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Anisotropy in the Antiferromagnetic MnF_2

FREDERIC KEFFER*
Department of Physics, University of California, Berkeley, California

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The major part of the anisotropy in the paramagnetic susceptibility of MnF_2 above the Curie point, as measured by Stout and Griffel, can be accounted for by magnetic dipole interactions. These interactions affect the anisotropy in different ways above and below the Curie point and lead to an anisotropy field of the order of 8800 oersteds at 0°K. Other sources of anisotropy in antiferromagnetics are discussed, in particular that due to crystalline fields which is also present in magnetically dilute paramagnetic salts. The anisotropy field below the Curie point can be measured by antiferromagnetic resonance. It is predicted that this will require wavelengths of 1 mm at 0°K increasing to perhaps 2 mm at $0.9T_c$. Or one may use centimeter waves and static fields of 1.0×10^5 oersteds at 0°K increasing to perhaps 1.7×10^5 oersteds at $0.9T_c$.

I. INTRODUCTION

SOURCES of anisotropy in an antiferromagnetic substance such as MnF_2 may be considered under two broad headings: (A) anisotropy dependent upon the relative spin orientation of pairs of paramagnetic ions and (B) anisotropy arising from interactions of individual paramagnetic ions with their surrounding crystalline fields.

Anisotropy of type (A) may be handled in a manner similar to Van Vleck's[1] treatment of ferromagnetic anisotropy. The simplest forces are long range magnetic dipole interactions; to these are added short range forces arising in a complicated way but which may be expanded in terms of dipolar, quadrupolar, etc., coupling between the spin pairs. Such a quadrupolar coupling has been used, for example, in the quantum-mechanical theory of antiferromagnetic resonance.[2] These short range forces may be due to directional properties of the superexchange or may come from the interplay between spin-orbit coupling within a paramagnetic ion and the crystalline field connecting pairs of ions.

Anisotropy of type (B) is similar to that found in magnetically dilute paramagnetic salts, where it gives rise to fine structure in the paramagnetic resonance spectra and may hence be measured with considerable precision. Such measurements cannot be made, however, on an antiferromagnetic such as MnF_2. This is because forces between spins, both isotropic and anisotropic, become important as the magnetic concentration increases; and the resonance curve becomes so broadened as to obliterate all traces of fine structure.

Both types of anisotropy give rise to the directional properties of the magnetic susceptibility which have been measured by Stout and Griffel.[3] Their data have been correlated with a phenomenological anisotropy constant by Yosida,[4] who finds an effective anisotropy field in MnF_2 of the order of 5×10^3 oersteds at 0°K. This is quite large, and one wonders which of the sources mentioned above is primarily responsible.

In this paper we show that the greater part of the measured anisotropy in the susceptibility may be accounted for by simple magnetic dipole forces and that the remainder may possibly be due to forces of type (B). Other methods of measuring anisotropy in antiferromagnetics are discussed, in particular, antiferromagnetic resonance. It is shown that the dipolar interactions enter into the anisotropy in different ways above and below the Curie point, a fact which may be of aid in determining the contribution to the anisotropy from other sources. This fact also forces us to revise Yosida's estimate of the anisotropy field at 0°K upward to ~8800 oersteds. This field should decrease with increasing temperature approximately as the saturation magnetization of a sublattice.

II. MAGNETIC DIPOLE ANISOTROPY

The crystal structure of MnF_2 is of the rutile type, tetragonal symmetry. The unit cell of Mn^{++} ions may conveniently be pictured as a body-centered cube compressed along the z (or c) axis. Lattice parameters, as determined from x-ray diffraction by Griffel and Stout,[5] are $c=3.3103$A and $a=4.8734$A. Erickson and Shull[6] have shown from neutron diffraction studies that below the Curie point the magnetization is such that the spins at the corners of the compressed cube are all pointing one way along the z axis, the spin at the center is pointing the opposite way. The simple two sublattice model, so often invoked as an approximation in theories of antiferromagnetism, appears to be correct for this crystal.

