

Volume dependence of magnetic hyperfine fields in Eu-intermetallic compounds

M. M. Abd-Elmeguid and H. Micklitz

Ruhr-Universität Bochum, Experimentalphysik IV, D-4630 Bochum, West Germany

G. Kaindl

Institut für Atom- und Festkörperphysik, Freie Universität Berlin, Boltzmannstrasse 20, D-1000 Berlin 33, Germany

(Received 5 May 1980)

High-pressure Mössbauer studies on ^{151}Eu intermetallics (EuAl_2 , EuAl_4 , EuCu_2 , EuCu_5 , EuSn_3 , $\text{Eu}_{0.5}\text{Yb}_{0.5}\text{Sn}_3$, EuZn_2 , and EuPt_2) provide information about the volume dependence of the effective hyperfine field B_{eff} at the Eu^{2+} nucleus. These measurements have been performed at 4.2 K and pressures up to 65 kbar. The results show that (i) the volume dependence of the transferred hyperfine field B_{thf} is the dominating contribution to $\partial B_{\text{eff}}/\partial \ln V$; (ii) the magnitude of $\partial B_{\text{thf}}/\partial \ln V$ can be explained only if one assumes the participation of s , p , and d conduction electrons in the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction responsible for B_{thf} ; and (iii) the exchange integrals for non- s conduction electrons ($J_{p,f}$ and/or $J_{d,f}$) are more sensitive to volume changes than that for s conduction electrons ($J_{s,f}$).

I. INTRODUCTION

The effective magnetic hyperfine field B_{eff} at the nucleus of $\text{Eu}^{2+}(4f^{7,8}S_{7/2})$ ions in metallic systems is commonly assumed to be composed of the following different contributions¹:

$$B_{\text{eff}} = B_c + B_{\text{cep}} + B_{\text{thf}} + B_{\text{dip}} ; \quad (1)$$

B_c represents the core polarization field, B_{cep} is the contribution from conduction-electron polarization by the magnetic ion itself, and B_{thf} the so-called transferred hyperfine field, stands for all other contributions from neighboring magnetic ions. The total dipolar field B_{dip} is the sum of the Lorentz field, the demagnetization field, and the contribution from neighboring magnetic dipoles; B_{dip} is usually small compared to the other three contributions. Such a model has been used to analyze the different contributions to B_{eff} in several Eu-intermetallic compounds,²⁻⁴ assuming $B_c = (-34 \pm 2)$ T (Ref. 5) and B_{cep} to be independent of the Eu concentration in magnetically diluted systems.

A study of the volume dependence of B_{eff} in intermetallic systems by means of high-pressure Mössbauer experiments provides further information on the applicability of such a model. We have shown previously⁶ that the magnitude of B_{eff} increased in the intermetallic systems EuSn_3 , EuAl_2 , EuAl_4 , EuCu_2 , and EuCu_5 and decreased in EuZn_2 (Ref. 6) with increasing pressure. In the meantime we have performed additional high-pressure Mössbauer experiments on EuPt_2 and on magnetically diluted EuSn_3 , i.e., on $\text{Eu}_{0.5}\text{Yb}_{0.5}\text{Sn}_3$. These experiments support the

qualitative discussion of $\partial B_{\text{eff}}/\partial p$ made in our previous paper. Furthermore, the dilution experiment offers the possibility to separate the different contributions to $\partial B_{\text{eff}}/\partial p$ and to propose a model for the mechanism involved in producing B_{thf} in these intermetallic compounds. This model will be discussed in connection with the calculation of the partial density of states at the Fermi surface in the model compound LaSn_3 .^{7,8}

II. EXPERIMENTAL DETAILS

The high-pressure Mössbauer experiments were performed with a Chester-Jones type high-pressure setup with B_4C anvils allowing Mössbauer transmission experiments at liquid-helium temperature with low γ -ray energies.⁹ The high-pressure cell is based on a pyrophyllite ring supported from outside by a steel belt which provides an almost quasihydrostatic pressure at the absorber up to about 65 kbar. Absorbers were in the form of epoxy-cast pellets with a typical size of ≈ 4 -mm diameter and ≈ 0.6 - 0.8 -mm thickness. A superconducting lead manometer¹⁰ was employed in the pressure cell for *in situ* measurements of the mean value of the pressure and the pressure profile across the absorber.

The compressibility data were obtained with a high-pressure cell especially constructed for x-ray-scattering measurements (Debye-Scherrer method) with low x-ray absorption (diamond anvils). NaCl was employed in the pressure cell for an *in situ* pressure calibration.

