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Publication Date
1981

Peer reviewed

LBL-12120

CONF-8010154--3

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

MASTER

Presented at the Workshop on Future Relativistic Heavy Ion Experiments, Gesellschaft für Schwerionenforschung, Darmstadt, W. Germany, October 7-10, 1980

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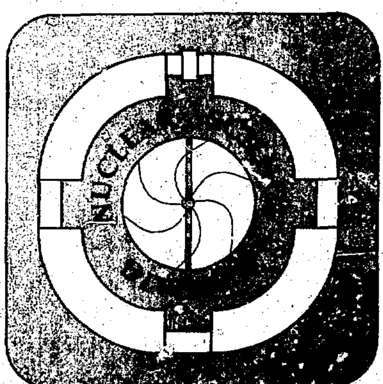
January 1981



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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EVIDENCE FOR ANOMALOUS NUCLEI AMONG RELATIVISTIC PROJECTILE FRAGMENTS AT BEVALAC ENERGIES

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When I arrived this afternoon to register for the Workshop, I was immediately approached by Reinhard Stock who asked me to give a resumé of the LBL-NRC Bevalac experiment on the "short-mean-free path" phenomenon.

"I'd be glad to ... which day and how much time?"

"Today, in a few hours from now, in fact, at the end of Bondorf's session... We can allow about 15-20 minutes, including discussion," Reinhard informed me.

After the appropriate pause for silence, followed by a rapid selection of a few transparencies (even the making of one), I find myself inescapably behind the lecturn.

First, let me introduce you to members of the LBL-NRC collaboration. In Fig. 1 I have reproduced the list of authors for our recent Physical Review Letter. [A reprint of this letter is given in the appendix which supplies the reader with the finer details of the experiment.]

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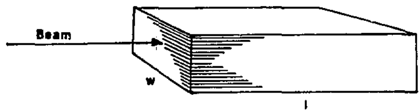
Fig. 1

Barbara Judek, NRC, carried out her part of the experiment using ^{16}O projectiles at 2.1 GeV/nucleon, whereas at LBL, Erwin Friedlander, Eberhard Ganssauge, Roy Gimpel, Yasha Karant and I used ^{56}Fe at 1.88 GeV/nucleon. The analysis of the data from each of the independent experiments was carried out at Berkeley. The results of both experiments were compatible with each other, hence combined to improve the statistical accuracy of the overall result.

Figure 2 shows a schematic diagram of the configuration of the emulsion stacks used in the experiment. The stacks were fabricated with ILFORD G.5, 600-μm-thick pellicles. Stack I (NRC) contained 50 pellicles, 15 x 30 cm^2; stack II (LBL) 41 pellicles, 7.5 x 12 cm^2. The stacks were exposed to the Bevalac beams normal to the face of entry to the stack, parallel to the emulsion surfaces. Scanning of the pellicles involved picking up the entering beam nuclei within a few mm from the entrance edge, following along each individual track until it either interacted or left the stack. All relativistic tracks $Z \geqslant 3$ emitted from the primary, secondary, tertiary, ... generations within a 100-mrad forward cone were followed until the topology of each event was completely determined.



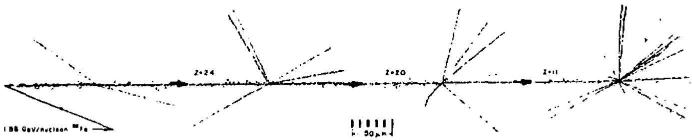
ILFORD G.5 EMULSION

600μm pellicles

Lab	Beam	Energy (AGeV)	l (cm)	w (cm)	# of pellicles
NRC	^{16}O	2.1	30	15	50
LBL	^{56}Fe	1.88	12	7.5	41

Fig. 2

Figure 3 is a microprojection drawing of an event of the type we observe in the experiment. Irrespective of what Howell Pugh told you this afternoon when he showed this same event, this is not our most impressive example of a linear chain of successive interactions--although admittedly it is not all that common either. In this event, an ^{56}Fe initiates a sequence of projectile fragmentations for which the charge of the leading fragment for each generation, second through fourth, is Z = 24, 20 and 11; the fourth generation fragment gives rise to a collision where no projectile fragment $Z \geq 3$ is produced, thus terminating the event for this experiment. Actually, the longest chain of this type was observed by Barbara Judek, where the sequence of fragmentations was $^{16}O \rightarrow N \rightarrow C \rightarrow B \rightarrow B \rightarrow B \rightarrow Be \rightarrow He$ (out stack), i.e., a 7-generation event.



