Confirmation of the Anomalous Behavior of Energetic Nuclear Fragments

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Cosmic-ray nuclei have been observed to produce 2072 secondary fragments in nuclear interactions detected in nuclear emulsions. These fragments produce 557 further interactions. Previous reports that these secondary nuclei show anomalously short mean free paths near their point of origin are confirmed. This effect can be interpreted as being due to all fragments having cross sections about twice normal for some 10^{-10} sec after creation, or to a small fraction having cross sections an order of magnitude greater than normal.

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The nuclear interactions of the nuclei in the cosmic radiation have been studied for many years. Most of the detailed information on these interactions has come from the exposure of targets of photographic nuclear emulsions on high altitude balloons to the ambient cosmic-ray beam. Such exposures have enabled us to study the characteristics of the individual interactions, to measure the mean free paths as a function of the atomic number, Z, of the energetic nuclei, and to determine the probabilities of producing lighter fragments in such interactions.[1-3] Since the earliest studies, observers have remarked on the occasional events in which a single incoming nucleus has initiated a rapid cascade of interactions, with the secondary fragments producing interactions and fragments that in turn produce more interactions.[4-6] *A priori* calculations of the probability of observing some of these events led to extremely small values and resulted in suggestions that some form of anomalous behavior was occurring. However, more systematic studies led to mixed conclusions. Freier and Waddington[3] were unable to confirm the existence of any statistically significant overproduction of secondary or tertiary interactions, although Judek[7] reported anomalously short mean free paths for some of the nuclear fragments produced in interactions. No plausible physical interpretations were advanced to explain such an effect.

When beams of relativistic heavy nuclei were made available at the Bevalac, it became possible to study these anomalous effects in a systematic manner. Friedlander *et al.*[8] examined the interactions produced by beams of oxygen and iron nuclei having energies of 2.1 and 1.88 GeV/amu, respectively, and found evidence for anomalously short mean free paths of the fragments produced in the interactions of these primary nuclei in a nuclear emulsion target. The magnitude of this effect was such that it was possible to fit the experimental data with a model that assumed that a small fraction of the fragments had a mean free path much less than normal. Various statistical tests place a high confidence level on the significance of the result; however, there is still no acceptable explanation for the effect.

Because of these considerations, we decided that it would be worthwhile to undertake a systematic study of all the cosmic-ray data available in our laboratory and to analyze it in a manner closely similar to that adopted by Friedlander *et al.* in order to see if we could obtain a similar result. As we will show, we do observe a similar effect at a similar level of significance, when we treat the data in this manner, even though our data cover a much wider range of primary energies and have a continuous range of primary charges.

We have used interactions detected by along-the-track scanning in four different stacks of nuclear emulsion exposed near the top of the atmosphere over India, Texas, and Canada. In every case the tracks of primary nuclei were found by scanning along a line near the top edge of the stack for tracks which satisfied various scanning criteria chosen to provide data to measure the charge and energy spectra of the primary cosmic rays. The nuclei in this sample are thus a composite from the various scans with charges ranging from 6 to 28 and energies >400 MeV/amu. Every track found was traced through the emulsions until the nucleus either interacted or left the stack. The charge of each nucleus was determined from a δ-ray count. Each interaction detected was recorded and the characteristics analyzed. All fragments of the primary nucleus with $Z \geqslant 3$ that survived these interactions were followed further until they in turn interacted or left the stack. The measured distances, l_i, traversed

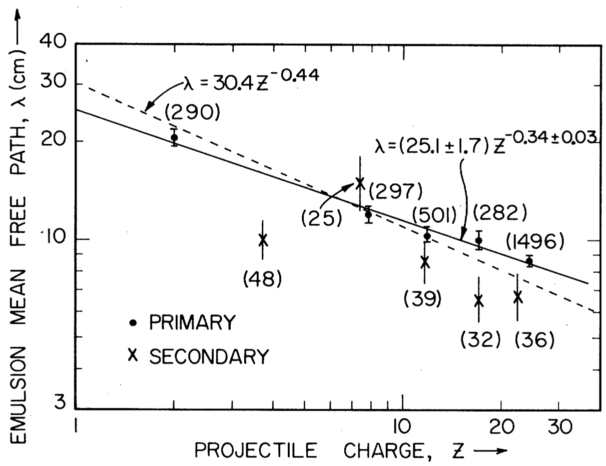

FIG. 1. The observed mean free paths, in centimeters, plotted as a function of the charge, with the numbers of interactions in each group. The best power-law fit to our primary data is shown as a solid line, that reported in Ref. 8 as a dashed line.

