

Gas-Phase Clusters: Spanning the States of Matter

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Gas-phase clusters, which are weakly bound aggregates comprised of either atoms or molecules, often display properties that lie between those of the gaseous and condensed states. Interesting questions arise concerning how large a cluster must be before it will display bulk properties. Currently there is extensive research activity directed toward studies of their formation and varying properties and reactivity as a function of the degree of aggregation. Results serve to elucidate at the molecular level the course of change of a system to be followed from the gas to the condensed state, thereby enabling a spanning of the states of matter.

STATES OF MATTER HAVE OFTEN BEEN DESCRIBED IN SIMPLE ways. For example, a gas expands to completely fill a container and a liquid takes on the shape of its container, whereas a solid requires considerable force to effect changes in its shape. However, such definitions are insufficient in a strict sense when we consider, for example, thixotropic fluids, which flow only upon considerable application of stress, or glasses, which are described as supercooled liquids instead of solids. These definitions become even more limited when we consider systems of small dimension, that is, clusters, which are aggregates of ions, atoms, or molecules that are weakly bound together and that have properties between those of the gaseous and the condensed states. The study of their properties in the gas phase has grown tremendously (1-5) and should help connect our understanding of the gaseous and condensed states of matter (6-8). Clusters provide a medium for investigating energy transfer and dissipation as well as the influence of solvation on reactions. Studies of clusters also bear on the nature of particle formation in interstellar media, in combustion processes, and in the atmosphere, and on applied areas such as catalysis and photography.

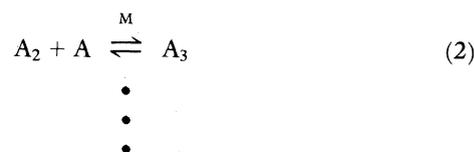
Some questions about clusters include, "What differentiates a cluster from a large molecule?" "What constitutes a condensed state?" and "How large does a cluster have to be before it displays properties of the bulk phase?" The latter two questions have no simple answer in that the answer varies with the properties measured and the material studied. The first question can be addressed more easily. Gas-phase clusters are generally created as a distribution in number of atomic or molecular units. That distribution can be readily shifted by some suitable change in the conditions used in their preparation [the theory of formation and the general design of suitable sources are discussed in (3) and (5)].

Even for a cluster containing several thousand individual components, an appreciable number of subunits is present on the surface of

the cluster at any time. The percentage of surface constituents falls from approximately 40 to 4% as a cluster grows from 10^3 to 10^6 atoms or molecules. Most work on gas-phase clusters is done on systems with fewer than a thousand constituents. On the small end, one might define a cluster as an aggregate comprised of as few as two constituents, although the properties of these dimers (commonly referred to as van der Waals molecules) usually bear little resemblance to ones of higher degrees of aggregation. In this article we do not discuss dimers except in cases where they bear specifically on the subject.

Nucleation

The nucleation of condensed phases from supersaturated gases proceeds through the formation of gas-phase clusters. The changing properties and behavior of gas-phase clusters as a function of their degree of aggregation find direct application in nucleation phenomena. A complete deterministic description of nucleation requires information about the kinetics of each individual forward and reverse step in the sequence of clustering reactions.



Clustering is expected to evolve with increasing size from three-body kinetics (in which a third particle M is required to remove the excess energy of the collision complex) to two-body kinetics (because of the increased degrees of freedom and hence increased lifetime of the collision complex for large clusters). At present, there are no general theories of association reactions that can be used quantitatively to predict the rates and describe the transition from three-body to two-body forward kinetics as cluster growth proceeds. Current interest centers in establishing the dependence of such reactions on temperature and collision energy (9).

Classical nucleation theory (10) circumvents the difficulties of making a complete kinetic description of the phenomena, by assuming that a quasi-steady-state population of clusters exists and that the rate of nucleation is determined by the rate of collision of gas molecules with clusters of a critical size. The vapor pressure of a drop (or cluster) increases as its size decreases (the Kelvin effect); a critical size exists for which clusters larger than this size tend to grow spontaneously and smaller ones tend to evaporate. Theoretical

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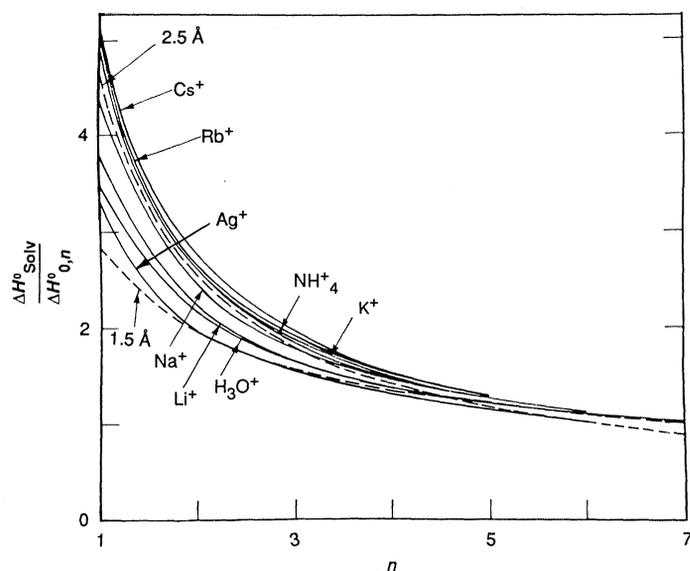


