Dipolar-stabilized first and second-order antiskyrmions in ferrimagnetic multilayers

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Abstract—Skyrmions and antiskyrmions are topologically protected spin structures with opposite vorticities. Particularly in coexisting phases, these two types of magnetic quasi-particles may show fascinating physics and potential for spintronic devices. While skyrmions are observed in a wide range of materials until now antiskyrmions were exclusive to materials with $D_{2d}$ symmetry. In this work, we show first and second-order antiskyrmions stabilized by magnetic dipole-dipole interaction in Fe/Gd-based multilayers. We modify the magnetic properties of the multilayers by Ir insertion layers. Using Lorentz transmission electron microscopy imaging, we observe coexisting skyrmions, Bloch skyrmions, and type-2 bubbles and determine the range of material properties and magnetic fields where the different spin objects form and dissipate. We perform micromagnetic simulations to obtain more insight into the studied system and conclude that the reduction of saturation magnetization and uniaxial magnetic anisotropy leads to the existence of this zoo of different spin objects and that they are primarily stabilized by dipolar interaction.

I. INTRODUCTION

Over the last few years, topological nontrivial magnetic quasi-particles have attracted a lot of attention. Especially, skyrmions have been investigated very actively over the last decade. These cylindrical-like magnetic domains were observed in bulk \cite{1, 5}, thin films \cite{6, 10}, and monolayer \cite{3, 11} systems. Many concepts to stabilize skyrmions exist, while the use of Dzyaloshinskii-Moriya interaction (DMI) being the most common. Here generally, the system’s inversion symmetry is broken whereby the asymmetric DMI locally tilts the uniform magnetic state \cite{1, 4, 6, 8}. An alternative approach is the use of the competition between long-range dipolar interaction, ferromagnetic exchange, and magnetic anisotropy. In this case, materials can not only host topological trivial bubbles (called type-2 bubbles) but also topologically protected chiral magnetic bubbles (type-1), resembling magnetic Bloch skyrmions \cite{12, 17}. These chiral bubbles or dipolar-stabilized skyrmions were intensively investigated in Fe/Gd multilayers by Montoya et al. \cite{16, 18, 19}. In order to simplify the distinction in this work, we call type-1 bubbles skyrmsions and type-2 bubbles bubbles.

Another novel magnetic quasi-particle that gained a lot of interest are magnetic antiskyrmions. They carry a negative vorticity ($m$) instead of the positive $m$ of skyrmions. Thus, the topological charge ($N_{sk}$) of a skyrmion and antiskyrmion with the same polarity ($p$) is opposite to each other ($N_{sk} = p \pm m$). These first-order antiskyrmions exhibit a two-fold symmetry and consist of alternating Néel- and Bloch-type domain walls that confine inside the out-of-plane magnetic moments from the surrounding antiparallel moments. While there have been many predictions of antiskyrmions stabilized by magnetic dipolar interaction \cite{20, 21}, interface DMI \cite{22, 23}, and non-centrosymmetric $D_{2d}$ symmetry \cite{20, 24, 25}, until now only the latter could be experimentally realized in Heusler compounds \cite{26, 29}. In dipolar dominated systems only local artificial antiskyrmions could be created and observed \cite{30}. Antiskyrmions with an additional iteration of a Néel- and a Bloch-type wall are called second-order antiskyrmions. They have the vorticity $m = -2$ and show a three-fold symmetry. While they have been theoretically predicted \cite{31}, they have not been observed experimentally yet. Antiskyrmions in themselves are of interest for spintronic devices, but especially magnetic phases with a multitude of topologically protected spin objects are predicted to show a variety of fascinating phenomena for possible skyrmion-antiskyrmion-based spintronics. These phenomena include different motion types of skyrmions and antiskyrmions \cite{32}, skyrmion-antiskyrmion liquids \cite{33}, rectangular lattices \cite{34}, phase separation \cite{35}, topological conversion by their collision \cite{20, 21, 32}, and annihilation that emits propagating spin waves \cite{21}. Furthermore, in the original racetrack concept information is stored by the distance between skyrmions. Due to defects and thermal fluctuation there is a significant source of error \cite{36} making it difficult to use. To overcome this issue, binary information given by two different topologically protected spin objects was proposed \cite{37, 39}. Very recently, the coexistence of antiskyrmions and
skyrmions was observed as well in D2d Heusler compounds \(^{40, 41}\). In these crystalline bulk systems, the spin objects exist only in a geometrical deformed state and in specific planes of the crystal.

In this work, we report on the observation of dipolar-stabilized antiskyrmions in Fe/Gd-based multilayers (MLs). The MLs were modified by Ir insertion layers to reduce the magnetic moment and anisotropy. We show coexisting phases of first and second-order antiskyrmions, Bloch skyrmions, and topological trivial bubbles. We evaluate their stability in the dependence on out-of-plane (oop) magnetic field and temperature. From the experimental results, additionally supported by micromagnetic simulations, we conclude that the reduced magnetic moment and anisotropy supports the formation of antiskyrmions via dipolar interaction. Moreover, the nucleation process of the antiskyrmions is analyzed experimentally and theoretically. Our findings show that antiskyrmions can be stabilized outside of bulk D2d crystals solely by dipolar interaction. Further, we observe second-order antiskyrmions. We hope that this easy-to-access range of different coexisting magnetic quasi-particles in thin films opens many possibilities for future magnetic quasi-particle interaction and dynamic experiments.

II. RESULTS

We prepared a series of \([\text{Fe}(0.35)/\text{Ir}(0.20)/\text{Gd}(0.40)]_{N_{\text{Ir}}} / [\text{Fe}(0.35)/\text{Gd}(0.40)]_{N_{\text{Gd}}-2N_{\text{Ir}}} / [\text{Fe}(0.35)/\text{Ir}(0.20)/\text{Gd}(0.40)]_{N_{\text{Ir}}}\) MLs (all thicknesses in nm) with different repetition numbers \(N_{\text{Ir}}\) of the Ir-containing layer stacks (\(N_{\text{Ir}}=0, 2, 5, 10, 20, 40\)), where \(N_{\text{Ir}}=0\) is equivalent to \([\text{Fe}(0.35)/\text{Gd}(0.40)]_{80}\) and \(N_{\text{Ir}}=40\) to \([\text{Fe}(0.35)/\text{Ir}(0.20)/\text{Gd}(0.40)]_{80}\). A schematic image illustrating the layer stack is presented in the method section (Fig. 1). The magnetization of the ferrimagnetic MLs is Gd dominant over all measured temperatures \(T\), as shown by the magnetic moment versus magnetic field \((M–H)\) hysteresis loops provided in the supplementary information (SI-Fig. 9).

