Progress in Spinconversion and its Connection with Band Crossing

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Spinconversion is a collective concept underlying spin mediated energy interconversion among electricity, light, sound, vibration, and heat. Particularly in the last couple of decades, the increasing research efforts result in enhancements of spinconversion efficiencies and the discovery of novel spinconversion mechanisms. Here, an overview of the progress in spinconversion is laid out. In particular, the involvement of band crossings at which quasiparticles are formed with consequences beyond that of efficient spinconversion are discussed.

1. Introduction

One of the global challenges we face nowadays is operate the ever-larger information and communication infrastructure, while reducing energy consumption.[1] This issue is a fundamental task incorporated in the sustainable development goals set by the United Nations.[2] Motivated by this challenge, spinconversion has attracted vast research attention in the last decade.[3] The spinconversion field aims to demonstrate the efficient transfer of spin information among various energy entities permeated in our daily life, such as electricity, light, sound, vibration, and heat. The most recurring spinconversion mechanisms are the direct and inverse spin Hall effect (ISHE), direct and inverse Rashba Edelstein effect (REE), SHE, spin Nernst effect, spin photovoltaic effect, and acoustic spin pumping. Each of those spinconversion effects has sustained steady progress in conversion efficiencies in the last decade. Furthermore, spinconversion research recently revealed novel spinconversion mechanisms, such as the magnetic SHE,[4] opening new avenues for applications. Moving forward in the spinconversion research, we can look at the strength of the coupling of the participating energy forms when spinconversion occurs. For instance, the magnon–phonon coupling strength dictates the energy transfer efficiency in acoustic ferromagnetic resonance at resonant condition. Beyond spinconversion, bringing the coupling strength between quasiparticles such as phonons, photons, magnons to the strong coupling regime can form novel hybrid quasiparticles, with repercussions in other research fields such as quantum information.

Needless to say, there is more than one way to classify the spinconversion effects. This review article divides our description in magnetoelectric spinconversion effects (SHE and REE), thermal and acoustic spinconversion (phononic), and photonic spinconversion. Then we give an overview and perspectives on the recent spinconversion based on symmetry considerations and spinconversion toward a strong coupling regime.

2. Magnetoelectric Spinconversion

The representative spin-charge interconversion mechanisms are the SHE and the REE, including the Edelstein effect occurring at the topological insulator surface state. The so-called direct SHE (DSHE) and direct REE (DREE) converts charge current to spin current, while the ISHE and inverse REE (IREE) converts spin current to charge current. The critical difference between SHE and REE regards their dimensionality. SHE occurs in the bulk, therefore 3D spinconversion, and REE occurs at interfaces and surfaces, therefore 2D spinconversion. Nowadays, there is a vast amount of literature reporting values of spinconversion efficiencies. Here, we will not provide a list of reported spinconversion values, which is a laborious task. However, we would like to point out that a significant number of studies in the literature report seemingly contradicting spinconversion efficiency values. For instance, comparing spin Hall angles in single heavy elements such as Pt resulted problematic. Two main mechanisms responsible for the spin Hall effect are an intrinsic mechanism tied up to the spin-dependent band structure and an extrinsic mechanism tied to side jump and skew scattering events with impurities. Note that side jump scales with resistivity but skew scattering does not. In general intrinsic mechanism scales with resistivity, Sagasta et al.[5] reported a scaling rule for the SHE in Pt, whose mechanism moved from an intrinsic to an extrinsic regime when decreasing the resistivity from a moderately dirty to clean metal, reconciling part of the spread values of...
spin conversion efficiencies of Pt in the literature. Notably, the method used by Sagasta et al.\cite{5} applies to other SHE systems. Also, there have been several attempts to compare the spin conversion efficiencies between SHE and REE; one can notice that this is not a straightforward task. If the reader is interested in this task, we refer to recent studies in this topic.\cite{6,7}

