Elastic properties of hidden order in URu_2Si_2 are reproduced by staggered nematic order

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URu_2Si_2 is a heavy fermion material with a continuous transition into a 'hidden order' (HO) phase whose broken symmetry is unknown. Under sufficient pressure it instead transitions into an antiferromagnet (AFM), with phase diagram in Fig. 2(a). It also has a superconducting phase within HO that is destroyed by AFM.

The modulus tensor of URu_2Si_2 anomalously softens over several hundred Kelvin and is cut off by the HO transition, seen in Fig. 3(b). **We show that only one order parameter symmetry is consistent with this softening and the topology of the phase diagram.** This choice reproduces other URu_2Si_2 phenomena and motivates new experiments.

Resonant ultrasound spectroscopy & irreducible strains

Resonant ultrasound spectroscopy drives a sample with sound and measures its resonances by looking for peaks in the response. Using the sample geometry and the location of sufficiently many resonances, the modulus tensor C—which gives the energetic cost of strain—can be calculated. **The structure of the modulus tensor and its temperature dependence yield a lot of information about symmetry breaking.**

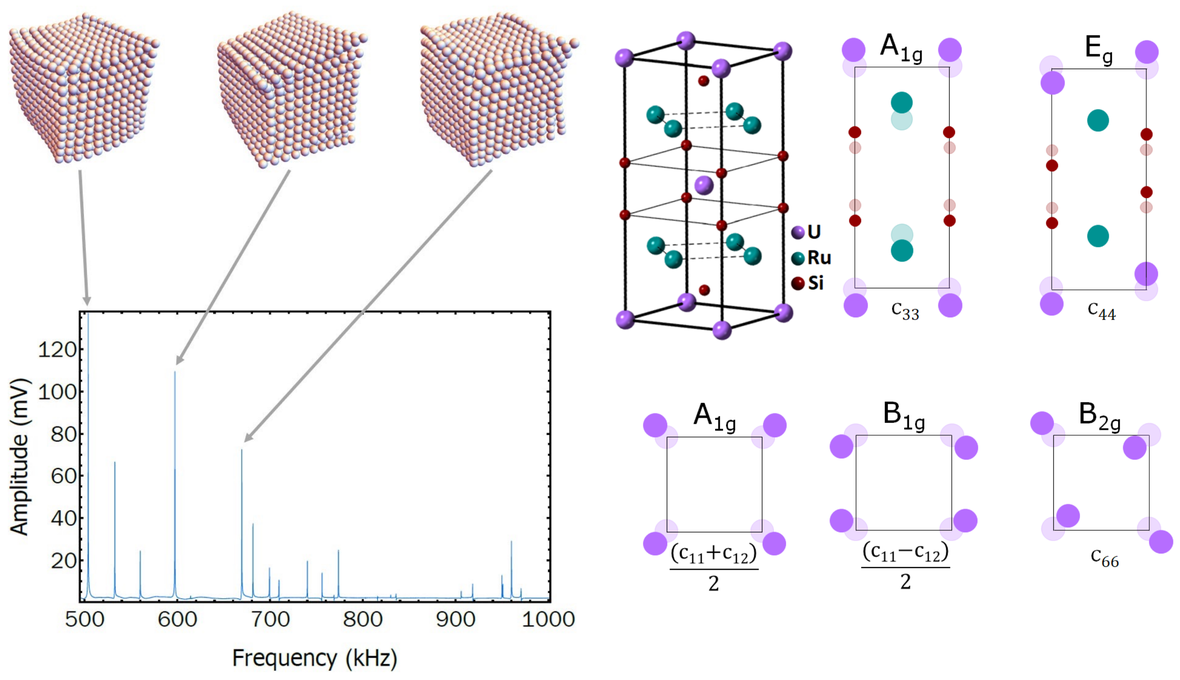

Figure 1: Left: Response versus driving frequency for a sample at some temperature. The spikes correspond to resonances, and the strains corresponding to a few dominant modes are depicted in the cartoons. **Right:** The crystal structure of URu_2Si_2 and the influence of the irreducible strains of D_{4h}.

The strain tensor ϵ has six independent components. These components can be divided into tuples that symmetry transformations of the crystal act on with irreducible representations (irreps) of its point group. **URu_2Si_2's point group D_{4h} yields five 'irreducible' strains, shown in Fig. 1.** Four are one-tuples (single-component). These are uniform compression in and out of the plane (A_{1g}) and in-plane shear along the faces and diagonals of the unit cell (B_{1g} and B_{2g}). One is a two-tuple (multi-component), and corresponds to out of plane shears (E_g).