Most of the Eu intermetallic compounds were prepared by the direct reaction of stoichiometric amounts of the elements in degassed and sealed molybdenum or tantalum (in the case of EuSn_3) crucibles. After about 1 h induction heating at temperatures between 900 and 1200 °C the samples were annealed for several days at ≈ 700 °C. EuZn_2 and $\text{Eu}_{0.75}\text{Sr}_{0.25}\text{Zn}_2$ were obtained by induction melting of the elements in a water-cooled copper boat in a pure argon atmosphere. EuPt_2 was prepared in the Phillips Research Laboratories, Eindhoven, The Netherlands. In all cases (with the exception of EuSn_3 , see Fig. 1) a Eu^{3+} contamination was not detectable in the Mössbauer spectra. For all samples the x-ray powder patterns showed only lines belonging to the corresponding crystal structures. Typical total absorber thicknesses were 40–70 mg/cm². The Mössbauer absorption spectra were taken with a sinusoidally moved $^{151}\text{SmF}_3$ source (100 mCi; ≈ 4 -mm active diameter). Both source and absorber were kept at 4.2 K during the Mössbauer runs.

III. RESULTS

Typical ^{151}Eu Mössbauer absorption spectra of some Eu-intermetallic compounds at different pressures are shown in Figs. 1–4. All spectra (with the exception of EuSn_3 and EuCu_5) have been fitted with a pure magnetically split hyperfine (hf) pattern (18 Lorentzian lines) assuming the theoretical intensity ratios as expected for polycrystalline absorbers without texture. In the case of EuSn_3 (see Fig. 1) an additional small Eu^{3+} line, probably due to some Eu_2O_3 contamination, had to be added. A quadrupolar interaction is clearly visible in the EuCu_5 spectrum (see Fig. 3); the observed electric field gradient of $V_{zz} = 2.5 \times 10^{-17}$ V/cm² did not change with pressure. In all other compounds the quadrupolar interaction was negligibly small. Due to the unresolved hf pattern in EuPt_2 we had to make assumptions on the linewidth W . For $\frac{1}{2}W = 1.5$ mm/s, as is typical for Eu-intermetallic compounds, we obtain $B_{\text{eff}} = 4.6 \pm 0.3$ T at 0 kbar, a value which is slightly higher

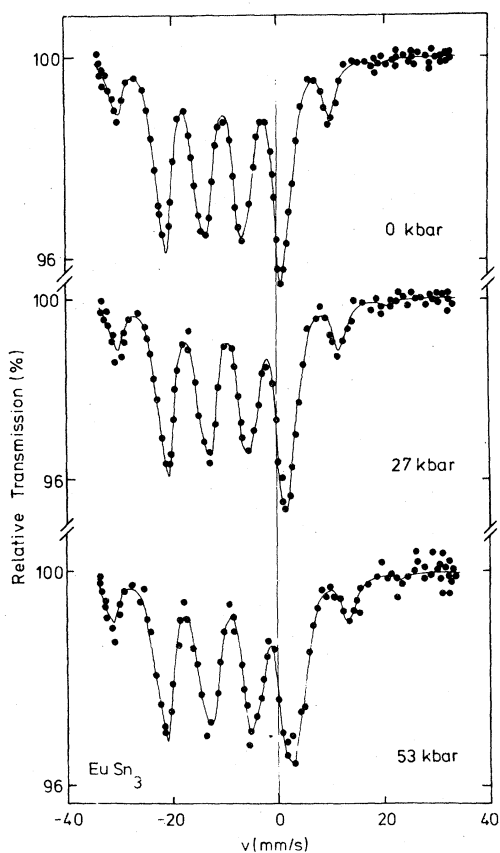


FIG. 1. ^{151}Eu Mössbauer absorption spectrum of EuSn_3 at 4.2 K and different pressures. Doppler velocity v is given relative to $^{151}\text{SmF}_3$ at 4.2 K.

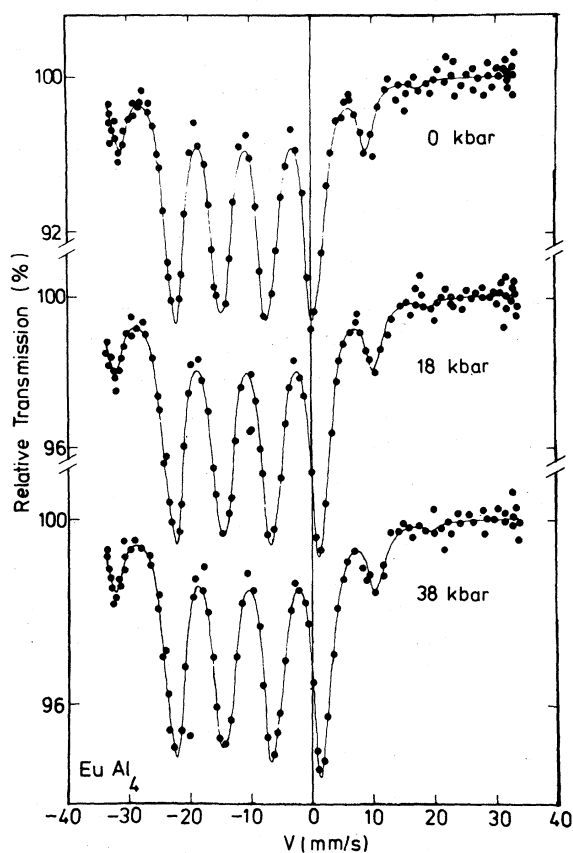


FIG. 2. ^{151}Eu Mössbauer absorption spectrum of EuAl_4 at 4.2 K and different pressures.

