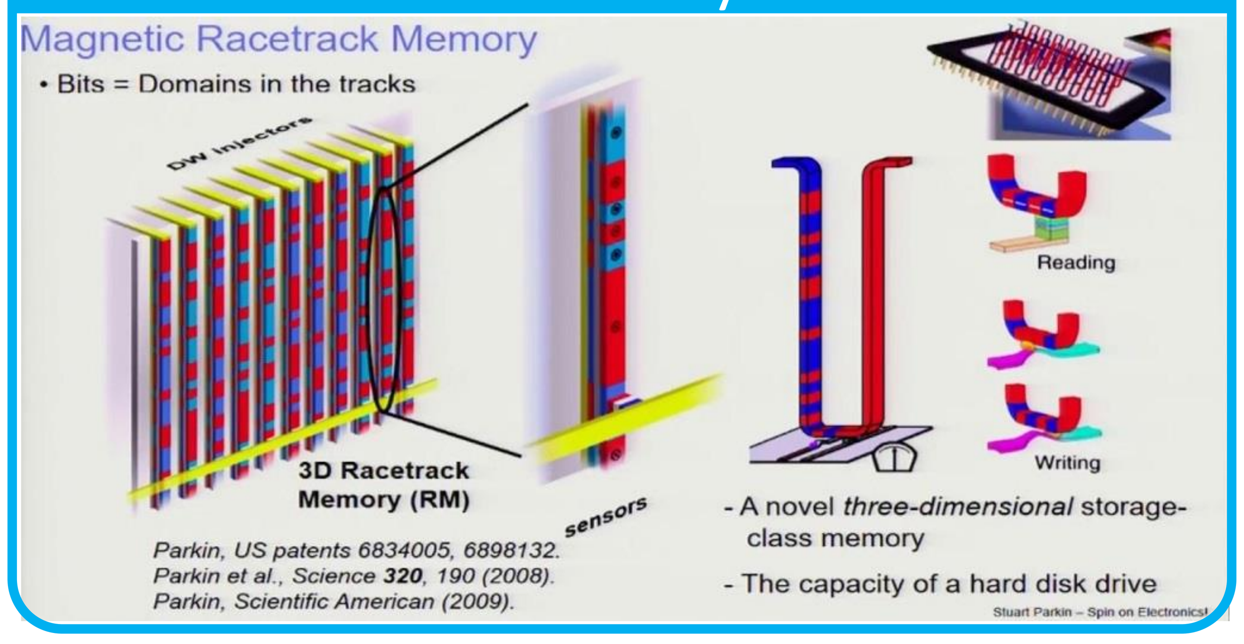
Domain walls and breathers in metamaterials constructed of magnetic molecules

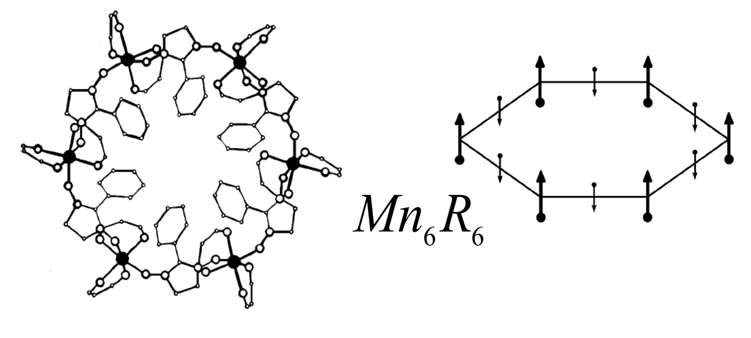
Oksana Charkina and Mikhail Bogdan

B.Verkin Institute for Low Temperature Physics and Engineering of the National Academy of Sciences of Ukraine

