HALF-INTEGER COMPLEXES OF VORTICES AND DISLOCATIONS IN SPIN DENSITY WAVES

N. Kirova

Laboratoire de Physique des Solides,

CNRS & Université Paris-Saclay, Orsay, France

Collaboration:

S. Brazovskii *LPTMS, CNRS & Université Paris-Saclay, Orsay, France*

Principal points:

- Non-local elastic theory due to Coulomb interactions
- Staggered magnetization vortices and domain walls in SDW
- Combined topological defects in SDW –
  half dislocation coupled to semi-vortex
- Double core dislocation + magnetic domain wall
  for the spin-orbital coupling

Non-local elastic theory for Density Waves.

$$W = \frac{\hbar\, vF}{4\pi} \Sigma\, |\varphi_k|^2 \left[k_{\|}^2 + \alpha k_{\perp}^2 + \frac{\kappa^2 k_{\|}^2}{k_{\|}^2 + k_{\perp}^2 + rscr^{-2}]}\right]$$

$$\kappa^2 = \frac{8\pi^2\gamma}{a_{\perp}^2} = \frac{1}{r_0^2} \sim 1A; \quad \gamma = \frac{e^2}{\hbar\, vF}; \quad \alpha \sim T_c^2; \quad \frac{1}{r_{scr}^2} = \kappa^2 \rho_n$$

At distances $r >> r_{scr}$: Coulomb hardening

$$W = \frac{\hbar\, vF}{4\pi} \Sigma\, |\varphi_k|^2 \left[\alpha k_{\perp}^2 + \frac{k_{\|}^2}{\rho_n}\right]$$

$$W = \frac{\hbar v_F}{4\pi}\left[C_{\|}\left(\partial_{\|}\varphi\right)^2 + C_{\perp}(\partial_{\perp}\varphi)^2\right] + W_C + W_{str}$$

Non screened Coulomb interactions (within the screening volume)

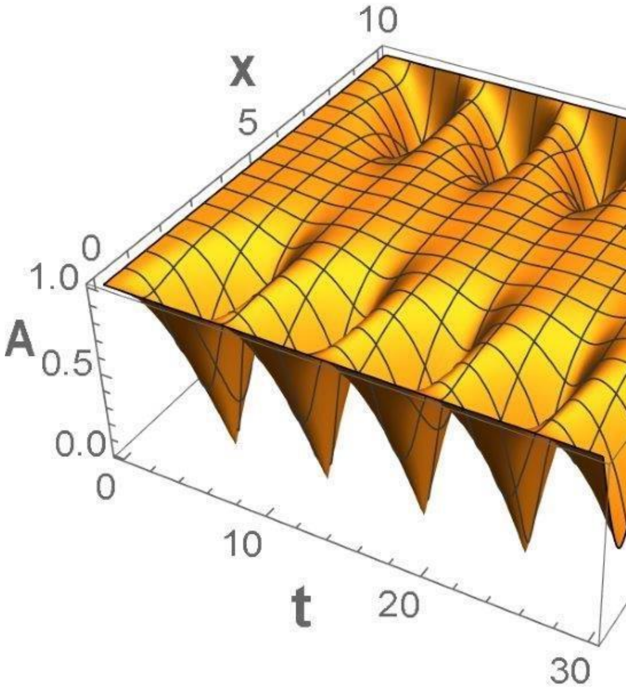
$W\{\varphi\} \sim [(\alpha/L_\perp^2)+\kappa^2 L_\perp^2 / L_{||}^2] L_{||} L_\perp^2$

