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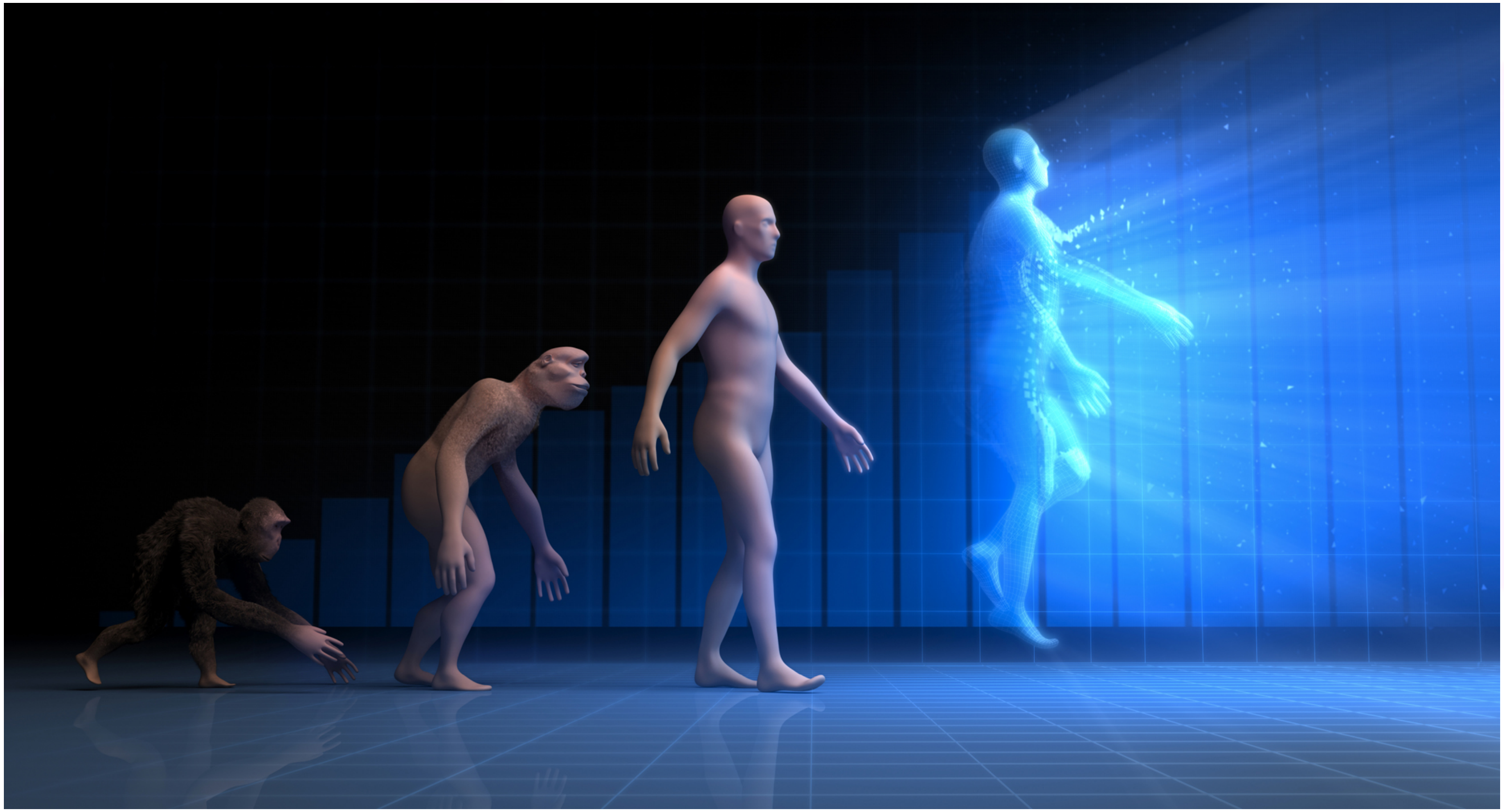

