

Nuclear Magnetic Resonance Study
of the Crystalline Compounds of the NbBe_x System

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Abstract

Nuclear magnetic resonance techniques have been employed to study powder samples of the compounds NbBe_2 , NbBe_3 , $\text{Nb}_2\text{Be}_{17}$, and NbBe_{12} . The nuclear quadrupole coupling constants and Knight shifts have been determined for the Nb sites in these compounds. The ^{93}Nb NMR from NbBe_2 is a single unsplit line with no quadrupole coupling constant and with a Knight shift of $0.70 \pm .03\%$. The ^{93}Nb NMR from NbBe_3 indicates the presence of three Nb sites identified by the values of $eqQ/h = 0 \text{ MHz}$, $24.2 \pm 0.2 \text{ MHz}$, $30.1 \pm 0.3 \text{ MHz}$ and corresponding Knight shifts of $0.693 \pm 0.03\%$, $0.724 \pm 0.03\%$, $0.532 \pm 0.03\%$. The first of these lines is identified as less than 2% impurity of NbBe_2 . The ^{93}Nb NMR of $\text{Nb}_2\text{Be}_{17}$ exhibits a quadrupole coupling, $eqQ/h = 5.93 \pm 0.15 \text{ MHz}$, and an anisotropic Knight shift, $K_{\text{axial}} = 0.014\%$ and $K_{\text{isotropic}} = 0.34 \pm 0.02\%$. The ^{93}Nb resonance from NbBe_{12} was split by a very large quadrupole interaction yielding $eqQ/h = 21.73 \pm 0.3 \text{ MHz}$ with a Knight shift of $0.552 \pm 0.02\%$. The beryllium NMR was examined yielding little information since no measurable quadrupole interaction or Knight shift were present. This study illustrates the variety of environments of the niobium nuclei among these beryllides and within a single beryllide. The NMR results are discussed in relation to the results of x-ray studies of these compounds.

INTRODUCTION

The intermetallic compounds of the system, NbBe_x are of interest because these materials are observed to have high strength, strength retention at elevated temperatures and thermal-shock resistance.¹ These refractory compounds also possess high melting points, low specific gravity and show good oxidation resistance.² The limiting use temperature of beryllides appears to be about 3000 F. The compounds investigated were $\text{NbBe}_{1/2}$, $\text{NbBe}_{1/3}$, $\text{Nb}_{2/3}\text{Be}_{1/3}$ and $\text{NbBe}_{1/2}$, all of which were so kindly supplied in the form of powders by the Brush Beryllium Company, Cleveland, Ohio. X-ray analysis has been performed³⁻⁵ prior to our experiments and the results are given in Table 1.

The work reported here illustrates the usefulness of nuclear magnetic resonance in the investigation of bonding configuration, crystalline structure and electron-nuclear interaction in these intermetallic compounds. The Nb nucleus is highly appropriate as a probe in such a study for it has a large nuclear electric quadrupole moment which will interact with an electric field gradient at the Nb sites. In these compounds the quadrupole interaction manifests itself as a perturbation on the nuclear magnetic energy levels resulting in characteristic splittings and broadening of the nuclear magnetic resonance (NMR) spectrum of Nb nuclei.⁶ An analysis of the quadrupole perturbation to the NMR provides information concerning the charge distribution in the compound. The presence of an electric field gradient at the site of a nucleus of spin I of half integer will produce pairs of satellite lines about $\frac{1}{2} \nu_0$ the Larmor frequency, for the nucleus in an external magnetic field H_0 . The separation between the pairs of $m \leftrightarrow m-1$ and $-(m-1) \leftrightarrow -m$ satellite transitions for a powder sample to third order perturbation are given by,

$$\Delta\nu = (m - 1/2) 3e^2qQ/2I(2I - 1) h, \quad (1)$$

where m is the magnetic quantum number, eq is the component in the principle

axis system of the electric field gradient tensor which is largest in magnitude, eQ is the nuclear quadrupole moment and e^2qQ/h is specified as the quadrupole coupling constant. In the case of ^{93}Nb nucleus with a spin $I=9/2$, four pairs of satellites would be expected, corresponding to the transitions $(\pm 9/2 \leftrightarrow \pm 7/2)$, $(\pm 7/2 \leftrightarrow \pm 5/2)$, $(\pm 5/2 \leftrightarrow \pm 3/2)$, $(\pm 3/2 \leftrightarrow \pm 1/2)$. The approximate relative intensity⁷ of the $m \leftrightarrow m-1$ transition is given by $I(I+1) - m(m-1)$. If the quadrupole interaction is sufficiently large, the central $(1/2 \leftrightarrow -1/2)$ transition will be altered, producing an asymmetrical NMR line close to ν_0 which can be characterized by a separation of the positive and negative peaks of the first derivative of the resonance line given by,⁶

$$\Delta\nu_{-p-p_0} = \frac{25}{16} \left(\frac{e^2qQ}{h} \right)^2 \frac{[I(I+1) - 3/4]}{[2I(2I-1)]^2} \frac{1}{\nu_0} \quad (2)$$

The above expression is correct to fourth order in a perturbation calculation. In Eqs. 1 and 2 the asymmetry parameter⁶ (η) for the field gradient has been taken as zero. From either expression (Eqs. 1 or 2) it is possible to determine the quadrupole coupling constants for nuclei in their different crystallographic positions.

Conduction electrons, since they have magnetic moments, may couple with the nuclear magnetic moments producing a shift to higher frequency of the NMR in an electronic conductor compared to the resonance of the same nuclei in a salt.⁸ The unshifted resonance which had occurred at the Larmor frequency ν_A now has a resonance at ν_0 where

$$\nu_0 = \nu_A (1 + K_{iso}) \quad (3)$$

and K_{iso} is defined as the isotropic Knight shift. If the Knight shift of a second order quadrupole split central transition is being measured, the center of the split $(1/2 \leftrightarrow -1/2)$ transition is not midway between the peaks, but rather a distance A from the low field peak where, $A = 9/25$ (separation between

the peaks). Because of the similarity in the NMR of the ^9Be nucleus in the NbBe_x compounds and because of the lack of any quadrupole perturbation or Knight shift, little useful information was obtained from the ^9Be resonances. The ^{93}Nb nucleus, however, exhibits a vastly different NMR for each compound with varying quadrupole interactions and Knight shifts. The ^{93}Nb NMR results for each compound are described separately in the following paragraphs.

