SEARCHES FOR EXOTIC PARTICLES

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1. Introduction

My group is engaged in an interdisciplinary attack on problems relating to astrophysics, particle physics, and relativistic heavy-ion physics. I shall discuss several examples of ways in which experiments in one of these disciplines may fundamentally advance our understanding of another of these disciplines.

Table 1 summarizes searches for exotic particles in progress or planned by members of my group. Because several of our searches involve CR-39 plastic track detectors, I shall begin with a brief description of track-etch techniques for particle location and identification. For a more detailed account, see ref. 1.

Table 1. Searches for Exotic Particles in Berkeley

	in progress	planned	proposed or to be proposed
1. GUT monopoles			
a) plastic scintillator, $\beta >$ few x 10^{-4}	20 m^2 sr yr, 600 g cm^{-2}	——	depends on outcome of low-β proton expts.
b) CR-39 track detectors, $\beta >$ few x 10^{-3}	75 m^2 sr yr, 600 g cm^{-2}	600 m^2 sr yr, 540 g cm^{-2}	
2. Lower-mass monopoles (CR-39 detectors)	PEP ($\sqrt{s}$ = 29GeV) $\sigma <$ few 10^{-37} cm^2	$\bar{p}p$, FNAL $\sqrt{s}$ = 2 TeV	e^+e^-, SLC, $\sqrt{s} \approx$ 120 GeV
3. Antinuclei, $\lvert Z\rvert > 20$, sensitivity $\bar{Z}/Z \gtrsim 10^{-7}$ (scint. + Cerenkov + CR-39)	——	——	~1 m^2 sr yr on balloons
4. Anomalons			
a) LBL Bevalac	2 GeV/u ^{40}Ar into CR-39	1 GeV/u ^{238}U into U & CR-39	——
b) future A-A collider	——	——	U + U, $\sqrt{s}$ = 20 GeV/u
5. Metastable or stable quark-matter droplet			
a) Bevalac or A-A collider	2 GeV/u ^{40}Ar	1 GeV/u ^{238}U	20 GeV/u U + U
b) Chacaltaya (CR-39)	75 m^2 sr yr	600 m^2 sr yr	——

2. Particle Detection and Identification with Plastic Track Detectors

The side view of a portion of a track-etch detector in Fig. 1(a) indicates schematically the submicroscopic region along a particle's trajectory within which the chemical reactivity of the solid is increased as a result of the breaking of chemical bonds by ejected electrons. After etching in an appropriate reagent for a time t_1, a thickness $v_G t_1$ of material has etched away at the general rate v_G, and a conical etch pit has developed at the intersection of the particle's trajectory with each surface. The shape of the etch pit depends on the combined action of (a) etching along the trajectory at a rate v_T that is an increasing function of Z/β and (b) the isotropic etching of freshly exposed material at the rate v_G. The circles in (b) indicate the graphical construction of etch pit shapes analogous to Huyghens wavelets and Cerenkov wave patterns. In this sketch the particle has slowed and the bottom etch pit is therefore larger than the top one. The mouth sizes (or depth) of successive etch pits along a particle's trajectory can be measured microscopically or by automated methods and used to determine its charge and velocity. If the etching is continued for a time t_2, as in (c), the two etch pits connect and the event can be located with an ammonia gas mapping technique.

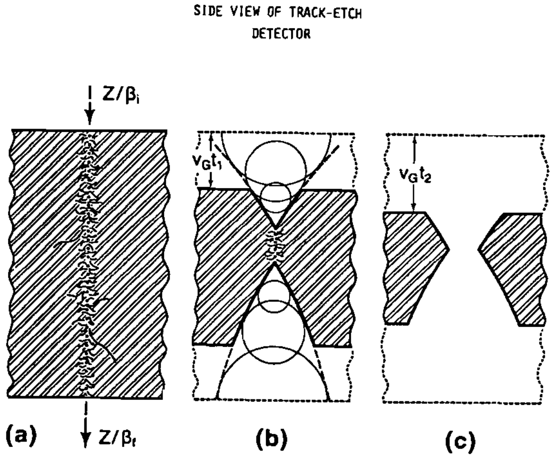

Fig. 1. Particle track in a plastic track detector before etching and after etching for times t_1 and t_2.

3. Grand-Unification (GUT) Magnetic Monopoles

Grand unified theories unify quantum chromodynamics with the Weinberg-Salam theory of electroweak interactions. Due to the extremely large energy at which symmetry breakdown occurs in these theories, it will be impossible to test them by studying interactions of particles in cosmic rays or at conceivable accelerators. Several predictions of GUT's can be tested by alternative means. For example, conditions in the early universe were favorable for the production of magnetic monopoles of mass $\sim 10^{16}$ GeV/c^2 which should exist, according to 't Hooft and Polyakov, within grand unified theories.

