

Horst Meyer

A. Brooks Harris¹

Received: 18 June 2016 / Accepted: 16 July 2016 / Published online: 26 July 2016
© Springer Science+Business Media New York 2016

Abstract In this note, I describe Horst Meyer as a warm person and an insightful scientist with whom I have had the privilege to have a long collaboration.

1 Horst, the Mensch

As they say, “Hindsight is 20/20.” Somehow, as a Harvard graduate student, I got involved in an experimental thesis under the supervision of Horst Meyer. That turned out to be a pivotal first step in reorganizing my education and was the beginning of a long and enjoyable collaboration. I still recall an incident during my thesis project which illustrates what we all know about Horst. As I was watching him adjust a dewar of liquid nitrogen around the sample holder, I accidentally knocked the stand on which the dewar was supported, thus causing the dewar to crash onto the floor and break. Horst was unperturbed—I will always remember that he did not do what many of us might do—namely, get upset with a clumsy graduate student making a negative contribution to the experiment. Thanks, Horst: I will never forget that. My thesis research, which he assigned to me, was to measure the specific heat of rare earth iron garnets and thereby gain an understanding of their magnetic properties [1,2]. This topic meshed nicely with my natural curiosity about the seemingly mysterious phenomenon of magnetism. This was another lucky break for me. A second memory I have is of getting back Horst’s corrections to the first draft of my thesis. I was seriously embarrassed that a nonnative speaker could find so very many errors in grammar and exposition. I learned much about the construction of a logical exposition, although my exposition still needs improvement! But man bites dog—later on at a conference in

✉ A. Brooks Harris
harris@physics.upenn.edu

¹ Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA

France I overheard Horst giving instructions to the desk clerk (all in French, of course) to call him the next morning because he was going out “la première chose.” I could not believe that this translated the way he meant it. Sure enough, the desk clerk did not understand that phrase. So Horst, famous for his “Horsticisms,” makes them in both English and French!

After graduate school, it was time to postdoc. One choice was to stay on (probably for a year) at Harvard to continue my experimental program. In retrospect, I made the crucial correct decision to instead join Horst at Duke where he encouraged me to start reinventing myself as a theorist. Looking back on this period, I now realize that doing an experimental thesis made me appreciate the nature of the connection between theory and experiment. Serendipitously, this training helped me greatly throughout my career.

Solid hydrogen has been the focus of much of my collaboration over the years with Horst [3], and this was a lucky result of my postdoc with him at Duke. I recall one amusing incident when I was visiting Horst at Duke in the early 1960s. I had gotten back a referee’s report on my NMR paper [4] which required several changes and explanations, which would result in a greatly improved paper. Horst asked me “What happened to your NMR paper?” I said, “the referee asked several questions and I have not gotten around to doing the necessary work to answer them properly.” He sat me down at his kitchen table and said, “We will have to do that right now, together.” So we did and afterwards he commented, “This may be the first time that a referee has had the opportunity to construct the author’s reply to himself.” But this is typical of Horst: to show interest in the progress of his junior colleagues and to encourage them.

2 Horst’s Physics

Horst is well known for his many contributions concerning the critical properties of the liquid helium, but I am not qualified to review them, other than to list a few of the most important papers [5–13]. (The titles provide a window into Horst’s research in this general area.) I would summarize this area of research as consisting of many sensitive tests of the modern scaling theory of phase transitions, a topic that was developed very actively as an outgrowth of the Renormalization Group. I was pleased to be able to quote one of Horst’s famous results (for the critical exponent β for the liquid–vapor coexistence curve of He³) [9] in an APS talk in 2007 in connection with the Onsager award.

