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Progress Report

RARE EARTH-TRANSITION METAL MAGNETOSTRICTIVE MATERIALS

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INTRODUCTION

In the past year our work on rare earth-transition metal intermetallic compounds and amorphous materials has taken on new directions with new personnel. Prof. Kiyoo Sato completed his time with us and returned to Toyama University in Japan, but he continues to collaborate with us and he came here to work for the month of June of this year. He has been replaced on the program by Dr. Y.J. Liu, a Ph.D. from the Applied Physics department of Yale University. Dr. Liu started a calculation on a random exchange model of an amorphous ferromagnet and a study of conductivity and displacement current effects on magnetoelastic surface wave propagation. Ray Abbundi studied the ^{161}Dy hyperfine splitting in $DyFe_2$, completed his dissertation and is now benefitting from a postdoctoral appointment with Dr. Clark's group at the Naval Surface Weapons Center. So our collaboration with him and with that group continues. Mr. William Pala, as his dissertation topic, has been studying the Mossbauer splitting in amorphous YFe_2. Kristl Hathaway, a fresh Ph.D. from Cornell, is working with us part time on magnetic field effects in a multisublattice magnetic system. William Ferrando worked at the Naval Surface Weapons Center with Drs. Clark and Savage on studies of the ΔE effect, the change in bulk modulus with magnetic field, of $Tb_x\ Dy_{1-x}\ Fe_2$, with a view toward developing tunable delay lines, a prospect which looks increasingly likely. Dr. Ferrando also studied domain patterns on $DyFe_2$ (100 easy) and in Tb-containing materials, (111 easy), in order to get some understanding of the magnetization process.

Letter on file

A

The research itself seems to be coming along. We have variously coauthored papers at the workshop on Magnetostrictive Materials in Orlando Florida, February 1976, at the IEEE Conferences on Magnetism and Magnetic Materials in Philadelphia in December and in Pittsburgh in June 1976, and shall have papers at the International Conference on Magnetism in Amsterdam, to be held in September 1976, and at the Second International Symposium on Amorphous Magnetism, at Rensselaer Polytechnic Institute in August 1976.

I. Models of the Amorphous Ferromagnet

There are three basic models of an amorphous ferromagnet. Gubanov[1] suggested very early that the amorphous ferromagnet is characterized by a distribution of exchange interactions. This plausible assumption has been pursued by a number of groups, and particularly by Anderson, Edwards, Kirkpatrick, Lubensky, and by Sherrington. Another view is that the exchange is uniform, but that the large single ion anisotropy is distributed uniformly in directions of easy axis over the unit sphere. This approach, first introduced by the McGill group[2] (Zuckerman, Plischke), has been pursued by Alben[3] at Yale. Still a third approach, the collective electron model,[4] is one we introduced and continue to work on. It is probably the right model for amorphous nickel, an intinerant ferromagnet in its crystalline phase, but is surely not descriptive of the rare earths. For the rare earth alloys neither the exchange nor the crystal field models have been carried to such agreement with experiment as to exclude the other from consideration, and there may be room for both models in describing different materials. Our own experiments[5] have been widely misinterpretated as supporting only the crystal field model, perhaps because of authorship. They do not. They simply show that the crystal field in an amorphous material may well be distributed in directions (which we cannot tell by Mossbauer spectroscopy) but it is surprisingly sharply defined in magnitude. The quadrupole splitting in an amorphous material is the same as it is in the crystalling phase!

And so we work on all three models. The exchange distribution picture seems intuitively to offer the right kind of qualitative results. One

expects that the substitution of a finite concentration of randomly scattered antiferromagnetic bonds, interspersed with the remaining ferromagnetic bonds, should lower the Curie point, reduce the moment, increase the susceptibility (the material will no longer be ferromagnetically saturated) and reduce the correlation length.

This problem has so far remained analytically intractable, at least to us. But it can be attacked by a computer, and Dr. Liu has been writing programs. The programs are so far too time consuming, because it is difficult to find the energetically lowest sets of spin directions for a given bond distribution. Bünder, Walker, and Domb have performed related calculations.

Another approach is to assume a constant J, but spread the easy axes over directions. Alben has studied this problem by machine calculation. Here we think we can learn something analytically, and we have made a little progress.

Consider an ion of dipole moment $\vec{\mu}$, whose orientation makes Euler angles θ and ϕ with the external field and magnetization, which are both assumed to be along the positive z direction. The easy axis of this ion is along Θ, Φ For uniaxial local anisotropy $\phi = \Phi$. The energy of the ion is then

$$E = - \vec{\mu} \cdot \vec{H}_{exchange} - \vec{\mu} \cdot \vec{H}_{external} - K \cos^2 (\Theta - \theta),$$

$$E = - \mu(\lambda M + H) \cos \theta - K \cos^2 (\Theta - \theta)$$

and this is a minimum when

$$\mu(H + \lambda M) \sin \theta = K \sin^2 (\Theta - \theta). \qquad (1)$$

Now what is the magnetization? Let us assume that we are in the upper quadrant of the hysteresis loop. That is, we are relaxing the external field back from infinity, at which field the magnetization was $n\mu$, (there are n spins per unit volume), toward zero field. Clearly, if there is no anisotropy the remanence at zero temperature will be $n\mu$. At the other extreme, if it is infinite the spins will be equally distributed over the positive hemisphere

and the remanence will be $0.5\, n_s \mu$. In general, in the first quadrant,

$$\frac{M}{n_s \mu} \equiv m = \int_0^{\pi/2} \cos\theta(\Theta) \sin\Theta \, d\Theta \qquad (2)$$

where θ as a function of Θ is to be inserted from equation (1). We note that this calculation is different from that of the polycrystal average, because in the amorphous magnet the intrinsic moment is itself self-consistently altered by its distribution over directions. The exchange here pulls the spins away from their easy axes, increasing the magnetization and the remanence.

Simultaneous solution of equations (1) and (2) gives the upper branch of the magnetization curves from saturation to remanence. In the dimensionless quantities

$$k \equiv K/\lambda n_s \mu^2 \; , \qquad h \equiv \frac{\mu H}{\lambda n_s \mu^2} \; , \qquad (3)$$

$$k \sin 2(\Theta - \theta) = (h + m)\sin\Theta \qquad (1a)$$

$$m = \int_0^{\pi/2} \cos\theta \sin\Theta \, d\Theta \; . \qquad (2a)$$

These can be solved by iteration in interesting limits.

Suppose the anisotropy is small ($k \ll h+1$). Then θ is small, and $m \cong 1 - \frac{4}{15}\left(\frac{k}{h+1}\right)^2$. The remanence is $1 - 4/15\, k^2$. The initial "permeability" is $dm/dh = \frac{8}{15} k^2$ and the approach to saturation at large H goes as $1 - \frac{4}{15}\left(\frac{K}{H}\right)^2$.

In the other limit, large anisotropy, $\theta \cong \theta'$. Then, by iteration, one finds in the limit $\lambda_R >> h+1$

$$m \cong 1/2 + \frac{1}{6\lambda_R} + \frac{h}{3\lambda_R} .$$

The remanence is $1/2 + 1/6\lambda_R$

and the initial "permeability" is

$$\frac{dm}{dh} = \frac{1}{3\lambda_R} .$$

Of course at sufficiently large h the magnetization again approaches saturation as $(K/H)^2$.

We are in the midst of investigating the behavior over the whole magnetization curve, and extending this to finite temperatures. What is observed experimentally is a large remanence and large coercive force at 0°K and an unusually rapid collapse of the energy product as the temperature is increased. We shall see if the anisotropy model can give this result.

References

1. A.I. Gubanov, Fiz. Tverd. Tela 2, 502 (1960)
   (Sov. Phys. Solid State 2, 468 (1961)).
2. R. Harris, M. Plischke, and M.J. Zuckerman, Phys. Rev. Lett 31, 160 (1973)
3. R. Alben, Conf. on Magnetism and Magnetic Materials, Pittsburgh, June 1976.
4. D.C. Shapero, J.R. Cullen and E. Callen
   Phys. Lett. 50 A, 303 (1974)
5. D. Sakar, R. Segnan, E.K. Cornell, E. Callen, R. Harris, M. Plischke and
   M.J. Zuckerman, Phys. Rev. Lett. 32, 542 (1974)

II. Magnetic Ordering in Amorphous YFe_2

Crystalline YFe_2 is a ferromagnet. Amorphous YFe_2 shows no macroscopic moment. Small angle neutron scattering measurements by Pickart, Rhyne, and Alperin (1) suggest a short correlation length and magnetic inhomogeneities or clusters. The presence of weakly interacting small magnetic clusters is confirmed by the magnetization measurements of Rhyne et al. (2). The same magnetization studies show that at temperatures below about 5° K a small coercivity and remanent magnetization develop which increase at lower temperatures to 1.8 kO_e and 0.4 emu/g respectively, at 4.2°K.

To elucidate these findings, we performed Mossbauer measurements on samples taken from the same bulk material used in the neutron and magnetization studies. In this research we collaborated with Dr. D. Forester of the Naval Research Laboratory. Most of the low temperature measurements were taken with the Mossbauer spectrometer and the cryogenic facilities at the Naval Research Laboratory.

