PHYSICAL REVIEW B VOLUME 40, NUMBER 13 1 NOVEMBER 1989

Thermally induced flux motion and the elementary pinning force in Nb thin films

M. J. Goldstein
Naval Coastal Systems Center, Code 2110 Building 110, Panama City, Florida 32401

W. G. Moulton
Department of Physics and Center for Materials Research and Technology, 411 Keen Building, Florida State University, Tallahassee, Florida 32306
(Received 22 May 1989)

The thermally induced flux motion and the elemental pinning force f_p for Nb thin films (1000–5000 Å) were measured for applied magnetic fields ranging from 0.3 to 7.5 G and temperatures from 4.22 to 5.72 K. The magnitude of $f_p(H,d,T)$ ranged from 10^{-12} to 10^{-11} N/m. This is approximately 6 orders of magnitude smaller than Lorentz-force depinning measurements made on thin-film Nb for the low-field regime (~7 G) of isolated or weakly interacting flux lines. Some of these results are similar to the work of Huebner *et al.*, who also found a large discrepancy in pinning-force values derived from Lorentz-force and thermal-force measurements for the high-field regime (flux-line lattice). Our results suggest that a transport current flows between the trapped flux lines such that the Lorentz force is minimized. This channeling produces a current density around a pinned flux line that is greatly reduced below the measured current divided by the cross-sectional area. This is believed to lead to a discrepancy in the value of the pinning force measured by thermal gradients with those obtained in transport current measurements. The $\Delta\Phi$ versus ΔT data, for small ΔT values, implied a spectrum of pinning-force values where the flux lines that were depinned had substantially weaker pinning forces than the vast majority of the flux lines that remained pinned. Using statistical arguments, the qualitative features of the $f_p(H,d)$ and $\Delta\Phi(H,d)$ data are explained. The data exhibited a magnetic-field threshold, below which there is no flux motion for the temperature range studied. This threshold field increased with increasing thickness.

I. INTRODUCTION

Conventional measurements of flux pinning in type-II superconductors are made at magnetic fields above H_{c1}. For this field regime, F_p, the pinning force per unit volume, is determined. This force is a summation carried over the collection of flux lines of the individual attractive forces which act on each flux line while taking into account the repulsive interaction between flux lines.[1] Due to their mutual repulsion, a symmetric flux line lattice (normally triangular) is established whose elastic properties permit flux lines to migrate towards pinning centers. The summation of individual pinning forces to yield F_p is complicated, and considerable disagreement exists as to the best method for summing individual pinning forces.[2,3]

Measurements made at sufficiently low fields can yield the maximum value of the pinning force of an individual flux line, f_p, due to a particular mechanism because interactions between flux lines become small, and the fluxoids are free to move towards the pinning centers.

It has been demonstrated that a temperature gradient can act as a driving force on trapped flux structures,[4–13] depin flux lines, and produce flux motion in superconductors. At the onset of the flux motion, the driving force is equal to the pinning force. Thus, a measurement of the driving at the onset of flux motion for an isolated flux line yields its pinning force. The thermal force arising from a temperature gradient is shown to be

$$f_p = S_\Phi \nabla T \ , \tag{1}$$

where the elementary pinning force f_p is the force per unit length of a single flux line, S_Φ is the transport entropy per unit length of flux line, and $\nabla T = dT/dx$ for a one-dimensional temperature gradient. For a type-II superconductor, S_Φ is is calculated from

$$S_\Phi = -(\Phi_0/4\pi)\frac{\partial H_{c1}(T)}{\partial T} \ , \tag{2}$$

where H_{c1} is the lower critical field and Φ_0 is the flux quantum. The form of Eq. (1) is valid only for small values of ∇T such that the density of superconducting electrons, n_s, S_Φ, and f_p do not vary significantly along the direction of the temperature gradient. For the case of the Lorentz force due to an electrical transport current

$$f_p = \mathbf{J}_c \times \mathbf{\Phi}_0 \ , \tag{3}$$

where $\mathbf{J}_c$ is the critical value of the current density (critical current) and $\mathbf{\Phi}_0$ is again the flux quantum. The value of f_p obtained by measuring the temperature gradient necessary to produce an onset of motion using (1) and (2) should be the same as the value of f_p obtained from measuring $\mathbf{J}_c$ and using Eq. (3) for the same pinning mechanism.

