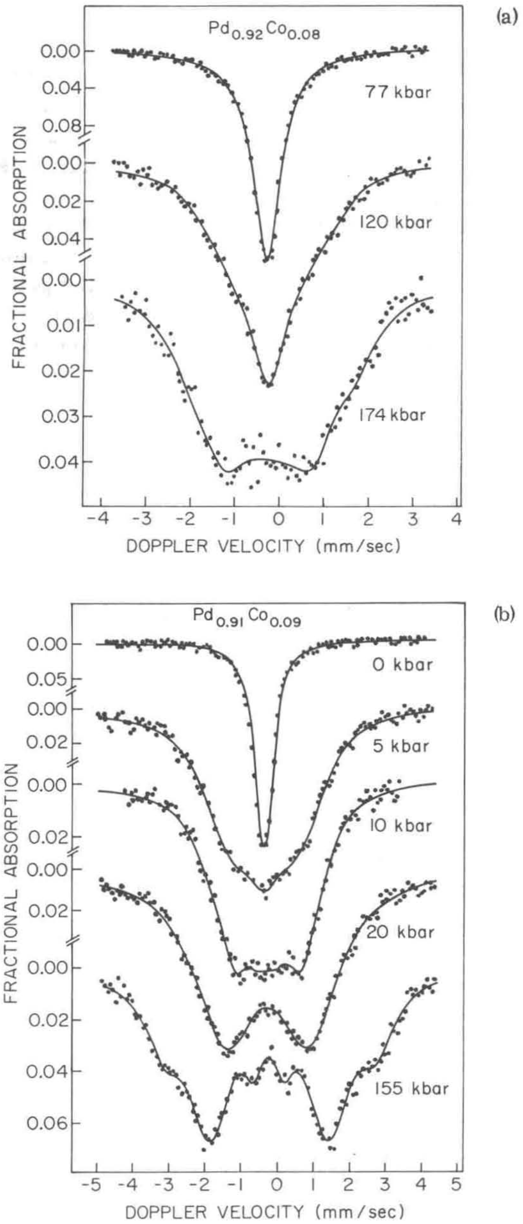

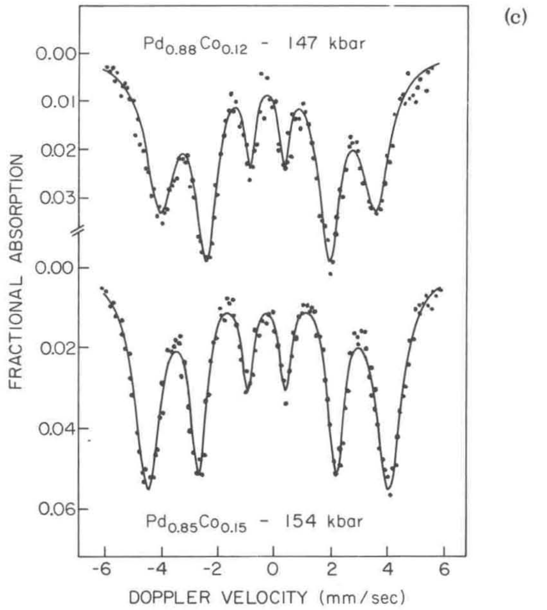

FIG. 2. Typical pressure-dependent Fe^{57} Mössbauer spectra for *Pd*Co alloys at 297 °K. The solid curves are computer-fit superpositions of Lorentzians to the experimental points.

through the data points for convenience of later analysis (cf. Fig. 4) and do not represent a theoretical fit to the data. The volume vs pressure relation used in the abscissa of Fig. 3 is not critical to the present analysis and is shown mainly for interest. The relations V/V_0 vs p for these alloys were obtained from the shock-wave data of Rice *et al.*[54] on pure Pd and Co.[43] Since V/V_0 is only ~ 0.5% less for Pd than for Co at $p = 200$ kbar, the curves V/V_0 vs p for the alloys, which are assumed to lie proportionally between those of pure Pd and pure Co, are virtually the same to the degree of accuracy required here.[55]

The data of Fig. 3 are replotted in Fig. 4 as $H_i(p)$ vs $T/T_C(p)$ for each alloy, where $T = \text{const} = 297$ °K and the pressure dependences of the Curie temperatures T_C are those determined by Holzapfel *et al.*[44] on the same specimens as used in the present work. In those measurements the values of $T_C(p)$ were found to increase linearly with pressure within experimental accuracy; the values T_C $(p=0)$ and dT_C/dp employed in Fig. 4 are given in Table I. It should be kept in mind that in Fig. 4 the (implicit) independent variable is pressure (or volume), not temperature as is usually the case in plots of this type. Superimposed for reference on the data of Fig. 4 is the molecular-field Brillouin-related spontaneous-magnetization function of spin $\frac{1}{2}$. The saturation value taken for this function at $T/T_C = 0$ is that determined by Nagle *et al.*,[16] who have shown that the Fe^{57} hyperfine field in $Pd_{1-x}Co_x$ for $T/T_C \ll 1$, at 1 atm, is nearly independent of compostion in the range $0.03 \leq x \leq 1.00$, with the value $H_i\,(T/T_C \approx 0) = -308 \pm 5$ kOe.

