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Technical Progress Report

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1 Overview

1.1 Experimental Program

This document describes the development and progress of our group's research program in high energy heavy ion physics.

We are a subset of the Yale experimental high energy physics effort (YAUG group) who became interested in the physics of high energy heavy ions in 1988. Our interest began with the possibility of performing significant searches for strange quark matter. As we learned more about the subject and as we gained experimental experience through our participation in AGS experiment 814, our interests have broadened.

Our program has focussed on the study of new particles, including (but not exclusively) strange quark matter, and the high sensitivity measurement of other composite nuclear systems such as antinuclei and various light nuclei. The importance of measurements of the known, but rare, nuclear systems lies in the study of production mechanisms. A good understanding of the physics and phenomenology of rare composite particle production is essential for the interpretation of limits to strange quark matter searches. We believe that such studies will also be useful in probing the mechanisms involved in the collision process itself.

We have been involved in the running and data analysis for AGS E814. We have also worked on the R&D for AGS E864, which is an approved experiment designed to reach sensitivities where there will be a good chance of discovering strangelets or of setting significant limits on the parameters of strange quark matter.

1.2 The Phenomenology of Strange Matter

Strange quark matter is a multiquark state of u, d, and s quarks. Though non-strange quark matter containing only u and d quarks is not stable (nuclear matter does not decay into non-strange quark matter), the strange matter states are made plausible by the exclusion principle which asserts that a three-quark state may be more stable than a comparably-sized state populated with just two quark flavors. In the approximation that quark matter is a Fermi gas enclosed in a bag, and for simplicity that the quarks are massless, the total energy of the system is proportional to

$$E \propto N_f^{-\frac{1}{4}},$$

where N_f is the number of quark flavors in the system. Increasing N_f from 2 to 3 gives an energy savings of $1 - (\frac{2}{3})^{\frac{1}{4}} \simeq 10\%$, or roughly 100 MeV/baryon. Though a massive strange quark would give less binding, this large energy savings may compensate for the inclusion of a massive quark.

Chin and Kerman first computed the binding energy of extended strange matter systems,[1] and concluded that such droplets with strangeness per baryon of order unity may be metastable with lifetimes of order 10^{-4} sec. Witten drew much attention to the topic when, in 1984, he alleged that strange matter systems may be the true ground state of matter.[2] About the same time, Farhi and Jaffe published a detailed study of both large systems of strange matter and small systems, which they called *strangelets*.[3]

Strange matter must have an energy per baryon less than nuclear matter if it is to be completely stable:

$$\frac{E}{A} < M_N - \epsilon_B,$$

where M_N is the nucleon mass and ϵ_B is the binding energy of the nuclear system. For the system to be metastable, the strangelet must be more tightly bound than the corresponding baryon matter:

$$\frac{E}{A} < f_s M_\Lambda + (1 - f_s) M_N - \epsilon_B \qquad \text{when} \qquad 0 \leq f_s < 1,$$

where f_s, called the *strangeness fraction*, is the number of strange quarks per baryon. Lifetimes of the metastable strangelets are expected to be as long as $\sim 10^{-4}$ sec for semileptonic decays.

Results of the study by Farhi and Jaffe, using the framework of the MIT Bag Model, are shown in Fig. 1. The minimum E/A (energy per baryon) is plotted versus A in the top curve; the bottom shows S (the number of strange quarks) vs. A. The conclusion of these curves is that strangelets with $A \gtrsim 8$

[1]S.A. Chin and A.K. Kerman, Phys. Rev. Lett. **43**, 1292 (1979).
[2]E. Witten, Phys. Rev. **D30**, 272 (1984).
[3]E. Farhi and R.L. Jaffe, Phys. Rev. **D30**, 2379 (1984).

may be metastable, and that the strangeness fraction which yields the most stability is in the range $0.4 \lesssim f_s \lesssim 0.8$.

One striking feature of strange matter is that it becomes more stable as A grows larger since the energy in "bending" the bag's surface decreases with the radius of the bag, and also because the coulomb repulsion of the system is small. The relationship between the strangeness fraction and the charge-to-baryon ratio is given by

$$\frac{Z}{A} \simeq \frac{1 - f_s}{2}.$$

For expected values of $0.4 \leq f_s \leq 0.8$, then Z/A will range from 0.1 to 0.3, thus the the growth of the system is uninhibited by coulomb repulsion.

Some of the expected properties of strange matter are dependent on the parameters used within the Bag Model. For example, a larger strong coupling constant will, for dynamical reasons, tend to favor a larger strangeness content if the strange quark mass is modest, leading to negatively-charged strangelets. The predicted binding is also subject to bag parameters. However, general features such as small coulomb repulsion and the increase in stability with size are expected regardless of the parameters used.

There are two classes of strangelet production models in heavy ion collisions. The first are quark–gluon plasma (QGP) based models, where the plasma preferentially emits antistrange quarks in the form of mesons, resulting in a strangelet. The second are coalescence models, where hyperons and nucleons are made in the interaction, and then the baryons near each other in ($\vec{x}$,$\vec{p}$) space bind to form a strangelet. Both models would predict strangelet production peaked at the center of mass, but they give very different results for cross sections. A plasma-based prediction[4] estimates that the probability of a strangelet being produced in a collision is between 1 and 10^{-6} per quark–gluon plasma produced. Though no formal coalescence calculation on strangelet production has been performed, it is expected that the production will be roughly 10^{-12} per collision for ^{28}Si beams and nuclear targets.