Minimum over $L_{||}$ $\quad L_{||} \sim L_\perp^2 \gamma / a_\perp$

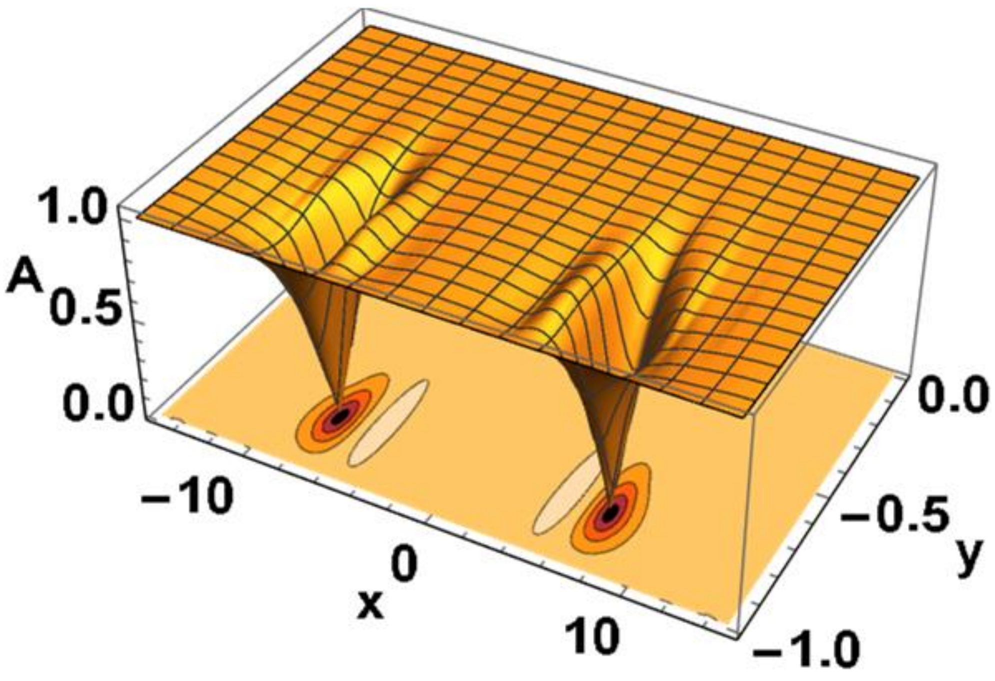
$W\{\varphi\} = \gamma E_0 N$

Not a usual perimetrical (lnN) but area law (~N)

At large distances the standard (lnN) law is restored but enhanced as $\sim\rho_n^{-1/2}$.



Phase slips sequence



Dislocations in
transverse electric field

Order parameter and allowed topological defects $\eta \to \eta$

CDW

$\eta_{CDW}=A\Delta_0\exp(i\mathbf{Qr}+\varphi)$

$\rho_{CDW}=|\eta_{CDW}|\cos(Qx+\varphi)$

- Phase vortex, dislocation, 2π translation:

  $\varphi\to\varphi+2\pi$

- Amplitude soliton : $\varphi=const$
- combined object :
- amplitude-phase soloton

$\varphi\to\varphi+\pi$, $A=-1\to A=+1$

SDW

$\eta_{SDW}=A\Delta_0\mathbf{m}\exp(i\mathbf{Qr}+\varphi)$

m is the unit vector of the staggered magnetization

$\rho_{SDW}=|\eta_{SDW}|^2\cos(2Qx+2\varphi)$

- normal dislocation, 2π translation:

$\varphi\to\varphi+2\pi$, $\mathbf{m}\to\mathbf{m}$

- normal **m** - vortex, 2π rotation:

$\mathbf{m}\to O_{2\pi}\,\mathbf{m}$, $\varphi\to\varphi$

- combined object :

$\varphi\to\varphi+\pi$, $\mathbf{m}\to O_{\pi}\,\mathbf{m}=-\mathbf{m}$

Phase vortex and magnetic vortex

Energy of the vortex with the winding number ν $W_m \sim T_c \rho_s \nu^2$

Energy of the dislocation (ν =1) : $W_\varphi \sim T_c(\rho_s/\rho_n)\nu^2$

In general if $\nu \rightarrow 2(\nu/2)$ then $W \rightarrow W/2$

Only smallest ν are stable

T~Tc : $W_\varphi \sim W_m$ all energies are comparable

- Normal dislocation
- Half-dislocation combined with semi-vortex
- Normal magnetic vortex

Result depends on numbers.

