EXCURSIONS IN CLUSTER SCIENCE; FROM DYNAMICS OF LARGE FINITE SYSTEMS TO ULTRACOLD CLOUDS

Joshua Jortner and Isidore Last, School of Chemistry, Tel-Aviv University, Tel-Aviv, Israel.

I. PROLOGUE

During the last two decades, the chemical physics group of Tel-Aviv University explored the structure, energetics, spectroscopy and dynamics of clusters, focusing on the energy landscapes, spatial structures and shapes, phase changes, superfluidity, energetics, level structure, electronic-vibrational spectroscopy, size effects, response and nuclear-electronic dynamics of large finite systems [1-22]. Recently, our dynamic studies were extended for the adiabatic nuclear dynamics of multicharged atomic and molecular clusters, which manifest unique fragmentation patterns, such as cluster fission and Coulomb explosion [23-34]. Concurrently, a fascinating analogy was established between Coulomb explosion of multicharged clusters and nuclear dynamics of finite, ultracold gases, i.e., optical molasses, in the temperature domain of T = 10μK–100μK [35, 36]. Cluster science constitutes the art of building bridges, i.e., bridging between the structure, energetics, thermodynamics, response and dynamics of molecular and condensed phase systems in terms of size scaling laws [11-14], bridging between the electron-nuclear dynamics and response of clusters and of nanostructures [37], and bridging between nuclear dynamics of clusters and of ultracold, large, finite, quantum systems [35,36].

II. FROM FISSION TO COULOMB EXPLOSION

The fragmentation of multiply charged finite systems driven by long-range Coulomb (or pseudo-Coulomb [35,36]) forces, i.e., nuclei [38], clusters [23-34,39-42], droplets [43,44], and optical molasses [35,36], raises the following interesting questions regarding the energetics and dynamics of dissociation:

(1) How does a finite system respond to a large excess charge or to an effective charge?

(2) What are the topography and topology of the multidimensional energy landscape that guide the system's shape evolution and fragmentation?

(3) What are the fragmentation channels and under what conditions are they realized?

(4) What is the interplay between fission, i.e., instability towards dissociation of the finite system into two (or a small number of) fragments and Coulomb explosion into a large number (~n, where n is the number of constituents) of ionic species?

The ubiquity of fission phenomena of droplets, nuclei, and clusters was traditionally described by the classically liquid drop model (LDM) [38, 44], where a classically charged drop deforms through elongated shapes to form separate droplets. The fissibility parameter X = E(Coulomb)/2E(surface) characterizes the relative contribution of repulsive (Coulomb) and cohesive (surface) energies to the fission barrier, separating between the bound initial states and the fission products. For $X < 1$, thermally activated fission over the barrier prevails. At the Rayleigh instability limit of $X = 1$ the barrier height is zero [38, 44]. Many features of nuclear and metal cluster fission require to account for quantum shell effects. Nevertheless, the simple LDM expression $X=Z^2e^2/16\pi R_0^3=(Z^2/n) / (Z^2/n)_{cr}$, with the proportionality factor $(Z^2/n)_{cr}=16\pi R_0^3/e^2$ (where γ is the surface tension, Z the total charge, R_0 the system's radius and r_0 the constituent radius), provided the conceptual framework for the fission of charged finite systems. All the diverse phenomena of fission were realized for fissibility parameters below the Rayleigh instability limit of $X = 1$, i.e., nuclear fission [45], the fission of metal clusters [42], and of hydrogen-bonded clusters [43]. Beyond the fissibility limit ($X > 1$) barrierless fission and other dissociative channels open up. We have transcended the Rayleigh instability limit ($X = 1$) for Coulomb instability of large finite systems, demonstrating the prevalence of a qualitatively different fragmentation pattern of Coulomb explosion beyond the Rayleigh instability limit [28]. We studied the fragmentation patterns and dynamics of highly charged Morse clusters by varying the range of the pair potential and of the fissibility parameters. The instability of multicharged Morse clusters directly reflects on covalently or dispersion-bound chemical and biophysical finite systems. The Rayleigh instability limit separates between nearly binary or tertiary spatially unisotropic fission for X<1 and spatially isotropic Coulomb explosion into a large number of ionic fragments for X>1 (Fig. 1).

