

(and hyperfine field) to compositional changes in the  $T=0$  host magnetization of  $\text{Pd}_{1-x}\text{Co}_x$ , as noted earlier.

### B. $\zeta(p)$

The phenomenological host-impurity coupling parameter  $\zeta$  of Eq. (5) is defined as the ratio of the exchange energy of the impurity to the ferromagnetic ordering energy of the host,

$$\zeta = g' S' \mu_B H_0^{\text{ex}} / k T_C, \quad (6)$$

where  $H_0^{\text{ex}}$  is the exchange field at  $T=0$  acting on the impurity moment  $\mu_0 = g' S' \mu_B$ .<sup>60</sup> Thus the pressure (or volume) dependence of the impurity exchange energy is

$$\frac{d \ln E^{\text{ex}}}{dp} = \frac{d \ln \zeta}{dp} + \frac{d \ln T_C}{dp} \quad (7)$$

or

$$\frac{d \ln H_0^{\text{ex}}}{dp} = \frac{d \ln \zeta}{dp} + \frac{d \ln T_C}{dp} - \frac{d \ln \mu_0}{dp}. \quad (8)$$

From above,  $d \ln \zeta / dp \sim -3 \times 10^{-3} / \text{kbar}$  for these alloys, while from Table I  $d \ln T_C / dp$  ranges from  $\sim + (0.7 \text{ to } 1.1) \times 10^{-3} / \text{kbar}$ . From Eq. (7) it is thus apparent that, in addition to the impurity's becoming *relatively* decoupled from the host as pressure increases (because  $d \ln \zeta / dp < 0$ ), the exchange energy of the impurity is decreasing *absolutely* with pressure. If, from previous discussions, it is assumed that the impurity moment is relatively insensitive to compression, then  $d \ln \mu_0 / dp \sim 0$  in Eq. (8), and it is also seen that the exchange field driving the impurity is decreasing in an absolute sense with pressure.

### C. $T_C(p)$

The pressure dependence of the Curie temperatures of these alloys has already been discussed by Holzapfel *et al.* in Ref. 44. However, further discussion is given below in conjunction with the  $\text{PdFe}$  alloys.

### D. $\text{PdFe}$

The pressure dependences of the Curie temperatures and  $\text{Fe}^{57}$  hyperfine fields of the alloys  $\text{Pd}_{1-x}\text{Fe}_x$  in the range  $0.06 \leq x \leq 0.20$  have been shown by Möller and Drickamer<sup>45</sup> to exhibit strikingly different behavior from those of the present  $\text{Pd}_{1-x}\text{Co}_x$  alloys. The  $\text{PdFe}$  Curie temperatures have very little pressure dependence,  $d T_C / dp$  being perhaps slightly negative toward the higher concentrations (of order  $\sim -0.05 \text{ }^\circ\text{K/kbar}$ ), in contrast to the strongly positive pressure dependence for  $\text{PdCo}$  shown in Table I. The  $\text{PdFe}$  hyperfine fields at room temperature exhibit none of the dramatic effects observed for  $\text{PdCo}$ : the fields  $|H_i|$  for  $x = 0.20$  and  $0.16$  decrease slightly at low pressures,

then increase again above  $\sim 80 \text{ kbar}$ , while  $|H_i|$  for  $x = 0.13$  decreases monotonically with pressure, most rapidly at the lower pressures. (See Fig. 1 of Ref. 45.) Since  $T_C$  for the  $\text{PdFe}$  alloys having  $x \leq 0.12$  is below room temperature, no hyperfine field was observed for those cases, similarly to the situation for  $\text{PdCo}$  with  $x \leq 0.08$  in this work.

We first consider the hyperfine fields. Assuming the maximum pressure dependence of the Curie temperatures allowed by the experimental uncertainties in Ref. 45, the pressure-dependent hyperfine fields for  $\text{Pd}_{1-x}\text{Fe}_x$  in Ref. 45 can be plotted in the manner of Fig. 4. This is done in Fig. 8, for the alloys  $x = 0.13, 0.16, \text{ and } 0.20$ . For reference in Fig. 8 the following spontaneous-magnetization curves are also plotted:  $\sigma(T)/\sigma_0$  for ferromagnetic iron and  $f(T/T_C)$  from the molecular-field theory with  $S = \frac{1}{2}$  and  $\frac{3}{2}$ . The saturation values  $H_0(p=0)$  for the  $\text{PdFe}$  alloys are taken from Craig *et al.*,<sup>18</sup> who have fitted the composition dependence of  $H_0(p=0)$  for  $\text{Fe}^{57}$  in this alloy system over the entire composition range.

