DESORPTION AND RELATED PHENOMENA RELEVANT TO FUSION DEVICES

EDITED BY A. KOMA

INSTITUTE OF PLASMA PHYSICS
NAGOYA UNIVERSITY

NAGOYA, JAPAN
DESORPTION AND RELATED PHENOMENA 
RELEVANT TO FUSION DEVICES

Edited by
Atsushi Koma*

Institute of Plasma Physics, Nagoya University
Chikusa-ku, Nagoya 464, Japan

April 1982

Permanent address:
*Institute of Materials Science, The University of Tsukuba
Abstract

Desorption and related phenomena involved in the plasma-wall interactions in fusion devices are briefly reviewed. Discussed are: ion-induced desorption (Section II), electron-stimulated desorption (III), photodesorption (IV), ion-induced re-emission of H, D and He atoms (V), chemisorption on carbide surfaces (VI), and theory of desorption (VII). A rather comprehensive bibliography is attached and typical data on the relevant quantities are shown when available.
I. Desorption on the First Walls of Nuclear Fusion Devices  
   A. Koma .................. 1

II. Ion Induced Desorption  
    A. Sagara .................. 6

III. Electron Stimulated Desorption  
     A. Ichimiya ................. 44

IV. Photodesorption  
    M. Kobayashi ............... 101

V. Ion Induced Detrapping, Replacement and Release of Hydrogen, Deuterium and Helium Atoms  
    R. Yamada .................. 108

VI. The Chemisorption on the Carbide Surfaces  
    C. Oshima .................. 122

VII. Present Status and Problems in the Theory of Desorption  
     M. Tsukada .................. 139
Desorption on the First Walls of Nuclear Fusion Devices

Atsushi Koma
Institute of Materials Science
Sakura-mura, Ibaraki 305

The surface of a solid is generally covered with foreign atoms and molecules. Those foreign atoms leave the surface and go into the vacuum due to the heat or the impact of incident atoms, ions, electrons and photons. This is so-called desorption and plays significant roles in the plasma-wall interactions in two ways, which occur at the surface of the first walls of the nuclear fusion devices. One is the impurity introduction process. Such impurity atoms as C or O on the first wall go into the plasma due to the desorption and cause the serious radiation loss. The other is the fuel gas recycling process. The hydrogen isotopes are adsorbed on the surface of the first wall and go back to the plasma due to the desorption. This process makes important contribution to the energy and particle balances of the plasma. Thus it is urgently needed to make clear the desorption on the surface of the first wall. This is the purpose of the present compilation of the data related to desorptions.

As for the impurity introduction process from the first wall into the plasma, sputtering has been mostly notified. Actually the desorption occurs much more easily than the sputtering. One
of the reason is the low binding energy (usually less than 1 eV) of the impurity atoms adsorbed to the surface of the first wall. This binding energy is considerably lower than the one involved in the sputtering. Even if such impurity atoms as C and O are chemically and strongly bound to the first wall, they react with impinging hydrogen isotopes and changes their forms into CD₄ or D₂O, which are bound to the surface physically and loosely. Thus the detailed understanding of desorption process is needed to reduce the impurity introduction to the plasma. The knowledge is also useful to the effective discharge cleaning of the surface of the first wall.

Various desorption processes occur on the surface of the first wall. Thermal desorption is the most popular one, and many data are available about them. Ion-induced, electron-induced and photo-induced desorptions are the ones characteristic to the plasma wall interactions. Section II, III and IV of the present report are devoted to those desorption processes, respectively. Comparison of the yield for each desorption mechanism is shown in Table 1 and Table 2. Table 1 is the results of Bauer's estimation for C and O on stainless steel[1]. It indicates that ion-induced desorption will make the largest contribution to the impurity introduction to the plasma due to the desorption. Table 2 shows the result of Wilson's estimation on the numbers of desorbed deuterons, which contribute to the fuel gas recycling. Again ion-induced desorption seems to be the leading desorption process in the fuel gas recycling.
Table 1. Evaluation of desorption of C and O on stainless steel[1]

<table>
<thead>
<tr>
<th>Incident Particles</th>
<th>Desorption Yield (atoms/particle)</th>
<th>Incident Flux (cm$^{-2}$s$^{-1}$)</th>
<th>Released Impurity (cm$^{-2}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>2</td>
<td>$1 \times 10^{16}$</td>
<td>$2 \times 10^{16}$</td>
</tr>
<tr>
<td>electron</td>
<td>$5 \times 10^{-3}$</td>
<td>$4 \times 10^{16}$</td>
<td>$2 \times 10^{14}$</td>
</tr>
<tr>
<td>photon</td>
<td>$4 \times 10^{-4}$</td>
<td>$10^{17}$</td>
<td>$4 \times 10^{13}$</td>
</tr>
</tbody>
</table>

Table 2. Evaluation of fuel gas recycling due to desorption[2]

<table>
<thead>
<tr>
<th>Incident Particle</th>
<th>Cross Section (cm$^2$)</th>
<th>Incident Flux (cm$^{-2}$s$^{-1}$)</th>
<th>Desorbed D /Adsorbed D</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>$10^{-16}$</td>
<td>$10^{16}$</td>
<td>1</td>
</tr>
<tr>
<td>electron</td>
<td>$10^{-17}$</td>
<td>$5 \times 10^{16}$</td>
<td>0.5</td>
</tr>
<tr>
<td>photon</td>
<td>$10^{-20} - 10^{-18}$</td>
<td>$10^{18}$</td>
<td>0.01 - 1</td>
</tr>
</tbody>
</table>

The followings are remaining problems to be solved for further understanding of the desorption process at the first walls of the nuclear fusion devices.

Even if a clean surface is once obtained by the discharge cleaning, there still remains a problem. There are a large amount of impurities inside the first wall materials, and large gradient of impurity concentration is formed by the removal of impurity atoms on the surface of the first wall. That concentration gradient acts as a motive force for the diffusion of the impurities from the inside of the wall to the surface. Thus the desorption process on the first wall must be made clear in connection with
the diffusion process in the first wall materials. In this connection Section V of the present report is devoted to the ion-induced detrapping, replacement and release of deuterium and helium atoms.

Such low z materials as graphite and carbides are promising candidate materials as limiter, armour and coating materials. But there are few data on the desorption on low z materials. It is needed to produce and compile desorption data for low z materials. In this connection chemisorption on the carbide surface is reviewed in Section VI of the present report.

Data for photo-desorption are also lacking. In addition to the data for cross-section, informations about intensity and energy distributions of photons impinging on the first wall are needed as well.

The knowledge about the coverage of hydrogen isotopes on the first wall material is needed in the estimation of desorption yield of hydrogen isotopes. But those data are lacking mainly because Auger electron spectroscopy or ion scattering spectroscopy, which are successfully used to check the surface coverage of atoms other than hydrogen isotopes, are essentially insensitive to hydrogen isotopes. Development of new technique is needed to detect hydrogen isotopes on the surface with high sensitivity.

Desorption and adsorption is much more sensitive to the surface conditions than sputtering. The surface of the first wall changes their forms by sputtering and blistering etc.. In some compound materials, the surface composition changes as well. Thus the data for those "technical" surfaces are needed for the reli-
able estimations of desorption yields at the actual first wall, which are lacking as well.

Finally theoretical analysis is also needed for systematic understanding of the process and to make reasonable estimation when few experimental data are available. Present status and problems in the theory of desorption are reviewed in Section VII of the present report.

REFERENCES


1. Introduction

Historically ion induced desorption of adsorbed species has been well known for many years as a phenomenon in glow discharge cleaning to obtain atomically clean surfaces [1-13]. The systematic studies, however, have been made only for this decade, giving the measured desorption yields (atoms/ion or molecules/ion) or the desorption cross section (cm$^2$) under well controlled surface conditions as to surface preparation [10-45].

As for the theoretical approach and computer simulations to ion induced desorption, there have been the theoretical estimates due to Winters and Sigmund [22] and computer simulations tried by Taglauer et al. [24, 26, 29, 39], both of which use the binary elastic collision model essentially. Agreement between experimental and theoretical values is not good about both of numerical values and their dependences on the primary ion energy and incident angle of ions.

2. Desorption Yields [10-20]

The measurements of desorption yields (atoms/ion or molecules/ion) have been performed mainly for the technological surfaces of vacuum devices in order to research the optimum conditions of vacuum bakeout and glow discharge cleaning [10-13, 18, 19]. And also, the yields for the condensed gas
layers on cryogenic surfaces have been measured [14-16].

(a) Measured systems (Table 1)
(b) Effect of vacuum bakeout temperature (Fig.1-Fig.8)
(c) Effect of glow discharge cleaning [9, 46, 47]
   (Fig.9- Fig.11)
(d) Condensed gas layers (Fig.12-Fig.14)
(e) Chemical aspects [9] (Fig.15)

3. Desorption Cross Sections [21-45]
   The desorption cross sections in cm² can be measured, without knowing the surface atomic density of adsorbates, from monitoring the relative change of the remaining surface coverage as a function of irradiating ion dose, by using surface analytical methods such as ion scattering spectroscopy (ISS) [25], Auger electron spectroscopy (AES) [28], secondary ion mass spectrometry (SIMS) [34], and the analysis using ion induced photon (IPP) [34]. There are other complicated methods which use residual gas analysis (RGA) [22,42]. As to the species of projectile, inert gas ions have been mainly used. Therefore the knowledge about the chemical effect on desorption due to chemically active gas ions are very lacked at present [9, 28, 41, 42].

(a) Measured systems (Table 2)
(b) Dependence on the ion energy (Fig.16-Fig.25)
(c) Theoretical estimates and computer simulations [22, 24, 26, 29, 39, 45] (Fig. 25, 30, 32 and 33)
(d) Dependence on the heat of adsorption (Fig.29 and 30)
(e) Dependence on the incident angle of ions (Fig.31-Fig.33)
(f) Effect of surface damages [40]
REFERENCES

   "The Disappearance of Gas in the Electric Discharge"

2) N.R. Campbell: Phil. Mag. 41 (1921) 685-706.
   "The Disappearance of Gas in the Electric Discharge"

   "On the Cleaning of Surfaces"

   "The Cleaning of Glass in a Glow Discharge"


   "Gas Discharge Cleaning of Vacuum Surfaces"

   "Investigation by Techniques of Electron Stimulated Desorption of the Merits of Glow Discharge Cleaning of the Surfaces of Vacuum Chambers at the CERN Intersecting Storage Rings"

   "Trapping and Removal of Oxygen in Tokamaks"

    "Ion Induced Gas Desorption Problems in the ISR"


   "The Effect of Cleaning and Other Surface Treatments on the Surface Composition of Technological Materials"

   "Desorption of Solid Hydrogen by Energetic Protons, Duterons, and Electrons"

   "Sputtering of Condensed Gases by Proton Bombardment"

   "Desorption of Adsorbed and Condensed Gases on Metals by Deuterons"

   "An Ion Desorption Test Instrument"

   "The Temperature Dependence of the Surface Composition and Electron and Ion Induced Gas Desorption Coefficients of Inconel 718 and 316 L + N Stainless Steel"

   "The Effect of Bakeout Temperature on the Electron and Ion Induced Gases Desorption Coefficients of Some Technological Materials"
"Ion Induced Desorption from Stainless Steel Studied
with Isotope Techniques"

"Sputtering of Chemisorbed Nitrogen with Ar+"

4760-4766.
"Sputtering of Chemisorbed Gas (Nitrogen on Tungsten)
by Low-Energy Ions"

on Plasma Wall Interaction, Jülich (Pergamon Press, 1976)
301-307.
"Desorption of Surface Contaminants by Low Energy
Particle Impact"

"Sputtering of Adsorbed Layers by Ion Bombardment"

(1977) 47-49.
"A Contribution to the Investigation of Ion Impact
Desorption by Ion Scattering"

"Study of the Sputtering of Adsorbates by Low Energy
Ions"

"A 2-100 keV, UHV Ion Impact Spectrometer for Ion-Solid Interaction Studies"


"H⁺ Ion Induced Desorption of Sulfur Adsorbed on Polycrystalline Ni Surfaces"


"Investigation of Ion Impact Desorption of Atoms and Molecules by Low Energy Ion Scattering (ISS)"


"A Study of the Sorption of CO on W and Ni single-crystal Surfaces by Ion Scattering"


"Ion Impact Desorption Cross Sections of Hydrogen and Oxygen from Metals by Light Ion Bombardment"


"Low-energy Ion Scattering Study of Adsorbed Layers on Molybdenum Surface"
33) W. Heiland and E. Taglauer: Symp. on Atomic and Surface Physics, Tirol (1978) 9-16.
    "Surface Studies by Low Energy Ions"
    "A Comparison of Surface Analysis using Ion Scattering, Ion-produced Photons, and Secondary Ion Emission"
    "The Influence of Adsorption Energies on Ion Impact Desorption of Surface Layers"
    "The Study of Sputtering Effects in Oxides and Metal-adsorbed-gas Systems using Combined Analytical Techniques"
    "ISS Observations of Molybdenum Samples as Llmiter and First Wall Materials after Various Preparation Methods"
    "The Effect of Adsorption on Ion and Photon Yields from Ion Bombarded Metal Surfaces"
    "Ion Beam Induced Desorption of Surface Layers"
   "Ion-induced Desorption of Adsorption Layers on Annealed and Prebombarded Surfaces"

   "Hydrogen Ion Impact Desorption of Sulfur from Stainless Steel"

   "Bombardment-induced Desorption of CO Adsorbed on 304 Stainless Steel by Low Energy (75-1000 eV) Light Active and Inert Gas Ions"

   "ISS Observations of Ti Film on Mo Substrate"

   "Ion Impact Desorption of Oxygen from Molybdenum Surface"

   "ISS Studies on Sputtering of Chemisorbed Gases by Low-energy Ions"

   "A Review of the Wall Problem and Conditioning Techniques for Tokamaks"

"Plasma-Surface Interactions in Tokamak"
Table Captions

Table 1  Substrate-adsorbate-ion combinations for the data compilation of ion induced desorption yields.

Table 2  Substrate-adsorbate-ion combinations for the data compilation of ion induced desorption cross sections.

Figure Captions

Fig. 1  Desorption yields as a function of vacuum bakeout temperature for 24 h [19].

Fig. 2  "

Fig. 3  "

Fig. 4  "

Fig. 5  "

Fig. 6  "

Fig. 7  Desorption yields as a function of $K^+$ ion energy for 316 L + N stainless steel after vacuum bakeout at 300°C for 24 h [18].

Fig. 8  Desorption yields as a function of the ion energy for the ISR stainless steel vacuum chamber (316 L + N) after vacuum bakeouts at 300°C and 340°C for 24 h (ISR proton beam current = 3A) [10].

Fig. 9  The dependence of the desorption yields on the ion energy (1) before and (2) after an Ar glow discharge cleaning (measured at 6.0 and 9.5 A ISR proton beam currents respectively). Negative yields indicate the phenomenon of beam pumping [10].
Fig. 10  The electron and K\(^+\) ion induced desorption yields for 316 L + N stainless steel before and after an in situ pure Ar glow discharge [11].

Fig. 11  The electron and K\(^+\) ion induced desorption yields for pure Al before and after an in situ pure Ar glow discharge [13].

Fig. 12  Initial yields of desorbed hydrogen as a function of condensed gas thickness when bombarded by 5 and 20 keV protons. The exposure of the surface to hydrogen to form the condensed layer is given. The surface temperature of Cu substrate is 3.2°K [14].

Fig. 13  Initial yields of desorbed CO as a function of CO exposure when bombarded by 5 keV protons. The surface temperature of Cu substrate is 4.2°K [15].

Fig. 14  Desorption yields of H\(_2\)O molecules by D\(^+\) ions as a function of incident ion energy. The surface temperature of the stainless steel substrate is 77°K [16].

Fig. 15  Desorption yields when bombarded by Ar\(^+\) ions (< 520 eV). The substrate 304 L stainless steel was baked at 270°C for more than 8 hr (marked B) and then exposed to CO\(_2\), H\(_2\), CO, air O\(_2\), CH\(_4\), Ar, H\(_2\)O or N\(_2\) at 1 × 10\(^{-5}\) Torr for 2 h [20].

Fig. 16  Ion energy dependence of desorption cross sections measured by Sagara et al. (43).

Fig. 17  Ion energy dependence of desorption cross sections measured by Taglauer et al. (23, 29, 33), McDonald et al. (34) and Sagara et al. (45).
Fig. 18  Ion energy dependence of desorption cross sections measured by Taglauer et al. (23, 26, 33), Van den Berg et al. (27).

Fig. 19  Ion energy dependence of desorption cross sections measured by Windawi and Katzer (28), Taglauer et al. (24) and Sagara et al. (45).

Fig. 20  The desorption cross section measured by Taglauer and Heiland (40).

Fig. 21  Ion energy dependence of desorption cross sections measured by Sagara et al. (37, 43, 45).

Fig. 22  Ion energy dependence of desorption cross sections measured by Tsuchidate et al. (44) and Sagara et al. (37, 45).

Fig. 23  Ion energy dependence of desorption cross sections measured by Sagara et al. (45).

Fig. 24  Ion energy dependence of desorption cross sections measured by Winters and Sigmund (22).

Fig. 25  Ion energy dependence of desorption cross sections measured by Taglauer et al. (29, 31).

Fig. 26  Desorption cross sections as a function of ion energy for S on 316 stainless steel by hydrogen ion impact at 45° incidence from normal to surface [41].

