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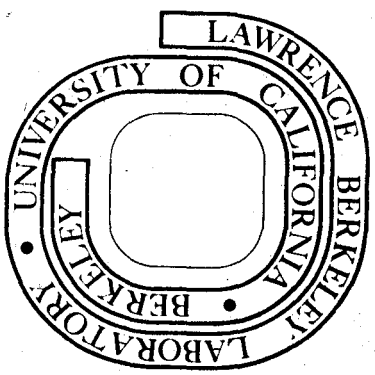

DISCLAIMER

TEMPERATURE INDEPENDENT HYPERFINE FIELD ON μ^+ IN NICKEL IN THE TEMPERATURE RANGE OF 0.12 - 300 K*

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ABSTRACT

The hyperfine field on a positive muon at interstitial site in a nickel single crystal has been measured by the muon spin rotation method in the temperature range from 0.12 K to 300 K. The hyperfine field in the low temperature limit was found to be -640.7 ± 2.2 Gauss. While the saturation magnetization decreases by 7% as the temperature increases from 0.1 K to 300 K, the hyperfine field seen by the muon remains nearly constant. Possible mechanisms for explaining this result are considered.

1. INTRODUCTION

The hyperfine field experienced by interstitial positive muons in ferromagnetic nickel was first measured by Foy et al using the asymmetric positron decay of the μ^+[1]. It was found to be -0.66 kG at 77 K by Patterson et al[2]. Some theoretical treatments of this hyperfine field have been made either by relating it to the magnetic moment density distribution in the interstitial site as observed by neutron diffraction[3], or by considering the screening of the muon charge by the polarized conduction electrons using a spin-dependent screening potential[4].

By extending these measurements to lower temperatures, we expect that the positive muon, which becomes less diffusive and tends to be frozen at the interstitial sites of a potential minimum, will feel a somewhat different aspect of the local hyperfine field. Particularly it is interesting to measure the hyperfine field as a function of temperature in order to see whether or not it follows the bulk magnetization of the sample. By doing this, we can hopefully observe how the diffusion of the muon affects the hyperfine field, and how the magnon excitation in the host material modifies the local magnetic field at the interstitial site. The studies at low temperature have another advantage: at low temperature near T = 0, the temperature dependence of the Ni magnetization is known to be entirely due to the magnon excitation. At higher temperature, higher-order effects like the magnon-magnon interaction make such an effect of the interstitial impurity on the local magnetic structure, if it exists, unclear.

To this aim, we carried out a positive muon spin rotation (μ^+SR)

experiment for a nickel single crystal at temperatures from room temperature down to 0.12 K using a ^{3}He - ^{4}He dilution refrigerator. A brief report of the results has already been given elsewhere[5].

II. EXPERIMENTAL PROCEDURES

The positive muon beam at the Lawrence Berkeley Laboratory 184 inch Cyclotron was used for the present experiment. An external proton beam of 30 nA was fully stopped in a copper target for pion production. The emerging 200 MeV/c pions selected by the first bending magnet (LEANDER) decayed into muons during their flight through a 20 foot straight section. The forward-decay positive muons were selected by the second bending magnet (TITAN) and guided towards a target which was placed at the centre of an air-core split solenoid (SAGANE). A polyethylene moderator surrounded with a lead collimater was used to produce stopped muons at a target of 4 cm x 4 cm size. Typically, 1.5×10^3 muons/sec, with a polarization around 80% were stopped inside the target.

The counter arrangement around the target is given in fig. 1. The fast logic was as follows:

$$\begin{aligned} \text{"stopped } \mu\text{"} &= B \cdot M \cdot S1 \cdot \overline{S2X} \ , \\ \text{"decay e"} &= S2X \cdot S2 \cdot E \cdot S3 \cdot \overline{(B+M+S1)} . \end{aligned} \tag{1}$$

The electronics logic and data acquisition system were similar to those used by Crowe et al [6]. The basic idea is as follows: after passing through the 'gates' of the fast logic, the timing signals from the M and E counters are fed to the clock of a Hewlett-Packward Computing Counter Model 5360 A to measure the time interval between these two signals to a precision of 0.1 nsec.

In order to avoid unnecessarily frequent starts, additional slow logic was constructed, and the timing signal from E selected by good events only is used as a start signal to the clock. The timing signal from M is delayed by 20 μsec using a recirculating delay in a bath of constant temperature. This clock is connected to a PDP-15 computer, where the time interval of the 20 μsec constant delay is checked and adjusted frequently. The $t = 0$ address is determined from the straight-through events (the anticoincidences in eq. (1) were removed). The overall time resolution is around 0.6 nsec (FWHM).

A large nickel single crystal of approximately ellipsoidal shape (6.0 × 3.0 × 1.2 cm) was served as a target and cooled by a dilution refrigerator[7]. An external field of 153 G was applied along the major axis, which was the same as the easy axis. The thermal connection between the mixing chamber and the target was attained by a thin copper rod, the lowest edge of which was soldered to the top of the target in order to minimize the background contributions. A schematic view of the dilution cryostat is presented in fig. 2.

The temperature was measured by using a calibrated carbon resistor, Matsushita 68 Ω 1/8 watt[8], which was soldered at the lowest edge of the target. Another resistor at the top of the mixing chamber was used to check the temperature homogeneity throughout the target. Typically the difference was within 0.01 K at 0.12 K.

III. RESULTS

The measurements of precession pattern were done at five different temperatures (0.12 K, 0.4 K, 4.2 K, 77 K and 300 K) in an external field of 153 Gauss. The constant background and the contributions from cryostat constituents which had a free muon precession frequency were subtracted from the raw time spectrum. Then, a fitting program was used to determine the precession frequency for the nickel target. Fig. 3 shows another representation of the results, in which are presented least-squares fits to the function,

$$N(t) = N_0 e^{-t/\tau_\mu}[1 - A\cos(2\pi ft + \phi)] \qquad (2)$$

with a variable precession frequency f.

The results of the precession frequency are summarized in table I. In this table we also give values of the local field, B_μ(Gauss) = f(kHz)/13.554 and the relative change of the saturation magnetization. The B_μ values are the same below 4.2 K and the decrease of B_μ is 0.84 (15)% at 77 K and 9.87 (27)% at 300 K, both of which are larger than those of magnetization.

The local field, B_μ, can be decomposed into the following four terms: external field, demagnetizing field, Lorentz field and hyperfine field,

$$B_\mu = H_{ext} + H_{demag} + \frac{4\pi}{3}M + H_{int} \qquad (3)$$

where we have neglected the dipolar field contribution within the Lorentz cavity because of the cubic symmetry of the μ^+ location. For an external applied field below the saturation, the first two terms should be cancelled within a few Gauss. The assumption was proved at each temperature by changing the external field in the range of nearly 0, 153 and 340 Gauss,

where we observed the same frequencies within the present errors. Therefore, the hyperfine field, H_{int}, can be obtained by subtracting the third term (the Lorentz field) from B_μ.