$\text{NbBe}_{1/2}$

The NMR spectrum of $\text{NbBe}_{1/2}$ was obtained at room temperature with a Varian spectrometer (Model V-4210A). Resonances (shown in Fig. 1) of the niobium nuclei were obtained at frequencies ranging from 6 MHz to 14 MHz. Analysis of the resonance spectra shows no satellite lines and that the peak to peak separation of the central transition is independent of the resonance frequency, indicating the absence of any nuclear quadrupole interaction. An intensity measurement was performed, comparing this signal with the spectrum from $\text{Nb}_2\text{Be}_{17}$ in which the individual satellite lines are readily identified (this $\text{Nb}_2\text{Be}_{17}$ spectrum will be discussed later). This comparison of integrated intensity of the resonance lines took into account the known number of nuclei present in both samples and indicated that all of the satellite transitions were present within the unsplit central transition from $\text{NbBe}_{1/2}$. If the satellites were not present, the signal intensity would have been reduced by a factor⁷ of (95/25). The absence of a nuclear quadrupole coupling interaction is consistent with the x-ray analysis of $\text{NbBe}_{1/2}$, which indicates that it has a fcc structure³ the symmetry of which would result in a vanishing electric field gradient at the niobium sites.

The width of this single resonance line is $7.6 \pm 0.5\text{G}$, and it is presumably due to the magnetic dipole-dipole interaction between the niobium nuclei and their neighbors;³ 12 Be atoms at 2.71 \AA and 4 Nb atoms at 2.83 \AA . The center of this resonance exhibits a Knight shift of $0.70\% \pm 0.03\%$ at room temperature

(measured using ^{79}Br NMR in KBr as a reference). This relatively large Knight shift is comparable to that of pure niobium metal, $^{9/}$ 0.82%. These similar shifts suggest that the bonding in $\text{NbBe}_{2/2}$ is highly metallic. In making the Knight shift measurements samples of $\text{NbBe}_{2/2}$ and KBr were simultaneously placed in the rf coil.

$\text{NbBe}_{3/3}$

The NMR spectrum of the niobium nuclei in $\text{NbBe}_{3/3}$ was investigated under experimental conditions similar to those employed with the $\text{NbBe}_{2/2}$ sample. The spectrum obtained is much more complex than that from $\text{NbBe}_{2/2}$. The many resonances that appeared (Fig. 2) had to be studied as a function of resonance frequency in order to properly categorize and identify them. As a result of this frequency analysis, it appears that there are three different niobium crystalline positions present in the sample yielding three separate families of lines. This result is supported in the following discussion. Line A in Fig. 2 is an unsplit central ($1/2 \leftrightarrow -1/2$) transition, while lines B and C are central transitions that are highly split by an electric quadrupole interaction. Since $\text{NbBe}_{3/3}$ should have only two distinct crystalline sites,³ one of the resonances is most likely due to an impurity. The analysis of these resonances was carried out by plotting the peak to peak separation of the derivative of each resonance versus $1/\nu$. The results are shown in Fig. 3. The spectra used in the plot were only those taken at higher frequencies, 12 MHz to 15 MHz. These data were employed because the extremely large splittings and the presence of some random broadening in the lines resulted in a decrease of the resolution of the spectrum at the lower frequencies. From Fig. 3 it is evident that a straight line relationship can be drawn through the data points. The slope of such a line will then yield the quadrupole coupling constant, e^2qQ/h . The average values of the quadrupole coupling constants obtained from such a plot are given in Table 2.

Analysis of line A reveals that the width is independent of the resonance frequency, to within the uncertainty in the measurements. Thus, the niobium nuclei which are contributing to this line must be in a highly symmetric environment. In Fig. 2, the sets of lines denoted by B' and C' are identified as the first order split ($\pm 3/2 \leftrightarrow \pm 1/2$) transitions of the lines B and C, respectively. The separations of the lines are a constant, within the uncertainty of measurement. The coupling constants for line B' and C' derived from first order perturbation theory yield the values given in Table 2. By comparing the coupling constants in Table 2 obtained from the second order perturbed central ($1/2 \leftrightarrow -1/2$) transitions with these obtained from the separation of the first order satellite lines (B' , C'), it is evident that there is good agreement between the values of the quadrupole coupling constants obtained in these two different manners. Since both methods give essentially the same results, third order effects are still too small to be observed at these resonance frequencies.

The centers of lines A, B, and C were found to exhibit Knight shifts, and the measured values of the Knight shifts, utilizing the positions of the central transitions, are found in Table 2. The shifts were measured using ^{79}Br NMR in KBr as a reference marker.

Line A in Fig. 2 appears to be the result of a contamination of $\text{NbBe}_{3/3}$ by a small amount of $\text{NbBe}_{2/2}$. This is substantiated by comparing the value of the quadrupole coupling constant, NMR line width, and the Knight shift of line A, with the corresponding values for NbBe_2 . The coupling constants are zero in both cases, and both Knight shifts are the same within the limits of error. In comparing the line widths, line A in Fig. 1 is found to have a width of 16G, which is of course, larger than that of niobium in NbBe_2 . However, this is due to overmodulation by a field modulation of 12G which was required to observe

the entire spectrum. Further investigation of this line, when examined at a slower scanning rate and slightly less modulation, reveals a much narrower line width similar to that seen in $\text{NbBe}_{2/2}$. Upon performing a double integration of the spectrum (Fig. 2), which yields a number that is proportional to the number of nuclei participating in the resonance, it was found, assuming all of the satellites were present in line A, that only about 1.5% of the niobium nuclei were in line A, the $\text{NbBe}_{2/2}$ contaminant. It was further discovered that approximately 61.5% of the nuclei were present in line B while about 37% were in line C. This ratio of Nb nuclei in lines B and C agrees quite favorably, when considering the inherent errors in integrating a highly split resonance line, with the two to one ratio predicted for the two different sites from x-ray analysis.³

$\text{Nb}_{7/2}\text{Be}_{1/2}$

The NMR spectrum of the niobium nuclei in $\text{Nb}_{7/2}\text{Be}_{1/2}$ was examined under the conditions similar to those employed to investigate the $\text{NbBe}_{2/2}$ and $\text{NbBe}_{3/3}$ samples. The ^{93}Nb spectrum exhibits a split central line ($1/2 \leftrightarrow -1/2$) and four pairs of satellites, corresponding to the ($\pm 3/2 \leftrightarrow \pm 1/2$), ($\pm 5/2 \leftrightarrow \pm 3/2$), ($\pm 7/2 \leftrightarrow \pm 5/2$) and ($\pm 9/2 \leftrightarrow \pm 7/2$) transitions. In Fig. 4 the split central line (A), shown in Fig. 5, and the three pairs (B, B'; C, C'; D, D') of the satellites are displayed. The central line is enlarged beyond the chart paper in order to show the satellites. The last pair of transitions ($\pm 9/2 \leftrightarrow \pm 7/2$), which are very weak, are not shown but have been observed. In order to resolve the satellites, high modulation amplitude, approximately equal to the line width, was required.

