Chapter

Magnetic Skyrmions and Quasi Particles: A Review on Principles and Applications

Birhanu Abera Kolech

Abstract

Skyrmions are topologically nontrivial, magnetic quasiparticles that are characterized by a topological charge. The field of magnetic skyrmions has been actively investigated across a wide range of topics during the last two decades. We mainly reviewed and discussed magnetic skyrmions, and quasiparticles: reviews on principles and applications. We concentrated on theoretical discoveries and advances in magnetic skyrmions, topological effects, the skyrmion Hall effect, and the dynamics of skyrmions. The skyrmion Hall effect causes a transverse deflection of skyrmions when they are driven by currents, whereas the first additional contribution to the Hall effect of electrons in the presence of a topologically non-trivial spin texture may become beneficial for detecting skyrmions. This means that when a current is applied along the racetrack, skyrmions are pushed toward the edge, causing pinning or possibly the loss of data. This is one of the reasons why there is currently no prototype for a spintronic device based on skyrmions. The anti-ferromagnetic and ferrimagnetic skyrmions were then discussed in relation to spintronics. Finally, we reviewed several potential applications based on magnetic skyrmions, including skyrmion race track memory, a skyrmion logical device, a skyrmion magnonic crystal, and skyrmion-based radio frequency devices.

Keywords: spintronic device, topological Hall effect, skyrmion hall effect, quasi particles, bimeron, ferromagnetic, antiferromagnetic skyrmions

1. Introduction

Information technology has significantly increased in relevance for our daily lives during the past few decades. The demand for energy-efficient data manipulation and storage has recently increased due to the recent dominance of modern information technology applications like streaming services and cloud storage. Although Moore's law is difficult for present electronic solutions to follow [1], new spintronic ideas have been put out and might soon become important [2].

The racetrack memory is one of the most promising and anticipated data-storing systems. The bits, which are encoded by the presence or absence of the magnetic object, are written, erased, relocated, and read on a restricted track. This method was first proposed for using domain walls as carriers of information [3–5]. This almost one-dimensional configuration can be stacked, opening the door to naturally three-dimensional data storage with far higher bit densities. In terms of lower energy consumption and quicker access times, this non-volatile idea outperforms conventional random access memory and hard disk drives [4].

This review focuses on non-collinear spin textures because topological matter, a promising study area outside of spintronics, is a focus of this work. The magnetic skyrmion [6] is the most notable example. A decade ago, this whirl-like nano-object was discovered [7]. Due to its topological protection, which offers it a tremendous amount of stability even at small scales, it has the potential to be an information carrier in the next generation of data storage devices, such as racetrack nano-devices [8–10].In addition to their high stability, the topological characteristics of skyrmions also lead to emergent electrodynamics, such as the topological Hall Effect and the skyrmion Hall Effect [11, 12]. The skyrmion Hall effect causes a transverse deflection of skyrmions when they are driven by currents, whereas the first an additional contribution to the Hall effect of electrons in the presence of a topologically non-trivial spin texture may become beneficial for detecting skyrmions [17, 18]. This means that when a current is applied along the racetrack, skyrmions are pushed toward the edge, causing pinning or possibly the loss of data. This is one of the reasons why there is currently no prototype for a spintronic device based on skyrmions.

While work to expand the use of magnetic skyrmions in spintronic devices will continue, various alternative nano-objects have been predicted and seen over the past six years. Research in this area will be further accelerated in the near future, as some of them hold even greater advantages over traditional skyrmions. We outline and discuss these additional magnetic quasiparticles in this review. We categorize the objects, describe how to stabilize them, and contrast their emergent electrodynamics with that of typical skyrmions.

2. Magnetic skyrmions

Tony Skyrme first proposed the existence of skyrmions in the context of particle physics in the 1960s. He demonstrated the existence of particle-like solutions with the characteristics of baryons and presented a field-theoretical explanation of interacting pions [13, 14]. Later, it was demonstrated that whereas pions themselves are bosonic, these solutions exhibit Fermi properties [15, 16]. The three-dimensional equivalents of what came to be known as “skyrmions” are the solitons, which are explained by a non-linear sigma model.

Skyrmions have recently been discovered in a number of physics domains, including string theory [20], liquid crystals [19], Bose-Einstein condensates [18], quantum Hall systems [17], and magnetism [7].

A skyrmion can be thought of in this context as a two-dimensional object that is trivially continued along the third dimension (**Figure 3a** and **c**). According to reciprocal-space measurements [7] and Lorentz transmission electron microscopy [21], these skyrmion tubes or strings were first discovered in MnSi in 2009 [21]. These objects’ magnetic textures confirmed the predictions made twenty years earlier [6]. Magnetic skyrmions in a ferromagnetic medium produce a non-trivial real-space topology in its core due to a constantly changing magnetization density that is oriented in opposition to the surroundings. These substances can exist as discrete particles or periodic lattices, as in the publications mentioned above [21, 22].

As these topics are necessary to comprehend the physics of the alternative magnetic quasiparticles, the treatment of conventional skyrmions is restricted to their geometrical characterization, stabilizing processes, and emerging electrodynamics. We cite one of the many review articles [23, 24] for a discussion of conventional skyrmions that goes beyond these issues.

2.1 History of Skyrmions in magnetism

For a very long time, skyrmions in magnetism have been explored. The most well-known magnetic Skyrmions are magnetic bubbles. From the 1960s through the 1980s, there was a lot of research done on these circular domains in an out-of-plane magnetized medium, partly because of the potential for use in solid state storage devices [25], which eventually led to commercial devices [26]. Industrial interest in bubble media was eventually lost due to the increasing efficiency of rotating hard disks in the 1980s, which was aided by the discovery of the gigantic magneto-resistance in 1988 [27, 28] and the development of flash memories[29]. However, research on current-induced domain wall motion [30] and racetrack memory devices [4] shows that the old idea of a store medium that is based on domains moving in a solid state device is once again receiving a great deal of attention. Skyrmions are promising candidates for the realization of such a device because of their remarkable mobility at extremely low currents, and it would be advantageous to repurpose the rich expertise of bubble-based technology. This thesis study, in which we examine the dynamics of magnetic bubbles at short (ns) time scales for the first time, could help to establish a connection between established bubble physics and cutting-edge work on domain wall physics for use in practical applications.

Kooy and Enz's work, which discovered an accurate theoretical model for the energetics and evolution of stripe domains and bubbles under the application of an external magnetic field [34], served as the catalyst for the initial research on bubble domains. The creation and manipulation of controlled bubbles began with this static model. The experimental development of operational bubble-based devices was afterward largely led by Andrew Bobeck and his Bell Laboratories team [25].

On the theoretical front, two turning points in our knowledge of bubble-domain dynamics must be emphasized. First, the one-dimensional model, developed to describe the motion of bubbles and which we will examine in more depth below, is quite successful in modeling the straight motion of magnetic domain walls, despite certain shoddy assumptions. The one-dimensional model is currently regarded as the accepted explanation for domain wall motion. The addition of the gyrocoupling vector to the equation describing the motion of magnetic bubbles was the second significant theory [31, 32]. The observation of the so-called skew deflections of bubbles [33] served as the impetus for Thiele's studies. It was discovered that the steady state velocity of a bubble has a sizable component perpendicular to the gradient rather than generally following the field gradient. Every bubble has a variable deflection angle, and it was even unpredictable whether the bubble would be redirected from the field gradient direction to the right or to the left.

2.2 Topology and characterization

A stereographic projection helps to explain the topological nature of a skyrmion. By rearranging the magnetic moments of a three-dimensional hedgehog, where all moments on a sphere point in the radial direction; a two-dimensional skyrmion can be

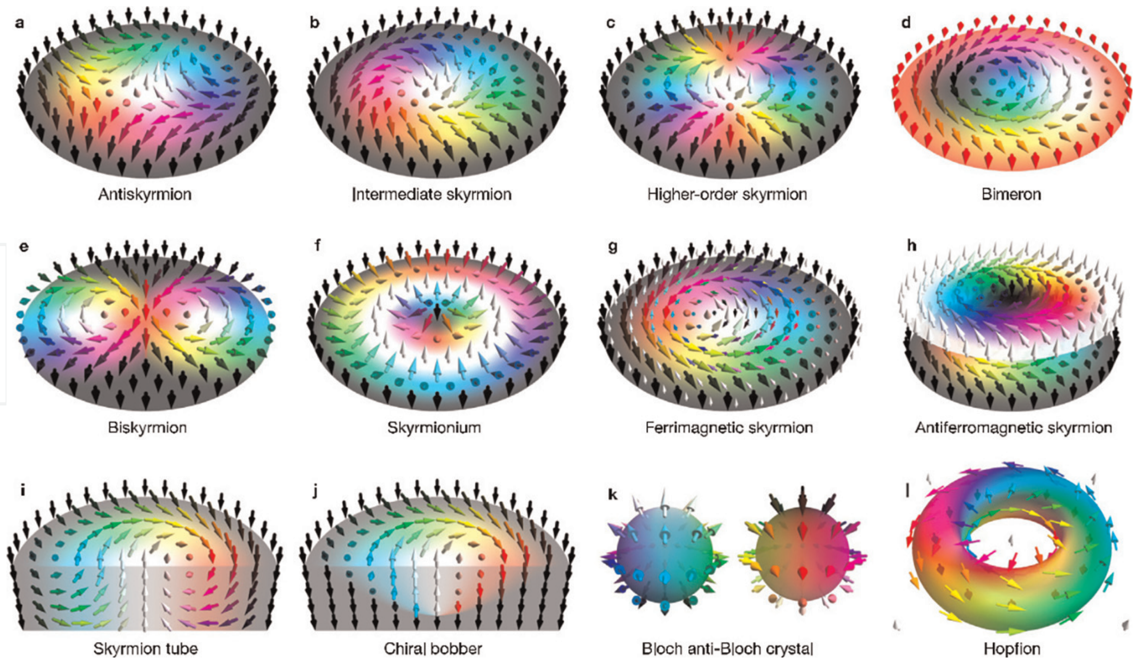

Figure 1.
Overview of the discussed topologically non-trivial spin textures [23].

created. Without altering the direction of the moments, this sphere gets split open at the bottom and flattened into a disk. The outcome is a two-dimensional magnetic entity that is topologically non-trivial (**Figure 1**).

The very first three products are various kinds of skyrmions, meaning they have different helices and vorticities: (a) an antiskyrmion with a vorticity of m = 1 and a topological charge of N_{Sk} = 1; (b) a skyrmion with an intermediate helicity of $\gamma = \frac{\pi}{4}$ among both Bloch and Néel type skyrmions and a topological charge of N_{Sk} = 1; and (c) a (d) Illustrates a magnetic bimeron made of two merons. Another interpretation is that it is a skyrmionic excitation in an in-plane magnetic medium, where N_{Sk} = 1. In the center row, two skyrmions are combined: (e) a biskyrmion with N_{Sk} = 2, (f) a skyrmionium with N_{Sk} = 0, and (g, h) ferrimagnetic and synthetic antiferromagnetic skyrmions, for which the topological charges of the two subskyrmions balance one another. The skyrmion tubes (possibly with varying helicity along the tube), the chiral bobber as a discontinued skyrmion tube, a pair of Bloch and anti-Bloch points serving as the building blocks of a three-dimensional crystal (hedgehog lattice), and the hopfion are all shown as extensions of skyrmions in the bottom row. The magnetic moment orientation is depicted by colored arrows. The positive and negative out-of-plane orientations are represented by white and black, respectively [23].