[4] H.C. Liu and G.L. Shaw, Phys. Rev. **D30**, 1137 (1984).

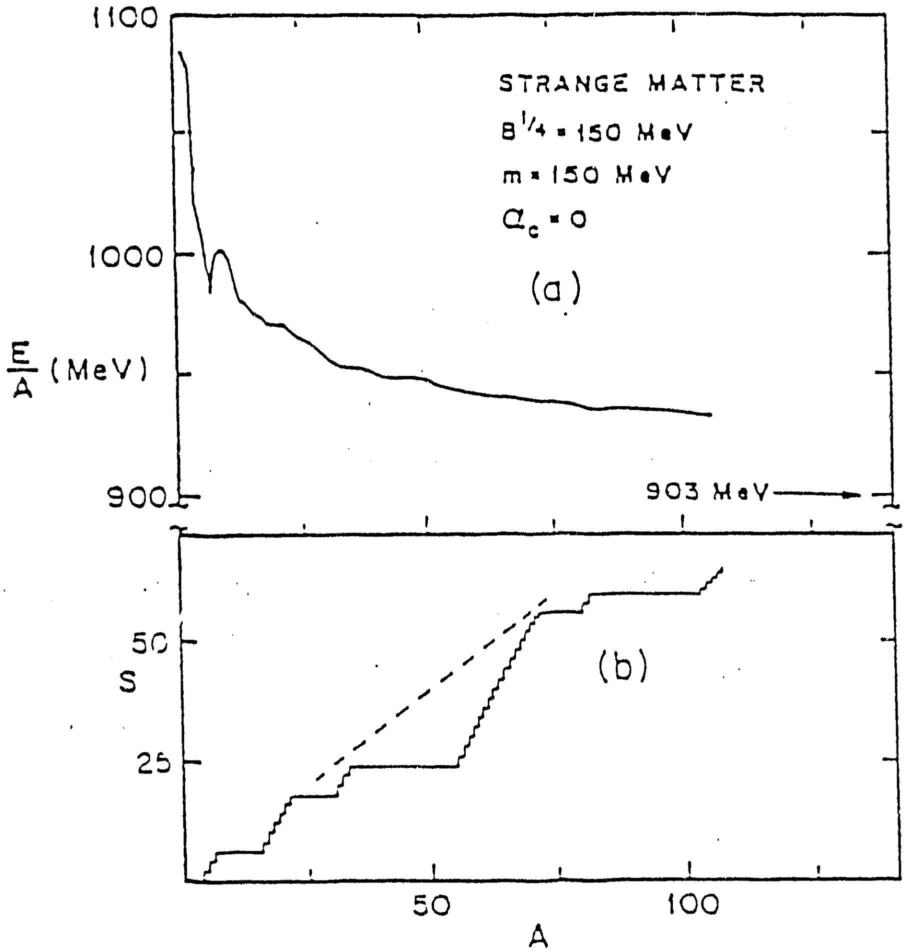

Figure 1: Results from the study by Farhi and Jaffe. See text for details.

2 Technical Progress: April 1990 – March 1991

2.1 Strangelet Search in E814

Heavy ion collisions at the AGS create regions with a high strangeness content and baryon density, and thus may be the best environment in which to search for strange matter. In 1988, this search was initiated in E814.

The E814 detector configuration is shown in Fig. 2. The apparatus was originally designed to study nuclear fragments from peripheral collisions of nuclei and the global event characteristics of central collisions. It combined 4π calorimetry around the target with a high resolution spectrometer for particles which pass through a 1° cone about the beam axis. The spectrometer was used to search for strangelets.

The spectrometer consisted of 2 magnets, 3 drift chambers for tracking, a scintillator hodoscope to measure the charge and time-of-flight (TOF) of particles, and calorimeters. The drift chambers had a momentum resolution of $\delta p/p = 1\%$ over the range of momenta we were concerned with. The scintillators the in hodoscope wall, located 31 m from the target, were read out by phototubes at the top and bottom of each slat. An example of the pulse height resolution is shown in Fig. 3 We achieved a time of-flight resolution of $\sigma_{TOF} = 0.379$ ns after slewing corrections as is shown in Fig. 4. The vertical position of hits in the scintillator wall were measured by subtracting the TDCs of the top and bottom tubes. A crude position measurement was made in the bend plane by the scintillators by noting which scintillator was hit by a particle (the scintillator slats are 10 cm wide).

The general approach of the strangelet search was to measure the mass of particles by calorimetry and TOF, and then to repeat the measurement using momentum and TOF. Any particles with $m \geq 10$ GeV/c^2 and a small, positive charge-to-mass ratio would be considered a candidate. E814 has concentrated its efforts on positive strangelets since most theoretical work has concluded that the most stable strangelets should be positive. However, this conclusion is by no means universal, so searches for negative strangelets were begun in E814 and will have great emphasis in E864 as discussed in a later section.