Fig. 1. Ratio of Randles' total enthalpy of solvation ($\Delta H_{\text{Solv}}^{\circ}$) to the partial gas-phase enthalpy of hydration ($\Delta H_{0,n}^{\circ}$) for positive ionic cluster size n . [Reprinted from (13), with permission from *The Journal of Colloid and Interface Science*]

formulations (11) need to be developed to quantify the free energy of formation of the cluster of critical size and thus determine the energy barrier to nucleation.

Experimental studies of the clustering of molecules onto ions in the gas phase have provided thermodynamic data for small clusters (5). A simple and often successful model used in nucleation theory is the liquid-drop model, in which the energetics of the critical nucleus are described in terms of macroscopic quantities such as surface tension and vapor pressure (10). Comparison of the experimental results with theoretical treatments of ion-induced nucleation has suggested that the major failing of the classical liquid-drop theory lies in the neglect of ordered structure in small cluster ions (12). The classical liquid drop model does remarkably well in evaluating the enthalpy changes and their trends for clustering onto ions, but the experimental entropy changes are considerably more negative than those calculated in the liquid-drop model.

Solvation

The clustering of solvent molecules onto a gaseous ion is related to the solvation of a gaseous ion into bulk solution (13). In the limit of a large number of solvent molecules, the clustering process differs in that it also involves solvent condensation. To compensate for the contribution from condensation and for the limitation on the number of solvent molecules, one can compare the difference in a thermodynamic quantity for two ions. As the number of solvent molecules increases, the difference should converge to the corresponding difference in the solution-phase data. More than half of the variation among ions in the solution-phase single-ion heats of hydration is accounted for by their variation in the enthalpy changes of the first four gas-phase hydration steps. By comparison of the differences between halide and alkali ions, Kebarle and co-workers (14) showed that the gas-phase data on the enthalpy change upon clustering were consistent with and supported one set of values for single-ion heats of hydration over another.

Another approach has been to consider the ratio of the single-ion heat of solvation to the total enthalpy change for clustering (13). For cations, this ratio as a function of cluster size behaves similarly to

that predicted by the simple liquid-drop model for both H_2O and NH_3 (Fig. 1). However, hydration data for anions deviate from the predicted trend in a manner that reflects a longer range influence in the solvent. However, in both cases a good estimate of the solution-phase single-ion heat of solvation can be made for an ion from the gas-phase data of the first four or five clustering reactions.

Studies of gas-phase clusters can also answer questions about the solvation of electrolytes and concomitant ion-pair formation. One question concerns the number of solvent molecules required to separate an electrolyte into solvated ions. Features in the distribution of clusters in the mass spectrum obtained by the electron impact ionization of nitric acid-water ($\text{HNO}_3 \cdot \text{H}_2\text{O}$) clusters are suggestive of ion pair formation from HNO_3 when at least five H_2O molecules are available (15). More recently, laser-induced fluorescence of α -naphthol(NH_3) $_n$ clusters with four or more NH_3 molecules exhibited emissions characteristic of a naphtholate (16). Calculations have shown that a similarly small number of solvent molecules may effect ion separation (17).

Gas-phase clusters allow caging effects of solvents to be studied. Lineberger and co-workers (18) have observed the cessation of Br_2^- photodissociation as the ion becomes clustered by CO_2 molecules; about ten molecules effectively trap the Br_2^- and prevent its photodissociation. A theoretical study (19) suggests that caging begins weakly at small sizes because of strong ion-induced dipole interactions, so that ionic clusters can have an attractive caging effect. With larger clusters, the repulsive caging caused by collisions with surrounding solvent molecules dominates. The influence of solvation on properties such as acidity and reactivity has also been examined (20).

Electron solvation by nonmetallic species has been a problem of long-standing interest. For example, negative ions of CO_2 , H_2O , and NH_3 are unstable, but electrons can be solvated in their condensed phases. How large a cluster is required to bind the electron, and what forces are responsible? For CO_2 , the negatively charged dimer is observed to be stable, and theoretical calculations (21, 22) indicate that the stable dimer ion is a bent CO_2^- solvated by a linear CO_2 molecule. Thus solvation of a molecular anion leads to its stability. Similarly, CO_2^- can be stabilized by a H_2O solvent molecule (23). Negative ions (24) of NH_3 and H_2O clusters may involve diffuse electron states as opposed to localization on a given molecule. The relative stability of surface states, trapped electrons, or dipole-bound electrons depends on cluster size (25).