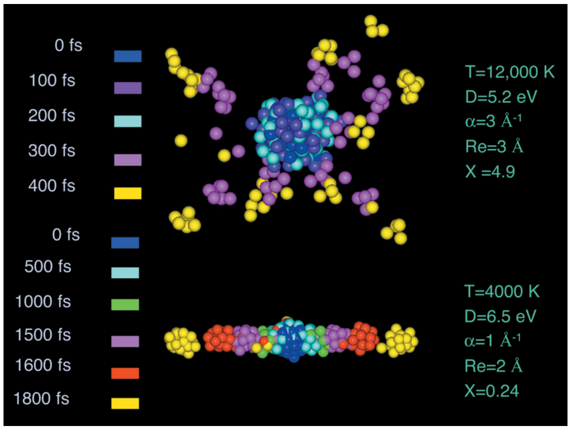

Figure 1. Time resolved nuclear dynamics of the fragmentation of highly charged $(A^+)_{55}$ Morse clusters (mass of A is 100 amu). The two panels show superimposed temporal patterns of the fragmentation, where each color corresponds to a different time for a one-color snapshot, as marked on the two panels. The Morse potential parameters and the fissibility parameter X are marked on the panels. The time t = 0 corresponds to the T jump to the final temperature (see text). Note the dramatic difference between the spatially isotropic Coulomb explosion (for X = 4.9) on the upper panel, and cluster fusion (for X = 0.24) on the lower panel. (See colored figure on back cover).

We explored the Coulomb instability of multicharged [23-34,39-44], or effectively charged [35,36], finite systems (Fig. 2). The majority of the currently available experimental information on the Coulomb instability of nuclei (i.e., X = 0.7 for ^{235}U and X = 0.9 for the recently discovered Z = 114 element [45]), of charged droplets (i.e., X = 0.7 – 1.0 for hydrogen bonded systems [43]), and of multiply charged metal clusters (X = 0.85 ± 0.07 for Na_n^{+z} clusters [42]) pertains to the fission limit, i.e., X < 1 (Fig. 2). How can the Rayleigh limit for the Coulomb instability of a finite system be overcome? The X >> 1 domain can be accomplished either by a marked enhancement of the repulsive Coulomb energy, or by a dramatic reduction of the cohesive surface energy (Fig. 2). The increase of E(Coulomb) can be attained by cluster multielectron ionization in ultraintense (peak intensity $I = 10^{15} – 10^{20}$ Wcm^{-2}) laser fields (section III), while the dramatic decrease of E(surface) can be accomplished in three-dimensional, ultracold optical molasses (section V), where pseudo-Coulomb forces result in isotropic cloud expansion, in analogy with Coulomb explosion [35,36].

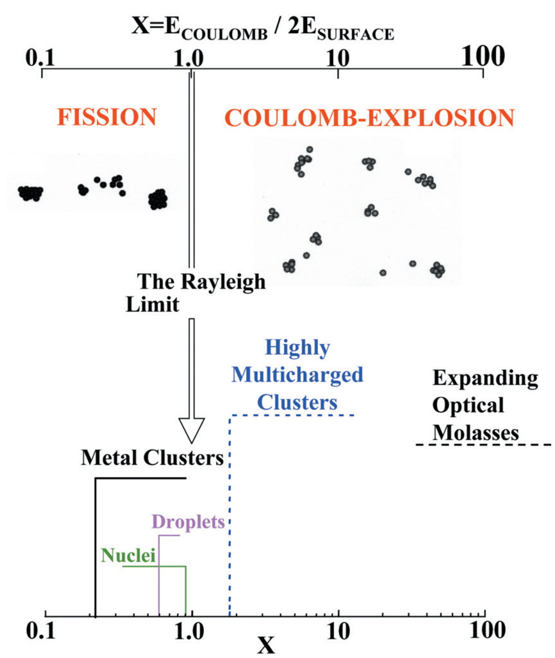

Figure 2. A classification of fragmentation patterns of multicharged and effectively charged large, finite systems.

The traditional view of Coulomb explosion involves uniform ion expansion. Such is the case for the explosion of multicharged homonuclear clusters (e.g., $(D_2)_{n/2}$ or $(Xe)_n$) with the expansion of (e.g., D^+ or Xe^{q+}) ions retaining a uniform spatial distribution (as is the case for X > 1 in Fig. 1), with an energy distribution being proportional to the square root of the energy, up light-heavy heteroclusters consisting of light and heavy ions, e.g., vertically ionized heteroclusters of hydrogen iodide, $(H^+I^{q+})_n$ or $(D^+I^{q+})_n$ (q = 7–35) [34]. In this case, kinematic overrun effects of the light ions (e.g., H^+ or D^+) will result in thin, two-dimensional shells of these light ions, with the monolayer expansion occurring on the femtosecond time scale (Fig. 3). Such an expanding nanoshell of light ions, corresponding to transient soft matter, is analogous to a 'soap bubble' characterized by negative surface tension and is being driven by Coulomb pressure. This transient halo of an expanding, regular monoionic spherical nanointerface manifests transient self-organization on the molecular level in complex systems [34]. Future experimental interrogations of these novel phenomena will emerge from the exploration of the energetics of the light ions in the Coulomb explosion of multicharged light-heavy heteroclusters, involving a narrow energy distribution with a low-energy cut-off [34]. An exciting experimental approach pertains to the application of ultrafast electron diffraction methods [46] for the exploration of the transient structure of the exploding clusters [34].

