Sticking and restitution in collisions of charged sub-mm dielectric grains

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Abstract
In microgravity experiments, dielectric spherical glass grains of 225 \( \mu \)m radius with electrical charges between \( 10^5 \) e and \( 10^7 \) e collide with a metal wall. Collision velocities range from about 0.01 m/s up to 0.2 m/s. Grains rebound from the wall down to a threshold impact velocity below which particles stick. This threshold velocity for sticking increases linearly from below 0.01 m/s to 0.15 m/s with increasing charge on the grains. This can be explained by non-homogeneous surface charges on the grains and mirror charges on the metal wall. The Coulomb attraction boosts the grain speed just prior to impact. This increases the energy dissipated upon impact, and grains can no longer escape the Coulomb field of the mirror charge if they are too slow. For rebounding particles, the final boost decreases the measurable, effective coefficient of restitution and induces a wide spread.

1. Introduction

Collisions of grains in a granular medium are important in many areas. These areas range from technical applications, such as silos, to research in an astrophysical context, such as on Saturn’s rings (Jaeger et al 1996, Spahn et al 2001). One important parameter is the coefficient of restitution \( c \) as the ratio between the rebound velocity and the collision velocity. The ratio quantifies the energy loss due to inelastic parts of the collision. Depending on the specific physical problem, \( c \) is considered to be constant, has a simple dependence on the collision velocity or needs to be described by a complex velocity dependence (Musiolik et al 2016, Takada et al 2017). The dissipation of energy leads to cooling, and in a granular gas this results in the formation of clumps or aggregates (Goldhirsch and Zanetti 1993, Heißelmann et al 2010, Harth et al 2017). During later cooling phases of a granular gas, not only clustering but also actual sticking by attractive forces can be important. Cohesion due to surface forces always occurs. There is a velocity threshold \( v_r \) below which all kinetic energy is dissipated and grains stick to each other. Cohesion is often ignored for sand-sized particles. Indeed, cohesive forces are small compared to gravity for this grain size (Musiolik et al 2017).

Based on research on volcanic eruptions and lightning during thunderstorms, we know that grains become highly charged by grain collisions (Van Eaton et al 2016). Charging can have a significant influence on cooling and aggregation in a granular setting (Wolf et al 1999, Siu et al 2014, Singh and Mazza 2017, Takada et al 2017, Yoshimatsu et al 2017). The work by Lee et al (2015) visualizes the attraction between charged grains very explicitly in experiments where grains become trapped in Coulomb potentials and form small aggregates. Regarding the charging of identical grains, the studies by Siu et al (2014) and Yoshimatsu et al (2016, 2017) imply that grains do not charge homogeneously in collisions. Thus, a non-homogeneous charge distribution seems to be very plausible, as charge transfer between dielectric grains is a highly local event. If so, this will strongly influence collisional outcomes.

However, low speed collisions at cm/s and especially the sticking threshold are not easily observed in the presence of gravity. The work presented here is a first step in quantifying the collisions of charged dielectric grains. Our choice of method is the direct observation of individual low-speed collisions under microgravity; we
concentrate on collisions between charged grains and a metal (copper) wall. We do not analyze the charging or the charge transfer during a single collision with the wall itself, although this is certainly an important part of the whole story (Lee et al 2018). Our aim is to quantify the threshold velocities below which grains stick to the wall and to quantify the coefficients of restitution depending on charge.

2. Experiments

As indicated above, measuring the rebound and especially the sticking of (sub)-mm size particles upon slow impact on a wall is virtually impossible under Earth’s gravity. For this reason, the following experiments were carried out under microgravity at the Bremen drop tower, which provides about 9 s of free-fall time with residual gravity at a level of less than $10^{-5}$ g. To see the effects of charge and not cohesion (as detailed below) we chose spherical sand-sized grains of $r = 225 \pm 12 \mu m$ radius. An image of the glass grains is shown in figure 1.

Prior to the beginning of the experiment, the glass grains, which are embedded in a 1 bar CO$_2$ atmosphere, are vibrated for about 10 minutes while the experiment is still on the ground. The collisions within the granular bed charge the grains. Although this process itself is interesting, it is not the focus of this work. Here, we analyze how grains, which were charged by many collisions prior to the measurements, interact with a metal wall.