Structure and Order

How do the structures of clusters compare or contrast with the corresponding bulk systems? This question can refer to coordination numbers for solvated ions (26), to crystal structures for ionic salts (27), to "magic numbers" in atomic clusters (discontinuities in otherwise smooth trends in cluster abundance versus cluster sizes) (28), and to order-disordered (or solid-liquid) transitions (29, 30). First, consider the applicability of the concept of coordination number to gas-phase ions clustered by solvent molecules. Figure 2A shows a plot of stepwise enthalpy change $\Delta H_{n-1,n}^{\circ}$ versus cluster size n for the gas-phase association of NH_3 onto alkali ions. For all alkali metal ions, $-\Delta H_{n-1,n}^{\circ}$ decreases monotonically with cluster size; the enthalpy change for any particular cluster reaction varies inversely with ionic radius. However, both the Na^+ and Li^+ systems display a somewhat more abrupt decrease between the fourth and fifth NH_3 association steps. A well-defined "coordination shell" may exist for some ion-ligand systems in the gas phase (26). Raman spectra studies with Li^+ in liquid NH_3 also indicate a coordination number of 4 for Li^+ . This effect, however, has not been observed (31) in the

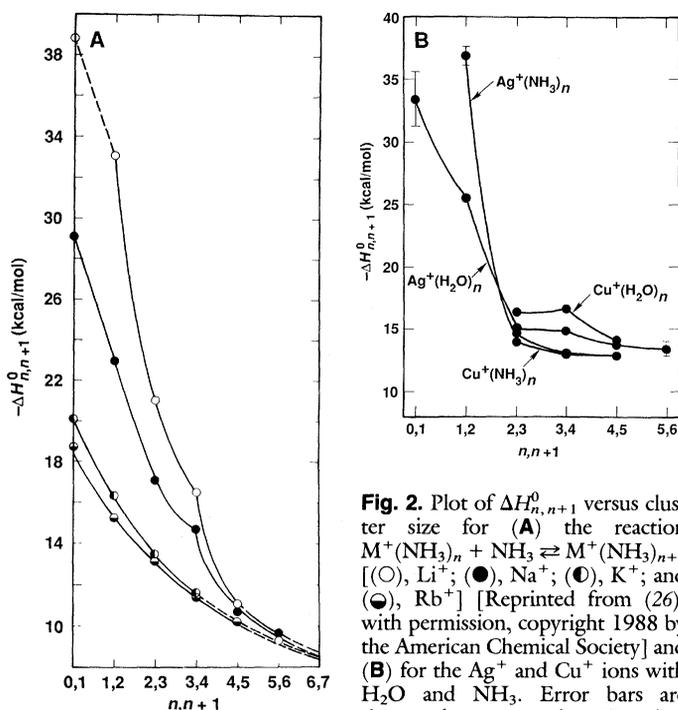


Fig. 2. Plot of $\Delta H_{n,n+1}^0$ versus cluster size for (A) the reaction $M^+(NH_3)_n + NH_3 \rightleftharpoons M^+(NH_3)_{n+1}$ [(○), Li⁺; (●), Na⁺; (◐), K⁺; and (◑), Rb⁺] [Reprinted from (26), with permission, copyright 1988 by the American Chemical Society] and (B) for the Ag⁺ and Cu⁺ ions with H₂O and NH₃. Error bars are shown where appropriate. [Reprinted from (32), with permission from *The Journal of Chemical Physics*]

case of H₂O clustered about alkali-metal ions.

Studies of transition-metal ion-ligand systems (32) have also provided data for interpreting the details of complexes in solution. The bonding by Cu⁺ and Ag⁺ ions strongly predisposes complexes to favor a linear structure because of the relatively small difference in energy between the filled *d* and unfilled *s* orbitals. Further mixing with the *p_z* orbital can then result in hybrid orbitals that can form linear covalent bonds to the two ligands. To accommodate a third ligand, the original linear structure might either become nonlinear at a cost in the original binding energy, or remain linear and present a sterically less favorable situation for the addition of the third ligand. The stepwise enthalpy changes for association of both NH₃ and H₂O in the gas phase show a strong preference for the bi-ligand complex (Fig. 2B). Furthermore, Ag⁺ shows a preference for NH₃, which is consistent with the coordination complex Ag⁺(NH₃)₂ known in aqueous solutions.

