On the Energy Spectrum and Magnetic Properties of low-dimensional spin systems of complex topology

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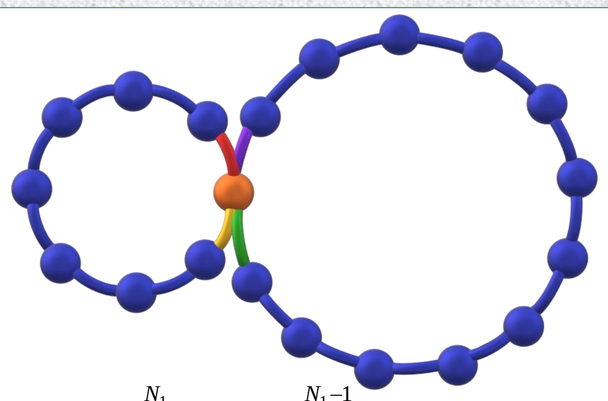
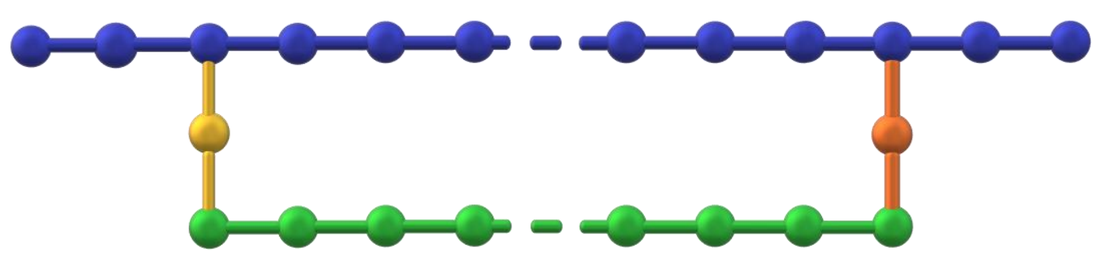
Low dimensional effective spin models of nanomagnets are permanently attracting big interest of the investigators due to their interesting physics and possible applications in nanoelectronics. We propose two exactly solvable quantum models based on finite spin-1/2 XX chains with additional Ising spin-S, connecting XX chains at fixed lattice sites.



$$\hat{\mathbf{H}}_1 = -g_1\mu_B H\sum_{n=1}^{N_1} S_{1,n}^z - J_1\sum_{n=1}^{N_1-1}\left(S_{1,n}^x S_{1,n+1}^x + S_{1,n}^y S_{1,n+1}^y\right)$$
$$-g_2\mu_B H\sum_{n=1}^{N_2} S_{2,n}^z - J_2\sum_{n=1}^{N_2-1}\left(S_{2,n}^x S_{2,n+1}^x + S_{2,n}^y S_{2,n+1}^y\right)$$
$$-g_0\mu_B H\tilde{S}_0^z - \left[J_{01}S_{1,1}^z + J'_{01}S_{1,N_1}^z + J_{02}S_{2,1}^z + J'_{02}S_{2,N_2}^z\right]\tilde{S}_0^z \qquad (1)$$



$$\hat{\mathbf{H}}_2 = -g_1\mu_B H\sum_{n=1}^{N_1} S_{1,n}^z - J_1\sum_{n=1}^{N_1-1}\left(S_{1,n}^x S_{1,n+1}^x + S_{1,n}^y S_{1,n+1}^y\right)$$
$$-g_2\mu_B H\sum_{n=1}^{N} S_{2,n}^z - J_2\sum_{n=1}^{N_2-1}\left(S_{2,n}^x S_{2,n+1}^x + S_{2,n}^y S_{2,n+1}^y\right)$$
$$-g_0\mu_B H\tilde{S}_{n_1}^z - g'_0\mu_B H\tilde{S}_{n_2}^z - J_0\tilde{S}_{n_1}^z\left(S_{1,n_1}^z + S_{2,1}^z\right) - J'_0\tilde{S}_{n_2}^z\left(S_{1,n_2}^z + S_{2,N_2}^z\right). \qquad (2)$$

