

Electron Spin Resonance Studies on Irradiated Heterogeneous Systems

VI. The Structure and Reactivity of Paramagnetic Centers in Silica Gel*

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The paramagnetic centers formed in silica gel γ -irradiated at 77°K have been identified from ESR spectra, microwave saturation behaviour, optical and thermal bleaching properties and influence of various gel pretreatments. Four main centers are formed, namely electrons trapped at oxygen vacancy sites at $g=2.0008$, electrons trapped at a limited number of sites, whose nature is not at present quite clear, at $g=2.0030$, hole centers trapped on the surface of the silica gel and located near to non-bridging oxygen atoms at $g=2.0070$, and finally centers attributed to holes located close to ^{27}Al nuclei at $g=2.011$.

Carbon dioxide present during the irradiation forms CO_2^- radicals by trapping electrons liberated in the silica gel, while the $g=2.0070$ centers are unaffected. This shows that in addition to a positive charge transfer to form cations and a hydrogen atom transfer demonstrated in previous papers of this series an electron transfer reaction also occurs. The reaction with other electron scavengers like oxygen and nitrous oxide was found to be more complex.

Silica gel has since long been known as a non-metal catalyst of the insulator type, whose most important characteristic is its dehydration ability. The freshly prepared gel has a cristobalite structure, consisting of SiO_4 -tetrahedra sharing corners with the Si-O-Si bonds distorted ¹ to 180°. In the amorphous material the tetrahedra are randomly arranged into a non-periodic structure, which prevents the existence of an electronic band structure except in local crystalline regions. No discrete Si^{4+} and O^{2-} ions are present, but the Si-O bond is predominantly ionic in character. Defects can occur in the structure as

* Previous paper in this series: V. Naphthalene, anthracene, phenanthrene and biphenyl adsorbed on porous silica gel. Kinell, P.-O., Lund, A. and Shimizu, A. *J. Phys. Chem.* **73** (1969) 4175.

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distortions of the tetrahedral structural units.² In gels having a high specific surface area the hydroxyl groups present on the surface and in micropores affect the properties of the gel.

In silica gels exposed to high energy radiation, electron spin resonance spectroscopy (ESR) has proved valuable in the study of the induced properties. Thus it has been reported that hydrogen adsorption³ and H/D exchange⁴ occur at paramagnetic hole centers localized close to aluminium impurity ions. It has been suggested that the adsorption of oxygen takes place at defects possessing an odd electron.⁵ Carbon dioxide and sulfur dioxide react with non-paramagnetic defects⁶ to produce paramagnetic species. Electron transfer occurs during UV irradiation.⁷ In one study where ethylene was adsorbed at -150°C on preirradiated silica gel⁸ a reaction occurred with the hydrogen atoms present on the surface and hydrocarbon radicals were formed. Other types of study in which a two component system was irradiated^{9,10} have provided evidence for energy transfer to the adsorbed phase, thus affecting the yields of final products. A mechanism for the interactions involving energy transfer through mobile electrons and holes has been proposed.⁹

In previous works¹¹⁻¹³ several different systems have been investigated by the ESR method following irradiation at 77°K . The aim of the present study was to characterize as far as possible the paramagnetic defects in silica gel, both in the pure system and in the presence of low molecular weight gases known as electron scavengers.

EXPERIMENTAL

Silica gel of 100-200 mesh purchased from Kebo Co. AB, Stockholm, had a BET area of $667\text{ m}^2/\text{g}$ and contained as main impurities Al (350 ppm) and Fe (136 ppm). This sample was used in the experiments unless otherwise stated. In order to remove surface impurities a sample was boiled for three months in 12 N hydrochloric acid. The impurity content was not measured. Gel which had previously been heated with 15 N nitric acid for three days was refluxed twice with D_2O for 12 h. By this treatment the hydrogen atoms of the surface silanol groups are replaced by deuterium.¹⁴ Silica gel was also prepared from SiCl_4 . In this case the main impurities were Al (5 ppm) and Fe (50 ppm). The specific surface area was not determined. The silica-alumina sample contained 13 % Al. The CO_2 and the N_2O gases were purified from oxygen and other substances volatile at 77°K by pumping at this temperature. The gels were degassed normally at 500°C for 17-24 h at an ultimate pressure of 10^{-4} - 10^{-5} torr. Small amounts, 0.5-10 %, of the gases were adsorbed on the gel in vacuum either before or after irradiation, which was carried out with a ^{60}Co γ -source at a dose rate of 300 krad/h.

