Strangelet Search in Pb-Pb Interactions at 158 GeV/c per Nucleon

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The NA52 experiment searches for long-lived massive strange quark matter particles, so-called *strangelets,* produced in Pb-Pb collisions at a beam momentum of $p_{\rm lab} = 158$ A GeV/c. Upper limits for the production of strangelets at zero degree production angle covering a mass to charge ratio up to 120 GeV/c^2 and lifetimes $t_{\rm lab} \gtrsim 1.2$ μs are given. The data presented here were taken during the 1994 lead beam running period at CERN. [S0031-9007(96)00235-9]

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The production of strange quark matter (SQM), so-called strangelets, has long been advertised as an ultimate signature for quark-gluon plasma (QGP) formation in ultrarelativistic heavy ion collisions. Strangelets could be formed from the QGP via a strangeness distillation process [1–4]. Their production is due to a cooling process of the plasma which results in a strong enhancement of the s quarks in the quark phase. The cooling mechanism of the plasma is started by the evaporation of pions, K^+ and K^0, which carry entropy and antistrangeness away from the system. The strong s-quark enhancement in the baryon rich environment of the plasma favors the formation of strangelets. In contrast to nuclear matter, strangelets consist of approximately the same number of u, d, and s quarks. On the basis of the Pauli exclusion principle such multiquark states become stable owing to the introduction of strangeness as an additional degree of freedom. Depending on the relative s-quark content, strangelets can exist in neutral or charged form. By virtue of the large s-quark content, the charge to mass ratio of strangelets is expected to be small ($Z/A < 0.1$), which is used as a prominent experimental signature. Bag model calculations indicate that for sufficiently large masses ($A > 10$ GeV/c^2) strangelets could be stable with respect to strong and weak nucleon emission and therefore detectable in mass spectrometer experiments [5–8]. Strangelet formation has also been considered in coalescence models [9]. Strange quark matter could even occur as a decay product of metastable exotic multihypernuclear objects (MEMO's) [10]. The discovery of strangelets would have profound implications beyond the confirmation of the QGP formation: it would establish the existence of strange quark matter (SQM) [11–13] in nature, thus lending strong support to astrophysical and cosmological hypotheses on the role of SQM in the Universe. If SQM were absolutely stable, it would represent a new, as yet unobserved, ground state of matter.

Strangelets with lifetimes $>10^{-7}$ s have been previously searched for in BNL [14–18] and CERN [19] heavy ion experiments as well as in cosmic rays [20]. A recent review is given in Ref. [21]. During the 1994 Pb period at CERN, the NA52 Collaboration took data to search for positively and negatively charged strangelets resulting from lead-on-lead collisions at an incident beam momentum of 158A GeV/c. Preliminary results have been already presented [22]. Now the full statistics have been analyzed and the final results are reported here.

The experimental setup (Fig. 1) makes use of the existing H6 beam line at the CERN-SPS to identify the secondary particles produced in the lead target. It is a single particle, double-bend focusing spectrometer transmitting charged particles within a momentum bite of 2.8% for rigidities $p/|Z|$ selectable between 5 and 200 GeV/c with full particle identification capabilities. It is operated at a production angle of 0° and has a solid angle acceptance of 2.2 μsr. Particles are identified by their mass and charge, which are determined with the help of time of flight (TOF) and energy loss measurements in eightfold segmented scintillator hodoscopes. Five such hodoscopes (TOF1–5) are placed at different positions along the beam line and have time resolutions of 74 to 105 ps. Multiwire proportional chambers (W1T–W5T, W2S–W3S) with 3 mm wire spacing are used to track particles through the beam line. The readout of the detector is subdivided into two parts with individual triggers. Each trigger consists of a coincidence of a TOF hodoscope and an unsegmented scintillation counter (B1 × TOF2, B2 × TOF4). Threshold Čerenkov counters (Č1-2) are used to veto and/or tag light particles at high momenta. The upstream part of the detector (up to TOF3, cf. Fig. 1) requires a lifetime $t_{\rm lab} \gtrsim 1.2$ μs for a

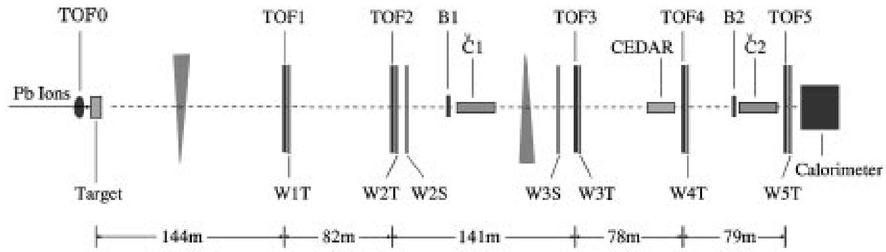

FIG. 1. The NA52 setup. The upstream trigger includes particle tracks until TOF3 ($t_{\rm lab} \gtrsim 1.2\ \mu$s), the downstream trigger until TOF5 ($t_{\rm lab} \gtrsim 1.7\ \mu$s).

particle to be detected, inclusion of the downstream trigger increases this limit to about 1.7 μs. For particles with a short mean lifetime τ a corresponding fraction $\exp(-t_{\rm lab}/\tau\gamma)$ is registered by the triggers. A differential Čerenkov counter (CEDAR) and a segmented hadron calorimeter add further particle identification capabilities and redundancy to the measurements. Incident lead ions are detected just in front of the lead target with a 0.4 mm thick, fourfold segmented quartz Čerenkov counter. It allows one to count the number of incident ions and provides precise timing information, which can be used in the TOF measurement. Further information about the detector components can be found in Ref. [23].

