Annealing and Confinement in Granular Crystallization

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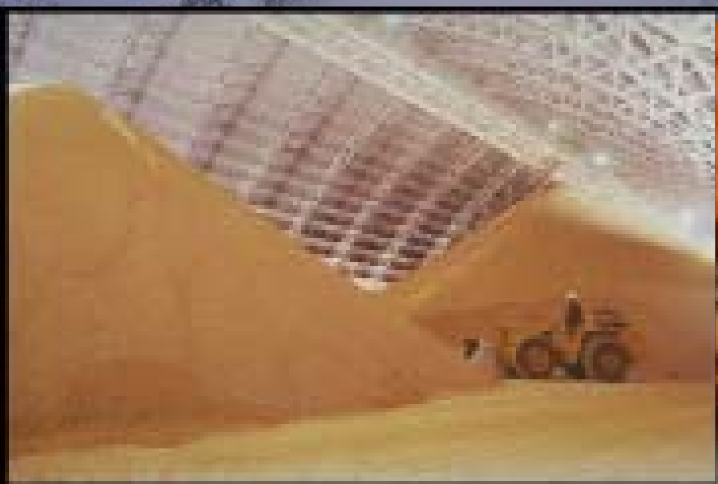
Cementos
Carbón
Productos
Farmacéuticos
Cereales

10,000 millones
de toneladas
anuales

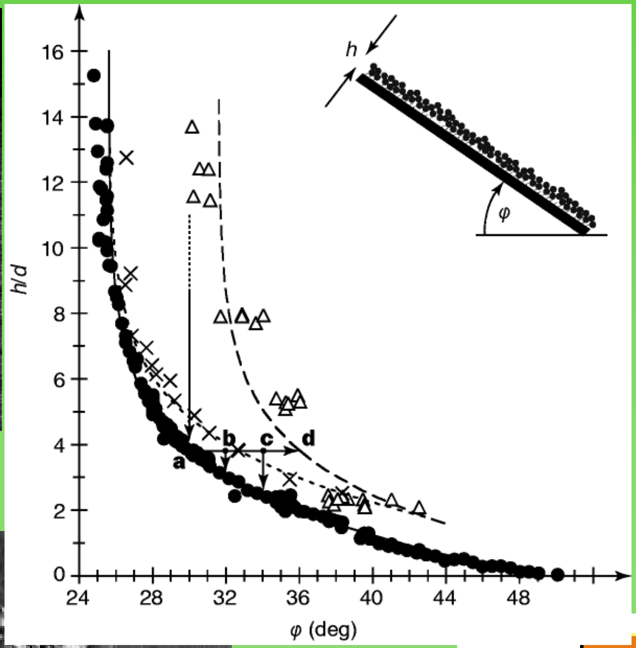




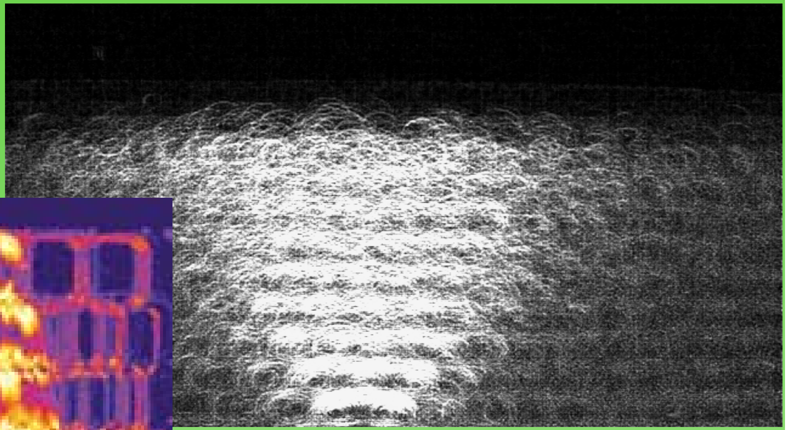


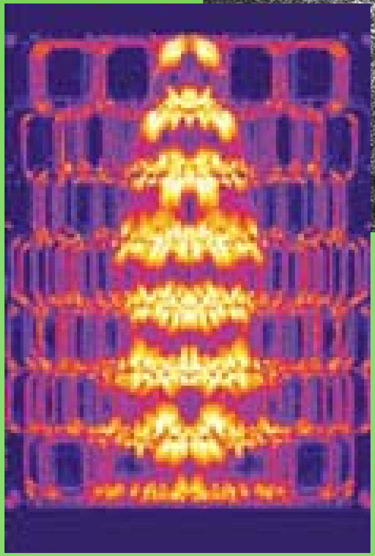

Propiedades Estáticas:

