Distillation of Strangelets for low initial μ/T

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Abstract

We calculate the evolution of quark-gluon-plasma droplets during the hadronization in a thermodynamical model. It is speculated that cooling as well as strangeness enrichment allow for the formation of strangelets even at very high initial entropy per baryon $S/A^{\rm init} \approx 500$ and low initial baryon numbers of $A_{\rm B}^{\rm init} \approx 30$. It is shown that the droplet with vanishing initial chemical potential of strange quarks and a very moderate chemical potential of up/down quarks immediately charges up with strangeness. Baryon densities of $\approx 2\rho_0$ and strange chemical potentials of $\mu_s > 350$ MeV are reached if strangelets are stable. The importance of net–baryon and net–strangeness fluctuations for the possible strangelet formation at RHIC and LHC is emphasized.

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Strangelets can be thought of as strange multiquark clusters which should be more compressed than ordinary nuclei and may exist as (meta-)stable exotic isomers of nuclear matter [1]. It was speculated [2] that strange matter might resolve the dark matter issue, if it would be absolutely stable.

The possible creation — in heavy ion collisions — of such long-lived remnants of the quark-gluon-plasma, cooled and charged up with strangeness by the emission of pions and kaons, was proposed by Liu and Shaw [3] and Greiner *et al.* [4,5]. Thus, strangelets can serve as unambiguous signatures for the creation of a quark gluon plasma. The detection of strangelets would verify exciting theoretical ideas with consequenses for our knowledge of the evolution of the early universe, the dynamics of supernova explosions and the underlying theory of strong interactions [6].

Here we want to point out that such exotic states of matter can be created in heavy ion collisions even at collider energies, where such a process has received no attention so far, because common belief was that the (strange) baryon densities vanish at midrapidity, both at RHIC and LHC. We argue, however, that this conclusion was premature. This is due to the following effects:

- fluctuations of the stopping power can provide finite baryochemical potential $\mu_{\rm B}$ at mid–rapidity in a small fraction of all events;
- fluctuations of the net–baryon and –strangeness content between different rapidity bins within *one* event can be quite large;
- strange (anti–)baryon enhancement due to collective effects (e. g. a chiral phase transition);
- strangeness and baryon distillery, which are inherent for the two–phase system (hadron gas/quark gluon plasma) for a wide parameter range.

The last point stresses the significance of the 'chemistry' of the system in the evolution of the phase transition.

In the following we adopt a model [5] for the dynamical creation of strangelets via the strangeness separation mechanism [4]. Consider a first order phase transition of the QGP to hadron gas. Strange and antistrange quarks do not hadronize at the same time for a baryon–rich system [4]. The separation mechanism can be viewed as being due to the associated production of kaons (containing $\bar{s}$ quarks) in the hadron phase, because of the surplus of massless quarks compared to their antiquarks. The strange quarks can combine to Λ-particles, but it is energetically favourable that s-quarks remain in the plasma, when hadronization proceeds. The ratio f_s of the net strangess over the net baryon number quantifies the excess of net strangeness. Both the hadronic and the quark matter phases enter the strange sector $f_s \neq 0$ of the phase diagram almost immediately, which has up to now been neglected in almost all calculations of the time evolution of the system. Earlier studies addressed the case of a baryon–rich QGP with rather moderate entropy per baryon [4,5,7]. Now we focus on *low initial baryon densities* and *high specific entropies*, to match the expected conditions of heavy ion collisions at RHIC and LHC, where the search for strangeness enters in the objective of the ALICE experiment [8].

The hadronization transition has been described by geometric and statistical models, where the matter is assumed to be in partial or complete equilibrium during the whole (quasi-)isentropic expansion. A more realistic scenario must take into account the particle radiation from the surface of the hadronic fireball before 'freeze out'. Our model [5] combines these two pictures. The expansion of the QGP droplet during the phase transition is described as a two-phase equilibrium; in particular the strangeness degree of freedom stays in chemical equilibrium because the complete hadronic particle production is driven by the plasma phase. The nonequilibrium radiation is incorporated by rapid freeze-out of hadrons from the outer layer of the hadron phase surrounding the QGP droplet. During the expansion, the volume increase of the system thus competes with the decrease due to the freeze–out. The global properties like (decreasing) S/A and (increasing) f_s of the remaining two-phase system then change in time according to the following differential equations for the baryon number, the entropy, and the net strangeness number of the total system:

$$
\begin{aligned}
\frac{d}{dt} A^{tot} &= -\Gamma \, A^{HG} \\
\frac{d}{dt} S^{tot} &= -\Gamma \, S^{HG} \\
\frac{d}{dt} (N_s - N_{\overline{s}})^{tot} &= -\Gamma \, (N_s - N_{\overline{s}})^{HG} \quad ,
\end{aligned} \tag{1}
$$

where $\Gamma = \frac{1}{A^{HG}} \left(\frac{\Delta A^{HG}}{\Delta t} \right)_{ev}$ is the effective ('universal') rate of particles (of converted hadron gas volume) evaporated from the hadron phase. The equation of state consists of the bag model for the quark gluon plasma and a mixture of relativistic Bose–Einstein and Fermi–Dirac gases of well established strange and non–strange hadrons up to in Hagedorn's eigen-volume correction for the hadron matter [4]. Thus, one solves simultaneously the equations of motion (1) and the Gibbs phase equilibrium conditions for the intrinsic variables, i.e. the chemical potentials and the temperature, as functions of time.

Fig. 1 illustrates the increase of *baryon concentration* in the plasma droplet as an inherent feature of the dynamics of the phase transition (cf. [2]). The origin of this result lies in the fact that the baryon number in the quark–gluon phase is carried by quarks with $m_{\mathrm{q}} \ll T_{\mathrm{C}}$, while the baryon density in the hadron phase is suppressed by a Boltzmann factor $\exp(-m_{\mathrm{baryon}}/T_{\mathrm{C}})$ with $m_{\mathrm{baryon}} \gg T_{\mathrm{C}}$. Mainly mesons (pions and kaons) are created in the hadronic phase. More relative entropy S/A than baryon number is carried away in the hadronization and evaporation process [5], i.e. $(S/A)^{HG} \gg (S/A)^{QGP}$. Ultimately, whether $(S/A)^{HG}$ is larger or smaller than $(S/A)^{QGP}$ at finite, nonvanishing chemical potentials might theoretically only be proven rigorously by lattice gauge calculations in the furure. However, model equations of state do suggest such a behaviour, which would open such intriguing possibilities as baryon inhomogenities in ultrarelativistic heavy ion collisions. In the early universe shrinking quark droplets may — in analogy — contain the accumulated baryon number with possibly very high baryon density [2]. This mechanism yields a primeval inhomegeneous nucleosynthesis [6,9], which is signaled by the abundances of the light elements.

What 'initial' conditions do we expect at collider energies? At RHIC energies one might see baryon stopping, $dN_B/dy > 0$, on the average, at midrapidity. This can be due to multiple rescattering, leading to a nonvanishing, positive quarkchemical potential μ_q [10]. On the other hand, relativistic meson–field models, which, at high temperature, qualitatitively simulate chiral behaviour of the nuclear matter, exhibit a transition into a phase of massless baryons [11]. Including hyperons and YY–interaction [12] it shows that at $\mu \approx 0$ the densities for all baryon species are of the order of ρ_0 near the critical temperature. Thus, the fraction of (anti–)strange quarks increases drastically. Several hundred (anti–)baryons, many of them (anti–)hyperons may then fill the hot midrapidity region (with net baryon number ≈ 0). Districts of non–vanishing net baryon (respectively anti–baryon) density with finite s ($\bar{s}$) content will then occur stochastically. Thus, the finite chemical potential is locally caused by the fluctuations of newly produced particles, not by the stopped matter. If such a phenomenon persists also for the deconfined phase, the effect of baryon concentration and strangeness separation may then result in the production of strangelets and anti-strangelets in roughly equal amounts.

Let us try to give a rough estimate of the possible size of fluctuations in the net baryon and net strangeness number to be expected at midrapidity (or fluctuations along different rapidity intervals) around their mean. The average number of initial quarks and antiquarks (before hadronization) in a rapidity interval is approximately $1/2dN_\pi/dy \cdot \Delta y$, if half of the pions are made by the quarks and the other half by the gluons. For RHIC energies dN_π/dy has been estimated to lie between 1100 and 1600 and for LHC energies to lie up to nearly 4000 in central Au+Au collisions [13]. Hence the quark number is roughly 500 for RHIC and up to 2000 for LHC in a rapidity interval $\Delta y \sim 1$. (In an equilibrated plasma the total number of quarks is $N \sim \rho_q \pi R^2 \Delta z$ within $\Delta z = 1 - 2$ fm in the early stage of the hydrodynamical expansion. According to $\rho_q = g\frac{3}{4\pi^2}T^3\zeta(3) \approx 1.1T^3$ for a degeneracy of g=12 these numbers correspond to temperatures of $T \sim 250 - 500$ MeV.) We take the number to be $N = 500$. A similar consideration holds for strange and antistrange quarks, and we take here $N_s = 200$. We now assume independent fluctuations according to Poissonians within this rapidity interval. In fact the actual width of the fluctuation at collider energies could be much broader (KNO–scaling of particle multiplicity distributions in elementary pp–collisions