T<<Tc : $W_\varphi >> W_m$

- Half-dislocation combined with semi-vortex –
- *obligatory decoupling of the dislocation*

ν_φ=1 → ν_φ =1/2, ν_m=1/2 → **W = (W_φ +W_m)/2 W_φ/2**

ν_φ=1 → ν_φ =1/2, ν_m=1/2 → **W = (W_φ +W_m)/2 W_φ/2**

1 Continuous route in 1D:

For a CDW, successful simulations of phase-slips has been achieved for two models.

1. The model driven by a difference of condensate densities at the boundaries:
2. The model driven by the applied longitudinal field fixed boundary conditions.

We can try to extend any of these approaches to the SDW case.

2 1D phase slips in the easy plane SDW

we should use the spherical vector for the 3-degrees of freedom of the planar SDW case

$$\vec{\Psi} = Ae^{i\varphi}\{\cos\theta, \sin\theta\} \Rightarrow$$

$$S = (u, v, w) = \{A\sin\theta\cos\varphi\ ,\ A\sin\theta\sin\varphi, A\cos\theta\}$$

$$\vec{\Psi} = (u+iv)\left\{\frac{\cos\theta}{\sin\theta}, 1\right\} = (u+iv)\left\{\frac{\pm w}{\sqrt{u^2+v^2}}, 1\right\}$$

$$A^2 = u^2+v^2+w^2\ ,\ \cos\theta = \frac{w}{A}\ ,\ \frac{v}{u} = \tan\varphi$$

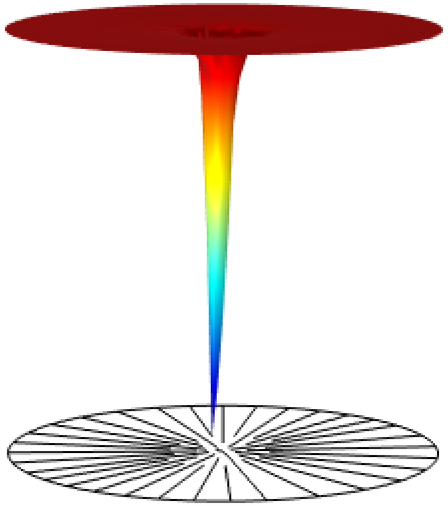
$$A\partial A = u\partial u + v\partial v + w\partial w\ ,\ \partial\varphi = \frac{u\partial v - v\partial u}{u^2+v^2}$$

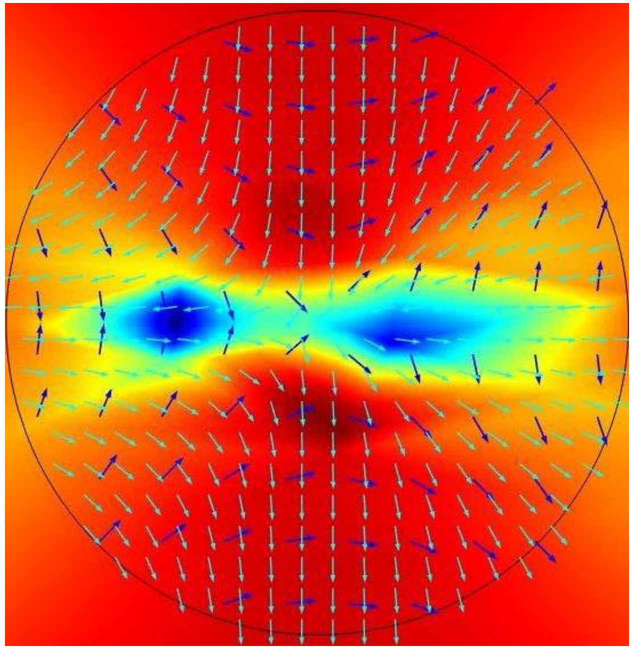
$$\partial\theta = \frac{w\partial A - A\partial w}{(u^2+v^2)^{1/2}A} = \frac{w(u\partial u + v\partial v) - (u^2+v^2)\partial w}{(u^2+v^2)^{1/2}A^2}$$

