Reply to “Comment on ‘Magnetic structure and magnetization of z-axis helical Heisenberg antiferromagnets with XY anisotropy in high magnetic fields transverse to the helix axis at zero temperature’ ”

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Reply to “Comment on: Magnetic structure and magnetization of z-axis helical Heisenberg antiferromagnets with XY anisotropy in high magnetic fields transverse to the helix axis at zero temperature”

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The Comment criticizes the assumptions of the model I used. I was certainly aware of the limitations of my model. However, my model is useful in being able to fit high-field magnetization versus transverse-field data for real helical Heisenberg antiferromagnets at temperatures much lower than their Néel temperatures and to estimate their critical fields. To my knowledge there existed no prior theory that could fit such experimental data over the entire field range of experiments. I welcome the Comment that calls for more accurate theory.

I calculated the $T = 0$ magnetization, energy, and magnetic structures of a helical Heisenberg spin system in high magnetic fields H transverse to the helix z axis in Refs. [1] and [2] using energy minimization. In the former paper I assumed infinite XY anisotropy thus confining the spins to the xy plane, whereas in the latter paper I removed this restriction and studied how the magnetic structure and phase diagram evolve with H and classical XY anisotropy field $H_{\rm A}$. In both papers I assumed a model in which the spins were classical, that the helix wave vector was commensurate with the spin lattice, and that the turn angle kd along the helix z axis between adjacent layers of spins was independent of field.

The purpose of these models was to fit experimental data we had been accumulating on large-spin (nearly classical) helimagnets containing Eu^{+2} spins-7/2. We previously successfully fitted the transverse low-field magnetic suseptibilities versus T in the antiferromagnetic state of such helimagnets in several papers by the molecular-field theory developed in Refs. [3] and [4], and I wanted to see what we could do to fit the high-field transverse $M(H)$ at low temperatures $T \ll T_{\rm N}$ where $T_{\rm N}$ is the AFM ordering temperature. In Ref. [1] I semiquantitatively fitted the $M(H)$ data up to $H = 14$ T for the helimagnet $EuCo_2P_2$ [5] using a commensurate $kd = 6\pi/7$ where the spins were confined to the xy plane and also obtained an estimate of the critical field $H_{\rm c} = 25.6$ T at which the magnetization per spin saturated to $\mu_{\rm sat} = gS\mu_{\rm B} = 7\ \mu_{\rm B}$. Then in Ref. [2], I estimated $H_{\rm A}$ in $EuCo_2P_2$ via an analysis of the anisotropic magnetic susceptibility $\chi(T)$ within molecular field theory. My H versus $H_{\rm A}$ phase diagram for $kd = 5\pi/6$ in Ref. [2] indicated that $EuCo_2P_2$ lies in a region where the spins are confined to the xy plane, as in the first analysis. The high-field $M(H)$ data were semiquantitatively fitted assuming $kd = 5\pi/6$ and yielded an extrapolated critical field $H_{\rm c} = 21.7$ T, similar to but somewhat smaller than in the first analysis.

The Comment by Vaia criticizes the assumptions of the models I used. I was certainly aware of the deviations of my assumptions from known theory as described in the papers cited in the bibliographies of Refs. [1] and [2] which showed, *e.g.*, that the helix turn angle should depend on the applied transverse field. However, my models were useful in being able to fit our low-T high-field $M(H)$ data and to estimate the critical field as described above. I am not aware of any other published theoretical results that can be used to fit transverse-field $M(H)$ data for Heisenberg helimagnets over the wide field range covered in real experiments.

I welcome the Comment by Vaia that calls for more accurate theory for $M(H)$, magnetic structures, and phase diagrams in the H-$H_{\rm A}$ plane at temperatures $T < T_{\rm N}$. Indeed, at the end of the Sec. V in Ref. [2], I suggested that classical Monte Carlo simulations might be useful to see how the magnetic structures versus H and the H-$H_{\rm A}$ phase diagrams obtained compare with those I derived in Refs. [1] and [2] for $T \ll T_{\rm N}$.

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[1] D. C. Johnston, Magnetic structure and magnetization of helical antiferromagnets in high magnetic fields perpendicular to the helix axis at zero temperature, Phys. Rev. B **96**, 104405 (2017); (E) **98**, 099903 (2018).
[2] D.C. Johnston, Magnetic structure and magnetization of z-Axis helical Heisenberg antiferromagnets with XY anisotropy in high magnetic fields transverse to the helix axis at zero temperature, Phys. Rev. B **99**, 214438 (2019).
[3] D. C. Johnston, Magnetic Susceptibility of Collinear and Noncollinear Heisenberg Antiferromagnets, Phys. Rev. Lett. **109**, 077201 (2012).
[4] D. C. Johnston, Unified molecular field theory for collinear and noncollinear Heisenberg antiferromagnets, Phys. Rev. B **91**, 064427 (2015).
[5] N. S. Sangeetha, E. Cuervo-Reyes, A. Pandey, and D. C. Johnston, $EuCo_2P_2$: A model molecular-field helical Heisenberg antiferromagnet, Phys. Rev. B **94**, 144422 (2016).