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G.E. Brodale, R.A. Fisher, N.E. Phillips,
and K. Matho

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APPROACH TO MAGNETIC SATURATION

IN CuMn and AgMn

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Abstract :

High field magnetic moment measurements on dilute CuMn and AgMn reveal that the magnetic state of an isolated Mn in solution may be compatible with the free ionic spin value $S_0 = 5/2$ and Landé factor $g_0 = 2$.

The most dilute sample of each system shows this directly, after extrapolation of M vs (H^{-1}) to $(H^{-1})=0$. Apparent moment reductions at higher concentrations may be due to residual antiferromagnetic bonds instead of a real change in the local S or g . From a theoretical model, the lowest moments of the bond distribution are determined for the CuMn case.

1. INTRODUCTION

When Mn is implanted in a noble metal, the "ionic" parameters are apparently altered by many body correlations involving the conduction electrons and either a single Mn-site (Friedel, Anderson, Kondo) or several Mn sites (RKKY). It is customary to assign phenomenological values $S \neq S_0 = 5/2$ and $g \neq g_0 = 2$ to the spin and Landé factor [1].

The literature values for S and g in dilute CuMn and AgMn are largely scattered [2-5]. The main uncertainty may be due to large error bars on the concentration C of Mn, with the tendency of losing Mn in solution. In order to clarify this point we performed high field magnetic measurements at low temperatures (however well above the Kondo temperature T_K) on samples of Mn in Cu and Ag for which the concentrations are determined by an analytical technique accurate to $\pm 1\%$ [6].

2. EXPERIMENTAL RESULTS

Here, we present high field magnetizations on two CuMn and two AgMn samples with C between 100-1000 ppm. The measurements were made by moving the sample at constant H between two opposed pick-up coils [6]. They were 40 mm diameter spheres

cut from ingots prepared by melting degassed 6-9's Cu or Ag and 5-9's Mn in sealed high purity quartz tubes. The melt was "quenched" by plunging the tube into water and the samples machined from the ingots were annealed under an argon atmosphere for two days at 950-975°C.

The magnetization, corrected for diamagnetism, is plotted as M vs. H^{-1} in figures 1 and 2, indicating also C and the ranges of H and T . Values of the product gS , as determined from linear extrapolation to $H^{-1}=0$ are listed in table 1. They are at least 10 % higher than usually reported. The error bars indicated result from ± 1 % accuracy in C combined with $\pm .5$ % accuracy in M , ± 2 % for the 104 ppm CuMn sample.

3. THEORETICAL RESULTS

We calculated the magnetization of an RKKY-system with quantum spins $S_0 = 5/2$, $g_0 = 2$ in the pair-approximation [7,8]. The distribution of bonds

is described by

$$p(W) = -\frac{1}{\pi} \operatorname{Im} \sum_{k=1,2} \frac{C_k}{W - U_k}, \quad \operatorname{Im} U_k < 0 \quad (1)$$

with two Cauchy singularities in the complex W -plane. This new "Ansatz" allows for skewness of the bond distribution and deviations from RKKY-scaling. The constants are uniquely determined by the first three moments, i.e. normalization of

$p(W)$, average bond $\langle W \rangle = \bar{W}$ and variance
 $\langle (W-\bar{W})^2 \rangle = \Sigma^2$ plus a constraint : $p(0)$ is a
 maximum. The latter expresses the fact that RKKY
 bonds asymptotically oscillate around $W = 0$ in real
 space. The ensemble averaged magnetization per spin
 is

$$m = \frac{1}{4} g \mu_B B_{2S}(z) - \text{Im} \sum_{k=1,2} \frac{C_k}{2\pi} \sum_{\ell=1}^{S(2S+1)} \frac{dW_\ell(z)}{dH} \cdot \psi\left(\frac{\beta(W_\ell(z) - U_k)}{2\pi i}\right) \quad (2)$$

Here, $\beta = (k_B T)^{-1}$, $z = \beta g \mu_B H$,

$\{W_\ell(z), \ell = 1, \dots, S(2S+1)\}$ are the roots of the
 equation $Z_2(\beta W, z) = 0$, where Z_2 is the pair parti-
 tion function [7], and ψ is the di-gamma function.