Estabilidad

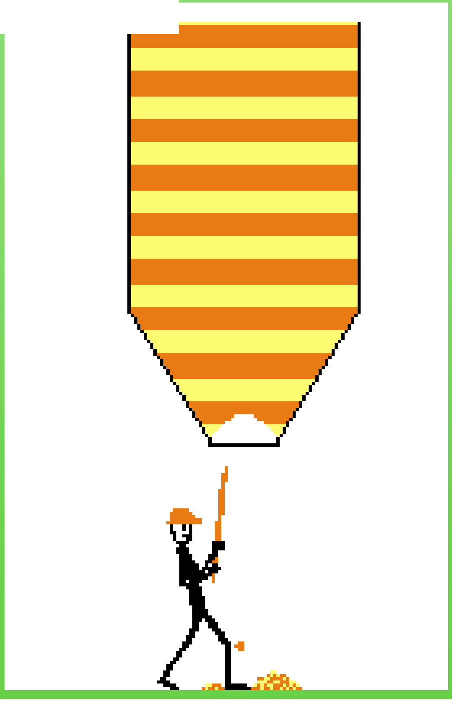


Rigidez

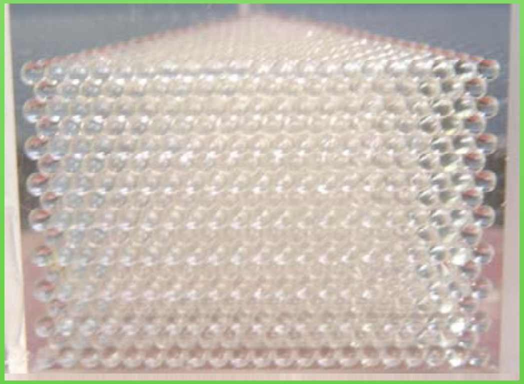


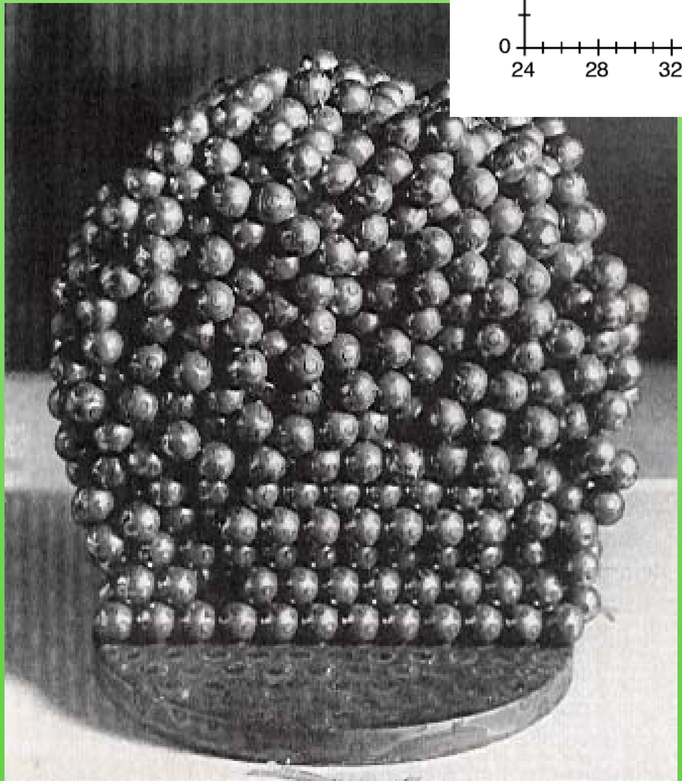


Arqueo



Compactación

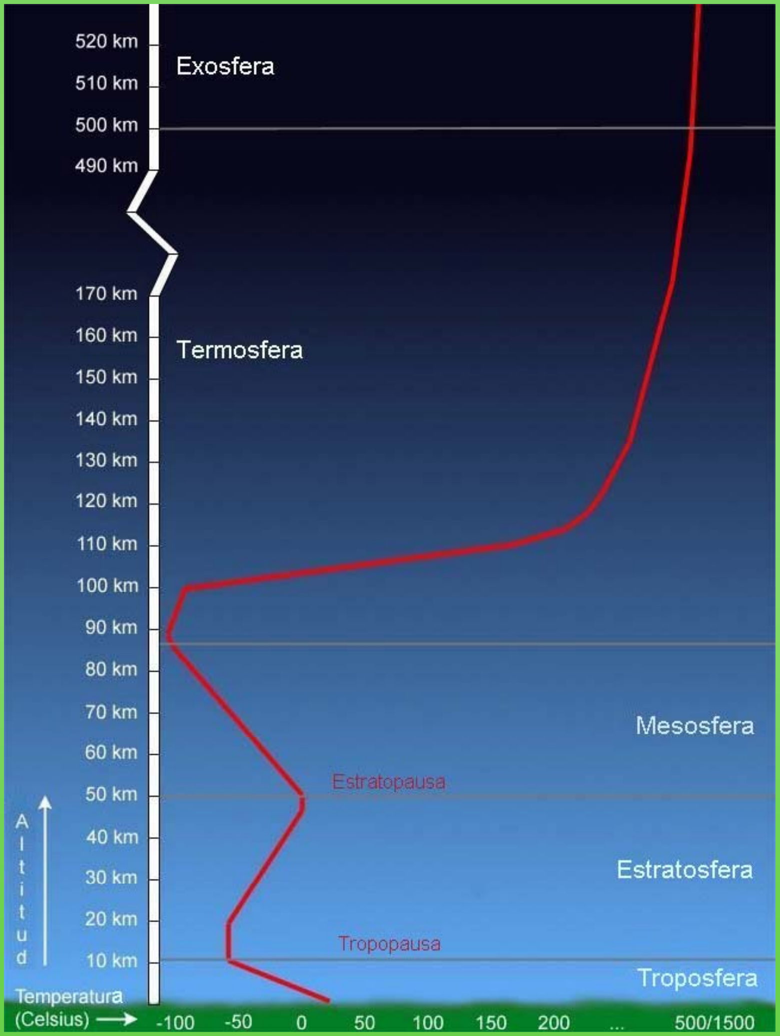


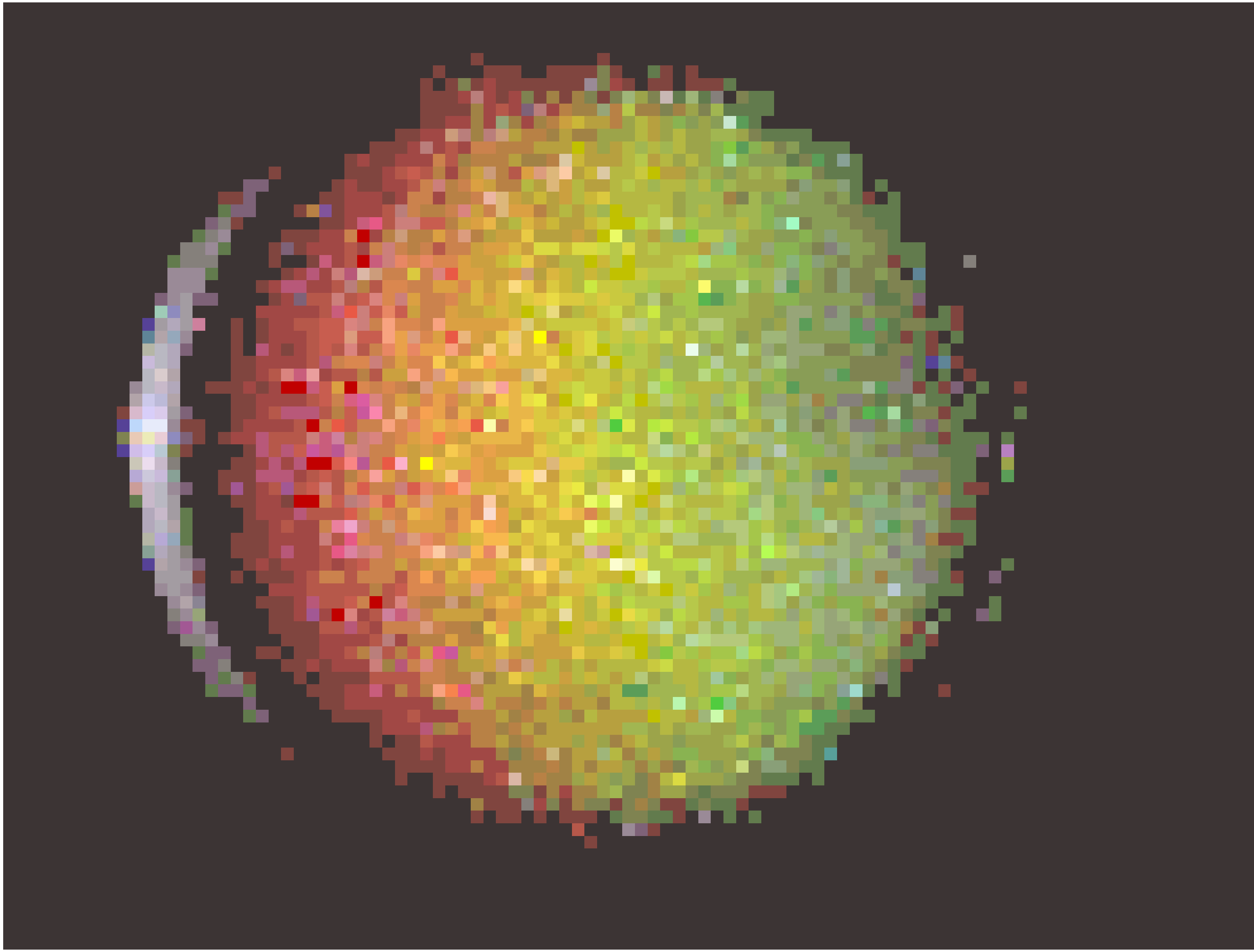


Propiedades Dinámicas

mgh kT

Para una molécula de N_2 : mgh << kT





- Ver Video

The Pursuit of Perfect Packing

- Kepler`s Conjecture (1591)

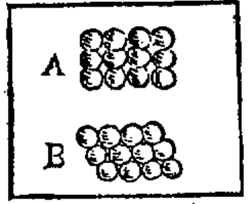
"A cubic close packing (FCC) of identical hard spheres is the densest packing achievable"

- Tom Hales Theorem (1999)

From hales@math.lsa.umich.edu Wed Aug 19 02:43:02 1998
Date: Sun, 9 Aug 1998 09:54:56 -0400 (EDT)
From: Tom Hales <hales@math.lsa.umich.edu>
To: Subject: Kepler conjecture
Dear colleagues,
I have started to distribute copies of a series of papers giving a solution to the Kepler conjecture, the oldest problem in discrete geometry. These results are still preliminary in the sense that they have not been refereed and have not even been submitted for publication, but the proofs are to the best of my knowledge correct and complete. Nearly four hundred years ago, Kepler asserted that no packing of congruent spheres can have a density greater than the density of the face-centered cubic packing. This assertion has come to be known as the Kepler conjecture. In 1900, Hilbert included the Kepler conjecture in his famous list of mathematical problems. http://www.math.lsa.umich.edu/~hales Tom Hales samf@math.lsa.umich.edu hales@math.lsa.umich.edu

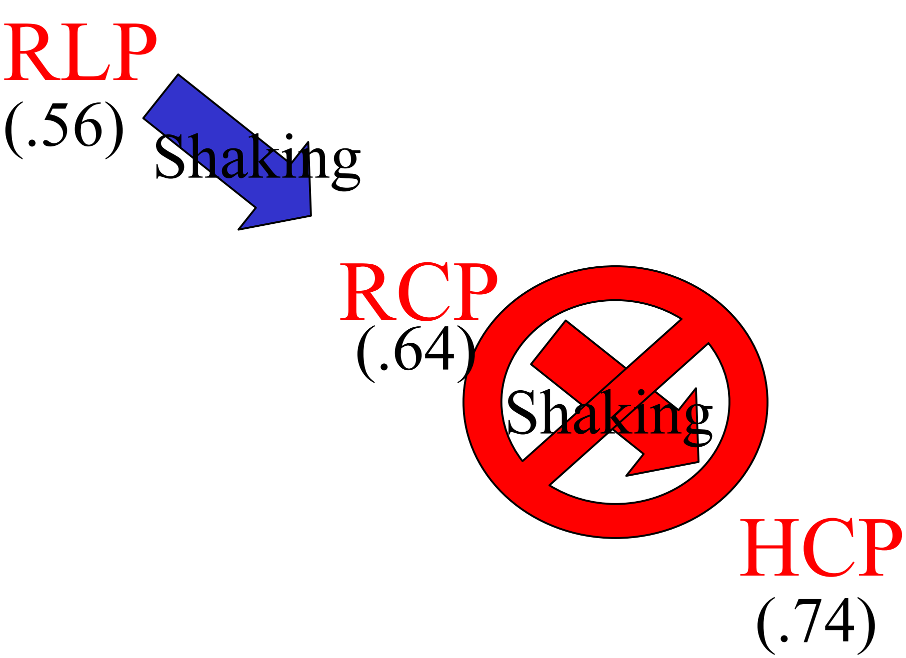
Nam si errantes in eodem plano horizontali globulos aequales coegeris in angustum, ut se mutuo contingant, aut triangulari forma coeunt, aut quadrangulari; ibi sex unum circumstant, hic quatuor: utrinque eadem est ratio contactus per omnes globulos, demptis extremis. Quinquanguli forma nequit retineri aequalitas, sexangulum resolvitur in triangula: ut ita dicti duo ordines soli sint.