[14]). To justify the assumption of independent fluctuations of B and $\bar{B}$ despite of the local compensation of quantum numbers, one has to estimate the typical relative momenta within a quark–antiquark pair. If one follows the parton cascade concept embodying perturbative QCD [15], the average $\sqrt{\hat{s}}$ of first parton–parton interactions ($gg \rightarrow q\bar{q}$ being the most important contribution) should be of the order of $5-10$ GeV at LHC energies. The produced B and $\bar{B}$, carrying about 0.4 of the (anti–)quark momenta, would thus be separated in rapidity by at least one unit (assuming a transverse momentum of about 500 MeV).

The net baryon number in the box described above will be $|B| > 30$ with a probability of 0.5 %. About 0.1 % of the events will reach $|B| > 30$ with a strangeness fraction $|f_{\rm s}| > 0.7$. Hence fluctuations are not negligible. If each pion carries about 3.6 units of entropy (which is true for massless bosons), the entropy per baryon content in the fireball is

$$\frac{S}{A_B} \approx 3.6 \, \frac{dN_\pi/dy}{dN_B/dy} \quad , \tag{2}$$

and thus for $dN_B/dy = 30$ a range of 60 to 250 is formed. If the plasma is equilibrated, the ratio of the quarkchemical potential and the temperature $|\mu|/T$ is directly related to the entropy per baryon number via

$$\left(\frac{S}{|A_B|}\right)^{QGP} \approx \frac{37}{15}\pi^2 \left(\frac{|\mu|}{T}\right)^{-1} \quad . \tag{3}$$

Accordingly the ratio then varies between 0.1 to 0.4.

We now consider various fireballs with an initial net baryon number of $A_B = 30$ and a net strangeness fraction f_s of either 0 or 0.7. The initial entropy per baryon ratios are chosen between 50 and 500. Table 1 summarizes the initial conditions (adjusted by the (initial) chemical potentials μ_q, μ_s and temperature) used to start the hadronization. It also shows the final parameters of the quark droplet like the saturated strangeness content and baryon number. One further, yet crucial input, is the bag constant employed to describe the equation of state of the (strange) quark matter droplet. Only for the bag constants $B^{1/4} \leq 180$ MeV strange matter does exist as a metastable state at zero temperature [4], being absolutely stable only for $B^{1/4} < 150$ MeV [2].

Fig. 2 shows the time evolution of the baryon number for $S/A^{\rm init} = 200$ and $f_s^{\rm init} = 0.7$ for varyous bag constants. For $B^{1/4} < 180$ MeV a cold strangelet emerges from the expansion and evaporation process, while the droplet completely hadronizes for bag constants $B^{1/4} \geq 180$ MeV (for $B^{1/4} = 210$ MeV hadronization proceeds without any significant cooling of the quark phase, although the specific entropy S/A decreases by a factor of 2 from 200 to only 100). The strangeness separation works also in these cases, as can be read off the large final values of the net strangeness content, $f_s \gtrsim 1.5 - 2$. However, then the volume of the drop becomes small, it decays and the strange quarks hadronize into Λ-particles and other strange hadrons.

Fig. 3 shows the evolution of the two-phase system for $S/A^{\rm init} = 200$, $f_s^{\rm init} = 0$ and for a bag constant $B^{1/4} = 160$ MeV in the plane of the strangeness fraction vs. the baryon density. The baryon density increases by more than one order of magnitude! Correspondingly, the chemical potential rises as drastically during the evolution, namely from $\mu^i = 16$ MeV to $\mu^f > 200$ MeV. The strangeness separation mechanism drives the chemical potential of the strange quarks from $\mu_s^i = 0$ up to $\mu_s^f \approx 400$ MeV. Thus, the thermodynamical and chemical properties during the time evolution are quite different from the initial conditions of the system.