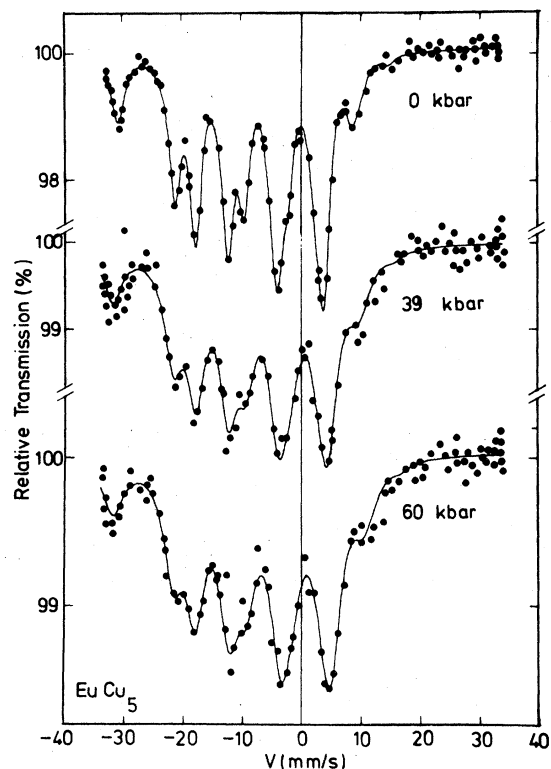


FIG. 3. ^{151}Eu Mössbauer absorption spectrum of EuCu_5 at 4.2 K and different pressures. The solid lines are the results of least-squares fits assuming a magnetically split hyperfine pattern plus a small quadrupolar interaction.

than that given by Kropp *et al.* from NMR measurements.¹¹ This discrepancy can be easily explained by a small Pt excess (≈ 5 at. %) in our EuPt_2 sample.¹²

The pressure dependence of the effective magnetic hyperfine field B_{eff} at the ^{151}Eu nucleus and of the ^{151}Eu isomer shift S (relative to the $^{151}\text{SmF}_3$ source) are shown in Figs. 5 and 6. In all cases B_{eff} and S vary approximately linearly with applied pressure p . The isomer shift increases, i.e., the electron density $\rho(0)$ at the ^{151}Eu nucleus increases in all compounds with pressure. The magnitude of B_{eff} increases in EuAl_2 , EuAl_4 , EuCu_5 , and EuSn_3 but decreases in EuZn_2 and EuPt_2 with increasing pressure.

In order to get more information about the main contribution to $\partial B_{\text{eff}}/\partial p$ we have studied magnetically diluted EuSn_3 , i.e., $\text{Eu}_{0.5}\text{Yb}_{0.5}\text{Sn}_3$, as a function of applied pressure. The results of this experiment are shown in Fig. 7: $\partial|B_{\text{eff}}|/\partial p$ is reduced from $\partial|B_{\text{eff}}|/\partial p = (6.5 \pm 0.5) \times 10^{-2}$ T/kbar for EuSn_3 to about half of that value for $\text{Eu}_{0.5}\text{Yb}_{0.5}\text{Sn}_3$ [$\partial|B_{\text{eff}}|/\partial p = (3.0 \pm 0.6) \times 10^{-2}$ T/kbar, see Table I]; the isomer shift S , however, is almost unchanged.

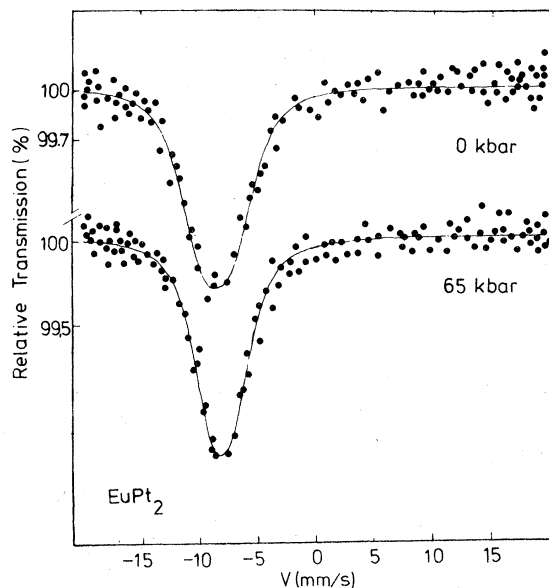


FIG. 4. ^{151}Eu Mössbauer absorption spectrum of EuPt_2 at 4.2 K and different pressures. The solid lines are the results of least-squares fits assuming a pressure independent quadrupolar interaction as given by Ref. 11 and a linewidth $\frac{1}{2}W = 1.5$ mm/s, independent of pressure.

