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Author

Friedlander, E.M.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

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E.M. Friedlander, R.W. Gimpel, H.H. Heckman,
Y.J. Karant, B. Judek, and E. Ganssauge

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Evidence for Anomalous Nuclei among Relativistic Projectile Fragments from Heavy Ion Collisions at Bevalac Energies

E.M. Friedlander, R.W. Gimpel, H.H. Heckman, and Y.J. Karant
Lawrence Berkeley Laboratory, Berkeley, CA 94720

B. Judek
Division of Physics, National Research Council, Ottawa K1A 0R6 Canada

and

E. Ganssauge
Fachbereich Physik, Phillips Universität, Marburg, Federal Republic of Germany

June 1980

ABSTRACT

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

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 since 1954[1-7]; 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 LBL Bevalac.

Our results, based upon 1460 events, can be summarized as follows: a) over the first few cm after emerging from a nuclear interaction ($\hat{=} \sim 10$ gm/cm^2 of matter traversed or $\sim 10^{-11}$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 and II: 1.88 GeV/nucleon ^{56}Fe). Stack I, pellicle size 15×30 cm^2, was scanned and measured at NRC[8]; stack II, 7.5×12 cm^2, at LBL.

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 $Z \geqslant 3$ emitted from all generations of the extra-nuclear cascade within a 100 mr 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.

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

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

By recording the total track length S followed until N interactions have been observed, a maximum likelihood estimate λ^* is obtained for λ from:[10]

$$\lambda^* = S/N \quad . \tag{2}$$

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 <u>at fixed Z</u>) the estimate distributions are highly skewed and Gaussian confidence limits do not apply.

To interpret our data we need a test of the null hypothesis (n.h.) that two estimates, λ_1^* and λ_2^*, represent samplings from a population with a unique λ.

The distribution of S is obtained from an N-fold convolution of Eq.(1). It follows that the quantity $h^2 \equiv 2S/\lambda$ is distributed like χ^2 with $\nu = 2N$ degrees of freedom. Then the ratio

$$F \equiv (h_1{}^2/\nu_1)/(h_2{}^2/\nu_2) = \lambda_1^* / \lambda_2^* , \qquad (3)$$

which is independent of any assumed value of λ, obeys the F (variance ratio) distribution with ν_1 and ν_2 degrees of freedom. To pool information from all fragment charges we map each F onto its integral probability

$$P(F) = \int_0^F W(F')dF' , \qquad (4)$$

where W is the probability density of F.

The numbers P determined for each Z must be uniformly distributed between 0 and 1, and a simple test of the n.h. is to check whether the mean value $\overline{P}$ obtained from all charges differs significantly from its expectation value 1/2.

In the energy range 0.2-2.1 GeV/nucleon, the λ of beam nuclei, $2 \leqslant Z \leqslant 26$, can be parameterized as:

$$\lambda(Z) = \Lambda Z^{-b} , \qquad (5)$$

where $\Lambda = \Lambda_{beam} = (30.4 \pm 1.6)$ cm and $b = 0.44 \pm 0.02$.[11,12] This parameterization is consistent with the trend of mfp's computed from cross sections based on geometrical-overlap models.[13] Using Eq.(5) for $\lambda(Z)$, the S values can be scaled and the additivity of χ^2-variables can be used to add all h^2 values and reduce the test of the n.h. to a single F-value. Now however the F-test, though independent of Λ, will depend on the assumed value of b. Hence, as a parametric n.h. we shall test the constancy of Λ assuming b=0.44. In Fig. 1 we present our observed dependence of Λ on distance D after emission. Note the low values of Λ in the first few centimeters; beyond $D \cong 5$ cm the estimated Λ is compatible with Λ_{beam}. By assuming that mfp estimates from different charges can be combined via Eq. 5 we obtain for $D \leqslant 2.5$ and > 2.5 cm estimates for Λ (displayed at the bottom of Table I) which differ by 3.4 S.D.

