Ion Desorption from Bulk Cesium Chloride at Moderate Temperature (< 500°C) under Electric Field*

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Desorption of positive ions as well as neutrals from bulk cesium chloride has been investigated in the moderate temperature (< 500°C), which is lower than its melting point (645°C). At this moderate temperature range, neutral Cs was slightly desorbed, but desorption of Cs⁺ ions was not observed. On the other hand, when the positive potential was applied to the sample, Cs⁺ ions were desorbed with abnormally high intensity. The ratio of the desorbed ions to neutrals (I_{Cs⁺}/I_{Cs}) showed a maximum at around 415°C. Based on the analysis using the Saha-Langmuir model, the observed high Cs⁺ desorption yield under electric field was interpreted by the changes in the surface work function caused by the phase transition of CsCl. The abnormally high Cs⁺ desorption yield at such low temperature under electric field would be applied to various fields such as ion production in accelerator and separation of cesium from complex systems through dry process. [DOI: 10.1380/ejssnt.2018.53]

Keywords: Ion desorption; Cesium chloride; Electric field; Surface ionization; Temperature programmed desorption

I. INTRODUCTION

When a solid is heated in a vacuum, a part of the surface layer desorbs as ions. This phenomenon, known as “surface ionization” (or thermal ionization), was already found in 19th century, and then its basic mechanism was formulated [1]. After that, surface ionization has been investigated in various fields such as production of ions in accelerator and sample preparation technique in mass spectrometry.

The mechanism of surface ionization has been extensively investigated for simple systems such as adsorbed atoms and molecules on metal substrates. It has been clarified that the ionic species are considerably hard to be desorbed compared with neutrals even for alkali metals with low-ionization potential [2]. As to compounds, the surface ionization from alkali-metal halide deposited on metal substrates has relatively been well investigated [3–17]. According to these previous works, it is generally accepted that the desorption temperature of alkali-metal ions is higher than that of neutrals. For example, Kawano et al. have measured temperature programmed desorption (TPD) spectra for thin films of various alkali-metal halides and found that the temperature of the ion desorption peak was about 300 K higher than that of neutrals [17]. Also, they found that the desorption yield of ions is less than 10⁻² of that of neutrals [17].

Compared with well-defined thin films on metal substrates, the surface ionization from bulk compounds has scarcely been investigated due to the complexity of the ion desorption process. In this work, we investigated the behavior of ionic and neutral desorption from bulk cesium chloride as well as the other alkali-metal chlorides. The mechanism of the surface ionization was concentrated on the moderate temperature region (300°C–500°C), which is lower than the melting points of cesium chloride (645°C). We found that the desorption of Cs⁺ ions from bulk cesium chloride is abnormally enhanced at this moderate temperature range, when electric field was applied to the sample. In contrast to the previous works, we also found that the desorption yield of Cs⁺ ions from bulk cesium chloride is much higher than that of neutrals under such electric field. The mechanism of the observed abnormally high ionic desorption yield is discussed based on the theoretical simulation using Saha-Langmuir model [18].

II. EXPERIMENTAL

The samples investigated were special grade of alkali-metal chlorides (NaCl, KCl, RbCl and CsCl) purchased from Wako Pure Chemical Industries. The powdered samples were used without any pretreatments.

For thermal desorption experiments, two kinds of heating system were used. One is the resistive heating system which was used for the measurements of neutral TPD spectra. The other is the electron bombardment (EB) heating system. The EB heating system was used for the measurements of ion desorption, because the crucible was electrically isolated from the ground, and the positive potential can be applied to the sample.

The schematic of the resistive heating system is shown in Fig. 1(a). The carbon block heater was used. The sample of 5 mg was put in an alumina pan. The pan was put on the heater. The temperature of the pan was measured by a type K thermocouple (Chromel/Alumel). The precise temperature of the sample was calibrated by ob-

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serving the melting of aluminum metal powder (660.3°C) using a pyrometer (LEC Company Ltd. L-1000). The temperature measured by the thermocouple was fed back to the power supply and the temperature of the pan was raised at a constant ramp rate. The typical ramp rate of the temperature was 0.5°C s⁻¹. The desorbed neutrals were measured through an aperture by a quadrupole mass spectrometer (PrismaPlus QMG 220, Pfeiffer Vacuum GmbH). The neutral species were ionized by the irradiation of electrons from tungsten hot filament. The kinetic energy of electrons in the ionizer was 70 eV. In the multiple mass analysis mode, the intensities of the different masses were simultaneously measured as a function of the temperature.