Fig. 27  Desorption cross sections as a function of ion energy for CO on 304 stainless steel by various ions at the normal incidence to surface [42].
Fig. 28 Calculated cross sections for the desorption of S from Ni (110) with projectiles of the given atomic species, MORLAY: numerical code; \( W + S \): theory of Winters and Sigmund [39].

Fig. 29 Dependence of the desorption cross sections for \( O_2 \) and CO on various metals as a function of the inverse heat of adsorption [35, 36, 39].

Fig. 30 Calculated desorption cross sections for oxygen on various metals. Here \( E_B \) corresponds to \( Q \) in Fig. 29. The dashed line is a linear fit to the data points including the origin [35, 36, 39].

Fig. 31 Dependence of the desorption cross section on the angle of the incoming ion beam relative to the surface for oxygen on Si (111) [39].

Fig. 32 Calculated and experimental values for the desorption cross section of CO on Ni as a function of the incident angle of \( Ne^+ \) ions relative to the surface [29].

Fig. 33 Measured and calculated dependence of the desorption cross section on the incident angle relative to the surface [24].
<table>
<thead>
<tr>
<th>Substrate</th>
<th>Adsorbate</th>
<th>Ion(keV)</th>
<th>Fig.no.</th>
<th>Method and references</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>residual gases</td>
<td>$^{15}_{2}{^+}\text{,}K^+(2)$</td>
<td>11</td>
<td>RGA*(12,13)</td>
<td>bake and Ar discharge</td>
</tr>
<tr>
<td>Cu (poly.)</td>
<td>$H_2$, $D_2$</td>
<td>$H^+$, $D^+(5-20)$</td>
<td>12</td>
<td>RGA(14)</td>
<td>discondensed at 2.5-4.2 K</td>
</tr>
<tr>
<td></td>
<td>He</td>
<td>$H^+$ (5)</td>
<td>13</td>
<td>RGA(15)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO, Ar</td>
<td>$H^+$ (5)</td>
<td></td>
<td>RGA(15)</td>
<td></td>
</tr>
<tr>
<td>Stainless steel</td>
<td>$H_2$O</td>
<td>$D^+(5-35)$</td>
<td>14</td>
<td>RGA(16)</td>
<td></td>
</tr>
<tr>
<td>304</td>
<td>CO</td>
<td>Ar$^+$ (1)</td>
<td></td>
<td>RGA(17)</td>
<td>.66 atoms/ ion</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>Ar$^+$ ($&lt;0.52$)</td>
<td>15</td>
<td>RGA(20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$HS_2$H</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$H_2$O, $O_2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO, Ar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>316L+M</td>
<td>residual gases</td>
<td>$H^+(0-3)$</td>
<td>8,9</td>
<td>RGA(10)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$K^+(2)$</td>
<td>10</td>
<td>RGA(11)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{15}N_2^+$, $K^+$</td>
<td>1,7</td>
<td>RGA(12,13)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.4, 0-2)</td>
<td></td>
<td>RGA(18,19)</td>
<td></td>
</tr>
<tr>
<td>Inconel 600</td>
<td></td>
<td>$K^+(1.4)$</td>
<td>3</td>
<td>RGA(13,19)</td>
<td></td>
</tr>
<tr>
<td>718</td>
<td></td>
<td>$K^+(1.4)$</td>
<td>4</td>
<td>RGA(18,19)</td>
<td></td>
</tr>
<tr>
<td>Al alloy 5086</td>
<td></td>
<td>$K^+(1.4)$</td>
<td>6</td>
<td>RGA(19)</td>
<td></td>
</tr>
<tr>
<td>6061</td>
<td>CO</td>
<td>Ar$^+$ (1)</td>
<td></td>
<td>RGA(17)</td>
<td>.76 atoms/ ion</td>
</tr>
<tr>
<td>Ti alloy 13V11Cr3Al</td>
<td></td>
<td>$^{15}N_2^+$ (2)</td>
<td></td>
<td>RGA(13)</td>
<td></td>
</tr>
<tr>
<td>14V6Al</td>
<td></td>
<td>$K^+$ (1.4)</td>
<td>2</td>
<td>RGA(19)</td>
<td></td>
</tr>
<tr>
<td>Cu-OFHC</td>
<td></td>
<td>$K^+$ (1.4)</td>
<td>5</td>
<td>RGA(13,19)</td>
<td></td>
</tr>
</tbody>
</table>

* RGA: Residual Gas Analysis
<table>
<thead>
<tr>
<th>Substrate</th>
<th>Adsorbate</th>
<th>Ion (keV)</th>
<th>Angle (from normal)</th>
<th>Method and references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si(111)</td>
<td>O₂</td>
<td>He (1.0)</td>
<td>20-75</td>
<td>ISS*₁ (39)</td>
</tr>
<tr>
<td>Ti</td>
<td>H₂</td>
<td>He (1.5)</td>
<td>45</td>
<td>RGA*₂ (43)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ar (1.5)</td>
<td>45</td>
<td>RGA (43)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>He (1.5)</td>
<td>45</td>
<td>ISS (43)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>He (0.5)</td>
<td>30</td>
<td>ISS (35, 36)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ar (1.5)</td>
<td>45</td>
<td>ISS (43)</td>
</tr>
<tr>
<td>Ni(poly.)</td>
<td>C₀</td>
<td>He,Ne (2.0)</td>
<td>45</td>
<td>ISS*₃ (34, 38)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ar (2.0)</td>
<td>45</td>
<td>IIP (34, 38)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>He,Ne(0.3-2.6)</td>
<td>45</td>
<td>ISS (45)</td>
</tr>
<tr>
<td>Ni(110)</td>
<td>C₀</td>
<td>He (0.5-1.2)</td>
<td>60</td>
<td>ISS (23, 35)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ne (1.0)</td>
<td>60</td>
<td>ISS (33)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>O₂</td>
<td>³He,Ne(0.6-1.6)</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H (0.5)</td>
<td>30</td>
<td>ISS (55)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ne (0.6)</td>
<td>75</td>
<td>ISS (27)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ar (0.5)</td>
<td>60</td>
<td>ISS (23)</td>
</tr>
<tr>
<td>Ni(111)</td>
<td>S</td>
<td>He,Ne,Ar (0.2-1.8)</td>
<td>60</td>
<td>ISS (24)</td>
</tr>
<tr>
<td>Cu(poly.)</td>
<td>O₂</td>
<td>He (0.5)</td>
<td>30</td>
<td>ISS (35, 40)</td>
</tr>
<tr>
<td>Mo(poly.)</td>
<td>C₀</td>
<td>He (0.5-2.5)</td>
<td>45</td>
<td>ISS (37)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ar (1.5)</td>
<td>45</td>
<td>ISS (43)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>He (0.5-2.5)</td>
<td>45</td>
<td>ISS (32, 37)</td>
</tr>
<tr>
<td>Mo(110)</td>
<td>C₀</td>
<td>He,Ne,Ar (0.4-2.6)</td>
<td>45</td>
<td>ISS (45)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>O₂</td>
<td>He,Ne,Ar (0.4-2.5)</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td>He,Ne,Ar (0.3-2.8)</td>
<td>45</td>
</tr>
<tr>
<td>Pd</td>
<td>O₂</td>
<td>He (0.5)</td>
<td>30</td>
<td>ISS (35)</td>
</tr>
<tr>
<td>Ta</td>
<td>O₂</td>
<td>He (0.5)</td>
<td>30</td>
<td>ISS (35)</td>
</tr>
<tr>
<td>W(poly.)</td>
<td>Ne</td>
<td>He,Ne,Ar,Kr,Xe (0.02-0.5)</td>
<td>0</td>
<td>flash filament (22)</td>
</tr>
<tr>
<td></td>
<td>³He</td>
<td>(0.8-1.8)</td>
<td>60</td>
<td>ISS (29, 31)</td>
</tr>
<tr>
<td>W(100)</td>
<td>³He</td>
<td>(0.8-1.8)</td>
<td>60</td>
<td>ISS (29, 31)</td>
</tr>
</tbody>
</table>
### Table 2 (No. 2)

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Adsorbate Ion(keV)</th>
<th>Angle (from normal)</th>
<th>Fig. No.</th>
<th>Method and references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt</td>
<td>O$_2$ He (0.5)</td>
<td>30</td>
<td>29</td>
<td>ISS (35)</td>
</tr>
<tr>
<td>Stainless steel 316</td>
<td>S II (0.3-1.0)</td>
<td>45</td>
<td>26</td>
<td>SIMS (41)</td>
</tr>
<tr>
<td>304</td>
<td>CO H$_2$D (0.1-0.5)</td>
<td>0</td>
<td>27</td>
<td>RGA (42)</td>
</tr>
<tr>
<td></td>
<td>He,Ne,Ar (0.2-0.9)</td>
<td></td>
<td>27</td>
<td>RGA (42)</td>
</tr>
</tbody>
</table>

*1 ISS : Ion Scattering Spectroscopy
*2 RGA : Residual Gas Analysis
*3 IIP : Ion induced Photon
*4 SIMS: Secondary Ion Mass Spectrometry
*5 AES : Auger Electron Spectroscopy
Fig. 7

Fig. 8
CO on Ti

ψ surface ref.
He⁺ • 45° thin filme 43
Ar⁺ □ 45° thin filme 43

Fig. 16
CO on Ni

- Surface ref.  
- $\psi$

+$\text{He}^+$
- $60^\circ (110) 23$
- $45^\circ (\text{poly.}) 34$
- $45^\circ (\text{poly.}) 45$
- $\triangle 60^\circ (110) 33$
- $\nabla 60^\circ (111) 29$
- $+ 45^\circ (\text{poly.}) 34$
- $\Delta 45^\circ (\text{poly.}) 45$
- $\text{Ar}^+$
- $\square 45^\circ (\text{poly.}) 34$

Desorption Cross Section (cm$^2$)

Ion Energy (keV)

Fig. 17

- 31 -
\( \text{O}_2 \) on Ni

<table>
<thead>
<tr>
<th>( \phi )</th>
<th>Surface</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>He(^+)</td>
<td>60(^\circ)</td>
<td>(110)</td>
</tr>
<tr>
<td>He(^+)</td>
<td>60(^\circ)</td>
<td>(110)</td>
</tr>
<tr>
<td>Ne(^+)</td>
<td>60(^\circ)</td>
<td>(110)</td>
</tr>
<tr>
<td>Ne(^+)</td>
<td>75(^\circ)</td>
<td>(110)</td>
</tr>
<tr>
<td>Ar(^+)</td>
<td>60(^\circ)</td>
<td>(110)</td>
</tr>
</tbody>
</table>

Desorption Cross Section (cm\(^2\))

Ion Energy (keV)

Fig. 18
Fig. 20

O₂ on Cu

ψ surface ref.
He⁺ ○ 30° (poly.) 40
CO on Mo

$\psi$ surface ref.

He$^+$ ○ $45^\circ$ (poly.) 37

He$^+$ ● $45^\circ$ (110) 45

Ne$^+$ ▲ $45^\circ$ (110) 45

Ar$^+$ □ $45^\circ$ (poly.) 43

Ar$^+$ ■ $45^\circ$ (110) 45

Desorption Cross Section (cm$^2$)

Ion Energy (keV)

Fig. 21
Fig. 22
Fig. 23

Desorption Cross Section (cm$^2$)

Ion Energy (keV)

- S on Mo

\[ \psi \] surface ref.

- He$^+$ ○ $45^\circ$ (110) 45
- Ne$^+$ ▲ $45^\circ$ (110) 45
- Ar$^+$ □ $45^\circ$ (110) 45
Fig. 24

$^{15}\text{N}_2$ on W

<table>
<thead>
<tr>
<th>Ion</th>
<th>Surface</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>He$^+$</td>
<td>O$^+$ (poly.)</td>
<td>22</td>
</tr>
<tr>
<td>Ne$^+$</td>
<td>O$^+$ (poly.)</td>
<td>22</td>
</tr>
<tr>
<td>Ar$^+$</td>
<td>O$^+$ (poly.)</td>
<td>22</td>
</tr>
<tr>
<td>Kr$^+$</td>
<td>O$^+$ (poly.)</td>
<td>22</td>
</tr>
<tr>
<td>Xe$^+$</td>
<td>O$^+$ (poly.)</td>
<td>22</td>
</tr>
</tbody>
</table>

Ion Energy (keV) vs. Desorption Cross Section (cm$^2$)
Fig. 25

H₂ on W

$^3\text{He}^+$  ○  60° (100) 29,31
Fig. 26

Fig. 27
Fig. 28

Ni (110)+S
\( \psi = 30^\circ \)
- - - - Morey
○ ○ ○ W+S

Fig. 29

He\(^+\) → Metal + O or CO
\( E_0 = 500 \text{ eV} \)
\( \psi = 60^\circ \)
He⁺ → Si (111) + O₂

$E_0 = 1$ keV

$\sigma_D$ [cm²]

$\psi$ [°]

0° 10° 20° 30° 40° 50° 60° 70°

$3 \times 10^{-16}$

$2 \times 10^{-16}$

$1 \times 10^{-16}$

Fig. 31
Fig. 32

Desorption with Ne
Ne → Ni + CO
$E_0 = 700\text{ eV}$

- Experiment Ni (III)
- Morley Ni(III) x4

Fig. 33

Ne → Ni (III) + S
$E_0 = 1\text{ keV}$

- Experiment
- Morley
Electron Stimulated Desorptions

Ayahiko Ichimiya
Department of Applied Physics, Faculty of Engineering, Nagoya university, Chikusa-ku, Nagoya 464

Many investigations of electron stimulated desorptions (ESD) have been carried out with various experimental techniques in the past ten years [1-357]. In this report results of ESD experiments are described shortly. Detail descriptions of ESD studies are given in the cited reviews [288, 306, 345].

ESD cross sections and mechanisms

ESD cross sections are mostly measured by decays of adsorbate concentrations. When electron current densities are high enough to cause the decay by ESD, the total ESD cross sections $\delta$ are determined from the time dependence of the concentrations:

$$\frac{dN}{dt} = -\delta N \frac{dn}{dt},$$

where $N$ is the density of adsorbed atoms, and $\frac{dn}{dt}$ the number of incoming electrons per unit time and area. Several energies of incoming electrons, between 10 eV and 3keV, were used in ESD experiments. Most of ESD cross sections were measured indirectly by the decay of signal intensities of the Auger electrons from adsorbates with low electron current densities. The values of ESD cross sections are shown in Table I. For ESD of neutral atoms the cross sections lie between $10^{-16}$ and $10^{-18}$ cm$^2$, while the cross sections for the desorption of ions are between $10^{-20}$ and $10^{-25}$ cm$^2$. 

-44-
In the ESD mechanisms electronic excitations are mainly involved. Two models are presented to explain the ESD experimental results [288, 345]. One of the models is described as follows: 

The Franck-Condon transition from the ground state of the adsorbate system to a repulsive neutral or ionic state of the complex of adsorbed and substrate atoms is induced by electron impact. The neutral or ionic particles move away from the surface. In the case of ionic desorption ions excited by the primary transition are reneutralized or recaptured by an electron tunneling from the metal substrate into the hole in the surface level. The ionic desorption probability $P_+$ is given by

$$P_+ = q_+ / q_{ex} = \exp(-\int_{x_0}^{\infty} R(x)/v(x)dx),$$

where $q_+$ is ionic cross section, $q_{ex}$ primary excitation cross section, $R(x)$ recapture probability at the distance $x$ from the surface, and $v(x)$ classical velocity of ions at $x$. This model of the recapture process is in good agreement with the experimental results of the isotope effects of ESD with Hydrogen and Deuterium adsorptions. Therefore

$$\ln(I(H^+)/I(D^+)) = -0.41 \ln(P_+(H^+)).$$

The experimental results for the isotope effects are shown in Table II. For $\beta_2$ state on W(100) and (110) surfaces values of calculated $q_{ex}$ from the experimental value of $I(H^+)/I(D^+)$ are in very good agreement with each other.

Recently another ESD mechanism was presented by Knotek and Feibelman [211] to explain threshold for ESD of positive ions ($O^+$, $OH^+$ and $F^+$) from metal oxides. From the experimental positive ion yields and the electron energy loss spectrum, they suggested that the desorptions induced by the interatomic Auger
type process are dominant compared with the direct ionization process of adsorbates.

Angular distributions of ESD ions

In many investigations of angular resolved ESD the experiment by Madey et. al. [296] is a new development of the experimental technique to show as visual patterns of the angular distributions by using a phosphorescent screen with a multi-channel-electron-multiplier-plate. The ESD-ion-angular-distribution (ESDIAD) patterns strongly depend on the adsorbate states. By assuming that the direction of the desorption agree with the direction of the potential gradient at the surface, the sites of adsorbed atoms are estimated from the symmetry and the orientation of the ESDIAD patterns.

For H$_2$ on W(100) surface single spot is observed in the ESDIAD patterns of H$^+$ ions in the direction normal to the surface. The peak width is about 21 degrees. Such single peak is observed in ESDIAD patterns of F$^+$ ions with about 10 degrees peak width from SF$_6$ on W(111) and (011) surfaces. For SF$_6$ on O$_2$ covered W-surfaces, the ESDIAD patterns, however, show the symmetries of the tungsten surfaces.

