Understanding Condensed Matter at Extreme Conditions: by Integrating Dynamic and Static Compression Methods

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Outline

• Extreme states of matter and dynamic compression
• Time-dependence and multiscale measurements
• Shock wave compression – recent highlights
• New developments in dynamic compression
• Unique role of static compression measurements
• Concluding remarks
States of Matter (Holmes, LLNL)
Features of Shock Wave Compression

- Pressure Range: 10 Kbar - 100 Mbar
- Time Scales: 100 fs - 10 μs
- Directionality of loading
- Non-isotropic loading
- Large temperature rise (after thermal equilibration)
- Nonlinear coupling between wave propagation and material response

Supersonic disturbance causing near-discontinuous changes in density, internal energy, particle velocity
Time-Dependent Material Response

- Material Phenomena
  - Phase changes
  - Inelastic deformation
  - Spall or tensile failure
  - Chemical reactions
- Loading Conditions
  - Temporal relevance
- Real-Time Measurements
  - Resolution and duration

Incorporation of time-dependent response in shock wave propagation has 40 plus years of history at WSU
Measurements at Different Scales

- **Continuum Scale**
- **Mesoscale**
- **Microscale**
- **Atomic/Molecular Scale**
Shock Compression – Time Dependence

Freezing of Water

D. Dolan, Ph.D. Thesis

M. Knudson, Ph.D. Thesis
Shock Compression (Knudson, Sandia)

Aluminum Data

Cumulative HE systems

Nuclear driven

Gas gun limit

Shock Compression (Collins et al., LLNL)

**Figure 1:**

- **Top Graph:**
  - X-axis: Density (g/cc), Y-axis: Pressure (GPa)
  - Various lines and data points indicating experimental and model data.

- **Middle Graph:**
  - X-axis: Particle Velocity (km/s), Y-axis: Shock Velocity (km/s)
  - Lines and data points showing different materials:
    - Sapphire
    - LiF
    - Quartz
    - Aluminum (U_s - 2)
  - Pressure markers (Mbar) at various velocities.

- **Bottom Graph:**
  - X-axis: Temperature (K), Y-axis: Reflectance
  - Lines showing reflectance data for fused silica and quartz.
  - Inset graph showing pressure dependence of reflectance.

**Text:**

Shocked Silica becomes more compressible and an electronic conductor above 1 Mbar.
Dynamic Compression – New Developments

- Magnetic launch – 34 km/s; expected to be 45-50 km/s in the future
- Laser shocks – tens of Mbar; Gbar on NIF
- Precompressed samples (DAC) subjected to laser shocks
- Ramp wave loading (rise times ~ tens to hundreds of ns)
Why Ramp Wave Loading?

- Shock compression produces high-pressure, high-temperature states
- Quasi-isentropic compression produces high-pressure, low-temperature states

HED facilities explore ultra-high pressure properties of materials

(Jim Asay)

(G. Collins)
Ramp Wave Loading -- Challenges

- Analysis of unsteady wave data
- Evolution into a shock wave
- Simulations of unsteady waves require care

(Jim Asay)
Novel properties of extended solids (Yoo, LLNL)

**Optical nonlinearity**
- During and after polymerization
  - CO$_2$-III
  - CO$_2$-V

**Superhard**
- High energy density
  - Polymeric CO

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<tr>
<th>Solids</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$B_0$ (GPa)</th>
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<tr>
<td>Diamond</td>
<td>3.50</td>
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<td>$\delta$-N$_2$</td>
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Mbar chemistry to exotic states (Yoo, LLNL)

Pressure-induced electron delocalization

Strong disparity in bonding results in a huge kinetic barrier (metastability); new opportunities for synthesis of exotic materials
Concluding Remarks – Looking Ahead

• Comprehensive approach to address scientific needs
  – Shock waves: compression, deformation, temperature, time
  – Ramp waves: separation of compression, temperature, loading rates
  – Static pressure: separation of compression, temperature, deformation
  – Theory/computations: provide insights at different length scales

• Need to integrate dynamic and static compression efforts more effectively

• How to carry out dynamic experiments routinely at facilities like CHESS, APS, and LCLS (to take advantage of diagnostics)?

The next twenty years in high pressure science promise to be exciting