The schematic of the EB heating system is displayed in Fig. 1(b). The sample of 5 mg was put in the crucible made of tantalum. Tungsten filament was placed around the crucible. The crucible was heated by the bombardment of electrons from the hot filament. The crucible was electrically isolated from the ground, and positive voltage can be applied to the crucible. The temperature of the crucible was measured by a type K thermocouple. The desorbed species were measured by a quadrupole mass spectrometer (RGA200, Stanford Research Systems, Inc.). For ion measurements, filament in the mass spectrometer was shut off, and the positive potential was applied to the crucible.

All experiments for the neutral and ion desorption were carried out under high-vacuum condition (base pressure: 10⁻⁶ Pa). During the desorption measurements, the pressure increased up to 10⁻⁴ Pa. To compare the desorption yield of ions with that of neutrals, a movable aluminum plate was put above the crucible. Desorbed ions or neutrals were deposited on the aluminum plate for a certain time, and then the surface of the aluminum plate was measured by X-ray photoelectron spectroscopy (XPS). The XPS measurements were performed at the soft X-ray beamline (BL-27A) of the Photon Factory in the High Energy Accelerator Research Organization (KEK-PF). The typical photon energy for XPS measurements was 3000 eV. Based on the ratio of the intensity of the Cs 3d₅/₂ peak to the Al 1s one, the amount of the desorbed cesium that is proportional to the desorption yield was estimated.

III. RESULTS AND DISCUSSION

A. Neutral desorption

Figure 2 shows the mass spectrum of neutral species desorbed from CsCl at 460°C. The H₂O peak is the most intense among all masses. This peak originates from water adsorbed on the surface of CsCl, because CsCl sample was used as received without any pretreatment. Among the fragments of CsCl, the intensity of the Cs peak is the highest reflecting the low ionization potential of Cs. The other fragments are Cl and double charged Cs. This mass spectral pattern is different from that of ion desorption.

FIG. 2. Mass spectrum for desorbed neutrals from CsCl at 460°C.
The melting point of the respective alkali-metal chloride is shown in each spectrum.

As to the spectral shape for all alkali-metals, it is seen that the desorption signal suddenly drops at the temperature a little higher than the peak temperature. Such TPD spectral pattern suggests that the desorption occurs according to the zero-order kinetics, which is frequently observed in simple molecules on a substrate [19]. For zero-order desorption, TPD peak temperature increases with the increase in the amount of the sample. The result for CsCl is shown in Fig. 4. Although the peak temperature slightly shifts to higher temperature side with the increase in the sample amount, the range of the peak shift is within 15°C. Also, the peak temperature of 5 mg spectrum is almost the same as that of 10 mg one. The result suggests that the ramp rate (0.5°C s⁻¹) was slow enough for the sample to reach equilibrium. This means that the peak temperature in the TPD spectra is certainly related to the property of the respective chlorides. In all TPD spectra in Fig. 3, the temperatures of the desorption peak are almost in agreement with the melting points of the respective alkali-metal chlorides. The results suggest that the alkali-metal chlorides are melted around the peak temperature, and then immediately evaporated due to high vapor pressure of liquid phase.

At low temperature region, the desorption signals of alkali metals gradually increased from the temperature lower by 200°C–300°C than the respective peak temperatures. For example, Cs began to desorb from around 400°C that is about 250°C lower than the desorption peak temperature. Next, we concentrate on the desorption of ions and neutrals at this low temperature region.

### B. Ion desorption

Figure 5 shows the mass spectra of positive ions desorbed from CsCl at 460°C. In this measurement, various positive potentials were applied to the crucible, which are shown in Y axis. When the crucible was grounded, no desorbed ions were observed. On the other hand, when the positive potential was applied to the crucible, Cs⁺ ions began to appear from around +50 V as well as the other ions originating from contaminants such as H₂O⁺. The intensity of the Cs⁺ ions almost saturates at +300 V.

