Mini-Colloquium

Soft Matter and Self-Assembly

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(This talk will be posted on my website under the “Research” page)
Outline

• Introduction to **Soft Matter**

• **My research** on soft matter
  – Recent works
  – Future projects

• Introduction to **Self-Assembly**

• **My research** on self-assembly
  – Recent works
  – Future projects

• Welcome to **joining my group**!
  – Expectations on students
  – What I will offer you
What Is Soft Matter?

• “Condensed matter WITHOUT a periodic lattice structure”

The good old “three states of matter”

• Examples:
  — Liquids
  — Glasses (random packings of atoms)
  — Polymers (very long molecular chains)
  — Colloids (one phase dispersed in another phase. e.g. milk is liquid in liquid, smoke is solid in gas, …)

Solids without periodic lattices
Why Do We Study Soft Matter?

• Fundamentally interesting
  – Crystals are relatively well understood, BUT most materials in our daily life are not crystals
  – How do we understand, e.g., stability, transport, phase transitions, ..., when all atoms are in disordered positions?
  – More basic: where are the atoms? (how to characterize the disordered structure)
Why Do We Study Soft Matter?

• Soft Matter makes high-performance materials
  – Metallic glass
    → extremely strong materials
  – Rubber
    → extremely stretchable materials
  – Liquid crystals

• Soft matter is everywhere in Biology
What Do We Know about Soft Matter?

- A few important soft matter systems
  - Glasses
    - How are glasses formed
    - Is glass transition a true transition? Is there a universality class?

![Diagram showing temperature vs. volume for different states of matter, including crystal, supercooled liquid, and glasses 1 and 2.](image)

![Graph showing relaxation time \(\tau\) vs. temperature \(T\) with a decreasing curve from \(T_g\) to higher temperatures.](image)
What Do We Know about Soft Matter?

- A few important soft matter systems
  - Polymers
    - What do the long chains do at finite temperature?
    - How does that affect the solution? (quickly increased viscosity)
    - Solids formed from polymers: rubber, gels, ...

— Many more to list!
• Mechanical instabilities in soft matter
  – “whether you can deform it without costing energy”
  – Most soft matter are “soft” (easily deformable)
  – Even glasses have “floppy modes”
  – Mechanical instability plays a key role at the formation of solid state soft matter

Solid with mechanical stability     Liquid without mechanical stability
The Isostatic Point

• How to characterize mechanical instability?
• Maxwell’s counting argument:
  \# of floppy modes = \# of degrees of freedom - \# of constraints
• Isostatic point:
  \# of degrees of freedom = \# of constraints
  onset of mechanical stability

Example: central-force square lattice
  \[ z = 4 = 2d \]
Transitions at Isostaticity

ISOSTATIC POINT

Metallic glasses

Colloidal glasses

Granular matter

Foams

Emulsions

Fiber networks

Network glasses
One Recent Work

• How can we make an unstable system gain mechanical stability (disordered)

• Approach: lattice models with weak disorder
  – Analytic theory with controlled approximations, exact solutions
  – Two examples
Central-force square lattice
- Floppy modes with open boundary condition
- Floppy modes with periodic boundary condition
- Addition of random NNN bonds → remove floppy modes

- Effective medium theory + simulation
- Phonon Density of States

Debye DOS for homogeneous media
\[ D(\omega) \sim \omega^{d-1} \]

Floppy modes at \( \omega = 0 \)
The Central Force Isostatic Point

• Agreement with real disordered systems

Nuclear inelastic scattering measurement of DOS of real glass

Chumakov et al., PRL 106 225501 (2011)
The Isostatic Point with Bending Forces

- Bending forces: more constraints
- Adding weak bending forces to a central force model: crossover

The Isostatic Point with Bending Forces

The cytoskeleton


Felt

Paper

Multiwalled carbon nanotube buckypaper
Summary of Our Research on Isostaticity

- Ordered
  - Kagome, Square
  - Twisted kagome
- Disordered
  - Jamming
  - Rigidity percolation

- Non-topological
- Topological
- Mean-field
- Non-mean-field

- Sierpinski triangle
- Penrose tilings
Future Projects on Soft Matter

Understand mechanical instability in presence of thermal fluctuations

Real experiments are done at finite temperature

\[ T \]

\[ K \]

Instability to other structures

Stable structure

Isostaticity, Mechanical instability, Floppy modes...