Operators of z-projections of additional Ising spins commute with models Hamiltonians and corresponding eigenvalues are the good quantum numbers. This property permits us to consider Hamiltonians (1) and (2), as the Hamiltonians of the finite XX-chain with an effective impurity spin S = 1/2 at some lattice sites. XX chain is the well known example of exactly solvable model [1-3]. The XX model Hamiltonian can be rewrited as the Hamiltonian of ideal gas of spinless fermions.

Dispersion relations

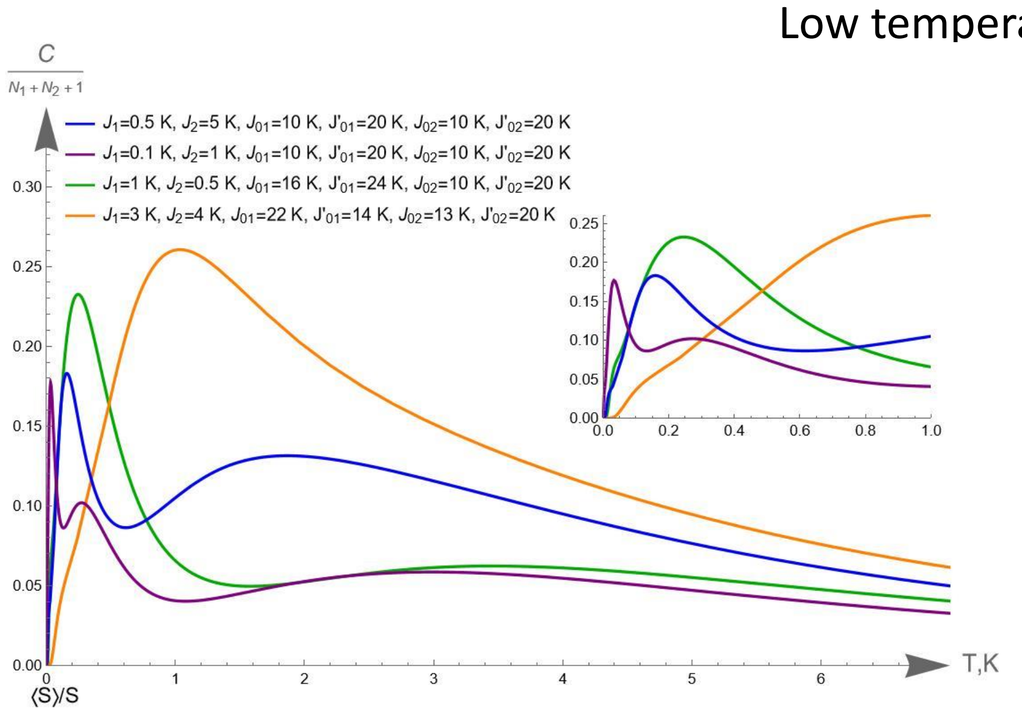
$$(\alpha_1 x_1 + 1)(\alpha'_1 x_1 + 1) - \left(\frac{\alpha_1}{x_1} + 1\right)\left(\frac{\alpha'_1}{x_1} + 1\right)x_1^{2(N_1+1)} = 0;$$