In the limit $U_1 \rightarrow 0, U_2 \rightarrow 0$, m goes to $g \mu_B B_S(z)$,
 the Brillouin function. Equation (2) is plotted in
 figure 1 for $T = .8K, 1.6K$ and $4.2 K$. The distribu-
 tions corresponding to the two samples are shown in
 figure 3 and the optimal parameters are listed in
 table 1. They show the tendency of building up an
 average antiferromagnetic bond $\bar{W} < 0$ as the concen-
 tration increases. The central peak is proportional
 to C^{-1} , yielding a roughly constant amplitude W_1 , as
 predicted by the RKKY scaling : $W_1 = (\pi^2 C_p(0))^{-1}$.

4. DISCUSSION

The experimental findings show for the first
 time a magnetic moment on isolated Mn sites in

noble metals which is compatible with the free ion state. This is relevant for the internal consistency of Friedel-Anderson-Kondo type theory applied to Mn : from the low Kondo temperature T_K one expects in fact that the Friedel resonance lies well below the Fermi level and contains close to 5 (3d) electrons.

Moment reductions are already apparent at $C \lesssim 1000$ ppm, when the linear extrapolation of M vs. H^{-1} is used. The experimental conditions $T \gg T_K$, $\mu_B H \gg k_B T_K$ and the C -dependence make it very unlikely that they should be due to the Kondo effect [1]. In our interpretation [7,8], they are due to residual antiferromagnetic bonds that can be decoupled by still stronger fields.

As shown in figure 1, the theory reproduces the experimental data, in particular their T -dependence. For $H^{-1} \rightarrow 0$ the theoretical M tends to $2.794 \cdot 10^4$ emu/mole or $5 \mu_B/\text{Mn}$, which is the assumed input. We conclude that also the 657 ppm data are compatible with an unchanged local moment of $5 \mu_B$. The theory allows a determination of the first moments of the bond distribution.

An ensemble calculation with a set of explicit clusters (discrete bond values) is not meaningful at this concentration. For example, at 657 ppm, only .5 % of all Mn atoms would be in one of the 13 clusters considered by Morgownik and Mydosh [9].

The skewness detected in the bond distribution suggests a non random Mn positions or a modification of the spatial RKKY-function at a length scale of ~ 6 nearest neighbour distances.

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Table 1

Sample	g.S	\bar{W}	Σ	W_1
Cu 104 ppm Mn	5.00 ± .12	- .53	1.79	765
Cu 657 ppm Mn	4.66 ± .05	- 1.52	3.58	735
Ag 426 ppm Mn	5.00 ± .06			
Ag 902 ppm Mn	4.84 ± .05			

Table caption : Products gS, determined from experimental data by means of linear extrapolation in the M vs. H^{-1} plot.

For CuMn : Optimized parameters characterizing the bond distribution of two samples ; average bond \bar{W} , variance Σ and RKKY amplitude W_1 [6,8].

FIGURE CAPTIONS

Fig. 1 : Discrete symbols represent experimental data at the temperatures indicated. Continuous curves a,b,c represent eq. (2) at $T = .8$ K, $T = 1.6$ K and $T = 4.2$ K, respectively. The theoretical limit, as $H^{-1} \rightarrow 0$, is $2.794 \cdot 10^4$ emu/mole.

Fig. 2 : Experimental results for AgMn.

Fig. 3 : The bond distributions $p(W)$ determined for the two CuMn samples of figure 1. They are characterized by the parameters listed in table 1.