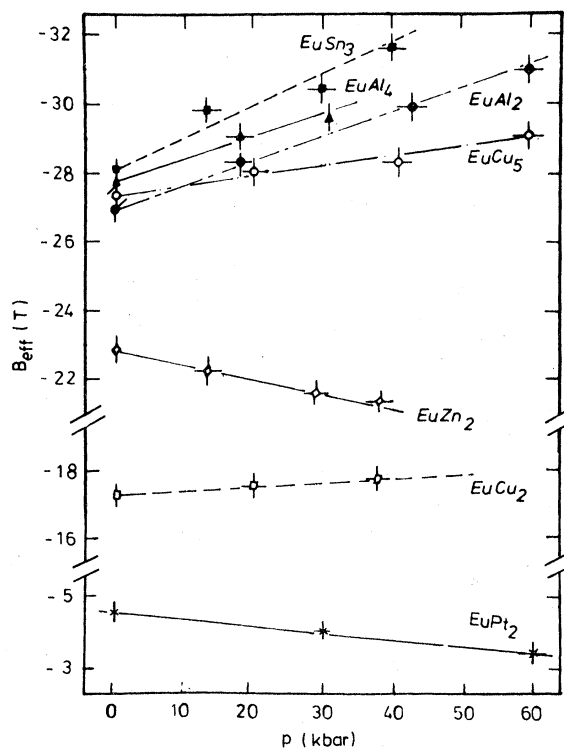


FIG. 5. Effective magnetic hyperfine field B_{eff} at the Eu^{2+} nucleus as a function of applied pressure for several Eu intermetallics at 4.2 K as obtained from least-squares fits.

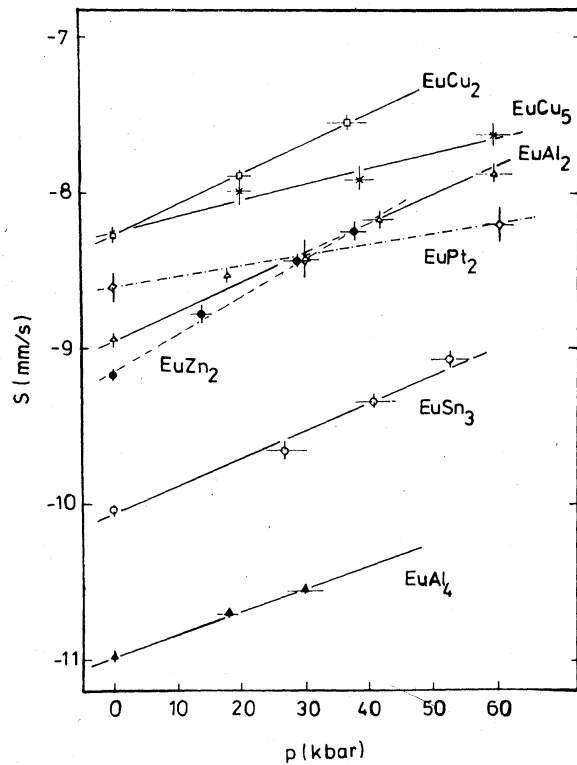


FIG. 6. ^{151}Eu isomer shift S as a function of applied pressure for several Eu intermetallics at 4.2 K. S values are given relative to $^{151}\text{SmF}_3$ at 4.2 K.

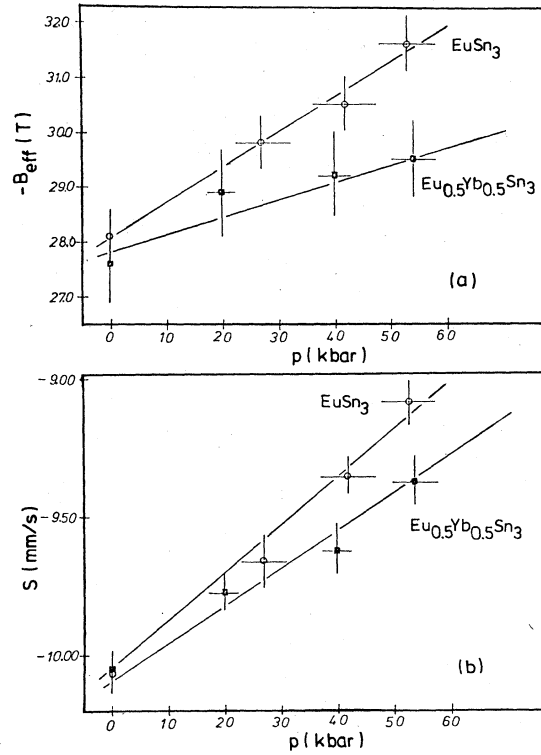


FIG. 7. (a) Pressure dependence of the effective magnetic hyperfine field B_{eff} at the Eu^{2+} nucleus for EuSn_3 and $\text{Eu}_{0.5}\text{Yb}_{0.5}\text{Sn}_3$. (b) Pressure dependence of the ^{151}Eu isomer shift S for EuSn_3 and $\text{Eu}_{0.5}\text{Yb}_{0.5}\text{Sn}_3$.

