

# Chapter 2

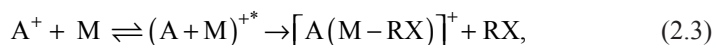
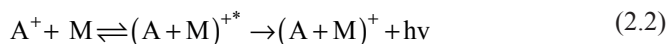
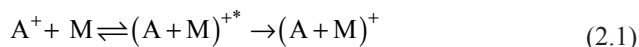
## Fundamentals of Ion Chemistry

Toshihiro Fujii

### 2.1 Termolecular Association Reactions

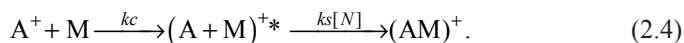
#### 2.1.1 Association Reaction Mechanism

It was experimentally found that the overall process of ion–molecule association reactions can more descriptively be schemed [1] as follows: collisional stabilization reaction (Eq. 2.1), radiative stabilization reaction (Eq. 2.2), and elimination reaction (Eq. 2.3) from ion–molecule complexes.



where  $(A + M)^{+*}$  is an intermediate complex of cation  $A^+$  and molecule  $M$ , which has enough internal energy to become stabilized with respect to dissociation,  $h\nu$  is the radiation, and  $RX$  is the component species of  $M$ .

Ion–molecule association reactions by collisional stabilization are of interest in all the fields of chemistry. The process is typically written as



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T. Fujii (✉)

C & V Technix Co., Ltd., 3-6-1 Higashi, Akishima, Tokyo 196-0033, Japan  
e-mail: fujii.toshihiro@c-vtechnix.com

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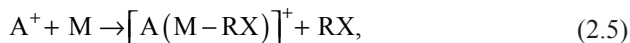
The collision rate constants,  $k_c$  and  $k_s$ , are given by Langevin theory [2, 3] nicely. It is detailed later in this section. It has already been pointed out (see Sect. 1.1) that this type of reaction is totally analogous to neutral radical combination reactions.

The ion–molecule reactions show a characteristic behavior; they present a very small or even no activation barrier. This behavior can be understood by considering a Lindemann type formalism [4, 5]. According to this model, an intermediate activated molecular complex is formed through a bimolecular collision. A subsequent collision of the intermediate activated complex  $(A+M)^{+*}$  with another molecule (third body, N) is necessary in order to release the excited energies. Furthermore, it is well known that ion–molecule complexes stick together by ion/dipole and ion/induced dipole forces, and these classical electrostatic forces between the components of an ion/molecule complex and the stability of this complex increase with the dipole moment and the polarizability of the neutral component, which varies with its size and the presence of functional groups.

**Radiative Association Reactions** The study of radiative association reactions, (Eq. 2.2), has been of considerable interest [6–8] in chemical kinetics, planetary and interstellar chemistry, flames, and a variety of other areas. The kinetic study makes it possible to model the formation of complex molecular species in the interstellar science. At the very low molecular number densities in interstellar environments, the probability of formation of the products of association reactions by collisional stabilization is very low. Therefore, the radiative association process becomes an extremely important one for the production of the complex molecular species observed by astronomical physicist. The methodology is either flowing afterglow (FA) or Fourier transform ion cyclotron resonance (FT-ICR) mass spectrometry. For the study of the apparent bimolecular rate constant for formation of association products as a function of pressure of a third body (N), the pressure should be set up to be sufficiently high in order to release the energy in the associated complex. Under the high pressure conditions collisional stabilization has competed with and usually dominated over radiative association. As a result, the radiative association rate was then extrapolated from the intercept of a plot of apparent rate constant versus pressure of a third body, N.

