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Anomalons as Pineuts Bound to Nuclear Fragments: A Possible Explanation

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Abstract:

We suggest that the properties of anomalons, the highly reactive heavy-ion reaction fragments observed in emulsions, can be explained by considering them to be "pineuts", i.e., a π^- bound hadronically to a neutron cloud extending out from the nuclear fragment.

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"Anomalons" is the name given to certain relativistic projectile fragments from high-energy heavy-ion collisions -- those fragments that have anomalously short reaction mean free paths (mfp's) immediately following their formation [1,2]. These were first postulated in 1954 from cosmic-ray evidence [3] and were seen subsequently by other groups scanning cosmic-ray emulsions [4-8]. Because of limited statistics and possible systematic uncertainties in and among the various experiments, these cosmic-ray results never attracted overmuch attention. With the advent of accelerator-produced relativistic heavy-ion beams, however, it has become possible to perform experiments that are more nicely controlled and have much greater statistics. Three more or less independent groups [1,2; 9; 10] have already reported positive results on observing anomalons, and many experiments, both with emulsions and with counters, are in progress by other groups [11].

The properties of anomalons can be summarized basically as follows (using numbers from Ref. 2, although Refs. 2, 9, and 10 are in essential agreement): When a high-energy (≈1-2 *A*GeV) heavy-ion beam (e.g., ^{16}O, ^{56}Fe) impinges on an emulsion, the primary heavy ions exhibit "normal" reaction mfp's, but, following a reaction star, the secondary and later generation projectile fragments do not. During the first few cm after their production, the mean free path for reactions is

abnormally small. The results are consistent with there being a small (≈6%) component having an anomalously short mfp (≈2.5 cm). This reduction in interaction mfp implies a correspondingly large increase in the reaction cross-section. Such an effect has not been observed for heavy-ion beams at lower energies, although extensive searches for anomalons produced below 1 *A*GeV have not been made. By the time some 5 cm has been traversed, the mfp's again agree with those of the primary projectiles. This implies that the anomalons either have all interacted or are decaying with a lifetime of $\gtrsim 10^{-10}$ sec. No "observable" decay particles appear to have been emitted along the track, from which it can be inferred that the decay proceeds by "neutral" emission, if any. The charges of the anomalons were determined by standard methods of nuclear emulsion research, and they were found to lie between 3 and 26, with the fractional effect on the cross-section greatest for the lower charge values, falling off until essentially "normal" behavior is reached at charge 26. (The effect for charge 2 is small, if it exists at all, and that for charge 1 is also questionable, although an anomalous component may have been seen in the work of Judek [1,11].) Finally, the anomalon tendency persists from generation to generation, i.e., tertiary and later generations of fragments produced by the interactions of anomalous secondaries show an even greater tendency toward anomalously short mfp's -- for tertiary and later generations the mfp is in fact shorter by ≈15% over that of the primaries [2].

Reference 1 concludes: "We are thus left in a predicament.

Conventional nuclear physics as well as systematics fail to explain the observations..." Actually, there have been a number of suggested explanations [12-18]. They range from postulating quasi-molecular nuclei and "bubble" nuclei to postulating the existence of a new quantum number. Mostly, however, they focus on rearrangements of quark states and on quantum chromodynamics. The difficulty is that none of them adequately explains the experimental observations.

To be considered viable, any explanation must be able to account for the following six points:

1) The energy range of production, i.e., $E \approx 1\text{-}2\ A\text{GeV}$.

2) The anomalously short mfp's themselves. (If this were purely a size effect, an increase of ≈50% in reaction cross-section would imply a decrease of ≈70% in the nuclear density.)

3) The average length of the "decay" paths, implying a mean lifetime of $\gtrsim 10^{-10}$ sec.

4) No charged particles emitted in the "decay" of anomalons.

5) The enhancement of the anomalon effect for fragments of low charge; however, with a drop-off at or exclusion of charges 2 and 1.

6) The existence of a memory effect; i.e., enhancement of the anomalon effect for tertiary and later generations produced by secondary fragments that were anomalons themselves.

We propose here a possible explanation of anomalons. It falls within the framework of "conventional" nuclear physics and requires no exotic or esoteric additions. Further, at least qualitatively, it explains

the aforementioned six points:

Anomalons could well result from a nuclear halo of "pineuts", hadronically bound states of a π^- and a few neutrons surrounding a nucleus. Although the *s*-wave π^--*n* interaction is repulsive, the *p*-wave is attractive [19]. Thus, the possibility exists that neutron-rich nuclei (or nuclei with locally neutron-rich domains, such as the neck in a fissioning system) might have a sufficiently attractive velocity-dependent potential to allow π^--*xn* hadronically bound "polyneutron" systems. This possibility was first considered by Ericson and Myhrer [20], who noted that a finite piece of nuclear matter might bind a π^- at lower than nuclear density and without absorption (or with diminished absorption). (Normally, even if such states were to exist, one would expect them to be strongly damped because of the strong absorption.) Based on a particular parametrization of the optical potential, they concluded that, although strongly-bound π^--nuclear states ought to exist in some neutron-rich medium-weight nuclei, such states would be the exception rather than the rule. Shortly thereafter, Friedman, Gal, and Mandelzweig [21,22], using a different parametrization taking into account new, precise data on 2*p* levels in pionic atoms, concluded that strongly-bound π^--nuclear systems should be the rule rather than the exception. The widths they obtained for such states, however, were prohibitively large for their observability except possibly in heavy nuclei. There have since been suggestions for experiments in which to look for π^--*xn* ("pineut") systems -- these focused on searching for

negatively-charged free π^--polyneutrons [23], which cannot decay by the strong interaction. (If the binding energy were to exceed the π-μ mass difference of 33.9 MeV, the weak-decay channel closes, as well.)