TABLE I. Summary of high-pressure Mössbauer and compressibility (κ) data for Eu intermetallics. The numbers in parentheses represent numerical errors in the last digit; i.e., $x(y) \equiv x \pm y$.

Compound	S (mm/s)	B_{eff} (4.2 K) (T)	$B_{\text{eff}}(0)$ (T)	B_{cep} (T)	B_{thf} (T)	κ ($10^{-3} \text{ kbar}^{-1}$)	$\partial S/\partial p$ ($10^{-2} \text{ mm/s kbar}$)	$\partial B_{\text{eff}} /\partial p$ ($10^{-2} \text{ T kbar}^{-1}$)
EuAl_2	-8.94(1)	-27.0(3)	-28.1(4)	+10.5(2.0) ^a	-4.5(1.0) ^a	1.11(6)	+1.8(1)	+6.0(5)
EuAl_4	-10.98(2)	-27.8(4)	-28.9(5)	+4(2) ^a	-1(1) ^b		+1.3(1)	+5.3(5)
EuCu_2	-8.27(4)	-17.3(3)	-18.4(5)	+14(2) ^a	0(1) ^a		+2.0(2)	+1.3(5)
EuCu_5	-8.26(2)	-27.4(3)	-27.5(4)	+7.6(5) ^c	-0.5(5) ^c		+1.0(1)	+2.7(5)
EuSn_3	-10.04(4)	-28.1(7)	-28.4(5)	+6.2(4) ^b	-0.6(6) ^b	1.01(7)	+1.7(1)	+6.5(5)
$\text{Eu}_{0.5}\text{Yb}_{0.5}\text{Sn}_3$	-10.09(7)	-27.6(7)	-27.9(8)	+6.2(4) ^b	-0.3(6) ^b		+1.5(2)	+3.0(6)
EuZn_2	-9.1(1)	-23.8(3)	-24.4(4)	+7.6(6)	+2(2)		+2.3(1)	-3.5(1)
EuPt_2	-8.6(1)	-4.6(3)	-4.6(3)	+10(5) ^d	+20(5) ^d	0.53(4)	+0.7(4)	-1.8(1)

^aReference 2.

^bReference 3.

^cReference 4.

^dReference 11.

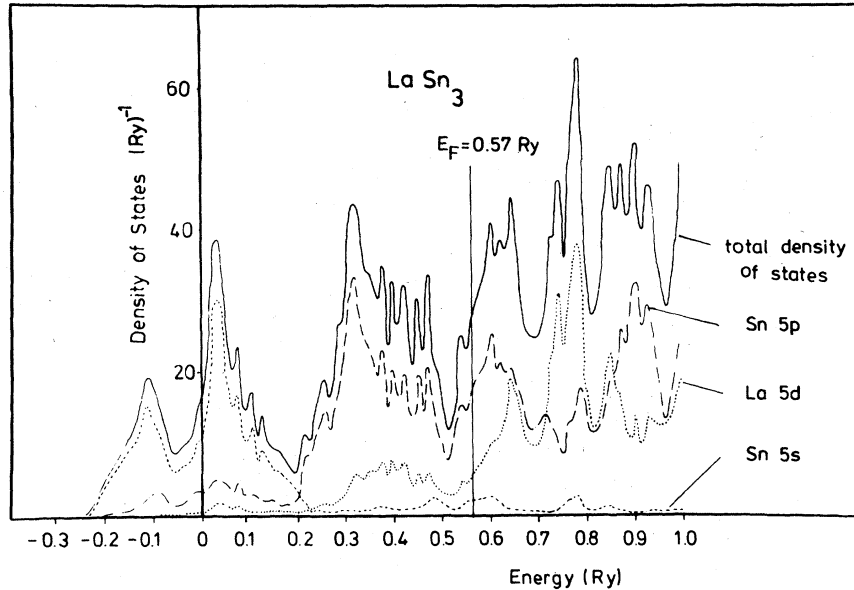


FIG. 8. Density of states for LaSn_3 calculated by Hackenbracht (Ref. 8). The partial densities of states ($\text{Sn}5s$, $\text{Sn}5p$, and $\text{La}5d$) as well as the total density of states per unit cell are shown.

A summary of all hf data together with some compressibility data and values for B_{cep} and B_{thf} as far as known are given in Table I. All S and B_{eff} values measured at 0 kbar (Table I, columns 1 and 2) are in agreement with the experimental errors given by other authors.²⁻⁴ $B_{\text{eff}}(0)$ is obtained from the measured value of B_{eff} at 4.2 K by extrapolating to $T = 0$ K using the known ordering temperatures and the Brillouin function for $S = \frac{7}{2}$. The value of B_{thf} for EuZn_2 has been obtained from B_{eff} in magnetically diluted $\text{Eu}_{1-x}\text{Sr}_x\text{Zn}_2$ with $x = 0.25$ and by extrapolating to $x = 1$ as described in Ref. 1. Since the dipolar field B_{dip} is unknown for all compounds, with the exception of EuCu_5 , it is included in the B_{thf} values given in Table I. For EuCu_5 the dipolar field $B_{\text{dip}} = 0.4$ T (Ref. 4) has been subtracted.