These results are also given in table I, and relative values normalized at the lowest temperature are shown in figs. 4 and 5, where we put also a relative change of the saturation magnetization (M) and the hyperfine field on Ni nuclei (H_n) measured by an NMR study[9]. In contrast to the others, the μ^+ hyperfine field is almost temperature independent: it decreases by less than 1% in the temperature range from 0.1 K to 300 K. Such a discrepancy has been observed at higher temperatures near the Curie point[2], but it has not been taken seriously presumably because of the possible systematic error associated with temperature ambiguities and also a lack of the lowest temperature data. In the low temperature limit, the hyperfine field was found to be -640.7 ± 2.2 Gauss. The discrepancy between this value and the former value (-0.66 kG)[2] obtained at 77 K was due to the incorrect value of the Lorentz field used in the latter case.

IV. DISCUSSION

We start our discussion with some speculations on the location and diffusion of the μ^+ based on the known experimental data on the diffusion properties of hydrogen impurities in nickel metal. At room temperature, hydrogen impurities are located at the octahedral site[10] and diffuse from site to site. The diffusion constant is written as follows:

$$D = D_0 \exp(-E_a/kT) \qquad (4)$$

The experimental value of E_a (activation energy) is 0.23 eV near 100 K[11]. The diffusion properties of hydrogen-like atoms are summarized in table 2. Although comparisons are made at higher temperatures than our temperature range, the values of E_a are almost independent of the mass of hydrogen-like impurities from hydrogen to tritium, and a simple extrapolation gives the same activation energy for the positive muon. A classical theory of diffusion[12]has predicted that the activation energy is likely to be independent of the mass, while the preexponential factor, D_0, should be proportional to $(\text{Mass})^{-\frac{1}{2}}$. A quantum theory of diffusion also supports this mass dependence in the case of some fcc crystals[13]. Then according to this theory the diffusion time becomes longer than 10^{-3} sec below 300 K.

In addition to the diffusion, the vibrational energy of hydrogen in nickel has been measured[14]. Using this data, we can expect the zero-point energy for the positive muon to be 0.18 eV. This value corresponds to the spatial uncertainty of 0.4 Å (root-mean-square). Combining these two effects we can say that the positive muon in our temperature range is well localized at octahedral interstices with the spatial broadening of around 0.4 Å. Probably it may still be diffusing by a temperature independent process such as tunneling. These speculations for the μ^+ location and diffusion are schematically shown in fig. 6.

Now let us consider some features of the hyperfine field on the μ^+. It can be described as an average of the interstitial magnetization, $m_{int}(\vec{r})$, which comes from the conduction electron polarization.

$$H_{int} = \int \frac{8\pi}{3} m_{int}(\vec{r})\, \rho_{\mu}(\vec{r})\, d\tau \qquad (5)$$

where $\rho_\mu(\vec{r})$ is the density distribution of the μ^+. Due to the screening of the muon charge by conduction electron, $m_{int}(\vec{r})$ is different from the unperturbed interstitial magnetization of the host metal, $M_{int}(\vec{r})$. When the perturbation is not so strong, $<m_{int}(\vec{r})>$ can be linearly related to $<M_{int}(\vec{r})>$,

$$<m_{int}(\vec{r})> = \alpha<M_{int}(\vec{r})> \qquad (6)$$

In the case of Ni at room temperature, α is found to be nearly unity[2], if the observed H_{int} is compared with the interstitial moment distribution, $M_{int}(\vec{r})$, obtained from the polarized neutron experiment[15]. This is also illustrated in fig. 6.

Negative spin density at interstitial sites can be attributed to the following two sources: (a) negative polarization of 4s-electrons at interstitial sites[16]due to the cancellation between s-d exchange polarization[17] and s-d hybridization[18], (b) negative polarization of 3d-electrons in the tail region of 3d wave functions due to a spin dependent radial form factor as predicted by band theory calculations[19]or the overlapping effect of neighbouring atoms[20].

Therefore both of polarized 3d- and 4s-electrons can contribute to the screening of the μ^+ to produce a contact field. Existing theories[3,4] consider only the contribution from the 4s-electrons and ignore the perhaps important effect of the 3d-electrons.

In the following, instead of going into the detail of the origin of the hyperfine field, we will try to understand the observed temperature dependence of the μ^+ hyperfine field by relating to the interstitial magnetization of neutron data, following the formula (5) and (6). We assume that

the temperature dependence of the unperturbed interstitial magnetization, M_{int}, is the same as that of the host magnetization, in other words, the spin-waves destroy the whole magnetic structure homogeneously. As for the adequacy of this assumption, we will discuss later.

(i) Thermal excitation of muon location

At higher temperatures, the thermal excitation of the μ^+ from the ground state might occur. We can take the following expression for the ratio of the population of the first excited state (P_1) to that of the ground state at a finite temperature.

$$P_1/P_0 = \exp(-\frac{h\nu}{kT}) \qquad (7)$$

where $h\nu$ is the vibrational energy (0.36 eV in our case). Then we get a negligibly small value for that ratio ($\sim 10^{-6}$) at 300 K. However, since the excited state is located above the potential barrier, there will be a process in which the μ^+ goes directly to the continuum state. Then in effect, the μ^+ location is broadened and the μ^+ will sample a wider interstitial region. If this takes place at all, and if α in the formula (6) is temperature independent, then, we expect a decrease of the magnitude of the hyperfine field, as far as M_{int} has a negative minimum at the octahedral site as indicated by the neutron experiment[15]. This is opposite to our result.

However, it seems to be difficult to determine precisely the spin-density distribution of the low-density interstitial region from the neutron experiment, and furthermore it is not simple to relate H_{int} to M_{int}. This question is enhanced in view of the discrepancy that in the fcc Pd metal the neutron

experiment[21]gave a positive spin density at the octahedral interstitial site, while the observed hyperfine field of the μ^+ was negative[22]. Moreover, the polarized neutron experiments on Pd[20]and $Pd_{0.987}Fe_{0.013}$ alloy[23]has shown that the minima of negatively polarized spin density are located somewhere between the Pd atomic site and the octahedral site. If such a situation does occur in Ni, it would be intriguing and confusing. There is no experimental study of the interstitial spin density at various temperatures except the one by Caglioti et al[24], which, however, shows that the interstitial spin density vanishes in the paramagnetic phase. The existing theories for the μ^+ hyperfine field are neither helpful nor capable of predicting the spatial distribution.

If the μ^+ location becomes to overlap with the Ni moment, the dipolar field term in equation (3) could not be completely cancelled. In such a case, we may require an additional temperature dependent correction term according to the thermal excitation of the μ^+ location. It is quite difficult to estimate this effect because of our ignorance about the realistic spatial distribution of the μ^+. As for the sign of the correction, the resultant dipolar field is positive. As the broadening increases, it gives a more negative correction to H_{int}, which makes $H_{int}(T)$ deviate even more strongly from $M_s(T)$. Therefore this effect is not adequate to explain the observed phenomena.