Here I will first review the results of Horst’s group and of my collaborations with him concerning magnetism. Our first collaboration (my thesis topic) involved measuring the specific heat of yttrium iron garnet (YIG) and rare earth iron garnets. At Horst’s instigation, we measured the specific heat of YIG and obtained one of the first observations of the very low temperature ($T < 4$ K) specific heat due to magnons (spin waves) [1]. Because the energy of a spin wave of wave vector \mathbf{k} is proportional to k^2 :

$$E(\mathbf{k}) = Dk^2 + \mathcal{O}(k^4), \quad (1)$$

the spin wave specific heat for $T < 4\text{K}$ is proportional to $T^{3/2}$. To separate this contribution from the lattice specific heat, which is proportional to T^3 , one analyzes the total specific heat, C , in the form [1,2]

$$C/T^{3/2} = A + BT^{3/2} + \dots \quad (2)$$

where A is proportional to $(1/D)^{3/2}$. Analyses of this type by various authors led to unexpected discrepancies. This tricky problem was experimentally clarified in a beautiful paper [14] by Horst's group, who showed that there was an additional term in the specific heat proportional to T , whose existence invalidates the analysis based on Eq. (2). Some theoretical models to explain such a term were proposed, and the status of the magnetic specific heat was comprehensively discussed.

For the rare earth iron garnets, the specific heat for $4\text{K} < T < 20\text{K}$ is dominated by the rare earth energy gap Δ arising from the effect of the iron exchange field acting on the rare earth ions, so that the magnetic specific heat C_M is

$$C_M/k_B \sim [\Delta/(k_B T)]^2 \exp(-\Delta/(k_B T)). \quad (3)$$

where k_B is Boltzmann's constant. By analyzing the measurements of C_M in Refs. [1] and [2], we were able to determine the exchange splitting (of order 25cm^{-1}), for several rare earth iron garnets. For YbIG, this splitting was later confirmed by far-infrared spectroscopy [15].

Horst's group also analyzed the temperature dependence of the spontaneous magnetization of YIG for $T < 50\text{K}$ due to spin waves, as

$$1 - M(T)/M(0) = AT^{3/2} + BT^{5/2} + \dots \quad (4)$$

where A and B are related to the coefficients in the dispersion relation for the spin wave energy as a function of wave vector which, in turn, are related to the exchange interactions between pairs of spins [16–18].

I now turn to Horst's work on the solid hydrogens. On arriving at Duke, I joined Horst's group which was working on the properties of solid hydrogen. At very low temperature, the molecules in solid hydrogen orientationally order into four orientational sublattices [19]. Horst's group used NMR to measure the order parameter which indicates the degree to which the molecules are aligned along the local axis of ordering [20]. Horst's group was also instrumental in measuring the nuclear magnetic resonance and relaxation properties of both orientationally ordered hydrogen and orientationally ordered deuterium. In a paper [21] which was a pleasing result of our collaboration, Horst's group investigated the NMR spectrum of solid hydrogen at very low ortho concentration. The para molecules give no NMR signal, so the spectrum dominantly reflects isolated single ortho molecules and pairs of neighboring ortho molecules. The isolated ortho molecules give rise to a central unsplit peak in the NMR spectrum. The NMR signal from ortho pairs consists of doublets, whose splittings indicate the degree of orientational ordering. Usually, one has only to consider the dipole–dipole interaction between protons in the *same* hydrogen molecule. Here, however, it was necessary to consider the effect of the dipole–dipole interaction between protons on

different molecules (within the pair of molecules being considered). Usually, interactions between different molecules lead to line broadening. Here they lead to small but distinct line splittings. Horst's group also measured the order parameter as a function of temperature [22] and ($J = 1$) concentration [23] for solid D_2 . I will not review here the various studies of the spin lattice relation times T_1 and T_2 which Horst has undertaken for both H_2 and D_2 in order to understand the orientational dynamics of the solid hydrogens. Instead I list a few of his most important papers in this area: Refs. [24–33].

All the work on solid hydrogen indicated to us that solid hydrogen was indeed “The Ideal Analog of an Antiferromagnet” [34]. In this connection, I would mention one of Horst's cutest experiments. It can be shown [35] that for solid hydrogen and deuterium

$$\partial p / \partial T|_V = \gamma_{\text{rot}} C_V / V, \quad (5)$$

where p is the pressure, T is the temperature, V is the volume, C_V is the constant volume specific heat, and the rotational Grüneisen coefficient γ_{rot} is $-\partial \ln E / \partial \ln V$, where E is the electric quadrupole–quadrupole (EQQ) energy and V is the volume. (The EQQ energy is known to vary with separation R as $E \sim R^{-5}$, so that $\gamma = 5/3$). The advantage of this formulation is that $\partial p / \partial T|_V$ can be measured accurately via a capacitance bridge, whereas it could be quite inconvenient to measure the specific heat accurately at low temperature. This technique was also used to effectively measure the very low temperature specific heat of solid helium-3 [36].