IV. DISCUSSION

We will describe the effective hyperfine field B_{eff} at the $^{151}\text{Eu}^{2+}$ nucleus as given by Eq. (1). For the discussion of the pressure dependence of B_{eff} we assume B_c to be pressure independent. Since B_c is caused by the polarization of the inner s shells by the $4f$ moment, any pressure effects on inner shells are neglected by this assumption. The pressure dependence of B_{dip} is generally given by $\partial \ln B_{\text{dip}} / \partial \ln V = -1$, which is very weak (see below) and will be neglected. The pressure dependence of B_{eff} is now

reduced to

$$\frac{\partial B_{\text{eff}}}{\partial p} \approx \frac{\partial B_{\text{cep}}}{\partial p} + \frac{\partial B_{\text{thf}}}{\partial p} \quad (2)$$

The positive values for B_{cep} in all compounds studied (see Table I) together with the usual assumption that the spin density of the conduction electrons increases with decreasing volume gives $\partial B_{\text{cep}} / \partial p > 0$ for all compounds. If $\partial B_{\text{cep}} / \partial p$ would be the dominant contribution to $\partial B_{\text{eff}} / \partial p$ one should observe a negative value for $\partial |B_{\text{eff}}| / \partial p$ for all compounds ($B_{\text{eff}} < 0$, see Table I). Since a negative value for $\partial |B_{\text{eff}}| / \partial p$ is only observed for EuZn_2 and EuPt_2 , we have to conclude that $\partial B_{\text{cep}} / \partial p$ is *not* responsible for the observed behavior of $\partial |B_{\text{eff}}| / \partial p$.

The influence of $\partial B_{\text{thf}} / \partial p$ on $\partial B_{\text{eff}} / \partial p$ can be discussed as follows: B_{thf} is positive for EuZn_2 and EuPt_2 and negative for all other compounds (see Table I). If we assume that the magnitude of B_{thf} increases with decreasing volume (a detailed discussion of this point will be given later), we obtain $\partial B_{\text{thf}} / \partial p < 0$ for EuZn_2 and EuPt_2 and $\partial B_{\text{thf}} / \partial p > 0$ for all other compounds. Putting this pressure dependence of B_{thf} in Eq. (2) we obtain the experimentally observed sign for $\partial |B_{\text{eff}}| / \partial p$, namely, $\partial |B_{\text{eff}}| / \partial p < 0$ for EuZn_2 and EuPt_2 and $\partial |B_{\text{eff}}| / \partial p > 0$ for all other compounds. Thus we come to the conclusion, that $\partial B_{\text{thf}} / \partial p$ is responsible for the observed behavior of $\partial |B_{\text{eff}}| / \partial p$.

This conclusion is further supported by the results

obtained from magnetically diluted EuSn₃: in Eu_{0.5}Yb_{0.5}Sn₃ the value of B_{thf} is about half that for EuSn₃. If our conclusion is correct the value of $\partial|B_{\text{eff}}|/\partial p$ in Eu_{0.5}Yb_{0.5}Sn₃ should be about half that for EuSn₃. This is exactly what we have observed (see above).

In the following we discuss the observed volume dependence of B_{thf} within the framework of the RKKY theory. The RKKY theory describes the long-range exchange interaction between localized spins \vec{S}_i and the conduction electrons which results in a conduction-electron polarization and thus in an effective transferred hyperfine field at the Eu²⁺ site. If the conduction electrons are described by s wave functions only, as it is usually done, one obtains¹³

$$B_{\text{thf}}^{\text{RKKY}} = \frac{9\pi n^2 A(s)}{2E_F g_n \beta_n} J_{sf} \langle \vec{S} \rangle_s; \langle \vec{S} \rangle_s = \sum_i F(2k_F R_i) \vec{S}_i \quad (3)$$

$A(s)$ represents the hyperfine coupling constant corresponding to the direct interaction of an unpaired $6s$ electron with the nucleus, g_n and β_n are the nuclear g value and the nuclear magneton, respectively, E_F is the Fermi-level energy, n is the conduction-electron-to-atom ratio, J_{sf} denotes the effective exchange integral that describes the coupling between the $4f$ moments and the s conduction electrons, $\langle \vec{S} \rangle_s$ stands for the spin polarization of the s electrons, F is the so-called Ruderman-Kittel function, k_F is the Fermi vector, and R_i the position of the i th localized spin \vec{S}_i .