Landau theory

The free energy must be invariant under symmetry transformations. This constrains the way fields can couple together. Two fields can linearly couple only if they correspond to the same irrep. Higher order couplings lead to thermodynamic discontinuities but not diverging responses. **The anomalous softening of URu_2Si_2 in Fig. 3(b) suggests the hidden order parameter couples linearly to strain.**

An A_{1g} order parameter results in first-order transitions and can't describe hidden order. If the order parameter η corresponds to any of the remaining irreps X present in strain, the free energy is $f = f_{\text{ELASTIC}} + f_{\text{INT}} + f_{\text{OP}}$, where

$$f_{\text{ELASTIC}} = \sum_{\text{X}} C^0_{\text{X}} \epsilon_{\text{X}} \epsilon_{\text{X}} \qquad f_{\text{INT}} = -b \epsilon_{\text{X}} \eta$$
$$f_{\text{OP}} = \frac{1}{2}\left[r\eta^2 + c_\parallel (\nabla_\parallel \eta)^2 + c_\perp (\nabla_\perp \eta)^2 + D_\perp (\nabla^2_\perp \eta)^2 \right] + u\eta^4 \tag{1}$$

The strain ϵ can be traced out exactly, which results in a free energy density with the form of f_{OP} but with $r \to \tilde{r} = r - b^2/2C^0_{\text{X}}$.

This theory has a *Lifshitz triple point* at $\tilde{r} = c_\perp = 0$. The three phases that meet are

- unordered ($\eta = 0$)
- uniform ($\eta \neq 0$)
- modulated ($\eta \propto \cos q_* x_3$)

Phase diagrams are in Fig. 2(b–c). The order of the transition between the uniform and modulated phases depends on the number of order parameter components: one-component theories have a first order transition while two-component theories are continuous. **The only order parameter irreps consistent with the first order transition between HO and AFM in URu_2Si_2 are B_{1g} and B_{2g}.**

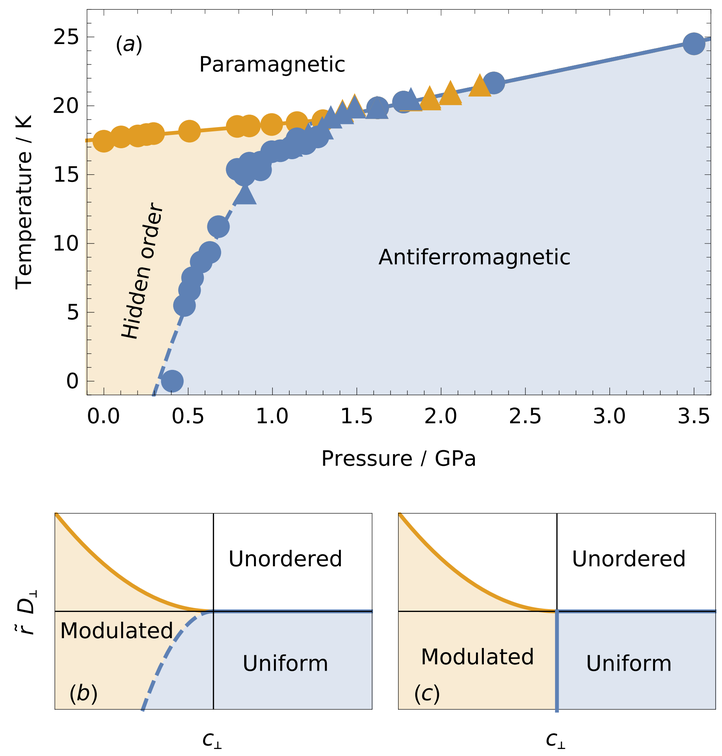

Figure 2: Phase diagrams for (a) URu_2Si_2 from Phys Rev B **77** 115117 (2008) (b) theory for a one-component order (B_{1g} or B_{2g}) (c) theory for a two-component order (E_g). Solid lines denote continuous transitions, while dashed denote first order.

Anomalous modulus response

The modulus C can be calculated like any other response function. Approaching the modulated phase, the modulus with the symmetry irrep X of the order parameter is

$$C_{\text{X}} = C^0_{\text{X}} \left[1 + \frac{b^2}{C^0_{\text{X}}} \left(D_\perp q_*^4 + |\Delta \tilde{r}| \right)^{-1} \right]^{-1} \tag{2}$$

At the critical point the modulus with the symmetry of the order parameter has an inverted cusp. Compared with experiments, this doesn't resemble the B_{2g} modulus in Fig. 3(a) but fits the B_{1g} modulus in Fig. 3(b). **This suggests hidden order is a B_{1g} nematic modulated along the *c*-axis.**

This theory explains the presence of the 0.4–0.5 inverse lattice constant scattering peak seen in some experiments and is consistent with B_{1g} symmetry breaking observed in the AFM phase. RUS experiments at pressure might resolve the divergence of the modulation wavevector q_* and the vanishing of the B_{1g} modulus at the Lifshitz point.

