Relativistic Projectile Fragment Interactions: Anomalons

Abstract. *Interaction mean free paths are calculated for projectile fragments from relativistic heavy-ion interactions in emulsions and plastic. There are important discrepancies between emulsion results and those from other techniques. "Anomalous" secondaries (anomalons) may prove to be interpretable by conventional nuclear physics: short mean free paths may be due to convoys of collinear light fragments from peripheral interactions (for example, with neutrons) or from low-excitation particle-unbound fragments that decay in flight.*

In 1980, Friedlander *et al.* (*1*) reported anomalous interactions of relativistic ^{16}O and ^{56}Fe projectiles in emulsions. Their measurements confirmed the results of earlier cosmic-ray studies indicating that, over the first few centimeters after emerging from a nuclear interaction, secondary projectile fragments (PF's) exhibit mean free paths significantly shorter than those derived from "normal" primary beams of the same nuclear charge. Explanations based on conventional nuclear physics were ruled out by the authors, provoking considerable speculation and interest (*2*). Until 1984, subsequent studies of mean free paths in emulsions (*3, 4*) and of charge-changing mean free paths in plastics (*5, 6*) reproduced the observations of Friedlander *et al.* The term "anomalon" has been associated with this phenomenon, which is evidenced entirely by the statistical appearance of the analyzed data but not by any physically distinguishing feature. I have modeled mean-free-path calculations and find that the observations may yet prove to be a manifestation of traditional phenomena ordinarily disregarded, owing to the inability of emulsions to completely resolve the outcome of an interaction.

The experimental interaction mean free path for absorber thickness Δx is

$$<\lambda> \equiv (N_t \Delta x + N_i L)/N_i \qquad (1)$$

where N_t and N_i are the number of observed transparencies and interactions, respectively; L is the average path distance to an observed interaction and can be calculated from the total interaction probability per unit path length (p) and the detection efficiency (ϵ).

For primary interactions of composite projectiles, ϵ is typically ~80 percent, consistent with acknowledged difficulties in detecting peripheral interactions where the change in charge $\Delta Z \leq 1$ in emulsion or $\Delta Z = 0$ with plastic track techniques. In deriving Eq. 1, the effective interaction probability per unit path length $p = \Sigma\epsilon_\nu n_\nu \sigma_\nu = \Sigma\epsilon_\nu/\lambda_\nu$ should really be used. The ratio λ_ν/ϵ_ν is an effective mean free path; n_ν is the number density of nucleus ν in the detection medium; σ_ν is the total reaction cross section of nucleus ν with the projectile; and ϵ_ν is the fraction of interactions with nucleus ν that are detectable. Results of recent studies of emulsion and plastic mean free paths for relativistic heavy ions are listed in Table 1. Also shown are the results of my calculation for the mean free path, using "soft-spheres" model σ_ν values (*7*).

Friedlander *et al.*, in order to improve statistics, scaled the mean free paths for different PF's at 2 GeV/A (where A is the mass number according to

$$<\lambda(Z)> = \Lambda Z^{-b} = (30.4 \pm 1.6)Z^{-0.44 \pm 0.02} \qquad (2)$$

a procedure followed by subsequent investigators as well. My soft-spheres calculations, functionalized as above (*8*), give scaled mean free paths $\Lambda = 25.2$ and $b = 0.43$; the difference in Λ values is ascribable to ϵ ~0.8.

After a primary interaction, the resulting secondary beam identified with charge Z is mixed in nature. Friedlander *et al.* hypothesized a two-component secondary beam of fractional intensities I_1 and I_2 having interaction probabilities in emulsion of p_1 and p_2, respectively (with $\epsilon = 1$). Their results are shown in Fig. 1, together with my calculated histogram with ^{16}O used as an illustration and with $p_1 = 0.0821$ and $p_2 = 0.333$ cm^{-1}, corresponding to effective mean free path $\lambda_2/\epsilon = 3.00$ cm. It is to such a transient second component that the "anomalous" sobriquet has been assigned and over which much recent theoretical and experimental activity has been aroused.