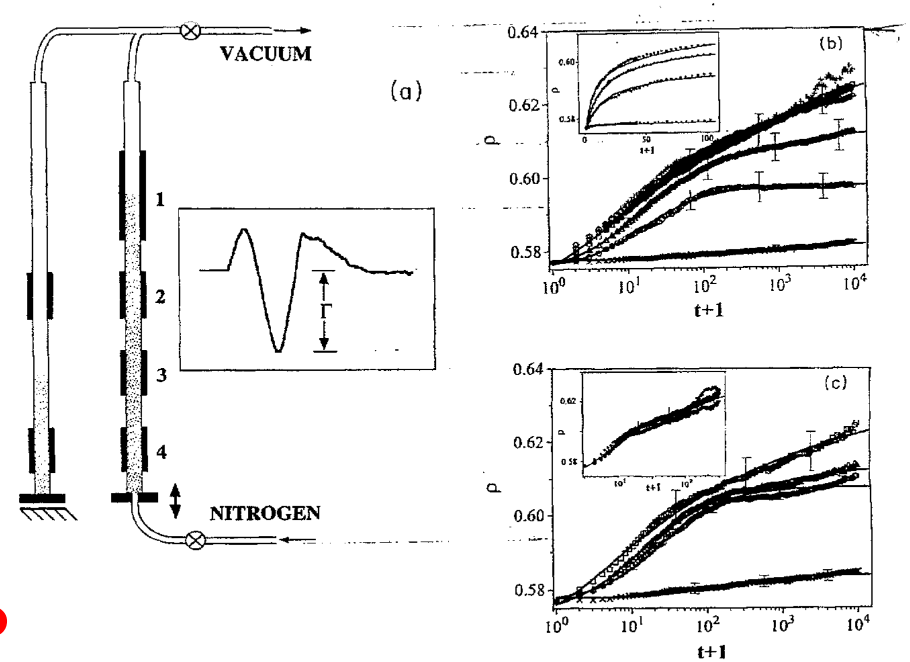
Quam si ad structuram solidorum quam potest fieri arctissimam progredieris, ordinesque ordinibus superponas, in plano prius coaptatos, aut ij erunt quadrati A aut trigonici: B si quadrati, aut singuli globi ordinis superioris singulis superstabunt ordinis inferioris aut contra singuli ordinis superioris sedebunt inter quaternos ordinis inferioris. Priori modo tangitur quilibet globus à quatuor circumstantibus in eodem plano, ab uno supra se, & ab uno infra se: & sic in universum à sex alijs, eritque ordo cubicus, & compressione facta fient cubi: sed non erit arctissima coaptatio. Posteriori modo praeterquam quod quilibet globus à quatuor circumstantibus in eodem plano tangitur, etiam à quatuor infra se, & à quatuor supra se, & sic in universum à duodecim tangetur; fientque compressione ex globosis Rhombica. Ordo hic magis assimilabitur octaedro & Pyramidi. Coaptatio fiet arctissima: ut nullo praeterea ordine plures globuli in idem vas compingi queant. Rursum si ordines in plano structi fuerint trigonici: tunc in coaptatione solida aut singuli globi ordinis superi[illegible] superstant singulis inferioris, coaptatione rursum laxa, aut singuli superioris, sedent inter ternos inferioris. Priori modo tangitur quilibet globus à sex circumstantibus in eodem plano, ab uno supra, & ab uno infra se, & sic in universum ab octo alijs. Ordo assimilabitur Prismati, & cõpressione facta fient pro globulis columnae senum laterum quadrãgulorum, duarumque basium sexangularum. Posteriori modo fiet idẽ, quod prius posteriori modo in



Compaction

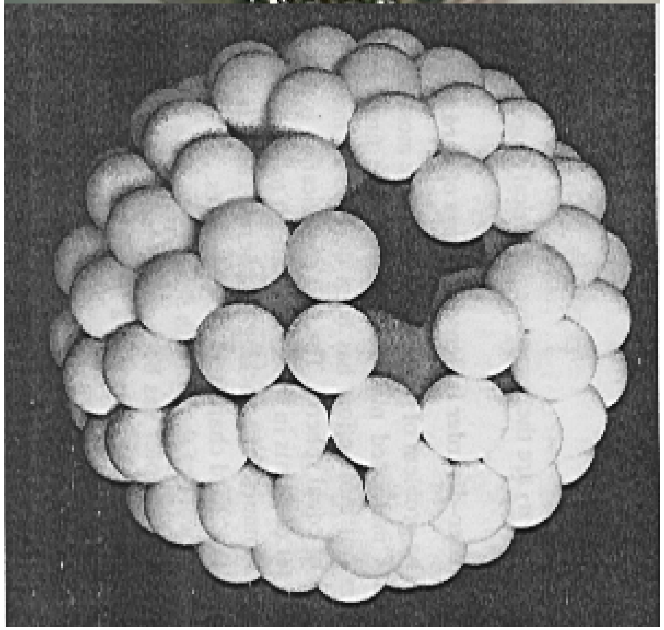
Jammed systems in glass like states




PHYSICAL REVIEW E VOLUME 51, NUMBER 5 MAY 1995

Density relaxation in a vibrated granular material

James B. Knight, Christopher G. Fandrich, Chun Ning Lau, Heinrich M. Jaeger, and Sidney R. Nagel
The James Franck Institute and the Department of Physics, The University of Chicago, Chicago, Illinois 60637
(Received 1 September 1994)



Partial Crystallization Induced by Shear

VOLUME 79, NUMBER 19 PHYSICAL REVIEW LETTERS 10 NOVEMBER 1997

Crystallization of non-Brownian Spheres under Horizontal Shaking

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LadHyX, CNRS UMR 156, École Polytechnique, 91128 Palaiseau Cedex, France
(Received 31 July 1997)

Until now, it has been observed that a collective handling of uniform spheres could only lead to a random close packing of 0.64 maximum volume fraction. In this Letter, we show that denser crystalline arrangements can be obtained when beads are poured at low flow rates into a horizontally shaken container. A parallel is suggested between this process and that of colloidal sedimentation which also yields crystalline structure. [S0031-9007(97)04421-9]

PACS numbers: 46.10.+z, 61.50.−f, 81.20.Ev, 83.70.Fn

Packings of uniform spheres have been extensively studied both by the powder technology community [1,2] and by physicists who consider hard spheres systems as a model for simple liquids [3]. It is well known (although not rigorously demonstrated [4,5]) that the volume fraction of the packing, defined as the ratio of the volume occupied by the spheres to the total volume, cannot exceed 0.74, corresponding to the regular crystal arrangements (for example, hexagonal or face-centered cubic). However, spheres simply released in a box do not spontaneously arrange into a crystalline formation. Even when vibrations are imposed to compact the arrangement, the maximum volume fraction obtained is 0.64 (in the limit of large boxes) [6–9]. This is called the random close packing limit and is commonly considered as the maximum density that can be reached by collectively handling the particles as reported by an anonymous author [10]: "ball bearings and similar objects have been shaken, settled in oil, stuck with paint, kneaded inside rubber balloons and all with no better result than a density of about 0.636."

0.67

Although this limit seems to be well defined, some studies in the literature report that higher densities corresponding to regular arrangements can be obtained. Scott *et al.* observed in a short note [11] that cyclic shear motion can induce packing with a density higher than 0.64. Owe Berg *et al.* [12] carried out experiments on the packing of spheres obtained under different shaking processes and concluded that "three dimensional shaking" (shaking with an horizontal component) can lead to a crystallization. More recently, Vanel *et al.* [13] obtained a regular packing of steel beads by vertically vibrating the container. However, all these experiments deal with a very small number of particles and the thickness of the crystal does not exceed 20 particles. Under such conditions, the packings are certainly dramatically influenced by the boundaries. To our knowledge, no process has been reported for creating large crystals of non-Brownian spheres.

On the other hand, in the case of Brownian hard spheres sensitive to thermal fluctuations, spontaneous crystallization can occur [14–17]. The slow sedimentation of colloidal spherical particles in a fluid with the same index of refraction (in order to minimize the van der Waals forces) yields a dense crystalline sediment of density around 0.67 [15]. The crystallization is in this case controlled by the temperature: as a result of Brownian motion, the spheres reaching the free surface of the sediment rearrange spontaneously into an equilibrium ordered state.

In this paper we present a method inspired by the colloidal crystallization for creating crystalline arrangements of non-Brownian spheres. The method consists in continuously pouring the spheres into a box subjected to horizontal vibrations. The vibrations allow the particles to rearrange and play a role similar to the temperature in the colloidal sedimentation. Whereas many reports have been devoted to the dynamics of a granular media [18,19] and its compaction [1,20,21] under vertical vibrations, few have been concerned with horizontal vibrations [22,23] and to our knowledge no crystallization results have been reported.