In calculating the magnetic dipole fields in such a structure it is convenient to define two types of dipole sums

$$\Phi_c' = -2N^{-1} \sum_j{}' [1-3\cos^2(z, r_{ij})] r_{ij}^{-3}, \tag{1}$$

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* Now at Department of Physics, University of Pittsburgh, Pittsburgh, Pennsylvania.

[1] J. H. Van Vleck, Phys. Rev. **52**, 1178 (1937).

[2] F. Keffer and C. Kittel, Phys. Rev. **85**, 329 (1952). We wish to correct a typographical error occurring in that paper. Equation (31) should read

$$\begin{aligned}(\omega/\gamma)^2 \cong 2H_AH_E + \tfrac{1}{2}H_0{}^2[1+(1-\alpha)^2\cos^2\theta] \\ \pm\tfrac{1}{2}H_0\{8H_AH_E(2-\alpha)^2\cos^2\theta \\ + H_0{}^2[\sin^4\theta + \cos^2\theta(2-\alpha)^2(2\sin^2\theta+\alpha^2\cos^2\theta)]\}^{\frac{1}{2}}.\end{aligned}$$

[3] J. W. Stout and M. Griffel, J. Chem. Phys. **18**, 1455 (1950).

[4] K. Yosida, Prog. Theoret. Phys. **6**, 691 (1951).

[5] M. Griffel and J. W. Stout, J. Am. Chem. Soc. **72**, 4351 (1950).

[6] R. A. Erickson and C. G. Shull, Phys. Rev. **83**, 208 (1951).

and

$$\Phi_c''=-2N^{-1}\sum\nolimits_j''[1-3\cos^2(z,r_{ij})]r_{ij}^{-3}. \tag{2}$$

Here $\sum_j'$ is taken over distances r_{ij} between a lattice point i and its neighbors j on the same sublattice; $\sum_j''$ is taken over distances to neighbors j on the other sublattice; $\frac{1}{2}N$ is the number of Mn^{++} ions per cm^3 in a sublattice. The summations are to be carried out within a Lorentz sphere; we shall consider only such sample shapes and combinations of sums that all contributions outside such a sphere vanish.

In the paramagnetic region we shall be interested in dipole sums over the entire lattice

$$\Phi_c=\tfrac{1}{2}(\Phi_c'+\Phi_c''). \tag{3}$$

Stout and Griffel[3] have measured, as a function of temperature, $\chi_{\|}-\chi_{\perp}$, or the difference in the susceptibility of a single crystal of MnF_2 taken along the c axis and along an a axis. The crystal had cylindrical symmetry about the remaining a axis; hence the sum $\Phi_c-\Phi_a$ should vanish beyond a Lorentz sphere. A simple calculation using Lorentz fields shows that for $T>T_c$ and assuming

$$M=CT^{-1}(H+\Phi M),$$

one obtains

$$\chi_{\|}=M_{\|}/H=CT^{-1}/(1-CT^{-1}\Phi_c);$$
$$\chi_{\perp}=CT^{-1}/(1-CT^{-1}\Phi_a).$$

These lead to

$$\begin{aligned}\chi_{\|}-\chi_{\perp}&=(\chi_{\perp}\chi_{\|})(\Phi_c-\Phi_a)\\&\cong\chi^2(\Phi_c-\Phi_a),\end{aligned} \tag{4}$$

where we assume the powder susceptibility χ is approximately given by $(\chi_{\perp}\chi_{\|})^{\frac{1}{2}}$. Even theories of paramagnetic susceptibility more exact that the Lorentz field approach, such as Van Vleck's[7] diagonal-sum method, although they give different theoretical evaluations of χ, lead to Eq. (4) for $\chi_{\|}-\chi_{\perp}$ in terms of χ. We shall insert the experimental values[8] of χ into Eq. (4).

The sum $\Phi_c-\Phi_a$ may be calculated by the Ewald-Kornfeld[9] method. We find for MnF_2

$$\begin{aligned}\Phi_c'-\Phi_a'&=9.25,\\ \Phi_c''-\Phi_a''&=-4.85,\\ \Phi_c-\Phi_a&=2.20.\end{aligned} \tag{5}$$

As a check, the value 9.25 compares well to rough estimates of Φ_c' and Φ_a' which may be obtained from a graph given by Mueller.[10] Also a simple summation out to next nearest neighbors gives 8.93, −3.01, 2.96 for the three quantities in Eq. (5).