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The observed increase in the Cs⁺ intensity with the crucible voltage is partly due to the change of the detection efficiency of ions by the mass spectrometer. But it is considered that this phenomenon is mainly caused by the real increase in the Cs⁺ desorption yields with the crucible voltage, because the enhancements of the ions were notably observed for Cs⁺ and double-charged Cs²⁺ as well as Cl⁺ ions, but not clearly seen for the other ions such as H₂O⁺ which comes from the water adsorbed on the CsCl surface.

The desorption of positive ions from a solid surface is sometimes observed by applying positive potential to the substrate, which is known as field ion emission (or field emission) [20]. However, the increase in the Cs⁺ desorption with the crucible potential is not due to the field ion emission, because such process happens by an extremely high electric field (ca. 1010 V/m) [21-23]. In the present experiment, the distance between the crucible and the head of the mass spectrometer was 0.15 m. Thus, the electric field induced by 300 V at the crucible was only about 2000 V/m.

The effect of such low electric field on the ion desorption was reported by Butman et al. [24] for thin films of alkali metal compounds. They discussed the enhancement of the ion desorption from KCl single crystal by positive electric field in terms of the excess charge depending on the surface topography such as steps and kinks [24]. However, the ion emission they treated plays a minor part in the total desorption, so the present results cannot be explained only by the surface topography. At present, we consider that the enhancement of ion emission by electric field is explained by the space charge effect as follows.

The electric field applied at the surface form a space-charge zone. This space-charge first hinders the ion emission. With increasing the potential of the extraction field, ions are extracted from the surface more efficiently resulting in the increase in the ion desorption. This phenomenon is known as Langmuir-Child behavior [25, 26]. Actually, in the study of ion source, it was reported that the emission of potassium and cesium ions from leucite-type materials is enhanced by the space charge following the Langmuir-Child law under small electric fields (< 1000 V/cm) [27]. Although further study is needed to clarify the effect of surface electric field on ion emission, we consider that the observed enhancement of Cs⁺ ion emission by the electric field is due the space charge effect produced at the surface.

Figure 6 shows the mass spectra of positive ions desorbed from CsCl at various temperatures in moderate temperature region (< 500°C). Crucible potential was +100 V. In this experiment, the crucible was isochronally heated for 1 min at each temperature. The desorption of Cs⁺ ions began at around 400°C. This temperature is close to the low-temperature threshold at which the neutrals begin to desorb (Fig. 3(d)). The mass spectral patterns of ions are different from that of neutrals (Fig. 2). The desorption yield of Cs⁺ ions is the highest in all mass range, and the intensity of the other contaminant ions such as H₂O⁺ are negligibly small. This clearly shows that the electric field selectively enhanced the desorption of Cs⁺ ions.

For comparison, mass spectra of positive ions desorbed from NaCl are shown in Fig. 7. Since the melting point of NaCl is higher by 156°C than that of CsCl, the desorption of Na⁺ began at higher temperature (~ 540°C) than that of Cs⁺. This temperature is also close to the low-temperature threshold of neutral desorption (Fig. 3(a)).
For all spectra in this temperature region, Na$^+$ is the most intense species as in the case of Cs.

C. Ion to neutral ratio

Next, we compare the desorption yield of ions and neutrals. Figure 8 shows the intensity ratios of ions to neutrals ($I_{Cs^+}/I_{Cs}$) desorbed from CsCl for various crucible voltages as a function of the temperature. In this experiment, the intensity of neutrals was measured by setting the voltage of the crucible to 0 V, where no Cs$^+$ ions was desorbed (see Fig. 5). In all crucible voltages, the $I_{Cs^+}/I_{Cs}$ value shows a maximum at around 415°C. This temperature is about 230°C lower than peak temperature of the neutral desorption in TPD spectrum (Fig. 3(d)). To the best of our knowledge, such high yield of ion desorption from alkali-metal halides at low temperature has not been reported. One plausible reason is that cesium has the lowest ionization potential (3.9 eV) among all the elements, so it is easily desorbed as positive ions. However, even for cesium compounds, it was reported that Cs$^+$ ions are desorbed from thin film of CsCl at the temperature higher than 700°C [17]. Further, in the study of ion sources, it was reported that the desorption of Cs$^+$ ions occurs at the temperature higher than 1000°C [28]. Next, we will discuss the origin of the maximum for the Cs$^+$ desorption yield at such low temperature.