ESDIAD patterns of O$^+$ for O$_2$ on W(100) surface depend strongly on the adsorbate states. For the 2$^2$ state of low coverage O$_2$ on W(100), adsorbed with $2 \times 10^{-6}$ Torr. Sec at 400K, the ESDIAD pattern at 300K has four hold symmetry as shown schematically in Fig. 1a. The pattern goes away for heating
the substrate up to 700K. For the $\beta_1$ state, which is prepared by heating the substrate after the adsorption of $O_2$ with $40 \times 10^{-6}$ Torr. Sec at 100K, the ESDIAD pattern shows very different behaviors from the pattern for the low coverage state ($\beta_2$ state). After the heating less than 600K the ESDIAD patterns taken at 100K show 45 degrees rotation from the orientation of the low coverage patterns as shown in Fig. 1b. For the heating more than 600K each spot in the pattern is splitted into two spots as shown in Fig. 1c. Different ESDIAD patterns for high coverage $O_2$ on W(100) adsorbed at high temperature above 700K are observed.

The patterns taken at 400K after adsorptions of $O_2$ with $20 \times 10^{-6}$ Torr. sec. at 700K and $40 \times 10^{-6}$ Torr. sec. at 795K show the same symmetry and the orientation of the pattern from low coverage surface. For adsorptions with $40 \times 10^{-6}$ Torr. sec. at 705K and $120 \times 10^{-6}$ Torr. sec. at 700K, the pattern observed above is added by the splitted 40° rotating four hold pattern. For adsorption with $40 \times 10^{-6}$ Torr. sec. at 630K the pattern is nearly the same as that shown in Fig. 1c.

For $O_2$ on W(111) a structureless circular spot is observed in ESDIAD pattern at low oxygen exposures (about $0.25 \times 10^{-6}$ Torr. sec.). The direction of the ions is normal to the surface. At high exposures more than $5 \times 10^{-6}$ Torr. sec. the ESDIAD pattern becomes the triangular shape. For heating after exposure of $40 \times 10^{-6}$ Torr. sec. at 100K the pattern depends on the heating temperatures above 600K. Above the temperature 600K the ESDIAD pattern becomes sharp, and no ion desorption can be observed in the direction normal to the surface. The angle of ion emission between the center of the pattern and the most intense regions of the spots is $34\pm4$ degrees. For the pattern without heating, the angle is 27 degrees.
For the adsorption of $40 \times 10^{-6}$ Torr.sec. exposures at about 400K, the ESDIAD pattern disappears after heating to about 600K, while the ESDIAD pattern for adsorption at 100K becomes sharp and intense for heating.

For adsorption of CO on W(111) ESDIAD single peak is observed in the direction normal to the surface. However, most of the observations show off-normal peaks in 5 - 20 degrees from normal direction for $O^+$ ions desorbed CO on metal surfaces (W, Mo, Pd, and Ru).

**Energy distributions**

Most of the energies of desorbed ions stimulated by electrons distribute below 15 eV. For one monolayer coverage of oxygen atoms on W(100), there is one symmetric peak at 300K and after annealing with above 950K with peak maximum at 7.5 eV and 8.0 eV respectively. The halfwidth of the respective peaks are 2.7 and 2.1 eVs. After the intermediate annealing temperature range an additional peak at 5.5 eV is measured. The peak energy depends on $O_2$ coverage. At 300K, the peak energy is 7.8 eV up to about 3/4 monolayer (ML) coverage and shifts to 7.5 eV for more than 3/4ML. The peak at 5.5 eV is observed between 1/2ML and 3/4ML. The maximum intensity is obtained at 0.6ML coverage. After 1100K annealing peak at 7.8 eV is shifted to 8.3 eV. These energy peak shifts are explained by adsorbate structural changes. For CO and $O_2$ on W(111) kinetic energy of the desorbing $O^+$ ions has a value of 6.3 eV after $O_2$ exposure and the value is shifted to 5.5 eV after CO exposure.
4th (1968) (P+1) 141-144 (Eng.)  
"Electronic desorption from metal surfaces."

2. L. Garwin Edward, W. Hoyt EaH, Rabinowitz Mario & Jurow Joseph  
4th (1968) (P+1) 131-136 (Eng.)  
"Electron-induced desorption of gases from aluminum."

Vac. Congr.  
4th (1968) (P+1) 137-140 (Eng.)  
"Electron-impact desorption of active gases from tungsten"

4th (1968) (P+1) 127-130 (Ger.)  
"Mass-spectrometric study of ion desorption caused by slow  
electric impact."

11 (11) 3200-3202 (Russ)  
"Kinetics of tungsten oxidation."

6. Mitsuaki Nishijima: Avail. Univ. Microfilms, Ann Arbor,  
Mich. Order No. 70-940  
(1969) 208pp. (Eng.)  
"Electron impact desorption of ions and neutrals from  
polycrystalline tungsten."

Electrokhimiya. 5 (10) (1969) 1174-   (Russ)  
"Conductometric study of palladium black."

Electrokhimia  
5 (10) (1969) 1175-1178 (Russ)  
"Electrical conductivity of a Raney nickel catalyst during  
removal of hydrogen from it in electrolyte solutions."
"Thermal desorption of hydrogen from reduced catalysts."

51 (12) (1969) 5352-5363 (Eng.)
"Interaction of hydrogen with (100) tungsten. I. Binding states."

11 (12) (1969) 3621-3624 (Russ)
"Mechanism of the thermal desorption of oxygen from the (100) face of a tungsten crystal."

7 (2) (1970) 289-293 (Eng.)
"Electron-induced ion desorption from the system platinum/hydrogen/carbon monoxide."

7 (1) (1970) (Jan/Feb) 182-187 (Eng.)
"Ion desorption by electron bombardment; relation to total and partial pressure measurement."

7 (3) (1970) 420-428 (Eng.)
"Kinetics of electron impact desorption of ions and neutrals from polycrystalline tungsten."

7 (3) (1970) 410-419 (Eng.)
"Apparatus for the study of the electron impact desorption of ions and neutrals from solid surfaces."

19 (1-2) (1970) 1-8 (Ger)
"Oxygen desorption of tungsten by electron impact."
17. John Dollimore, C.M. Freedman, B.H. Harrison & P.F. Quinn
Carbon 8 (5) (1970) 587-596 (E)
"Surface complexes on carbon. I. Surface oxygen complex
on a nongraphic carbon."

18 (1-2) (1970) 49-53 (Ger.)
"Thermal desorption of carbon monoxide from metals."

9 (4) (1970) 255-266 (Eng.)
"Inelastic interactions of slow electrons with adsorbed
particles."

20. Theodore E. Madey, John T. Yates Jr. & David Anthony King
"Isotope effect in electron stimulated desorption; Oxygen
chemisorbed on tungsten."

21. Henri Le Bail : Commis Energ. At. (Fr.) Note. 1970,
24 (11) (1970) 21420
"Desorption in nitrogen on in hydrogen of the oxygen
chemisorbed on graphite."

Carbons Graphite, Pap. 3rd.
"Energetic nature of the surface of graphite by the thermal
desorption of the surface oxygen complex."

23. A. Klopfer : Vak-Teck
19 (7) (1970) 167-170 (Ger)
"Desorption of hydrogen from tungsten by electron impact."
24. Ivor G Newsham, James V. Hogue & Donald R. Sandstrom
Report (1970) RLO-2221-T-7-4, 14pp. (Eng.) Avail Dep. NTIS.
from Nucl. Sci. Abstr.
"Electron-stimulated desorption of excited neutrals Carbon
monoxide on tungsten."

Microfilms, Ann Arbor, Mich., Order No. 70-16, 802
From Diss Abstr. Int. B (1970) 31 (3), 1482
"Electron-impact desorption of carbon monoxide from
tungsten: ion energy distribution"

75 (2) (1971) 227-234 (E)
"Binding states of hydrogen and of nitrogen on the (100)
plane of molybdenum"

30 (4), (1971), 1076-1082 (E)
"Surface Potential of carbon monoxide on the single crystal
surface of tungsten."

234 (50), (1971), 134-135 (Eng.)
"surface studies on graphite"

26 (2), (1971), 572-586 (E)
"Absorption of oxygen on molybdenum (111). Effect of
trans impurities"

37 (2), (1971), 325-331 (E)
"Chemisorption of several diatomic gases onto a tungsten
(210) plane and a polycrystalline tungsten surface."
"Use of partial-pressure mass spectrometry in the study of the thermal desorption and oxidation of carbon and graphite."

"Electron impact desorption applied to adsorption--desorption kinetics."

"Interaction of oxygen with polycrystalline tungsten. I. Sticking probabilities and desorption spectra."

"Binding states of hydrogen on tungsten."

"Electron-stimulated desorption as a tool for studies of chemisorption Review."

"Photodesorption of carbon monoxide from tungsten."

"Thermal desorption of carbon monoxide from polycrystalline tungsten in residual vacuum."
"Threshold energy and mechanism in electron-impact desorption and photo desorption of adsorption layers on metals."

"Study of surface phenomena on carbon by EDR."

"Gas release from microchannel electron multiplier arrays."

"Field emission study of the formation and desorption of oxide layers on tungsten surfaces."

"Sorption of oxygen on tungsten studied by a molecular beam ionization method"

43. Jose M. Lopez-Sancho & Jose L. Segovia : Surface Sci. 30 (2), (1972), 419-439 (Eng.)
"Adsorption kinetics and electron desorption of molecular oxygen on polycrystalline tungsten"

44. Kiyoshi Senzaki : Denshi Gijutsu Sogo Kenkujo Iho 36 (8/9), (1972), 616-622 (Japan)
"Field emission microscopy study of adsorption and dissociation of carbon monoxide on a tungsten surface."

"Desorption from gas covered surfaces by electron impact."
32 (2), (1972), 459-465 (Eng.)
"Combined Auger electron spectroscopy and electron impact desorption studies of silicon surface"

30 (3), (1972), 601-616 (Eng.)
"Chemisorption of carbon monoxide on tungsten Correlation of reflection-adsorption infrared spectra with Carbon monoxide binding state population"

9 (2), (1972), 936-941 (Eng.)
"Quantitative analysis of thermal desorption spectra. Chemisorption of carbon monoxide in tungsten"

49. Iroro G. Newsham, James V. Hogue & Donald R. Sandstrom
J. Vac. Sci. Technol. 9 (2), (1972), 596-599 (Eng.)
"Electron-stimulated desorption of exited neutrals Carbon monoxide on tungsten"

11 (9), (1972), 1363-1371 (Eng.)
"Absorption and dissociation of carbon monoxide on tungsten"

32 (3), (1972), 479-505 (Eng.)
"Chemisorption of carbon monoxide on tungsten (100) combined flash desorption and electron stimulated desorption study. 1"

52. L. R. Clavenna & L. D. Schmidt : Surface Sci.
33 (1), (1972), 11-26 (Eng.)
"Decomposition of carbon dioxide on (100) tungsten."
53. Marian Vesely & Gert Ehrlich: Surface Sci. 34 (3), (1972), 547-560 (E)
"Field evaporation Model and experiment."

54. G. Peltogrini,
EURATOM Rep. No. 5060, (1972), 341-343 (E)
"Basal plane thermal expansion of pyrocarbons produced in a fluidized bed as coatings for H. T. G. R. [high-temperature gas-cooled nuclear reactor] fuel particles."

55. P. C. Aben, H. Vander Eijk & J. M. Oelderik
717-729 (E)
"Characterization of the metal surface of alumina-supported platinum catalysts by temperature-programmed desorption of chemisorbed hydrogen."

56. Theodore E. Madey: Surface Sci. 29 (2), (1972), 571-589 (Eng.)
"Absorption and displacement processes on tungsten (111) involving methane, molecular hydrogen, and molecular oxygen."

"Chemisorption and decomposition of tetramethylsilane over tungsten and iron surface."

"Mechanism of desorption and activated adsorption of oxygen on unexposed and UV-exposed zinc oxide."

59. Kenichi Tanaka & George Blyholder: J. Phys. Chem. 76 (22), (1972), 3184-3187 (Eng.)
"Adsorbed oxygen species on zinc oxide in the dark and under illumination."
   68 (P+7), (1972), 1347-1359 (Eng.)
   "Interaction of oxygen with polycrystalline tungsten 3
   Electron stimulated desorption"

61. Michel Coulon, Patrice Gadelle & Lucien Bonnetain
   "Variation of the electron work function of carbon by
   atomic and molecular hydrogen adsorption"

   "Replacement of hydrogen by carbon monoxide on a tungsten
   surface"

63. Michel Coulon, Patrice Gadelle & Lucien Bonnetain
   819-823 (Fr.)
   "Variation of the electron work function of carbon by
   atomic and molecular hydrogen adsorption"

64. Ivor Gilbert Bewsham : Avail. Univ. Microfilmes, Ann Arbor,
   Mich., Order No. 73-67 From Diss. Abstr. Int. B.
   33 (7), (1972), 3241-3242
   "Electron-stimulated desorption of ions and excited
   neutrals. Carbon monoxide on tungsten."

65. Toshio Sugita, Shigeo Ebisawa & Kaji Kawasaki : Denshi
   Gijutsu Sogo Kenkyujo Iho,
   36 (8/9), (1972), 580-593 (Japan)
   "Replacement of chemisorbed gases on metal surface"

   Main) 80 (1-2), (1972), 71-81 (E)
   "Adsorption of hydrogen and nitrogen on (110) molybdenum"
Vide Revetements Etats Surface, C. R.
2nd, (1972) (Pub. 1972)
"Adsorption-diffusion model of gas-metal interaction in high vacuum."

35 (1), (1973), 271-287 (E)
"Carbon monoxide adsorption kinetics on molybdenum (100)."

"Chemisorption of carbon monoxide on tungsten 1. Desorption spectra and electron stimulated desorption."

10 (1), (1973), 39-42 (E)
"Time-of-flight analysis of ions and excited neutrals released by ESD [electron-stimulated desorption] of carbon monoxide on (100) tungsten."

71. B. S. Mukanova, N. M. Popova & D. V. Sokol'skii
Vestn. Akad. Nauk Kaz. SSR. 29 (11), (1973), 45-49 (Russ.)
"Thermodesorption of hydrogen from reduced nickel catalysts on clay containing chromic oxide and iron additives."

72. C. Benndorf & F. Thieme : Z. Phys. Chem. (Frankfurt am Main) 87 (1-3), (1973), 40-59 (Ger.)
"Desorption of hydrogen from polycrystalline nickel evaporated films."

73. N. M. Popova, L. V. Bebankova & G. A. Savel'ev
5, (1973), 129-137 (Russ)
"Role of hydrogen in the genesis of metal catalysts for hydrogenation."
"Reflection-adsorption infrared spectrum of alpha carbon monoxide chemisorbed on polycrystalline tungsten."

75. Clarence G. Goymour & David A. King : Surface Sci. 35 (1), (1973), 246-270 (E)
"Coadsorption of oxygen ad carbon monoxide on tungsten Desorption spectra, electron stimulated desorption, and field emission microscopy."

"Chemisorption of hydrogen on tungsten (211)."

77. W. Jelend & D. Menzel : Vide 28 (164), (1973), 86-87 (E)
"Deuterium isotope effect in electron impact desorption of hydrogen from tungsten."

78. Theodre E. Madey : Surface Sci. 36 (1), (1973), 281-294 (E)
"Chemisorption of molecular hydrogen on tungsten-(100) Absolute sticking probability, coverage, and electron stimulated desorption."

"Chemisorption of carbon monoxide on tungsten (100). Combined flash desorption and electron stimulated desorption study. II."

"Field emission microscopy of the interaction of laser radiation with a tungsten single crystal."
81. David A. King: Vide 28 (164), (1973), 98-100 (E)
"Models for adsorption and desorption kinetics. Nitrogen and Carbon monoxide on tungsten."

59 (8), (1973), 4184-4191 (E)
"Oxidation of carbon on (100) tungsten and (100) Molybdenum"

28 (9), (1973), 1792-1800 (Russ.)
"Kinetics of gas-metal interaction applied to the determination of gases in metals by the methods of vacuum melting and isotope dilution. Z. kinetic of gas evolution in the determination of oxygen and carbon in metals by the methods of oxidative and reductive fusion"

39 (2), (1973), 397-404 (E)
"Simultaneous SIMS [secondary ion mass spectrometry] and EID [electron-induced desorption] investigation on the interaction of oxygen with a tungsten (100) surface."

40 (2), (1973), 295-310 (E)
"Electron impact desorption of hydrogen on tungsten I. Pure hydrogen layers."

21 (1), (1973), 178-180 (E)
"Deuterium isotope effect in electron impact desorption of hydrogen on tungsten."

62 (8), (1973), 1308-1313 (E)
"Use of thermal gravimetric analysis, GLC, [gastiquid chromatography] and mass spectrometry in sorption studies. III. Evaluation of clustering functions of ethanol. water. polyurethane system."
"AES [Auger electron spectroscopy] measurements of adsorption isobans for oxygen on tungsten at low pressure and high temperature"

89. Gerhard Hoerz & Klaus Lindenmaier: Z. Metallk 64 (3), (1973), 161-169 (Ger.)
"Kinetics of the degassing of oxygen-containing niobium in an acetylene flow by carbon monoxide formation."

90. T. Engel, H. Niehus & E. Bauer: Vide 28 (164), (1973), 82-83 (E)
"Adsorption of oxygen on the (110) plane of tungsten."

"Adsorption of carbon dioxide on X-and Y-type zeolites."

"Method for studying surface mobility and desorption of oxygen on solid carbon."

"Calculation of the efficiency of cocurrent-flow and cocurrent-flow-whirling-flaw devices of mass transfer apparatus."

"Interaction of oxygen with the (III) face of a tungsten single crystal studied by a flash method."
"Electron impact desorption of hydrogen on tungsten. II. Hydrogen in mixed adsorption layers."

"Crystallographic distribution of hydrogen on catalytic surfaces."