1. Magnetic Domain-Wall Racetrack Memory

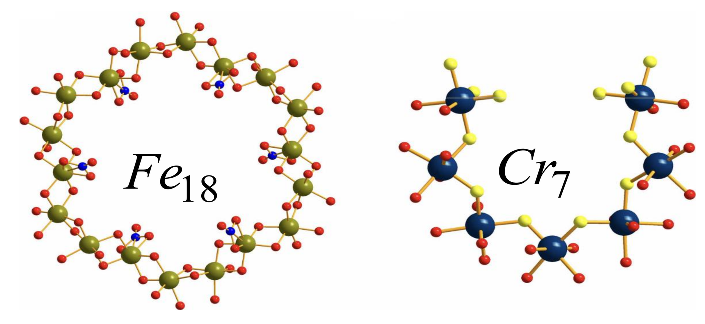


2. Magnetic nanoclusters in molecular crystals



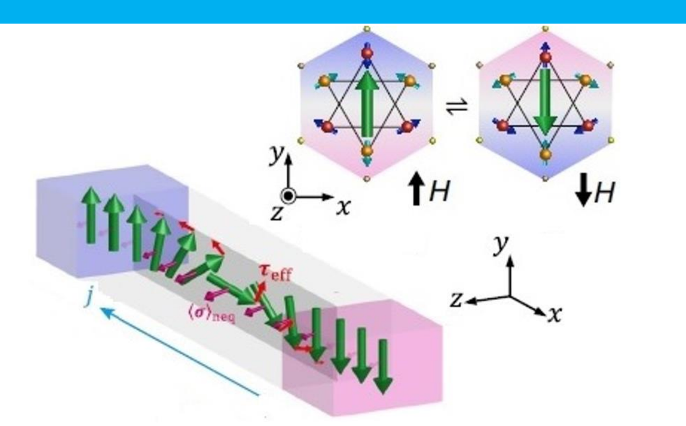
Ferrimagnetic molecules

V.V. Kostyuchenko, I.M. Markevtsev, et al., *Phys. Rev. B: Condens. Matter* **67**, 184412 (2003)



Antiferromagnetic molecules

N.P. Konstantinidis, A. Sundt, J. Nehrkorn et al., *JPCS* **303**, 012003 (2011)

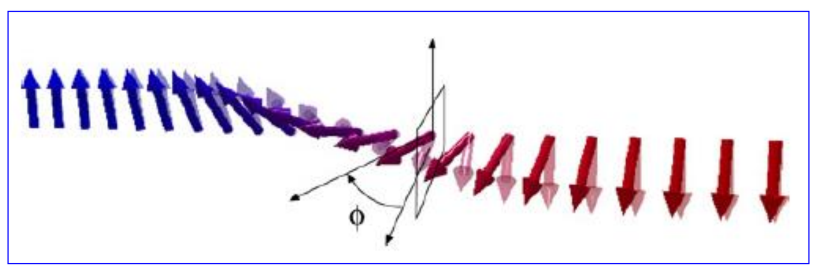


Magnetic Octupole DW

Mingxing Wu, Taishi Chen, Takuya Nomoto et al., *Nature Communications* 15:4305 (2024)

3. The Takeno-Homma model and the Kosevich-Kovalev equation

The purpose of the work is the analytical and numerical study of the magnetic nonlinear waves, domain walls and their bound states such as breathers and complexes in metamaterials built of the magnetic molecules, which are molecular nanoclusters including magnetic cyclic, chained and octupole molecules.



The theoretical description is carried out within the framework of the Takeno-Homma (TH) model, which generalizes the discrete sine-Gordon model and accounts for the exchange interaction between spins, and its continuous limit, namely the Kosevich-Kovalev equation.

$$\mathcal{H}=\sum_{n=1}^{N}\dot{\varphi}_n^2-\lambda\sum_{n=1}^{N}\cos(\varphi_n-\varphi_{n-1})-\frac{1}{2}\sum_{n=1}^{N}\cos^2(\varphi_n)\qquad \lambda=\frac{J}{A}$$

S. Takeno and S. Homma, *Prog. Theor. Phys.* **70**, 308 (1983)

$$\frac{d^2\varphi_n}{dt^2}+\lambda\big(\sin(\varphi_n-\varphi_{n-1})-\sin(\varphi_{n+1}-\varphi_n)\big)+\cos(\varphi_n)\sin(\varphi_n)=0$$

The Takeno-Homma equation (THE) for the spin azimuthal angle variable φ_n

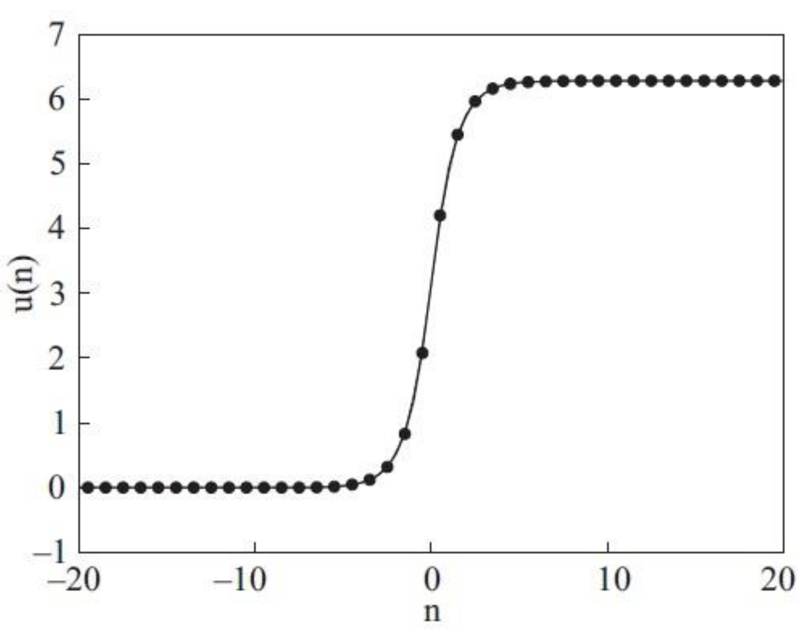
$$u_{tt}-u_{xx}+\sin u-\beta u_{xxxx}+\frac{3}{2}\beta u_x^2u_{xx}=0$$

