Strangelet search and light nucleus production in relativistic Si+Pt and Au+Pt collisions

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(Received 8 November 1995)

A strangelet search in Si+Pt and Au+Pt collisions at alternating-gradient synchrotron (AGS) energies, using a focusing spectrometer, sensitive to mass per charge of 3–14 GeV/c^2 was conducted during the 1992 and 1993 heavy ion runs at the AGS. The null results thereof are presented as upper limits on the invariant production cross section, in the range of $10^{-5}-10^{-4}$ mb c^3/GeV^2, and model dependent sensitivity limits in the range of $10^{-7}-10^{-5}$ per collision. Measurements of the production cross sections of several nonstrange nuclear systems, from p to ^{7}Be and ^{8}Li, the background of the strangelet search, are also presented. [S0556-2813(96)50607-2]

PACS number(s): 25.75.Dw, 12.38.Mh, 24.85.+p

Strange quark matter (SQM), that is, a multiquark system composed of roughly equal numbers of up (u), down (d), and strange (s) quarks [1,2], is thought to be producible in small droplets (''strangelets'') [3–6] in relativistic heavy-ion collisions, owing to the high energy and particle content of the colliding systems. Strangelets have even been proposed as the ''smoking gun'' signaling the formation of the elusive quark-gluon plasma (QGP) [7–9] in such collisions. The strangeness content of these systems should increase their mass per baryon number, while the tendency towards (roughly) equal number of each flavor should decrease the charge per baryon. An expected signature of strangelets, therefore, is an anomalously large mass to charge ratio (M/Z). Predictions of production rates in models that presuppose the creation of QGP are at levels accessible to current experiments, if the strangelets so produced are long lived. Coalescence-based predictions, in which a group of baryons coalesce to form a hypernucleus following a heavy-ion collision, and proceed to collapse into a strangelet, are generally several orders of magnitude lower than QGP ones, and have so far been out of the reach of experiments. However, predictions for the production rate of the hypernuclei are quite high [10], and offer a way to limit the branching ratio into strangelets. In addition, Ref. [11] discusses the possible stability of multistrange hypernuclei, whose signature, like strangelets, would be an unusual M/Z. No production rate estimates are given.

The question of lifetime is important for long flight-path spectrometers, which have been utilized by all fixed target heavy-ion experiments to date [12–15]. Several theoretical works address strangelet stability against particle emission, and some estimate the lifetimes of such systems. In Ref. [16] the lifetime of metastable strangelets is estimated to be on the order of 3×10^{-7} s, quite accessible to experiments.

We have conducted a high sensitivity study of 14.6A GeV/c Si and 10.8A GeV/c Au collisions with a Pt target at the alternating gradient synchrotron (AGS) of the Brookhaven National Laboratory (BNL), searching for new particles characterized by unusual M/Z ratios (e.g., strangelets). Target thickness was 4.5 cm during the Si run and negative polarity Au run, and 2.0 cm during the positive-polarity Au run. In addition, thin targets (a few mm) were used during both the Si and Au runs for calibration measurements. Our search was conducted using the 2 GeV/c D-6 beam line [17] at the AGS as a focusing spectrometer, with a second measurement provided by its associated open geometry dipole spectrometer, directly downstream of the beam line. The total flight path was ~30 m. The spectrometer covered a region of production angles from 4.0° to 7.4°, and a momentum bite of 1.8 GeV/$c\pm3$%. The beam line is equipped with two electrostatic separators that, along with the two associated dipole magnets, provide M/Z selection capabilities. These were used during the Si run to reduce the incidence on the trigger counters, but not during the Au run

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when the rates were low. Throughout the following discussion the beam line and open spectrometers will be referred to as ''front'' and ''rear'' spectrometers, respectively. The M/Z of particles produced within the acceptance of the beam line was determined by simultaneous measurement of their magnetic rigidity (p/Z) and velocity (β). The p/Z was determined by trajectory reconstruction using space point information produced in various drift chambers along the beamline, while β was obtained by measuring the time-of- flight (TOF) between pairs of plastic scintillators, separated by approximately 15 m. Particle charge (Z) was deduced from pulse height measurements in an energy-loss counter, consisting of four closely-spaced plastic scintillators located between the front and rear spectrometers. Velocity and rigidity measurements were made similarly in the rear spectrometer, providing a redundant measurement of p/Z and β for each event. The M/Z resolution (rms) in the front and rear spectrometers was 2.1% and 2.4%, respectively. Further information regarding the experimental apparatus and techniques can be found elsewhere [17–21].