To be independent of the validity of Eq. 5, a non-parametric n.h . is to assume that at fixed Z any two estimates of λ should be consistent. For example, if λ is measured within a distance D (a few cm's) after emission of a PF and also at larger distances, the results should be compatible, because we expect only small deviations of λ from the values measured on primary beams. These deviations arise from the different cross sections of isotopes off the line of stability and long-lived nuclear excited states, and are small because of the dominant contribution of the AgBr component in emulsion to the (geometric) reaction cross sections.

We plot in Fig. 2a the observed frequency of the probability $P_D(<F_D)$, where $F_D = \lambda^*(D \leqslant 2.5 \text{ cm})/\lambda^*(D>2.5 \text{ cm})$. Since there might be differences in PF's from ^{16}O and ^{56}Fe, we compute P_D for the different primary beams separately. We obtain the mean $\overline{P}_D = 0.323 \pm 0.053$, which is 3.4 S.D. from the value of 1/2 expected under the n.h. This result is independent of any assumption about the functional dependence of λ upon Z, and indicates that within the first few cm 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.

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 the n.h. is evident at small x, particularly for the case $T_1 = 3$ cm where it amounts to 3 S.D. 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 $\lambda_a << \lambda$, leaving a fraction 1-a that obeys the parametric n.h., 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.[14] Predictions based on the assumption of an admixture with the above parameters are drawn as solid curves in Figs. 1 and 3; they obviously account well for the observations.

Comparison of the mfp's estimated from the secondary PF's and those of later generations in the extra-nuclear cascade shows an mfp shorter by ∿15% in the third and later generations. The distribution of $P_{gen}(<F_{gen})$ [defined again via Eqs.(3) and (4) with λ_1^* referring to the third and later generations, and λ_2^* to the second generation] is shown in Fig. 2b. The probability for this distribution to be uniform between 0 and 1 is $\sim 8 \times 10^{-3}$.

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 non-uniform 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, as well as the normal pattern of target fragmentation, strongly excludes objections related to isotopic effects, mesonic atoms, hypernuclear decay in flight, etc.

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 extra-nuclear 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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FOOTNOTES AND REFERENCES

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10. We stress that the estimation of λ via Eq.(2) is independent of stack size in the case of primary beams or of the distance from the emission point of PF's because the total length of both interacting and non-interacting tracks is used.
11. H.H. Heckman, D.E. Greiner, P.J. Lindstrom, and H. Shwe, Phys. Rev. C 17, 1735 (1975), and present work (^{4}He, ^{12}C, ^{14}N, ^{16}O, ^{40}Ar, and ^{56}Fe).
12. 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 NRC, $\Lambda_{beam} = 28.9 \pm 2.5$ cm, $b = 0.43 \pm 0.04$; for LBL, $\Lambda_{beam} = 32.2 \pm 2.1$ cm, $b = 0.44 \pm 0.03$.
13. P.J. Karol, Phys. Rev. C 11, 1203 (1975).
14. Assuming (sic!) Eq. 5 can be extrapolated to $\lambda_a \cong 2.5$ cm, this corresponds to a preposterous $Z \cong 300$.
15. See LBL report no. 10573 for a more comprehensive version of this paper.

Table I. Weighted estimates for the mean free path λ and the parameter Λ (Eq.5) at different distances D from the origins of PF's for grouped charges. Expected values assuming Eq.5 are given in the last column.