A skyrmion with a magnetization density of m(**r**) in a continuous picture cannot shift to a ferromagnetic state without discontinuous changes in the density. This is an example of the topology of real space that is not trivial as measured by the topological charge:

$$N_{SK} = \int n_{SK}(\boldsymbol{r})d^2r \tag{1}$$

which is as an integral over the topological charge density

$$n_{SK} = \frac{1}{4\pi}\boldsymbol{m}(\boldsymbol{r}).\left[\partial\frac{\boldsymbol{m}(\boldsymbol{r})}{\partial x}x\partial\frac{\boldsymbol{m}(\boldsymbol{r})}{\partial y}\right] \tag{2}$$

The following transformation makes it easier to infer a skyrmion's topological charge from its appearance. One expresses the magnetization density in spherical coordinates with the azimuthal angle θ and the polar angle Φ and expresses the position vector in polar coordinates **r** = r(cos φ, sin φ). Exploiting the radial symmetry of the out-of-plane magnetization density θ = θ(r), the topological charge reads [23]

$$N_{SK} = \int_0^\infty dr \int_0^{2\pi} d\varnothing \frac{\partial \varnothing(\varnothing)}{\partial \varnothing} \frac{\partial \theta(r)}{\partial r} sin\theta(r) = -\frac{1}{2} cos\theta(r) \Big|_{r=0}^{\infty} \cdot \frac{1}{2\pi} \varnothing(\varnothing) \Big|_{\varnothing = 0}^{2\pi} \tag{3}$$

The out-of-plane magnetization of a skyrmion is reversed comparing its center with its confinement. This is quantified by the first factor, the polarity

$$p = -\frac{1}{2} cos\theta(r) |_{r=0}^{\infty} = \pm 1 \tag{4}$$

The sign is dependent on the skyrmion host's out-of-plane magnetism. The polar angle can only wrap around in multiples of 2 since the magnetization density is continuous, which determines the second element, the vorticity.

$$m = \frac{1}{2\pi} |_{\varnothing = 0}^{2\pi} = 0, \pm 1, \pm 2, \dots . \tag{5}$$

The two-dimensional integral has been simplified to a product of the polarity and the vorticity [34]

$$N_{SK} = m.p = \pm 1, \pm 2, \dots . \tag{6}$$

$$\Phi = \mathrm{m}\varphi + \gamma \tag{7}$$

with an offset γ. This quantity is called helicity.

We have developed the three characteristic quantities for the various types of skyrmions, which are commonly stated as polarity, vorticity, and helicity.

$$N_{SK}(r) = \begin{pmatrix} \left(\frac{x \ cos\,\gamma}{r} - m\frac{y}{r}\, sin\,\gamma\right) \sin\left(\frac{\pi}{r_o} r\right) \\ \frac{x\ sinr}{r} + m\frac{y}{r}\ cos\,\gamma) \sin\left(\frac{\pi}{r_o} r\right) \\ pcos\left(\frac{\pi}{r_o} r\right) \end{pmatrix} \tag{8}$$

For $0 < r < r_o$. Note, that the out-of-plane magnetization profile is simplified as a cosine function (radius r0) and that the exact profile depends on the interaction parameters, the sample geometry, defects, and the presence of other quasiparticles.

As an example, the skyrmion in **Figure 2a** has a positive polarity p = +1 and vorticity m = +1 leading to a topological charge of NSk = +1. Since the in-plane component of the magnetization is always pointing along the radial direction, the helicity, in this case, is γ = 0. This type of skyrmion is called Néel skyrmion and is typically observed at interfaces [35]. Different from this type of skyrmions are the skyrmions in MnSi (e. g., from the initial observation [7]). They are called Bloch skyrmions. There, the in-plane components of the magnetization density are oriented perpendicularly with respect to the position vector. This toroidal configuration is

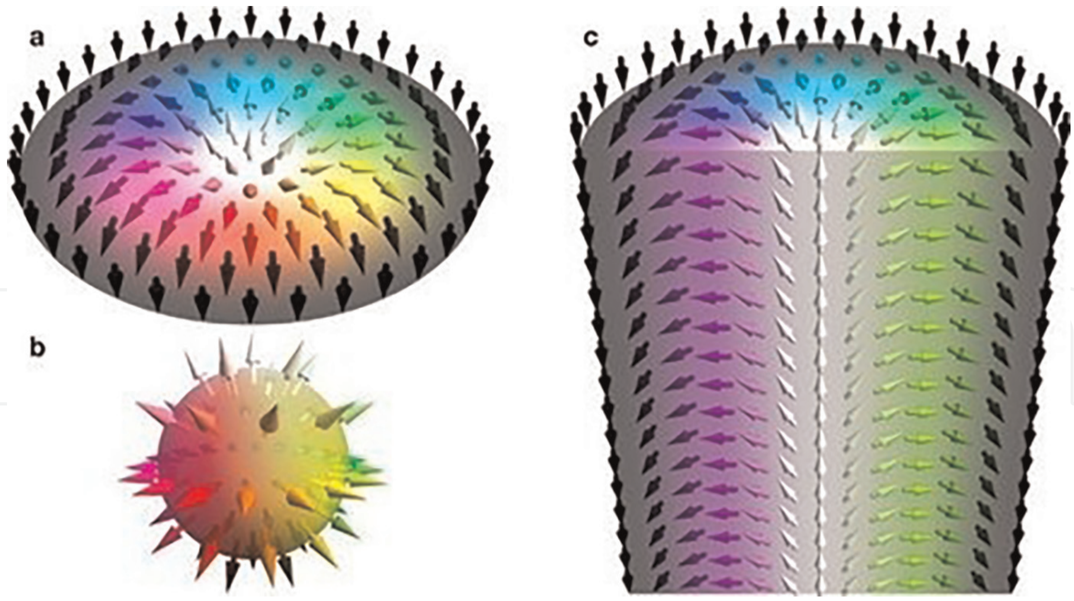

Figure 2.
Magnetic skyrmions are fundamentally non-trivial excitations in ferromagnets. (a) A two-dimensional magnetic symmetry; (b) a three-dimensional Bloch point or hedgehog that is stereographically projected to form (c) The skyrmion frequently extends trivially in three dimensions as a skyrmion tube [23].

characterized by a helicity of $\gamma = \pm\pi/2$. In contrast to the polarity and the vorticity, the helicity is a continuous parameter allowing for skyrmions as intermediate states between Bloch and Néel skyrmions, as shown in **Figure 3b**. Furthermore, the vorticity can in principle take any integer value constituting, for example, antiskyrmions for $m = -1$ (**Figure 3a**) or higher-order (anti)skyrmions for $|m| > 1$ (**Figure 3c**). Out of this manifold, Bloch [7], Néel skyrmions [35], and skyrmions with an intermediate helicity [36], as well as antiskyrmions [37] have been observed experimentally. Higher-order skyrmions [38, 39] have been predicted.

2.3 Skyrmions in more materials

2.3.1 Bulk crystals

A flurry of fresh trials on various materials was conducted after this initial observation. **Table 1** provides a summary.

The list includes everything from metals [7, 40–43] to doped semiconductors [44, 45] to insulators [46–51]. FeGe has the highest critical temperature on the list because a skyrmion lattice can nearly always be seen at room temperature. The magneto-electric properties of the insulator Cu_2OSeO_3, which allow it to be controlled by both magnetic and electric fields [48, 52–54], are one of its specialties. These discoveries were accompanied by magnetic [55–58] and ultrasonic [59] resonance studies, which show good agreement between theory and experiment.

A skyrmion lattice was also seen in 2015 by Tokunaga et al. [60] in -Mn-type Co-Zn Mn alloys. These alloys exhibit broken inversion symmetry in the bulk, however, they have space groups $P4_132$ or $P4_332$ instead of the materials' $P2_13$ space group. It is interesting to note that the altered composition causes both a bigger length scale for the magnetic structures and a higher temperature for the observation of the skyrmion lattice. At room temperature [61] and even higher [60], skyrmions can be seen depending on the composition ($Co_xZn_yMn_z$ with $x + y + z = 20$).

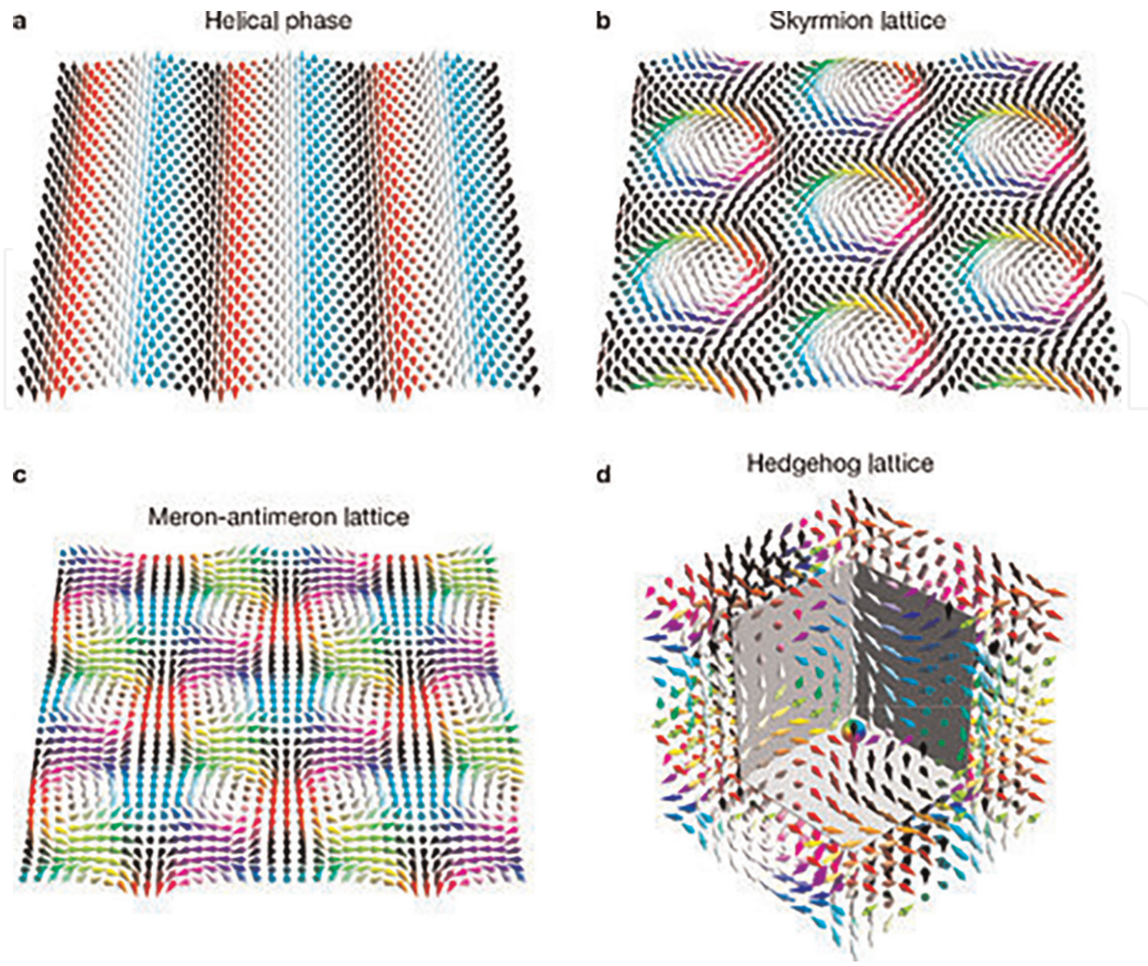

Figure 3.
Changing textures periodically. (a) A single Q vector designates the helical phase. (b) As seen in [39], a skyrmion lattice or skyrmion crystal is formed by superimposing three helices with Q vectors angled at a 120° angle. According to MnSi, a B20 material, the skyrmions (vorticity m = 1) are of the Bloch type (helicity$\gamma = \frac{\pi}{2}$) and form a hexagonal superlattice. Antimerons (vorticity m = −1) with a negative net magnetization (black) and merons (vorticity m = 1) with a positive net magnetization try to compensate the meron-antimeron lattice in (c) (white). The lattice has a positive net topological charge because both objects have a topological charge of NSk = +1/2. (d) The hedgehog lattice, also known as the Bloch anti-Bloch crystal, is created by superimposing three helices in three dimensions. The magnetization density in a continuous description has singularities. These Bloch or anti-Bloch points do not have a definite magnetization. A colored sphere, the Bloch point, is used to draw attention to one of these points [23].