Inter-particle potential, Pressure, Density, External field...
Future Projects on Soft Matter

• Novel materials based on isostaticity

- Bulk modulus
  \[ B = 0 \]

- Poisson’s ratio
  \[ \sigma = \frac{B - G}{B + G} = -1 \]

• Negative Poisson’s ratio
• Holographic control

Potential value in materials science

Sun, Souslov, Mao, and Lubensky, PNAS, 109, 12369 (2012)
Future Projects on Soft Matter

General classification of structures near the isostatic point
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What is Self-Assembly?

Bottom up approach to produce new materials

Spontaneous formation of ordered structures
Why Do We Study Self-Assembly?

- Easy way to produce large samples (in contrast to “Top down” approaches)
- Help us to understand how nature put itself together!
Categories of Self-Assembly

- Molecular self-assembly: chemistry, nano-technology
Categories of Self-Assembly

- Colloidal self-assembly: soft matter


Mao, Chen, & Granick, accepted by *Nature Materials*.
Categories of Self-Assembly

- Macroscopic self-assembly: mechanical engineering

Images: Whiteside group
Our Recent Work

• Open structures

Simple examples of open periodic lattices:

- kagome
- honeycomb
- diamond

Why it is interesting

- Structural Openness
- Controllable Flexibility
- Functions
Our Recent Work

- Open Lattices

- Applications in materials science
  - Photonics
  - Porous medium, catalyst

- Theoretical interest: floppy modes
  - Structural phase transitions
  - Negative thermal expansion
  - Negative Poisson ratio
  - Edge states

- Why it is difficult?

\[
\begin{align*}
kagome & : z = 4 = 2d \\
honeycomb & : z = 3 < 2d \\
diamond & : z = 4 < 2d = 6
\end{align*}
\]
Janus Particles and Degenerate Valency

- **Restore stability through thermal fluctuations?**
- **Janus particles:** *easy to realize in experiments*

![Janus particles](image)

- **Degenerate valency**
  - *no direct addition of constraints*

Collaborators: Steve Granick’s group at University of Illinois at Urbana-Champaign
Degenerate Ground States

Kagome

Twisted kagome

Roman mosaic

Hexagonal


Mao, Chen, and Granick, accepted by *Nature Materials*.
Preliminary Results: Rotational Entropy

\[ \Delta \alpha = \left( \alpha - \alpha' \right)/2 \]

Floppy modes lifted to finite free energy

Mao, Chen, and Granick, accepted by *Nature Materials.*
Comparison with Experiment

- Bond-angle bending stiffness in lattice dynamics: \( \kappa = \frac{k_B T}{(\phi - 30^\circ)^2} \)
- Mode Structure:

Overlap with floppy modes: \( \langle \psi | \psi_0 \rangle \) 0 0.5 1

Mao, Chen, and Granick, accepted by Nature Materials.
Degenerate Ground States

120°

Kagome

Twisted kagome

Roman mosaic

Hexagonal

120°
Preliminary Results: Vibrational Entropy

Calculate free energy via Harmonic lattice dynamics

Floppier structure enjoys more vibrational entropy

Degenerate Valency

Selection of Open Structures

\[ \kappa = \frac{k_B T}{(\phi - 30^\circ)^2} \]

Central force spring const. between NN pairs

Mao, Chen, and Granick, accepted by Nature Materials.
Preliminary Results: Phase Diagram

Kagome

Hexagonal

Rotational entropy

Mechanical stability

Vibrational entropy

Excess patch-size

Selection of Open Lattices

Mao, Chen, and Granick, accepted by *Nature Materials.*
Future Projects

Guidelines for 3D self-assembly
Future Projects

Controllable transitions of assembled structures → smart materials

(a)

Low $B$ field: $\pi$ rotation symmetry positive Poisson’s ratio, open photonic band-gap

(b)

High $B$ field: broken $\pi$ rotation symmetry negative Poisson’s ratio, closed photonic band-gap
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What Do I Expect on Students?

• Enthusiastic about research interest in physics, future career path, ...
• Willing to work hard on difficult problems
• Previous training: statistical mechanics, solid state physics, etc
  – Analytical theory: field theoretical tools
  – Numerical simulations
What Do I Offer?

• My best effort to support students
• Help you to become **independent** in research
  – Good taste: “what problems should I work on?”
  – Deal with difficult problems: take many approaches + don’t give up too easily!
  – Skills you need to “sell your ideas”: presentations, writing papers, ...
  – Fresh experiences on career

**My general strategy:** try to be **ahead of the market**!
Thank You!