97. S. M. Ko & L. D. Schmidt: Surface Sci. 42 (2), (1974), 508-524 (Eng.)
"Adsorption and solution of hydrogen and nitrogen by tantalum and niobium."

"Hydrogen adsorption in lanthanum-nickel (LaNi₅) and related compounds. Experimental observations and their explanation."

"Adsorption of oxygen at tungsten single crystal. The (110) face"

"Angular distributions of electron stimulated desorption ions. Oxygen on tungsten (100)"

"Study of solid surfaces by a electron impact desorption technique."
"Surface characterization by electron, ion, photon, and surface wave induced desorption."

103. Mitsuaki Nishijima, Kenzo Fujiwara & Toshio Moritani: Shinku 17 (5), (1974), 154-160 (Japan)
"Study of solid surfaces by electron impact desorption technique."

"Electron desorption of adsorbates."

"Isothermal adsorption of nitrogen, oxygen, and carbon monoxide on catalyst support materials."

"Thermal desorption of carbon monoxide adsorbed on tungsten surface."

"Variation in the thermo-electronic work function of powdered semiconductors submitted to electromagnetic radiation. III. Adsorption of oxygen by titania (anatase)."

"Hydrogen and carbon monoxide low-coverage coadsorption on polycrystalline tungsten."
"ESCA study of carbon monoxide and oxygen adsorption on tungsten."

"Adsorption of oxygen on the face of a tungsten single crystal."

"Quasiequilibrium treatment of the coverage of oxygen on tungsten at high temperature and low pressure."

"Electron-stimulated desorption of oxygen on the single crystal surface of tungsten."

"Study of the reducing and absorbing properties of nickel-molybdenum systems."

"Mass spectrometric determination of oxygen."

"Gas release from low-Z materials under hydrogen bombardment."
"Mixed adsorption of carbon monoxide and oxygen on tungsten (100), (110) and (111) single crystal faces."

"Chemisorption of carbon dioxide on tungsten."

118. M. R. Shanabarger: Surface Sci. 52 (3), (1975), 689-696 (E)
"Chemisorption kinetics of hydrogen on evaporated iron films"

119. N. P. Katrich, N. M. Lifshits & G. T. Adonkin: Monokristally I Tekhnika (11), (1975), 33-36 (Russ.)
"Thermal desorption of hydrogen from high-melting metals."

"Chemisorption kinetics of hydrogen on evaporated iron films."

121. E. Bechtold, L. Wiesberg & J. H. Block: Z. Phys. Chem. (Frankfurt am Main) 97 (1-2), (1975), 97-112 (Ger.)
"Field electron microscopy of molecular sulfur and hydrogen sulfide adsorption on tungsten."

"Further evidence for equilibrium surface segregation in the copper-nickel alloys. Carbon monoxide and hydrogen chemisorption."
123. Y. Margoninski, D. Segal & R. E. Kirby: Surface Sci. 53 (1), (1975), 488-499 (Eng.)
"The interference of an electron beam with the surface reaction between oxygen and germanium."

"AES study of electron-beam stimulated desorption of oxygen from a semiconductor surface."

"Gas surface interaction studied by SX ADS [soft X-ray appearance potential spectrometry]"

"Electron scattering study of clean (100) tungsten and its interaction with oxygen at low coverage."

"Investigation of different adsorption states of hydrogen on platinum powder by TPD method."

"Adsorption of copper, bismuth and palladium resulting from the ionization of hydrogen adsorbed on platinum."

"Recombination dynamics of hydrogen on a tungsten surface."

"Adsorption of hydrogen and carbon oxides and mechanism of methanation over nickel catalysts."
131. G. N. Crisp, R. A. Sherlock & A. F. G. Wyatt: 
Proc. Int. Conf. Law Temp. Phys., 14th (l), 
(1975), 455-458 (Eng.) 
"Desorption of helium -4 atoms by phonons. "

U.S. NTIS. AD Rep., AD-A020524, (1975), 26pp (Eng.) 
"Ion angular distributions in electrons stimulated 
desorption: oxygen and carbon monoxide on tungsten (111)"

12, (1975), 32-37 (Russ.) 
"Kinetics of thermal desorption of gases from high-melting 
metals."

134. G. Tremblay, F. J. Vastola & P. L. Walker Jr.: 
12 (1975), 177-178 (E) 
"Characterization of graphite surface complexes by 
temperature programmed desorption."

135. S. Brumbach & M. Kaminsky: 
Report (1975), CONF-751125-71, 8pp(Eng.) 
"X-ray impact induced desorption of gases from stainless 
steel surfaces."

47 (9), (1976), 3868-3872 (Eng.) 
"AES study of electron-beam-induced interactions between 
oxxygen and the germanium (111) surface"

137. R. J. Breakspere, T. A. Egerton & A. P. Morgan: 
Chem. Scr. , 9 (3), (1976), 114-115 (Eng.) 
"Temperature programmed desorption of oxygen on 
magnesium oxide"
138. Junichi Kubota & Katuhiko Azuma:
23 (3), (1976), 190-192 (Eng.)
"FEM observation of water vapor on tungsten."

139. R. V. Bucur, V. Meceea & E. Indrea:
J. Less-Common Met.
49 (1976), 147-158 (Eng.)
"The mechanism of hydrogen sorption by thin palladium layers I. Desorption"

140. M. U. Kislyuk, I. I. Tretyakov & V. N. Korchak:
Kinet. Katal., 17 (4), (1976), 963-967 (Russ.)
"Elementary rate constants of recombination of atomic hydrogen on platin"m

141. Toshio Sakura & Homer D. Hagstrum:
Phys. Rev. B.
14 (4), (1976), 1593-1596 (Eng.)
"Interplay of the monohydride phase and a newly discovered dihydride phase in chemisorption of hydrogen on silicon (100) 2 x 1"

142. S. Brumbach & M. Kaminsky:
Report CONF-760209-15 (1976), 13pp (Eng.)
"X-ray impact induced desorption of gases from surfaces"

143. V. N. Ageer, S. T. Dzhalilov, N. I. Ionov & N. D. Potekhima
Zh. Tekh. Fiz., 46 (5), (1976), 1019-1029 (Russ.)
"Electron-stimulated desorption of oxygen from tungsten"

144. J. H. Neare & B. A. Joyce:
J. Phys. D.
9 (15), (1976), 2195-2200 (Eng.)
"The origin of spurious peaks in mass spectra"

145. R. V. Bucur, V. Meceea & T. B. Flanagan:
Surface Sci.
54 (2), (1976), 477-488 (Eng.)
"The kinetics of hydrogen (deuterium) sorption by thin palladium layers studied with a piezo electric quartz crystal microbalance."
146. V. P. Vezirova & G. G. Krimcheeva:  
Ingibirovanie Passivirovanie Met.  
(1976), 22-28 (Russ.)  
"Hydrogen absorption by St-3 steel in neutral and weakly acid electrolytes"  

(Bundesminist. Verteidigung)  
(1976), (BMVg-FBWT 76-20, Luft-Raumfahrt, Teil2), 151-160 (Ger.)  
"The interaction of hydrogen and nitrogen on polycrystalline iron films at low pressures."  

(1976), (BMVg-FBWT 76-20, Luft-Raumfahrt, Teil2), 151-160 (Ger.)  
"The interaction of hydrogen and nitrogen on polycrystalline iron films at low pressures."  

24 (12), (1976), 965-973  
"The temperature-programmed desorption of oxizenes from vanadium pentoxide."  

150. Joel. I. Gersten, Richard Janow & Narkis Tzoar:  
Phys. Rev. Lett., 36 (11), (1976), 610-613 (E)  
"Theory of ion angular distributions in electron--stimulated desorption."  

34 (1), (1976), 131-134 (Eng.)  
"Adsorption and desorption properties of hydrogen on silicon films and comparison with single-crystal properties"  

44 (2), (1976), 259-270 (Eng.)  
"Temperature-programmed desorption studies of the hydrogenizing oxide system."
"A method for elimination of side effects on electrochemical measurements of single crystals. Additional test of adsorption systems silver-lead ion and gold-curie ion."

"Electron-and Photon-induced desorption."

"Desorption studies from molybdenum surfaces."

156. C. Benvenuti, R. Calder & G. Passardi: J. Vac. Sci. Technol. 13 (6), (1976), 1172-1182 (Eng.)
"Influence of thermal radiation on the vapor pressure of condensed hydrogen. (and isotopes)"

"The displacement of hydrogen by carbon monoxide on the (100) face of tungsten"

158. E. Roman & Jose L. De Segovia: Electron. Fis, Appl. 19 (1), (1976), 40-41 (Span.)
"Desorption kinetics of hydrogen on polycrystalline tungsten."

159. Sachio Asaoka, Koji Masamizu, Kaoru Fujimoto & Taiseki Kunugi: Nippon Kagaku Kaishi (3), (1976), 388-393 (Japan.)
"Catalysis by carbon. II. Hydrogen spillover and reverse-spillover on active charcoal catalysts."
"Activation studies in graphiooxidation"

161. Masanori Kobayashi, Muntaek Kim & Yutaka Tuzi :
"Measurements of the angular distributions of molecules desorbed from molybdenum surface."

162. A. Mathewson, R. Calder, A. Grillot & P. Verbeek :
Proc. Int. Vac. Congr., 7th 2 (1977), 1027-1030 (E)
"Thermal desorption of carbon monoxide from some stainless steels."

"Adsorption and desorption of oxygen on stepped tungsten surfaces."

"High performance SIMS system"

165. N. Sh. Inoyatov, T. S. Lyubovskaya & T. E. Nurseitora :
Kinet. Katal., 18 (3), (1977), 814 (Russ.)
"Study of the surface characteristics of aluminum-chromium-molybdenum oxide catalysis."

166. S. V. Krishnaswamy & E. W. Mueller :
Z. Phys. Chem. (Frankfurt am Main), 104 (1-3), (1977), 121-130 (Eng.)
"Metal hydrides in pulsed field evaporation."

"The effect of the method of preparing nickel films on the adsorption kinetics and forms of hydrogen adsorbed."
"Kinetic theory description of electron stimulated desorption"

"Desorption from powdered zinc oxide during electron bombardment and interaction with atomic hydrogen."

"Isotope effects in electron impact desorption of carbon monoxide and molecular oxygen adsorbed on the (110) plane of tungsten."

171. Richard Harvey Janow :
Avail Xerox Univ. Microfilms, Ann Arbor, Mich., Order No. 77-7643 From Diss Abstr. Int. B 37 (10), (1977), 5193
"Theory of angle resolved electron stimulated desorption and photo desorption. Ion angular distributions for desorption of atomic oxygen (+) from the (111) and (100) surface of tungsten."

"Electron stimulated desorption acritical review."

"Evidence for the conformation of water adsorbed on ruthenium (001)"

"Negative ion emission during electron-stimulated desorption"
16 (2), (1977), 945-946 (E)
"Relation between electron-stimulated desorption and non-dissociative chemisorption."

39 (15), (1977), 965-968 (E)
"Quantum scattering theory of electron stimulated desorption: ion angular distributions."

66 (9), (1977), 4252-4253 (Eng.)
"The kinetics of molecular deuterium desorption of nitrogen trifluoride in argon."

64 (2), (1977), 425-436 (Eng.)
"Kinetics of adsorption and desorption using Auger electron spectroscopy: application to xenon covered (0001) graphite."

(1977), AD-A042069, 37pp. (Eng.)
"Kinetic theory description of electron stimulated desorption."

15 (12), (1977), 5522-5534 (Eng.)
"Oxygen adsorption on molybdenum studied by low-energy secondary-ion mass spectrometry and electron-induced desorption."

66 (2), (1977), 596-612 (Fr.)
"Carbon monoxide chemisorption on the surface of molybdenum (110). I. Experimental study of the carbon monoxide/molybdenum(110) adsorption-desorption."
67 (1), (1977), 21-44 (Eng.)  
"Molecular hydrogen and carbon monoxide on the (110) plane of tungsten; LEED, XPS, and Auger measurements."

183. Theodore E. Madey & John T. Yates Jr. :  
"Evidence for the structures of adsorbed ammonia and water on ruthenium (001)"

7th 3 (1977), 2277-2280 (E)  
"Simultaneous AES-SIMS measuring method."

7th, 2, (1977), 1285-1288 (E)  
"High electron energy ESD of hydrogen (+) and fluorine (+) from stainless steel, platinum and niobium."

186. Theodore E. Madey & John T. Yates Jr. :  
"Evidence for the structures of adsorbed ammonia and water on ruthenium (001)."

69 (1), (1977), 253-272 (E)  
"Kinetic theory description of electron stimulated desorption"

188. K. Kawasaki, T. Kioka, H. Miki & T. Kodama :  
"Coadsorption of carbon monoxide and hydrogen on metal surface"

"Chemisorption of hydrogen on polycrystalline tungsten."
7th, 2 (1977), 971-974 (E)  
"Desorption kinetics of hydrogen monolayer adsorbed on tungsten (poly) at 300 K."

7th, 2 (1977), 1089-1092 (E)  
"Interaction of ammonia with molybdenum at low and high temperatures studied by thermal desorption mass spectrometry."

68, (1977), 305-311 (E)  
"Field emission study of ammonia adsorption planes."

30 (12), (1977), 654-656 (Eng.)  
"Study of chemisorbed oxygen on tungsten using secondary ion mass spectrometry."

194. Jean Fusy, Georges Antoine, Marie Jean & Jacques Jupille :  
J. Microsc. Spectrosc. Electron. 2 (3), (1977), 267-278 (Fr.)  
"Ionic desorption induced by electrons in the case of oxygen adsorption on tungsten and rhenium."

7th 2 (1977), 885-888 (E)  
"A comparison of the adsorption of oxygen and carbon monoxide on molybdenum using low-energy SIMS and EID."

7th, 2, (1977), 1285-1288 (E)  
"High electron energy ESD of hydrogen (+) and fluorine (+) from stainless steel, platinum and niobium."
"Studies of electron stimulated desorption (ESD) in a LEED system"

"Combined AES, ELS and EID studies of nitric oxide absorption on UHV-cleaved silicon (111) surfaces."

"Study of the reaction of oxygen with niobium by the method of electron-stimulated desorption."

"An ion desorption test instrument."

201. L. S. Kanevskii, V. I. Lushikov & A. M. Skundin : Electrokhimiya 13 (11), (1977), 1728-1731 (Russ.)
"Sorption of oxygen by glassy carbon."

"Study of the interaction of water and oxygen with the surface and characteristic loss spectroscopies."

"Temperature flash and electron-stimulated desorption methods."

"Carbon monoxide and carbon dioxide interaction with tan talm "

-76-
205. J. M. Heras, L. Viscido & V. Amorebieta:
Z. Phys. Chem. (Wiesbaden), 111(2), (1978), 257-260 (Ger.)
"Decomposition of water molecule on pure cobalt surfaces"

(1978)
"Decomposition of formic acid on nickel (100)-p(2x2) C"

207. Seijirau Suda & Masaki Uchida:
Kogakuin Daigaku Kenkyu Hokoku (45), (1978), 58-65 (E)
"Mixing effects of different types of hydrides"

208. R. E. Clausing, L. C. Emerson & L. Heatherly:
"Studies of hydrogen recycle from the walls in tokamaks using a plasma-wall interaction stimulator."

76-77 (1-2), (1978), 328-331 (E)
"Ion impact desorption cross section of hydrogen and oxygen from metals by light ion bombardment."

15 (2), (1978), 141-148 (E)
"Oxygen adsorption on the tungsten (110) plane. Electron impact and thermal desorption at high temperatures."

40 (14), (1978), 964-967 (E)
"Ion desorption by core-hole Auger decay."

212. M. J. Drink Wine & D. Lichtman: J. Vac. Sci. Technol
15 (1), (1978), 74-85 (E)
"Study of ESD from type 304 stainless steel in relation to CTR first wall applications."
213. M. Miyamura, Y. Sakisaka, M. Nishijima & M. Onchi: 
Surface Sci., 72 (2), (1978), 243-252 (E)
"Adsorption of hydrogen chloride and hydrogen bromide on 
silicon (111) AES, ELS and EID studies."

149 (1-3), (1978), 605-608 (E)
"Investigation of ion impact desorption of atoms and 
molecules by low energy ion scattering (ISS)."

15 (2), (1978), 141-148 (E)
"Oxygen adsorption on the tungsten (110) plane. Electron 
impact and thermal desorption at high temperatures."

71 (3), (1978), 695-718 (E)
"Adsorption of oxygen on tungsten (110) II. The high 
coverage range."

217. Kaoru Fujimoto, Haruto Hashimoto & Taiseki Kunigi: 
Sekiyu Gakkai Shi, 21 (2), (1978), 135-138 (Japan)
"Hydrogenation of carbon monoxide over supported palladium 
catalysts."

77 (2), (1978), L379-L383 (E)
"Carbon monoxide/hydrogen surface complex on tungsten 
(100)"

16 (1), (1978), 35-39 (E)
"Thermal desorption analysis of oxygen surface complexes 
on carbon"

16 (2-3-4), (1978), 24-25 (E)
"Coadsorption of carbon monoxide and hydrogen on akickel 
(111) surface. "

-78-
221. G. Wedler, K. G. Colb, W. Heinrich & G. McElhiney: 
"The interaction of hydrogen and carbon monoxide on 
polycrystalline iron films."

222. Koji Kawasaki, Makoto Shibata, Hirofumi Miki & Toshihide Kioka 
Surface Sci., 81(2), (1978), 370-378 (Eng.)
"Coadsorption of carbon monoxide and hydrogen on polycrystalline 
rodium"

15 (4), (1978), 1298-1310 (E)
"Reaction of oxygen with zinc oxide-1010 surface"

82 (7), (1978), 714-756 (E)
"Reactivity, electronic structure and geometry of nonpolar 
zinc oxide surface."