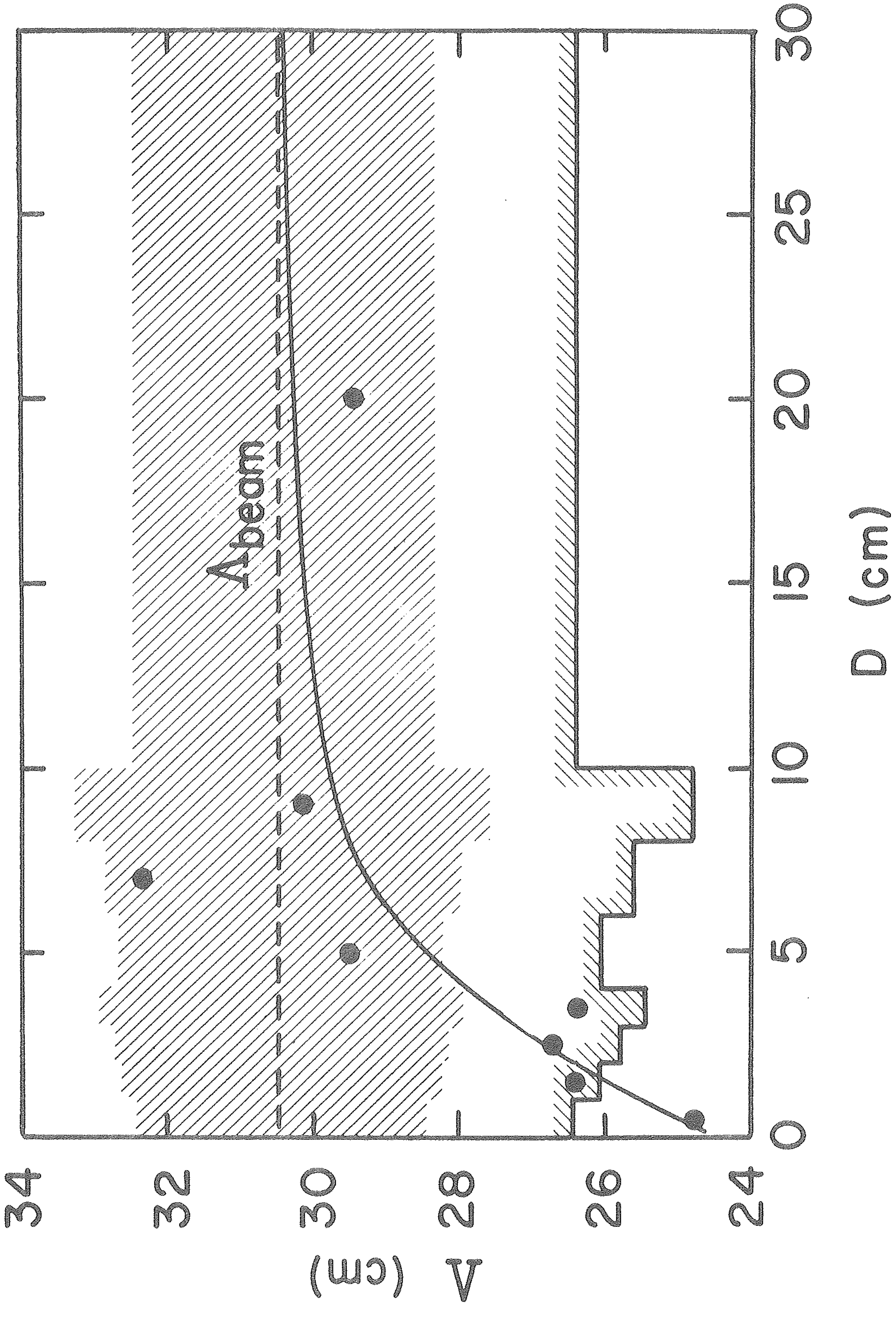
Z	$\bar{\lambda}$ ($D \leqslant 2.5$ cm) (cm)	$\bar{\lambda}$ ($D > 2.5$ cm) (cm)	$\langle \lambda \rangle$ (cm)
3-8	12.4 ± 0.7	14.0 ± 0.5	14.6
9-16	8.3 ± 0.7	11.6 ± 1.0	10.6
17-26	6.0 ± 0.6	8.0 ± 0.8	8.4
	Λ($D \leqslant 2.5$ cm) (cm)	Λ($D > 2.5$ cm) (cm)	$\langle \Lambda \rangle$ (cm)
3-26	25.0 ± 1.1	30.0 ± 1.0	30.4

FIGURE CAPTIONS

Fig. 1. Estimated values of the parameter Λ (Eq.(5)) at different distances D from the origins of PF's: full circles, experiment; dashed line, n.h. prediction; shaded region, 1 S.D. (68%) confidence interval; shaded line, lower limit of the 2 S.D. (95%) confidence interval; solid line, prediction assuming a 6% admixture of PF's with λ_a = 2.5 cm.