Woodin and Beauchamp have pioneered the study for rapid radiative association of  $\text{Li}^+$  with a variety of carbonyl compounds at low pressure in a trapped-ion ion cyclotron resonance experiment [6]. More recently, Dearden et al. [9] have presented convincing evidence for very rapid radiative association of laser-desorbed various alkali ions with thermally vaporized valinomycin. These reactions are observed so readily, since they are exothermic processes with no third body present to release the excess energy. Collisions with neutral samples at the pressures of FT-ICR trapping cell are too infrequent to account for collisional stabilization of the complexes, so these reactions are most likely stabilized by emitting the excess energy as infrared (IR) photons.

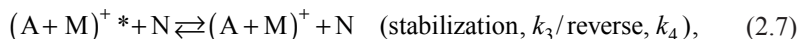
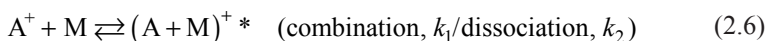
**Elimination Reactions** Possible elimination reactions of the type (Eq. 2.5) have been investigated, using ion cyclotron resonance (ICR) [10, 11].



where RX is either alkali halide or organic halide. The occurrence of such a process implies that the reaction is exothermic and hence  $BDE(R-X) > BDE[A-(M-RX)]$  if the reactants are at thermal energies. To investigate such elimination reactions, Bueachamp et al. [10] have performed trap ion experiments using the thermionic source, which was mounted inside the source region of an ICR cell. For instance, association of an alkali ion and organic halide leads to the formation of an activated species which eliminate RX to give lithiated alkene, with the alkali ion remaining bound to alkene species. Interestingly, they also reported that intermediates dissociate to an alkali halide and carbonium ion. These observations indicate the possibility of determining the relative binding energies of alkali ions to various bases.

### 2.1.2 Termolecular Reaction Kinetics

The kinetics of termolecular ion association reaction is usually approximated by a two-step mechanism and is described as the general form:



where A denotes a positively charged ion, M and N are neutral species, and  $k_1, k_2, k_3$ , and  $k_4$  represent the reaction rate constants for the combination (or association), decomposition, stabilization, and reverse reaction, respectively [12, 13]. As indicated, most association reactions are reversible. It has been pointed out that an ion–molecule association reaction is a process very similar to the combination of two atoms or two free radicals. The association process is considered to proceed via an intermediate complex  $(A+M)^+*$ , which has a characteristic lifetime,  $\tau (=1/k_2)$ , against unimolecular decomposition back to the reactants  $A^+$  and M. An initial combination step proceeds by ion–permanent dipole or ion–induced dipole attraction between the reactants. The energy thus accumulated in the reaction complex could then be liberated by collision with a third body, N. It is expected that  $k_1$  contains no activation energy term and that it has thus no temperature dependence to a first approximation. It was experimentally found that ion–molecule reactions have negative temperature dependence, deviating from an Arrhenius plot. On the contrary, stabilization rate constants,  $k_3$ , should depend on the identity of N;  $k_3$  may have some slight temperature dependence, since the excess energy to be lost may be distributed according to Maxwell–Boltzmann statistics. The bonding between ion and neutral species is generally found to be weak relative to normal chemical bond strengths.

Employing the steady-state approximation for the activated intermediate complex  $(A+M)^{+*}$ , the expression for the overall second-order reaction rate constant,  $k(2)$ , is given by:

$$k(2)_{\text{overall}} = k_1 k_3 [N] / (k_2 + k_3 [N]). \quad (2.8)$$

If the time interval between the formation of the activated intermediate complex and the collision for stabilization is long compared to the lifetime ( $\tau$ ,  $1/k_2$ ) of the intermediate product,  $(A+M)^{+*}$ , the activated complex will decompose back to the initial reactants. Since the formation of the association products depends on the collision with the third-body gas molecules ( $N$ ), the entire process is a competition between intermolecular collisional energy transfer and intramolecular vibrational energy redistribution of the excess energy of the activated intermediate complex among its degrees of freedom.