Preparation of the sample from the bulk state to the powdered absorber and sealing of it into an air tight holder was done in an argon dry-box to prevent oxidation of the sample. The Mossbauer spectrometers at the American University (A.U.) and the Naval Research Laboratory (N.R.L.) were used in the constant acceleration mode and also in the zero velocity single channel mode for a thermal scan to help in determining the Curie temperature of the system. Mossbauer spectra were taken in the range 4.2K to 300K concentrating in the region below 80K. The work at A.U. was done using a ^{57}Co in chromium source and the liquid helium work at N.R.L. was done using a ^{57}Co in rhodium source controlled at 78K.

Nuclear hyperfine magnetic and quadrupolar interaction data were obtained from the Mossbauer spectra. Fig. II-1 shows representative spectra in the paramagnetic region showing the quadrupolar interaction splitting. This

splitting decreases monotonically from 0.495 ± 0.006 mm/sec at 78°K to 0.449 ± 0.006 mm/sec at 300°K, which is lower than the D_y Fe_2 value of 0.51 mm/sec at 300 °K [3]. Fig. II-2 shows the onset of order and the growth of a hyperfine field as a function of temperature. These spectra display the same overall features as magnetically ordered amorphous rare-earth-Fe_2 alloys [3,4] and are quite similar to amorphous $Fe_{44}Pd_{36}P_{20}$ [5]. The hyperfine structure is seen to collapse smoothly, with no sharp transition indicative of superparamagnetism, into the quadrupolar doublet. The average magnetic hyperfine field, H_{eff} (T), is displayed in fig. II-3, along with an S = 1 Weiss molecular field curve (solid line). H_{eff} (0), i.e. the hyperfine field at saturation, was determined to be 233 ± 6 kO_e. The similarity between the S = 1 Brillouin function and the experimental data is good, but should not be taken to mean much in itself. The saturation hyperfine field $H_{eff}(0)$ in YFe_2 (233 ± 6 kOe) is slightly smaller than the $GdFe_2$ value of 248kOe and very close to the $DyFe_2$ value of 225kOe. Since the magnetic moment is proportional to $H_{eff}(0)$, we conclude that the iron moment in YFe_2 is of the same magnitude as that in other amorphous R-Fe_2 alloys. Previous measurements on amorphous R-Fe_2 alloys have shown that the iron moment is dependent on the value of the de Gennes factor;

$$G = (g - 1)^2 J (J + 1),$$

of the rare-earth. Since the G for YFe_2 is zero this does not follow the general trend of decreasing $H_{eff}(0)$ with decreasing rare-earth moment (G = 15.75 and G = 7.08 for $GdFe_2$ and $DyFe_2$, respectively).

The Curie temperature of YFe_2 was determined to be T_c = 55K ± 5K from the temperature dependence of H_{eff} (T).

We can try to explain our data by using the model proposed by Pickart et al. and Rhyne et al based on short-range order below T_c and spin clustering above T_c. At about 80K we observe a sharply defined quadrupolar splitting with

evidence of short lifetime magnetic inhomogeneities of approximately 7 Å size (7). As the temperature is lowered the size of the scattering regions increases, and they gradually freeze in. Below T_c we consider YFe_2 to be a concentrated spin glass, with no net moment, but a weakly correlated disordered frozen spin system. We picture something like a spiral with a wandering $\vec{q}$ $(\vec{r})$.