However, the thermodynamically stable skyrmion lattice can be found in a very tiny pocket of the (universal) B-T-phase diagram, which is a feature shared by all bulk magnets. This finding is consistent with theoretical hypotheses supported by both analytical [7, 79] and numerical study [80] research (Monte Carlo). One method for expanding the pocket is to take advantage of the skyrmion's (topological) stability. Bloch points, also known as emergent monopoles, are single and thus energy-dense spin configurations that must destroy one skyrmion string or join two skyrmions together [81–84].

2.4 The interactions of skyrmions

Skyrmions interact with edges, flaws, magnetic textures, and especially other skyrmions while they are inside the nanostructure. According to simulations, skyrmions are attracted to both edges and other skyrmions [85–87].

This is true only if the trade relationship is not stifled, though [39, 88]. Additionally, if the backdrop is not out-of-plane polarized but rather polarized in another direction [89, 90] and conical [91, 92], the interaction of skyrmions with both other skyrmions and edges becomes appealing.

The idea to also include the racetrack's surface was just recently put out, as in the suggestion in Ref. [93], where it was demonstrated that a scratch in the surface can draw skyrmions and serve as a track without physical edges.

2.5 Pushing skyrmions

The concept of using spin-polarized currents to move the skyrmions along the track has been addressed [94–97]. Keep in mind that the mass of the skyrmions has no bearing in these circumstances. It should be emphasized, however, that Dzyaloshinsky-Moriya interaction-stabilized skyrmions are more rigid and have a low mass [96], whereas huge skyrmions, which typically require strong dipolar contacts, can readily deform and have a non-negligible mass [98, 99].

Due to their interaction with magnons, skyrmions may also be moved in this manner. Early simulations revealed that skyrmions in a temperature gradient gravitate toward the source of heat [100], which may be regarded as a source of magnons. More in-depth investigations revealed [101–105] that the source of magnons does, in fact, draw skyrmions. This theory can be applied to control the skyrmions in

Material	Sample	conduction	ΔT_{sky}/K	λH/nm	Type	Refs.
MnSi	Bulk	Metal	28–29.5	18	Bloch	[7, 40–42]
MnSi(press)	Bulk	Metal	5–29	18	Bloch	[62–65]
MnSi	Film(∼ 50 nm)	Metal	<5–23	18	Bloch	[66, 67]
$Fe_{1-x}Co_xSi$	Bulk	Semi -metal	25–30	37	Bloch	[44, 45]
$Fe_{0.5}Co_{0.5}Si$	Film(∼ 20 nm)	Semi- metal	5–40	90	Bloch	[21]
FeGe	Bulk	Metal	273–278	70	Bloch	[43]
FeGe	Film(∼ 75 nm)	Metal	250–270	70	Bloch	[43, 69]
FeGe	Film(∼ 15 nm)	Metal	60–280	70	Bloch	[68]
Cu_2OSeO_3	Bulk	Insulator	56–58	60	Bloch	[46–51]
Cu_2OSeO_3	Film(∼ 100 nm)	Insulator	<5–57	50	Bloch	[47, 70]
$Co_8Zn_8Mn_4$	Bulk	Metal	284–300	125	Bloch	[61]
$Co_8Zn_9Mn_3$	Bulk	Metal	311–320	>125	Bloch	[60]
$Co_8Zn_9Mn_3$	Film(∼ 150 nm)	Metal	300–320	>125	Bloch	[60]
GaV_4S_8	Bulk	Semi- metal	9–13	17.7	Nȇel	[72]
Fe/Ir/(111)	Monolayer	—	∼ 11	∼ 1	Nȇel	[36, 71, 73]
PdFe/Ir/(111)	Bilayer	—	∼ 4.2	∼ 1	Nȇel	[71, 73–77]
$(Ir/Co/Pt)_{10}$	Multilayer	Metal	*RT*	30–90	Nȇel	[78]
Pt/CoFeB/MgO	Multilayer	Metal	RT	480	Nȇel	[78]

The second column in the table includes information on bulk materials, thin films, and layer materials. The third column contains information about the conductivity, if it is known. The temperature range T_{sky} at which skyrmions were spotted, the helical/stripe phase's wavelength λH, and the skyrmion's texture are all listed in the ensuing columns.

Table 1.
Materials chosen that are known to contain skyrmion lattices or individual skyrmions.

nanostructures [106]. For more information, however, it should be noted that the interaction of magnons with edges and other textures is non-reciprocal in nature [107, 108]. A tilted background field combined with an oscillating superposition, which breaks enough symmetry once again to occupy the translational mode of a skyrmion, makes up a more macroscopic but related mechanism [109].

The stability of the skyrmions' trails has also been researched. Equidistant skyrmions should cover the same distances in the same amount of time if a storage device uses them. With the exception of interactions between skyrmions, which were previously thought to be completely pure, this can be assumed to be true. Studies on interactions between skyrmions and random defects such as vacancies or holes, as well as localized changes in magnetic properties, revealed that interactions between skyrmions and defects can exhibit behavior other than repulsive behavior. As calculated in effective particle models [91] and simulations of tracks made up of patches with changing anisotropy, the motion of a skyrmion can appear unexpected when combined with the gyroscopically dominated dynamics, as predicted from tests [110] (**Figure 4**).

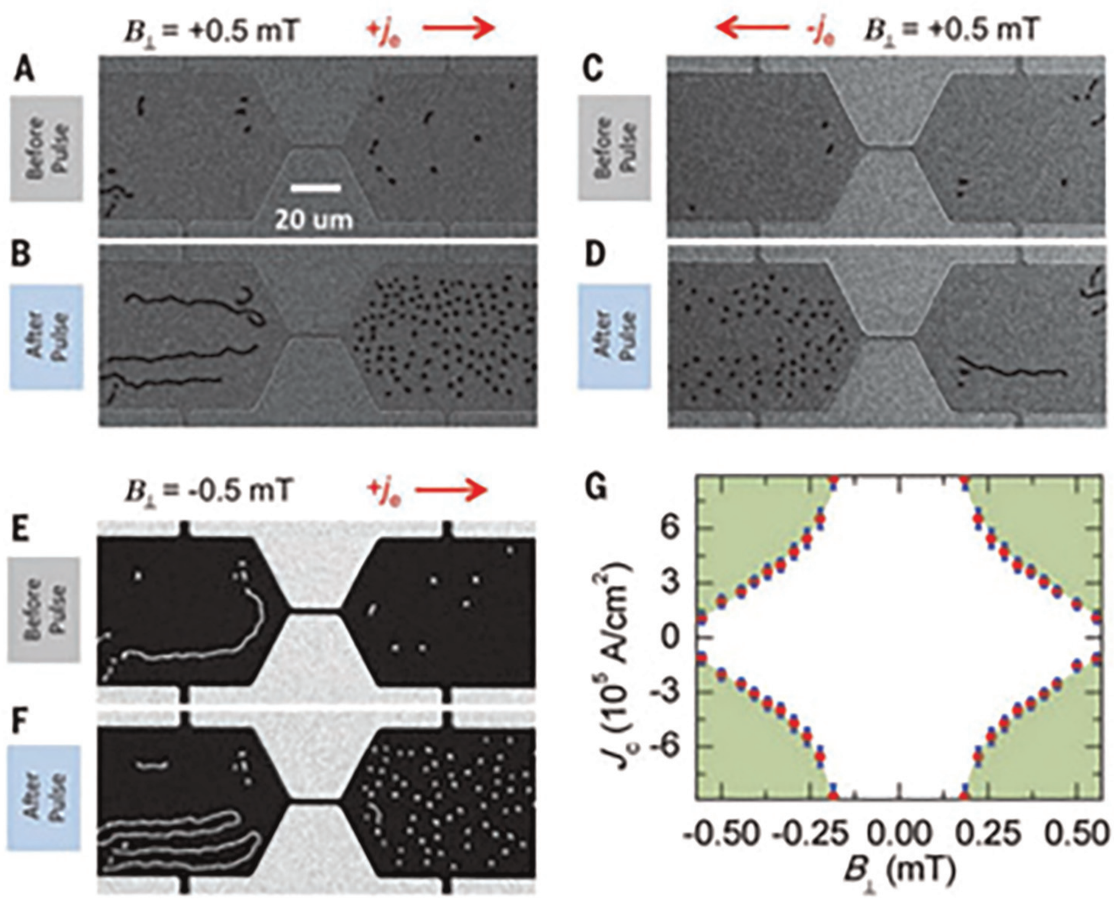

Figure 4.
Observational research as described by Jiang et al. [111]. We scanned and nanostructured a trilayer made up of Ta (5 nm)/Co20Fe60B20(CoFeB) (1.1 nm)/TaOx (3 nm). In panels (E) and (F), the trilayer-covered portions stand out as distinct black zones. These are skyrmions or extended skyrmions, which are the smaller structures in this region (bimeronsThe trilayer is exposed to a magnetic field B that is perpendicular to it. Note that the magnetic field is pointing in the opposite direction in (E) and (F), and as a result, the contrast is reversed. The initial states before any current is applied are shown in (A), (C), and (E). The magnetization is shown in (B), (D), and (F) following the application of a current pulse in the direction denoted by the red arrows. As a result, skyrmions gather in the direction of the current. The skyrmion proliferation is seen above the current densities Jc and fields B, as indicated by the green patches in the phase diagram (G) [111].