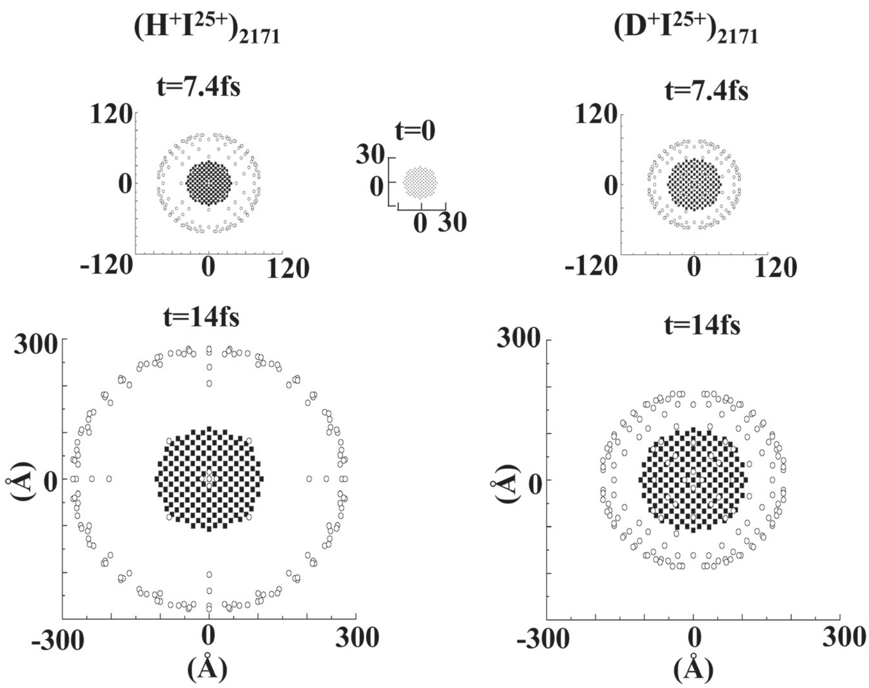

Figure 3. A 2-dimensional picture of the spatial structure of Coulomb expanding $(H^+I^{25+})_{2171}$ light-heavy heteroclusters at t = 0, 7.4 fs and 14 fs, obtained from molecular dynamics simulations. Black squares (■) represent I^{25+} ions, while circles (O) represent H^+ ions. This pictorial representation reveals the formation of narrow expanding shells of the light ions.

III. ULTRAINTENSE LASER – CLUSTER INTERACTIONS

Table top lasers delivering an energy of 1 Joule per pulse on the time scale of ~ 100 fs, can deliver a power of ~ 10^{20} Wcm^{-2}, constituting the highest light intensity on earth. Highly charged molecular clusters can be prepared by the irradiation of a cluster beam by ultrashort (tens of fs) and ultraintense (intensity $I = 10^{15}$–10^{20} Wcm^{-2}) laser pulses (Fig. 4).

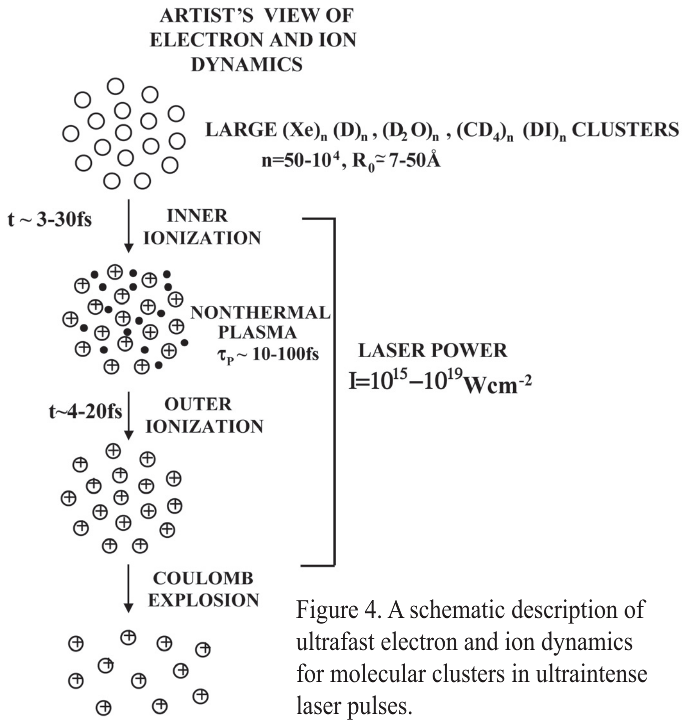

Figure 4. A schematic description of ultrafast electron and ion dynamics for molecular clusters in ultraintense laser pulses.