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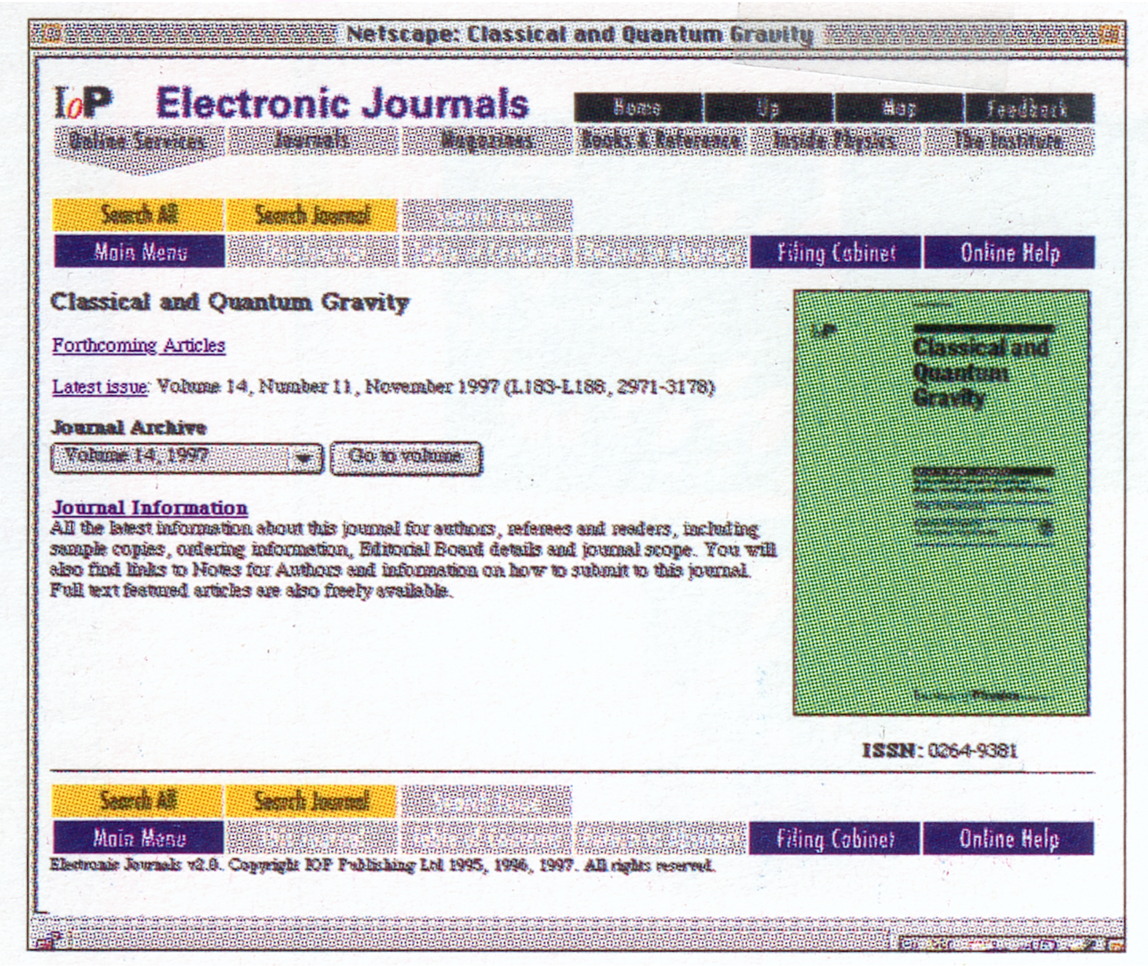

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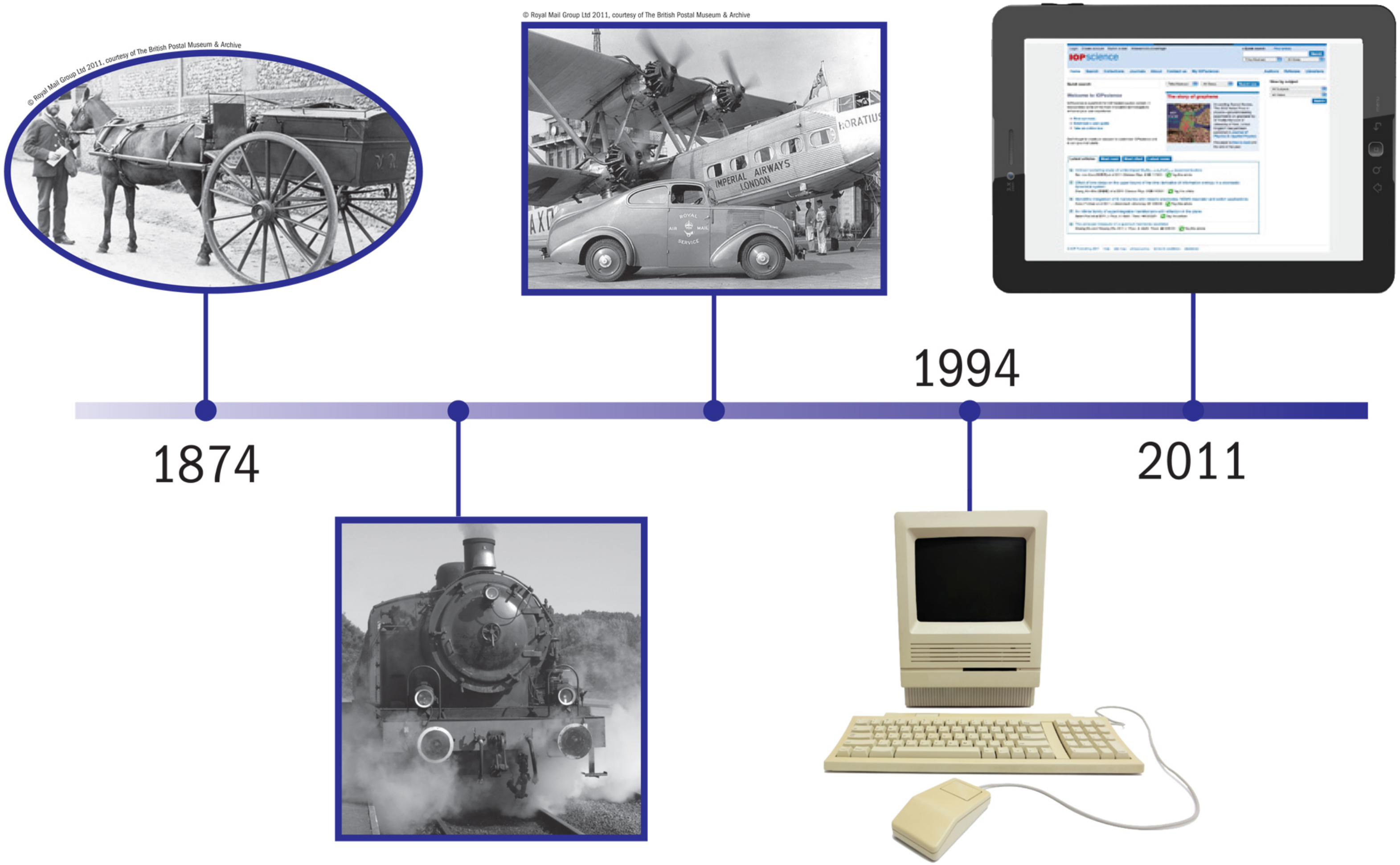

