Abstract. We provide a status report on the progress of searching for negatively charged strangelets using the E864 spectrometer at the AGS. About 200 million recorded events representing approximately 14 billion 10% central interactions of Au + Pt at 11.5 GeV/c taken during the 1996-1997 run of the experiment are used in the analysis. No strangelet candidates are seen for charges \( Z = -1 \) and \( Z = -2 \), corresponding to a 90% confidence level for upper limits of strangelet production of \( \sim 1 \times 10^{-8} \) and \( \sim 4 \times 10^{-9} \) per central collision respectively. The limits are nearly uniform over a wide range of masses and are valid only for strangelets which are stable or have lifetimes greater than \( \sim 50 \) ns.

1. Introduction

The discovery of quarks nearly 30 years ago solidified the understanding of hadrons as multi-quark systems. To this day, no clear evidence has been found for the existence of larger quark systems (with more than three quarks). However, theoretical calculations [1,2,3] using the MIT Bag Model of quark confinement [4] predict the possibility that such quark systems with roughly equal numbers of \( u, d, \) and \( s \) quarks in color-singlet states, or Strange Quark Matter (SQM), might be metastable, stable, or even the true ground state of hadronic matter.

Because stability of SQM mandates similar quantities of \( u, d, \) and \( s \) quarks, such systems are expected to carry only a light overall charge, if any, despite high mass. Searches for small SQM systems, termed strangelets, have relied upon this property of low charge-to-mass ratios. Recent calculations have even shown that negatively charged strangelets may be the most favorable for stability [1].

Strangelets have been postulated to be producible in the baryon-rich environment of heavy ion collisions [5]. Mechanisms for strangelet production include the coalescence model [6], thermal model [7], and Quark-Gluon Plasma (QGP) distillation [8,9]. The coalescence and thermal models rely on the production of hyperfragments, which may then decay into more stable strangelet states. This scenario is difficult to achieve for negatively charged strangelets in heavy ion collisions because of the extremely rare production of large, negatively charged or neutral hyperfragments.
In QGP distillation, large numbers of $s\bar{s}$ quark pairs are believed to be abundantly produced inside the QGP. Subsequently, $\bar{s}$ quarks are evaporated more readily by forming kaons with the copiously available $u$ and $d$ quarks, leaving a QGP which is strangeness-rich. Such an environment is ideal for strangelet formation. However, even QGP formation has not been indisputably observed [10]. That strangelets may be distilled is even more speculative [11]. Observing negatively charged strangelets in such collisions would therefore be strong evidence for the formation of QGP.

A status report of the search for negatively charged strangelets with the E864 apparatus is presented in this contribution. The expected limits from this search are shown and compared with previous experiments. The implications for QGP formation are also discussed and presented.

2. The Apparatus

The E864 experiment is devised specifically to search for low charge to mass ratio ($-1 < Z/A < +1$) long-lived ($\tau \geq \sim 50$ ns) exotic particles produced near midrapidity ($y_{cm} \pm 0.5$) in fixed target heavy ion collisions at a beam momentum of 11.5 GeV/c per nucleon [12,13,14,15]. At this momentum, the beam rapidity is $\sim 3.2$ in the lab frame. For this purpose, E864 is a non-focusing spectrometer with an open geometry configuration, permitting searches over a wide range of masses simultaneously.

The layout of the experiment is shown in Figure 1. The spectrometer consists of two dipole analyzing magnets (M1 and M2), three hodoscope scintillator planes (H1, H2, and H3), three sets of straw tube tracking stations (S1, S2, and S3) with X, U, and § S1 is present, but not used in this analysis.
V planes, and a hadronic calorimeter (CAL). The straw tubes and hodoscopes are highly segmented and combine to perform precision tracking, while the hodoscopes also provide time-of-flight and charge measurements. This allows particle identification with a mass resolution of $\sim 3\%$ at high mass. A redundant measurement of the mass is provided by the calorimeter, which is comprised of an array of $58 \times 13$ lead - scintillating fiber towers [16]. Energy and time resolutions ($\Delta E/\sqrt{E} = 0.344/\sqrt{E} + 0.035; \sigma_t \approx 400 \text{ ps}$) of the calorimeter are sufficient to reject candidates from scattered particles which yield erroneous tracking momenta. Uninteracted beam and beam fragments are transported above the experiment apparatus in vacuum.