That the dipolar interactions account for the major part of the observed anisotropy may be seen from Fig. 1.

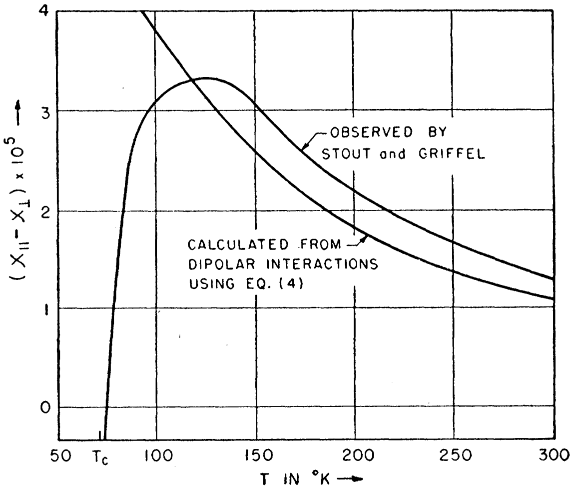

FIG. 1. Observed and calculated anisotropy in the molal susceptibility of MnF_2.

Below the Curie point (~73°K) $\chi_{\|}-\chi_{\perp}$ is negative, since exchange forces completely determine the directional nature of the susceptibility once long-range order has set in. It would appear from Fig. 1 that short-range order must begin to set in at around twice the Curie temperature, a result in agreement with neutron diffraction experiments of Shull[11] *et al.* on other antiferromagnetics.

III. EFFECT OF THE CRYSTALLINE FIELD

The remainder of the anisotropy in MnF_2 may of course be due to any or all of the mechanisms mentioned in Sec. I. We propose to make what seems to be the only feasible type of calculation at this time, namely, a rough estimate of the anisotropy of type (B) assuming MnF_2 wholly ionic. This assumption is necessary in order to calculate the crystalline field; it may well lead to an erroneous estimate of the type (B) anisotropy. Also this assumption throws out all anisotropy arising from the overlap of Mn^{++} and F^- wave functions. We wish to caution, therefore, that the following calculation is intended to illustrate orders of magnitude only.

Abragam and Pryce[12] explain anisotropy of type (B) in Mn^{++} salts as due to coupling of the $(3d)^5\,{}^6S$ ground state with the $(3d)^4 4s\,{}^6D$ state via the combined action of the crystalline potential V and the magnetic spin-spin interaction between pairs of electrons in an ion. If the crystalline field is distorted from cubic symmetry such that an additional tetragonal component is present,

$$V_{\mathrm{tet}}=H'(2z^2-x^2-y^2), \tag{6}$$

then there will be a contribution of the form DS_z^2 to the Hamiltonian of an individual ion. This is of lower order than the (quartic) contribution from the cubic

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[7] J. H. Van Vleck, J. Chem. Phys. **5**, 320 (1937).

[8] H. Bizette and B. Tsai, Compt. rend. **209**, 205 (1939).

[9] H. Kornfeld, Z. Physik **22**, 27 (1924).

[10] H. Mueller, Phys. Rev. **47**, 947 (1935).

[11] Shull, Strauser, and Wollan, Phys. Rev. **83**, 333 (1951).

[12] A. Abragam and M. H. L. Pryce, Proc. Roy. Soc. (London) **A205**, 135 (1951).

part of the field and hence should be much larger. Pryce[13] calculates D to be equal to H' multiplied by a complicated function of the overlap of the $3d$ and $4s$ wave functions of Mn^{++}. Since most of the anisotropy in a magnetically dilute Mn^{++} salt is due to this cause, measurement of anisotropy in the susceptibility of such a salt gives a direct determination of D. This may be double-checked by comparison with the (absolute) magnitude of D obtained from the fine structure of the paramagnetic resonance spectra.