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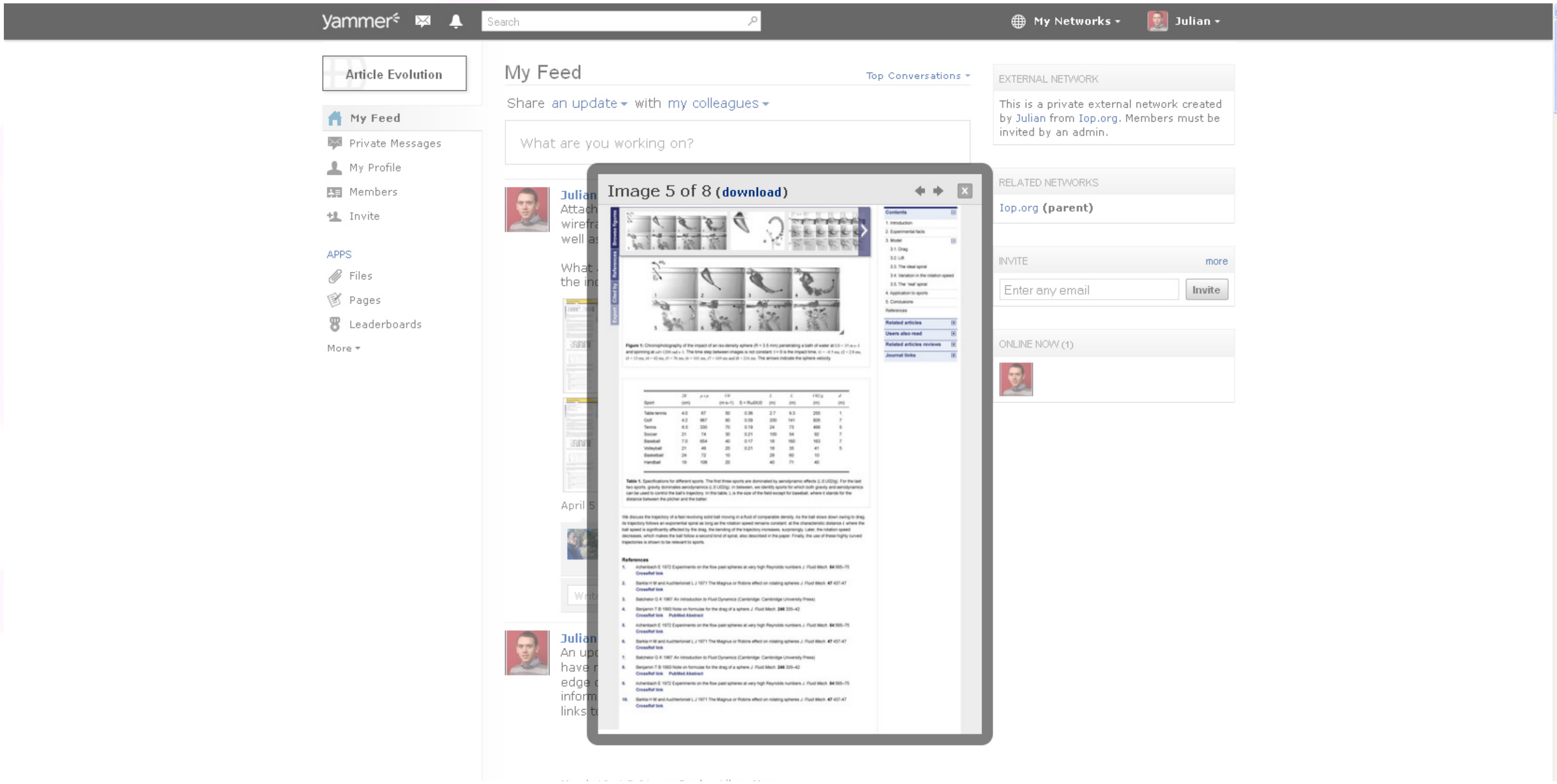

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The phase diagram for coexisting d-wave superconductivity and charge-density waves: cuprates and beyond

Toshikazu Ekino[1], Alexander M Gabovich[2], Mai Suan Li[3], Marek Pękała[4], Henryk Szymczak[3] and Alexander I Voitenko[2]

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Toshikazu Ekino *et al* 2011 *J. Phys.: Condens. Matter* **23** 385701
doi:10.1088/0953-8984/23/38/385701
Received 11 April 2011, in final form 15 July 2011
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Abstract

Phase diagrams of d-wave superconductivity characterized by an order parameter Δ coexisting with charge-density waves (CDWs) characterized by an order parameter Σ were constructed for the two-dimensional Fermi surface (FS) appropriate to, e.g., cuprates. CDWs were considered as an origin of the pseudogap appearing at antinodal FS sections of the $d_{x^2-y^2}$ superconductor. Two types of the Σ-reentrance were found: with the temperature, *T*, and with the opening of the CDW sector, 2α. The angular plots in the momentum space for the resulting gap profile over the FS ('gap roses') were obtained. The gap patterns are rather involved, giving insight into the difficulties of the interpretation of photoemission spectra. It was shown that the Σ–Δ coexistence region exists even for the complete dielectric gapping due to the distinction between the superconducting and CDW order parameter symmetries. The checkerboard and unidirectional CDW configurations were examined, and both the phase diagrams and the behavior with *T* and α of the order parameters were found to differ. A more general case with a non-zero mismatch angle β between the superconducting lobes and the CDW sectors was analyzed, the case β = π/4 corresponding to the d_{xy} symmetry of the superconducting order parameter. The phase diagrams were found to be sensitive to β-variations, showing that internal strains and external pressure can drastically affect the behavior of Σ(*T*) and Δ(*T*).

