

New evidence for anomalously large nuclear fragments

Since 1954 there have been sporadic reports that very strange things can happen in the first few centimeters after an energetic nucleus fragments in photographic emulsion. Before the Berkeley Bevalac came along in the mid 1970s to accelerate middle-weight ions to kinetic energies of 2 GeV per nucleon, such reports came entirely from cosmic-ray exposures of very limited statistics. Indeed the anecdotal tone of the early reports generated more skepticism than excitement.

Although the skepticism has by no means vanished, much has changed over the past two years. Three emulsion experiments have been reported—two from Bevalac exposures^{1,2} and, most recently, a reanalysis of an old series of cosmic-ray balloon flights³—that appear to agree quite well among themselves that this long-suspected anomalous nuclear phenomenon is very probably real. With a total of almost 3000 secondary interactions of fragments of energetic incident nuclei, the three groups find (at a level of about five standard deviations when all the data are combined) that in the first few centimeters after a nuclear collision the projectile fragments exhibit anomalous mean free paths so short that they cannot be understood in terms of standard nuclear theory.

The appellation "anomalons" that has now become standard for these briefly appearing, bloated nuclear fragments began with a typographical error.

When Erwin Friedlander (Lawrence Berkeley Lab) reported the results of the LBL-National Research Council (Ottawa) collaboration at Irvine in 1980, the announcement of his talk inadvertently metamorphosed the word "anomalous" in the title to anomalons. This inspired Fred Reines of Irvine to declare "now you have a name for your beast." The name stuck.

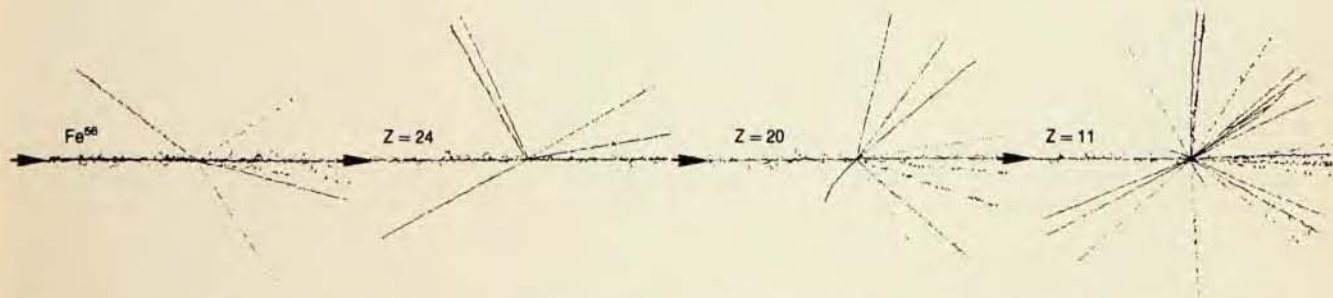
The extensive and tenacious cosmic-ray work carried on at the National Research Council by Barbara Judek since the mid-1960s is widely credited as the pioneering work on the anomalon effect. "When Barbara got hold of it," Friedlander told us, "she held on like a bulldog to a trouser seat."

The Berkeley-Ottawa collaboration, led by Judek at NRC and Friedlander, Harry Heckman and Yasha Karant at LBL, combined the analyses of two Bevalac emulsion exposures from the mid-1970s. The Canadian group scanned and measured emulsions exposed to 2.1-GeV/nucleon O^{16} ions while the Berkeley group did the same for an Fe^{56} exposure at 1.88 GeV/nucleon. From a combined analysis of 1460 secondary interactions of projectile fragments produced in previous (usually beam) collisions with emulsion nuclei, the collaboration concluded that about 6% of such fragments were highly anomalons—exhibiting a mean free path in emulsion of only about 2.5 cm, an order of magnitude shorter than normal nuclei of the same charge. In

effect, the group was asserting, a small subpopulation of fragment nuclei produced in high-energy collisions have effective collision cross sections an order of magnitude higher than normal. "We seem to be seeing magnesium nuclei with cross sections that look like lead" (more than eight times the mass of magnesium), Friedlander told us.

A mean free path of 2.5 cm implies a lifetime for those anomalous high-cross-section states of at least 10^{-11} seconds. There's the rub. One can imagine nuclear excitations that would enhance cross sections, but they should revert to normal in times on the order of 10^{-23} sec (for hadronic transitions) or, at best, 10^{-16} sec (for electromagnetic transitions). A substantial cross-section enhancement persisting for at least 10^{-11} sec appears to require a radically new theoretical explanation. The situation is reminiscent, Friedlander suggests, of the need to introduce strangeness conservation in the 1950s to explain the fact that new particles produced in pion-nucleon collisions were living thirteen orders of magnitude too long.