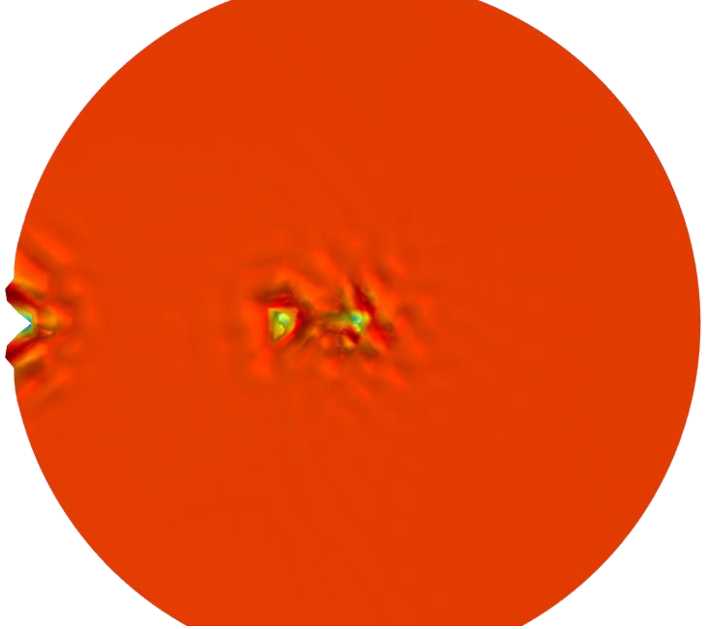
$$\pi n_c = A^2\partial_x\varphi\ ,\ \pi j_c = -A^2\partial_t\varphi\ ,\ \pi n_s = A^2\partial_x\theta\ ,\ \pi j_s = -A^2\partial_t\theta$$

$$F = \int dxdy \left[\begin{array}{l} \frac{C}{2}(A^2-1)^2 + \frac{K_{Ax}}{2}(\partial_x A)^2 + \frac{K_{Ay}}{2}(\partial_y A)^2 + A^2 \Phi \partial_x \varphi/\pi - H A^2 \partial_x \theta \\ + \frac{K_{cx}}{2} A^2 (\partial_x \varphi)^2 + \frac{K_{cy}}{2} A^2 (\partial_y \varphi)^2 + \frac{K_{sx}}{2} A^2 (\partial_x \theta)^2 + \frac{K_{sy}}{2} A^2 (\partial_y \theta)^2 \end{array} \right]$$

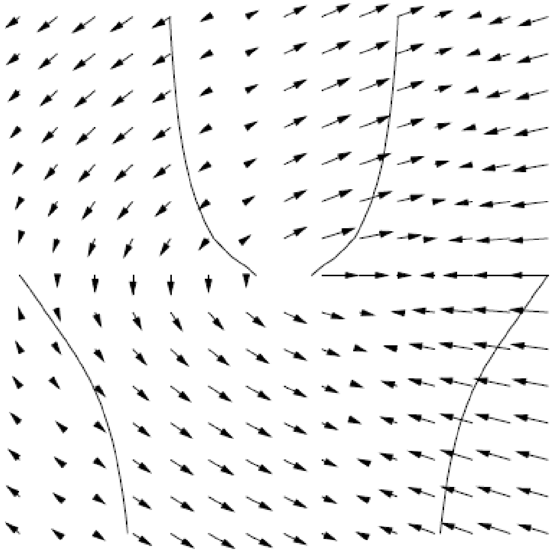
$$\tau_A \partial_t A = -\delta F/\delta A \ , \ \tau_c A^2 \partial_t \varphi = -\delta F/\delta \varphi - A^2 \pi E_{ext} \ , \ \tau_s A^2 \partial_t \theta = -\delta F/\delta \theta$$







The vector field of the local SDW magnetization for the a hymer. The chain axis is horizontal.



