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Structures and Dynamics of Two-Dimensional Dust Lattices with and without Coulomb Molecules in Plasmas *

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Structures and dynamics of two-dimensional dust lattices with and without Coulomb molecules in plasmas are investigated. The experimental results show that the lattices have the crystal-like hexagonal structures, i.e. most particles have six nearest-neighboring particles. However, the lattice points can be occupied by the individual particles or by a pair of particles called Coulomb molecules. The pair correlation function is used to compare the structures between the lattices with or without the Coulomb molecules. In the experiments, the Coulomb molecules can also decompose and recombine with another individual particle to form a new molecule.

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The crystal-like structures[1−11] formed by the strongly coupled charged particles with a finite number have been extensively studied since the beginning of the last century, for example, the ionic crystals based on the electrostatic energy were discussed by Madelung[1] and the regular crystal structure of electrons resulting from the coulomb interactions was presented by Wigner.[2] The Coulomb crystal formed by the charged dust particles is a typical characteristic of a strongly coupled plasma system.[11] Normally the dust particles possess negative charges due to the higher thermal mobility of electrons compared with that of ions, and could be elevated by the sheath electric field in the vertical direction, balancing the gravitational force on the particles. In a glow discharge plasma, generally the dust particles have a large charge and low temperature, which could result in a strong Coulomb coupling between the particles. When the interparticle coupling becomes sufficiently strong, an ordered crystal structure will be formed by the particles. Compared with the ionic or electron crystals, the dust Coulomb crystals can be easily detected by a video camera or even by naked eyes due to the considerably large size (from micron to centimeter) of the particles or fractals.[12] In dusty plasmas, several layers of the dust particles could be formed along the vertical direction.[12,13] The phase transition of the two-dimensional (2D) layer (lattice) can be observed by varying the system temperature. It has been shown that the dust crystal has unique transition characteristics, i.e. a middle hexatic state could exist in the transition process from crystal to liquid state.[14] In the crystals mentioned above, the lattice points are only occupied by the individual particles, and the interparticle forces are mainly repulsive.[15,16] However, in our experiments, we also observed that new-type of lattices could be formed, in which some lattice points are occupied by a pair of dust particles instead of the individual particles. We refer the pair of particles as Coulomb molecule. In this Letter, we concentrate on the experimental comparison between the structures and dynamics of the different lattices with and without the Coulomb molecules.

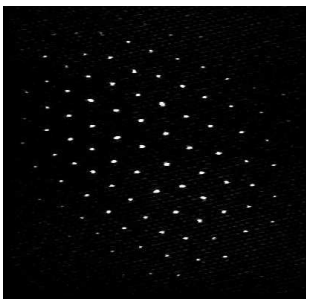

Fig. 1. A typical 2D lattice formed by the charged dust particles.

The dust particles are produced by gas discharge in a capacitively coupled rf (13.56 MHz) plasma system. The apparatus was described in detail in Refs. [12,16]. In this study, the mixed gas of 100–200 Pa with a fixed partial pressure ratio ($SiH_4/Ar/C_2H_4 = 5/95/100$) is used. The dust particles could be observed within several seconds after onset of discharge. By decreasing the rf power and gas pressure, the dust crystal could be formed. A sheet-like He-Ne laser beam is used to illuminate the 2D dust crystals. Figure 1 is a typical lattice formed by the charged dust particles when the rf power is 1 W and the gas pressure is 40 Pa. In Fig. 1, the average radius of the particles is 87 μm, and the average interparticle distance is 0.72 mm. The particles are confined by a circularly symmetrical potential in the 2D plane. Here we can see that the particles with a larger size are located in the inner area and those with a smaller size are in the outer area,

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which is determined by the total energy minimization of the system.[17] The large-sized particles will feel more inward confinement forces, and have a trend to move towards the system center. The phenomena of the large-sized particles occupying the inner area of the system and small-sized particles in the outer area have been verified by molecular dynamics (MD) simulations.[18] In fact, in Fig. 1, the whole 2D lattice is in a circular shape, but some small-sized particles located in the outer area could not be seen clearly due to their weak ability to scatter light. In the 2D lattice, despite the different sizes of the particles, most of the particles have six nearest particles, forming a typical 2D hexagonal-like crystal. When the interparticle forces are mainly repulsive, such hexagonal-like lattice is easily formed,[15] which has been verified by MD simulations.[18]