Two cases should be considered as a function of the buffer gas concentration  $[N]$ . In the high-pressure region, the stabilization process occurs much faster than the dissociation of the activated intermediate complex. In this case,  $k_3[N] \gg k_2$  and the reaction rate becomes:

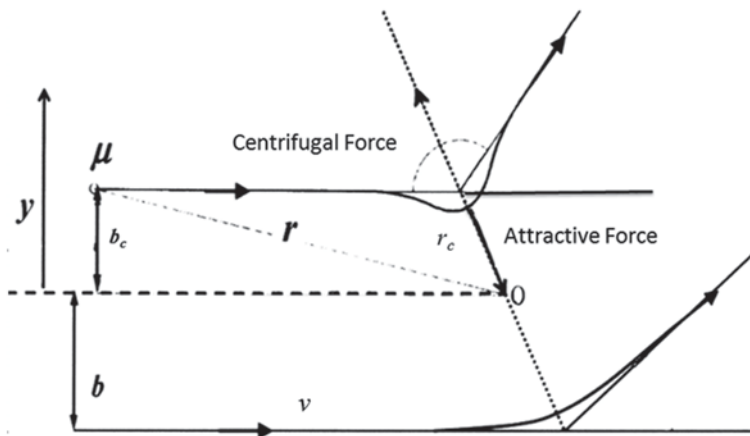
$$k(2)_{\text{overall}} = k_1. \quad (2.9)$$

From Eq. 2.9, it can be seen that in this regime, the overall second-order reaction rate is equal to ion–molecule association reaction rate,  $k_1$ , and does not depend on the buffer gas pressure. In the low-pressure region, the condition  $k_3[N] \ll k_2$  is fulfilled, and the rate determining step is represented by the collisional energy transfer to the buffer gas. The reaction rate in this case is given by:

$$k(2)_{\text{overall}} = k_1 k_3 [N] / k_2. \quad (2.10)$$

These considerations clearly explain the experimental finding that the order of the reaction rate constant changes from second order in the high-pressure regime to third order in the low-pressure limits. The expression for  $k(2)_{\text{overall}}$  can be determined when  $k_1$ ,  $k_2$ , and  $k_3$  are known.  $k_1$  and  $k_2$  can be calculated by using the Langevin collision theory. For the calculation of the dissociation rate constant,  $k_2$ , statistical models like Rice–Ramsperger–Kassel–Marcus (RRKM) theory [14, 15] are used. The Langevin and RRKM theories will be presented briefly in the next section and detailed in Chap. 3.

**Langevin Theory** The theoretical treatment of ion–molecule reactions is presented. This is a useful aid in understanding the collision dynamics of two species. The collision rate for an ion and a polarizable molecule having no permanent dipole moment is given by the Langevin theory [2, 3] as follows. For an ion and a molecule approaching each other with a relative velocity  $v$  and impact parameter  $b$  (Fig. 2.1), the Langevin theory describes the molecular interaction potential between an ion



**Fig. 2.1** Schematics of ion molecule collisional behavior for critical impact parameter  $b_c$ . The particles orbit the scattering center with  $r_c$ . For the impact parameter  $b$  greater than  $b_c$ , the particles are simply scattered at large values of the relative intermolecular distance  $r$

and a nonpolar molecule. According to this, the effective interaction potential is given at an ion/molecule separation  $r$  by the following expression:

$$V_{\text{eff}}(r) = U(r) + L^2 / 2\mu r^2 = -1/2(ae^2 / r^4) + L^2 / 2\mu r^2, \quad (2.11)$$

where  $\alpha$  represents the polarizability of the neutral molecule,  $e$  denotes the elementary charge,  $\mu$  is the reduced mass, and  $L$  represents the classical angular momentum. The angular momentum has the form  $L = \mu v b$ . Equation 2.11 contains an attractive ion/induced dipole term ( $\sim r^{-4}$ ) from standard electrostatic forces and is referred to as the central potential term. The second term describes the repulsive term ( $\sim r^{-2}$ ) between the two particles and is referred to as the centrifugal term.