The extreme cluster multielectron ionization process involves the removal of valence electrons or complete stripping of all the electrons in light first-row atoms or molecules [25-27,29], or the formation of highly charged ions, e.g., up to Xe^{36+}, from heavy atoms [29-31,41]. The compound multielectron ionization mechanism of clusters is distinct from that of a single constituent. It involves three sequential processes of inner ionization (due to the semiclassical barrier suppression mechanism for each constituent with a contribution of impact ionization), the formation and response of a nonequilibrium, high energy (100eV–3keV) nanoplasma within the cluster, and outer ionization (induced by barrier suppression for the entire cluster and by quasiresonance effects) [24,30,31]. Femtosecond [24,30,31] electron dynamics of inner ionization on the time scale of ~ 1–5 fs and of outer ionization on the time scale of ~ 5–20 fs results in multielectron ionization. For the intensity domain of $I = 10^{16}–10^{17}$ Wcm^{-2} the cluster molecules loose all their valence electrons, with the nanoplasma being persistent, while for the highest intensity range of $10^{18}–10^{19}$ Wcm^{-2} both valence and inner shell electrons can be stripped off, with the nanoplasma being completely depleted [31]. The Coulomb instability of a highly charged finite cluster triggers simultaneous and concurrent ultrafast Coulomb explosion [24-29,32,33,41] on the time scales of 10–200 fs (Fig. 4). Analytical expressions for the fs time scales of Coulomb explosion and of (divergent) scaling laws for the energetics of the highly charged ions were derived [25-27,32,33] and were confirmed by molecular dynamics simulations with attosecond time steps describing fs dynamics. Ultrahigh ion energies in the range of 1keV–1MeV are released by cluster Coulomb explosion, as portrayed in Fig. 5 for deuterium containing homonuclear and heteronuclear clusters, where deuteron energies in the range of 1–100keV can be obtained.

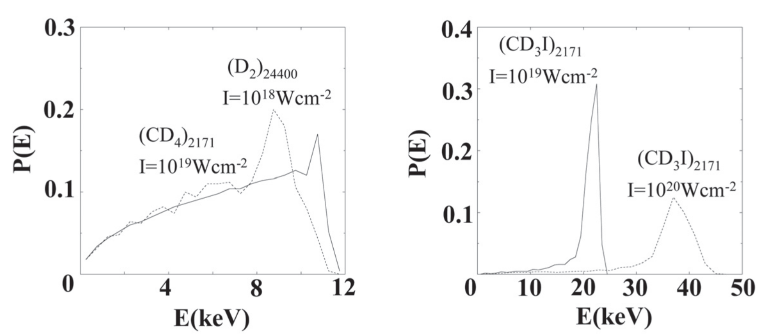

Figure 5. Energy distributions of D^+ ions from Coulomb explosion of $(D^+)_n$ homonuclear clusters ($n = 2.44\cdot10^4$) and deuterium containing heteronuclear clusters $(C^{6}+D_4^{+})_n$ ($n = 2171$) and $(C^{+4}+H_3^{+}I^{q+})_n$ ($n = 2171$, $q = 25$ at $I = 10^{19}$ Wcm^{-2}, and $q = 35$ at $I = 10^{20}$ Wcm^{-2}).

A significant implication of these high ion energies pertains to nuclear fusion reactions of highly energetic D^+ (as well as T^+ or H^+) ions produced by Coulomb explosion of multicharged clusters in extreme multielectron ionization in ultraintense laser fields, which will be addressed in section IV. Cluster dynamics is moving from ultrafast femtosecond to picosecond nuclear dynamics, towards ultrafast attosecond to femtosecond electron dynamics, and towards electron-nuclear dynamics in ultraintense laser fields. 'Pure' electron dynamics constitutes new dynamic processes in chemistry and physics. Ultrafast cluster dynamics is not limited to the dynamics of ions on the time scale of nuclear motion, but is extended to the realm of electron dynamics, which bypasses the constraints imposed by the Franck-Condon principle [47].

IV. NUCLEAR FUSION DRIVEN BY CLUSTER COULOMB EXPLOSION

Eighty years of search for table-top nuclear fusion, driven by bulk or surface chemical reactions, which involved catalytic dissociation or electrochemical productions of deuterium, reflects on a multitude of experimental and conceptual failures [29]. In 1926 the German physicist Fritz Paneth reported on the apparent observation of helium from hydrogen absorbed on powdered palladium, which might have originated from nuclear fusion. A year later this claim was retracted. In 1935 Adalbert Farkas and Ladislaus Farkas, the founders of physical chemistry in Israel, worked on ortho- and parahydrogen and on deuterium chemistry in the Department of Colloid Science at Cambridge University, England, where they found shelter as refugees from Germany. When passing deuterium gas through a palladium tube, they seemed to observe traces of helium, which might have originated from dd (D^++D^+) nuclear fusion. However, a search for neutron emission in this system, conducted by Lord Rutherford at the request of the Farkas brothers, was negative and eliminated any possibility of nuclear fusion. In this category of negative results for nuclear fusion belongs the widely publicized 1989 "cold fusion" controversy, which did not provide any acceptable scientific information.