The peak to peak separation of the split central transition shown in Fig. 5, taken from the derivative curve, was plotted against the inverse of the resonance frequency (Fig. 6). Table 3 is also presented to clearly indicate the values of the line widths and their associated uncertainties in measurement. A straight line cannot be fitted within the error bars to include both the low frequency

data and the high frequency data. If only the low frequency data points are considered, that is, from 6 MHz to 2.5 MHz, a straight line can be fitted. The slope of such a line yields a quadrupole coupling constant of 5.92 MHz with a residual line width of approximately zero gauss. However, if the higher frequency data, from 8 MHz to 14 MHz are fitted with a straight line, its slope is greater than that of the lower frequency data and the intercept of the line when extrapolated to infinite frequency is $-4.3G$. This negative line width that is predicted when the electric quadrupole interaction has vanished is of course non-physical. Thus some other interaction must be distorting the signal, and this distortion becomes more prominent at higher frequencies. This interaction when added to the quadrupole interaction has the effect of narrowing the resonance. This narrowing of the resonance, has been found to be due to a slight anisotropy in the Knight shift.

Bloembergen has discussed in detail the first order effects of an anisotropic shift tensor on the line shape of the resonance of a conductor in the absence of electric quadrupole effects.¹⁰ In the case of an axially symmetric shift tensor, all of the $2I + 1$ pure Zeeman levels are shifted by an equal amount in first order, with the result that only a single resonance line appears for the case of a single crystal.¹⁰ The frequency of the line from a single crystal is given by,

$$\nu = \nu_L (1 + K_{iso}) [1 + K_{ax} (3 \cos^2 \theta - 1) / (1 + K_{iso})], \quad (4)$$

where θ is the angle between the Z axis of the principle axes system of the shift tensor and the direction of the applied external magnetic field.

If an anisotropic Knight shift interaction is present in a powder sample in which a second order quadrupole interaction is present, it is possible to determine the resulting separation, $\Delta\nu = \nu_{Hi} - \nu_{Lo}$ of the singularities in the probability distribution which would determine the separation of the observed

peaks of the derivative of the resonance curve for the central $1/2 \leftrightarrow -1/2$ transition. If in addition it is assumed that the axially symmetric magnetic shift tensor has its principle axis coincident with that of an axially symmetric electric field gradient tensor, then the separation between the derivative peaks (Δv) can be written, as derived by Jones, Graham and Barnes,¹¹ as

$$\Delta v = 25b/9\nu_Q - 5a \nu_Q/3 + a^2 \nu_Q^3/4b, \quad (5)$$

where $b = \frac{2}{3} [I(I+1) - 3/4]/16$, $a = K_{ax}/(1 + K_{iso})$ and $\nu_Q = 3e^2 qQ/2I(2I-1)h$. In arriving at this expression account has been taken of the presence of an isotropic Knight shift by replacing ν_Q with ν_Q (See Eq. 3). Analyzing the above equation, the first term is the splitting due to the second order quadrupole interaction, see Eq. 2. The second term is the contribution due to the anisotropic Knight shift. Note, if $K_{ax} > 0$ than $a > 0$, this will then cause the separation between the peaks to be less than if only the electric quadrupole interaction were present and hence explain the data obtained from the $Nb_{2}Be_{17}$ powdered sample. The third term depends upon a^2 and can be neglected because of the smallness of a . If there is a finite dipolar line width (σ) present, then the separation can be written as,¹¹

$$\Delta v = 25b/9\nu_Q - 5a \nu_Q/3 + 1/2 \sigma. \quad (6)$$

A least squares calculation was performed fitting Eq. 6 without the dipolar contribution, since the low frequency data if extrapolated indicated an extremely small amount of dipolar broadening. The resulting equation is,

$$\Delta v = 0.255/\nu_Q - 0.000238\nu_Q. \quad (7)$$

In Fig. 6 a curve is drawn to show the fit to the data. Utilizing the values obtained in Eq. 7, the quadrupole coupling constant and the axial component of the shift tensor may be computed, yielding $e^2 qQ/h = 5.93 \pm 0.15$ Mhz and

$K_{ax} = 0.014\%$. In addition to these parameters a more accurate value of K_{iso} , other than that value obtained by neglecting the small shift of the center of the split central transition due to K_{ax} , can be determined by plotting the relative shift of the low field derivative peak, given by,¹¹

$$K_H = (\nu_{Hi} - \nu_L) / \nu_L = K_{iso} - a + b / \nu_L^2 \quad (8)$$

against the inverse of the resonance frequency squared. Note, that the difference between ν_L and the actual resonance frequency in the denominator is insignificant in this particular calculation. The magnetic field was measured using ^{79}Br in KBr. The plot of K_H vs $1/\nu^2$ is shown in Fig. 7. A least squares fit yields the following equation,

$$K_H = 0.0032 + 0.1064 / \nu^2 \quad (9)$$

The infinite frequency intercept determines $K_{iso} = 0.334\% \pm 0.02\%$, once the value of "a" is known from Eq. 6. Note the value of K_{iso} obtained by neglecting any shift due to the effects of K_{ax} and defining the center of the resonance as in Eq. 3, $K_{iso} = 0.34\% \pm 0.02\%$, which coincides with the previous value within the uncertainties of the measurement. This fairly small Knight shift as compared with the previously examined beryllides indicates that there are relatively fewer s-state electrons in the conduction band.

When applying Eq. 6 to the data for $\text{Nb}_2\text{Be}_{17}$, the contribution to the line width due to dipolar broadening was omitted. This is due to the fact that if only the low frequency (6 MHz or less) data were utilized where the effects of K_{ax} is diminished, the straight line relationship between the separation of the peaks of the derivative curve and the inverse of the resonance frequency, could be applied. When this line is extrapolated to infinite frequency, the intercept indicates a residual line width of approximately zero gauss. The resonance of $\text{Nb}_2\text{Be}_{17}$ at 15 MHz still exhibits a sharply split line, that is the

two peaks are not smeared into one another due to a large dipole-dipole interaction, see Fig. 5. An estimate of the dipole-dipole width may be obtained by comparing the interatomic spacing³ between niobium atoms in NbBe_2 which is 2.830 Å, with the spacing⁴ between niobium atoms in $\text{Nb}_2\text{Be}_{17}$ which is 3.463 Å. Since the dipole-dipole interaction varies as the reciprocal of the cube of the lattice spacing, a ratio of the cubes of the lattice spacing will yield the inverse ratio of their dipole broadening. In this approximation, the effect of the beryllium atoms is considered to be essentially the same in both phases. This results from spacing between the niobium and beryllium being very closely the same. The niobium nucleus also possesses a magnetic moment that is of the order of six times larger than that of beryllium, thus the dipole-dipole interaction due to Nb atoms is presumed to overshadow any of the differences that occur because of the packing of Be atoms about the Nb atoms in the two different structures. Thus by using the value (7.5 gauss) of the line width due to dipolar broadening in NbBe_2 determined earlier and the ratio of the cubes of the Nb-Nb spacing, a line width due to dipolar broadening of approximately 4G is predicted for the niobium resonances from $\text{Nb}_2\text{Be}_{17}$.