Figure 1a displays an exemplary Lorentz transmission electron microscope (LTEM) image of the \([\text{Fe/Ir/Gd}] / \text{Fe/Ir/Gd}]_{76} / [\text{Fe/Ir/Gd}]_{2}\) sample taken at 260 K in an applied oop magnetic field \(\mu_0H_z\) of 108 mT. The image was acquired in 2.5 mm underfocus in Fresnel mode. Various spin objects are observed, as displayed in more detail in Fig. 1b-f (panel I) along with theoretical LTEM contrast images (panels II) and corresponding spin textures (panel III), showing a counterclockwise (ccw) Bloch skyrmion (Fig. 1b), a clockwise (cw) Bloch skyrmion (Fig. 1c), a type-2 bubble (Fig. 1d), a first-order antiskyrmion (Fig. 1e), and a second-order antiskyrmion (Fig. 1f).

The theoretical contrast of the spin textures in Fig. 1b-f (panel II) was simulated by calculating the cross product of the two-dimensional in-plane (ip) components of the spin objects (Fig. 1b-f panel II) and the incident electron beam multiplied by a deflection factor. The resulting smoothed histograms are plotted in Fig. 1b-f (panel II). Comparing the experimental results with the theoretical ideal contrasts, we conclude that our samples exhibit up to five different spin objects at a time. While Bloch skyrmions and type-2 bubbles are well-known spin structures that have been previously observed in similar Fe/Gd ML systems \(^{12, 17}\), antiskyrmions have, to the best of our knowledge, never been observed experimentally outside of compounds with D2d symmetry. We also observe antiskyrmions of second-order, which exhibit a threefold symmetry instead of the twofold symmetry of first-order antiskyrmions. The different spin objects have similar sizes of around 200-250 nm in diameter. Type-2 bubbles differentiate themselves from skyrmions by domain walls consisting of both Néel- and Bloch-type pointing roughly in one ip direction. Because of this, they also exhibit no rotational symmetry. The elliptical shape in Fig. 1d, I and II arises from the one-fold symmetry of the spin configuration displayed in Fig. 1d, III. In addition, the second-order antiskyrmions appear to have the largest size due to the additional domain wall alteration between Bloch- and Néel-type. The different spin objects are randomly distributed over the whole imaged area revealing no preferred orientation and appear at different locations after resetting the magnetic state. Jiang et al. \(^{42}\) showed that Néel skyrmions exhibit no LTEM contrast when the film is normal to the electron beam. Considering this, we tilted our film samples by up to 30 degrees revealing no indication of the existence of pure Néel-type spin objects.

Using LTEM imaging and superconducting quantum interference device - vibrating sample magnetometry (SQUID-VSM), we explore the dependence on applied oop magnetic field and temperature which results in the formation and stabilization of different spin objects. Figure 2a shows the oop and ip \(M–H\) hysteresis loops of \([\text{Fe/Ir/Gd}]_{2} / [\text{Fe/Ir/Gd}]_{76} / [\text{Fe/Ir/Gd}]_{2}\) at 250 K. Moreover, corresponding LTEM images at different applied oop fields are presented in Fig. 2b, which were captured at the same location while sweeping the field from zero towards magnetic saturation. Both the oop and ip hysteresis loops saturate at similar fields and have a saturation magnetization of around 270 kA/m, although their courses differ greatly. The oop loop exhibits a linear growth of magnetization with only a small opening up to around 60 mT. This can be connected to the reversible continuous growth of stripes parallel to the field. At larger fields, the hysteresis loop opens because of irreversible processes, like the formation and annihilation of cylindrical spin textures \(^{43}\). In the LTEM images, we identify different ranges of stability of the different spin objects. Starting from zero field, the film exhibits two different kinds of stripe domains up to 63 mT: broader dark and bright stripes and narrower stripes with less contrast and half the periodicity of the broader stripes (Fig. 2b, I). While the technical limitations of the experimental apparatus limit the analysis of such magnetic domains, they seem to be similar to domains seen in previous works \(^{16, 17}\) and described in detail in \(^{44}\). The bordering in-plane components are aligned mostly parallel to the stripes. Antiparallel in-plane moments on the opposite sides of the stripe result in larger high-contrast stripes, while parallel aligned Bloch walls result in a narrower stripe pattern. In other words, the "broader" stripes exhibit domain walls with a chirality, while the "narrower" ones exhibit no chirality. However, the underlying periodicity of the magnetic stripes is about 250 nm and the same for both
Fig. 1. a) Underfocused LTEM image of [Fe/Ir/Gd]$_2$/[Fe/Gd]$_{76}$/[Fe/Ir/Gd]$_2$ taken in an applied oop magnetic field of 108 mT at 260 K. Five different coexisting spin objects are observed. The images b-f, I) show the measured zoomed-in spin objects and b-f, II) display the simulated LTEM contrast caused by the theoretical spin textures shown in b-f, III). In b-f, III the arrows and their color depict the directions of the ip components, with their sizes displaying the strengths. b) Bloch skyrmion with counter- and c) with clockwise rotation, d) type-2 bubble, e) first-order antiskyrmion, and f) second-order antiskyrmion.

Fig. 2. a) Oop and ip $M - H$ hysteresis loops of [Fe/Ir/Gd]$_2$/[Fe/Gd]$_{76}$/[Fe/Ir/Gd]$_2$ at 250 K. The colored regions mark the stability ranges of the spin objects coming from zero field. b) LTEM images of the sample at different oop magnetic fields which are also marked in the oop loop in a). Panel I shows stripe domains with chirality (broader bright and dark stripes) and without (thinner stripes). At 63 mT disordered stripes coexist with Bloch skyrmions (II). Between 80 and 89 mT type-2 bubbles start to appear (III-IV). In panel V all stripes disappeared and antiskyrmions nucleated at 102 mT. Antiskyrmions, skyrmions, and bubbles coexist in this field range. At 115 mT only skyrmions are stable and observable (VI).

