

有

Crystalline Electric Field Effects in *f*-Electron Magnetism

Edited by

Robert P. Guertin

*Tufts University
Medford, Massachusetts*

and

**Wojciech Suski and
Zygmunt Zołnierak**

Polish Academy of Sciences

PLENUM PRESS • NEW YORK AND LONDON

IG ADDRESS

ounds
ed became
1 other

y con-
vice
Academy
Laboratory
since

congratu-
rthday
y as a
participants
cess in

CONTENTS

SECTION 1: SINGLET GROUND STATE

Singlet Ground State System in Amorphous Rare Earth Alloys (Invited) A.K. Bhattacharjee and B. Coqblin.....	1
Magnetic Properties and Neutron Spectroscopy of Inter-metallic Praseodymium Compounds (Invited) F.J.A.M. Greidanus, L.J. de Jongh, W.J. Huiskamp, A. Furrer and K.H.J. Buschow.....	13
Pressure Induced Changes in the Magnetism of Crystal Field Split Systems (Invited) R.P. Guertin.....	25
Van Vleck Paramagnets in High Magnetic Fields (Invited) E. Leyarovski, L. Leyarovska, C. Popov and N. Iliev.....	41
Singlet Ground State and Combined Electron-Nuclear Magnetism in Praseodymium (Invited) K.A. McEwen, W.G. Stirling and C. Vettier.....	57
Study of the Crystalline Electric Field in Praseodymium Intermetallics (Invited) W. Matz, B. Lippold, E.A. Goremychkin, A. Andreeff, H. Greissman and T. Frauenheim.....	69
Magnetic Excitations in TbP under Hydrostatic Pressure A. Loidl, K. Knorr and C. Vettier.....	83
Transport Properties of the Intermetallic PrAl ₃ H. Müller, E. Hegenbarth, W. Matz, E. Mrosan and A. Schmeltzer.....	89

Effects of Crystalline Fields on the Physical Properties of PrB ₄	
M. Kasaya, K. Takegahara, A. Yanese and T. Kasuya.....	95

SECTION 2: RESONANCE SPECTROSCOPY, NEUTRON SCATTERING

Crystal Electric Field Effects in the ESR of Dilute Alloys (Invited)	
K. Baberschke.....	101
Crystal Field Interaction in Rare Earth Hydrides: EPR and Low Temperature Specific Heat Measurements (Invited)	
H. Drulis.....	113
Crystal Fields and Conduction Electron Effects in Intermetallic Compounds and Alloys (Invited)	
M. Loewenhaupt, S. Horn and B. Frick.....	125
Positive Muons as Local Probes in Paramagnetic Rare Earth Systems (Invited)	
H. Wehr, K. Knorr, F.N. Gygax, A. Schenk and W. Studer.....	137
Mossbauer Studies of the Er ₆ (Fe _{1-y} Mn _y) ₂₃ H _x System	
J. Zukrowski, G.A. Stewart, G. Kalkowski, G. Wortmann and G. Wiesinger.....	149
¹⁴¹ Pr-NMR Investigations on the Dielectric van Vleck Paramagnetic Compound Pr ₂ (SO ₄) ₃ ·8H ₂ O at Very Low Temperatures	
G. Feller, M. Staudte and M.A. Teplov.....	157
Crystal Field Effects on the ESR Spectra of Rare Earths in CePd ₃	
C. Rettori, E. Weber, G.E. Barberis, J.P. Donoso and F.C. Gandra.....	163
²⁷ Al-NMR Investigations on PrAl ₂ and Pr _x La _{1-x} Al ₃ , x=1.0, 0.5, 0.25	
G. Feller, A. Frieser, B. Lippold and M. Mühle.....	171
Magnetic Behavior of TbF ₃	
M. Piotrowski.....	177
Crystal Field Splitting in Light Rare Earth Dicarbides Studied by Neutron Spectroscopy	
W. Wegener, A. Furrer, W. Buhrer and S. Hautecler.....	185