No transition decay back to a normal state has been observed for these anomalons. Friedlander and his colleagues simply assume that they are stable on the time scale involved in passing through the emulsion stack. With this assumption, a best fit to the data arrives at 2.5 cm for the anomalous mean free path and 6% for the



A cascade of four consecutive nuclear collisions in photographic emulsion, seen by the Berkeley-Ottawa collaboration. Only 5.7 cm separate the first collision from the last, suggesting an anomalously short mean free path. Successive leading fragments of the incoming

2-GeV/nucleon Fe^{56} nucleus from the Bevalac beam have charges $Z = 24, 20$ and 11 after the first, second and third collision, respectively. Such cascades suggest that anomalous projectile fragments may have "memory" that survives subsequent nuclear collisions.

fraction of anomalons among the projectile fragments emerging from primary beam collisions. The disappearance of the anomalons after a few centimeters would then be accounted for simply by attenuation due to the very high collision rate of these objects. This might explain why, despite their longevity, anomalons have not been seen in detectors with much coarser spatial resolution than emulsions.

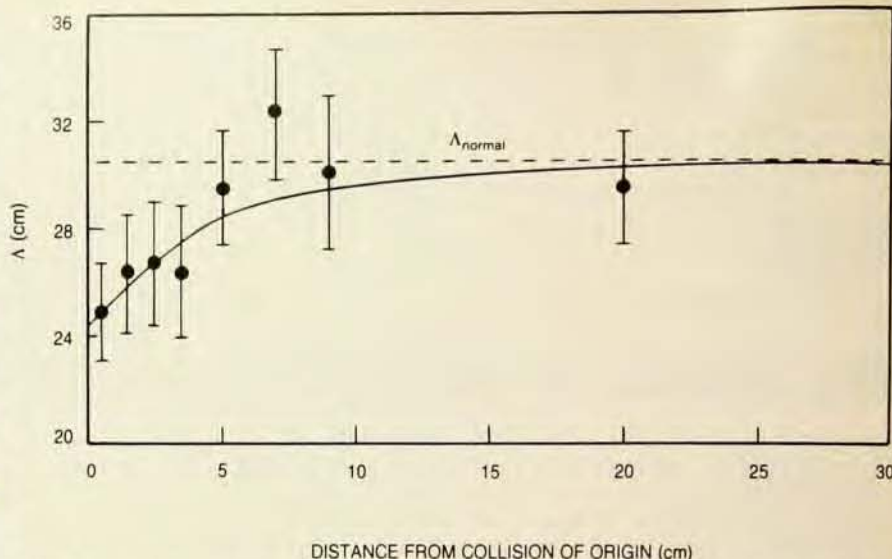
The data are however consistent with an alternative picture. One could suppose that the anomalons decay spontaneously to normal nuclei after about 2.5 cm (corresponding to a proper lifetime of about 3×10^{-11} sec). Such a decay would have to be undetectable in the emulsion (only neutral byproducts and very little momentum transfer). In that case one would not have a small subpopulation of anomalons with an order of magnitude increase in cross sections, but rather a more modest increase in cross section experienced by the majority (perhaps all) of the projectile fragments.

This latter picture is the one favored by the University of Minnesota cosmic-ray group, led by Phyllis Freier and Jake Waddington, whose recent reanalysis of three balloon exposures from 1964 to 1968 have turned them into believers. "We went into this as skeptics, after we saw the Berkeley-Ottawa results," Freier told us. But after the analysis of their 557 secondary interactions she concluded that "the probability that we're seeing a statistical fluke or making some unconscious blunder is less than 5%."

Waddington pointed out that their data admit of both interpretations—a small, stable population of very reactive anomalons or a large population of decaying anomalons with cross-section enhancements only about a factor of two above normal. "But even a factor of two is an enormous increase to explain away for 10^{-11} seconds," he added. Friedlander told us that the Berkeley-Ottawa data could also be fit by assuming an anomalon lifetime of a few times 10^{-11} seconds. But then, he pointed out, the χ^2 fit requires that the fraction of anomalons must be very close to 100%.

Piyare Jain's emulsion group at the State University of New York at Buffalo has carried out the other Bevalac emulsion experiment that supports the reality of anomalons. Their exposure of emulsions to 2-GeV/nucleon beams of Fe^{56} and Ar^{40} ions has produced 865 secondary interactions of projectile fragments. The Buffalo results are in good overall accord with the Minnesota and Berkeley-Ottawa findings.