Figure 2 compares the flux of GUT monopoles, based on the possible detection of one monopole by Cabrera,[2] with the calculated upper limits[3] based on compatibility with the known Galactic magnetic field and the mass density in the Galaxy and universe. Dimopoulos et al.[4] have argued that the high Cabrera flux could be reconciled with the Parker limit[3] if monopoles cluster in the solar systems of galaxies, forming orbiting clouds with velocities similar to those of meteorites ($\sim 10^{-4}$ c) at the radial distance of earth from the sun. To maintain the reservoir of orbiting monopoles with an estimated residence time of $\sim 10^8$ yr requires a source of $\sim 10^9$ monopoles/sec. To distinguish between the two suggested sources--the sun and the Galaxy--one would have to measure the monopole velocity spectrum with a detector of very large collecting power. A galactic source would provide a flux of fast ($\sim 10^{-3}$ c) monopoles at the Parker limit, $\sim 10^{-3}$ m^{-2} yr^{-1}; a solar source would probably have a much lower flux of monopoles with velocities this large.

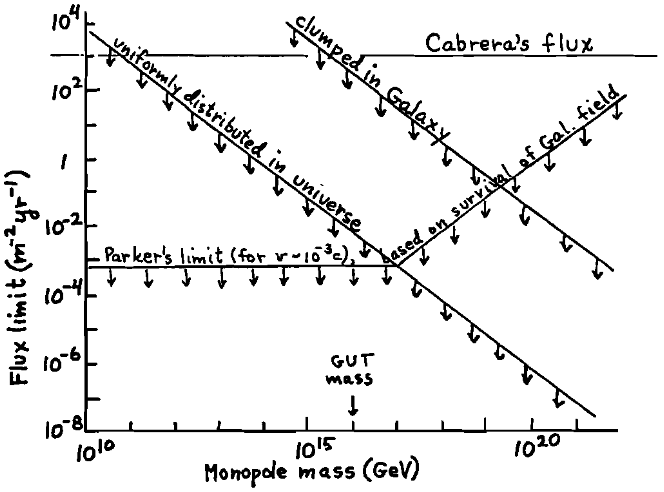

Fig. 2. Upper limits[3] on fluxes of supermassive monopoles based on their gravitational effects and on their tendency to extract energy from the Galactic magnetic field.

Regardless of whether the Cabrera event will turn out to be a real monopole, it is important for astrophysics, particle physics, and cosmology to search for GUT monopoles with a detector of enormous collecting power (up to $\sim 10^3$ m^2) and ability to measure velocities to well below 10^{-3} c. A positive result would be a triumph for grand unified theories, would support the standard model of the early universe, and would force us to revise astrophysical views of sources and sinks of the Galactic magnetic field and of the matter content of the Galaxy.

Ahlen and Kinoshita[5] have recently calculated the electronic stopping power of a slow monopole in a condensed medium. They find that, for $\beta \lesssim 0.01$, dE/dx is proportional to the monopole velocity and that the stopping power of a monopole with twice the Dirac charge is at least as large as that for a proton with the same velocity. This important result is a prerequisite to designing monopole detectors. Other mechanisms of energy loss associated with magnetic effects such as Zeeman line-splitting may increase the total energy loss rate in certain media.

Kinoshita and I[6] have used an array of CR-39 detectors at the summit of White Mountain, CA (603 g/cm^2) to set a 95% CL upper limit of 0.4 m^{-2} yr^{-1} on the flux of monopoles with the Dirac charge, $g = e/2\alpha$, above some minimum detectable velocity that we originally estimated as ~ 0.02 c. Our estimate was based on calibrations showing that charged particles with $Z/\beta \gtrsim 12$ were detectable by our rapid scanning technique, and on the assumption that total energy-loss rate is the relevant quantity for track formation by low-velocity monopoles in CR-39. We now think that the minimum detectable velocity is somewhat below 0.01 c.

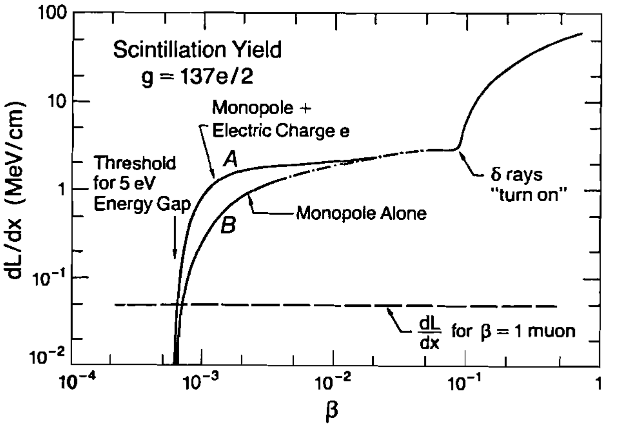

Fig. 3. Scintillation response as a function of monopole velocity calculated for NE110 (ref. 7).