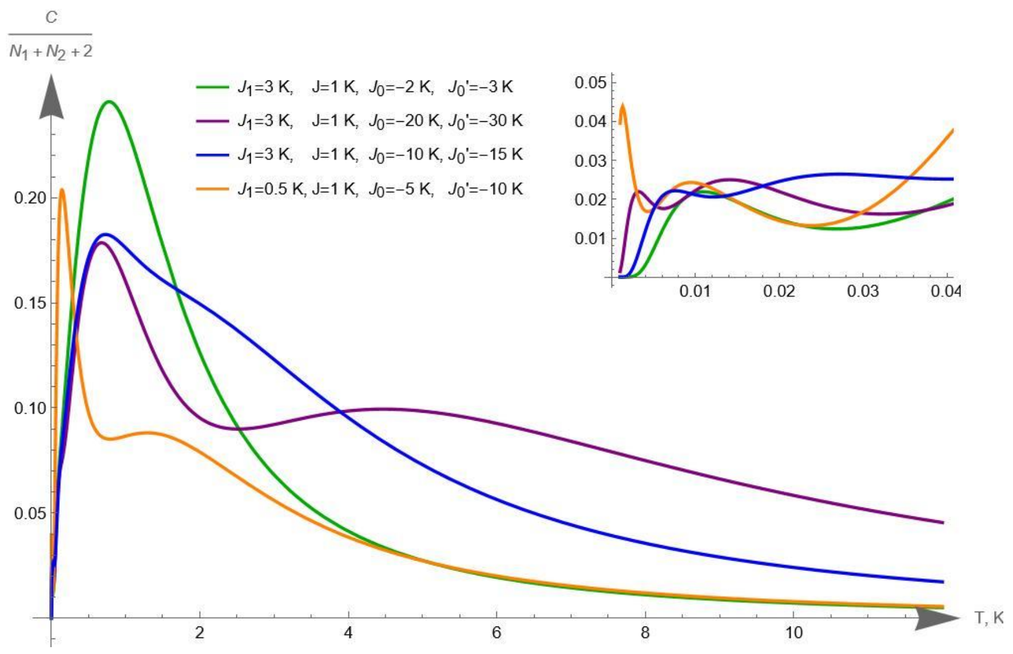
$$(\alpha_2 x_2 + 1)(\alpha'_2 x_2 + 1) - \left(\frac{\alpha_2}{x_2} + 1\right)\left(\frac{\alpha'_2}{x_2} + 1\right)x_2^{2(N_2+1)} = 0;$$

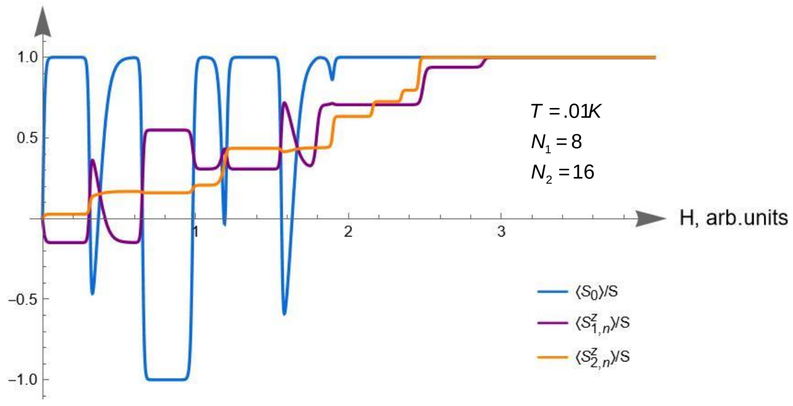
$$\left(1+\beta_1 x_1\frac{1-x_1^{-2n_1}}{x_1^2-1}\right)\left(1+\beta_2 x_1\frac{\left(1-x_1^{-2(N_1+1-n_2)}\right)}{x_1^2-1}\right)x_1^{N_1+1} - \left(1+\beta_1 x_1\frac{\left(1-x_1^{2n_1}\right)}{1-x_1^2}\right)\left(1+\beta_2 x_1\frac{\left(1-x_1^{2(N_1+1-n_2)}\right)}{1-x_1^2}\right)x_1^{-(N_1+1)} = 0;$$

$$(\alpha_1 x_2 + 1)(\alpha_2 x_2 + 1)x_2^{-(N_2+1)} - (\alpha_1 + x_2)(\alpha_2 + x_2)x_2^{(N_2+1)} = 0;$$