Secondary beam rigidities of ±100 and ±200 GeV$/c$ were chosen in order to search for heavy particles with a small $|Z|/m$ ratio. At these rigidities, particles with a mass to charge ratio of 10 to 40 GeV$/c^2$ are near midrapidity. For the $+200$ GeV$/c$ setting a 16 mm Pb target was selected and both the upstream and downstream triggers were required in coincidence. For the other settings we took a 40 mm target and only the upstream trigger was required. The recorded number of interactions at the various spectrometer settings are summarized in Table I.

For each event we calculate the ratio $(m/Z)^2$ from the TOF measurements and the known beam line rigidity p/Z. Figure 2 shows $(m/Z)^2$ distributions obtained at -100 GeV$/c$. Heavy particles like $\overline{d}$ and $\overline{t}$ are identified by the threshold Čerenkov counter Č1. Figure 2(b) shows the subsample of particles which were also recorded in the downstream part of the beam line. Here, additional information from the CEDAR is available, which was used to tag antiprotons.

TABLE I. Accumulated statistics at the four rigidity settings. The employed targets, the numbers of sampled Pb-Pb interactions, the covered mass to charge ranges, and the lifetime requirements $t_{\rm lab}$ are shown. At $+200$ GeV$/c$ both triggers, upstream and downstream, were required, which increases the lifetime to 1.7 μs for a particle to be detected.

p/Z (GeV$/c$)	Pb target (mm)	Interactions ($\times10^{11}$)	$m/\lvert Z\rvert$ range (GeV$/c^2$)	$t_{\rm lab}$ (μs)
-100	40	1.1	5–60	$\gtrsim$1.2
-200	40	1.2	10–120	$\gtrsim$1.2
$+100$	40	2.1	5–60	$\gtrsim$1.2
$+200$	16	1.1	10–120	$\gtrsim$1.7

The spectrometer accepted all charges. However, no heavy object with a mass to charge ratio $m/|Z|$ between 5 and 60 GeV$/c^2$ at $p/Z = \pm100$ GeV$/c$ and no event between 10 and 120 GeV$/c^2$ at $p/Z = \pm200$ GeV$/c$ has been observed. The production of antinuclei will be discussed in a forthcoming paper [24].

Based on these results we calculate an upper limit for the production of long-lived strangelets. Our sensitivity is

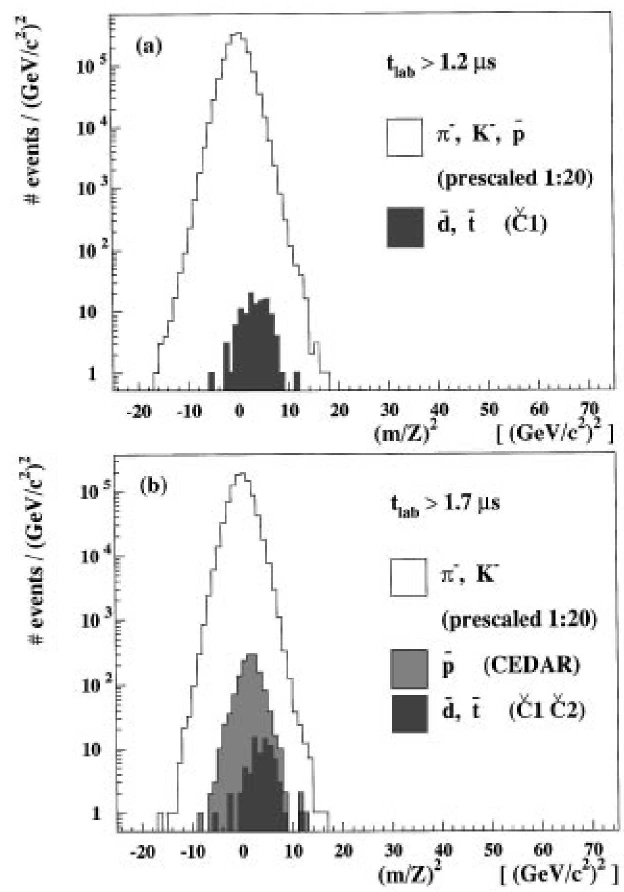

FIG. 2. Mass distributions at -100 GeV$/c$: (a) Events taken with the upstream trigger. (b) Events triggering upstream and downstream. Here, $\overline{p}$ are identified with the help of the CEDAR. The $(m/Z)^2$ distributions are derived from time of flight (TOF) measurements. The widths of the distributions are due to the finite TOF resolution (negative values can therefore occur). The particles selected by the Čerenkov counters are indicated by the hatched histograms. Note that the very light particles are prescaled.