It is possible that a more rigorous analysis of the mechanism of track formation in CR-39, coupled with direct measurements of etching of tracks of singly charged particles, would indicate that the minimum detectable velocity of a Dirac monopole is as low as 10^{-3} c. We plan two kinds of experiments. The first is to study the etching of tracks of tritons at velocities down to 10^{-3} c in CR-39 using a scanning electron microscope to resolve the sub-micron etch pits. (The estimated range of a 6 keV triton in CR-39 is 0.1 μm.) The second is to bombard CR-39 with monoenergetic neutrons of energies such that elastic proton recoils (from hydrogen in the polymer structure) extending up to the energy of the neutrons are distributed throughout the sample. One then measures the increase in bulk etching rate v_G resulting from the distributed low-energy protons, whose ionization rates can be quantitatively related to that of a Dirac monopole.

Plastic scintillators are much more sensitive than CR-39 to high-velocity particles and may also be capable of detecting monopoles at lower velocities than will CR-39. Ahlen and Tarlé[7] have used data on the scintillation yield of protons in the plastic scintillator NE110 and a model in which organic scintillators are approximated as insulators with 5 eV band gaps to show that there should be a scintillation response threshold at $\beta \sim 6 \times 10^{-4}$. Figure 3 shows the scintillation yield as a function of velocity calculated by Ahlen and Tarlé for a Dirac monopole alone and bound to a particle with charge e. Ahlen and Tarlé, with a student, T.M. Liss, are preparing to measure the response of scintillators to recoil protons from elastic collisions of slow neutrons at energies down to 100 eV, which will allow them to test the calculated response down to $\beta = 5 \times 10^{-4}$.

We are constructing a monopole detector based on plastic scintillators of initial collecting power 20 m^2 sr. If the recoil proton results show that monopoles should be detectable at velocities lower than 10^{-3} c, we will proceed with plans for a detector of vastly greater collecting power, based on either plastic scintillator or CR-39, depending on which has the lower threshold velocity.

4. Search for Exotic Particles at High-energy Colliders

Kinoshita, Fryberger and I[8] have used thin sheets of CR-39 to look for particles with ionization rates greater than that of a nucleus with $Z/\beta = 20$, produced in e^+e^- annihilations at a center-of-mass energy of 29 GeV at PEP. The 95% CL upper limit on cross section, 1×10^{-36} cm^2 in ref. 9 and $\sim 3 \times 10^{-37}$ cm^2 in a more recent experiment, applies to monopoles of mass up to ~14 GeV/c^2 and to electrically charged particles within a range of charges and masses shown in Fig. 4 and governed by the necessity to traverse a certain thickness of beam pipe and detector with an ionization rate such that $Z/\beta > 20$. If, as De Rujula, Giles, and Jaffe speculate,[9] free quarks can be produced (albeit at a very low cross section) in e^+e^- annihilations, they would "eat" nucleons in traversing matter, producing quark-matter droplets that might have high enough ionization rate to be detectable in CR-39.

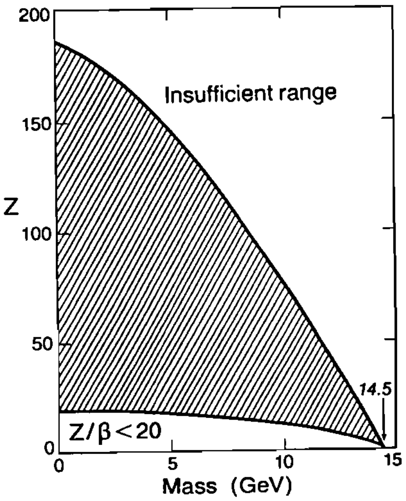

Fig. 4. Region of charge and mass studied in search for highly ionizing charged particles produced in e^+e^- annihilations (ref. 8).

Kinoshita and I have been motivated by this and other speculative papers to design further CR-39 experiments that could search for exotic particles at higher center-of-mass energies. Our proposed search at the Fermilab $\bar{p}p$ collider ($\sqrt{s} = 2$ TeV) has been approved, and we have submitted a letter of intent to propose a search at the Stanford Linear Collider.