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1. Introduction

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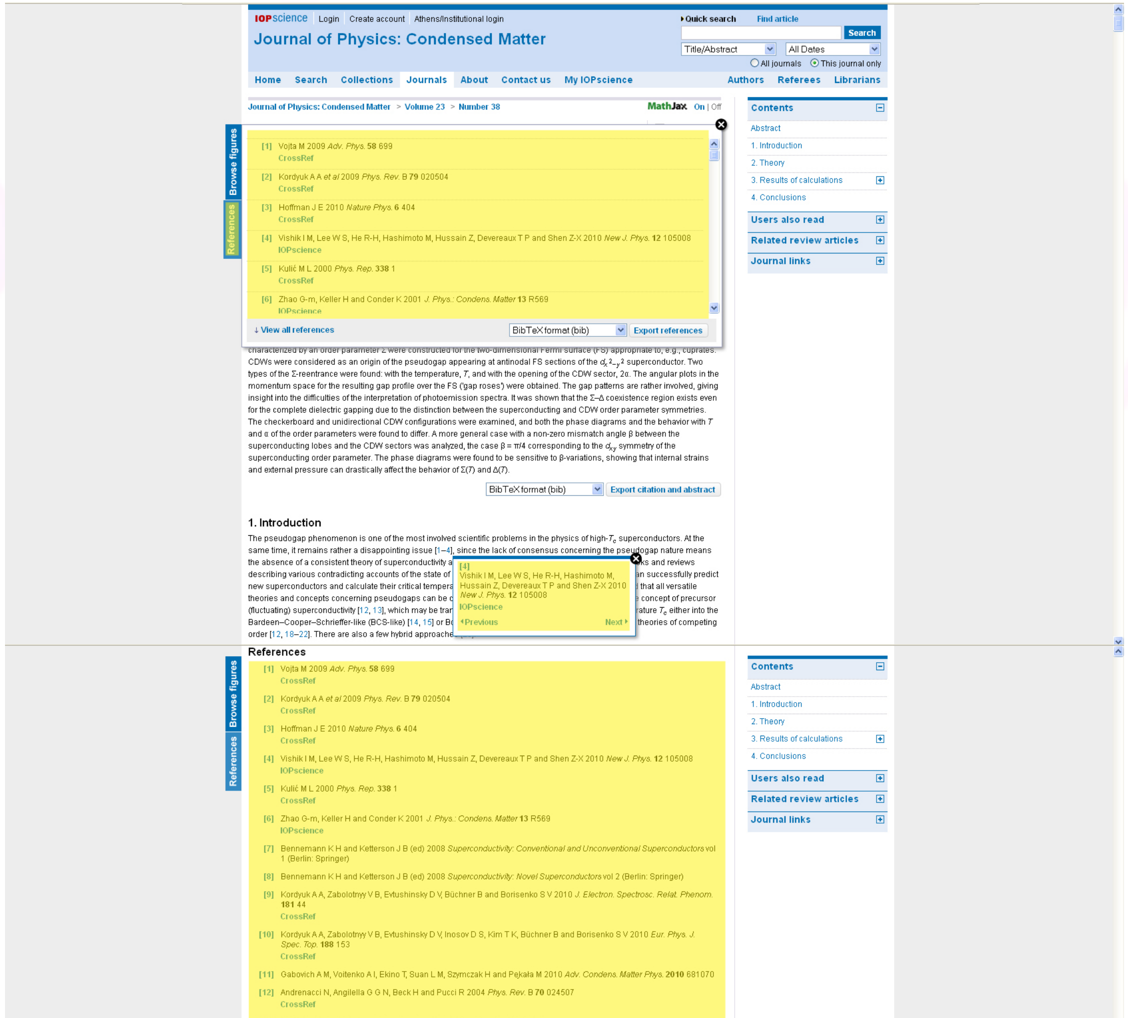

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Toshikazu Ekino[1], Alexander M Gabovich[2], Mai Suan Li[3], Marek Pękała[4], Henryk Szymczak[3] and Alexander I Voitenko[2]

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1. Introduction

The pseudogap phenomenon is one of the most involved scientific problems in the physics of high-T_c

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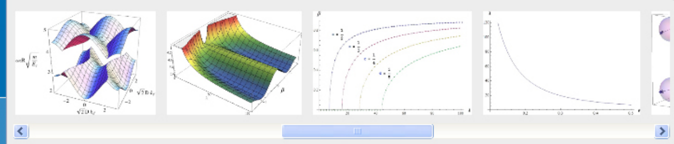

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3.2. Quantum phase transition

It is not *a priori* obvious what will happen in the quantum mechanical case at zero temperature, since the quantum confinement introduces a new energy scale. Rather than solve for the variational ground state of an $N \times N$ system directly, it was assumed that the quantum ground state would possess the same symmetry as the classical system, so that only a 2 × 2 unit cell of an (assumed) infinite system was analyzed. This has the advantage of following the correspondence principle as $\lambda \to \infty$. A plot of the variational energy for $\epsilon = \frac{1}{2}$, reveals that, at small values of the coupling constant, λ, a single minimum exists, figure 6. This minimum corresponds to β = 0, i.e. a uniform distribution for the electronic wavefunction. As λ increases past a critical value, two new minima emerge at $\beta = \pm\frac{\pi}{4}$, indicating a quantum phase transition. These values correspond to charge localizing normal to the plane. Furthermore, nearest neighbors polarize in opposite directions.