SECTION 3: THEORY

Linewidth of Crystal Field Excitations in Metallic Rare Earth Systems (Invited)	
K.W. Becker and J. Keller.....	191
Electronic Structure of LaIn ₃ and LaSn ₃	
A. Hasegawa.....	201
The Application of the Self-Consistent Mori Formalism to Analyze the Dynamical Response of van Vleck Systems in the Vicinity of the Curie Point	
L. Kowalewski, A. Lehmann-Szweykowska, M. Thomas and R. Wojciechowski.....	207
The Origin of the Crystal Field for 4f ⁿ Ions in Insulators	
F. Anisimov and R. Dagys.....	215
Conduction Electron Effects on Localized Spin Excitations in the RKKY-Theory of Magnetism	
V. Christoph, A.L. Kuzemsky and T. Frauenheim.....	219
Magnetic Field Dependence of the Conduction Electron Mass in Praseodymium	
P. Fulde and R.M. White.....	227

SECTION 4: LATTICE EFFECTS

Phonon Coupling Mechanisms in Intermetallic Rare Earth Compounds (Invited)	
B. Lüthi, M. Nicksch, R. Takke, W. Assmus and W. Grill...	233
Quadrupole Interaction at ¹⁶⁹ Tm in Cubic TmZn	
G.A. Stewart.....	245
Field Dependence of the Magnetic Anisotropy of Gadolinium at 4.2°K under High Pressures	
J.J.M. Franse, R. Gersdorf and E. Koops.....	249
Magnetostriction of an Yttrium Monocrystal Doped with Terbium Impurities	
P. Pureur, G. Creuzet and A. Fert.....	255
Crystal Field Splitting and Thermal Expansion in Dilute Magnesium-Rare Earth Crystals	
M.H. de Jong, J. Bijvoet and P.F. de Châtel.....	261

Magnetostriction in Dilute Alloys of Rare Earths G. Creuzet and I.A. Campbell.....	267
A Martensitic Transformation Triggered by Magnetic Ordering J. Pierre and B. Hennion.....	275
SECTION 5: TETRAGONAL MATERIALS	
Neutron Diffraction Studies of Magnetic Ordering in Rare Earth and Actinide Intermetallics of the CeAl ₂ Si ₂ Type (Invited) J. Leciejewicz.....	279
Quadrupole Effects in the Lattice Parameters and Magnetic Ordering Temperatures of RECu ₂ Si ₂ (RE=Rare Earth) (Invited) W. Schlabit, J. Baumann, G. Neumann, D. Plümacher and K. Reggentin.....	289
Influence of the Crystal Field on Dy ³⁺ Ions in DyM ₂ Si ₂ Compounds as Revealed by Investigations of Their Magnetic Properties and Nuclear Hyperfine Interactions E.A. Görlich, R. Kmieć, B. Janus and A. Szytuła.....	301
Magnetic Properties of RCo ₂ Si ₂ and RCo ₂ Ge ₂ Compounds M. Kolenda, A. Szytuła and A. Zygmunt.....	309
¹⁶⁹ Tm Mossbauer Study of TmCu ₂ Si ₂ G.A. Stewart and J. Zukrowski.....	319
Magnetic Properties of TbCo ₂ Si ₂ and TbCo ₂ Ge ₂ J. Leciejewicz, S. Siek, A. Szytuła and A. Zygmunt.....	327
Magnetostriction of Rare Earth Impurities in YCu ₂ Si ₂ N. Rüssman, H.U. Häfner and D. Wohlleben.....	333
SECTION 6: CERIUM COMPOUNDS	
Electronic Transport Properties of Metallic Ce Systems (Invited) F. Steglich, K.H. Wienand, W. Klämke, S. Horn and W. Lieke.....	341
Fermi Surface and p-f Mixing Mechanism in CeSb (Invited) T. Suzuki, H. Kitazawa, M. Sera, I. Oguro, H. Shida, A. Yanase and T. Kasuya.....	357

Mechanism of Unusual Magnetic Anisotropy in the Cerium Monopnictides (Invited) K. Takegahara, H. Takahashi, A. Yanase and T. Kasuya.....	367
Equilibrium and Dynamic Behaviors of Cubic Ce ³⁺ Systems with Anisotropic Coqblin-Schreiffer and Crystal Field Interactions (Invited) D. Yang and B.R. Cooper.....	381
Large Pressure Effects on the Magnetic Phase Diagrams of CeSb and Ce _x (La _{0.76} Y _{0.24}) _{1-x} Sb Compounds H. Bartholin, J.M. Effantin, P. Bulet, J. Rossat- Mignod and O. Vogt.....	393
Crystal Field Excitations in CeAg _{1-x} In _x Compounds H. Wehr, K. Knorr, A.P. Murani and W. Assmus.....	401
Magnetoconductivity of Cerium Compounds Y. Lassailly, A.K. Bhattacharjee and B. Coqblin.....	407
Low Temperature Magnetic Phase Transitions of CeBi and CeSb Studied by Magnetoelastics T. Nakajima, T. Suzuki, M. Sera and T. Kasuya.....	415
Anomalous Behavior of Cerium in RMg ₃ and RInAg ₂ Compounds R.M. Galera, A.P. Murani and J. Pierre.....	423