As the result of high-energy interactions, PF's are frequently produced in consort with light companion secondary particles, in particular (but not necessarily restricted to) neutrons. Should some number, j, of companion particles be essentially collinear with the heavy projectile remnant, their interactions would be visible in emulsion, but the true multiplicity of the "convoy" track would be obscured since $\Delta Z \leq 1$, barely affecting Z assignment (ΣZ^2). Successive generations of anomalous behavior would be attributable to the convoy. There are thus two classes of PF tracks expected for each Z assignment: one of intensity I_1 in which companion particle interactions, if any, are geometrically resolvable from the track of the major PF, the latter interacting with "normal" mean free path $\lambda_1 = \epsilon_1/p_1$; and another of intensity I_2' in which one or more consort secondaries are virtually collinear with the major PF and which convoy interacts in emulsion with $\lambda_2' = (p_2')^{-1} = (\Sigma p_j)^{-1}$.

An example of my hypothesis would be direct nucleon knockout in which 34-GeV ^{16}O projectiles produce ^{13}O + 3n, all at ~0° to the beam. The emulsion track would behave as $Z = 8$; $p_1 = 0.0821$ cm^{-1} for ^{16}O; $p_2' = 0.170$ cm^{-1} for ^{13}O ($\lambda = 11.5$ cm) plus three companion (trackless) neutrons ($\lambda = 31.9$ cm). Experiments have shown that neutron removal ($\Delta Z = 0$) cross sections are 10 to 25 percent of the total reaction cross section (*9*). Reasonably estimating 15 to 20 percent to represent the probability of such missed events, the multiple-component model generates the histograms (mean free path versus depth D) for

Table 1. Interaction mean free paths. Experimental relativistic projectile interaction mean free paths in emulsion (in centimeters) and charge-changing mean free paths in CR-39 plastic (in grams per square centimeter) compared with theoretical results based on the use of my "soft spheres" model (5). For composite projectiles, theory/experiment = 80 percent = ϵ.

Projectile	Energy (GeV/A)	Mean free path: Theory	Mean free path: Experiment	Reference
		Emulsion		
^{4}He	2.1	18.6	21.8 ± 0.7	(*9*)
^{12}C	2.1	11.9	13.8 ± 0.5	(*9*)
^{14}N	2.1	11.2	13.1 ± 0.5	(*9*)
^{16}O	2.1	10.6	13.0 ± 0.5	(*9*)
^{20}Ne	1.8	9.4	12.9 ± 0.2	(*15, 16*)
^{40}Ar	1.8	7.2	9.6 ± 0.15	(*15, 16*)
^{56}Fe	1.7	6.3	8.4 ± 0.2	(*18*)
^{84}Kr	1.52	5.46	6.65 ± 0.15	(*12*)
^{238}U	~0.9	3.5	3.78 ± 0.15	(*19*)
		Plastic		
^{20}Ne	2.1	14.5	18.7 ± 1.2	(*5, 6*)
^{40}Ar	1.85	9.8	12.6 ± 0.6	(*5, 6*)
^{56}Fe	1.7	8.7	10.4 ± 0.4	(*5, 6*)