For molecular ions, the influence of the availability and number of specific sites is often evident. The clustering of NH₄⁺ by both NH₃ (33) and H₂O (34) shows notable incongruities in the stepwise enthalpy changes between the fourth and fifth association steps. The explanation is that NH₄⁺ has four specific bonding sites, represented by the hydrogen atoms, where the addition of one ligand with its dipole oriented along the N-H bond is relatively facile. Addition of the fifth ligand, however, occurs where all the immediate sites are already occupied. Thus this ligand must either add to the outside of the cluster or considerably reduce the bond energy of at least one of the preceding ligands in order to crowd into the inner shell.

Studies of gas-phase clusters have also given new perspectives on the growth of crystals. Secondary ion mass spectra of salts including NaCl, CsI, and CuBr yield M₁₄X₁₃⁺ as a particularly prominent species. Theoretical considerations suggest that M₁₄X₁₃⁺ has a rock-salt crystal structure for all three salts, even though CsI has a cesium-chloride-type structure and CuBr has a zinc-blende structure in the bulk (27).

Other questions pertain to whether a cluster is liquidlike or solidlike and what are the freezing or melting temperatures of these finite-sized systems. Calculations indicate that the melting tempera-

ture of clusters decreases with decreasing size, although not necessarily monotonically (1), and that clusters may have two different sharp melting and freezing temperatures bracketing a coexistence region (29, 30). These temperatures eventually must converge for large clusters. Electron diffraction on supersonic beams containing clusters is being used to address these questions (35). These studies are relevant to the general question of the applicability of thermodynamics to small systems (36).

Spectroscopy

Spectroscopic transitions of clusters vary as a function of cluster size. Visible-ultraviolet spectra are of value in unraveling the influence of local domains within a condensed phase on the electronic spectrum, whereas infrared (IR) spectra enable the probing of the onset of modes that are associated with the collective effects of a bulk phase. One goal is to probe how the environment and its extent affect electronic, vibrational, and rotational structure. One may examine these effects on a chromophore in a solvent, or matrix, or on a surface. In homogeneous media, one may wish to follow the evolution of an optical spectrum from an atomic or molecular spectrum to a metallic, crystal, or liquid spectrum.

The IR spectra from vibrational predissociation of H₂O clusters (37, 38), from the trimer and larger, exhibit some similarity with IR spectra of the liquid, whereas the spectra of the monomer and dimer are significantly different. The interpretation is that the trimer is the smallest cluster in which each H₂O molecule can be simultaneously a hydrogen donor and acceptor, so that the bonding in the trimer is more similar to bulk H₂O than it is to the dimer. A discussion of vibrations in clusters, microcrystals, and bulk material is given by Martin (39).

Changes in electronic transitions are seen both in frequency and linewidth. For example, the S₀ → S₁ electronic transition of phenylacetylene is red shifted by 28 cm⁻¹ when clustered by one argon (Ar) atom and by 53 cm⁻¹ when clustered by two Ar atoms (40). Clusters with 3 to 22 Ar atoms resulted in a red shift of 50 to 60 cm⁻¹ with broader spectral features (Fig. 3). Jortner and co-workers (41) observed an asymptotic approach to a red shift comparable to values for aromatic molecules in Ar matrices in the case of tetracene clustered by Ar, although the sizes of the clusters were not identified. The broadening may have several sources, including thermal broadening, in which the heat of condensation causes warming, inhomogeneous broadening from coexisting structural isomers with similar transitions, and the appearance with increasing numbers of low-frequency van der Waals modes that arise from intermolecular motions.

Ionization

The ionization potential of a cluster changes with its size. Experimental measurements can be compared with theoretical calculations and can be related to the properties of the condensed state. In principle, as a cluster increases in size, its ionization potential should approach the work function *W*_∞ of the bulk material. Similarly, the ionization potential and electron affinity should converge. Ionization has received more attention and will be discussed here. The few measurements of electron affinities do exhibit an increase (toward the work function) as cluster size increases (42-44).

Extensive studies have been made of the trends in ionization potential as a function of cluster size for alkali metals (45-47) because of their comparatively simple electronic configurations and the relatively straightforward theoretical interpretation of the experi-

mental results. The quantum mechanical treatment of a jellium model that assumes that valence electrons are delocalized and that the remainder of the cluster is represented as a uniformly positively charged cloud has been fairly successful (47). The solution of this model yields a shell structure analogous to the quantum mechanical treatment of an atom and has accounted for "magic numbers" in alkali metal clusters. In classical mechanics, the finite size of a cluster modifies the work function by the influence of the ion image potential. By assuming spherical symmetry, the ionization potential of a cluster expressed in terms of a size-dependent work function $W(R)$ is given by

$$W(R) = W_{\infty} + Ae^2/R \quad (4)$$

where R is the radius of the equivalent sphere supporting an elementary charge e . The value of the prefactor A depends on how the image potential is considered. Several metal systems reasonably follow this simple classical theory with a prefactor of $3/8$ (48) (see Fig. 4A). The apparent validity of the correlation is interesting in that, for iron and nickel, rather large variations in ionization potential are found at certain cluster sizes. Obviously, the correlation is an oversimplification.

