Search for strangelets in Pb + Pb collisions at 158 A GeV/c

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Abstract. The NA52 experiment at CERN has investigated lead–lead collisions at 158 A GeV/c and searched for long-lived strange quark matter droplets, so-called strangelets, with a unique signature of a high mass-to-charge ratio. This ratio was measured in a focusing spectrometer equipped with a time-of-flight system. A total of $3 \times 10^{11}$ Pb + Pb interactions at positive and $10^{13}$ at negative spectrometer polarities have been recorded. No strangelet has been observed, which sets experimental upper limits (90\% CL) for the strangelet production at $3 \times 10^{-9}$ per interaction for positively charged and at $2 \times 10^{-10}$ per interaction for negatively charged strangelets.

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1. Introduction

The search for strange quark matter was motivated by the high matter densities observed in neutron stars. They are suggestive of the existence of a possibly new form of matter, the so-called strange quark matter (SQM) [1,2]. In contrast to ordinary matter, SQM consists of a multi-quark bag with approximately equal numbers of u, d and s quarks. On the basis of the Pauli exclusion principle such multi-quark states could become stable owing to the introduction of strangeness as an additional degree of freedom. The stability of SQM depends essentially on two parameters, the strange quark mass and the bag pressure. SQM can exist in neutral or charged form. Because of the large s-quark content, the mass-to-charge ratio of SQM is expected to be considerably larger than that of ordinary matter, a circumstance which is used as a prominent experimental signature. The anticipated mass range for SQM lies between the masses of light nuclei and those of neutron stars (\(A \approx 10^{57}\)). Light SQM droplets are called strangelets. Witten [3] discussed the possibility of SQM drops being formed in the early universe during the transition from a deconfined quark and gluon phase to a confined hadron phase. These SQM drops could also be candidates for the missing matter in the universe.

The NA52 experiment was designed to search for strangelets in relativistic heavy ion collisions. It was also motivated by the possibility that these objects can be formed from a quark–gluon plasma (QGP) via a strangeness distillation process [4]–[6]. Thus, if stable strangelets were to be found, it would confirm the existence of an as yet unseen ground state of matter and it would indicate the existence of a QGP, which on cooling has served as a source of SQM. Bag model calculations indicate that strangelets with sufficiently large masses (\(m > 4 \text{ GeV}/c^2\)) can be stable enough to be detected in our spectrometer [7]. The formation of SQM has also been considered in coalescence models [8] as well as in the decay of metastable exotic multi-hypernuclear objects [9].

The NA52 experiment used a well instrumented focusing mass spectrometer which allowed us to search for strangelets in a mass to charge range of 4–120 GeV/c² with high sensitivity and low background. It is the only experiment dedicated to SQM search at CERN. Early results of this experiment have already been published [10, 11]. An overview of the various experimental strangelet searches can be found in [12]. In this paper we present the final results of the NA52 strangelet search, which will also be compared to those of other experiments and to theoretical predictions.

2. Experimental set-up

NA52 made use of the secondary H6 beam line in the north area of the SPS at CERN as a single-particle, double-bend focusing spectrometer, transporting charged particles within a momentum bite of 2.8%, selectable for rigidities \(p/Z\) between ±5 and ±200 GeV/c. The spectrometer was operated near zero degree production angle with a solid angle acceptance of \(2.2 \mu\text{sr}\). A schematic layout of the experimental set-up is shown in figure 1.

The particles are identified by their mass and charge with the help of time-of-flight (TOF) and energy loss measurements \((dE/dx)\) in five segmented scintillator hodoscopes (TOF1–TOF5) and unsegmented scintillation counters (B0–B2, BT and BS). The unsegmented counters B1 and B2 (each with the dimensions 12 × 12 × 0.5 cm³) are read out by two photomultipliers on opposite ends allowing for a TOF measurement. Additional counters BT, B0 and BS with the same dimensions as B1 and B2 were installed in order to improve the TOF and energy loss.
Figure 1. Schematic layout of the H6 beam line equipped with an incident beam counter (TOF0), time-of-flight hodoscopes (TOF1–TOF5), scintillation counters (BT, BS and B0–B2), threshold Čerenkov counters (Č0–Č2), a CEDAR, multi-wire proportional chambers (W1T–W5T, W2S, W3S, W0B and WSB) and a calorimeter. In this layout no focusing elements (quadrupoles and sextupoles) of the spectrometer are shown. Strings of bending magnets are indicated as triangles.

