LOW-ENERGY ELECTRON INTERACTIONS

WITH ATOMS & MOLECULES

조　　혁

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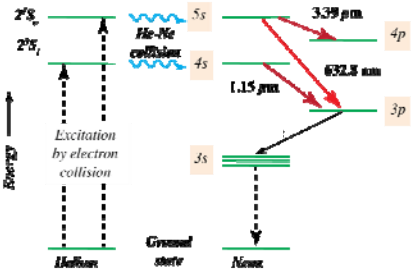
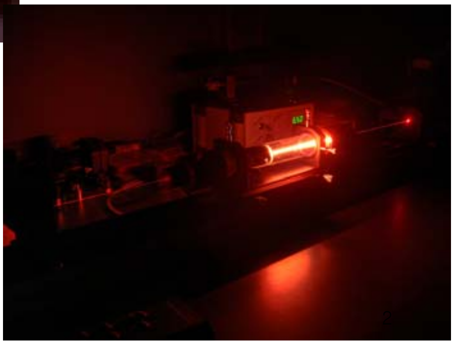
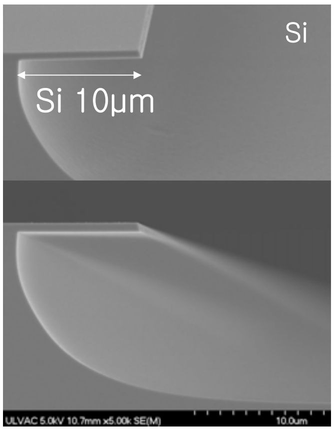


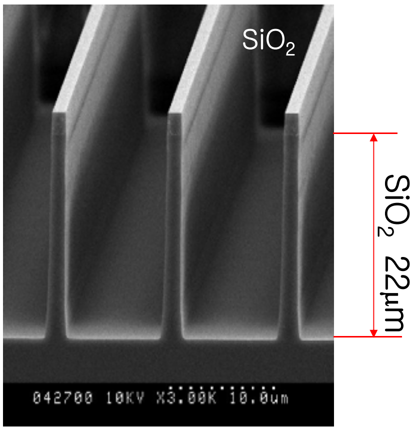


Etching

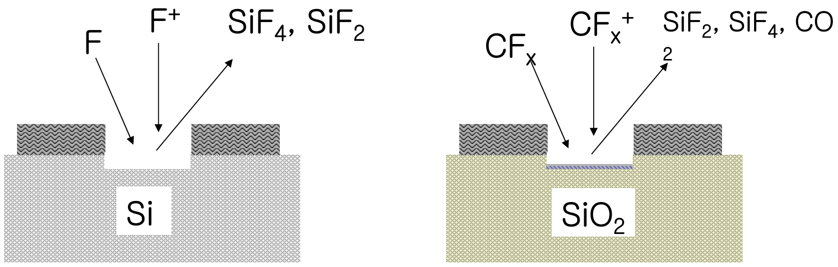
F radical (atom) etching



CF_x^+ ion etching



etching

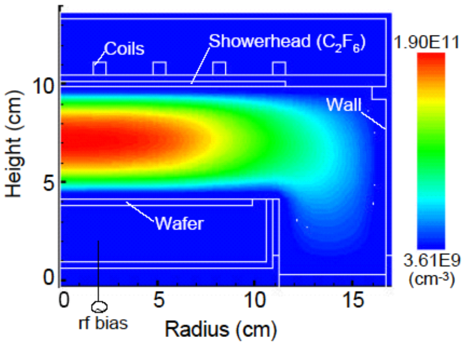


C_2F_6 ETCHING of Si

- Simulations of C_2F_6 etching of Si in an ICP reactor were performed.
- Representative gas phase reactions:

$e + C_2F_6 \rightarrow CF_3^+ + CF_3 + e + e$
$e + C_2F_6 \rightarrow CF_3 + CF_3 + e$
$e + CF_3 \rightarrow CF_2 + F + e$
$e + CF_3 \rightarrow CF_2 + F + F^-$
$e + CF_4 \rightarrow CF_2 + F + F + e$
$e + CF_4 \rightarrow CF_3^+ + F + e + e$
$F + F + M \rightarrow F_2 + M$
$CF_3 + CF_3 + M \rightarrow C_2F_6 + M$
$CF_2 + F_2 \rightarrow CF_3 + F$
$CF_3 + F_2 \rightarrow CF_4 + F$
$CF_2 + CF_3 \rightarrow C_2F_5$
$C_2F_5 + F \rightarrow CF_3 + CF_3$
$CF_3 + F \rightarrow CF_4$
$CF_2 + F \rightarrow CF_3$

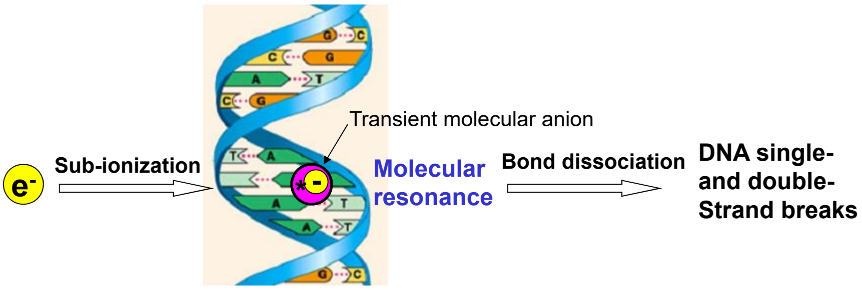
- Electron Density



- C_2F_6, 10 mtorr, 200 sccm, 650 W ICP, 100 V bias

T. E. F. M. Standert et al, J. Vac. Sci. Technol., A16 239 (1998)

Interaction of Electrons with Biomolecules



Electron-driven processes are everywhere !!

- radiation chemistry
- environmental chemistry
- stability of waste repositories
- plasma-enhanced chemical vapor deposition (CVD)
- plasma processing of materials for microelectronic devices and other applications
- novel light sources for research and everyday lighting
- life sciences
- chemical synthesis
- planetary atmospheres
- environmental remediation applications.

Ubiquitous !!

Statistical behavior of electrons in a plasma

- governed by the electron energy distribution function (EEDF).
- **Transport properties of electrons** are directly dependent on EEDF.
- **In a low-temperature molecular plasma, the electron-molecule collisions play the central role in determining EEDF.** Particularly important are the elastic scattering and the rotational and vibrational excitations of molecules.

Energy supplied from the applied field mainly goes to the electrons.

→ Those electrons collide with molecules to **produce various active species** (ions, radicals, excited atoms and molecules, and high-energy photons).

→ Those active species are **utilized for practical applications** mentioned previously.

(계속)

→ requires **knowledge of the basic collision processes** taking place:

i.e. quantitative understanding of the fundamental electron collision processes in terms of **cross sections** and **rate coefficient** is important

공정 플라즈마**(processing plasma)**의 경우, 그 안에서 일어나는 다양하고 복잡한 원자/분자 충돌과정을 시간대별로 나누면 다음 세 단계로 나누어 볼 수 있다:

- **1**단계 **Physical stage:** 전자 충돌에 의한 분자의 들뜸**(excitation),** 해리 **(dissociation),** 이온화
- **2**단계 **Physico-Chemical stage:** 들뜬 분자에 의해 방출 되는 광자에 의한 광자 충돌, 이온이나 **free radical**과 같은 **reactive species** 등의 반응
- **3**단계 **Chemical stage : 2**단계 생성물의 추가적인 화학 반응

$e + C_2F_6 \rightarrow CF_3 + CF_3 + e$
$e + CF_3 \rightarrow CF_2 + F + e$
$e + CF_3 \rightarrow CF_2 + F + F^-$
$e + CF_4 \rightarrow CF_2 + F + F + e$
$e + CF_4 \rightarrow CF_3^+ + F + e + e$
$F + F + M \rightarrow F_2 + M$
$CF_3 + CF_3 + M \rightarrow C_2F_6 + M$
$CF_2 + F_2 \rightarrow CF_3 + F$
$CF_3 + F_2 \rightarrow CF_4 + F$
$CF_2 + CF_3 \rightarrow C_2F_5$

Electron Collision Processes

(1) Elastic scattering (Q_{elas})

$e + AB \rightarrow e + AB$

(2) Rotational transition (Q_{rot})

$e + AB(J) \rightarrow e + AB(J')$

where J (J') is the rotational quantum number of the initial (final) state of the molecule.

(3) Vibrational transition (Q_{vib})

$e + AB(v) \rightarrow e + AB(v')$

where v (v') is the vibrational quantum number of the initial (final) state of the molecule.

(4) Excitation of electronic state (Q_{exc})

$e + AB \rightarrow e + AB^*$

(5) Dissociation (Q_{dis})

$e + AB \rightarrow e + A + B^{(*)}$

(6) Ionization (Q_{ion})

$e + AB \rightarrow 2e + AB^{+(*)}$

or $e + AB \rightarrow 2e + A + B^{+(*)}$

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(7) Electron attachment (Q_{att})

$e + AB \rightarrow A + B^-$, or

$e + AB + M \rightarrow AB^- + M$.

(8) Momentum-transfer cross-section (Q_m)

This quantity gives the **degree of momentum-transfer during the collision**. It plays a fundamental role in determining **electron transport in plasmas**.

(9) Emission cross-section (Q_{emis})

In some collision processes, the final product emits radiation immediately after the collision.