The separation between the ($\pm 3/2 \leftrightarrow \pm 1/2$) satellite transitions is measured to be $254 \pm 3\text{G}$ and is constant within the frequency range it is observed, 4 to 14 MHz. This width being a constant again indicates that first order perturbation due to the quadrupole interaction would still be valid. The individual satellite lines possess a width which is due to over modulation. This extra width can be subtracted off using the method given by Adams et al¹² and the quadrupole coupling constant can be again calculated. A coupling constant of 5.8 ± 0.2 MHz is obtained in this manner. This value is in good agreement with the corrected value obtained from the central transition.

NbBe_{12}

The last beryllide to be investigated was NbBe_{12} , which has the highest

atomic ratio of beryllium to niobium. The NMR spectrum of the niobium nuclei observed at room temperature was extremely weak due to the low abundance of ^{93}Nb nuclei present, consequently, high gain and high modulation amplitude were necessary to resolve the signal. The resonance frequencies at which the sample was investigated ranged from 10 MHz to 15 MHz. The spectra contained an extremely split central transition, Fig. 8. The ($\pm 3/2 \pm 1/2$) transitions could also be seen, but they were extremely weak. A graph was made of the peak to peak separation of the central transition against the inverse of the resonance frequency, resulting in a straight line. This indicates the resonance line is split by the second order quadrupole perturbation. An electric quadrupole coupling constant of $21.73 \text{ MHz} \pm 0.3 \text{ MHz}$ was determined by a least squares fit. This large interaction caused by strong electric field gradients is the consequence of non cubic tetragonal crystal structure⁵ of NbBe_{12} .

A Knight shift was observed and measured at room temperature using ^{79}Br in KBr and ^{93}Nb metal powder resonances as references. A value of $0.552\% \pm 0.02\%$ was determined.

Conclusion

The different compounds of the niobium and beryllium are easily identifiable and can be categorized through their NMR spectrum. The quadrupole splitting and Knight shifts are strikingly different for each compound. The relative amounts of niobium in the various phases as well as any uncombined niobium nuclei may be calculated by the process of a double integration of the resonance curve as outlined previously.

In the case of NbBe_3 , x-ray analysis³ stated that the niobium nuclei were in the form of a linear chain of three. The two niobium nuclei at each end of the chain have the beryllium atoms packed around them in the same configuration

as in $\text{NbBe}_{7/2}$. The NMR signal caused by these nuclei are identified as line B in Fig. 2 since this was the most intense line. The comparable Knight shift of line B with that of the niobium nuclei in $\text{NbBe}_{7/2}$ indicates that the Knight shift depends heavily upon the beryllium configuration about the niobium nuclei. The quadrupole coupling constant, however, is greatly different in these two resonances indicating that the configuration of the large niobium nucleus greatly alters the electric field gradients.

It should be noted that ^9Be NMR yielded very little information since the weak signals from all compounds consisted of unsplit lines with no measurable Knight shift. These resonances were easily power saturated, indicating that there existed very little interaction between the beryllium nuclear quadrupole moment, which is relatively small, and any electric field gradient, and also indicating very little interaction between the beryllium nuclei and the conduction electrons. The line widths remained constant as a function of magnetic field, and for $\text{NbBe}_{3/3}$, $\text{Nb}_{2/2}\text{Be}_{17/17}$ and $\text{NbBe}_{12/12}$, the line widths were all within 7.5 ± 1.0 gauss. The line width in $\text{NbBe}_{7/2}$ was 9.3 ± 2.0 gauss and was extremely weak. Thus very little information was obtained from the ^9Be NMR other than that of the absence of large quadrupole coupling and electron-nuclear interactions.

It would be of interest to compare the Knight shift values for these compounds with magnetization and conductivity measurements which might enable one to gain further insight into the electronic configuration in these materials.

TABLE 1
 Crystal Structure* of NbBe_x Samples

Beryllide	Structure	a ₀ (Å)	c ₀ (Å)	c ₀ /a ₀
NbBe ₂	fcc	6.535		
NbBe ₃	rhombohedral	7.495		
Nb ₂ Be ₁₇	rhombohedral	5.599		
NbBe ₁₂	tetragonal	7.356	4.258	.577

*Determined by x-ray analysis.³⁻⁵

TABLE 2
 Quadrupole Coupling Constants and Knight Shifts of NbBe₃

Line	e ² /qQ/h	Knight Shift
A	0 MHz	0.683% ± 0.03%
B	24.31 MHz ± 0.45 MHz	0.724% ± 0.03%
C	30.57 MHz ± 0.74 MHz	0.532% ± 0.03%
B'	24.19 MHz ± 0.2 MHz	
C'	30.10 MHz ± 0.3 MHz	

TABLE 3

NMR Line Width of ^{93}Nb in $\text{Nb}_2\text{Be}_{17}$ at Various Frequencies

Frequency (MHz)	Line Width (gauss)
14 MHz	14.23G \pm 0.5G
12 MHz	17.75G \pm 0.3G
10 MHz	22.07G \pm 0.45G
8 MHz	28.64G \pm 0.5G
6 MHz	39.56G \pm 0.5G
4 MHz	59.8G \pm 1.0G
3 MHz	81.9G \pm 2.0G
2.5 MHz	96.6G \pm 2.0G