The thermal diffusion of skyrmions may potentially result in other issues [96]. Here, it is suggested that the racetrack be divided into parking lots utilizing a variety of techniques, such as voltage gating [112]. For skyrmion systems, antiferromagnetic coupling of layers has been proposed to remove the complex gyroscopic motion [113], which is well known for its beneficial effects on acceleration in conventional domain wall racetracks. Other ideas include antiferromagnetic rather than ferromagnetic nearest neighbor exchange interactions [114], which already solves the issue of stray fields.

3. Topological Hall effect, Skyrmion Hall effect, and Skyrmion dynamics

The internal structure of magnetic materials may have some peculiar features that have been the subject of decades of research. One illustration is the Hall Effect. Due to this finding, applying a magnetic field to a conductor that is carrying current causes a voltage drop across the conductor that is perpendicular to the current and transverse to both the applied magnetic field and the current [115]. When a ferromagnet is taken into account, the related influence on the Hall resistivity has two terms. The charged particles deflecting as they move with a velocity perpendicular to the applied field cause the first component, known as the Hall term, which is proportional to the applied field. The anomalous or spontaneous Hall term, the second term, is inversely proportional to magnetization. Smit and Volger [116] concluded that this term is likely caused by the ferromagnets internal magnetic field, which is caused by dipoles. This term was then linked to the spin-orbit effect by Smit [117]. It was also known that electrons in a magnetic field that were hopping between atoms might develop a phase factor. The Berry phase is the common name for this variable, which is dependent on the magnetic vector potential [118]. This phase component in a chiral magnet would depend on the effective field owing to the spin chirality, which would depend on the topological and geometrical characteristics of the lattice, as realized by Taguchi et al. [119]. This phase could be empirically seen as changes in the conductivity of chiral materials, as realized by Binz et al. [120]. In other words, the system's chiral structure, or topology, would cause a Hall effect. This is significant because, as will be discussed shortly, similar topological effects have been found in substances like MnSi that may host skyrmions.

The topological Hall effects in MnSi were seen by Neubaeur et al. [40] and Lee et al. [62]. Under a variety of pressures, Lee et al. observed a stepwise field profile in the Hall conductivity, while Neubaeur et al. [40] observed a Hall effect in the T-B areas, which corresponded to the A-phase of MnSi, or the skyrmion lattice phase. The variations in Hall conductivity, however, were not like the typical anomalous Hall effect. Neubaeur et al. came to the conclusion that the reason for the unusual conductivity behavior was the coupling of the applied current's spins to the chiral skyrmion lattice. The finding was that the effective internal magnetic field created by the skyrmion lattice caused the conduction electrons that make up the current to acquire a Berry phase. The skyrmion lattice's effective field in standardized unit vectors is [40]:

$$B^{\mu} = \frac{1}{8\pi}\frac{h}{e}\epsilon_{\mu\nu\lambda}\hat{n}.(\partial_{\nu}\hat{n}x\partial_{\lambda}\hat{n}) \tag{9}$$

i.e., a magnetic field that is proportional to the topological charge. Now $\epsilon_{\mu\nu\lambda}$ is the antisymmetric tensor. The topological Hall effect for skyrmions causes a voltage drop in the direction opposite to the applied current and the magnetic field, which is itself perpendicular to the current, much like the normal Hall effect does [40].

Zang et al. [121] explored the associated Skyrmion Hall Effect analytically and quantitatively. They used the conventional exchange, Zeeman, and DMI energies to investigate the collective dynamics of a skyrmion lattice in a thin film. In the end, Zang et al. discovered that the introduction of an electric current could move the skyrmion lattice as a whole, and that the skyrmions would move with a trajectory at an angle to the current. The Skyrmion-Hall effect is the name given to these phenomena. By examining deformations of the skyrmion lattice in terms of a stiff approximation of the spin vectors, such that n (r, t) = n(r u(r, t)), Zang et al. considered this process analytically. This holds true for an elastic deformation that slowly varies with regard to the skyrmion lattice scale.

As stated by Zang et al. [121], the skyrmion lattice as a whole, which in the rigid approximation will have a velocity$\dot{\boldsymbol{u}} = \boldsymbol{v}$, is driven by an applied current. The subscript denotes that this is the component of the velocity in the direction of the current. The moving skyrmion lattice will then induce an internal electric field,$\boldsymbol{E} = \frac{1}{c}\boldsymbol{v}\|\boldsymbol{xB}$ due to its internal structure, which has the internal magnetic field **B**. Hence, Zang et al. noted that applying a current to the skyrmion lattice will generate an electric current transverse to the direction of $\boldsymbol{v}\|$, and this current is determined by the internal magnetic field of the skyrmion, which in turn is determined by its topology. A voltage drop will result in a direction that is opposite to the direction of the applied current. This can be understood as the topological Hall effect for the moving skyrmion lattice, or the previously described skyrmion Hall effect (SHE), which causes the skyrmion lattice to move at an angle to the initially applied current, according to Zang et al. [121]. Moreover, Zang et al. [121] showed that the transverse component of the skyrmion lattice velocity, **v**⊥ is due to dissipation as a result of the skyrmion lattice's internal field. Specifically, Zang et al. showed that the dissipation arises from the coupling of the conduction electrons in the applied current with the local magnetic moments of the film. One can define the corresponding skyrmion Hall angle as $\theta = \frac{v}{v}$, where **v**⊥ is proportional to the topological charge. The internal magnetic fields of the skyrmion are ultimately responsible for the topological and/or skyrmion Hall effects, which result in step-like behavior in the Hall conductivity or skyrmion trajectories that are perpendicular to the applied current, respectively. Be aware that Jiang et al. [111] directly observed the spin Hall effect in an experiment a few years later.

Skyrmions can be driven by very low current densities, several orders of magnitude smaller than domain walls, which is encouraging for potential applications even though the spin Hall effect is not ideal for applications involving skyrmions because the skyrmion will not be driven precisely along the current direction. For instance, Yu et al. [122] demonstrated this in the material FeGe at a temperature close to ambient. Yu et al. used Lorentz transmission electron microscopy to examine the translational and rotational motion of the skyrmion lattice, with the spin-transfer torque serving as the primary driving force. This procedure entails the transfer of spin via a polarized current, causing the skyrmion to experience a torque and move along as a result. According to Yu et al., the depinning of domain walls and the depinning of skyrmions from defects both require a tiny threshold current, but the threshold current required to depin skyrmions is substantially less. As was previously mentioned, the Skyrmion Hall effect will result in some transverse velocity.

Iwasaki et al.'s [94] investigation of the spin transfer torque's role in driving a skyrmion With the exception of the Gilbert factor being replaced by the time derivative of the magnetization, they numerically solved the Landau-Lifshitz-Gilbert equation, which is equivalent to the Landau-Lifshitz equation describing the dynamics of magnetization [123]. Iwasaki et al. showed numerically that there is a linear current-velocity relation for the spin transfer torque-driven skyrmion for the component of the velocity along the direction of the applied current for the system with the exchange, Zeeman, Dzyaloshinsky-Moriya interaction, and random anisotropy.

This velocity component is also independent of the Gilbert damping, impurities, and non-adiabatic effect due to the interaction of the spins of the magnetic moment with the spin-polarized current. This supports the conclusions reached by Zang et al. [121]. Iwasaki et al. hypothesized that this was due to the skyrmion's ability to alter its lattice structure or alter its individual shape in order to avoid being trapped by contaminants. However, because skyrmions rotate around impurity centers, impurities do affect the transverse component of velocity and, consequently, the skyrmion Hall angle.

In order to demonstrate that temperature gradients can also be used to drive skyrmions, Kong et al. [100] examined the dynamics of skyrmions in a thin layer. The Landau- Lifshitz-Gilbert equation with the exchange, Zeeman, and Dzyaloshinsky-Moriya interaction was numerically solved and thermal fluctuations were included as a random field to analyze this. The random fields caused the skyrmions to move. The velocity was random at any given time, according to Kong et al. The drift velocity, however, was not zero and was going in the opposite direction of the temperature gradient. Additionally, the velocity's longitudinal component correlated with the temperature gradient [100].

3.1 Antiferromagnetic skyrmions

In antiferromagnets [124, 125] and artificial antiferromagnetic bilayers [113], the dynamic characteristics and stability of single antiferromagnetic skyrmions were first predicted. They were soon expanded to include two-sub lattice antiferromagnetic skyrmion crystals [126]. Antiferromagnetic skyrmions can be thought of as the union of two skyrmions with mutually reversed spins, just as with skyrmioniums. As a result, they are distinguished by a vanishing topological charge. The subskyrmions in this instance, however, are not spatially separated but rather entangled. These results in the local disappearance of the magnetization density and the magnetization can be replaced by the Néel order parameter, which is the primary order parameter for antiferromagnets. Using this parameter to determine the topological charge yields a result of± 1. Thus, from the perspective of topology, antiferromagnetic skyrmions are still skyrmions, but they behave differently from ferromagnetic skyrmions. The Thiele equation, albeit with the Néel order parameter, can also explain these antiferromagnetic dynamics [127].

An antiferromagnetic skyrmion moves without the skyrmion Hall effect due to the compensated topological charge for magnetization, as proposed for skyrmionium [124, 113]. The two subsystems, on the other hand, are considerably more strongly connected and prevent a deformation brought on by a pairwise opposing transverse motion, as was the case for the skyrmionium. The antiferromagnetic skyrmions can be pushed by currents significantly more quickly than normal skyrmions, which is characteristic of antiferromagnetic spin textures. Simulated speeds in the kph range have been recorded [128].

Antiferromagnetic skyrmions are therefore the best information carriers for data storage systems. Additionally, it was theoretically demonstrated that, in contrast to their ferromagnetic counterparts, antiferromagnetic skyrmions have a high diffusion constant [124] in systems with low damping, suggesting a potential for driving them using temperature gradients. They also do not show stray fields, which would enable a denser stacking of almost one-dimensional racetracks when creating a three-dimensional storage device.

The stabilization of antiferromagnetic skyrmions is not difficult given the necessary Dzyaloshinsky-Moriya interaction [124, 129]. A skyrmion with mutually reversed spins—that is, one with opposite polarity and a helicity difference of—is also energetically stable when one takes into account the kind of skyrmion that the Dzyaloshinsky-Moriya interaction in a system prefers energetically (given by the symmetry). The antiparallel alignment of the respective magnetic moments also requires rather significant antiferromagnetic coupling between the two subskyrmions. In fact, the bilayer-type antiferromagnetic skyrmions have just lately been seen in room-temperature synthetic antiferromagnets [130, 131]. In Ref. [130], magnetic force microscopy was used to identify the tiny stray fields that resulted from the bilayer arrangement. The authors of Ref. [131] describe how to create synthetic antiferromagnets with a variable net moment. They prepared a system with a tiny net moment in addition to a fully corrected system so they could undertake magneto-optical Kerr effect experiments.