The first E814 strangelet search data was taken in December 1988, and the

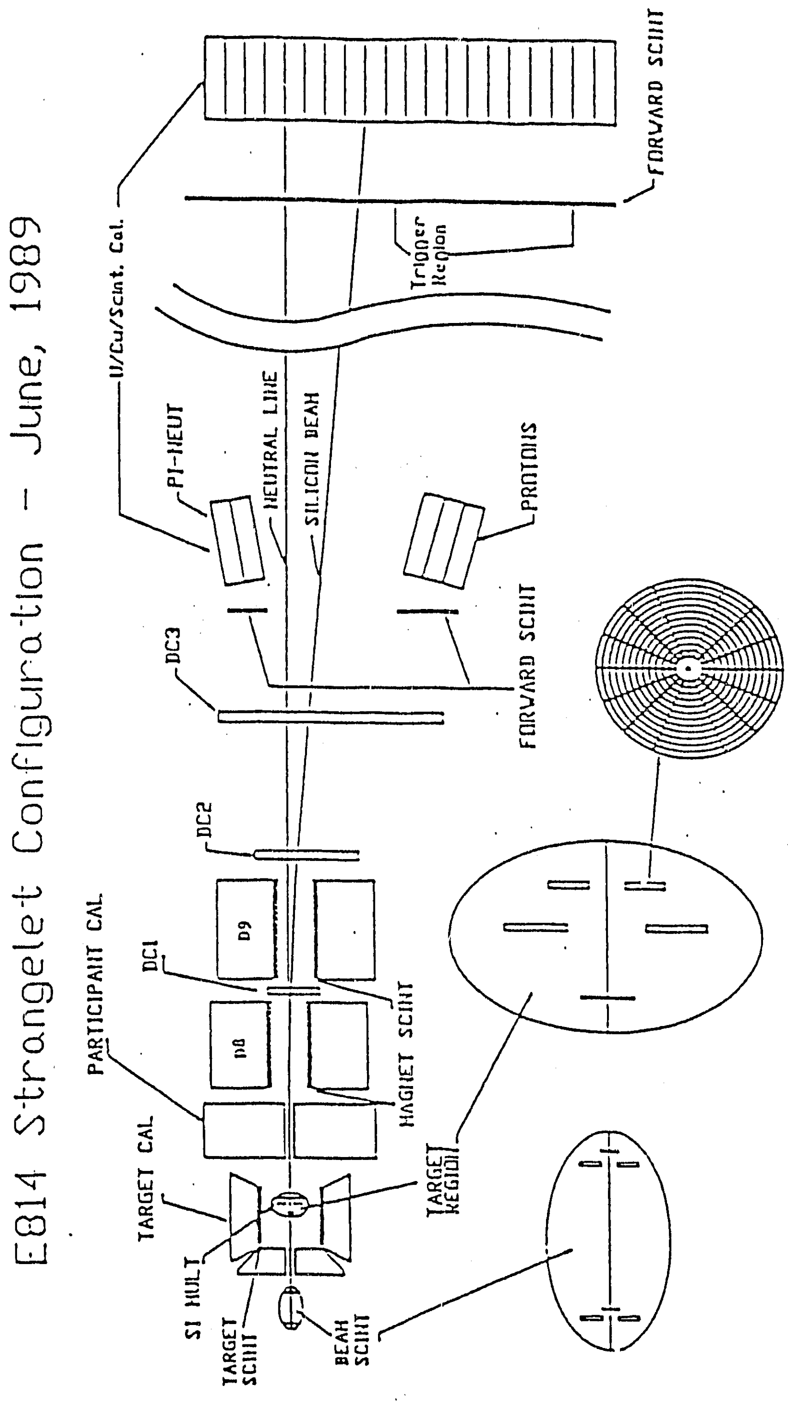

Figure 2: The E814 detector configuration combined 4π calorimetry around the target with a high resolution spectrometer.

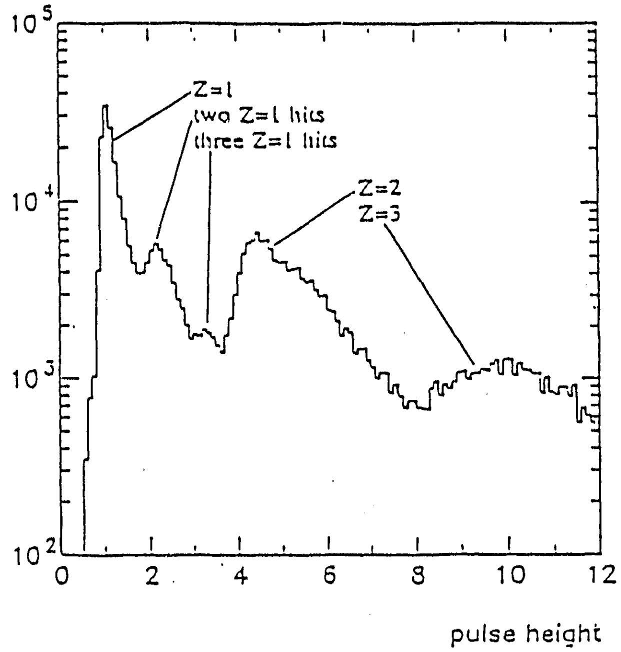

Figure 3: An example of the pulse height resolution of the scintillator wall.