To do so, the experiment is launched and once microgravity is established, grains are released into a capacitor with applied electrical fields between 6250 V/m and 83000 V/m. The charged grains are accelerated toward one side of the capacitor, depending on their individual charge sign. The grains collide with the wall, stick or rebound, as sketched in figure 2. Example trajectories as observed by a camera with 180 frames per second are seen in figure 3.

As the electrical field within the capacitor is constant, the basic motion is a parabola. In figure 4 the distance to the capacitor wall is plotted over the time and a parabolic function is fitted. There is no significant deviation of a parabolic motion within the resolution of the optical system. Gas-grain coupling only occurs on longer timescales, and we do not consider gas drag here. This is consistent with grains moving on parabolas.

From the trajectories before and after impact, the acceleration of the grains and the collision velocities and rebound velocities can be determined.

In the current setup, only two-dimensional information can be gained. Therefore, particle motion before and after an impact along the focal direction cannot be resolved. This induces some uncertainty when figuring the total energy balance. Further uncertainty is induced by the lack of knowledge on the rotational state of the grains. However, as particles are accelerated by the electrical field in the direction perpendicular to the capacitor plates, this speed component is the largest. Examples taken of the visible tangential velocity component show that this only varies by 10% in general before and after an impact. Due to symmetry, this is also valid for the unseen component along the line of focus. This is small compared to the variations toward or away from the plates. In addition, the model of mirror charges given below selectively works in this direction. Therefore, we neglect the two velocity components parallel to the capacitor planes. As the mass of the identical grains ($m = 0.1 \text{ mg} \pm 0.015$) is as well known as the electrical field, also the net charge can be determined from the acceleration.

For the optical system, 1 pixel corresponds to 75 $\mu m$. If particles do not visibly rebound off a pixel, we define this as a sticking collision. We note that below our resolution limit, slow rebounds might still be rebounds. They might not instantly stick due to surface forces. However, as shown below such rebounds are bound to return to the wall and stick even without a capacitor field. This qualifies them as sticking events in any case. This is in contrast to particles that leave the proximity of the capacitor wall and are then free from the electrode and only

Figure 1. SEM image of the grains, each with a 225 $\mu m$ radius.
Figure 2. Sketch of the experiment. Electrodes are copper and measure 10 cm × 10 cm. The distance between the electrodes is 4.8 cm. Under microgravity, charged grains are accelerated to the respective electrodes.

Figure 3. Superposition of particle positions to show trajectories of colliding and rebounding grains. In addition, many grains sticking to the electrode are visible.

Figure 4. Distance of the grain to the capacitor wall over time with a parabolic fit to the data. The exact collision time is determined by the intersection between the inbound and rebound trajectory, which also sets the collision and rebound velocity.
subject to trajectory changes by the capacitor field. While the capacitor sets the basic velocities at which a particle approaches the electrodes, we see no further influence of the electrical field on the collision and do not consider any dependence in the further sections.

3. Results

Due to the capacitor field the trajectories are biased toward central collisions. In the following, we only consider the distance to the capacitor as a spatial coordinate and the corresponding velocity component perpendicular to the capacitor walls. Tangential components are not considered. As outlined above, the tangential components do not change much. This is due to the fact that the capacitor walls are flat and the grains are almost perfectly spherical. In addition, only the tangential components can be transferred to rotation or vice versa but the force perpendicular to the wall always acts along the center of the particle and does not induce a rotational moment. Last but not least, our model of mirror charges given below adds a force only to the perpendicular component. We therefore ignore all tangential velocities, before and after rebound. Each impact can be characterized by the initial velocity $v_i$ (without any acceleration due to mirror charge), the net grain charge before impact $q$ and the rebound velocity $v_r$ if the grains do not stick upon impact. The charge after rebound can be and was also measured, but the change due to impact is typically well below 10% of the original net charge. For simplicity, we do not consider a change in charge to take place for the further analysis. We define the coefficient of restitution for the non-elastic collisions based on the measurements as $c_{re} = v_r / v_i$. Figure 5 shows one example of the coefficients of restitution for one of the microgravity experiments where all grains with charges larger than $6 \cdot 10^6$ e are plotted. For completeness, we note that the electrical field was 41600 V/m in this case.