Candidate events with M/Z in the range of interest were selected online by TOF in the front spectrometer and energy loss, and were written to magnetic tape. For clean particle identification in the off-line analysis, we rejected events with more than one particle observed in the front spectrometer, the passing rate for this cut being 92%. Additional cuts available were a good χ^2 requirement of the fit to the space point information, an agreement between the M/Z measurements in the front and in the rear within 3.0 standard deviations, and the requirement that the measured p/Z value in the rear spectrometer be less than or equal to that in the front spectrometer, the maximum allowable rigidity shift being three times that expected from the average energy loss in traversing the various counters. These additional cuts were applied in some small ranges of M/Z as needed, and combined with the overall single track requirement resulted in an efficiency of approximately 74%.

A summary of the positive-polarity Au data is represented in Fig. 1, where the pulse height in the energy-loss counter is plotted against the M/Z in the front spectrometer. The lines in this plot represent the expected most probable pulse-height for $Z=1,2,3$, and 4 according to Vavilov's theory, modified by nonlinearities in plastic scintillator response [22]. The rear spectrometer information is used in the plot for the M/Z agreement and p/Z difference cuts, discussed above. This plot demonstrates the good particle identification capability of the apparatus, and gives an indication of the sensitivity of the search. We were able to identify cleanly π, K, p, d, t, ^{3}He, ^{4}He, ^{6}He, ^{8}He, ^{6}Li, ^{7}Li, ^{8}Li, and ^{7}Be, using TOF and pulse height alone, and calculated the invariant production cross sections for the ions. In addition to the live time, detection, and analysis efficiency corrections, thick-target related effects were taken into account that included momentum shifts due to energy loss in the target, beam line acceptance changes, survival efficiency of produced systems in the target, and production by secondary reactions [21]. If we assume that all detected ions are produced in primary Au+Pt interactions, the resulting cross sections are shown by the horizontal lines in Fig. 2. However, some ions are produced by secondary interactions of the outgoing ions in the target. The contribution of these has been estimated using an extension of a coalescence-model fit made to thin-target data [19]. The cross sections, $Ed^3\sigma/dp^3$, corrected for this effect, are listed in Table I, where the multiplicity for each ion is given as well. The numbers listed for ^{6}He through ^{7}Be come from the thick-

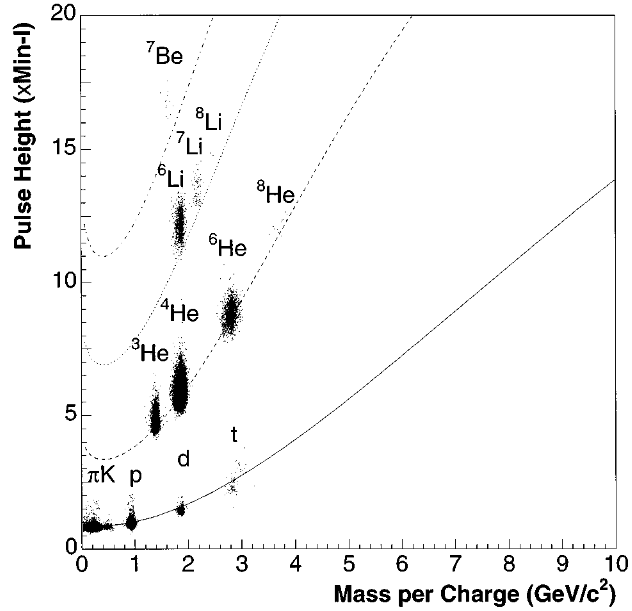

FIG. 1. Pulse heights plotted against M/Z. Since different groups of particles came from different data sets, the relative multiplicities in this plot are not representative of actual ones. The lines represent the expected most-probable pulse height for different charges, according to Vavilov's theory, modified by nonlinearities in scintillator response.

