correlations through the relative p-wave term in Eq. (10). Although this term is smaller in magnitude than the relative s-wave term, its effect is greatly magnified because of suppression (due to small overlap with the final state) of the relative s wave in the region of interesting $\bar{Z}$.

Under the less realistic assumption $Z_1 = 1$ and $Z_2 = 2$ and using a Hartree-Fock wave function for the initial state (it can be shown that these assumptions are essentially equivalent to those made in Ref. 1), one obtains after some manipulation the ratio $\sigma_+/\sigma_{++} = 210$ which is very close to the value computed in Ref. 1 using the sudden approximation. However, if we include angular correlation by using the wave function given in Eq. (10), we find that the agreement with experiment is considerably worsened: $\sigma_+/\sigma_{++} = 275$.

It should be noted that the experimental ratio $\sigma_+/\sigma_{++} \cong 200$ which we used above is inferred from the work of Kistemaker et al.[4] below an incident electron energy of 1 keV. Beyond this energy, a serious departure of σ_{++} from a $(\log E_i)/E_i$ dependence seems to appear.[3,4] This cannot be explained by the approach discussed above. In fact, it is possible that higher terms of the Born series, whose size will not be reduced because of small overlaps (which was the case above for the first Born contribution to σ_{++}) could contribute significantly to σ_{++} up to rather large energies. Also to be considered are terms proportional to $1/E_i$ coming from the first Born approximation. Thus, although we conclude that the asymptotic behavior of σ_{++} at sufficiently high energy must be of the form $(\log E_i)/E_i$, it is difficult to ascertain precisely how large this energy should be. In view of the implications of these results for the understanding of ionization phenomena and multiparticle scattering theory, it is important that further experimental studies at high energies be carried out.

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†Alfred P. Sloan Foundation Fellow.

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NUCLEAR RELAXATION STUDIES OF IMPURITY MOMENTS IN FERROMAGNETIC METALS

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The Mn^{55} nmr of dilute impurities of Mn in Fe exhibits a temperature dependence to the frequency for resonance ν_T below T_c which is distinctly different from the corresponding behavior of the iron-host magnetization σ_T.[1] This dependence has been interpreted[2,3] as direct evidence for the existence of a localized moment on the Mn ion of fixed magnitude S. The behavior of the thermal average $\langle S_T \rangle$, to which ν_T is proportional, relative to σ_T indicates that the Mn-Fe exchange coupling is substantially weaker than the Fe-Fe interaction. Neutron scattering experiments[4] appear to contradict these results, suggesting instead that a negligible spin magnetization, either "local" or not, resides on the Mn site. The interpretation and results of recent Mössbauer studies[5] of the Fe near neighbors to a given Mn seem

to conflict with both the nmr and neutron experiments.

To elucidate further the properties intrinsic to the nmr studies we have examined the Mn^{55} longitudinal and transverse relaxation times, T_1 and T_2, using spin-echo techniques.[6] We believe this to be the first impurity relaxation study in a ferromagnet or antiferromagnet.

A concentration-independent, inhomogeneously broadened line profile was observed for the Mn^{55} nmr in the concentration range[7] 0.5% to 2.0% Mn in Fe. Its width, ~200 Oe, is similar to that found for the Fe^{57} nmr in pure iron. The temperature range investigated extended from 1 to 400°K. Care has been taken to record echo signals from nuclei in the domains and not of those in the walls. Two methods were employed to ensure this result. First, rf fields large enough to produce $\theta = \pi/2 - \pi$ excitations of nuclei in the domains were used. Since for the nuclei in the walls $\theta \gg 2\pi$, because of the larger enhancement of the rf field in the walls, the contribution to the echo[8] from these nuclei will be confined to a time shorter than is resolvable in our experimental apparatus. Second, rf fields small enough to excite only the nuclei in walls were followed by a dc magnetic field pulse sufficiently large to move the wall a distance such that all the excited nuclei would reside in domains and relax accordingly.[6] Most satisfactory agreement was found between the results obtained from these two methods. An exponential dependence on time was found both for the decay of the amplitude $I(t)$ of the echo (T_2) and the recovery of the magnetization (T_1). T_2 is operationally defined by the relation $I(2\tau) = I(0)\exp(-2\tau/T_2)$.

The measured values of $1/T_1$ and $1/T_2$ versus temperature T are shown in Fig. 1. Below 100°K both relaxation rates are proportional to T (see inset to figure for enlarged $1/T_1$-vs-T plot in this region) indicating that the primary source of nuclear spin relaxation at low temperatures is itinerant-electron spin and/or orbital scattering. We have calculated the s-contact,[9] d-orbital,[10] and d-spin core-polarization[11] contributions to $1/T_1$ for Mn in Fe using the methods and approximations previously employed for the ferromagnetic transition metals.[12] For simplicity it has been assumed that the local s- and d-state densities at E_F, $\eta(E_F)$, are the same as that of pure Fe metal. Values of $\eta_d(E_F)$ and $\eta_s(E_F)$ are obtained from measurements of the electronic specific heat. By far the largest contribution to $1/T_1$ comes from the orbital interaction. A comparison of calculated (orbital) and observed values of $1/T_1$ for Mn in Fe, Fe, Co, and Ni are shown in Table I. Unlike the nonferromagnetic transition metals, where the previously involved mechanisms satisfactorily account[11] for the observed $1/T_1$'s, no satisfactory explanation of the relaxation rates in the ferromagnetic metals is found.[12]