225. S. Lehr & H. Pagnia: Phys. Status Solide A 
49 (1), (1978), 83-91 (E)
"Work function of irradiated real and cleaned indium 
antimonide surface."

226. R. Erlandsson, U. Birkholz & S. E. Karlsson: 
"Study of silicon telluride (Si2Te3) surface reaction 
with Auger electron spectroscopy."

"Quantitative determination of the angular and energy 
distribution by electron stimulated desorption: oxygen 
on tungsten (100)."

Microfilms Int, Order No. 7804485. from Diss. Abstr. Int. 
B. 1978, 38 (10), 4871


235. H. Siehus : Ned Tijdschr. Vacuumtech. 16 (2-3-4), (1978), 51-52 (E) "Adsorption of atomic oxygen and carbon monoxide on tungsten (111), a surface analysis with AES, LEED and angular resolved ESD emission. (ESDIAD)

-- 80 --
"Model calculations on the adsorption and desorption of hydrogen on tungste."

"Rairenterptation of electron-stimulated desorption data from chemisorption system."

"Electron stimulated desorption studies of some halocarbons (difluorodicholoromethane. difluoroethylene & hexafluoroethone) adsorbed on polycrystalline tungsten."

"Studies of hydrogen recycle from the walls in tokamaks using a plasma-wall interaction simulator."

"Surface properties and reactions of coal."

"Interactions of tin oxide surface with oxygen, water and hydrogen"

"Chemisorption of water on the silicon (111) 7x7 surfaces."
   "The distribution of adsorbed hydrogen with depth in mild steel as a function of the electrochemical treatment conditions in pure alkaline medium."

244. R. Kramer & M. Andre: J. Catal. 58 (2), (1979), 287-295 (Eng.)
   "Adsorption of atomic hydrogen on alumina by hydrogen spillover."

   "Coadsorption of thorium and hydrogen on a tungsten surface."

   "Decomposition of formaldehyde on copper/nickel (110) single"

   "Surface structure and composition from electron stimulated desorption."

   "Slow electron stimulated desorption from oxides: theoretical models of selected experiments."

249. K. Christman: Z. Naturforsch A. 34A(1), (1979), 22-29 (Eng.)
   "Adsorption of hydrogen on a nickel (100) surface."

   "Study of platinum-hydrogen interaction. I. Flash thermal desorption from platinum wire after adsorption under high pressure."
"Preexponential factors for hydrogen desorption from single crystal metal surfaces."

252. T. S. Chou & H. J. Halama: J. Vac. Sci. Technol. 16 (1), (1979), 81-82 (Eng.)
"Effects of Neutron radiation on cryocondensation pannels."

"Nifacell material for treating infected wounds, trophical ulcers and purulent process in cavities."

254. W. F. W. M. Van Heugten, A. Van Veen & L. M. Caspers: PTB-Mitt. 89 (1), (1979), 7-12 (Ger.)
"Born-Mayer type molybdenum-helium and helium-helium interaction potentials, fitted to the results of the helium desorption experiments."

"TPD studies of hydrogen adsorption on group VIII metals"

256. H. Niehus: Surface Sci. 80 (1979), 245-252 (Eng.)
"Adsorption of oxygen on tungsten (111), a surface analysis with AES, LEED and angular resolved ESD emission (ESDIAD)"

257. S. Bellard: Surface Sci., 80 (1979), 450-458 (Eng.)
"Electron desorption cross sections with oxygen at tungsten (100)."
"Electron stimulated desorption of oxygen (+1) ion and oxygen (-1) from oxygen chemisorbed on tungsten"

"The effects of electron bombardment on the surface composition of tungsten trioxide oxidized tungsten and tantalum films"

"Observation of positive and negative oxygen ions during electron bombardment of oxygen-covered molybdenum (100) surface"

"Electron-and photon-stimulated desorption as hydrogen probes."

"Negative ion ESD from hydrogen on tungsten"

"Adsorbate core ionization as primary process in electron and photon-stimulated desorption from metal surface."

264. I. M. Novosellskii & M. G. Khakimov : Elektrokhimiya 15 (8), (1979), 1188-1193 (Russ.)
"Voltammetry of a reversible redox reaction under high (>kT) energy conditions for intermolecular interactions of adsorbed reduction particles."
265. I. M. Novosel'skii & M. G. Khakimov: Elektrokhimiya 15 (8), (1979), 1193-1196 (Russ.)
"Voltammetry of reversible redox reactions occurring on sections of a homogeneous surface without talking into account the interaction of adsorbed reduction particles."

266. B. J. Schumacher: Ber. Forschungsanlage Julich (1979), Jul-1628, 126pp (Ger.)
"Pseudostatistical time-of-flight determination of hydrogen desorbing on nickel surface."

"Electron beam effects during adsorption of hydrogen on palladium"

"Electron impact removal"

269. A. Benninghoven, P. Beckman, K. H. Mueller & M. Schemmer: Surface Sci. 89 (1-3), (1979), 701-709 (E)
"Investigation of multi-component surface reactions by SIMS: the interaction between hydrogen and oxygen on polycrystalline nickel."

270. E. Taglauer, W. Heiland & U. Beitat: Surface Sci. 89 (1-3), (1979), 710-717 (E)
"The influence of adsorption energies on ion impact desorption of surface layers."

"Desorption of ions from aqueous electrolyte solutions"

273. H. Niehus : Surface Sci., 92 (1), (1980), 88-96 (E) "Adsorption studies of carbon monoxide on molybdenum (100)"


"Ion beam induced desorption of surface layers."

"Thermal desorption studies on hydrogen-and oxygen-terminated graphite surfaces."

"Thermal desorption measurements of hydrogen-isotope retention in the Alcator-A tokamak"

"Hydrogen desorption from UH'-cleaved vanadium hydride"

"Effect of surface reaction on the interaction rate of hydrogen with aluminum"

"Characterization of hydrogen species on titanium dioxide by electron-stimulated desorption"

"Stability and reactivity of (5x20) and (1x1) platinum (100) surface"

"Time-resolved spectroscopic studies of surface reaction"
287. D. Bhaśavanich & E. M. Williams: Vacuum
30 (2), (1980), 91-92 (E)
"The influence of pre vacuum surface conditioning on the
response with electron stimulated desorption at stainless
steel surface in uhv."

47, (1975), 370-383
"Electron stimulated desorption: principles and recent
developments"

"Ion angular distributions in electron stimulated
desorption: adsorption of O₂ and H₂ on W(100)"

"Electron stimulated desorption of sodium and
measurement of surface diffusion on MgO(001) by auger
spectroscopy"

353-364
"Electron beam effects in auger analysis of physisorbed xenon"

13 (1976), 228-232
"Electron-stimulated processes at solid surfaces"

293. F. E. Domann: Surface Sci., 54 (1976), 529-539
"A radiotracer study of slow electron interaction with
CO on polycrystalline Mg"

"Evidence for electron emission stimulated desorption
from negative electron affinity GaAs surfaces"
"Surface crystallography, adsorbate structure, adsorption kinetics and surface reactivity carbon suboxide (C$_3$O$_2$) on Pt (110)"

"Ion angular distributions in electron stimulated desorption: oxygen and CO on W(111)"

"Chemisorption, surface structural chemistry, and electron impact properties of carbon on Ru (101)"

"Electron stimulated desorption of fluorine and barium from tungsten"

"A low temperature precursor to chemisorbed oxygen on tungsten (110)"

300. B. Bell et al.: Surface Sci., 61 (1976), 656-658
"Comment on 'Quantum theory of electron stimulated desorption' by W. Brenig"

"Reply to: comment on 'Quantum theory of electron stimulated desorption'"

"Kinetics of the generation of atomic hydrogen and its adsorption of Si (110)"
"W (100) + O₂ : adsorption and reaction"

"Electron beam interactions with CO on W (100) studied by auger electron spectroscopy"

"Threshold behaviour in the process of electron stimulated desorption"

"Desorption methods as probes of kinetics and bonding at surfaces"

"Hydrogen on W (100) : electron stimulated desorption and a structural model"

"Hysteresis and ion yield minimum during electron stimulated desorption of oxygen on W (100)"

309. P. H. Dawson: Surface Sci., 65 (1977), 41-62
"SIMS studies of the adsorption of O₂, CO and CO₂ on titanium using low primary energies"

"The diamond surface"
66 (1977), 67-100  
"Adsorption of CO on the (110) plane of tungsten electron impact, thermal desorption, and work function measurements"

67 (1977), 21-44  
"The adsorption of CO on the (110) plane of tungsten: LEED, XPS and auger measurements"

67 (1977), 489-500  
"Chemisorption, surface structural chemistry and electron impact properties of carbon monoxide on rhodium (110)"

68 (1977), 338-345  
"Low beam current density auger spectroscopy and surface analysis"

69 (1977), 253-272  
"Kinetic theory description of electron stimulated desorption"

15 (1), (1978), 74-85  
"Study of ESD from type 304 stainless steel in relation to CTR first wall applications"

"The adsorption of CO on molybdenum studied by low energy SIMS and EID"

"Effects of an electron beam on adsorption and desorption of ammonia on ruthenium (0001)"
319. M. Miyamura, Y. Sakisaka, M. Nishijima & M. Onchi: 
Surface Sci., 72 (1978), 243-252  
"Adsorption of HCl and HBr on Si (111): AES, ELS and 
EID studies"

72 (1978), 678-692  
"Electron beam induced desorption and dissociation of 
CO chemisorbed on Ir (111)"

321. H. Frederick Dylla & John G. King: Surface Sci.,  
74 (1978), 141-167  
"The adsorption of CO on planar and oxygen-etched 
silicon surfaces"

322. R. H. Prince & G. R. Floyd: Surface Sci.,  
74 (1978), 342-354  
"Electron stimulated desorption study of oxygen 
adsorption on tungsten"

"Studies of clean and oxidized tellurium surfaces"

324. S. Prigge, H. Niehus & E. Bauer: Surface Sci.,  
75 (1978), 635-656  
"Electron stimulated desorption ion energy distribution 
(ESDIED) and surface structure: O on W (100)"

"Calculation of energy spectra for ESD of H+ from H2 
adsorbed on tungsten"

"Electron beam-induced decomposition and desorption: 
ZnO"
"Reneutralization in electron stimulated desorption"

328. W. Brenig: Surface Sci., 75 (1978), L800
"Comment on 'Reneutralization in electron stimulated desorption' by W. L. Clinton"

"The adsorption of cycloparaffins on Ru (001) as studied by temperature programmed desorption and electron stimulated desorption"

"Adsorption of carbon monoxide on the molybdenum (100) surface"

"Electron stimulated desorption of negative ions from gases adsorbed on molybdenum"

"Electron stimulated desorption from ordered WO$_3$ layers"

"The geometry of CO on Ru (001): Evidence for bending vibrations in adsorbed molecules"

"The influence of an electron beam on the adsorption of CO and CO$_2$ onto A Ni (110) surface"

335. J. Lagowski: Surface Sci., 84 (1979), L223-L226
"Electron beam induced desorption of oxygen : CdS"
336. Ming L. Yu. : Surface Sci., 84 (1979), L493-L396
"Effect of Cs on electron stimulated desorption of negative ions"

"A comparative study of ESD of positive and negative ions from CO on tungsten"

"Electron stimulated desorption of O\textsuperscript+ ions : energy dependence of the desorption efficiency from adsorbed oxygen on metal surfaces and ITS bearing on the mechanism"

"Oxygen and carbon monoxide adsorption on W(111) : an investigation with angular resolved ESD, AES LEED"

"The interaction of oxygen with the Mo (100) surface"

"Electron energy-loss spectra of co-adsorbed Ni (100) surfaces"

342. B. Krahl-urban & H. Niehus : Surface Sci., 88 (1979), L19-L24 "Electron stimulated desorption of oxygen on a stepped W (100) surface"

343. A. M. Bradshaw & F. M. Hoffmann : Surface Sci., 89 (1979), 370-380
"Evidence for 'inclined' CO on Pd (210)"

-94-
"Stability of ionically bonded surfaces in ionizing environments"

"Mechanisms of desorption due to electrons or photons"

"Characterization of hydrogen species on TiO₂ by electron-stimulated desorption"

"The reconstruction of the W (100) surface in the presence of half a monolayer of oxygen"

"Adsorption sites of CO on Mo (100)"

"ESDIAD from CO on W (100): evidence for non-vertically adsorbed CO"

"Interactions of NO with a Ni (100) surface"

"Computer simulations of electron stimulated desorption patterns from oxygen on W (100) and (111) surfaces"

"The role of steps and defects in electron stimulated desorption: oxygen on stepped W (110) surfaces"
"Estimation of relaxation energy from electron-stimulated desorption and photoemission data"

"The gas supply function in field ion microscopy"

"On the origin of electron stimulated desorption of H+ from metal surfaces"

"Evidence for a thermally induced state conversion in low coverage states of hydrogen on platinum"

"Hydrogen on W(100) : temperature dependence of LEED and angle-resolved ESD"
<table>
<thead>
<tr>
<th>Adsorbates Substrates</th>
<th>Cross sections (cm²)</th>
<th>$E_p$ (eV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$ ($\beta_2$) W(100)</td>
<td>$6 \times 10^{-23}$ for H$^+$</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>(K) W(110)</td>
<td>$5 \times 10^{-22}$ for H$^+$</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>(K) CO/W(100)</td>
<td>$8 \times 10^{-20}$ for H$^+$</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>W(100)</td>
<td>$1.5 \times 10^{-19}$</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>CO Mo</td>
<td>$3.7-16 \times 10^{-17}$</td>
<td>50-300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$7-14 \times 10^{-20}$ for C</td>
<td>50-300</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>$3 \times 10^{-18}$, $8.6 \times 10^{-20}$</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2 \times 10^{-21}$ for $\beta$</td>
<td>2.5keV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$1.55 \times 10^{-18}$ for $\alpha_2$</td>
<td>2.5keV</td>
<td></td>
</tr>
<tr>
<td>Rh(110)</td>
<td>$10^{-22}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ir</td>
<td>$0.8-1.7 \times 10^{-17}$</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$1 \times 10^{-17}$</td>
<td>2.5keV</td>
<td></td>
</tr>
<tr>
<td>O$_2$ W</td>
<td>$6 \times 10^{-20}$ for high cover.</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2 \times 10^{-19}$ for low cover.</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$7 \times 10^{-15}$ for O$_2$</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-15}$ for O$^+$</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Te</td>
<td>$3 \times 10^{-18}$</td>
<td>2keV</td>
<td></td>
</tr>
<tr>
<td>F W</td>
<td>$3 \times 10^{-19}$ (total)</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3 \times 10^{-20}$ for F$^+$</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Na MgO</td>
<td>$2 \times 10^{-18}$</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>S C(diamond)</td>
<td>$5 \times 10^{-20}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xe Ni</td>
<td>$1 \times 10^{-17}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba W</td>
<td>$6 \times 10^{-20}$ (total)</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$4.4 \times 10^{-22}$ for Ba$^+$</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>
Table II

<table>
<thead>
<tr>
<th>State</th>
<th>$q_+ (H^+)$ cm$^2$</th>
<th>$I(H^+)/I(D^+)$</th>
<th>calc. $q_{ex}$ cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_2$/W(100)</td>
<td>$6 \times 10^{-23}$</td>
<td>154</td>
<td>$1.4 \times 10^{-17}$</td>
</tr>
<tr>
<td>$\beta_2$/W(110)</td>
<td>$5 \times 10^{-22}$</td>
<td>68</td>
<td>$1.3 \times 10^{-17}$</td>
</tr>
<tr>
<td>$\kappa$/CO on W(100)</td>
<td>$8 \times 10^{-20}$</td>
<td>5.7</td>
<td>$6 \times 10^{-18}$</td>
</tr>
</tbody>
</table>
Figure captions

Fig. 1 Schematic ESDIAD patterns for O$_2$/W(100).
(a) low coverage $\beta_2$ state.
(b) high coverage $\beta_1$ state annealed at below 600K.
(c) high coverage $\beta_1$ state annealed at above 600K.
Fig. 1
Photodesorption

Masanori Kobayashi
National Laboratory for High Energy Physics
Ohho-machi, Ibaraki 305

Photodesorption is the desorption caused by incident photon flux. Thermal and quantum mechanical processes are considered in photodesorption. In the thermal mechanism photodesorption is essentially the same as thermal desorption. In the quantum mechanical mechanism the adsorbed atoms are knocked off due to the direct interactions with incident photons or by photoelectrons produced by incident photons. Although only limited data are available on photodesorption, the cross-section of photodesorption is estimated as about $10^{-10}$ cm$^2$.

In the followings published papers related to photodesorption are listed. Papers on photodesorption on the metal surfaces are listed in the first group, and those on the semiconductor surfaces and theoretical ones are listed in the second and the third groups, respectively.
Photo Desorption from Metal Surfaces

γ-ray region

"Radiation induced outgassing in an aluminum system."

H. Galron: Vacuum 22 (1972) 229,
"Desorption of water vapour by gamma irradiation."

H. Dobrozembsky: J. Vac. Sci. Technol. 13 (1976) 467,
"Operating experience with an UHV system in the vicinity of a fission-reactor core."

X-ray region

S. Brumbach & M. Kaminsky: J. Appl. Phys. 40 (7) (1976) 2844,
"Gas release from Al₂O₃ and stainless steel surfaces under X-ray irradiation."