These spectacular failures

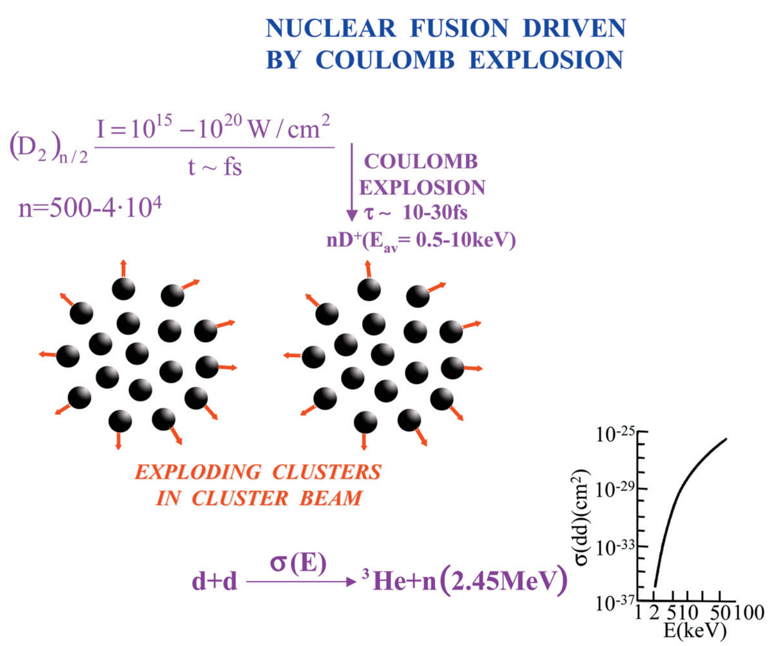

Figure 6. dd nuclear fusion driven by Coulomb explosion of deuterium clusters. Top: Multielectron ionization in ultraintense laser fields ($I > 10^{17}$ Wcm^{-2}) strips the $(D_2)_{n/2}$ clusters of all their valence electrons via consecutive inner and outer ionization. Parallel and concurrent with outer ionization, cluster Coulomb explosion of $(D^+)_n$ clusters occurs. In the size domain of $n = 459–7.6\cdot10^4$ the D^+ average energy increases from 0.3keV to 9.0keV. Energetic deuterons (D^+ ions) emerging from different clusters in the cluster beam undergo dd nuclear fusion. Bottom: Energy dependence of the cross sections σ(dd) for dd fusion adopted from the data of reference [48].

are not surprising as, to the best of our knowledge, no theoretical evidence is available to support any valid mechanism of nuclear fusion driven by chemical reactions in infinite bulk or surface systems [29]. The fragmentation dynamics of large finite systems involves an alternative avenue for the induction of nuclear fusion by chemical reactions, e.g., the dd (D^++D^+) nuclear fusion reaction $D^+ + D^+ \rightarrow {}^3He^{2+} + n(2.45MeV) + 3.27MeV$, with the production of neutrons (n). Coulomb explosion of extremely multicharged finite molecular systems strives towards the exploration of new areas that are alien to the majority of the chemical physics community. These areas involve nuclear fusion driven by Coulomb explosion of deuterium containing homonuclear and heteronuclear clusters [25-27,29,31-33,49-51]. High-energy Coulomb explosion of an assembly of multicharged, deuterium containing, molecular clusters produces high-energy (1–100keV) deuterons (Fig. 5) in the energy domain of nuclear physics. The high energy deuterons originating from different clusters undergo dd nuclear fusion. During the last four years compelling experimental [49,50] and theoretical [25,26,32] evidence was advanced for nuclear fusion driven by Coulomb explosion (NFDCE) in an assembly of deuterium clusters (Fig. 6). Completely ionized $(D^+)_n$ clusters are produced by multielectron ionization of homonuclear $(D_2)_{n/2}$ ($n = 500–4\cdot10^4$, $R_0 = 10–75$Å) clusters in ultraintense laser fields ($I > 10^{17}$ Wcm^{-2}), stripping the clusters from all their electrons (section III). For Coulomb explosion of very large homonuclear deuterium $(D^+)_n$ clusters ($n = 3.8\cdot10^4$ and cluster radius $R_0 = 72$Å), the average deuteron (D^+) energy is $E_{av} = 9$keV and the maximal energy is $E_M = 13$keV [25,26,32]. For these deuteron energies the cross section for dd (D^++D^+) nuclear fusion is $\sigma(dd) \simeq 10^{-28}cm^2$ (Fig. 6) [48], being sufficiently high to induce the dd fusion reaction [25,26,32]. Collisions between energetic deuterons, which originate from Coulomb explosion of different deuterium clusters (Fig. 6), result in NFDCE [25,26,32], which was experimentally observed in the Lawrence-Livermore laboratory [49,50]. Our theoretical and computational work [25-27,29-34] proposed and demonstrated that an effective way to produce highly energetic d nuclei (D^+ ions) for nuclear fusion involves multielectron ionization and Coulomb explosion of molecular heteroclusters of deuterium bound to heavy atoms. Highly ionized heteroclusters for high-energy Coulomb explosion involve heavy water clusters $(D^+D^+O^{q+})_n$ ($q = 6–8$), heavy methane clusters $(C^{q+}(D^+)_4)_n$ ($q = 4–6$), or deuterated hydroiodic clusters $(D^+I^{q+})_n$ ($q = 7–35$) in the size domain of $n = 55–4\cdot10^3$ ($R_0 = 10–40$Å). A dramatic energy enhancement of deuteron energy from these heteroclusters, as compared to deuterons from homonuclear deuterium clusters, is manifested (Fig. 5). For Coulomb explosion of heteroclusters the heavy multicharged ions (e.g., C^{4+}, C^{6+}, O^{6+}, O^{8+}) act as energetic triggers driving the light