There are two other topics which stand out in my mind. The first is Horst's study of quantum diffusion. I think he first noticed (in solid hydrogen) that at low ortho concentration the pair spectrum showed a time-dependent increase in amplitude [37]. This is reported in more detail in Ref. [38]. He realized that this indicated that the number of ortho pairs was increasing over its random value. This did not mean that molecules were moving—rather it means that the quantum angular momentum label J was being exchanged. This effect has also been observed using other techniques [39]. The second topic I would mention concerns the nature of the percolation phenomenon which occurs when ($J = 1$) molecules are replaced by ($J = 0$) molecules as ortho hydrogen spontaneously converts to para hydrogen. As Horst's group [40] discuss, quadrupolar order does not propagate down a chain of molecules as it would do for vector (magnetic) order. Instead loop-like connections are required to develop long-range order. Thus, quadrupolar ordering in solid hydrogen provides a very nice physical realization for what field theorists [41] have called “biconnectedness.”

Finally, I will note one curious result which involves the structure of solid hydrogen and solid deuterium. The crystal structure of both orientationally ordered solid hydrogen and deuterium was determined to be that of the cubic space group Pa3. (When Gen Shirane once asked me what I did, I told him that I was working on solid hydrogen. Of course, his question was, “What structure does that have?” When I told him “Pa3,” his reply was “That's a very interesting space group,” from which I realized that he must have had an intimate knowledge of all 230 space groups.) Now the reader may wonder, why do I mention these things. Well, it so happens that orientationally ordered C_{60} was identified as having a unit cell with the four icosahedral C_{60} molecules in the

unit cell having one of their fivefold axes aligned along a different [111] direction. Of course, I noticed that this was very similar to the way that the four sublattices of orientationally ordered hydrogen molecules are arranged in the unit cell. However, in C_{60} , the structure was initially identified as being that of space group $Pn\bar{3}$ [42]. I remember mentioning to my colleague Paul Heiney that this was somewhat like what happens for $Pa\bar{3}$ solid hydrogen. On closer inspection, R. Sachidanandam and I saw that a better fit to the experimental scattering result could be obtained if the structure was identified as $Pa\bar{3}$ [43], and this was later [44] independently verified [45]. To me, it is remarkable that the multipole interactions of a linear molecule like H_2 or (N_2) lead to the same space group on a cubic lattice, $Pa\bar{3}$, as they do for a nearly spherical (actually icosahedral) molecule like C_{60} . In fact, symmetry indicates [46] that $Pa\bar{3}$ is one of the few cubic space groups that are appropriate for orientationally ordered C_{60} on an fcc lattice. This work led me to give greater attention [47] to crystal structure, which I might profitably have done much earlier.

3 Summary

In this article, I could only capture a small fraction of Horst's research and I have not addressed several significant areas. But in all his work, I am struck by the precision of his thinking. This characteristic made it very easy for me to interact with him.