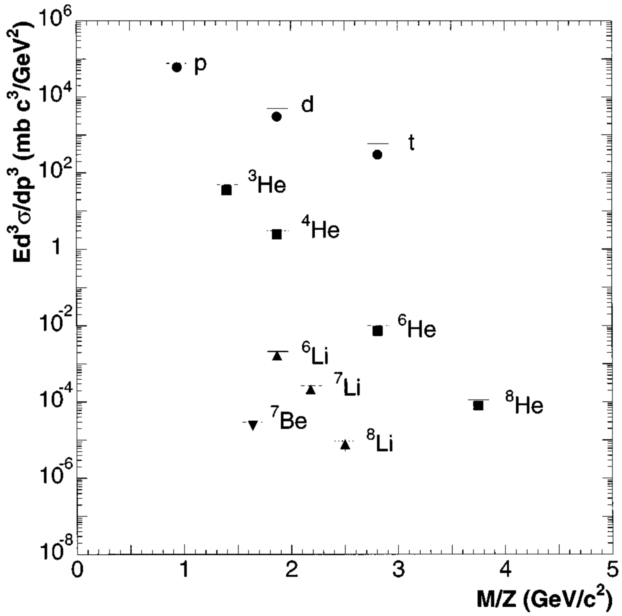

FIG. 2. The invariant production cross sections for the ions identified in the thick-target data set. The horizontal lines denote the values that result from a straightforward calculation, not taking secondary reactions into account. The symbols denote the values obtained from an extention of a coalescence fit to the thin-target data.

TABLE I. Au+Pt data summary.

Ion	Total count ± stat.	Invariant cross section mb c^3/GeV^2
p	$(1.136\pm0.002)\times10^{10}$	$(6.04\pm0.18)\times10^{4}$
d	$(5.508\pm0.003)\times10^{8}$	$(3.0\pm0.1)\times10^{3}$
t	$(4.95\pm0.10)\times10^{7}$	$(3.00\pm0.35)\times10^{2}$
^{3}He	$(2.00\pm0.06)\times10^{7}$	$(3.2\pm0.5)\times10^{1}$
^{4}He	$(1.06\pm0.15)\times10^{6}$	$(2.4\pm0.6)\times10^{0}$
^{6}He	2628 ± 82	$(7.37\pm3.03)\times10^{-3}$
^{8}He	23 ± 5	$(7.94\pm5.56)\times10^{-5}$
^{6}Li	1629 ± 43	$(1.67\pm0.47)\times10^{-3}$
^{7}Li	187 ± 15	$(2.16\pm0.71)\times10^{-4}$
^{8}Li	6 ± 2	$(7.73\pm5.42)\times10^{-6}$
^{7}Be	45 ± 7	$(2.61\pm0.78)\times10^{-5}$
$\bar{p}$	$(5.4\pm0.67)\times10^{6}$	$(1.75\pm0.03)\times10^{1}$

target data, while the rest come from the thin-target data, and all correspond to the symbols in Fig. 2. The errors reflect the uncertainties in the corrections for secondary reactions in the thick target, as well as statistical and analysis-related errors. The systematics, stemming mainly from incident beam normalization and beamline transport uncertainties, are estimated to be between 10% and 15%, and are not shown in the figure nor listed in the table.

Except for those appearing in the figure and the table, no other systems were detected during the entire Si and Au runs. Strangelets are expected to be found in the region to the right of all detected ions, along the lines of integer charge, within the expected pulse-height resolution. Most events found in this region were determined to be accidental triggers, since they had pulse heights consistent with π or p, much lower than that expected for slow (high M/Z) systems, with $Z=1$. In addition, the ratio of these events to fully identified events was in very good agreement with predictions for accidental rates, based on counting rates in the trigger detectors. These were therefore easily rejected by TOF and the pulse height. All other candidate events were rejected by the requirement of consistency in momentum and M/Z between front and rear spectrometers.

The null results of both the Si+Pt and Au+Pt searches are given in the form of 90% CL upper limits on invariant cross section in Figs. 3 and 4. For comparison with other experiments with colliding systems and phase-space coverages that differ from ours, and with theoretical models, it is more convenient to express the results as the sensitivity, which is defined as the upper limit on the total number of a given particle produced per collision. This requires knowledge of the phase-space distribution of the produced particles of interest, to relate total cross sections to the differential cross sections measured in a restricted region of phase space. This distribution is unknown for strangelets, but fits to nonstrange systems' distributions are used to try to guess its shape. The one used for the sensitivity limit in this work is given by

$$E\,\frac{d^3n}{dp^3}\propto\exp\left[-\frac{1}{2}\left(\frac{y-y_0}{\sigma_y}\right)^2\right]\exp\left[-\frac{M_t-M}{T}\right],$$