REFERENCES

1. S. J. Pickart, J. J. Rhyne, and H. A. Alperin, Phys. Rev. Lett. 33, 424 (1974)

2. J. J. Rhyne, J.H. Schelleng, and N.C. Koon, Phys. Rev. B10, 4672 (1974)

3. D. W. Forester, R. Abbundi, R. Segnan, and D. Sweger, AIP Conf. Proc. 24, 115 (1975).

4. N. Heiman, K. Lee, and R. I. Potter, 1975 Conf. on Mag. and Mag. Mats. (to be published in AIP Conf. Proc., 1976).

5. T. E. Sharon and C. C. Tsuei, Phys. Rev. B5, 1047 (1972).

6. N. Heiman and K. Lee, Phys. Lett. A55, 297 (1975).

7. D. W. Forester, W. P. Pala, and R. Segnan (paper in preparation).

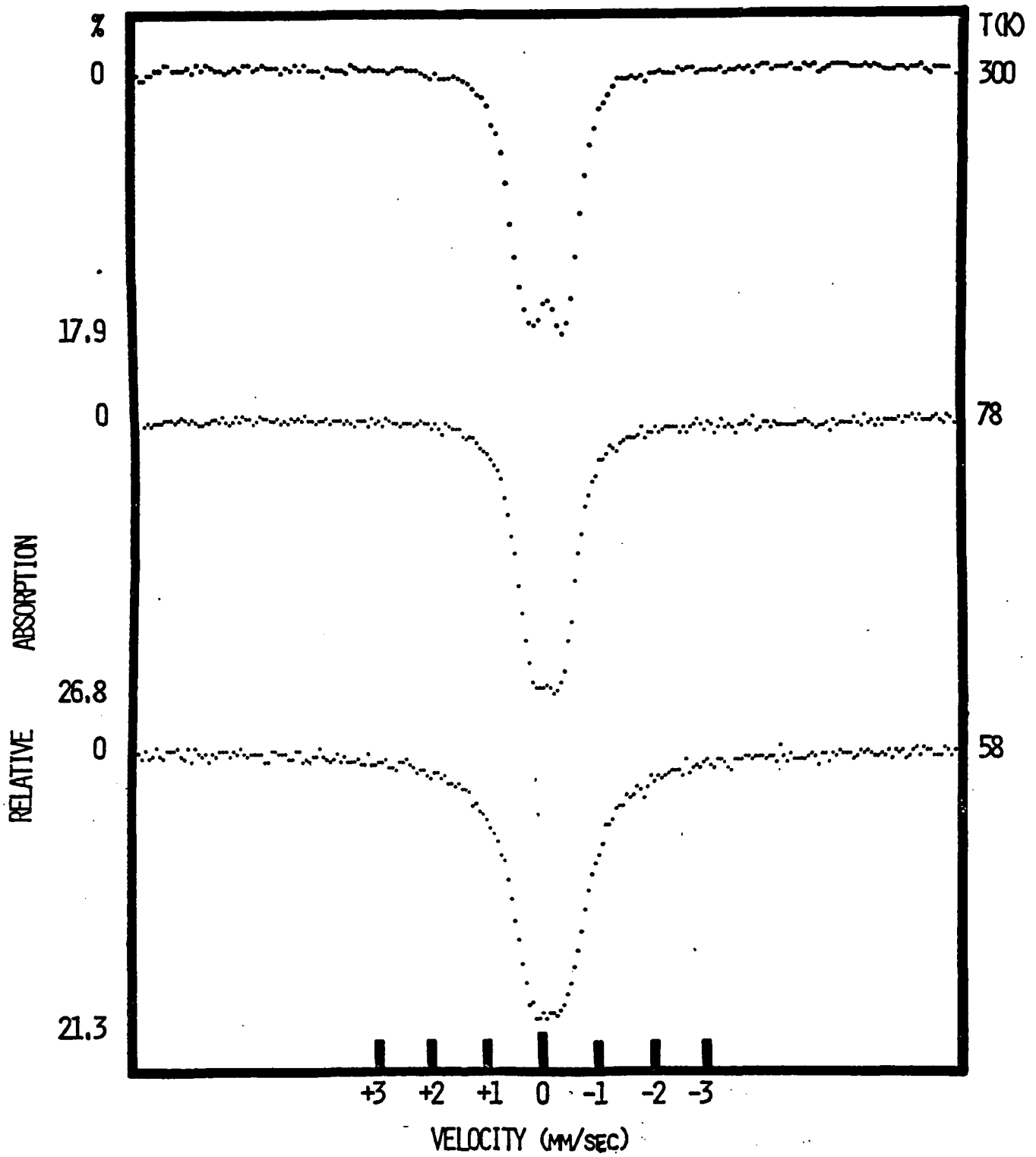


FIG. 1. ^{57}Fe MÖSSBAUER SPECTRA IN AMORPHOUS—YFe_2

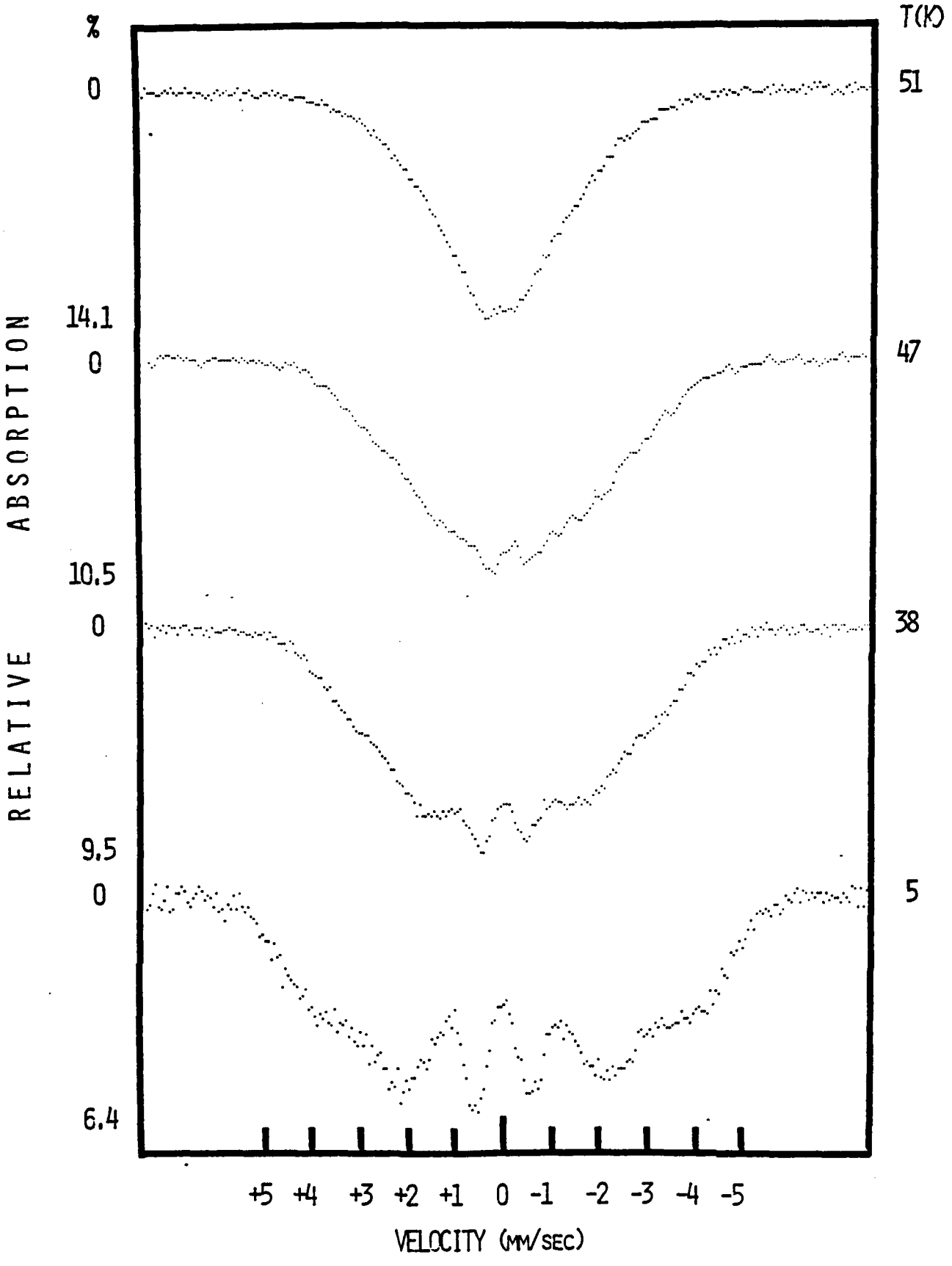


FIG. 2. ^{57}FE MÖSSBAUER SPECTRA IN AMORPHOUS-YFe_2.

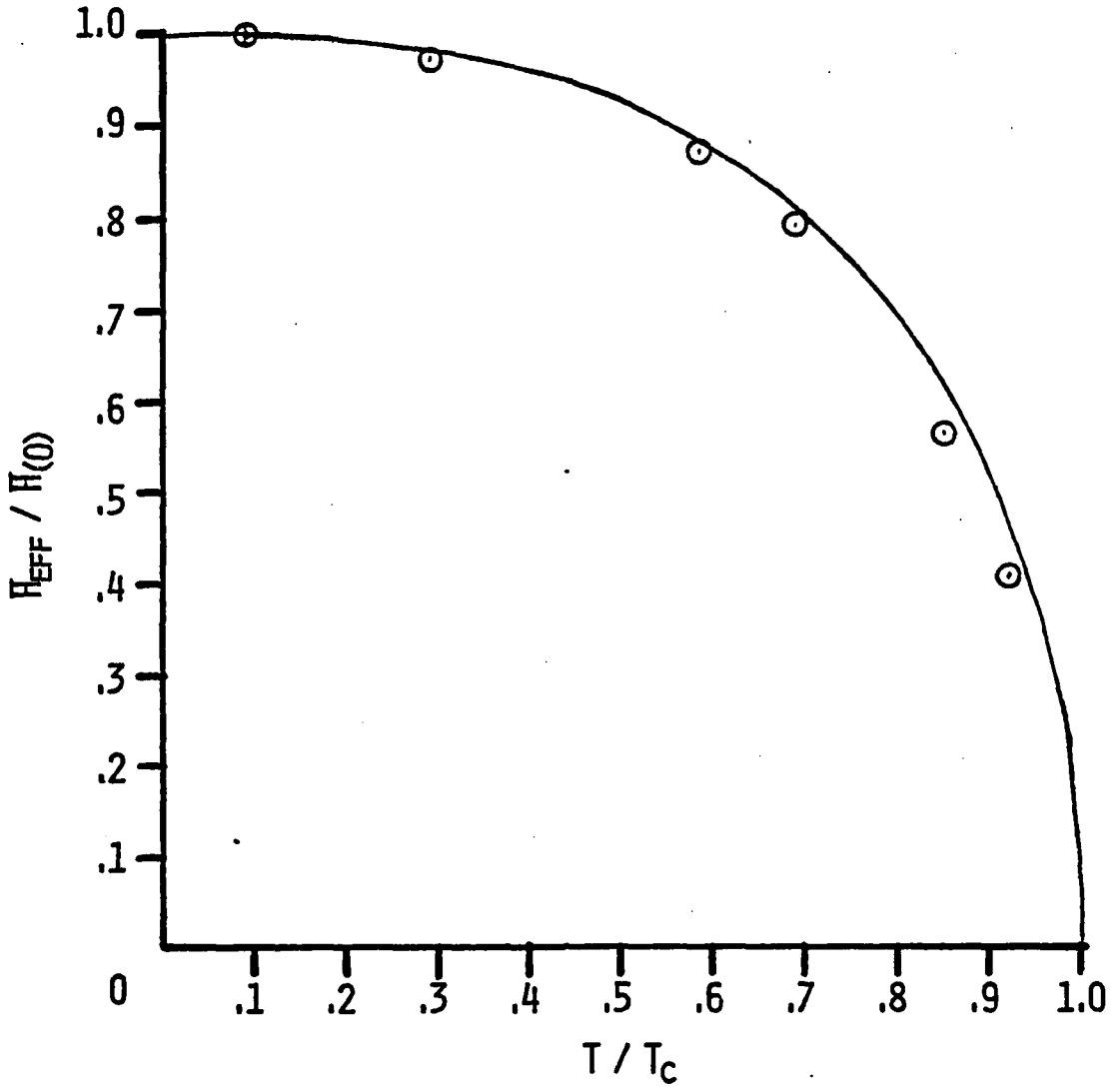
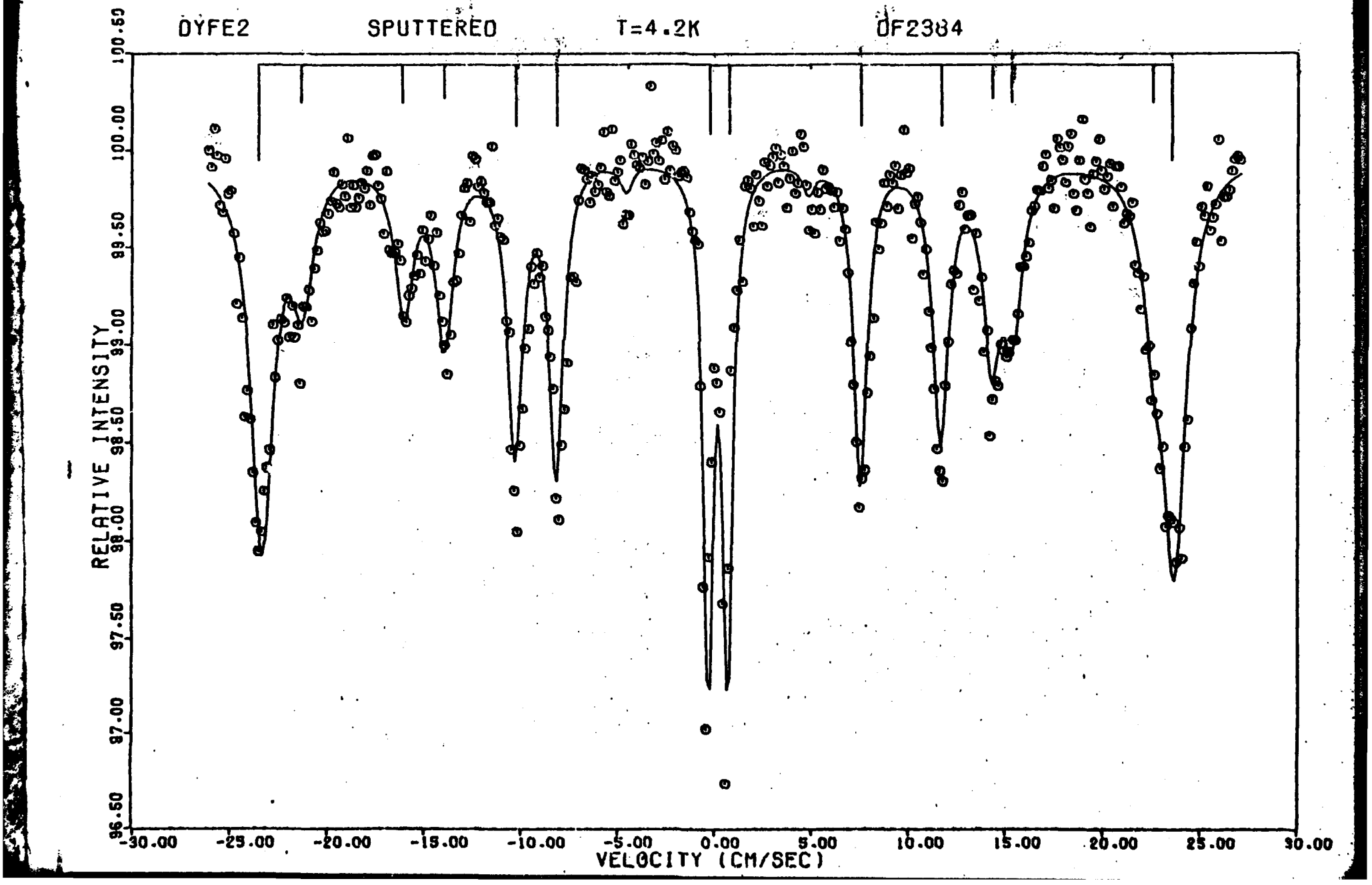