(10) Total scattering cross-section (Q_{tot})

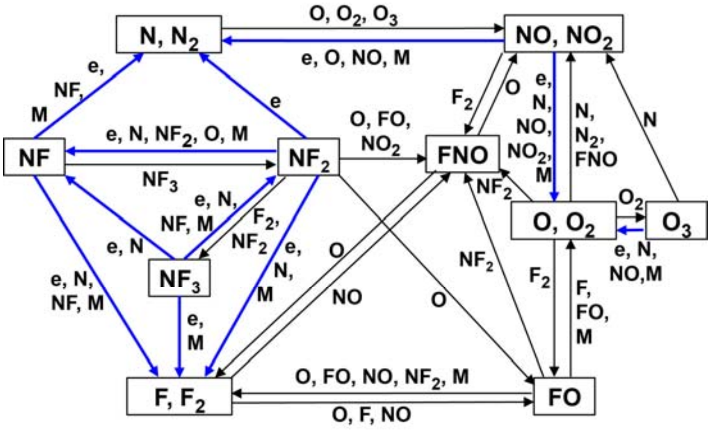
This is defined as a sum of all the cross-sections for the individual processes (1)-(7).

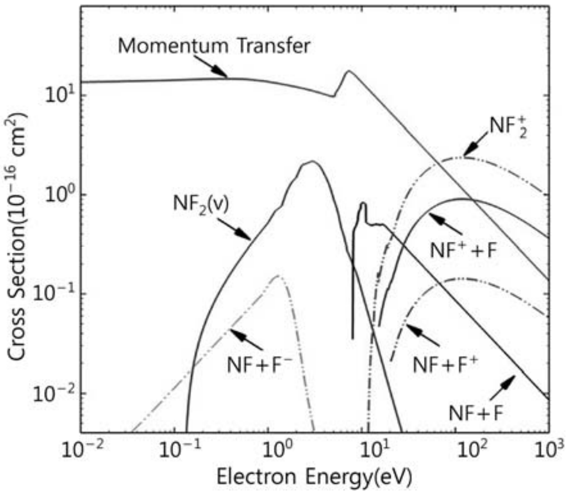
(11) Stopping cross-section (S)

This indicates the amount of energy transfer during the collision. Or more precisely it shows **how much the incoming electron loses its energy**.

Si_3N_4의 플라즈마 식각에서는 NF_3와 O_2의 혼합물을 사용해 NF_X, N, FNO_X (x=1-3)를 생성하고 이것들이 웨이퍼를 식각. 이 시스템을 모델링하려면 이 분자종들과 이들 사이의 상호작용에 대해 알아야 한다 [Bartschat(2016)].

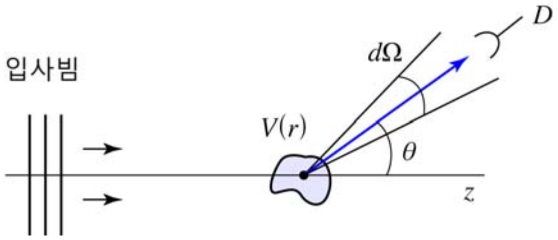
NF_3/O_2 혼합물에서의 상호작용 메커니즘:





앞 그림에 기술된 과정 중, 일부에 대한 NF_2의 전자충돌 단면적 [Bartschat(2016)]

Cross Sections: definitions



Cross Sections: definitions

Consider a collision A + B. B is a target fixed in space and A is

a projectile incident along *z* axis.

J_{in} : flux of the incident particle

$J_{out}(\theta,\phi)\,d\Omega$: number of particles outcoming per unit time and

per solid angle $d\Omega$ in the direction (θ,φ) after collision

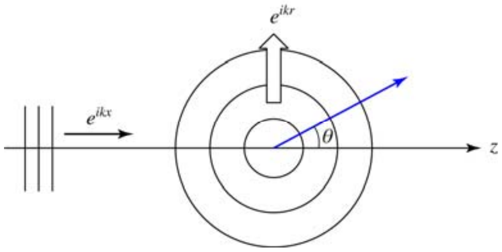
Differential Cross Section (DCS):

$$q(\theta,\phi) = \frac{J_{out}(\theta,\phi)}{J_{in}}$$

$$d\sigma/d\Omega$$

Integral Cross Section (ICS): $Q = \int d\Omega\; q(\theta,\phi)$

$$\sigma(T) = \int_0^{2\pi}\int_0^{\pi}\frac{d\sigma}{d\Omega}\sin\theta\, d\theta\, d\phi.$$



$$\Psi \xrightarrow{r\to\infty} e^{i\vec{k}\cdot\vec{r}} + f(\vec{k}|\theta,\phi)\frac{e^{ikr}}{r}$$

$$\frac{d\sigma}{d\Omega} \equiv q(\theta,\phi) = |f(\vec{k}|\theta,\phi)|^2$$

Experimental methods for cross sections:

- Beam method: DCS, TCS
  single-collision condition !!

- Different methods for the different collision processes

- Swarm method
  strictly speaking, not a collision experiment.

Beam Methods : DCS Measurements

- Collide a well-collimated electron beam of a fixed kinetic energy with a molecular beam at low pressure
  → analyzes the kinetic energies of scattered electrons
  → leads to differential cross sections (DCS)
- Provides much more detailed information, and reflects the dynamics of electron collisions

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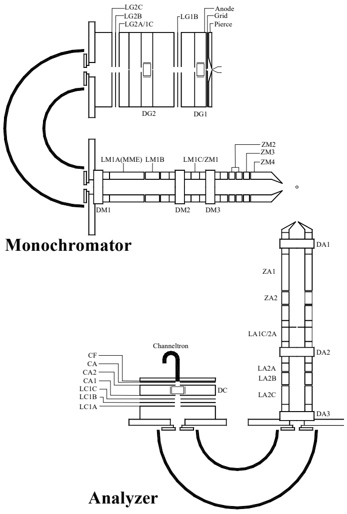
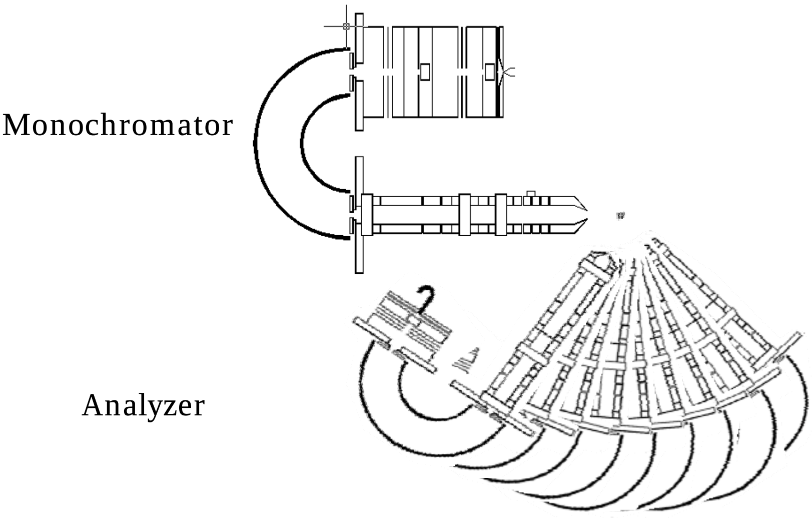
Electron Spectrometer

- **Electron beam**
  - **Current 0.5 to 5 nA**
  - **50-60 meV resolution**
  - **~1 mm diameter**
- **Molecular beam**
  - **Single capillary**
  - **0.3 mm diameter**
- **Accessible angles**