Upon closer inspection, we note that there are some clear trends.

- There is a threshold velocity below which the grains stick to the wall. This threshold strongly depends on the grain charge, which is described in detail later.
- For rebounds, the variation of the coefficient of restitution seems very large compared to the usually well-confined values for glass grains.

To quantify this further, we determined the threshold velocity for sticking for all experiments depending on grain charge. We divided each data set of tracks that could be analyzed in an individual experiment in 3 to 4 charge bins according to the number of data points available. This gives between 15 and 30 data points per bin, which we consider an appropriate compromise between showing the charge dependence and averaging over a suitable number to account for the statistical variations. For each charge bin, we calculate the velocity between the last sticking collision and the first rebounding collision as the sticking velocity, e.g., the dotted line in figure 5.

Figure 6 shows the sticking velocities for all experiments and charge bins. Included in the figure is a linear prediction of the model detailed below, which agrees reasonably well with the data. Note that this is not a linear regression to the data but rather a plausibility check. Due to the unknown exact charge distribution on the grains, the data should vary. However, the model with only a few typical parameters agrees quantitatively beyond the expected variation based on principle terms.

To evaluate the coefficients of restitution, we take all data from rebounding collisions and calculate an average value for the coefficient of restitution and the collision velocity.
Figure 7 shows the coefficients of restitution and their standard deviations over velocity for all charge bins and experiments in figure 6.

As indicated above, the data show a great deal of variation in $c_m$. The average value increases slightly with $v_r$. Again, a prediction from the model calculations is overplotted that is described in the next section, which also matches the data very well.

4. Model

Our first goal is to explain the sticking threshold velocity. To pin down the nature of the sticking events, we first calculate the sticking threshold $v_{st}$ that we would expect for an uncharged grain due to cohesion. That would be the standard mechanism being responsible for sticking. We take the sticking velocity from Thornton and Ning (1998)

$$v_{st} = 1.84 \left( \frac{(\gamma/r_s)^{1/2}}{\rho E^*} \right)^{1/2}$$

with $E^* = E/(1 - \nu^2)$. Here, $E$ is Young’s modulus, $\gamma$ is the surface energy, $\nu$ is Poisson’s ratio and $\rho$ is the density. For glass as used in the experiments, it is approximately $E = 6.9 \cdot 10^{10}$ Pa, $\gamma = 0.3$ J/m$^2$, $\nu = 0.21$, $\rho = 2460$ kg/m$^3$. For the grains of $r = 225$ $\mu$m used here we can calculate an expected cohesive sticking velocity of

$$v_{st} = 1 \text{ mm/s}.$$  

This is only approximately 1% of the measured sticking velocities of highly charged particles. As expected for sand-sized grains used here, cohesion is not of prime importance. We therefore do not consider cohesion as the main driver for the observed sticking collisions, even if sticking is eventually occurring due to cohesion. Regarding this, Dominik and Tielens (1997) point out that there is cohesion only when particles are in direct contact. Therefore, cohesion is at the lower limit of attracting forces and electrostatic attraction can act far beyond that stage.
In the following, we present a model that explains all findings consistently based on grain charges. In short, the main part of the explanation is the effect of a mirror charge on the metal wall. As shown below, the grain charge has to be off-center. Due to the square distance dependence of the Coulomb attraction, the mirror charge becomes important during the final approach of a grain. A net charge (offset charge) especially allows the attracting mirror charge to boost the grain’s impact speed prior to impact. While the relative amount of energy dissipated might be constant (\(c = \text{const}\)), the absolute amount of energy is increased due to the higher collision velocity. If the loss is large enough, the grain might rebound but stays trapped in the Coulomb field below the optical resolution limit. This finally leads to cohesive sticking.