A regulated generation procedure is required for antiferromagnetic skyrmion-based logic [129] or racetrack [124] applications. For instance, conventional skyrmions have been produced via directed, deterministic methods like spin torques or magnetic fields [23]. However, these methods are challenging to apply to antiferromagnetic skyrmions because all vectorial quantities would either have to act on one of the two subskyrmions alone, causing the other to generate automatically due to the strong antiferromagnetic coupling, or they would have to act on both subskyrmions with the opposite sign. Both strategies are hardly practical since, for instance, magnetic fields cannot alter their sign on the lattice constant-length scale. In this case, stochastic processes seem to be more favorable, such as the creation of nano-objects at flaws or from confinement (as demonstrated for ordinary skyrmions [74, 134]). When an antiferromagnetic skyrmion crystal needs to be stabilized, the stability of antiferromagnetic skyrmions becomes considerably more difficult. Using skyrmion crystals as an example, a stabilizing magnetic field is necessary. For each of the two subsystems, it must be aligned along z. A hypothetical antiferromagnetic skyrmion host might be grown on top of a collinear anti-ferromagnet with the same crystal structure at the interface to get around this issue. The exchange interaction at the contact imitates a staggered magnetic field as a result [126].

Another problem is detecting antiferromagnetic skyrmions in a single layer (rather than in a synthetic anti-ferromagnet bilayer). Global and local compensation is made for both the magnetization and topological charge density of the magnetization (middle and bottom panels). For real-space techniques like magnetic force microscopy or Lorenz transmission electron microscopy, these antiferromagnetic skyrmions would consequently appear to be undetectable. Additionally, there are no aberrant or topological Hall signatures. Fortunately, a different characteristic, the topological spin Hall effect, has been proposed [132–136]. The resulting signal is an analog of the traditional spin Hall effect, but it comes from the spin texture's non-collinearity.

It is easiest to understand the topological spin Hall effect if one makes the assumption that there are two electronically uncoupled sub skyrmions. Because of the opposing spin orientation, the emergent fields of the two subskyrmions are oriented in opposition. The electrons are transversely deflected in opposing directions as a result. Due to the opposite spin alignment, the two species of electrons can be thought of as having “spin up” and “spin down” states depending on how well their spins line up with their respective textures. However, the foregoing concept of an emergent magnetic field becomes problematic because the sublattices are truly connected. Additionally, a non-Abelian formulation must be taken into consideration to account for the sublattice-degenerate bands in order to calculate the spin Hall conductivity from the reciprocal space properties. Similarly, the spin-polarization of an electron moving through an antiferromagnetic skyrmion is no longer perfectly aligned with the texture. The conduction electrons’ orbital motion becomes significant and spin-dependent [137, 138]. Nevertheless, a topological spin Hall effect emerges.

In conclusion, there is a reason for optimism regarding the use of antiferromagnetic skyrmions in spintronic devices in the future. Recently, the current-driven motion of synthetic antiferromagnetic skyrmions has been accomplished [131]. Synthetic antiferromagnetic skyrmions have been seen. Skyrmions with a single layer of anti-ferromagnetism have also been suggested. Despite fully compensated magnetizations, stray fields, and topological charge densities of the magnetization, the topological spin Hall effect may be crucial for viewing these things. The skyrmions might also be moved by heat gradients or electrically generated anisotropy gradients, even in antiferromagnetic insulators, as was predicted.

As a last point, we would like to point out that the concept of combining skyrmions on various surfaces has been generalized in a number of publications. For instance, three skyrmion crystals can be entangled and stabilized using Monte Carlo simulations [139, 140]. However, because the topological charge for the magnetization in these objects is finite, they do not display the benefits of antiferromagnetic skyrmions.

3.2 Ferrimagnetic skyrmions

For a related entity, the ferrimagnetic skyrmion, signs of the favorable emerging electrodynamics of antiferromagnetic skyrmions have also been observed [141, 142]. Like the antiferromagnetic skyrmion, it consists of two linked subskyrmions with mutually reversible spins. Although the magnetic forces on the two sublattices are of different magnitudes, this results in an uncompensated magnetization, which made it possible to identify ferrimagnetic skyrmions in GdFeCo films using X-ray imaging [141]. There is a certain temperature where the skyrmion Hall effect does not exist when these particles are powered by spin currents [142]. Due to differing gyromagnetic ratios for the magnetic moments in the various sublattices at this temperature, the angular momentum is adjusted at this temperature even though the magnetization is not [142]. A reduced skyrmion Hall angle of θSk = 20° has been seen at room temperature [141], but this full correction of the skyrmion Hall effect has yet to be observed experimentally. Furthermore, it has recently been experimentally discovered that domain walls driven by SOT may travel at speeds of up to 6 km/s in ferrimagnetic insulators close to the compensation temperature [143], suggesting that ferrimagnetic skyrmions may also be able to move at these speeds in the future.

Due to their indigent magnetization, ferrimagnetic skyrmions have the benefit of being easier to detect and interact with than antiferromagnetic ones. They promise similar benefits to antiferromagnetic skyrmions in terms of their emergent electrodynamics. However, a straight-line motion along a driving current is only anticipated to function at a specific temperature (angular momentum adjustment), which restricts the use of spintronics.

DOI: http://dx.doi.org/10.5772/intechopen.110448

4. Applications of magnetic skyrmions

For information and communications technology, magnetic skyrmions may present a special opportunity to incorporate topology into room-temperature electronic systems. Although topological properties are present in many of the most fascinating recent developments in condensed matter physics, such as high-temperature interfacial superconductivity, the quantum Hall effect, or topological insulators, magnetic skyrmions take on a special significance because they are arguably the most promising candidates to be used in consumer-grade low-energy nanoscale spintronic devices in the medium term.

There are still many problems to be solved in the newly emerging field of study exploiting skyrmion topological features, as discussed in earlier parts. However, all of the fundamental operations of writing information (nucleation of individual skyrmions), processing information (displacement, creation/annihilation of skyrmions, excitation of skyrmion modes), and reading information (electrical detection of individual skyrmions) have already been individually demonstrated, though frequently only at low temperatures and for a skyrmion lattice rather than for a single skyrmion at room temperature.

The next major hurdle will be incorporating all three of these features into a single, tiny integrated device while operating at ambient temperature. Following, we briefly go through some of the more intriguing skyrmionic device concepts that have lately been put forth (for an extensive review of the application of skyrmions, we refer to W. Kang et al. [144].

4.1 Skyrmion race track memory

The first is referred to as the "Skyrmion racetrack memory," whose theory is quite similar to the one based on domain walls put forward by S. S. P. Parkin [5]. A series of individual skyrmions in a magnetic track can encode information by taking advantage of the solitonic nature of skyrmions [8, 145]. The great level of integration that skyrmions have over domain walls is one of their advantages [87]. By narrowing the track, the calculated diameter of a compact skyrmion can be reduced by several orders of magnitude, and as a result, in current-induced motion, the skyrmion accurately moves along the center of the track.

The distance between neighboring skyrmions in a track can be of the order of the skyrmion diameter, as simulations [87] have also demonstrated. As a result, one can anticipate a higher density with skyrmions than with domain walls in racetrack memory. Regarding energy consumption, despite the fact that the flexibility of the skyrmions' shape and/or trajectories should allow them to move with incredibly small depinning currents, as observed in skyrmion lattices in bulk materials [122], the ratio of velocity over current density is not expected to differ significantly between domain wall and skyrmions. Skyrmions have the additional benefit of being guided by the confinement of the track's edges, which makes it so that their motion by spin torques will be similar in both straight and curved sections of the track. The motion of domain walls, on the other hand, will be influenced by curved sections of the racetrack because torques in the wall behave differently in the inner and outer parts of the track. Finally, it is possible to count the number of skyrmions going over a track using conventional tunnel magneto-resistive devices, such as domain walls, or older methods that relied on unique transport signatures related to the topological character of skyrmions, such as the topological Hall effect. It is interesting how quickly a nanoscale voltage-gated skyrmion transistor can be created using this skyrmion race-track concept. By including a gate in a specific section of the track, X. Zhang et al. [112] proposed this new function, which controls whether or not the skyrmion equivalent of a transistor's "on/off" switch passes. This new function locally modifies the magnetic properties of the magnetic medium, specifically the perpendicular anisotropy or the Dzyaloshinsky-Moriya interaction, by applying an electric field.

4.2 Skyrmionic logic devices

The possibility of a skyrmion functioning as a standalone "particle" has also led to the conceptualization of a number of spin logic devices based on skyrmions. The majority of them are based on results from micromagnetic simulations [146] performed in nanoscale wires of varying widths that demonstrate how a single skyrmion can be converted into a domain-wall pair and vice versa. By creating certain nanostructures, this conversion process theoretically enables basic logical operations such as the duplication or merger of skyrmions at will. Recently, X. Zhang et al. [147] developed skyrmion logic gates AND and OR based on these extra functionalities, realizing the first step toward a comprehensive logical architecture with the goal of surpassing the current spin logic devices, particularly in terms of their level of integration.

4.3 Skyrmion magnonic crystal

Skyrmions can be artificially arranged in a periodic pattern in a 1 dimensional or two-dimensional nanostructure by applying a local magnetic [146], electric [148, 149], or spin-polarized current [95] field, for example, locally applying a local electric [148, 150] or magnetic field, or injecting spin-polarized current [95]. The propagation of spin waves inside this innovative sort of "meta material" can then be tailored using such skyrmion lattices as a periodic modulation of the magnetization. Indeed, F. Ma et al. [150] recently demonstrated through numerical simulations that such skyrmion-based magnonic crystals have a significant advantage over more conventional ones (based on a periodic modulation of the magnetic properties induced typically by the lithography process) in that they can be dynamically reconfigured by simply adjusting the diameter of the skyrmions (by applying a magnetic field), altering the periodicity of the lattice, or even erasing it. Also take note of the fact that skyrmion crystals at the nanoscale scale are conceivable, although typical magnonic crystals made using current lithography techniques are not [95].

By utilizing this functionality, it should be possible to dynamically switch between the full rejection and full transmission of spin waves in a waveguide. The spin waves themselves may be in a topological phase while propagating in a two-dimensional atomic-size skyrmion lattice, which should enable the realization of the spin-wave counterpart of the anomalous quantum Hall effect for electrons [151].

4.4 Skyrmion-based radio frequency devices

The topological character of skyrmions may cause a disruptive step in nanoscale radio frequency devices, another class of component. The low-frequency breathing mode, for instance, is a dynamical mode of a single skyrmion in a dot that is representative of its topological nature [152]. It has been suggested [153] that if the skyrmion-containing dot is a component of a magneto-resistive device like a spin valve or a magnetic tunnel junction, the skyrmion breathing mode brought on by spin torques can be utilized to produce a radio frequency signal.

The fact that the resulting skyrmion-based spin torque oscillator is based on a localized soliton makes it less vulnerable to external perturbation and more likely to exhibit a coherent dynamic than, say, a spin torque oscillator based on a vortex. The concept of a skyrmion-based microwave detector, which relies on the resonant excitation of the breathing mode when the frequency of the external radio frequency signal equals the breathing mode's frequency (that can be significantly changed by the application of an external perpendicular field, for example), and the conversion of this resonant dynamics into a direct current mixed voltage, is another function numerically investigated by G. Finocchio et al. [154].

Finally, F. Garcia-Sanchez et al. [155] recently presented a novel sort of skyrmion-based spin torque oscillator that is based on the self-sustained gyration resulting from the competition between confinement from boundary edges and the spin forces owing to an inhomogeneous spin polarizer. There is no threshold current for the start of the skyrmion dynamics; hence, the corresponding gyro tropic frequency is about an order of magnitude lower than in typical vortex-based spin torque oscillators.