FIG. 3. REDUCED HYPERFINE FIELD V.S. REDUCED TEMPERATURE OF YFe_2 WITH $T_C = 55K$ AND $H(0) = 233$ kOE. THE TEMPERATURE DEPENDENCE OF THE $H_{EFF}(T)$ CLOSELY FOLLOWS A WEISS MOLECULAR FIELD MODEL FOR SPIN $S = 1$ (SOLID LINE).

III. Magnetic Hyperfine Structure in Amorphous $DyFe_2$.

We have completed the study of the magnetic hyperfine interaction in amorphous $DyFe_2$. Previously (see ONR Progress Report, March 1975) we reported our measurements on this alloy below about 150K. In the present phase of the work we completed the measurements between 150K and T_c which for amorphous $DyFe_2$ is 278°K. The Mossbauer spectra were detected both at the ^{57}Fe and ^{161}Dy nuclei. Figs. III-1 to III-6 show the Mossbauer spectra for ^{161}Dy at various temperatures. From these data and those obtained for ^{57}Fe (not shown) we notice some important differences in the temperature dependence of the magnetic hyperfine field, $H_{eff}(T)$, as measured at the dysprosium and the iron sites. The Mossbauer absorption lines at the iron site are quite broad at low temperatures (14K which corresponds to about $T/T_c = 0.05$). As the temperature is increased the lines are substantially unchanged up to about $T/T_c = 0.8$. Above this temperature the Mossbauer pattern collapses into a central doublet which of course becomes well defined at and above T_c. The doublet is due to the quadrupolar interaction. By contrast, the Mossbauer absorption spectra are quite sharp at low temperatures ($T/T_c = 0.01$). As the temperature is increased the Mossbauer spectra gradually broaden (see the data for 4.2°K, 90°K, 149°K). Again above $T/T_c = 0.80$ the Mossbauer pattern collapses into the (complex) set of lines which above T_c correspond to the quadrupolar interaction. We can interpret our data by assuming that at both the iron and dysprosium sites the magnetic hyperfine interaction is nearly constant in magnitude but random in direction. However, because of the gradual broadening of the Mossbauer spectra at the dysprosium site, presumably there is a distribution of local exchanges in magnitude at Dy in addition to their random orientation.


DYFE2
SPUTTERED
T=4.2K
DF2384
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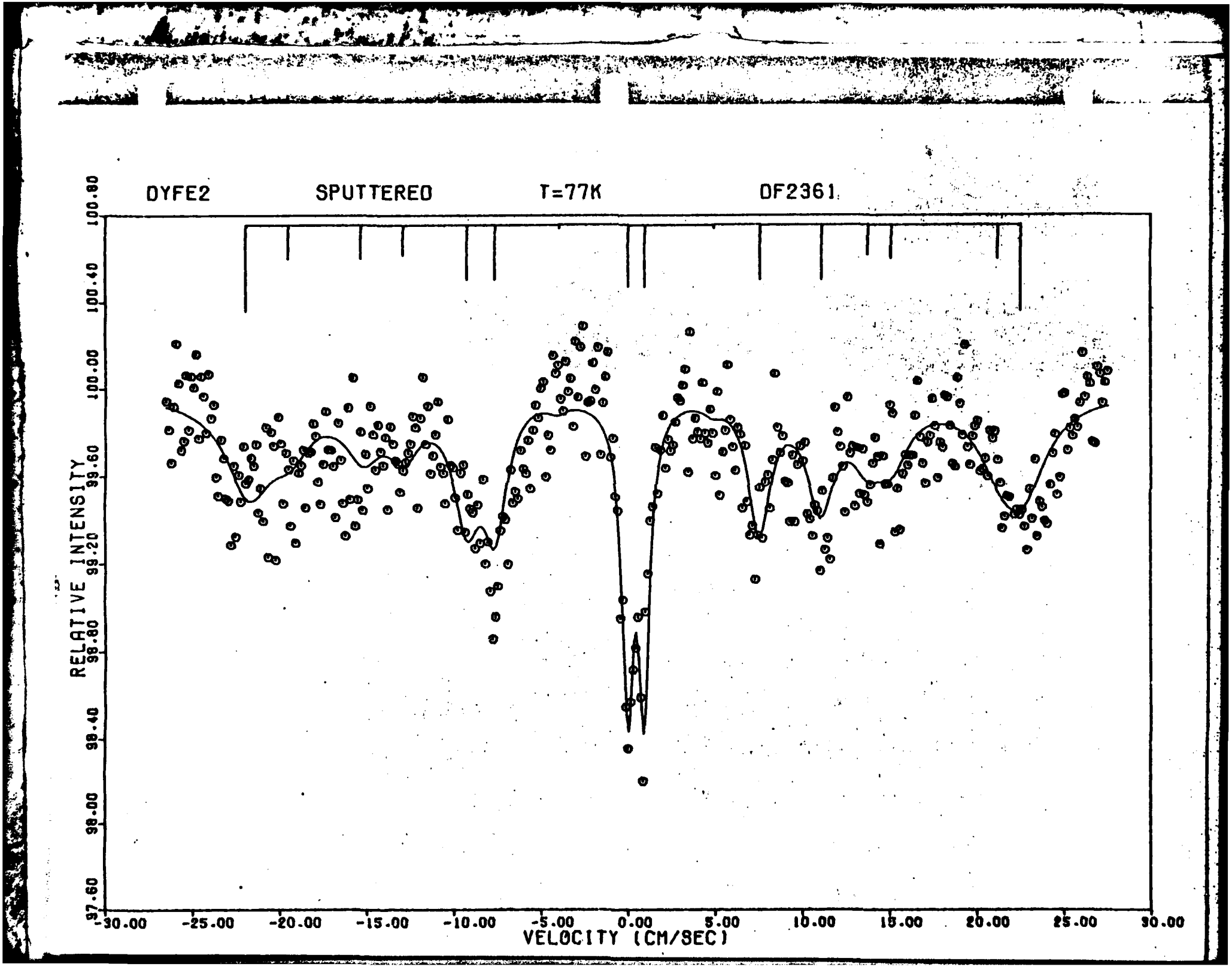
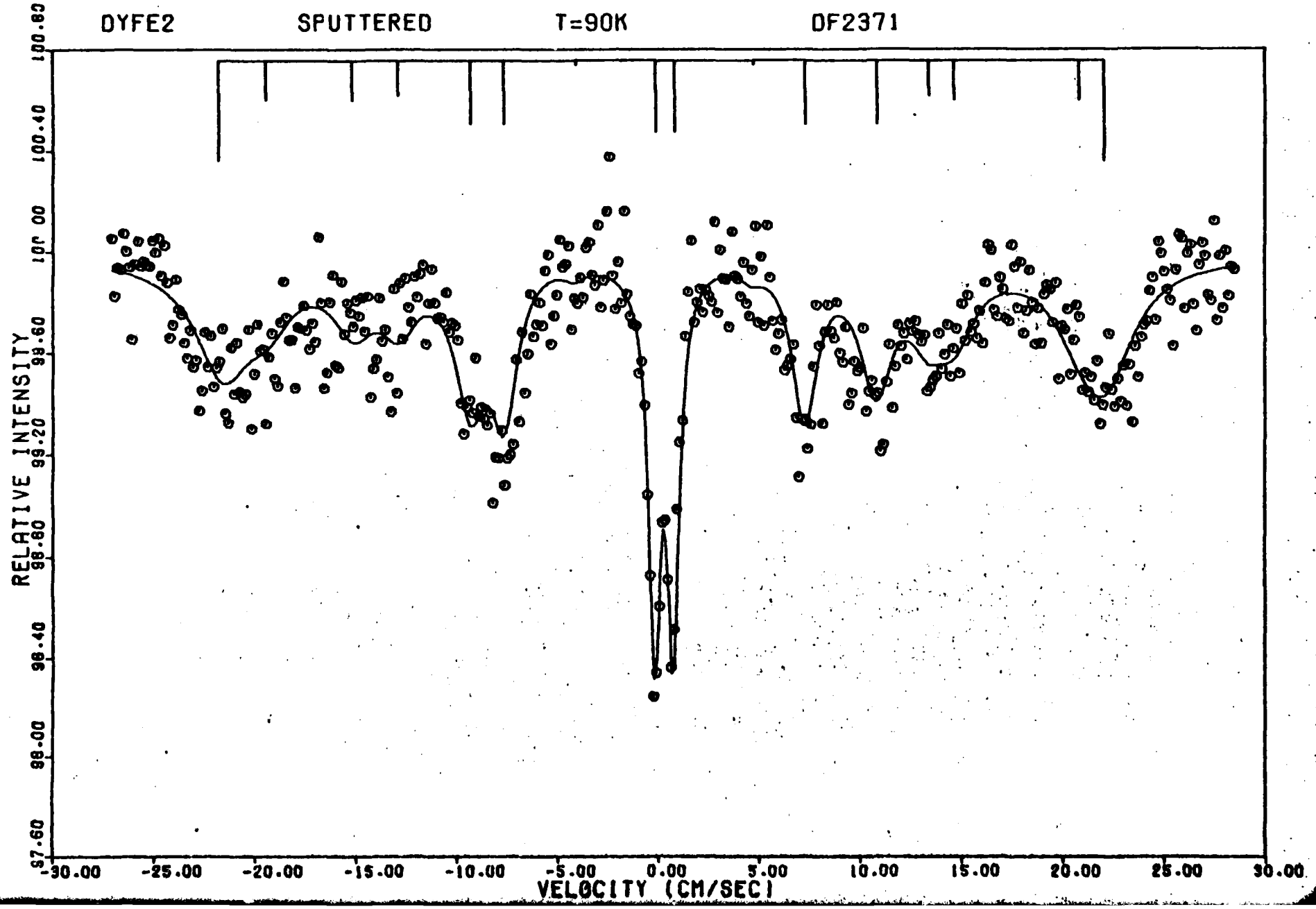
100.50
100.00
99.50
99.00
98.50
98.00
97.50
97.00
96.50
-30.00
-25.00
-20.00
-15.00
-10.00
-5.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
VELOCITY (CM/SEC)