Soft X-ray region

"Vacuum design problems of high current electron storage rings"

M. Bernardini & L. Malter: J. Vac. Sci. Technol. 2 (1965) 130,
"Vacuum problems of electron and positron storage rings."

R. Franchy & D. Menzel: Proc. Intern. Vac. Congr. 7th(2) (1977 Vienna) 1209,
"Photodesorption at high photon energies."
"Adsorbate core ionization as primary process in electron-
and photon-stimulated desorption from metal surfaces."

R. Jaeger, J. Feldhaus, J. Haase, J. Stohr, Z. Hussain, 
"Surface extended X-ray absorption fine structure by means of 
Photon-stimulated ion desorption; O on Mo (100)."

VUV, Visible region

W. J. Lange: J. Vac. Sci. Technol. 2 (1965) 74,
"Photodesorption of carbon monoxide."

"Photodesorption."

P. Genequand: Surf. Sci. 25 (1971) 643,
"Photodesorption."

J. Peavey & D. Lichtman: Surf. Sci. 27(3) (1971) 649,
"Photon induced desorption using synchrotron radiation."

Chem. 75(10) (1971) 1074, (G)
"Threshold energy and mechanism in electron-impact desorption 
and photodesorption of adsorption layers on metals."

P. Kronauer & D. Menzel: Adsorption-Desorption Phenomena, 
Proc. Intern. Conf. 2nd. 1971(Pub. 1972) 313,
"Photodesorption of carbon monoxide from tungsten."

Y. De Ribaupierre: Surf. Sci. 34(3) (1972) 732, (Fr.)
"Thermodesorption and photodesorption of potassium 
adsorbed on copper."

M. Suzuki: Japan. J. Appl. Phys. 12(3) (1973) 477,
"Anormalous photodesorption from metals."

"Photodesorption of carbon monoxide from polycrystalline nickel."

V. K. Ryabchuk, L. L. Basov, A. A. Lisachenko & F. I. Vilesov: 
Zh. Tekh. Fiz. 43(10) (1973) 2148, (Russ.)
"Determination of the kinetic energy of photodesorption 
products by the time of flight method. Nitrogen oxide 
aluminum oxide system."

G. W. Fabel, S. M. Cox & D. Lichtman: Surf. Sci. 40(3) (1973) 571, 
"Photodesorption from 304 stainless steel."


Photo Desorption from Semi Conductor Surfaces

VUV, V sible region


"Variation of the thermoelectronic extraction function of powdered semiconductors under electromagnetic radiation. II, Photodesorption of oxygen from titanium dioxide(anatase)."

"Spectra; dostrobution of the surface photopotential for a cadmium sulfide single crystal under condition of oxygen and water vapour adsorption."


"Photostimulated adsorption and desorption of oxygen on SnO₂ and TiO₂: Some new experimental date and a phenomenological model."

"Variation of the thermoelectric work function of powdered semiconductors submitted to the action of electromagnetic radiation. IV. Photoadsorption and photodesorption of oxygen on titanium dioxide."

"Mechanism of oxygen photodesorption from cadmium sulfied films."

"Photoassisted surface reactions studied by dynamic mass spectrometry."

D. Eger, Y. Goldstein & A. Many: RCA Rev. 36(3)(1975) 508,
"Oxygen chemisorption and photodesorption processes on zinc oxide surfaces."

"Photostimulated desorption from a cadmium sulfided surface."


"Charging of the traps in an oxide surface film on a lead sulfide single crystal by photodesorption."


"Photoelectrochemical process of oxygen desorption and n-type passive silicon oxidation in sulfuric acid."

"Role of photodissociation in the desorption of water molecules from a glass surface during flash illumination."
"Photoactivated desorption of oxygen from the surface of cadmium sulfide and selenide."

"Dynamics of photoinduced surface reactions on semiconductors studied by a pulsed-laser-dynamic mass-spectrometer technique."

C.P. Voronin, N.M. Mukkamedzhanova: Zh. Fiz. Khim. 54(2) (1980) 486,
"Photodesorption and saturated vapour pressure of cesium over cesium - tin alloys."

Theory of Photo Desorption

P.A. Redhead: Can. J. Phys. 42(1964)886,
"Interaction of slow electrons with chemisorbed oxygen."

D. Menzel and R. Gomer: J. Chem. Phys. 41(1964) 3311,
"Desorption from metal surfaces by low-energy electrons."

D. Menzel and R. Gomer: ibid 41(1964) 3329,
"Electron-impact desorption of carbon monoxide from tungsten."

"Theory of photodesorption."

T.B. Grimley: Faraday Discuss. Chem. Soc. 58(1975) 7,
"Theoretical aspects of photoemission, photo-desorption and photochemistry of adsorbates."

"Ion desorption by Core-Hole decay."

"Reinterpretation of electron-stimulated desorption data from chemisorption system."

D. Lichtman: Surf. Sci. 90(2)(1979) 579,
"Mechanisms of desorption due to electron or photons."

"Quantum-stochastic approach to laser-stimulated desorption dynamics and population distributions of chemisorbed species on solid surfaces."

"Model for electron-and photon-stimulated desorption."

"Reneutralization bottleneck in Auger initiated desorption."
Ion Induced Detrapping, Replacement and Release of Hydrogen, Deuterium and Helium Atoms.

R. Yamada Japan Atomic Energy Research Institute

Particle fluxes from wall to plasma in magnetically confined fusion devices are classified by three groups: wall atoms released by erosion processes such as sputtering and blistering; surface impurity atoms, which are adsorbed on the wall, desorbed by energetic ions and neutrals; and working gas from the wall released by energetic ions and neutrals. Understanding the behavior of working gas, that is recycling, is important for estimation of tritium inventory and control of plasma density in the devices [1-3].

Recycling of working gas is controlled by several processes, i.e., backscattering of incident ions, trapping, energetic particle-induced release of trapped atoms, thermal diffusion of trapped atoms and desorption of working gas adsorbed on the surfaces. It has recently been recognized that energetic particle-induced release plays an important role in recycling [3]. The physical mechanism of the release process is still not fully understood, but in practice the probability of release can be easily described by release cross section, since recent results of isotopic replacement experiments show that there is a region where the release rate of trapped atoms decreases exponentially with time, i.e., the release cross section \( \sigma \) is given by

\[
- \frac{dn}{dt} \propto \exp (-J_0 \sigma t)
\]

where \( n \) is areal density of retained gas and \( J_0 \) is incident flux of isotopic ions used to release the trapped gas.

The release cross sections of deuterium from stainless steels by proton bombardment reported [4-7] are shown in Fig.1. The result that the release
cross section at 300 K (curve (a)) has larger value than that at 77 K (curve (b)) indicates that the ion induced release depends on the temperature of the target [4]. Thomas [5] has measured similar temperature dependence, which was obtained by using the relation that $\sigma$ is inverse saturated areal density of deuterium and not using subsequent proton bombardment for releasing deuterium atoms. It has been reported by Blewer et al.[6] that the decrease of retained deuterium atoms by subsequent bombardment with protons, which was measured by $D^3He, ^4He$ nuclear reaction analysis, was fitted by a two-term inverse exponential function which is given as follows:

$$n_D = n_1\exp(-\sigma_1n_H) + n_2\exp(-\sigma_2n_H)$$

where $\sigma_1$ and $\sigma_2$ are two release cross sections, and $n_1$ and $n_2$ are the corresponding areal densities of trapped deuterium atoms at saturation. The values of $\sigma_1$ and $\sigma_2$ are shown as the curves of (c) and (d) in Fig. 1.

The release cross sections of deuterium from graphite by proton bombardment have been investigated by a few groups[8-10] as shown in Fig. 2. Underwood et al.[9] have reported the results of replacement experiments using not only the same energy for deuterons and protons but also the 10 keV deuterons and the protons whose energies ranged from 10 to 30 keV in order to investigate mechanisms of the ion induced release. Erents [10] has pointed out that HD production must be considered for calculation of the magnitude of release cross section, suggestion that inclusion of HD production makes the cross section be lower than the value of higher energy measurement which neglected HD production [8].

The release cross section of deuterium from molybdenum by subsequent proton bombardment has been investigated [11], using not only same energy for deuterons and protons from 0.5 to 6 keV but also the 1 keV deuterons and the protons whose energy ranged from 0.5 to 6 keV. In Fig. 3 are shown
the release cross sections apparently obtained by the initial decrease of
the measured release rates, although the release curves were fitted by two
release cross sections in ref. [11]. The cross section strongly depends on
the pre-implanted deuterium dose, i.e., the cross section decreases with
increasing deuterion dose which can be ascribed to radiation damage effect.

The experiments described above are concerned with the replacement of
deuterium by hydrogen at low incident energy. There is a series of experiment
of detrapping by incident ions whose energy is more than 100 KeV.
The importance of investigating high energy ion induced detrapping is increasing,
since high energy He ions produced by D-T burning in fusion devices impact
absorbed D and T in the wall. Scherzer et al. [12] have reported the radiation-
induced detrapping of deuterium in BeO by 790 KeV He\(^+\) and by 2.2 MeV H\(^+\).
Their results show that the decrease of trapped deuterium atoms can be fitted
by two-term inverse exponential function as similarly as the results of 316 SS
[6] and that the value of \(\sigma_1\), which dominates the initial detrapping of
deuterium atoms in BeO by 790 KeV He\(^+\) ions is almost 2 orders of magnitude
larger than the value of \(\sigma_1\) obtained by low energy H\(^+\) ions in 316 SS.
Roth et al. [13] have reported the release cross sections of deuterium in
graphites, whose materials are pyrolytic graphite and high purity flexible
graphite known as Papyex, due to bombardments with H\(^+\), He\(^+\) and Ne\(^+\) ions at
high incident energy. In Fig. 4 are shown the above results, indicating
that the release cross section increases strongly with increasing the atomic
number of the incident ions for subsequent bombardment.

The above detrapping process due to high energy bombardments is different
from the replacement process of implanted gas by subsequent implantation of
another gas whose projected range is not far-off range of the previous implant-
tation [4 – 11], because the ranges of the H\(^+\) and He\(^+\) ions are far beyond
the implanted deuterion Layer. Scherzer et al. [12] have suggested that the
detrapping may be induced by electronic excitation rather than by nuclear
collision cascades because of the high value of detrapping coefficient and the ratio of initial detrapping yields for 790 KeV \( \text{He}^+ \) to 2.2 MeV \( \text{H}^+ \) bombardment which is similar to the ratio of electronic stopping powers.

The mechanism of the replacement of implanted gas by subsequent bombardment with isotopic ions at low energy is not fully understood. Three possible mechanisms can be considered at least to describe experimental isotope exchange data. The first model assumes that the trapped gas atoms are activated by collision cascades caused by incoming particles and energetically ejected from the surface as a result of collision cascades like sputtering. The second model assumes that \( n \) atoms can be bound at each trapping site and the binding energy of traps decreases drastically when the saturation value is exceeded and weakly bound atoms escape. This model assumes ideal mixing between the newly implanted and the previously trapped gas, which means that if saturation is reached, the ratio of isotope which are released is proportional to the ratio of local concentration of atoms in a trapping site. The third model proposes that trapped gas atoms are expelled from sites by the action of the ion beam and migrate by bombardment-induced diffusion until they find unsaturated traps, eventually reaching the surface by a repetition of the trapping and detrapping processes.

The exponential decrease of release rate with time can be expressed by the first model as follows:

\[
\frac{dn}{dt} = -J_0 \sigma n = -J_0 \sigma n_0 \exp (-\sigma J_0 t)
\]

where the notations are the same as the previous formula. Braganza et al. [4] have pointed out that this expression can not explain the threshold dose required before any release process in 304 SS. They have proposed that there are two types of sites, i.e., shallow site with low binding energy and deep site with high binding energy, and that release process occurs, after deep sites are
fully saturated, assuming in the above expression \( n \) is proportional to the fraction of shallow sites which are filled. The second model can predict the threshold dose for release assuming only one type of trapping site.

Hydrogen replacement of deuterium can be expressed in this model as follows:

\[
D = n_{sat} \exp(-\sigma n_H) \quad \text{and} \quad \sigma = 1/n_{sat}
\]

where \( n_{sat} \) is the maximum areal density at saturation and \( n_D \) is the number of D remaining in the lattice after a replacement dose of \( n_H \) has been incident. This \( \sigma \) corresponds to the release cross section in the first model. Since the replacement of D in 316 SS [6] was described by a two-term inverse exponential function, Blewer et al. have proposed two kinds of trapped atoms such as an easily replaced component of trapped deuterium and a replacement resistant component, even though their model is based on the ideal mixing. Doyle et al. [14] have reported that the replacement behavior of D in 316 SS measured by Blewer et al. is in good agreement with an ideal mixing model providing the depth dependence of its model is taken into account, assuming only two parameters, i.e., the range distribution and saturation concentration without knowledge of the number of the types of trapping sites. Underwood et al. [9] have supported the mixing model on the base of their experimental results that the release rate of deuterium atoms pre-implanted at 10 KeV is effectively zero for subsequent bombardment with the 30 KeV protons. They have ascribed the results to very small range overlap between the 10 KeV deuterons and the 30 KeV protons, whereas the damage profile of 30 KeV protons still overlaps the range of 10 KeV deuterons to a large extent. Hotston [15] have introduced a model which assumes two different trapping sites, namely, shallow ones and deep ones, and also assumes radiation-induced diffusion due to the incoming flux. This model also describes the Blewer's results well by assuming reasonable values for the concentration of deep trapping sites, the cross sections for collisions between beam ion and trapped atoms in both shallow
sites and deep sites, respectively, and scattering function describing the scattering of the protons as they penetrate the target. Schulz et al.[16] have reported the release of implanted He by subsequent bombardment with deuterons and vice versa at low energy. From the experimental result that the initial release is independent of whether the range of the He is larger, equal or smaller than the range of the D ions, they have concluded that the release process is not simple exchange in saturated traps, but it may be dominated by bombardment-induced diffusion in a near-surface layer. The results of Yamada et al.[11] also show that the release cross sections of the 1 keV deuterons by the proton bombardment depends weakly on proton energy compared with the cross sections of deuterons whose energies have the same as proton energies, whereas the energy of proton bombardment has influence on the amount of release of deuterium atoms preimplanted at 1 keV.

These models described above can give fairly good explanation for the experimental results of the trapping and the release of deuterium with a suitable choice of parameters, but several questions about the mechanism of release are still unresolved and it is difficult to choose one mechanism for the release process. For example, the number of types of trapping sites assumed in these models is not necessarily the same as the number of types of trapping sites obtained by the results desorption. It seems difficult to relate the number of the release cross sections directly to the number of types of trapping sites. Since the release curve is obtained as a result that the gas atoms are released after they go through a lot of traps with several activation energies, the concept of release cross section is too simple to explain the release data, even though it is useful to evaluate quantitative amount of release. A model to explain the release mechanism must take the number and the properties of trapping sites into account more exactly and then it should include the damage effect on the number of trapping sites and properties of sites. In order to understand the release mechanism, the energy and temperature effect on the release process
should be investigated intensively, where the wide range of incident energy for replacement must be employed to study not only the effect of incident energy transfer to both gas atoms and lattice atoms but also the effect of range overlap between the pre-implanted ions and the subsequent implanted ions.
References

"Recycling Process in Tokamaks"

"Re-cycling Experiments in the DITE Tokamak"

"Recycling and Surface Erosion Processes in Contemporary Tokamaks"

"Ion-Induced Release of Deuterium Trapped in Stainless Steel"

"Retention and Re-emission of 0.125–1 keV Deuterium in Stainless Steel"

"Trapping and Replacement of 1–14 keV Hydrogen and Deuterium in 16 Stainless Steel"

"Thermal Desorption and Bombardment-Induced Release of Deuterium Implanted into Stainless Steel at Low Energy"

"Interactions of 5–30 keV Deuterons with a Carbon Surface"

"Experimental Measurements of Hydrogen Isotope Exchange in Carbon Surfaces under Ion Bombardment"
"Low Energy Proton Induced Re-emission of Deuterium from Carbon"

"Dose and Energy Dependence of Ion Induced Release of Deuterium from Molybdenum by Low Energy Hydrogen Ions"

"Radiation Induced Detrapping of Implanted Deuterium in BeO by High Energy $^3$He and Proton Irradiation"

"Trapping, Detrapping and Replacement of KeV Hydrogen Implanted into Graphite"

"Saturation and Isotopic Replacement of Deuterium in Low-Z Materials"

"A Current Induced Diffusion Model of Gas Sputtering"

"Trapping and Mutual Release of D and $^3$He in Molybdenum"
Figure Captions

Fig. 1 Cross section for the release of deuterium from stainless steels by proton bombardment as a function of incident energy. The proton beams have the same energy as the deuteron beams do. 
(a) 304 SS target at 300 K [4]; (b) 304 SS target at 77 K [4]; 
(c) $\sigma_1$ of 316 SS target at -120 C [6]; (d) $\sigma_2$ of 316 SS target at -120 C [6]; (e) 304 SS target at room temperature [7]; (f) 304 SS target at 300 K [5]; (g) 304 SS target at 90 K [5].

Fig. 2 Cross section for the release of deuterium from graphites by proton bombardment as a function of incident energy. Target temperature is 300 K. The proton beams have the same energy as the deuteron beams do, for the cases of (a), (c) and (d). In the case of (b) [9], the 10 keV deuterons implanted are released by the protons whose energy ranges from 10 to 30 keV.