Here, we focus our discussion on a fundamental aspect of spin conversion, its relation with its band structure, precisely the connection with band crossing. Early on, it was recognized that the intrinsic contribution to the spin Hall conductivity relates to the band structure and its links to Berry curvature and the anomalous transverse velocity.\cite{8,9} The spin Hall conductivity can be defined as

\[ \sigma_{\text{SH}} = \int f(e_k) \Omega_k dk \]

where \( f(e_k) \) is the Fermi–Dirac distribution function, and \( \Omega_k \) is the Berry curvature. Importantly, the Berry curvature ultimately depends on the wavefunction distribution in \( k \) (\( \psi_i(k) \)) and band distributions, which are strongly linked to the crystal symmetries and orbital hybridization. A reasonable strategy to maximize the SHE is to maximize the Berry curvature. With this in mind, Derunova et al.\cite{10} suggested the following: search for materials with band crossings and a hybridization gap induced by spin-orbit coupling (SOC), forming what is known as anticrossing, with the Fermi energy lying inside the gap. The integration of the Berry curvature of each occupied band would generate a large SHE. Derunova et al.\cite{10} scenario explains the giant SHE in \( \beta-W \) and predicts large SHE in new compounds such as \( W_3TA \) and \( Ta_3Sb \). Interestingly, band anticrossing may also play an important role in Rashba systems. One ongoing debate is the existence of Rashba systems with efficient spin conversion and seemingly low SOC. Recently, Mera Acosta et al.\cite{11} proposed an explanation with the energy band anticrossing at the center of the argument. As it is well-known, the magnitude of the spin conversion in Rashba systems is strongly linked to the so-called Rashba parameter \( \alpha_R = E_R / 2k_b \gamma \) where \( E_R \) is the spin splitting energy, and \( k_b \) is the momentum offset. One can immediately recognize that a large \( \alpha_R \) requires large-spin splitting energy \( E_R \) and small momentum offset \( k_b \). The existence of spin anticrossing can accomplish this scenario. Figure 1 (reproduced from ref. \cite{11}) shows the schematic representations of Rashba systems with noncrossing bands (top panels) with and without interacting orbitals and SOC, and Rashba systems with anticrossing bands (bottom panels) with and without interacting orbitals and SOC. As it is visible from Figure 1, the largest expected values for \( \alpha_R \) are those from Rashba systems with interacting orbitals and SOC. The hypothesis given by Mera Acosta et al.\cite{11} could also explain the efficient spin conversion in non-centrosymmetric topological insulators, as band anticrossing is ubiquitous to topological insulators.

### 3. Thermal and Acoustic (Phononic) Spinconversion

In the last decade, there has been a reignited interest in magnetization interacting with lattice vibrations, particularly under resonant conditions. As first described by Kittel,\cite{12} the dispersion relations of spin waves (magnons) and acoustic waves (phonons) conveniently converge at GHz frequencies in ferromagnetic materials. As it turns out, this resonant magnon–phonon interaction resulted in spin conversion mechanisms either driven by temperature gradients or acoustic excitation.\cite{13,14} In the following, we describe further the spin conversion driven by thermal and acoustic phonons individually, and their relation with band crossings.

Thermal spin conversion refers to the generation of spin currents \( J_s \) by thermal gradients \( \Delta T \).\cite{15} Although the voltage generation due to the spin Seebeck effect is not tied up to a resonant condition between magnons and phonons, Kikkawa et al.\cite{13} reported evidence of additional peak-like features in the spin Seebeck voltage when magnon and phonon dispersions converge. Figure 2 shows the spin Seebeck voltage in \( Pt/Y_{1/2}FeO_{12} \)\((YIG)\) measured by Kikaw et al.\cite{13} at a temperature \( T = 50 K \) under a temperature gradient of \( \Delta T = 1.73 K \). Additional to the conventional spin Seebeck voltage, two resonant peak-like features appear around 2.6T and 9.3T. These resonant peaks were explained by Boltzmann transport theory and the mixed magnon–phonon modes, which correspond to the band crossing point between the magnon dispersion and a transverse acoustic mode for the resonant peak at low fields and longitudinal acoustic mode for the resonant peak at high fields.\cite{16} More recently, it was demonstrated that by tuning the magnon dispersion curve of a magnetic compound, it is possible to achieve significantly larger resonant voltage at room temperature, enabling device developments.\cite{17} Further details on the measurement geometry of spin Seebeck in these experiments can be found in ref. [13].