measurement for short-lived particles and the background recognition. The five TOF hodoscopes have the same lateral dimensions of $10 \times 10$ cm$^2$. Each TOF counter consists of eight scintillator elements with a width varying from 8 mm, at the centre, to 20 mm, at the outside, in order to obtain approximately the same rate in each element. At each end of every hodoscope element, the scintillation light is collected via a plastic light guide onto a photomultiplier. In order to keep the amount of material in the spectrometer as small as possible only the TOF counters which are essential for obtaining a good TOF resolution (TOF1, TOF3 and TOF5) are equipped with 1 cm and the others (TOF2 and TOF4) with 0.5 cm thick scintillators. Custom made constant fraction discriminators are used. Typical intrinsic time resolutions of $(74 \pm 1)$ ps for the 1 cm and $(105 \pm 1)$ ps for the 0.5 cm thick TOF counters were obtained. Downstream of each TOF counter a proportional wire chamber (W1T to W5T) was installed to provide tracking of the particles. The chambers W0B, W2S, WSB and W3S are used to improve the intrinsic momentum resolution of the beam spectrometer. The size of the chambers is $96 \times 96$ mm$^2$, covering the full beam aperture. The wire spacing is 3 mm in all chambers. The chambers W1T, W2T, W4T and W5T were equipped with $x$, $y$ and 45° inclined $v$ and $u$ planes while the other chambers are instrumented with $x$ and $y$ planes only. The beam spectrometer, equipped with the proportional chambers, yields a momentum resolution for particles with $p > 50$ GeV/c of $\Delta p/p = 0.85 \times 10^{-3}$. Threshold Čerenkov counters (Č0, Č1, Č2) are used to veto and/or tag light particles at high momenta. The CEDAR Čerenkov counter is employed to tag specific particles. A segmented scintillator/uranium calorimeter (7.1 interaction lengths deep), at the downstream end of the spectrometer, provides additional charge information by combining its energy with the rigidity measurement of the spectrometer for long-lived particles. In addition it is used to distinguish between electrons, muons and hadrons. The incident lead ions are monitored by a segmented quartz Čerenkov counter (TOF0) with a diameter of 13 mm and a thickness of 0.4 mm. The counter is azimuthally divided into four individual sectors. The produced Čerenkov light is guided through quartz fibres onto four photomultipliers. After amplification and shaping, the signals of the four sectors are transmitted over a distance of about 300 m to the electronic hut using laser-driven optical fibres. A high single-rate capability of the four channels is obtained by employing a time demultiplexing system with a pulse-to-pulse resolution of 7 ns. A similar time demultiplexing system is used for the BT and B0 counters. Beam intensities of up to $2 \times 10^8$ Pb ions.
Figure 2. Example of the fit to the timing information for a typical antideuteron event. From the difference of the slope compared to the slope of pions a mass to charge ratio of \(\frac{m}{|Z|} = (1.85 \pm 0.01) \text{ GeV}/c^2\) is extracted.

ions per spill were recorded. The spill duration is 5 s. The TOF0 counter, with its intrinsic time resolution of 74 ps, is also used as a prominent counter in the TOF measurements.

A lead target of 40 mm length was used for the strangelet search. Some data were also taken with targets of 4, 8 and 16 mm length.

The read-out of the detectors, which are distributed over 524 m length, is subdivided into two parts, A and B, with individual triggers. Each trigger consists of a coincidence of a TOF hodoscope and an unsegmented scintillation counter (trigger \(A = B1 \times \text{TOF2}, \text{trigger } B = B2 \times \text{TOF4}\)). Trigger A requires a particle with a decay time of \(\tau_{\text{lab}} > 0.9 \mu s\) in order to be detected. The inclusion of the downstream trigger B increases this limit to \(\tau_{\text{lab}} > 1.7 \mu s\). The arrival time of the signals from the TOF and B counters are registered by time-to-digital converters (TDCs) with a 120 ns linear range and 50 ps resolution. In addition, the hit pattern of the TOF counters is recorded every 10 ns approximately from 1.25 \(\mu s\) before to 1.25 \(\mu s\) after the occurrence of the trigger. This additional information is important for the background recognition.