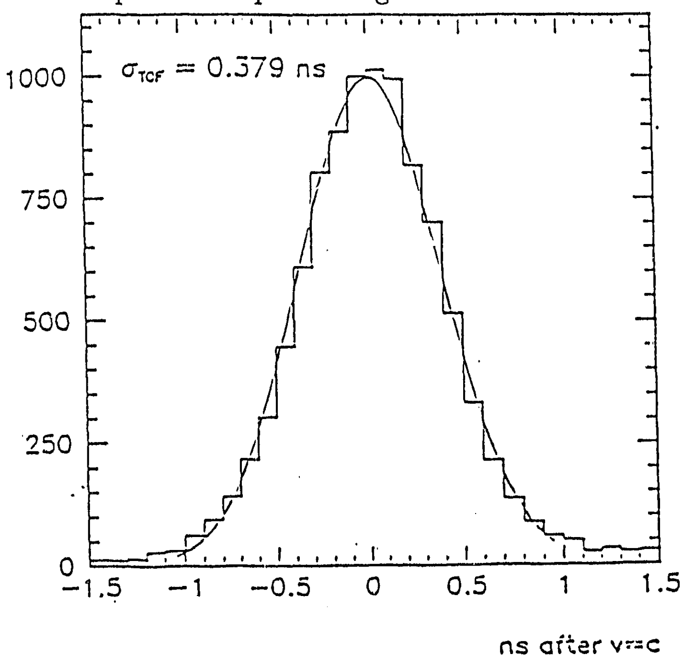

Figure 4: TOF resolution achieved from the scintillator wall is $\sigma_{TOF} = 0.379$ ns.

analysis of this data was completed and published.[5] The experiment utilized a ^{28}Si beam and a Cu target, and the spectrometer magnets were tuned to be sensitive to particles with charge-to-mass ratios between 0.1 and 0.3 $(\mathrm{GeV/c^2})^{-1}$. The upper limits achieved in this run were $\sigma_S/\sigma_{int} < 8.3 \times 10^{-4}$ for singly-charged strangelets, and $\sigma_S/\sigma_{int} < 1.2 \times 10^{-4}$ for multiply-charged strangelets, where σ_S and σ_{int} are the strangelet and nuclear interaction cross sections, respectively. Different limits were set for the different charge states because of the crude trigger used in this initial search.

A second strangelet data run was made in June 1989. The analysis of this run's data was the topic of F.S. Rotondo's thesis, which was completed in May 1991. Many of the experimental conditions were kept the same as in the previous run: a ^{28}Si beam and Cu target were used, and the spectrometer acceptance was set to accept charge-to-mass ratios between 0.1 and 0.3 $(\mathrm{GeV/c^2})^{-1}$. However this run used a more sophisticated trigger which selected events with particles produced near the center-of-mass rapidity. The trigger consisted of a pretrigger and a time-of-flight trigger. The pretrigger required a good beam particle and also a modest charged particle multiplicity of about 20 in the silicon multiplicity detector and target paddles located around the target (refer to Fig. 2). The TOF trigger applied an online slewing correction to the scintillator timing signals and accepted particles with a TOF that was between 2 ns and 28 ns later than a v=c particle would take to traverse the apparatus. This TOF requirement accepted particles produced within 1 unit of rapidity centered about the collision center-of-mass, which is the regime in which strangelets are expected according to both production models. The online TOF trigger gave a rejection of about 20.

No strangelet candidates were found in the June 1989 data. To obtain a limit on the strangelet production, we assumed a strangelet production model which is exponential in $p_\perp$ and gaussian in rapidity:

$$\frac{d^2\sigma}{dp_\perp dy} = \sigma_S \left[\left(\frac{< p_\perp >}{2} \right)^2 p_\perp e^{\frac{-2p_\perp}{<p_\perp>}} \right] \left[\frac{1}{\sqrt{2\pi} w} e^{\frac{-(y-y_{cm})^2}{2w^2}} \right],$$

where $< p_\perp >$ is the mean transverse momentum, y_{cm} is the center-of-mass rapidity, and $w = 0.5$ is the standard deviation of the rapidity distribution of the strangelet. The mean transverse momentum was modeled as a "random walk" process of the accretion of baryons with each baryon carrying a $p_\perp \simeq$

[5] J. Barrette *et al.*, Phys. Lett. **B252**, 550 (1990).