Acoustic spin conversion refers to generating spin currents \( J_s \) by acoustic waves, typically Rayleigh type surface acoustic waves (SAW).\cite{14} Surface acoustic waves can drive ferromagnetic resonance (FMR) via magnetoelastic coupling at the band crossing between magnon and phonon dispersions. Consequently, the acoustic ferromagnetic resonance generates spin current.\cite{18–20} One prospect of surface acoustic wave devices in spin conversion is the possibility of engineer resonant acoustic cavities. An acoustic cavity is formed by one pair of acoustic reflector gratings
Figure 2. Resonant spin Seebeck voltage in Pt/YIG. a) Spin Seebeck voltage in Pt/YIG at a temperature $T = 50$ K under a temperature gradient of $\Delta T = 1.73$ K. Two voltage peaks are visible at b) 2.6 T and c) 9.3 T, which are attributable to the band crossing of the magnon dispersion with the transverse acoustic phonon (TA) and longitudinal acoustic phonon (LA) dispersions, respectively. Figure reproduced from ref. [13].

Figure 3. Acoustic spin pumping in an acoustic cavity device. a) Illustration of an acoustic cavity device. The top of the illustration shows a pair of interdigital transducers (IDTs) with an active layer in between for acoustic spin pumping experiments, similar to those reported in ref. [20]. The bottom illustration shows the structure with a pair of IDTs with the addition of two reflectors separated by a distance equal to a multiple of the acoustic wavelength $\lambda_{\text{SAW}}$, forming an acoustic cavity device, similar to those reported in ref. [21]. b) In-plane field angle dependence of acoustic ferromagnetic resonance power absorption for an acoustic cavity device (blue circles) and a device with no cavity (red squares). Fitting expression can be found in ref. [21]. c) SAW excitation power dependence of acoustic spin pumping output voltage at in-plane field angle $\phi = 45^\circ$, for devices with (blue circles) and without (red squares) acoustic cavity. The inset shows the spin pumping spectra at the resonance field. Reproduced with permission [21]. Copyright 2020, AIP Publishing.

Photovoltaics is a vast field of research mainly devoted to developing efficient photovoltaic cells in the solar spectrum. Nevertheless, the prospects of having photovoltaic generation with spin information have also motivated research in photonic spin conversion. It was immediately recognized that the circular polarization of light could transfer the angular momentum to electrons, polarizing the spin. In early works, the photon energy was absorbed by a semiconductor material with well-defined optical absorption energy such as GaAs, coupled to a spin Hall material such as Pt for a spin to charge conversion [22]. Interestingly, modifications to the band structure due to spatial symmetry breaking at interfaces can induce new routes for optical absorption and spin conversion via the Rashba–Edelstein effect [23, 24], enabling studies of photonic spin conversion in a larger number of heterostructures. The so-called shift current is another intriguing
phenomenon linked to the band structure, particularly the band crossing. The shift current is associated with an unidirectional shift of the electronic Bloch wavefunction, given by an asymmetric optical charge transfer. As it turns out different from electron drift and photovoltaic diffusion mechanisms, the propagation distance and directions of the shift current are dependent on the difference in Berry curvatures of the ground and excited states. The expectation value of the shift current \( J_{sc} \) is defined by\(^{25}\)

\[
J_{sc} = \int \frac{\pi E^2}{2v^2} \frac{\Gamma}{\sqrt{2\pi \Gamma^2}} \delta(d_{ij})|\phi_{ij}^0|^2 \left[ \frac{d}{dk} \text{Im}(\log \nu_{12}) + a_{ij} - a_{ii} \right]
\]

(2)

where \( E \) and \( v \) are the electric field and frequency of light, respectively, \( \Gamma \) is the relaxation of the electrons and \( a_{ij} \) and \( a_{ii} \) are the Berry connection of the conduction and valence bands, respectively. Thus, \( \Gamma/\sqrt{E^2 + \Gamma^2} \) describes the competition between neutral relaxation and induced emission, and \( \text{Im}(\log \nu_{12}) + a_{ij} - a_{ii} \) is the gauge-invariant shift of the intracell coordinate in a 2x2 Hamiltonian. Due to its topological protection, the shift current is negligibly affected by defects, which is a highly regarded property toward device developments.\(^{26,27}\) Recent studies have also linked the shift current mechanism to the photovoltaic conversion in perovskites.\(^{27,28}\) Although shift current points out as the dominant mechanism in the bulk photovoltaic effect, other nonlinear processes such as the ballistic current, many-body effects, and quasiparticles are also relevant.\(^{29}\)

5. Novel Spinconversion Based on Symmetries

Spatial symmetry \( S \), time-reversal symmetry \( T \), and chirality CT are general concepts in many solid-state phenomena. Regarding spinconversion, one of the most celebrated mechanisms is the Rashba spin-orbit coupling, ubiquitous in systems with spatial inversion symmetry breaking. In a short description, the spatial inversion symmetry breaking makes the spin-orbit coupling odd in the momentum \( p \) of the electron, with various consequences, including RER and SHE spinconversion mechanisms. We have discussed the RER and SHE spinconversion previously. We will not elaborate further here; instead, we will discuss the novel spinconversion mechanisms reported recently and their dependence on symmetries. In particular, we focus our discussion on 2D Weyl semimetals and antiferromagnets.