Event 33/1

XBL 794-9277

Fig. 3

The results of our experiment are based on a total of 1460 interactions over all generations. For each projectile fragment (PF) we measured its charge Z, its potential path T available for interaction in the detector, and the distance x to the interaction point if it interacted.

The principal aspects of our experiment I wish to present are concerned with the distributions of the interaction distances x̲ and the mean-free-path (mfp) given by:

$$\lambda_Z^* = \Sigma S_i / N_Z \quad . \tag{1}$$

The quantity ΣS_i is the total path length followed for both interacting on noninteracting PFs of charge Z that leads to N_Z interactions. I remind you that the estimate λ_Z^* by this method is independent of the size of the detector.

Because our title uses the word "anomalous", we imply we know what "normal" is. Normal behavior, by definition, is that exhibited by primary beam nuclei; incidentally, this behavior is well approximated by known nuclear physics. An important result of our measurements of λ of beam nuclei, $2 \leqslant Z \leqslant 26$ is that they can be parameterized as

$$\lambda_Z = \Lambda Z^{-b} \quad , \tag{2}$$

where the Λ for beam nuclei Λ_{beam} = 30.4 ± 1.6 cm and b = 0.44 ± 0.02. By use of Eq. (2), we are able to combine all λ_Z^*, Eq. (1), to obtain an estimate of the parameter Λ, given by the expression

$$\Lambda^* = \sum_Z \lambda_Z^* N_Z Z^b / \sum_Z N_Z \quad . \tag{3}$$

Equations (1-3) completely describe the basic arithmetic of the experiment.

Now, let's look at some results.

Figure 4 shows two distributions for the interaction distances x̲ for projectile fragments (all generations) with potential paths $T \geqslant T_1$ = 3 and 9 cm. The solid histogram presents the data of the experiment, the dashed histogram is the prediction from Λ_{beam}. An excess of events over that predicted is evident at small x̲, particularly for the case T_1 = 3 cm. For T_1 = 9 cm, the number of events also shows an excess at small x̲, but, within the errors of the data, becomes "normal" at distances $\underline{x} \gtrsim 4$-5 cm. Similar behavior is also seen in Fig. 5, where the mean-free-path parameter Λ^* is plotted as a *function of the* distance D from the origin of emission of the projectile fragment. For the first few centimeters Λ^* is low, becoming compatible with Λ^*_{beam}

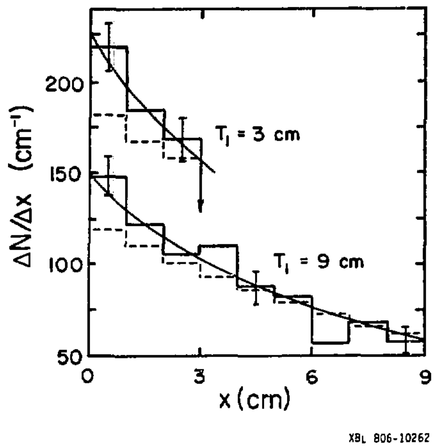


Fig. 4

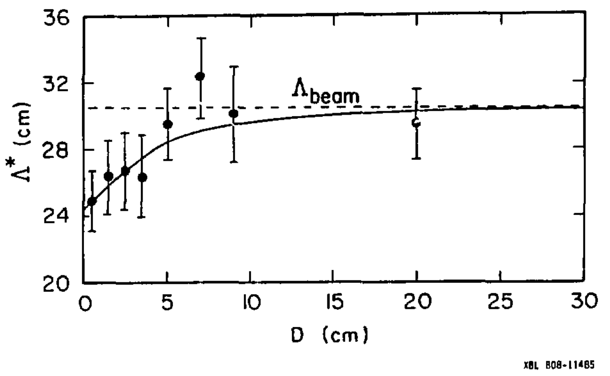


Fig. 5

for $D \gtrsim 5$ cm. The differences between the observations and the expectations based on beam calibrations illustrated in Figs. 4 and 5 exceed 3-3.4 standard deviations.

To gain some insight as to the nature of this excess in the number of interactions that PFs undergo at small distances we make the following assumption: In addition to normal nuclei, there is an "anomalous" component of PFs produced with probability a, having a constant "short" mfp, λ_a. Estimates of a and λ_a by χ^2-minimization from the data give $a^* \cong 6\%$, and $\lambda_a^* \cong 2.5$ cm. (For comparison: $\lambda_{^{56}Fe} \approx 7.5$ cm, $\lambda_{^{4}He} \approx 22$ cm.) Calculations based on this admixture of projectile fragments with the above parameters are shown as solid curves in Figs. 4 and 5; they are clearly compatible with the experimental data.