In this manner Bleaney and Ingram[14] obtained $D=0.024\ \mathrm{cm}^{-1}$ at 230°K for the Tutton salt manganese ammonium sulfate. If now the values of H' are known for this salt and for MnF_2, the size of D in MnF_2 can be estimated. Assuming the $3d$ and $4s$ wave functions of Mn^{++} to be roughly the same in the two salts, D should be roughly proportional to H'.

To estimate H' for the Tutton salt we note that the Mn^{++} ions are surrounded by an octahedron of water molecules elongated along a main axis connecting two of the molecules. With this axis in the z direction the field has tetragonal symmetry about z. It is impossible to calculate this field accurately since the exact locations of the water molecules are not known. Polder[15] has estimated $H'=0.4\times10^{14}$ esu for similar salts of Cu^{++} and we may take this value as being roughly correct for Mn^{++}.

Now we estimate H' for MnF_2 assuming the salt ionic. According to Griffel and Stout[5] the crystalline field is produced by a distorted octahedron of six F^- ions at (1.51, −1.51, 0), (−1.51, 1.51, 0), (1.08, 1.08, ±1.65), (−1.08, −1.08, ±1.65) for one of the Mn^{++} ions in the unit cell, and at (1.51, 1.51, 0), (−1.51, −1.51, 0), (1.08, −1.08, ±1.65), (−1.08, 1.08, ±1.65) for the other Mn^{++} ion. Here the number triples are distances in angstroms from the Mn^{++} ion along (a, a, c) axes. It is seen that these fields for the two Mn^{++} ions in the unit cell are orthogonal to each other and that if we treat the crystal as a whole as pointed out by Yosida,[4] we may consider the fields as tetragonally symmetric about the $z\ (=c)$ axis. Subtracting out the cubically symmetric part of the field one readily finds $H'=-0.2\times10^{14}$ esu.

Crude as these estimates are, they should represent orders of magnitude fairly well.† It is of interest to note that although the field from the water molecules of the Tutton salt is due to the dipole moment of water, it is roughly the same size as the field from F^- ions.

We may now estimate

$$D(\mathrm{MnF}_2)/D(\mathrm{Tutton})=H'(\mathrm{MnF}_2)/H'(\mathrm{Tutton})$$

or

$$D(\mathrm{MnF}_2)=0.024\ \mathrm{cm}^{-1}(-0.2/0.4)=-0.012\ \mathrm{cm}^{-1}.$$

On using Yosida's relation,[4,16]

$$\chi_{\parallel}-\chi_{\perp}=\chi(-D/kT)[0.4S(S+1)-0.3], \tag{7}$$

we find, with $S=5/2$, $\chi_{\parallel}-\chi_{\perp}=0.21\times10^{-5}$ at 295.7°K and 0.34×10^{-5} at 185.1°K. A glance at Fig. 1 shows that this is exactly what is necessary to make the calculated anisotropy agree with the observed. The agreement now is entirely too good, and we wish to caution again that the calculation of this section is meant to indicate orders of magnitude only.

IV. ANISOTROPY BELOW THE CURIE POINT

A. Magnetic Dipole Fields

Below the Curie point for a two sublattice antiferromagnetic with tetragonal symmetry, we expect the anisotropy energy to be of two macroscopic types,[17]

$$f_A'=(K_1/2)(\alpha_1^2+\beta_1^2+\alpha_2^2+\beta_2^2), \tag{8a}$$

and

$$f_A'''=K_3(\alpha_1\alpha_2+\beta_1\beta_2), \tag{8b}$$

where α_1, β_1, γ_1 and α_2, β_2, γ_2 are the direction cosines of the macroscopic magnetization vectors of the two sublattices.