It is well established that the intrinsic SHC is closely connected to the symmetry of the crystal under analysis.\(^{30}\) A prime ruling imposed by high space group symmetries in the spin Hall effect is that spin polarization \( (k) \), spin current \( (i) \), and charge current \( (j) \) are mutually orthogonal. Thus, in conventional spin Hall materials with at least two mirror symmetries (i.e., cubic), the allowed SHC tensor elements have the form \( \sigma_{ij}^k \) with \( k \neq i \neq j \). Exploring the consequence of altering the symmetry in spinconversion experiments is an intriguing route. Few layered MoTe\(_2\) (Weyl semimetal) turned out to be a good candidate for these studies.\(^{31}\) In bulk, MoTe\(_2\) possesses the space group Pmn\(_2\), with two mirror symmetries, behaving similarly to conventional spin Hall materials. However, when MoTe\(_2\) is reduced to few monolayers, it loses one of the mirror symmetries (along the thickness) and the space group becomes Pm\(_{11}\). Table 1 extracted from ref. \(^{31}\) shows additional off-diagonal elements to the conventional SHE elements, the space group Pm\(_{11}\) allows the SHC matrix with the form \( \sigma_{ij}^k \). In this case of the \( z \)-axis, the direction of the charge current is parallel to the spin polarization, and both are perpendicular to the spin current direction (\( x \)-axis). Not only the experiments demonstrated an out of plane spin polarization under out of plane charge current injection, but analysis of nonlocal voltage measurements in few-layered MoTe\(_2\) resulted in simultaneous large spin Hall angle (\( \theta_{SHE} = 0.32 \)) and considerable spin diffusion length (\( L_{sd} = 2.2 \) \( \mu m \)), something mutually exclusive in conventional spin Hall materials with at least two mirror symmetries.

Now, let us explore the consequences of breaking time-reversal symmetry in spinconversion. One crucial characteristic of spin-orbit coupling is that it preserves the time-reversal symmetry. Thus SHE is unaltered under magnetization reversal. Kimata et al.\(^{4}\) demonstrated that an unconventional SHE could occur in the noncollinear antiferromagnet Mn\(_3\)Sn, where the time-reversal symmetry is broken. Figure 4\( a \) shows the schematic of the experiment performed in ref. \(^{4}\). The schematic shows the spin accumulation induced by the spin Hall effect in Mn\(_3\)Sn, as spin-dependent chemical potential measurement detected a voltage drop across a ferromagnetic NiFe and nonmagnetic Cu electrodes. Figure 4\( b, c \) shows the magnetoresistance measurement under two opposite spin textures in Mn\(_3\)Sn, induced under an initial large saturation field (\( \pm 0.75T \)). The voltage drop across NiFe and Cu electrodes measures the spin accumulation in Mn\(_3\)Sn which reverses sign when the Mn\(_3\)Sn sublattice moments, forming inverse triangle structure, are reversed, as is schematically shown in the insets. The unexpected sign change indicates that the dominant contribution to the SHE in Mn\(_3\)Sn is odd under time reversal \( T \). Interestingly, the time-reversal symmetry breaking is given not by the vanishing net magnetization but the large Berry curvature with the origin of Weyl points in the momentum space of the chiral spin structure.

6. Outlook: Spinconversion toward Strong Coupling

Whereas many spinconversion experiments occur under resonant conditions, limited attention has been committed to understanding and manipulating of the coupling strength of the
quasiparticles participating in spin-conversion. One case in point that demonstrates the benefits of studying in-depth the coupling strength is the research in light–matter interaction. In light–matter interaction, the investigation into the strong coupling regime started with a concept known as the Purcell’s effect,[32] which demonstrates that modifications of the density of final states of an atom inside a resonant cavity lead to improvements of the spontaneous emission. Surrounding this pioneering idea, the concept of cavity quantum electrodynamics (QED) was well-established.[31] Table 2 shows a sample of the phenomena studied and developed in light-matter interaction through QED, which has already impacted our society. Here, we briefly describe the possible routes of spin-conversion studies toward strong coupling interaction.