The discrepancy between theory and experiment is still more glaring when we consider $1/T_2$. In the absence of spin-orbit coupling, the fluctuations in the orbital current of the itinerant d electrons are isotropic in the ferromagnetic as well as paramagnetic state of a transition metal. This, taken together with the required isotropy in the hyperfine interaction of a nucleus of an atom occupying a position of cubic point symmetry, necessitates that $(1/T_2)_{orb} = (1/T_1)_{orb}$. We observe, however, that $1/T_2 \simeq 5(1/T_1)$ in the region below 100°K

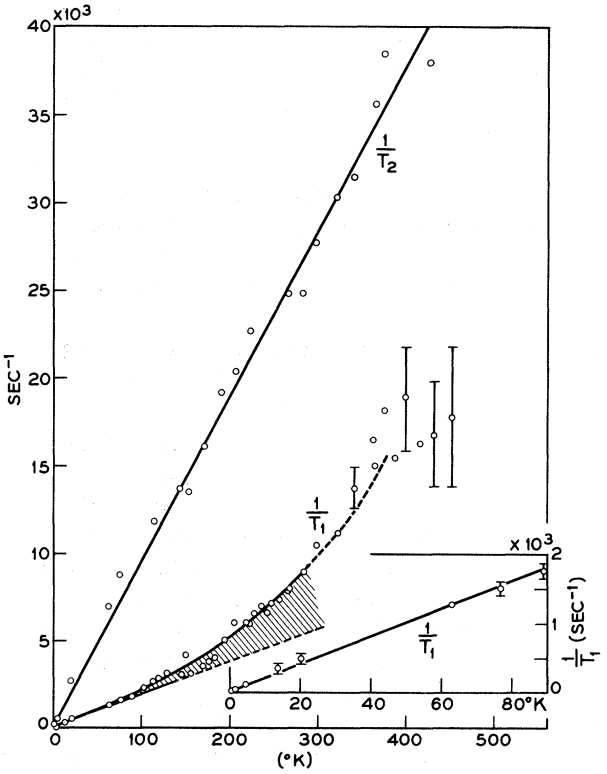

FIG. 1. A plot of $1/T_1$ and $1/T_2$ versus temperature for the Mn^{55} nmr of 1.5% Mn in Fe. The inset in the right-hand side of the figure is an enlarged part of the $1/T_1$-vs-T behavior at low temperatures. The shaded area represents the deviation of $1/T_1$ from $1/T_1T$ = const. When not indicated, experimental errors are less than 10%.

Table I. The calculated nuclear spin-orbital current relaxation rates and the observed relaxation rates for the ferromagnetic transition metals shown. The computed extremal values are obtained from the assumption $[\eta_d(E_F)]_\uparrow = [\eta_d(E_F)]_\downarrow$ and $[\eta_d(E_F)]_\uparrow = 0$, respectively. The calculated s-contact and d-spin core-polarization contributions are much smaller than the orbital rates and are not given.[a] If only orbital current and/or s-contact relaxation were responsible for $1/T_2$, then $1/T_2 = 1/T_1$.

	Mn^{55} in Fe	Fe^{57} in Fe	Co^{59} in Co	Ni^{61} in Ni
$(\gamma_N^2 T_1 T)^{-1}_{\text{orb}} \times 10^7$	0.29-0.58	0.44-0.87	0.56-1.2	2.1-4.1
$(\gamma_N^2 T_1 T)^{-1}_{\text{exp}} \times 10^7$	5.1	5.4	3.1	15.3
$(\gamma_N^2 T_2 T)^{-1}_{\text{exp}} \times 10^7$	~25	b	c	~45

[a]See Ref. 12.

[b]Precise values of $1/T_2T$ are not available for Fe^{57} in unenriched iron.

[c]The Co^{59} (100%) nuclear dipole contribution to $1/T_2$, which is independent of T, dominates all processes discussed here.

where both are proportional to T. A similar behavior was observed[6] in Ni metal where $1/T_2 \simeq 3(1/T_1)$.

The ferromagnetic transition metals differ from metals such as V in two important ways: (1) The d-spin itinerant-electron susceptibility χ_d is anisotropic below T_C, and (2) there is appreciable enhancement of the real and imaginary parts of χ_d to be expected over and above that which one would calculate knowing $\eta_d(E_F)$. Now the nuclear relaxation rates $1/T_1$ and $1/T_2$ are proportional to certain sums involving the transverse and longitudinal parts of the wave-number-dependent susceptibility $\chi_d''(q)$, respectively.[13] It is possible that exchange enhancement and anisotropy of χ_d could, through d-spin induced processes alone, explain both the magnitudes of $1/T_1$ and $1/T_2$ and their inequality.