Irradiation and ESR measurements were usually carried out in the dark. The filtered light from a 1000 W iodine lamp was used to bleach at wavelengths $\lambda > 515\text{ nm}$ and $\lambda > 1000\text{ nm}$, respectively. ESR spectra were recorded at X-band using a Varian V-4502-11 spectrometer employing 100 kc/s field modulation and supplied with a V-4532 dual cavity. The number of unpaired spins in a sample was estimated as described earlier.¹⁵ The microwave power level was measured with a General Microwave 454 A power meter connected to the cavity arm of the bridge *via* a 9.3 dB directional coupler. Average *g*-factors were estimated by comparison with the signal of solid DPPH (α,α' -diphenyl-2-picrylhydrazyl), $g = 2.0037$, at the point of intersection of the derivative spectrum with the base line. The components of the *g*-tensors were obtained by comparison with compiled spectra¹⁵ and by simulations using a computer code called MARLEF.* The line widths were measured between the maximum and minimum points of the derivative line.

* Kindly put at our disposal by Dr. Jean Maruani, Centre de Mécanique Ondulatoire Appliquée, Paris.

RESULTS

Spectra at 77°K. In the spectrum from silica gel irradiated at 77°K to a dose of 0.8 Mrad three lines could be resolved, centered at $g_1=2.0070\pm 0.0005$, $g_2=2.0030\pm 0.0002$, and $g_3=2.0008\pm 0.0002$ (Fig. 1a) while at 0.1 Mrad only the two former peaks could be detected. At 10 Mrad the line at $g=2.0030$ was almost smeared out. The line shape of the $g=2.0070$ signal could be reasonably fitted to an axially symmetric g -tensor with the values $g_{\perp}=2.0062\pm 0.0005$, $g_{\parallel}=2.0105\pm 0.0005$. This absorption is bleached by light with $\lambda>1000$ nm, and is absent after illumination at $\lambda>515$ nm. The species at $g=2.0030$ is also bleached at the shorter wavelengths, while the absorption at $g=2.0008$ is not much affected. After bleaching a broad background spectrum is observed at $g=2.011\pm 0.001$, possessing several incompletely resolved peaks separated by 8 G (Fig. 1b).

The $g=2.0070$ and the $g=2.0030$ signals are formed predominantly following irradiation of samples degassed at temperatures of 500°C or higher, while the $g=2.0008$ absorption strength decreases slightly with temperature. Silica gel treated with boiling hydrochloric acid before irradiation exhibits a spectrum

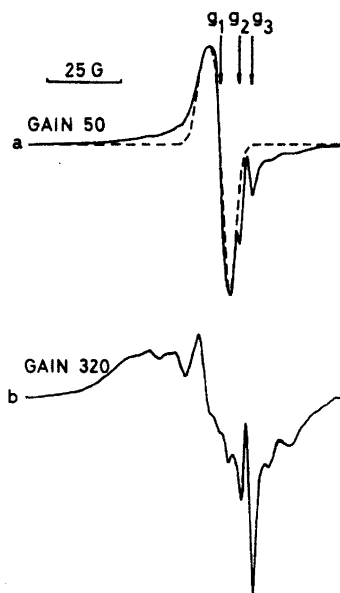


Fig. 1. a) ESR-spectrum of silica gel at 77°K and a microwave power level of about 1 mW after irradiation to a dose of 0.8 Mrad in the dark. The dashed line represents a computed lineshape with the parameters $g_{\perp}=2.0062$, $g_{\parallel}=2.0105$ and a Gaussian line width $\Delta H=4.5$ G. b) The ESR-spectrum of the same sample after photo-bleaching at $\lambda\geq 515$ nm.