5. Heavy Antinuclei and the Question of a Baryon-symmetric Universe

Advocates of grand unified theories argue that the same baryon-number nonconserving interactions that mediate proton decay allow an initial state of the universe that is symmetric between matter and antimatter to evolve into one that consists entirely of matter with a baryon to photon ratio of $\sim 10^{-10}$, as observed. Ahlen, Salamon, Tarlé and I[10] have shown, however, that the strongest evidence against antimatter, namely the absence of energetic heavy antinuclei in the cosmic rays at the level ~1 part in 10^4, applies only to the contents of our own Galaxy. There is as yet no evidence that matter and antimatter do not both exist, separated on the scale of galactic clusters. On the basis of our estimate that extragalactic cosmic rays with energies greater than 1 GeV/u should be able to penetrate into our Galaxy with an attenuation no greater than a factor of 10, and using another estimate that the ratio of metagalactic to galactic cosmic rays just outside our Galaxy is 10^{-5} to 10^{-4}, we conclude that a new search for antimatter in cosmic rays at a concentration of 10^{-6} to 10^{-7} would sample the contents of numerous distant galaxies. The discovery of just one antinucleus heavier than antihelium would establish the existence of antistars (since nucleosynthesis did not proceed beyond $|Z| = 2$ in the big bang), would throw into question the grand unified theories, and would alter our view of cosmology and the present universe.

Previous searches used magnetic spectrometry or calorimetry, both of which have an unfavorable ratio of collecting power to weight that makes it difficult to detect concentrations as low as 10^{-5}. Figure 5 shows positive results of a search for antiprotons at low energies, with calorimetry,[11] and at higher energies, with a superconducting magnet.[12] Although the low-energy antiproton concentration is difficult to understand in present models of cosmic ray dynamics, because of the ease with which antiprotons can be made in cosmic ray interactions it would be unwarranted to attribute the observed $\bar{p}p$ ratio to large-scale concentrations of antimatter.

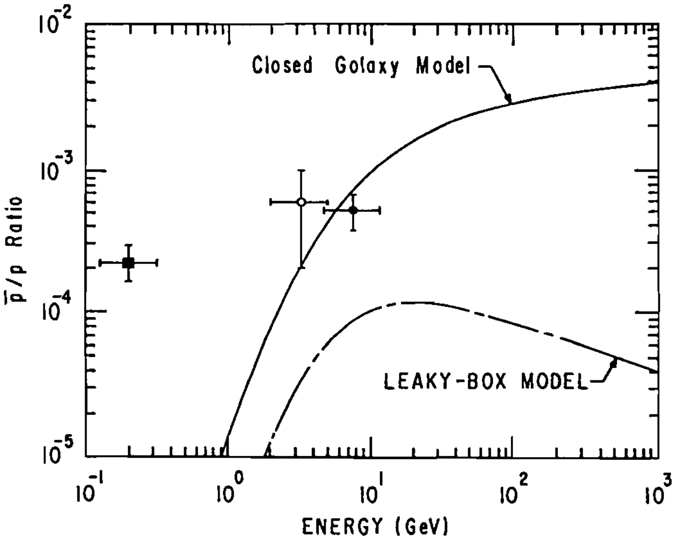

Fig. 5. Ratio of measured antiproton to proton flux as a function of energy compared with two models of cosmic ray propagation. The excess of antiprotons at low energies, if confirmed, is hard to understand within cosmic ray models.

We have conceived a new method of detecting heavy antinuclei ($|Z| \geq 20$) that has a collecting power greater than 10 m^2 sr and can reach the 10^{-7} level in 10 days of balloon exposure.[13] The method relies on well-established principles of energy loss processes of fast heavy ions in matter. By incorporating the relativistic Mott and Bloch corrections to stopping power, Ahlen et al.[13] have shown that the stopping power of relativistic charged particles for Z = 1 to 26 can be predicted to an accuracy of 0.1%. For a given velocity the stopping power of an antiiron cosmic ray particle is ~6% less than that of an iron cosmic ray, a consequence of the contribution of odd powers of Z in the Mott correction. Almost all of the Mott correction involves collisions with energy transfers to electrons greater than several keV. We have shown that almost 90% of the signal produced by relativistic iron nuclei in plastic scintillators is due to energy transfers greater than 11 keV (because of strong ionization quenching in the track core) and that the difference in scintillator response to Fe and $\overline{\mathrm{Fe}}$ will be ~15% for a given velocity. CR-39 is complementary to plastic scintillator in that it responds only to energy transfers less than 5 keV, which means it is insensitive to the Mott correction and responds the same to Fe and $\overline{\mathrm{Fe}}$. The intensity of Cerenkov radiation has been shown experimentally and theoretically to be immune to charge-asymmetric effects for Z up to 26.

Our technique combines all three types of detectors in a single instrument. As Fig. 6 shows, the magnitude of the particle charge and its velocity are determined by the signals from the CR-39 and Cerenkov detectors. The sign of the particle charge can then be determined from the scintillator signal, as shown in Fig. 7. A total of 12 layers of CR-39, 2 plastic scintillators, and 2 Cerenkov counters enable Fe and $\overline{\mathrm{Fe}}$ to be distinguished without confusion from nuclear interactions and other backgrounds. We hope to construct this instrument and reach a sensitivity of ~3 x 10^{-7} (95% CL) in a total of five two-day balloon flights.