Above 100°K, $1/T_1$ rapidly increases above the extrapolated low-temperature value $1/T_1T$ = constant. (See shaded area in figure.) We assume this excess relaxation to arise from thermal fluctuations associated with the hyperfine field produced by the localized moment and to be independent of the relaxation caused by the itinerant electrons as discussed above. Thus $1/T_1 = (1/T_1)_{\text{itin}} + (1/T_1)_{\text{loc}}$. This surmise is supported by the fact that, to within the experimental errors, the excess relaxation is proportional to the time-averaged local magnetization as determined from the Mn^{55} nmr frequency: i.e.,

$$\left(\frac{1}{T_1}\right)_{\text{loc}} = K\frac{\nu(0)-\nu(T)}{\nu(0)},$$

with $K \simeq 3\times 10^4$ sec^{-1}.

To explain this latter fact we may take as a crude model for the Mn local moment in Fe that of a paramagnetic atom in a large magnetic field H. For $g\beta H \gg kT$ the deviation of the local magnetization from saturation behaves as $\exp(-g\beta H/kT)$, as does the autocorrelation function $\langle \delta S_z(t)\delta S_z(0)\rangle$ for the component of the spin deviation of the local moment along the direction of field. This yields a T_1 mechanism provided there are off-diagonal elements (e.g., A_{yz}) to the electron-nuclear interaction. Similar conclusions can be obtained from consideration of the temperature dependence of the two-magnon nuclear Raman scattering and that of the magnetization deviation using an Einstein model for the magnon spectrum.

The two distinct relaxation processes $(1/T_1)_{\text{itin}}$ and $(1/T_1)_{\text{loc}}$ may be thought of as arising from d-electron single-particle and collective excitations, respectively. Although the collective excitations are primarily responsible for the temperature dependence of the magnetization in Fe, Co, and Ni, and both impurity and host sites for the Mn-in-Fe case, the single-particle excitations appear to dominate completely nuclear-relaxation processes for the ordinary ferromagnetic transition metals. This latter result is attributable to the relatively small magnon state density at low energies as compared to the large single-particle state density at all energies about E_F. Mn in Fe proves to be exceptional because of the low position of the impurity state in the spin-wave band. The increased magnon scattering is largely confined to the impurity site because the spectral density of the collective excitations only have large amplitude there.

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INCOHERENT SCATTERING OF MICROWAVES BY UNSTABLE ELECTRON PLASMA OSCILLATIONS*

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The possibility of using incoherent scattering of electromagnetic waves by plasma oscillations as a diagnostic tool has received considerable attention recently.[1] The importance of this method for the investigation of unstable plasmas has been emphasized by Ichimaru, Pines, and Rostoker[2] and by Drummond.[3] Arunasalam and Brown[4] have observed incoherent scattering from the unstable ion-acoustic mode in a dc discharge, and scattering by driven plasma oscillations has been demonstrated in two recent publications.[5]

In this Letter we report the observation of incoherent scattering of microwaves by high-frequency oscillations resulting from a beam-plasma instability. The experimental arrangement is sketched in Fig. 1. An electron beam of 0.5 A, 15-21 keV, and 2 μsec duration is injected into the afterglow of a pulsed discharge in neon at a pressure of 3×10^{-2} Torr. Discharge and electron beam are triggered at a repetition frequency of 15 cps. By varying the delay between the initiation of the discharge and the injection of the beam, the beam can be exposed to plasma densities in the range between 10^{13} and 10^{11} electrons/cm^3. The decay time for the plasma is 300 μsec so the plasma density can be taken as constant during the time the beam is on. In the region of interest the plas-

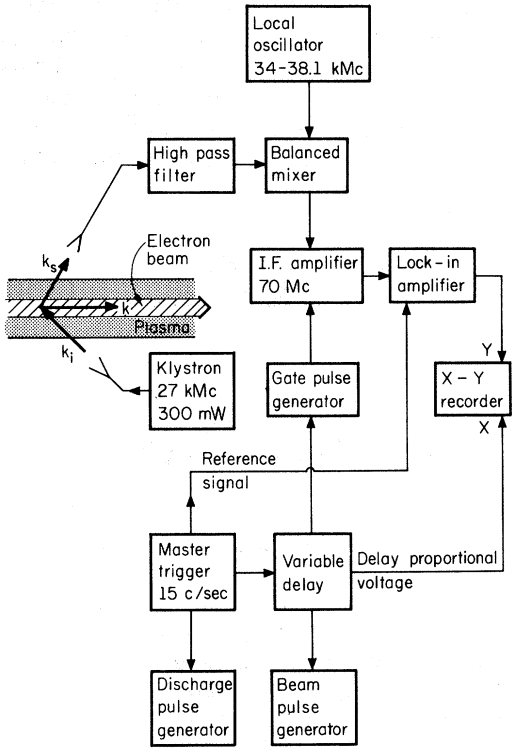

FIG. 1. Schematic of the experiment. The plasma diameter is 4 cm, the beam diameter 1 cm.