To quantify this idea, we consider the energy balance for grains approaching and rebounding off the wall. We ignore the constant capacitor field, which provides a drift velocity \(v_i\) if a grain starts some distance away from the wall; this is negligible on the final approach to the wall. Therefore, close to the wall only the interaction between the charged grain and its mirror charge within the wall has to be considered. This is also consistent with the fact that we do not see any dependence of sticking thresholds or coefficients of restitution on the electric field other than constraining the range of velocities. Therefore, we only have two kinetic energies and the energy within the mirror charge field. In terms of energy conservation, before a collision it is

\[
\frac{1}{2} m v^2 + \frac{1}{4 \pi \varepsilon_0} \frac{q^2}{4d} = \frac{1}{2} m v_i^2
\]  

(3)

This gives the local velocity \(v\) depending on the distance to the capacitor wall \(d\). As free parameters, we have the charge \(q\) and the initial velocity \(v_i\). Both can be determined in the experiments. Note that \(v_i\) is not the collision velocity but the velocity at a distance where the mirror charge has no significant effect yet as calculated from the parabolic trajectories to the motion within the capacitor, as outlined above. After the inelastic collision, we get an energy loss. The fraction lost is

\[
E_{\text{loss}} = \frac{1}{2} m v_{\text{max}}^2 (1 - c^2)
\]  

(4)

where \(v_{\text{max}}\) is the real speed upon impact for a minimum distance \(d_{\text{min}}\) between the net charge within the grain and the wall at the impact time. With this the energy balance after the collision for the rebounding particle reads

\[
\frac{1}{2} m v^2 - \frac{1}{4 \pi \varepsilon_0} \frac{q^2}{4d} = \frac{1}{2} m v_f^2 - \frac{1}{2} m v_{\text{max}}^2 (1 - c^2)
\]  

(5)

Both equations, equation (3) and equation (5), can be solved for \(v\). Figure 8 shows a general example of the velocity over distance to the wall of a grain with \(q = 5 \cdot 10^6\) e approaching the capacitor wall with \(v_i = 2.4\) cm/s. It shows results for different distances of the charge to the wall \(d_{\text{min}}\). \(c = 0.6\) was used as the coefficient of restitution.

As far as \(d_{\text{min}}\) goes, it should be noticed that this is not the distance of the center of mass of the grain but the effective location of the net charge. At contact the center of mass will always be \(225\) \(\mu\)m away from the wall. However, the charge can be closer (or farther away) if it is not distributed homogeneously. Therefore, a collision can occur at a (charge) distance smaller than the grain radius. This is a very likely case due to alignment of a grain with an offset charge in the capacitor field. The grain will always align so that any offset charge is rather at the front of the particle. Some asymmetry has to be expected from the way the charge was produced by collisions. In

Figure 8. Speed of a grain with a charge of \(q = 5 \cdot 10^6\) e as it approaches the wall with 2.4 cm/s. Depending on the position of the charge (\(d_{\text{min}}\)), it rebounds with different velocities (tracks 3, 4, 5). The closer the charge to the wall, the smaller the coefficient of restitution. If the charge gets closer, the grain is trapped by the mirror charge and only rebounds a certain distance below the resolution limit (track 1, 2).
fact, the central assumption in our model is that the inhomogeneous charge distribution can be approximated by a net charge being off-center with respect to the geometric center of the glass grain.

As it can be seen in figure 8, for small $d_{\text{min}}$ the energy loss can be large enough that the particles rebound slightly, so the maximum distance to the wall is very small. These grains are trapped and will stick to the wall. Even if they do not stick initially, their fate is sealed. The rebound part has such low amplitudes that this cannot be resolved with the current optical resolution. The initial rebound can be below the resolution of the experiment and is then measured as a sticking event. If the charge is slightly further away from the wall upon impact (larger $d_{\text{min}}$), then rebound is possible and particles are free to leave and return to their parabolic trajectories within the capacitor field. However, in this case the measurable rebound velocity $v_r$ and therefore the measured coefficient of restitution as defined above can be greatly reduced.