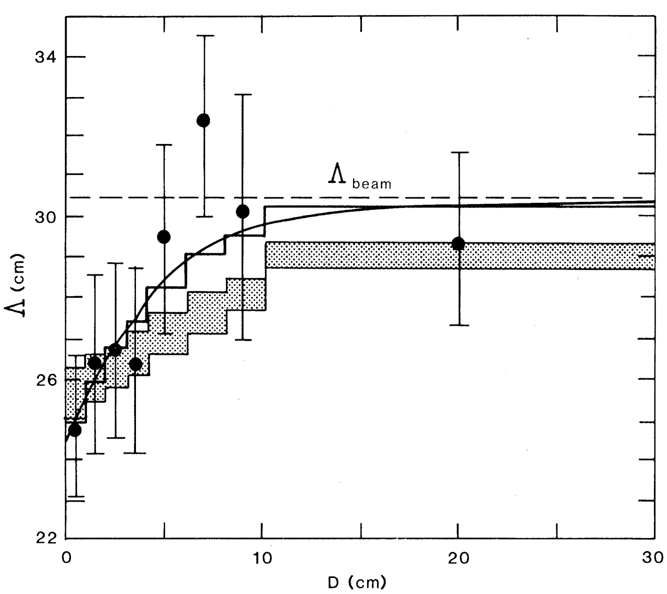
secondaries that are shown shaded in Fig. 1. I have not tried to optimize the fit but rather to demonstrate that the convoy qualitatively and quantitatively mimics "anomalous" behavior.

Friedlander *et al.* (*1*) briefly addressed the question of neutrons through a discussion of relatively rare background events. Yet if a very conservative estimate of one out of five interactions produces a low-transverse-momentum neutron, the neutron-induced "stars" along the tracks should be many times more abundant than they acknowledge. It is my hypothesis that, by and large, neutron-induced interactions have not been resolved from accompanying fragment tracks in emulsion (*10*).

Nucleon knockout with the projectile leading to a fragment and a convoy of one or more light particles on a common track is not the only class of conventional phenomena leading to short mean free paths. A second class is one in which the PF is in a low-lying particle-unstable state, ^{8}Be, for example. For a 17-GeV ^{8}Be PF, the laboratory (emulsion) angle between its decay α particles emitted isotropically in the moving frame would be $\leq 0.1°$. The two α particles would leave a track density close to that for lithium but with a shorter mean free path; $\lambda_{2\alpha}' = \lambda_{\alpha}/2 = 10.9$ cm compared to $\lambda_{Li} \sim 15$ cm. Conceptually, the familiar ^{8}Be example can be generalized to include any fragment left in a low-lying unbound short-lived state, for instance, ^{8}B* (0.78 MeV), ^{9}B, and ^{6}He* (1.8 MeV) among lighter nuclides, and is supported by the absence of anomalous mean free paths in deuteron-deuteron interactions (*11*) and in α-emulsion interactions (*3, 4*). It is important to recognize, however, that isotropic particle evaporation from highly excited fragments ($E^* \geq 8$ MeV) would yield tracks likely to be resolved, owing to greater opening angle.

The ability to resolve close tracks (or stars from tracks) in emulsions is routinely considered excellent. Regarding this question, Friedlander *et al.* (*1*) referred to a "distance of confusion" parameter, *d*: the distance short of which two resolved tracks appear merged into one. Their 1983 analysis of the number of resolved track-pairs plotted against *d* yields a *d* of 100 μm. However, their published graph clearly requires a two-component fit through which I calculate 100 μm plus a 20 percent component with $d = 500$ μm. Moreover, (i) the actual extent to which neutron-induced interactions are excluded by Friedlander's analysis, inherently restricted to both species being ionizing, is undeterminable and (ii) if a percentage of the tracks are collinear convoys, those are excluded de facto from the tautological resolution analysis. In this regard, Jain *et al.* (*12*) very recently reported PF's from 128-GeV ^{84}Kr with anomalous mean free paths of ~ 1 cm in emulsion. They observe 13 secondary interactions within 50 μm of their primary vertices compared to only one expected. In all, ΔZ was "very small," suggesting peripheral interactions. This behavior, convincingly supported by Jain's photographic illustrations, is precisely what is expected for a fragment plus convoy and is inconsistent with current anomalon hypotheses.