The experimental setup is presented in Fig. 1. A glass box 12 cm × 12 cm × 25 cm is fixed on a table which can horizontally move on linear bearings. A

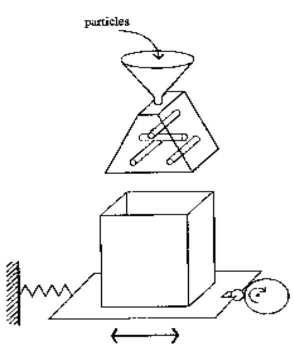
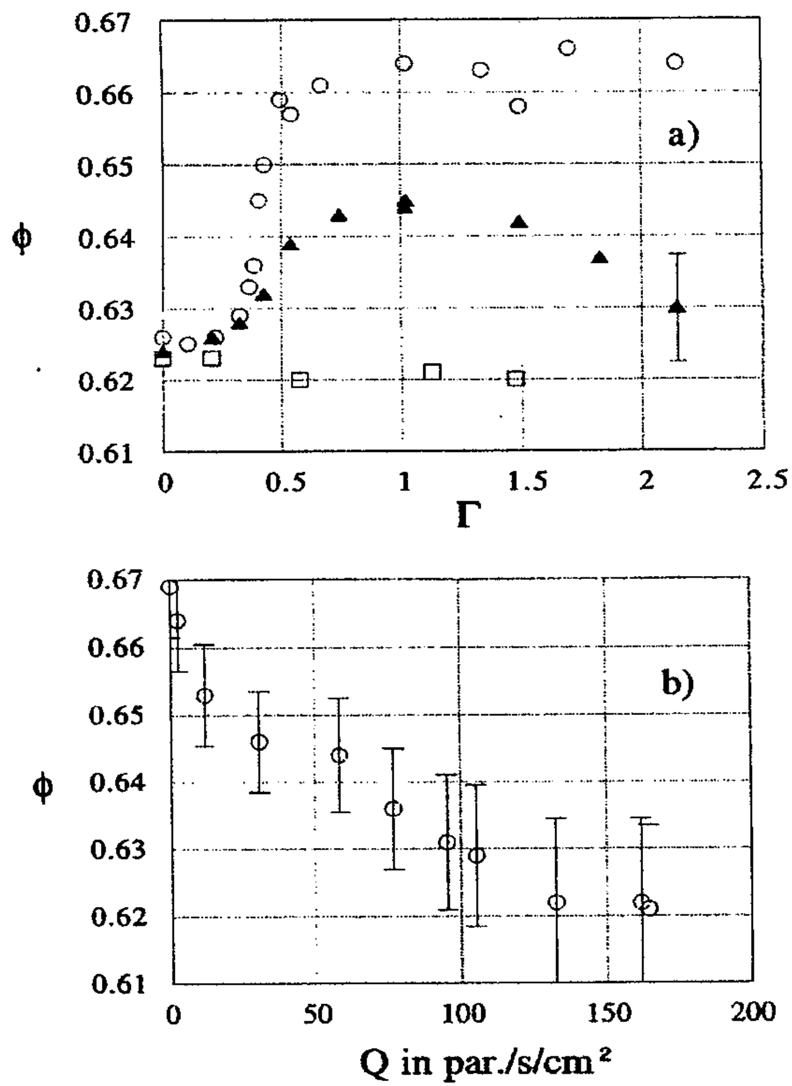
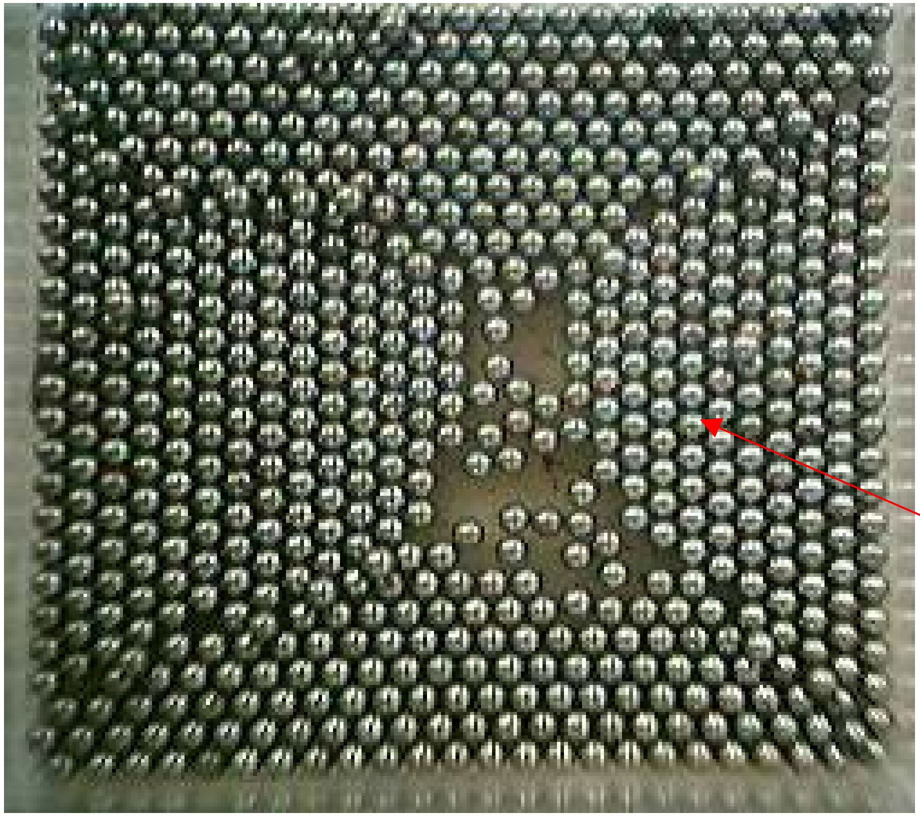


FIG. 1. Experimental setup.



Incommensurable



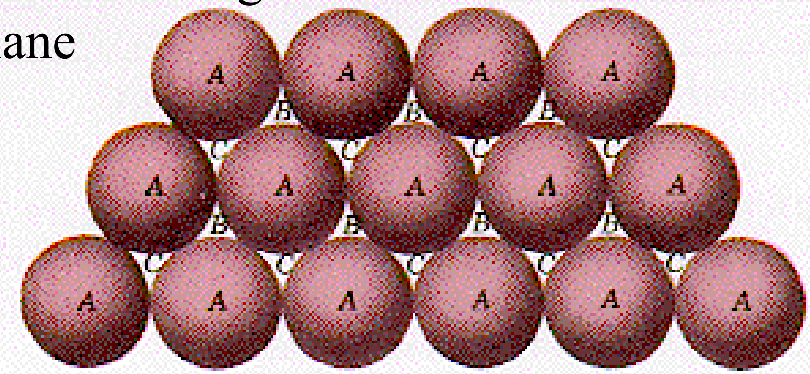
Hexagonal packing

Square cell

Impossible to grow a “square” packing in this cell ?

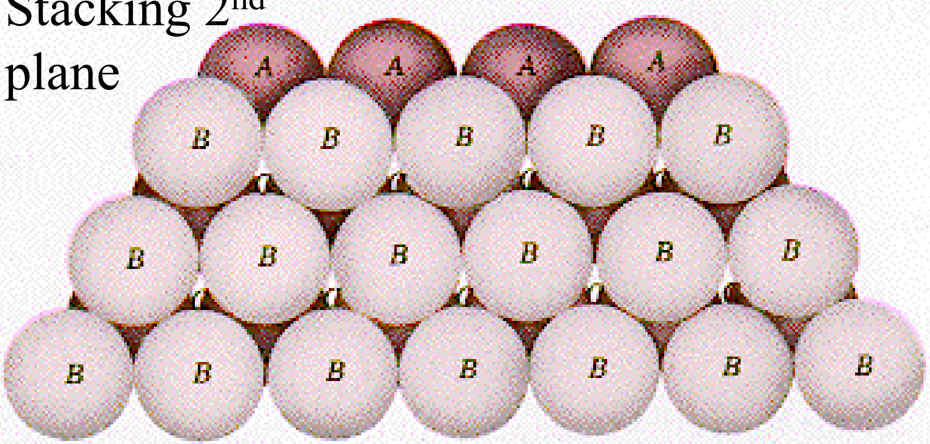
Crystal Structure

Hexagonal Close Packing Plane

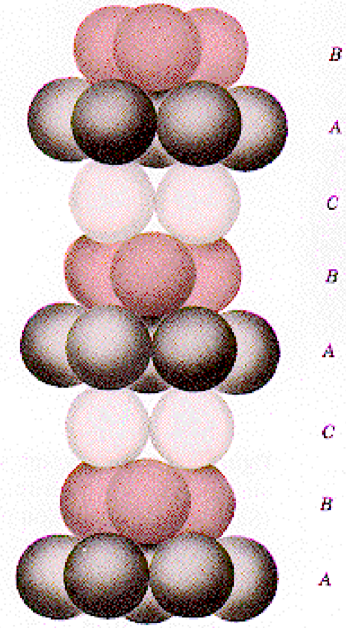


(a)

Stacking 2nd plane

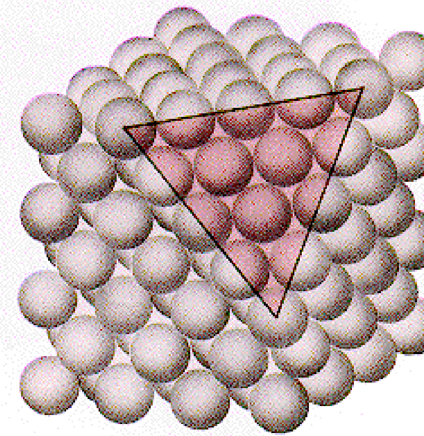


(b)