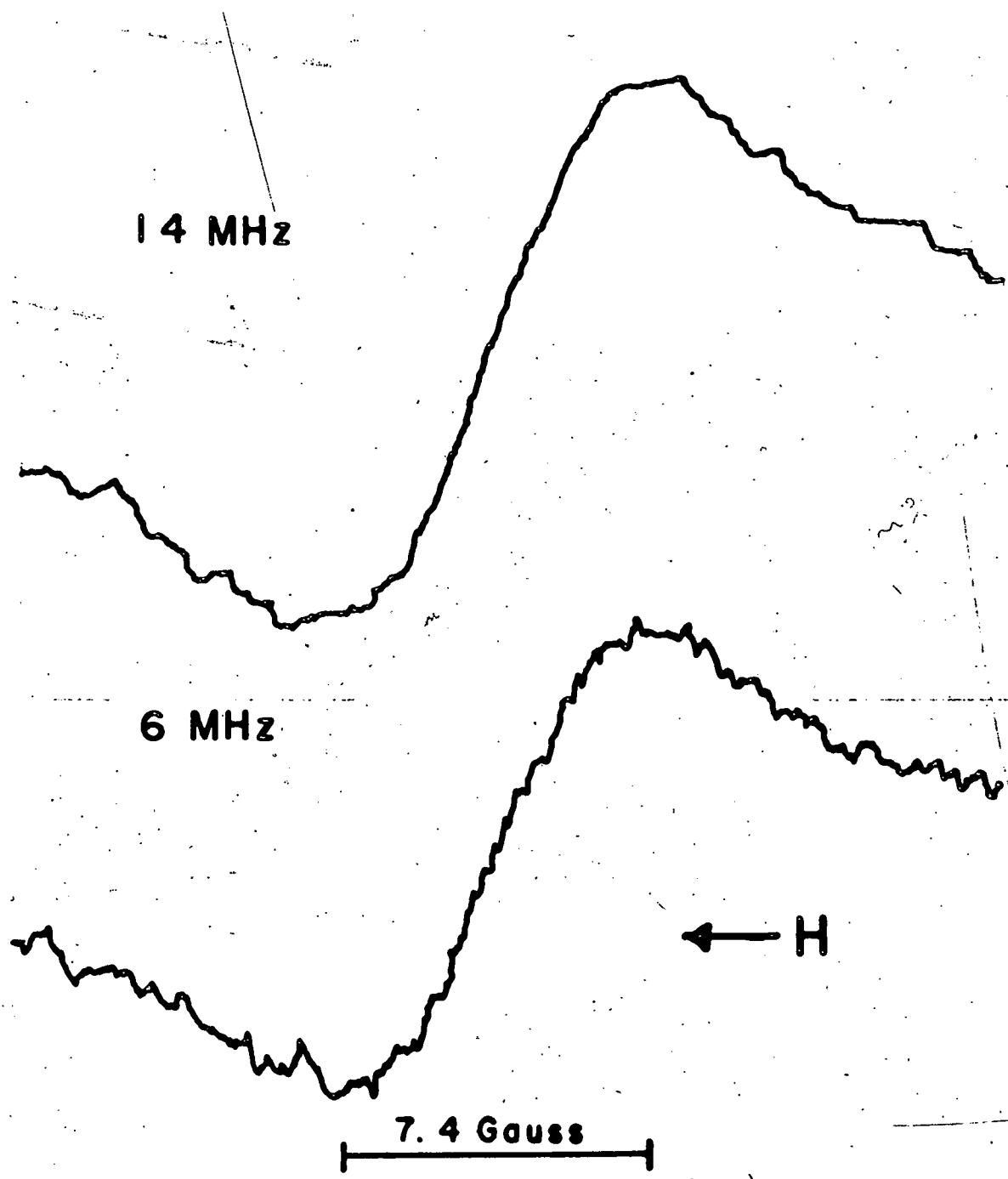
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FIGURES

Figure

1. First derivative of the ^{93}Nb resonance in NbBe_{12} at 14 MHz and 6 MHz.
2. First derivative of the ^{93}Nb resonance in NbBe_3 at 14 MHz. Lines marked A, B and C are the central ($1/2 \leftrightarrow -1/2$) transitions. Lines marked B' and C' are first order split ($\pm 3/2 \leftrightarrow \pm 1/2$) transitions.
3. Separation of the peaks of the derivative curve for the ($1/2 \leftrightarrow -1/2$) transition of lines A, B and C from ^{93}Nb in NbBe_3 versus $1/\nu$.
4. First derivative of the ^{93}Nb resonance in $\text{Nb}_2\text{Be}_{17}$ at 14 MHz. Line A is the ($1/2 \leftrightarrow -1/2$) transition. Lines B and B', C and C', D and D' are the ($\pm 3/2 \leftrightarrow \pm 1/2$), ($\pm 5/2 \leftrightarrow \pm 3/2$), ($\pm 7/2 \leftrightarrow \pm 5/2$) transitions, respectively.
5. First derivative of the central ($1/2 \leftrightarrow -1/2$) transition of the ^{93}Nb resonance in $\text{Nb}_2\text{Be}_{17}$ at 15 MHz.
6. Separation of the peaks of the derivative curve for the ($1/2 \leftrightarrow -1/2$) transition of ^{93}Nb in $\text{Nb}_2\text{Be}_{17}$ versus $1/\nu$. Solid curve is a plot of Eq. 7.
7. K_H versus $1/\nu^2$ for $\text{Nb}_2\text{Be}_{17}$.
8. First derivative of the ^{93}Nb resonance in NbBe_{12} at 14 MHz.