The Kosevich-Kovalev equation (KKE) for $u=2\varphi$ is the long-wavelength limit of the THE, where the dispersion parameter $\beta=\frac{1}{12\lambda}<<1$

4. Asymptotic solution for the oscillating domain wall

$$u(x)=4\arctan\exp(x)-\beta\left(\frac{x}{\cosh x}-6\frac{\sinh x}{\cosh^2 x}\right)$$

$$u=2\arctan\exp(\kappa_0x-i\delta_0)+2\arctan\exp(\kappa_0x+i\delta_0)$$



$$\kappa_0=1-\beta/2\qquad \delta_0=\sqrt{6\beta}$$

$$u_V(n)=\pi+2\arctan\left(\frac{\sinh\kappa(t)(n-n_0)}{\cos\delta(t)}\right)$$

The variational approach is proposed to describe the oscillating domain wall and. It is shown that obtained analytical expressions fit well the numerical solutions.

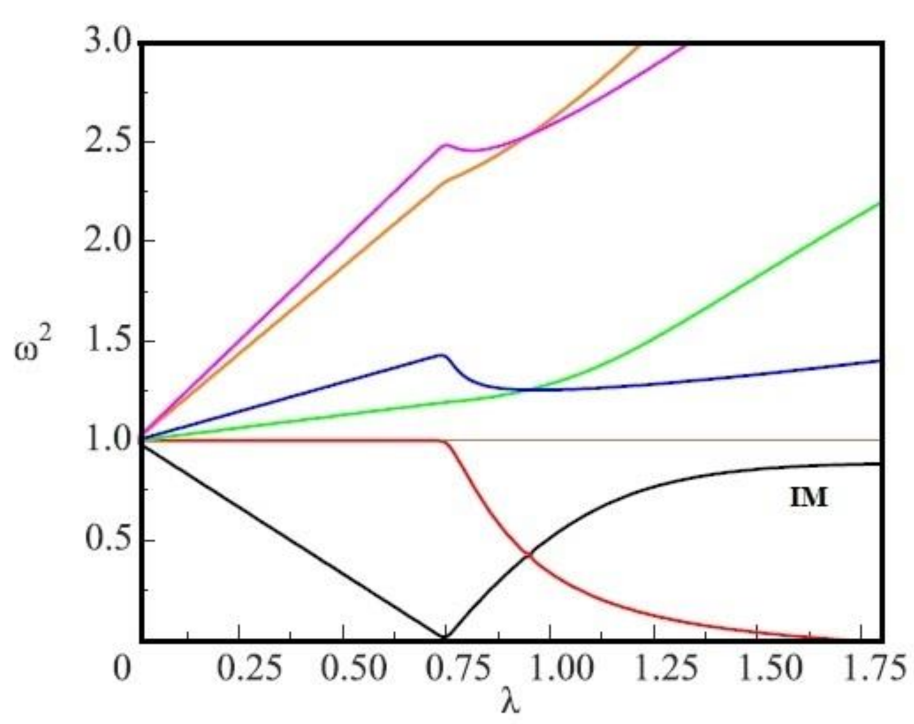
The spectral problem of the internal mode oscillations of a domain wall

$$\Delta u_n(t)=u_n(t)-u_n^0(t)<<1$$

$$\Delta u_n(t)=\psi_n\exp(-i\omega t)$$

O.V. Charkina, V.I. Belan, M.M. Bogdan, *Low Temp.Phys.* **47**, 1096 (2021)

The internal and continuous spectrum oscillating modes of the domain wall



$$\lambda\big((\psi_n-\psi_{n-1})\cos(u_n^0-u_{n-1}^0)+(\psi_n-\psi_{n+1})\cos(u_n^0-u_{n+1}^0)\big)+\cos(2u_n^0)\psi_n=\omega^2\psi_n$$