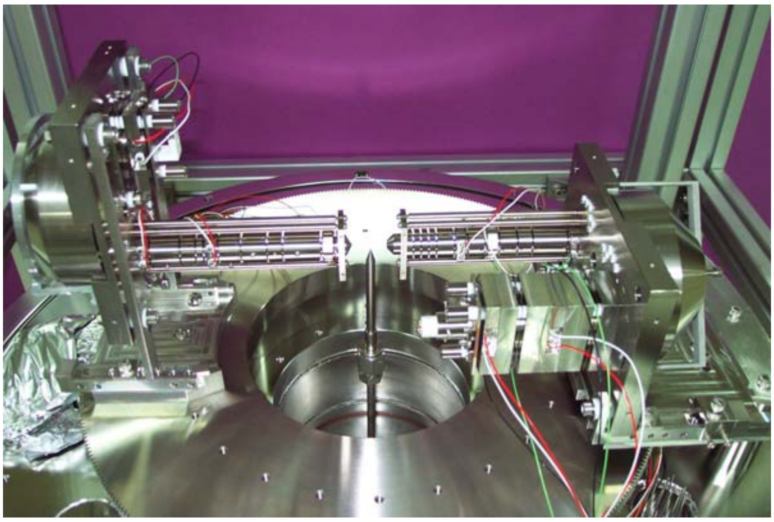
  -15° and 125°



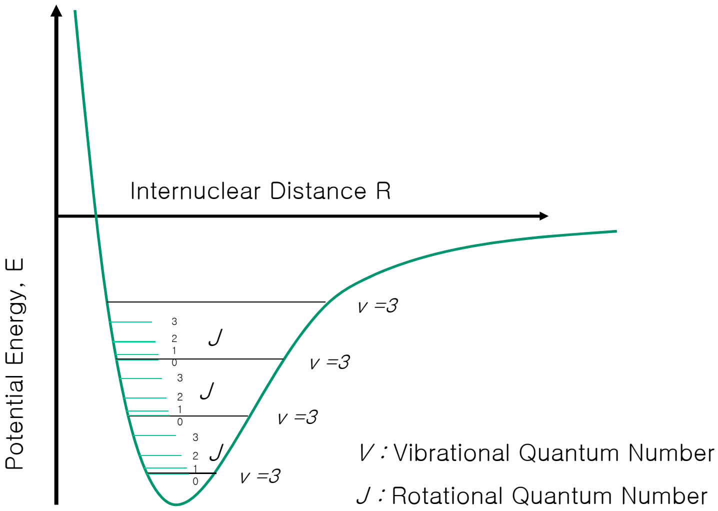
Electron Spectrometer



Electron Spectrometer

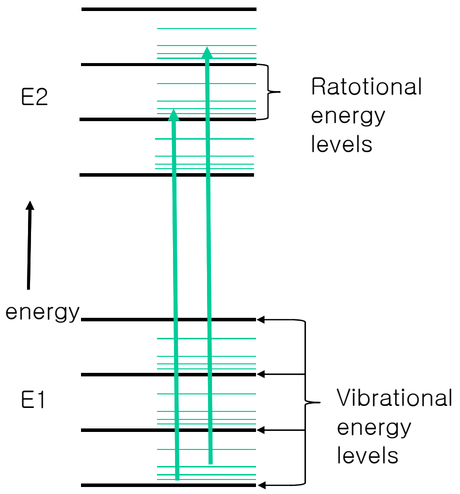


Electron Spectrometer



V : Vibrational Quantum Number

J : Rotational Quantum Number



1. Elastic Scattering

Since the elastic scattering has **no threshold**, Q_{elas} has a considerable magnitude even at a very low energy.

Due to the **recoil** of the target, the KE change of electron is given by

$$(\triangle E)_{elas} = 2\frac{m_e}{M}E_e(1-\cos\theta)$$

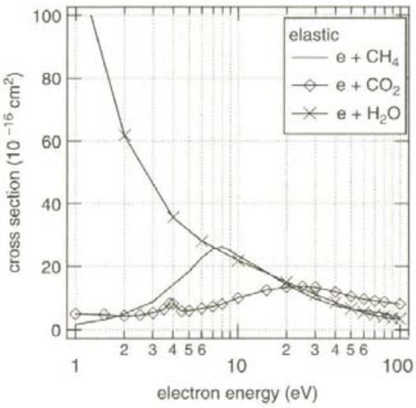
m_e and M are the masses of electron and the molecule, respectively

θ is the scattering angle.

The transition energy of **rotational state** of a molecule $(\triangle E)_{rot}$ is normally of the order of meV or less.

→ much smaller than the experimental energy resolution, so that it is difficult to discriminate the rotational transition from the elastic scattering

→ Thus the **elastic cross-section determined with an EELS measurement includes the cross-section for rotational transitions**.

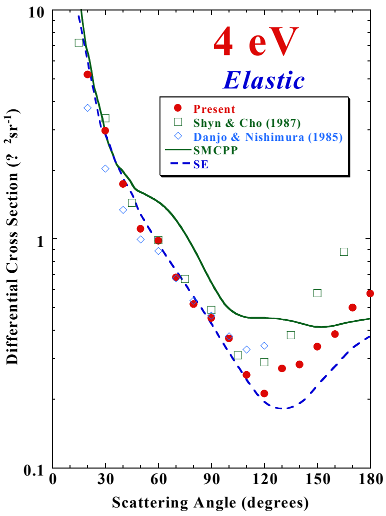


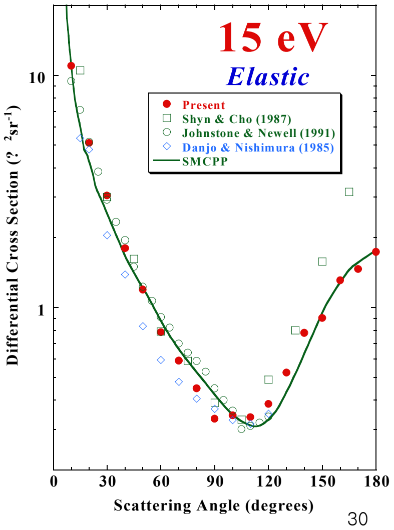
Elastic scattering cross-sections

Due to its **large electric dipole moment**, H_2O has a large rotational cross-section at very low energy.
[그림에서 보듯, 낮은 에너지에서 매우 큰 cross section]

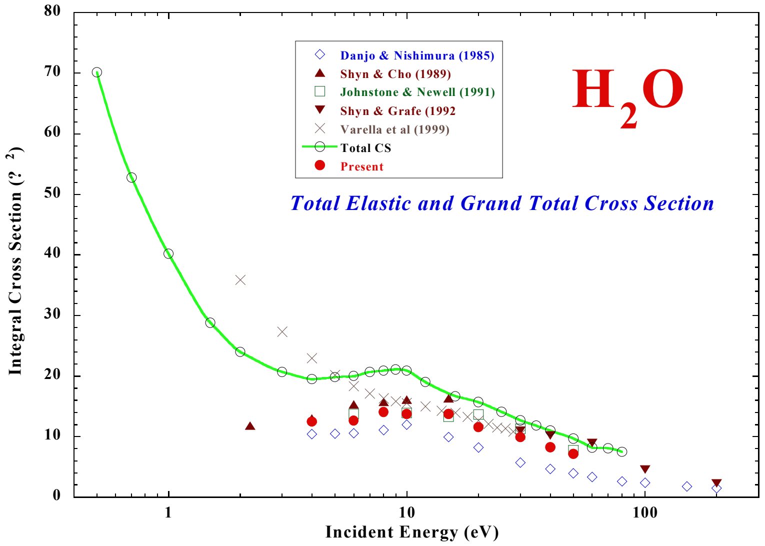
주의!! 이 그림은 실험으로 측정한 **ELASTIC cross section**을 보여주고 있음.

H_2O DCS





H_2O Elastic Integral CS



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2. (Elastic) Momentum Transfer

$$Q_m = 2\pi \int_0^{\pi} (1-\cos\theta)\, Q_{elas}(\theta) \sin\theta\, d\theta$$

In a plasma, **electron transport** is primarily governed by Q_m.

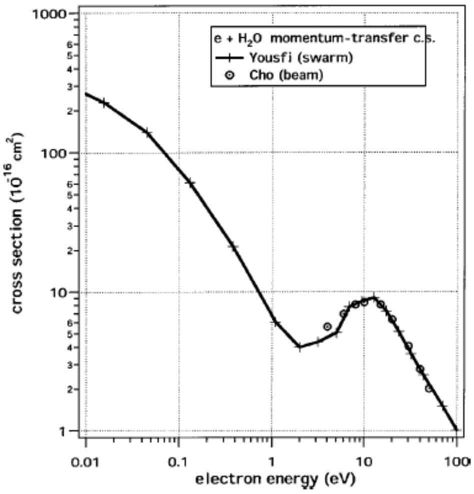
Consider, for instance, **electric conduction**:

- Under the application of **electric field**, electrons move along the direction of the field.

- Upon a collision with a molecule, the electron starts to **move away from the field direction**. The deviation of the electron trajectory from the field direction is determined by the **momentum transfer** during the collision.

- If Q_m is large, the deviation from the field direction is large and the electron motion **less contributes to the electric conduction**.

H_2O Momentum Transfer Cross Section

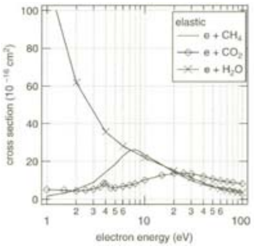


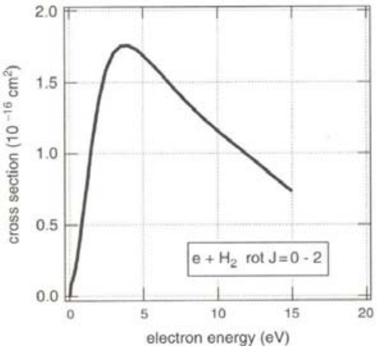
3. Rotational Transition

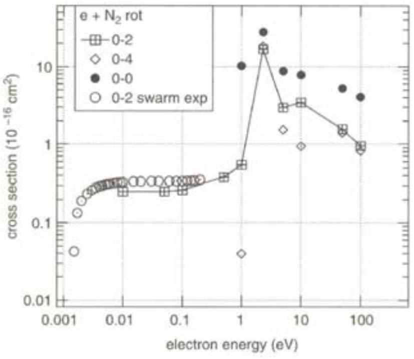
If the **charge distribution** in a molecule is **anisotropic**, the incoming electron exerts a **torque** on any molecule to rotate.

When the molecule has a permanent **electric dipole moment**, the electron-dipole interaction is the primary cause of the rotational transition. (long-range interaction ~ r^{-2})

특히 polar molecule의 경우 e-dipole interaction에 의해, 0.01 eV 근처의 아주 낮은 에너지에서 아주 큰 rotation cross section (10^{-13} cm^2). 따라서, polar molecule의 경우, 약 1 eV 이하의 낮은 에너지에서는 rotational excitation이 dominant !