Fig. 1

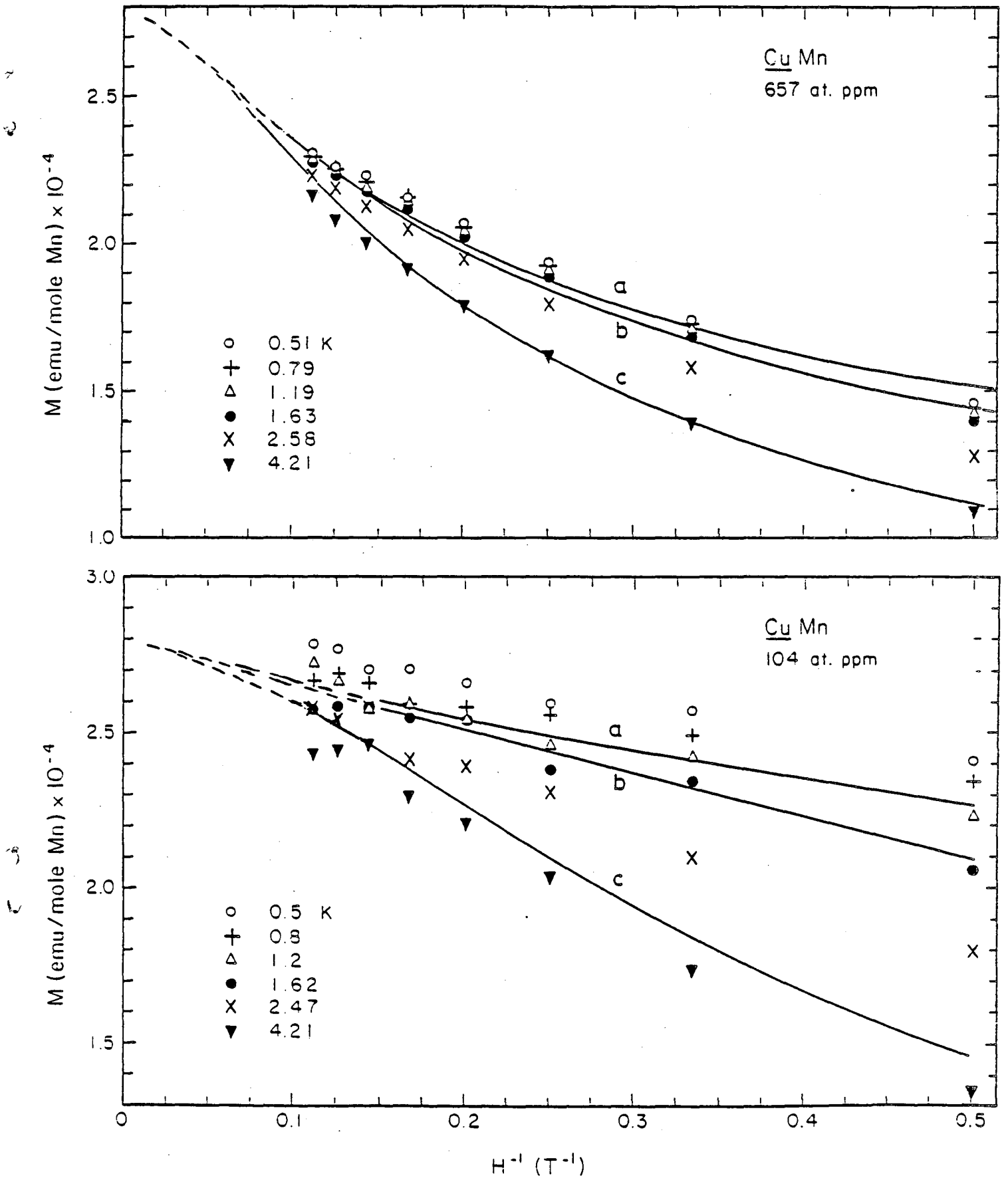


Fig. 2