(ii) Volume expansion effect

Our measurements of the μ^+ hyperfine fields versus temperature have been carried out at atmospheric pressure. These values must, in

principle, be reduced to those at constant volume in order to be compared with the saturation magnetization (M) which is also reduced to a constant volume value. In fact, the temperature dependences of M and the nuclear hyperfine field (H_n), which are not the same at constant pressure (as shown in fig. 5) become to agree closely with each other when corrections are made for constant volume[9](to the same dashed line shown in fig. 5).

The expected size of the difference for H_{int} can be estimated using the following thermodynamical relation,

$$\left[\frac{\partial(\ln H_{int})}{\partial T}\right]_P = \left[\frac{\partial(\ln H_{int})}{\partial T}\right]_V + \frac{\left[\frac{\partial(\ln H_{int})}{\partial P}\right]_T \left[\frac{\partial(\ln V)}{\partial T}\right]_P}{\left[\frac{\partial(\ln V)}{\partial P}\right]_T} \qquad (8)$$

In table III, we list the pressure coefficients of the host magnetization and the nuclear hyperfine fields of various transition-metal impurities in Ni and Fe metal. So far, there is no satisfactory explanation of the pressure dependence of the impurity hyperfine fields. Our experimental value of $(\partial(\ln H_{int})/\partial T)_p$ would be able to reproduce the $(\partial(\ln H_{int})/\partial T)_V$ that follows the magnetization curve at constant volume, if we were to assume $\partial(\ln H_{int})/\partial P = -4.2 \times 10^{-6}\ (kg/cm^2)^{-1}$. This value of the pressure coefficient has the opposite sign to those for Ni and Co impurity hyperfine fields in Ni and the same sign as that of the host magnetization, but its magnitude is one order greater than that of M. Therefore, the volume correction to the μ^+ hyperfine field is an unlikely explanation for the observed phenomena.

(iii) Localized-moment formation

The internal field at some impurity nuclei in a ferromagnetic transition metal departs markedly from the host magnetization. This effect has been explained by the localized-moment formation at the impurity site whose magnetization, m_I, is given by a molecular field:

$$m_I = B_S(\lambda\beta M) , \qquad (9)$$

where B_S is the Brillouin function corresponding to the spin S of the impurity, M is the magnetization of the host, $\beta = 1/kT$ and λ is the phenomenological coupling constant[27,28].

In fig. 7, we summarize the temperature dependence of hyperfine fields on various impurity nuclei in Ni. All of these data were taken at constant pressure. After correction for the constant volume, the ^{61}Ni data agree with the magnetization[9], while ^{59}Co and ^{57}Fe data deviate more strongly from the magnetization, that is, a much weaker temperature dependence than the host magnetization[29,30]. Both Co and Fe data can be fitted by eq. (9) using a host-impurity interaction which is stronger than the host-host interaction, for example, $\lambda = 2.6\ T_c$ for Fe. On the other hand, the curve of ^{99}Ru (and lots of other impurity nuclei) shows a significantly stronger temperature dependence than the host magnetization. This type of deviation can be explained using the host-impurity coupling, λ, which is weaker than the host-host interaction, like ^{55}Mn in Fe[27].

A strong host-impurity coupling seems to contradict the molecular-field picture. However studies on the effects of magnetic impurities on spin waves which have given a physical basis for the above picture predict that the

molecular-field model is also a good approximation in the case of strong host-impurity interaction [31,32]. This theory can be described briefly as follows: an impurity more strongly coupled than elsewhere distorts the spin-wave band upward in the vicinity of the impurity. It behaves like a repulsive potential for spin-wave scattering. The spin waves whose wave length is comparable to the range of the potential are strongly scattered and have small amplitude at the impurity. After lengthy calculation of such an effect, the local magnetization at the impurity is found to be approximated by eq. (9).

It is clear from fig. 7 that the μ^+ has the same temperature dependence as those impurities which have a strong coupling with the host. Therefore, if we try to explain the observed effect only by this localized-moment formation, we must assume both (i) that a localized moment formation of a 1s like electron is formed around the μ^+, and (ii) that the localized moment strongly couples with the host moment and perturbs spin wave. It is quite difficult to justify the first assumption because the conduction electrons in metallic Ni should destroy such a bound state quite easily. The weak μ^+ hyperfine field (0.64 kG) observed in Ni compared to the muonium hyperfine field (0.33 MG) indicates the absence of such a bound state. Probably there will be a quasi-bound state with substantially reduced amplitude of the 1s state with small effective moment which might perturb the spin wave. However, such a reduced moment could not couple with the host moment so strongly compared with the host-host interaction. This contradicts the second assumption.

In conclusion, we feel we should exclude the effect of the localized-moment formation from the possibilities to explain the observed phenomena.

(iv) Local magnetic ordering among neighbouring atoms

As we mentioned above, a part of the negative conduction electron polarization can be attributed to the 3d electrons whose long tail has a negative spin density. When a positive muon is put into the interstitial sites, it is expected to attract more 3d electrons in such a way that the local d-d coupling in the nearest neighbour region is increased. This situation may be called local enhancement of the ferromagnetic ordering, which may be essentially a counterpart of the local enhancement of the antiferromagnetic ordering in MnO when a negative muon is trapped by the oxygen[33]. In such a situation the magnon excitation does not destroy the local spins so much as it does the bulk spin, and therefore the local magnetization around the μ^+ has a weaker temperature dependence than the host magnetization.

However, there have been some experiments which contradict the above explanation: non-magnetic impurities at interstitial sites like C, N and B seem to give up most of their screening electrons to the d-band of the matrix and thus reduce the magnetic moment of the neighbouring atoms[34]. Such a reduction of the moment happens also for the neighbouring host atoms surrounding non-magnetic impurities at substitutional sites. In the case of Co and Fe metals with Sn impurities, the nuclear hyperfine fields of the neighbouring atoms with reduced moment were found to follow completely the host magnetization[35,36], suggesting the magnetic structure of the neighbouring atoms are unaffected by the impurity.

V. SUMMARY

The hyperfine field on μ^+ in Ni was found to be almost temperature independent from 0.1 K to room temperature. Although they are unlikely, we cannot rule out the following three possible explanations for these results: (A) the existence of a spatial distribution of the interstitial spin density that produces a stronger average field as a result of the increase of the broadening of the μ^+ location; (B) an anomalous pressure dependence of the muon hyperfine field; or (C) a local enhancement of the ordering among the nearest neighbours induced by the positive charge of the μ^+.

As for (A), we require a more sophisticated theory for the μ^+ hyperfine field which can predict a correct radial distribution of the spin density. In this connection we have raised questions as to the relation between the μ^+ hyperfine field and the interstitial spin density. As for (B), the measurements of the pressure dependence of the μ^+ hyperfine field will give further information. If the observed effect was entirely attributed to this effect, we should be able to see a strong pressure dependence: at room temperature, an applied pressure of 10^4 bar could compensate the discrepancy between H_{int} and M. As for (C), we need more information about local magnetic ordering induced by the interstitial impurities.

So far, we have assumed that the temperature dependence of the unperturbed interstitial magnetization of host Ni is the same as that of the host magnetization. Concerning this assumption, two recent experiments have revealed a possibility that the unperturbed conduction electron polarization might have a different temperature dependence from that of the host magnetization.