DYFE2
SPUTTERED
T=77K
DF2361
RELATIVE INTENSITY
100.80
100.40
100.00
99.60
99.20
98.80
98.40
98.00
97.60
-30.00
-25.00
-20.00
-15.00
-10.00
-5.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
VELOCITY (CM/SEC)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SPUTTERED
T=90K
DF2371
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100.40
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98.40
98.00
97.60
-30.00
-25.00
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-15.00
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25.00
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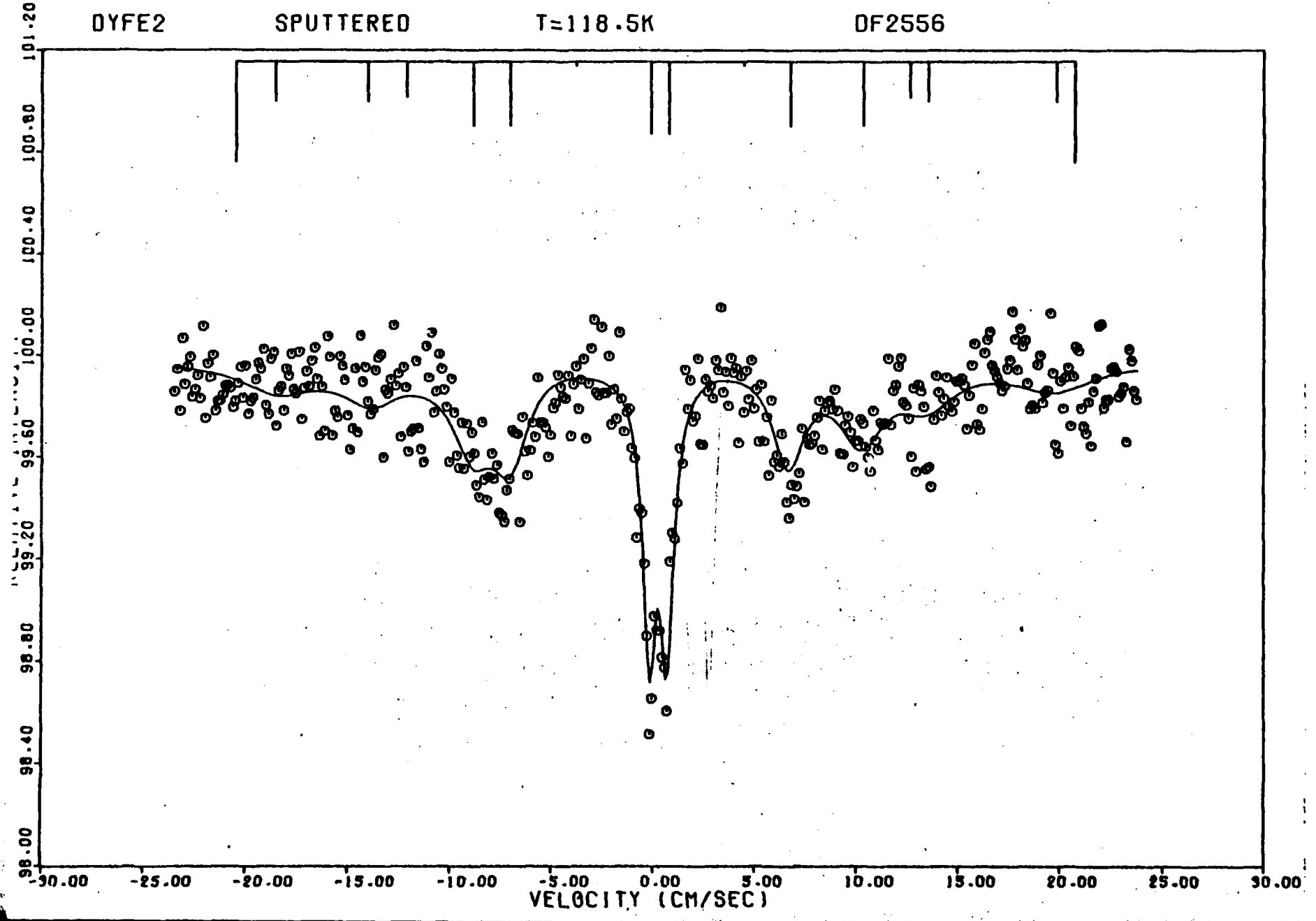
VELOCITY (CM/SEC)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100.40
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99.20
98.80
98.40
98.00
-30.00
-25.00
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-15.00
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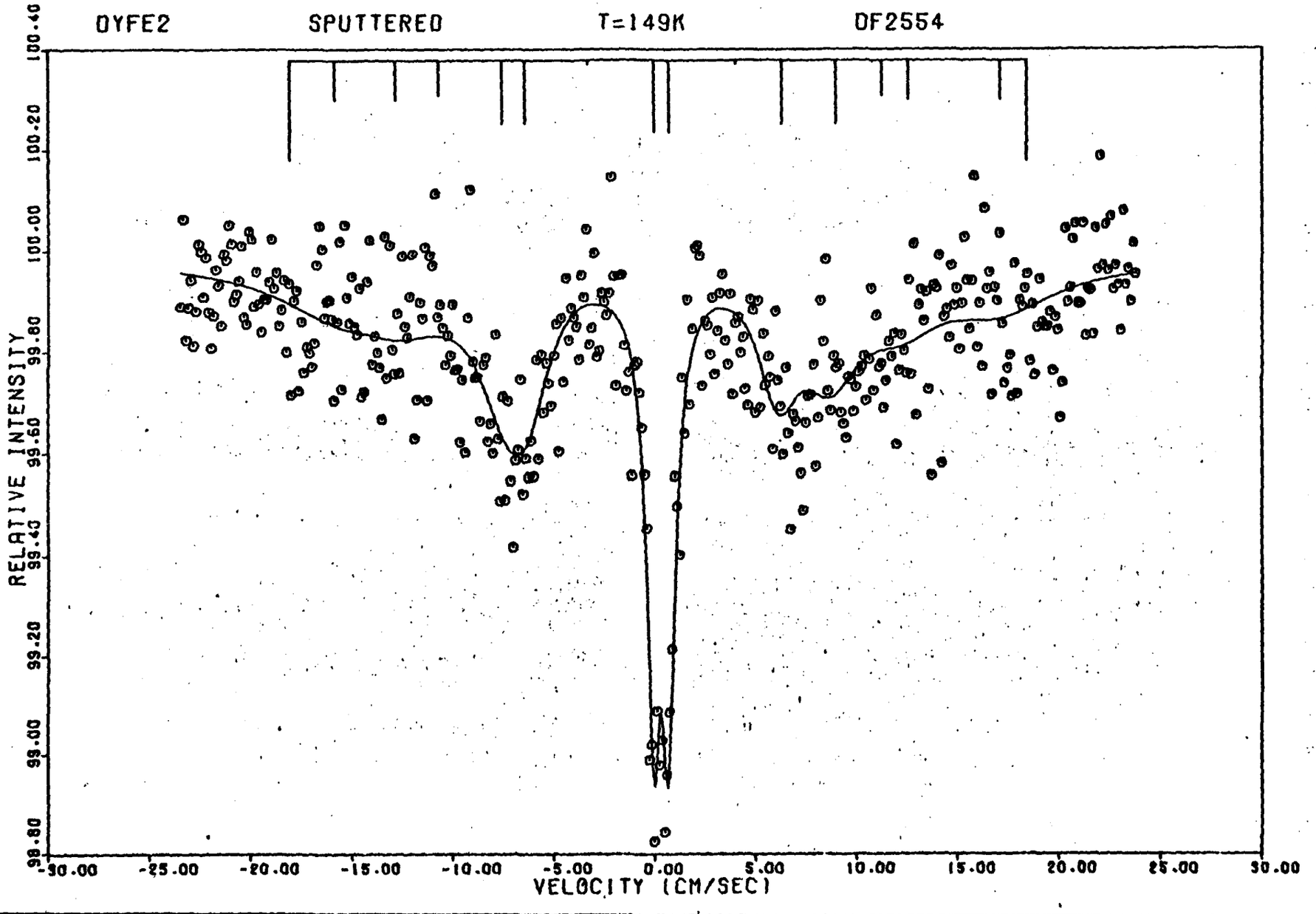
VELOCITY (CM/SEC)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99.00
98.80
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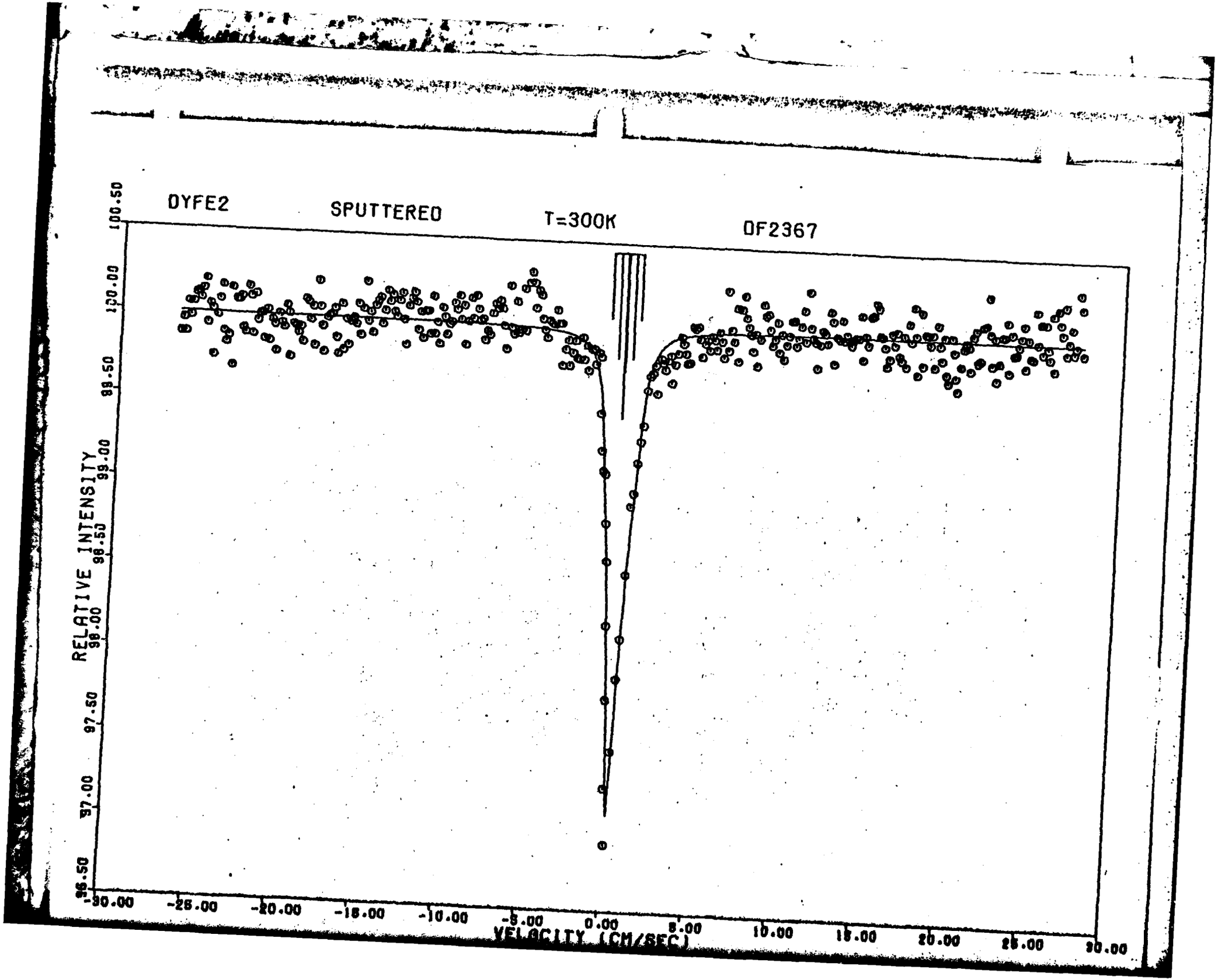
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-10.00
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VELOCITY (CM/SEC)

