion based on the normalization at Fe. The agreement is astonishingly good. We conclude that $\Delta Z/Z\approx3\,\%$ for emulsion and 1% for Lexan. For emulsion it proves appreciably easier to calibrate a stack containing stopping nuclei, with the help of Lexan, than to calibrate a stack exposed only to relativistic nuclei,[2] where Lexan does not provide such assistance.

Table I. Identification of slowing cosmic rays with emulsions and Lexan detectors.

Lexan data		Emulsion data		Energy at stack entry
Z	No. of sheets	Z	No. of sheets	(MeV/amu)
26		26		
40	19	39	3	245
44	19	44	3	315
52	30	50	4	355
71	71	70	1	550
78	104	76	9	8000
92	14	92	2	300
77	2	73	1	57

The main limitation on charge resolution for stopping nuclei, in principle, is the spread in signal for different isotopes of the same element. This spread is largest in the region $Z\sim50$, where the number of stable isotopes of even-Z elements is highest. Here the signals from the most neutron-rich isotope of even element Z, from the stable isotope of the odd element $Z+1$, and from the most neutron-poor isotope of the even element $Z+2$ are very similar. At the cosmic-ray source it seems unlikely that neutron-rich and neutron-poor nuclei will be present in comparable abundance. However, it is likely that at detector level an appreciable proportion of the detected particles are spallation products following nuclear collisions in interstellar space and in the overlying air. An appreciable fraction of these spallation fragments are likely to be very neutron poor. Thus at this stage one cannot be confident of the ratio of neutron-rich to neutron-poor nuclei at the detector level.

We draw the following conclusions: (1) In this study of particles of measured range and velocity, there is even stronger evidence than heretofore of the existence of extremely heavy nuclei extending into the radioactive region beyond $Z=83$. (2) Even with only seven events, an r-process abundance peak at $N=126$, $Z=76$-78, seems to be present for low-energy heavy nuclei. These two events, together with those accumulated at relativistic energies,[1,2] support the conclusion that the heavy cosmic rays have lifetimes less than 10^7 yr, too short for completion of the Pb peak from radioactive decay of transbismuth nuclei. (3) Within our limited statistics, in the energy interval ~0.5 to 1 GeV/amu the abundance ratio of extremely heavy nuclei to the Fe-group nuclei is similar to that at higher energies. (4) Previous assignments of charges to relativistic nuclei by both plastics and emulsions are basically correct, though somewhat uncertain because of uncertainty in velocity. (5) Unless there is an unpredictable mixture of neutron-rich and neutron-poor nuclides, we believe we have demonstrated resolution of $\Delta Z \approx \pm 1$. In future flights with a larger area-time factor we are confident that as statistics accumulate, abundance peaks of high-Z nuclei will be recognizable.

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[‡] Present address: University of California, Berkeley, Calif. 94720.

[1] P. H. Fowler, J. M. Kidd, and R. T. Moses, Proc. Roy. Soc., Ser. A 318, 1 (1970).

[2] P. B. Price, P. H. Fowler, J. M. Kidd, E. J. Kobetich, R. L. Fleischer, and G. E. Nichols, Phys. Rev. D (to be published).

[3] R. L. Fleischer, P. B. Price, R. M. Walker, M. Maurette, and G. Morgan, J. Geophys. Res. 72, 355 (1967).

[4] D. J. Barber, I. Hutcheon, P. B. Price, R. S. Rajan, and H. R. Wenk, Proceedings of Apollo 12 Lunar Science Conference, Houston, Texas, 11-14 January 1971 (to be published).

[5] P. B. Price, R. L. Fleischer, D. D. Peterson, C. O'Ceallaigh, and D. O'Sullivan, Phys. Rev. Lett. 21, 630 (1968).

[6] D. D. Peterson, Rev. Sci. Instrum. 41, 1254 (1970).

[7] The charge assignments are rather insensitive to the precise form of the relation for effective charge, because this relation also enters into the range-energy calculation in a compensating way.

[8] R. M. Sternheimer, Phys. Rev. 103, 511 (1956).

[9] R. Katz and E. J. Kobetich, Phys. Rev. 186, 344 (1969).

[10] L. V. Spencer, private communication.

Investigation of the Forward Structure in Charge-Exchange $K^{*0}(890)$ Production*

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We present an investigation of the reaction $K^-p \to K^{*0}(890)n$ at 3.9 and 4.6 GeV/c incident momenta. The order-of-magnitude increase in statistics with respect to previous analysis allows an investigation of the $K^{*0}(890)$-production properties in the very forward region of momentum transfer and also provides a quantitative test of the absorption-modified one-pion exchange model. This model gives an excellent description of the differential cross sections and decay correlations at the two energies.

Numerous models have been proposed to explain hadron interactions.[1] Each has had limited success with the common feature that data are fitted quite well in certain reactions and poorly in others. In particular, production of particles in the extreme forward direction, whether photoproduced or meson produced, has served as a sensitive test of these theories. Currently a great deal of interest has focused on charge-exchange vector-meson production. Analysis[2] of ρ^0 production via the reaction $\pi^-p \to \rho^0 n$ has been rather thorough; comparable data on $K^{*0}(890)$ production has not been available. The present experiment, which investigates the final state $K^-p \to K^{*0}(890)n$, negates this deficiency with at least an order-of-magnitude increase in data. This, and the fact that it is a neutron and not a proton recoiling, allows us to investigate the structure in the region of momentum transfer to the $K^{*0}(890)$ less than m_π^2. We find no strong forward structure (i.e., steep increases or dips) in the differential cross sections or diagonal elements of the density matrix at both 3.9 and 4.6 GeV/c. In addition, the present statistics allow us to make a quantitative test of the absorption model due to Gottfried and Jackson,[3] which is known to be successful in describing ρ^0 production via pseudoscalar exchange. The excellent agreement between this