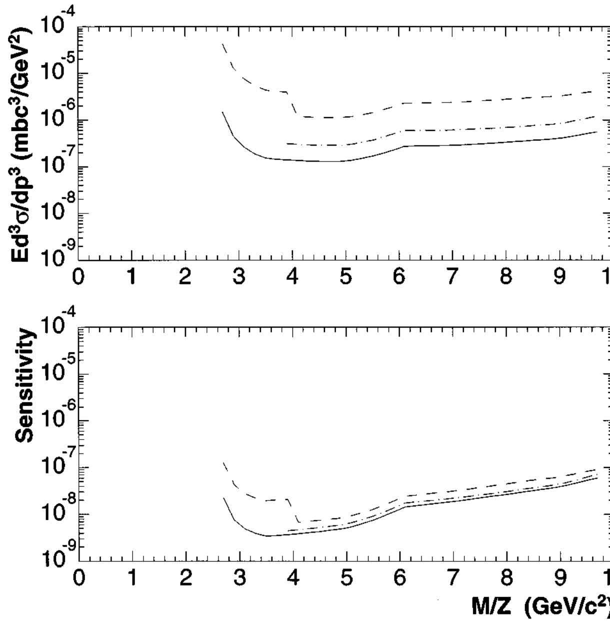

FIG. 3. The 90% upper limit on invariant cross section (upper plot) and sensitivity (lower plot), deduced from the Si run. The three curves are, from top to bottom, for $Z=1,2$, and 3. Two different mass tunes were used during that run, which leads to the kink in the plot around $M/Z=6$. The step in the $Z=1$ curve around $M/Z=4$ is due to the additional cuts needed to clean the residual tail from the tritons, as described in the text.

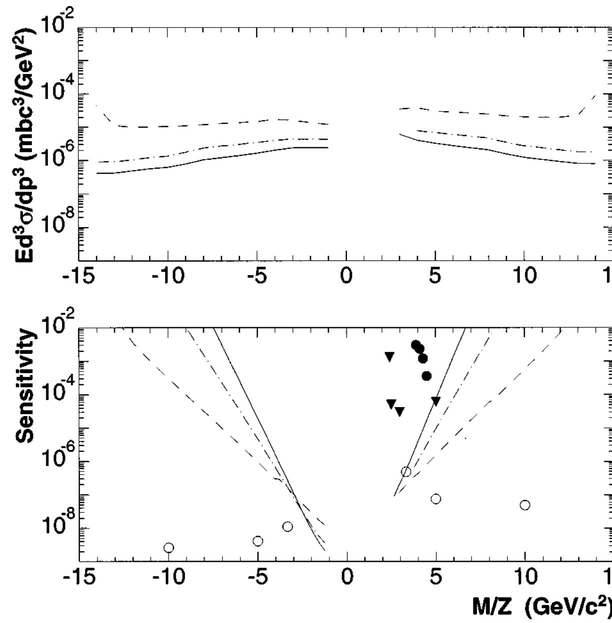

FIG. 4. The 90% upper limit on invariant cross section (upper plot) and sensitivity (lower plot), for stable strangelets, from the Au run. The three curves are, from top to bottom, for $Z=1,2$, and 3. The predictions of Ref. [8] for strangelets with $A=10$, $S=-1$ and $Z=-3,-2,-1,1,2$, and 3 are marked with empty circles. The hypernuclear systems of Ref. [10] are marked with triangles, and are, starting with the upper-most one and proceeding counter clockwise, ${}^{5}_{\Lambda}$He, ${}^{5}_{\Lambda\Lambda}$He, ${}^{6}_{\Lambda\Lambda}$He, and ${}^{5}_{\Lambda\Lambda}$H. The full circles give the predictions of Ref. [9] for strangelets of $A=4$ and, from top to bottom, $S=-1,-2,-3$, and -4.

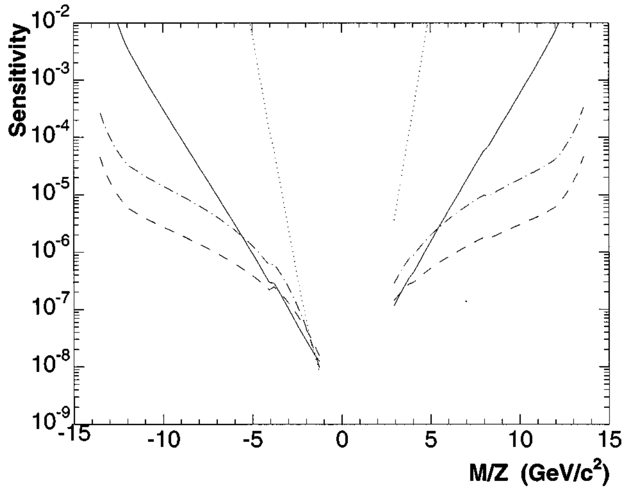

FIG. 5. The present results for Au+Pt collisions, for $Z=\pm 1$, expressed as sensitivities. The curves are for the four assumptions about the form of σ_y discussed in the text; from top to bottom they are $\sigma_y=0.5/\sqrt{A}$, $\sigma_y=1/\sqrt{A}$, $\sigma_y=0.5$, and $\sigma_y=1$.