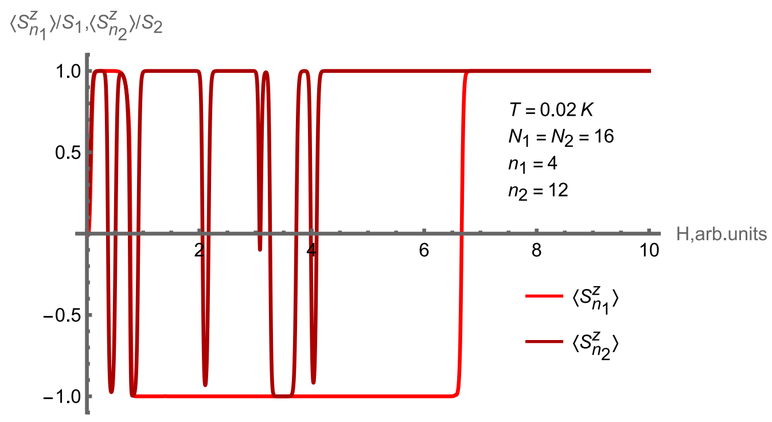
Low temperature thermodynamics

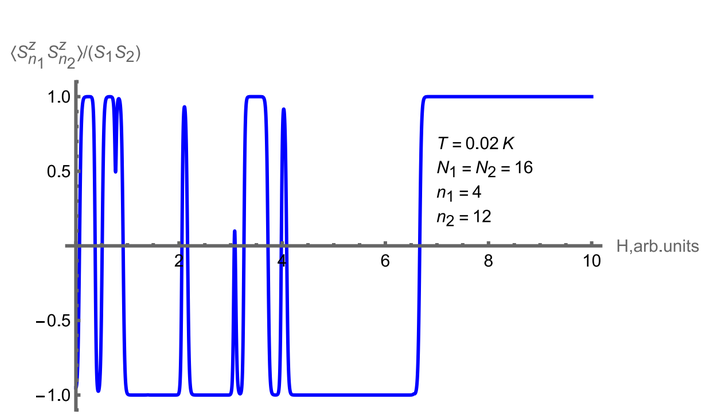






$$S = 1/2;\ g_1 = 1; g_2 = 2; J_1 = 3K; J_2 = 5K;$$
$$J_{01} = J'_{02} = -1K; J_{02} = J'_{01} = -2K;$$





$$S_1 = S_2 = 1/2;\ J_1 = 10K; J_2 = 20K; J_0 = -8K; J'_0 = -6K;$$
$$g_1 = g_2 = 3; g_0 = 1.2; g'_0 = 1.3;$$

Summary:

- We derived exact dispersion equations for the stationary states with one inverted spin for all cases of our models. These spectra consist of two quasi-continuous zones and several localized impurity levels. We obtained and analyzed the analytical inequalities for the values of critical parameters of the models describing the appearance of local energy impurity levels above and below the quasi-continuous zones.
- Field and temperature dependencies of the main thermodynamic characteristics of the models were studied numerically. It is shown that the appearance of localized levels near impurities may effects significantly on the thermodynamics properties at low temperatures, leading to additional features in the field and temperature dependences of the thermodynamic characteristics considered.
- The field dependence of the average z-projection of total spin and the field dependence magnetization at zero temperature should have finite jumps associated with both the quasi-continuous spectrum and impurity levels. Remnants of these jumps are clearly visible at very low temperatures.

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References

[1] 5A. A. Zvyagin, Quantum Theory of One-Dimensional Spin Systems (Cambridge Scientific Publishers, Cambridge, 2010).
[2] E.H. Lieb, D.C. Mattis, J. Math. Phys., 3, 749-751 (1962). DOI: 10.1016/0003-4916(61)90115-4
[3] Е. В. Езерская, В. М. Цукерник, ФІЗИКА НИЗЬКИХ ТЕМПЕРАТУР: Том 9 № 10 (1983)