Let's take the characteristic distance $\lambda_a^* = 2.5$ cm as physically significant and ask the following question, first posed by Erwin Friedlander: Does the mfp of a tertiary PF depend on the interaction distance x of the secondary PF that produces it? Specifically, do the Λ^*s for tertiary PFs that originate from secondary interactions at distances i) $x_{sec} \leq 2.5$ cm and ii) $x_{sec} > 2.5$ cm differ? From Fig. 6 we learn that, with good probability, the answer is, amazingly, yes.

Plotted in Fig. 6 are the likelihood curves of Λ^* for tertiary PFs when x_{sec} ≶ 2.5 cm. If we examine first the case where the production sites of the tertiary fragments are $x_{sec} > 2.5$ cm from the primary beam interaction we see that the likelihood curve is broad, with a maximum at $\Lambda^*(>2.5) \approx 30$ cm, consistent with Λ^*_{beam}. The likelihood curve for $x_{sec} \leq 2.5$ cm, on the other hand, is significantly narrower and has a maximum of $\Lambda^*(\leq 2.5) \approx 12$ cm. Note that at 30 cm the likelihood function for $\Lambda^*(\leq 2.5)$ is $\approx 10^{-2}$ of that for $\Lambda^*(>2.5)$. This result demonstrates

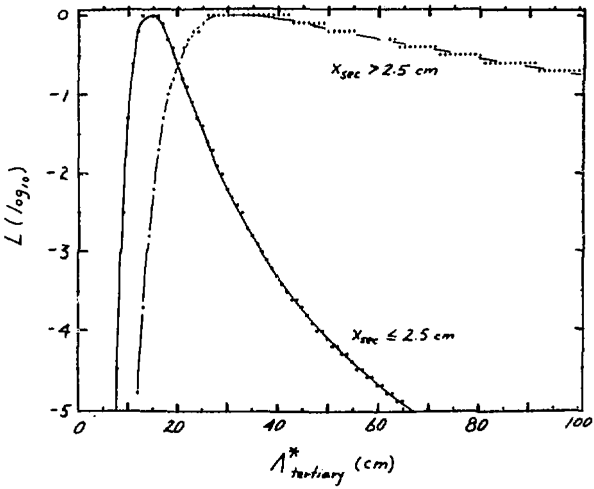


Fig. 6

that there is a correlation between the interaction distance x of the secondary PF and the mfp of the resultant tertiary PF. This property can only arise if anomalous PFs possess "memory"; that is, the "anomalous" character of projectile fragments tends to persist in subsequent fragmentation reactions. The consequence of this observation is the prediction that the value of the mfp estimated from tertiary and later generations of PFs should be less than that estimated from secondary PFs. This, in fact, is observed, with λ_Z^* for the tertiary and higher generation PFs showing an mfp shorter by ~15% than for secondary PFs.

The salient results of the experiment are as follows:

a) Over the first several centimeters after emerging from an interaction, PFs are observed to have shorter mfps than those obtained from (normal) beam nuclei of the same charge Z; b) at distances greater than $\approx$ 5 cm, the mfps are compatible with being "normal"; c) under the assumption that there are two populations of PFs, normal and anomalous, a best fit to the data is obtained when $\sim$6% of the PFs have an anomalously short mfp $\lambda_a \approx 2.5$ cm ($\sim$94% of the PFs behave normally); and d) the anomalous property of PFs persists (shows "memory") in subsequent fragmentation reactions.

Appendix

Evidence for Anomalous Nuclei among Relativistic Projectile Fragments from Heavy-Ion Collisions at 2 GeV/Nucleon

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Two independent emulsion experiments using Bevalac beams of ^{16}O and ^{56}Fe at ~2 GeV/nucleon find with >99.7% confidence that the reaction mean-free paths of projectile fragments, $3 \leq Z \leq 26$, are shorter for a few centimeters after their emission than at larger distances, or than predicted from experiments on beam nuclei. This effect, which is enhanced in later generations of fragments, can be interpreted by the relatively rare occurrence of fragments that interact with an unexpectedly large cross section.