by each nucleus, together with the number of interactions observed, N, can then be used to calculate interaction mean free paths, λ:

$$\lambda = \sum_i l_i / N. \qquad (1)$$

In principle such values of λ could be found for each Z; in practice the limited statistics make it necessary to consider λ only for charge groups. In Fig. 1 we show our values for $\lambda(Z)$ as a function of Z for the primary nuclei. We also show a new value obtained in this laboratory for the cosmic-ray primary helium nuclei of 20.7 ± 1.2 cm. Examination of this figure shows that the variations of λ with Z can indeed be represented by a power-law relation of the form

$$\lambda(Z) = \Lambda Z^{-b} \qquad (2)$$

as suggested by Friedlander *et al.*[8] Our data give values of $\Lambda = 25.1 \pm 1.7$ cm and $b = 0.34 \pm 0.03$ which are significantly different from the values of 30.4 ± 1.6 cm and 0.44 ± 0.02 reported previously.[8] The use of either set of values does not significantly change the conclusions that we draw, as we will show in Fig. 4. The difference between these sets of values comes almost entirely from the slightly smaller value of $\lambda(2)$ and slightly larger value of $\lambda(23\text{–}28)$ found by us. Also shown in this figure are values of $\lambda(Z)$ for groups of secondary nuclei determined over just the first centimeter of track from the point of the producing interaction. It can be seen that while the statistics are poor, the trend of the values is

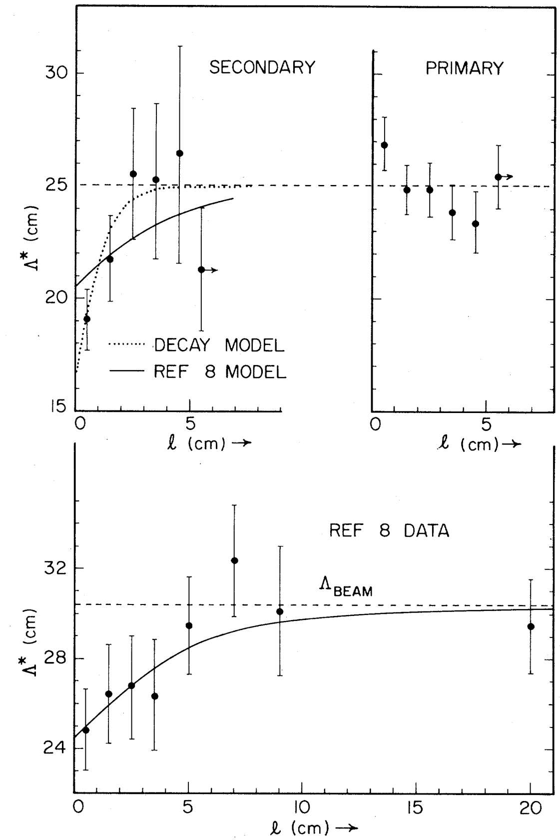

FIG. 2. Plot of Λ^* vs l for the secondary and primary nuclei observed in this work, compared with a similar plot for the secondary nuclei observed in Ref. 8. Also shown are the predictions from a decay model (see text), and from the model of Ref. 8 with our values of Λ and b.

for the mean free paths to be indeed shorter.

Following the analysis of Friedlander *et al.*,[8] we can use Eq. (2) to combine the mean free paths at different Z by determining the charge-reduced mean free path, Λ^*, in each interval of path from

$$\Lambda^* = \sum_i (l_i Z_i^{\,b}) / N. \qquad (3)$$

Λ^* has been calculated for 1-cm intervals of path length both for the primary nuclei from the point of first detection and for the secondary nuclei from the point of formation. The results are shown in Fig. 2, together with the equivalent figure for the secondary nuclei reported by Friedlander *et al.* For our data, the errors shown are solely those due to the counting statistics. Clearly both our secondary fragments, and those reported previously, show a similar decrease in Λ^*

at small distances from the point of creation. The Berkeley group fitted their results with a model that assumed that 6% of the secondary fragments had an anomalous short mean free path of 2.5 cm. Rather than applying this model to our data by adjusting the parameters, we have chosen instead to fit our data with a different phenomenological model discussed below.

An alternative manner of looking at these data is to calculate in each interval of range, the number of interactions that would be expected from the number of nuclei incident on that interval, assuming normal exponential absorption as measured for the primary nuclei, and to compare these predicted numbers with those actually observed. The results of this analysis are shown in Fig. 3, both for the primary and secondary nuclei. Again we observe significantly more secondary interactions in the first two centimeters than could be expected, whereas the primary data are quite consistent with the predictions.

The estimation of the true significance of this observation is not straightforward, because of the non-Gaussian nature of the various distributions. Rather than reproducing the statistical tests used by Friedlander *et al.*,[8] which give us similar results, we have attempted to estimate the significance from a Monte Carlo simulation of the results expected if there were no anomalous effect. In our data there were 1778 secondary nuclei that had at least 1 cm of available range in which to interact. This data file has been used to calculate the distribution in the expected number of interactions in the first centimeter. The result is shown in Fig. 4, where it can be seen that in only one run out of the 2000 made would we have expected as many as the 179 interactions that were observed. The same program can also calculate the distribution of Λ^* expected in the first centimeter, and again shows that in only one run out of 2000 do we get a value as low as that measured here. Hence both representations of the data lead to similar estimates of the significance. If instead we assume an anomalous component of the type proposed by Friedlander *et al.*,[8] then the Λ^* distribution that we obtain is compatible with the measured value of 19.1 cm, having a mean at $\Lambda^* = 21.1 \pm 1.6$ cm.