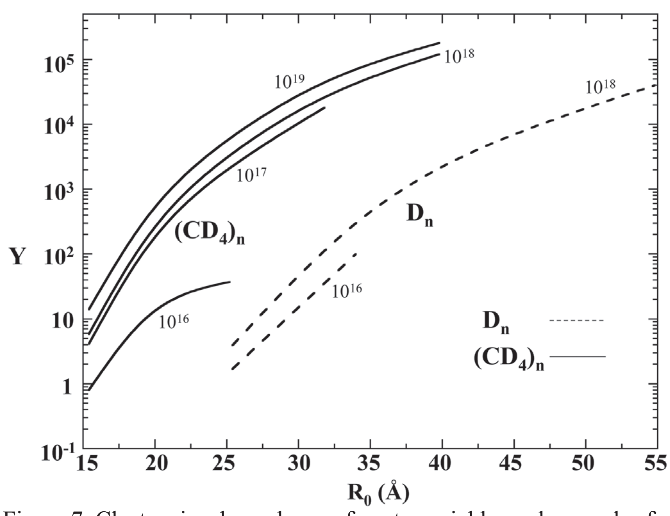

Figure 7. Cluster size dependence of neutron yields per laser pulse for dd NFDCE in an assembly of $(CD_4)_n$ (n = 55–4213) heteroclusters (solid curves), and of $(D_2)_{n/2}$ (n = 55–33573) homonuclear clusters (dashed curves) in the laser intensity range $I = 10^{16}–10^{19}$ Wcm^{-2}. Data adopted from reference 33. The NFDE for heteronuclear clusters manifests a considerably larger neutron yield than for homonuclear clusters of the same size, exhibiting energetic and kinematic effects, as discussed in the text.

D^+ clusters to considerably higher kinetic energies than for totally ionized deuterium clusters of the same size. In addition, kinematic effects, which manifest a sharp energy maximum in the vicinity of E_M, in the energy spectra of the D^+ ions from heteronuclear clusters, provide a supplementary contribution to the efficiency of the NFDCE [25,27,33,34]. The effects of energetic and kinematic triggering on the energetics of the D^+ ions in Coulomb explosion of multicharged deuterium containing homonuclear and heteronuclear clusters are manifested by the neutron yields for NFDCE (Fig. 7) calculated [26,32,33] under the conditions of the Lawrence-Livermore experiment [49,50]. The neutron yields per laser pulse (Fig. 7) for laser intensities of $I > 10^{17}$ Wcm^{-2} are higher by 2–3 orders of magnitude for Coulomb explosion of $(CD_4)_n$ clusters than for $(D_2)_{n/2}$ clusters of the same size [27,32,33]. This theoretical prediction [27] was confirmed by the experiments of the Saclay group [51], which demonstrated a marked enhancement of neutron yields from dd fusion in an assembly of Coulomb exploding $(CD_4)_n$ clusters, as compared to $(D_2)_{n/2}$ clusters.