PACS numbers: 25.70.Hi, 25.70.Bc

Evidence for anomalously short reaction mean free paths (mfp) of projectile fragments (PF) from high-energy heavy-ion collisions has been persistently reported in cosmic-ray studies[1-7] since 1954; however, because of limited statistics, these results have not gained recognition. To overcome this limitation, we have performed two independent similar experiments with beams from the Lawrence Berkeley Laboratory Bevalac.

Our results, based upon 1460 events, can be summarized as follows: (a) Over the first few centimeters after emerging from a nuclear interaction (~10 gm/cm^2 of matter traversed or ~10^{-11} s proper time) the PF's exhibit significantly shorter mfp's than those derived from "normal" beams of the same charge Z; (b) at larger distances from the emission point, the mfp's revert to "normality" in the above sense; (c) the data are incompatible with a homogeneous lowering of the mfp and require the presence among PF's of at least one component with an unexpectedly high reaction cross section.

Two stacks of Ilford G5 nuclear research emulsion pellicles, 600 μm thick, were exposed to relativistic heavy-ion beams parallel to the emulsion surfaces (I, 2.1-GeV/nucleon ^{16}O; II, 1.88-GeV/nucleon ^{56}Fe). Stack I, pellicle size 15×30 cm^2, was scanned and measured[8] at National Research Council of Canada; stack II, 7.5×12 cm^2, at Lawrence Berkeley Laboratory.

Interactions, defined as events showing emission of at least one target- or projectile-related track, were collected by scanning along the tracks of beam nuclei. Relativistic tracks of charge $Z \geq 3$ emitted from all generations of the extra-nuclear cascade within a 100-mrad forward cone were followed until they either interacted or left the stack. By extra-nuclear cascade we mean the sequence of nuclear collisions induced by the beam nucleus and the products of successive fragmentations. Events have been observed up to the seventh generation in stack I, and up to the fifth in stack II. For each PF we measured its charge Z to a precision of one charge unit, the distance T available for interaction in the detector (the potential path) and, if it interacted, the distance x to the interaction point. The high spatial resolution of emulsion enabled us to discriminate between centers of successive interactions and/or adjacent tracks to distances of the order of 1 μm. For $x < 200$ μm this allowed unambiguous assignment of interactions to individual PF's and makes nuclear emulsion an ideal detector for this investigation.

For each PF the energy loss up to the point of its interaction was computed assuming it was produced at the rapidity of its parent projectile.[9] We calculate that the energy loss due to nuclear interactions and ionization results in a mean energy ~1.5 GeV/nucleon and would not have degraded any PF below about 1 GeV/nucleon. Multiple-scattering measurements in stack I, as well as the topologies of our events, were fully consistent with the above conclusions.

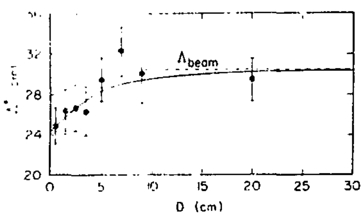

FIG. 1. Estimates Λ^* for the parameter Λ [Eq. (2)] at different distances D from the origins of PF's: full circles, experiment; dashed line, prediction from Λ_{beam}; solid line, prediction assuming a 6% admixture of PF's with $\lambda_a = 2.5$ cm.

In an inhomogeneous target-detector-like emulsion one measures reaction mfp's rather than cross sections. For a homogeneous beam of nuclei *of charge Z* the mfp, denoted by $\lambda = \lambda_Z$, is defined via the distribution of interaction distances x:

$$f(x)dx = \exp(-x/\lambda)dx/\lambda. \qquad (1)$$

A maximum-likelihood estimate λ^* is obtained for λ^* from the quotient $\lambda^* = S/N$, where S is the total length of both interacting and noninteracting tracks followed until N interactions have been observed. This estimate is therefore independent of stack size or of the location of the track segment in which λ is measured. The relative rms deviation of λ^* is rigorously $N^{-1/2}$ but, unless N is very large (which is not the case for our samples *at fixed Z*), the estimate distributions are highly skewed and Gaussian confidence limits do not apply.

