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Have We Seen a Heavy Antinucleus?*

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The hypothesis of the first observed heavy antinucleus is proposed for the event of Price *et al*. This hypothesis demands depletion of the high-energy knock-on electrons, which should be clearly evident in the nuclear emulsion. This hypothesis does not directly contradict any previous antimatter search; and conflict with extrapolations from previous searches is of small statistical significance.

The cosmic-ray event of Price *et al.*[1] has received much critical comment. Several authors have proposed alternative hypotheses to the originally claimed identification.[2-5] Experimental interpretation of this event will be briefly discussed and a specific experimental recommendation will be made to help settle the experimental controversy. I will furthermore propose that the experimental descriptions of the particle to date suggest identification as an antinucleus. Quantitative predictions must be matched by the nuclear emulsion data to substantiate the antinucleus hypothesis. The cosmological consequences of the observation of a heavy antinucleus would be considerable. Let us consider, in turn, the results from each of the detectors.

As nuclei slow, their ionization rises steeply. This particular particle had so high an ionization rate ($|Z/\beta|\approx 114$) that, were it any nucleus previously seen among the cosmic rays, it should have slowed measurably in passage through the 0.9-g/cm^2 Lexan stack.[1] For instance, a uranium nucleus would be expected to have its Z/β increased by three units.[1] Nevertheless, its ionization did not rise.[1] *This particle appears to be the most penetrating particle with such a high ionization seen to date.*[1] However, interpretation of this observation has led to controversy.

It is agreed that the Lexan data cannot be reasonably reconciled with any slow ($\beta \leq 0.6$) normal nucleus, fragmenting or otherwise.[1,4,5] Given a possible, but unlikely, chain of fragmentations, normal nuclei with speeds $\beta > 0.65$ have been considered to fit the Lexan data.[1-5] The Lexan data better match nuclei with higher speeds so that, for fast normal nuclei ($\beta > 0.8$), agreement is reasonably within experimental tolerances.[1-5]

It has long been known that negative particles are more penetrating than their charge conjugates.[6] The difference is due to higher-order electrodynamics. It has not been universally realized how large these corrections can be for heavy nuclei. Using order-Z^3 calculation for the distant collisions[7] (which is a tiny correction) together with an exact form for the close collisions,[8] I find that the stopping powers for nuclei and their charge conjugates differ by 15% to 25% in the appropriate realm. These differences arise predominantly from close collisions. Thus, *we should expect the heaviest antinuclei to be the most penetrating particles of any given ionization seen to date.* Because Lexan responds predominantly to distant collisions,[9] we expect its response to reflect $|Z/\beta|$ independently of the sign of Z.

It has been pointed out, for instance in Refs. 2–5, that reactions which noncataclysmically diminish $|Z_{\mathrm{projectile}}|$ allow the projectile to appear more penetrating. Such interactions are featured in normal-nucleus explanations of the event with $0.65 \leq \beta \leq 0.80$.[1-5] One wonders whether such processes might occur when antinuclei penetrate the Lexan. I have no cross sections for specific channels of charge loss in collisions of antinuclei with normal nuclei excepting $(\bar{p},p)$ and $(\bar{p},d)$. In the appropriate speed range, the $(\bar{p},p)$ cross sections are 3–4 times greater than the (p,p) cross sections.[10] One intuitively thinks of all $(\bar{Z}_1, Z_2)$ collisions as being cataclysmic because interpenetration of nuclear matter of opposite signs would involve total annihilation. Recent experiments indicate, however, that interactions with small charge loss (among normal nuclei) occur at very large impact parameters[11] so that little interpenetration may actually occur. Most of the interaction cross section (among normal nuclei) is seen to have small charge loss.[12] In conclusion, I expect that, compared with normal nuclei, antinuclei probably have larger cross sections for small charge losses. Moreover, I expect that, in Lexan, interactions causing small charge loss are more likely for antinuclei than for normal nuclei.

