Evaluation of the transfer entropy between two skyrmions confined in a square cell

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In recent years, there has been extensive research on computational devices that utilize the randomness or probabilistic properties in systems, such as Brownian computing, quantum annealing, and p-bit devices. In these systems, it is not always obvious how information is propagated to obtain results, unlike deterministic electrical wiring. Such a flow of information can be visualized by the transfer entropy [1]. The transfer entropy represents the directional information transfer between two stochastic time-evolutional data sets. Here, we have focused on skyrmions, which exhibit stochastic behavior in solids in the ambient temperature. Skyrmion is a topologically stable spin structure and a suitable information carrier for applications in artificial intelligence with p-bits and/or thermodynamic information reservoirs. This study quantitatively evaluates the transfer entropy between two skyrmions in the Brownian motion confined in a square cell.

Our sample structure is SiO2 substrate | Ta (5.0 nm) | CoFeB (1.26 nm) | Ta (0.23 nm) | MgO (1.5 nm) | SiO2 (3.0 nm) capping layer. On top of that, an additional layer of SiO2 (0.5 nm) patterned into a square was deposited. In such samples, skyrmions are confined in the square region [2]. Figure 1 shows two skyrmions confined in the square region, as observed by MOKE microscopy. The yellow line indicates the moving trajectory of Skyrmion A. We evaluated the transfer entropy by using this time series data sets. Figure 2 shows the analysis results of the transfer entropy. j indicates the time interval. The pink line and blue dashed line depict the transfer entropy flowing from Skyrmion A and Skyrmion B to Skyrmion B after an elapsed time of j. In both cases, the information is observed to relax over time in j. This method will be visualization technique of a flow of information in complex systems with randomness and probability distributions. This research was supported by ULVAC, Inc., JST CREST Grant number JPMJCR20C1 Japan and JSPS Grant-in-Aid for Scientific Research (S) Grant Number JP20H05666.

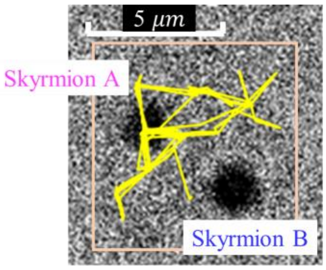

Fig. 1, The moving trajectory of Skyrmion A

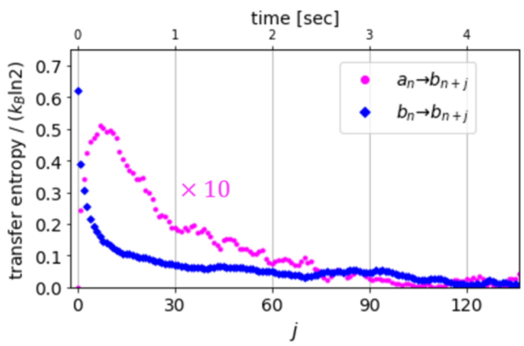

Fig. 2, The transfer entropy between Skyrmion A and Skyrmion B

[1] T. Schreiber, *Phys. Rev. Lett.* **85**, 461 (2000)

[2] Y. Jibiki *et al.*, *Appl. Phys. Lett.* **117**, 082402 (2020)