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# A Method for Measuring Magnetization to High Pressures

C. R. Johansen

Mark H. Nelson

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**Authors**

C. R. Johansen, Mark H. Nelson, and J. H. Gardner

that of a polycrystalline wire. At low energies, the trapped gas may play a significant role in addition to other factors such as crystalline transparency.

The author is indebted to Dr. E. V. Kornelsen for permission to use his unpublished data on saturation numbers of inert gas ions in tungsten. Thanks are also due to Dr. D. G. Worden for reading the manuscript.

<sup>1</sup> R. V. Stuart and G. K. Wehner, *J. Appl. Phys.* **33**, 2345 (1962).

<sup>2</sup> D. Rosenberg and G. K. Wehner, *J. Appl. Phys.* **33**, 1842 (1962).

<sup>3</sup> H. G. Scott, *J. Appl. Phys.* **33**, 2011 (1962).

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<sup>5</sup> R. C. Bradley, *Phys. Rev.* **93**, 719 (1954).

<sup>6</sup> G. J. Ogilvie, J. V. Sanders, and A. A. Thomson, *J. Phys. Chem. Solids* **24**, 247 (1963).

<sup>7</sup> E. V. Kornelsen, *Can. J. Phys.* **42**, 364 (1964).

<sup>8</sup> E. V. Kornelsen and M. K. Sinha, *Appl. Phys. Letters* **9**, 112 (1966).

<sup>9</sup> The value of the sticking probability  $S_0$  used is that for a wire.<sup>7</sup> It is felt that if all ions strike the specimen normally, the value of  $S_0$  and hence,  $N_{\text{sat}}$  will be larger. Experiments with single crystals<sup>12</sup> and W polycrystal for normally incident ions tend to confirm this view.

<sup>10</sup> A. L. Southern, W. R. Willis, and M. T. Robinson, *J. Appl. Phys.* **34**, 153 (1963).

<sup>11</sup> G. S. Magnuson and C. E. Carlston, *J. Appl. Phys.* **34**, 3267 (1963).

<sup>12</sup> E. V. Kornelsen and M. K. Sinha (unpublished).

## A Method for Measuring Magnetization to High Pressures\*

C. R. JOHANSEN,<sup>†</sup> H. M. NELSON, AND J. H. GARDNER  
*Department of Physics, Brigham Young University, Provo, Utah*  
(Received 6 November 1967)

A partially successful attempt has been made to measure the magnetic moment per unit volume of ferromagnetic materials as a function of pressure to the 100-kbar region. The apparatus, an early version of which has been described previously,<sup>1</sup> consists basically of two opposed Bridgman flat anvils of alumina. One anvil also acts as a dielectric-filled microwave resonant cavity for an x-band spectrometer, allowing electron spin resonance studies to be made to high pressure. The sample to be studied is placed in contact with the anvil-cavity and covered with a pressure-transmitting medium which in turn is encircled by a flat pyrophyllite gasket. Indium has proven to be the most suitable pressure transmitting medium. This system consistently performs well to pressures above the Bi I-II transition ( $\sim 26$  kbar) and somewhat less reliably to pressures about the Bi III-V transition ( $\sim 76$  kbar). Bismuth transitions are used as calibration points.

The following technique is used to measure the magnetization of a ferromagnetic sample as a function of pressure. A small flat disk which will fit inside the pyrophyllite washer is formed from the sample material. A very thin coating of DPPH is placed on the bottom of the disk and in contact with the cavity anvil. The pressure assembly and sample is then as shown in Fig. 1. In this

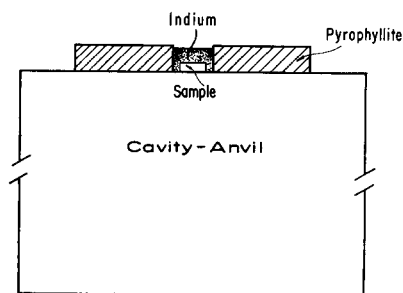


FIG. 1. A drawing showing the sample arrangement relative to the pressure seal and the cavity anvil.

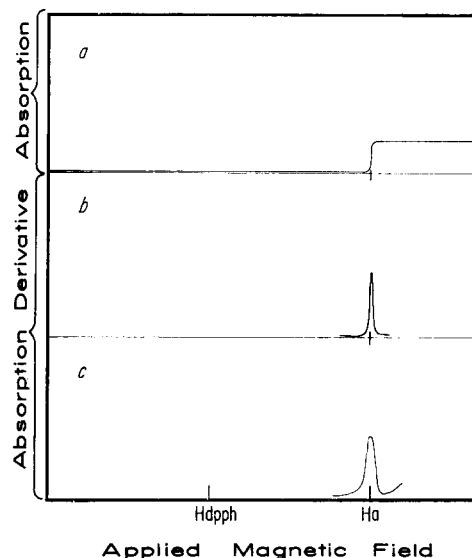


FIG. 2. (a) Idealized EPR absorption vs magnetic field graph for DPPH on the face of a uniformly magnetized disk. (b) Derivative graph of idealized absorption graph in (a). (c) Experimental tracing of DPPH on the face of a uniformly magnetized disk of nickel. (Not to scale.)