SECTION 7: RARE EARTH METALLIC AND SEMI-METALLIC COMPOUNDS

Magnetism and Crystal Fields in Ternary Superconductors (Invited) G.K. Shenoy, G.W. Crabtree, D. Niarchos, F. Behroozi, B.D. Dunlap, D. Hinks and D.R. Noakes.....	431
A Novel Kind of Metal-Rich Lanthanide Compound (Invited) A. Simon.....	443
Magnetic Properties and Quadrupolar Interactions in PrAg P. Morin and D. Schmitt.....	455
Experimental Determination of the Electrostatic Contribution to the Crystalline Electric Fields in Non-cubic Metals R.A.B. Devine and Y. Berthier.....	461

Crystal Field Influence on the Specific Heat and Schottky Effect in Rare Earth Monosulfides L.N. Vasil'ev, A.V. Golubov, A.G. Gorobetz, V.S. Oscotsky, I.A. Smirnov and V.V. Tikhonov.....	467
Interpretation of the ζ -Holmium Sesquiselenide Magnetic Susceptibility L. Pawlak, M. Duczmal and S. Pokrzywnicki.....	473
Electronic Structure and Crystal Field in Sm_3Se_4 and Sm_3Te_4 M. Sugita, S. Kunii, K. Takegahara, N. Sato, T. Sakakibara, P.J. Markowski, M. Fujioka, M. Date and T. Kasuya.....	479
Strong Crystal Field Effects in TmNi_5 D. Gignoux, B. Hennion and A. Nait Saada.....	485
Magnetic Properties of Some Solid Amorphous Rare Earth Alloys A. Apostolov, H. Hristov, T. Mydlarz, M. Mihov and V. Skumriev.....	493

SECTION 8: URANIUM COMPOUNDS

Magnetic Phase Diagrams of Some Uranium Monopnictides and Monochalcogenides (Invited) J. Rossat-Mignod, P. Bulet, S. Quézel, O. Vogt and H. Bartholin.....	501
Ligand Field of Uranium (4+) Antiprismatic Cluster in LCAO MO Approach J. Mulak and Z. Gajek.....	519
Magnetic Structure and Lattice Deformation in UO_2 V.L. Aksenov, T. Frauenheim and V. Sikora.....	525
Crystal Field and p-f Mixing Effects in Uranium Pnictides K. Takegahara, A. Yanase and T. Kasuya.....	533
Magnetic Properties of the Uranium Trichalcogenides B. Janus, W. Suski and A. Blaise.....	539
Magnetization of U_3P_4 in Magnetic Fields up to 500 kOe K.G. Gurtovoj, A.S. Lagutin, R.Z. Levitin and V.I. Ozhogin.....	545

Temperature Dependence of Magnetization in U_3P_4 and U_3As_4 Single Crystals P.J. Markowski, S. Kunii, K. Takegahara, T. Suzuki, Z. Henkie and T. Kasuya.....	549
LIST OF SENIOR AUTHORS.....	557
LIST OF PARTICIPANTS.....	561
SUBJECT INDEX.....	569
MATERIALS INDEX.....	577

CONDUCTION ELECTRON EFFECTS ON LOCALIZED SPIN EXCITATIONS IN THE
RKKY-THEORY OF MAGNETISM

V. Christoph, A.L. Kuzemsky and Th. Frauenheim

Joint Institute for Nuclear Research, Dubna, 10100 Moscow
P.O. Box 79, USSR

INTRODUCTION

The magnetic scattering of thermal neutrons is a unique technique for establishing both the static and the dynamic properties of magnetic correlations. For interpreting neutron inelastic magnetic scattering data on heavy rare earth metals, the calculations of the magnetic susceptibility and the magnetic excitation spectrum are of particular interest¹⁻¹¹. In rare earth metals the exchange interaction between the localized 4f electrons and the extended (conduction) electrons (RKKY exchange) is basic for understanding their magnetic and electric properties¹.