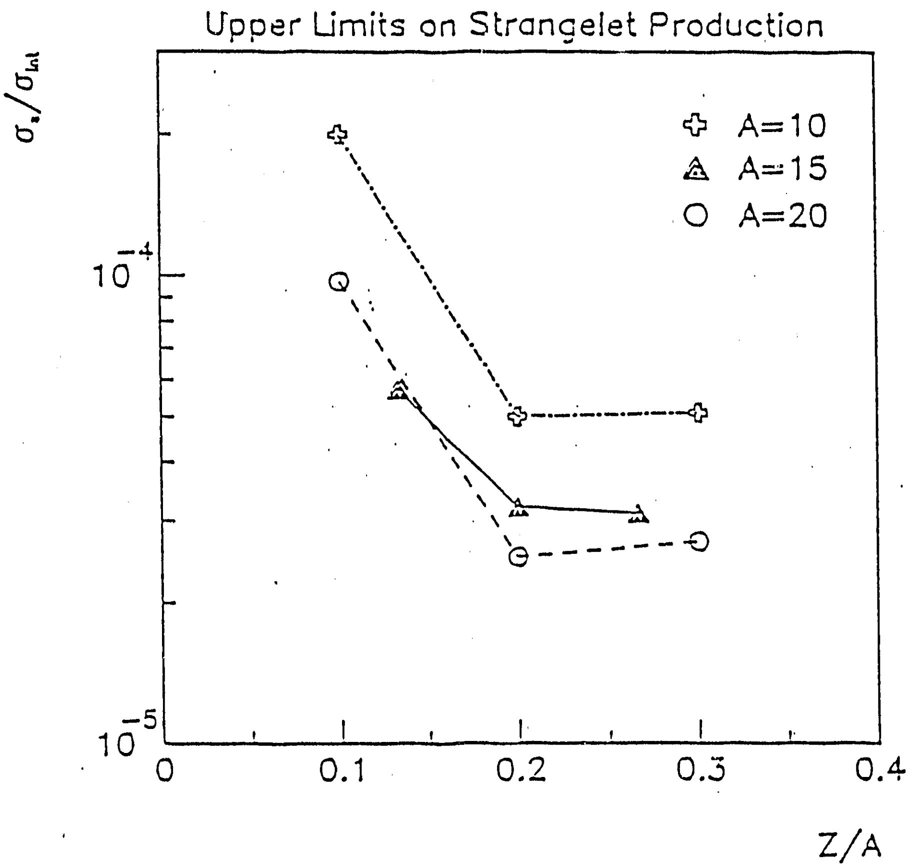

Figure 5: 90% C.L. upper limits on strangelet production. See text for details.

0.7 GeV/c, giving $< p_\perp >= 0.7\sqrt{A}$ GeV/c. Figure 5 shows the 90% C.L. upper limit on σ_S/σ_{int}. Varying the production parameters over a reasonable range does not change the upper limits by more than a factor of 2.

In February 1991, additional strangelet data was collected. A new trigger was developed which required a spatial match between a late hit in the forward scintillation counters and a preset amount of energy in the appropriate region of the uranium calorimeters. Positively-charged strangelet running was repeated, and the spectrometer's magnetic field was reversed so that negative strangelet data was collected as well.

2.2 Measurement of Antiproton Production and the Coalescence of Light Nuclei in Heavy Ion Collisions

More recently, E814 extended its physics program to study the coalescence production of light nuclei and production of antimatter in heavy ion collisions. Coalescence has been shown to work well at the BEVALAC, but it has not been tested at AGS energies and is an important step in understanding strangelet production levels which may be expected at Brookhaven. Antimatter production may also be useful as a sensitive probe into the space–time evolution of the baryon density in the collisions.

The measurement of the production systematics of antimatter and composite nuclear systems will provide a variety of tests of production models. In almost any model, composite yields are sensitive to the overlap in momentum and configuration space (phase space density) of the particles resulting from a collision. E814 thus began a program to measure the production of antimatter and light nuclei resulting from heavy ion collisions.

The antimatter study in E814 started during the June 1989 run and continued with a major run in 1990. Data were taken with a ^{28}Si beam on Al, Cu, and Pb targets. The antimatter data was taken using the same TOF trigger discussed above. During this run, the spectrometer magnets were set to optimize the acceptance of antiprotons in the spectrometer.

In February 1991, the new trigger discussed above (which required a spatial match between a late hit in the forward scintillation counters and a preset amount of energy in the appropriate region of the uranium calorimeters) was used to collect data optimized to detect $Z/A = 0.5$ particles. This increased the trigger rejection by a factor of $2 - 4$ without reducing the efficiency for heavier species of composites.

Longer running time, better running efficiency, and the improved trigger allowed for more than one physics goal to be met. Strangelet running was performed as discussed above. We also collected data with the spectrometer's magnetic field set to accept centrally-produced $Z/A = 0.5$ particles on Al, Cu, and Pb targets. This will provide a first look at the coalescence of light nuclei.

2.3 Design of E864

E864 was conceived to be significant test of strange matter, since it was designed to attain sensitivities at the coalescence production level of strangelets: it will have a good chance at discovering strangelets if they exist, or will severly constrain the parameters of strange quark matter.

Many of E864's goals will overlap with that of E814's, such as the positive and negative strange matter searches, and the study of the production of nuclei and antimatter. However, E864 will achieve 5 to 6 orders of magnitude more sensitivity than E814 – enough to probe the coalescence production levels for strangelets.

But there is a more general motivation for a relativistic heavy ion experiment with high sensitivity and broad reach. These collision systems produce a region of high baryon and strangeness density, and thus represent a new, unexplored regime which could result in otherwise inaccessible states. Strange matter is the best known of such states, but there are others as well. The SU(3) chiral soliton (Skyrme) model predicts light ($A = 2, 3, 4$) clusters with multiple strangeness which may be stable with respect to strong or even weak decays.[6] These predictions, while speculative, are important and warrant an experimental test. Moreover, heavy ion interactions are dynamically different from elementary particle collisions. It has been speculated that states of bare color may be more readily produced in heavy ion collisions than in simpler collision systems.