5. Conclusion

This review's summary has covered stability, emergent electrodynamics, associated alternative magnetic quasiparticles, and potential magnetic skyrmion-based applications. Fundamental excitations (both topologically trivial and non-trivial), excitations' variations, and extensions make up the diversity of particles. Skyrmions with an arbitrary helicity and antiskyrmions have been suggested as being the most technologically useful kinds of fundamental excitations. Topological excitations in a varied magnetic field and the fusion of numerous subparticles are two examples of variations. Antiferromagnetic and ferrimagnetic skyrmions have been thoroughly covered in this chapter. All of these things can be arranged in two dimensions (both periodically and ad hoc) and extended along a third dimension, which is what is meant by the term "extension." Bloch points, chiral bobbers, and other naturally three-dimensional objects have been the focus of our attention.

Antiferromagnetic skyrmions are frequently regarded as the best parts for spintronic applications out of the items that have been given. They can be driven by currents at extremely high speeds of up to several kilometers per second because of their corrected magnetic texture, and the absence of the Skyrmion Hall effect eliminates the issue of bit pinning at the margins. Additionally, due to their local adjustment of magnetization, stray fields are reduced, enabling the three-dimensional stacking of many racetracks in close proximity to one another.

Magnetic skyrmions may offer a unique chance for room-temperature electronic devices to incorporate topology in information and communications technologies. Magnetic skyrmions assume a special significance because they are arguably the most promising candidates to be used in consumer-grade low-energy nanoscale spintronic devices in the medium term. Topological properties are present in many of the most fascinating recent developments in condensed matter physics, such as high-temperature interfacial superconductivity, the quantum Hall effect, and topological insulators. Skyrmion racetrack memory, a skyrmion logical device, a skyrmion magnetic crystal, and skyrmion-based radio frequency devices are some of the numerous practical benefits based on magnetic skyrmions.

Acknowledgements

We acknowledge Mrs. Bezawit Alemneh for typing the first draft of the chapter.

Funding

There is no funding for this work.

Conflict of interest

The author confirms that there is no conflict of interest.

Data availability

All the data used to support the findings of this study are included in the chapter.

Author details

Birhanu Abera Kolech
Department of Physics, Natural and Computational Science, Mekdela Amba University, Tulu Awuliya, Ethiopia

*Address all correspondence to: birhanuabera643@gmail.com

References

[1] Moore GE. Cramming more components onto integrated circuits. IEEE Solid-state Circuits Society Newsletter. 1965;**38**(8):114

[2] Waldrop MM. The chips are down for Moore's law. Nature News. 2016; **530**(7589):144

[3] Parkin SS. International Business Machines Corp, assignee. Shiftable magnetic shift register and method of using the same. United States patent US 6,834,005. 2004

[4] Parkin SS, Hayashi M, Thomas L. Magnetic domain-wall racetrack memory. Science. 2008;**320**(5873): 190-194

[5] Parkin S, Yang SH. Memory on the racetrack. Nature Nanotechnology. 2015; **10**(3):195-198

[6] Bogdanov AN, Yablonskii DA. Thermodynamically stable "vortices" in magnetically ordered crystals. The mixed state of magnets. Zh. Eksp. Teor. Fiz. 1989;**95**(1):178

[7] Mühlbauer S, Binz B, Jonietz F, Pfleiderer C, Rosch A, Neubauer A, et al. Skyrmion lattice in a chiral magnet. Science. 2009;**323**(5916):915-919

[8] Sampaio J, Cros V, Rohart S, Thiaville A, Fert A. Nucleation, stability and current-induced motion of isolated magnetic skyrmions in nanostructures. Nature Nanotechnology. 2013;**8**(11): 839-844

[9] Fert A, Cros V, Sampaio J. Skyrmions on the track. Nature Nanotechnology. 2013;**8**(3):152-156

[10] Yu G, Upadhyaya P, Shao Q, Wu H, Yin G, Li X, et al. Room-temperature skyrmion shift device for memory application. Nano Letters. 2017;**17**(1): 261-268

[11] Hamamoto K, Ezawa M, Nagaosa N. Purely electrical detection of a skyrmion in constricted geometry. Applied Physics Letters. 2016;**108**(11): 112401

[12] Maccariello D, Legrand W, Reyren N, Garcia K, Bouzehouane K, Collin S, et al. Electrical detection of single magnetic skyrmions in metallic multilayers at room temperature. Nature Nanotechnology. 2018;**13**(3):233-237

[13] Skyrme TH. A non-linear field theory. Proceedings of the Royal Society of London. Series a. Mathematical and Physical Sciences. 1961;**260**(1300): 127-138

[14] Skyrme TH. A unified field theory of mesons and baryons. Nuclear Physics. 1962;**31**:556-569

[15] Finkelstein D, Rubinstein J. Connection between spin, statistics, and kinks. Journal of Mathematical Physics. 1968;**9**(11):1762-1779

[16] Adkins GS, Nappi CR, Witten E. Static properties of nucleons in the Skyrme model. Nuclear Physics B. 1983; **228**(3):552-566

[17] Sondhi SL, Karlhede A, Kivelson SA, Rezayi EH. Skyrmions and the crossover from the integer to fractional quantum Hall effect at small Zeeman energies. Physical Review B. 1993;**47**(24):16419

[18] Al Khawaja U, Stoof H. Skyrmions in a ferromagnetic Bose–Einstein condensate. Nature. Jun 2001;**411** (6840):918-920

[19] Fukuda JI, Žumer S. Quasi-two-dimensional Skyrmion lattices in a chiral nematic liquid crystal. Nature Communications. 2011;**2**(1):1-5

[20] Vilenkin A, Shellard EP. Cosmic Strings and Other Topological Defects. Cambridge: Cambridge University Press; 1994

[21] Yu XZ, Onose Y, Kanazawa N, Park JH, Han JH, Matsui Y, et al. Real-space observation of a two-dimensional skyrmion crystal. Nature. 2010; **465**(7300):901-904

[22] Bogdanov A, Hubert A. Thermodynamically stable magnetic vortex states in magnetic crystals. Journal of Magnetism and Magnetic Materials. 1994;**138**(3):255-269

[23] Nagaosa N, Tokura Y. Topological properties and dynamics of magnetic skyrmions. Nature Nanotechnology. 2013;**8**(12):899-911

[24] Zhou Y. Magnetic skyrmions: Intriguing physics and new spintronic device concepts. National Science Review. 2019;**6**(2):210-212

[25] Bobeck AH, Bonyhard PI, Geusic JE. Magnetic bubbles—An emerging new memory technology. Proceedings of the IEEE. 1975;**63**(8):1176-1195

[26] Davies J, Clover R, Lieberman B, Rose D. Reliability considerations in the design of one-megabit bubble memory chips. IEEE Transactions on Magnetics. 1980;**16**(5):1106-1110

[27] Grünberg P, Barnas J, Saurenbach F, Fuβ JA, Wolf A, Vohl M. Layered magnetic structures: Antiferromagnetic type interlayer coupling and magnetoresistance due to antiparallel alignment. Journal of magnetism and magnetic materials. 1991 Feb 1; **93**:58-66

[28] Binash G, Gruuberg P, Saurenbach F. Enhanced magnetoresistance in layered magnetic interlayers exchange giant magnetoresistance. Physical Review B. 1989;**39**:4828-4834

[29] Masuoka F, Momodomi M, Iwata Y, Shirota R. New ultra high density EPROM and flash EEPROM with NAND structure cell. In: 1987 International Electron Devices Meeting. Kawasaki: VLSI research center, IEEE; 1987. pp. 552-555

[30] Malinowski G, Boulle O, Kläui M. Current-induced domain wall motion in nanoscale ferromagnetic elements. Journal of Physics D: Applied Physics. 2011;**44**(38):384005

[31] Kooy C. Experimental and theoretical study of the domain configuration in thin layers of BaFe_< 12> O_< 19. Philosophical Research Reports. 1960;**15**(7):1180-1186

[32] Thiele AA. Steady-state motion of magnetic domains. Physical Review Letters. 1973;**30**(6):230

[33] Malozemoff AP, Slonczewski JC. Magnetic Domain Walls in Bubble Materials. New York: Academic Press; 1979

[34] Tretiakov OA, Tchernyshyov O. Vortices in thin ferromagnetic films and the skyrmion number. Physical Review B. 2007;**75**(1):012408

[35] Heinze S, Von Bergmann K, Menzel M, Brede J, Kubetzka A, Wiesendanger R, et al. Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. Nature Physics. 2011; **7**(9):713-718

[36] Garlow JA, Pollard SD, Beleggia M, Dutta T, Yang H, Zhu Y. Quantification

of mixed Bloch-Néel topological spin textures stabilized by the Dzyaloshinskii-Moriya interaction in Co/Pd multilayers. Physical Review Letters. 2019;**122**(23):237201

[37] Nayak AK, Kumar V, Ma T, Werner P, Pippel E, Sahoo R, et al. Magnetic antiskyrmions above room temperature in tetragonal Heusler materials. Nature. 2017;**548**(7669):561-566

[38] Leonov AO, Mostovoy M. Multiply periodic states and isolated skyrmions in an anisotropic frustrated magnet. Nature Communications. 2015;**6**(1):1-8

[39] Rózsa L, Palotás K, Deák A, Simon E, Yanes R, Udvardi L, et al. Formation and stability of metastable skyrmionic spin structures with various topologies in an ultrathin film. Physical Review B. 2017;**95**(9):094423

[40] Neubauer A, Pfleiderer C, Binz B, Rosch A, Ritz R, Niklowitz PG, et al. Topological Hall effect a phase of MnSi. Physical Review Letters. 2009;**102**(18):186602

[41] Adams T, Mühlbauer S, Pfleiderer C, Jonietz F, Bauer A, Neubauer A, et al. Long-range crystalline nature of the skyrmion lattice in MnSi. Physical Review Letters. 2011;**107**(21):217206

[42] Mühlbauer S, Kindervater J, Adams T, Bauer A, Keiderling U, Pfleiderer C. Kinetic small angle neutron scattering of the skyrmion lattice in MnSi. New Journal of Physics. 2016;**18**(7):075017

[43] Huang SX, Chien CL. Extended skyrmion phase in epitaxial FeGe (111) thin films. Physical Review Letters. 2012;**108**(26):267201

[44] Adams T, Mühlbauer S, Neubauer A, Münzer W, Jonietz F, Georgii R, et al. Skyrmion lattice domains in Fe1− xCoxSi. Journal of Physics: Conference Series. 2010;**200**(3):032001

[45] Münzer W, Neubauer A, Adams T, Mühlbauer S, Franz C, Jonietz F, et al. Skyrmion lattice in the doped semiconductor Fe 1− x Co x Si. Physical Review B. 2010;**81**(4):041203

[46] Adams T, Chacon A, Wagner M, Bauer A, Brandl G, Pedersen B, et al. Long-wavelength helimagnetic order and skyrmion lattice phase in Cu 2 OSeO 3. Physical Review Letters. 2012;**108**(23):237204

[47] Seki S, Yu XZ, Ishiwata S, Tokura Y. Observation of skyrmions in a multiferroic material. Science. 2012;**336**(6078):198-201