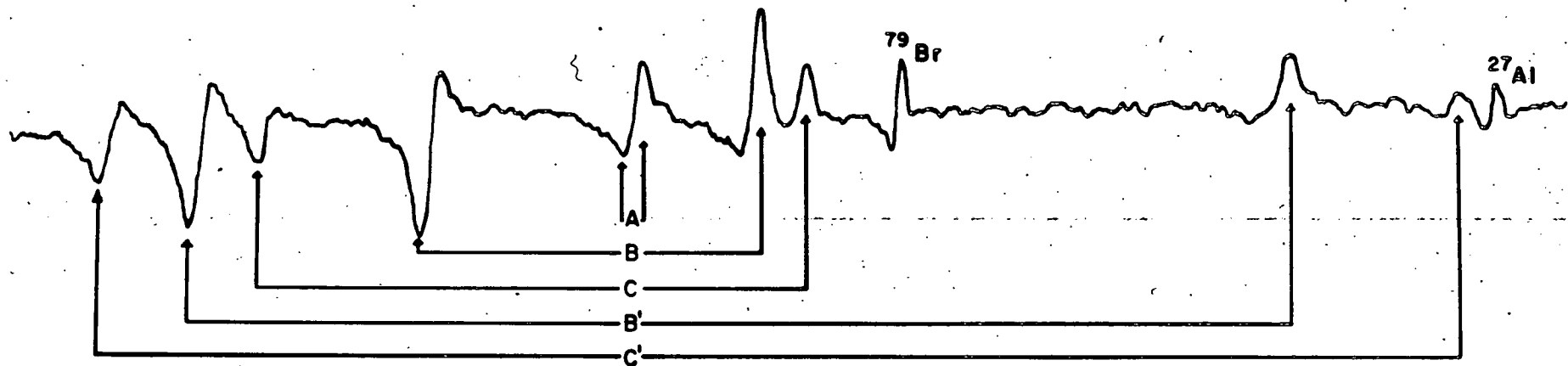
14 MHz

6 MHz

← H

7.4 Gauss

14 MHz



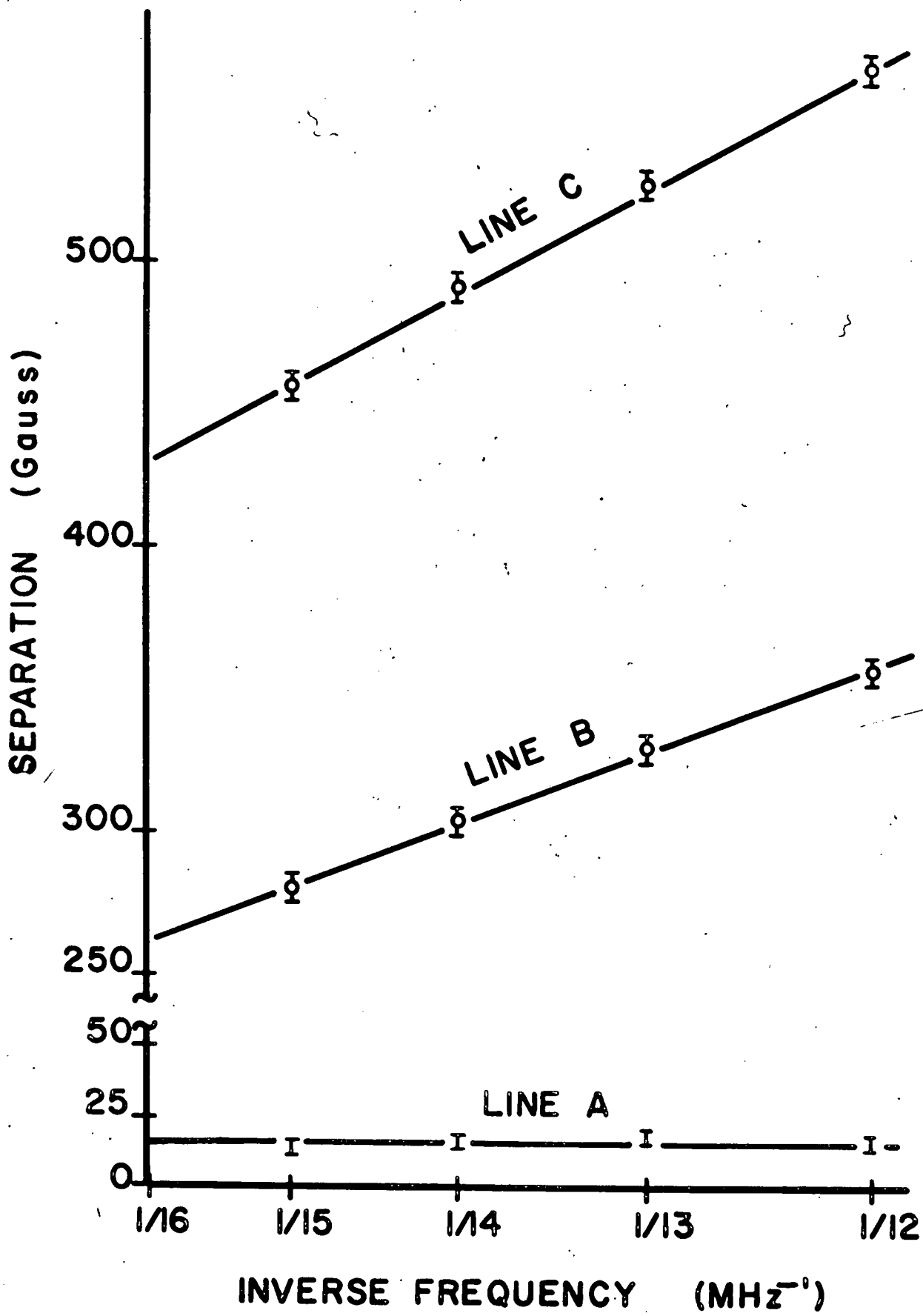
^{79}Br

^{27}Al

A
B
C
B'
C'