types. The existence of only one underlying periodicity was also confirmed by additional magnetic force microscopy measurements (SI-Fig. 12). The different chiralities of the stripes can determine the type of spin objects that can form under oop magnetic field. When an oop field is applied, domains with magnetization parallel to the field grow at the expense of stripes antiparallel to the field. At 63 mT the first Bloch skyrmions start to form (Fig. 2b, II). We observe that they preferably arise from collapsed stripe domains with the same chirality. Equal numbers of counterclockwise (white) and clockwise (black) Bloch skyrmions appear when averaged over the whole sample. When we further increase the magnetic field to 80 mT, type-2 bubbles start to form out of the stripes without chirality (Fig. 2b, III). At 89 mT the majority of stripes has vanished or shrank down to circular spin objects. The number of skyrmions stayed constant from 80 mT while the number of type-2 bubbles further increased (Fig. 2b, IV). The first isolated antiskyrmions appear at 102 mT when all remaining stripes have vanished (Fig. 2b, V). The number of topologically unprotected bubbles is also strongly reduced.
Fig. 3. Magnetic field and temperature dependence of the stability ranges of the different spin objects of [Fe/Ir/Gd]$_2$ / [Fe/Ir/Gd]$_6$ / [Fe/Ir/Gd]$_2$. The diagram was constructed using the data from the LTEM measurements (black points). A pure antiskyrmion phase (purple checkerboard pattern) is not observable. They always coexist with Bloch skyrmions (blue) and sometimes with stripes and/or bubbles (green stripes). The stability range of antiskyrmions is also smaller than the one of skyrmions for both temperature and field. Second-order antiskyrmions were only observable at 260 K but stayed stable for larger magnetic fields in comparison to first-order antiskyrmions.

at these higher fields. The last LTEM image was captured at 115 mT (Fig. 4 b, VI). Only randomly distributed Bloch skyrmions are left. Their size decreased with increasing field down to around 100 nm and they dissipate at around 130 mT. All six panels also show microstructural defects as black dots which are slightly smaller than the skyrmions and unaffected by the magnetic field. In Fig. 4 II-V one of the counterclockwise skyrmion is pinned to one of these defects. We conclude that Bloch skyrmions are stable over the largest field range, while bubbles and antiskyrmions only exist in rather limited field ranges.

We repeated this procedure for different temperatures between 100 and 300 K. The observed stability ranges of the different spin objects of [Fe/Ir/Gd]$_2$ / [Fe/Gd]$_6$ / [Fe/Ir/Gd]$_2$ are displayed in Fig. 3. The diagram was constructed using the data from the LTEM measurements marked by the black dots. The area in between the experimental data was filled under the assumption that stability transitions happen in the middle of the measured data points. As already mentioned, the domain morphology and position of the different spin objects seem to be randomly distributed for every new field sweep starting from zero field after saturation. At the same time, the range of stability of the different spin objects stayed the same for every field sweep. Further, we did not observe a pure antiskyrmion phase. They always coexisted with Bloch skyrmions and sometimes with type-2 bubbles and/or stripes. It was also evident that the stability range of antiskyrmions is smaller than the one of skyrmions for both temperature and field. Second-order antiskyrmions were only observable at 260 K, but stayed stable for larger magnetic fields in comparison to first-order antiskyrmions.

We also measured and created phase diagrams of the five other samples of our series ($N_t = 0, 5, 10, 20, 40$). The other phase diagrams (SI-Fig. 11), hysteresis loops (SI-Fig. 9), and additional LTEM images (SI-Fig. 13) are available in the supplementary information. Generally, more Ir insertion layers decrease both magnetization and uniaxial magnetic anisotropy (SI-Fig. 10). Because of a too low magnetization, it was not possible to image the sample with $N_t = 40$ by LTEM. The other five samples showed antiskyrmions at room temperature. While samples with $N_t = 0, 2, 10$, and 20 only show antiskyrmions at larger temperatures, the sample with $N_t = 5$ exhibits antiskyrmions at all measured temperatures. First-order antiskyrmions were observed at a wide range of temperatures in every sample of our series besides $N_t = 40$, however, second-order antiskyrmions were only observed at 260 K in $N_t = 2$ and at 300 K in $N_t = 20$. In all cases, they were quite rare in comparison to the other spin objects. Because of that, we cannot rule out their existence at other temperatures and fields but conclude that their nucleation process is less likely in our samples in comparison to first-order (anti-)skyrmions.

Micromagnetic simulations were performed based on the finite differences method where the magnetization dynamics was investigated by means of numerical integration of the Landau-Lifshitz-Gilbert (LLG) equation to reproduce our experimental findings. Here we considered only the magnetic exchange, uniaxial magnetic anisotropy, demagnetization and Zeeman fields, using an exchange stiffness constant $A_{ex} = 6\mu\text{m}^2$, an uniaxial magnetic anisotropy constant $K_u = 22.35\text{kJ/m}^3$, a saturation magnetization $M_s = 225\text{kA/m}$, and a film thickness of 62 nm as material parameters which is in the range of our experimental values (SI-Fig. 10). Details about the simulation method can be found in the methods section. In order to confirm the dipole-dipole interaction as stabilization mechanism for antiskyrmions, no DMI was included in the simulations. The results are displayed in Fig. 4. The simulations did not show significant differences in their spin configuration along the film thickness. Figure a-d show the domain morphology at a larger scale with the color illustrating the $z$-component of the magnetization. Figure e-g display an enlarged portion with black vectors showing the $x$- and $y$-components of the magnetization. Figure e and f display the relaxed magnetization state at zero field showing stripes with different chiralities bristled with Bloch lines. In Fig. 4 h an external out-of-plane magnetic field of $\mu_0H_z = 50\text{mT}$ is applied and the stripes start to shrink down forming skyrmions. An external magnetic field of $\mu_0H_z = 88\text{mT}$ reveals the coexistence of type-2 bubbles, Bloch skyrmions with both cw and ccw chiralities, and antiskyrmions (Fig. 4 c and f). In Fig. 4 d and g only topologically protected spin structures (skyrmions/antiskyrmions) remain at 95 mT. The micromag-
Fig. 4. Micromagnetic simulations of the domain morphology using magnetic parameters close to the sample [Fe/Ir/Gd]/ [Fe/Gd]/ [Fe/Ir/Gd]. a-d) show the domain morphology at a larger scale with the color illustrating the z-component of the magnetization. e-g) display an enlarged portion with black vectors showing the x- and y-components of the magnetization. a) and e) display the relaxed magnetization state at zero field showing stripes with different chiralities bristled with Bloch lines. In b) an external magnetic field of $\mu_0 H = 50 \text{ mT}$ is applied, stripes and skyrmions are coexisting. An external magnetic field of $\mu_0 H = 88 \text{ mT}$ reveals the coexistence of type-2 bubbles, Bloch skyrmions with both cw and ccw chiralities, and antiskyrmions (c and f). In d) and g) only topologically protected spin structures (skyrmions/antiskyrmions) remain at 95 mT.