3. Analysis

The TOF information is used to determine the mean inverse velocity of the particles with the help of a linear fit to the individual timing information \(\Delta t\) at the various detector positions \(\Delta L\).
from the production target
\[
\left\langle \frac{\Delta t}{\Delta L} \right\rangle = \frac{1}{c} \left( \frac{1}{\beta} - \frac{1}{\beta_\pi} \right),
\]
where \(\beta = \frac{v}{c}\) is the velocity of the particle relative to the speed of light and \(\beta_\pi\) the corresponding velocity of pions. Pions were taken as reference, since they are copiously produced and identified by Čerenkov counters. In figure 2 the timing information of an antideuteron event is shown. From the slope \(\left\langle \frac{\Delta t}{\Delta L} \right\rangle\) we extract the mass to charge ratio
\[
\left( \frac{m}{Z} \right)^2 = \left( \frac{p}{Z} \right)^2 \left[ \left( \left\langle \frac{\Delta t}{\Delta L} \right\rangle \right) + \sqrt{\frac{1}{c^2} + \left( \frac{m_\pi}{p_\pi} \right)^2} \right]^2 - \frac{1}{c^2},
\]
where \(m_\pi\) and \(p_\pi\) are the mass and the momentum of the pions. The dynamic range of the TOF system covers a velocity range of \(0.85 < \beta < 1.0\), which corresponds to an \(m/Z\) range which extends to approximately \(0.6c \times p/Z\).

The charge of the particles is determined from the mean of the energy losses measured with the individual scintillators.

4. Results

We have collected a total of \(10^{13}\) Pb + Pb interactions looking for negatively charged strangelets at spectrometer rigidities of \(-20, -40, -70, -100\) and \(-200\) GeV/c and \(3 \times 10^{11}\) Pb + Pb interactions for positively charged ones at rigidities of \(+40, +100\) and \(+200\) GeV/c. A sample TOF spectrum obtained at the rigidity of \(-20\) GeV/c is shown in figure 3. No evidence for the production of strangelets has been found. A previously observed candidate [13] with a negative charge of \(Z = -1\) and a mass of \(m = (7.0 \pm 0.4)\) GeV/c was not confirmed with a factor of ten times more statistics and with an increased redundancy in the TOF detection system.

As no strangelet has been observed we quote upper limits (90% CL) for the differential production cross sections derived from
\[
E \frac{d^3\sigma}{dp^3} = \frac{E}{p^3} \frac{2.3}{N_{\text{Pb}a\text{nn}}},
\]
Figure 4. Upper limits (90% CL) of the SQM production cross sections at zero degrees production angle for various spectrometer rigidities for positively charged (a) and negatively charged (b) strangelets.
Figure 5. (a) Assumed phase space distribution for strangelets and (b) superimposed the acceptance of the H6 beam line spectrometer for various rigidity settings for a strangelet with a mass-to-charge ratio of $8 \text{ GeV}/c^2$. The rapidity of the centre of mass in the laboratory system $y_{cm}$ is indicated. See text for explanation.

where $N_{Pb}$ is the number of incident Pb ions, $\alpha$ is the spectrometer acceptance and $n$ is the number of target nuclei per unit area. The resulting upper production cross section limits for positively and negatively charged strangelets are shown in figure 4. The differential cross sections are given for various selected spectrometer rigidities near zero degrees production angle. The rapidity $y$ in the laboratory frame is indicated at the bottom of each region. For a given mass different limits are obtained at different rigidities.

In order to quote total production limits (corresponding to the reached sensitivities) one has
Figure 6. Experimental sensitivity for the detection of long-lived strangelets produced in lead–lead collisions as obtained by the NA52 experiment. The two plots give the upper limits (90% CL) of SQM production of positive charge (a) and negative charge (b), respectively. The sensitivity is compared to predictions by Crawford et al [14] (filled symbols) and Schaffner-Bielich et al [7] (open circles, $\frac{1}{2} \sigma_S$).
to assume a phase space distribution of the produced strangelets. We use a distribution which is Gaussian in rapidity $y$ and exponentially decreasing in the transverse momentum $p_\perp$:

$$
\frac{d^2N}{dy \, dp_\perp} = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left(\frac{(y - y_{cm})^2}{2\sigma_y^2}\right) \frac{4p_\perp}{\langle p_\perp \rangle^2} \exp\left(-\frac{2p_\perp}{\langle p_\perp \rangle}\right)
$$

where $y_{cm} = 2.9$ is the rapidity of the centre of mass in the laboratory system. The width of the rapidity distribution is chosen to be $\sigma_y = 0.5$ and the mean transverse momentum $\langle p_\perp \rangle = 0.1\sqrt{m \cdot \text{GeV}}$. The production model and its overlay with the acceptance of the H6 spectrometer is shown in figure 5 for a strangelet with $m/Z = 8 \text{ GeV}/c^2$. The widths of the needle-like shapes correspond to the accepted momentum bite of the spectrometer, while their length is determined by the angular acceptance.

