# A Nuclear Puzzle Emerges at Berkeley

*No existing particle can explain the results of an accelerator experiment*

"A man shouldn't bear a child," says Erwin Friedlander of the Lawrence Berkeley Laboratory (LBL). "Even if it happened only once in a million, something would be wrong with biology." This rather unarguable assertion also applies in spirit to the results of some recent accelerator experiments at Berkeley in which investigators have found a small number of events that are sufficiently bizarre that no phenomena within the framework of known nuclear physics can explain them. The events seem to imply the existence of a new form of nuclear matter, although physicists can offer little more than top-of-the-head speculation about what the new matter may be.

When high energy particles (from cosmic rays or accelerators, for example) strike a target, two things happen. The incoming particles lose a little energy by ionizing atoms in the target, and from time to time the particles collide head on or nearly so with target nuclei. In the experiments at Berkeley, the incoming particles were sometimes oxygen and other times iron nuclei from LBL's Bevalac accelerator, and the target was a special form of photographic emulsion enriched in silver bromide, which is used by nuclear physicists for particle detection. The ionization of atoms in the emulsion causes it to be "exposed" where the particles have passed, leaving a visible track. At points where collisions occur, parts of the incident nuclei are stripped off, and a star pattern is formed by the fragments of the struck nucleus flying in all directions. Moreover, the remains of the original nuclei, called the projectile fragments, continue on their way, suffering additional collisions and becoming further fragmented. The collisions occur randomly, but on the average there is a characteristic distance, the mean free path, between these violent interactions.

Put rather dryly, the investigators [Friedlander, Roy Gimpel, Harry Heckman, and Yasha Karant from LBL, Barbara Judek from the National Research Council (NRC) of Canada, and Eberhardt Ganssauge from Philipps University, Marburg, West Germany] have found that about 6 percent of the fragments have anomalously short mean free paths, up to ten times smaller than their companions. A tenfold decrease in the mean free path is the same as a tenfold increase in the collision cross section. Nothing within the realm of conventional nuclear science has a cross section this big. It must be something new.

**The 6 percent of the fragments that have unusually short mean free paths evidently undergo some change that alters their character during the collisions that produce them.**

The first report of anomalously short mean free paths apparently was made by cosmic-ray researchers at an Italian physics meeting in 1954. Since then, the phenomenon has popped up sporadically in cosmic-ray conference presentations and in the literature. But so little data were available that most experimenters regarded the effect as unlikely to be genuine, and it has been far from a hotly debated topic. Lack of earlier interest is one reason why it may take theorists a shade longer than usual to concoct models to explain the Berkeley results.

One investigator, Judek, pursued anomalous mean free paths with more tenacity than others and also shifted the focus of experimental work from cosmic rays to accelerators. Accelerators produce beams of particles with energies much lower than those of cosmic rays, but the properties of the beam are controllable and the flux of particles is much higher, so that there are more data and they are of higher quality. In 1973 experiments with the Bevalac, Judek exposed nuclear emulsions to beams of oxygen nuclei accelerated to 2.1 GeV per nucleon. The experiments confirmed the earlier cosmic-ray results, but did not noticeably improve their statistical significance.

Some years later, an upgraded version of the Bevalac that could accelerate nuclei as heavy as iron became available. It was at this point that Heckman, Friedlander (who had been involved in some of the cosmic-ray experiments), and their Berkeley co-workers began studies of their own with the heavier particles. The iron nuclei were accelerated to 1.9 GeV per nucleon in the most recent experiments. By this summer the LBL-NRC collaborators had collected nearly 1500 events of which 6 percent exhibited anomalously short mean free paths.

The usual method of measuring mean free paths is to add the lengths of all the tracks in an emulsion and divide by the number of collision events. In this procedure, the effect of a few events with anomalously short collision distances would simply be to shorten the measured mean free path by a small amount. The problem was to sort out two populations of projectile fragments, one characterized by the normal mean free path and the other by a shorter average collision distance. To accomplish this, the researchers resorted to some statistical analyses that Friedlander describes as "more sophisticated than most physicists are used to, but still well within the realm of textbook methods."

The tests were based on the notion that a collection of events made up of nuclei that have traveled long distances before colliding will be dominated by normal nuclei, whereas a sample made up of events with short collision distances will be more heavily weighted by the abnormal particles. Most fragments are, in fact, normal nuclei and come in sizes ranging from that of helium (alpha particles) up to those of oxygen or iron nuclei from the Bevalac. The mean free paths (which vary with the atomic number of


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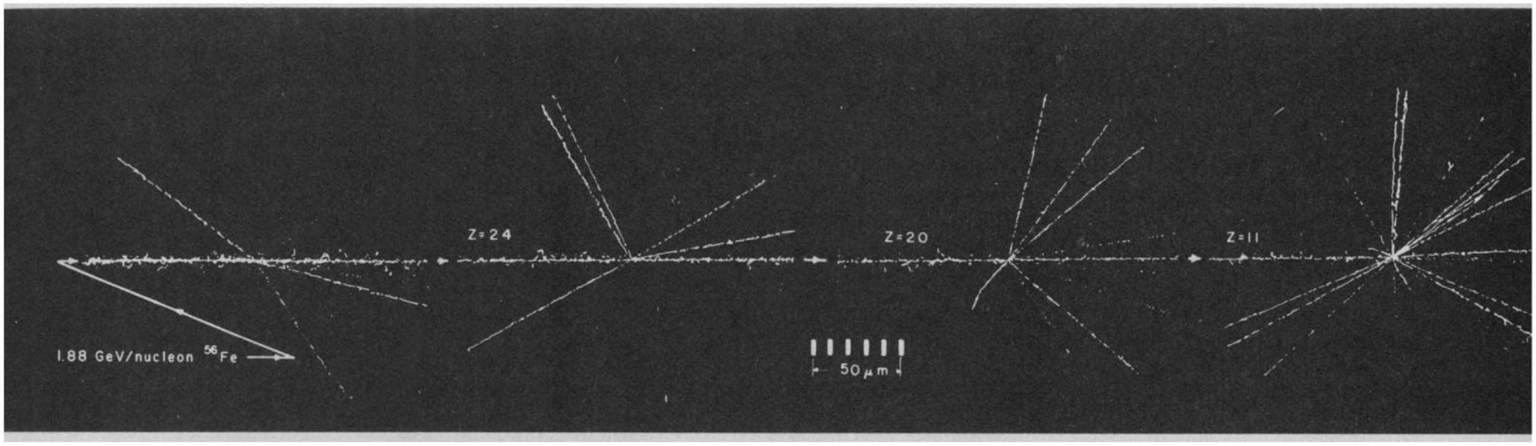