That antinuclei are more penetrating makes their fit to the Lexan data better than that of their charge conjugates. Thus, let us consider as fitting the Lexan data the charge conjugates of the normal nuclei which have been previously proposed, i.e., antinuclei with speeds $0.65 \leq \beta \leq 0.85$. Because of the constraint, $|Z/\beta| = 114$, this corresponds to $-96 \leq Z \leq -75$. Among these candidates, the lighter antnuclei must fragment to fit the Lexan while the heavier ones need not. If such antinuclei can fit the remainder of the experiment, my hypothesis is supported.

A nuclear emulsion records, in convoluted form, the production of knock-on electrons from close encounters. My Monte Carlo study of energy deposition in emulsions[13] allows the following generalizations: (1) Saturated darkening (at the core of an emulsion track) reflects knock-on energies $1\ \text{keV} \lesssim E \lesssim 50\ \text{keV}$, while unsaturated darkening (in the halo, namely 10–30 μm from the core) reflects $25\ \text{keV} \lesssim E \lesssim 1000\ \text{keV}$. (2) Given my constraint, $|Z/\beta| = 114$, the energy deposition in the core is virtually independent of Z. (3) Among the positive nuclei with $\beta > 0.6$ and $Z/\beta = 114$, energy deposition in the halo depends only weakly on Z. These facts are in line with the predictions of earlier crude models. The preceding knock-on energy ranges will define core and halo for the remainder of this Letter. These definitions correspond to emulsion regions commonly studied in cosmic rays, and should be noncontroversial in interpretation.[14] Thus, if one can show that the energy deposition in the halo was significantly depleted from that expected for $\beta > 0.6$ with $Z/\beta = 114$, the particle is then proved to be unique. This is what was claimed by Price *et al.*—normal R_1, "core radius," and *diminished* R_2, *"halo radius."* Their measurement schemes, however, have provoked controversy.[2-4]

The core is insensitive to the identity of the particle, so I will omit it from further discussion. The "halo-radius" measurement scheme has drawn criticism for a number of reasons.[2-4] These objections center technically around the fact that the reported "halo radii," typically 50–100 μm, are large compared with the region where dependable signal is uncontroversially expected.[14] Regardless of what may be measured beyond 50 μm, we must wonder whether the halo region really was depleted. This question could be readily addressed by the publication of photomicrographs of various tracks.[15] I propose that this be done. These photos would allow appraisal of the halo in the region where dependable signal is expected.[14] If the halo in question is not obviously smaller than the halos of normal nuclei with large Z/β, the issue will be dead, and the particle will be presumed a fast, normal nucleus. If the halo is obviously small, the pitch of the controversy drops to the more workaday questions such as calibrating the particular emulsion sheet, statistical fluctuations, etc. These questions are not yet completely answered. Comparing tracks of similar pitch angles would eliminate preferential effects due to surface loss of electrons, which have been emphasized by Friedlander[2] and Fowler.[3]

The appropriate cross section for the production of knock-on electrons in emulsions is the Mott exact-phase-shift formula.[16] Table I exhibits relevant ratios of these cross sections for appropriate antinuclei to that of one normal nucleus which would fit the Lexan acceptably. We can see that *the halo region will be depleted from that expected for a normal nucleus if the particle of Price et al. is an antinucleus.* To estimate the statistical distance between the emulsion halos of the entire populations of positive and negative nuclei which might fit the Lexan, I have integrated the appropriate cross sections. Among all such normal nuclei, the halo has > 3000 electrons with summed kinetic energy > 380 MeV. Among all such antinuclei, the halos have < 2400 electrons totaling < 240 MeV. These differences would be impressive: An antinucleus with $Z/\beta = -114$ should have an emulsion track similar to those of positive nuclei with $75 \lesssim Z/\beta \lesssim 85$, examples of which are commonly observed among cosmic rays, whereas a positive nucleus with $Z/\beta = 114$ should have one of the darkest tracks ever seen. *The antinucleus hypothesis is untenable if the*

TABLE I. Knock-on energy spectra. The ratio of $d\sigma/dE$ for various antinuclei to $d\sigma/dE$ for $Z=92$, $\beta=0.81$. The ratios vanish when $E>E_{\text{cutoff}}$. The ratios on this table are computed from cross sections obtained via interpolation from Doggett and Spencer (Ref. 8). The stated ratios have uncertainties of ± 0.02.