The experimental curves of Fig. 8 indeed have little in common with those of Fig. 4. The major disparity results from the differences of  $T_C(p)$  in the two systems. In fact the small pressure dependence of  $T_C$  has little effect on the hyperfine fields of the  $x = 0.20$  and  $x = 0.16$   $\text{PdFe}$  alloys, whose behavior must be determined by the other two relevant parameters here:  $\zeta(p)$  and  $H_0(p)$ . The effect of a decreasing  $T_C(p)$  is felt by the  $x = 0.13$  alloy, however, as seen in Fig. 8, and is the reason for the overall decrease of  $|H_i|$  with pressure in that case. This result can be seen from Eqs. (4) and (A3), which indicate the effect of  $T_C(p)$ , with  $H_0$  and  $\zeta$  constant, is that  $H_i(p)$  must follow its  $T$ -dependent  $p=0$  baseline  $g_0(T/T_C)$ . The large negative slope of the baseline for  $x = 0.13$  (being in the region  $T/T_C \lesssim 1$ ) thus imposes an overall negative slope on  $|H_i(p)|$ . The curvature of  $|H_i(p)|$  relative to the baseline of the  $x = 0.13$  curve is qualitatively the same as that of the higher-concentration alloys and must similarly result from the effects of  $\zeta(p)$  and/or  $H_0(p)$ .

We expect the parameter  $\zeta(p)$  to be relatively unimportant here, unlike the situation for the  $\text{PdCo}$  alloys where the  $\text{Fe}^{57}$  parent atom is a bona fide impurity, having, for instance, a different moment ( $\sim 3 \mu_B$ ) than the average Co atom ( $\sim 2 \mu_B$ ).<sup>5,6</sup> This conclusion follows from the work of Craig *et al.*,<sup>20</sup> who have measured both  $\sigma(T)/\sigma_0$  and  $H_i(T)/H_0$  at  $p=0$  for  $\text{Fe}^{57}$  in the ferromagnetic alloy  $\text{Pd}_{0.9735}\text{Fe}_{0.0265}$ . They found an accurate proportionality to hold over extended ranges of temperature and applied external field, i. e., the thermal response of the impurity magnetization follows that of the host closely, as it does in pure ferromagnet-

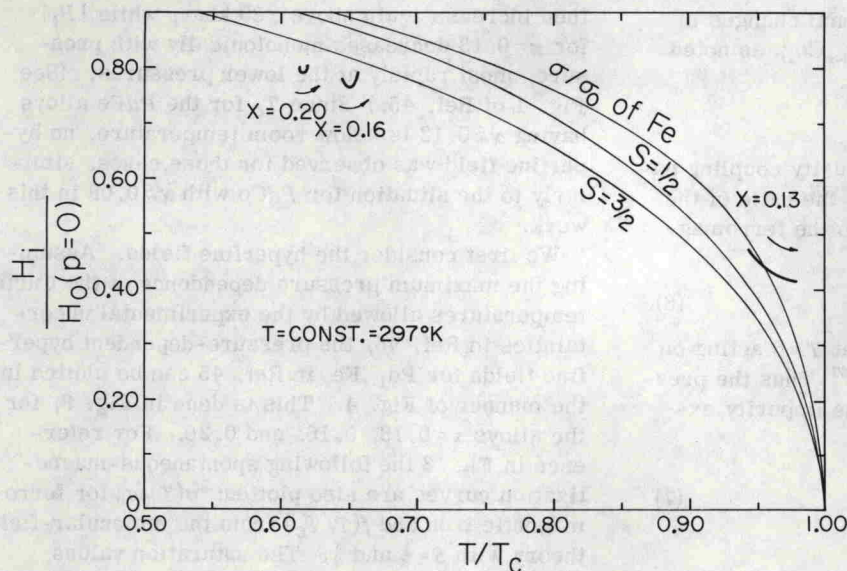


FIG. 8. Analog of Fig. 4 for  $\text{Pd}_{1-x}\text{Fe}_x$  alloys, from the data of Ref. 45 as described in the text. Also shown are the spontaneous-magnetization curve for iron and the molecular-field curves for spin- $\frac{1}{2}$  and spin- $\frac{3}{2}$ .

ic iron, even for this relatively dilute  $\text{PdFe}$  alloy. The exchange field driving the  $\text{Fe}^{57}$  "impurity" is thus determined mainly by the Fe moments which also drive the host, so even under pressure the relative response of impurity to host should not be significantly altered. This result should be particularly true at the higher concentrations  $0.13 \leq x \leq 0.20$  considered in Fig. 8.