The total production limits are calculated by integrating $d^2N/dy \, dp_\perp$ over the spectrometer acceptance in $y$ and $p_\perp$ and by extrapolating to the full phase space. The resulting sensitivities are shown in figure 6 as a function of the mass-to-charge ratio for positively and negatively charged strangelets. It should be noted that we measure inclusive cross sections using a minimum-bias trigger. Only tracks which reach at least the TOF3 hodoscope at $L/c = 1.2 \mu s$ downstream of the target have been considered. Figure 7 shows how the sensitivity decreases as a function of the lifetime $\tau$ for three negatively charged strangelets with mass-to-charge ratios of $-7$, $-14$ and $-50 \text{ GeV}/c^2$. To search for strangelets with short lifetimes $\tau$ we also looked at short tracks. The shortest tracks recorded reach the trigger counter B1 which is located at $L/c = 0.9 \mu s$ downstream of the target. In the data taking run of 1998 we were able to study the short tracks with an increased number of TOF and track position measurements by adding the counters BT and B0 and the wire chamber W0B. However, short tracks often have large angles to the beam axis for which the Čerenkov counter efficiency drops low. They therefore suffer from a large background of particles with a small $m/|Z|$. No strangelets have been observed among the short tracks. The gain in sensitivity taking short tracks into account as a function of the strangelet

Figure 7. The sensitivity for strangelets with a limited lifetime for three negatively charged strangelets with mass-to-charge ratios of $-7$, $-14$ and $-50 \text{ GeV}/c^2$. 

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Figure 8. The gain in sensitivity due to the inclusion of short tracks as a function of the strangelet lifetime for strangelets with mass-to-charge ratio $m/Z = -14 \text{ GeV}/c^2$.

lifetime is shown in figure 8. In this figure an example of strangelets with $m/Z = -14 \text{ GeV}/c^2$ has been selected. A factor of 1.6 gain in sensitivity is obtained if one assumes a lifetime of $\tau = 50 \text{ ns}$. The dark region in figure 9 shows the gain in sensitivity due to the inclusion of short tracks with $L/c > 0.9 \mu s$ as a function of the mass to charge ratio for a strangelet with a lifetime of $\tau = 50 \text{ ns}$. As a result we can quote our best upper production limit of $8 \times 10^{-10}$ per interaction for a negatively charged strangelet with lifetime $\tau = 50 \text{ ns}$ and mass-to-charge ratio $m/Z = -14 \text{ GeV}/c^2$.

5. Discussion

Our search for strangelets is complementary to searches at lower incident momenta performed at BNL-AGS (E858 [15, 16], E878 [17], E886 [18], E864 [19] and E814 [20, 21]). A comparison of the sensitivities reached by different experiments for long-lived strangelets with $Z = -1$ and $+1$ are given in figures 10 and 11 respectively. Also shown are limits by NA52 in S–W collisions [10]. To allow for a comparison with minimal systematic uncertainties the curves are scaled to a specific parameter selection for the phase space distribution (4) with $\sigma_y = 0.5$ and $\langle p_t \rangle = 0.5, \ldots, 0.7 \sqrt{m} \text{ (GeV)}$. However, it should be kept in mind that this compilation contains sensitivities from experiments with different colliding systems such as $\text{Si + Cu, Si + Pt, S + W, Au + Au, Au + Pt and Pb + Pb}$ at different energies and different centrality selections (minimum bias for E814, E878, E886, NA52 and 10% most central for E864).

The coalescence model of [8] predicts production probabilities of $10^{-2}$ per minimum-bias Au + Au collision for $\Lambda^3 \text{He}$ and $10^{-6}$ per collision for $\Lambda \text{He}$. These predictions are ruled out by the experimental results. For positively charged strangelets $^A\text{St}^Z_S$ (with $A$ the atomic mass, $Z$ the charge and $S$ the strangeness) thermodynamical model calculations [22] give production probabilities of $10^{-12}$ per central Au + Au collision for $^{10}\text{St}^{1-}_S$ and $10^{-27}$ per collision for $^{20}\text{St}^{2-}_{16}$. 