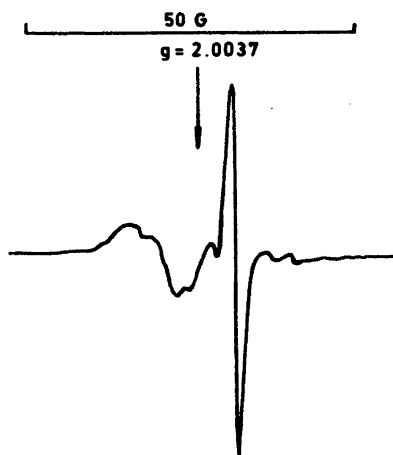


Fig. 2. ESR-spectrum of silica gel at 77°K in the dark after irradiation to a dose of 3.2 Mrad. The microwave power is kept at 0.01 mW.

in which the intensities of the $g=2.0030$, $g=2.0070$, and $g=2.011$ signals are lower than in the ordinary gel. Only very small amounts of deuterium atoms bleachable by visible light could be detected in a deuterated sample.

The spectrum from the silica gel sample prepared from silicon tetrachloride only differed significantly from that of the commercial gel after photobleaching. In this case the $g=2.011$ signal was not observed.

Variation of the microwave power showed that the component at $g=2.0008$ was saturated at the power level 1 mW usually applied. When the microwave power was lowered to 0.01 mW this line became the most predominant (Fig. 2) and contributed roughly 30 % to the integrated intensity. In these experiments the signal from the suprasil quartz sample tubes was annealed by heating in a torch before the measurements.

Temperature effects. When a silica gel sample was stored at 77°K for 55 days after irradiation the absorption intensity in the $g=2.0070$ region decreased. The amplitudes of the $g=2.0008$ and $g=2.0030$ signals remained constant while the broad background signal approximately doubled its intensity. The signal strength of the $g=2.0070$ absorption decayed almost com-

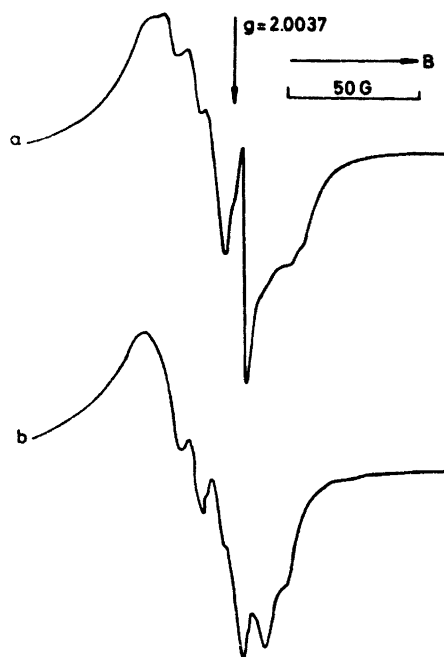


Fig. 3. a) ESR-spectrum of silica gel irradiated and recorded at 300°K. The dose is 3.4 Mrad and the microwave power is of the order 50 mW. b) ESR-spectrum of silica-alumina irradiated and recorded at 77°K. The dose is 3.4 Mrad, and the microwave power is about 1 mW.

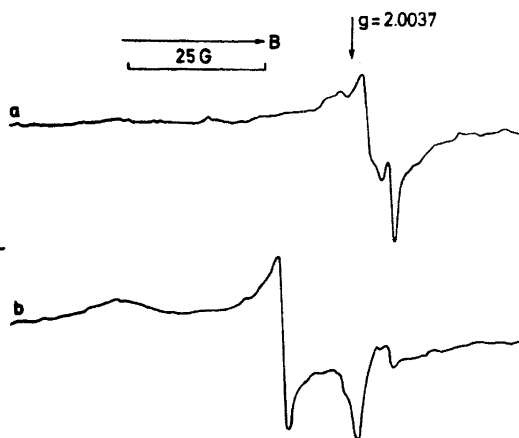


Fig. 4. a) The ESR signal recorded at 300°K and at a microwave power of about 1 mW from silica gel irradiated to a dose of 3.4 Mrad at 77°K. b) The spectrum obtained after air admission.

pletely within 10 min at 160°K while the components at $g=2.0030$ and $g=2.0008$ were more stable. At 300°K the absorption at $g=2.0070$ had completely disappeared. The remaining signal was similar to a component in a sample irradiated at 300°K which could not be saturated (Fig. 3a). The broad spectrum having an envelope line width of about 35 G is centered at $g=2.011$ and contains several peaks separated by 8G. The narrow line has $g=2.0029$. The spectrum obtained from the silica-alumina gel (Fig. 3b) has a similar absorption at $g=2.011$.