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Figure 6. A plot of the energy functional from the quantum variational calculation for the 2D square lattice. Here, $\epsilon = \frac{1}{2}$, thus the ratio of shell radius to separation is at a maximum (the close-packed condition). A single minimum for small values of the coupling constant, λ, occurs at β = 0, where β is the mixing parameter found in the variational wavefunction. This state corresponds to a uniform charge distribution. As λ increases, two minima emerge at $\beta = \pm\frac{\pi}{4}$. These values correspond to charge localizing normal to the plane of the lattice.

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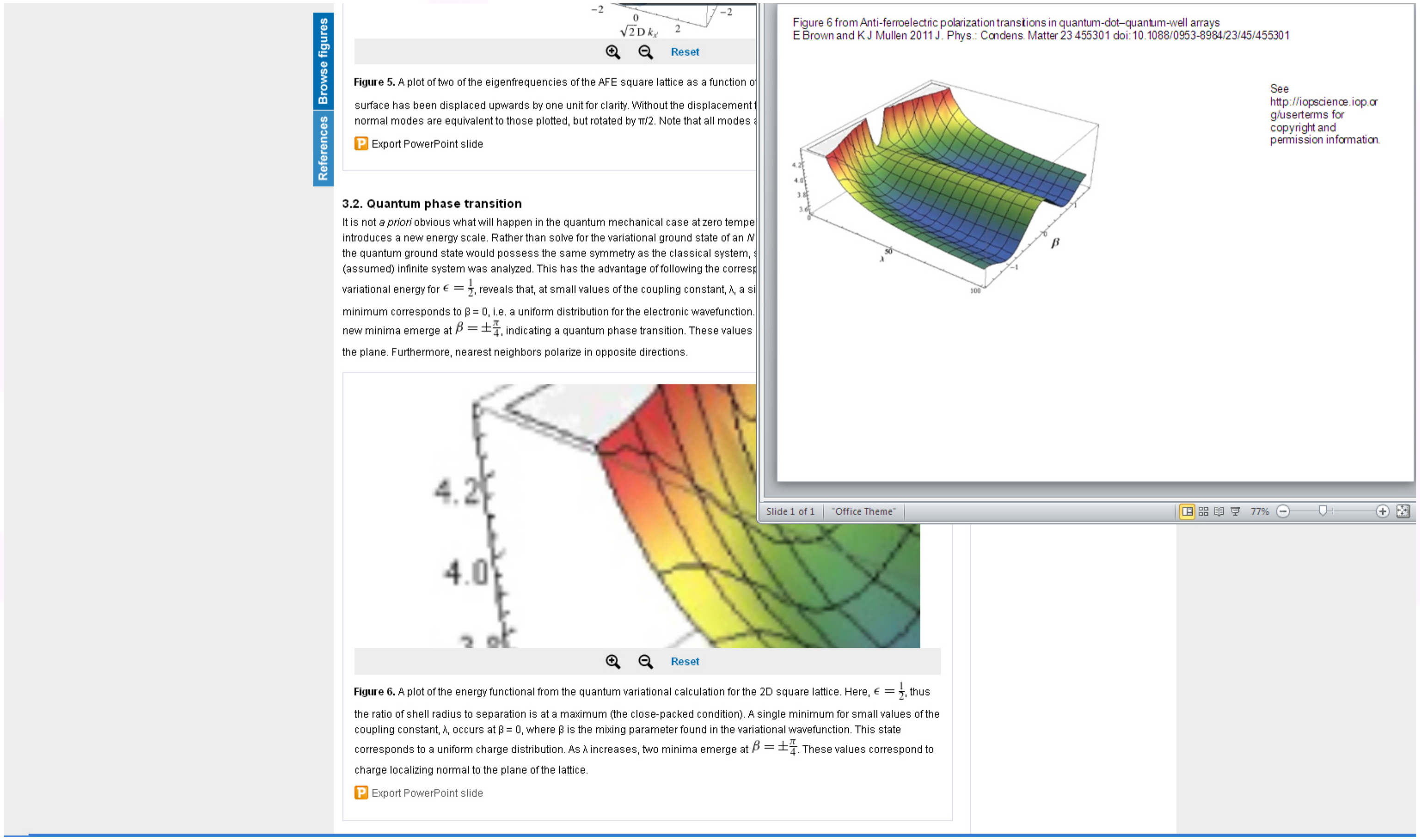

