Coleman and Chandra Reply: Is the fluctuation-induced melting of a quantum helimagnet a multistage process? Within the "quantum fluids" approach of Chandra, Coleman, and Larkin (CCL) [1-3], we have proposed an intermediate phase *without* conventional dipolar antiferromagnetism that preserves the two-spin (quadrupolar) order

$$Q_{\mu\nu}(x,x') = \langle S_\mu(x) S_\nu(x')\rangle_I - \tfrac{1}{3}\delta_{\mu\nu}\langle \mathbf{S}(x)\cdot\mathbf{S}(x')\rangle_I \qquad (1)$$

($\langle AB\rangle_I = \langle AB\rangle - \langle A\rangle\langle B\rangle$) present in the original helimagnet. The Sp($2N$) approach of Read and Sachdev [4] also yields a two-phase "melting" via a "deconfined" spin liquid with infinite spin correlation length in the absence of long-range order. By contrast, in the preceding Comment Ceccatto, Gazza, and Trumper (CGT) [5] find a direct transition to the disordered regime with short-range spin correlations. Clearly the "quantum melting" of a 2D helimagnet is a delicate issue; the key element in this controversy is that different decoupling procedures have different realms of application. However, we can search for inconsistencies in a given mean-field theory, and thus determine its realm of reliability.

A crucial difference between the methods of CGT and CCL is the choice of order parameter. The spin pairing fields of CGT are inherently *singlet*, so that spin anisotropy in the zero-temperature helimagnet is only present in the Schwinger boson condensate. Such an approach will never yield a phase with *nematic* spin correlations at the mean-field level; the irreducible two-spin correlations are determined by the Bose condensations, and are consequently proportional to the square of the magnetization

$$\langle S_\mu(x) S_\nu(x')\rangle = \langle S_\mu(x)\rangle\langle S_\nu(x')\rangle = M_\mu(x) M_\nu(x) \qquad (2)$$

and the nematic order

$$Q_{\mu\nu}(x,x') = [\langle S_\eta(x) S_\zeta(x')\rangle - \langle S_\eta(x)\rangle\langle S_\zeta(x')\rangle] \times [\delta_{\mu\eta}\delta_{\nu\zeta} - \tfrac{1}{3}\delta_{\mu\nu}\delta_{\eta\zeta}] = 0 \qquad (3)$$

vanishes. This is not the case in a large S quantum helimagnet, where nematic two-spin order coexists with incommensurate magnetic order. Furthermore, the method of CGT does not reproduce the proper magnon spectrum for a classical helimagnet at large S [6]; rather than

$$\omega_{\mathbf{q}}^{\text{classical}} = S\{[J(\mathbf{q}) - J(\mathbf{Q})][\tfrac{1}{2}(J(\mathbf{q}+\mathbf{Q}) + J(\mathbf{q}-\mathbf{Q})) - J(\mathbf{Q})]\}^{1/2} \qquad (4)$$

it yields the dispersion relation

$$\omega_{\mathbf{q},\sigma}^{\text{CGT}} = S\{[J(\mathbf{q}) - J(\mathbf{Q})][J(\mathbf{q}+\sigma\mathbf{Q}) - J(\mathbf{Q})]\}^{1/2} \quad (\sigma = \pm 1), \qquad (5)$$

where $J(\mathbf{q})$ is the Fourier transform of the bond strengths.

In developing the quantum fluids approach, we were mindful of the fact that zero-point fluctuations in a quantum helimagnet *are anisotropic*, generating irreducible two-spin correlations at finite S. These correlations can be computed in an unbiased way within leading order spin-wave theory. We maintain that the quadrupolar order carried by the zero-point fluctuations is not rigidly fixed with respect to dipole order. At finite S, modes where the two order parameters rotate together develop Goldstone modes; modes where they rotate out of phase develop a gapful spectrum giving rise to quantum exchange gaps. Our decoupling procedure *precisely* reproduces both the large S magnon excitation spectrum and the essential leading order nematic correlations through the inclusion of triplet spin pairing that breaks spin rotation symmetry. (There are *no factors of 2*, as suggested in the preceding Comment). As in the large S approach, to compute the dispersion of the Goldstone modes at finite S we need to consider joint rotations of the dipole order, carried by the magnons, and the fluctuations of the irreducible two-spin order. When these are considered, we do indeed recover a gapless spectrum [1].

To summarize the difference of opinions: We maintain that helimagnets possess nematic two-spin order carried by the fluid of spin fluctuations; quantum exchange gaps are the *physical* manifestation of an out-of-phase rotation of dipole and nematic order. Most importantly, anisotropy in the fluid of fluctuations is independent of the dipole order and may survive the loss of an ordered moment. CGT describe a theory that fails to reproduce the correct semiclassical limit: In their picture there is no incipient quadrupolar order and accordingly the quantum exchange gaps are absent. The presence or absence of quantum exchange gaps in helimagnets can in fact be tested experimentally; at an analytic level, we contest that the only reliable way to address this issue is to use an approach that correctly reproduces the limit of classical magnetism.

P. Coleman[1] and P. Chandra[2]
[1]Serin Physics Laboratory
Rutgers University
P.O. Box 849
Piscataway, New Jersey 08854

[2]NEC Research Institute
4 Independence Way
Princeton, New Jersey 08540

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