Let us first define the weak and strong coupling regimes in terms of a coupling strength energy $g$ and energy losses of two quasiparticles $\gamma_q$ and $\kappa_q$, such that if the coupling energy is smaller than the energy losses $g/(\gamma_q, \kappa_q) < 1$, we are in the weak coupling regime, however, if the coupling energy is larger than the energy losses $g/(\gamma_q, \kappa_q) > 1$ we are in the strong coupling regime. Although we are not dealing with ultra-strong coupling here, we would like to point out that the definition of ultra-strong coupling does not compare the coupling strength $g$ with the energy losses in the system but rather with the excitation frequency $\omega$, such that $0.1 > g/\omega < 1$ delimits the ultra-strong coupling regime. If the reader is interested in the physics of the ultra-strong coupling regime, we refer to a comprehensive review in the topic.[34]

As mentioned in previous sections, in the case of on-chip acoustic cavities as presented in Figure 3, even in the weak coupling regime, it is possible to achieve enhancements of acoustic ferromagnetic resonance and consequent enhancements of the spin current generation. Although the spin current enhancements reported by Hwang et al.[21] are mainly the result of improvements of SAW collection. It would be interesting to explore the effects of spin current with a higher quality factor of the acoustic cavities, such as nonlinear behavior under large oscillator strengths. Moving toward the strong coupling regime between magnon and phonons $g/(\gamma_{\text{phonon}}, \kappa_{\text{magnon}}) > 1$, it is clear that in addition to the minimization of phonon losses ($f_{\text{phonon}}$) by acoustic cavities, we have to minimize the magnon losses ($\kappa_{\text{magnon}}$) by employing low damping magnets such as YIG. As a matter of fact, YIG is the material of choice for strong coupling studies reported recently[35,36]. Figure 5a,b extracted from ref. [35] show strong coupling experiments with a millimeter size YIG sphere inside of a microwave photon cavity; when the microwave cavity mode enters in resonance with the magnon Kittel mode, we can observe the magnon–photon anticrossing; the vertical axis in the plot shows the probe microwave frequency, and the horizontal axis is the static magnetic field shown as applied current $I$ to the superconducting coil. At this point, it is important to note that the coupling strength $g$ in these experiments is directly proportional to the square root of the number of participating spins $\sqrt{N}$, which can be conveniently tuned by the dimensions of the magnetic system, a degree of freedom not available in most of the exciton–polaritons. YIG on gadolinium gallium garnet (GGG) turned out to be also an ideal platform for magnon–phonon coupling. Figure 5c,d extracted from ref. [36] show the coupling of YIG magnons with phonons in a single-crystal GGG layer; in the experiment, we can observe the interaction of the YIG Kittel mode with multiple modes of the nth standing shear acoustic waves. It would be desirable to combine planar acoustic cavities as illustrated in Figure 3a with YIG layers as magnetic systems. Another intriguing prospect of magnon–phonon coupling is the formation of Bose–Einstein condensates (BEC). Both magnons

**Figure 4.** Spin accumulation in the noncollinear antiferromagnet, Mn$_3$Sn. a) Schematic of the experiment performed in ref. [4]. The schematic shows the spin accumulation induced by the spin Hall effect in Mn$_3$Sn, which is detected by the chemical potential measurement via a voltage drop across NiFe and Cu electrodes orthogonally aligned to the current. b,c) Magnetoresistance measurements under two opposite configurations of spin textures induced by applying an initial large saturation field. Reproduced with permission.[4] Copyright 2019, Springer Nature.