The flux pinning and flux motion for Nb thin films were studied for applied magnetic fields ranging from 0.3 to 7.5 G. The thermal force of a longitudinal temperature gradient was used to depin flux lines and generate flux motion. This field regime is well below H_{c1} and the density of flux lines is such that they should act individually, and the collective pinning effects associated with higher fields and a flux-line lattice should be negligible. In this regime the elementary pinning force can be directly measured.

The minimum temperature gradient necessary to induce an onset of flux motion was measured, and from Eqs. (1) and (2) f_p was derived. $f_p(H,T,d)$ was also determined. $\Delta_\Phi(\Delta T,T,d,H)$, the amount of flux depinned as a function of the temperature change, mean film temperature, sample thickness, and applied field was measured to yield information about the spectrum of pinning forces and the probability for depinning.

II. EXPERIMENTAL

The Nb films used in these experiments were prepared by Pierce of the Florida State University Physics Department. The films were deposited on fused silica substrates (0.1-cm thick) cut to 1.3×3.8 cm^2. The films had superconducting transition temperatures of approximately 8.9–9.1 K and residual resistance ratios ranging (RRR's) from 5.1 to 9.1. Films made under identical conditions[14] with similar T_c and RRR values were found to have equiaxed grains with average grain sizes of 250–300 Å for the thickness range studied (1000–5000 Å).

Figures 1 and 2 show the experimental system and the sample can. The magnet, which contains 450 turns of wire with a 1.4-cm diameter, is placed directly below the film's center without touching its surface. (It is not shown in Fig. 2.) This coil provides the perpendicular applied field. Calibrated silicon diode thermometers are used to measure the temperatures at the ends of the film. A calculation[12] of the substrate's heat transfer properties revealed that the temperature gradient established is very close to linear. A 0.13-cm loop of 8-ml NbTi wire serves as a superconducting pickup loop which is placed directly above the film's center, well away from the sample edges to eliminate edge effects, but not in thermal contact with the sample. This loop is inductively coupled to a SHE model 330 rf SQUID system which detects flux motion and depinning in the film as a change in the flux through the pickup loop. The sample can is in direct thermal contact with a liquid-helium bath so that the film remains at a constant 4.2 K unless heated via the noninductively would manganin wires which serves as heaters. The sample can, the SQUID, and the conduit that houses the NbTi pickup wire are all magnetically shielded by thick Nb foil. The entire probe system is placed inside a mu-metal room where the ambient magnetic field is reduced to less than 10 mG. Calibration of the system is made by passing a small, known, current through the magnet, which was calibrated with a Hall probe, and observing the output of the SQUID. A field corresponding

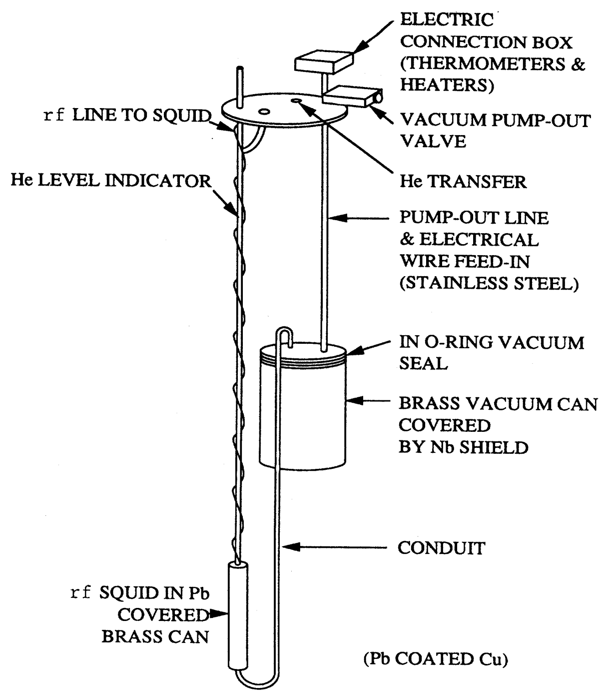

FIG. 1. Experimental apparatus; probe for flux pinning experiment.

to $0.05\Phi_0$ gives a one-to-one signal-to-noise ratio with no superconducting film in place.