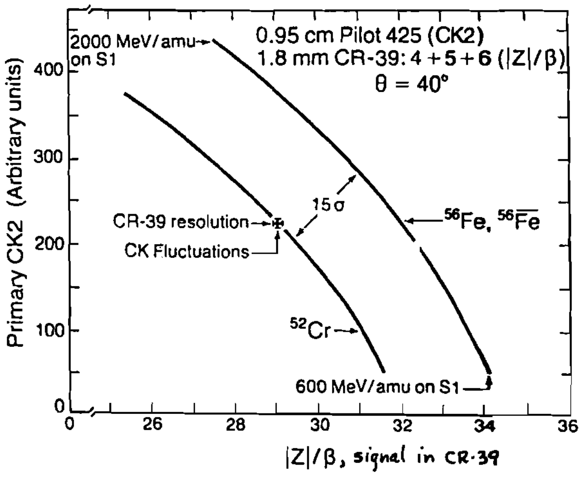

Fig. 6. Predicted response of Cerenkov counter as a function of response of CR-39, which measures |Z|/β. Error bars are single measurement standard deviations based on measured detector response (ref. 10).

6. Anomalons

Probably the most important result to come from research at the LBL Bevalac, if it can be convincingly established, is the observation,[14] using nuclear emulsions as both target and detector, that some projectile fragments of 2 GeV/u nucleus-nucleus collisions have shorter interaction mean free paths than do primary nuclei. The effect disappears within the first several centimeters after collision and has so far been demonstrated only on a statistical basis. Figure 8 shows the mean free path as a function of distance for fragments of iron and oxygen nuclei.[14] The calculated curve, which represents an acceptable fit to the data, results from assuming that 6% of all projectile fragments with Z $\geq$ 3 have the exceedingly short mean free path of 2.5 cm.

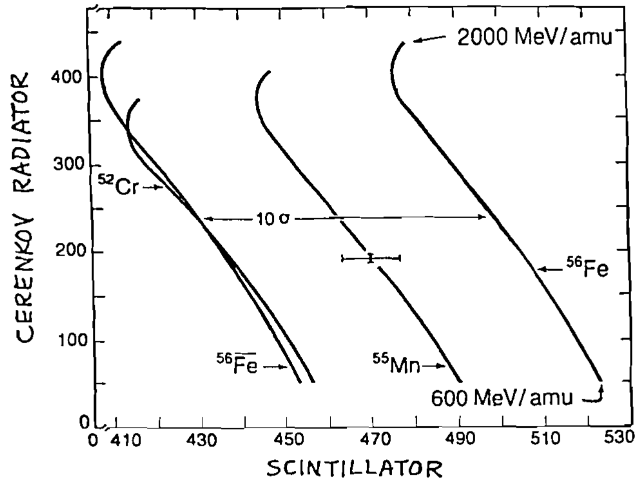

Fig. 7. Predicted response of Cerenkov counter as a function of scintillator response for various projectiles (ref. 10).

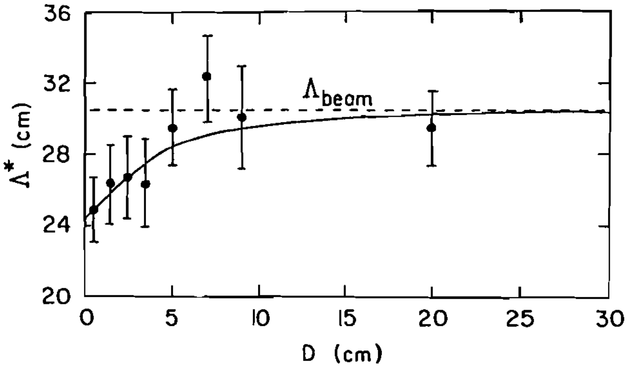

Figure 8. Estimates of Λ^* for the mean free path parameter Λ at various distances D from the origins of projectile fragments. Λ takes into account the expected dependence of mean free path on nuclear size via the relation $\lambda = \Lambda Z^{-b}$, where Z is the measured charge of a fragment and b has been determined to be ~0.4 for stable beam nuclei (ref. 14).

Jain and Das[15] have obtained quite similar results using 2 GeV/u beams or argon and iron; Barber et al.[16] have obtained similar results using cosmic ray nuclei at a variety of energies and charges as projectiles.