200 Gauss

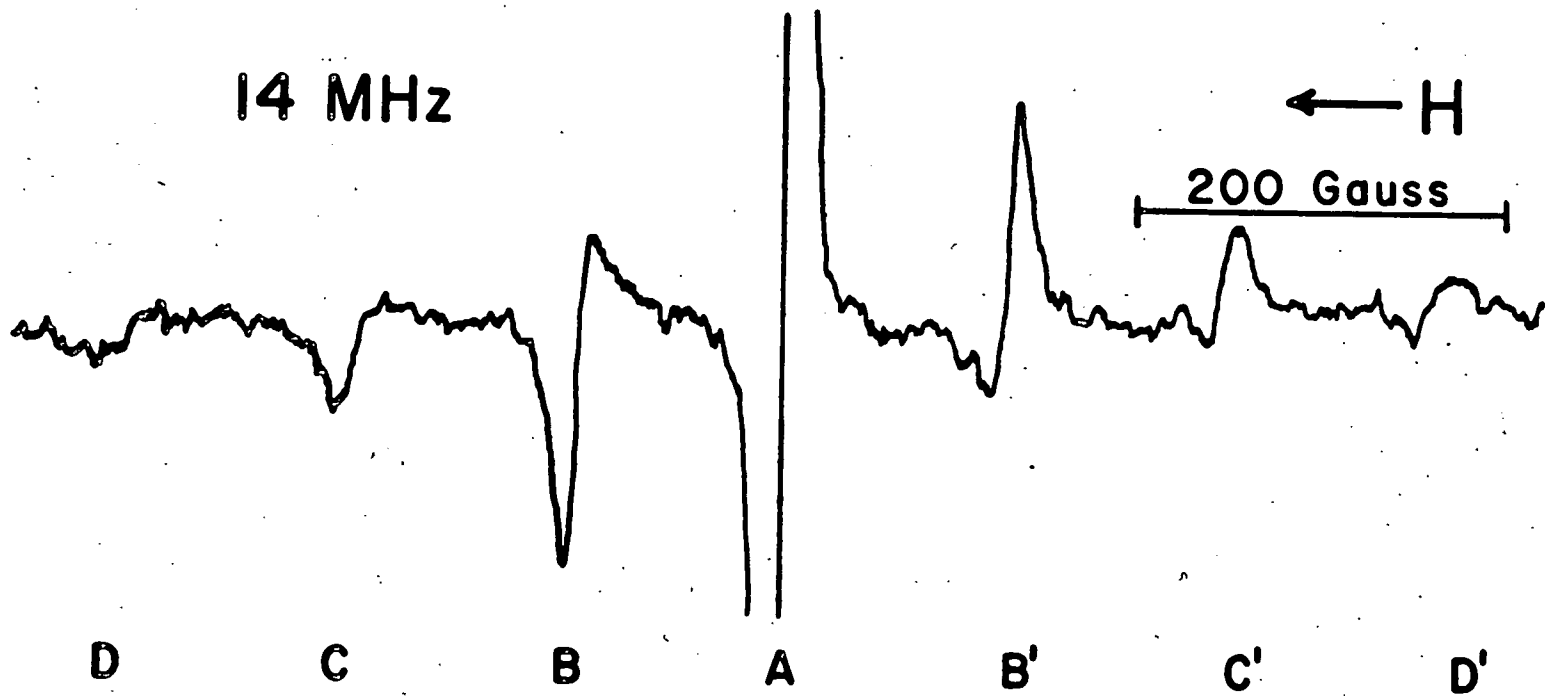
← H

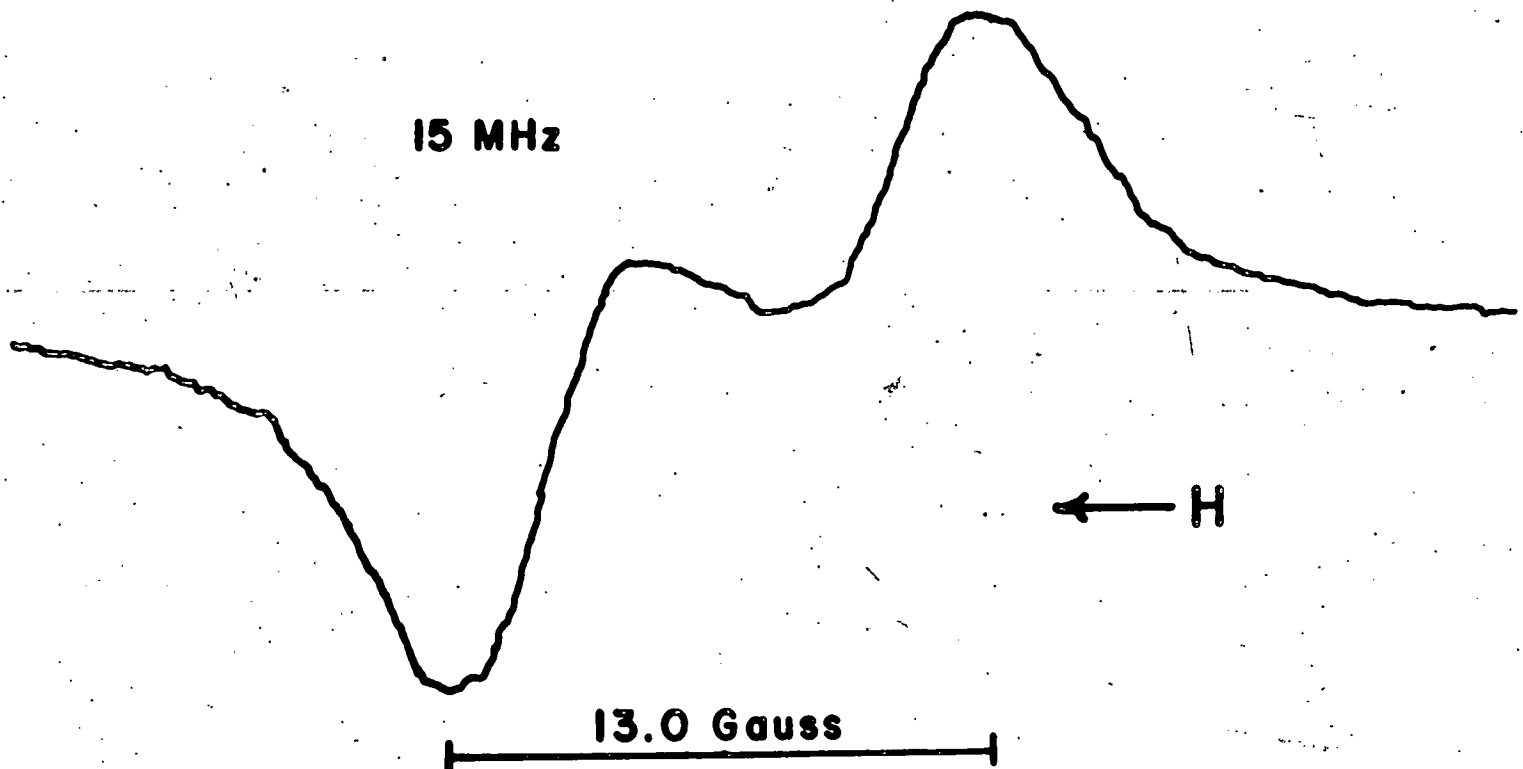


14 MHz

← H

200 Gauss