Reactions with adsorbed gases. The addition of air at 300°K to a silica gel sample which had previously been irradiated at 77°K and annealed at 300°K (Fig. 4a) gives a spectrum (Fig 4b) which may arise from species with an anisotropic g -tensor having the components $g=(2.025, 2.010, 2.003)$. When oxygen was adsorbed on a room temperature irradiated gel, essentially the same spectrum was observed. In these cases the reaction occurred within 30 min. The spectrum differs considerably from that obtained when a sample containing 1 % oxygen was irradiated at 77°K (Fig. 5). In the latter case the line shape is characteristic of an axially symmetric g -tensor having $g_{\parallel}=2.0085 \pm 0.0005$, $g_{\perp}=2.0037 \pm 0.0005$ and a Gaussian single line width $\Delta H=4$ G, as seen by comparison with the calculated spectrum.

When a sample containing 3 % CO_2 was irradiated at 77°K to a dose of 3.4 Mrad a spectrum composed of the absorption at $g=2.0070$ and a different species centered at $g=2.0015$ (Fig. 6a) was recorded. After thermal annealing at 160°K for about 10 min only the latter signal remained (Fig. 6b). The line

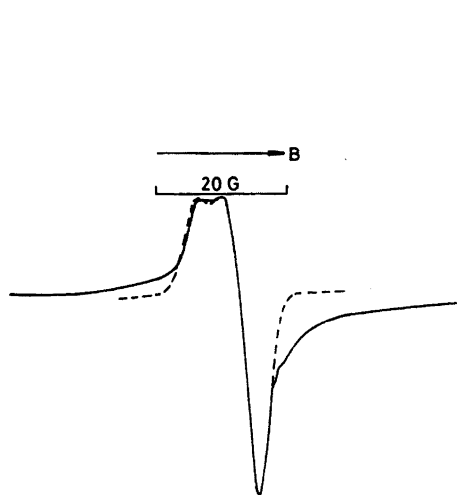


Fig. 5. ESR-spectrum from silica gel irradiated in the presence of 1 % O_2 to a dose of 3.4 Mrad at 77°K. The dotted line represents a computed lineshape with the parameters $g_{\perp}=2.0037$, $g_{\parallel}=2.0085$ and a Gaussian single crystal line width $\Delta H=4$ G.

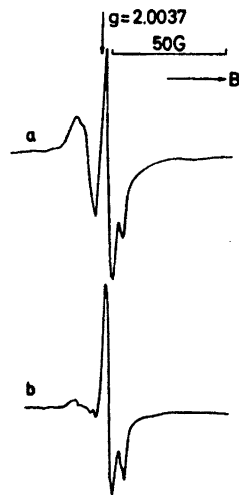


Fig. 6. ESR-spectrum from silica gel irradiated in the presence of 3 % CO_2 to a dose of 3.4 Mrad at 77°K. a) at 77°K. b) after annealing at 160°K.

shape indicates axial symmetry $g_{\perp}=2.0024$, $g_{\parallel}=1.9971$. The radiation chemical yield of this species depends on the amount of CO_2 present. When a correction for the difference in temperature was applied it was found that the

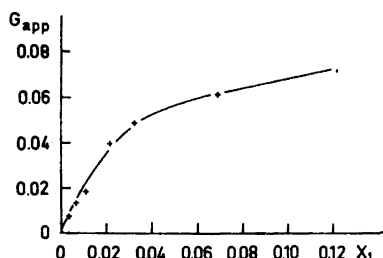


Fig. 7. The yield of CO_2^- radicals G_{app} per 100 eV energy dissipation in the composite system as a function of the electron fraction X_1 of CO_2 present.

signal intensity remained unchanged after warming to 300°K. The number of radicals formed by 100 eV energy absorbed by the entire system. G_{app} has been estimated as a function of the electron fraction of CO_2 (Fig. 7). Within the limits of experimental error the $g=2.0070$ signal has the same line shape and intensity as in the pure gel.