Mercury, however, did not appear to conform to this simple model, which raised a question about the accuracy of the bulk work function (48). Rademann *et al.* (49) measured the ionization potentials of mercury clusters from Hg_2 to Hg_{70} (Fig. 4B). A transition, rather than a simple linear relation expected on the basis of Eq. 4, is apparent near Hg_{35} . The small clusters deviate strongly from the expected relation, whereas the larger ones appear to merge smoothly into the bulk value of the metal. This observation is suggestive of a nonmetal-metal transition during cluster growth.

The presence of adsorbed species tends to lower the ionization potential of a cluster in a manner analogous to the known effect of impurities on the bulk work function of a metal. For example, the presence of an oxygen atom on the sodium tetramer lowers (50) its ionization potential by about 0.35 eV compared with a lowering of about 0.45 eV for macroscopic sodium surfaces. Similar trends have been seen for clusters of iron and nickel (51).

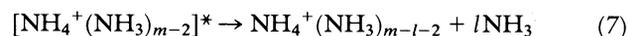
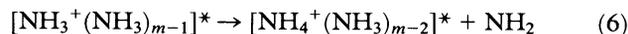
For clusters comprised of materials that in bulk act as insulators, the ionization potential is also generally expected to decrease with

increasing cluster size (see Fig. 5A). The dependence is linear with the inverse of the number of molecules in the cluster. This relation has been justified on the basis of a quantum mechanical independent systems model (52), but the model fails when strong bonds and local binding effects occur in the ionic system (53). For most systems the solvent atoms or molecules are more strongly bound to the ion than to the neutral species and a lowering of ionization potential is expected. The ionization potentials (54) of *p*-xylene-argon clusters (Fig. 5B) decrease approximately linearly (about 120 cm^{-1} per atom) with the number of Ar atoms.

Energy Transfer

The dissipation of energy from a site of absorption in a molecular or condensed system is of considerable interest. Clusters are excellent systems in which to study the effects of intermolecular interactions in relaxation processes, because the extent of the medium is finite and each molecule may be intimately involved in the energy dissipation of the system. Furthermore, the number of degrees of freedom of the system can be tailored in a comparatively easy fashion through increasing the number of aggregating subunits, while the chemical character of the system remains relatively unchanged. The processes of interest may include (i) the electronic relaxation of an excited species, (ii) the vibrational relaxation of the internal modes of a probe molecule and energy redistribution into intermolecular modes, and (iii) energy flow and relaxation of intermolecular vibrations (41). An important consideration in vibrational relaxation is the role of vibrational predissociation under conditions in which the vibrational energy available for redistribution exceeds the energy of an intermolecular bond. In these cases, the size of the cluster and its ability to redistribute the energy throughout the system are crucial. Experiments with mixed clusters enable the study of energy transfer in systems of widely disparate modes. We discuss two modes of excitation: one involves ionization and the second deals with photon absorption into a well-defined state.

As with molecules, ionization of a cluster usually results in a change in the equilibrium geometry, and relaxation of the freshly ionized cluster may proceed through dissociation or radiative emission. An ionized molecule within a cluster may react with a neighboring molecule. Upon dissociation, an excited cluster loses internal energy through the energy required to break a cluster bond and relative kinetic energy imparted to the departing fragments. An example (55, 56) of these processes is shown below for the multiphoton ionization of NH_3 clusters.



By metastability evidenced in mass spectrometry, as many as six NH_3 molecules have been observed to dissociate ("evaporate") from $\text{NH}_4^+(\text{NH}_3)_8$ in the time scale of microseconds to tens of microseconds after ionization (55). Whether the loss of molecular units occurs sequentially or simultaneously, and whether vibrational predissociation is dominating on all time scales is not known. Also, the contribution of kinetic energy release to energy disposal and the dependence of the extent and rate of dissociation on the ionization energy and initial size of the cluster are poorly understood.

The importance of dissociation upon ionization of *p*-xylene clustered by Ar was demonstrated (54) through one- and two-color resonance-enhanced multiphoton ionization. For a small cluster, the initial size was identified by its characteristic spectroscopic shift. Fragmentation of larger clusters was evident based on features in the