J’=2: Swarm exp
J’=0,2,4: theory

Peak at 2.3 eV: shape resonance

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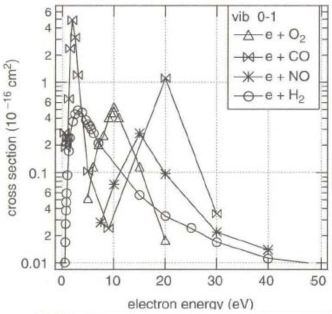
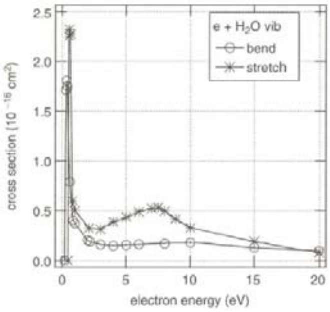
4. Vibrational Transition





Vibrational excitation cross-sections for *v* =0→1:

All the cross-sections peaks are ascribed to the **shape resonance**.

Vibrational excitation cross-sections for the lowest transition in H_20 :

- Bend: bending mode(v_2),

-Stretch: combined cross-sections for the symmetric and antisymmetric stretching modes.

Sharp peaks near thresholds: immediately above the threshold, the electron interacts strongly with the molecular dipole. This strong interaction may make the threshold peak.

Dipole Interaction (permanent dipole): long range $\left(\sim \frac{1}{r^2}\right)$

(1) Incident electron의 에너지가 낮으면 전자가 target 가까이 오지 못하고 멀리서 머무는 시간이 많다. 따라서, 멀리 작용하는 dipole interaction이 dominant.

→ 그러므로, dipole interaction에 의해 생기는 IR-active mode도 낮은 에너지 (near threshold)에서 더 잘 일어난다.

IR-active mode of vibration can be easily excited by electron collisions through the dipole term of the electrostatic interaction. Because of its long range, the dipole interaction is most effective in collisions at low energies.

[dipole-allowed transition]

(2) 또, long-range interaction의 특징은 전자가 약간만 scatter 된다는 것이다. (작은 scattering angle)

An IR-active mode is the vibrational mode which can be excited through an absorption of IR radiation.

IR spectrum - permanent dipole 없으면 불가

Electron-impact vibrational excitation:

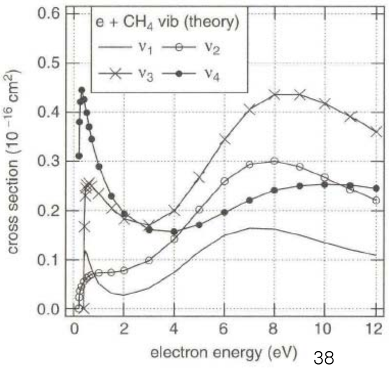
대칭적 excitation이면 IR-inactive (ex. symmtric stretching in CO2)

Otherwise, IR-active

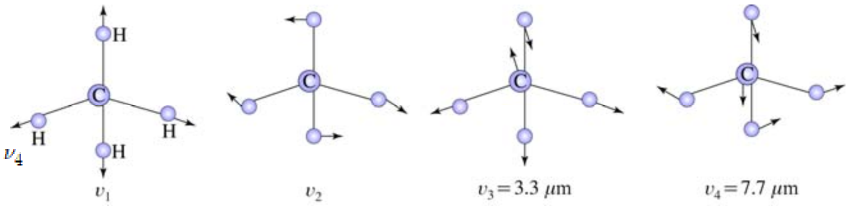
→ Electron interaction과 photon interaction은 다른 selection rule에 따름.

CH_4 : $v3$, and $v4$ are IR-active.
Near the respective **thresholds**, the IR-active modes have a large cross-section compared with other modes.
[뒷 페이지 CH_4 진동모드 그림 참조]

As the **collision energy increases**, other effects (especially the shape resonance) mask the dominance of the IR-active modes.



CH_4의 진동 모드



symmetric stretching

twisting

antisymmetric stretching

scissoring

Role of vibrational excitation in the electron transport in a molecular plasma :

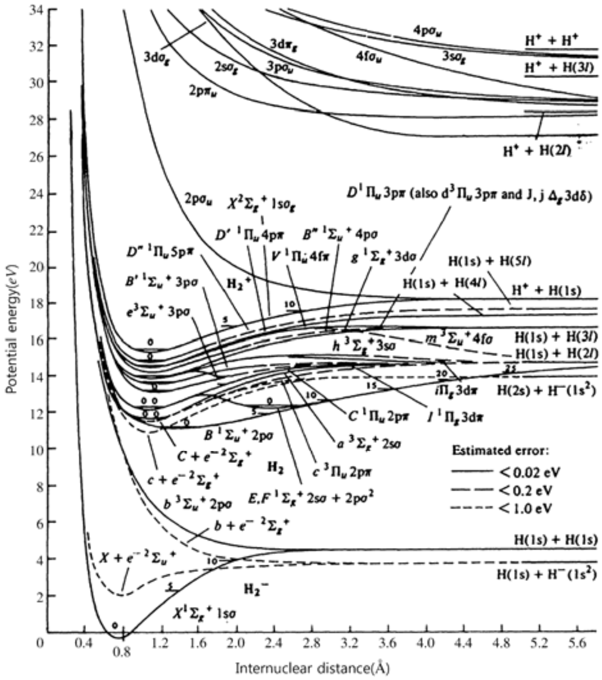
Vibrational cross-section has a sizable magnitude in the energy region below about 10 eV.

In this sense the **vibrational excitation is the most important energy loss process of electrons in a low-temperature molecular plasma**.

[Or it is the most significant process of **deposition of the electron energy** to the plasma.]

Once vibrationally excited, the molecule **decays to the lower state** through emission of radiation.

If the vibrational mode is **not IR-active**, the excited molecule remains for a long time. Through collisions with other particles in a plasma, they release their internal energy and start other (secondary) collision processes.



H_2^-, H_2, H_2^+

퍼텐셜에너지 곡선

[Steinfeld(1985)]

5. Electronic Excitation

H_2O

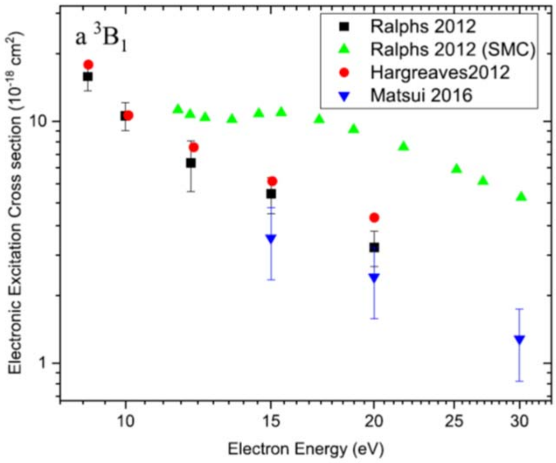


FIG. 15. Cross sections for the electron impact electronic excitation of the $\tilde{a}\ ^3B_1$ state obtained by Hargeaves *et al.*,[99] Ralphs *et al.*,[100] and Matsui *et al.*[69]

5. Electronic Excitation

Fate of the electronically excited molecules:

- decay either through emission of radiation or
- decay through dissociation.
- If neither of the two processes has a considerable probability, they change their states **via collisions** with other plasma particles or by hitting to the **wall** of the apparatus.

For the **radiative decay** to occur, the excited state has to be connected with lower states through **dipole-allowed** transitions. The lifetime against such a radiative decay is of the order of 10^{-10} to 10^{-8} s.

[플라즈마 진단]

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6. Ionization

For a diatomic molecule:

1. Production of **parent** molecular ion

$$e + AB \rightarrow AB^+ + 2e.$$

2. Dissociative ionization

$$e + AB \rightarrow A^+ + B + 2e,$$
$$A^+ + B^+ + 3e.$$

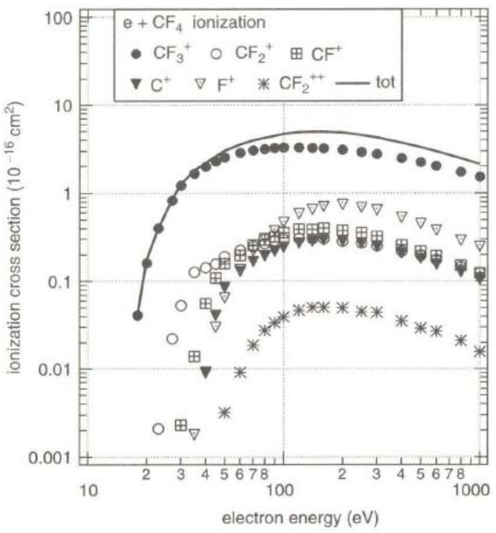
For polyatomic molecules: various kinds of ions are produced. In some polyatomic molecules (e.g. CF_4), no parent molecular ions are produced. Whenever any electron is picked out from such a molecule, it dissociates.

[주의] Spectrometrical detection cannot distinguish the ions with the same (or close) charge-to-mass ratio. For example, the signal of N^+ includes that of N_2^{2+}.