(A) Recent magnetization studies of Ni have been interpreted to show that the decrease of the magnetization due to a Stoner single particle excitation is not negligible, but almost as large as the spin-wave contribution[37]. If this is true, as suggested by Benedek and Armstrong[26,38], the thermal excitation of d-electrons to higher states in the d-band combined with a strong energy dependent hyperfine coupling constant results in a T^2 dependence for the ratio of $H_{int}(T)$ to $M_s(T)$. Our result can be fitted by such a correction: $H_{int}(T) \propto (1 + 7 \times 10^{-7}T^2)M_s(T)$.

(B) The measurement of the temperature dependence of the hyperfine field of various non-magnetic impurities in Fe have been carried out by Khoi et al.[39] as showing that the conduction electron polarization has a different temperature dependence from the host magnetization, while the local core polarization field on Fe follows the host magnetization. They concluded that this phenomenon can be explained by the effect of thermal vibration of the lattice on the conduction electron polarization through the radial dependence of the RKKY spin density oscillation.

Although the above understanding of these experimental results is still dubious, it is important to pursue theoretical studies along these lines. Also polarized neutron studies at different temperatures are highly recommended.

Recently NMR experiments have been done for the temperature dependence of the hyperfine field on ^{12}B nuclei in Ni which, like the μ^+, stay also at the octahedral interstitial site[40], and it was found to deviate strongly from the magnetization in the same direction and the deviation was almost same as the μ^+ results (fig. 7). It is quite interesting to extend this type of measurements to various ferromagnetic materials by using different interstitial

probes, and to see whether or not such an effect is inherent to the interstitial character of the probe. Also, since essentially the same effect has been observed by the two different probes with quite different masses, we may have the possibility of another criterion to see if this phenomenon is connected to a thermal excitation of the location. Detailed experimental or theoretical studies on the diffusion properties of light impurities including B and N will lead us to a much clearer conclusion.

Finally we would like to emphasize the μSR method as a powerful new technique for studies of solid state physics at low temperature. Stopped muons with sufficiently high intensity (10^6/sec) deposit only a small amount of heat (1 μWatt) to the target, which permits use of any kind of refrigeration device to produce low temperature down to 10 mK or less.

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Table I - Summary of the μ^+SR Experiment in Ni at H_{ext} = 153 G

Temp (K)	Frequency (MHz)	B_μ (G)	$\frac{4\pi}{3} M^{\dagger)}$ (G)	H_{int} (G)	$H_{int}/H_{int}(0)$	$M/M(0)$
300	18.449 (55)	1361.2 (41)	1996.4	-635.2 (41)	.9916 (64)	.9345
77	20.101 (25)	1483.1 (18)	2125.9	-642.8 (18)	1.0034 (28)	.9951
4.2	20.277 (27)	1496.1 (20)	2136.4	-640.3 (20)	.9992 (31)	1.0000
0.40	20.270 (28)	1495.6 (21)	2136.4	-640.8 (21)	1.0000 (33)	1.0000
0.12	20.270 (28)	1495.6 (21)	2136.4	-640.8 (21)	1.0000 (33)	1.0000

†) For the values of $M_s(T)$, we used the relative values of the data cited in ref.[9] with $M_s(0) = 510.0$.

Table II - Diffusion properties of hydrogen-like atoms[a)]

	E_a (eV)	D_0 (cm^2/sec)	Temperature Range (K)
Hydrogen	0.41 ± 0.03	6×10^{-3} b)	400 ∿ 950
	0.23 ± 0.04	2×10^{-10} b)	110 ∿ 250
Deuterium	0.401	5.27×10^{-3}	720 ∿ 1270
Tritium	0.395	4.32×10^{-3}	720 ∿ 1270

a) Data have been taken from ref.[11] and J. Völkl and G. Alefeld, in Diffusion in solids, ed. A.S. Nowick and J.J. Burton (Academic Press, New York, 1975) p. 232.

b) Converted using the formula of $\tau = L^2/6D$ where τ^{-1} is a jumping frequency and L is interatomic spacing.

Table III - The pressure dependence of the host magnetization (M) and internal field (H_n) of impurity nuclei

Host	$\partial(\ln M)/\partial P \cdot 10^7$ $(kg/cm^2)^{-1}$	Nucleus	$\partial(\ln H_n)/\partial P \cdot 10^7$ $(kg/cm^2)^{-1}$
Ni	-3.1 a)	^{61}Ni	+ 8.81 ± 0.18 c)
		^{59}Co	+13.8 ± 0.5 c)
Fe	-2.78 ± 0.25 b) or -1.7 b)	^{59}Co	+1.6 c)
		^{63}Cu	-3.0 c)
		^{57}Fe	-1.6 c)

a) Reference [25]

b) Data cited in Reference [26]

c) Data cited in Reference [29]

FIGURE CAPTIONS

Fig. 1. Experimental arrangement for the counters and the target enclosed inside the cryostat.

Fig. 2. A schematic view of the dilution cryostat, in which the Ni sample is cooled down to 0.1 K. The locations of carbon resistors are not presented.

Fig. 3. The chi-squares versus precession frequency for the μ^+ in Ni single crystal measured at 0.12 K (upper) and room temperature (lower).

Fig. 4. Temperature dependence of the μ^+ hyperfine field, the nuclear hyperfine field (H_n) and the magnetization of Ni (M), all of which are normalized at the lowest temperature. Temperature is shown in a logarithmic scale.

Fig. 5. Temperature dependence of the μ^+ hyperfine field with the external field of 0 G, 153 G and 340 G, as well as the nuclear hyperfine field (H_n) and the magnetization of Ni (M), all of which are normalized at the lowest temperature. Also the corrected value of the magnetization and the hyperfine field to constant volume is shown (both agree with each other to within 0.5%). The upper broken line shows the experimental tendency of the μ^+ hyperfine field.

Fig. 6 Schematic illustration of the μ^+ location in Ni lattice. (a) Lattice and octahedral interstice. (b) The positive muon bound in a potential. Its depth and the energy levels are inferred from the hydrogen data. (c) Distribution of the magnetic dipole moment along the direction of the μ^+ motion as observed by neutron scattering [15].

Fig. 7. Summary of the temperature dependence of the hyperfine fields on various impurity nuclei in Ni; ^{61}Ni from ref.[9], ^{57}Fe from ref.[29], ^{59}Co from ref.[30], ^{99}Ru from ref.[28] and ^{12}B from ref.[40]. In addition, the data for the μ^+ is also presented; the curve labelled $\mu^+(1)$ shows the present result, while the curve labelled $\mu^+(2)$ shows also the μ^+ hyperfine field which is obtained from ref.[1] after correction for the Lorentz field. These are normalized by our present data at the lowest temperature.