The general procedure for running an experiment is as follows: The film is heated above T_c; the magnet is

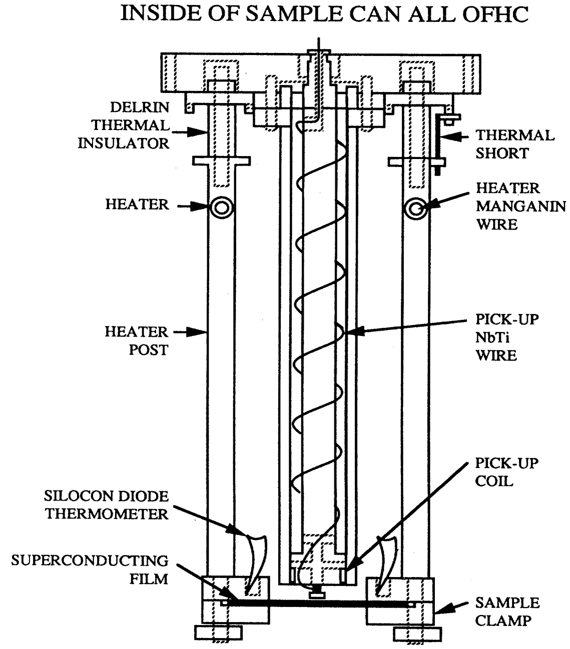

FIG. 2. Illustration of the experimental features inside the sample can.

turned on to produce the perpendicular field; the heater currents are slowly decreased and the film is allowed to cool in the field through T_c to trap flux. When the desired baseline film temperature is achieved, a SQUID output baseline signal to established. After a few minutes of baseline response, a small temperature gradient is slowly established and slowly increased until a change in the SQUID signal is noted. The heaters are then adjusted to bring the film back to the initial uniform temperature. No signal change has ever been observed during this heat reduction phase. Runs with a Cu film under the same conditions gave no observable signals. The heaters are then adjusted to bring the film back to the same temperature gradient that first induced the irreversible signal change. It is always observed that this second heating procedure, identical to the initial procedure, produces no additional signal changes. These heater adjustment phases can be repeated for a third or fourth time with the same results for the second identical gradient produced; we conclude that no additional irreversible signal changes occur unless subsequent heater adjustments produce a larger temperature gradient than the original gradient produced by the first heater adjustment procedure. The film end's temperature can be ramped up and down to yield the amount of flux depinned, $\Delta\Phi$, as a function of the difference in film end temperature ΔT. After the ramping procedure, the film is heated above T_c to expel all trapped flux, and then allowed to cool again in an applied perpendicular field. These procedures are repeated for various values of the applied field, mean sample temperature, and sample thickness.

III. RESULTS

The minimum or critical temperature change across the film ends (ΔT_{min}) necessary to produce an onset of flux motion was measured. Assuming a linear temperature gradient, $\Delta T_{\text{min}}/2.6\ \text{cm}=\nabla T$. Using Eqs. (1) and (2), the elementary pinning force per unit length of flux line f_p, was calculated. In calculating the transport entropy per unit length of flux line, S_Φ, from Eq. (2), we have assumed a reported bulk value[19] for $H_{c1}(T)$. This may introduce some error in the calculation of f_p. Representative numbers are 40 mK for ΔT_{min} and 1375 Oe for H_{c1} at 4.7 K.

Figure 3 shows the dependence of the pinning force,

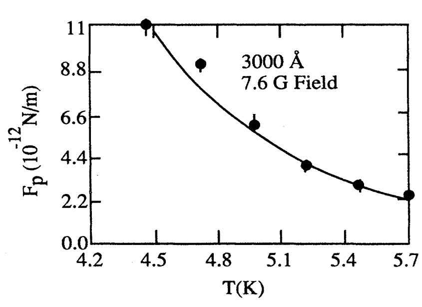

FIG. 3. The elementary pinning force is plotted as a function of temperature. The sample is 3000 Å thick and was cooled in a 7.5-G perpendicular field.

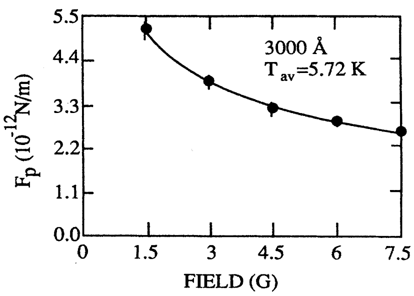

FIG. 4. The elementary pinning force plotted as a function of applied field. The sample is 3000 Å thick and the mean temperature is 5.72 K.