| Table 2. Samples of phenomena in light–matter interaction under weak ($g/(\gamma_q, \kappa_q) < 1$), strong ($g/(\gamma_q, \kappa_q) > 1$) and ultra-strong coupling ($0.1 > g/\omega < 1$) regimes; $g$ is the coupling strength energy, $\gamma_q$ and $\kappa_q$ are the energy losses of two given quasiparticles, and $\omega$ is the excitation frequency. |
|-----------------|-----------------|-----------------|
| Coupling strength phenomena in light–matter interaction | Weak coupling $g/(\gamma_q, \kappa_q) < 1$ | Strong coupling $g/(\gamma_q, \kappa_q) > 1$ | Ultra-strong coupling $0.1 > g/\omega < 1$ |
| Purcell effect | −Purcell effect | −Rabi oscillations | −Light–matter decoupling |
| Laser technology | −Laser technology | −BEC | −Virtual excitations |
| Weak nonlinearities | −Weak nonlinearities | −Strong nonlinearities | −Novel nonlinearities |
and phonons are bosonic quasiparticles; ergo, they follow the Bose–Einstein statistics, and form BECs. The experimental challenge in achieving BECs is accommodating many quasiparticles within a single quantum state with the lowest energy. In other words, place many quasiparticles under de Broglie wavelength such that, following the Heisenberg uncertainty principle, the wavefunction of adjacent atoms overlap, making the atoms indistinguishable, obeying now the laws of quantum statistics. To get deeper insight, we look at the definition of the de Broglie wavelength $\lambda_{DB} = \sqrt{2\pi\hbar/k_B m T}$, where $m$ is the atomic mass and $T$ the temperature of the gas. Looking at this definition of $\lambda_{DB}$ we can understand why the formation of BECs with atoms occurs when the system temperature $T$ lowers. However, there is a caveat in the formation of BECs with magnon quasiparticles. Reducing the temperature reduces the number of thermal magnons inducing the BEC, limiting the formation by merely reducing the temperature. Nevertheless, increasing the number of coherent magnons above the thermal equilibrium is still possible to achieve condensation at elevated temperatures, even at room temperature, due to the lower effective mass $m$ of the quasiparticles. An excess of magnons can be obtained by out-of-resonance parametric excitation, where magnons are excited above the ferromagnetic resonance frequency $\omega_{\text{FMR}}$. Then, the magnons thermalize to the lower dispersion region via the four magnon scattering process as shown in Figure 6, taken from ref. [38]. After reaching a critical density of magnons, a BEC can be formed in the dispersion minima. Interestingly, nearby the band crossing between magnons and phonons, the transfer of magnons to the BEC is significantly diminished, and instead, an accumulation of magnon–phonon hybrid quasiparticles is observed. Further understanding of this novel condensation phenomenon of hybrid quasiparticles is highly beneficial for fundamental physics and applications. Unlike magnon BECs, the condensation of hybrid magnon–phonon quasiparticles possesses nonzero group velocity, making them attractive as information carriers.

Regarding photonic cavities, in principle, we can readily take advantage of the photonic Purcell effect and couple those photons with well-defined angular momentum to materials for spinconversion and explore whether or not modifications of the spinconversion efficiencies are observed. Furthermore, Morimoto and Nagaosa[39] theoretically demonstrated that it is possible to extract a measurable DC photocurrent from the exciton–polariton state when the dispersion of cavity photons and excitons form an anticrossing band dispersion with upper and a lower polariton branches. We note that the DC photocurrent of exciton–polaritons has its origins in the diamagnetic coupling between electrons and photons, which is a higher order
coupling generally dismissed in the weak light–matter interaction. However, this diamagnetic coupling takes relevance in the strong coupling regime in cavity QED. The photocurrent from the exciton–polariton state also requires spatial symmetry and time reversal symmetry breaking. While the spatial symmetry breaking can be achieved by using noncentrosymmetric systems, time reversal symmetry breaking can be obtained by applying external magnetic fields or photons with circular polarization, adding angular momentum in the photocurrent.

7. Conclusion
We have presented a review of recent spin conversion works with connections to the band crossing at resonance conditions. Research on band crossing and symmetry has regained attention in recent years, mainly driven by the phenomena surrounding the Berry phase. Looking ahead, the enhancement of coupling strengths of the quasiparticles at band crossing in the spinconversion phenomena can have significant consequences beyond the spin current generation. In the strong coupling regime, higher order interaction terms are now relevant to the underlying observables in experiments such as nonlinearities and higher harmonic generation. BECs are at the forefront in condensed matter research, as they possess intriguing properties, acting as a macroscopic quantum object. Only recently, a novel type of condensation was reported formed by hybrid magnon–phonon quasiparticles, with properties that diverge from standard BECs, such as nonzero group velocity. The physics behind strong coupling in spin conversion experiments is only surfacing in the research community, as the fields of condensed matter, spintronics, and quantum information are finding their inevitable intersections.

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Conflict of Interest
The authors declare no conflict of interest.

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