It is seen that f_A' depends only upon the dipole fields produced at a sublattice site by members of the same sublattice, whereas f_A''' depends upon the members of the other sublattice. Since the two sublattices are oppositely directed below the Curie point, we now want a minus rather than plus sign in Eq. (3). If M is the absolute value of the magnetization of a sublattice, it is easily seen that

$$K_1=M^2(\Phi_c'-\Phi_a'); \tag{9a}$$

$$K_3=M^2(\Phi_c''-\Phi_a''). \tag{9b}$$

The effective anisotropy field due to dipoles will be

$$(H_A)_d=(K_1-K_3)/M. \tag{10}$$

Using Eq. (5) one sees that for MnF_2, in which $M_0=590$ gauss at 0°K,

$$(H_A)_d=14.1M=8300(M/M_0)\ \text{oersteds}. \tag{11}$$

A similar result can be obtained from a quantum-mechanical derivation of the antiferromagnetic resonance equations as is done in *KK* except that now magnetic dipole coupling is to be introduced rather than quadrupolar coupling. In this derivation one replaces S_j^z with average values, assumed to be $2M_1^z/Ng\beta$ for members of one sublattice and $2M_2^z/Ng\beta$ for members of the other sublattice. This is a little too

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[13] M. H. L. Pryce, Phys. Rev. **80**, 1107 (1950).

[14] B. Bleaney and D. J. E. Ingram, Proc. Roy. Soc. (London) **A205**, 336 (1951).

[15] D. Polder, Physica **9**, 709 (1942).

† *Note added in proof:* Mr. M. H. Cohen has pointed out to me that one should include electrostatic fields from more distant neighbors, both F^- and Mn^{++}, in estimating H'. This might affect the result by a factor of two or so.

[16] A similar relation for paramagnetics is given by B. Bleaney, Phys. Rev. **78**, 214 (1950).

[17] See Sec. IV of reference 2, hereafter referred to as *KK*, for a discussion of anisotropy in antiferromagnetics. We use the notation of that reference.

crude since, as is well known, the ground-state wave function of an antiferromagnetic is not of the simple form $\alpha_1\beta_2\alpha_3\beta_4\alpha_5\cdots$, even in the absence of magnetic dipole interactions. Also there will be fluctuations from the average values of S_j^z due to zero point motion. Tessman[18] has shown that such fluctuations in a cubic array of parallel magnetic dipoles lead to dipolar anisotropy fields of the order of $0.2M/S$ or 50 oersteds for $M=590$; $S=5/2$. It is not unreasonable to suppose that quantum-mechanical effects in an antiparallel array such as MnF$_2$ will be of the same order of magnitude. We shall therefore neglect such effects in comparison with our calculated anisotropy.

On following through the quantum-mechanical derivation of antiferromagnetic resonance one finds that in case $|M_1^z|\neq|M_2^z|$, or the z components of the magnetizations of the two sublattices differ in size due to the presence of a field H_0, the effective anisotropy field for resonance is

$$(H_A)_d=7.05(M_1^z-M_2^z). \tag{12}$$

This field is to be inserted into the resonance relation (Eq. (26) of *KK*)

$$\omega/\gamma\cong H_0(1-\tfrac{1}{2}\alpha)\pm[2H_EH_A+(\tfrac{1}{2}\alpha)^2H_0^2]. \tag{13}$$

Here it is assumed that the static field H_0 is applied parallel to the domain axis; H_E is the effective exchange field which, in terms of an exchange parameter λ, equals $\frac{1}{2}\lambda(M_1^z-M_2^z)$; $\alpha=\chi_{\|}/\chi_{\perp}$; $\gamma=ge/2mc$ is the magnetomechanical ratio.

B. Remainder of the Anisotropy

We consider the remainder of the anisotropy as expressible by a term $\sum_j D(S_j^z)^2$ in the Hamiltonian, where the summation is taken over all ions of both sublattices. The anisotropy field is easily obtained from a quantum-mechanical derivation of the resonance relation

$$(H_A)_r=-(2D/Ng^2\beta^2)(M_1^z-M_2^z)+(D/g\beta). \tag{14}$$

Here $\frac{1}{2}N$ is the number of ions per cm^3 in a sublattice, β is the magneton, $g=2$ for Mn^{++}. The last term of Eq. (14) is to be used only near saturation and should be dropped near the Curie point.[19] Using the value of D obtained in Sec. III we find for the remainder of the anisotropy

$$(H_A)_r\simeq 0.55(M_1^z-M_2^z)-130; \tag{15}$$

and hence for the total effective anisotropy field to be inserted into Eq. (13)

$$H_A\simeq 7.6(M_1^z-M_2^z)-130, \tag{16}$$

where the 130 should be dropped near the Curie point.

