X-Type Antiferromagnetic Stacking: Defying Magnonic Arithmetic

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In physics, our expectations for system behavior are often guided by intuitive arithmetic. For systems composed of identical units, we anticipate synergy of the contributions from these units, where $1 + 1 = 2$. Conversely, for systems built from opposing units, we expect cancellation of their contributions, where $1-1 = 0$. This intuitive arithmetic has long underpinned our understanding of physical properties of materials, from electronic transport to optical responses. However, scientific breakthroughs often occur when nature reveals ways to circumvent these seemingly fundamental rules, opening new possibilities that challenge our deepest assumptions about material behavior.

In the rapidly evolving field of magnon spintronics, this arithmetic finds a particularly compelling manifestation. Magnons—the quantized spin waves in magnetic materials—have emerged as promising information carriers for next-generation low-power computing. Their ability to transmit spin angular momentum without accompanying charge flow makes them ideal for reducing energy consumption in information processing. The performance ceiling of any magnonic device, from logic elements to interconnects, is fundamentally determined by one key parameter: the strength of the magnon spin current.

This performance requirement has traditionally led researchers to ferromagnetic (FM) materials, where the aligned magnetic moments naturally follow the "$1+1 = 2$" paradigm. Under a thermal gradient, magnons in FMs collectively propagate with aligned spin directions, summing constructively to produce substantial spin currents. Recent advances have further enhanced this effect through dimensional confinement, where reducing materials to ultrathin films intensifies magnon spin conductivity by modifying density of states and suppressing certain scattering channels.[1] However, these FM systems face intrinsic limitations: their dynamics remain confined to gigahertz frequencies, and their stray fields present significant challenges for device integration and scaling.

The logical alternatives are antiferromagnetic (AFM) materials, whose antiparallel spin sublattices promise terahertz-speed dynamics and negligible stray fields—advantages that could revolutionize high-speed, dense spintronic circuits.[2] Yet, here lies the predicament: the Bose–Einstein distribution ensures that magnon states across all energies from both opposing sublattices are populated according to a thermal distribution that does not discriminate between the chiralities of magnon modes. Consequently, the spin currents they carry, being equal and opposite in conventional antiferromagnets, perfectly cancel out, rigorously enforcing the "$1 - 1 = 0$" rule. This compensation is not just a conceptual limitation but a mathematical certainty derived from the fundamental statistics governing these excitations.

Even in ferrimagnets or unconventional antiferromagnets like altermagnets[3,4]—where sublattice contributions can differ—the cancellation remains severe, sometimes leaving only a feeble remnant: the "$1.1 - 1 = 0.1$" effect. While theoretically finite, these residual spin currents prove vastly inferior to their FM counterparts, rendering them impractical for real applications. The Bose–Einstein distribution acts as a relentless equalizer, ensuring that asymmetry in band structure gets averaged out over the thermally populated states, maintaining strong compensation across the entire energy spectrum.

A study by Wang *et al.* published in *Chinese Physics Letters* fundamentally rewrites this long-standing paradigm.[5] The authors demonstrate that in X-type magnets—that is, systems with X-type AFM stacking, where opposing magnetic sublattices form orthogonal, intersecting one-dimensional chains[6]—the usual "compensatory arithmetic" is ingeniously circumvented. The unique cross-chain geometry spatially locks magnon transport to specific lattice directions, enabling an unprecedented outcome: "$1 - 1 \approx 1$".

The power of the X-type stacking lies in how it manipulates the fundamental transport parameters. In conventional AFM systems, both sublattices contribute significantly to transport along any given direction, making cancellation inevitable under Bose–Einstein statistics. However, in the X-type stacking, the orthogonal chain structure means that when a thermal gradient is applied along one chain direction, the magnons from the parallel chain dominate the transport with high group velocity, while the contribution from the orthogonal, opposing chain is largely silenced due to its minimal group velocity in that specific direction. This is not merely band splitting—it is a complete reorganization of the transport landscape where the

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opposing sublattice becomes essentially "invisible" along the current direction. Crucially, the system maintains pronounced quasi-one-dimensional (quasi-1D) characteristics, significantly enhances magnon spin conductivity beyond conventional magnetic systems.

This ingenious spatial decoupling provides an elegant bypass of the pervasive cancellation imposed by Bose–Einstein statistics. The statistics still apply—magnons still populate both sublattices according to Bose–Einstein distribution—but the transport becomes so anisotropic that the opposing contributions simply do not interact in the same spatial channel. The result effectively transforms the frustrating "$1-1=0$" into a revolutionary "$1-1\approx 1$" outcome, where the net spin current approaches the magnitude of what would be expected from a single sublattice operating alone.

What makes this breakthrough particularly significant is its generality. The X-type stacking principle provides a materials design strategy that can be applied across the entire spectrum of antiferromagnetically-coupled materials. This is not a delicate effect requiring fine-tuning of specific parameters but a robust geometric principle that creates inherently superior transport characteristics. The work demonstrates that by engineering the spatial arrangement of magnetic sublattices, we can create materials where the intrinsic advantages of AFM coupling (speed, stability, zero stray field) are no longer compromised by the traditional drawback of spin current compensation.

By providing a geometric solution that simultaneously suppresses compensation and enhances conductivity through quasi-1D confinement, this work enables practical spintronic devices that no longer force a trade-off between speed, stability, and signal strength. It redefines what is possible in magnonic materials engineering—ushering in terahertz-speed, low-power computing architectures that fully harness the potential of AFM dynamics.

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References

[1] Wei X Y, Santos O A, Lusero C S, Bauer G, Youssef J B, and Wees B J van 2022 *Nat. Mater.* **21** 1352

[2] Baltz V, Manchon A, Tsoi M, Moriyama T, Ono T, and Tserkovnyak Y 2018 *Rev. Mod. Phys.* **90** 015005

[3] Šmejkal L, Sinova J, and Jungwirth T 2022 *Phys. Rev. X* **12** 031042

[4] Cui Q, Zeng B, Cui P, Yu T, and Yang H 2023 *Phys. Rev. B* **108** L180401

[5] Wang Z A, Li B, Zhang S S *et al.* 2025 *Chin. Phys. Lett.* **42** 110713

[6] Zhang S S, Wang Z A, Li B *et al.* 2025 *Newton* **1** 100068