The data set used in this analysis is taken from the 1996-1997 run of the experiment using a Au beam at 11.5 GeV/c per nucleon on a 60\% interaction length Pt target. The analyzing magnets are set to -0.75T to sweep positively charged particles out of the spectrometer, and improve acceptance for negative particles. A multiplicity detector located near the target [17] provides a measure of centrality [18] and is used with counters that define a good beam in the level I event selection trigger. The centrality requirement is imposed from the expectation that strangelets are formed only in the high density conditions found in highly central collisions.

The fact that the calorimeter can provide a mass measurement by itself is utilized for a level II, Late-Energy trigger (LET). The energy and time measurements of individual calorimeter towers are digitized and fed into electronic, two-dimensional lookup tables [19]. The lookup tables are programmed to provide a trigger when an energy and time corresponding to a slow, massive particle are read out from the calorimeter. The LET allows the experiment to record only events in which high mass candidates are detected. In this particular data set, only one in $\sim 77$ events which pass the level I trigger are accepted by the level II trigger. The nearly 200 million events recorded therefore represent approximately 14 billion sampled central collisions.

Further analysis of the data set includes requirements on the quality of the linear track fits through the apparatus ($\chi^2$), and an upper limit on rapidity (the mass resolution $\sigma_m/m$ scales with $\gamma^2$ while scattering background is worst at high rapidity). A clean corresponding calorimeter shower with reasonable mass (energy and time) agreement is required for consideration as a strangelet candidate [20].

3. Results

3.1. Strangelets

The spectra of charge $Z = -1$ and $Z = -2$ candidates are shown Figure 2 as a function of tracking and calorimeter masses. A significant background exists at high tracking masses from multiple scattering and neutron-proton charge exchange interactions downstream of the first analyzing magnet. These are identified as having low mass by the calorimeter and are not considered candidates. In particular, the background in the charge $Z = -2$ spectrum yields calorimeter masses consistent with scattered $^3\text{He}$ particles. Further
Figure 2. Spectrum of strangelet candidates for charges $Z = -1$ and $Z = -2$. Calorimeter mass agreement of $\pm 2\sigma$ curves are also shown.

work is underway to understand the sources of background at low calorimeter masses. No high mass candidates are observed.

In order to calculate production limits, a production model must be assumed to determine acceptance. Two models are used assuming the following form:

$$
\frac{d^2N}{dy \, dp_t} \propto p_t e^{-\frac{2p_t}{<p_t>} \frac{(y-y_{mid})^2}{2\sigma_y^2}}
$$

where $<p_t> = 0.6\sqrt{A}\text{GeV/c}$ is the mean transverse momentum and $y_{mid} = 1.6$ is midrapidity. In models I and II $\sigma_y = 0.5$ and $\sigma_y = 0.5/\sqrt{A}$ respectively. However, the large acceptance of the E864 spectrometer makes the results largely mass- and model-independent.
Figure 3. 90% C.L. limits for production of charge $Z = -1$ and $Z = -2$ strangelets in 10% central heavy ion collisions. Dashed lines represent limits using production model I; solid lines represent model II. Previous E864 limits are from the 1995 run of the experiment. NA52 results are shown using a model similar to model I, but are for 158 GeV/c per nucleon Pb + Pb collisions [22]. Also shown are the predictions of a QGP production model [23].

Figure 3 shows the expected upper limits calculated at the 90% Confidence Level (C.L.) for production of charge $Z = -1$ and $Z = -2$ strangelets in 10% central heavy ion collisions. These represent the best limits in the world to date [21] and are about (averaged over all masses) $1 \times 10^{-8}$ and $4 \times 10^{-9}$ for charge $Z = -1$ and $Z = -2$ respectively.