There may be an energy threshold for the effect. Aggarwal et al[17] claim that their data at a projectile energy of 1 GeV/u show no effect. Such a strong assertion is unwarranted in view of the large statistical errors, which are also consistent with a positive effect of magnitude comparable to that at 2 GeV/u. Recent data on projectile fragments of 4 GeV/u carbon beams reported by Badawy[18] can be fitted by assuming that the fraction of projectile fragments with a 2.5 cm mean free path has increased from 6% to 16%. The exposure was done at Dubna. Unless a decision is made to produce heavy ion beams at the CERN PS, it will not be possible to follow up on this exciting result until VENUS or some other new U.S. high-energy heavy ion accelerator is built.

All four of the above results have been obtained with nuclear emulsions. It is essential to establish whether the effect can be seen using a different detector free from systematic errors that may be associated with nuclear emulsions. It is also essential to find some property or decay mode that identifies which fragments are "anomalons." Several of the numerous papers aimed at interpreting anomalons have proposed objects with unusually large cross sections and relatively long ($\gtrsim 10^{-10}$ sec) lifetimes for decay into normal nuclei via emission of high-energy gamma rays. Liss, Ahlen, Tarlé and I[19] have used lead-glass detectors to search for delayed high-energy gamma rays emitted from projectile fragments of 940 MeV/u ^{56}Fe interactions with a steel target. Our negative result casts doubt on models in which anomalous states decay electromagnetically to normal nuclei. However, in view of the possibility of a strong energy dependence for anomalon production, this experiment needs to be repeated at a higher beam energy.

Several theoretical groups, stimulated by the pioneering work of De Rujula et al.[9] on broken QCD, have proposed that anomalons are objects with unusual quark configurations or are droplets of quark matter, possibly stabilized by an unconfined quark.[20-24] My group and I[25] have recently exploited the extraordinarily high charge resolution of CR-39 track-etch detectors in a rigorous search for fragments with fractional charge, such as 13-1/3, that would signify a colored quark-matter droplet. Figure 9 is a schematic cross section through a portion of a stack of CR-39 sheets that were bombarded at normal incidence by 1.85 GeV/u ^{40}Ar ions and then chemically etched. Figure 10 shows the distribution of charges of projectile fragments measured in sixteen successive sheets within 2 cm after the fragmentations occurred. We found not one particle out of 1100 with electric charge differing from an integer multiple of e by as much as ± 1/3 e. This result rules out an explanation of anomalons in terms of fractionally charged objects.

We are continuing our analysis of projectile fragments in the CR-39 stack, and we are beginning a search for anomalons using plastic detectors to identify fragments of 955 MeV/u ^{238}U ions that were successfully produced at the Bevalac in September, 1982. The main goals are (1) to study anomalous mean free paths of projectile fragments using a detector quite different from nuclear emulsion and thus subject to different, probably fewer, systematic errors, and (2) to see if the production rate of anomalons increases in heavy projectiles.

Current theoretical studies[26] indicate that hadronic matter may undergo a phase transition to quark matter at energy densities above about 2 GeV/fm^3. Such an energy density cannot be achieved at Bevalac energies but would be attained in the early universe, possibly at the center of a massive neutron star, probably in a uranium-uranium central collision at a lab energy above about 20 GeV/u, and probably in central collisions of common heavy cosmic rays such as iron in the earth's atmosphere at lab energies of ~10^2 to 10^3 GeV/u. (The latter conclusion is based partly on the observation of rapidity densities dN/dy as high as 200 in central collisions of high-energy Si and Ca in nuclear emulsion.[27]) These studies further show that nucleus-nucleus collisions are more likely than pp collisions to produce quark matter because they are more likely to achieve high energy densities for a long enough time to attain kinetic or chemical equilibrium. The main justification for LBL's proposal to construct the VENUS nuclear accelerator is to reach energy densities sufficient to produce quark matter.

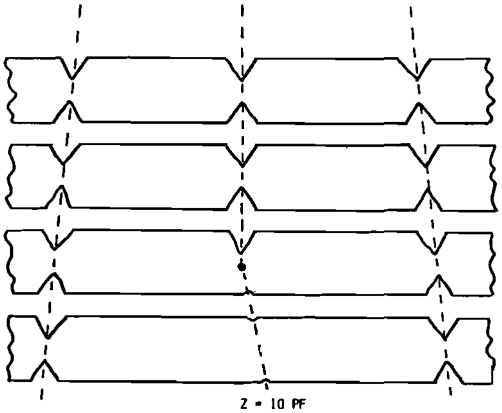

Fig. 9. Sketch showing the change in appearance of a sequence of etch pits indicating fragmentation of a 1.85 GeV/u ^{40}Ar projectile into a fragment with Z = 10 and noticeable transverse momentum. Very light accompanying particles are undetectable.

Anomalons remain an enigma. Their possible relevance to particle physics and QCD is unclear. One cannot yet completely rule out the possibility that they may be an artifact of the detection method used.