Spin – orbital coupling (Anisotropy)

Spin anisotropy → the free rotation of spins is prohibited.

Pure "easy plane" or "easy axes" (for *H* > *H*sf exceeding the spin-flop field *H*sf ~ 1 T)– no changes

Other cases:

The both π phase vortices will be bound by a string - the Neel domain wall.

Spin-flop field $H_{s\text{-}f}$ ~ 1T originates the string of the length ~0.1μm.

At higher magnetic fields only a small in-plane anisotropy is left so that the string length may reach the sample width.

$W_m = v_F[a(\partial_i m_\alpha)^2 + l^{-2} m_z^2]$ l - the DW width is determined via spin-flop field.

π semi-vortex → 180° domain wall W_{mDW} ~1K/chain, $l \sim 10\xi_0 \sim 10^4$A

Splitting of the isolated 2π vortex→
two π vortices confined by the string of the180º domain wall

$r<r_{scr}$:

Energy lost $W_m = W_{mDW} N$, $W_{mDW} \sim 1K/chain$

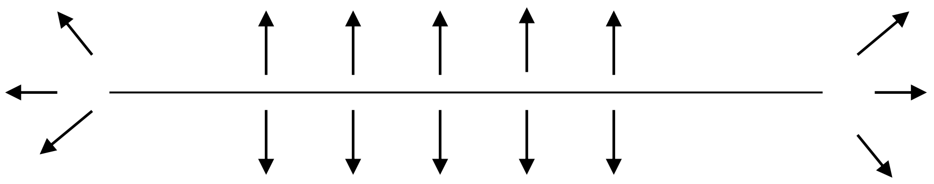
Energy gain $W_{Disl.} = -E_0 N/2$,

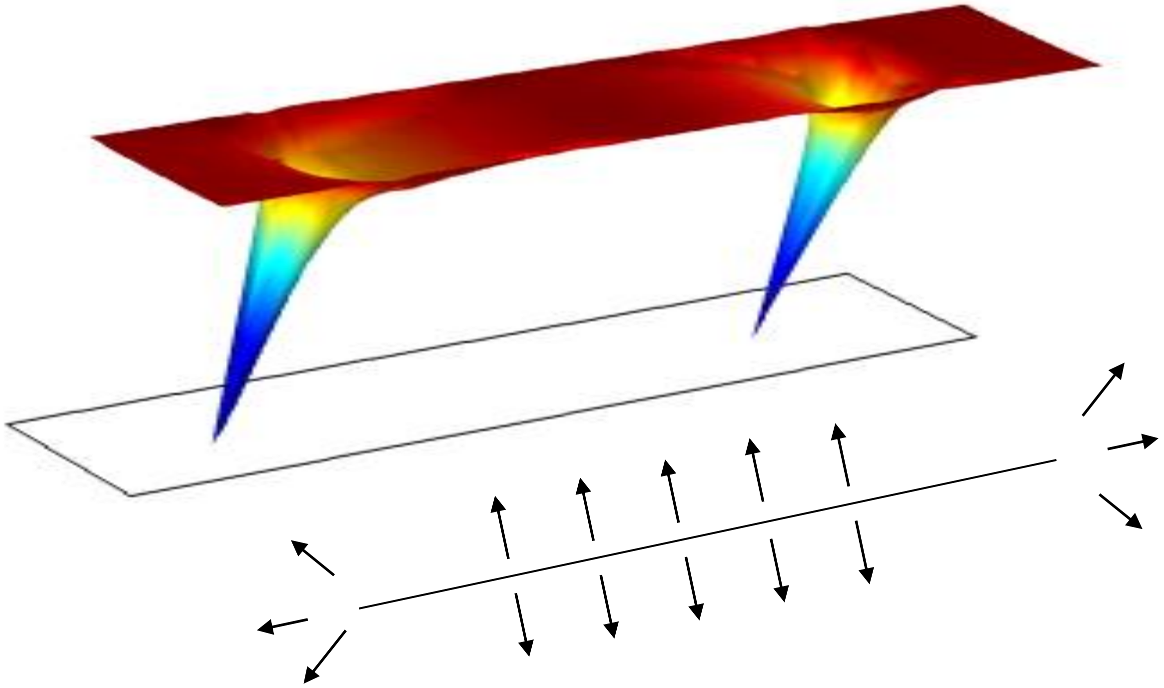
$E_0 > W$ - ***constant repulsion wins against constant attraction***