IV. Clustering in $Tb_x Fe_{1-x}$

The low temperature average moment per ion of amorphous iron is 0.8 μ_B. As Tb is added, the moment drops, going to zero at about x = .16. Upon further substitution the moment rises again, being dominated by the rare earth, which goes in antiparallel to the iron. Curie temperature and hysteresis curves show the Curie temperature to rise rapidly with small additions of Tb, reach a maximum around x = .25 and then fall again. The magnetic transition is well defined near x = .25, but there are tails on the magnetization vs. temperature curves at low and high x. Furthermore, hysteresis curves are clean near x = .25, but there is a lack of saturation and large high field susceptibility at both low and high x, and at high x the Tb moment appears to be reduced from its small x value ($gJ = 9\ \mu_B$).

We feel we understand what is going on [1,2]. In the pure amorphous iron there are both positive and negative exchange interactions, leading to a disordered angled structure with a net average moment of 0.8 μ_B (although the individual iron ion has a moment of about 2 μ_B). As Tb is added, each Tb clothes itself with a cluster of N_c Fe neighbors, each of which aligns antiparallel to the Tb, which is itself antiparallel to the background iron. Let N_F be the number of free background iron ions per unit volume, and N_R be the density of rare earths. The magnetization density is then

$$M = - 0.8\ N_F + (9 - 2\ N_c)\ N_R.$$

Letting V_F be the volume of an iron ion, and

$$V_R \equiv W\ V_F$$

be that of a rare earth, the concentration x is

$$x = \frac{N_R}{\frac{1}{V_F} + N_R\ (1 - W)}$$

and at low concentrations

$$N_R = x/V_F$$

Then at small x

$$\frac{dM}{dx} = \frac{1}{V_F} (9 + 0.8\ W - 1.2\ N_c)$$

From the atomic radii, W = 2.7, and from our experimental data on $\frac{dM}{dx}$ we find that at small x

$$N_c \cong 6.2$$

Each rare earth initially surrounds itself with about 6 aligned irons. As further Tb is added the size of the cluster drops. Clearly at x = .25, there are 3 Fe ions to each Tb, and the average cluster size can be at most 3, and at x = .33 the cluster size is at most 2 (and there are no free irons). We assume that the cluster size drops linearly with x from 6.2 at x = 0 to 3 at x = .25 (this straight line also goes through 2 at x = .33), and we find the compensation composition (that at which $M = 0$) to be that which is experimentally observed.

Since at around x = .25 and x = .33 all the iron is aligned antiparallel to Tb in a colinear structure, we can understand why the magnetization curves show the least high field susceptibility in this composition range. We believe there is also a negative (antiferromagnetic) cluster-cluster interaction, inducing non-alignment of the Tb "sublattice" at higher concentrations. This is why one again finds high field non-saturation and an apparent reduction in Tb moment at large x.

We also calculate the effect of Tb addition on the Curie temperature. At small x we need consider only background-background, and cluster-background interaction constants, λ_{Fe-Fe} and λ_{C-Fe}.

By molecular field theory

$$\frac{dT_c}{dx} = T_c(0)\left[\left(\frac{\mu_c}{\mu_{Fe}}\right)^2\left(\frac{\lambda_{c-Fe}}{\lambda_{Fe-Fe}}\right)^2 - N_c - W\right]$$

Here μ_c is the cluster moment and μ_{Fe} that of the background iron. Substituting and from our measurements of $\frac{dT_c}{dx}$ and of $T_c(0)$ (=200°K), we find

$$\lambda_{c-Fe} \cong 0.8\,\lambda_{Fe-Fe}$$

which seems plausible.

REFERENCES

1. H. Alperin, J. Cullen and A. Clark, 21st Conference on Magnetism and Magnetic Materials, Philadelphia, December 9-12, 1975.

2. H. Alperin, J.R. Cullen, A. Clark and E. Callen, International Conference on Magnetism, Amsterdam, September 1976, paper to appear.