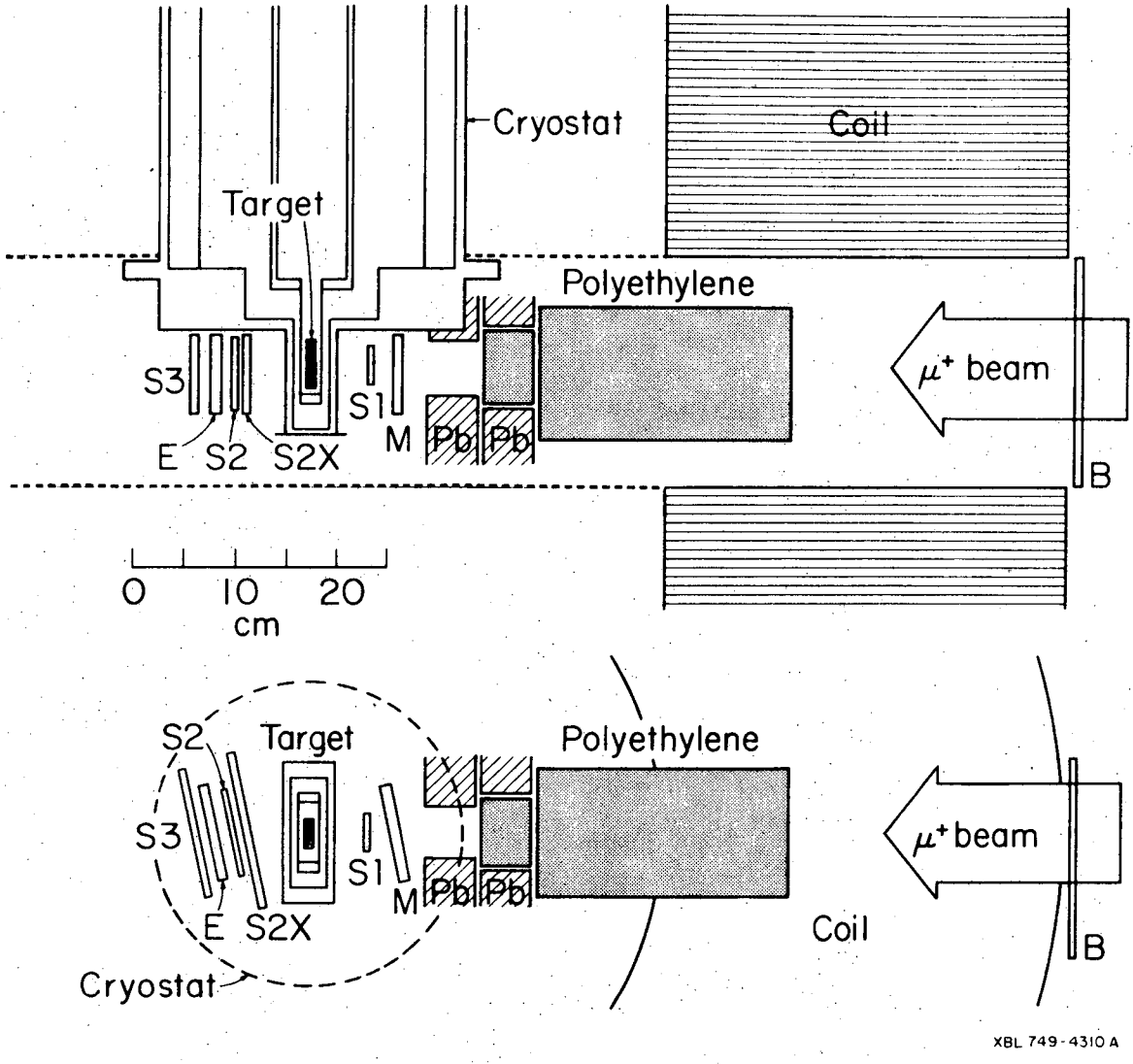
Cryostat
Coil
Target
Polyethylene
S3
S1
E
S2
S2X
M
Pb
Pb
μ+ beam
B
0
10
20
cm
S2
Target
Polyethylene
S3
S1
E
S2X
M
Pb
Pb
Cryostat
Coil
μ+ beam
B
XBL 749-4310 A