DISCUSSION

Nature of paramagnetic centers

The paramagnetic resonances observed in four-fold coordinated oxides have mostly been associated² with defects which are either due to oxygen vacancies or to oxygen ions. The former types of defect serve as traps for electrons, while the paramagnetic states of oxygen ions act as trapped holes. Spin-orbit interaction makes the g -factors deviate from the free electron value $g_e=2.0023$. However, as shown by Weeks,² the electron traps may possess principal values $>g_e$, while for holes g -factors $<g_e$ can occur, in contrast to the usual expectation. In the absence of characteristic hyperfine structure the components must therefore be differentiated by other methods such as optical and thermal bleaching behaviour, microwave saturation properties and reactions with adsorbed species. Comparison with the results of previous investigators^{3,6-8,16} reveals a critical dependence of the type of gel used, sample degassing, influence of adsorbed gases, and temperature effects. Clearly, in order to make comparisons, it is necessary to take into account the differences in gel structure which may arise through the pretreatment and from the influence of impurities.

$g=2.0008$ Component. A narrow easily saturated line around $g=2.0010$ has previously been reported to appear in quartz single crystals¹⁷ and fused silica as well as in high surface area silica samples^{7,18}. This component is also present in irradiated hydrocarbon/silica gel systems.¹² The absorption has been assigned to an electron trapped in an oxygen vacancy in the SiO_2 network.¹⁷

It appears that the center is a bulk rather than a surface defect. This conclusion is supported by the observation that modification of the surface struc-

ture caused by the different heat treatments only slightly affects the signal intensity, by the insensitivity of line width to deuteration and by the lack of reactivity towards adsorbed gases.^{7b}

g = 2.0030 Component. The line at $g = 2.0030$, which at 3.4 Mrad constitutes 5–10 % of the total absorption, seems to be associated with a centre localized to a limited number of traps since its contribution to the spectra becomes less at high doses. Wong and Willard⁶ observed a pronounced singlet at $g = 2.0028$ in a silica gel under similar conditions. They suggested that the absorption may be caused by electrons trapped in voids of the type responsible for the trapping in glassy materials, which is not necessarily associated with oxygen vacancies. A singlet of this type seems to appear¹⁶ also in a silica gel free of impurities, indicating that it is not associated with the presence of iron or aluminium.

g = 2.0070 Component. The absorption predominant before photobleaching (Fig. 1a) seems to be associated with a species with an axially symmetric g -tensor $g_{\perp} = 2.0062$, $g_{\parallel} = 2.0105$. Since the center is easily bleached and since the intensity depends markedly on the heat pretreatment it appears reasonable to suppose that it is localized to the surface. There are several indications that this resonance is caused by trapped holes. First, the presence of an electron scavenger such as carbon dioxide during the irradiation does not decrease the signal intensity. However, benzene completely quenches the formation of the $g = 2.0070$ absorption and at the same time hydrocarbon cations are formed.¹³ In the presence of hexane¹² a gradual decrease of the intensity with increasing alkane content takes place. Secondly, the signal does not saturate easily at increased microwave power. Finally, the resonances observed from trapped electrons in irradiated quartz¹⁷ are located at $g < g_e$.

The optical bleaching at $\lambda > 1000$ nm may occur through an electron transition from an electron trap. The upper limit of the energy required to make the electron mobile is then 1.25 eV. The electron traps seem to be different from those detected by their resonance absorption since the latter signals disappear less readily upon optical or thermal bleaching than the $g = 2.0070$ center.

The formation of holes associated with molecular oxygen ions appears less likely following irradiation of the evacuated samples. For O^- in a crystal field with axial symmetry, the situation $g_{\perp} > g_e$, $g_{\parallel} = g_e$ is to be expected.² In the MO^- type of center studied in alkali glasses, however, the observation $g_{\perp} < g_{\parallel}$ was made (cf. Ref. 2). This may be due to a change of the relative ordering of the energy levels in the molecular orbitals of MO^- compared to those of O^- in conjunction with a lower (rhombic) symmetry² of the crystal field. As the silica gel contains no glass-modifying cations, the formation of non-bridging oxygens of the type observed in the alkali silicate glasses² must be of minor importance. In the silica gel a hole centered at a non-bridging oxygen may be formed by the rupture of an O–H bond in a surface silanol group. The assignment of the observed signal to such a species is supported by the observation that an electron scavenger like carbon dioxide does not affect the intensity of the absorption. Centers formed by electron loss show an increased stability under these conditions due to the trapping of electrons which could otherwise recombine with the holes.¹⁹ A non-bridging oxygen attached to a surface aluminium ion seems to be ruled out as the centre also dominates

in the synthesized sample. A species with similar properties has been detected in boron containing silica,¹⁸ in which case the hole was considered to be localized mainly on the 2s and 2p orbitals of a non-bridging oxygen next to a boron atom, giving hyperfine interaction. In this case $g_{||} = 2.0100$ and $g_{\perp} = 2.0023$ was observed being consistent with the theoretical model proposed.