In addition to the arguments above, I wish to point out that the confidence with which emulsion studies are assumed to reveal the complete interaction picture is very seriously challenged when one compares fragmentation product distributions inferred from emulsions to those obtained by independent methods. Figure 2 illustrates the striking discordancy in ^{56}Fe fragment *Z*-distributions determined in emulsions (*1, 3, 4*) as compared with those determined by particle identification and radiochemical techniques (*13, 14*). Since the anomalon



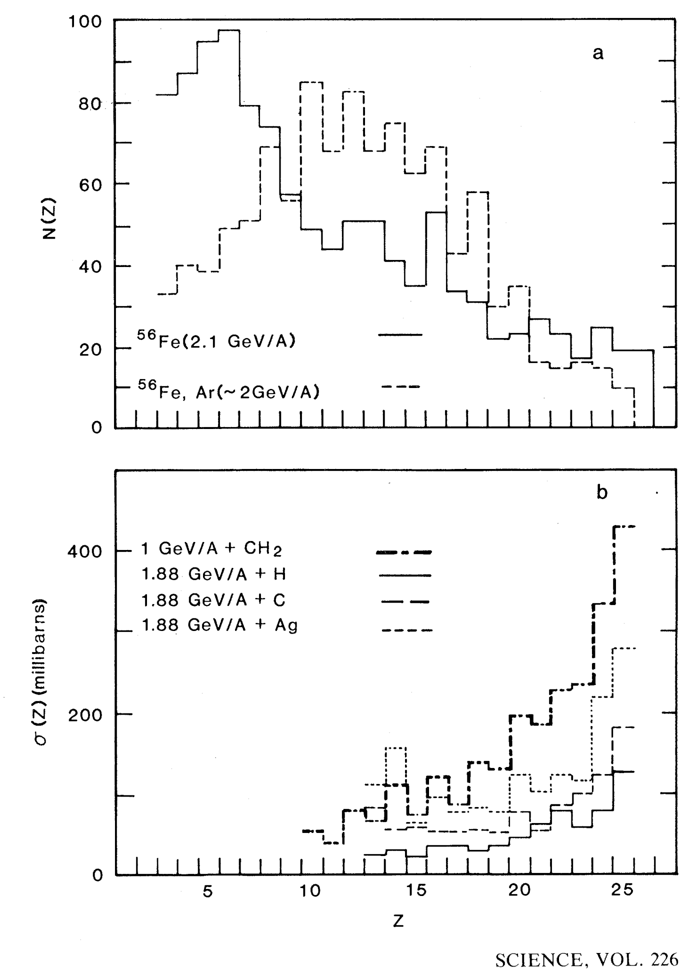


Fig. 1 (left). Scaled mean free paths (Λ) for secondary projectile fragments versus the depth (*D*) of their point of origin in emulsion. The experimental points and the smooth two-component curve are those of Friedlander *et al.* (*1*); the heavy histogram is my "anomalon" calculation for two components with $I_2 = 8$ percent; the shaded histogram is my "conventional" calculation for the convoy example in the text with $I_2 = 15$ to 20 percent. Fig. 2 (right). Discordant *Z*-distributions of fragments from 2-GeV/*A* ^{56}Fe: (a) in emulsion, from table IV of Friedlander *et al.* (*1*) (solid curve) and figure 1 of Jain and Das (*4*) (dashed curve, $\times 0.5$; includes fragments from ^{40}Ar); (b) in hydrogen, carbon, and silver from Westfall *et al.* (*13*) and at 1 GeV/*A* in "CH_2" from Webber and Brautigam (*14*).

phenomenon is predicated first on correct identification of events and only then by statistical analysis, established validity of the latter (*1*) becomes extraneous if the former is uncertain.

In 1983, the results of anomalon studies in which track-etching techniques were used in CR-39 plastic became available. The track method has excellent Z resolution and is sensitive to relativistic heavy ions with $Z > 8$ to 10 and to interactions with $\Delta Z \geq 1$. My convoy explanation is not clearly able to account for those observations by Heinrich *et al.* (*5*) and Tincknell *et al.* (*6*) in plastic which qualitatively appear to support those in emulsion. However, in 1984, both Stevenson *et al.* (*15*) and Symons *et al.* (*16*) reported the probable absence of anomalous mean free paths in plastic as the result of excellent statistics in conjunction with Cherenkov counting techniques. Moreover, in 1984, Heinrich *et al.* (*17*) improved their track-etching experiment and did not observe statistically significant anomalous mean free paths in plastic.