An initial design of E864 was conceived in 1989–1990, after two open meetings were held at Brookhaven which were attended by about 35 interested physicists. This design was proposed to the AGS, as P864, in May 1990 under the title *Production of Rare Composite Objects in Relativistic Heavy Ion Collisions.* This initial proposal consisted of 4 fine-grained scintillator hodoscopes for tracking, time-of-flight, and charge identification, and a calorimeter for energy and time-of-flight measurement. In June 1990 this proposal was deferred, pending further developments in understanding physics backgrounds, costs, and some technical questions.

The proposal was resubmitted in October 1990 with the title *Update to P864: Production of Rare Composite Objects in Relativistic Heavy Ion Collisions.* The improved scheme included 2 straw tube planes for tracking, which would help to reduce backgrounds and improve momentum measurements.

[6] V.B. Kopeliovich *et al.*, Phys. Lett. **B242**, 145 (1990).

The PAC concluded that the experiment had merit both for its discovery potential and its study of the production of nuclei and antinuclei. However, the PAC felt a panel of experts should be convened to study the proposal and to determine: (i) if the experiment could achieve the needed sensitivity, (ii) could be constructed within the $6M estimated cost (not including the beam line), and (iii) if the collaboration had sufficient strength to achieve its goals.

A third straw tube plane was added to the detector configuration in the design proposed to the review panel, while one of the four scintillator planes was removed.

The panel, chaired by Doug Bryman (TRIUMF), included Hank Crawford (LBL), Hugh Brown (BNL), and Craig Woody (BNL). This panel concluded that the above three requirements were met, and that the experiment would be an exciting addition to the AGS physics program.

In March 1991, Brookhaven's PAC decided to approve E864 for 1200 hours of running for positive particles; the additional time we requested for negatives was deferred because at the time the Bryman Committee met, only positive running was reviewed.

The spectrometer, influenced by experience in E814 and extensive Monte Carlo study, will measure the magnetic rigidity, charge, time-of-flight, and energy of particles. Redundancy, resolution, and high rate capability are needed to achieve high sensitivity, and the large acceptance allows for a broad physics program and is amenable to surprises.

The detector layout is shown in Fig. 6. M1 and M2 are magnets. H1, H2, and H3 are scintillation counter hodoscopes. S1, S2, and S3 are straw tube stations. The calorimeter is a tower geometry, "spaghetti" design.

Tracking with the straw tubes will measure the rigidity of a track. Each of the hodoscopes will measure the charge, time-of-flight, and vertical position of a particle. The calorimeter will measure the shower energy and its time-of-flight. Thus, individual measurements will have great redundancy: time-of-flight will be measured 4 times (3 times by the hodoscopes, and once by the calorimeter), charge will be measured 3 times in the hodoscopes, and particles will make spatial hits in the each of the straw stations and hodoscope planes. Furthermore, the charged particle masses will be measured twice, once using momentum and time-of-flight, and once using cluster energy and time-of-flight.

