Institute for Molecules and Materials
USCM

Prof. Dr. A.V. Kimel

Heyendaalseweg 135
6525 AJ Nijmegen
P.O. Box 9010
6500 GL Nijmegen

Telephone +31 24 3653026

www.ru.nl/science/uscm

Dagmar Zádrapová
Doktorské studium MFF UK
Ke Karlovu 3
121 16 Praha 2

Our reference	Your reference	Telephone	Date
		53026	October 3, 2023
Subject		E-mail	
Thesis João Pedro Martins Godinho		A.Kimel@science.ru.nl	

Report on the doctoral thesis by João Pedro Matins Godinho titled "Electro and thermal magneto-transport in antiferromagnetic systems".

Dear Dr. Kulich,

The thesis by João Pedro Matins Godinho titled "Electro and thermal magneto-transport in antiferromagnetic systems". The work of the PhD candidate represents an essential contribution helping to understand mutual interdependence of the electronic transport and magnetic properties of metallic antiferromagnets. Antiferromagnetic materials were discovered relatively recently, but, nevertheless, they have been in the focus of fundamental research in magnetism for more than 60 years. For instance, the very first report in English literature appeared in 1980 (In Russian it was published in 1976, but the paper was not translated) K. B. Vlasov, E. A. Rozenberg, A. G. Titova, *et al.*, Fiz. Tverd. Tela (Leningrad) **22**, 1656 (1980) [Sov. Phys. Solid State **22**, 967 (1980)]. I must admit, however, that the novelty of this work is its focus on metallic antiferromagnets, while the previous studies were predominantly focused on oxides, whose electronic structure is very different from metals and the nature of electric conductivity is not trivial and the conductivity is rather poor. Another strength of the work is that the studies were done at the level of devices. Such a downscaling is so far not yet possible for most of dielectric antiferromagnets. The candidate has an impressive list of publications in respected scientific journals and this only confirms my statement that the PhD contains novel and original results. The thesis consists of 7 chapters. Four of them are introductory chapters, one contains the original experimental results and the last two are dedicated to the outlook and conclusions. In Chapter 1 the candidate clearly formulates the research question – How to electrically control and detect identify the antiferromagnetic Neel vector in antiferromagnets? Such a clear formulation is very important. It is supposed to show how the work is supposed to go beyond the state-of-the-art. Unfortunately, this chapter is not long. Consequently, the candidate overlooks many interesting aspects of physics of antiferromagnets with PT-inversion symmetry. For instance, soon after the very discovery of antiferromagnetism I. E. Dzyaloshinskii reported that antiferromagnetic Cr2O3, which has the PT-inversion symmetry, should possess some interesting properties allowing, in particular, visualization of antiferromagnetic domains. R. R. Birss summarizes some important aspects of physical

phenomena in antiferromagnets in his book “Symmetry and magnetism” (North-Holland Publishing Company, 1964). The thesis is, however, quite minimalistic in the description of the state-of-the-art. Hence, although the chapter clearly formulates the goal, I find that the motivation is rather weak.

Chapter 2. Is dedicated to the theory of spin dynamics in antiferromagnets. This is the weakest chapter of the whole thesis. Practically all equations are written without showing if the quantities are scalars or vectors. Many of the equations are thus simply unreadable. Since the candidate discusses spin dynamics in antiferromagnets, it is obvious that a single LLG equation can describe the dynamics. One should write either coupled LLG equations for each of the antiferromagnetic sublattices or write LL equations in terms of **L** and **M** vectors or use Lagrangian mechanics and write Lagrange-equation of motion in terms of **L**. The fact, that the chapter is quite minimalistic makes it also very superficial.

Chapter 3 introduces the physics of magneto-transport measurements in metallic magnets. Reference [34] is not complete.

Chapter 4 is dedicated to antiferromagnets. I very much like the logic that the candidate follows in the description of physics of antiferromagnetism and the main physical principles of magneto-transport phenomena in antiferromagnets. I find it a pity, however, that very important symmetry consideration of the magneto-transport phenomena in antiferromagnets on page 20 is so short and, to be honest, can be quite confusing. For instance, it is referred to Neumanns’ principle, but it would be important just to give the formulation of the principle in the thesis. Symmetry analysis of the nonlinear magneto-transport phenomena, which seem to play the key role in the detection of antiferromagnetic spins, has not been performed. I wonder if earlier studies of the nonlinear Hall effect in antiferromagnets (see, for instance, E. A. Turov, Antiferromagnetic hall effect nonlinear in the electric current, Journal of Experimental and Theoretical Physics volume 90, 689–694 (2000)) are relevant to this work.
I also would like to pay the attention of the candidate to the fact that in multi-domain samples with 90-degree domains symmetry analysis is not trivial. By the way, also current-induced control of antiferromagnetic 90-degrees domains can have an additional and a more robust mechanism than the Neel torque. Due to anisotropic magneto-resistance, different domains are heated differently and thus the domain can more as a result of the temperature gradient.

Chapter 5 reports about investigation of the magneto-properties in synthetic antiferromagnets, CuMnAs and Mn3Sn. Moreover, an original and powerful technique of visualization of antiferromagnetic domains in conducting antiferromagnets is introduced. The technique combines the principles of scanning probe imaging and transport phenomena. I believe this technique has a great potential for future applications in studies of metallic antiferromagnets and their surfaces. It is a very strong chapter, which could easily be explained into four chapters. Outlook and conclusions are again quite minimalistic. They briefly summarize the main findings of chapter 5 and propose some obvious research direction for further studies.
To conclude, I find that the scientific contribution(s) of João Pedro Matins Godinho to the field of antiferromagnetic spintronics and physics of metallic antiferromagnets is substantial. The

results are of high scientific quality and their level correspond to the level internationally accepted for awarding PhD degree in physics. PhD thesis is not written well. *The thesis, in principle, shows the ability of the candidate for creative scientific work*, but I strongly advice to rewrite chapter 2 and pay credits to the earlier studies of antiferromagnetic Hall effects, before the thesis becomes public.

Kind regards,

Prof.dr. A. Kimel