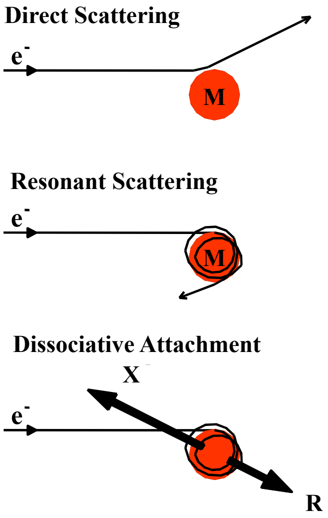
[주의] 다음 두 채널에서 오는 A^+ 가 가능. Coincidence를 사용해 구분.

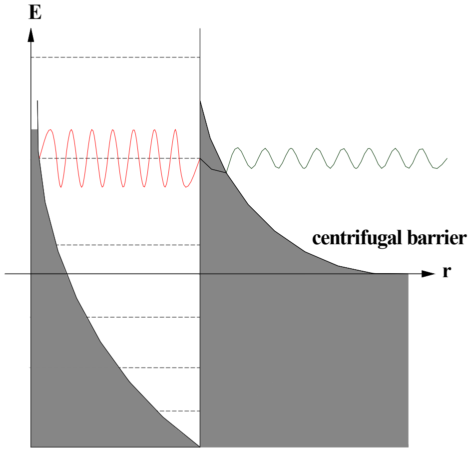
$$e + AB \rightarrow A^+ + B + 2e,$$
$$A^+ + B^+ + 3e.$$

Ionization cross-sections for CF_4. Cross-section for CF^+ may have a contribution of CF_3^{2+}. No other multiply charged ions than CF_2^{2+} and CF_3^{2+} are detected



8. Dissociative Electron Attachment. Resonance.



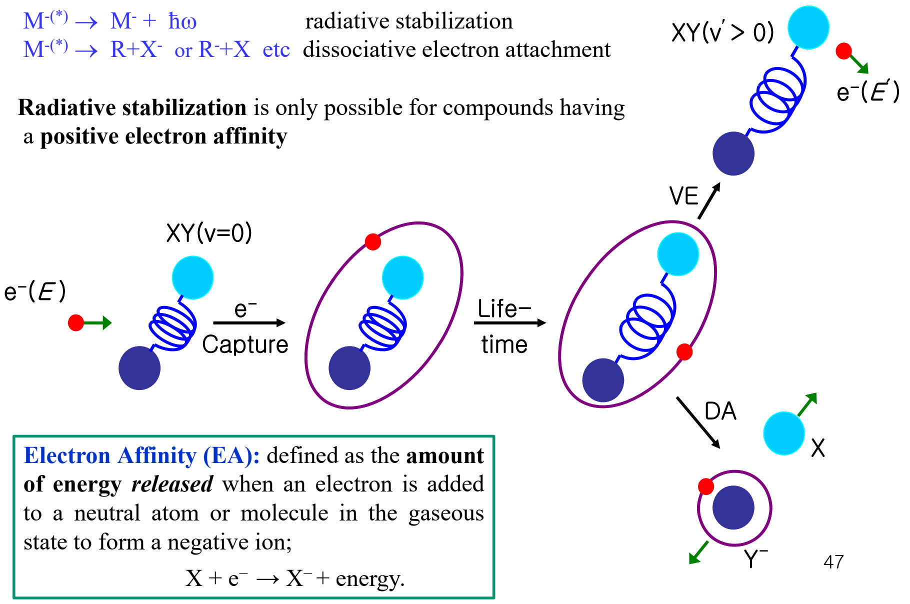


Fate of a polyatomic temporary anion formed by resonant electron capture

The molecular anion can react via the following channels

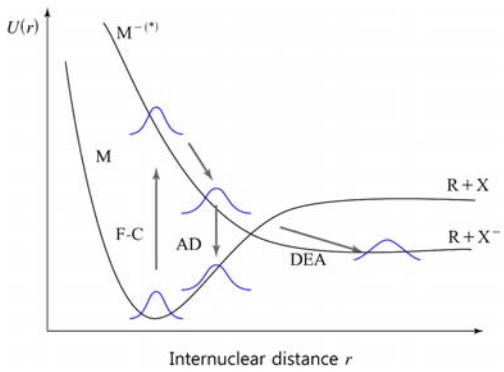
$M^{-(*)} \rightarrow M^{(*)} + e^-$	autodetachment
$M^{-(*)} \rightarrow M^- + \hbar\omega$	radiative stabilization
$M^{-(*)} \rightarrow R + X^-$ or $R^- + X$ etc	dissociative electron attachment

Radiative stabilization is only possible for compounds having a **positive electron affinity**



Electron Affinity (EA): defined as the **amount of energy *released*** when an electron is added to a neutral atom or molecule in the gaseous state to form a negative ion;

$$X + e^- \rightarrow X^- + \text{energy}.$$



M	molecule
F-C	Franck-Condon
AD	autodetachment
DEA	dissociative electron attachment

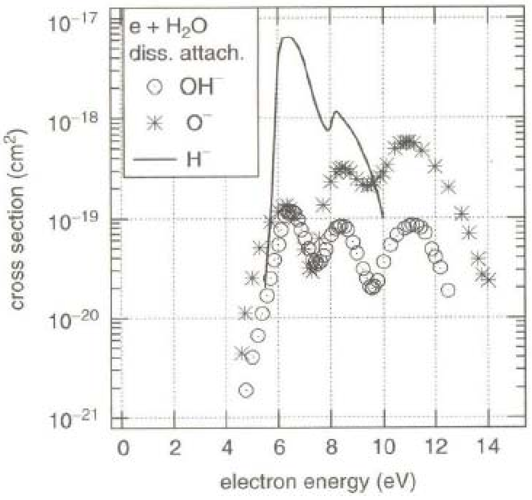
Dissociative Electron Attachment

$$e^- + XY \rightarrow (XY^-)^* \rightarrow X + Y^-$$

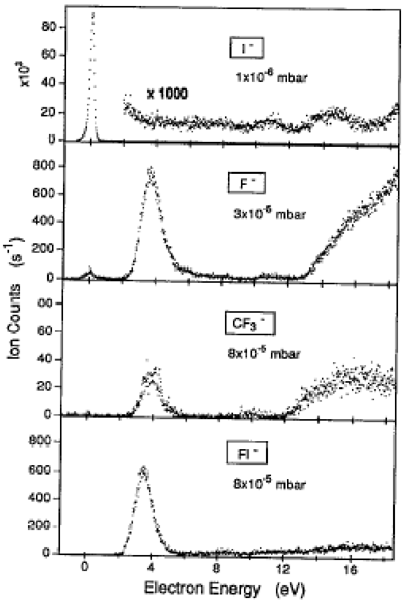
- In chemical etching, electron collisions with halogen-containing molecules often lead to **negative ion production** through dissociative electron attachment :

$$e^- + CF_4 \rightarrow (CF_4^-)^* \rightarrow CF_3^- + F$$

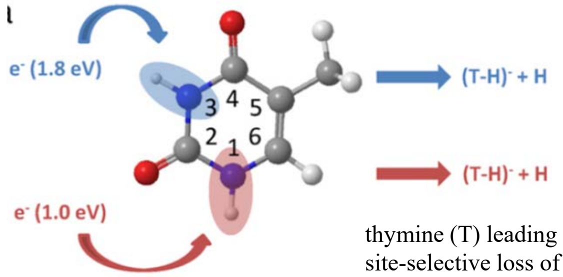
$$\text{or} \quad CF_3 + F^-$$



Ex : DEA of CF$_3$I

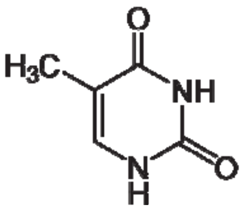


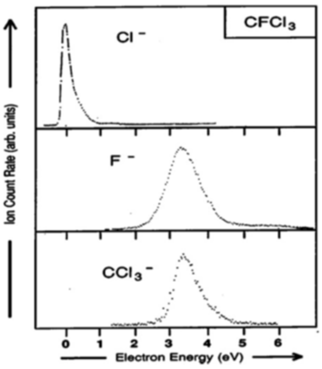
- Illenberger (1993)



이전엔 이런
실험이 레이저로만
가능하다고 생각!!!

thymine (T) leading to bond- and site-selective loss of H





Selective bond cleavage induced
by dissociative electron attachment to CFCl$_3$

Poor man's Porsche

---

e-gun: poor man's laser?

레이저에 비해 e-gun이 가지는

장점: - 싸다
- 장치 크기가 작다
- 에너지 변조가 용이하고, 변조 폭이 넓다

단점: - 에너지 폭이 넓다

그러나, 전자와 광자가 각기 다른 방식으로 분자와 상호작용하고 용도가 다르기 때문에, 하나가 다른 하나의 대체품이 되기는 어렵다.

Dissociative electron attachment has a special practical importance

The threshold energy of DA is given by

$$\Delta E(AB \rightarrow A + B^-) = D(AB \rightarrow A + B) - E_{aff}(B \rightarrow B^-)$$

Here D and E_{aff} are the dissociation energy and the electron affinity, respectively.

If electron affinity of B is sufficiently large, **DA can occur even at zero-energy** of electrons.