defined as $S(m) = 1/N_{\text{int}} f(m)$, where N_{int} is the number of interactions, and $f(m)$ is the detection probability for a strangelet within the acceptance of the beam line. In order to calculate $f(m)$, a strangelet production model with a factorized phase space distribution is used [25,26],

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

Here, y is the rapidity of the strangelet, y_{cm} is the rapidity of the center of mass system of nucleons participating in the interaction ($y_{\text{cm}} = 2.9$ for Pb-Pb at $158A$ GeV/c), σ_y is the width of the rapidity distribution which was taken to be $\sigma_y = 0.5$, and $\langle p_\perp \rangle$ is the mean transverse momentum of the strangelet. The fraction $f(m)$ can then be calculated by integrating $d^2N/dy\,dp_\perp$ over the acceptance in y and $p_\perp$ of the spectrometer [19]. The absolute values of the sensitivity strongly depend on the assumed model parameters, in particular, on the mean transverse momentum $\langle p_\perp \rangle$ of the strangelets which is unknown. The shape of the sensitivity curves is determined by the assumed Gaussian rapidity distribution, while their absolute values reflect the overlap between the assumed transverse momentum range of the strangelets and the angular acceptance of the beam line. The two kinematic regions of 100 and 200 GeV/c have been added by means of combining the individual sensitivities of each polarity to derive a common upper limit for the production probability of charged strangelets. The resulting upper limits are shown in Fig. 3 for various assumptions of $\langle p_\perp \rangle$. Since the true mean transverse momentum of the strangelets is unknown, various possibilities have been considered. For example, the observed production of protons and lambdas in sulfur-nucleus collisions at $200A$ GeV/c favors $\langle p_\perp \rangle = (0.5\text{–}0.7)\sqrt{m(\text{GeV})}$ [27,28]. However, as strangelets can be regarded as cooled remnants of a quark-gluon plasma it is reasonable to assume smaller $\langle p_\perp \rangle$ values. Crawford *et al.* calculated production probabilities for long-lived strangelets ($\tau > 2 \times 10^{-7}$ s) of masses $A = 20$, 30, and 40 in Pb-Pb collisions [29]. Some of those points ($-4 \leq Z \leq +4$) are also marked in Fig. 3. Assuming low values of $\langle p_\perp \rangle$ the experimental upper limits begin to overlap the predictions.

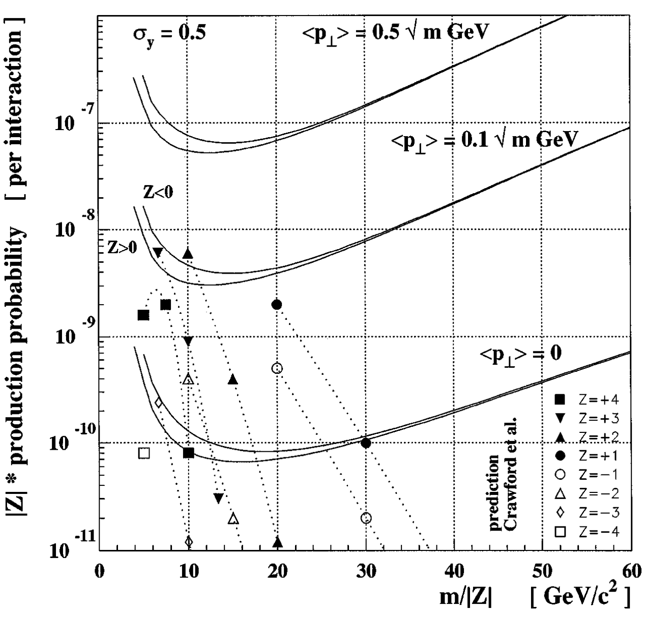

FIG. 3. Experimental upper limits (lines) for strangelet production assuming various mean transverse momenta $\langle p_\perp \rangle = 0.5\sqrt{m(\text{GeV})}$ and $0.1\sqrt{m(\text{GeV})}$ (see text). There are two lines for each $\langle p_\perp \rangle$; the upper ones result from adding the data at -100 and -200 GeV/c, the lower ones from $+100$ and $+200$ GeV/c. Although the covered $m/|Z|$ range of this experiment extends to 120 GeV/c^2, upper limits only up to $m/|Z| = 60$ GeV/c^2 are shown. The experimental upper limits are compared to the expected production yields (dotted curves) calculated by Crawford *et al.* [29].

To conclude, no evidence for the production of charged strangelets with lifetimes $t_{\text{lab}} \gtrsim 1.2$ μs in Pb-Pb collisions at $158A$ GeV/c was found. The accumulated statistics and beam line acceptance allow one to set a limit on the invariant differential production cross section for strangelets in the order of 50 nb GeV^{-2} c^3. A similar sensitivity has been obtained previously in S-W collisions at 200 GeV/c per nucleon [19] by this group. It is planned to continue data taking in the forthcoming lead periods at CERN to further improve the experimental sensitivity.

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