The example in figure 8 considers the minimum distance as a parameter for fixed charge and fixed initial velocity $v_i$, showing a transition between trapped and free grains. If we assume that $q_{\text{min}}$ on average is the same for all grains, then depending on the charge there is a maximum initial velocity $v_i = v_{\text{p}}$ for which sticking would occur as the data show (see figure 6). This dependence $v_{\text{p}}(q)$ can be calculated. The threshold velocity $v_{\text{p}} = v_i$ between the bound grain and the bouncing grain is given if the energy loss equals the initial kinetic energy or

$$v_i^2 = v_{\text{max}}^2 (1 - c^2)$$

The maximum velocity can be calculated from the energy equation (3) as

$$v_{\text{max}}^2 = \frac{1}{8 \, m \pi \varepsilon_0 / d_{\text{min}}} + v_i^2$$

Inserted in equation (6) this gives

$$v_i = q \cdot \sqrt{\frac{1}{8 \, m \pi \varepsilon_0 / d_{\text{min}}} (1 - c^2)}$$

This linear behavior on charge agrees to the observed behavior of the threshold velocity for sticking (figure 6). The only free parameter is the minimum charge distance $d_{\text{min}}$ which we assume to be $d_{\text{min}} = 25 \, \mu \text{m}$. This is smaller than the grain radius but not yet close to the contact. The inclination of the fit in figure 6 is then $8.5 \cdot 10^{-9} \, \text{m/}(s \cdot \text{e})$ which fits the data well. We note, though, that the data still allow different dependencies. Large charges might be distributed more homogeneously if the charge density on the surface approaches the maximum value, which is equivalent to approaching $d_{\text{min}} = r$. This effectively reduces the sticking threshold as the closest distance approaches the grain radius, so a great deal of detail might still be hidden in the unknown charge distribution. In addition, somewhat larger values for $d_{\text{min}}$ are still in agreement to the data. However, the charge cannot always be distributed homogeneously as the inclination would then be too low with all data being above the model.

For rebounds, variations in $d_{\text{min}}$ are visible as the detailed rebound velocity depends on it. As the observed coefficient of restitution relates the velocities upon approach and rebound far away from the target (ignoring the influence of the capacitor) this introduces a variation. The value for uncharged grains is reduced by varying amounts. This is consistent with the observed variations, which are larger than expected. The coefficient of restitution increases slightly with the average collision velocity. These facts can also be quantified by the model. With the given energy loss, the rebound velocity far away from the wall is

$$v_r^2 = v_i^2 - v_{\text{max}}^2 (1 - c^2)$$

or as the squared measured coefficient of restitution

$$c_r^2 = 1 - \frac{v_{\text{max}}^2}{v_i^2} (1 - c^2)$$

Again, from equation (3) it is

$$v_{\text{max}}^2 = v_i^2 + \frac{q^2}{8 \pi \varepsilon_0 m d}$$

which in total gives

$$c_r = \sqrt{a - \frac{b}{v_i^2}}$$

and

$$a = c^2$$

$$b = \frac{q^2}{8 \pi \varepsilon_0 m d_{\text{min}}} (1 - c^2)$$
Taking a charge of \( q = 10^6 \text{e} \) as representative, \( d_{\text{min}} = 25 \mu\text{m} \) in agreement with the results on sticking thresholds, and assuming \( c = 0.6 \) as a plausible value for glass grains (not critical), we get a good agreement with the average data as plotted in figure 7. The constant \( b \) includes the charge \( q \) and \( d_{\text{min}} \) which vary for individual grains. Even if the undisturbed coefficient of restitution \( c \) would be constant, this induces a variation in \( c_{\text{em}} \) which is also in agreement to the data.

In conclusion, the average data can be well modeled by an offset net charge. Rough constraints by comparison to the extremes would put typical values of \( d_{\text{min}} \) in a range smaller than about 50 \( \mu\text{m} \), which is only a fraction of one grain’s radius.

5. Discussion

If two particles collide in a central collision with each other in the absence of any other force, the relative velocities at great distances are essentially constant. For rebounding collisions, this defines a collision velocity, a rebound velocity and a coefficient of restitution \( c \). For uncharged particles, the coefficient of restitution might be depending on the collision velocity or be considered as constant. However, for perfect spheres there is little room for variation and the coefficient of restitution is restricted to a small range. The sticking velocity is determined by cohesion and is also a single value.