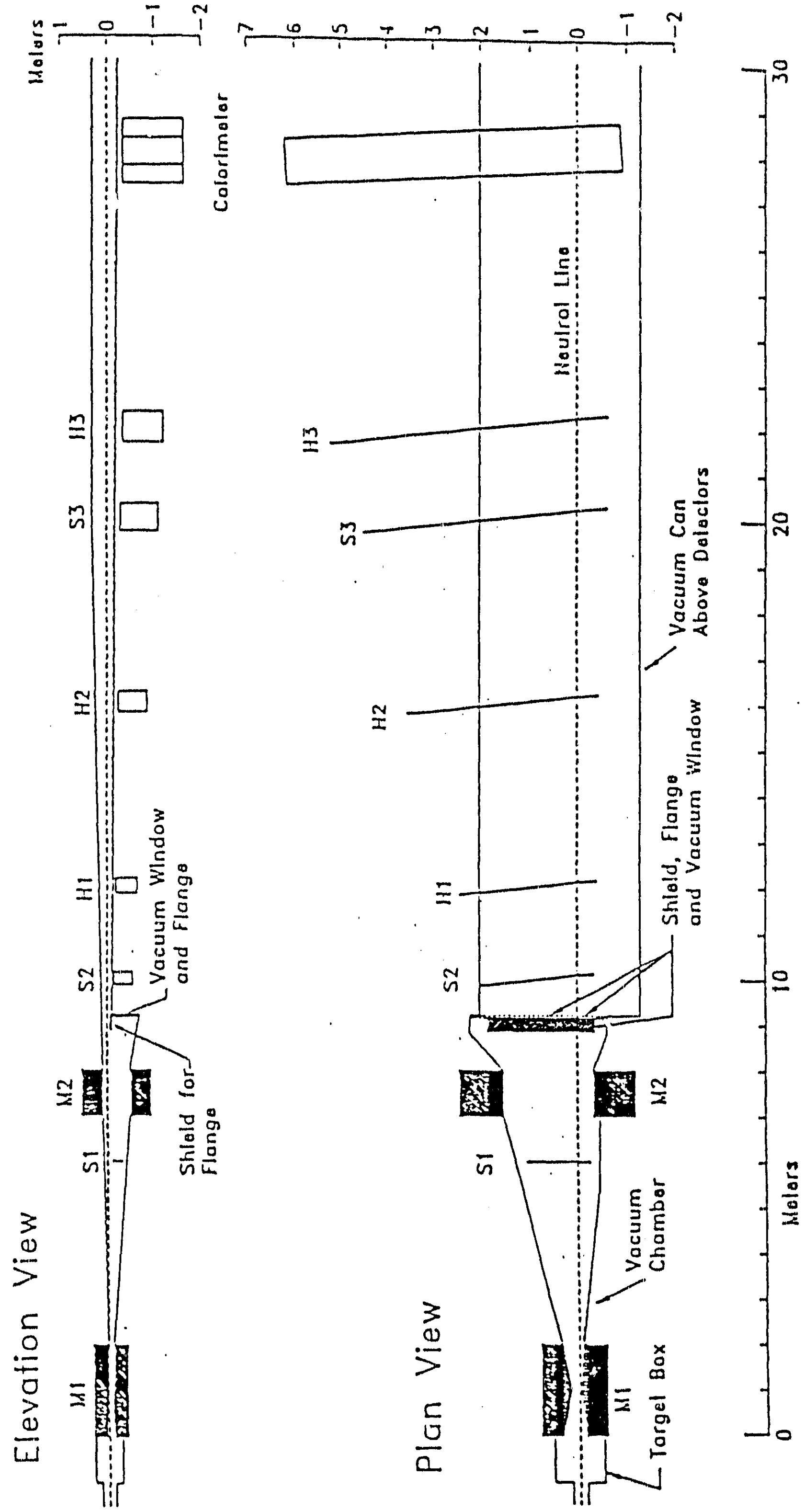

Figure 6: The E864 detector layout.

3 Technical Progress: April 1991 – March 1992

3.1 Strangelet Search in E814

In this period, analysis of strangelet data collected in February 1991 was begun. The sensitivity of the positive strangelet search should be increased by at least an order of magnitude over June 1989 data. Further, the expected sensitivity of the negative strangelet search should reach the level of $10^{-4} - 10^{-5}$ per interaction, which is a comparable sensitivity to the positive strangelet run of June 1989.

3.2 Measurement of Antiproton Production and the Coalescence of Light Nuclei in Heavy Ion Collisions

Our efforts in E814 continued with the analysis of antiproton data collected in June 1990 and February 1991. The antiproton analysis, presently under way, will be completed in 1992, and will be the subject of S.V. Greene's thesis. An example of the mass spectrum of $Z = -1$ particles is shown in Fig. 7. Clear antiproton and K^- peaks are evident. A first draft of a paper summarizing the antiproton results has been completed and should be published in 1992. We expect to publish cross sections, and also spectra such as dN/dy, dN/dE_t, and dN/dM, where E_t is the transverse energy, and M is the charged particle multiplicity in the pseudorapidity range $1.2 < \eta < 4.0$.

The light nucleus production analysis is presently under way and will be complete in 1993. This will be the subject of J.V. Germani's thesis and will also result in a publication. The sensitivity achieved should allow for the study of coalescence up to $A = 4$ nuclear species. Though the analysis is not yet complete, there are very encouraging preliminary mass spectra. Figure 8 shows the mass spectrum of $Z = 1$ isotopes. Protons, deuterons, and tritons are clearly visible. Figure 9 shows the mass spectrum of some $Z = 2$ isotopes; ^{3}He and ^{4}He peaks are evident. The data is presently being corrected for acceptance, so that cross sections can be determined and coalescence can be studied.