D. Mechanism of Cs$^+$ desorption at moderate temperature range (≤ 500°C)

When the CsCl molecules are firstly dissociated in the surface and then atomic neutrals and ions desorb, the ratio of ions to neutrals ($Y_{Cs^+}/Y_{Cs}$) desorbed from a surface is expressed by the Saha-Langmuir equation [18],

$$Y_{Cs^+}/Y_{Cs} = \frac{g_{Cs^+}/g_{Cs}}{n} \exp \left[-\frac{(E_i - \phi)/kT}{n} \right]$$

where $g$ is the statistical weight (degeneracy), $E_i$ is the ionization potential of cesium, $\phi$ is the surface work function, $k$ is the Boltzmann constant, and $T$ is the Kelvin temperature. The subscripts Cs$^+$ and Cs indicate the ions and neutrals, respectively. (In case the molecules firstly desorb and then they are decomposed and ionized, the value of $E_i$ is substituted by a dissociative ionization energy [8].)

The experimentally obtained $I_{Cs^+}$ and $I_{Cs}$ values are expressed as

$$I_{Cs^+} = \varepsilon_{Cs^+} Y_{Cs^+}$$

$$I_{Cs} = \varepsilon_{Cs} Y_{Cs}$$

where $\varepsilon$ is the detection efficiency of the mass spectrometer. Thus, the $I_{Cs^+}/I_{Cs}$ value is shown as

$$I_{Cs^+}/I_{Cs} = A \exp \left[-(E_i - \phi)/kT \right]$$

where $A$ is the constant corresponding to $(\varepsilon_{Cs^+}/\varepsilon_{Cs})(g_{Cs^+}/g_{Cs})$. Equation (4) shows that when $E_i$ is larger than $\phi$, the value of $I_{Cs^+}/I_{Cs}$ increases with the temperature, and when $E_i$ is smaller than $\phi$, the value of $I_{Cs^+}/I_{Cs}$ decreases with the temperature. Since the values of $E_i$ are constant ($E_i = 3.9$ eV), the observed maximum of the $I_{Cs^+}/I_{Cs}$ value in Fig. 8 seems to be due to the changes in the work function $\phi$ depending on the temperature. It is known that the work function sometimes changes with the temperature. In the case

![Figure 8. Temperature dependence of the desorbed intensity ratio of ions to neutrals ($I_{Cs^+}/I_{Cs}$) for various crucible potentials.](image)

![Figure 9. Simulation of the experimental data for 150 V crucible voltage (Fig. 8) using the Saha-Langmuir equation. At the temperature lower than 415°C, the slope of the data is fitted by setting $\phi = 2.0$ eV. At the temperature higher than 415°C, the slope of the data is fitted by setting $\phi = 4.6$ eV.](image)

TABLE I. Results for the XPS measurement of the aluminum plate located above the crucible. Cesium was deposited for 30 s at 460°C at various crucible potentials. Thickness of the Cs layer (number of Cs layer) was calculated by the intensity ratio of the Cs 3d$_{5/2}$ peak to the Al 1s peak ($I_{Cs3d_{5/2}}/I_{Al1s}$). Detailed calculation procedure was described elsewhere [33].

| Crucible potential | 0 V | +100 V | +200 V |
|--------------------|-----|--------|--------|
| $I_{Cs3d_{5/2}}/I_{Al1s}$ | 0.202 | 0.213 | 0.72 |
| Thickness of Cs layer (nm) | 0.235 | 0.248 | 2.29 |
| Number of Cs layer | 0.570 | 0.602 | 5.56 |

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of simple metals, for example, the surface work function changes depending on temperature because of the thermal vibrations of the atoms. Compared with simple metals, work functions of compounds are difficult to determine both theoretically and experimentally. Also, there have been not so many data on the work function of compounds. For alkali-metal halides, the reported values of the work function are widespread [29, 30]. Considering the gradient of the $I_{Cs^+)/I_{Cs}$ values, it is deduced that the work function at the temperature lower than 415°C is smaller than $E_i$, and that at the temperature higher than 415°C is larger than $E_i$.