$r>r_{scr}$:

Energy lost $W_m = W_{mDW} N$ Energy gain $W_{Disl.} = -(E_0/\rho_n^{1/2}) \ln N + W_{mDW} N$

Equilibrium distance between half dislocations $N \sim E_0 / (\rho_n^{1/2} W_{mDW})$





Effect of rotational anisotropy:
String tension binds semi-vortices

Narrow Band Noise Generation

Sliding Charge/Spin Density Waves generate the Narrow Band Noise (NBN) a coherent periodic unharmonic signal with the fundamental frequency Ω being proportional to the mean dc sliding current j with the universal ratio Ω /j .

CDW

Ω /j= π two electrons per CDW wave length λ. $\rho_{CDW} = |\eta_{CDW}| \cos(Qx+\varphi)$

SDW

Ω /j =2π if only electron density is $\rho_{SDW} = |\boldsymbol{\eta}_{SDW}|^2 \cos(2Qx+2\varphi)$

involved

Ω /j = π if spins are relevant.

Competing models:

The Wash-Board Frequency (WBF) model : NBN is generated *extrinsically* while the DW modulated charge passes through the host lattice sites or its defects.

But :

(i) ***The interaction between the rigid DW and the regular host lattice $V_{host} \sim cos(n\varphi)$,*** usually $n=4 \rightarrow$ an n-fold WBF **contrary to experiments.**

(ii) ***Interaction with the host impurities*** $V_{imp} \sim \cos(Qx_i + \varphi)$ the positionally random phase shifts $-Qx_i$

prevent any coherence in the linear response

***The Phase Slip Generation (PSG) model*:** the NBN is generated by the phase slips occurring near injecting contacts.

But:

a regularity as shown by a remarkably high coherence of the NBN in experiments

DW does not slide at the sample side surface , coupling $\cos(\varphi_{bulk} - \varphi_{surface})$ with $\varphi_{bulk} \propto t$ and $\varphi_{surface} = cnst$ provide a necessary WBF. Bridge to PSG model

Our point of view: **Contrary to CDW the fundamental ratio NBN frequency to DC current is not the universal parameter**, changing from ½ near Tc to 1 at T<< Tc and being restorted to ½ in case of magnetic anisotropy.

Conclusion

- In SDW at low temperature conventional dislocations loose their priority in favor of "hymers" – the complex topological objects: a half-integer dislocation combined with a semi-vortex of the staggered magnetization .
- The combined topological objects are stabilized by lowering the Coulomb energy of dislocations especially important at low temperatures (Coulomb hardening)
- At the presence of magnetic anisotropy the two combined objects are connected by the string – Neel domain wall.
- **Contrary to CDW the fundamental ratio NBN frequency to DC current is not the universal parameter**, changing from ½ near Tc to 1 at T<< Tc and being restorted to ½ in case of magnetic anisotropy.