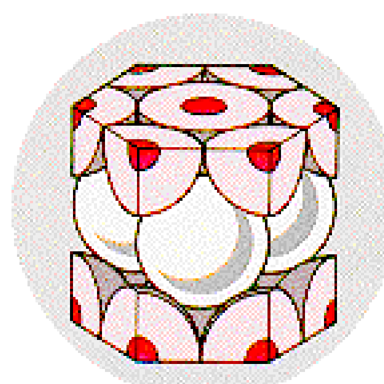


(a)

FCC

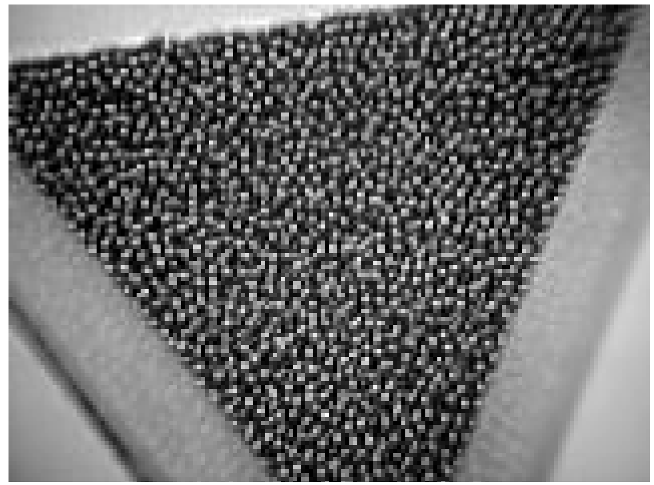


(b)



HCP

Crystallization Dynamics



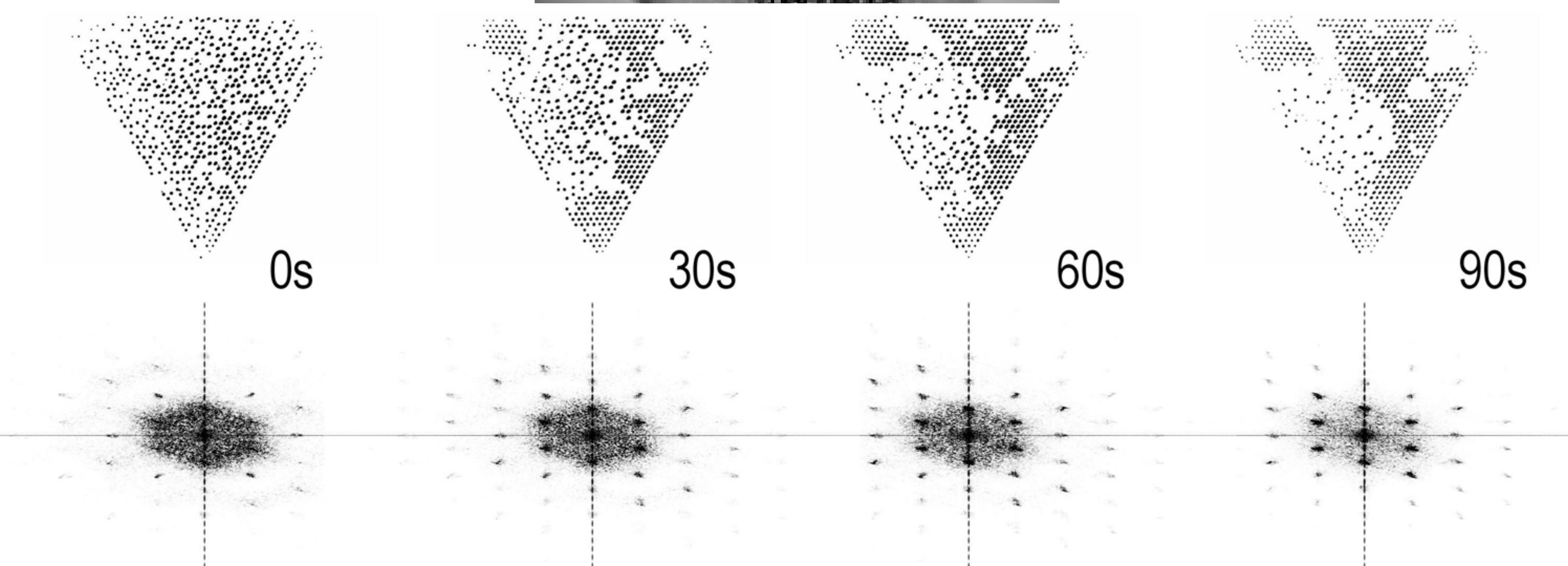
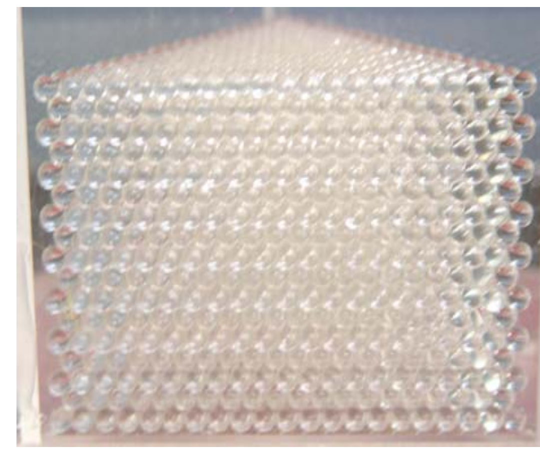
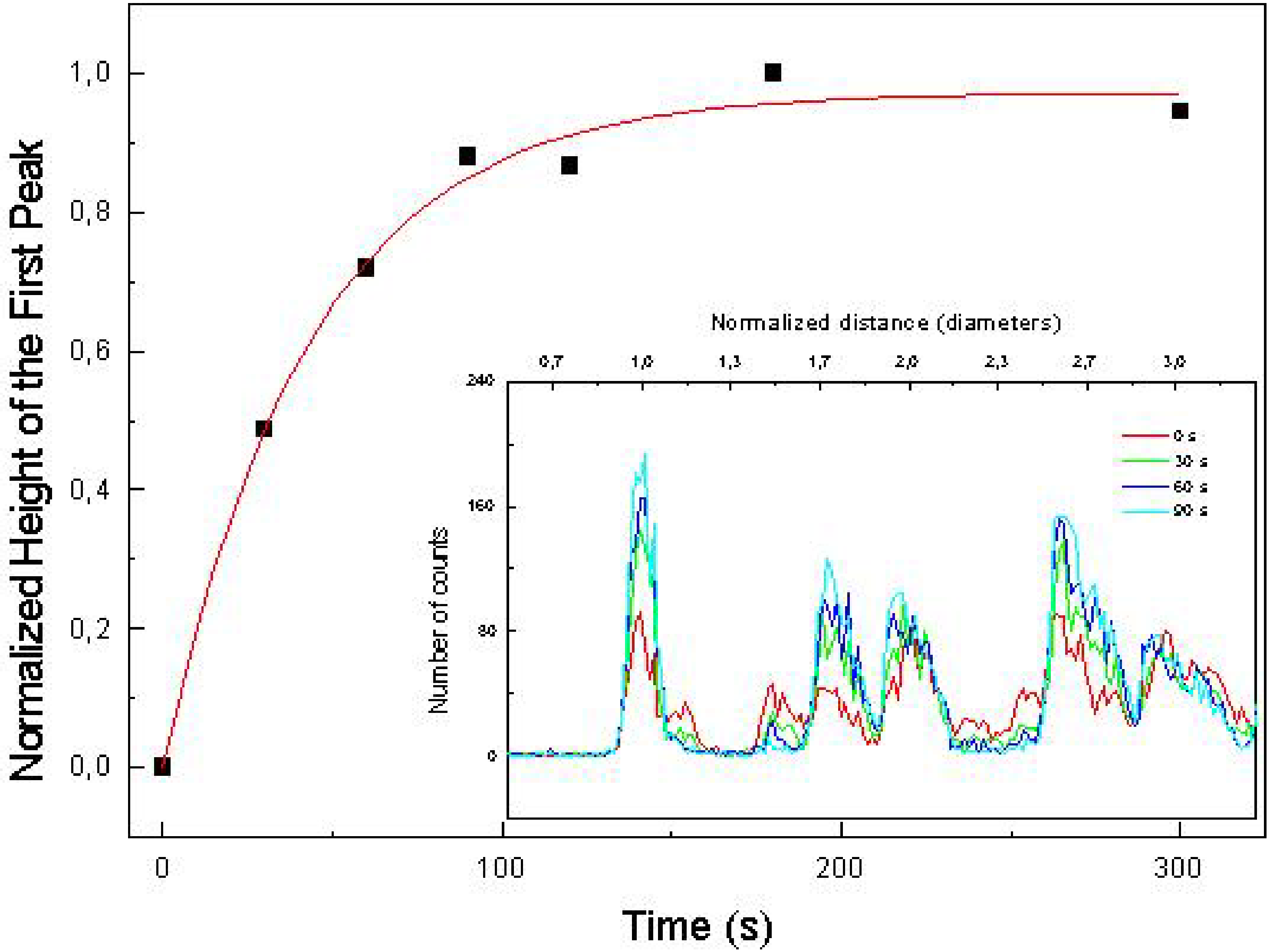


FIG. 1. Single hcp granular crystals grown by the epitaxial method. Left: Crystal with 5 cm side and 18 cm height, containing approximately 8000 steel ball bearings. The crystal was grown in about 2 h. Right: Crystal with 8 cm side and 11.5 cm height, containing approximately 13 000 steel ball bearings. The crystal was grown in about 3 h.