The shape of the curves  $H_i(p)$ , then, must result primarily from the effects of  $H_0(p)$  which, as discussed earlier, is  $A(p)\mu_0(p)$  for the localized impurity case or  $A(p)\sigma_0(p)$  for the homogeneous case. The situation for  $\text{Fe}^{57}$  in  $\text{PdFe}$  apparently lies somewhere between the above two extremes, since the  $\text{Fe}^{57}$  hyperfine field is sensitive to the itinerant Pd 4d-band polarization as well as to the local 3d Fe moment.<sup>18</sup> If, as expected,  $d \ln A / dp > 0$  (as it is<sup>58</sup> for  $\text{Fe}^{57}$  in Fe) and  $d \ln \sigma_0 / dp < 0$  (as is known to be the case, for example, in Fe, Co, Ni, and  $\text{PdNi}$ <sup>58,41</sup>), the nonlinearity in  $H_0(p)$  indicates that either  $A(p)$  or the appropriate combination of  $\mu_0(p)$  and  $\sigma_0(p)$  is nonlinear in  $p$ , with the decreasing moments dominating at low  $p$  and the increasing hyperfine-coupling constant dominating at higher  $p$ .

It is interesting to note that the situation observed here for  $H_0(p)$  in  $\text{PdFe}$  and  $\text{PdCo}$  may be related to the fact that  $d \ln H_0 / dp$  for  $\text{Fe}^{57}$  in pure iron is negative,<sup>49,69</sup> whereas in pure cobalt it is positive,<sup>68</sup> at least to moderate pressures.<sup>76</sup> According to the present ideas, for  $\text{Fe}^{57}$  in cobalt,  $H_0 = A\mu_0$ , and the positive pressure dependence of  $|A|$  dominates since the pressure dependence of  $|\mu_0|$  is small; for  $\text{Fe}^{57}$  in iron,  $H_0 = A\sigma_0$ , and the negative pressure dependence of  $|\sigma_0|$  is dominant.

#### E. $T_C(p)$ for $\text{PdFe}$ and $\text{PdCo}$

The qualitatively different pressure dependences observed for  $T_C(p)$  in the  $\text{PdFe}$  and  $\text{PdCo}$  systems

over the composition range  $0.05 \lesssim x \lesssim 0.20$  suggest a reexamination of the point of view taken previously in Ref. 44. In that work the composition dependence of  $dT_C/dp$  for the  $\text{PdCo}$  system was successfully fitted in terms of the dilute-impurity model of Takahashi and Shimizu<sup>13</sup> and of Kim,<sup>14</sup> with two adjustable parameters. If in fact the dilute-alloy model is applicable here, the implication is that the alloys  $\text{PdCo}$  and  $\text{PdFe}$  should behave similarly, since it is well known that the dilute  $\text{PdCo}$  and  $\text{PdFe}$  systems have very similar magnetic properties.<sup>6,10-14,77</sup> On the other hand, in the nondilute regime significant differences appear. For example, as  $x$  increases toward 0.25 the composition dependences of the Curie temperatures, which are qualitatively the same for small  $x$ , differ radically:  $T_C(x)$  for  $\text{Pd}_{1-x}\text{Co}_x$  continues to rise smoothly with  $x$ , while  $T_C(x)$  for  $\text{Pd}_{1-x}\text{Fe}_x$  peaks at  $\sim x = 0.25$  and then decreases with increasing  $x$ .<sup>78</sup> This behavior is reminiscent of the somewhat analogous systems  $\text{NiCo}$  and  $\text{NiFe}$ : In the former case  $T_C(x)$  rises smoothly with increasing  $x$  (despite the existence of an ordered phase at  $x = 0.25$ ), while in the latter case  $T_C(x)$  reaches a maximum near  $x = 0.35$ , then decreases.<sup>79</sup> This phenomenon in  $\text{NiFe}$  is associated with the onset of Invar effects, which occur notoriously in that alloy system but which do not occur in  $\text{NiCo}$ . Invar effects have also been observed in the system  $\text{PdFe}$ ,<sup>80-82</sup> but not in  $\text{PdCo}$ . Thus, one expects dissimilar behavior from the nondilute alloys  $\text{PdFe}$  and  $\text{PdCo}$ . The fact that the quantities  $dT_C/dp$  for the two systems are quite different in the concentration range under consideration suggests this to be a nondilute regime, where direct impurity-impurity interactions (i.e., Fe-Fe or Co-Co) are significant.<sup>83</sup>

The sign of the qualitative difference of  $dT_C/dp$  in the two systems supports the above picture. The