Even for high initial entropies, $S/A \approx 100 - 500$, in the quark blob the entropy in the remaining droplet approaches zero at the end of the evolution (assuming $B^{1/4} = 160$ MeV). High initial entropies per baryon require more time for kaon and pion evaporation in order to end up finally with the same configuration of (meta–)stable strange quark matter.

In conclusion, we have shown in the present model that the evolution of quark-gluon-plasma droplets during their hadronization may result in the formation of strangelets even at very high initial entropy per baryon $S/A^{\rm init} \approx 500$ and low initial baryon numbers of $A_{\rm B}^{\rm init} \approx 30$. The distillation of very small strangelets of a size $A_B \leq 10$ (see Table 1) is possible. We note that finite size effects of describing small strangelets neglected here might become of crucial importance [16]. Special (meta-)stable candidates are the quark-alpha [17] with $A_B = 6$ and the H-Dibaryon state with $A_B = 2$ [18]. Local net–baryon and net–

strangeness fluctuations can provide suitable initial conditions for the possible strangelet creation at RHIC and LHC. Droplets with vanishing initial chemical potential of strange quarks and a small chemical potential of up/down quarks quickly charge up with strangeness and baryon–number: if strangelets are stable, the droplet reaches strange chemical potentials of $\mu_s > 350$ MeV and two times ground state nuclear matter density!

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REFERENCES

[1] A. R. Bodmer, Phys. Rev. D**4**, 1601 (1971); S. A. Chin and A. K. Kerman, Phys. Rev. Lett. **43**, 1292 (1979); J. D. Bjorken and L. D. McLerran, Phys. Rev. D**20**, 2353 (1979)

[2] E. Witten, Phys. Rev. D**30**, 272 (1984); E. Farhi and R. L. Jaffe, Phys. Rev. D**30**, 2379 (1984)

[3] H.-C. Liu and G.L. Shaw, Phys. Rev. D**30**, 1137 (1984)

[4] C. Greiner, P. Koch and H. Stöcker, Phys. Rev. Lett. **58**, 1825 (1987); C. Greiner, D. H. Rischke, H. Stöcker and P. Koch, Phys. Rev. D**38**, 2797 (1988)

[5] C. Greiner and H. Stöcker, Phys. Rev. D**44**, 3517 (1992)

[6] Proc. Int. Workshop on Strange Quark Matter in Phys. and Astr., Nucl. Phys. (Proc. Suppl.) **24B**, 1-299 (1991), see H. Kurki–Suonio 67, and S. Bonometto 54

[7] K. S. Lee, U. Heinz, Phys. Rev. D**47**, 2068 (1993)

[8] Letter of Intent, CERN/LHCC/93–16/LHCC/I 4; J. P. Coffin, project presentation, meeting of the ALICE technical board, April 23 (1995)

[9] J. H. Applegate and C. J. Hogan, Phys. Rev. D**31**, 3037 (1985)

[10] A. Dumitru, D. H. Rischke, T. Schönfeld, L. Winckelmann, H. Stöcker and W. Greiner, Phys. Rev. Lett. 70, 2860 (1993)

[11] J. Theis, G. Graebner, G. Buchwald, J. Maruhn, W. Greiner, H. Stöcker, J. Polonyi, Phys. Rev. D**28** (1983) 2286

[12] J. Schaffner, C. Greiner, C. B. Dover, A. Gal, H. Stöcker, Phys. Rev. Lett. **71** (1993) 1328

[13] X.-N. Wang and M. Gyulassy, Phys. Rev. D.**44**, 3501 (1991); K. Geiger, Phys. Rev. D**47**, 133 (1992)

[14] UA5 collab., G. J. Alner et al., Phys. Rep. 154 (1987) 247

[15] K. Geiger and B. Müller, Nucl. Phys. **B 369** (1992) 600

[16] J. Madsen, Phys. Rev. Lett. **70**, 391 (1993) and Conf. on Strangeness and Quark Matter, Crete, Greece (1994)

[17] F. C. Michel, Phys. Rev. Lett. **60**, 677 (1988)

[18] R. L. Jaffe, Phys. Rev. Lett. **38**, 195 (1977)