7. Metastable or Stable Quark-matter Droplets

Several years ago Kinoshita and I began a series of exploratory experiments[6] with large arrays of CR-39 detectors at the tops of White Mountain, CA (603 g cm^{-2}) and Chacaltaya (540 g cm^{-2}) and in the NASA Kuiper Airborne Observatory[28] (186 g/cm^2 average depth). We were motivated partly by the celebrated Centauro events,[29] which in some respects resembled the hypothetical explosive disassembly of ~ 10^2 nucleons that had somehow survived in bound form through a thickness of ~500 g cm^{-2} of air before fragmenting. Askary, Tarlé and I[30] calculated the expected fluxes of cosmic ray nuclei at various depths in the atmosphere, taking into account their initial charge and energy distribution, ionization loss, and various modes of fragmentation. Our calculated fluxes of heavy nuclei at 186 g cm^{-2} agreed with the measurements of Price and Kinoshita.[28] We calculated that the flux of heavy nuclei such as iron surviving to the altitude of Chacaltaya is too low by a factor ~10^{10} to account for Centauro events.

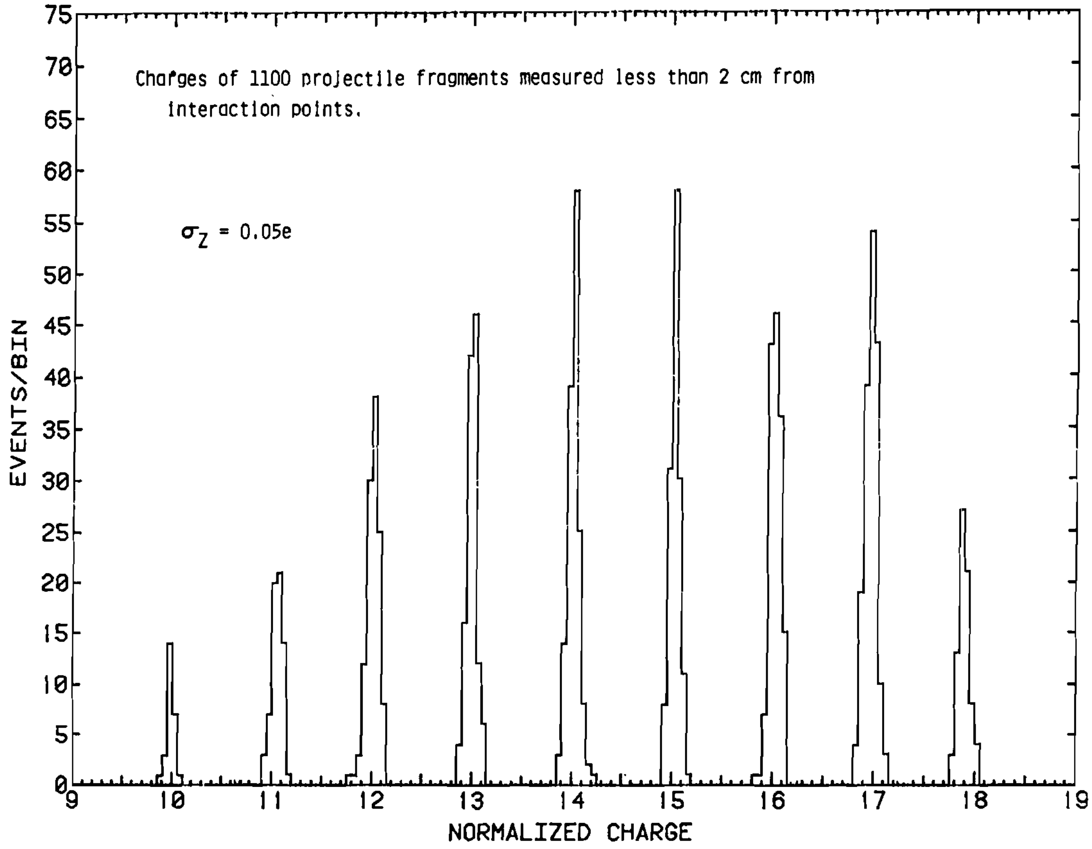

Fig. 10. Preliminary data from ref. 25 showing negative results of a search for quark-nucleon composites that would be signified by one-third integral charges. All of the 1100 charges were measured within 2 cm from the points of fragmentation.