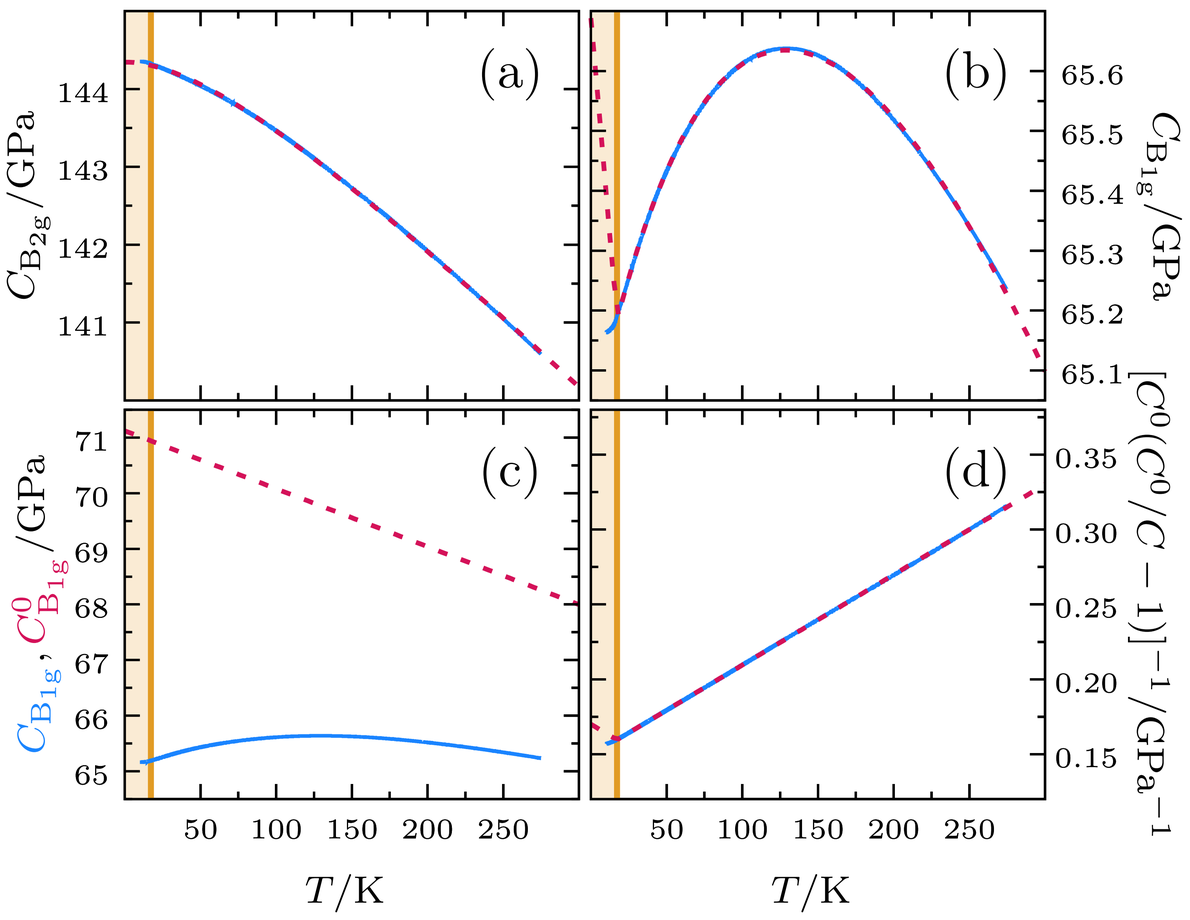

Figure 3: RUS measurements of URu_2Si_2's moduli as a function of temperature from `arXiv:1903.00552 [cond-mat.str-el]` (blue, solid) alongside fits to this theory (magenta, dashed). The solid yellow region shows the HO phase. (a) B_{2g} modulus data and a fit to standard form. (b) B_{1g} modulus data and a fit to (2). (c) B_{1g} modulus data and the fit of the *bare* B_{1g} modulus. (d) B_{1g} modulus data and fit transformed in way predicted from (2) to be an absolute value function.