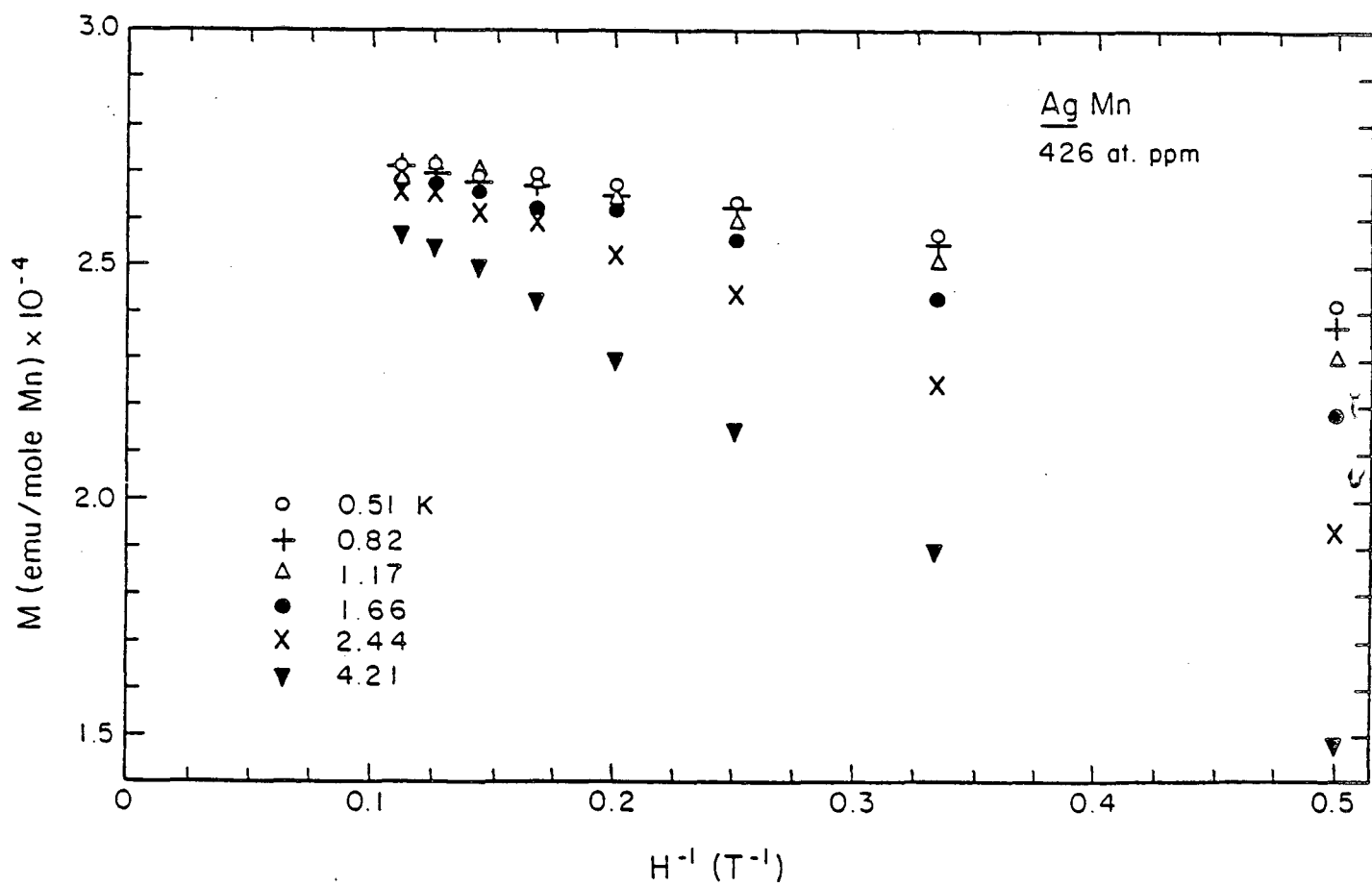
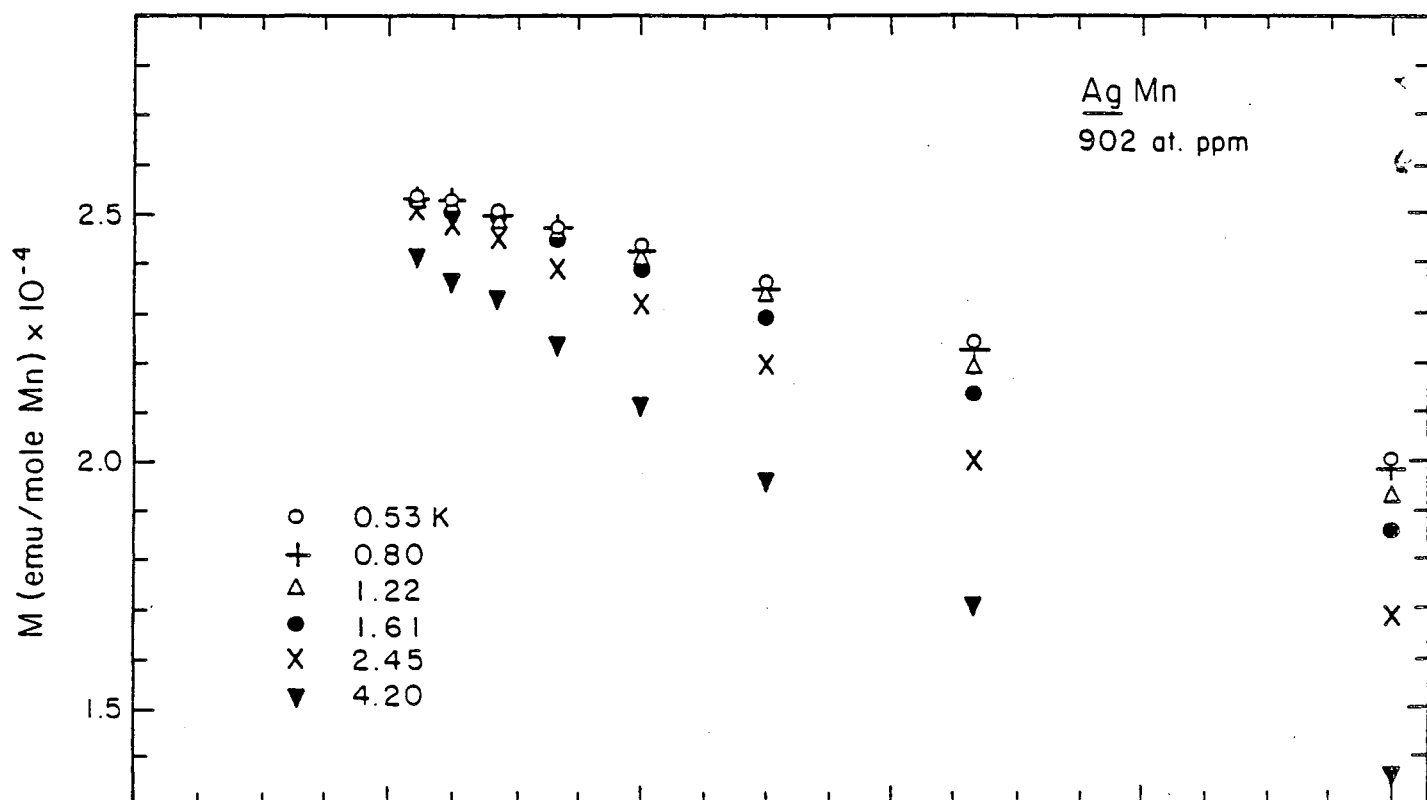