V. Magnetoelastic Surface Wave Propagation

Surface acoustic wave devices have a number of useful features - ease of excitation and detection for instance.

Magnetoelastic surface wave devices have even more attractive aspects. They can be tuned with a magnetic field, and because the magnetization is a pseudovector, they are non reciprocal devices. They have been proposed for isolators, and for variable delay lines. Magnetoelastic surface waves have been observed in YIG [1] and their properties carefully analyzed [2].

YIG has many advantages. It is an insulator, so there are no eddy current losses. It is ionically very well ordered - the right ions are on the right sites - so the exchange fields are sharply defined, and the Landau-Lifshitz magnetic damping losses are small. In fact, in resonance applications the line width is limited by the smoothness of the polished surface rather than by intrinsic losses. Nevertheless, YIG has some disadvantages too. The magnetostriction of YIG is small, and so the insertion losses are high (greater than 60 db) because magnetoelastic waves are not strongly excited.

The materials we study, $Tb_{.27}Dy_{.73}Fe_2$ for example, has a magnetostriction of 1500 ppm at room temperature, 100 times that of YIG, and a coupling constant of 0.6. And so one expects far smaller insertion losses using RFe_2 compounds than with YIG. But the RFe_2 compounds are conductors, and they are magnetically less tidy than YIG. Hence we have have studied the effects of finite conductivity and of Landau-Lifshitz damping on magnetoelastic Rayleigh-type surface waves [3,4].

The external field is assumed parallel to the surface, and we study propagation along the field direction. There are seven modes (2 "electromagnetic", 3 "acoustic" and 2 "magnetic", clockwise and anticlockwise). The seven normal modes, combinations of the above, with complex propagation

vector can be found, in general only by machine diagonalization, and with appropriate boundary conditions. The coupling between the helicon-like electromagnetic mode and one of the shear modes is strong near the resonance frequency $\omega_o = \gamma H_o$. Eddy current losses are increased near ω_o by the coupling with the magnetic system, and are disadvantageously large here. But near ω_o the effect of the external field on propagation properties-frequency, velocity, attenuation - is large. The device is highly tuneable. At frequencies an order of magnitude below ω_o the tuneability is low, which could be useful where stability is desired rather than tuneability. And at these lower frequencies the eddy current losses and magnetic losses are not large. In contrast, in YIG the tuneability is practically independent of frequency.

REFERENCES

1. F.W. Voltmer, R.M. White, and C.W. Turner, Appl. Phys. Lett. 15, 153 (1969).

2. J.P. Parekh and H.L. Bertoni, J. Appl. Phys. 45, 434 (1974).

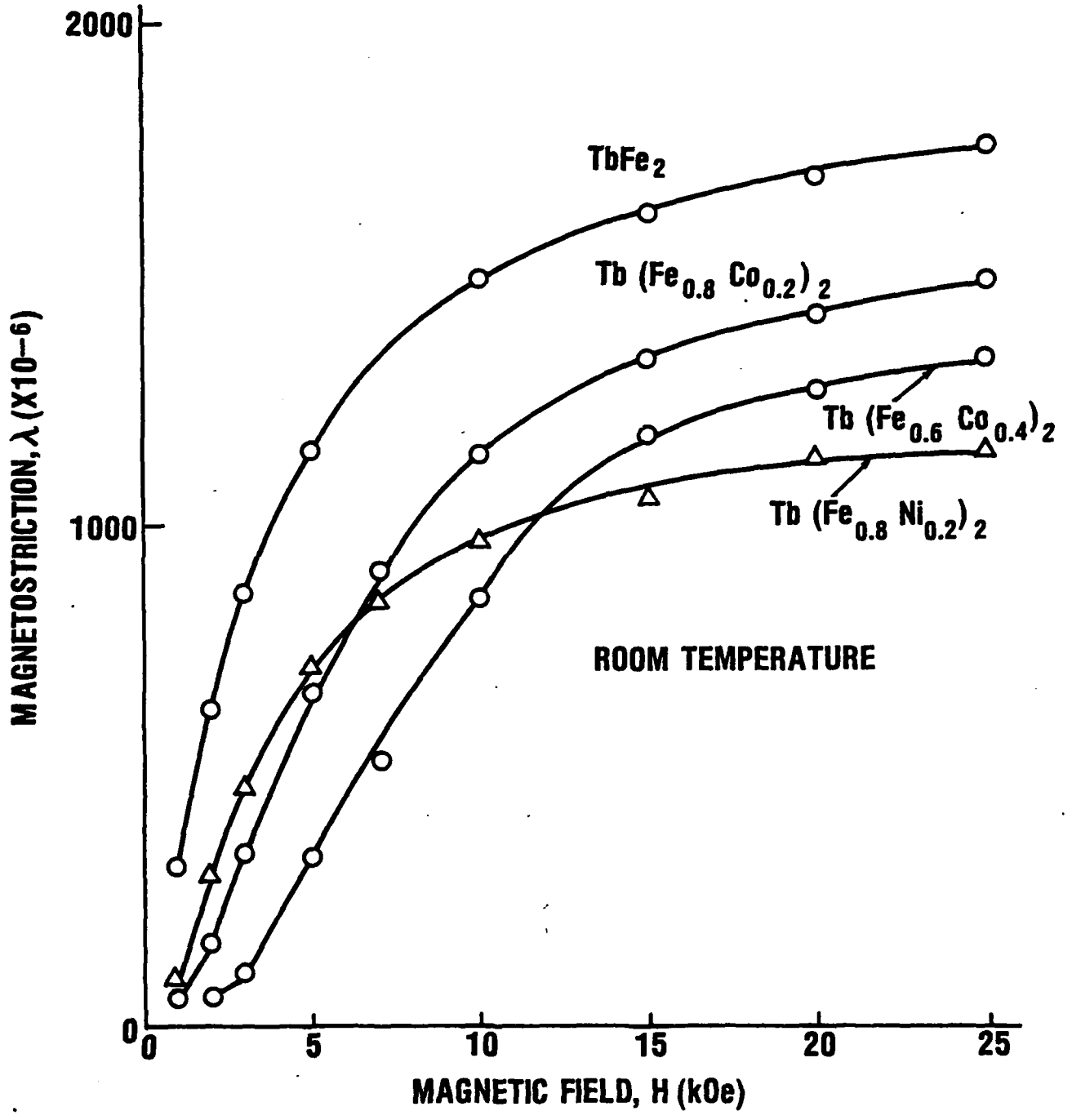
3. Y.J. Liu, H.T. Savage, J.R. Cullen, A.E. Clark and E. Callen, International Magnetism Conference, Pittsburgh, June 1976.

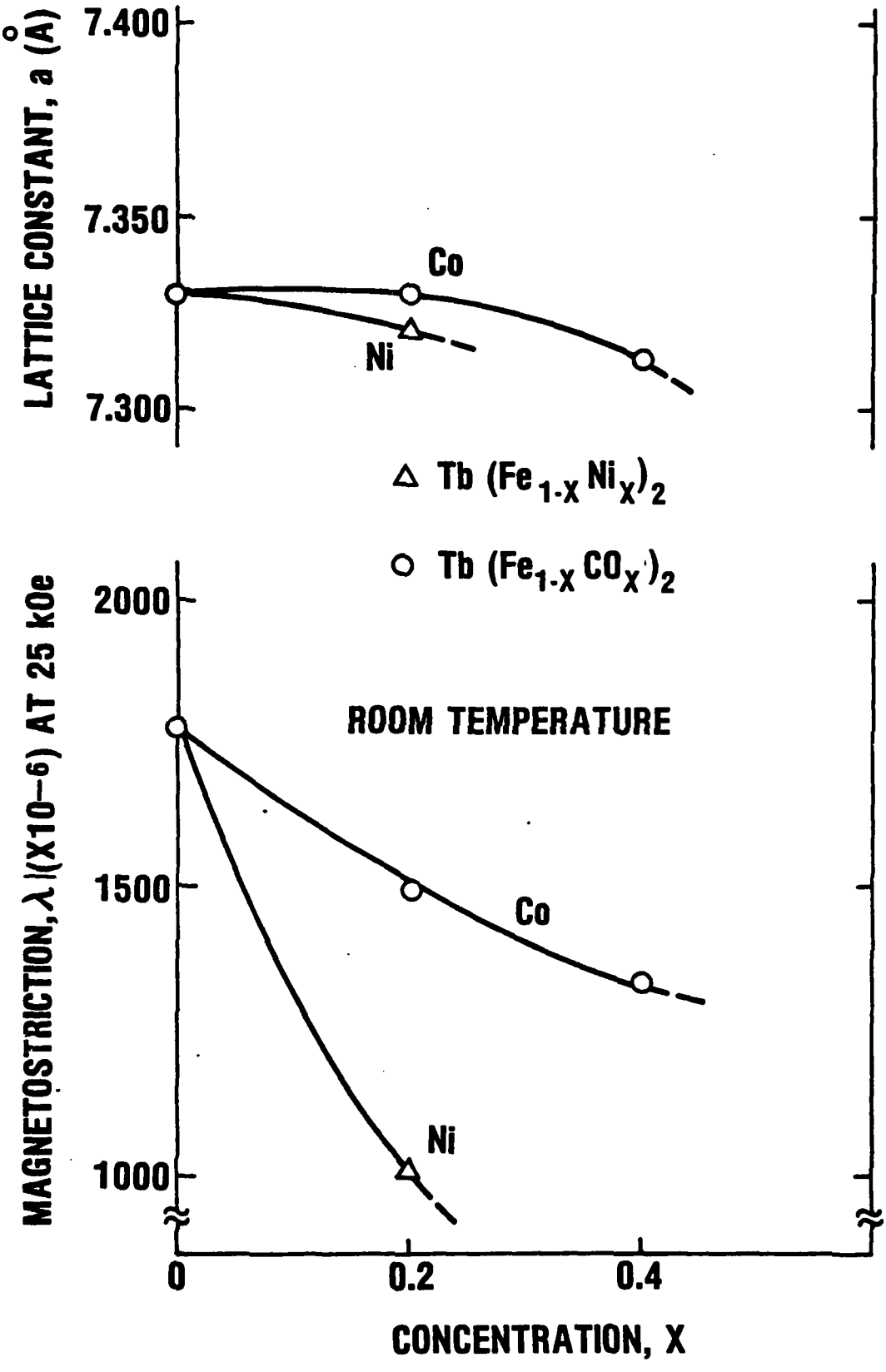
4. Y.J. Liu and H.T. Savage, International Conference on Magnetism Amsterdam, September 1976.