Fig. 5. a-d) Nucleation process of an antiskyrmion starting from a crossing point of three stripes without a chirality (a) imaged by LTEM. b) and c) show the crossing point with only two and one stripe connected after the field was increased to 86 and 95 mT, respectively. The crossing point resembles a Bloch line and acts as the nucleation point of the antiskyrmion after the final stripe shrank down at 105 mT (d). As a comparison the nucleation process in the micromagnetic simulations is displayed in e-h). The simulation parameters are the same as in Fig. 4. A very similar process is observed here.

Micromagnetic simulations are in good agreement with our experiments (Fig. 5b). They exhibit the same coexistence of bubbles, skyrmions, and antiskyrmions with a decreasing density of bubbles for larger applied fields.

To confirm the metastable state of antiskyrmions in our system, micromagnetic simulations of the energy barrier using a hybrid finite- and boundary elements method were performed. They showed a clear energy barrier between the antiskyrmion state and the skyrmion/saturated state (SI-Fig. 19). Thus, we conclude that the observed antiskyrmions are metastable and primarily stabilized by dipole-dipole interaction.

To learn how to achieve this state, we took a closer look at the nucleation process of an antiskyrmion both with LTEM imaging and micromagnetic simulations. Figure 5a-d shows a specific location of the [Fe/Ir/Gd]/ [Fe/Ir/Gd]/ [Fe/Ir/Gd] sample at 200 K where an antiskyrmion eventually forms. We observed the distinct feature that in all samples at $T < 250 \text{ K}$ antiskyrmions always nucleated from a crossing point of three stripes. One of these crossing points is displayed in Fig. 5a. Three stripes without a chirality meet and due to the resulting in-plane components, one stable Bloch line emerges resulting in a contrast very similar to an antiskyrmion. With increasing field, the stripes shrink down and one of them disconnects at 86 mT (Fig. 5b). At 95 mT the Bloch line remains only connected to the very end of a single stripe. This stripe decreases in size until an isolated antiskyrmion is left at 105 mT (Fig. 5d). It is important to note that these crossing points of three stripes also exist in samples that do not exhibit antiskyrmions. Also, not all triple crossings of stripes with Bloch lines necessarily nucleate antiskyrmions, if antiskyrmions exist. While the starting chirality of the crossing stripes does not seem to play a role, with increasing fields the antiskyrmion always nucleated at the end of a stripe without chirality resembling a Bloch line. Very similar nucleation processes can be found in the micromagnetic simulation, as displayed in Fig. 5e-h. The process also starts at a crossing point of three stripes (Fig. 5e) and ends with an isolated antiskyrmion (Fig. 5h). In our simulation, antiskyrmions exclusively originate from these triple crossing points for saturation magnetization values larger than 175 kA/m using a $K_u$ value of 22.35 kJ/m$^3$. This behavior agrees well with our experimental data. Additional nucleation processes of the other spin objects are displayed in the supplementary information (SI-Fig. 14 and 15).

To get a better understanding of the necessary parameter space to stabilize the different spin objects, the relevant
magnetic properties were measured. We extracted $M_s$ from magnetometry measurements while ferromagnetic resonance (FMR) measurements were carried out to determine the $K_u$ values. Due to the inclusion of heavy metal materials in the form of Ir in our MLs, an interface DMI contribution has to be considered. It was also shown that bulk DMI can even exist in inhomogeneous ferrimagnetic alloys [45]. We measured the DMI constant $D$ by Brillouin light scattering (BLS) [46]. The Fe/Gd ML without Ir showed no measurable DMI, while the ML with five Ir layers at the top and bottom ($N_{Ir}=5$) exhibited a $D$ value of $(0.10 \pm 0.01) \text{mJ/m}^2$. This value is more than an order of magnitude smaller than typical values for DMI-stabilized skyrmions [47]. Previous works [16][18] established that the ratio of $K_u$ and $M_s$ is crucial for the formation of stripe domains and skyrmions [48][49]. In Fig. 6 we plot the $M_s$ and $K_u$ values of our samples obtained for temperatures between 100 and 300 K, and mark the corresponding topologically protected spin objects that were experimentally observed. In addition, results reported by Montoya et al. [16] obtained for similar systems are included exhibiting exclusively Bloch skyrmions at higher $M_s$ values (blue triangles). The purple squares correspond to samples that showed antiskyrmions under the investigated applied oop magnetic fields. These antiskyrmions always coexisted with skyrmions and sometimes with bubbles. Blue and white squares correspond to the existence of sole skyrmions and in-plane domains without further spin objects, respectively. Figure 6 reveals the importance of low saturation magnetization values satisfying the condition $\frac{1}{2}\mu_0M_s^2 > K_u$ for stabilizing (anti-)skyrmions. In order to get an understanding of how $M_s$ and $K_u$ affect the underlying spin texture, additional micromagnetic simulations were performed. The simulations were carried out with zero DMI and a constant film thickness of 62 nm. For different thicknesses and DMI values, additional simulations were conducted, showing only a minor impact on the formation and stability of the spin objects in the analyzed parameter range (SI-Fig. 18). However, for DMI values greater than 0.2 mJ/m$^2$ antiskyrmions do no longer exist and skyrmions dominate. The starting spin configuration for the simulations was an isolated Bloch skyrmion and an isolated antiskyrmion. Their stability was probed at different applied oop fields between 0 and 125 mT. The regions where these spin objects are at least stable at one of the fields are marked by color in Fig. 6. The blue region marks the parameter range in which the initial antiskyrmion stays stable. The blue region marks parameters in which the skyrmion is stable. The underlying diagrams for specific fields and initial states are displayed in the supplementary information (SI-Fig. 16 and 17). It is important to note that the simulations do not convey the possible formation path of (anti-)skyrmions. This leads to stable skyrmions and antiskyrmions at very low $K_u$ values while experimentally this parameter range leads to pure in-plane domains instead of stripe domains which are necessary to form the described spin objects (white squares). The simulations reveal a pocket in the phase diagram at small $K_u$ and $M_s$ where antiskyrmions are at least metastable. In agreement with our experiments, there is no exclusive antiskyrmion phase. The simulations also show that various spin objects exist if the magnetic shape anisotropy ($\frac{1}{2}\mu_0M_s^2$) is larger than $K_u$ (right side of the dashed line). The simulation matches our experimental data very well, revealing a delicate balance of interactions that we achieved for our samples by the insertion of Ir layers moving our samples’ parameters further to a novel phase region of metastable antiskyrmions.