configuration it is the resonance of the DPPH which is displayed by the spectrometer. DPPH is a strongly resonant free radical which exhibits a narrow absorption peak. Separate investigation has shown that the DPPH resonant position is independent of pressure to above the pressure of the Bi III-V transition. Consequently, any change in the magnetization of the ferromagnetic sample is observed as a shift in the expected resonance position of the DPPH. This is due to a change in the demagnetizing field of the sample in which the DPPH finds itself.

The demagnetizing field of a thin disk lends itself to the above measurement. The disk is first uniformly magnetized in the  $z$  direction chosen along a diameter. The important direction of the demagnetizing field for observational purpose is also the  $z$  direction. This component of the demagnetizing field has a magnitude on the surface of the disk which has a relative minimum at the axis of the disk. The apparent resonant field of the DPPH is both raised and spread out as a result of the demagnetizing field; however, there is a sharp lower edge to the resonance because of the relative minimum. Figure 2 shows the calculated absorption curve for DPPH in the demagnetizing field, the first derivative of the absorption, and a recorder tracing from the spectrometer for a nickel sample. The spectrometer presentation is a first derivative presentation. The demagnetizing field  $H_D$  is then given by  $H_D = H_a - H_{\text{DPPH}}$ , where  $H_a$  is the apparent resonant field of the DPPH at the center of the sample and  $H_{\text{DPPH}}$  is the actual DPPH resonant field. Saturation magnetization of the sample can now be calculated from  $H_D$ :  $M_s = [(a^2 + t^2)^{1/2} / \pi t] H_D$ , where  $t$  is the thickness of the sample and  $a$  is the radius. While this is possible, it is not too useful since sample dimensions become very critical in the calculation, and measurement of sample dimensions introduces the limiting error. A more useful approach is to use a known value of  $M_s$  at zero pressure for each sample and find the proportionality constant for each sample. This constant is then used for subsequent computations at higher pressures. It should be noted that the proportionality constant does not depend on the absolute dimensions of the sample but only on the sample shape. As a result, assuming uniform sample compressibility and no deformation, the same constant of proportionality is valid to high pressures.

Small sample disks of nickel and iron were prepared. The disks were about 0.010 in. thick and 0.060 in. in diameter. In the case of nickel, the applied magnetic field necessary to cause saturation

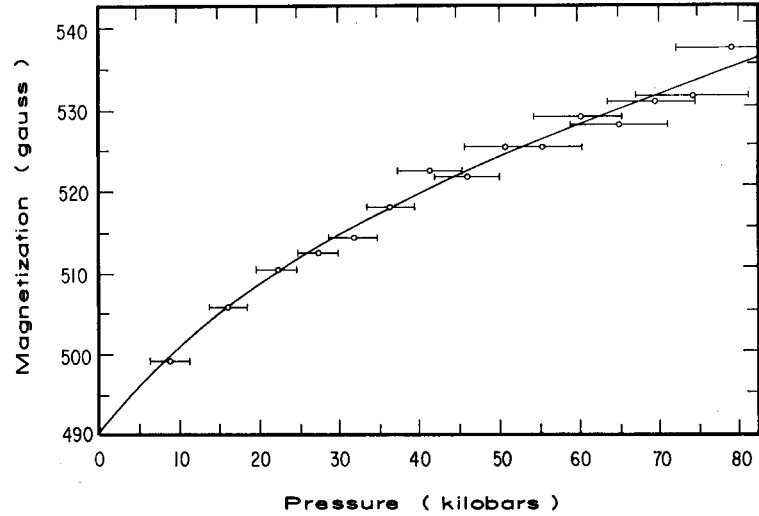


FIG. 3. Saturation magnetization for nickel as a function of pressure. Error flags indicate standard deviation.

is approximately the same as the field necessary for DPPH resonance at x-band. The results obtained for nickel are shown in Fig. 3. The magnetization data is accurate to  $\pm 1$  G while the error in pressure is 5 kbar or 20%, whichever is greater. This data can be compared with that of other workers.<sup>2-4</sup> No valid results could be obtained for iron since at x-band the resonance of DPPH occurs at magnetic fields well below the applied field necessary to saturate iron. The resulting magnetization of the iron is non-uniform and the accompanying demagnetizing field does not provide useful data.