VI. Magnetic Properties of Tb $(Fe\text{-}Co)_2$ and Tb $(Fe\text{-}Ni)_2$ Alloys

For magnetostrictive transducer applications the important factors are a large magnetostriction λ_s and a small anisotropy energy. Therefore we are interested in finding materials with simultaneously large magnetostriction and small anisotropy. Among the materials with large magnetostriction, the system with the largest room temperature λ_s discovered so far is $TbFe_2$. On the other hand, the Fe-Co alloy series has small anisotropy energies ($Fe_{0.6}\ Co_{0.4}$ has almost zero anisotropy). In an attempt to maximize λ_s and minimize the anisotropy, we performed measurements on a series of both Tb $(Fe\text{-}Co)_2$ and Tb $(Fe\text{-}Ni)_2$ alloys.

We prepared the polycrystalline samples by mixing appropriate quantities of (Fe-Cc) and (Fe-Ni) in Tb and melted buttons in an argon atmosphere. We used high purity Tb (99.3%), Fe (99.99%), Ni (99.99%) and Co (99.99%). We made the following alloys: $(Fe_{0.8}\ Co_{0.2})\ Tb_2$, $(Fe_{0.6}\ Co_{0.4})\ Tb_2$, and $(Fe_{0.8}\ Ni_{0.2})\ Tb_2$. On these samples we measured the magnetostriction as a function of magnetic field strength, at room temperature. Fig. VI-1 shows the magnetic field dependence of the magnetostriction at room temperature. In Fig. VI-2 are shown the lattice constants for the three alloys and the concentration dependence of the magnetostriction at room temperature. We conclude that it is disadvantageous, from the viewpoint of the magnetostriction alone, to substitute Ni or Co for Fe. Whether the reduction in λ_s will be more than compensated by a reduction in anisotropy, leading to an improved figure of merit as a transducer material, will be known only after anisotropy measurements are performed. We do not have single crystals of these materials.


2000
1000
0
0
5
10
15
20
25
MAGNETOSTRICTION, λ (X10−6)
MAGNETIC FIELD, H (kOe)
TbFe2
Tb (Fe0.8 Co0.2)2
Tb (Fe0.6 Co0.4)2
Tb (Fe0.8 Ni0.2)2
ROOM TEMPERATURE


LATTICE CONSTANT, a (Å)
7.400
7.350
7.300
Co
Ni
△ Tb (Fe1-X NiX)2
○ Tb (Fe1-X COX)2
MAGNETOSTRICTION, λ ‖(X10−6) AT 25 kOe
2000
1500
1000
ROOM TEMPERATURE
Co
Ni
0
0.2
0.4
CONCENTRATION, X

Publications Supported
by ONR Contract

I. Publications in
1975 - 1976

1) W. P. Pala, D.W. Forester and R. Segnan, Magnetic Order, Cluster Phenomena and Hyperfine Structure in Amorphous YFe_2, talk at Intermag. Conf., Pittsburgh, June 1976 and paper (to appear).

2) D.W. Forester, W.P. Pala and R. Segnan, Localized Moment and Spin-Glass like Behavior in Amorphous YFe_2, Second International Symposium on Amorphous Magnetism, Troy, N.Y., August 1976.

3) H.T. Savage and W.A. Ferrando, Magnetomechanical Coupling, ΔE Effect and Magnetization in Rare Earth-Iron Alloys. Magnetostrictive Materials Workshop, Orlando, Florida, February 1976.

4) R. Abbundi, R. Segnan, J.J. Rhyne and D.M. Sweger, Hyperfine Fields in the Absence of Magnetic Order in Dy-Sc Alloys, 21st Conf. on Magnetism, Philadelphia, December 1975; AIP Conf. Proc. 29, 352.

5) A.E. Clark, J.R. Cullen, O.D. McMasters and E.R. Callen, Rhombohedral Distortion in Higly Magnetostrictive Laves Phase Compounds, 21st Conf. on Magnetism, Philadelphia, Dec. 1975; AIP Conf.Proc. 29, 192.

6. YJ. Liu, H.T. Savage, J.R. Cullen, A.E. Clark and E. Callen; Effect of Conductivity on Magnetoelastic Surface Wave Propagation, Conf. on Magnetism and Magnetic Materials, Intermag., Pittsburgh, June 1976.

7. YJ. Liu and H.T. Savage, Magnetoelastic Surface Wave Attenuation in Ferromagnetic Conductors, International Conf. on Magnetism, Amsterdam, Sept. 1976.

8. Magnetic Properties of Bulk Amorphous Tb_xFe_{1-x}, H. Alperin, J.R. Cullen, A. Clark and E. Callen, International Conf. on Magnetism, Amsterdam, Sept. 1976.

II. Publications from Inception of Contract to 1975

1) A.E. Clark, H.S. Belson, and N. Tamagawa, Huge Magnetocrystalline Anisotropy in Cubic Rare Earth-Fe_2 Compounds, Physics Lett., 160 (1972).

2) A.E. Clark, H.S. Belson, and N. Tamagawa, Magnetocrystalline Anisotropy in Cubic Rare Earth-Fe_2 Compounds, AIP Conference Proceedings No. 10, 749 (1972).

3) A.E. Clark and H.S. Belson, Magnetostriction of Terbium-Iron and Erbium-Iron Alloys. IEEE Trans on Magnetics, MAG-8, 477 (1972).

4) A.E. Clark and H.S. Belson, Giant Room Temperature Magnetostriction in $TbFe_2$ and $DyFe_2$, Phys. Rev. B, 5, 3642 (1972).

5) J.J. Rhyne, S.J. Pickart and H.A. Alperin, Direct Observation of an Amorphous Spin-Polarization Distribution, Phys. Rev. 29, 1562 (1972)

6) A.E. Clark, N. Tamagawa, H. Belson and E. Callen, Magnetic Properties of Rfe_2 Compounds, Proc. Int'l. Conf. on Magnetism, Moscow, August 22-28, (1973).

7) A.E. Clark, High-Field Magnetization and Coercivity of Amorphous Rare Earth-Fe_2 Alloys. Appl. Phys. Lett., 23, 642 (1973).

8) D.C. Shapero, J.R. Cullen and E. Callen, A Calculation of the Susceptibility near the Onset of Order in an Amorphous Ferromagnet Phys. Lett. 50 A, 303 (1974).

9) D. Sarkar, R. Segnan, E.K. Cornell, E. Callen, R. Harris, M. Plischke and M.J. Zuckerman, Crystal Fields in Amorphous Rare-Earth-Iron Alloys Phys, Rev. Lett. 32, 542 (1974)

10) H.T. Savage, A.E. Clark, S.J. Pickart, J.J. Rhyne, and H.A. Alperin, Effects of Annealing on the Coercivity of Amorphous $TbFe_2$, IEEE Trans, on Magnetics, MAG-10 (1974).

11) A.E. Clark, Magnetic and Magnetoclastic Properties of Highly Magnetostrictive Rare Earth Iron Laves Phase Compounds, AIP Conference Proceedings, No. 18, 1015 (1974).

12) D. Sarkar, R. Segnan, and A.E. Clark, Mossbauer Effect Studies in Amorphous $TbFe_2$, $DyFe_2$, $HoFe_2$ and $ErFe_2$, AIP Conference Proceedings No. 18, 636 (1974).

13) H.T. Savage, A.E. Clark and J.M. Powers, Magnetomechanical Coupling and ΔE Effect in Highly Magnetostrictive Rare Earth-Fe_2 Compounds, Intermay Conference, London (1975).

14) A.E. Clark, J.R. Cullen and K. Sato, Magnetostriction of Single Crystal and Polycrystal Rare Earth-Fe_2 Compounds, AIP Conference Proceedings No. 24 (1975).

15) D. Forester, R. Abbundi, and R. Segnan, Magnetic Hyperfine Structure in Amorphous $DyFe_2$, AIP Conference Proceedings, No. 24 (1975).