III. Conclusion

We demonstrated the possibility of stabilizing antiskyrmions primarily by dipole-dipole interaction at room temperature. With LTEM imaging we observe second-order antiskyrmions experimentally and first-order antiskyrmions outside of $D_{2d}$ Heusler compounds. The novel spin objects coexist in Fe/Gd-based multilayers together with Bloch skyrmions and topological trivial type-2 bubbles. Phase diagrams of the spin objects were created in dependence on magnetic oop field, temperature, saturation magnetization, and uniaxial magnetic anisotropy. Micromagnetic simulations confirmed the phase pocket of metastable antiskyrmions for low saturation magnetization and for the uniaxial magnetic anisotropy values

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**Fig. 6.** Phase diagram including both experimental and simulation results depending on the uniaxial magnetic anisotropy and saturation magnetization. The squares correspond to LTEM measurements that show antiskyrmions and skyrmions coexisting (purple), solely skyrmions (blue), and no visible spin objects (white) and their $K_u$ and $M_s$ values at the measured temperature. The triangles are experimental data points reported by Montoya et al. [16] obtained for similar Fe/Gd systems which show exclusively skyrmions. The colored areas of the diagram correspond to the parameter regions in which skyrmions (blue) and antiskyrmions (purple) are stable in our simulations. In white regions neither of them are stable. The dashed line shows $K_u = \frac{1}{2}\mu_0M_s^2$. 

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satisfying the condition $\frac{1}{2}\mu_0 M^2 > K_m$. Further, we investigated the nucleation process of antiskyrmions and revealed the necessity of a crossing point of three magnetic stripe domains to form an isolated antiskyrmion with an open magnetic field. This discovery significantly simplifies future investigations of antiskyrmions. Additionally, the coexisting phases of different topologically protected spin objects provide great potential for further studies on quasi-particle interactions, spin dynamics as well as for possible future applications in spintronics.

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**METHODS**

**Sample preparation and characterization.** The ML samples were prepared at room temperature by dc magnetron sputtering from elemental targets on 30 nm thick SiN membranes for LTEM imaging and on Si(001) substrates with a 100 nm thick thermally oxidized SiO$_2$ layer for magnetic characterization. The sputter process was carried out using an Ar working pressure of 5 x 10$^{-3}$ mbar in an ultra-high vacuum chamber (base pressure < 10$^{-8}$ mbar). First, a series of [Fe(0.35)/Gd(t$_{Gd}$)]$_{80}$ (all thicknesses in nm) was prepared with the Gd thickness t$_{Gd}$ ranging from 0.35 nm to 0.50 nm. For all samples, 5 nm-thick Pt seed and cover layers were used to protect the films from corrosion. The thicknesses of the layers were estimated from the areal densities measured by a quartz balance before deposition. It is important to note that the deposition of layers in the sub-0.1 nm range is not precisely possible with this technique. Reproducibility can only be accomplished within one sputter run. It was previously reported that the structure of the MLs exhibits intermixing [1].

A composition that exhibits skyrmions at room temperature was achieved for t$_{Gd}$ = 0.40 nm and was further modified by inserting 0.20 nm-thick Ir layers from the top and bottom. Samples with different numbers of insertion layers (N$_{Ir}$ = 0, 2, 5, 10, 20, 40) were prepared. A schematic image of the [Fe(0.35)/Ir(0.20)/Gd(0.40)]$_{80}$ layer stack is displayed in Fig. 7.

The MLs were investigated by a variety of techniques at temperatures between 50 and 350 K. The integral magnetic properties of the MLs were probed by superconducting quantum interference device - vibrating sample magnetometer (SQUID-VSM). $M$–$H$ hysteresis loops were measured in oop and ip configuration for all samples at 50, 100, 150, 200, 250, 300, and 350 K (SI-Fig. 3) and the $M_s$ values were extracted.

The uniaxial magnetic anisotropy constant $K_u$ was evaluated using ferromagnetic resonance (FMR) measurements performed with a Bruker spectrometer and a conventional X-band resonator at a microwave frequency $f = 9.45$ GHz. FMR spectra were recorded in the temperature range 100-300 K for different orientations of the static magnetic field with respect to the Fe/Gd ML plane (polar angular dependence). The g-factor was extracted from frequency-dependent FMR measurements at room temperature with a co-planar wave-guide and microwave generator. The angular-dependent resonance field was analyzed within Smit-Beljers approach which yields the value of the effective magnetization. One extracts the uniaxial magnetic anisotropy constant $K_u$ using the known value of the saturation magnetization.

The interface Dzyaloshinskii-Moriya interaction (DMI) was extracted from non-reciprocal spin wave dispersion using Brillouin light scattering (BLS) measurements. The wave-vector-resolved BLS in backscattering geometry [2] was conducted at room temperature using a monochromatic continuous-wave solid-state laser with a wavelength of 473 nm. The incident angle was $\theta$ with respect to the normal axis of the film (z-axis). The external field $H$ was applied along the y-axis. Backscattered light was collected and processed with a six-pass Fabry–Perot interferometer TFP-2 (JRS Scientific Instruments). In this configuration, magnetostatic surface spin waves (MSSW) [3] with wave vectors $K_{\text{stokes}}$ and $K_{\text{anti-stokes}}$ were excited in the MLs. By varying the incident angle, the wave vectors were tuned. MSSW propagating along opposite directions led to resonance peaks of Stokes and anti-Stokes signals in the BLS spectra. The two peaks are asymmetric in both peak intensity and frequency. The intensity difference is attributed to the non-reciprocity of MSSWs. The frequency difference $\Delta f$ originates from the asymmetry of the dispersion relations resulting from the interface DMI. $\Delta f$ is used to determine the interface DMI constant $D$ according to [4]. The linear fitting of this function was made at four different external fields and an average value of the interface DMI constant of $(0.10 \pm 0.01)$ mJ/m$^2$ was extracted. Error bars indicate the standard deviation of the four fitted values.