The low intensity of the absorption in samples preheated at 350°C may be due to adsorbed water which is known²⁰ to prohibit the formation of this species.

g = 2.011 Component. The spectrum at 77°K remaining after photobleaching, in which a structure is barely resolved (Fig. 1b), is probably of the same origin as the broad signal at $g = 2.011$ observed after room temperature irradiation of silica gel (Fig. 3a). An analogous absorption has also been reported in fused quartz irradiated with neutrons.²¹ This spectrum, which had a width of about 50 G, was assigned to a center showing hyperfine interaction with the ²⁷Al nucleus present as an impurity. Similar defects have been observed in smoky quartz, and a theoretical model has been proposed²² to explain the parameters $g_{||} = 2.06$, $g_{\perp} = 2.00$, $A_x = 5.1$ G, $A'_x = A'_y = 6.0$ G. Although it seems very likely that the observed splittings are caused by ²⁷Al hyperfine interaction, these parameters do not fit the experimental spectrum. According to Vedrine *et al.*²³ in silica-alumina two centers V_1 and V_2 account for the broad background signal. These are attributed to holes trapped at non-bridging oxygens bonded to trigonally coordinated aluminium ions. The resolved structure is caused by a hole trapped on an oxygen atom in an AlO_4 unit. Although the detailed interpretation of Vedrine *et al.* is not conclusive, the close similarity between the spectra from silica alumina and that from silica gel (Fig. 1, 3) gives strong evidence for the formation of hole centers associated with aluminium ions present as an impurity. Further evidence for the assignment is that the absorption intensity was reduced in an acid treated gel and was not observed in the synthesized gel.

The apparent increase in intensity upon storage at 77°K has been attributed to a line narrowing caused by an increased ordering of the crystal structure.³ Possibly also a transformation of the $g = 2.0070$ line into the $g = 2.011$ signal has occurred.

Paramagnetic centers in the presence of electron scavengers

Electron transfer between molecules having high electron affinity such as O_2 , N_2O , CO_2 and electron sites in the irradiated silica,^{6,7,11} silica-alumina²⁴ and magnesium oxides²⁵ has been observed in several instances. The identification of O_2^- by its g -tensor may be ambiguous since the principal values depend on the matrix (*cf.* Ref. 2). This also holds true for O^- , which is formed by dissociative electron attachment²⁶ to N_2O . On the other hand the CO_2^- radical has been unambiguously identified by its g -tensor and ¹³C splitting.⁷ Evidence for electron migration during irradiation¹¹ was obtained with the use of scavengers such as galvinoxyl, alkyl halides, biphenyl and naphthalene.

Oxygen. The change in spectral appearance when oxygen is admitted at room temperature by the reaction with trapped electrons in the preirradiated silica gel (Fig. 4) has been attributed to the formation of O_2^- ions.⁵ Centers of

this type are also formed by the reaction with electrons in silica-alumina.²⁴ A similar reaction has been observed on a pre-irradiated MgO surface.²⁵ The formation of O_2^- rather than O^- was inferred from the ^{17}O hyperfine splitting and is also favoured on energetic grounds.²⁴

The resonance observed from silica gel irradiated at 77°K in the presence of oxygen (Fig. 5) has previously been reported by Kohn.²⁷ As judged from the g -factors the absorption may be caused by centers of the type O^- and MO^- , similar to those found in the pure gel. The rate of formation of these centers would then be increased considerably in the presence of oxygen, $G=1.2$ molecules/100 eV compared to $G=0.25$ at the same dose, 3.4 Mrad, in the silica gel. This agrees with the suggestion of Hentz and Wickenden¹⁹ that O_2 and N_2O act as traps for free electrons and enhance the positive hole signal of silica-alumina. Another reasonable explanation is that centers of the type O^- and MO^- are formed from the condensed gases. Due to this difficulty in the interpretation, the use of CO_2 as an electron scavenger seemed more advantageous and was chosen for a quantitative study.