Fig. 3 Cross section for the release of deuterium from molybdenum by proton bombardment as a function of incident energy at room temperature [11]. The same energy is used for the deuterons and the protons for the cases (a) and (b), and the deuteron energy is fixed at 1 keV in the cases of (c) and (d). The pre-implanted deuteron dose are $1.1 \times 10^{18}$ D$^+$/cm$^2$ for (a) and (c), and $2.3 \times 10^{17}$ D$^+$/cm$^2$ for (b) and (d).

Fig. 4 Cross section for the release of deuterium from BeO and Graphites by high energy H$^+$, $^3$He$^+$, N$^+$ ion bombardments [12,13]. Energy of deuteron bombardment, species of ions for subsequent bombardment, target and target temperature are written in the figure. The value of $\sigma_1$ and $\sigma_2$ are shown in the figure if the detrapping cross sections were determined by assuming a two-term inverse exponential function.
Sample: S.S.

$H^+ \rightarrow D$

Fig. 1

Proton Energy (keV)

Release Cross Section (cm$^2$)
Sample: Graphite
$H^+ \rightarrow D$

Proton Energy (keV)

Release Cross Section (cm$^2$)

Fig. 2
Sample: Mo

$H^+ \rightarrow D$

Proton Energy (keV)

Release Cross Section (cm$^2$)

Fig. 3
Fig. 4
The Chemisorption on the Carbide Surfaces

Chuhei Oshima

National Institute for Research in Inorganic Materials
, Namiki 1-1, Sakura, Niihari, Ibaraki, 305.

Recently, some carbides such as SiC, TiC have received a
great attention as a low-Z material in plasma device. Therefore,
a lot of experiments on coating and sputtering have been carried
out, but there are a little investigation of chemisorption and
desorption. Here, we cite the recent literature devoted to research
on the chemisorption on some carbides including SiC and TiC.
Since those experiments are yet limited, at present, an individual
difference of the chemisorption character on the carbide surface
can not be clearly realized; however, those data suggest commom
property of the carbide surface concerning to chemisorption, which
is described as follows.

(1) The initial sticking probability of some gases on the
carbide surface is smaller than that in the pure-metal surface.
Moreover, the probability decreases rapidly with increase in uptake,
an amount of adsorbates. Table 1 shows the initial sticking
probability of some gases on the carbides. The values of 0.01-0.05
in Table 1 are one or two order of magnitude smaller than that of
pure metals such as Ti, Ta and Mo.
Fig.1 - Fig.3 show the change in the sticking probability as a
function of the uptake. The curve of the probability declines
monotonically with increasing uptake. There is no constant region
of the probability, which largely differs from the metal surfaces:
this fact suggests that those adsorbates do not form a mobile precursor
to chemisorption on the carbide.

(2) There is a tendency that bonds of adatoms on the carbide surfaces (or the carburized surface) are weak. In fact, the binding energy of adsorbates to the carburized surface decreases depending on the degree of carburization. Consequently, the following three types of changes in chemisorption are observed, when we change the substrate from the pure metal to the metal carbide (or the carburized surface).

[2-a] In the first case, the gases that are able to be chemisorbed on the pure-metal surfaces can not be chemisorbed on the carbide surfaces (or the carburized surface). No chemisorption is found at room temperature in the following systems, although it occurs on the pure metals under the same conditions.

<table>
<thead>
<tr>
<th>System</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2$ / TaC (poly.)</td>
<td>27</td>
</tr>
<tr>
<td>$\text{H}_2$ and $\text{N}_2$ / TiC (100)</td>
<td>23</td>
</tr>
<tr>
<td>N ions / W$_2$C (poly.)</td>
<td>41</td>
</tr>
<tr>
<td>$\text{H}_2$ / W$_2$C (poly.)</td>
<td>41</td>
</tr>
<tr>
<td>$\text{H}_2$ / Carburized W (100)</td>
<td>42</td>
</tr>
</tbody>
</table>

[2-b] In the second case, the molecules are chemisorbed undissociatedly on the carbide surfaces (or the carburized surface), although the same molecules are dissociated on the same pure-metal surface.

<table>
<thead>
<tr>
<th>System</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO / Carburized W (100)</td>
<td>42</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}$ / TiC (100)</td>
<td>23</td>
</tr>
</tbody>
</table>
In the last case, without an apparent drastic change described above, only the binding energy of adsorbates becomes small as compared with that of the pure metal. Fig. 4 shows the flash desorption spectra of CO from the three kinds of Ni surfaces: clean surface, carbide surface and graphitized surface. The desorption peak moves toward lower temperatures, when we change from the clean Ni surface to the carbide surface. The similar tendency is also observed in the case of H₂O in Fig. 5.

Because the chemisorption character both on the TiC (100) surface and the carburized W surface resemble those of relatively inactive metals such as Pt, those materials are now widely examined as a catalyst (see reference).

(3) The surface chemical composition of the carbide is apt to change by various surface treatments, because the carbides are binary compounds that have a lot of carbon defects. For example,heatings of higher than 1500°C remove preferentially the Si atoms from the SiC surface, which results in the formation of graphite layer on SiC surface. On the other hand, TiC is relatively stable against the heatings up to 1600°C under ultra high vacuum condition. However, oxygen atoms chemisorbed on the TiC surface are desorbed in the form of CO or CO₂ molecules at high temperature, which removes the carbon atoms from the surface. Similar phenomenon is also reported on the system of hydrogen chemisorbed on the carburized W. The desorption of the hydrogen atoms results in the decreasing in carbon content.

Some chemisorbed-oxygen atoms penetrate easily into the carbide lattice at ~1000°C, forming a trinary compound of TiCₓO₁₋ₓ′.
since TiO has a large solubility in the TiC crystal. Those changes in surface chemical composition may affect the chemisorption character, but it is not yet clearly understood.

(4) The chemisorption character strongly depends on the carbon content of the topmost layer. With increase in the degree of carburization, an initial sticking probability of $N_2$, $H_2$ and $CH_4$ decreases on the Mo (100) surface. The chemisorption character of TiC single crystal differs from one crystallographic face to the other face. The (100) surface composed of nearly stoichiometric composition is relatively inactive for the reaction with residual gases; on the contrary, the (111) surface mainly consisting of Ti atoms is very active similar to the active metals such as Ti and W. Hence, the surface property of the carbides is not due to the carbide itself, but to the surface atomic arrangement.
References

SILICON CARBIDE [SiC]
"The interaction of Oxygen with Silicon Carbide Surfaces"
"LEED and Auger Electron Observation of the SiC (0001) Surfaces"
"Room Temperature Gas Adsorption on Silicon Carbide"

IV a METAL CARBIDE [TiC,ZrC]
"Die Glühemission Hochschmelzender Verbindungen und Stoffe"
"Field Emission Studies of TiC Single Crystal"
"Die Glühemission Von Cermets Auf Grudlage Hochschmelzender Karbide"
"X-ray Photoelectron Spectrum and Band Structure of TiC"
"Electronic Structure of the Transition Metal Carbides"
9 A.L. Hagstrom, L.I. Johanson, B.E. Jacobsson and S.B. Hagstrom:
"Valence Band Structure of Single Crystal TiC Studied by Soft X-ray
and Ultraviolet Photoelectron Spectroscopy"

Ser. 40 (1976) 103.
"Work Function of ZrC in Hydrogen"

11 L.I. Johansson, A.L. Hagstrom, B.E. Jacobsson and S.B. Hagstrom:
"ESCA Studies of Core Levels Shifts and Valence Band Structure in
Nonstoichiometric Single Crystals of TiC"

12 A.L. Hagstrom, L.I. Johansson, S.B. Hagstrom and A.N. Christensen:
"Photoemission Studies of Single Crystals of TiC"

13 R.F. Voitovich and E.I. Golovko: Poroshkovaya Metallurgiya 183
(1978) 55.
"Oxidation of TiC at Various Oxygen Pressures"

"TiC-Kathoden mit Erhoher Emission"

"Work Function of ZrC-Oxygen"

"Adsorption von H an ZrC und leg. mit Re."
"Reaktorbestrahlung auf die Eig. von ZrC und NbC"

"Reduction of Nitrogen Oxides in Automobile Exhaust over Various Carbide Catalysts"

"Catalytic Activities of TiC, WC and TaC for Hydrogeneration of Ethylene"

"Electronic Structure and X-ray Photoelectron Spectra of TiC and ZrC"

"Electronic Structure of TiC and NbC; A Photoelectron Spectroscopy Study"

"Angle-Resolved Photoemission Studies of TiC (111) and TiC (100)"

"Clean TiC (001) Surface and Oxygen Chemisorption Studied by work function Measurement, ARXPS, ARUPS and ISS"
"Outgassing Characteristics of TiC and TiB₂"

"Carbon Monoxide Isotope Exchange with Tantalum Monocarbide"

"The chemisorption of Carbon Monoxide on Tantalum Monocarbide"

"The Chemisorption of Hydrogen on Tantalum Monocarbide"

"Work Function of TaC and Effects of Adsorption and Sputtering of Cesium"

"Cinetique De Decomposition Du Pentane Sous 10⁻⁵-10⁻⁷ Torr A La Surface Du Tantale Et Des Carbures Ta₂C Et TaC, Entre 1300Et 2000K"

"Catalytic Activity of TaC for Hydgeneration of Benzene"

"Catalytic Activity of Powdered TaC for Hydrogeneration of Benzene"
"Work Function of Tungsten Carbide"

"Adsorption und Anodiche Oxydation von Wasserstoff an wolframcabid"

"Pt-Like Behavior of Tungsten Carbide in Surface Catalysis"

"Surface Electronic Properties of Tungsten, Tungsten Carbide, and Platinum"

"Electronic Structure of Tungsten Carbide and its catalytic Behavior"

"Surface Characterization of Catalytically Active Tungsten Carbide (WC)"

"Electronic Structure and Catalysis Behavior of Metal Carbides"

"Crystal Face Specify in Ammonia Synthesis on Tungsten Carbide"
"The relation of Surface Structure to the Electrocatalytic Activity of WC"

"The Characterization of Surface Carbides of Tungsten"

42  P.M. Stefan, C. R. Helms, S.C. Perino, and W. E. Spicer:
"UPS Studies of H₂, O₂ and CO Adsorption on Ordered Carbon Overlayers"

"The Decomposition of Formic Acid on W (100) and W (100)- (5 x 1)C Surface"

"Reactions of Formaldehyde on W(100) and W (100)- (5 x 1)C"

"Reactions of Methanol on W (100) and W (100)- (5 x 1)C"

"Adlayer Effects on Adsorption/Desorption Kinetics: N₂, H₂, C₂H₄ and CO on Mo (100)-C"

"The adsorption of CO, H₂, CO₂ and H₂O on carburized and graphitized Ni(110)"

"Vibration EELS Studies of CO Chemisorption on Clean and Carbided (111), (100) and Nickel Surface"

"The Oxidation of Carbodic Monolayers on Ni (110)"
Table I The sticking probability of some gases on the carbides.

<table>
<thead>
<tr>
<th>System</th>
<th>Initial sticking probability</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ / SiC (polycry.)</td>
<td>0.01</td>
<td>3</td>
</tr>
<tr>
<td>H₂ / TaC (polycry.)</td>
<td>0.04</td>
<td>27</td>
</tr>
<tr>
<td>CO / TaC (polycry.)</td>
<td>0.05</td>
<td>26</td>
</tr>
<tr>
<td>O₂ / TiC (100)</td>
<td>0.02</td>
<td>23</td>
</tr>
<tr>
<td>H₂ / Carburized Mo (100)</td>
<td>0.02</td>
<td>41</td>
</tr>
</tbody>
</table>
Figure Captions

Fig.1 The pressure dependence of the sticking probability of hydrogen on TaC at 295K. ○ = 1.5 x 10^{-8} Torr, △ = 2.8 x 10^{-8} Torr, □ = 3.9 x 10^{-8} Torr.

Fig.2 The pressure dependence of the sticking probability of carbon monoxide (β phase). ● = 5 x 10^{-8} Torr, ■ = 7.5 x 10^{-8} Torr, □ = 1 x 10^{-7} Torr, △ = 2.5 x 10^{-7} Torr, ○ = 5 x 10^{-7} Torr.

Fig.3 The sticking probability of oxygen as a function of the normalized oxygen peak intensity.

Fig.4 The flash desorption spectra of CO from clean Ni (110), carbide and graphitized surfaces.

Fig.5 The flash desorption spectra of water from clean Ni (110), carbide and graphitized surfaces.
Fig. 1
Fig. 2
Fig. 3
CO/Ni (110) C

TEMPERATURE (K)

CARBON MONOXIDE SIGNAL

10^{-8} A

150 200 250 300 350 400 450 500

TEMPERATURE (K)

CARBIDE

GRAPHITE

CLEAN

Fig. 4
Fig. 5
Present Status and Problems in the Theory of Desorption
Masaru Tsukada
Institute for Molecular Science,
Myodaiji-cho, Okazaki, Aichi-ken*

§1 Introduction

Although considerable progress has been made recently for their theoretical study, many of the fundamental features of the desorption phenomena are not well understood as yet. Roughly speaking, the equilibrium desorption rate of an atom from the surface with the temperature T is expressed as

\[ \kappa \propto s \exp(-Q/kT). \]  

(1)

In the above Q, ν are respectively the activation barrier height of the desorption and the number of the trial per unit time to surmount the barrier. The factor s is equal to the sticking probability for the simple one-dimensional model. The quantities Q and ν are determined by the Born-Oppenheimer adiabatic potential energy surface, which can be in principle obtained by first-principle electronic structure calculations. Such calculations, however, are quite laborious and require huge computation time. Hence calculations of the adatom/surface potential energy surface have been so far performed only for simple model cluster systems.

The prefactor s is determined not only by the structure of the potential energy surface, but also by the gas-surface stochastic

* Present address: Department of Physics, University of Tokyo,
   Tokyo 113
interaction. Determination of s as well as many other features of desorption phenomena which are beyond the scope of absolute rate theory are the targets of recent theoretical works. The problems investigated include
1) the transient behaviour of desorption,
2) the angle and the energy distribution of the desorbed particles,
3) the influence of macroscopic and/or microscopic properties of the substrate such as phase transition,
4) deviations from the simple Frenkel-Arrhenius type relation (1),
5) effect of non-adiabatic process on the desorption rate, such as electron-hole excitations in the substrate.

A wide variety of theoretical approaches have been reported in literatures. In the following we describe briefly the characteristics, main results and mutual relations of dominant theoretical approaches.

§2 Various theoretical approaches for desorption
2-1) Classical theory based on the thermal equilibrium hypothesis [ref.1)~6)]

In this approach the behavior of each coordinate of motion is statistically determined by the thermal equilibrium hypothesis. Therefore the real stochastic behavior of the adparticle can not be taken into account. However the structural detail of the potential energy surface can be incorporated with this approach. A lot of works have been performed beginning from the simple linear truncated harmonic oscillator model to a realistic three dimensional
Recently, the delay time of the molecular beam interacting with surface, \(^6\) the effect of adsorbate lateral motion \(^4\) and the angular distribution of the desorbed gases \(^1\) have been investigated, as well as the deviations from the simple Frenkel Arrhenius type relation (1).

2-2) Stochastic classical trajectory approach [ref.7\textasciitilde16)]

This approach is powerful for the study of the general dynamic interactions between an adatom and a harmonic lattice system. Stochastic trajectories are obtained by the direct numerical integration of the generalised Langevin equation (GLE):

\[
\ddot{X}(t) = F_R(X(t), Y(t), Z^0) \tag{2}
\]

\[
\ddot{Y}(t) = F_P(X(t), Y(t), Z^0) - (\Omega_P^2 - \Lambda(o))Y(t) - \Lambda(t)Y(0) - \int_{-\infty}^{t} \Lambda(t-t')Y(t')dt' + R(t) \tag{3}
\]

In the above \(X(t)\); \(Y(t)\), \(Z^0\) are the coordinate of gas atom, surface atoms in the primary zone and the equilibrium positions of the atoms in the secondary zone. \(F_R\), \(F_P\) are the forces due to adatom/surface interaction, and \(\Omega_P^2\) is the effective dynamical matrix of the primary zone. The correlation function of the stochastic force \(R(t)\) is related with the friction Kernel \(\Lambda(t)\) by the following,

\[
\kappa T \Lambda(t) = \langle R(t)R^+(0) \rangle \tag{4}
\]
The key point of the trajectory calculation is that not the stochastic force \( R(t) \), but the impulse \( I_n = \int_{t_{n-1}}^{t_n} R(t) \, dt \) during the integration mesh appears in the numerical integration. The random variable \( \{ I_n \} \) are generated by the Gaussian distribution which are determined by eq. (4). The diagonal elements of \( \Lambda(t) \) are obtained by the surface phonon spectrum.

Based on this approach inelastic atom-surface scattering, sticking, desorption and the mean residence time have been investigated. Typical stochastic trajectory by Shugard et al. are shown in Fig. 2.