**Typical sequence of collision events when iron-56 passes through a nuclear emulsion**

*An iron nucleus with an energy of 1.88 GeV per nucleon enters the emulsion on the left. The track is caused by ionization of the atoms in the emulsion as the incident particle loses energy. The "stars" are tracks left by fragments of nuclei of atoms in the emulsion created by head-on collisions between the iron and the nuclei. Successive "stars" are caused by fragments of the iron which continue on their way and suffer additional collisions. In the figure, iron (atomic number 26) breaks up into chromium (atomic number 24) in the first collision, and into calcium (atomic number 20) and sodium (atomic number 11) in the second and third collisions. The final fragment, which leaves the emulsion, is an alpha particle (helium nucleus).* [*Source: Erwin Friedlander, Lawrence Berkeley Laboratory*]

the nucleus) of these fragments are the same as those measured for the same nuclei coming directly from the accelerator; that is, the fact that they were formed by the fragmentation process does not change their properties in any way. The 6 percent of the fragments that have unusually short mean free paths evidently undergo some change that alters their character during the collisions that produce them. One constraint on what the change could be is imposed by the fact that the abnormal nuclei travel a few centimeters in the emulsion before colliding, which means their lifetime must be at least $10^{-10}$ second. This is much too long for any known elementary particles that decay by the strong nuclear force (the force the holds nuclei together); that is, the abnormal entities are relatively stable.

One well-known way to achieve such stability, comments Kurt Gottfried, a Cornell University theorist, is by way of a phase transition. Gottfried suggests superconductivity in metals as an analogy. Superconductivity does not involve new types of particles; instead, well-known particles (electrons) interact in a new way and give rise to a phase transition from normal metallic behavior to the superconductive state when the temperature is lowered to cryogenic levels.

A model proposed last year by William Romo and Peter Watson of Carleton University in Ottawa follows this line of thinking. In their model, quarks, currently believed to be the constituents of most of the elementary particles, are the focus of attention. In particular, the protons and neutrons in the atomic nucleus each consist of three quarks. Romo and Watson conjecture that in the collision process the six quarks of one proton and one neutron, for example, become rearranged into a single entity. The proton and neutron dissolve into their constituent quarks, as it were. Karant at LBL has independently proposed a very similar explanation for the anomalously short mean free path phenomenon.

Picturing nuclear particles as conglomerations of quarks is not new in itself. Stanley Brodsky of the Stanford Linear Accelerator Center and Peter Lepage of Cornell, for example, have recently reviewed the theory of the forces between quarks, called quantum chromodynamics, as applied to the deuteron. Nuclear physicists ordinarily view the deuteron as a proton and neutron bound together by the strong nuclear force. But in quantum chromodynamics, theorists must deal with a mélange of six quarks whose color "charges" can be arranged in more than one way. (Color is a quantity that plays a role analogous to electrical charge in electromagnetism and is the source of the force between quarks.) Protons and neutrons are color neutral, but the deuteron can become color polarized in a way similar to the electrical polarization of a molecule when its positive and negative charges become slightly displaced. Brodsky says that the latest experimental results support this quantum chromodynamics picture.

The conventional quantum chromodynamics treatment of the deuteron does not come close to accounting for the anomalous results at Berkeley, however, because it does not account for the enlarged collision cross section or the exceptional stability of the abnormal nuclei. The six-quark picture of the deuteron validated by high energy physics experiments may be accurate only for $10^{-23}$ second or less during a collision. Thus, Romo and Watson have proposed a rather special configuration of six quarks arrayed approximately like the points of a child's jack. The Canadian theorists have rough calculations indicating that the resulting spatially large object would be able to increase the collision cross section of an abnormal nucleus by the required factor of 10. Moreover, the conglomeration is relatively stable with a lifetime of about $10^{-9}$ second.

Watson cautions, however, that there are many other possible models one could dream up. Moreover, detailed calculations that make specific predictions do not exist yet; models proposed so far are in the nature of descriptions. Finally, the present experimental data are not of the right type to enable theorists to make comparisons with predictions, even if they existed.

The Berkeley findings fall in the crack between nuclear and elementary particle physics and have therefore not attracted a lot of attention as yet. At the Washington meeting of the American Physical Society last spring, for example, Friedlander gave an invited talk on the anomalous mean free path phenomenon. But many attendees had found the preceding talk so interesting that they followed the speaker out into the halls and left Friedlander with a much reduced audience. If additional experimental evidence is forthcoming and if theorists can produce "interesting" models for the effect, the level of excitement should rise noticeably. "It has the potential," says Gottfried, "of being one of the most important experiments of recent years."

—ARTHUR L. ROBINSON