We note that at 0°K the total anisotropy field is approximately 8800 oersteds, of which 8300 oersteds comes from dipolar interactions and 500 oersteds from interactions with the crystalline field. The last figure is probably more accurate than our calculation of Sec. III would indicate since we may consider our value of D as being given by Stout and Griffel's[3] measurements. We are assuming that all types of anisotropy other than magnetic dipole may be expressed by a term $\sum_j D(S_j^z)^2$ in the Hamiltonian.

C. Measurement of Anisotropy

One method of measuring H_A below the Curie point has been discussed by Yosida.[4] This consists of applying a sufficient field H_0 along the easy (c) axis to cause the magnetizations to flop to the hard (a) axis. This flop takes place since $\chi_{\perp}>\chi_{\|}$, and hence the free energy can be lowered if the magnetization can partake of perpendicular susceptibility. It will occur for a field H_0 at which $\omega=0$ in Eq. (13), for at this point there is no restraining torque. This condition is

$$(H_0)_{\text{crit}}=[2H_EH_A/(1-\alpha)]^{\frac{1}{2}}. \tag{17}$$

In estimating H_E we shall use molecular field theory to assume $H_E=\lambda M=\chi_{\perp}^{-1}M$. Molecular field theory is known to give poor estimates of the exchange integral and hence of the field parameter λ. However, as is shown in the quantum-mechanical derivation in *KK*, only exchange interactions between members of different sublattices enter into antiferromagnetic resonance. It is precisely these interactions which are also effective in determining $\chi_{\perp}$. That $\lambda=\chi_{\perp}^{-1}$ is a good approximation for our purposes is confirmed by a spin-wave calculation of $\chi_{\perp}$ and of the resonance condition near 0°K.

Stout and Griffel[3] show $\chi_{\perp}$(molal) as dropping from 0.028 to 0.024 between 0°K and the Curie point. We shall for simplicity take it equal to 0.026 per mole or 0.0011 per cm^3. Thus

$$\begin{aligned} H_E&=(0.0011)^{-1}(M/M_0)M_0\\ &=5.4\times10^5(M/M_0)\text{ oersteds,} \end{aligned} \tag{18}$$

where M_0 is the saturation magnetization of one sublattice, or 590 gauss. Combining this with the result of Sec. IVB, namely,

$$H_A=8800(M/M_0)\text{ oersteds,} \tag{19}$$

we have

$$(2H_EH_A)^{\frac{1}{2}}=1.0\times10^5(M/M_0)\text{ oersteds.} \tag{20}$$

Thus $(H_0)_{\text{crit}}=1.0\times10^5$ oersteds at 0°K. This is larger than Yosida's[4] estimate of 0.7×10^5 oersteds since our anisotropy field is larger than his (due to subtraction of dipole field factors).

The temperature dependence of $(H_0)_{\text{crit}}$ may be obtained from Eq. (17) using the Stout and Griffel[3] measurements of α combined with Eq. (20). We note

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[18] J. Tessman, Phys. Rev. **85**, 752 (1952) and private communication.

[19] It comes from using the approximation

$$(S_j^xS_j^z+S_j^zS_j^x)=[\langle S_j^z\rangle_{\text{Av}}+\tfrac{1}{2}]S_j^x.$$

The $\frac{1}{2}$ is necessary only near saturation and leads to the term in question.

that (M/M_0) varies as the Brillouin function for $S=5/2$. It is found that $(H_0)_{\text{crit}}$ rises nearly linearly from 10^5 oersteds at $0.2T_c$ to 1.7×10^5 oersteds at T_c. This is essentially the same dependence as given by Yosida.[4]

Another method of measuring H_A is by means of antiferromagnetic resonance. Here in the absence of a field H_0 the resonance frequency is given by

$$\omega/\gamma\cong(2H_EH_A)^{\frac{1}{2}}=1.0\times10^5(M/M_0), \qquad (21)$$

where use has been made of Eq. (20). This frequency corresponds to a wavelength[20] of 1.1 mm at 0°K and about 2 mm at $0.9T_c$. Above this temperature our theory should break down as there is no justification for a simple two-sublattice picture near the Curie point.