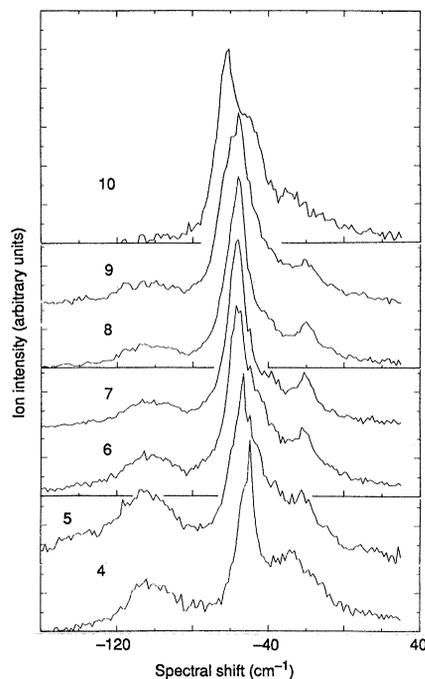


Fig. 3. The resonant two-photon ionization of phenylacetylene (PA) clustered by argon. The ion currents are recorded at the mass-to-charge (m/e) ratios corresponding to $\text{PA} \cdot \text{Ar}_n$ ($4 \leq n \leq 10$); the spectra from $n = 10$ to 22 are essentially identical. The spectral shift is the one-photon energy relative to the S_1 electronic origin of phenylacetylene. The ion current scale is arbitrary for each spectrum. [Reprinted from (40), with permission from *Chemical Physics Letters*]

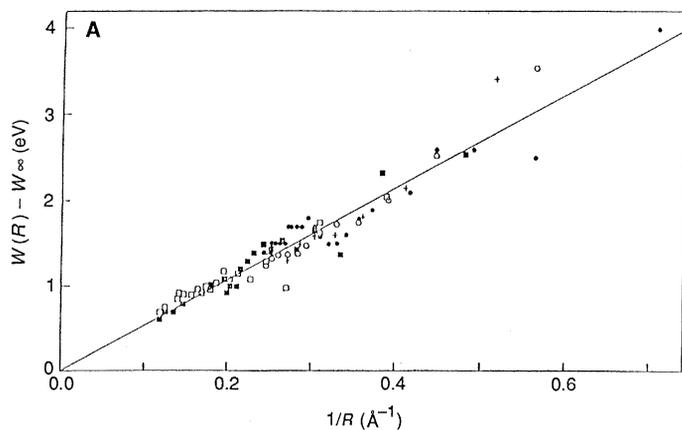
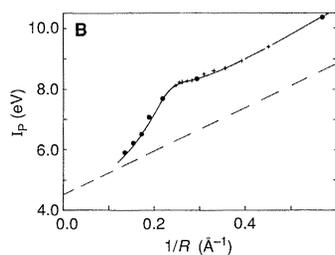


Fig. 4. (A) "Reduced" ionization potentials, representing the difference between measured ionization potential and extrapolated bulk work function, based on a best fit of the data to the classical electrostatic equation, for five metal systems plotted versus $1/R$ [see (48)]; (B) plot comparing the experimentally determined ionization potential data (●) with the predictions of the classical spherical droplet model (-----). The ionization potential was plotted versus $1/R$, with R the radius of a sphere with the same volume as an n -atom metal cluster (assuming atomic volume derived from bulk metallic density) [see (49)].



spectrum of the photoion p -xylene⁺ when clusters were ionized with about 0.66 eV excess energy through the one-color scheme. When ionization near threshold was accomplished with a two-color experiment, the relative intensity of spectral features due to larger clusters was diminished and the extent of fragmentation was considerably decreased. In some cases, a certain specific number of molecular units were lost. As an example, sputtering of solid N₂ produced charged clusters (57) that lost two to three N₂ molecules at a time, depending on size. These characteristic intervals were correlated with vibrational energy stored within molecules of the cluster and the heat of vaporization of solid N₂.

The extent of dissociation and kinetic energy release following photoabsorption have been somewhat better explored than in the case of ionization. In the photodissociation studies of (CO₂)_n⁺, a constant average neutral mass loss per unit photon energy absorbed was observed as the cluster became sufficiently large (58). From the number of CO₂ molecules lost versus photon energy, an upper limit of 4.9 kcal/mol was found for the dissociation energy of a CO₂ molecule from these large clusters. An interesting comparison can be made with the 5.7 kcal/mol required for sublimation of CO₂ from dry ice.

Measurements on the photodissociation of CO₃⁻(H₂O)_n (1 ≤ n ≤ 3) indicated that the same intermediate state was responsible for the photodissociation (59). Each H₂O molecule is bound to CO₃⁻ by about 0.6 eV, yet loss of all three H₂O molecules from the trihydrate occurred upon the absorption of photons with about 2 eV of energy. Dissociation is believed to involve the internal conversion of energy from a bound electronic excited state to high-lying vibrations in the ground state. However, the usual predisposition for a vibrational transition $\Delta v = \pm 1, \pm 2$ is insufficient for the loss of three H₂O molecules in this system.

Relaxation time scales have been determined from the analysis of fluorescence decay rates. For instance, Jortner and co-workers (41)

have found that the vibrational relaxation of tetracene in large Ar clusters occurs on a nanosecond time scale, which is about two orders of magnitude slower than is typical for aromatics in rare gas solids. The relaxation time apparently continues to decrease with increasing cluster size (inferred from changes due to stagnation pressure in the cluster source), although the spectral shift no longer varied. Spectroscopically, tetracene appears to be in an environment like a solid Ar matrix, but dynamically the large clusters are not efficient heat baths for vibrational relaxation.