In conclusion, recent Cherenkov and track measurements have refuted the evidence for the anomalon effect in plastics. The authors of those studies rightly state that their results do not eliminate the possible production of anomalons on the heavier silver and bromine nuclei of emulsions. However, I have called attention to serious problems with the emulsion results vis-à-vis fragment Z-distributions at odds with counter and radiochemical measurements. I also have shown that the increased reaction probability evident in emulsion tracks of relativistic projectile fragments during their first few centimeters can be explained by a conventional model which includes two different final-state descriptions: (i) the possibility that multiple components of the forward-peaked projectile fragmentation process share a common track, and (ii) the likelihood that some fragments are produced in transient, low-excitation particle-unbound states that decay in flight into collinear products. In each separate situation, only a fraction (≤ 20 percent) of the observed events needs to be of the more complex but conventional nature summarized above. Both would reasonably be expected to contribute to explaining the seemingly anomalous values consistently obtained for experimental interaction mean free paths in emulsion via the prescribed but suspect procedure.

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Geological Rhythms and Cometary Impacts

Abstract. *Time-series analysis reveals two dominant, stable long-term periodicities approximately equal to 33 ± 3 and 260 ± 25 million years in the known series of geological and biological upheavals during the Phanerozoic Eon. Because the cycles of these episodes agree in period and phase with the cycles of impact cratering on Earth, these results suggest that periodic comet impacts strongly influence global tectonism and biological evolution. These two periodicities could arise from interactions of the solar system with interstellar clouds as the solar system moves cyclically through the Galaxy.*

The geological record has long been suspected of being periodic (*1–3*). Several collections of geological data possess enough homogeneity, precision, and completeness to permit statistically meaningful searches for long-term periodicities. One such data set is the list of geological ranges of marine organisms compiled by Sepkoski (*4*). Statistical analysis of the small subset covering Cenozoic and Mesozoic times [the past 250 million years (m.y.)] has revealed an approximate periodicity of either ~26 m.y. (*5*) or ~30 m.y. (*6*) in marine mass extinctions. We present here statistical evidence that this periodicity and another long-term periodicity (at ~260 m.y.) dominate the geological record of global tectonism over Phanerozoic time (the past 600 m.y.).

To avoid any possibility of subjective bias in selecting the data to be analyzed, we have accepted, deliberately without revision, the published lists of dates of the various tectonic phenomena to be studied. These lists are possibly incomplete and may accidently include a few local or minor episodes; furthermore, some dates have large estimated errors, including rounding to the nearest 5 or 10 m.y., especially for the Paleozoic Era. This means that we cannot expect to find a perfect correlation between the dates of related, or possibly related, tectonic phenomena in different data sets. Furthermore, phase lags may well exist and unrelated mechanisms may be at work among the different kinds of tectonic phenomena. Thus a fair amount of noise in the data is inescapable.

Simple inspection, often used in the past, is a poor method of analyzing data of this kind for periodicities, since it sometimes fails to reveal periods at all and, at best, cannot predict the statistical significance of any periods detected. We have therefore adopted an objective, nonparametric method of time-series analysis, specifically designed for records in which just the dates (and not the amplitudes) of the events are recorded and noise is a problem (*7*). In this method, the observed times t are fitted to a linear formula of the type $t = t_0 + nP$ (where P is a trial period, t_0 is a trial value for the most recent epoch, and n is an integer), and the resulting sums of the squares of the residuals are minimized at each trial period. By subtracting the resulting spectrum of residuals for the different trial periods from the continuous part of this spectrum, a spectrum of signal peaks ("residuals indices") is obtained. The mean time interval for N