References

1. H. Meyer, A.B. Harris, Specific heat of some rare earth iron garnets and YIG at low temperatures. *J. Appl. Phys.* **31**, 49S (1960)
2. A.B. Harris, H. Meyer, Calorimetric determination of energy levels in rare-earth and yttrium-iron garnets. *Phys. Rev.* **127**, 101 (1962)
3. Below I will refer to several of Horst's papers on solid hydrogen. The most cited of our joint papers is A. B. Harris and H. Meyer, "Orientational Ordering Solid ortho-para H_2 Mixtures and Analogy with a Spin Glass". *Can. J. Phys.* **63**, 3 (1985); Erratum, **64**, 890 (1986)
4. A.B. Harris, Properties of solid hydrogen. II. Theory of nuclear magnetic resonance and relaxation. *Phys. Rev. B* **2**, 3495 (1970)
5. G.R. Brown, H. Meyer, Study of specific heat singularity of He^3 near its critical point. *Phys. Rev. A* **6**, 364 (1972)
6. G. Goellner, R. Behringer, H. Meyer, Thermodynamic properties of liquid He^3 - He^4 mixtures near tricritical point. 1. Vapor-pressure measurements and their thermodynamic analysis. *J. Low Temp. Phys.* **13**, 113 (1973)
7. A.B. Kogan, H. Meyer, Heat transfer and convection onset in a compressible fluid: He^3 near the critical point. *Phys. Rev. E* **63**, 056310 (2001)
8. G. Goellner, H. Meyer, Chemical potential of He^3 - He^4 solutions near tricritical point. *Phys. Rev. Lett.* **26**, 1534 (1971)
9. C. Pittman, H. Meyer, Equation of state and critical exponents of He^3 and He^3 - He^4 mixtures near the liquid-vapor critical point. *Phys. Rev. B* **20**, 3678 (1979)
10. E.K. Riedel, H. Meyer, R.P. Behringer, Thermodynamic properties of liquid He^3 - He^4 mixtures near tricritical point 2. Data analysis by scaling field method. *J. Low Temp. Phys.* **22**, 309 (1976)
11. B. Wallace, H. Meyer, Equation of state of He^3 close to critical point. *Phys. Rev. A* **2**, 1563 (1970)
12. D.B. Roe, H. Meyer, Ultrasonic dispersion and attenuation near liquid gas critical point of He^3 . *J. Low Temp. Phys.* **30**, 91 (1978)
13. H. Ramm, P. Pedroni, J.R. Thompson, H. Meyer, Nuclear susceptibility of liquid He^3 —I. *J. Low Temp. Phys.* **2**, 539 (1970)