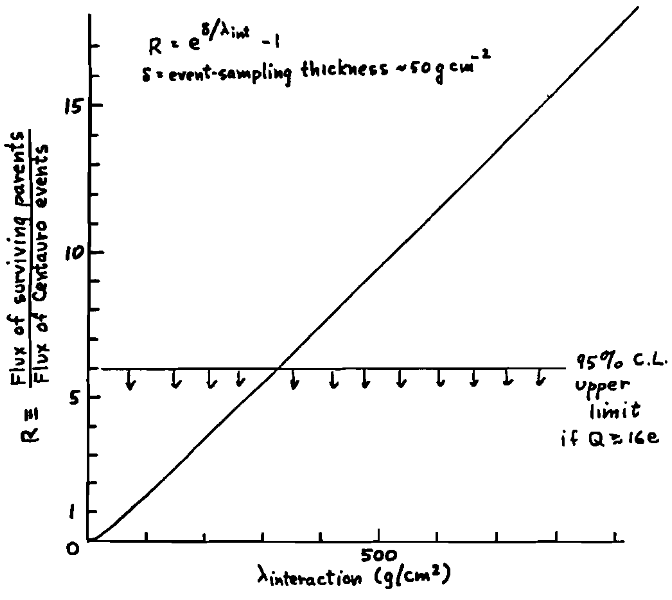

Fig. 11. The 95% CL upper limit of 0.4 m^{-2} yr^{-1} on the flux of particles with $Z \gtrsim 16$ obtained in ref. 6 shows that Centauros are not caused by such particles unless their interaction lengths are less than ~300 g cm^{-2}.

Figure 11 expresses the negative result of the first search for penetrating, highly ionizing particles done by Kinoshita and me[6] at White Mountain. The diagonal line gives the ratio, $R = \exp(\delta/\lambda_{int}) - 1$, of the flux of surviving parents to the flux of Centauro events as a function of λ_{int}, the interaction mean free path of the parents, with the event-sampling thickness δ taken to be ~50 g cm^{-2}. Our 85% CL upper limit of 0.4 m^{-2} yr^{-1} for parents with electric charge greater than 16 e rules out values of λ_{int} greater than ~300 g cm^{-2}. In our second search, carried out at Chacaltaya in collaboration with the Brazil-Japan emulsion chamber group, we found no highly charged particles in a 15 m^2 yr exposure, which gives a 95% CL upper limit of 0.2 m^{-2} yr^{-1}. My students and I are now analyzing three 15 m^2 tiers of CR-39 that were exposed at White Mountain for one year.

Although it is discouraging to continue to get negative results, I believe this kind of exploratory experiment is important to do. In addition to the questions of the origin of Centauro events and of the existence of GUT magnetic monopoles, there is the hope of seeing metastable droplets of quark matter made in very high-energy interactions of heavy cosmic rays in the atmosphere. Bjorken and McLerran[31] proposed quark globs, stabilized against decay by speculative finite size effects, as the origin of Centauro events. McLerran has recently argued[32] that the breakup of quark globs may account for the peculiar interactions named Chiron events by the Brazil-Japan group.[29]

Although the charge of the quark globs discussed by Bjorken and McLerran may be too small for them to be recorded in CR-39, it is not inconceivable that finite quark droplets of another type might be detectable. We have found that the addition of a concentration of 10^{-4} of an antioxidant during the production of CR-39 detectors greatly retards degradation of their surfaces during prolonged exposure in air. It is now possible to detect vertically incident particles with Z/β as low as 6 in CR-39 if the background of extraneous tracks is kept low. We, therefore, may be able to extend the scope of the search for anomalously penetrating highly charged objects to lower charges than our previous limit[6] of ~16 e.

Table 2 shows the flux of cosmic rays with $Z > 16$ at energies above various levels hitting the top of the atmosphere. It is interesting to note that in a one year exposure of a 40 m^2 CR-39 array one can set quite low limits on the fraction of atmospheric collisions of such nuclei that lead to relatively long-lived ($\tau \gtrsim 10^{-6}$ s), tightly-bound, highly charged products that penetrate to the top of White Mountain or Chacaltaya. As the last column in Table 2 shows, even for cosmic ray nuclei at energies greater than 10^4 GeV/u the CR-39 array could detect a fraction of interactions as small as 5×10^{-4} that produced exotic objects that penetrated the ~500 g cm^{-2} to mountain altitude with charge $\gtrsim 6$. In a search for metastable fragments of quark matter this approach is, in some respects, competitive with what could be done with a VENUS accelerator. The three key ingredients are the availability of heavy nuclei extending to extremely high energies, the use of 500 g cm^{-2} of atmosphere to filter out fragments of nuclei, and the use of a very large detector.

Table 2. Detectability of Exotic, Metastable, Highly Charged Objects

E_0 (GeV/u)	N (> E_0) (m^{-2} yr^{-1})	Minimum detectable fraction of interactions leading to an exotic object*	Minimum cross-section for detectability
10	3.3×10^6	8×10^{-9}	20 nb
10^2	8.1×10^4	3×10^{-7}	600 nb
10^3	2080	1×10^{-5}	20 μb
10^4	52	5×10^{-4}	1 mb

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* Defined as having $\tau > 10^{-6}$ s, $\lambda_{survival} \gtrsim 500$ g cm^{-2}, and $Z > 6$.

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