Fig. 1

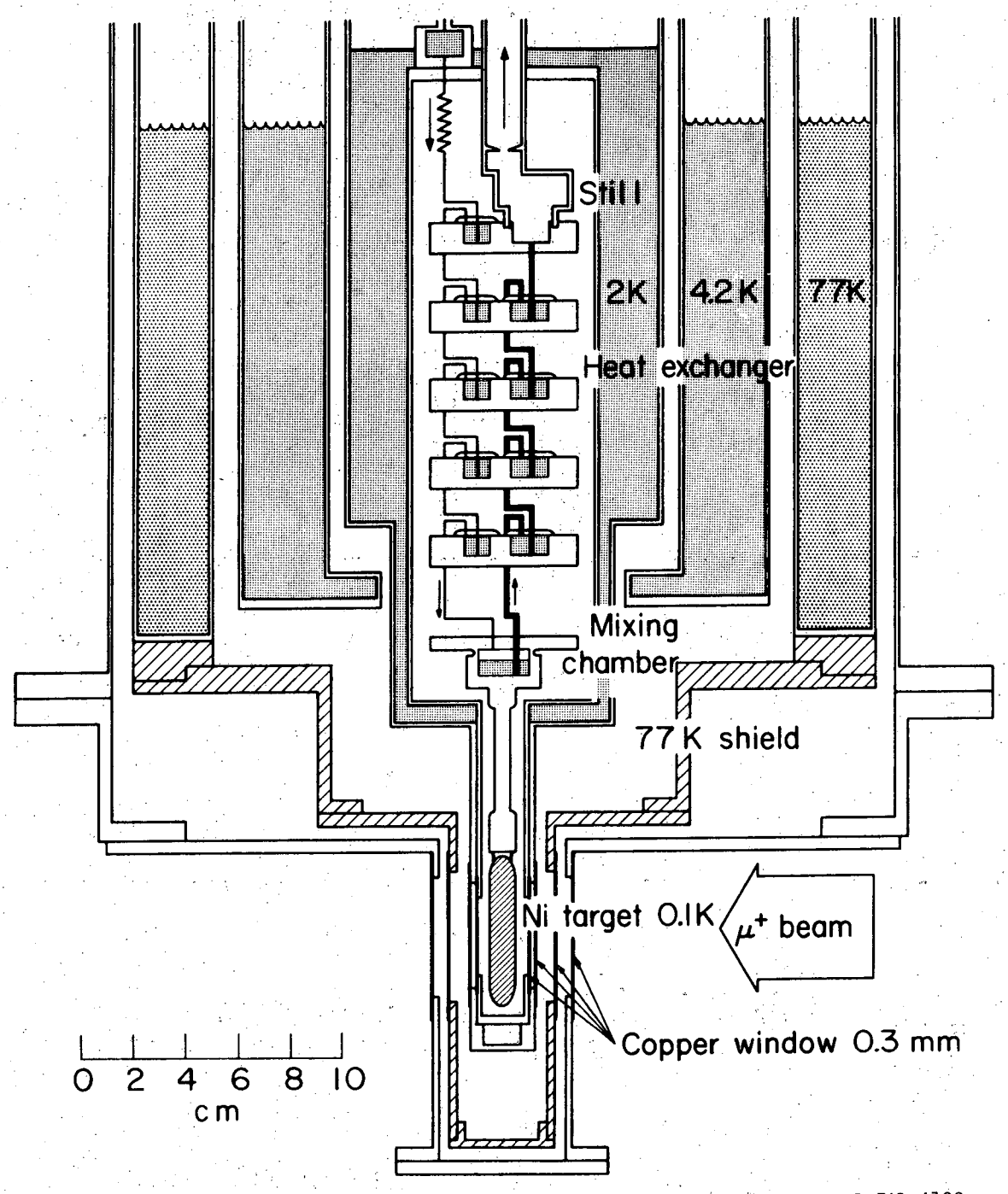

Fig. 2

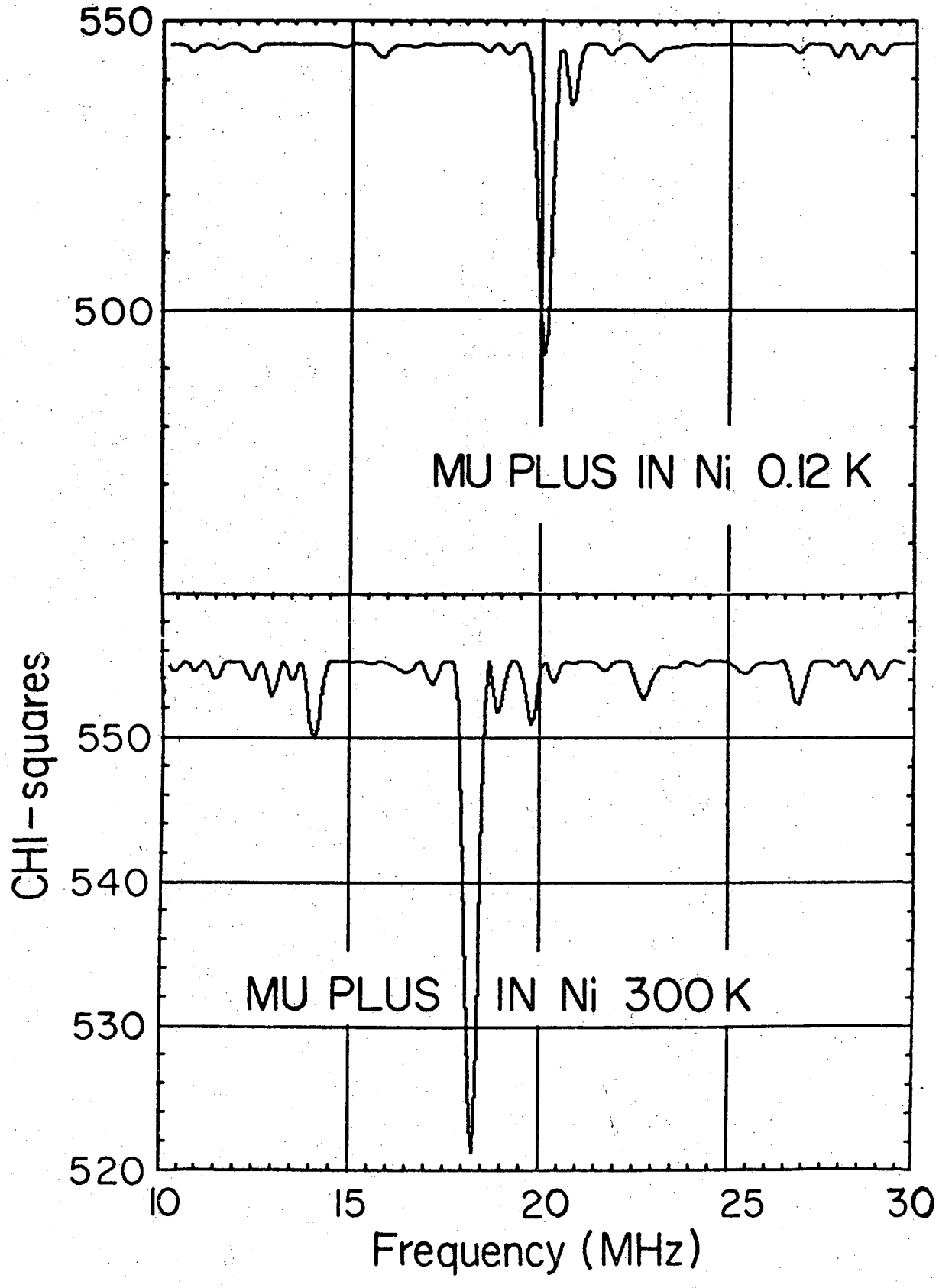
550
500
MU PLUS IN Ni 0.12 K
550
540
530
520
MU PLUS IN Ni 300 K
CHI-squares
10
15
20
25
30
Frequency (MHz)