In order to avoid the difficulties connected with crystal field and anisotropy effects, we restrict our consideration to rare earth metals like Gd. Recent detailed experimental and theoretical examinations⁹⁻¹⁴ confirm the spin moment of the Gd ion to be a good quantum number. The d-band, having a width of 5-7 eV, lies well above the 4f level and is about one fourth occupied. The density of states of the d-electrons at the Fermi level is much higher than the density of states of the s(p) electrons⁸⁻¹². The general conclusion drawn from these investigations was that the conduction electrons, which play an essential role in the mechanism of RKKY exchange in the heavy rare earth metals, cannot be considered as free s-electrons as assumed in early papers^{2,3}, but rather as similar to tight-binding d-electrons in transition metals⁴⁻¹⁴. In particular, the magnetic excitation spectrum of Gd has been calculated¹¹ taking into consideration the d-like character of the extended electrons. Starting with an APW calculation of the band structure and wave functions, the RKKY exchange matrix elements were obtained. Agreement of the calculated magnon spectrum with the experimental one¹⁵ could be

obtained by reducing the calculated values by a scale factor of about four. In a more recent paper¹⁶ the generalized spin susceptibility has been calculated using the KKR method.

In the present report the generalized spin susceptibility and the magnon spectrum of Gd metal has been calculated. The tight-binding d-like character of the conduction electrons and the electron-electron and electron-phonon interaction are taken into account in a unified manner. The contributions of different interactions to the magnon damping are estimated, and the lower temperature dependence of the magnon width is calculated. As has been noted¹⁷, the magnon lifetime investigations in Gd at low temperature should give information on different interactions and their roles and significance in the heavy rare earth metals.

RARE EARTH METAL MODEL

Neglecting crystal field and anisotropy effects, we describe the rare earth metal by localized 4f spins, interacting with d-like tight-binding conduction electrons. We take into consideration the electron-electron and electron-phonon interactions in the framework of a model given by S. Barisic et al.¹⁸. The Hamiltonian¹⁸ is a generalization of the well known Hubbard Hamiltonian¹⁹ and has been investigated in detail in Ref. 20.

The total Hamiltonian is:

$$H = H_d + H_{d-f} + H_{d-ph} + H_{ph}, \quad (1)$$

where

$$H_d = \sum_{k\sigma} E(k) \alpha_{k\sigma}^+ \alpha_{k\sigma} + \frac{U}{2N} \sum_{kk'} \alpha_{k+q\sigma}^+ \alpha_{k\sigma}^+ \alpha_{k'-q, -\sigma}^+ \alpha_{k'}^-, \quad (2)$$

is the Hubbard Hamiltonian¹⁹. For the tight-binding d-electrons we use $E(k) = 2t \sum_{\alpha} t(\vec{a}_{\alpha}) \cos(k \cdot \vec{a}_{\alpha})$, where $t(\vec{a}_{\alpha})$ is the hopping integral between next nearest neighbors¹⁸, and \vec{a}_{α} ($\alpha=1,2,3$) denotes the lattice vectors in a simple lattice with inversion center. The second term in (2) describes the Coulomb interaction of electrons with opposite spins at the same lattice site. The RKKY Hamiltonian describing the interaction of the total 4f spin \vec{S} with the spin density of the conduction electrons has the form

$$H_{d-f} = -\frac{J}{\sqrt{N}} \sum_{kq} \{ (\alpha_{k\uparrow}^+ \alpha_{k+q\uparrow} + \alpha_{k\downarrow}^+ \alpha_{k+q\downarrow}) S_{-q}^z + (\alpha_{k\uparrow}^+ \alpha_{k+q\downarrow} S_{-q}^+ + \text{c.c.}) \} \quad (3)$$

where J is the local RKKY exchange integral. In general the exchange integral strongly depends on the wave vectors \vec{k} and \vec{q} having maximum values at $k=q=0$ ¹¹. For simplicity we restrict ourselves to a local exchange. The generalization to non-local exchange is straightforward. For the electron-phonon interaction we use¹⁸:

$$H_{d-ph} = \sum_{kq} \sum_{\sigma} v^{\nu}(k, k+q) Q_{q\nu} \alpha_{k+q\sigma}^+ \alpha_{k\sigma} \quad (4)$$

where

$$v^{\nu}(\vec{k}, \vec{k}+\vec{q}) = \frac{2iq_0}{\sqrt{NM}} \sum_{\alpha} t(\vec{a}_{\alpha}) e_{\nu}^{\alpha}(\vec{q}) \{ \sin \vec{a}_{\alpha} \cdot \vec{k} - \sin \vec{a}_{\alpha} \cdot (\vec{k}+\vec{q}) \}. \quad (5)$$

In (5) q_0 is the Slater coefficient originating in the exponential decrease of the d-functions¹⁸, N is the number of unit cells in the crystal, and M is the ion mass. $\vec{e}_{\nu}^{\alpha}(\vec{q})$ ($\nu=1,2,3$) are the polarization vectors of the phonon modes.

For the vibrating ion system we have

$$H_{ph} = \frac{1}{2} \sum_{q\nu} (P_{q\nu}^+ P_{q\nu} + \omega_0^2(q\nu) Q_{q\nu}^+ Q_{q\nu}) \quad (6)$$

where $P_{q\nu}$ and $Q_{q\nu}$ are the normal coordinates and $\omega_0(q\nu)$ are the acoustical phonon frequencies. Thus, as in the Hubbard model, the d- and s-(p) bands are replaced by one "effective" band in our model¹. However, the s-electrons give rise to screening effects and are taken into account by choosing proper values of J , U and the acoustical phonon frequencies $\omega_0(q\nu)$ ²¹.

GENERALIZED SPIN SUSCEPTIBILITY

We are interested in the Fourier transform of the generalized susceptibility of the localized f-spins $\langle\langle S_k^+ | S_{-k}^- \rangle\rangle$ where

$$\langle\langle S_k^+(t) | S_{-k}^-(0) \rangle\rangle = -i\theta(t) \langle [S_k^+(t) S_{-k}^-(0)] \rangle \quad (7)$$

is the usual double-time commutator Green's function²² and \vec{S}_k is the Fourier transform of the f-spin \vec{S}_i . For the calculation of $\langle\langle S_k^+ | S_{-k}^- \rangle\rangle$ we use the irreducible Green's function technique²³ already applied to the Hubbard model in the atomic and band limits²⁴.

The method of calculation is based on using the generalized matrix Green's function

$$\vec{G} = \begin{pmatrix} \langle\langle S_k^+ | S_{-k}^- \rangle\rangle & \langle\langle S_k^+ | \sigma_{-k}^- \rangle\rangle \\ \langle\langle \sigma_k^+ | S_{-k}^- \rangle\rangle & \langle\langle \sigma_k^+ | \sigma_{-k}^- \rangle\rangle \end{pmatrix}, \quad (8)$$

where the Fourier components of the conduction electron spin densities, $\sigma_k^+ = \sum_q \alpha_{k\uparrow}^+ \alpha_{k+q\downarrow}$ and $\sigma_k^- = \sum_q \alpha_{k\downarrow}^+ \alpha_{k+q\uparrow}$, have been introduced. It may be shown that the equation of motion for G [Eq.(8)] may be exactly transformed to the Dyson equation by using the irreducible Green's functions with an explicit representation of the mass operator. The exact Dyson equation is given by

$$\vec{G} = \vec{G}_0 + \vec{G}_0 \vec{M} \vec{G}, \quad (9)$$

where \bar{M} is the mass operator and \bar{G}_0 is the mean field Green's function. Hence the determination of \bar{G}_0 has been reduced to the determination of \bar{G}_0 and \bar{M} , when the mean field Green's function \bar{G}_0 coincides with the RPA-result^{2,5}.