[48] Okamura Y, Kagawa F, Seki S, Tokura Y. Transition to and from the skyrmion lattice phase by electric fields in a magnetoelectric compound. Nature Communications. 2016;**7**(1):1-6

[49] Zhang SL, Bauer A, Berger H, Pfleiderer C, Van Der Laan G, Hesjedal T. Resonant elastic x-ray scattering from the skyrmion lattice in Cu 2 OSeO 3. Physical Review B. 2016;**93**(21):214420

[50] Zhang SL, Bauer A, Berger H, Pfleiderer C, Van Der Laan G, Hesjedal T. Imaging and manipulation of skyrmion lattice domains in Cu2OSeO3. Applied Physics Letters. 2016;**109**(19):192406

[51] Zhang SL, Bauer A, Burn DM, Milde P, Neuber E, Eng LM, et al. Multidomain skyrmion lattice state in Cu2OSeO3. Nano Letters. 2016;**16**(5):3285-3291

[52] Seki S, Ishiwata S, Tokura Y. Magnetoelectric nature of skyrmions in a

chiral magnetic insulator Cu 2 OSeO 3. Physical Review B. 2012;**86**(6):060403

[53] White JS, Levatić I, Omrani AA, Egetenmeyer N, Prša K, Živković I, et al. Electric field control of the skyrmion lattice in Cu2OSeO3. Journal of Physics. Condensed Matter. 2012;**24**(43):432201

[54] Milde P, Neuber E, Bauer A, Pfleiderer C, Berger H, Eng LM. Heuristic description of magnetoelectricity of Cu2OSeO3. Nano Letters. 2016;**16**(9):5612-5618

[55] Onose Y, Okamura Y, Seki S, Ishiwata S, Tokura Y. Observation of magnetic excitations of skyrmion crystal in a helimagnetic insulator Cu 2 OSeO 3. Physical Review Letters. 2012;**109**(3): 037603

[56] Mochizuki M. Spin-wave modes and their intense excitation effects in skyrmion crystals. Physical Review Letters. 2012;**108**(1):017601

[57] Schwarze T, Waizner J, Garst M, Bauer A, Stasinopoulos I, Berger H, et al. Universal helimagnon and skyrmion excitations in metallic, semiconducting and insulating chiral magnets. Nature Materials. 2015 May;**14**(5):478-483

[58] Kugler M, Brandl G, Waizner J, Janoschek M, Georgii R, Bauer A, et al. Band structure of helimagnons in MnSi resolved by inelastic neutron scattering. Physical Review Letters. 2015;**115**(9): 097203

[59] Nii Y, Kikkawa A, Taguchi Y, Tokura Y, Iwasa Y. Elastic stiffness of a skyrmion crystal. Physical Review Letters. 2014;**113**(26):267203

[60] Tokunaga Y, Yu XZ, White JS, Rønnow HM, Morikawa D, Taguchi Y, et al. A new class of chiral materials hosting magnetic skyrmions beyond room temperature. Nature Communications. 2015;**6**(1):1-7

[61] Karube K, White JS, Reynolds N, Gavilano JL, Oike H, Kikkawa A, et al. Robust metastable skyrmions and their triangular–square lattice structural transition in a high-temperature chiral magnet. Nature Materials. 2016;**15**(12): 1237-1242

[62] Lee M, Kang W, Onose Y, Tokura Y, Ong NP. Unusual Hall effect anomaly in MnSi under pressure. Physical Review Letters. 2009;**102**(18):186601

[63] Ritz R, Halder M, Franz C, Bauer A, Wagner M, Bamler R, et al. Giant generic topological Hall resistivity of MnSi under pressure. Physical Review B. 2013; **87**(13):134424

[64] Chacon A, Bauer A, Adams T, Rucker F, Brandl G, Georgii R, et al. Uniaxial pressure dependence of magnetic order in MnSi. Physical Review Letters. 2015;**115**(26):267202

[65] Nii Y, Nakajima T, Kikkawa A, Yamasaki Y, Ohishi K, Suzuki J, et al. Uniaxial stress control of skyrmion phase. Nature Communications. 2015; **6**(1):1-7

[66] Tonomura A, Yu X, Yanagisawa K, Matsuda T, Onose Y, Kanazawa N, et al. Real-space observation of skyrmion lattice in helimagnet MnSi thin samples. Nano Letters. 2012;**12**(3):1673-1677

[67] Yu X, Kikkawa A, Morikawa D, Shibata K, Tokunaga Y, Taguchi Y, et al. Variation of skyrmion forms and their stability in MnSi thin plates. Physical Review B. 2015;**91**(5):054411

[68] Yu XZ, Kanazawa N, Onose Y, Kimoto K, Zhang WZ, Ishiwata S, et al. Near room-temperature formation of a skyrmion crystal in thin-films of the

helimagnet FeGe. Nature Materials. 2011;**10**(2):106-109

[69] McGrouther D, Lamb RJ, Krajnak M, McFadzean S, McVitie S, Stamps RL, et al. Internal structure of hexagonal skyrmion lattices in cubic helimagnets. New Journal of Physics. 2016;**18**(9): 095004

[70] Rajeswari J, Huang P, Mancini GF, Murooka Y, Latychevskaia T, McGrouther D, et al. Filming the formation and fluctuation of skyrmion domains by cryo-Lorentz transmission electron microscopy. Proceedings of the National Academy of Sciences. 2015; **112**(46):14212-14217

[71] von Bergmann K, Kubetzka A, Pietzsch O, Wiesendanger R. Interface-induced chiral domain walls, spin spirals and skyrmions revealed by spin-polarized scanning tunneling microscopy. Journal of Physics. Condensed Matter. 2014;**26**(39):394002

[72] Kézsmárki I, Bordács S, Milde P, Neuber E, Eng LM, White JS, et al. Néel-type skyrmion lattice with confined orientation in the polar magnetic semiconductor GaV4S8. Nature Materials. 2015;**14**(11):1116-1122

[73] Wiesendanger R. Nanoscale magnetic skyrmions in metallic films and multilayers: A new twist for spintronics. Nature Reviews Materials. 2016;**1**(7):1-1

[74] Romming N, Hanneken C, Menzel M, Bickel JE, Wolter B, von Bergmann K, et al. Writing and deleting single magnetic skyrmions. Science. 2013;**341**(6146):636-639

[75] Romming N, Kubetzka A, Hanneken C, von Bergmann K, Wiesendanger R. Field-dependent size and shape of single magnetic skyrmions. Physical Review Letters. 2015;**114**(17): 177203

[76] Schmidt L, Hagemeister J, Hsu PJ, Kubetzka A, Von Bergmann K, Wiesendanger R. Symmetry breaking in spin spirals and skyrmions by in-plane and canted magnetic fields. New Journal of Physics. 2016;**18**(7):075007

[77] Hanneken C, Kubetzka A, Von Bergmann K, Wiesendanger R. Pinning and movement of individual nanoscale magnetic skyrmions via defects. New Journal of Physics. 2016;**18**(5):055009

[78] Moreau-Luchaire C, Moutafis C, Reyren N, Sampaio J, Vaz CA, Van Horne N, et al. Additive interfacial chiral interaction in multilayers for stabilization of small individual skyrmions at room temperature. Nature Nanotechnology. 2016;**11**(5):444-448

[79] Kruchkov AJ, Rønnow HM. Skyrmion lattices in electric fields. arXiv preprint arXiv:1702.08863. 2017.

[80] Buhrandt S, Fritz L. Skyrmion lattice phase in three-dimensional chiral magnets from Monte Carlo simulations. Physical Review B. 2013;**88**(19):195137

[81] Nagaosa N, Yu XZ, Tokura Y. Gauge fields in real and momentum spaces in magnets: Monopoles and skyrmions. Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences. 2012;**370**(1981): 5806-5819

[82] Schütte C, Rosch A. Dynamics and energetics of emergent magnetic monopoles in chiral magnets. Physical Review B. 2014;**90**(17):174432

[83] Schütte C. Skyrmions and monopoles in chiral magnets & correlated heterostructures (Doctoral dissertation, Universität zu Köln).

[84] Milde P, Köhler D, Seidel J, Eng LM, Bauer A, Chacon A, et al. Unwinding of a skyrmion lattice by magnetic monopoles. Science. 2013; **340**(6136):1076-1080

[85] Bogdanov A. New localized solutions of the nonlinear field equations. Jetp Letters. 1995;**62**(3):247-251

[86] Lin SZ, Reichhardt C, Batista CD, Saxena A. Particle model for skyrmions in metallic chiral magnets: Dynamics, pinning, and creep. Physical Review B. 2013;**87**(21):214419

[87] Zhang X, Zhao GP, Fangohr H, Liu JP, Xia WX, Xia J, et al. Skyrmion-skyrmion and skyrmion-edge repulsions in skyrmion-based racetrack memory. Scientific Reports. 2015;**5**(1):1-6

[88] Rózsa L, Deák A, Simon E, Yanes R, Udvardi L, Szunyogh L, et al. Skyrmions with attractive interactions in an ultrathin magnetic film. Physical Review Letters. 2016;**117**(15):157205

[89] Leonov AO, Kézsmárki I. Asymmetric isolated skyrmions in polar magnets with easy-plane anisotropy. Physical Review B. 2017;**96**(1):014423

[90] Leonov AO, Kézsmárki I. Skyrmion robustness in noncentrosymmetric magnets with axial symmetry: The role of anisotropy and tilted magnetic fields. Physical Review B. 2017;**96**(21):214413

[91] Leonov AO, Monchesky TL, Loudon JC, Bogdanov AN. Three-dimensional chiral skyrmions with attractive interparticle interactions. Journal of Physics: Condensed Matter. 2016;**28**(35):35LT01

[92] Leonov AO, Loudon JC, Bogdanov AN. Spintronics via non-axisymmetric chiral skyrmions. Applied Physics Letters. 2016;**109**(17):172404

[93] Purnama I, Gan WL, Wong DW, Lew WS. Guided current-induced skyrmion motion in 1D potential well. Scientific Reports. 2015;**5**(1):1-9

[94] Iwasaki J, Mochizuki M, Nagaosa N. Universal current-velocity relation of skyrmion motion in chiral magnets. Nature Communications. 2013;**4**(1):1-8

[95] Iwasaki J, Mochizuki M, Nagaosa N. Current-induced skyrmion dynamics in constricted geometries. Nature Nanotechnology. 2013;**8**(10): 742-747

[96] Schütte C, Iwasaki J, Rosch A, Nagaosa N. Inertia, diffusion, and dynamics of a driven skyrmion. Physical Review B. 2014;**90**(17):174434

[97] Everschor-Sitte K, Sitte M. Real-space Berry phases: Skyrmion soccer. Journal of Applied Physics. 2014;**115**(17): 172602

[98] Makhfudz I, Krüger B, Tchernyshyov O. Inertia and chiral edge modes of a skyrmion magnetic bubble. Physical Review Letters. 2012;**109**(21): 217201

[99] Büttner F, Moutafis C, Schneider M, Krüger B, Günther CM, Geilhufe J, et al. Dynamics and inertia of skyrmionic spin structures. Nature Physics. 2015;**11**(3): 225-228