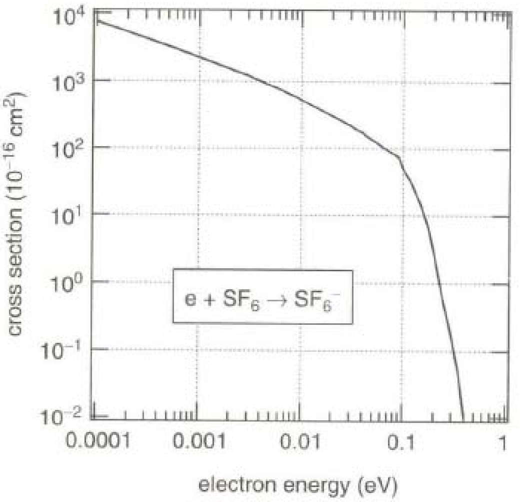
In the case of $CC1_4$,

the DA cross-section for $CC1_4 \rightarrow CCl_3 + Cl^-$ increases with decreasing energy and reaches 4.6×10^{-13} cm^2 at 0.001 eV.

Electron Attachment

1. Radiative attachment: $e + AB \rightarrow AB^- + h\nu$ (very small cross section)
2. Three-body attachment: $e + AB + M \rightarrow AB^- + M$
3. Dissociative attachment (DA): $e + AB \rightarrow A + B^-$

- Negative ions play particular roles in molecular plasmas [ex. Earth's ionosphere]
- The **presence of negative ions** alters the discharge operation. The dominance of negative ions much **distorts the electron energy distribution**. Thus, it is a fundamental issue to know what kind of, and how many, negative ions are present in the molecular plasma considered.
- Electron-attaching gas (e.g.,SF_6) is commonly used as an **insulator** in high-voltage technology.



참고:

Three-Body Attachment

When a molecule AB itself has a **positive electron affinity**, a negative ion of the parent molecule, AB^-, can be formed.

In principle, a two-body collision, e + AB, cannot produce AB^-, because the **conservation of energy and momentum** is violated. But if a **third body** is participated in the collision and takes away the excess energy from the colliding two-body system, the product AB^- is stabilized to appear.

Metastable Negative Ion

In some cases of **large polyatomic molecules**, an incoming electron can be captured **with no third body** present.

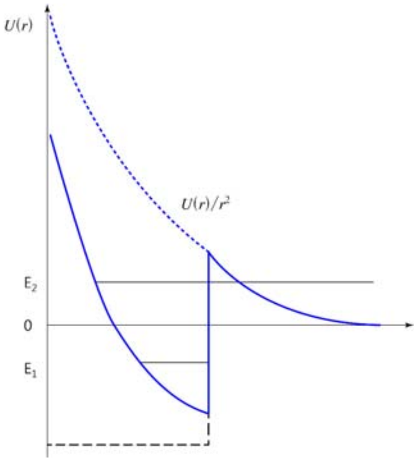
Such molecules have a large number of normal modes of vibration. The energy gained by the attachment of electron is spent on the **excitation of those vibrational motions** - the energy is distributed widely over the vibrational modes.

The resulting negative ion of the parent molecule is **not stable**, but has a rather **long lifetime.**

Resonance in electron collisions with atoms and molecules

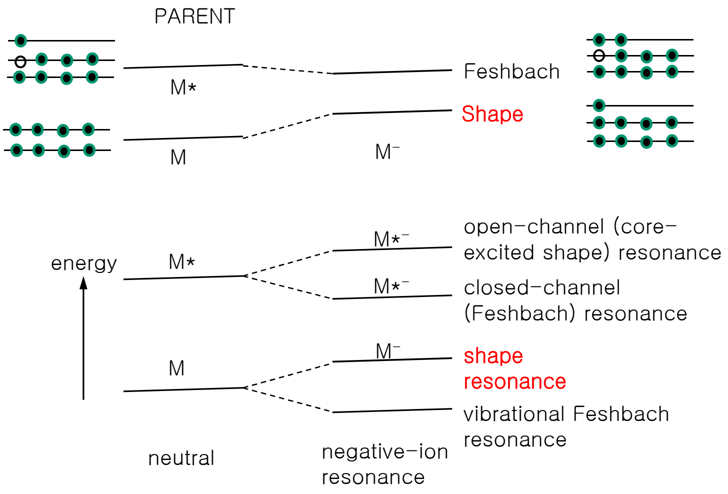
shape resonance

모양 공명(shape resonance)은 퍼텐셜의 “모양(shape)”에 의해 입사전자가 가두어져서 생기는 공명이다. 즉, 입사전자가 전자–분자의 퍼텐셜 장벽에 잡히는 것이다



shape resonance

- broad (shape resonance lies energetically above its parent electronic states → often dacays into the parent states very efficiently → short lifetime)



PARENT

M*

M

Feshbach

Shape

M^-

energy

M*

$M*^-$

open−channel (core−excited shape) resonance

$M*^-$

closed−channel (Feshbach) resonance

M

M^-

shape resonance

vibrational Feshbach resonance

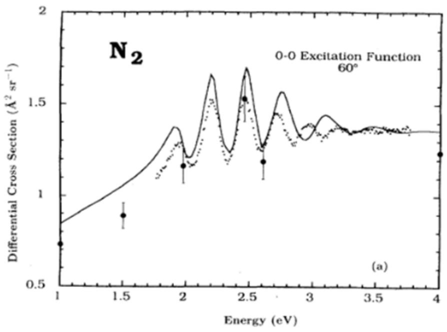
neutral

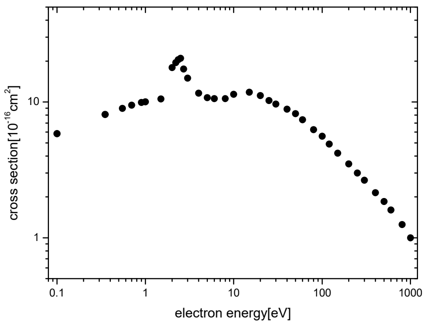
negative−ion resonance

---

shape resonance

- shape resonance can appear in elastic, MTCS and TCS and also in the cross-sections for the excitation of rotational and vibrational states.

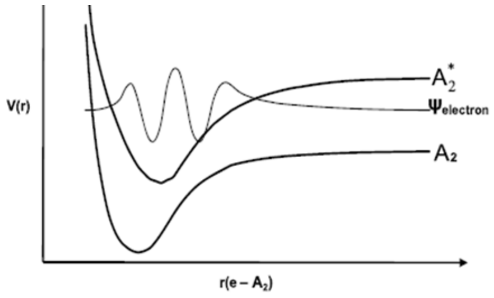




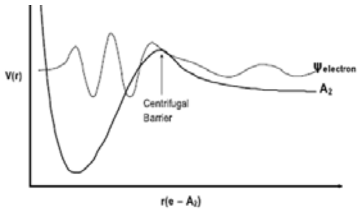
Elastic

Feshbach resonance

- by **exciting the target** molecule, electron loses its energy, **become negative** and coincide with one of the bound-state energy



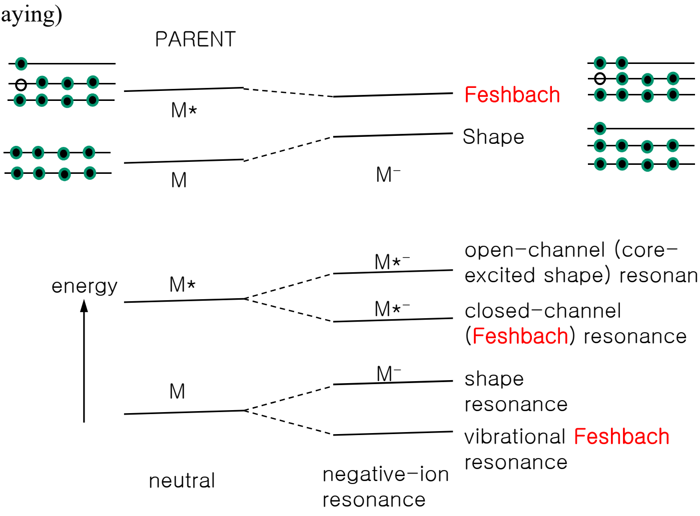
Core-excited Feshbach
[electron **trapped in the bound state of the excited state** which is embedded into the dissociation or ionization continuum of the initial state.]



shape
[electron trapped in the centrifugal barrier]

Feshbach resonance

- by exciting the target molecule, electron loses its energy, become negative (i.e. lying below excited state) and coincide with one of the bound-state energy
- sharp, vibrational structure (long-lived, therefore can make many vibration before decaying)



PARENT

M*

M

Feshbach

Shape

M⁻

energy

M*

M*⁻

open−channel (core−excited shape) resonance

M*⁻

closed−channel (Feshbach) resonance

M

M⁻

shape resonance

vibrational Feshbach resonance

neutral

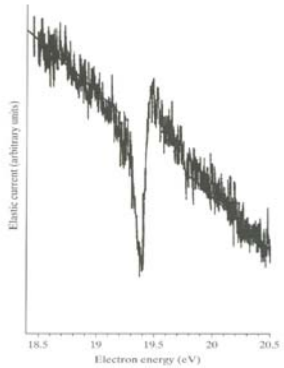
negative−ion resonance

Feshbach resonance

$e^- + He(1^1S) \rightarrow He^-$ (metastable)

$\rightarrow e^- + He(1^1S)$ [simplest, *elastic* channel]

A resonance corresponding to a ^2S state of He^- appear at 19.4 eV, which is just below the energy of the first excited-state (2^3S) of helium at 19.8 eV.