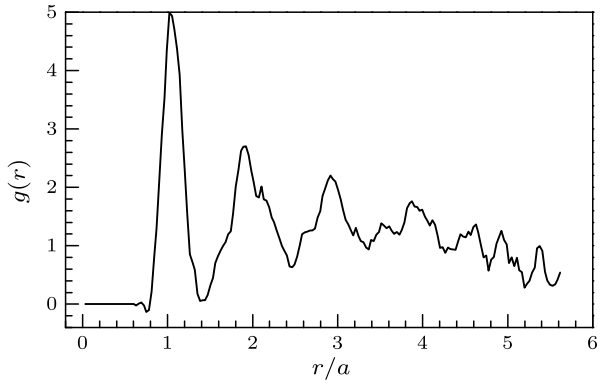

Fig. 2. The pair correlation function of the lattice shown in Fig. 1.

The structure order of a condense system can be characterized by the pair correlation function $g(r)$,[14] which represents the probability of finding two particles separated by a distance r. For a 2D system, the pair correlation function is defined as $g(r) = \left(\frac{S}{N}\right)\frac{N(r,\Delta)}{2\pi r\Delta}$, where S is the area of the whole system, N is the total number of particles occupying the area, and $N(r,\Delta)$ is the number of particles located between $r-\frac{\Delta}{2}$ and $r+\frac{\Delta}{2}$ ($\Delta = 0.1a$, where a is the average interparticle distance). Figure 2 presents the calculated $g(r)$ for the 2D lattice shown in Fig. 1. From Fig. 2, one can see that $g(r)$ has a highest peak near the position $r = a$, which means that the nearest shell surrounding a particle is formed. It is characteristic that the first peak is apparently higher than the other peaks in $g(r)$ for a liquid or amorphous state. From Fig. 2, we also see that there appears a shoulder on each peak but the first one, which indicates that an amorphous structure is formed in the 2D lattice.

The stability of the lattice shown in Fig. 1 can be investigated by tracing the trajectories of all the particles in the system. From our experiment, we can observe that the lattice structure can exist stably for a long time. In Fig. 3, we only show the trajectories of the particles for a time period of 2 s. One can see that the particles only move in a small area around their equilibrium positions, so the hexagonal-like structures of the lattice (two small hexagonal structures are highlighted in Fig. 3) are not broken by the movements of the particles, and the lattice structure can exist stably for a long time. Therefore, we can conclude that the lattice is in a stable amorphous state at the applied low rf power (1 W).

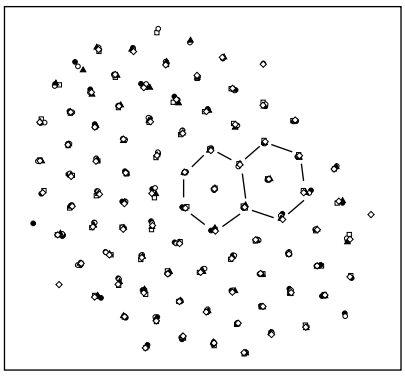

Fig. 3. The trajectories of the particles shown in Fig. 1 for a time period of 2 s.

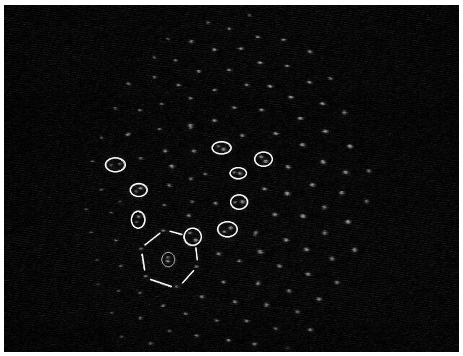

Fig. 4. A typical lattice with Coulomb molecules.