DAMPING OF SPIN WAVES IN THE COUPLED LOCAL MOMENT-ELECTRON SYSTEM

In order to estimate the damping of the localized spin excitation spectrum due to electron-magnon and electron-phonon scattering, we calculate the local spin susceptibility for small k and ω

$$\langle\langle S_k^+ | S_{-k}^- \rangle\rangle_\omega = \frac{2N^{-1/2} \langle S_0^z \rangle}{\omega - \epsilon_k - 2N^{-1/2} \langle S_0^z \rangle \Sigma(k, \omega)}, \quad (10)$$

which contains the matrix elements of the mass operator $\bar{M} = (M_{ij})$ in a linear approximation

$$\Sigma(k, \omega) = M_{11} + (M_{12} + M_{21}) \frac{J^{1/2} \chi_0^{df}}{1 - U \chi_0^{df}} + \frac{J^2 N (\chi_0^{df})^2 M_{22}}{(1 - U \chi_0^{df})^2}. \quad (11)$$

Here we have used the notations

$$\begin{aligned} \langle S_0^z \rangle &= \langle S_0^z \rangle \left(1 + \frac{N_\uparrow - N_\downarrow}{2N^{1/2} \langle S_0^z \rangle} \right); \quad \chi_0^{df} = \chi_0^{df}(k, \omega) = \frac{1}{N} \sum_q \frac{f_{q+k} - f_{q,k}}{\omega_{q,k}} \\ \omega_{q,k} &= \omega + E(q) - E(q+k) - \Delta; \quad N_\sigma = \sum_f \sum_q \langle n_{q\sigma} \rangle \\ \Delta &= 2JN^{-1/2} \langle S_0^z \rangle + UN^{-1} (N_\uparrow - N_\downarrow). \end{aligned} \quad (12)$$

The spectral density of the spin wave excitations with wave vector k then reads

$$g(k, \omega) = -\frac{1}{\pi} \text{Im} \langle\langle S_k^+ | S_{-k}^- \rangle\rangle = \frac{2N^{-1/2} \langle S_0^z \rangle \Gamma(k, \omega)}{[\omega - \epsilon_k - \Delta(k, \omega)]^2 + [\Gamma(k, \omega)]^2}, \quad (13)$$

where

$$\begin{aligned} \Delta(k, \omega) &= 2N^{-1/2} \langle S_0^z \rangle \text{Re} \Sigma(k, \omega), \\ \Gamma(k, \omega) &= -2N^{-1/2} \langle S_0^z \rangle \text{Im} \Sigma(k, \omega + i\epsilon) \end{aligned} \quad (14)$$

describes the shift and the damping of the acoustical magnons.

Finally we estimate the temperature dependence of $\Gamma(k, \omega)$ due to the mass operator terms in (11). Considering the first contribution in (11) at low temperatures we obtain

$$\text{Im} M_{11} \sim T. \quad (15)$$

The other electron-magnon contributions to $\Gamma(k, \omega)$ can be treated in the same way, where M_{12} , M_{21} and the electron-magnon contribution to M_{22} are proportional to T also. For the electron-phonon contribution to M_{22} we find

$$\text{Im} M_{22}^{\text{ph}} \sim T^3. \quad (16)$$

Hence the damping of the acoustical magnons at low temperatures can be written as

$$\Gamma(k, \omega) \Big|_{k, \omega \rightarrow 0} \sim \Gamma_1 + \Gamma_2 T + \Gamma_3 T^3 \quad (17)$$

where the coefficients Γ_i ($i=1,2,3$) vanish for $k=\omega=0$. For the case when $J=0$, the electron-electron term Γ_1 vanishes in (17).

DISCUSSION

In the present paper the spectrum of the elementary magnetic excitations and their lifetimes have been calculated for the microscopic model of heavy rare earth metals. In the model used the electron-electron interaction of the extended (conduction) electrons and the electron-phonon interaction in the Barisic-Labbe-Friedel manner have been taken into account. Neglecting the damping terms the result obtained (10) coincides with that of L.C. Bartel^{2,5}, obtained in the RPA. Furthermore, using a generalized matrix Green's function here the expressions for the spin susceptibility of the conduction electrons and mixed terms have been derived. Therefore, starting with this formalism the contribution of the extended (conduction) electrons to the total magnetization of the rare earths^{4,5} may also be considered.