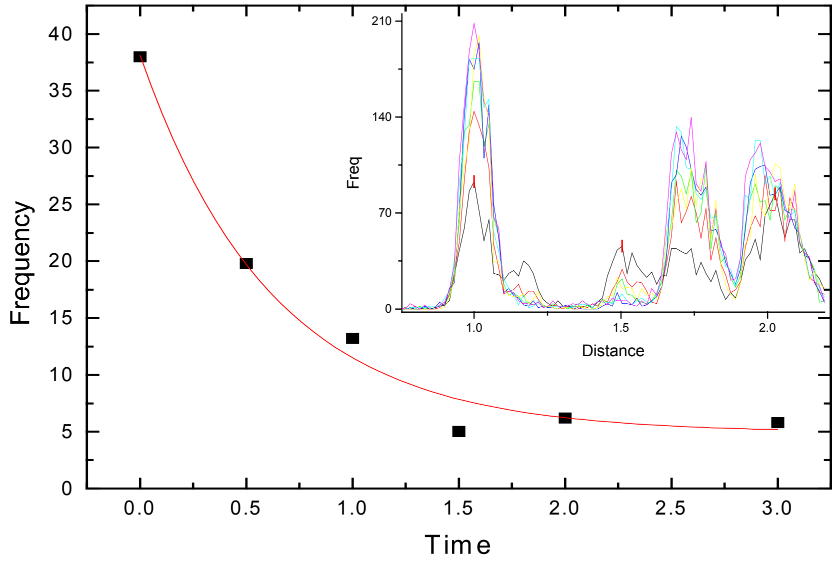
PRL 89, 264302 (2002)

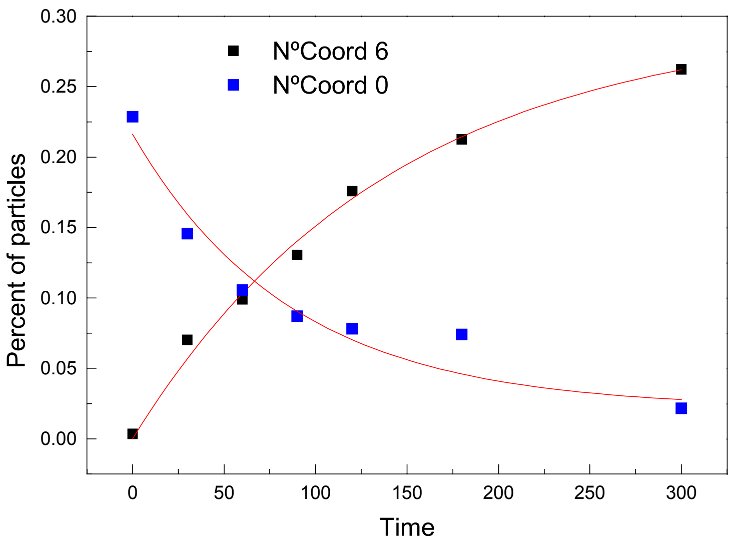


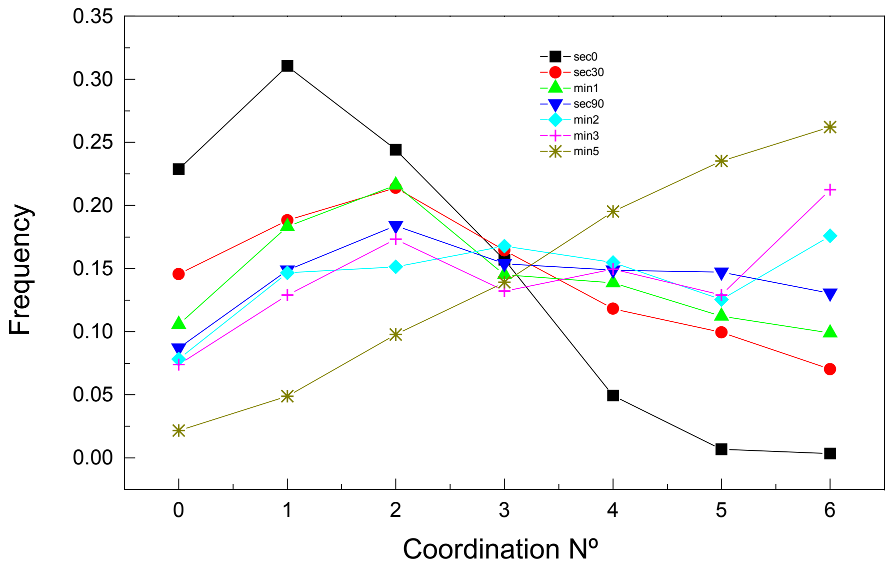
Crystallization Dynamics



Clustering & Coarsening



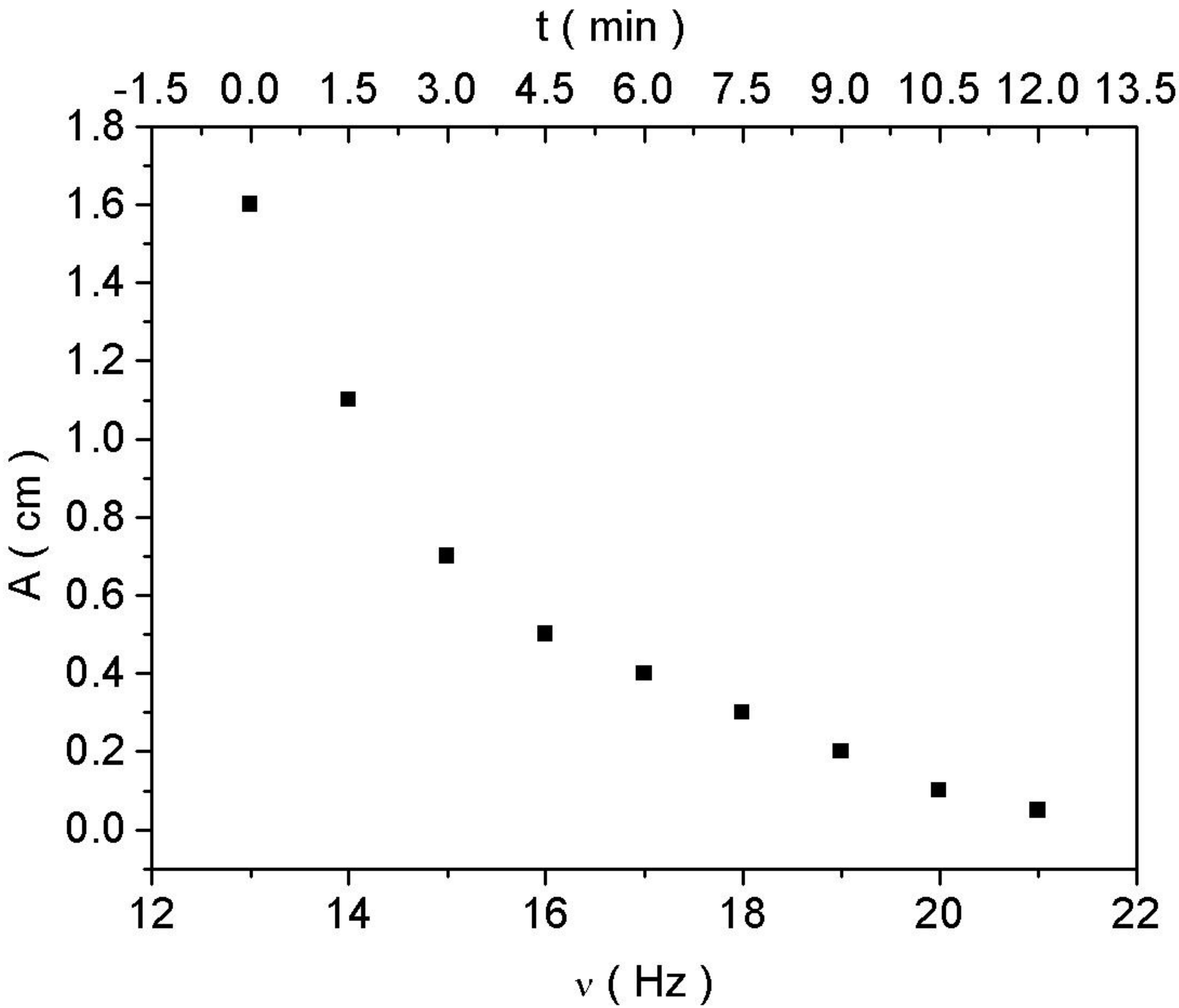




- Confinement drastically affects structural correlations, dynamical properties and the location of phase transitions in molecular or colloidal systems.