For oppositely charged grains, the outside view is the same. While the Coulomb attraction is a long-range force its effects for sandlike grains are only visible on grain-sized (sub-)mm scales. From a viewpoint further away, one can still define a coefficient of restitution \( c_{\text{em}} \) and observe if particles have bounced off each other or are stuck together. However, in this case the threshold for sticking is no longer constant. It depends on the charge and the nature of sticking changes character. Particles bouncing off each other get trapped in their mutual Coulomb field, and then collide again until they finally stick due to cohesion. From the outside, which does not resolve this process it looks like sticking and has the same effect. Therefore, the sticking velocity becomes charge dependent. Already small deviations from elasticity play an important role in the trapping.

Quantitatively, our results can only be explained if the charge on the grain is not distributed homogeneously over the surface. Otherwise, the closest approach was the particle radius and that could not sufficiently boost the velocity prior to impact to lead to trapping. The average behavior of our data can be explained by keeping the idea of only one net charge. However, it has to be assumed that the net charge is significantly off-center. The variations between individual grains are likely due to the specific charge distribution on a grain and more complex charge patterns over the surface. How the charge distribution on a grain looks in detail is unknown to date. More data are needed to specify the exact charge/sticking dependence. In addition, resolving the approach of a charged grain in higher spatial and time resolution would help in constraining the charge distributions. This is feasible in principle, but is beyond the scope of this paper. Until more data is available, our simplified model of an offset charge might suffice to quantify sticking and restitution.

For bouncing collisions, the same local effect of energy dissipation based on a boosted collision velocity generates variation in the rebound velocity if the charge is not homogeneously distributed on the grain. Again (not visible for an observer who is not resolving the collision), the net effect is a reduction and larger variation in coefficients of restitution. In the end, there are two things that can be learned from the experiment.

- For a granular gas, the definition of a coefficient of restitution based on the inbound and outbound velocities according to \( c_{\text{em}} \) in our experiments might be a natural one. If we focus on the total ensemble without resolving individual collisions, grain charging might go unnoticed in trajectories. The boost of two oppositely charged grains is only effective at the latest approach. We only saw the charge due to the electrical field of the capacitor. Otherwise, the effects of charge on wall collisions were hidden. However, charged grains can mimic—and effectively lead to—much higher sticking velocities than calculated by simple adhesion. It also alters the effective coefficients of restitution.

- Besides this, our data are only consistent with inhomogeneous charge distributions on the spherical grains. To first order, it is sufficient to consider the net charge to be offset from the center of mass of the grain to describe the data. It has to be closer to the electrode to account for higher collision velocities, larger absolute energy losses and higher sticking thresholds. It is important at low velocities studied here that net charge is not the only parameter in charged collisions but the charge distribution matters. As we generated the charges by collisions, this also implies that grains do not acquire a homogeneous charge distribution in support of charging models, e.g., by dipoles (Siu et al 2014, Yoshimatsu et al 2017).

The main idea from this work is sketched in figure 9. The charge distributions and the effect on sticking and restitution are important in the context of a collisionally cooling granular gas. If the grains are charged inhomogeneously, even sand-sized grains can stick together or locally cool faster than expected, especially at late
times when slow collisions dominate. We note, however, that grain-grain collisions will be different from aligned grains colliding with a metal wall.

6. Conclusion

In microgravity experiments, we observed glass grains of sub-mm size that were charged up to $\sim 10^6$e on average. They collided with a metal wall with velocities up to 0.2 m/s. The grains stuck to the wall below a certain threshold velocity. This threshold varied from 0.01 m/s to 0.15 m/s. The threshold depended linearly on the grain charge. We also observed that the coefficient of restitution is lower for slow initial velocities and shows more variation.

All these findings can be explained by assuming a mirror charge on the metal wall and energy loss upon impact by a slight inelasticity. Crucial to this model is—at least for the grain size and velocities studied here—an inhomogeneous charge distribution on the grains’ surfaces. This allows a closer approach of charge and mirror charge than the particle diameter, which provides a last-minute boost of the impact velocities. For the given parameter set, these effects are important for slow collisions well below 1 m/s. They might go unnoticed for larger impact speeds as the kinetic energy then dominates over the Coulomb boost. Related effects on sticking and coefficient of restitution should be observable for collisions between two oppositely charged grains instead of a grain and a wall. This will then certainly change the evolution of a cooling charged granular gas significantly during the later slow velocity phases.