$f_p(T)$. The data were fit to a power $f_p \propto (1-T/T_c)^n$, to compare with other low-field measurements[16] on the thin-film Nb. The methods of least squares yields $n=3.5\pm0.4$, which is in excellent agreement with the other measurements.[16]

Figure 4 shows the pinning force as a function of the field in which the film was cooled through its transition temperature, $f_p(H)$. The data show a monotonic decrease in f_p with increasing H.

Figure 5 is the dependence of f_p on film thickness, $f_p(d)$. The data show a monotonic increase of f_p with respect to increasing d.

Figure 6 is a plot of the number of flux lines moved by the thermal force $\Delta\Phi$ versus the film end temperature difference ΔT for the 1000-Å Nb sample. The data show that $\Delta\Phi$ is monotonically increasing in ΔT and $d^2\Phi/dt^2$ is positive. As the ΔT value is increased by some fixed increment, additional flux lines exhibit flux motion.

From the data, it appears that there is a distribution of pinning-force values. The distribution for the first hundred or so flux lines that are depinned may be calculated from the $\Delta\Phi$ versus ΔT data. For a particular value of ΔT and a linear temperature gradient, the corresponding f_p value can be calculated from Eqs. (1) and (2). The $\Delta\Phi$ value associated with this particular ΔT value is the number of flux lines with this f_p value that were moved by the thermal force. Thus, the $\Delta\Phi$ versus ΔT data are a scaled representation of the number of flux lines, n, with a par-

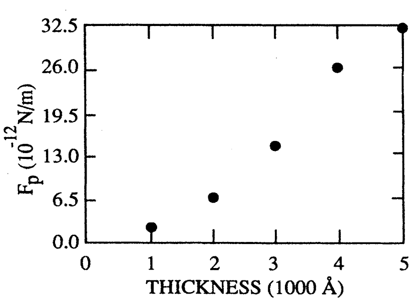

FIG. 5. The elementary pinning force is plotted as a function of film thickness. The applied field is 7.5 G and the mean temperature is 5.72 K.

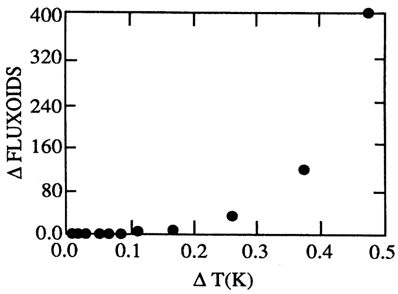

FIG. 6. $\Delta\Phi$ vs ΔT plotted for a 1000-Å film cooled in a 7.5-G field with a mean temperature of 4.52 K. $\Delta\Phi$ is the amount of flux moved, and ΔT is difference in film end temperature.

ticular pinning-force value, f_p. Figure 7 is a plot of $n(f_p)$ where n is the number of flux lines with a particular f_p value. Due to the large number of pinned flux lines that do not exhibit flux motion, this distribution of pinning forces represents the low pinning tail of a larger spectrum of pinning force values.

IV. DISCUSSION

The most striking result of these experiments is a six orders of magnitude discrepancy between f_p values derived in this thermally induced flux motion experiment and those values derived from Lorentz-force measurements for the same low-field regime and for thin-film Nb.[16] It is also interesting to note that all of the flux lines did not have similar f_p values, and a broad spectrum of pinning-force values may exist. Some preliminary remarks concerning data interpretation in the low-field regime are presented before the discrepancy in the magnitude of f_p and a comparison with other f_p experiments are addressed.

In order to interpret the experimental results we must understand the significance of the $\Delta\Phi$ versus ΔT data. The $\Delta\Phi$ versus ΔT data yield information about how many flux lines are moved by a particular value of the driving force which can be used to determine the distribution of pinning-force values. The onset value of ΔT or

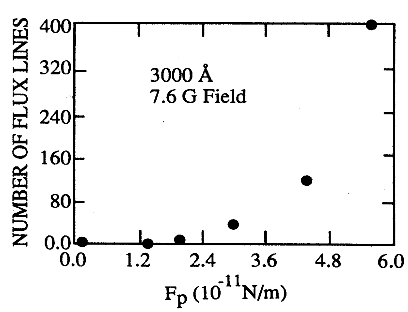

FIG. 7. $n(F_p)$, the number of flux lines depinned as a function of pinning force, plotted for a 1000-Å film cooled in a 7.5-G field with a mean temperature of 4.52 K.