FIGURES

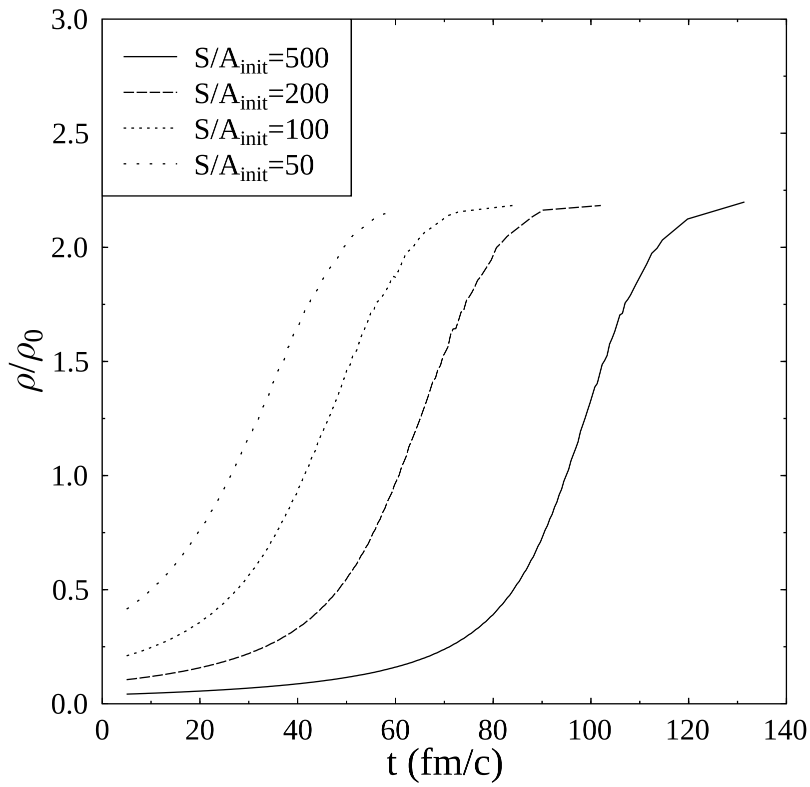

FIG. 1. Time evolution of the net baryon density of a QGP droplet. The initial conditions are $f_s^{\rm init} = 0$ and $A_{\rm B}^{\rm init} = 30$. The bag constant is $B^{1/4} = 160$ MeV.

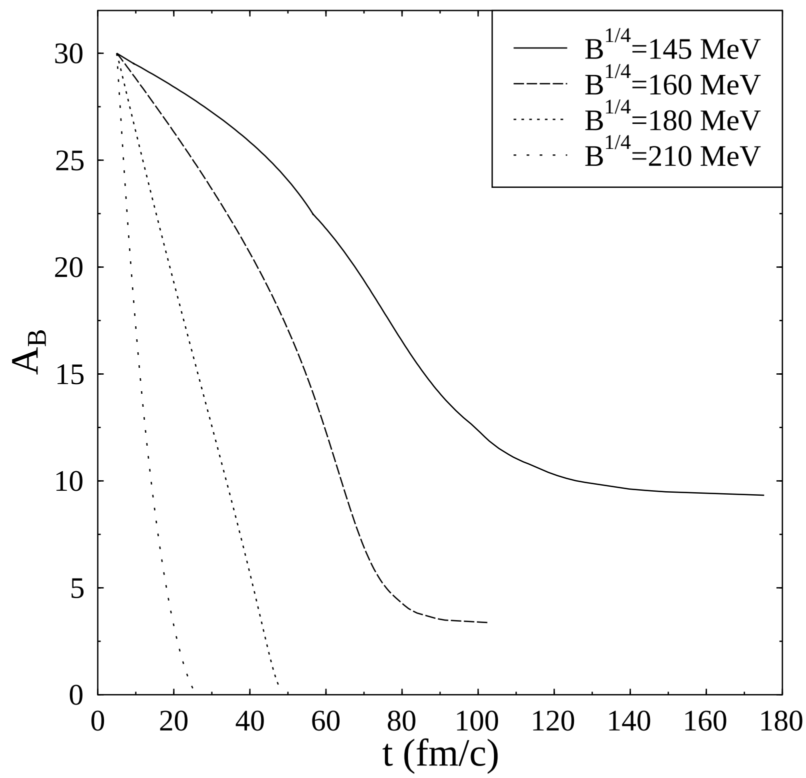

FIG. 2. Time evolution of the baryon number for a QGP droplet with $A_{\rm B}^{\rm init} = 30$, $S/A^{\rm init} = 200$, $f_s^{\rm init} = 0.7$ and different bag constants.