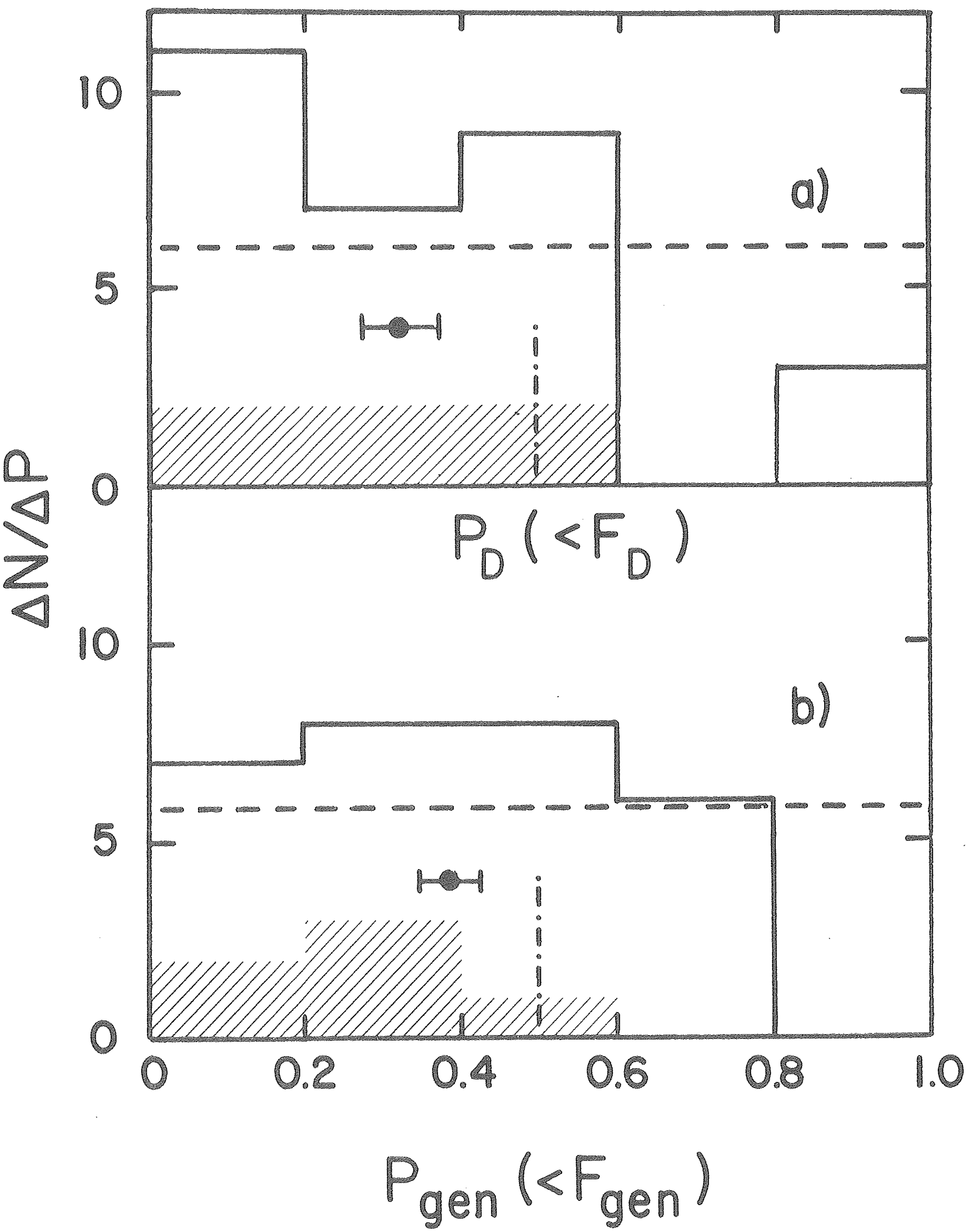
Fig. 2. Experimental frequency distribution of: a) $P_D(<F_D)$, b) $P_{gen}(<F_{gen})$, see text; the dashed line is the uniform distribution expected under the n.h.; the points with error bars are the experimental means $\overline{P}$, to be compared to their expectation $\langle P \rangle = 1/2$ under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

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.