∇ is used in determining f_p, but this f_p value corresponds to the lowest pinning force of an ensemble of $\sim 10^7$ flux lines. This is not an average or typical pinning-force value for a collection of weakly interacting ($H \ll H_{c1}$) flux lines. Over the range of ∇T studied, from 10 mK/cm to 1 K/cm, only $\sim 10^2$ flux lines were depinned. In the low-field regime with very weakly interacting flux lines, the most weakly pinned flux lines move first. This holds for a random distribution of flux lines, a weakly interacting flux-line lattice, and small clusters of flux lines that do not form a strongly interacting miniature flux-line lattice.

Hyun *et al.*[17] measured the elementary pinning force for a single flux line trapped in one of the superconducting layers of a cross-strip Josephson junction at temperature close to the transition temperature. The driving force was the Lorentz force of an electrical current. The transport current moved the flux line from one strong pinning site to several others before exiting the junction. The position of the vortex was imaged and the flux motion inferred from the diffraction pattern in the Josephson critical current versus applied parallel fields, I_c versus B. The pinning force was computed from I_pB, where I_p is the depinning current.

Low-field measurements, where the response of the most weakly hundred or so out of $\sim 10^7$ pinned flux lines is used to determine f_p, can be compared to the measurements of a single or a few individual fluxoids trapped in a Josephson junction.[17,18] The f_p for single flux-line experiments will probably be averaged or larger than average values of the spectrum of available pinning sites, whereas these measurements will select the lowest occupied pinning sites. A single flux line trapped in a junction can chose from many vacant strong pinning sites.

V. COMPARISON OF THE MAGNITUDE OF f_p

This is the only experimental work we are aware of to determine $n(f_p)$ for weakly interacting flux lines by thermal gradient methods, but the magnitude of the pinning force at the onset of flux motion can be compared with the results of Allen and Claassen using a SQUID.[16] They measured the critical value of the current, J_c, by detecting an irreversible signal change in their SQUID's output characteristic of flux motion occurring in their film. The applied perpendicular field in their experiment was $\sim$1G, their pick loop area was one order of magnitude larger than one used by us, and their SQUID had comparable sensitivity. Hence the number of flux lines monitored by their system was comparable or slightly greater than the number of flux lines in our work. Allen and Claassen[16] were detecting an onset of flux motion produced by an induced transport current. Their critical value of the transport current generated a small irreversible signal change in the SQUID and not a large signal change corresponding to a large fraction of the flux lines moving at J_c. Our results for $f_p(T,H,d)$ ranged from 10^{-11} to 10^{-12} N/m. The $f_p(T)$ of Allen and Claassen for 200-Å molecular-beam epitaxy technique (MBE) grown Nb was 10^{-5} to 10^{-6} N/m. This is a six orders of magnitude discrepancy. One would expect a 200-Å MBE Nb film to have weaker pinning than a thicker *E*-beam film because the *E*-beam film should have smaller, and more plentiful grains.

Heubner *et al.*[11–13] first compared the value of the pinning force per unit volume F_p derived from Lorentz-force depinning measurements with F_p derived from thermal force experiments for the same samples at identical applied fields. For applied fields of ~ 1500 G, they measured the transverse Nernst voltage due to a thermally-induced flux motion, and also a current-induced longitudinal voltage. For Nb foils,[11] they found a one to two order of magnitude discrepancy between the two F_p values. The type-I materials they studied,[12,13] Pb, In, and Sn, had between a two and three orders of magnitude discrepancy in F_p values. They proposed a model[11–13] where the transport current flows predominantly along the surface and between the flux lines such that the Lorentz force between the transport current and trapped flux lines is minimized.

In calculating $\mathbf{J}\times\mathbf{\Phi}_0$, one assumes $J(x)$ is uniform throughout the sample and that the state of flux pinning does not significantly perturb the uniform flow of a transport current. The determination of $J(x)$ involves assumptions about the flux distribution in the sample and the effect of screening currents in the sample. J is determined by measuring the current I and dividing by the cross-sectional area A and assuming uniform current flow. If $J(x)$ is highly inhomogeneous and is greatly reduced in the vicinity of a pinned flux line, then the actual pinning force inferred from equating $\mathbf{J}\times\mathbf{\Phi}_0$ or $\mathbf{J}\times\mathbf{B}$ with the pinning force per unit length or volume will be overestimated. The transport current could channel between flux lines when the flux density is low (~ 7 G). At this flux density, assuming uniform flux-line spacing, the flux lines are separated by ~ 40 coherence lengths or flux line diameters. If the transport current is shielded several coherence lengths away from the pinned flux lines, then the six orders of magnitude discrepancy might be accounted for.