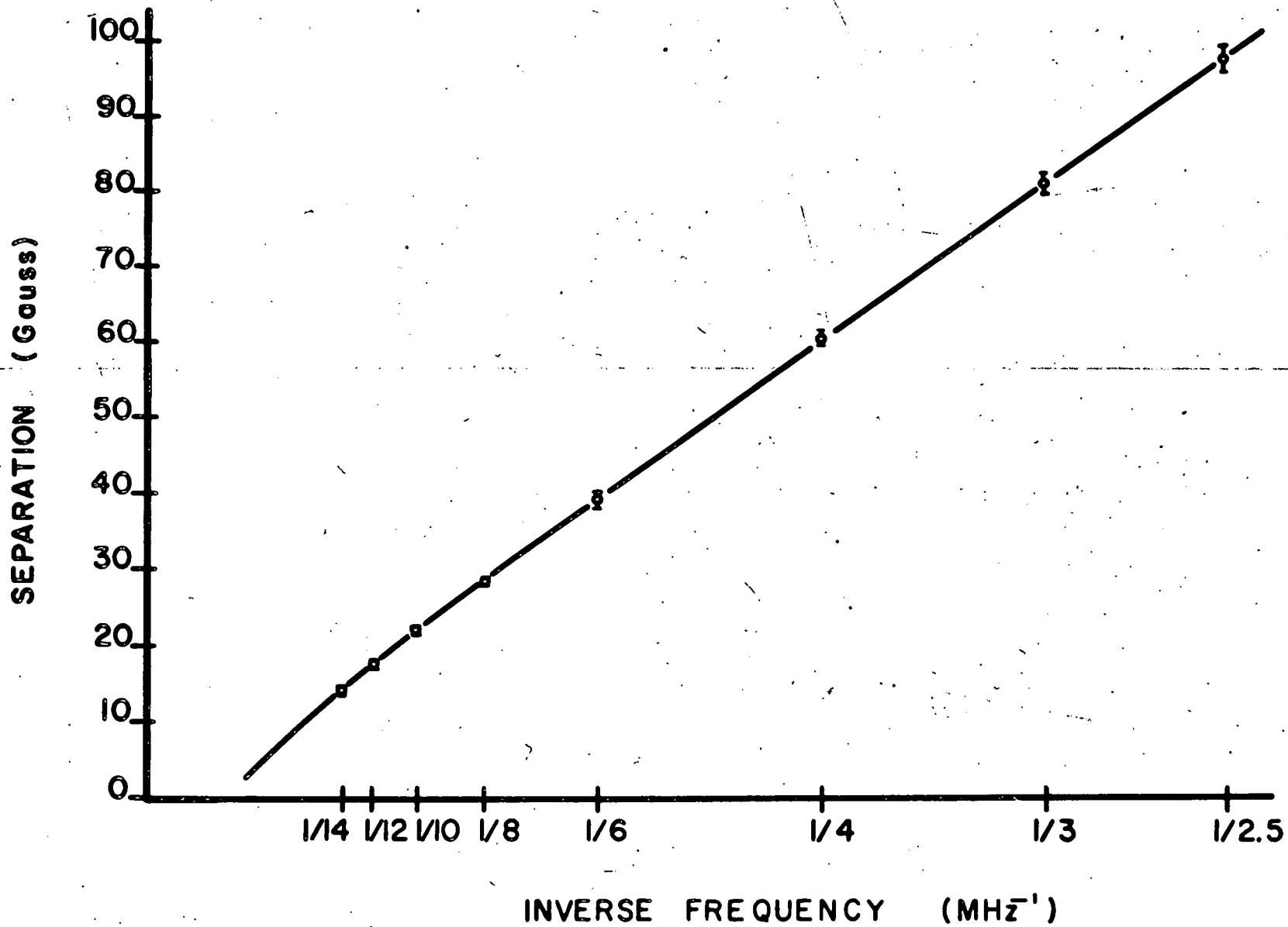


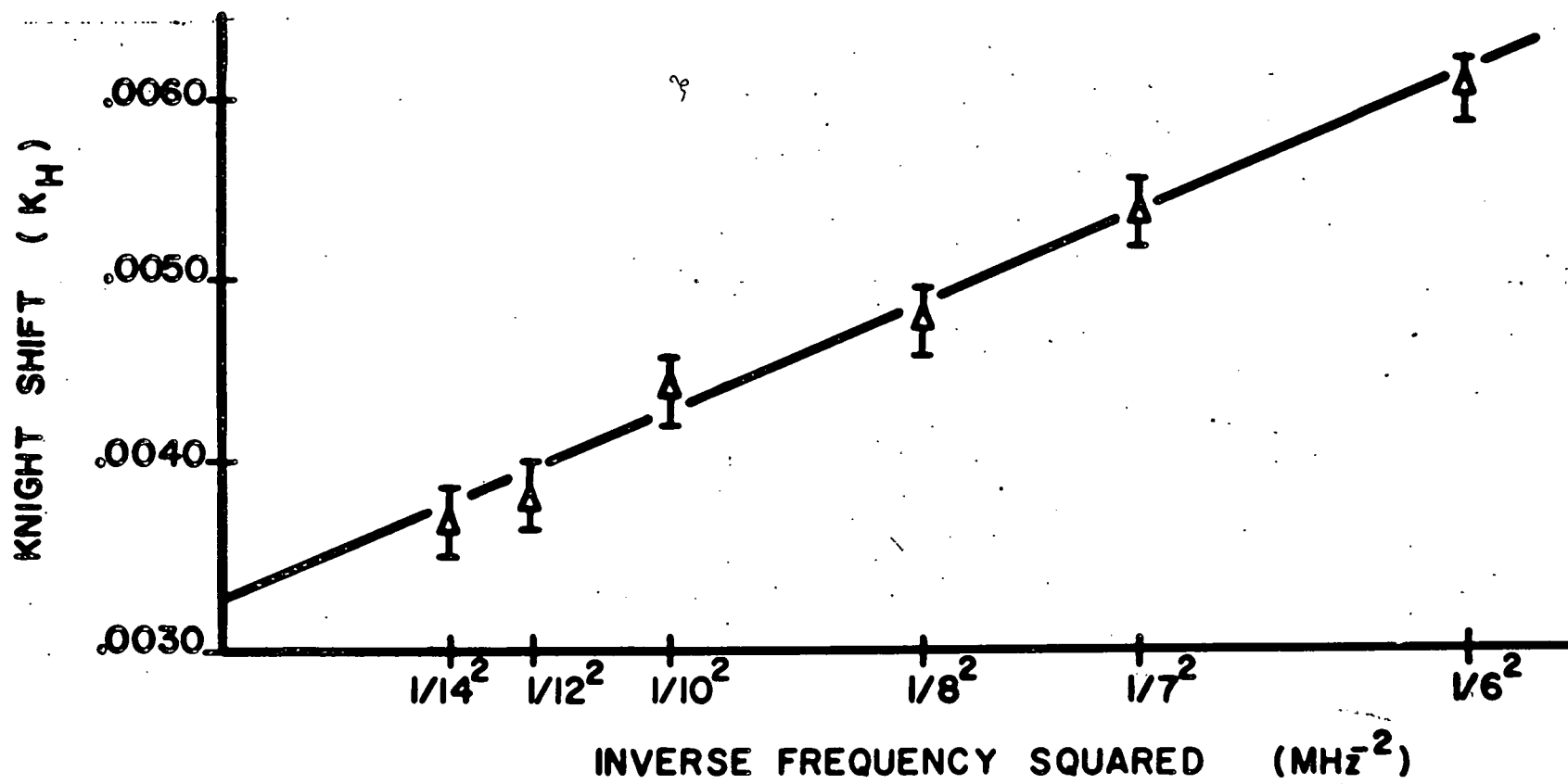


15 MHz

13.0 Gauss

← H





14 MHz

← H

245 Gauss

