magnetized sample and that the illumination favors domain-wall movement by releasing the local anisotropy of Co^{2+} ions or defects.

In summary, we have demonstrated that light irradiation changes the magnetization of such an amorphous insulating spin-glass. This photoinduced magnetic effect is not a thermomagnetic effect and may be used to obtain a better knowledge of the spin-glass state. As we have mentioned earlier,[2] starting from a zero-field–cooled process, it is easy to achieve rapidly the in-field magnetic state at equilibrium under illumination, allowing us to study the behavior of the TRM without heating the sample above T_f. Further investigations are under way to improve our knowledge of the origin of photomagnetism.

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Magnetoresistance Measurement of the Electron Inelastic Scattering Time in Two-Dimensional Al Films in the Presence of Superconducting Fluctuations

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Magnetoresistance measurements of thin Al films ($1\ \Omega/\square < R_\square < 60\ \Omega/\square$) between 2.5 and 30 K are reported and analyzed within the framework of localization theories. The influence of superconducting fluctuations is felt far above the critical temperature, in agreement with the theory of Larkin. The electron inelastic scattering is inversely proportional to the temperature in accordance with Abrahams *et al.* Its absolute value, which agrees with phase-slip-center measurements, is 1 order of magnitude larger than predicted.

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A fairly complete theoretical picture of electron localization effects in two dimensions[1] has emerged in the last few years, and most of the predicted effects[2] have been observed experimentally in thin metallic films and in metal-oxide-semiconductor field-effect transistor devices.[3] However there seems to be at this point one serious disagreement between theory and experiment, related to the dependence of the inelastic scattering time τ_i on the temperature T and on the coefficient of diffusion D. Magnetoresistance (MR) measurements which lead to a determination of τ_i (Ref. 4) in thin films[5-13] have failed until now to verify the prediction by Abrahams *et al.*[14] that τ_i is dominated by electron-electron scattering, and is inversely proportional to $T \ln T$ and proportional to D. In particular, Bergmann[15] has found in quench-condensed metal films $(\tau_i)^{-1} \propto T^{1.65}$,

TABLE I. Relevant parameters for the studied films.

Sample	d (Å)	Rate (Å/s)	$R_{\square}^{4.2}$ (Ω/□)	RR	l (Å)	T_c (K)	$H_i^{4.2}$ (10^{-4} T)	$\tau_i^{4.2}$ (expt.) (10^{-10} s)	$\tau_i^{4.2}$ (theor.) (10^{-11} s)
A	95	≃ 5	8.15	1.47	160	1.82	1.12	1.35	1.71
B	194	2.5	3.28	1.72	245	1.52	0.60	1.64	2.50
C	193	9	1.46	2.15	391	1.48	0.38	1.67	3.78
D	194	0.8	5.12	1.65	221	1.70	0.84	1.32	2.28
E	75	9.5	58.26	1.26	88	2.05	6.46	0.43	1.00

and almost independent of D.

We have measured the MR in thin Al films, and find that the temperature dependence of $(\tau_i)^{-1}$ is linear below 10 K; the data are also consistent with $\tau_i \propto D$. The absolute value of τ_i, however, is larger than the predicted one.

Our experiments have been performed in the framework of the extensively studied superconducting fluctuation effects.[16] They verify the recent prediction by Larkin[17] that fluctuations modify the MR which becomes positive and large when the critical temperature T_c is approached. We note that the data analysis is done at temperatures far away from T_c (see inset Fig. 2) and at very low magnetic fields (see Fig. 1) in contrast to previous superconducting fluctuation experiments.

Our reasons for selecting Al were essentially that (i) Al is a light element for which spin-orbit effects are too weak[18] to cause by themselves a large positive MR,[13,19] in the range of temperature studied; (ii) ions of the common magnetic elements do not have a moment in Al, and hence the results should not be sensitive to a weak contamination by magnetic impurities; (iii) continuous films of Al with thicknesses $d < 200$ Å and a mean free path $l > d$ can easily be prepared.

The experimental procedure is similar to that used before.[13] The Al films (4.00×0.235 mm^2) were prepared by evaporating MRC 99.9995% pure Al onto a glass substrate held at room temperature in a vacuum better than 10^{-6} Torr. Table I contains the essential parameters for the Al films. $R_{\square}^{4.2}$ is the sheet resistance at 4.2 K, $RR = R_{300}/R_{4.2}$ is the resistance ratio, and l is the effective electron mean free path (taking into account surface scattering) at 4.2 K obtained from RR with the assumption of the validity of Mathiessen's rule and $\rho l = 9 \times 10^{-12}$ Ω cm^2 (see Ref. 20). T_c is the measured critical temperature defined as the temperature of the midpoint of the resistive transition.