Analytical approach in the framework of the regularized KKE

$$u_{tt}-u_{xx}+\sin u-\beta u_{ttxx}+\frac{3}{2}\beta u_x^2u_{tt}=0$$

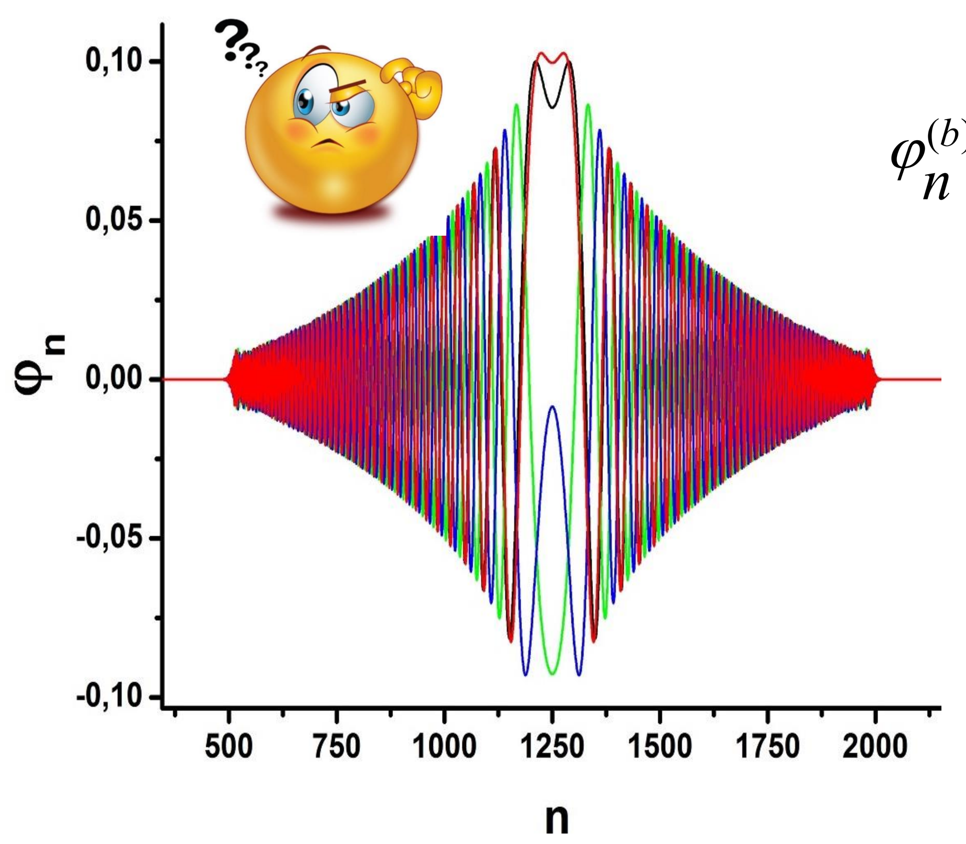
$$u(x,t)=4\arctan(\exp(x))+\psi(x)\exp(-i\omega t)$$

$$\left\{-\left(1-\beta\omega^2\frac{\partial^2}{\partial x^2}\right)+1-\omega^2-\frac{2}{\cosh^2(x)}(1+3\beta\omega^2)\right\}\psi=0$$

$$\sqrt{\frac{1}{4}+2\cdot\frac{1+3\beta\omega^2}{1-\beta\omega^2}}-\sqrt{\frac{1-\omega^2}{1-\beta\omega^2}}=n+\frac{1}{2},\qquad n=1$$

Internal Mode (IM)

5. The breather of the TH equation



$$\varphi_n^{(b)}(t)=2\arctan\left(\frac{\sinh\frac{\kappa}{2}}{\omega(\kappa)}\cdot\frac{\sin(\omega(\kappa)t)}{\cosh(\kappa n)}\right)$$

$$\omega(\kappa)=\sqrt{1-4\lambda\sinh^2\frac{\kappa}{2}}$$

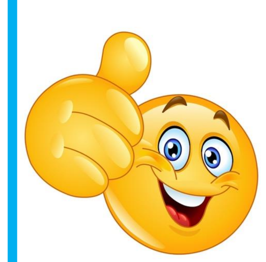
The discrete breather in the Takeno-Homma equation radiates spin waves due to the interaction of its third harmonics with continuous spectrum waves.