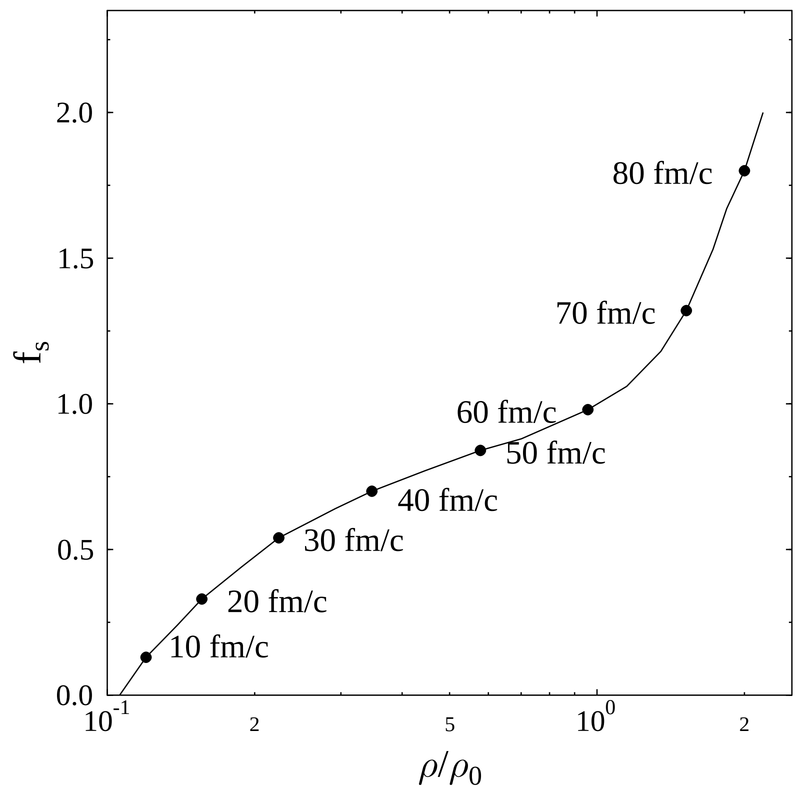

FIG. 3. Evolution of a QGP droplet with baryon number $A_{\mathrm{B}}^{\mathrm{init}} = 30$ for $S/A^{\mathrm{init}} = 200$ and $f_s^{\mathrm{init}} = 0$. The bag constant is $B^{1/4} = 160$ MeV. Shown is the baryon density and the corresponding strangeness fraction.

TABLES

TABLE I. Various situations of an hadronizing plasma droplet. In the first column the bag constant for describing the plasma phase is listed. Then the initial conditions follow. The final values for the baryon number, the strangeness fraction and the two chemical potentials at the end (or after) hadronization are listed in the last four columns.

$B^{1/4}$ (MeV)	$S/A^{\rm init}$	$f_s^{\rm init}$	$A_{\rm B}^{\rm init}$	$\rho_B^{\rm init}$ (fm^{-3})	$\mu_q^{\rm init}$ (MeV)	$\mu_s^{\rm init}$ (MeV)	$\mu/T^{\rm init}$	$f_s^{\rm final}$	$A_{\rm B}^{\rm final}$	$\rho_B^{\rm final}$ (fm^{-3})	$\mu_q^{\rm final}$ (MeV)	$\mu_s^{\rm init}$ (MeV)
160	500	0	30	0.0067	6.55	0	0.060	1.99	2.36	0.352	224.3	396.0
160	500	0.7	30	0.0068	5.02	4.01	0.046	1.96	2.71	0.339	216.9	386.0
160	200	0	30	0.017	16.36	0	0.150	2.0	2.79	0.349	224.7	396.9
160	200	0.7	30	0.017	12.55	10.04	0.115	2.0	3.37	0.350	223.7	396.3
160	100	0	30	0.034	32.60	0	0.300	1.99	2.93	0.350	225.2	396.7
160	100	0.7	30	0.034	25.07	20.09	0.185	2.0	3.96	0.352	223.4	396.2
160	50	0	30	0.066	64.23	0	0.599	1.94	2.75	0.344	219.7	385.8
160	50	0.7	30	0.067	49.81	40.26	0.463	1.99	4.56	0.350	223.3	395.6
145	200	0.7	30	0.012	11.23	9.52	0.114	1.60	9.33	0.270	234.6	347.6
180	200	0.7	30	0.024	14.20	10.76	0.116	(1.83)	0	(0.349)	(146.8)	(315.7)
210	200	0.7	30	0.039	16.74	11.99	0.117	(1.58)	0	(0.063)	(19.5)	(50.5)