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which are far below present experimental limits. For strangelets produced in Pb + Pb collisions as cool remnants of a QGP state [5] production probabilities were calculated by Crawford et al [14, 23]. The predictions for positively and negatively charged strangelets with lifetimes \( \tau > 10^{-7} \) s are shown in figure 6 (filled symbols). As can be seen the experimental limits start to rule out also some of these predictions. In other calculations [7, 24] the emphasis has been put on decay schemes of arbitrary quark compositions. Combining these results with a simple coalescence model of [25] production probabilities proportional to \( 10^{3-A-|S|} \), shown in figure 6 as open circles, have been derived. Rather high production probabilities for the lighter strangelets are predicted. Some are already ruled out by our experimental result.

NA52 has also measured particle and antiparticle cross sections over a wide range of rapidity [26]. From these we can extract thermodynamical variables which can be used to make predictions on the production of strange clusters. The baryochemical potential \( \mu_B \), the charge-chemical potential \( \mu_Q \) and the strangeness-chemical potential \( \mu_S \) are extracted from ratios of the production cross sections of deuterons to antideuterons \( (d/\bar{d}) \), protons to antiprotons \( (p/\bar{p}) \) and kaons to antikaons \( (K^+/K^-) \). The temperature is derived from \( \mu_B \) and the \( p/d \) ratio. We obtain

\[
T = (127 \pm 3) \text{ MeV} \\
\mu_B = (135 \pm 20) \text{ MeV}; \quad \mu_Q = (23 \pm 14) \text{ MeV}; \quad \mu_S = (12 \pm 12) \text{ MeV}.
\]

The temperature derived from our analysis using proton and deuteron yields is lower than the chemical freeze-out temperature of \( T \approx 160–170 \) MeV derived from ratios of hadrons [27, 28]. This is due to the fact that deuterons and antideuterons are mainly formed by coalescence at a later stage of the collision than hadrons. A further discussion of this can be found in [29, 30]. The source volume \( V = (1530 \pm 36) \) fm\(^3\) is extracted from the deuteron cross section using a coalescence model [31].

**Figure 9.** Gain in sensitivity due to the inclusion of short tracks up to B1 \((L/c > 0.9 \mu s)\) compared to the long tracks up to TOF3 \((L/c > 1.2 \mu s)\) as a function of the strangelet mass-to-charge ratio. For a strangelet with \( m/Z = -14 \text{ GeV}/c^2 \) and lifetime 50 ns the sensitivity increases by a factor of 1.6.
Figure 10. Compilation of obtained sensitivities by different experiments for long-lived strangelets with $Z = -1$.

Figure 11. Compilation of obtained sensitivities by different experiments for long-lived strangelets with $Z = +1$.

The predictions for the production cross sections of strange clusters at $y = y_{cm}$ are shown (filled dots) in figure 12 for positive and in figure 13 for negative charges together with the measured particle cross sections of NA52 (triangles). They can be compared to the measured NA52 strangelet production limits, which are also shown as lines in figures 12 and 13. One can see that some of the lightest negatively charged strange clusters are excluded, while positively charged clusters are below the limits.
Figure 12. Predictions for the production cross sections of positively charged strange clusters at $y = y_{cm}$ are shown (filled dots) together with the measured particle cross sections of NA52 (triangles). The measured NA52 strangelet production limits are shown as lines.

6. Conclusions

The final results of the NA52 strangelet search show no evidence for the production of charged strangelets in $Pb + Pb$ collisions at 158 $A$ GeV/$c$ over a wide mass range. We quote upper limits (90% CL) for the production of long-lived strangelets of the order of $3 \times 10^{-9}$ per collision for the positively charged ones and of the order of $2 \times 10^{-10}$ per collision for the negatively charged ones. The data exclude some of the theoretical model predictions for long-lived strangelets. They also exclude some strange clusters predicted from a thermodynamical model using the temperature, the chemical potentials and the source volume derived from the particle cross sections at central rapidity measured by NA52. So far experiments have been restricted to searches for long-lived strangelets. However, short-lived metastable candidates are, from a theoretical point of view, more favourable. Therefore a significant improvement of the detection of short-lived states would be desirable in future searches.
Figure 13. Predictions for the production cross sections of negatively charged strange clusters at $y = y_{cm}$ are shown (filled dots) together with the measured particle cross sections of NA52 (triangles). The measured NA52 strangelet production limits are shown as lines.

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