Yield of electron elastically scattered through 72° by helium

---

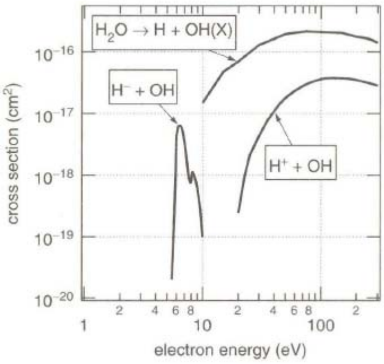
8. Neutral Dissociation

- Production of neutral species in the ground or metastable state.
- Important, because most of the dissociation products are **active species** (e.g., radicals) and have a **considerable kinetic energy**.

[Ex] $e + H_2 0 \rightarrow H^+ + OH + 2e$ dissociative ionization (higher threshold)

$H^- + OH$ disso. attach. (small CS, limited energy)

$H + OH + e$ **neutral dissociation**



Radicals in Atmosphere

smog formation
depletion of the ozone layer

Radicals in Biology

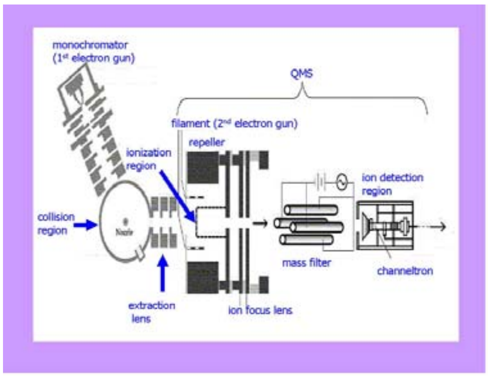
necessary
- intracellular killing of bacteria by neutrophil granulocytes
- certain cell signalling processes

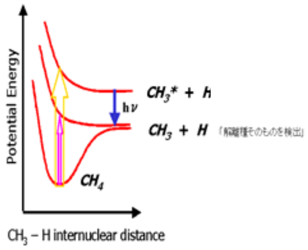
unwanted
- cell damage
- symptoms of aging
- alcohol-induced liver damage
- Radicals in cigarette smoke ……

Radicals in Plasma

Slide prepared by Prof. H. Tanaka (Sophia University, Japan)

Neutral Radical Detection- *ionization threshold spectroscopy*





$$e + CH_4 \rightarrow CH_3 + H + e$$

$$\downarrow$$

$$e + CH_3 \rightarrow CH_3^+ + 2e$$

Table 1. Ionization thresholds

Parent neutral	CH_4^+	CH_3^+	CH_2^+	CH^+	C^+
CH_4	12.6	14.3	15.1	22.2	25
CH_3		9.8	15.1	17.7	25
CH_2			10.3	17.4	20.2
CH				13.0	20.3
C					16.8

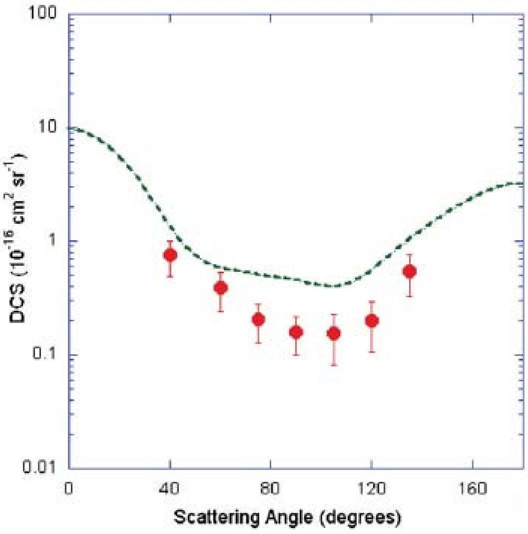


Figure 5. Absolute cross section (10^{-16} cm^2 sr^{-1}) for elastic electron scattering from the CF_2 radical for an incident electron energy of 25 eV. The present data (●) are compared to the results from an SEP calculation (- - -) [6].

When an electron collides with a molecule in its electronically and vibrationally ground state, AB(X, $v^{(x)}=0$), **different schemes of dissociation** are possible:

(1) Transition to the vibrational continuum of the electronically ground state

$AB \rightarrow AB(X, v^{(X)}=\text{continuum})$ [다음 쪽 그림]

(2) Transition to the vibrational continuum of an electronically excited state

$AB \rightarrow AB^*(n, v^{(n)}=\text{continuum})$

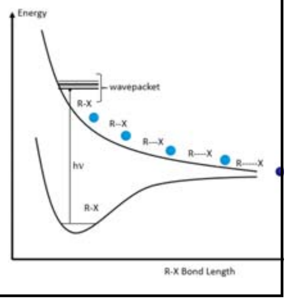
(3) Transition to a repulsive electronically excited state

$AB \rightarrow AB^*(\text{repulsive})$

(4) Predissociation through the coupling of bound and repulsive excited states

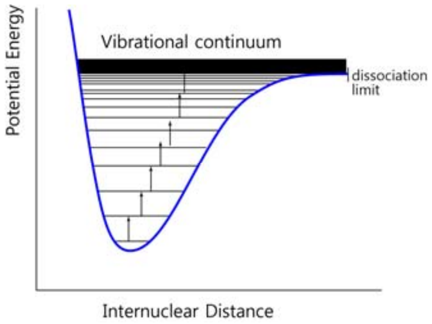
$AB \rightarrow AB^*(p, v^{(p)})$

$\rightarrow AB^*(\text{repulsive})$ [다음 쪽 그림]



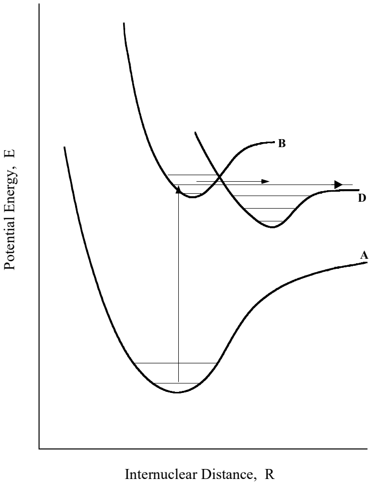
Transition to the vibrational continuum of the electronically ground state

AB → AB(X, $v^{(X)}$=continuum)

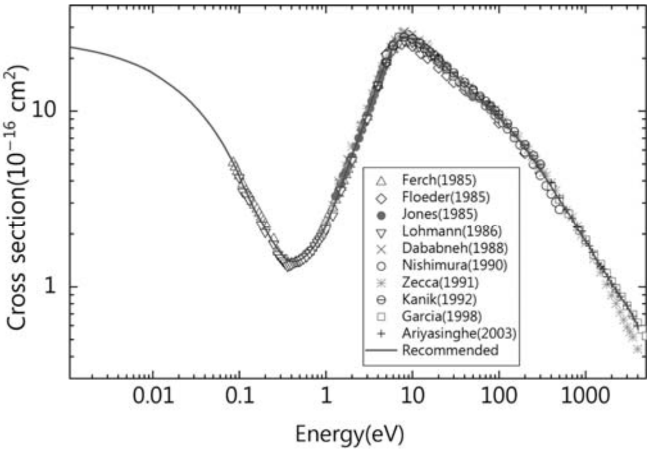


Predissociation through the coupling of bound and repulsive excited states

$$AB \rightarrow AB^*(p,\ v^{(p)})$$
$$\rightarrow AB^*(\text{repulsive})$$



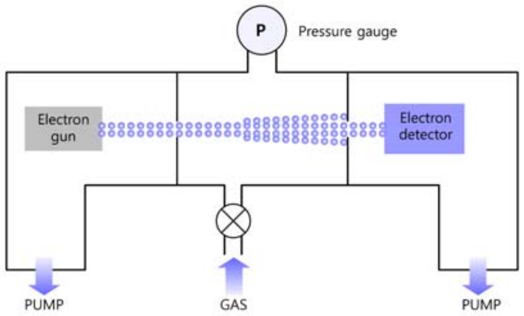
9. Total Cross Section



CH_4 Total Cross Section (TCS)

TCS

- High precision
- Provides upper bound of the cross sections
- Time-of-Flight techniques used for determination of electron kinetic energies

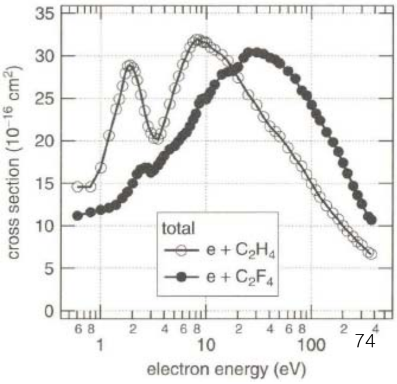


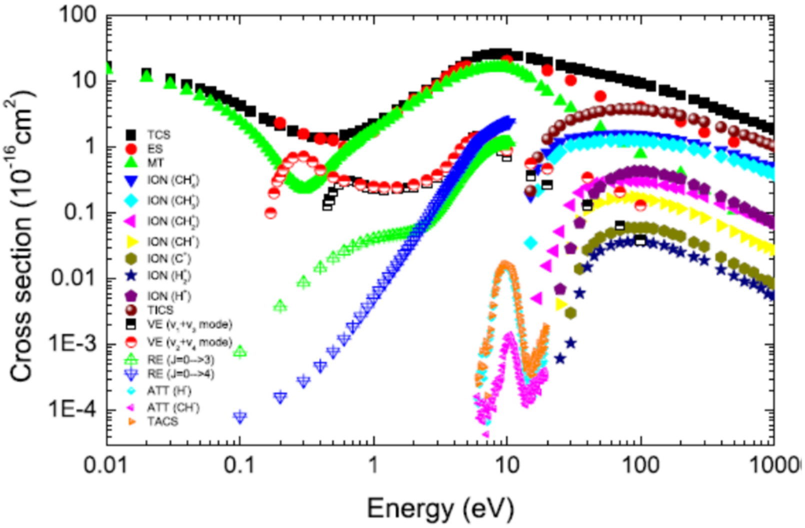
$$\sigma_t = \frac{1}{\rho l}\ln\left(\frac{I_v}{I_g}\right)$$

σ_t total cross section
ρ 기체충돌셀 내의 gas density
l 기체충돌셀의 길이
I_v, I_g 기체셀에 gas가 없을 때와 있을 때 detector에서의 전자전류

C_2F_4 & C_2H_4

- In the energy range above **100 eV**, Q_{tot} for any molecule has a similar trend. It decreases with increasing energy.
- In the lower energy range (i.e.,< **100 eV**),
  - Q_{tot} reflects the characteristics of each molecule. The cross-section of C_2H_4 has a sharp peak at around 2eV. This may be due to a resonance.
  - C_2F_4 has a larger number of electrons than C_2H_4. This may be reflected in the cross-section at the higher collision energies.