More recently the Buffalo group has addressed two important questions upon which the other experiments had been able to shed very little light. To



Mean free path parameter λ for nuclear projectile fragments as a function of distance from the collision of origin. λ is determined from "local" measurements of the mean free paths λ for different nuclear charges Z by assuming that $\lambda = \lambda Z^{-b}$ gives the dependence of λ on Z . We see from the Berkeley-Ottawa emulsion data that λ is well below its "normal" value for the first few centimeters after a collision. Fitted curve assumes a 6% admixture of stable "anomalons" with a mean free path of only 2.5 cm, an order of magnitude shorter than normal.

investigate the energy dependence of the anomalon effect, they have analyzed⁴ a 1-GeV/nucleon Fe^{56} Bevalac exposure. At this lower energy, Jain told us, they find no evidence for anomalon production. The other groups had seen no diminution of the effect with decreasing energy in the energy spread provided by the cosmic-ray spectrum and energy losses in the emulsions; but their statistics at 1 GeV/nucleon were too small to permit serious conclusions.

Jain and his colleagues have also looked more systematically than the other groups for anomalon fragments with nuclear charge $Z = 2$: anomalous alphas. Analyzing 3400 alpha fragments with 700 secondary interactions, they do not find⁵ an anomalously short mean free path. This null result bears on the question of whether the anomalon effect is a peculiar nuclear-physics phenomenon or something still more exotic.

The analysis of the emulsion data is not altogether straightforward. One is looking for a rather subtle effect with limited statistics. One might think that an order-of-magnitude increase in cross sections would be strikingly evident. But it is thought to occur only in a small subpopulation that has thus far vouchsafed us no other signature of its identity; the effect is thus largely washed out in overall averages.

Matters are further complicated by the fact that the normal nuclear mean free path, λ , decreases with Z . In these experiments one is looking at projectile fragments with Z ranging from 3 (lithium) up to the charge of the beam

nuclei. The fragment charge is determined (to within about one unit) by measuring the ionization density of the (relativistic) fragment's track in the emulsion. At these energies one distinguishes substantial nuclear fragments of the incident projectile nucleus from other collision debris (target fragments, protons, deuterons, alphas and pions) by requiring that they emerge from a collision within 100 milliradians of the incident direction, with an ionization density indicating a relativistic particle with $Z > 3$. To minimize the dependence of the data analysis on assumptions about the functional dependence of the normal mean free path on Z , one wants to study λ separately for each subsample of projectile fragments with a given Z . But when one divides a few thousand projectile fragments up among all the Z values, the data sample for each charge class becomes quite small.

In all three emulsion experiments every projectile fragment was followed with a movable-stage microscope from the primary (or secondary, or tertiary...) collisions in which it originated all the way out to the end of the emulsion or to a subsequent collision. The sum of all these track lengths for a given Z (interacting and noninteracting) divided by the number of observed interactions gives an estimate of the mean free path independent of the geometry of the finite emulsion stack.

The principal method used by the three groups to test the anomalon hypothesis was to measure λ separately for the first 2.5 cm after a collision and beyond 2.5 cm. If one ignores ioniza-

tion energy loss, a mean-free-path measurement can begin anywhere one likes on a track, just as one can begin a lifetime measurement at any arbitrary starting time, so long as the decay is exponential (that is to say, the particle has no memory of its past). At these energies, ionization losses are in fact sufficiently small and normal cross sections sufficiently energy independent that one can indeed ignore these losses.

If there are no anomalous, the two mean-free-path measurements for each charge class, $\lambda_{<2.5}$ and $\lambda_{>2.5}$, will be sampling the same statistical population. In that case, Friedlander argues, the ratio $F = \lambda_{<2.5} / \lambda_{>2.5}$ measured for the different charge classes should be statistically distributed according to the well-known "variance-ratio" distribution. But this is not what was found. Whereas the standard variance-ratio function anticipates an F distribution symmetric between any F and its reciprocal, all three groups agree that the observed distribution is significantly lopsided, indicating that $\lambda_{<2.5}$ is systematically lower than $\lambda_{>2.5}$. This effect is seen to hold over the entire range of projectile fragment charges.

Plotting Z -averaged "local" mean free paths as a function of distance from the collision in which the projectile fragment originates, the three emulsion experiments find that λ begins at about 25 to 50% below its normal value, which it approaches asymptotically after 5 or 10 cm. These curves can be fit by Monte Carlo models that assume either a small admixture of stable anomalous with a mean free path of about 2.5 cm (an order of magnitude below normal), or a much larger population of unstable anomalous with mean lifetime corresponding to a few centimeters and λ about a factor of two below normal.