By using 1-cm waves Hutchison[21] has found a complete disappearance of the paramagnetic resonance line of MnF_2 as the temperature drops below 67°K.

In the absence of millimeter waves one could take advantage of the minus sign in Eq. (13) and employ large fields H_0 to bring the resonance into centimeter range.[22] This requires fields just short of the critical field, i.e., fields increasing from 10^5 oersteds at 0°K to 1.7×10^5 oersteds near the Curie point. The reason the fields must be just short of the critical field is that the critical field represents the size of H_0 necessary to bring the resonance frequency to zero.

I should like to express my thanks to Professor Kittel for many stimulating discussion of antiferromagnetism. This research was assisted in part by the ONR.

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[20] The reader is cautioned that these estimates are subject to the uncertainties in H_E and H_A mentioned above.

[21] C. A. Hutchison (private communication to Professor Kittel).

[22] This possibility was first pointed out by C. Kittel, Phys. Rev. **82**, 565 (1951).

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Cross Sections of the D(T,*n*)He^4 Reaction for 80- to 1200-Kev Tritons

H. V. Argo, R. F. Taschek, H. M. Agnew, A. Hemmendinger, and W. T. Leland
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

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Gas targets of deuterium with an aluminum entrance foil of 1.5 mg/cm^2 were bombarded by tritons. Straggling and scattering of the tritons by the foil have been carefully considered and found to introduce reasonably small corrections. Energy loss in the entrance foil was determined by assuming that the sharp resonance peak in the reaction occurs at 165-kev triton energy as measured by T. W. Bonner, and then making use of the dE/dx curve of S. D. Warshaw. Neutrons from the reaction were observed by means of a BF_3 long counter whose energy response has been investigated. Angular distributions of the neutrons were measured and found to be isotropic in the c.m. system below 600 kev. Near 1 Mev the distributions deviate from isotropy, more neutrons coming off at the back angles. The maximum cross section is 4.93 barns at the resonance. The limit of error on cross sections is ±10 percent. A one-level nuclear dispersion formula has been fitted to the experimental curve and the resonance is ascribed to a level in the He^5 compound nucleus, arising from an S-wave interaction of the T and D, with quantum numbers $J=\frac{3}{2}$, $l=2$.

I. INTRODUCTION

THE reaction

$$\mathrm{T}+\mathrm{D}\rightarrow\mathrm{He}^4+n+17.577\pm0.02\ \mathrm{Mev}$$

has proved to be a very useful laboratory source of high energy monoenergetic neutrons. Although many experimenters have been making use of the reaction for a neutron source, the yield in the low energy region has not been well known. Early experimenters[1] have shown that the yield is very high and indicated the existence of a strong nuclear resonance in the vicinity of 200-kev incident triton energy. In the region between 200- and 1500-kev triton energy the cross section is particularly poorly known. There have been arguments that the rise at 200 kev may not be a resonance.[2] The above uncertainties and the general interest in the reaction inspired the present investigation. The measurements described in this paper were made during the summer of 1950.

The earlier measurements showed an isotropic yield in the c.m. system at the low energies. Since the angular distribution is very helpful in the assignment of states it was decided to check the isotropy near 200 kev and also at the higher energies.

II. EXPERIMENTAL PROCEDURE

The experimental method followed in determining the absolute cross section for the D(T,*n*)He^4 reaction was to

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[1] Baker, Holloway, King, and Schreiber, Atomic Energy Commission Declassified Report No. 2226 (1943); E. Bretscher and A. P. French, Phys. Rev. **75**, 1154 (1949); Taschek, Everhart, Gittings, Hemmendinger, and Jarvis, Atomic Energy Commission Declassified Report No. 2250 (1948); D. L. Allan and M. J. Poole, Nature **164**, 102 (1949); D. L. Allan and M. J. Poole, Proc. Roy. Soc. (London) **204**, 488 (1951); D. L. Allan and M. J. Poole, Proc. Roy. Soc. (London) **204**, 500 (1951).

[2] D. L. Allan and M. J. Poole, Proc. Roy. Soc. (London) **204**, 488 (1951).