CH_4 Cross Sections

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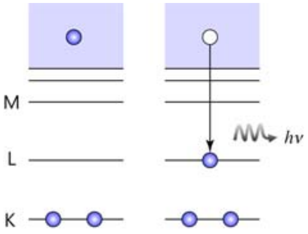
10. Recombination

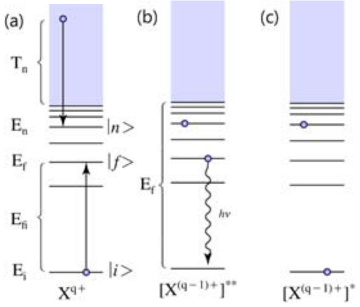
radiative recombination



dielectronic recombination

$e + X^{q+} \rightarrow [X^{(q-1)+}]^{**}$

$\rightarrow [X^{(q-1)+}]^{**} + h\nu$

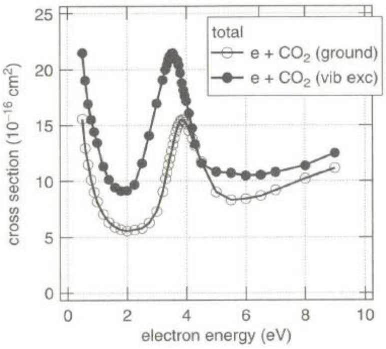


dissociative recombination: 전자가 분자 이온에 결합하면서 분자가 dissociation

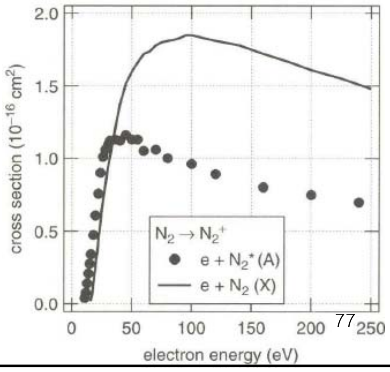
11. Collisions with excited molecules

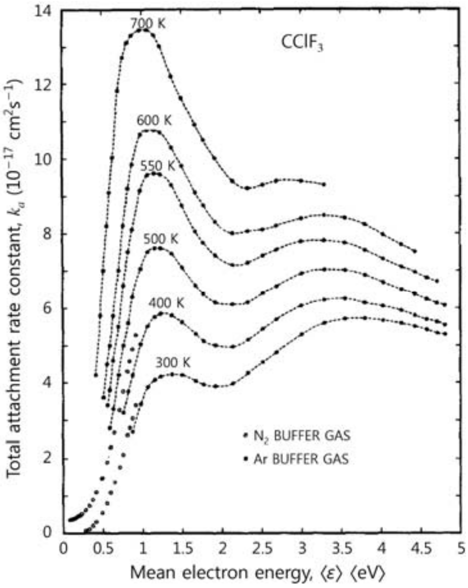
원자를 예로 들면, 일반적으로 바닥상태에서 dipole moment가 0이지만 들뜬 상태에서는 큰 dipole polarizability을 가지며 long-range dipole interaction이 주된 상호작용 메커니즘이 되어 큰 상호작용 단면적을 갖게 된다.

Total cross-sections for CO_2 in its **vibrationally** excited and ground states



Ionization cross-section for **electronically** excited $N_2^*(A)$, compared with that for the ground-state molecule





Legend 그림 구분:
N_2는 blank,
Ar은 solid circle.

CClF$_3$ 분자의 attachment rate const.를 mean electron energy 함수로 나타냄. 분자의 온도는 300, 400, 500, 550, 600, 700K [Spyrou(1985)]

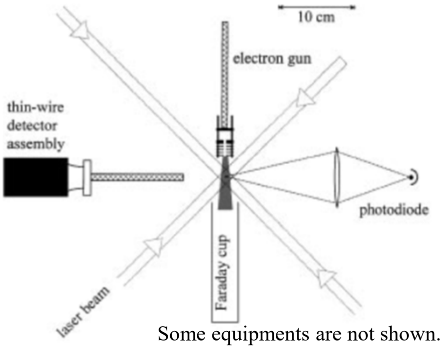
Electron collision with cold atoms

Absolute Electron-Impact Ionization Cross Section Measurements Using a Magneto-Optical Trap

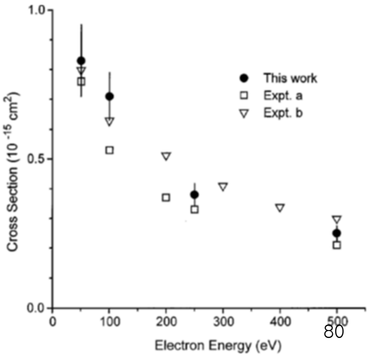
PRL 76, 4328 (1996)

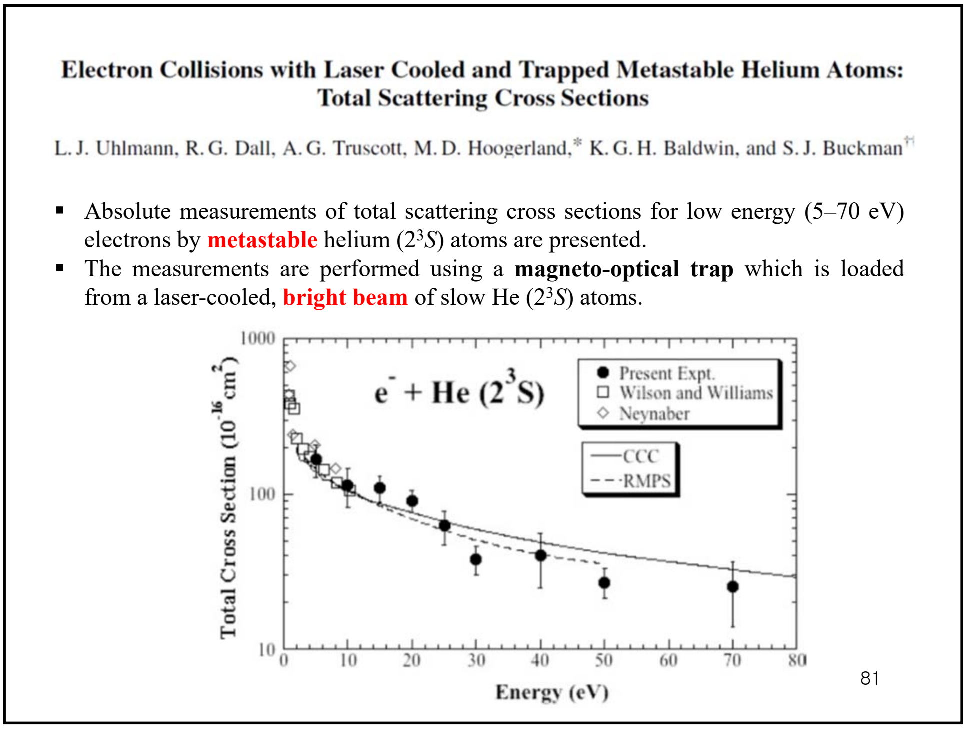
R. S. Schappe,* T. Walker, L. W. Anderson, and Chun C. Lin

- present a new method for measuring absolute total electron-impact ionization cross sections of rubidium-85
- technique measures fractional **loss rates** from a magneto-optical trap due to electron-impact ionization.
- the method requires only **relative measurements of the number of target atoms** and therefore eliminates a major source of difficulty in previous experiments



Some equipments are not shown.





Electron Collisions with Laser Cooled and Trapped Metastable Helium Atoms: Total Scattering Cross Sections

L. J. Uhlmann, R. G. Dall, A. G. Truscott, M. D. Hoogerland,* K. G. H. Baldwin, and S. J. Buckman†‖

- Absolute measurements of total scattering cross sections for low energy (5–70 eV) electrons by **metastable** helium (2^3S) atoms are presented.
- The measurements are performed using a **magneto-optical trap** which is loaded from a laser-cooled, **bright beam** of slow He (2^3S) atoms.

81