In the above discussions, the lattice does not contain any Coulomb molecules, i.e. each lattice point is only occupied by one individual particle. In our experiments, we also observe that some lattice points could be occupied by the Coulomb molecules (a pair of particles). Figure 4 is a typical lattice structure containing Coulomb molecules. Some Coulomb molecules are highlighted by the circles around them in Fig. 4. We can see that the Coulomb molecules could stay at the center as well as the six vertices of a hexagonal structure (highlighted by a hexagon in Fig. 4). The distance between the two particles contained in one Coulomb molecule is much smaller than the average interparticle spacing, which is due to the balance between the competing interparticle attractive and repulsive forces. The interparticle attractive force comes from the interaction between the negatively charged particles and the ion-electron plasma background.[13,19,20] It is known that a negatively charged dust particle is screened by the positive ions in the background plasma, and its field is very weak outside the screening region, also called the Debye sphere (DS).[13,21] When

the dust particles move close enough to each other, their individual DSs overlap, and the interaction between the negatively charged dust particles and the positive ions in the DSs generates an attractive force in addition to the repulsive force between the dust particles. The existence of dust Coulomb molecules is the result of the strong coupling between the dust particles and the positive ions in the DSs of the background plasma. According to Ref. [13], when the individual DSs of the dust particles overlap, there exists a minimum in the total electrostatic potential energy of the particle system. When the kinetic energy (say from thermal fluctuations) of the dust particles is less than the maximum energy difference (i.e. the maximum depth) of the potential well, the dust particles remain in the potential well, and a dust pair (Coulomb molecule) is formed. Oppositely, if the kinetic energy of the dust particles exceeds the maximum potential energy difference of the well, the formed Coulomb molecules can also be decomposed (as shown later). From our experiments, we also notice that the particles near to the Coulomb molecules have a higher mobility than that of the particles far away from the molecules, while the whole lattice structure is still similar to that without any Coulomb molecules as shown in Fig. 1. The local lattice structure far away from the Coulomb molecules also has a similar stability as that in the system without any Coulomb molecules as shown in Fig. 1, namely the particles only move in a small area around their equilibrium positions, and make the local lattice structure very stable.

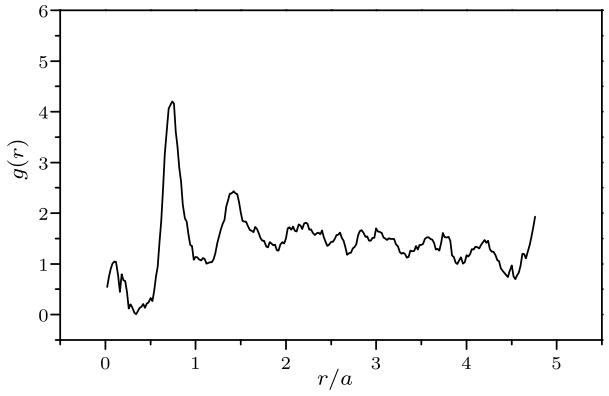

Fig. 5. The pair correlation function of the lattice with Coulomb molecules shown in Fig. 4.

Figure 5 is the pair correlation function of the lattice shown in Fig. 4. Compared with Fig. 2, Fig. 5 shows two new features: (i) there appears a small peak in the region $0 < r < 0.5a$, which means that the nearest interparticle distance is much smaller than the average interparticle distance; (ii) the highest peak is located at a position $r < a$. These results can be explained by the existence of the Coulomb molecules containing two particles separated by a very small distance in the lattice. From Fig. 5, we can also see that the lattice has some amorphous characteristics, i.e. the second peak is much higher than the other peaks, and there appear small shoulders on the other peaks.