In the free-electron model the sum $\sum_i F(2k_F R_i) \vec{S}_i$ is volume independent ($k_F \propto V^{-1/3}$, $R_i \propto V^{1/3}$). We assume that the volume dependence of $B_{\text{thf}}^{\text{RKKY}}$ is mainly given by the volume dependence of the exchange interaction J_{sf} ,

$$\partial \ln B_{\text{thf}}^{\text{RKKY}} / \partial \ln V \approx \partial \ln J_{sf} / \partial \ln V$$

It is expected that $\partial \ln J_{sf} / \partial \ln V$ is of the order of -1 or even smaller.¹⁴ From the measured pressure dependence of B_{eff} we obtain the following $\partial \ln B_{\text{thf}} / \partial \ln V$ values for the compounds whose compressibilities are known (see Table I): -1.7 for EuPt₂, -12 for EuAl₂, and -100 for EuSn₃. The value for EuPt₂ can be explained within the RKKY model as described above. The high values of $\partial \ln B_{\text{thf}} / \partial \ln V$ for EuAl₂ and especially for EuSn₃, however, are physically unreasonable if they are discussed within this model. In order to explain the high $\partial \ln B_{\text{thf}} / \partial \ln V$ values, B_{thf} has to be an effective sum of at least two (or more) contributions with different signs and different volume dependences. Such a sum would result from the participation of non- s -like conduction electrons in the RKKY interaction. Similar considerations have been made by other authors discussing the exchange interaction in intermetallic rare-earth compounds.^{15,16}

In order to confirm the importance of p and d conduction electrons for the RKKY interaction the partial density of states at the Fermi surface has been calculated for LaSn₃ (model compound for EuSn₃, which shows the largest $\partial \ln B_{\text{thf}} / \partial \ln V$ value) by Hackenbracht,⁸ using the method given in Ref. 7. The result of this calculation can be seen in Fig. 1: the main contribution to the total density of states comes from the Sn $5p$ electrons ($\approx 60\%$) and La $5d$ electrons ($\approx 20\%$). A modification of $B_{\text{thf}}^{\text{RKKY}}$, which takes non- s -like conduction electrons into account is therefore needed for EuSn₃ and all the other intermetallics which show high $\partial \ln B_{\text{thf}} / \partial \ln V$ values. In this case B_{thf} can be written as

$$B_{\text{thf}}^{\text{RKKY}} = (B_{\text{thf}}^{\text{RKKY}})_s + (B_{\text{thf}}^{\text{RKKY}})_{\text{non-}s} \\ = \frac{9\pi n^2}{2E_F g_n \beta_n} [A(s) J_{sf} \langle \vec{S} \rangle_s + A(p) J_{pf} \langle \vec{S} \rangle_p \\ + A(d) J_{df} \langle \vec{S} \rangle_d + \dots] \quad (4)$$

where $\langle \vec{S} \rangle_p$ and $\langle \vec{S} \rangle_d$ stand for the spin polarization of the p and d conduction electrons, respectively. The effective exchange integrals J_{sf} , J_{pf} , and J_{df} are of the same order of magnitude.¹⁶ The hyperfine parameters $A(s)$, $A(p)$, and $A(d)$, however, differ in their signs and their magnitudes: $A(p) \approx A(d) \approx -0.1A(s)$.^{17,18} Using these values, Eq. (4) can be simplified in the following form:

$$B_{\text{thf}}^{\text{RKKY}} \approx (\text{const}) A(s) \\ \times [J_{sf} \langle \vec{S} \rangle_s - 0.1(J_{pf} \langle \vec{S} \rangle_p + J_{df} \langle \vec{S} \rangle_d)] \quad (5)$$

Equation (5) shows that the magnitude and the sign of $B_{\text{thf}}^{\text{RKKY}}$ is determined by the relative magnitudes of the s - and non- s (p, d) contributions. A small, negative B_{thf} is observed for all Eu-intermetallic compounds given in Table I with the exception of EuPt₂. One has to conclude, therefore, that the non- s conduction-electron contribution to B_{thf} is slightly larger than the s conduction-electron contribution in these compounds. For EuPt₂ the value of B_{thf} is large and positive [$(+20 \pm 5)$ T] which clearly shows the dominant s contribution to B_{thf} [see Eq. (5)]. This explains why the value of $\partial \ln B_{\text{thf}} / \partial \ln V$ for EuPt₂ fits within the RKKY model using only s conduction electrons.

The observed volume dependence of B_{thf} offers now the possibility to get an information about the volume dependences of J_{sf} and J_{pf} or J_{df} . The volume dependence of $B_{\text{thf}}^{\text{RKKY}}$ as deduced from Eq. (4) is

$$\frac{\partial B_{\text{thf}}^{\text{RKKY}}}{\partial \ln V} = \left(\frac{\partial B_{\text{thf}}^{\text{RKKY}}}{\partial \ln V} \right)_s + \left(\frac{\partial B_{\text{thf}}^{\text{RKKY}}}{\partial \ln V} \right)_{\text{non-}s} \quad (6)$$