3.2. QGP

While the strangelet limits cannot tell us whether a QGP is ever formed in heavy ion collisions, they can tell us about a particular kind of QGP: that which decays into strangelets. The probability that such a QGP is formed can be considered a branching fraction for the result of a central heavy ion collision, while the probability that such a QGP decays into a charge $Z = -1$ or $Z = -2$ strangelet can also be considered a branching fraction. An upper limit is then calculated for each branching fraction as a function of the other, as shown in Figure 4.

4. Conclusion and Future Prospects

E864 has found no clear evidence for negatively charged strangelets in central Au + Pt collisions at 11.5 GeV/c per nucleon. We have set 90% C.L. upper limits of $\sim 1 \times 10^{-8}$ and
~4 × 10^{-9} per central collision for production of charge $Z = -1$ and $Z = -2$ strangelets with proper lifetimes $\tau \geq \sim 50$ ns respectively. While it is difficult to make any statements about coalescence and thermal model production mechanisms, upper limits have been calculated on the formation of a QGP which distills into such strangelets.

Further work on this front includes looking for strangelets which have charge $Z \leq -3$ in the data set, and conducting a search for strangelets which may interact as antimatter in the E864 calorimeter. The final sensitivities from E864 will be further enhanced by combining the results of this data set (taken at -0.75T) with those from the +1.5T data set taken during the same running period. These limits will likely be the ultimate results for negatively charged strangelet searches at the AGS [21].

5. Acknowledgements

The E864 collaboration wishes to thank the AGS staff for their support. This work was supported by the Department of Energy’s High Energy and Nuclear Physics Divisions, the U.S. National Science Foundation, and the Instituto di Fisica Nucleare of Italy.

References

[1] Schaffner-Bielich J et al 1997 J. Phys. G.: Nucl. Part. Phys. 23 p 2107
[2] Madsen J 1995 Strangeness in Hadronic Matter (S ’95) ed J Rafelski (New York: AIP) p 32
[3] Jaffe R L and Farhi E 1984 Phys. Rev. D30 p 2379
[4] Jaffe R L 1977 Phys. Rev. Lett. 38 p 195
[5] Chin S A and Kerman A K 1979 Phys. Rev. Lett. 43 p 1292
[6] Baltz A et al 1994 Phys. Lett. B325 p 7
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[7] Braun-Munzinger P and Stachel J 1995 J. Phys. G: Nucl. Part. Phys. p L17
[8] Liu H and Shaw G L 1984 Phys. Rev. D30 p 1137
[9] Greiner C et al 1987 Phys. Rev. Lett. 58 p 1825
[10] Ogilvie C These proceedings
[11] Greiner C These proceedings
[12] Sandweiss J et al 1991 E864 Proposal: Measurements of Rare Composite Objects and High Sensitivity Searches for Novel Forms of Matter Produced in High Energy Heavy Ion Collisions
[13] Barish K N 1997 J. Phys. G: Nucl. Part Phys. 23 p 2127
[14] Armstrong T A et al 1997 Phys. Rev. Lett. 79 p 3612
[15] Armstrong T A et al 1997 Nucl. Phys. A625 p 494
[16] Armstrong T A et al 1998 Nucl. Instrum. Methods A 33 p 100
[17] Haridas P et al 1997 Nucl. Instrum Methods A bf 385 p 412
[18] Barish K 1996 PhD Thesis, Yale University
[19] Hill J et al Nucl. Instrum. Methods A (to be published)
[20] Van Buren G 1998 PhD Thesis, MIT
[21] Sandweiss J These proceedings
[22] Appelquist G et al 1996 Phys. Rev. Lett. 76 p 3907
[23] Crawford H et al 1992 Phys. Rev. D45 p 857; Crawford H et al 1993 Phys. Rev. D48 p 4474