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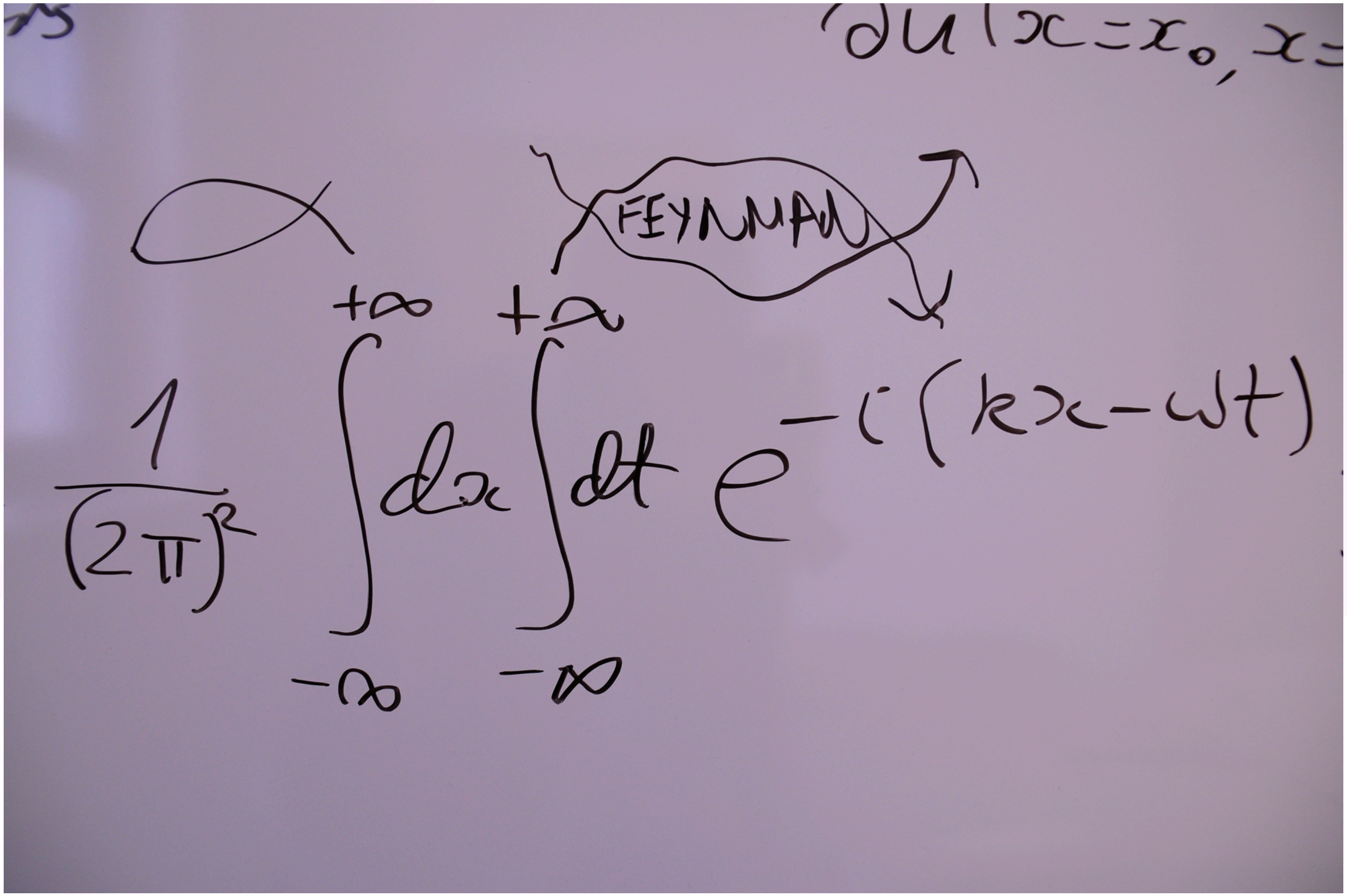

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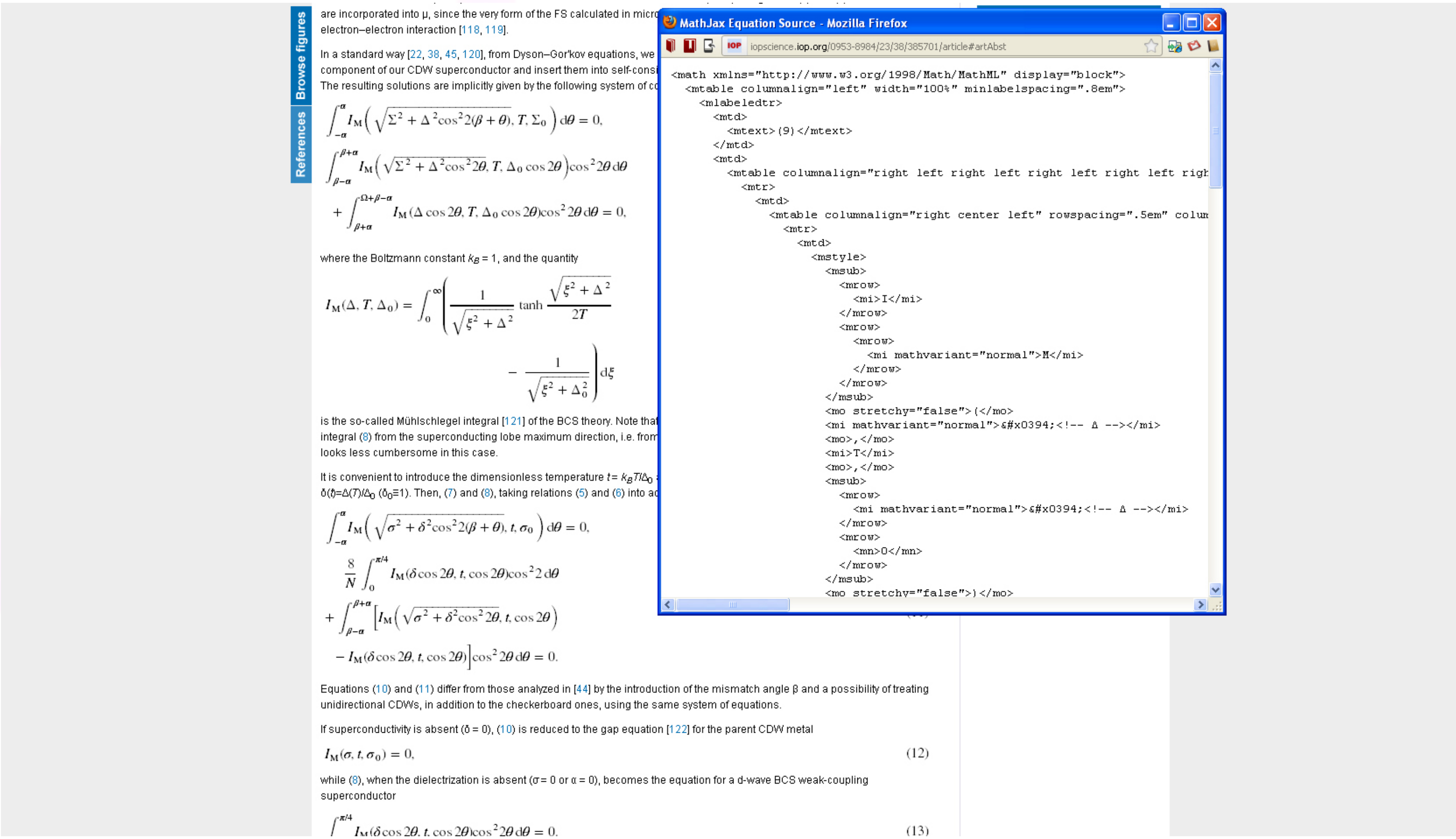