Some examples

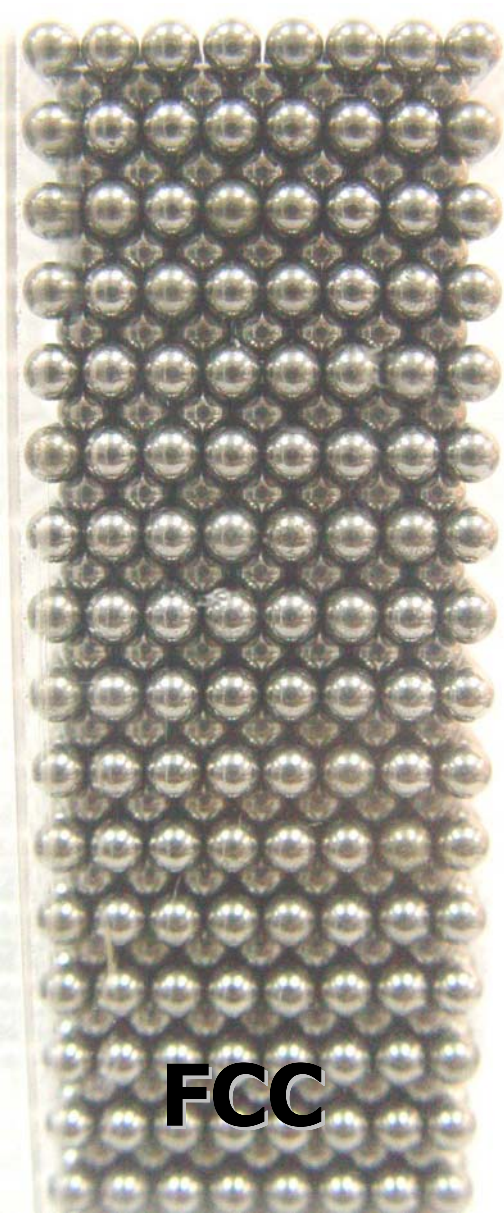
- Phase-separation: capillary condensation.
- Commensurate-incommensurate transitions.
- Freezing transitions of hard spheres.
- Confinement-induced attractions.

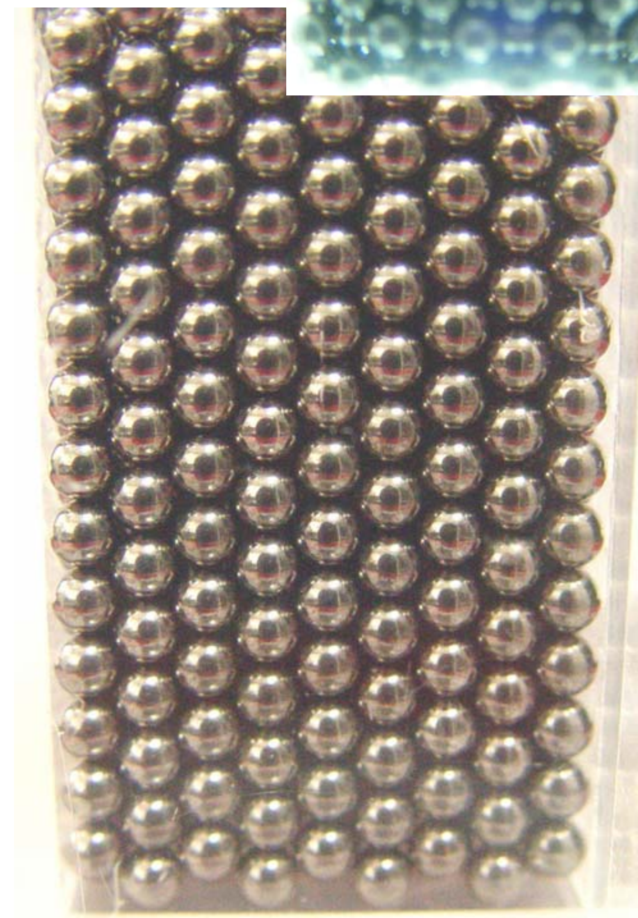


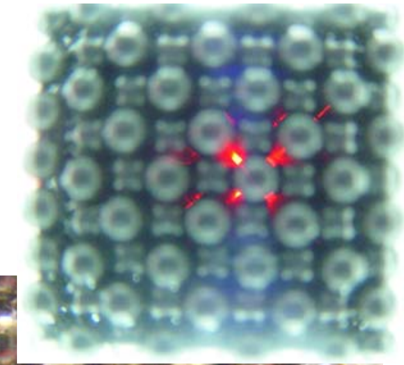
t (min)
-1.5
0.0
1.5
3.0
4.5
6.0
7.5
9.0
10.5
12.0
13.5
A (cm)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
12
14
16
18
20
22
ν (Hz)

