Realization of different timescales in a heterogeneous atomic Boltzmann machine

Hermann Osterhage[1], Kira Junghans[1], Werner M. J. van Weerdenburg[1], Niels P. E. van Mullekom[1], Ruben Christianen[1], Eduardo J. Domínguez Vázquez[1], Hilbert J. Kappen[1], and Alexander A. Khajetoorians[1]

[1]*Radboud University, Nijmegen, The Netherlands*

The Boltzmann machine (BM) is an energy-based neural network consisting of an ensemble of coupled Ising spins [1]. Realizing such a network in a physical system requires stochastically fluctuating units with competing long-range interactions as the prerequisite for creating a multi-well energy landscape. To realize the dynamics of both neurons and synapses in this model, the stochastic dynamics need to take place on different timescales. The challenge in a physical system is to realize a separation of timescales, in which the dynamics mutually influence each other.

Recently, an atomic Boltzmann machine (BM) was realized by using an array of cobalt atoms, each of which exhibits orbital memory. [1]. Orbital memory is characterized by bistable valence states of an atom, carrying two distinct magnetic moments. Separation of timescales was realized by patterning Co atoms in specific geometries, exploiting the anisotropic electronic properties of the BP substrate [1]. This is however disadvantageous because it requires precise atomic patterning of the atoms as well as always separating atoms depending on dimensionality. The latter can limit the scalability of the concept. Recently, we found that Fe atoms can also exhibit orbital memory, but with an inherently different characteristic timescale than Co [2,3]. Therefore, if different species of orbital memory atoms can be coupled such that their mutual stochasticity is modified, the atomic scale BM can be constructed differently.

Here, we show how a separation of timescales can be realized by coupling Fe and Co orbital memory states. We study the stochastic dynamics in heteroatomic dimer and trimer configurations with scanning tunneling microscopy (STM). We investigate the influence of coupling on the dynamics of the various states and how this relates to synaptic behavior. Further, we discuss the prospect of building a heterogeneous atomic BM from different atomic species with inherently different orbital dynamics.

[1] B. Kiraly et al., Nat. Nanotechn. 16, 414 (2021).
[2] B. Kiraly et al., Nat. Comm. 9, 3904 (2018).
[3] B. Kiraly et al., Phys. Rev. Research 4, 033047 (2022).