where y, M, and M_t are the produced system rapidity, mass, and transverse mass, respectively, and y_0 the collision center-of-mass rapidity. Our upper limits, expressed as sensitivities, are shown in the lower set of curves in Figs. 3 and 4, where we used the above expression with $\sigma_y=1/\sqrt{A}$ and $T=0.15$ GeV (see below). As in the case of the production cross sections for the ordinary nuclei, corrections were made for the analysis and detection efficiencies, as well as thick-target related corrections as described earlier.

The values extracted for the sensitivity depend on the form chosen for σ_y in the above expression for the invariant cross section. In Refs. [23,24], a value of $\sigma_y=1$ was deduced from an analysis of pion production. Coalescence models suggest that σ_y should vary with $1/\sqrt{A}$, and in the analysis of Beavis *et al.* [15], the forms $\sigma_y=1/\sqrt{A}$ and $\sigma_y=0.5/\sqrt{A}$ were used, as well as a constant value of $\sigma_y=0.5$. To illustrate the effect of this, Fig. 5 shows the sensitivities extracted from the present results for Au+Pt, Z$=\pm 1$, for the above four assumptions for σ_y.

In Ref. [8], the production rates for both positive and negative strangelets are given, presupposing the creation of QGP in relativistic heavy-ion central collisions, which are taken to be 10% of all collisions. The numbers given for some systems are represented by open circles in Fig. 4. The prediction for $Z=+1$ is comparable to the present limit. Thus it is possible that, for some assumptions for the form of σ_y, this system could have been detected had it been produced at the predicted rate, and was sufficiently long lived. The absence of signal can be used to limit the lifetimes to a few 100 ns, deny the formation of the system, or deny the formation of QGP in the reactions studied in this experiment. The black triangles represent predicted production rates for some of the single- or double-hypernuclear systems discussed in Ref. [10]. The absence of signal here can be used to limit the lifetime, or limit the branching ratio for decay of these systems into strangelets.

Another estimate of strangelet production has been published by Árvay *et al.* [9], and results in the predictions for $A=4$ systems, indicated as full circles in Fig. 4. As in the work of Crawford *et al.* [8], they assume that a QGP is formed in central collisions, and they study how the plasma condenses out into hadrons, including strangelets. The cooling of the hadronic droplets is not treated in detail in Ref. [9]. As a result, the authors point out that their predictions of absolute rates are not reliable, but they claim that their predicted *ratios* of strange to nonstrange systems for a given baryon number should not be strongly affected. Thus in applying their calculations, we multiplied this ratio from their paper by the number of nonstrange nuclei we observed experimentally for the same *A*. In doing so, we involve the same assumptions as in applying Crawford's work, i.e., the formation of a QGP and that the strangelet lifetimes are long enough. In addition, we have to assume that a portion of the yield we observe for ordinary nuclei results from condensation from the QGP rather than from other sources such as coalescence. This was done by assuming that QGP was produced in every central collision, which was taken to be 10% of all collisions.

In summary, we report the null result of a high sensitivity search for strangelets, limited to a single, small area of phase space and lifetimes greater than a few 100 ns. The results, given in the form of limits on invariant cross section and on model-dependent sensitivity, can be used to place limits on QGP-based production models, but do not challenge coalescence-based production models, which predict much lower production rates [8,24]. They are the most sensitive results reported in Si + Pt, among the first reported in Au + Pt collisions, and are complementary to the results of the few experiments that reach similar sensitivity in these and other reactions [14,15]. Our acceptance for $Z=3$ systems enables us to set limits on systems with baryon number up to $A\sim 50$. The two spectrometer approach made the search very near known systems possible, cleaning up the background unique to experiments using only one focusing spectrometer. The reported cross sections for light nuclei from p to ^{8}Li, spanning some ten orders of magnitude, are relevant to coalescence model calculations, and can be used to gauge the sensitivity of our search.

The authors would like to thank the BNL accelerator and support staff for their efforts during these runs, especially for the successful commissioning of the Au program. This work was supported in part by the U. S. Department of Energy under Contracts No. DE-FG02-91ER40609, No. DE-AC02-76H00016, and No. DE-FG04-88ER40396, by the German Federal Minister for Research and Technology (BMFT) under Contract No. 06 FR 652, by the United Kingdom SERC, and by the Japanese Society for the Promotion of Science.

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