In Fig. 9, the slopes of the experimental data for 150 V crucible voltage (Fig. 8) are simulated using Eq. (1) by setting arbitral $A$ value and two different $\phi$ values. At the temperature lower than 415°C, the slope is fitted by setting $\phi = 2.0$ eV. This value is close to the work function of metallic Cs. At the temperature higher than 415°C, $\phi = 4.6$ eV well reproduces the slope. Although the reason of such changes in the work function is not clear, it can be qualitatively explained as follows.

As to the structure of CsCl, it has two polymorphic form; the CsCl-type and NaCl-type. The crystal structure of CsCl changes from CsCl-type structure to NaCl-type one around 445°C [31]. Also, the molar volume of CsCl increases about 16% at this temperature [32]. With this phase transformation, the standard enthalpy of CsCl formation i.e., lattice energy increases at the transition temperature [29]. The increase in the lattice energy induces the increase in the work function. Although the temperature of the $I_{Cs^+)/I_{Cs}$ maximum is tens of degree lower than the phase transition temperature, we consider that the changes in the structure from CsCl-type to NaCl-type is the origin of the work function change at this moderate temperature region, which induces the maximum of $I_{Cs^+)/I_{Cs}$ value.

It should be noted that the values of $I_{Cs^+)/I_{Cs}$ shown in Fig. 8 are only relative values. A question may be raised as to which of ions or neutrals desorb with higher desorption yield in these temperature range. So, finally we compared the absolute desorption yield of ions with that of neutrals using the aluminum plate located above the crucible shown in Fig. 1(b). Desorbed ions or neutrals were deposited on the aluminum plate for 30 s at 460°C. Then, the surface of the aluminum plate was measured by XPS. Table I shows the photoelectron intensity ratio of Cs 3d$^{5/2}$ to Al 1s peaks ($I_{Cs3d5/2}/I_{Al1s}$) for two different crucible potentials. The data with a crucible potential of +200 V is about ten times higher than that of neutrals with a crucible potential of 0 V. This is surprising result, because the desorption yield of ions is generally few orders less than that of neutrals for most of the compounds as described in the introduction. Also, desorption of ions by surface ionization happens at the temperature higher than the desorption temperature of neutrals. At present, we consider that this phenomenon is specific to cesium, because it has unique property that the ionization potential is the lowest in all the elements.

In conclusion, we have found the abnormally high desorption yield of Cs$^+$ ions from bulk CsCl under electric field at moderate temperature region, which is lower than the melting point. The ion desorption yield relative to the neutral one shows the maximum at around 415°C. The observed high desorption yield of Cs$^+$ ions at relatively low temperature would be applied to various fields such as ion extraction in accelerator. Another possible application is the separation of cesium from complex systems through dry process by selectively desorbing cesium as Cs$^+$ ions. In this aspect, one of the most important technologies that must be urgently developed is the decontamination of radioactive cesium that was released by the accident of the Nuclear Power Plant. For this purpose, technology of selective Cs desorption from clay minerals by surface ionization is now under development in our laboratory.

IV. SUMMARY

We have investigated the desorption of ions as well as neutrals from bulk alkali-metal chlorides concentrated on CsCl at the temperature range lower than the melting points. In the neutral TPD spectra for CsCl, the main desorption peak was observed around 645°C, which is close to its melting point. In the lower temperature region (< 500°C), desorption of Cs$^+$ ions was enhanced, when the positive potential was applied to the crucible. The enhancement of ion emission by electric field is explained by the space charge effect following the Langmuir-Child law. The ratio of the desorbed ions to neutrals ($I_{Cs^+)/I_{Cs}$) has a maximum around 415°C. Based on the analysis using the Saha-Langmuir model, the observed temperature dependence of the $I_{Cs^+)/I_{Cs}$ ratio is ascribed to the changes in the surface work function due to the phase transition of CsCl. As to the absolute desorption yield, the yield of Cs$^+$ ions with a crucible potential of +200 V is about ten times higher than that of neutrals. The observed high desorption yield of Cs$^+$ ions at relatively low temperature would be applied to various fields such as ion production in accelerator and separation of cesium from complex systems through dry process.