A typical set of MR measurements in a perpendicular field is shown in Fig. 1. At high temperatures ($T \geq 20$ K) the MR at low magnetic fields is negative, as predicted by localization theory for the case of a weak spin-orbit interaction. [The turnover at high fields ($H \geq 1$ T) is due to the normal MR.] Below 15 K, one can distinguish three field regions: a low-field region (up to 0.1 T) where the resistance increases as a function of H; an intermediate region (from 0.1 to 1 T) where it goes down; and a high-field region where it goes up again. We note that the MR is strongly

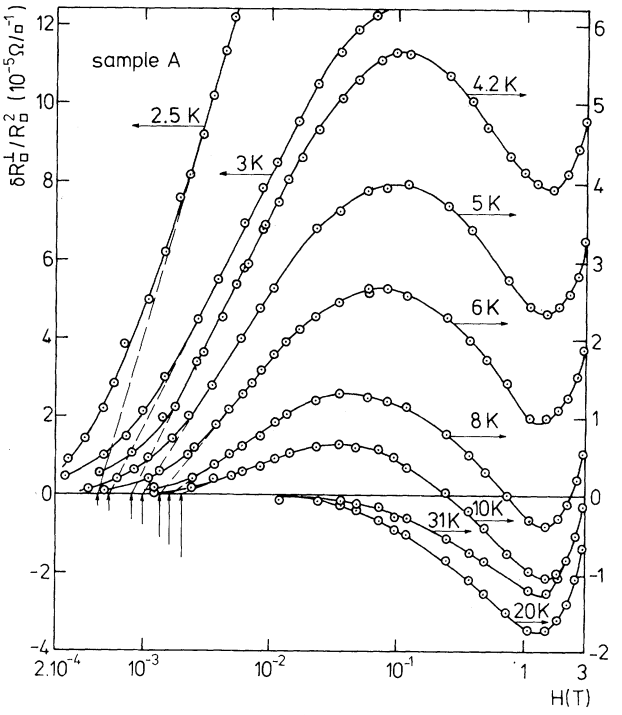

FIG. 1. Typical magnetoresistance curves of an Al film (sample *A*) at different temperatures. The dots are measured and the full curves are a guide to the eye. The vertical arrows correspond to the field $H = 7.12 H_i$. Note the change in vertical scale for the data measured at $T < 4.2$ K and at $T \geq 4.2$ K.

anisotropic. For instance, at 4.2 K, the MR in a parallel field is positive and picks up around 600 G, compared with about 10 G for the perpendicular orientation.

The change in sign of the low-field MR seen around 15 K could in principle be due to the spin-orbit interaction. However, we reject this interpretation for our Al films for the following reasons: (i) the slope of MR versus $\ln H$ is strongly temperature dependent and diverges at T_c (Figs. 1 and 2); (ii) no sign of a positive MR was found in the neighboring element Mg,[12] and even in Cu films of similar sheet resistances[5,8,13] the MR is essentially negative; (iii) from values of the spin-orbit scattering time $\tau_{s.o.}$ measured by Tedrow and Meservey[18] in thin Al films with $d = 40$ Å we estimate that for our films with $d \simeq 200$ Å, $\tau_{s.o.} \simeq 1\times10^{-10}$ sec, comparable to τ_i (see below) at 4.2 K. Hence, above 4.2 K the positive MR cannot be due to spin-orbit effects.

We therefore conclude that the low-field positive MR seen below 15 K is due to the scattering of electrons by superconducting fluctuations, as suggested by Larkin,[17] and analyze our results with his expression for the MR,

$$\frac{\delta R_\square{}^\perp}{R_\square{}^2} = \frac{e^2}{2\pi^2\hbar}\left[\beta\left(\frac{T}{T_c}\right) - \alpha\right] Y\left(\frac{H}{H_i}\right), \tag{1}$$

where

$$H_i = \hbar c/4eD\tau_i \tag{2}$$

and $Y(x) = \ln(x/7.12)$ for $x \gg 1$, $Y(x) = x^2/24$ for $x \ll 1$. Here $\alpha = 1$ for $\tau_i \ll \tau_{s.o.}$ and $\alpha = -\frac{1}{2}$ in the opposite limit, and the function β [Eq. (8) in Ref. 17] diverges near T_c and goes to zero at high temperatures. Equation (1) is valid at applied fields which are not sufficiently strong to affect superconductivity. We attribute the change in slope of the MR in the intermediate field region to the destruction of superconductivity.