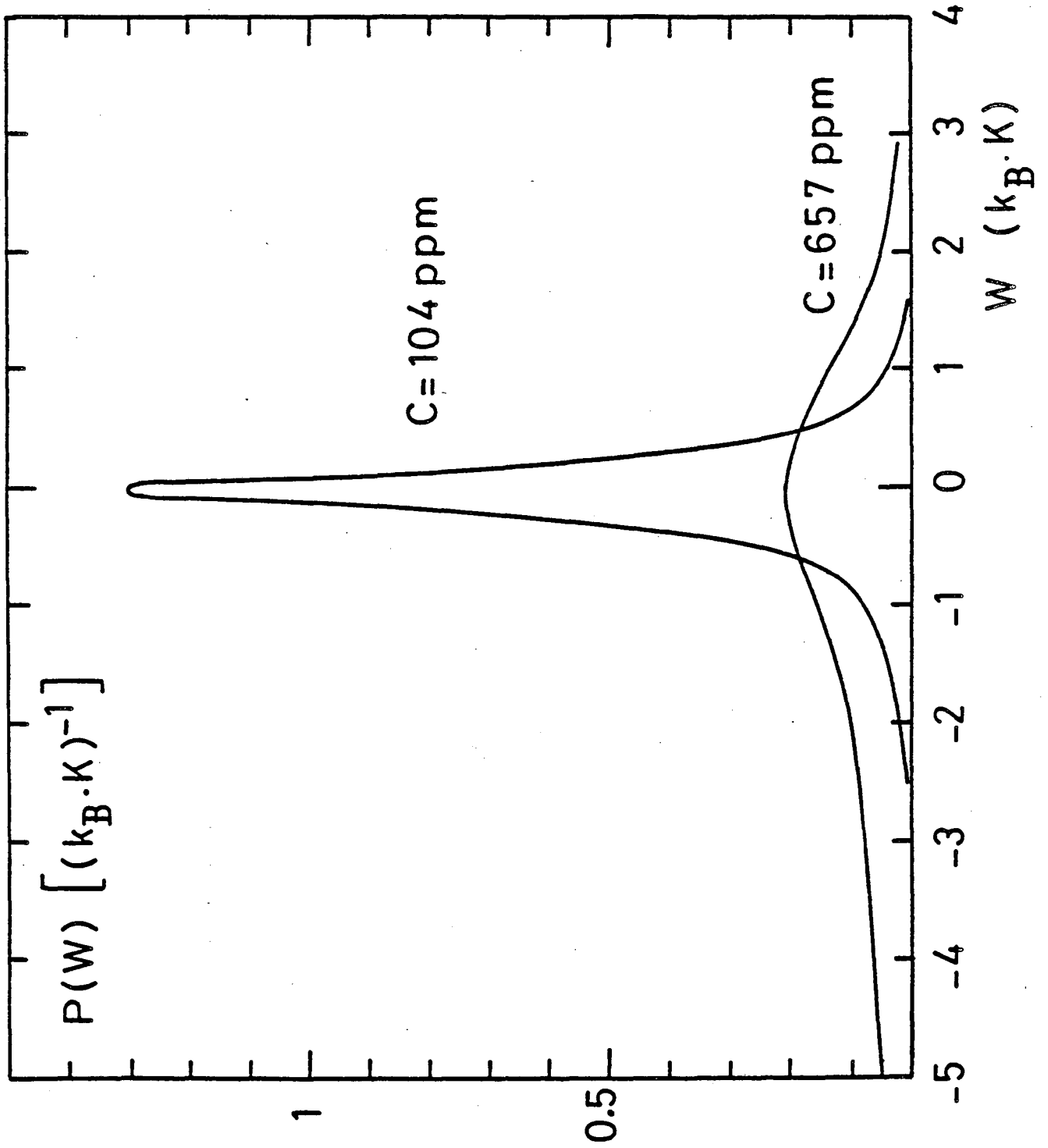


Fig. 3



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