The temperature dependence of the acoustical magnon damping is given mainly by the electron-magnon and electron-phonon interactions. The electron-electron contribution Γ_1 is almost temperature independent, but vanishes at $J=0$, also. It should be emphasized here that the real electronic structure of a rare earth metal such as Gd is much more complicated than given by our tight-binding model^{1,4-14}. For a realistic first principle calculation of the stiffness constant about ten bands should be included^{4,5,8,10,11}. Furthermore, the dependence of the RKKY exchange integral $J(k, k+q)$ on the wave vector should be taken into account¹¹. Nevertheless, taking into consideration all interactions playing a part in the rare earth metals, this estimate of the temperature dependence of the magnon damping should

be reasonable. Unfortunately there are no neutron scattering measurements of the low temperature magnon damping in Gd^{17} . Such measurements and their theoretical interpretation would greatly improve our understanding of the interactions in the heavy rare earth metals.

REFERENCES

1. A.J. Freeman, in: *Magnetic Properties of Rare Earth Metals*, ed. R.J. Elliott (Plenum Press, New York, 1972) Chap. 6.
2. S.H. Liu, *Phys. Rev.* 121, 451 (1961).
3. T.A. Kaplan, D.H. Lyons, *Phys. Rev.*, 129, 2072 (1963).
4. A.J. Freeman, J.P. Dimmock, R.E. Watson, *Phys. Rev. Lett.* 16 94 (1966).
5. R.E. Watson, A.J. Freeman, J.P. Dimmock, *Phys. Rev.* 167, 497 (1968).
6. W.E. Evenson, S.H. Liu, *Phys. Rev. Lett.* 21, 432 (1968).
7. W.E. Evenson, S.H. Liu, *Phys. Rev.* 178, 783 (1969).
8. S.C. Keeton, T.L. Loucks, *Phys. Rev.* 168, 672 (1968).
9. J.F. Herbst, D.H. Lowy, R.E. Watson, *Phys. Rev.* B6, 1913 (1972).
10. B.N. Harmon, A.J. Freeman, *Phys. Rev.* B10, 1979 (1974).
11. P.A. Lindgard, B.N. Harmon, A.J. Freeman, *Phys. Rev. Lett.* 35, 383 (1975).
12. J.F. Herbst, R.E. Watson, J.W.E. Wilkins, *Phys. Rev.* B13, 1439 (1976); *Phys. Rev.* B17, 3089 (1978).
13. A.J. Freeman, J.P. Desclaux, *Int. J. Magnetism* 3, 311 (1972).
14. A.J. Freeman, *Physica* 91B, 103 (1977).
15. W.C. Koehler et al., *Phys. Rev. Lett.* 24, 16 (1970).
16. J.F. Cooke, *J. Appl. Phys.* 50, 1782 (1979).
17. A.R. Mackintosh, *J. Magn. Magn. Mat.* 15-18, 326 (1980).
18. S. Barisic, J. Labbe, J. Friedel, *Phys. Rev. Lett.* 25, 919 (1970).
19. J. Hubbard, *Proc. Roy. Soc.* A276, 238 (1963).
20. A. Holas, N.M. Plakida, A.L. Kuzemsky, *Communications JINR*, p.17-80-741, Dubna, 1980.
21. E.G. Brovman and Yu.M. Kagan, *Uspekhi Fiz. Nauk.* 112, 369 (1974).
22. S.V. Tyablikov, *Methods in the Quantum Theory of Magnetism*, Plenum Press, NY (1967).
23. N.M. Plakida, *Phys. Lett.* A43, 481 (1973).
24. A.L. Kuzemsky, *Teor. Math. Phys.* 36, 208 (1978).
25. L.C. Bartel, *Phys. Rev.* B7, 3153 (1973).

COMMENTS

GREIDANUS: What is your argument for the statement that in the neutron spectrum of $PrNi_2$, the observed linewidth cannot be explained by dispersion effects?

FRAUENHEIM: I believe that dispersion averaging is important only if you average over the whole Brillouin zone, but not if you average over the directions in a polycrystal at a fixed momentum trans-

fer. As known from the single crystal neutron inelastic measurements in $PrAl_2$, direction averaging in a polycrystal does not give such a linewidth effect. Maybe the new theoretical results from Dr. Keller's lecture may give the explanation.

OLES: You mentioned quite a big discrepancy between the measured and the theoretical values of the exchange constant in Gd . What is your explanation of that?

FRAUENHEIM: I have no explanation for the $J(\vec{q})$ reduction in Gd . I am only sure that the electron correlation effects would lead to an enhancement of the $J(\vec{q})$ value, which is in contrast to J. F. Cooke's explanation.