An extreme way to attain highly effective energetic and kinematic triggering for driving deuterons to very high energies can be achieved for Coulomb explosion of deuterated methyl iodide $(C^{6+}D_3^+I^{q+})_n$ and hydroiodic acid $(D^+I^{q+})_n$, which produces heavily charged I^{q+} ions in very intense laser fields, i.e., $q = 25$ at $I = 10^{19}Wcm^{-2}$ and $q = 35$ at $I = 10^{20}Wcm^{-2}$ [34]. For such iodine containing heteroclusters (with $n \simeq 4213$, $q = 25$ and $R_0 \simeq 40$Å) the deuteron energies are $E_{av} = 40$keV, being considerably higher than those for homonuclear $(D_2)_{15000}$ ($E_{av} \simeq 2.8$keV) and heteronuclear $(CD_4)_{4213}$ clusters ($E_{av} = 10$keV) of the same size. When the D^+ energy increases by a numerical factor of 3, the cross section for dd fusion and the neutron yield increase by 2-3 orders of magnitude (Fig. 6) [48]. We infer from the data of Fig. 7 and from the foregoing discussion that the neutron yields for Coulomb explosion of deuterium containing homonuclear and heteronuclear clusters with $R_0 = 40$Å are predicted to be $Y = 10^3$ neutrons/laser pulse for $(D_2)_{15000}$, $Y = 10^5$ neutrons/laser pulse for $(CD_4)_{4213}$, and $Y = 10^8$ neutrons/laser pulse for $(DI)_{4213}$. A semi-quantitative confirmation of these predictions was provided from experiments for Coulomb exploding $(D_2)_n$ and $(CD_4)_n$ clusters [51]. The dream of table-top nuclear fusion in the chemical physics laboratory came true.

IV. PERSPECTIVES

The NFDCE of molecular clusters induced by multielectron ionization and Coulomb explosion involves a "cold-hot" fusion mechanism, where the cluster beam constitutes a cold (or even ultracold) target, while Coulomb explosion of the assembly of clusters provides the high energy required to induce nuclear fusion. Of considerable interest are the perspectives of the NFDCE of deuterium (or tritium) containing homonuclear and heteronuclear clusters for the production of short (100ps–1ns) neutron pulses [26,50], which may be instrumental in the exploration of time–resolved structural studies of biomolecules or large molecules. The utilization of NFDCE of deuterium containing heteronuclear clusters will greatly enhance the intensity of the neutron pulse. In addition, some nuclear fusion reactions involving protons and heavy nuclei, e.g., the $^{12}C^{6+}+H^+ \rightarrow {}^{13}N^{7+}+\gamma$ reaction, are of astrophysical interest for the carbon-nitrogen-oxygen (CNO) cycle in hot stars. The CNO cycle of nuclear fusion, which supplies energy to the hot stars, is catalyzed by $^{12}C^{6+}$, which is regenerated. The $^{12}C^{6+}+H^+$ NFDCE [27] can be induced by multielectron ionization of sufficiently large methane clusters ($R_0 = 120$Å), providing information on the cross sections and dynamics of elemental nuclear processes in astrophysics.

Some novel and fascinating phenomena relating to cluster size effects and dynamics pertain to the nuclear dynamics and phase changes in finite, ultracold, gases in the temperature domain of

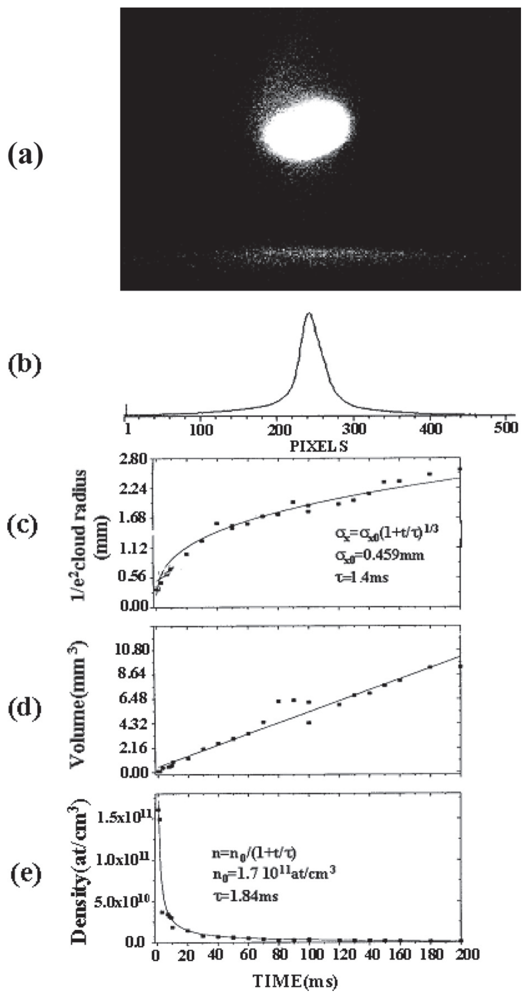

Figure 8. Nuclear dynamics of the spatial extension of optical molasses of Rb, as reported in reference 35. (a) A photograph of the irradiated cloud at t = 0. (b) Distribution of excited atoms in an irradiated cloud at t = 0. (c) Time dependence of the radius of the irradiated cloud. Characteristic expansion time τ = 1.4ms. (d) Time dependence of the volume of the irradiated cloud. (e) Time dependence of the density of the irradiated expanding cloud. Characteristic expansion time τ = 1.8ms.