The agreement between our results and those reported by Friedlander *et al.*[8] enhances our confidence in the reality of this effect. Similarly, the clear difference between the behavior of a coherent set of primary and secondary nuclei that we observe in the first few centimeters shows that the effect is not an artifact of the method of analysis. Finally, it should be noted that even using quite dissimilar Λ and b parameters does not alter the conclusions.[9]

An alternative model for this anomalous effect is to assume that a fraction of the secondary fragments f have an interaction cross section that is initially enhanced by a factor m and revert without nuclear breakup from this anomalous state to the normal in a characteristic distance, t.[10] This

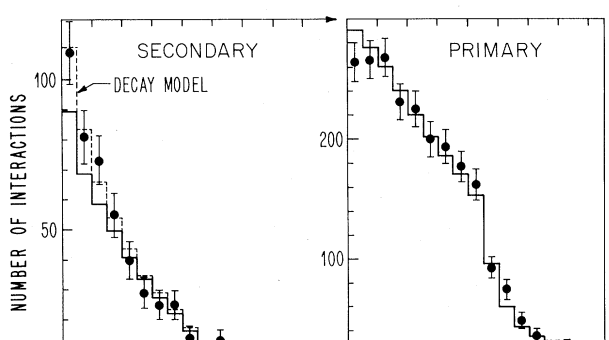

FIG. 3. Plot of the number of interactions observed compared with the number *expected* (see text), both for primary and secondary nuclei. The large break in the primary data at 4.5 cm reflects the geometry of the stacks used. Also shown are the predictions of the decay model.

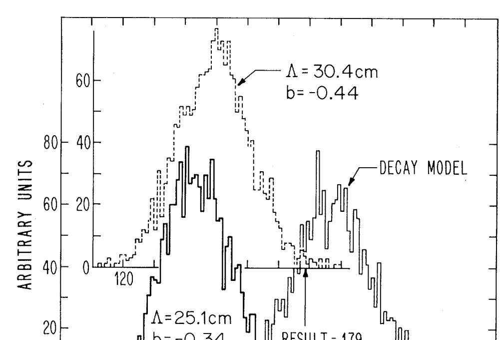

FIG. 4. Predicted number of interactions of secondaries in the first centimeter calculated from a Monte Carlo simulation, compared with the observed number. The upper curve shows the predictions assuming values of Λ and b from Ref. 8, while the "decay model" gives the right-hand distribution.

model can be expressed analytically and is similar to one proposed by Judek.[7] Taking account of the loss of secondary fragments from the targets, anomalous interactions, decay, and normal interactions, allows us to find approximate best fit values of $m = 1.54$ and $t = 0.85$ cm, assuming that $f = 1$. The resulting fit to the data over all intervals is shown in Fig. 3. A Monte Carlo simulation was then used to produce a distribution of the number of interactions expected in the first centimeter, Fig. 4. Our data are thus compatible with the assumption that all fragments are created with an enhanced cross section[11] and only revert to the normal state after a comparatively long period. Such a model would predict that there should be an energy dependence, with t increasing with energy, and it may, or may not, result in an enhanced effect among the later generation fragments such as that reported previously.[8] Our present data, although taken over a range of cutoff rigidities, do not show a clear energy dependence.

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[1]C. J. Waddington, Prog. Nucl. Phys. 8, 1 (1960), and references therein.

[2]M. W. Friedlander, K. A. Neelakantan, S. Tokunaga, G. R. Stevenson, and C. J. Waddington, Philos. Mag. 8, 1691 (1963).

[3]P. S. Freier and C. J. Waddington, Astrophys. Space Sci. 38, 419 (1975).

[4]A. Milone, Nuovo Cimento Suppl. 12, 354 (1954).

[5]H. Yagoda, Bull. Am. Phys. Soc. 2, 64 (1956).

[6]S. Tokunaga, T. Ishii, and K. Nishikawa, Nuovo Cimento 5, 517 (1957).

[7]B. Judek, Can. J. Phys. 50, 2082 (1972), and references therein.

[8]E. M. Friedlander, R. W. Gimpel, H. H. Heckman, Y. J. Karant, B. Judek, and E. Ganssauge, Phys. Rev. Lett. 45, 1084 (1980).

[9]H. B. Barber, P. S. Freier, and C. J. Waddington, in Proceedings of the Seventeenth International Cosmic Ray Conference, Paris, 13–25 July 1981 (to be published).

[10]Time would be more physical but analytically less convenient.

[11]An interaction cross-section enhancement of 1.5 implies a doubling of the geometrical cross section of the fragment when using an emulsion target.