XBL 806-10261

Fig. 1



XBL 806-10260

Fig. 2

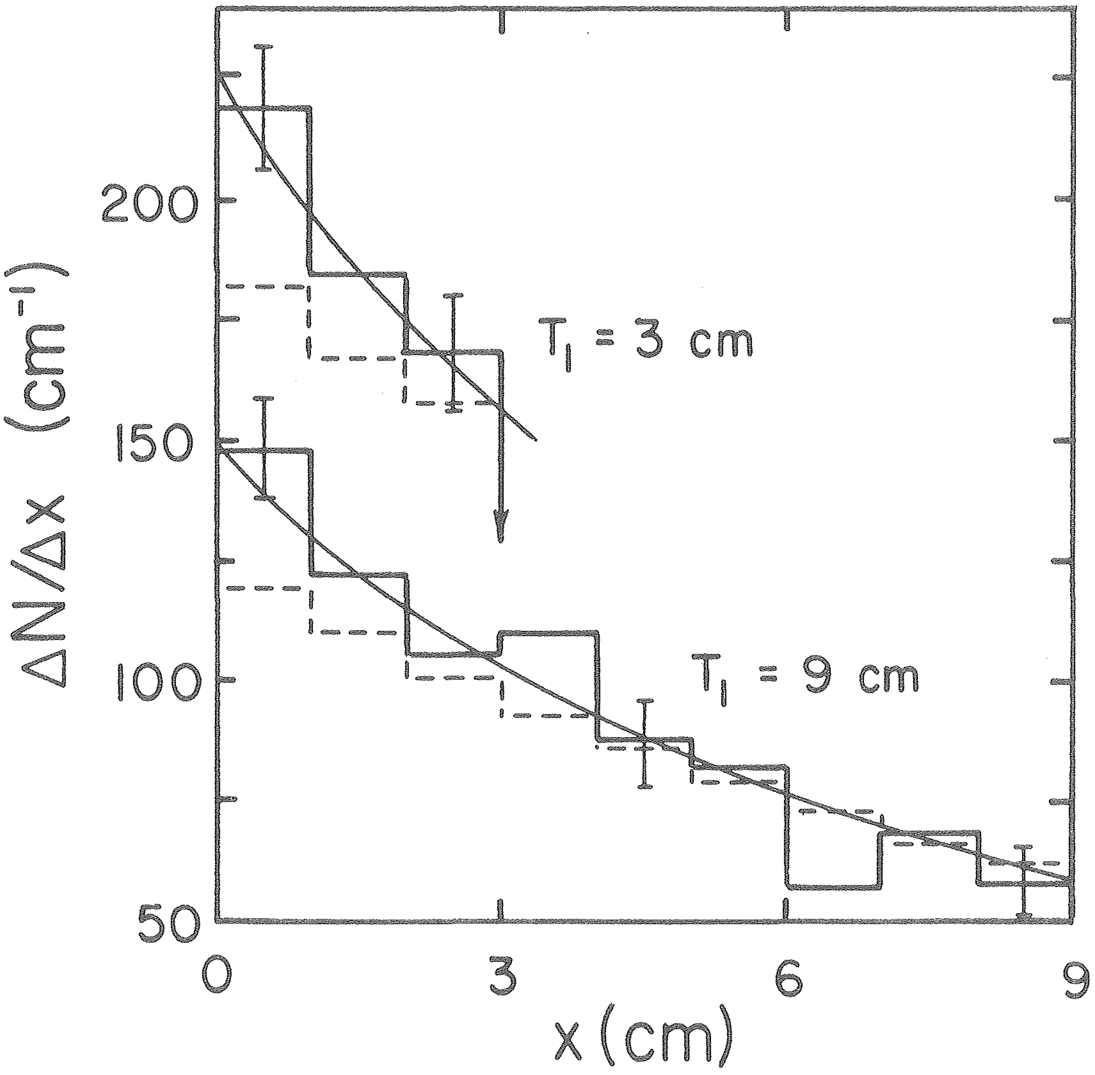


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Fig. 3

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UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720