The measured value of $\partial B_{\text{thf}} / \partial \ln V$ is negative for

EuPt₂ [(-35 ± 5) T] and positive (approximately the same magnitude) for the other compounds [(+55 ± 5) T for EuAl₂ and (+65 ± 5) T for EuSn₃]. Using Eq. (6) together with the fact that

$$(B_{\text{thf}}^{\text{RKKY}})_s \approx (B_{\text{thf}}^{\text{RKKY}})_{\text{non-s}}$$

for all compounds, with the exception of EuPt₂ (see above) where $(B_{\text{thf}}^{\text{RKKY}})_{\text{non-s}} \approx 0$, we obtain

$$(\partial \ln B_{\text{thf}}^{\text{RKKY}} / \partial \ln V)_{\text{non-s}} \approx 2(\partial \ln B_{\text{thf}}^{\text{RKKY}} / \partial \ln V)_s$$

If we take into account that $\langle \bar{S} \rangle_s$, $\langle \bar{S} \rangle_p$, and $\langle \bar{S} \rangle_d$ do not change with volume (see above) and assume that $A(s)$ and $A(d)$ are essentially volume independent, we get

$$\partial \ln J_{\text{non-s},f} / \partial \ln V \approx 2 \partial \ln J_{s,f} / \partial \ln V$$

We want to point out that this result does *not* depend on any assumption regarding the magnitudes of $J_{s,f}$, $J_{p,f}$, and $J_{d,f}$. A stronger volume dependence of the exchange integrals for non- s conduction electrons compared to that for s conduction electrons is expected from theoretical arguments¹⁹: the overlap of the non- s -like states with the $4f$ states is more sensitive to a volume change than that for s -like states.

V. CONCLUSION

High-pressure Mössbauer studies of the effective hyperfine field B_{eff} at the Eu²⁺ nucleus in Eu-intermetallics offer the possibility to study the volume dependences of the different contributions to B_{eff} . We could show that (i) $\partial B_{\text{thf}} / \partial \ln V$ is the dominant contribution to $\partial B_{\text{eff}} / \partial \ln V$ and (ii) the magnitude of $\partial \ln B_{\text{thf}} / \partial \ln V$ can be explained only if one assumes the participation of p and d conduction electrons in the RKKY interaction responsible for B_{thf} . This was confirmed by a calculation of the partial density of states at the Fermi surface of LaSn₃ (representative for EuSn₃). Thus our high-pressure Mössbauer studies together with these calculations lead to the conclusion that the magnitude of B_{thf} is an effective sum of different contributions due to the participation of s , p , and d conduction electrons in the RKKY interaction. Furthermore, the volume dependence of B_{thf} shows that the exchange integrals for non- s conduction electrons ($J_{p,f}$ and/or $J_{d,f}$) are more sensitive to volume changes than that for s conduction electrons ($J_{s,f}$).

ACKNOWLEDGMENTS

Helpful discussions with J. Kübler, J. S. Schilling, and W. B. Holzapfel are acknowledged. The EuZn₂ data were taken by F. Röhler to whom the authors are grateful for the permission to include the results in the discussion prior to publication.

- ¹S. Hüfner and J. H. Wernick, Phys. Rev. **173**, 448 (1968).
²M. Loewenhaupt, Z. Phys. **258**, 209 (1973).
³I. Nowik, B. D. Dunlap, and J. H. Wernick, Phys. Rev. B **8**, 238 (1973).
⁴F. J. van Steenwijk, Ph.D. thesis (Rijksuniversiteit te Leiden, 1976) (unpublished).
⁵J. M. Baker and F. I. B. Williams, Proc. R. Soc. London Ser. A **267**, 283 (1962).
⁶M. M. Abd-Elmeguid and G. Kaendl, Hyper. Inter. **4**, 420 (1978); F. Röhler, Diplom thesis (Ruhr-Universität, Bochum, 1979) (unpublished).
⁷A. R. Williams, J. Kübler, and Jr. C. D. Gellatt, Phys. Rev. B **19**, 6094 (1979).
⁸D. Hackenbracht, Diplom thesis (Ruhr Universität, Bochum, 1979) (unpublished).
⁹J. S. Schilling, U. F. Klein, and W. B. Holzapfel, Rev. Sci.

- Instrum. **45**, 1353 (1974).
¹⁰A. Eichler and J. Wittig, Z. Angew. Phys. **25**, 319 (1968).
¹¹H. Kropp, W. Zipf, E. Dormann, and K. J. H. Buschow, J. Magn. Magn. Mater. **13**, 224 (1979).
¹²M. M. Abd-Elmeguid and H. Micklitz (to be published).
¹³K. Yosida, Phys. Rev. **106**, 893 (1957).
¹⁴S. H. Liu, Phys. Rev. **127**, 1889 (1962).
¹⁵D. Davidov, K. Maki, R. Orbach, C. Rettori, and E. P. Chock, Solid State Commun. **12**, 621 (1973).
¹⁶E. Dormann and M. Huck, Z. Phys. **627**, 141 (1977).
¹⁷N. Narath and D. W. Aldermann, Phys. Rev. **143**, 328 (1966).
¹⁸B. N. Harmon and A. J. Freeman, Phys. Rev. B **10**, 1979 (1974).
¹⁹A. J. Freeman (private communication).