To pool information from many samples, each at fixed Z, we use the fact that in the range 0.2–2.1 GeV/nucleon, the λ of beam nuclei, $2 \leq Z \leq 26$, can be parametrized as:

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

where $\Lambda = \Lambda_{beam} = 30.4 \pm 1.6$ cm and $b = 0.44 \pm 0.02$.[10,11] This parametrization is consistent with the trend of mfp's computed from cross sections based on geometrical-overlap models.[12] Given Eq. (1), one is able to show that the quantity $2N\lambda_Z^*/\lambda_Z$ is distributed like χ^2 with $2N$ degrees of freedom. From the additivity of χ^2 variables it follows that a maximum-likelihood estimate for Λ^* for Λ, *at fixed b*, is provided by the

TABLE I. Mean estimates for the mean free path λ and the parameter Λ [Eq. (2)] at different distances D from the origins of PF's for grouped charges. Expected values assuming Eq. (2) are given in the last column. For $Z = 3-26$, we have $\Lambda^*(D \leq 2.5\ \text{cm}) = 25.0 \pm 1.1$ cm, $\Lambda^*(D > 2.5\ \text{cm}) = 30.0 \pm 1.0$ cm, and $\langle\Lambda\rangle = 30.4$ cm.

Z	$\bar{\lambda}^*(D \leq 2.5$ cm) (cm)	$\bar{\lambda}^*(D > 2.5$ cm) (cm)	$\langle\lambda\rangle$ (cm)
3–8	12.4 ± 0.7	14.0 ± 0.5	14.6
9–16	8.3 ± 0.7	11.6 ± 1.0	10.6
17–26	6.0 ± 0.6	8.0 ± 0.8	8.4

expression

$$\Lambda^* = \sum_Z \lambda_Z^* N_Z Z^b / \sum_Z N_Z. \qquad (3)$$

This estimate is *also* independent of detector size. We computed Λ^* for a number of independent segments after the point of emission of a PF and obtained the dependence of Λ^* on the distance D after emission, presented in Fig. 1. Note the low values of Λ^* in the first few centimeters; beyond $D \simeq 5$ cm, Λ^* is compatible with Λ_{beam}; for $D \leq 2.5$ and > 2.5 cm, the values of Λ^* (displayed at the bottom of Table I) differ by 3.4 standard deviations.

In order to substantiate this conclusion in a way independent of the validity of Eq. (2) we perform the following test. For each charge Z of the PF's and for each primary beam we obtain a pair of λ^* values, say λ_1^* and λ_2^* for $D \leq 2.5$ cm. *A priori*, we expect only small deviations of λ^* from λ_{beam} to arise from the different cross sections of isotopes off the line of stability and long-lived nuclear excited states because of the dominant contribution of the AgBr component in emulsion to the (geometric) reaction cross section. To each such pair we assign a number $P_D(<F_D)$ which is the integral probability of the ratio $F_D \equiv \lambda_1^*/\lambda_2^*$. (This ratio propitiously obeys the F, or variance-ratio, distribution provided that λ_1^* and λ_2^* represent samplings from a population with a practically constant λ.) As such, the distribution of P_D values should be uniform between 0 and 1, and the simplest test is to check whether the mean $\overline{P}_D$ differs or not from its expected value $\langle P_D \rangle = \frac{1}{2}$. The distribution of P_D values from our thirty λ_1^*/λ_2^* ratios (5 charges from stack I, 24 from stack II) is shown in Fig. 2(a). We find $\overline{P} = 0.323 \pm 0.053$, which is 3.4 standard deviations away from $\frac{1}{2}$, a difference exceeded with a probability of 3×10^{-4}. *This result is independent of any assumption about the functional dependence of λ upon Z, and indicates that within the first few centimeters after* PF *emission, λ is significantly less than at larger distances.* We display in Table I charge-grouped estimates for λ which illustrate that this effect is present in all charges of PF's.

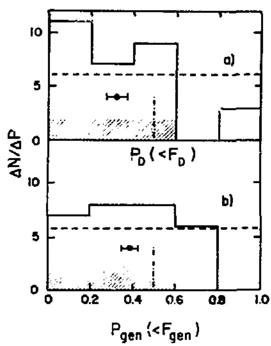

FIG. 2. Experimental frequency distribution of (a) $P_D(<F_D)$ and (b) $P_{gen}(<F_{gen})$; see text; the dashed line is the expected uniform distribution; the points with error bars are the experimental means $\overline{P}$. to be compared to their expectation $\langle P \rangle = \frac{1}{2}$; the shaded area refers to the results from stack I (^{16}O primaries).