14. A.J. Henderson Jr., D.G. Onn, H. Meyer, J.P. Remeika, Calorimetric study of yttrium and rare-earth iron garnets between 0.4 and 4.5 K. *Phys. Rev.* **185**, 1218 (1969)
15. A.J. Sievers III, M. Tinkham, Far infrared spectra of rare-earth iron garnets. *Phys. Rev.* **129**, 1995 (1963)
16. A.B. Harris, Spin-wave spectrum of yttrium and gadolinium iron garnet. *Phys. Rev.* **132**, 2398 (1963)
17. R. Gonano, E. Hunt, H. Meyer, A.B. Harris, Sublattice magnetization in several rare-earth and yttrium iron garnets by means of ^{57}Fe NMR. *J. Appl. Phys.* **37**, 1322 (1966)
18. A.B. Harris, Sublattice magnetization of yttrium iron garnet at low temperatures. *Phys. Rev.* **155**, 499 (1967)
19. O. Nagai, T. Nakamura, Quadrupole interactions in crystals. *Progr. Theor. Phys.* **24**, 432 (1960)
20. L.I. Amstutz, S.M. Myers, D.C. Rorer, H. Meyer, A study of NMR line shapes in solid H_2 below 4 K. *Phys. Rev.* **181**, 589 (1969)
21. A.B. Harris, L.I. Amstutz, H. Meyer, S.M. Meyers, Observation of the pair interaction between ortho molecules in solid H_2 . *Phys. Rev. B* **175**, 603 (1968)
22. B. Maraviglia, F. Weinhaus, H. Meyer, R.L. Mills, NMR in solid D_2 near the orientational ordering transition. *Solid State Commun.* **8**, 815 (1970)
23. B. Maraviglia, F. Weinhaus, H. Meyer, R.L. Mills, Orientational order parameter in cubic D_2 . *Solid State Commun.* **8**, 16835 (1970)
24. L.I. Amstutz, S.M. Myers, H. Meyer, R.L. Mills, Longitudinal nuclear relaxation measurements in hcp H_2 . *J. Chem. Solids* **30**, 2687 (1969)
25. F. Weinhaus, H. Meyer, Nuclear longitudinal relaxation in hcp H_2 . *Phys. Rev. B* **7**, 2974 (1973)
26. F. Weinhaus, S.M. Myers, B. Maraviglia, H. Meyer, Nuclear longitudinal relaxation times in hcp D_2 . *Phys. Rev. B* **3**, 626 (1971)
27. F. Weinhaus, H. Meyer, S.M. Myers, A.B. Harris, Nuclear-spin relaxation in rotating frame in solid D_2 . *Phys. Rev. B* **7**, 2960 (1973)
28. L.I. Amstutz, H. Meyer, S.M. Myers, R.L. Mills, Longitudinal nuclear relaxation measurements in HCP H_2 . *J. Phys. Chem. Solids* **30**, 2693 (1969)
29. R.F. Buzerak, M. Chan, H. Meyer, NMR relaxation measurements in solid H_2 at low ortho- H_2 concentrations. *J. Low Temp. Phys.* **28**, 415 (1977)
30. F. Weinhaus, H. Meyer, Nuclear longitudinal relaxation in hexagonal close-packed H_2 . *Phys. Rev. B* **7**, 2974 (1973)
31. S. Washburn, M. Calkins, H. Meyer, A.B. Harris, Pulsed NMR-studies in solid H_2 . 3. Spin-lattice relaxation-times. *J. Low Temp. Phys.* **53**, 585 (1983)
32. S.A. Dickson, H. Meyer, Nuclear magnetic resonance in solid H_2 and D_2 under high pressure. *Phys. Rev.* **138**, 1293 (1965)
33. S. Washburn, I. Yu, H. Meyer, Nuclear-relaxation in solid H_2 glass. *Phys. Lett. A* **85**, 365 (1981)
34. A.B. Harris, Solid hydrogen: the ideal analog of an antiferromagnet. *J. Appl. Phys.* **42**, 1574 (1971)
35. J.F. Jarvis, H. Meyer, D. Ramm, Measurement of $(\partial P/\partial T)_V$ and related properties in solidified gases. II. Solid H_2 . *Phys. Rev.* **178**, 1461 (1969)
36. M.F. Panczyk, R.A. Scribner, G.C. Straty, E.D. Adams, Evidence of nuclear spin ordering in solid helium³. *Phys. Rev. Lett.* **19**, 1102 (1967)
37. L.I. Amstutz, J.R. Thompson, H. Meyer, Observation of molecular motion in solid H_2 below 4 K. *Phys. Rev. Lett.* **21**, 1175 (1968)
38. R. Schweizer, S. Washburn, H. Meyer, NMR of dilute o- H_2 in solid p- H_2 at temperatures below 1 K. *Phys. Rev. Lett.* **40**, 1035 (1978)
39. W.N. Hardy, A.J. Berlinsky, A.B. Harris, Microwave absorption by ortho- H_2 pairs in solid hydrogen. *Can. J. Phys.* **55**, 1150 (1977)
40. J. Adler, R.G. Palmer, H. Meyer, Transmission of order in some unusual dilute systems. *Phys. Rev. Lett.* **58**, 882 (1987)
41. A.B. Harris, T.C. Lubensky, Field-theoretic approaches to biconnectedness in percolating systems. *J. Phys. A* **16**, L365 (1983)
42. P.A. Heiney, J.E. Fischer, A.R. McGhie, W.J. Romanov, A.M. Denenstein, J.P. McCauley Jr., A.N. Smith III, D.E. Cox, Orientational ordering transition in solid C_{60} . *Phys. Rev. Lett.* **66**, 2911 (1991)
43. R. Sachidanandam, A.B. Harris, Comment on 'Orientational ordering transition in solid C_{60} '. *Phys. Rev. Lett.* **67**, 1467 (1991)
44. Ref. [43] was received 21 June, 1991. Ref. [45] was received 18 August, 1991

45. W.I.F. David, R.M. Ebberson, J.C. Matthewman, K. Prassides, T.J.S. Dennis, J.P. Hare, H.W. Kroto, R. Taylor, D.R.M. Walton, Crystal structure and bonding of ordered C_{60} . *Nature* **353**, 147 (1991)
46. A.B. Harris, R. Sachidanandam, Orientational ordering of icosahedra in solid C_{60} . *Phys. Rev. B* **46**, 4944 (1992)
47. A.B. Harris, Landau analysis of the symmetry of the magnetic structure and magnetoelectric interaction in multiferroics. *Phys. Rev. B* **76**, 054447 (2007), erratum, **77**, 019901 (2008)