When  $E_{\text{trans}}(r)$  is defined as the translational energy along the line of the center of the collision, the total relative energy of the system is given as follows,

$$E(r) = E_{\text{trans}} + V_{\text{eff}}(r). \quad (2.12)$$

The variation of  $V_{\text{eff}}(r)$  with  $r$ , depends on the value of the impact parameter  $b$ . In the special case ( $b = b_c$ ) where the centrifugal term equals to  $E(r)$ , namely,  $V_{\text{eff}}(r) = E(r)$ , the particles will orbit the scattering center with a constant ion/molecule separation  $r_c$ . For impact parameter values  $b \leq b_c$ , the capture collision probability is  $p = 1$  while for  $b > b_c$ , the capture reaction does not occur and  $p = 0$ .

Similar to the hard-sphere collision model, the capture collision cross section or the Langevin cross section is defined as:

$$\sigma(v) = \pi b_c^2. \quad (2.13)$$

From the conditions that a  $\delta V_{\text{eff}}(r)/\delta r=0$  and  $V_{\text{eff}}(r)=E(r)$ , at  $r=r_c$ , a capture collision cross section and collision rate constant are deduced by

$$\sigma_c(v) = \pi b_c^2 = (2\pi q/v)(\alpha/\mu)^{1/2} \quad (2.14)$$

$$k_c = v\sigma_c(v) = (2\pi q)(\alpha/\mu)^{1/2}. \quad (2.15)$$

As can be seen from Eq. 2.14, classical theory predicts the capture cross section should vary inversely as the relative velocity of the colliding pair and hence the Langevin rate constant, should be independent of the relative velocity and the temperature. Equation 2.15 predicts reasonably well the rate constants for ion–molecule reactions involving only ion-induced dipole interactions. This indicates that a reaction occurs on every collision for many ion/molecule pairs; there can be no activation energy for the reaction. The rate constant predicted is of the order of  $1 \times 10^{-9} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ .

### 2.1.3 Kinetic Data Base

The techniques for measuring rate constants and product distribution (branching ratios) for ion–molecule reactions are varied, but the majority of the data have been determined using the FA, drift-tube (DT), selected ion flow tube (SIFT), high-pressure mass spectrometric techniques, or ICR. These methods are detailed in Chap. 4. A number of surveys of all classes of ion–molecule reactions have appeared in the literature; Ferguson [16], Sieck et al. [17], Albritton [18], Anicich et al. [19], Ikezoe et al. [20], some of which include termolecular reactions or are limited to selected methods. Anicich listed [21] an index to the literature for gas phase bimolecular positive ion–molecule reactions as a comprehensive survey of ion–molecule reaction kinetics and product distribution of the reactions. Over 2300 references are cited. This index covers the literature from 1936 to 2003. It was limited to selected reactions, listed by reactant ion, that were important for chemical modeling ionic processes in planetary atmospheres, cometary comas, and interstellar clouds.

Compared to the enormous amount of study devoted to the subject of bimolecular ion–molecule reactions, the subject of termolecular ion reactions is comparatively small. Consequently, kinetic data on the ion association are relatively sparse. The measurement has been largely confined to systems of planetary or interstellar atmospheres with experiments like SIFT operated at high pressure. An extensive study of the Li ion attachment has been carried out by Ferguson et al. [22]. Some reaction rates at termolecular kinetics are very large and near the Langevin collision rate. The association of  $\text{Li}^+$  with the water, rare gases,  $\text{N}_2$ , and some organics has also been reported in drift tubes and ICR. Passarella et al. [23] reported rate coefficients for the association of  $\text{HCl}$ ,  $\text{CO}_2$ ,  $\text{NH}_3$ ,  $\text{ND}_3$ ,  $\text{SO}_2$ , and  $\text{CH}_3\text{OH}$  with  $\text{Na}^+$ . At ambient temperature three-body rates in helium are found to range from  $1.6 \times 10^{-30}$