We present in Fig. 3 two distributions of interaction distances x for events with potential paths $T \geq T_1 = 3$ and 9 cm, respectively; an excess of events over the number predicted from Eq. (2) is evident at small x, particularly for the case $T_1 = 3$ cm where it amounts to 3 standard deviations. Let us assume as a first approximation that, in addition to normal nuclei, there is a fraction α of "anomalous" PF's with a constant "short" mfp $\lambda_\alpha << \lambda$, leaving a fraction $1-\alpha$ that obeys Eq. (2), as confirmed by our observations at large distances after emission. This assumption inherently predicts an excess of PF interactions at small x. We have made estimates of α and λ_α by χ^2 minimization from these data and obtain $\alpha^* \cong 6\%$, $\lambda_\alpha^* \cong 2.5$ cm.[13] Predictions based on the assumption of an admixture with the above parameters are drawn as solid curves in Figs. 1 and 3; they

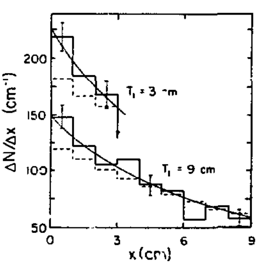

FIG. 3. Distributions of interaction distances x for events with potential paths $T \geq T_1$; dashed and solid lines have the same meanings as in Fig. 1.

obviously account well for the observations.

Comparison of the mfp's estimated from the *secondary* PF's and those of *later generations* in the extranuclear cascade shows an mfp shorter by ~15% in the third and later generations. The distribution of $P_{gen}(<F_{gen})$ (defined in analogy with P_D and F_D, $\lambda_1{}^*$ referring to the third and later generations, and $\lambda_2{}^*$ to the second generation) is shown in Fig. 2(b). The probability for this distribution to be uniform between 0 and 1 is ~8 $\times 10^{-3}$.

The anomalous (short-mfp) component needed to explain the foregoing results would naturally lower the expected value of F_{gen} (hence of $\bar{P}_{gen}$), because of the shorter average potential paths available in the third generation. However, if we correct for this effect, *assuming the different generations to be uncorrelated* (i.e., assume the same value of a at emission in all generations), we find that it would lower F_{gen} by only about 2%; nonetheless, the corrected P_{gen} distribution remains nonuniform with better than 99% confidence. This result suggests at least partial persistence of the high cross section in the fragmentation process of the anomalous PF's.

We are not aware of explanations within the framework of conventional nuclear physics for the results of this experiment. The direct and standard methods of observation, measurement, and data reduction employed, virtually eliminate all conceivable scanning biases. The diminution in the measured mfp of PF's at distances a few centimeters from their emission points strongly excludes explanations related to isotopic effects, whereas the normal pattern of target fragmentation does so for mesonic atoms, hypernuclear decay in flight, etc.[14]

Under preparation is a more comprehensive report,[15] including a detailed discussion of the systematics, PF's of $Z=2$, additional details of the interrelationship between the second and third generations of PF's in the extranuclear cascade, and the dependences of the topologies of PF interactions on the distance x. Experiments are in progress to elucidate possible reaction mechanisms characteristic of the short-mfp component.

The authors wish to acknowledge the contribution to the experiment by the Bevalac operations staff. The technical assistance given by H. Dykman, J. Hodges, R. Smith, M. E. Stott, G. Williams, and H. Yee is much appreciated. We have benefited much from the many discussions with our colleagues within, and beyond, our laboratories.

This research was supported in part by the Nuclear Physics Division of the U. S. Department of Energy under Contract No. W-7405-ENG-78 and by the Deutsch Forschungsgemeinschaft, Federal Republic of Germany.

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[11]To account for possible differences in scanning efficiencies, in keeping with the independence of the experiments, we actually use two fits to primary beams. For National Research Council of Canada, $\Lambda_{beam}=28.9 \pm 2.5$ cm, $b=0.43\pm 0.04$; for Lawrence Berkeley Laboratory, $\Lambda_{beam}=32.2\pm 2.1$ cm, $b=0.44\pm 0.03$.

[12]P. J. Karol, Phys. Rev. C 11, 1203 (1975).

[13]If we *assume* that Eq. (2) can be extrapolated to $\lambda_a \cong 2.5$ cm, this corresponds to a preposterous $Z\cong 300$.

[14]E.g., to eliminate hypernuclear decay, we note that (a) we observe no relative excess of events characteristic of hypernuclear decay in flight, namely, events consisting of relativistic tracks only and, moreover, (b) the measured hypernucleus production cross section is orders of magnitude too small [K. J. Nield *et al.*, Phys. Rev. C 13, 1263 (1976)].

[15]See Lawrence Berkeley Laboratory Report No. 10573 (unpublished), for a more comprehensive version of this paper.