2-3) Approach based on Fokker-Planck equation [ref. 17) - 24)]

The time evolution of the adatom/surface system is described by the distribution function \( F(q,p,t) \) of the point along the reaction path. The distribution function is determined by the Fokker-Planck equation (FPE),

\[
\frac{\partial f}{\partial t} + P \frac{\partial f}{\partial q} + F(q) \frac{\partial f}{\partial p} = \eta \frac{\partial}{\partial p} (p f + M k T \frac{\partial f}{\partial p}),
\]

where \( M \) and \( F(q) \) are the mass and the force along the reaction path, respectively. The friction constant \( \eta \) is given by the correlation function of the random force, \( \hat{F} \), due to the microscopic electron or spin density fluctuations of the surface,

\[
M \eta \sim \text{Re} \frac{1}{k_B T} \int_0^\infty d\tau \langle \hat{F} \hat{F}_0(\tau) \rangle.
\]

The relations (5), (6) are valid for the case that the correlation time is much shorter than the oscillation period of the adatom.
It should be noted that in the limit of very small correlation time of \( R(t) \), the GLE system (2) - (4) is described by the similar FPE as eq. (5). It is seen by the relation (6) that \( \eta \) is essentially determined by the physical properties of the solid, such as the dielectric constant or spin susceptibility. Therefore anomalous enhancement of \( \eta \) is expected around the phase transition temperature, which affects the desorption behaviour.\(^{17}\)

The desorption rate \( \kappa \) tends to zero in the both limit of \( \eta \to 0, \eta \to \infty \). Therefore substantial deviation from the Frenkel-Arrhenius relation is expected in the region of very small or large \( \eta \) value. For the simple one dimensional model as shown in Fig. 3, \( \kappa \) is approximately expressed as\(^{23}\)

\[
\kappa \approx (1 - e^{-B\eta Q/kT\omega_0}) \left( (1 + \eta^2/4\omega_C^2)^{1/2} - \eta/2\omega_C \right) \times \omega_0 \exp(-Q/kT),
\]

where \( B \) is the numerical constant of about 3.0, \( Q, \omega_0, \omega_C \) are defined in Fig. 3.

2-4) Random walk approach in energy space [ref. 25] - 31)]

The desorption process is also formulated as the random walk problem in energy space. The basis of this approach is the master equation,

\[
\frac{\partial P_n}{\partial t} = -\sum_{m} W_{n \rightarrow m} P_n(t) + \sum_{m} W_{m \rightarrow n} P_m(t)
\]

which determines the stochastic behaviour of the adparticle in the energy space. In the above \( P_n(t) \) is the probability of the
adatom existing in the vibrational level \( n \) of the potential surface, and \( W_{n \rightarrow m} \) is the transition probability from the state \( n \) to \( m \). The transition matrix element \( W_{n \rightarrow m} \) due to the adatom-lattice interaction is obtained by the linear coupling approximation or by more general models.

Gortel et al.\(^{29}\) discussed the isothermal desorption time for a physisorption system with many bound states. Exact solutions of the master equation are given for Morse potential. Isothermal desorption times of physisorption systems correspond fairly well with experimental observations. Efrima et al.\(^{26}\) found that the activation energy of the desorption time is smaller than the depth of the potential energy surface. This is because the transition probabilities from the shallow vibrational level to the continuum is very large. The Frenkel-Arrhenius relation is found to hold only in a limited temperature range.

The diffusion equation in energy space, which is the classical limit of eq.\((8)\) was also investigated by Pagni, Keck.\(^{31}\) Adatom energy distributions were found to be significantly non equilibrium as opposed to the assumption of the approach 2-1).

2-5) Discussions

Each theoretical approach in previous subsections lays its emphasis on a different aspect of the desorption phenomena. For example, the approach 2-1) focusses its attention on elucidating dependence of the realistic features of the potential energy surface on the desorption rate, while the other approaches stress the stochastic process in the adatom/surface system. In the approaches 2-2) and 2-4) the coupling between the adatom and the
lattice vibration is studied, whereas the coupling between the adatom and electron density fluctuation is treated in the approach 2-3). Therefore, although the inclusion of the adatom/electron coupling as in approach 2-3) is indispensable for the chemisorption system, desorption of the physisorbed atom is conveniently studied by the approaches 2-2) and 2-4). The Brownian motion approach 2-3), as it stands, is not sufficient for the description of the desorption of the chemisorbed atom, because the energy dissipation to the lattice is ignored.

The most important quantity which characterizes the adsorption and desorption phenomena is the order of the kinetic energy dissipation $\Delta E$ during the oscillation period (one round trip) of the adsorbate (gas atom). For example the order of sticking probability $s$ and desorption rate $\kappa$ is roughly estimated as,

\[
s \sim (1 - \exp(-\Delta E/\kappa T)) \quad (9)
\]
\[
\kappa \sim s\exp(-Q/\kappa T) \quad (10)
\]

for a simple one-dimensional model. (More detailed expressions are found in ref.46.) In Table I, magnitude of the friction constant $\eta$, the time scale of the friction kernel $\Lambda(t)$ and the order of $\Delta E$ are listed for some energy dissipation mechanisms. Since the contribution to $\Delta E$ from the lattice vibration can be the same order as that from the electron system, the both coupling mechanisms can be treated on an equal footing. Furthermore the many electron-hole excitations$^{32-36}$ would be also an important effect which dissipates the kinetic energy of
the chemisorbed atom. This effect is not incorporated with the approach 2-3). Basic mechanism of the desorption of the chemisorbed atom is not enough clarified as yet.

§3 Theory of electron stimulated (impact) desorption [ref.52, 72])

Dominant features of ESD can be understood by the two-step mechanism by Menzel and Gomer 67) and Redhead 70);

i) the electron impact causes a Franck-Condon transition from the ground state of the adsorbate system to a repulsive neutral or ionic states.

ii) Radiationless transitions occur while the adatom is moving away from the surface. These transitions transfer excitation energy to the solid from the adsorbate, which falls back to its ground state without desorption in most cases.

Quantum theory of ESD was developed by Brenig. 53) It was shown within the adiabatic approximation that desorbing ions decay predominantly via antibonding neutral states. The lifetime of the antibonding neutrals 72) due to the many electron-hole excitations of transition metals were evaluated to be \( \approx 10^{-15} \) sec, which corresponds well with experimental observations.

For the case of ionic adsorbates on the metal surface, the initial excitation process includes the interatomic Auger transitions. 58) In this model one of the adatom valence electron falls into the metal core hole state produced by the electron
impact. At the same time one or two other electrons are removed from the adatom. Thus produced positive adatom is strongly repelled from the surface by the Madelung potential. This model explains quite well why positive ions are desorbed from the negative chemisorption charge states, as well as the major desorption threshold energies. This mechanism is very sensitive to the coordination state of the metal atom to which the adsorbate is attached.

Some trajectory calculations\textsuperscript{58,68} have been performed to analyze the ion angular distribution (ESDIAD) of desorbed ions. By assuming appropriate chemisorption geometries, the experimental ESDIAD is reproduced by the theoretical calculations.
References

Theory based on the thermal equilibrium hypothesis or RRKM model

   "Classical theory of desorption rate velocity distribution of desorbed atoms: Possibility of a compensation effect"

   "The scattering of atoms from surfaces"

   "Lattice influence on gas-solid desorption: RRKM model"

   "The theory of desorption from a general potential"

   "The interaction of adsorbed molecules with surfaces: II Dissociation"

   "The theory of atomic desorption for general potential"

Trajectory approach

   "Brownian Motion and Chemical Dynamics on Solid Surfaces"

   "Generalized Langevin equation approach for atom/solid surface scattering: General formulation for classical scattering off harmonic solids"
   "Generalized Langevin theory for gas/solid processes:
   Dynamic solid models"
    "Generalized Langevin theory for gas-solid processes:
    Continuum elastic treatment of surface lattice dynamics"
    "The energetics of diatom/solid dissociative adsorption"
    "Generalized Langevin theory for gas-solid processes:
    inelastic scattering studies"
    "A model potential for chemisorption: H₂ + W(001)"
    "Dynamics of gas-solid interactions: Calculation of energy
    transfer and sticking"
    "Dynamics of gas-surface interactions: 3D generalized
    Langevin models applied to fcc and bcc surfaces"
    "Molecular dynamics of surface diffusion I. The motion of
    adatoms and clusters"
Approach based on Fokker-Planck equation

   "Brownian motion model of the interactions between chemical species and metallic electrons: Bootstrap derivation and parameter evaluation"

   "Reaction kinetics at solid surfaces"

   "Effect of adatom-phonon coupling on desorption kinetics in the heavy-adatom limit"

   "Time-Dependent Escape Rate from a Potential Well"

   "Reaction kinetics at surfaces in terms of response characteristics of the substrate"

   "Escape rate for a Brownian particle in a potential well"

   "Numerical Brownian-motion model reaction rates"

   "Exact Time-Dependent Desorption From a Surface"
Random walk approach in energy space

   "Microscopic theory of thermal desorption and dissociation processes catalyzed by a solid surface"

   "A one-dimensional microscopic model for thermal desorption of an atom. Applications to the case of weak binding"

   "Quantum-dynamical model for thermal desorption of gases from solid surfaces"

   "Quantum statistical theory of flash desorption"

   "Desorption by phonon cascade for gas-solid systems with many physisorbed bound states"

   "Mean First Passage Time for a Random Walker and Its Application to Chemical Kinetics"

   "Diffusion theory for adsorption and desorption of gas atoms at surfaces"
Theory of non-adiabatic surface processes

"The electron-hole mechanism for sticking of adsorbates: A soluble model"

"Non-adiabatic processes in adsorption/desorption phenomena"

34. B.Kasemo, E. Törnqvist, J.K. Nørskov and B.I. Lundqvist:
"Photon and electron emission as indicators of intermediate states in surface reactions"

"Theory of rate processes at metal surfaces.II. The role of substrate electronic excitations"

"Correlation between sticking probability and adsorbate-induced electron scattering"

"Localized dynamic perturbations in metals"

"Sticking probability on metal surfaces: Contribution from electron-hole-pair excitations"

Other approaches and problems in desorption theory

"Phonon-Induced Desorption of Adatoms from Crystal Surfaces I. Formal Theory"
   "Kinetic Theory of Thermal Desorption"
   "A "hydrodynamic" theory of Surface reaction rates"
   "Rate expressions for adsorption and desorption kinetics
   with precursor states and lateral interactions"
   "Peak widths of elementary first and second order desorption
   transients"
   "Desorption times in flash desorption and isothermal
   desorption experiments"
   "Quantum Statistical Theory of Adsorption and Desorption of
   a Gas at a Solid Surface"
   "Kinetic theory of gas-surface interaction"
   "Multiphonon theory of scattering of atoms from solid
   surfaces: Tetradic scattering approach"
   "On the Kisliuk model for adsorption and desorption kinetics"
   "Inelastic atom-surface scattering: A comparison of classical and quantum treatments:"

   "Desorption kinetics of one- and two-step mechanisms"

   "Phonon-induced desorption of adatoms from crystal surfaces II. Numerical computations for a model system"

Theorey of electron or photon stimulated desorption

   "Comment of "Quantum theory of electron stimulated desorption" by W. Brenig"

   "Quantum theory of electron stimulated desorption"

   "Reply to: Comment on "Quantum theory of electron stimulated desorption"

   "Reneutralization in electron stimulated desorption"

   "Quantum scattering theory of electron-stimulated desorption: ion angular distributions"

   "Reneutralization bottleneck in Auger initiated desorption"
"Reinterpretation of electron-stimulated desorption data from chemisorption systems"

"Theory of Ion-angular distributions in electron-stimulated desorption"

"Theory of photodesorption"

"Relation between electron-stimulated desorption and nondissociative chemisorption"

"Theoretical aspects of photoemission, photodesorption and photochemistry of adsorbates"

"Kinetic theory description of electron stimulated desorption"

"Calculation of energy spectra for ESD of H+ from H2 adsorbed on Tungsten"

"Stability of ionically bonded surfaces in ionizing environments"

"Quantum-stochastic approach to laser-stimulated desorption dynamics and population distributions of chemisorbed species on solid surfaces"
"Desorption from Metal Surfaces by Low-Energy Electrons"

"Computer simulations of electron stimulated desorption patterns from oxygen on W(100) and (111) surfaces"

"Interaction of slow electrons with chemisorbed oxygen"

"Laser-stimulated migration of adsorbed atoms on solid surfaces"

"On the lifetime of Certain excited states of chemisorbed atoms"
<table>
<thead>
<tr>
<th>Dissipation mechanism</th>
<th>lattice vibration</th>
<th>electron density fluctuation</th>
<th>many electron-hole pair excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>order of time scale of ( \Lambda(t) )</td>
<td>( \omega_D^{-1} )</td>
<td>( (E_F/\hbar)^{-1} )</td>
<td></td>
</tr>
<tr>
<td>order of magnitude of ( \eta ) ( (\eta = \int_0^\infty \Lambda(t) dt) )</td>
<td>( \omega_D )</td>
<td>( m_e ) ( E_F/\hbar )</td>
<td></td>
</tr>
<tr>
<td>order of ( \Delta E )</td>
<td>( \frac{\eta \omega M}{0 \omega_D^3} )</td>
<td>( \eta Q/\omega_0 )</td>
<td>( \frac{\partial \epsilon_s}{\partial z} ) ( z = Z_0 )</td>
</tr>
</tbody>
</table>

\( \omega_D \): Debye freq., \( m_e \): electron mass, \( M \): adatom mass, \( \omega_0 \): adatom vibrational frequency, \( E_F \): Fermi energy, \( Q \): Chemisorption energy, \( V, \Gamma \) : velocity and the level width of the adatom at the position \( Z_0 \), where the anion level crosses with Fermi level.
Figure Captions

Fig.1 A simple model of adatom interacting with solid surface. Only the atoms in the primary zone (shown by full circle) directly interact with the adatom. Other atoms in the solids (shown by dotted circle) are called as the secondary zone atoms.

Fig.2 An example of the trajectory in which an Ar atom impinging on W surface is trapped and desorbed. Morse potential is assumed for the Ar-W interaction. The substrate temperature and the adatom initial kinetic energy are assumed as 200 K and 1.2 kcal/mol, respectively.

Fig.3 A simple one-dimensional model of the adiabatic potential energy surface for desorption. Depth of the binding energy is denoted as Q. The adatom vibrational frequency in the well and the (imaginary) frequency at the barrier are assumed as ω₀, ωc respectively.

Fig.4 Numerical result of the desorption rate κ as the function of η for the model of Fig.3. The value of κ determined by Frenkel-Arrhenius relation is shown by dashed line.
Fig. 1

Fig. 2

Ar atom

$W_{\text{substrate atom}}$

position (bohrs)

time ($10^{-13}$ sec)
<table>
<thead>
<tr>
<th>Report</th>
<th>Title</th>
<th>Authors/Editors</th>
<th>Publication Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPPJ-AM-3</td>
<td>&quot;Grotrian Diagrams of Highly Ionized Iron FeVIII-FeXXVI&quot;</td>
<td>K. Mori, M. Otsuka, and T. Kato (1977)</td>
<td>[Published in Atomic Data and Nuclear Data Tables 23, 196 (1979)]</td>
</tr>
<tr>
<td>IPPJ-AM-5*</td>
<td>&quot;Charge Transfer between a Proton and a Heavy Metal Atom&quot;</td>
<td>S. Hiraide, Y. Kigoshi, and M. Matsuzawa (1978)</td>
<td></td>
</tr>
<tr>
<td>IPPJ-AM-9</td>
<td>&quot;Charge Changing Cross Sections for Heavy-Particle Collisions in the Energy Range from 0.1 eV to 10 MeV I. Incidence of He, Li, Be, B and Their Ions&quot;</td>
<td>Kazuhiko Okuno (1978)</td>
<td></td>
</tr>
<tr>
<td>IPPJ-AM-10</td>
<td>&quot;Charge Changing Cross Sections for Heavy-Particle Collisions in the Energy Range from 0.1 eV to 10 MeV II. Incidence of C, N, O and Their Ions&quot;</td>
<td>Kazuhiko Okuno (1978)</td>
<td></td>
</tr>
<tr>
<td>IPPJ-AM-11</td>
<td>&quot;Charge Changing Cross Sections for Heavy-Particle Collisions in the Energy Range from 0.1 eV to 10 MeV III. Incidence of F, Ne, Na and Their Ions&quot;</td>
<td>Kazuhiko Okuno (1978)</td>
<td></td>
</tr>
<tr>
<td>IPPJ-AM-12*</td>
<td>&quot;Electron Impact Excitation of Positive Ions Calculated in the Coulomb-Born Approximation – A Data List and Comparative Survey –&quot;</td>
<td>S. Nakazaki and T. Hashino (1979)</td>
<td></td>
</tr>
</tbody>
</table>
IPPJ-AM-15 "Cross Sections for Charge Transfer Collisions Involving Hydrogen Atoms"
Y. Kaneko, T. Arikawa, Y. Itikawa, T. Iwai, T. Kato, M. Matsuzawa,

IPPJ-AM-16 "Two-Centre Coulomb Phaseshifts and Radial Functions"

IPPJ-AM-17 "Empirical Formulas for Ionization Cross Section of Atomic Ions for
Electron Collisions –Critical Review with Compilation of Experimental
Data–"

IPPJ-AM-18 "Data on the Backscattering Coefficients of Light Ions from Solids"

IPPJ-AM-19 "Recommended Values of Transport Cross Sections for Elastic Collision and
Total Collision Cross Section for Electrons in Atomic and Molecular Gases"
M. Hayashi (1981)

IPPJ-AM-20 "Electron Capture and Loss Cross Sections for Collisions between Heavy
Ions and Hydrogen Molecules"
(1981)

IPPJ-AM-21 "Surface Data for Fusion Devices – Proceedings of the U.S–Japan Work-
shop on Surface Data Review Dec. 14-18, 1981”

IPPJ-AM-22 "Desorption and Related Phenomena Relevant to Fusion Devices”
Ed. by A. Koma (1982)

Available upon request to Research Information Center, Institute of Plasma Physics, Nagoya
University, Nagoya 464, Japan, except for the reports noted with*.