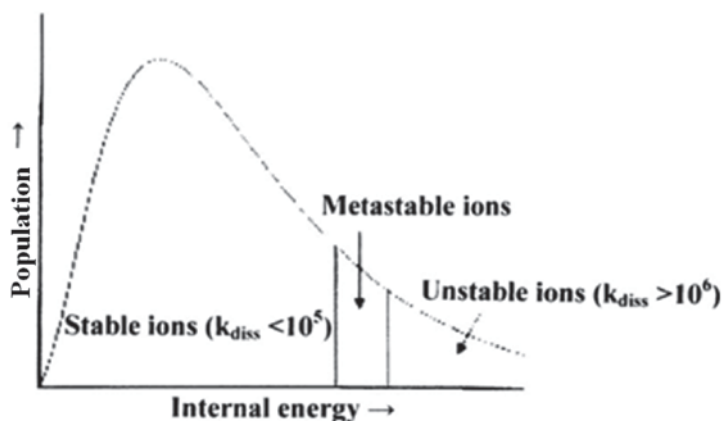
to  $6.3 \times 10^{-28}$  cm<sup>6</sup>/s, increasing in magnitude from ligand to ligand. Ikezoe et al. listed the termolecular reactions whose rate constants are in the range of  $7 \times 10^{-26}$  to  $2 \times 10^{-32}$  cm<sup>6</sup>/s. Termolecular reactions that have reaction rate constants faster than  $10^{-26}$  cm<sup>6</sup>/s appear to be competitive with bimolecular reactions. These are called then the pseudo-bimolecular or saturated termolecular reactions.

## 2.2 Dissociation Reaction

### 2.2.1 Unimolecular Dissociation

The basic theory of unimolecular dissociations of the ionized molecules under the condition of mass spectrometry are discussed in this section. Useful monograph of the development of the theory as applied to unimolecular reactions have been presented by Forst and by Baer and Hase [24, 25]. Historically, the unimolecular dissociative properties of gaseous precursor ions were studied by fragmentations occurring either in the ion source by electron ionization (EI) or by metastable ion decompositions during an ion's flight from the ion source to the detector. This is followed by tandem mass spectrometry (MS-MS), which involves the activation of a precursor ion formed in the ion source and the mass analysis of the precursor and product ions. The ion activation method determines what types of products result. Several ion activation techniques have been developed over the past 50 years. The advent of soft ionization techniques, such as fast atom bombardment (FAB), electrospray ionization (ESI), and matrix-assisted laser desorption/ionization (MALDI), extended the range of application of mass spectrometry to biological, thermally labile compounds. However, these ionization techniques primarily yield quasimolecular species with little or no fragmentation and limit the structural information available in a single-stage mass spectrum. Consequently, collision-induced dissociation (CID) was introduced in most MS-MS applications. While CID remains the most common dissociation technique, several new methods have become increasingly useful for specific applications, complementing conventional CID mass spectra. These include surface-induced dissociation (SID), electron-capture dissociation (ECD), electron-transfer dissociation (ETD), and infrared multiphoton dissociation (IRMPD). Blackbody infrared radiative dissociation (BIRD) can thermally activate ions in quadrupole ion trap and FT-ICR instruments. These activation techniques can be used to determine the bond energies (ion affinities) of metal ion/molecule complexes and to obtain the structural information in chemical and biological applications. Lastly, in-source decay (ISD) and post-source decay (PSD) in MALDI is presented with a focus on significance of the structural elucidation. A brief description of each of these methods is also presented in this section.