An analysis of the high-temperature ($T > 10$ K) low-field negative MR in terms of localization theory[19] is very difficult because of the fact that (i) superconducting fluctuations are still present but weakened: $\beta \neq 0$,[17] and (ii) $\beta \simeq \alpha$ since $\delta R_\square{}^\perp / R_\square{}^2 \simeq 0$ up to 2×10^{-2} T. The high-field MR behavior at $T > 10$ K is probably due to a decrease of β as a function of field: a regime in which the theory of Larkin[17] is not applicable.

In Fig. 2 we have plotted the slopes $\Delta R_\square{}^\perp / R_\square{}^2$ of the MR curves as a function of T/T_c for the Al samples. Here $\Delta R_\square{}^\perp / R_\square{}^2$ measures the variation of $\delta R_\square{}^\perp / R_\square{}^2$ over one decade of H in the region where $\delta R_\square{}^\perp \propto \ln H$. The experimental points all

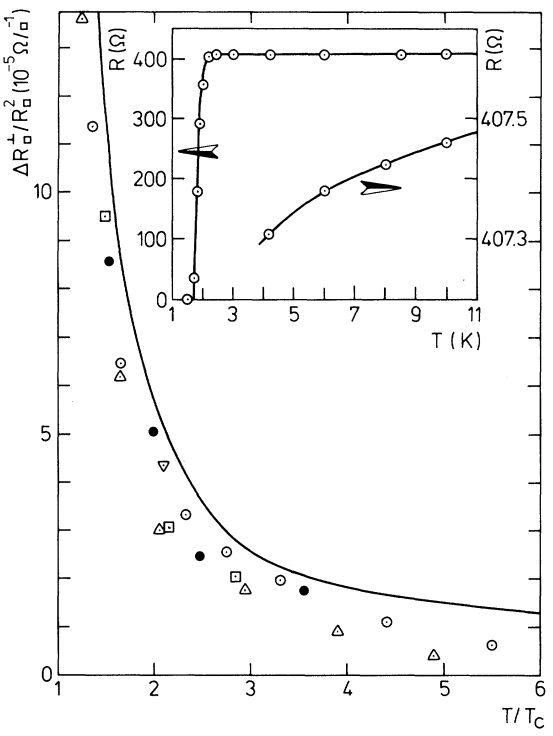

FIG. 2. The slopes $\Delta R_\square{}^\perp / R_\square{}^2$ of the magnetoresistance curves as a function of the measured T/T_c for the Al samples listed in Table I (sample A, open circles; B, inverted triangle; C, squares; D, solid circles; E, triangles). The solid line is calculated with the theory of Larkin. The inset shows R vs T for an Al sample with $T_c = 1.82$ K.

fall slightly below the curve representing the function $\beta(T)(e^2/2\pi^2\hbar)\ln 10$, indicating as expected that $\alpha > 0$ (weak spin-orbit interaction). Since there are no adjustable parameters, we consider that there is good agreement between our data and the theory of Larkin. For metals with weak spin-orbit coupling, it seems indeed possible to detect superconductivity by MR measurements up to $T \simeq 10T_c$.

The field H_i is determined at each temperature by extrapolating the region of the MR curves where $\delta R_\square{}^\perp \propto \ln H$. Clearly, this procedure is only accurate at sufficiently low temperatures where the MR curves have a well developed $\ln H$ part. High-temperature measurements become increasingly difficult especially for clean specimens for which the data are therefore limited, as shown in Fig. 3. However, there is sufficient data to show that $(\tau_i)^{-1} \propto T$. According to Abrahams *et al.*[14]

$$\frac{1}{\tau_i} = \frac{kT}{2Dm}\ln\left(\frac{T_1}{T}\right), \tag{3}$$

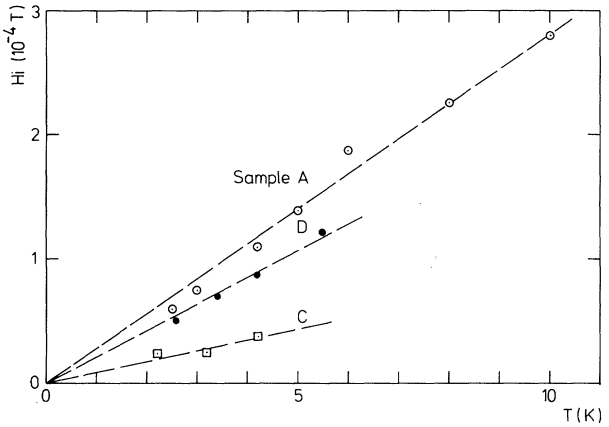

FIG. 3. The temperature dependence of H_i ($\propto 1/\tau_i$) for the samples A, D, and C.

where $T_i = 1.86\times 10^5 (k_F l)^3$ and $D = \frac{1}{2} v_F l$ in our two-dimensional films for which $l > d$ (see Table I). We have calculated D with $v_F = 1.3\times 10^8$ cm/sec, and T_i with the band value $k_F = 1.05$ Å^{-1} (see Ref. 21). According to Eq. (3), $\tau_i \propto D$ and hence we expect from Eq. (2) that $H_i \propto 1/D^2$. This is consistent with the results shown in Table I. We note in this respect that the value for τ_i given by Bergmann[12] for Mg at 4.2 K is smaller than our value for Al by about a factor of 10, which is roughly the ratio of the mean-free-path values.