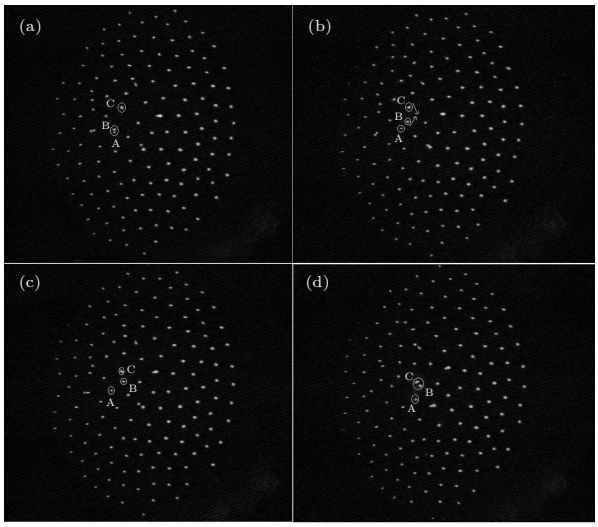

Fig. 6. The decomposing process of the Coulomb molecule (a), (b) and (c); the recombining process of the decomposed molecule with a new particle to form another molecule (d).

In fact, in our experiments, the two particles contained in a Coulomb molecule can be very close to each other, but still remain separated from each other due to the sufficient interparticle repulsive force. It is worth discussing another interesting phenomenon that is the two particles contained in one molecule even can depart from each other, and one of them moves towards another single particle to form a new molecule. Figure 6 shows the decomposing and recombining process of the Coulomb molecule. In Fig. 6(a), particle A and B are contained in one molecule highlighted by a circle, and particle C (highlighted by a circle) is near to this molecule. In Fig. 6(b), particles A and B begin to depart from each other, and particles B and C move towards each other along the directions denoted by the arrows. In Fig. 6(c), the molecule has been completely decomposed, and the distance between particles A and B is approximately equal to the average interparticle distance in the lattice. At the same time, the distance between particles B and C becomes smaller. In Fig. 6(d), particles B and C are combined, forming a new Coulomb molecule. This experimental result indicates that the formation of a Coulomb molecule is determined by the dynamical balancing between the competing interparticle repulsive and attractive forces in the system.

During the decomposing and recombining process of the Coulomb molecules, the local lattice structure encircling them will be deformed accordingly. Figure 7 shows the lattice deformation during this process. In Fig. 7(a), a Coulomb molecule (highlighted by a circle around it) composed of particles A and B is located at the center of a small pentagonal lattice structure (denoted by the plotted pentagon), and particle C is at a vertex position of the structure. In Fig. 7(b) particles

A and B begin to depart from each other, and particle B moves towards particle C along the direction denoted by the left arrow. At the same time, particle C moves towards particle B in the direction denoted by the right arrow. In Fig. 7(c), particles B and C finally form a new molecule (highlighted by a circle around it) due to the interparticle attractive force. In the experiment, such a decomposing and recombining process could be finished very fast, even within a time period less than 1 s. This behavior of the molecule transition also leads to the deformation of the local lattice structure encircling the molecules. From Fig. 7(c), we can see that after transition, particle A becomes the center of the pentagonal structure (denoted by the plotted pentagon), and the new-formed molecule composed of particles B and C is located at a vertex position in the structure. Compared Fig. 7(a) with Fig. 7(c), one can see that the original pentagonal structure is slightly deformed after the molecule transition, as shown in Fig. 7(c). Therefore, we can conclude that during the decomposing and recombining process, the positions of the particles composed of the Coulomb molecules are properly changed, but the local lattice structure encircling the molecules is only slightly deformed, and still keeps its original pentagonal shape. We also notice that during the transition process, the particles far away from the Coulomb molecules have a lower mobility compared with those near the molecules, which implies that the structure of a lattice without the Coulomb molecules will be more stable than that with the Coulomb molecules in a system.