Reactivity

Reactions on clusters have analogies with reactions on surfaces and are important for understanding catalysis, etching, and adsorption (51, 60–63). Reactions of a species that is clustered by solvent molecules reveal on a molecular level the role of solvation (64) in influencing reactions and the nature of the participation of the solvent molecules. Reactions within a cluster can be induced by ionization or photoabsorption (65–67). Dissociation and formation reactions of clusters have been discussed above.

The study of reactions of molecules with metal and semiconductor clusters has provided insight into reaction on surfaces. The dissociative chemisorption of molecular hydrogen and deuterium on cobalt, niobium, and iron clusters depends dramatically on the number of atoms in the aggregate. The relative rates vary by more than four orders of magnitude with cluster size over the range from Fe₆ to Fe₆₈. Clusters with comparatively low ionization potentials add molecular hydrogen more effectively. The relative rates of reaction display a pattern corresponding to the electron binding energy. Kaldor and co-workers (51) explained the results in terms of the requirement for metal-to-hydrogen transfer of charge in order to activate the H₂ bond.

The effect of the degree of solvation on reactivity of gas-phase clusters has been most explored in the case of ions, although the number of solvent molecules has not exceeded about four. Several types of reactions have been investigated (68), including solvent exchange, nucleophilic displacement, charge transfer, and proton transfer. Generally, the rate coefficients decrease with increased solvation of the ion. In some systems, the decrease is attributable to the decreased collision rate as a result of increased reduced mass. This effect is usually seen for strongly exothermic reactions. In other cases, orders of magnitude decreases are observed in the rate coefficient. These reactions tend to be weakly exothermic in the case of the unsolvated ion. In these cases, the presence of solvent molecules may create an activation energy barrier, or the energetics for the solvation of the product ion are sufficiently poor compared with the reactant ion, such that the overall reaction becomes endothermic. Many reactions do involve the transfer of solvent molecules from the reactant to the product ion.

Clusters are also being explored as a medium in which to carry out and study reactions. Reactions that occur within a cluster following the ionization of one moiety can be compared to isolated gas-phase ion-molecule reactions. An example (67) is that of intracuster reactions of methanol clusters following ionization. Several competitive reaction channels were found. One led to a sequence of protonated CH₃OH clusters as a result of the reaction of CH₃OH⁺ with CH₃OH resulting in the loss of a CH₃O group from the cluster. In the gas phase, protonated CH₃OH will react with another CH₃OH molecule to yield protonated methyl ether (CH₃OCH₃) and H₂O. The same reaction occurs in the ionized cluster H⁺(CH₃OH)₂. Larger clusters, however, fail to show loss of H₂O. For larger clusters, a channel corresponding to the retention

of H₂O in the cluster and to the loss of an ether molecule was observed. Thus the preferred reaction pathway can depend on the size of a cluster.

Conclusions

Cluster research is providing insights into properties of matter as it transforms from the gas state to the condensed state that are not possible to attain through studies of the respective bulk states themselves. The display of condensed, bulk state properties by clusters depends on the effect under consideration. In terms of energetics associated with the solvation of ions, differences between similar systems are washed out at sizes far smaller than those that contribute to the full magnitude of the heat of solvation. Likewise, the difference spectroscopically between clusters and the bulk is very small when the number of solvent molecules reaches one or two shells in size. However, energy transfer and relaxation processes may be considerably different because of the available degrees of freedom in the respective systems. In terms of ionization potentials, many metals rapidly approach the bulk work function if correction is made to account for the ion image potential. The effects in insulators are evidently long range, and more work is needed on these systems. A

potentially fruitful area of future study is that of metals imbedded in insulators. Clusters are a particularly good medium for investigating the influence of solvation on reactions; a few recent results of specificity with cluster size hint that this will be a rewarding area for continued work.