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are incorporated into μ, since the very form of the FS calculated in micro… electron–electron interaction [118, 119].

In a standard way [22, 38, 45, 120], from Dyson–Gor'kov equations, we … component of our CDW superconductor and insert them into self-consi… The resulting solutions are implicitly given by the following system of c…

$$\int_{-\alpha}^{\alpha} I_{\mathrm{M}}\left(\sqrt{\Sigma^2+\Delta^2\cos^2 2(\beta+\theta)}, T, \Sigma_0\right) \mathrm{d}\theta = 0,$$

$$\int_{\beta-\alpha}^{\beta+\alpha} I_{\mathrm{M}}\left(\sqrt{\Sigma^2+\Delta^2\cos^2 2\theta}, T, \Delta_0\cos 2\theta\right)\cos^2 2\theta\,\mathrm{d}\theta + \int_{\beta+\alpha}^{\Omega+\beta-\alpha} I_{\mathrm{M}}(\Delta\cos 2\theta, T, \Delta_0\cos 2\theta)\cos^2 2\theta\,\mathrm{d}\theta = 0,$$

where the Boltzmann constant $k_B = 1$, and the quantity

$$I_{\mathrm{M}}(\Delta, T, \Delta_0) = \int_0^{\infty}\left(\frac{1}{\sqrt{\xi^2+\Delta^2}}\tanh\frac{\sqrt{\xi^2+\Delta^2}}{2T} - \frac{1}{\sqrt{\xi^2+\Delta_0^2}}\right)\mathrm{d}\xi$$

is the so-called Mühlschlegel integral [121] of the BCS theory. Note tha… integral (8) from the superconducting lobe maximum direction, i.e. from… looks less cumbersome in this case.

It is convenient to introduce the dimensionless temperature $t = k_B T/\Delta_0$ … $\delta(t)=\Delta(T)/\Delta_0$ ($\delta_0 \equiv 1$). Then, (7) and (8), taking relations (5) and (6) into ac…

$$\int_{-\alpha}^{\alpha} I_{\mathrm{M}}\left(\sqrt{\sigma^2+\delta^2\cos^2 2(\beta+\theta)}, t, \sigma_0\right)\mathrm{d}\theta = 0,$$

$$\frac{8}{N}\int_0^{\pi/4} I_{\mathrm{M}}(\delta\cos 2\theta, t, \cos 2\theta)\cos^2 2\,\mathrm{d}\theta + \int_{\beta-\alpha}^{\beta+\alpha}\left[I_{\mathrm{M}}\left(\sqrt{\sigma^2+\delta^2\cos^2 2\theta}, t, \cos 2\theta\right) - I_{\mathrm{M}}(\delta\cos 2\theta, t, \cos 2\theta)\right]\cos^2 2\theta\,\mathrm{d}\theta = 0.$$

Equations (10) and (11) differ from those analyzed in [44] by the introduction of the mismatch angle β and a possibility of treating unidirectional CDWs, in addition to the checkerboard ones, using the same system of equations.

If superconductivity is absent (δ = 0), (10) is reduced to the gap equation [122] for the parent CDW metal

$$I_{\mathrm{M}}(\sigma, t, \sigma_0) = 0, \quad (12)$$

while (8), when the dielectrization is absent (σ = 0 or α = 0), becomes the equation for a d-wave BCS weak-coupling superconductor

$$\int^{\pi/4} I_{\mathrm{M}}(\delta\cos 2\theta, t, \cos 2\theta)\cos^2 2\theta\,\mathrm{d}\theta = 0. \quad (13)$$

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The role of glassy dynamics in the anomaly of the dielectric function of solid helium

Jung-Jung Su[1,2,3,4], Matthias J Graf[1] and Alexander V Balatsky[1,2]
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Abstract

We propose that the acousto-optical (electro-elastic) coupling of the electric field to strain fields localized around defects in disordered ^{4}He causes an increase of the dielectric function with decreasing temperature due to the arrested dynamics of defect excitations. A distribution of such low-energy excitations can be described within the framework of a glass susceptibility of a small volume fraction inside solid ^{4}He. Upon lowering the temperature the relaxation time $\tau(T)$ of defects increases and an anomaly occurs in the dielectric function $\epsilon(\omega,T)$ when $\omega\tau(T) \sim 1$. Since $\epsilon(\omega,T)$ satisfies the Kramers–Kronig relation, we predict an accompanying peak in the imaginary part of $\epsilon(\omega,T)$ at the same temperature that the largest change in amplitude occurs at a fixed frequency. We also discuss recent measurements of the amplitude of the dynamic dielectric function that indicate a low-temperature anomaly similar to that seen in the resonance frequency of the torsional oscillator and shear modulus experiments.