Fig. 3

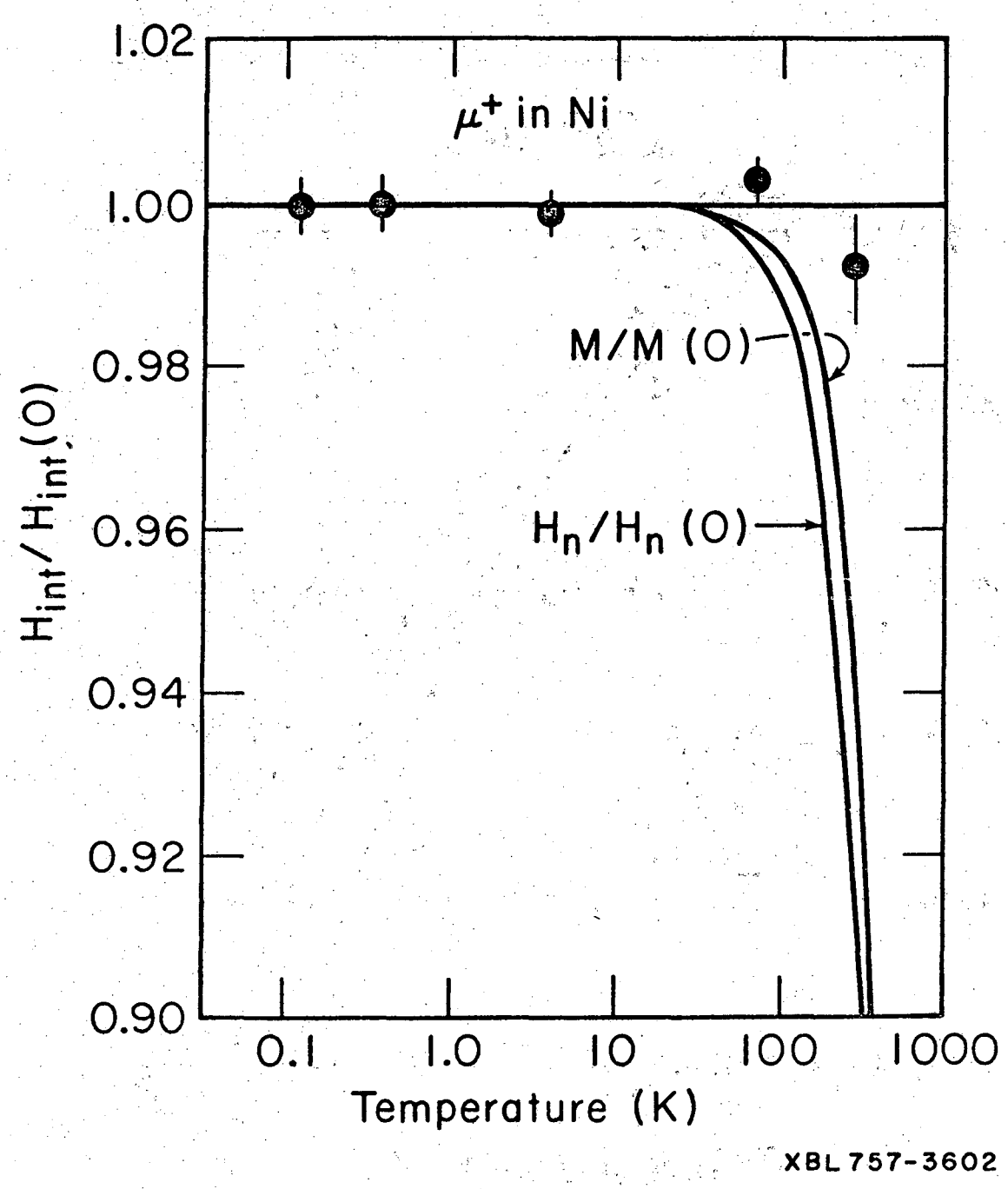

Fig. 4

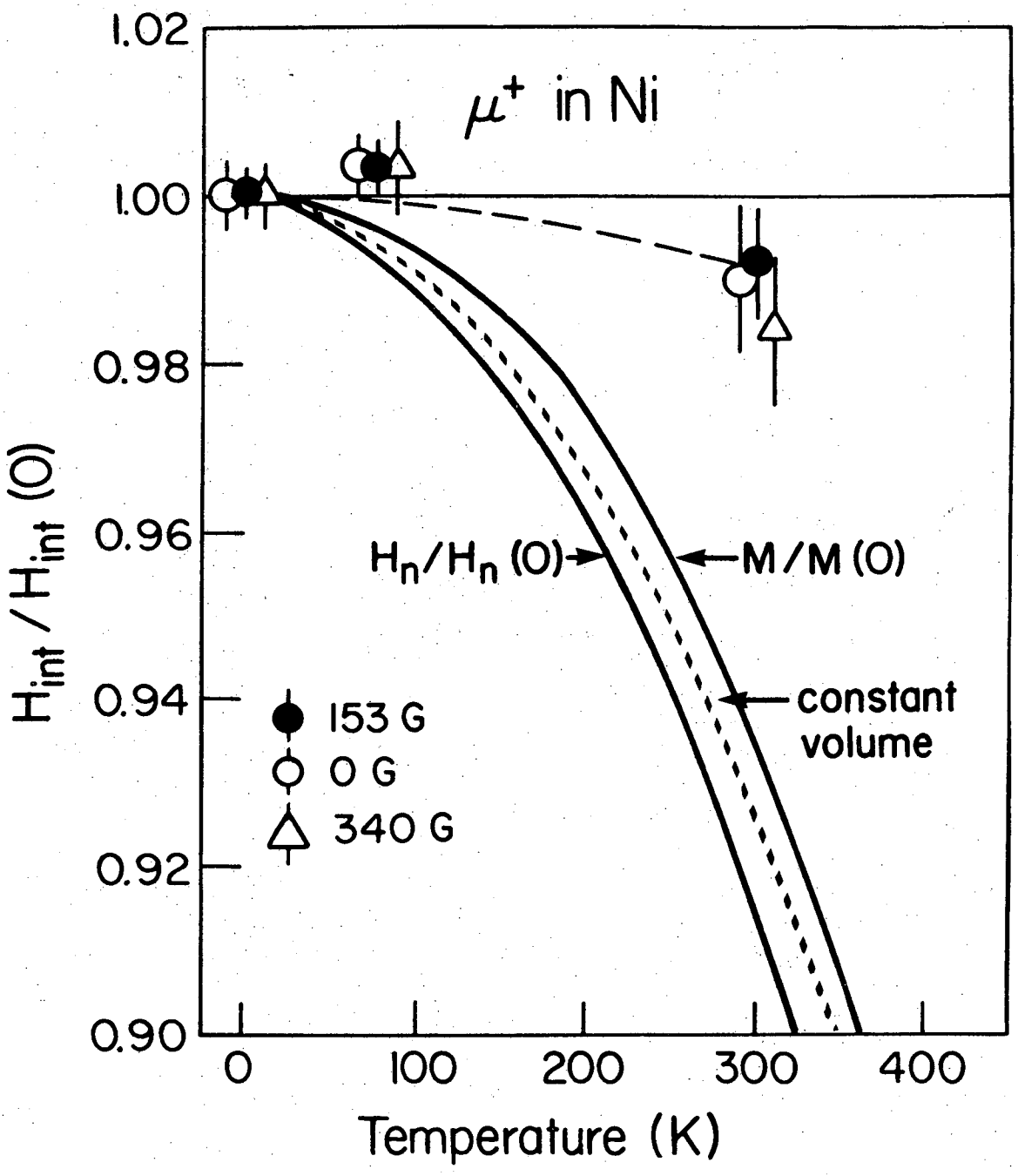
μ+ in Ni
1.02
1.00
0.98
0.96
0.94
0.92
0.90
H_int / H_int (0)
H_n/H_n (0)
M/M (0)
constant volume
153 G
0 G
340 G
0
100
200
300
400
Temperature (K)