[100] Kong L, Zang J. Dynamics of an insulating skyrmion under a temperature gradient. Physical Review Letters. 2013; **111**(6):067203

[101] Mochizuki M, Yu XZ, Seki S, Kanazawa N, Koshibae W, Zang J, et al. Thermally driven ratchet motion of a skyrmion microcrystal and topological magnon Hall effect. Nature Materials. 2014;**13**(3):241-246

[102] Iwasaki J, Beekman AJ, Nagaosa N. Theory of magnon-skyrmion scattering in chiral magnets. Physical Review B. 2014;**89**(6):064412

[103] Lin SZ, Batista CD, Saxena A. Internal modes of a skyrmion in the ferromagnetic state of chiral magnets. Physical Review B. 2014;**89**(2):024415

[104] Schütte C, Garst M. Magnon-skyrmion scattering in chiral magnets. Physical Review B. 2014;**90**(9): 094423

[105] Schroeter S, Garst M. Scattering of high-energy magnons off a magnetic skyrmion. Low Temperature Physics. 2015;**41**(10):817-825

[106] Zhang X, Ezawa M, Xiao D, Zhao GP, Liu Y, Zhou Y. All-magnetic control of skyrmions in nanowires by a spin wave. Nanotechnology. 2015; **26**(22):225701

[107] Garcia-Sanchez F, Borys P, Vansteenkiste A, Kim JV, Stamps RL. Nonreciprocal spin-wave channeling along textures driven by the Dzyaloshinskii-Moriya interaction. Physical Review B. 2014;**89**(22):224408

[108] Seki S, Okamura Y, Kondou K, Shibata K, Kubota M, Takagi R, et al. Magnetochiral nonreciprocity of volume spin wave propagation in chiral-lattice ferromagnets. Physical Review B. 2016; **93**(23):235131

[109] Wang W, Beg M, Zhang B, Kuch W, Fangohr H. Driving magnetic skyrmions with microwave fields. Physical Review B. 2015;**92**(2):020403

[110] Kim JV, Yoo MW. Current-driven skyrmion dynamics in disordered films. Applied Physics Letters. 2017;**110**(13): 132404

[111] Jiang W, Zhang X, Yu G, Zhang W, Wang X, Benjamin Jungfleisch M, et al. Direct observation of the skyrmion Hall effect. Nature Physics. 2017;**13**(2): 162-169

[112] Zhang X, Zhou Y, Ezawa M, Zhao GP, Zhao W. Magnetic skyrmion transistor: Skyrmion motion in a voltage-gated nanotrack. Scientific Reports. 2015;**5**(1):1-8

[113] Zhang X, Zhou Y, Ezawa M. Magnetic bilayer-skyrmions without skyrmion Hall effect. Nature Communications. 2016;**7**(1):1-7

[114] Rodrigues DR, Everschor-Sitte K, Tretiakov OA, Sinova J, Abanov A. Spin texture motion in antiferromagnetic and ferromagnetic nanowires. Physical Review B. 2017;**95**(17):174408

[115] Hall EH. On a new action of the magnet on electric currents. American Journal of Science. 1880;**3**(111):200-205

[116] Smit J, Volger J. Spontaneous Hall effect in ferromagnetics. Physical Review. 1953;**92**(6):1576

[117] Smit J. The spontaneous Hall effect in ferromagnetics II. Physica. 1958;**24**(1–5):39-51

[118] Berry MV. Quantal phase factors accompanying adiabatic changes. Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences. 1984;**392**(1802):45-57

[119] Taguchi Y, Oohara Y, Yoshizawa H, Nagaosa N, Tokura Y. Spin chirality, Berry phase, and anomalous Hall effect in a frustrated ferromagnet. Science. 2001;**291**(5513):2573-2576

[120] Binz B, Vishwanath A, Aji V. Theory of the helical spin crystal: A candidate for the partially ordered state

of MnSi. Physical Review Letters. 2006; **96**(20):207202

[121] Zang J, Mostovoy M, Han JH, Nagaosa N. Dynamics of skyrmion crystals in metallic thin films. Physical Review Letters. 2011;**107**(13):136804

[122] Yu XZ, Kanazawa N, Zhang WZ, Nagai T, Hara T, Kimoto K, et al. Skyrmion flow near room temperature in an ultralow current density. Nature Communications. 2012;**3**(1):1-6

[123] Lakshmanan M. The fascinating world of the Landau–Lifshitz–Gilbert equation: An overview. Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences. 2011;**369**(1939):1280-1300

[124] Barker J, Tretiakov OA. Static and dynamical properties of antiferromagnetic skyrmions in the presence of applied current and temperature. Physical Review Letters. 2016;**116**(14):147203

[125] Zhang X, Zhou Y, Ezawa M. Antiferromagnetic skyrmion: Stability, creation and manipulation. Scientific Reports. 2016;**6**(1):1-8

[126] Göbel B, Mook A, Henk J, Mertig I. Antiferromagnetic skyrmion crystals: Generation, topological Hall, and topological spin Hall effect. Physical Review B. 2017;**96**(6):060406

[127] Tveten EG, Qaiumzadeh A, Tretiakov OA, Brataas A. Staggered dynamics in antiferromagnets by collective coordinates. Physical Review Letters. 2013;**110**(12):127208

[128] Jin C, Song C, Wang J, Liu Q. Dynamics of antiferromagnetic skyrmion driven by the spin Hall effect. Applied Physics Letters. 2016;**109**(18): 182404

[129] Bessarab PF, Yudin D, Gulevich DR, Wadley P, Titov M, Tretiakov OA. Stability and lifetime of antiferromagnetic skyrmions. Physical Review B. 2019;**99**(14):140411

[130] Legrand W, Maccariello D, Ajejas F, Collin S, Vecchiola A, Bouzehouane K, et al. Room-temperature stabilization of antiferromagnetic skyrmions in synthetic antiferromagnets. Nature Materials. 2020;**19**(1):34-42

[131] Dohi T, DuttaGupta S, Fukami S, Ohno H. Formation and current-induced motion of synthetic antiferromagnetic skyrmion bubbles. Nature Communications. 2019;**10**(1):1-6

[132] Liang X, Xia J, Zhang X, Ezawa M, Tretiakov OA, Liu X, et al. Antiferromagnetic skyrmion-based logic gates controlled by electric currents and fields. Applied Physics Letters. 2021; **119**(6):062403

[133] Everschor-Sitte K, Masell J, Reeve RM, Kläui M. Perspective: Magnetic skyrmions—Overview of recent progress in an active research field. Journal of Applied Physics. 2018; **124**(24):240901

[134] Jiang W, Upadhyaya P, Zhang W, Yu G, Jungfleisch MB, Fradin FY, et al. Blowing magnetic skyrmion bubbles. Science. 2015;**349**(6245):283-286

[135] Buhl PM, Freimuth F, Blügel S, Mokrousov Y. Topological spin Hall effect in antiferromagnetic skyrmions. (RRL)–Rapid Research Letters. 2017; **11**(4):1700007

[136] Akosa CA, Tretiakov OA, Tatara G, Manchon A. Theory of the topological spin Hall effect in antiferromagnetic skyrmions: Impact on current-induced motion. Physical Review Letters. 2018; **121**(9):097204

[137] Cheng R, Niu Q. Electron dynamics in slowly varying antiferromagnetic texture. Physical Review B. 2012;**86**(24): 245118

[138] Gomonay O. Berry-phase effects and electronic dynamics in a noncollinear antiferromagnetic texture. Physical Review B. 2015;**91**(14):144421

[139] Rosales HD, Cabra DC, Pujol P. Three-sublattice skyrmion crystal in the antiferromagnetic triangular lattice. Physical Review B. 2015;**92**(21):214439

[140] Díaz SA, Klinovaja J, Loss D. Topological magnons and edge states in antiferromagnetic skyrmion crystals. Physical Review Letters. 2019;**122**(18): 187203

[141] Woo S, Song KM, Zhang X, Zhou Y, Ezawa M, Liu X, et al. Current-driven dynamics and inhibition of the skyrmion Hall effect of ferrimagnetic skyrmions in GdFeCo films. Nature Communications. 2018;**9**(1):1-8

[142] Kim SK, Lee KJ, Tserkovnyak Y. Self-focusing skyrmion racetracks in ferrimagnets. Physical Review B. 2017; **95**(14):140404

[143] Zhou HA, Dong Y, Xu T, Xu K, Sánchez-Tejerina L, Zhao L, Ba Y, Gargiani P, Valvidares M, Zhao Y, Carpentieri M. Compensated magnetic insulators for extremely fast spin-orbitronics. arXiv preprint arXiv: 1912.01775. 2019

[144] Kang W, Huang Y, Zhang X, Zhou Y, Zhao W. Skyrmion-electronics: An overview and outlook. Proceedings of the IEEE. 2016;**104**(10):2040-2061

[145] Kang W, Huang Y, Zheng C, Lv W, Lei N, Zhang Y, et al. Voltage controlled magnetic skyrmion motion for racetrack memory. Scientific Reports. 2016;**6**(1): 1-1

[146] Zhou Y, Ezawa M. A reversible conversion between a skyrmion and a domain-wall pair in a junction geometry. Nature Communications. 2014;**5**(1):1-8

[147] Zhang X, Ezawa M, Zhou Y. Magnetic skyrmion logic gates: Conversion, duplication and merging of skyrmions. Scientific Reports. 2015;**5**(1): 1-8

[148] Hsu PJ, Kubetzka A, Finco A, Romming N, Von Bergmann K, Wiesendanger R. Electric-field-driven switching of individual magnetic skyrmions. Nature Nanotechnology. 2017;**12**(2):123-126

[149] Schott M, Bernand-Mantel A, Ranno L, Pizzini S, Vogel J, Béa H, et al. The skyrmion switch: Turning magnetic skyrmion bubbles on and off with an electric field. Nano Letters. 2017;**17**(5): 3006-3012

[150] Ma F, Zhou Y, Braun HB, Lew WS. Skyrmion-based dynamic magnonic crystal. Nano Letters. 2015;**15**(6): 4029-4036

[151] Roldán-Molina A, Nunez AS, Fernández-Rossier J. Topological spin waves in the atomic-scale magnetic skyrmion crystal. New Journal of Physics 2016;**18**(4):045015

[152] Kim JV, Garcia-Sanchez F, Sampaio J, Moreau-Luchaire C, Cros V, Fert A. Breathing modes of confined skyrmions in ultrathin magnetic dots. Physical Review B. 2014;**90**(6):064410

[153] Carpentieri M, Tomasello R, Zivieri R, Finocchio G. Topological, non-topological and instanton droplets driven by spin-transfer torque in materials with perpendicular magnetic anisotropy and

Dzyaloshinskii–Moriya interaction. Scientific Reports. 2015;**5**(1):1-8

[154] Finocchio G, Ricci M, Tomasello R, Giordano A, Lanuzza M, Puliafito V, et al. Skyrmion based microwave detectors and harvesting. Applied Physics Letters. 2015;**107**(26):262401

[155] Garcia-Sanchez F, Sampaio J, Reyren N, Cros V, Kim JV. A skyrmion-based spin-torque nano-oscillator. New Journal of Physics. 2016;**18**(7):075011