**Quasi-Equilibrium Theory (QET)** Ionization process in an EI source is very fast, taking  $< 10^{-16}$  s, which forms molecular ions in ground and excited states. Ionization occurs by a vertical transition, and therefore the interatomic distances remain



**Fig. 2.2** Hypothetical distribution of internal energies of ions formed in a typical beam-type instrument. Ions with dissociation rate constants  $<10^5 \text{ s}^{-1}$  remain intact on the timescale of the mass spectrometer ( $10^{-5} \text{ s}$ ). Those with rate constants  $>10^6 \text{ s}^{-1}$  are unstable ions and fragment in the ion source, while the intermediate situation ( $10^6 \text{ s}^{-1} > k_{\text{diss}} > 10^5 \text{ s}^{-1}$ ) represents metastable ions that fragment between the source and the detector. (Reprinted with permission from [26]. ©2004, John Wiley and Sons)

largely unchanged (Franck–Condon principle). Excited molecular ions redistribute their internal energy ( $E$ ) over the degrees of freedom in a statistical manner. It is postulated that all quantum states have equal statistical probability and all the degrees of freedom participate with the same probability in the energy distribution. After the accumulation of internal energy into appropriate modes, unimolecular dissociation (fragmentation) of the ion occurs. The whole system is described with a three-dimensional potential energy surface (PES) over the reaction coordinate, indicating the possible dissociation channels. Observed fragmentations in EI result from unimolecular dissociations. The QET or, equivalently, the RRKM theory can be used to explain unimolecular dissociations in the gas phase in high vacuum conditions.

The rate constant  $k(E)$  for unimolecular dissociation defines the resulting EI mass spectra [26]. Ions with dissociation rate constants  $k(E) < 10^5 \text{ s}^{-1}$  can reach the detector as molecular ions since the total time in mass spectrometers  $\sim 10^{-5} \text{ s}$ . Those with rate constants  $k(E) > 10^6 \text{ s}^{-1}$  are unstable ions and fragment in the ion source, while the intermediate situation ( $10^6 \text{ s}^{-1} > k(E) > 10^5 \text{ s}^{-1}$ ) represents metastable ions (see below) that fragment between the ion source and the detector. Figure 2.2 illustrates the relative portions of stable, metastable, and unstable ions in an internal energy distribution curve.

**Metastable Ion Decomposition** Molecular ions formed in the ion source to dissociate (fragment) spontaneously in a field-free region between the source and the detector are defined as metastable ions (see Fig. 2.2). These fragments are unimolecular dissociation products decomposed in the field-free regions of a mass spectrometer. Beynon et al., in the early 1970s, used a reverse geometry sector instrument, in which the magnetic analyzer (B) is placed in front of the electro-



static analyzer (E) [27]. Metastable ions (precursor ions) are chosen with a constant  $B$  values in the magnetic sector and then scanned by  $E$  for detecting metastable ion decompositions in sector instruments. This technique is called mass-analysed ion kinetic energy spectroscopy (MIKES). A MIKES experiment allows not only the study of fragmentation pathways, but also a direct measurement of this kinetic energy released during the fragmentation between the two sectors by measuring the width of the resulting peak.

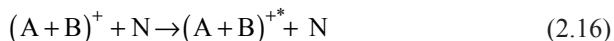
The MIKES scans can also be applied very nicely with a collision cell placed between the two sectors for CID. Consequently, several scan types are developed for recording the products of metastable or CID. The linked scan with holding the electric field ( $E$ ) and the magnetic field ( $B$ ) of an analyser constant ( $B/E$ -linked scan) and the  $B^2/E$  constant scan are very common among them. The  $B/E$ -linked scan is useful in both EB and BE geometry instruments and the resolution is enhanced as compared to the MIKES experiment. The  $B^2/E$ , constant scan, is useful for identifying a family of compounds present in a mixture. Another technique, the defocusing method, accelerating voltage scan, can be used to determine the precursor ions for a given fragment formed in the source of a single focusing instrument.