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[1] P. A. Redhead, J. Vac. Sci. Technol. A 16, 1394 (1998).
[2] G. D. Alton, Rev. Sci. Instrum. 59, 1039 (1988).
[3] W. A. Chapka, J. Chem. Phys. 30, 458 (1959).
[4] I. V. Sidorova, A. V. Gusarov, and L. N. Gorokhov, Int. J. Mass Spectrom. 31, 367 (1979).
[5] F. A. Bencsath and F. H. Field, Anal. Chem. 58, 679 (1986).
[6] M. F. Butman, J. Nakamura, and H. Kawano, Appl. Surf. Sci. 78, 421 (1994).
[7] M. F. Butman, J. Nakamura, S. Kamidori, and H. Kawano, Appl. Surf. Sci. 89, 323 (1995).
[8] T. Suzuki, H. Iwabuchi, K. Takahashi, M. Nomura, M. Okamoto, and Y. Fuji, Int. J. Mass Spectrom. Ion Proc. 145, 131 (1995).
[9] H. Iwabuchi, M. Nomura, K. Iio, Y. Fujii, and T. Suzuki, Vacuum 47, 501 (1996).
[10] H. Kawano, S. Kamidori, H. Shimizu, K. Ushimaru, and H. Asada, Appl. Surf. Sci. 100-101, 174 (1996).
[11] H. Kawano, Y. Zhu, S. Kamidori, H. Shimizu, and M. Udaka, Thermochim. Acta 299, 59 (1997).
[12] M. F. Butman, A. A. Smirnov, and L. S. Kudin, Appl. Surf. Sci. 126, 185 (1998).
[13] Y. Zhu, T. Maeda, and H. Kawano, Thin Solid Films 339, 225 (1999).
[14] H. Kawano, K. Ohgami, S. Matsu, and Y. Zhu, Appl. Surf. Sci. 144-145, 404 (1999).
[15] H. Kawano, Y. Zhu, J. Nakamura, and S. Sugimoto, Thin Solid Films 375, 114 (2000).
[16] M. F. Butman, L. S. Kudin, A. A. Smirnov, and Z. A. Munir, Int. J. Mass Spectrometry 202, 121 (2000).
[17] H. Kawano, Y. Zhu, and S. Sugimoto, Appl. Surf. Sci. 175-176, 105 (2001).
[18] M. J. Dresser, J. Appl. Phys. 39, 338 (1968).
[19] G. A. Attard and C. Barnes, Surfaces Chap. 2.7 (Oxford University Press, Oxford, U.K., 1998).
[20] H. D. Beckey and H.-R. Schulten, Angew. Chem. 14, 403 (1975).
[21] C. J. Rothfuss, V. K. Medvedev, and E. M. Stuve, J. Electroanal. Chem. 554-555, 133 (2003).
[22] H. Utsugi and R. Gomer, J. Chem. Phys. 37, 1720 (1962).
[23] L. W. Swanson, R. W. Strayer, and F. M. Charbonnier, Surf. Sci. 2, 177 (1964).
[24] M. F. Butman and H. Dabringhaus, Surf. Sci. 540, 313 (2003).
[25] C. D. Child, Phys. Rev. Series I 32, 492 (1911).
[26] I. Langmuir, Phys. Rev. 2, 450 (1913).
[27] T. Kolling, A. Schlemmer, C. Pietzonka, B. Harbrecht, and K.-M. Weitzel, J. Appl. Phys. 107, 014105 (2010).
[28] G. Kuskevics and B. Thompson, Rev. Sci. Instrum. 37, 710 (1966).
[29] L. S. Kudin, A. M. Dunaev, M. F. Butman, and A. S. Kryuchkov, Russ. J. Phys. Chem. A 85, 260 (2011).
[30] A. M. Dunaev, L. S. Kudin, M. F. Butman, and V. B. Motalov, ECS Trans. 46, 251 (2013).
[31] M. Watanabe, M. Tokonami, and N. Morimoto, Acta Crystallogr. A 33, 294 (1977).
[32] J. M. Christian and D. W. Lynch, J. Chem. Phys. 40, 248 (1964).
[33] Y. Baba, I. Shimoyama, and N. Hirao, Appl. Surf. Sci. 384, 511 (2016).
[34] N. D. Bhaskar, C. M. Kahla, and L. R. Martin, Carbon 28, 71 (1990).