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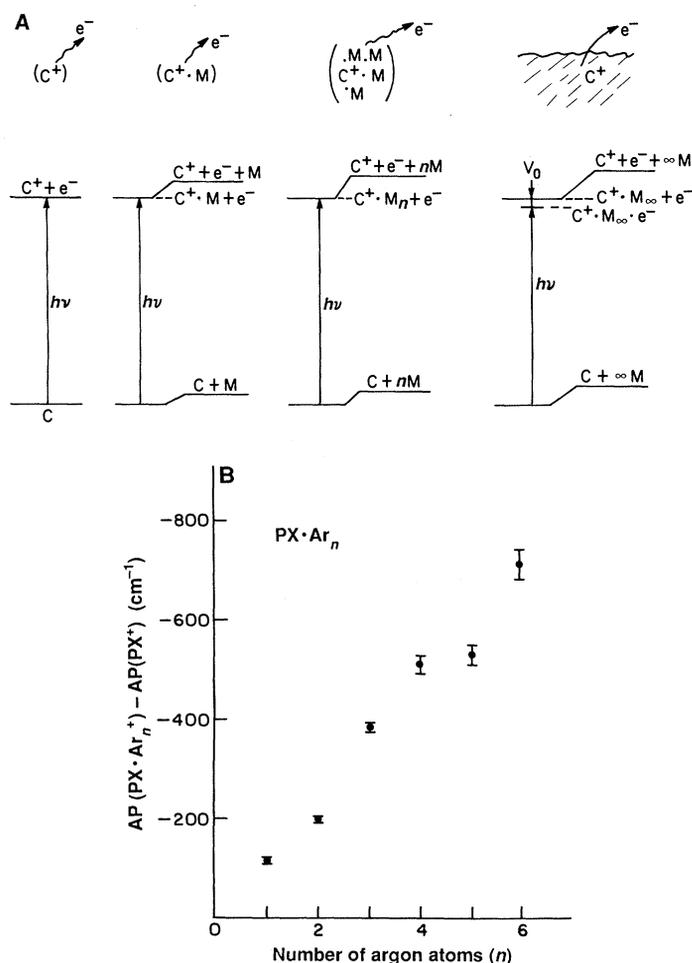


Fig. 5. (A) A schematic depiction of the influence of solvent molecules (or atoms) M on the ionization potential of chromophore C as a function of degree of aggregation. (B) Decrease in appearance potential (AP) of $(p\text{-xylene} \cdot \text{Ar}_n)^+$ with increasing cluster size. [Reprinted from (54), with permission from *Chemical Physics Letters*]

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The Protein Kinase Family: Conserved Features and Deduced Phylogeny of the Catalytic Domains

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In recent years, members of the protein kinase family have been discovered at an accelerated pace. Most were first described, not through the traditional biochemical approach of protein purification and enzyme assay, but as putative protein kinase amino acid sequences deduced from the nucleotide sequences of molecularly cloned genes or complementary DNAs. Phylogenetic mapping of the conserved protein kinase catalytic domains can serve as a useful first step in the functional characterization of these newly identified family members.

THE PROTEIN KINASES ARE A LARGE FAMILY OF ENZYMES, many of which mediate the response of eukaryotic cells to external stimuli (1, 2). The number of unique members of the protein kinase family that have been described has recently risen exponentially (3) and now approaches 100. The surge in the number of known protein kinases has been largely due to the advent of gene cloning and sequencing techniques. Amino acid sequences deduced from nucleotide sequences are considered to represent protein kinases if they include certain key residues that are highly conserved in the protein kinase "catalytic domain."

Two different molecular approaches have been most instrumental in the isolation of novel protein kinase-encoding genes or cDNAs: (i) complementation or suppression of genetic defects in invertebrate regulatory mutants, and (ii) screening DNA libraries by using protein kinase genes as hybridization probes under low stringency conditions. Recently, an approach that uses degenerate oligonucleotides as probes has led to the identification of several novel putative

protein kinase genes and cDNAs (4, 5). The oligonucleotide probes are designed to recognize target sequences that encode short amino acid stretches highly conserved in protein kinase catalytic domains.

In this article, we present an alignment of catalytic domain amino acid sequences from 65 different members of the protein kinase family, including many putative protein kinase sequences recently deduced from nucleotide sequence data. Based on this alignment, we first identify and discuss conserved features of the catalytic domains and then provide a visual display of the various intersequence relations through construction of a catalytic domain phylogenetic tree. Catalytic domains from protein kinases having similar modes of regulation or substrate specificities are found to cluster together within the tree. This clustering would appear to be of predictive value in the determination of the properties and function of novel protein kinases.

Catalytic Domain Amino Acid Sequences

Protein kinase catalytic domains range from 250 to 300 amino acid residues, corresponding to about 30 kD. Fairly precise boundaries for the catalytic domains have been defined through an analysis of conserved sequences (1, 6, see below) as well as by assay of truncated enzymes (7, 8). The location of the catalytic domain within the protein is not fixed but, in most single subunit enzymes it lies near the carboxyl terminus, the amino terminus being devoted to a regulatory role. In protein kinases having a multiple subunit structure, subunit polypeptides consisting almost entirely of catalytic domain are common. All protein kinases thus far characterized with regard to substrate specificity fall within one of two broad classes, serine/threonine-specific and tyrosine-specific. Although both classes of protein kinase have very similar catalytic domain primary structures, certain short amino acid stretches appear to characterize each class (4), and these regions can be used to predict whether a putative protein kinase will phosphorylate tyrosine or serine/threonine.

Members of the protein-serine/threonine kinase and protein-

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