This electron paramagnetic resonance method of measuring magnetization is very sensitive and the resonance position itself can be measured with high precision because of the narrowness of the free radical resonance line. This method has the added advantage of being independent of sample compressibility and search coil areas and/or deformation. A limitation of this technique is the requirement of magnetic saturation at low magnetic fields. This limitation could be removed, perhaps, by choosing in place of DPPH a probe material which requires higher fields for resonance at x-band, or by using a higher frequency microwave spectrometer. In practice other problems also arise which are associated with the press. The particular geometry in which the sample is mounted is very sensitive to any difficulty in the pressure anvil assembly and pressure transmitting medium, often resulting in nonhydrostatic loading and bulk deformation of the sample. Additionally, accurate *in situ* calibration of this type of press is very difficult leading to pressure measurement as a limiting source of error.

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† Present address: Department of Physics, Western Washington State College, Bellingham, Wash.

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### On the Effective Index of Refraction of Plasmas

A. D. POULARIKAS

University of Rhode Island, Kingston, Rhode Island

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It is known that the propagation of an electromagnetic wave in an isotropic plasma is similar to the propagation of the wave in

a dielectric medium. When, in addition, there exist coagula of finite dimensions and are much smaller than the wavelength of the propagating wave, their effect can be studied (a) by considering the concentrations as scatterers, or (b) by considering an effective index of refraction. Papas<sup>1</sup> has found the equivalent index of refraction of a spatially periodic plasma and he applied his results to plasmas with periodically spaced spherical coagula. In this note we develop an effective index of refraction when the inhomogeneities are not periodically located and, in addition, there exist  $k$  number different coagula embedded in the plasma.

Generalizing the works of Odelevskii<sup>2</sup> and Korneenko,<sup>3</sup> we assume that we have  $k$  different types of coagula, each type having a specific volume concentration  $\beta_{ik}$  and a specific electron density. Next we take a volume  $V_0$  whose total surface is  $S_0$ . The surface  $S_0$  is composed of the outside surface  $S$ , the surfaces  $S_{ik}$  around the  $i$ th coagulum belonging to the  $k$ th type and the surfaces belonging to cuts from the outside surface  $S$  to  $S_{ik}$ . Using the divergence theorem

$$\int_{V_0} \nabla \cdot (\phi_0 \nabla \psi) dV = \int_{V_0} \nabla \phi_0 \cdot \nabla \psi dV, \quad (\nabla^2 \psi = 0), \quad (1)$$

we find the relation

$$\oint_S \phi_0 \nabla \psi \cdot d\vec{S} - \sum_{k=0}^k \left( \sum_{i=0}^i \oint_{S_{ik}} \phi_0 \nabla \psi \cdot d\vec{S} \right) = \int_{V_0} \nabla \phi_0 \cdot \nabla \psi dV, \quad (2)$$

where the subscripts 0 and  $i$  indicate that the quantities involved belong to the volume  $V_0$  or  $V_i$ .

Choosing first  $\nabla \phi_0 = -\vec{E}_0$  and  $\nabla \psi = \vec{n}$  ( $\vec{n}$  unit vector  $\perp$  to the surface  $S$ ) Eq. (2) becomes

$$-\int_{V_0} \vec{E}_0 \cdot \vec{n} dV = \oint_S \phi_0 \nabla \psi \cdot d\vec{S} - \sum_{k=1}^k \left( \sum_{i=0}^i \oint_{S_{ik}} \phi_0 \nabla \psi \cdot d\vec{S} \right). \quad (3)$$

The boundary conditions at the surfaces between the inclusions and the host medium are  $\phi_0 = \phi_{av}$  ( $\vec{E}_{av} = -\nabla \phi_{av}$ ) and  $\phi_0 = \phi_{ik}$ . Introducing these conditions into Eq. (3) we find the relation

$$-\int_{V_0} \vec{E}_0 \cdot \vec{n} dV = -\int_V \vec{E}_{av} \cdot \vec{n} dV + \sum_{k=1}^k \left( \sum_{i=0}^i \int_{V_{ik}} \vec{E}_{ik} \cdot \vec{n} dV \right). \quad (4)$$

Using average values for the field quantities, Eq. (4) becomes

$$V \vec{n} \cdot \vec{E}_{av} = V_0 \vec{n} \cdot \vec{E}_0 + \sum_{k=1}^k \left( \sum_{i=0}^i V_{ik} \vec{n} \cdot \vec{E}_{ik}^* \right), \quad (5)$$

where  $V = V_0 + \sum_k (\sum_i V_{ik})$ , and the symbol \* indicates the average value of a quantity.

Introducing the new relations  $\nabla \psi_0 = -\vec{E}_0$  and  $\nabla \phi = \vec{n}$ , and the boundary conditions  $\epsilon_k \nabla \psi_{ik} = \epsilon_0 \nabla \psi_0 = \epsilon_{av} \nabla \psi_{av}$  into Eq. (1), we