Exploiting valence fluctuations in Ce-based intermetallic ferromagnets for permanent magnets

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Rare-earth permanent magnets (REPM's) are used in traction motors of electric vehicles and robotics. It is expected that they will play a core role in SDGs in realizing sustainable industrial developments. Good understanding and better control of various properties of REPM's are in high demand and we are trying to answer practical and fundamental questions combining our theoretical and experimental data. Permanent magnets require strong magnetization, accordingly strong magnetic anisotropy of Ising type, and reasonably high Curie temperature covering up the typical operation temperature range. Magnetization and high Curie temperature is brought about by *3d*-electron ferromagnetism in Fe-group elements, while magnetic anisotropy is provided *4f*-electrons in rare-earth elements. The famous example is the champion magnet made of $Nd_2Fe_{14}B$.
The key nature of *4f*-electrons from which the essential magnetic anisotropy is originated, being localized and thus a preferable direction is fixed by the imposed crystalline electric field, can also be a source of a bottleneck of the same magnetic anisotropy at finite temperatures, since the *4f*-electron anisotropy can be transmitted to *3d*-electron magnetization only indirectly and weakly via *5d*-electrons. To resolve such intrinsically unavoidable trade-off, it would be great if *4f*-electrons can be coupled to *3d*-electorns more directly and magnetic anisotropy is fully exploited at high temperatures. We claim valence-fluctuating Ce provides an ideal playground in this regard and colossal magnetic anisotropy is realized in valence-fluctuating compounds in $Ce(Co_{0.7}Cu_{0.3})_5$. We tracked the trend in the magnetic properties and the valence state of Ce in $Ce(Co_{1-x}Cu_x)_5$ as a function of chemical composition and temperature [1]. The latter is done through soft X-ray absorption spectroscopy (XAS) in PF, KEK and HiSOR. In the middle of the crossover between Ce^{4+} and Ce^{3+} we theoretically observe a jump in the *4f*-electron state depending on the direction of magnetization and associated colossal enhancement of magnetic anisotropy energy. Trend in the XAS data is in line with what we monitor theoretically. Also Ce can be beneficial for magnetization: in an analogy with electron-doped cuprates, Ce^{4+}-doped REPM can sometimes get enhanced magnetization via a generalized Slater-Pauling curve in the host systems with the lattice sufficiently small. Recent developments on doped $SmFe_{12}$ [2] is discussed along this line and peculiar utility of Ce in $(Nd,Ce)_2(Fe,Co)_{14}B$ recently revealed [3] may also be understood in this context.

References

[1] H. Shishido, MM, T. Ueno, K. Saito *et al.*, in preparation.
[2] MM, T. Hawai, K. Ono, preprint.
[3] X. Tang, H. Sepehri-Amin, MM, T. Okubo, K, Hono, Acta Materialia **175**, 1 (2019).