The magnetic domain morphology was imaged by Lorentz TEM using a FEI Titan and a JEOL NEOARM-200F system with a defocus of -2.5 mm in Fresnel mode. The temperature was controlled by the Gatan Double Tilt Liquid Nitrogen Cooling Holder Model 636 for the low temperature measurements. The theoretical contrast of the spin textures in Fig. 1b-f (panel II) was simulated in the following way: Parallel incoming electrons are modeled as vectors to impinge on the spin structure on a discrete 2D grid at an angle of 90°. Analytical functions of the ip component of the 2D spin objects are used to model the internal magnetic field as vectors. In the magnetic field of the structure, electrons are deflected by the Lorentz force into a direction perpendicular to their own velocity and the local magnetization direction of the spin structure. In the code, the cross product of the magnetic field vectors and the incoming electron vectors are multiplied by a scaling factor to adjust for weaker or stronger deflection. After iterating over all electrons/vectors in the image and calculating their impact points on the virtual detector, the collected data is
converted to a continuous probability density using the kdeplot function from the seaborn Python library, implementing a kernel density estimation. The result is a continuous grayscale image, where bright areas indicate areas towards which many electrons/vectors are deflected, whereas dark regions indicate regions with a below-average electron/vector incident count. The program additionally plots a representation of the spin structure, the arrows’ colors are mapped to their direction indicate the local orientation and magnitude of the spin structure. The arrows’ colors are mapped to their direction on a HSV spectrum using the arctan2 function from the Python matplotlib library. 

**Micromagnetic modeling.** The micromagnetic simulations were performed by using simulation codes based on both finite differences method, magnum.af [5] and hybrid finite- and boundary elements method, magnum.fe [6]. While the former was used to reproduce the experimental results and investigate the formation process of experimentally observed spin structures, the latter was employed to investigate the stability of isolated skyrmions and antiskyrmions by varying the material parameters of the system. In both cases the magnetization dynamics was investigated by means of numerical integration of the Landau-Lifshitz-Gilbert (LLG) equation [7][9].

\[
\frac{\partial m}{\partial t} = -\frac{\gamma}{1 + \alpha^2} m \times H_{\text{eff}} - \frac{\alpha \gamma}{1 + \alpha^2} m \times \left( m \times H_{\text{eff}} \right),
\]

where \(\alpha\) is the Gilbert damping constant, \(\gamma\) the reduced gyromagnetic ratio, \(m\) the magnetization unit vector, and \(H_{\text{eff}}\) is the effective field term, which includes the considered energy contributions.

To reproduce the field driven magnetization dynamics in a Fe/Gd multilayer, we discretize a continuous film with a length \(l = 5\mu m\), width \(w = 5\mu m\) and a thickness \(t = 62nm\) in magnum.af. The cell volume is chosen according to the exchange length \(l_{ex}\) of 13 nm as \(l_x \times l_y \times l_z = 10 \times 10 \times 8.85 nm^3\). First, each cell is randomly magnetized. We relax the structure to its ground state at vanishing external fields, where we model the effective field term \(H_{\text{eff}}\) in such a fashion that it includes only the micromagnetic exchange, uniaxial magnetic anisotropy, and demagnetization fields, where the exchange stiffness constant \(A_{ex} = 6pJ/m^2\), uniaxial magnetic anisotropy constant \(K_u = 22.35kJ/m^3\), and saturation magnetization \(M_s = 225kA/m\) are used as material parameters. To investigate the dynamics of the system, the sample is subject to the time-dependent Zeeman field, where \(H_{\text{Zeeman}} = H(t)\hat{e}_z\), with \(e_z\) being the unit vector in the oop direction. \(\mu_\text{eff}H(t)\) is chosen to increase linearly from 0mT to 200mT over 40ns. The role of DMI was investigated by repeating the simulations, where DMI energy was modeled into the effective field term using \(D = 0.10mJ/m^2\).

In order to investigate the stability of an isolated spin object, we use magnum.fe. Here, we use a rectangular finite element mesh of dimensions \(l = 300nm\), \(w = 300nm\), and \(t = 62nm\). We chose simple parameterizations of the (anti-)skyrmions as initial magnetization states and solve the LLG for 10ns at high damping \(\alpha = 1\) in the presence of Zeeman fields with magnitudes between 0 and 125mT. To reproduce the effect of isolation in an infinite film, we set a very large oop uniaxial magnetic anisotropy constant in the outer region of a circle in the \(xy\)-plane with radius \(r = 150nm\), well above the (anti-)skyrmion size, where \(K_u = 1MJ/m^3\). We vary \(M_s\) and \(K_u\) and calculate the integer topological charge \(N_{sk}\) of the final magnetization states, defined by

\[
N_{sk} = \int \frac{1}{4\pi} m \cdot \left( \frac{\partial m}{\partial x} \times \frac{\partial m}{\partial y} \right) \, dx dy.
\]

If \(N_{sk}\) of the relaxed magnetization state is \(N_{sk} = -1\), an antiskyrmion is stable for the particular pair of \(M_s\) and \(K_u\), while a skyrmion is assumed to be stable for \(N_{sk} = +1\). The exchange stiffness constant is chosen constant at \(A_{ex} = 6pJ/m^2\).

**DATA AVAILABILITY**

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

**CODE AVAILABILITY**

The Python code used to simulate the spin object contrasts is available under [10]. The micromagnetic simulations were executed using the magnum Python library.
performed using the closed source code of magnum.af\textsuperscript{[5]} and magnum.fe\textsuperscript{[6]}.

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ACKNOWLEDGMENTS

The funding of this project by the German Research Foundation (DFG) within the Transregional Collaborative Research Center TRR 80 “From electronic correlations to functionality”, by the Bavarian-Czech Academic Agency (project no. 8E18B051), and SNSF via Sinergia project 171003 (Nanoskyrmionics) is gratefully acknowledged. CzechNanoLab project LM2018110 funded by MEYS CR is gratefully acknowledged for the financial support of the LTEM measurements at CEITEC Nano Research Infrastructure. The computational results presented have been achieved, in part, using the Vienna Scientific Cluster (VSC). We thank Ms. Babli Bhagat (UDE) for the help with FMR measurements.