Table I gives at $T = 4.2$ K the values of τ_i(expt.) obtained from H_i through Eq. (2), and the values of τ_i(theor.) calculated from Eq. (3). Although the experiments verify that $\tau_i \propto D/T$, the absolute experimental value is larger than the theoretical one. We have no explanation for this disagreement.

We now compare our results with those obtained by the study of phase-slip centers in Al strips. Stuivinga, Mooij, and Klapwijk[22] give $\tau_i = 1.6\times 10^{-9}$ sec at $T = 1.2$ K for samples with $d \simeq 400$ Å, $l \simeq 1000$ Å. This value is essentially in agreement with ours, if we take into account the predicted dependence of τ_i on l and T as given by Eq. (3). The values of τ_i given by Chi and Clarke[23] are larger ($\simeq 1\times 10^{-8}$ sec), but we note that those films are thicker ($d > 1000$ Å) and have a rather short mean free path ($l/d < 1$), and are therefore probably not in the two-dimensional limit. We have indeed observed that in a sample with $l \lesssim d$, the temperature dependence of H_i is somewhat stronger than linear. The short mean free path of Bergmann's[15] quench-condensed samples ($l \simeq 10$ to 20 Å, $l/d \simeq 0.2$) may also be the reason for the disagreement between his results and the functional dependence predicted by Eq. (3).

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Positron Surface States on Clean and Oxidized Al and in Surface Vacancies

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This Letter reports on the first discrete-lattice calculation of positron surface states on the surfaces of Al. The authors reproduce the observed values and anisotropy of the binding energies on clean surfaces, and predict the surface-state lifetimes. The temperature-independent lateral diffusion constant is calculated. Monovacancies on surfaces are predicted not to trap positrons. The effect of ordered chemisorbed monolayers of oxygen is investigated: Oxidation makes the surface state unstable with respect to positronium emission.

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Intense, monoenergetic beams of slow (100 eV to 10 kev) positrons are emerging as a potentially powerful surface probe.[1] The momentum and lifetime spectroscopies of positrons interacting with solid surfaces convey useful information about both the atomic and the electronic structure. One particularly interesting facet of the positron-surface interaction is the image-induced surface state,[2] which has been the subject of extensive recent research, both experimental[3,4] and theoretical.[5]

In this Letter we report on the results of the first atomistic, discrete-lattice calculations of positron surface-state properties on the low-index surfaces of Al.

We have developed a general-purpose computational scheme[6] for positron states and their annihilation characteristics. The main steps are (i) construction of the positron potential, (ii) full *three-dimensional* solution (with proper boundary conditions) of the positron Schrödinger equation using numerical relaxation techniques, and (iii) calculation of the annihilation rates using the electron and positron states as input. In the present application, we construct the electron density and Coulomb potential by superimposing free atoms.[7] The correlation potential $V_{corr}(\vec{r})$ to the metal side of the image plane is obtained from the local-density approximation.[8]

On the vacuum side of the surface, we use a simple expression for the image interaction. Along a fixed reference line normal to the surface,

$$V_{corr}(\vec{r}) = -[4(z - z_0)]^{-1}, \quad (1)$$

where z is the perpendicular coordinate, and z_0 defines the effective image-plane position. Furthermore, the image potential is constructed to have the same constant-value surfaces (corrugations) as the electron density, i.e., for any point $\vec{r}$ [electron density $n(\vec{r})$], it has the value equal to the one which corresponds to the density $n(\vec{r})$ on the reference line. The constant z_0 has been chosen to be 0.75 Å ($z = 0$ defines the nominal surface plane half an interlayer spacing outside the outermost atom layer) along a reference line on top of a (100)-surface atom. This value, which is close to that estimated from jellium calculations,[9] reproduces well the observed binding energies on clean surfaces. As first pointed out by Hodges and Stott,[2] the classical expression (1) is unphysical near $z = z_0$; a natural cutoff to V_{corr} is the positronium binding energy of −6.8 eV, which we also impose. This "corrugated-mirror" model of Eq. (1) is an approximation to the rather complicated dynamic and nonlocal image interaction.[5] However, by an appropriate choice of the image surface one can obtain a