Even though a two-stage sector MS-MS experiment is rather obsolete and complex methods, it may be applied for specific applications [28]. There are a number of important data for fundamental studies of the intrinsic, gas-phase chemistry of specific types of products, such as complexes between alkali-metal ions and biological molecules [29, 30]. Furthermore, analytical applications of such metal ion association reactions have resulted in new approaches for structural elucidation of large biological molecules. These applications have basis in the early work of Rollgen et al., who first reported mass spectra of collision-induced decompositions (CID) of  $(M+Cat)^+$  ions formed by  $Li^+$ ,  $Na^+$ , and  $K^+$  ion attachment under field desorption (FD) conditions, in which  $M$  = monosaccharide molecule and  $Cat$  = alkali-metal ion [31]. It is shown that the elimination of the alkali ions is determined by the alkali ion affinities of the molecules ( $M$ ) and competes with a fragmentation of  $M$  which is almost independent of the alkali ion attached. Correspondingly, the alkali ion is predominantly retained in the fragment ions. The usefulness of this method is demonstrated by showing that CID of cationized complexes can be significantly different from CID of analogous protonated  $(M+H)^+$  ions. The CID and structure determination of complexes between alkali-metal ions and more complicated biological molecules such as peptides are very interesting. These are detailed in the Chap. 7.

The unimolecular dissociation of ions has been analyzed with the aid of statistical theory, which is based on the assumption that excited states rapidly convert their energy into vibrational energy of the ground electronic state [24, 25, 32]. The statistical theory for unimolecular reactions is known as RRKM, QET, transition state theory (TST), variational transition state theory (VTST), transition state switching model, or phase space theory (PST) [15], although the basic assumptions in these versions are identical. The significance of the theory is the calculation of the rate constant for unimolecular dissociation from the energy barrier for dissociation and a given reactant state (see details in Sect. 3.2).

### 2.2.2 Collisional Dissociation

**CID** The CID process is assumed to occur by a two-step mechanism; the activation (excitation) of the precursor ions,  $(A+B)^+$ , and their fragmentations.



The second step of this mechanism is a unimolecular dissociation of an excited ion. Therefore, the subsequent dissociation of activated ions is adequately explained by RRKM (or QET). Fragmentation of a precursor ion can occur if the collision energy is sufficiently high enough to be excited beyond its threshold for dissociation. Collisions between the precursor ion and a neutral target gas, N, are accompanied by an increase in internal energy, which induces dissociation with improved probability of fragmentation as compared with metastable ion decompositions (see the previous section). By varying the translational energy of the  $(A+B)^+$  ions in activation reaction (Eq. 2.16) and detecting the appearance of the  $A^+$  product ions, the threshold energy for CID can be determined and directly related to the bond dissociation energy, BDE, of  $(A+B)^+$  [26, 33]. Since the powerful CID methods can potentially address bond dissociation energies (bond strengths) and conformational information between a metal ion and biologically important materials, such as a peptide or small protein, these have been applied to many systems [34].

**SID** As analogy to CID, SID method represents an activation procedure, which uses a solid surface as a collision target instead of an inert gas molecule [35, 36]. Kinetic energy of the projectile ion is transferred into potential energy upon collision with a solid surface, with resulting activation of the precursor ions and subsequent dissociation.

**Threshold Collision-Induced Dissociation (TCID)** In the TCID method, a tandem mass spectrometer is used to isolate the parent ion by mass, accelerate or decelerate the ions to a controlled kinetic energy, collide them with an inert target gas under single collision conditions, and then mass analyze the fragment ions [37]. The reaction process is given above by Eqs. (2.16) and (2.17). Xenon is preferred as the target gas, N, because it is heavy and polarizable, promoting efficient energy transfer. In TCID, the apparent cross section for formation of the fragment ion  $A^+$  is measured as a function of the relative ion/target collision energy in the center-of-mass frame. The threshold energy for dissociation,  $E_0$ , is equal to the 0 K reaction endothermicity of the dissociation.

TCID experiments employ tandem mass spectrometers of various types. Guided ion beam (GIB) instruments use a radio frequency octopole in the interaction region for high-efficiency collection of scattered products and low-energy ions. These instruments typically use a magnetic sector or Wien filter for initial mass analysis and

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