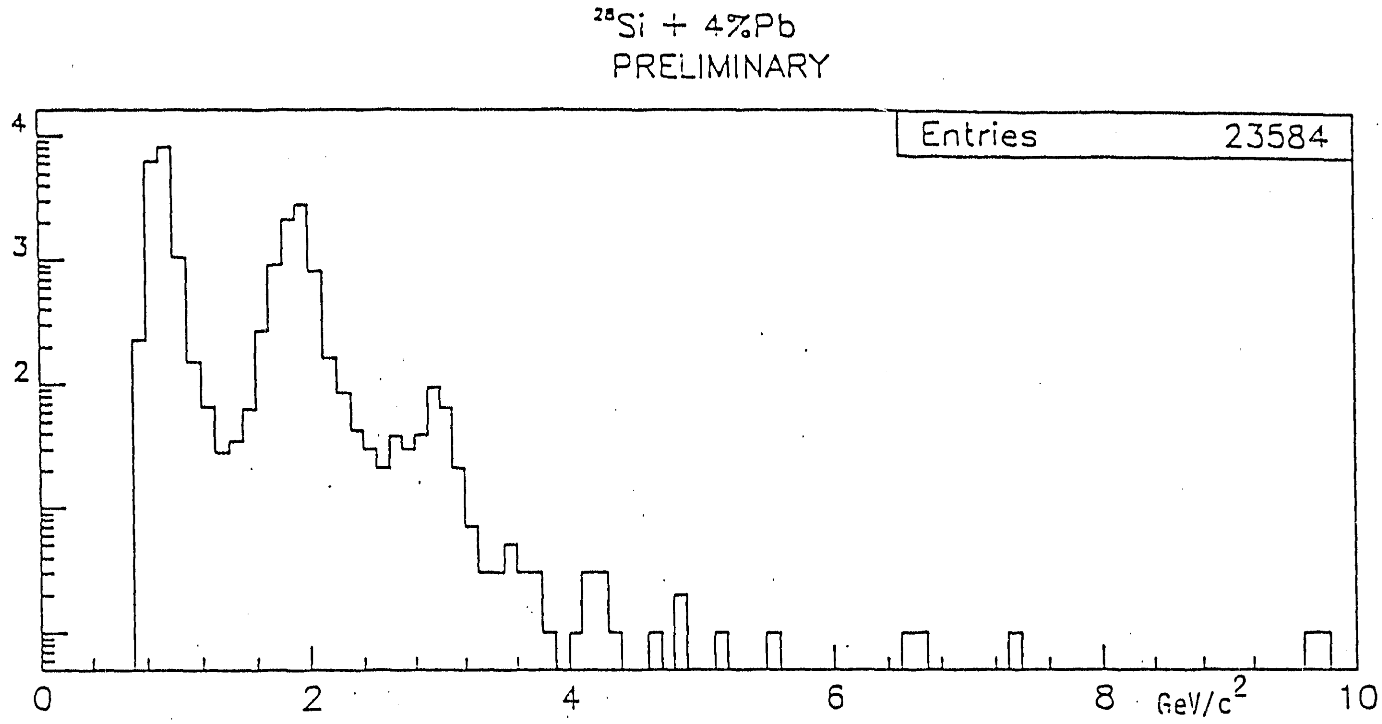

Figure 7: $Z = -1$ mass spectrum from ^{28}Si on Pb data from June 1990.

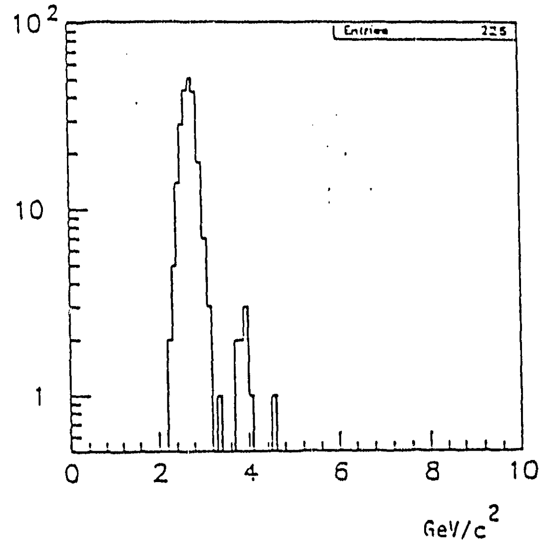

Figure 8: Preliminary mass spectrum for $Z = 1$ particles collected during the $Z/A = 1/2$ run of ^{28}Si on Pb. The spectrum is not corrected for acceptance.

3.3 R&D for E864

Since receiving approval of the Brookhaven Program Advisory committee, E864 has undergone an R&D effort to decide on the design of the detector systems.

Cosmic ray bench tests have determined the phototube and scintillator to be used in the hodoscope systems. Extensive computer simulations of the spaghetti calorimeter have lead to a design of the detector. Calorimeter construction techniques have been discussed with industry and also with other experiments that have successfully used spaghetti calorimeters. A conceptual design of the multiplicity counter was made using HIJET simulations of heavy ion collisions. We have also worked with industry and colleagues from other experiments to optimize the electronics and DA systems used in the experiments while lowering the cost as compared to our previous estimates.

We have also actively worked with the Nuclear and Particle Physics Divisions of the Department of Energy, as well as with the administration of Brookhaven National Laboratory, to plan the funding profile of the experiment. This effort has been encouraging thus far, and we expect the funding scenario to be settled shortly.

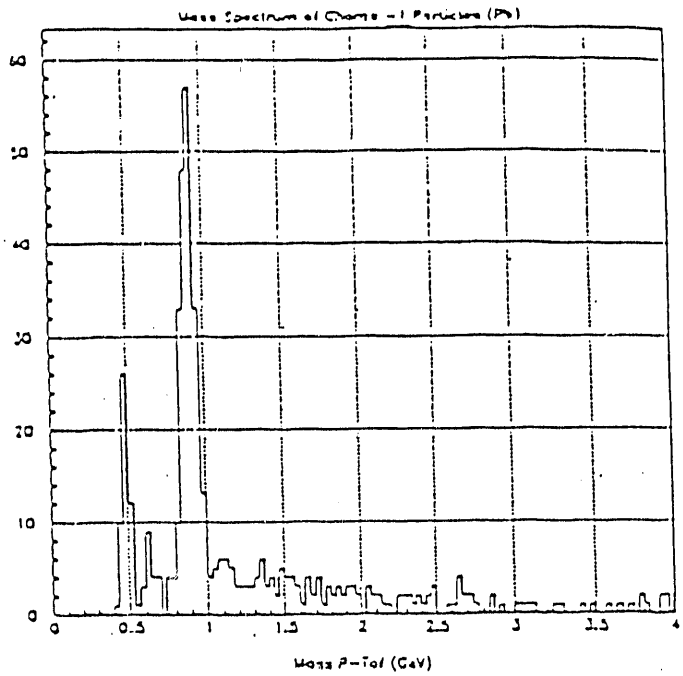

Figure 9: Preliminary mass spectrum for $Z = 2$ particles collected during the $Z/A = 1/2$ run of ^{28}Si on Pb. The spectrum is not corrected for acceptance.

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