		$(d\sigma/dE)_{Z,\beta}/(d\sigma/dE)_{Z=92,\beta=0.81}$ Energies (keV)					
Z	β	$E=30$	$E=100$	$E=300$	$E=700$	$E=1000$	E_{cutoff} (keV)
−92	0.81	0.88	0.78	0.53	0.32	0.27	1909
−82	0.72	0.87	0.76	0.52	0.31	0.26	1096
−78	0.68	0.88	0.78	0.53	0.32	0.00	900
−75	0.66	0.87	0.76	0.53	0.32	0.00	780

above prediction is not met. We must expect that the above prediction is qualitatively met by the data on the basis of the descriptions of their event by Price *et al.*[17]

A Čerenkov detector was also used in Ref. 1. The concept behind this device is to record the edge of the burst of Čerenkov light on a fast photographic emulsion. Price *et al.* stated that "at this point in the reanalysis of the previously reported Čerenkov data, no definitely proved limits on the size of the Čerenkov spot can be supported."[18]

We must consider whether this antinucleus interpretation can be reconciled with previous experimental observations, in particular the previous searches for antinuclei.[19] These searches have yielded no certain discoveries of heavy antinuclei. The total collected flux of all previously reported antinucleus searches is about four orders of magnitude smaller than the collecting power of the plastic/emulsion experiments so that no nuclei approaching the appropriate magnitude ($|Z| \geq 75$) could have been expected in the previous searches. Furthermore, almost all of the previous searching was done at high rigidity, whereas the particle of Price *et al.*—if an antinucleus—was of rather low rigidity. Thus, *there is no direct negative experimental evidence against our interpretation.*

It is not obvious that either the charge spectrum or the rigidity spectrum must be locally identical for positive and negative nuclei. Even so, if we assume that, for all rigidities and all charges, the antimatter fraction is no larger than the most rigorous upper limit obtained to date, I conclude that *the discrepancy, if any, with indirect experimental inference is not of great statistical significance.* This results from the ambiguity in assigning a "flux" on the basis of a single event. Even if the particle of Price *et al.* exactly matches the antinucleus hypothesis, it is always necessary to confirm any single-event observation—expanded searches for antinuclei should be conducted among the highly charged, lower-rigidity cosmic rays. The differences between electron knock-on cross sections for positive and negative nuclei might be exploited to expand economically the previous antimatter searches by orders of magnitude.

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[13]These calculations used an exact form for multiple scattering, together with an exact form for large-angle scatters; scattering from the bound electrons was also included together with range straggling, all describing the transport of electrons in media. The emulsion was described as a mixture, not as any single "element." Edge loss of electrons was included. The Mott cross section [N. F. Mott, Proc. Roy. Soc. London, Ser. A 135, 429 (1932)] was used to describe knock-on electron production. My calculations should accurately describe expectations and fluctuations in energy deposition in emulsions.

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[15]*Note added.*—Photodensitometry of the halo might provide a more quantitative basis than comparison of photos. This must be considered with the proviso that the tracks in question not have been intensively observed prior to the photodensitometry because of incidental physical and optical changes which accompany intensive observation. Photos may exist of the emulsion before intensive examination.

[16]Mott, Ref. 13. Please note that this formula is *not* the famous first-Born-approximation result, also due to Mott, which involves a factor of $(1-\beta^2 \sin^2\theta/2)$ multiplying the Rutherford formula, but a rather more complicated result reflecting exact integration of the Dirac equation. The whole issue of Coloumb scattering is treated lucidly in J. W. Motz, Haakon Olson, and H. W. Koch, Rev. Mod. Phys. 36, 881 (1964).

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