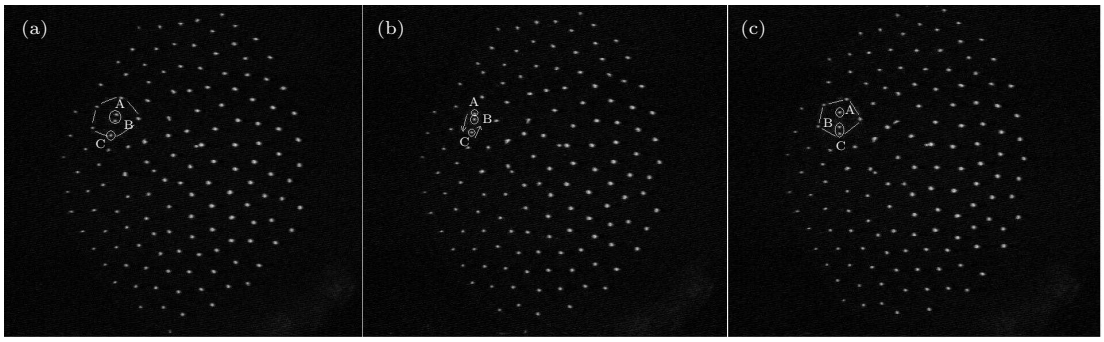

Fig. 7. The deformation of the local lattice structure during the decomposing (a) and (b) and the recombining (c) process of the Coulomb molecules.

In summary, the structure and dynamics of a 2D dust lattice with or without Coulomb molecules (a pair of dust particles) in dusty plasmas have been investigated by using the pair correlation function and tracing the trajectories of the particles in the system. The results show that the lattice without the Coulomb molecules represents the amorphous characteristics, and most of the particles have six nearest-neighboring particles. The whole lattice is stable, and the particles only move around their equilibrium positions. In contrast, the lattice with the Coulomb molecules shows some new features: the nearest interparticle distance is much less than the average interparticle distance, which is due to the fact that the distance between the two particles contained in one molecule is very small. In our experiments, the two particles contained in one Coulomb molecule can be sufficiently close to each other, but still remain separated due to the delicate balancing between the competing interparticle repulsive and attractive forces. The Coulomb molecules can be decomposed and recombined with another single particle to form a new molecule. During the molecule transition process, the positions of the particles composing the molecules are properly changed, but the local lattice structure encircling the molecules is only slightly deformed. It is also worth mentioning that in the transition process, the particles far away from the Coulomb molecules have a lower mobility compared with that near to the molecules, which implies that the structure of a lattice without the Coulomb molecules is more stable than that with the Coulomb molecules.

References

[1] Madelung E 1918 *Phys. Zs.* **19** 524
[2] Wigner E 1934 *Phys. Rev.* **46** 1002
[3] Chu J H and I L 1994 *Phys. Rev. Lett.* **72** 4009
[4] Thomas H et al 1994 *Phys. Rev. Lett.* **73** 652
[5] Pieper J B et al 1996 *Phys. Rev.* E **54** 5636
[6] Mohideen U et al 1998 *Phys. Rev. Lett.* **81** 349
[7] Juan W T et al 1998 *Phys. Rev.* E **58** 69470
[8] Morfill G E and Thomas H 1996 *J. Vac. Sci. Technol.* A **14** 490
[9] Quinn R A et al 1996 *Phys. Rev.* E **53** 2049
[10] Kamimura T et al 2007 *Phys. Plasma* **14** 123706
[11] Hua J J et al 2003 *Chin. Phys. Lett.* **20** 155
[12] Huang F et al 2004 *Plasma Sci. Technol.* **6** 2571
[13] Chen Y P et al 1999 *Phys. Plasma* **6** 699
[14] Liu B et al 2003 *Chin. Phys.* **12** 765
[15] Miao Y H and Liu Y H 2008 *Phys. Scr.* **78** 035802
[16] Huang F et al 2004 *Chin. Phys.* **13** 1896
[17] Liu Y H et al 2006 *Phys. Rev.* E **73** 047402
[18] Huang F et al 2006 *Chin. Phys. Lett.* **23** 1853
[19] Chen Z Y, Yu M Y and Luo H Q 2001 *Phys. Scr.* **64** 476
[20] Liu Y H et al 2008 *Phys. Rev.* E **78** 066405
[21] Wang L 1999 *Comments Plasma Phys. Controlled Fusion* **1** 117