B. Parametrization

In order to discuss the significance of Fig. 4, we first review briefly the phenomenological parameters involved. The thermal behavior of the spontaneous magnetization σ of a ferromagnet in zero external field is described by a relation of the form

$$\sigma(T) = \sigma_0 f(T/T_C)\,, \qquad (1)$$

where $\sigma_0 \equiv \sigma(T=0)$, f is the "spontaneous-magnetization function" which falls from $f(0) = 1$ to $f(1)$

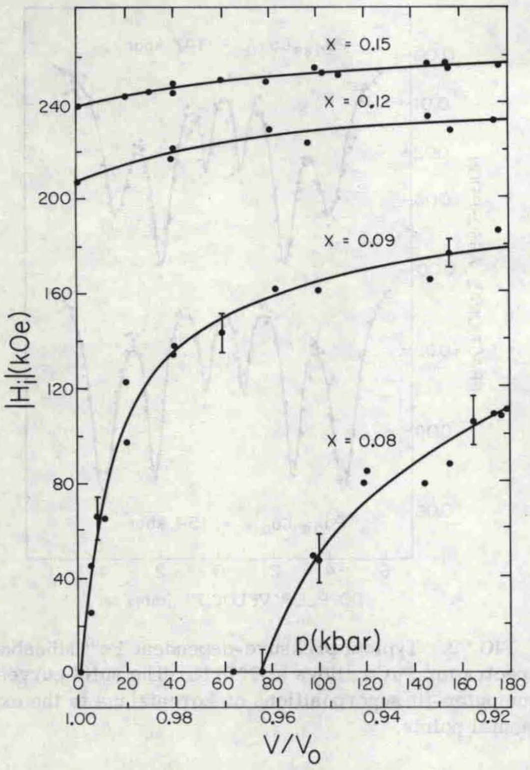

FIG. 3. Pressure and volume dependences of the Fe^{57} hyperfine fields in $Pd_{1-x}Co_x$ alloys at 297 °K. Dots mark the hyperfine field values obtained from the line splittings of computer-fit Mössbauer spectra. Typical error bars are shown for $x = 0.08$ and 0.09; experimental uncertainties for $x = 0.12$ and 0.15 are the size of the dots themselves. The pressures are accurate to ±5%–10%. The solid lines are simply smoothed curves drawn through the data points.

$= 0$, and T_C is the ferromagnetic Curie temperature.[56,57] In the molecular-field approximation the function f is related to the Brillouin function B_S having the appropriate "effective spin" S. Thus, under pressure at constant temperature, the major effects on $\sigma(T)$ occur via $\sigma_0(p)$ and $T_C(p)$. Smaller effects are possible from a pressure dependence of the function f itself, for example through a pressure dependence of S in the molecular-field approximation, but both σ_0 and T_C are much more strongly dependent on S than is the function f.[57] For our purposes any pressure dependence of the function f can be neglected.

The hyperfine field H_i observed at the nucleus of a *homogeneous* parent atom within a ferromagnet (e.g., at an Fe^{57} site in iron metal or Ni^{61} in nickel) also obeys a relation of the form

$$H_i(T) = H_0 f(T/T_C) , \qquad (2)$$

where $H_0 \equiv H_i(T=0)$ and the function f is nearly identical with that of Eq. (1). Disregarding relaxation effects,[20] the T_C of Eq. (2) is the same as that of Eq. (1). Thus $H_i(T)/H_0 \approx \sigma(T)/\sigma_0$, and the hyperfine field "follows" the spontaneous magnetization of the sample as a function of temperature. Since for the homogeneous case the "spin" associated with the parent atom is simply the magnetization per atom of the host, the nearly constant ratio $H_i(T)/\sigma(T) \simeq H_0/\sigma_0 \simeq A$ is just the hyperfine coupling constant, i.e., the magnitude of "field" seen by the nucleus per unit of "spin" associated with its parent atom. From Eq. (2) the pressure dependence of $H_i(T)$ at constant T is determined by $H_0(p)$ and $T_C(p)$, but $H_0(p)$ is the product of $\sigma_0(p)$ and $A(p)$. Hence in observing hyperfine fields the complication arises that the coupling between the spin of the parent atom and the field sensed by the nucleus can be, and generally is, pressure dependent.[58,59]

The situation in which the hyperfine field is measured at the nucleus of an *impurity* atom in a ferromagnetic host (for example, Fe^{57} in nickel) is substantially more complex. We consider here only the case in which the impurity atom has a well-defined localized moment, as is often the case for the Fe^{57} impurity. The thermally averaged moment μ associated with the impurity atom has a temperature dependence given by

$$\mu(T) = \mu_0 g(T/T_C) , \qquad (3)$$

where, analogously to Eq. (1), $\mu_0 \equiv \mu(T=0)$ and the function $g(T/T_C)$ also decreases from 1 at $T=0$ to 0 at $T=T_C$. In general, however, $g(T/T_C) \neq f(T/T_C)$; the impurity magnetization does not follow the host magnetization with temperature and can deviate significantly from it. The reasons, within the molecular-field picture, are twofold: (i) the impurity atom may have a different spin than that of the average host atom, hence will respond differently to the molecular or exchange field driving it; and (ii) the exchange field driving the impurity can be different from the average molecular field driving the host. Both effects are included in a phenomenological quantity ζ which parametrizes the strength of the impurity's thermal response to the host magnetization f.[60–64] Thus the function g depends on the function f via a relation involving the parameter ζ: $g(T/T_C) = g[\zeta, f(T/T_C)]$. This

TABLE I. Values of $T_C(p=0)$ and dT_C/dp for the present $Pd_{1-x}Co_x$ alloys, determined by Holzapfel *et al.*[a]

x (±0.005)	$T_C(p=0)$ (°K)	dT_C/dp (°K/kbar)
0.05	196 ± 2	+0.10 ± 0.02
0.08	283 ± 2	+0.20 ± 0.03
0.09	292 ± 2	+0.23 ± 0.03
0.12	356 ± 2	+0.37 ± 0.04
0.15	417 ± 2	+0.45 ± 0.06

[a] Reference 44.