6. Complexes of domain walls in the KKE

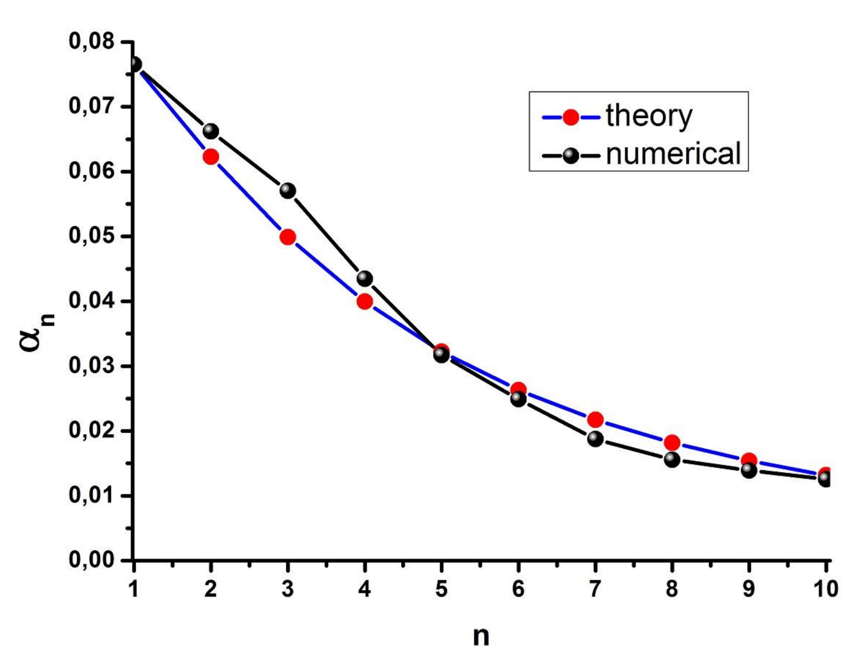
Radiationless motion of bound soliton complexes

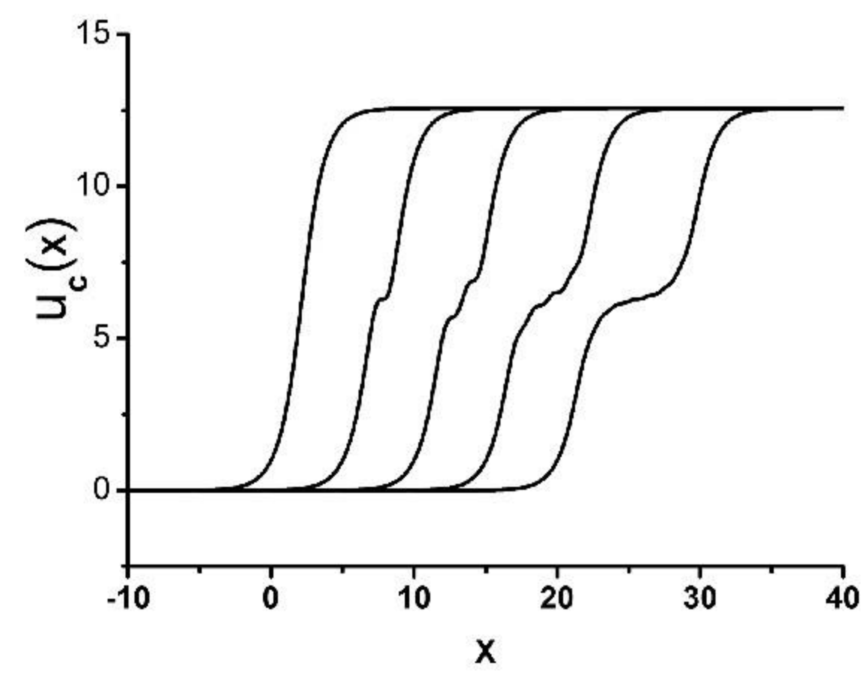
Exact complex solution: $u_c(x)=8\arctan\exp(\varepsilon(x-Vt))\qquad u_x^2=F(u)$

Nonlinear eigenvalue problem: $F+\alpha\left(FF_{uu}-\frac{1}{4}F_u^2+\frac{3}{4}F^2\right)=2(1-\cos(u))$



$$\alpha=\frac{\beta}{(1-V^2)^2}\qquad \alpha_n=\frac{2[(n+1)(n+2)+24]}{[n(n+3)+24]^2}\qquad V_n=\sqrt{1-\sqrt{\frac{\beta}{\alpha_n}}}$$





7. Conclusion

The presented results can be used in designing and developing basic elements of computer memory units, based on a new class of low-dimensional metamaterials with predicted here nonlinear properties of magnetic excitations.

charkina@ilt.kharkov.ua charkina@ukr.net