Carbon dioxide. The species observed (Fig. 6) has an axial g -tensor $g_{11}=1.9971$, $g_{\perp}=2.0024$ in close agreement with the parameters observed for CO_2^- in the silica gel/carbon dioxide system during UV irradiation.⁷ In the adsorbed state the small difference between the largest components of the g -tensor is not resolved, and similarly the ^{13}C structure can only be observed in ^{13}C enriched samples.^{7b}

Reactivity of the gel

The radiation induced reactions on the surface of silica gel has been investigated in the presence of molecules known as electron scavengers¹¹ and with olefins⁸ and aromatic compounds^{13,28} which could accept hydrogen atoms and also become ionized. It appears that three different types of transfer reaction take place, namely electron transfer, positive charge transfer, and hydrogen atom transfer from the silica gel to the adsorbed molecules. Evidence for the two last reactions was presented previously¹³ and will not be discussed here.

Electron transfer. The deviation from linearity when G_{app} is plotted against X_1 , the electron fraction of adsorbed molecules, has previously been noted in hydrocarbon/silica gel systems.^{12,13} This behaviour is indicative of some interaction between the phases, and it was suggested that energy was transferred¹² from the gel to the adsorbed molecules.

The present results (Fig. 7) suggest that electrons originally liberated in the gel become trapped at carbon dioxide molecules to yield CO_2^- . This may occur at a limited number of sites with a yield G_{ads} . From a previously proposed model¹² and the data of Fig. 7 a least squares fit yields $G_{ads}=2.1\pm 0.8$, $X_1^s=0.037\pm 0.08$. The errors given are twice the standard deviations. X_1^s is the electron fraction of carbon dioxide when all sites are saturated and the value found corresponds to a distance of about 1.0 nm between the molecules. An electron originally created in the interior of the gel must be transferred to the surface before it can react with the adsorbed molecules. This distance can be estimated from the surface area to be of the order 1.5 nm. At lower

coverage the probability of CO_2^- ion formation is decreased since the electron must travel a longer path and can then become stabilized at other traps or escape. In scavenger experiments using galvinoxyl¹¹ the yield of electrons was considerably higher, demonstrating that not all of the radiolytically liberated electrons become trapped as CO_2^- . This gives further evidence that only a limited number of sites are available for CO_2^- formation.

CONCLUSIONS

In discussing the paramagnetic species induced in silica gel by γ -irradiation it seems necessary to take into account the differences in gel structure caused by various pretreatments and by impurities. Further, the absence of hyperfine structure and the uncertainty in the interpretation of the shift of the g -factor values from that of the free electron makes it necessary to differentiate the species by their optical and thermal bleaching properties.

The assignment of the $g = 2.0008$ absorption, which constitutes about 30 % of the total absorption, to an electron trapped at an oxygen vacancy site and as a bulk property of the silica gel seems very well supported. The $g = 2.0030$ absorption appears in a smaller amount and it also saturates quantitatively at higher doses. No unambiguous assignment can be made on the basis of the evidence at present available, but the species are probably due to electrons trapped in a limited number of sites.

The identification of the $g = 2.0070$ absorption as a hole center trapped on the surface of the silica gel seems very plausible. However, its detailed structure is still unclear, but the hole is most probably located near to a non-bridging oxygen atom. The center at $g = 2.011$ is also attributed to a hole, which is located close to a ^{27}Al nucleus. An apparent increase in intensity upon storage indicates a line narrowing due to increased order of the matrix or to a turnover of the first hole center into the second one.

The study of the influence of adsorbed molecules on the formation of the centers gives evidence for three types of transfer reactions, *i.e.* firstly, transfer of electrons from the interior of the gel to the surface, where they attach to electron scavenging molecules, secondly, hole transfer, which occurs with varying efficiency depending upon the trapping ability of the adsorbate, and thirdly, transfer of hydrogen atoms.

Acknowledgements. The authors are much indebted to Dr. Ove Edlund and Mr. Christer Andersson for their help during various parts of the work. The expert mastering of the authors' manuscript drafts by Mrs. Inger Edvardsson is most gratefully acknowledged.

This work has been financially supported by *The Swedish Atomic Research Council* and *The Swedish Board for Technical Development*. AB Atomenergi kindly placed their radiation source at our disposal.

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Received March 20, 1970.