One could argue, Waddington told us, that any one of these experiments is a statistical fluke. But when three experiments agree as well as these do, he added, such a fluke is most unlikely. Some may object that three experiments employing very similar emulsion techniques could be subject to a common hidden bias that generates the anomalous effect as spurious artifact. But Waddington stresses that the cosmic-ray experiment, with its spread of incident energies and directions, is sufficiently different from the other two to counter this objection.

Theoretical speculation, at this point, has very little to go on. The detailed character of the anomalous effect, if it exists at all, is still unclear. What are the peculiar characteristics of anomalous-producing collisions, and how prolific are they? How large is the cross-section enhancement, and what is its lifetime? Does the anomalous effect extend to low- Z objects: alphas, deuter-

ons and perhaps even protons?

At an anomalous workshop organized by Heckman at Berkeley in February, experimental plans for addressing these crucial questions were described, formulated and coordinated by groups as far afield as Sweden, Germany, Italy and India. An anticipated tenfold increase in emulsion statistics will be complemented by etchable-plastic exposures and experiments with electronic detectors that can study what becomes of anomalous in vacuum (or air). "We should have some definitive answers a year from now," Ingvar Otterlund (University of Lund, Sweden) told the workshop in his summary talk.

The workshop also heard a sampling of the theoretical speculations that have proliferated in the past several years. These speculations (most have not yet reached the stage of detailed calculations and predictions) fall broadly into two classes: extraordinary nuclear states and extraordinary quark configurations. The former category would be in difficulty if the anomalous effect turns out to occur in nuclei as small as helium or if the cross section enhancement is much more than a factor of two.

The theorists have the difficult task of explaining simultaneously the cross-section enhancement and its amazingly long lifetime. The quark theories basically argue that although quantum chromodynamics demands that free particles must be "color singlets," this applies strictly only to the nucleus as a whole and not necessarily to its confined nucleons. It may be, they suggest, that nuclear collisions can rearrange the quarks so they are no longer confined in color-singlet nucleon "bags." The resulting color polarization inside the nucleus, they argue, could give rise to longer-range forces, similar to the intermolecular van der Waals forces, which would effectively enlarge the nuclear collision cross sections. The ideas put forward by William Romo and Peter Watson⁶ (Carleton University, Ottawa), Sverker Fredriksson and Magnus Jandel⁷ (Stockholm) and Karant⁸ fall into this category.

George Chapline (Livermore) speculates⁹ that anomalous may carry an extra quark, resulting in overall fractional charge and an unconfined gluon field that extends the range of the hadronic force. But, he cautions, there is as yet no good QCD-breaking theory that could underlie this picture. Richard Weiner, Sibaji Raha (both at Marburg University, Germany) and Gerald Fowler (Exeter) also speculate¹⁰ on free quarks and color polarization, as well as another idea—"coherent superscattering" resulting from a coherent state of the quarks in the two colliding nuclei.

A field-theoretic prediction¹¹ of novel nuclear excitation states by John Boguta (LBL) drew particular attention at the workshop. Boguta has for some time been urging a Lagrangian field-theoretic approach (with fundamental nucleons and meson fields) to a broad range of nuclear-physics problems. His field equations, it turns out, appear to possess unusual "hadroid" solutions with nontrivial topological quantum numbers—somewhat like the winding numbers encountered in non-abelian gauge theories of elementary particles. In such an anomalous solution, he explains, the repulsive intranuclear force takes on a long-range coulombic character yielding an enlarged, almost hollow nuclear configuration. The long decay time of such a state would be explained by the approximate conservation of this new topological quantum number; the system cannot unwind to normal topology on a hadronic time scale. Furthermore, the hollow nuclear configuration reduces overlap integrals sufficiently, he suggests, that the electromagnetic decay time is prolonged by several more orders of magnitude. Another idea of Weiner and his colleagues is somewhat similar to Boguta's picture; they suggest the possibility of nuclear-density solitons.

Benjamin Bayman, Paul Ellis and Y. C. Tang (Minnesota) argue that the anomalous might be quasi-molecular nuclear states—excited configurations in which the nucleus is effectively an ephemeral bound state of smaller constituent nuclei. They calculate that such states could have cross sections enhanced by as much as a factor of three, with lifetimes longer than 10^{-10} seconds. Tang told us that such states should occur only for $Z > 12$. The statistical evidence for anomalous mean free paths at low Z is in fact weaker than for $Z > 12$, Waddington told us. —BMS

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