In the future some magnetic decoration experiments should be done on Nb at low fields. The exact flux structure is unknown. Also, the field around a flux line $H(r)$ is not exactly known for a $k \sim 1$ and $\lambda \sim d$ superconductor. Until the low-field flux structure and the $H(r)$ are known, a quantitative treatment of a channeling model cannot be made. A possible source of error in calculating f_p is the value $H_{c1}(T)$ used in Eq. (2). Since $H_{c1}(T)$ was not measured, we used the bulk value.[19] However, it is extremely unlikely that this could account for more than a one order of magnitude discrepancy.

The data at all fields and film thickness are assumed to arise from a spectrum or distribution of f_p values, $n(f_p)$. If there was not a broad spectrum of f_p values such that all the flux lines had similar f_p values, then for a critical temperature gradient, most or all of the pinned flux lines would move. But this is not seen experimentally. The hundred or so flux lines that are depinned by the maximum value of the temperature gradient constitute a very small fraction of the total number of flux lines pinned at the film's center.

The argument for the dependence of f_p on thickness goes as follows: A longer flux line has the increased probability of more pinning centers acting on it such the probability that all of its pins being abnormally weak is diminished with increasing thickness. For fairly constant microstructure, the number of pins per unit length on the average should remain constant, but the probability of having at least one high pinning center increases for increasing thickness. The assumed uniformity of microstructure as a function of thickness is based on electron microscopy and x-ray diffraction studies[17] on Nb films made under identical conditions.

The argument for the applied field dependence of f_p is similar. For smaller applied fields, the probability of finding an extremely weakly pinned flux line is lower because the flux lines are more likely to all find high pinning sites since fewer of them will be occupied. The probability of finding an abnormally weakly pinned flux line increases with increased numbers of flux lines.

VI. CONCLUSION

We have developed a thermal gradient technique to measure the elementary pinning force as a function of temperature, film thickness, and applied field at low fields. This technique does not involve significant assumptions concerning the uniformity of the driving force because the state of flux pinning does not affect the thermal driving force. This work generates some information on the spectrum of pinning force $n(f_p)$ for a large collection of trapped flux lines. The magnitude of f_p was found to strongly disagree with previous measurements on thin-film Nb.[16] A channeling model was proposed to account for this large discrepancy. This work raises some questions as to the assumption of uniform current flow in a superconductor containing pinned vortices.

ACKNOWLEDGMENTS

The portion of these experiments performed at Florida State University were partially supported by the Defense Advanced Research Projects Agency (DARPA) under Contract No. MDA972-88-J-1006.

[1]R. Labush, Cryst. Lattice Defects **1**, 1 (1969).
[2]A. M. Cambell and J. E. Evetts, Adv. Phys. **21**, 199 (1972).
[3]H. R. Kerchner, J. Low Temp. Phys. **50**, 337 (1983).
[4]A. T. Fiory and B. Serin, Phys. Rev. Lett. **16**, 308 (1966).
[5]P. R. Solomon and F. A. Otter, Jr., Phys. Rev. **164**, 608 (1967).
[6]J. Lowell *et al.*, Phys. Lett. **24A**, 376 (1967).
[7]R. P. Huebner, Phys. Lett. **24A**, 651 (1967).
[8]R. P. Huebner, Phys. Lett. **25A**, 588 (1967).
[9]R. P. Huebner, Solid State Commun. **5**, 947 (1967).
[10]F. A. Otter, Jr. and P. R. Solomon, Phys. Rev. Lett. **16**, 681

(1966).
[11]R. P. Huebner and A. Seher, Phys. Rev. **181**, 701 (1969).
[12]R. P. Huebner and A. Seher, Phys. Rev. **181**, 710 (1969).
[13]V. A. Rowe and R. P. Huebner, Phys. Rev. **185**, 666 (1969).
[14]J. H. Johnson and W. G. Moulton (unpublished).
[15]M. Bonencini (private communication).
[16]L. H. Allen and J. H. Claassen, Phys. Rev. B **39**, 2054 (1989).
[17]O. O. Hyun *et al.*, Phys. Rev. Lett. **58**, 599 (1987).
[18]J. Mannhart *et al.*, Phys. Lett. A **122**, 439 (1987).
[19]D. K. Finnemore *et al.*, Phys. Rev. **149**, 231 (1966).