angular momentum. Thus, the alignment decreases and the anisotropy plummets.

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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.

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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 $x \gtrsim 200$ 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.

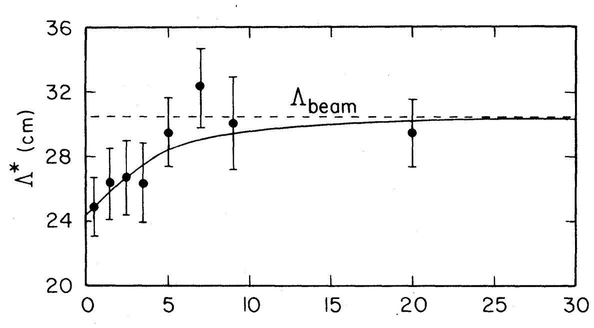

FIG. 1. Estimates Λ^* for the parameter Λ [Eq. (2)] at different distances D from the origins of PF's: full circles, experiment; dashed line, prediction from Λ_{beam}; solid line, prediction assuming a 6% admixture of PF's with $\lambda_a = 2.5$ cm.

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:

$$f(x)dx = \exp(-x/\lambda)dx/\lambda. \tag{1}$$

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:

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

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

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

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 $D \cong 5$ cm, Λ^* is compatible with Λ_{beam}; for $D \leqslant 2.5$ 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 $\lambda_1{}^*$ and $\lambda_2{}^*$ for $D \lesssim 2.5$ 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 $\lambda_1{}^*$ and $\lambda_2{}^*$ 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 $\lambda_1{}^*/\lambda_2{}^*$ ratios (5 charges from stack I, 24 from stack II) is shown in Fig. 2(a). We find $P = 0.323 \pm 0.053$, 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.

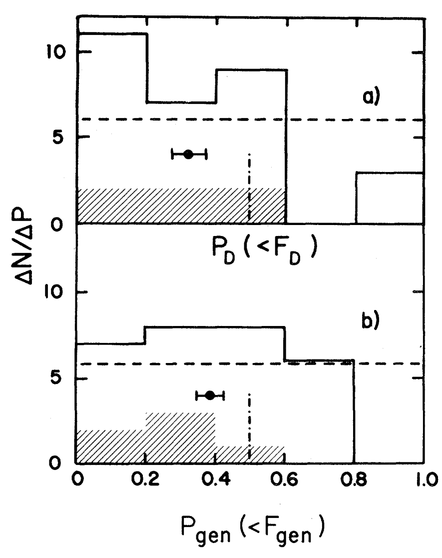

FIG. 2. Experimental frequency distribution of (a) $P_D (< F_D)$ and (b) $P_{\mathrm{gen}} (< F_{\mathrm{gen}})$; see text; the dashed line is the expected uniform distribution; the points with error bars are the experimental means $\overline{P}$, to be compared to their expectation $\langle P \rangle = \frac{1}{2}$; 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 $T \geqslant T_1 = 3$ 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 a of "anomalous" PF's with a constant "short" mfp $\lambda_a \ll \lambda$, leaving a fraction $1 - a$ 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 a and λ_a by χ^2 minimization from these data and obtain $a^* \cong 6\%$, $\lambda_a{}^* \cong 2.5$ 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

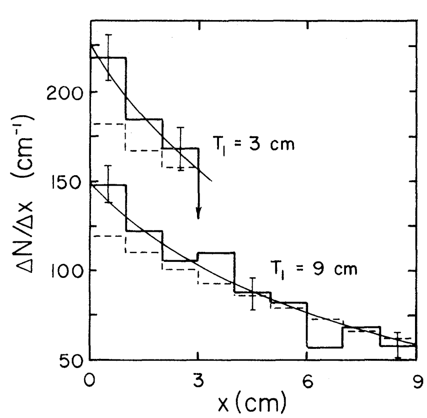

FIG. 3. Distributions of interaction distances x for events with potential paths $T \geqslant T_1$; dashed and solid lines have the same meanings as in Fig. 1.

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, λ_1^* referring to the third and later generations, and λ_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 $\overline{P}_{gen}$), 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.

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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, $b=0.44\pm 0.03$.

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[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.