Fig. 5

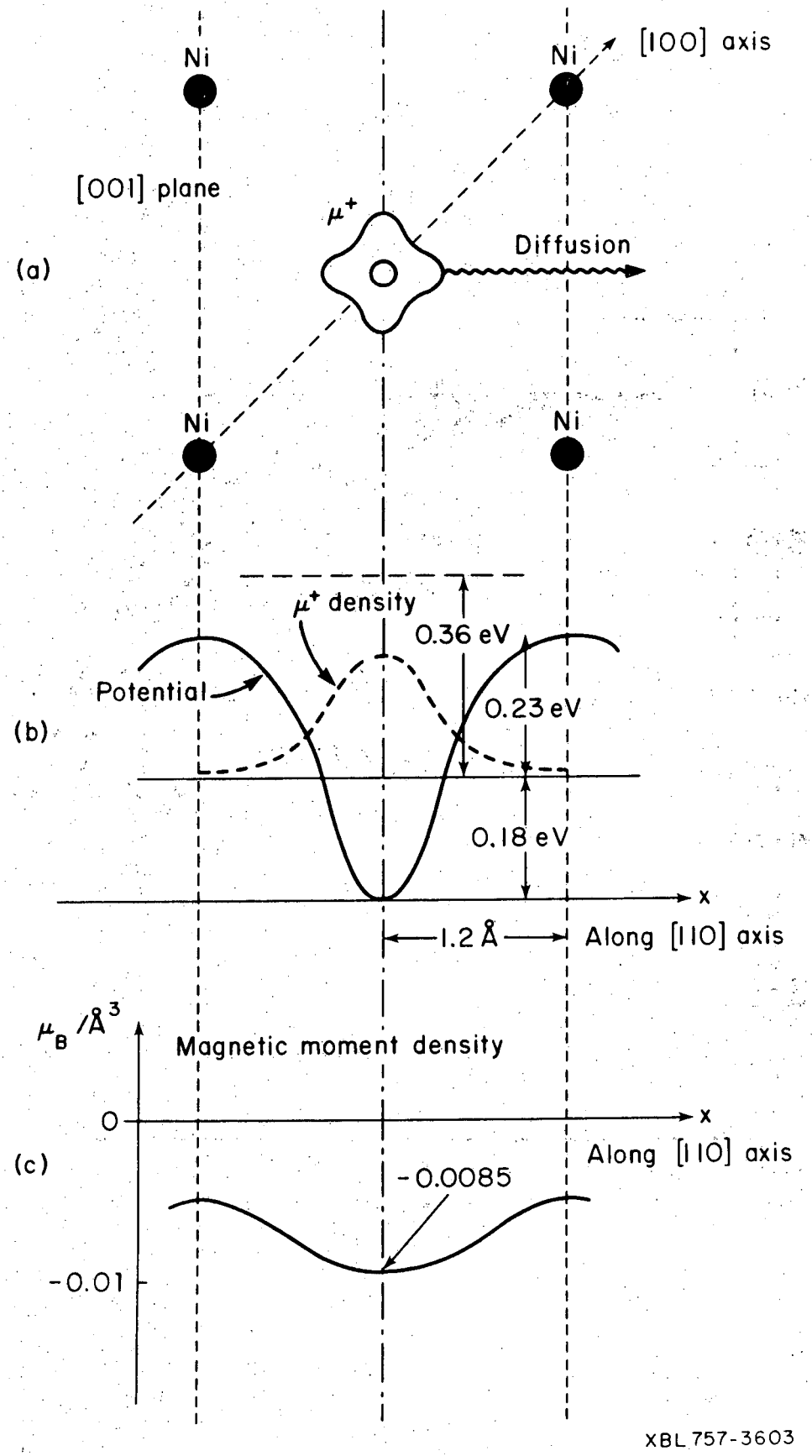
Ni
Ni
[100] axis
[001] plane
μ^+
(a)
Diffusion
Ni
Ni
μ^+ density
0.36 eV
Potential
(b)
0.23 eV
0.18 eV
x
1.2 Å
Along [110] axis
μ_B /Å^3
Magnetic moment density
0
x
(c)
Along [110] axis
-0.0085
-0.01
XBL 757-3603

Fig. 6

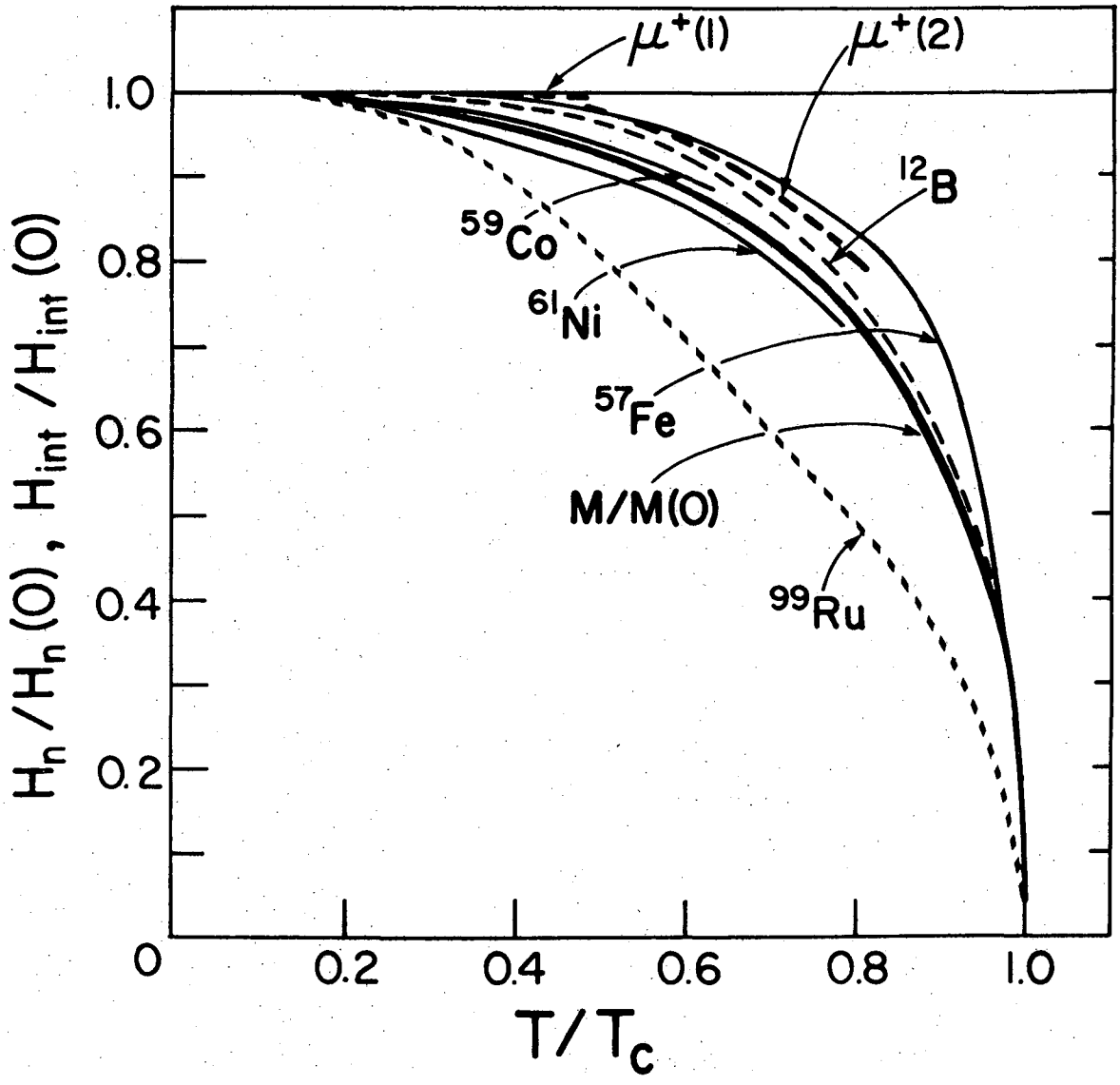
$\mu^+(1)$
$\mu^+(2)$
^{12}B
^{59}Co
^{61}Ni
^{57}Fe
M/M(0)
^{99}Ru
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
$H_n/H_n(0)$, $H_{int}/H_{int}(0)$
T/T_c

Fig. 7

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