Relativistic heavy-ion collisions provide the best opportunity for forming such states, for it has been found that not only are π^-'s produced in copious quantities in these collisions, but also they are Coulomb-focused near the same velocity as the projectile and target fragments (as opposed to π^+'s, which are defocused) [24,25]. Thus, the target nuclei are bathed in a localized, intense flux of π^-'s. Further, the excited nuclear fragments may have neutrons in barely-bound orbitals with wave-functions tailing out well beyond the normal nuclear radius. (The Coulomb potential will relatively suppress the analogous tailing out of the proton wave-functions.) Whether or not free π^--xn clusters are bound, the conditions are optimal for forming a nuclear stratospheric halo enriched in pineut clusters.

This explanation of anomalons meets the six requisite conditions as follows:

1) The production energy range is satisfied. The π^-'s are produced abundantly above the $\Delta(1232)$ threshold ($\approx$0.7 *A*GeV lab). Note that the anomalon observations are below the region of abundant associated production of kaons and lambdas and below the threshold for producing anti-protons, so alternative explanations in terms of quark rearrangements encounter more serious difficulties.

2) We know that ordinary pionic atoms lifetimes are not

long enough to allow such atoms to qualify as anomalons, unless they were to have the π^- in rather high Rydberg orbitals. For example, Fig. 8 of Backenstoss [26] shows widths of ≈1 keV and 0.7 eV for the $2p$ and $3d$ levels, respectively, of $Z = 20$. Possibly the $4f$ levels could approach having anomalon lifetimes, but there seems no likelihood of injecting π^-'s into high Rydberg orbitals in the numbers needed to explain the ≈6% anomalon component. We thus turn for a model to a π^--dineutron (or possibly π^--polyneutron) cluster orbiting the nucleus at a distance such that the overlap of the π^- with any proton wave-function is small. This larger object would clearly exhibit an enlarged cross-section on emulsion nuclei, but it would cause reactions of the ordinary sort, as required by observations on anomalons. Examination of the shell-model level diagrams of Meldner [27,28] shows usually at least one oscillator shell of bound but unoccupied neutron levels above the normally occupied levels. For excited nuclei or nuclei nearer the neutron drip line we may find slightly bound, large neutron orbitals available. If we approximate neutron wave functions by a simple exponential, the r.m.s. radius = $3.23\ B_n^{-1/2}$ fm, with B_n in MeV.

3) The mean life of a free π^- is 26 nsec, and in a "free" pineut system (without protons and absorption), this would be increased as the binding energy is increased. (The phase space for weak decay would decrease until the π-μ mass difference was reached, whereupon such a "free" system would become stable with respect to this decay mode.) In the proposed pineut/anomalon systems, however, there *are* protons, and the

limiting factor will be keeping the π^--p wave-function overlap as small as possible. Lifetimes of $\gtrsim 10^{-10}$ sec might be attained for non-s-wave pineut orbitals outside the parent nucleus. That this is true is demonstrated by the behavior of π^-'s on the lightest elements [29,30]. The intrinsic odd parity of the pion necessitates that it annihilate from at least a p-state, which introduces geometrical complications that retard the decay. [See also under point 4).]

4) The predominant decay mode of the orbiting pineut might well be a neutral decay, with the π^- mass being given to a pair of neutrons, as occurs with pionic ^{2}H. This decay mode occurs by interaction of the π^- with the virtual π^+ of a proton in a correlated p-n pair, necessary for the conservation of momentum. (This capture mode is most often accompanied by some photon emission.) There is also the possibility of a 2γ branching mode if the π^- charge exchanges on a proton to form a π^0, which subsequently decays. This decay mode occurs of necessity with pionic ^{1}H, but it has also been seen from pionic ^{3}He, where the p-n correlation introduces geometrical complications. These decay modes are discussed in greater detail elsewhere [31-33].

5) The peaking of the effect for low-charge fragments follows straightforwardly, for the pineut halo would have the greatest effect as part of a small fragment. The effect would lessen as the size of the fragment increased, so that the mfp's of anomalons would tend to become rather independent of charge, as has been, in fact, observed. On the other hand, the diminished effect (if any effect does exist) for charges smaller than 3 also follows, for here the requisite neutron excess (or

tailing of the neutron wave-functions) is not available.

6) The existence of memory enhancement is also a straightforward consequence of our model. A prime requisite for the anomalon effect is this neutron excess (or tailing). This would be expected to persist more or less from generation to generation.

Several predictions and tests of our explanation come to mind immediately. First, the anomalon effect should be enhanced whenever there is an excess of neutrons. Thus, the effects from neutron-rich beams such as ^{48}Ca should be investigated, and comparisons between, say, ^{40}Ca and ^{48}Ca beams should be made. Also, very heavy beams such as ^{238}U should be tested, for these provide very neutron-rich domains, especially in their necks while fissioning. Second, photons from the radiative capture or charge exchange mode should be looked for. A shadowed, drift experiment downstream from the target could possibly enable these to be seen above the photon background from other effects, for example, those originating from the decay of free π^0's. Third and finally, the falling off of the anomalon effect with very small charge should be examined very carefully, inasmuch as our model predicts that the effect should be quite small, if not vanishingly small, for ^{4}He and especially for ^{3}He.

Our proposed explanation of anomalons as pineuts must perforce remain qualitative at this time for two reasons. First, quantitative calculations of pineut properties are beyond present theory and will require time for development. Second, even the experimental anomalon

data are themselves only qualitative at this point, so considerably more experimental data are needed. The existence of anomalons is by now reasonably well established -- although there are still some doubters[11]. If they do exist, they mark a new and exciting frontier in nuclear science. We hope our suggestions will aid in extending this frontier.

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