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GENERAL SCIENTIFIC SUMMARY

Introduction and background. Since the discovery of anomalous behavior of solid ^{4}He below 200 mK, it has been believed that helium enters into an exotic phase of matter—a supersolid, which is a quantum state that exhibits superflow and crystalline order at the same time. This finding revitalized the quest for supersolidity in quantum solids. At the same time, an increasing number of follow-up experiments showed that defects are critical for observing these anomalies. The central debate is then whether defects merely enhance the supersolidity phenomenon, or if they exhibit their own dynamics, which dominate at low temperatures. Addressing this question requires a thorough understanding of glassy dynamics and the dynamics of correlated defects.

Main results. We consider the effects of defects and their glassy dynamics on the dynamic dielectric function. We postulate that local defects create short-ranged strain fields that contribute to the dielectric function through acousto-optical or electro-elastic coupling. We obtain the dynamic behavior of the dielectric function anomaly whose magnitude is consistent with recent experiments. Moreover, we predict the existence of an accompanying dissipation peak, which is the signature of defects' glassy dynamics.

Wider implications. The proposed model of glassy defect dynamics successfully describes the low-temperature anomalies of solid helium. It may be further generalized to other nonconventional glass systems with frozen-in nonequilibrium configurations.

1. Introduction

The reported anomalies in resonance frequency and dissipation of torsional oscillators [1–9] and in the dynamic shear modulus [10–12] at low temperatures are the subject of intensive study as they have been suggested to be signatures of supersolidity. It is now generally agreed that disorder plays an essential role in observing these effects. The challenge in

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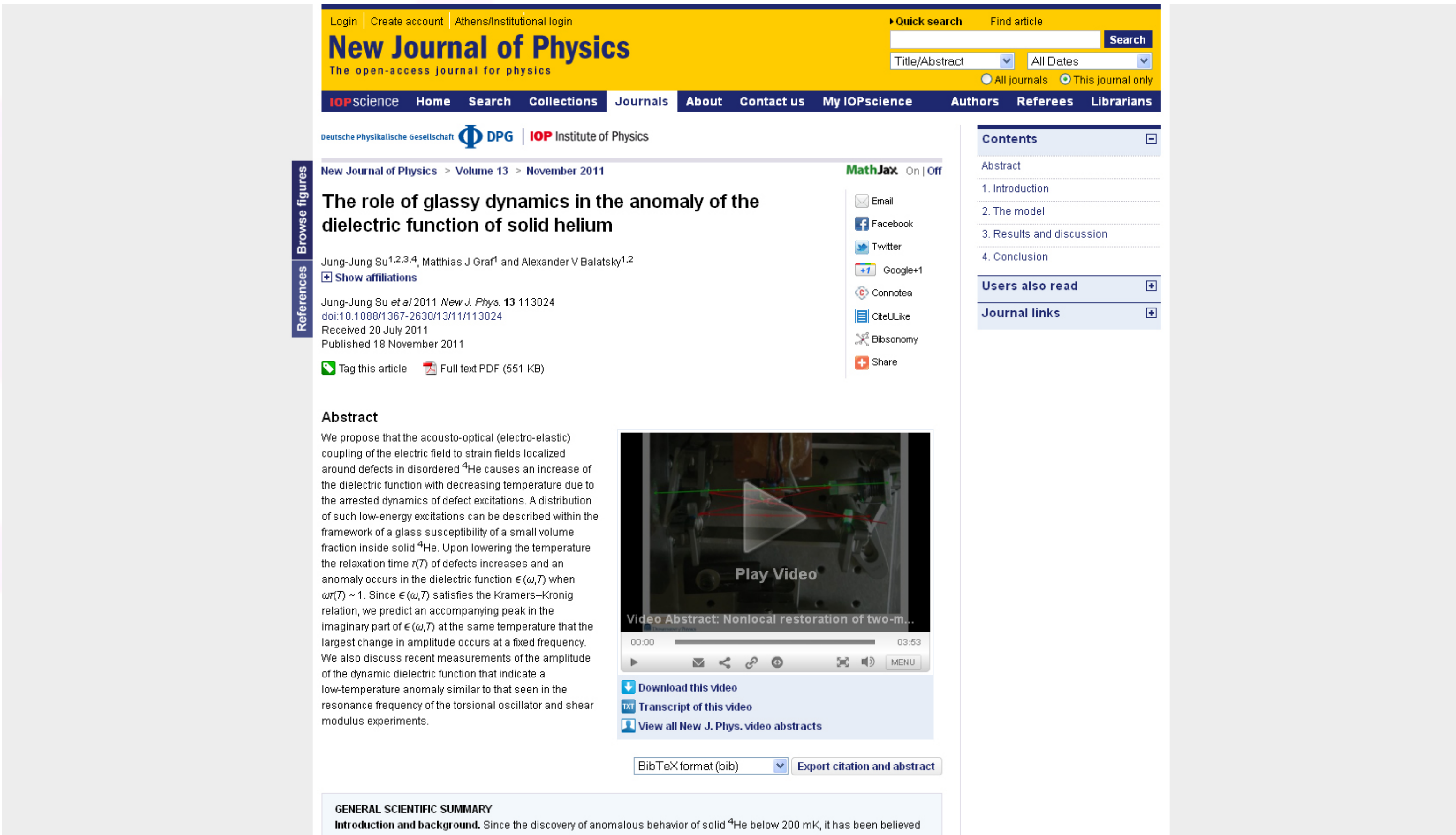

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