AUTHOR CONTRIBUTIONS

M.A. and M.H. designed the experiments. M.H. prepared the samples and performed the magnetic characterization by SQUID-VSM. S.K., R.K., C.V., D.S., and C.A. performed the micromagnetic simulations. M.V., A.U., J.H., M.U., and M.H. carried out the LTEM measurements and discussed and analyzed the experimental data. A.S. and M.F. measured and analyzed the DMI measurements. T.S. performed SQUID-VSM measurements and MFM pre-characterization. All authors contributed in writing and reviewing the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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SUPPLEMENTARY INFORMATION

**SQUID-VSM measurements.** All measured $M - H$ hysteresis loops of the $[\text{Fe}(0.35)/\text{Ir}(0.20)/\text{Gd}(0.40)]_{80}$, $[\text{Fe}(0.35)/\text{Gd}(0.40)]_{80 - 2N_{\text{Ir}}}$, $[\text{Fe}(0.35)/\text{Ir}(0.20)/\text{Gd}(0.40)]_{N_{\text{Ir}}}$ MLs in oop and ip geometry for temperatures between 50 and 350 K are displayed in Fig. 9. Due to the decrease in magnetization with temperature, we conclude that all Fe/Gd-based MLs are Gd dominant over all measured temperatures. The formation of spin textures is sometimes revealed by the presence of an opening in the oop loop close to saturation.

Figure 10 shows the dependence of the saturation magnetization $M_s$ (a) and the uniaxial magnetic anisotropy $K_u$ (b) on $N_{\text{Ir}}$. The insertion of Ir layers reduces linearly the saturation magnetization (Fig. 10 a). If all 80 layers have additional Ir insertion layers, $M_s$ almost vanishes completely ($N_{\text{Ir}}=40$). Thus, we conclude that Ir insertion layers reduce the total moment of the adjacent Fe and Gd layers to nearly zero. It is also important to note that while the moment decreases with the increasing number of Ir insertion layers, the shape of the loops stays relatively similar due to the approximately constant ratio of magnetic shape and magnetic uniaxial anisotropy. Furthermore, all samples reveal rather small $K_u$ values, which decrease with increasing $N_{\text{Ir}}$, as summarized in Fig. 10b for different temperatures.

**Further phase diagrams.** Phase diagrams of the discussed sample series dependent on the oop magnetic field and temperature are displayed in Fig. 11. No pure antiskyrmion phase is observable. Antiskyrmions always coexist with Bloch skyrmions and sometimes with type-2 bubbles. It is also evident that the stability range of antiskyrmions is smaller than the one of skyrmions for both temperature and field for all samples. For five of the six samples, it was possible to stabilize antiskyrmions even at room temperature. While we observed first-order antiskyrmions in every sample of our series besides $N_{\text{Ir}}=40$ at a wide range of temperatures, second-order antiskyrmions were only observed at 260 K in $N_{\text{Ir}}=2$ (Fig. 11b) and at 300 K in $N_{\text{Ir}}=20$ (Fig. 11e). In all cases, they were quite rare in comparison to the other spin objects. Because of that, we can not rule out their existence at other temperatures and fields. For $N_{\text{Ir}}=40$ no magnetic LTEM contrast was observable due to the low magnetization of the sample (see Fig. 11f).

**Magnetic force microscopy image.** To confirm the underlying magnetic periodicity of our samples, magnetic force microscopy images were captured. Figure 12 shows the LTEM image (Fig. 12a) of $[\text{Fe}/\text{Gd}]_{80}$ in comparison to an exemplary MFM image (Fig. 12b). Both images were captured in zero field at room temperature. Note that the images do not show the same region of the sample but share the same scale. The size of the magnetic domains captured by the images match roughly the size of the larger high-contrast black and white stripes in the defocused LTEM image.

**Additional LTEM images.** Some additional LTEM images of selected samples at various temperatures and oop magnetic fields are shown in Fig. 13. Figure 13 a-d displays LTEM images of the $[\text{Fe}/\text{Ir}/\text{Gd}]_2$, $[\text{Fe}/\text{Gd}]_{76}$, $[\text{Fe}/\text{Ir}/\text{Gd}]_2$ ML at 260 K. Image a) is captured in a magnetic field of 92 mT and
nucleate in this sample and at this temperature at 67 mT (j), while type-2 bubbles and first-order antiskyrmions appear at 115 mT (k). At 134 mT only the topologically protected (anti-)skyrmions are visible (l). Figure 13 m-p shows LTEM images of the [Fe/Ir/Gd]_{20} / [Fe/Gd]_{40} / [Fe/Ir/Gd]_{20} ML at 300 K. The contrast is weaker for this sample because of the reduced magnetic moment (Fig. 10a). Although image n) exhibits only magnetic stripes with chirality at zero field, image n) shows type-2 bubbles at 32 mT. At 35 mT skyrmions and antiskyrmions start to nucleate while the bubbles vanish (o). The sample is saturated at 45 mT (p).

**Micromagnetic simulations.** In addition to the simulations presented in the paper, further calculations were performed. In addition to Fig. 4 we provide in Fig. 14 the formation process of a clockwise (CW) and counterclockwise (CCW) Bloch skyrmions. Figure 15 illustrates the magnetization states at chosen magnitudes of the applied Zeeman field during the formation of a second-order antiskyrmion in a system with weak DMI using $D = 0.1 \text{mJ/m}^2$. The DMI energy is modelled in our micromagnetic simulations as

$$E_{\text{DMI}} = \int_{\Omega_m} D(m \cdot \nabla (e_d \cdot m) - (\nabla \cdot m)(e_d \cdot m)) dx,$$

where $\Omega_m$ is the magnetic region, $e_d = (0, 0, 1)$, $D$ is the DMI constant, and $m$ is the normalized magnetization vector.

It is noteworthy that in our micromagnetic investigations the second-order antiskyrmions only appear in the presence of weak DMI, where $D = 0.1 \text{mJ/m}^2$. However, they are really rare and we can not rule out their presence in systems without DMI.

In order to investigate the stability of skyrmions and antiskyrmions in infinite films, we simulate their magnetization dynamics in a confined system where we chose a rough parametrization as start configuration. Furthermore, to avoid the decay of the topological structure by moving out of the confined system, we set a high anisotropy of $K_u = 1 \text{MJ/m}^3$ in the outer ring of the simulated structure. If this anisotropy barrier is placed at a sufficient distance from the topological structure, this procedure is assumed to accurately account for possible annihilation processes in infinite films, while keeping the computational cost at a feasible level.

Figure 16 illustrates the obtained stability phase maps of an antiskyrmion for a system free of DMI at different Zeeman fields. To obtain these results, we apply the Zeeman fields constantly for 10 ns, while solving the LLG, Eq. (1), in a system where a parametrization of an antiskyrmion is the initial magnetic configuration. The exchange stiffness constant is chosen as constant at $A_{ex} = 6 \text{pJ/m}$. The final magnetization state $m(10 \text{ns})$ is then evaluated by means of the finite element method and the integer topological charge $N_u$ is calculated integrating Eq. (2) over the entire volume, and dividing the result by the thickness of the sample, which is 62 nm.