The collisions of charged grains induce a velocity dependence of the coefficient of restitution not seen in that way before. Our glass grains are rather elastic in general with little variation in the coefficient of restitution at higher speeds. For other dissipating systems, this might be different. According to experiments and models by Musiolik et al (2017), Thornton and Ning (1998) or Higa et al (1998), the coefficient of restitution increases towards lower velocities. Schwager and Pöschel (1998) argue that such a velocity dependence will slow down cooling, which makes sense as collisions get more elastic as a granular gas cools. Most of these models have a minimum velocity below which collisions always lead to sticking. The strong decrease and sticking toward very low velocities might usually be of little concern, especially if the sticking velocity is low. However, for charged grains this sticking limit is shifted to velocities that are already significant in terms of particle motion in a laboratory setting. This implies that cooling proceeds faster. Even if particles with like charges bounce off as usual, the capture of differently charged grains in each others Coulomb potential suggests that there will be a rapid transition between normal cooling and fast cooling, which eventually might lead to aggregation. How spontaneous this aggregation proceeds is subject to further research, but aggregation as the ones observed by Lee et al (2015) during short microgravity of a free fall might only be the beginning of larger aggregates forming. How the charge distribution within such growing aggregates changes the situation also remains to be seen. There is little doubt, though, that collisional charging takes place frequently. We used identical grains for our studies, but it is well known that grains of different size charge differently, i.e., the small grains typically charge negatively while the large grains charge positively (Waitukaitis et al (2014), Duff and Lacks (2008)). In this case, collisions
between small and large grains will eventually be biased toward more sticky collisions and again aggregation might be eased at low collision velocities. Under Earth’s gravity, velocities will more often be beyond the limit where the effects of mirror charges are visible. It all depends on the exact velocity distributions available within the granular gas, however. The application to situations under reduced gravity might be significant in any case.

As an example of a special application under microgravity at low speeds we mention planet formation here. This might also be a means to enhance aggregation in granular gases. Besides cohesion by the van der Waals force, the electrostatic force can lead to sticking or fortifies the attraction between two particles. Thus, aggregates can be formed more easily and are more stable against impacts or mechanical stress. The aggregation of charged particles can help overcome the so-called bouncing barrier in the context of planet formation (Zsom et al. 2010, Kelling and Wurm 2009, Kruss et al. 2016, 2017, Demirci et al. 2017). When particles grow to a certain size, they do not stick any more after a collision but bounce off. To what extent our model can be used to interpret the collisions of identical particles remains to be seen in future work. However, charged aggregation might help conquering the bouncing barrier and seed planet formation.

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Appendix

In figure 5 one example of measured coefficients of restitution is shown and a threshold velocity for sticking can be identified. To enhance the model in figure 5, more threshold velocities were used. Plots of all groups of charge are shown in figure 10. Note that the data from figure 5 were divided into two groups of charge to enhance the resolution. Small deviations from the sticking thresholds are due to the fact that the number of charges is not homogeneous but binned in reasonable intervals.
Figure 10. Threshold velocities for sticking that are dependent on charges.

(a) \( q < 3 \cdot 10^6 \) e; \( E = 41600 \) V/m

(b) \( 3 \cdot 10^6 e < q < 6 \cdot 10^6 \) e; \( E = 41600 \) V/m

(c) \( q < 2 \cdot 10^6 \) e; \( E = 41600 \) V/m

(d) \( 2 \cdot 10^6 e < q < 4 \cdot 10^6 \) e; \( E = 41600 \) V/m

(e) \( q > 4 \cdot 10^6 \) e; \( E = 41600 \) V/m

(f) \( 0 < q < 5 \cdot 10^5 \) e; \( E = 6250 \) V/m

(g) \( 5 \cdot 10^5 < q < 2 \cdot 10^6 \) e; \( E = 6250 \) V/m

(h) \( q > 2 \cdot 10^6 \) e; \( E = 6250 \) V/m
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