Melting and Annealing

Epitaxial

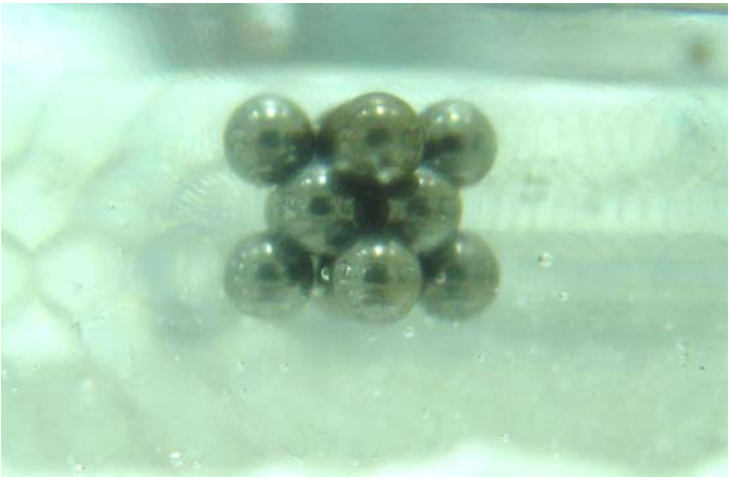


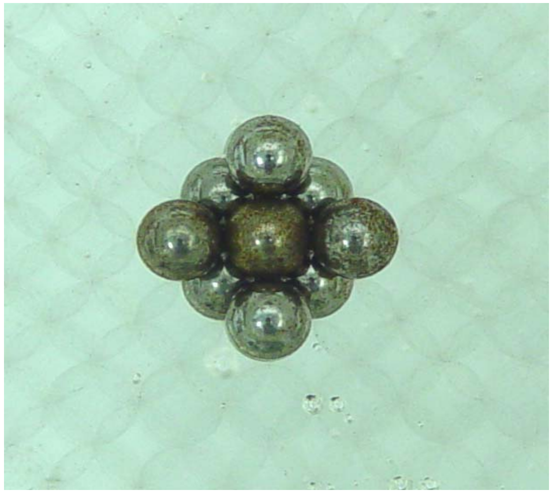




BCT

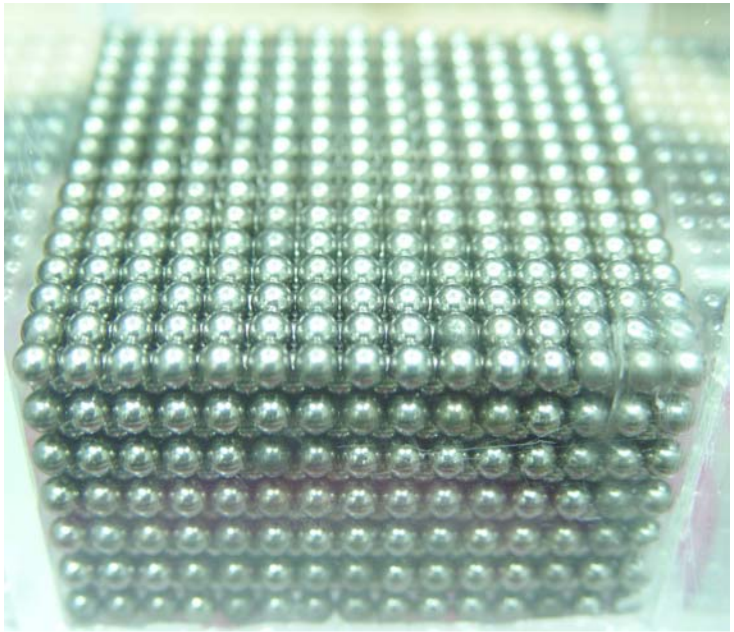
Primitive cell FCC

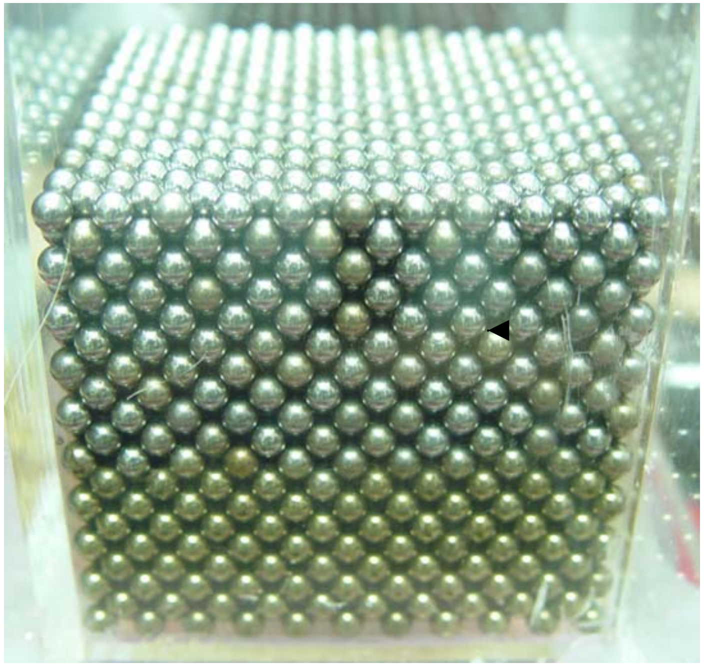


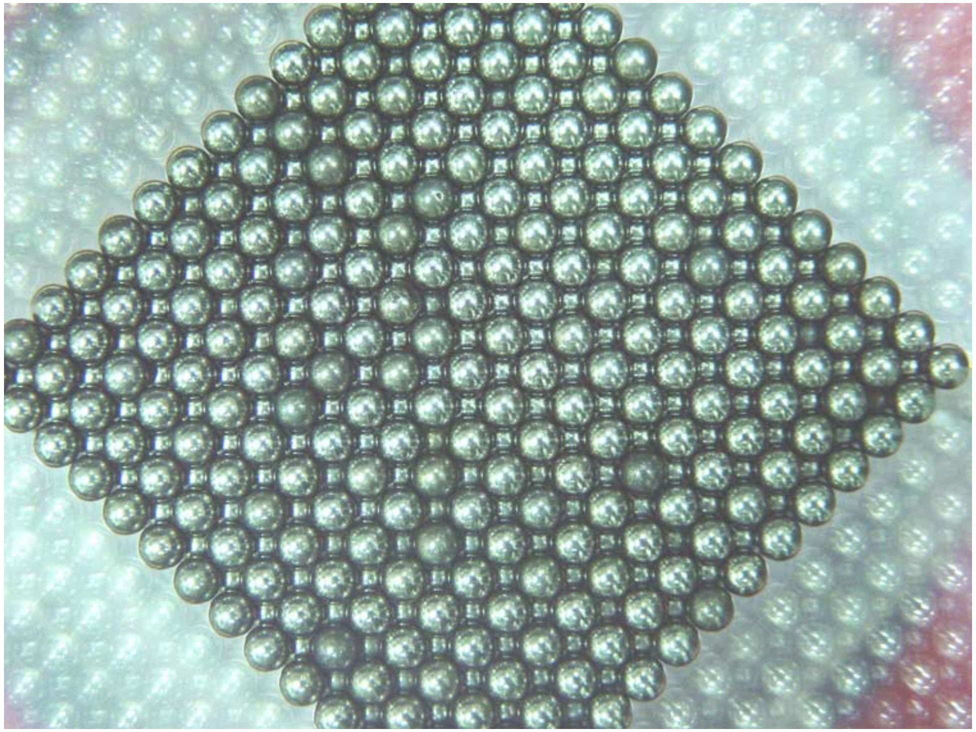
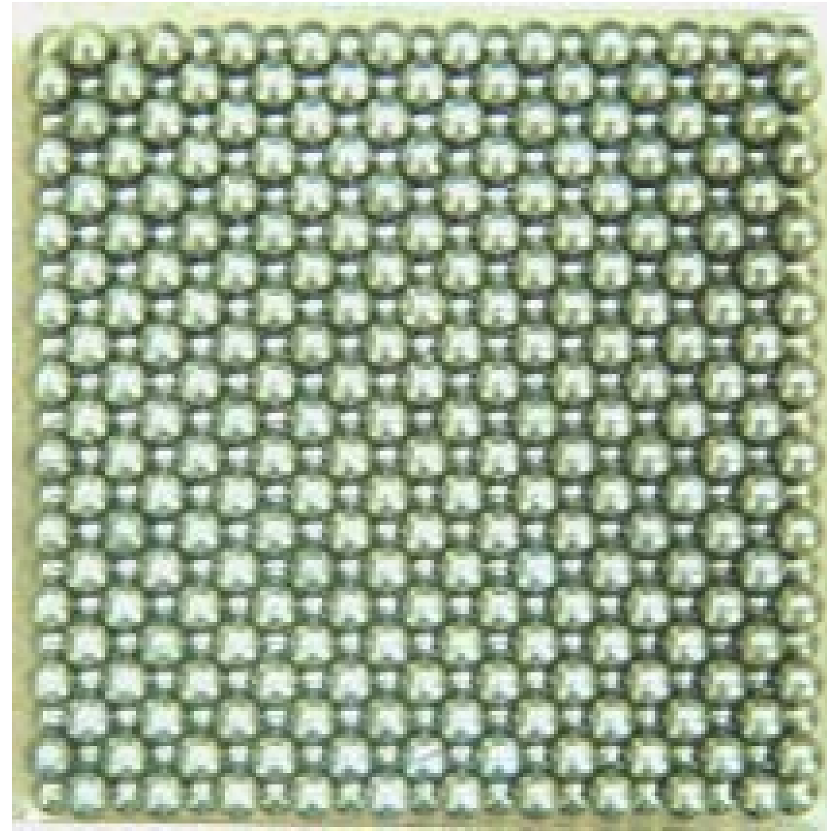


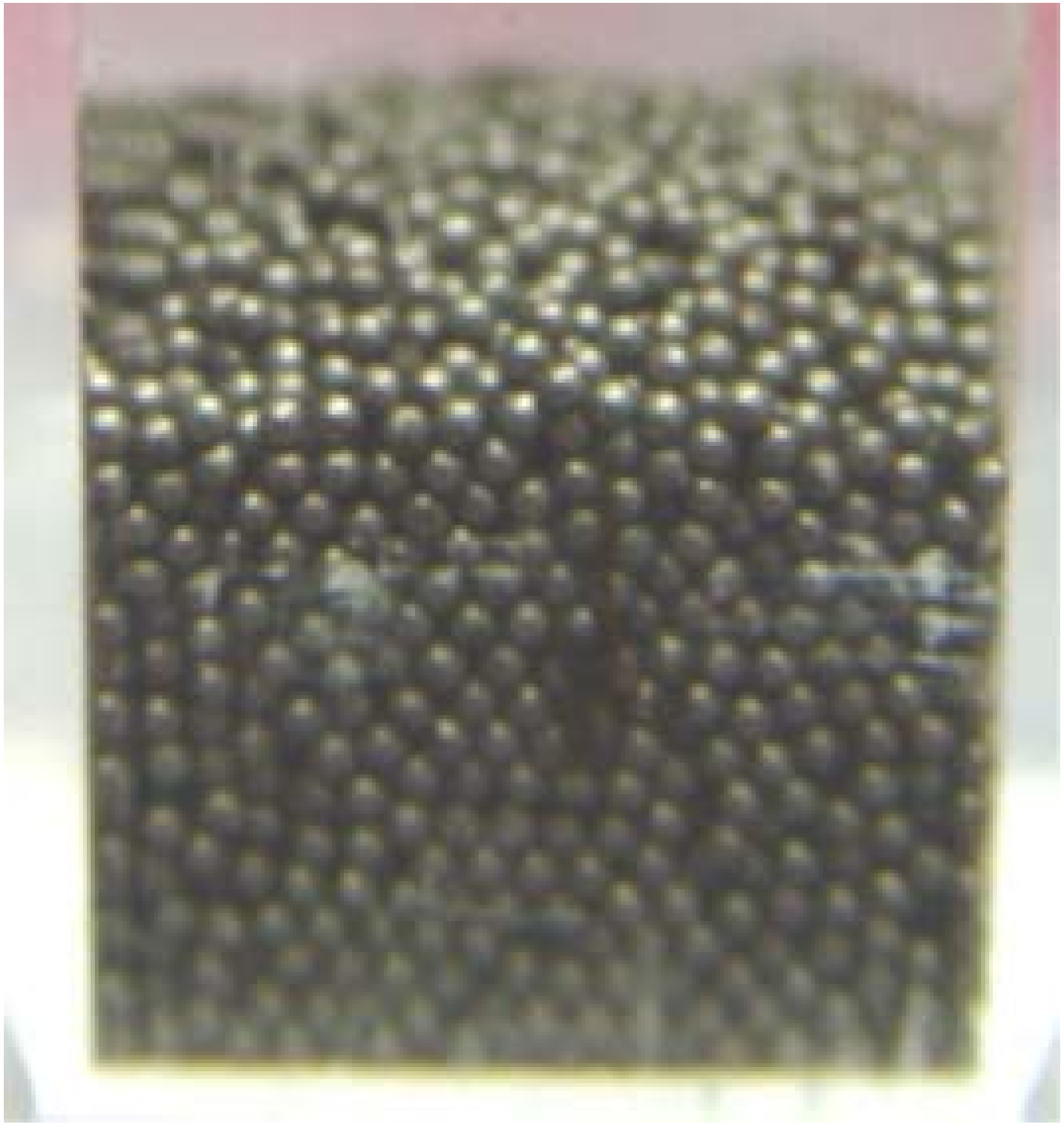
FCC → FCC-45

Melting-Annealing







Applications

- Photonic crystals ($\lambda \approx$ mm´s)
- Acoustic crystals
- Model systems to study stress propagation
- Methods for packing or storage.

Conclusions

•It is possible to avoid the glassy state in a granular hard-sphere system by means of an annealing method.

•Dissipation and gravity drive the crystallization process.

•Commensurability and confinement are important . The shear produced by close walls during annealing gives place to different crystal packings.