In order to show the coexistence of the skyrmions in the regimes where an antiskyrmion is dipolar-stabilized, we repeated the micromagnetic simulations shown in Fig. 16 by using a Bloch skyrmion as the initial magnetization state.

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Fig. 10. a) Saturation magnetization $M_s$ and b) uniaxial anisotropy $K_u$ as a function of repetition number $N_u$ of Ir insertion layers.
Fig. 11. Magnetic field and temperature dependence of the phases of the different spin structures. The magnetic phase diagrams of a) [Fe/Gd]_{10}, b) [Fe/Ir/Gd]_{12} / [Fe/Gd]_{10}, c) [Fe/Ir/Gd]_{15} / [Fe/Gd]_{10}, d) [Fe/Ir/Gd]_{15} / [Fe/Gd]_{60}, e) [Fe/Ir/Gd]_{20} / [Fe/Gd]_{40}, and f) [Fe/Ir/Gd]_{80} are displayed.
phase maps obtained from these simulations are illustrated in Figs. 17.

To show, that the spin objects with \( N_{\text{sk}} = -1 \) can be found only in a very restricted regime, we chose to investigate the role of the DMI in their stability. Figure 18 a shows that our experiments are exactly in the regime, where these structures can be nucleated and stabilized. By making use of a different composition of Fe/Gd-layers and the introduction Ir insertion layers, our experiments show particularly low values for \( M_s \) and \( K_u \), an aspect of crucial importance. We see in Fig. 18 a that a DMI value higher than \( D_{\text{max}} = 0.2 \text{ mJ/m}^2 \) leads to a system where the antiskyrmion is no longer a stable configuration, and skyrmions dominate.

Additionally, the dipolar-stabilization dominates the systems in such manner that the exchange interactions do not have any crucial influence on the stability of the antiskyrmions, as it is shown in Fig. 18 b. Nevertheless, for increasing \( M_s \) and \( A \) we notice that the integer topological charge starts to deviate from \( N_{\text{sk}} = -1 \), as the antiskyrmions start to deform at the edges. These simulations have been performed without DMI and an uniaxial magnetic anisotropy constant \( K_u = 22.35 \text{ kJ/m}^3 \) was used.

To show that the total thickness of the investigated samples does not influence the stability of the antiskyrmions, we vary the thickness of our magnetic material together with \( M_s \). Further material parameters are chosen as \( A = 6 \text{ pJ/m} \) and \( K_u = 22.35 \text{ kJ/m}^3 \). Figure 18 c shows the phase diagram using a system free of DMI. It is very clear that the thickness does not lead to any deformations or instabilities in the investigated thickness range.

In order to exclude the possibility that the spin textures are stable in the micromagnetic simulations because of numerical errors and simulation artifacts, we perform energy barrier simulations applying a full micromagnetic model. Namely, we calculate the minimum energy paths to annihilate an antiskyrmion to obtain a saturated magnetic configuration along the \( e_z \)-direction and to transform an antiskyrmion in a skyrmion. The former is shown in Fig. 19 a and the latter in Fig. 19 b. Both simulations show a clear energy barrier, reflecting the metastable nature of the antiskyrmion state. It is also observed that other energetically more favorable states need to be overcome in order to transition to skyrmions or to the saturated state, making these transformations very costly from an energetic point-of-view. It has to be mentioned that, due to the change of the topological number \( N_{\text{sk}} \) from \(-1\) to \(1\), Bloch like states are formed and a micromagnetic treatment with a mesh size larger than the lattice constant underestimates the atomistic barrier.

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Fig. 13. Exemplary LTEM images of selected samples at various temperatures and oop magnetic fields $H$. a-d) displays $[\text{Fe/Ir/Gd}]_2 / [\text{Fe/Gd}]_{76} / [\text{Fe/Ir/Gd}]_2$ at 260 K. e-h) shows $[\text{Fe/Ir/Gd}]_5 / [\text{Fe/Gd}]_{30} / [\text{Fe/Ir/Gd}]_5$ at 300 K and i-l) at 100 K. m-p) shows $[\text{Fe/Ir/Gd}]_{20} / [\text{Fe/Gd}]_{40} / [\text{Fe/Ir/Gd}]_{20}$ at 300 K.
Fig. 14. Formation process of a (counter-)clockwise skyrmion and antiskyrmion without DMI.

Fig. 15. Formation process of a second-order antiskyrmion in a system with weak DMI $(D = 0.1 \text{ mJ/m}^2)$. 
Fig. 16. Spin object phase maps of \( M_s \) and \( K_u \) (10 kJ/m\(^3\) \( \sim \) 0.7 \( \mu \)eV/atom \([5]\)) dependent stability of an isolated antiskyrmion obtained from micromagnetic simulations without DMI and with constantly applied Zeeman fields of strength a) \( \mu_0 H = 0 \) mT, b) \( \mu_0 H = 10 \) mT, c) \( \mu_0 H = 30 \) mT, d) \( \mu_0 H = 50 \) mT, e) \( \mu_0 H = 70 \) mT, f) \( \mu_0 H = 100 \) mT, and g) \( \mu_0 H = 125 \) mT. The integer topological charge \( N_{sk} \) is \(-1\) for an antiskyrmion, 1 for a skyrmion, and 0 for a magnetization state with no topologically protected spin object.

Fig. 17. Same as Fig. 16, except, a skyrmion is parametrized as the initial magnetization state and relaxed for 10ns at high damping \( \alpha = 1 \). The integer topological charge \( N_{sk} \) is 1 for a skyrmion, and 0 for a magnetization state with no topologically protected spin object.
Fig. 18. Role of material parameters in the stabilization process of an isolated antiskyrmion, as obtained by micromagnetic simulations performed at vanishing fields, where a) shows the influence of the DMI constant $D$ ($1 \text{mJ/m}^2 \sim 340 \mu\text{eV/atom}$ [5]), b) the exchange stiffness constant $A$, and c) the thickness $t$ of the film. An antiskyrmion was initially parametrized in the system and then relaxed for 10ns at high damping $\alpha = 1$. The integer topological charge $N_{sk}$ is $-1$ for an antiskyrmion, 1 for a skyrmion, and 0 for a magnetization state with no topologically protected spin object.

Fig. 19. Minimum energy paths for a) the annihilation of an antiskyrmion and its transition to a saturated state along $e_z = (0, 0, 1)$, and b) for the transition of an antiskyrmion to a Bloch skyrmion.