T = 100nK–100μK, involving gases in magneto-optical traps, optical molasses and Bose-Einstein condensates [36]. A striking analogy was established between the nuclear dynamics of ultracold optical molasses (T = 10–100 μK) and Coulomb explosion of multicharged atomic clusters [35,36]. The optical molasses involve a cloud of trapped, laser irradiated, neutral atoms, e.g., Rb, in a magnetic trap (Fig. 8) which is characterized by a density of $\rho = 10^{11}$–10^{13} atoms/cm^3 and by an interatomic distance of $r_0 \simeq 10^4$Å. When the magnetic trap is suppressed, the cloud expands via the radiative trapping force, which prevails between radiation–emitting and reabsorbing atoms [35]. An isomorphism was established [35,36] between the radiative trapping force and the electrostatic Coulomb force, with the effective charge characterizing the radiative trapping force being $\sim 4 \cdot 10^{-5}$e, with e being the electron charge. The theory of the dynamics of cluster Coulomb explosion of multicharged molecular clusters [23,25,32,33] was applied for the expansion of optical molasses [35,36]. While the Coulomb explosion time of $(Xe^+)_n$ clusters is 10^{-13}s [23], the expansion time of optical molasses of Cs atoms was predicted to be 10 orders of magnitude longer, i.e., $\sim 10^{-3}$s [35]. This estimate is in accord with experiments (Fig. 8) [35,36]. These studies, together with the exploration of superfluidity of helium–4 clusters [22], bridge between the dynamics of clusters and ultracold, large finite quantum systems.

During the last decade, cluster science explored new fascinating scientific territories, bridging between cluster electron-nuclear dynamics and nuclear dd fusion, and bridging between cluster dynamics and ultracold quantum clouds.

REFERENCES

[1] A. Amirav, U. Even and J. Jortner (1980). Spectrocsopy of Large Molecules in Inert-Gas Clusters. Chem. Phys. Lett. 72, 16.

[2] M.J. Ondrechen, Z. Berkovitch-Yellin and J. Jortner (1981). Model Calculations of Potential Surfaces of van der Waals Complexes Containing Large Aromatic Molecules. J. Amer. Chem. Soc.

103, 6586.
[3] A. Amirav, U. Even and J. Jortner (1981). Microscopic Solvation Effects on Excited-State Energetics and Dynamics of Aromatic Molecules in Large van der Waals Complexes. J. Chem. Phys. 75, 2489.
[4] N.R. Kestner and J. Jortner (1984). Studies of the Stability of Negatively Charged Water Clusters. J. Phys. Chem. 88, 3818.
[5] J. Jortner (1984). Level Structure and Dynamics of Clusters. Ber. Bunsengesellsch. Phys. Chemie 88, 188.
[6] U. Landman, D. Scharf and J. Jortner (1985). Electron Localization in Alkali-Halide Clusters. Phys. Rev. Lett. 54, 1860.
[7] M. Bixon and J. Jortner (1989). Energetic and Thermodynamic Size Effects in Molecular Clusters. J. Chem. Phys. 91, 1631.
[8] E. Shalev, N. Ben-Horin and J. Jortner (1991). Radiative Lifetimes of van der Waals Heteroclusters. J. Chem. Phys. 94, 7757.
[9] E. Shalev, N. Ben-Horin, U. Even and J. Jortner (1991). Electronic Spectral Shifts of Aromatic Molecule-Rare-Gas Heteroclusters. J. Chem. Phys. 95, 3147.
[10] D. Bahatt, U. Even, E. Shalev, N. Ben-Horin and J. Jortner (1991). Isomer-Specific Radiative Lifetimes of Molecular Heteroclusters. Chem. Phys. 156, 223.
[11] J. Jortner (1992). Cluster Size Effects. Z. Phys. D24, 247.
[12] J. Jortner and N. Ben-Horin (1993). Spectroscopic Cluster Size Effects. J. Chem. Phys. 98, 9346.
[13] J. Jortner (1994). Dimensionality Scaling of Cluster Size Effects. Zeit. Physik. Chem. 184, 283.
[14] J. Jortner (1995). Cluster Size Effects Revisited. J. Chim. Phys. 92, 205.
[15] J.E. Combariza, N.R. Kestner and J. Jortner (1994). Energy-Structure Relationships for Microscopic Solvation of Anion in Water Clusters. J. Chem. Phys. 100, 2851.
[16] J.E. Combariza, N.R. Kestner and J. Jortner (1994). Surface and Interior States of Iodide-Water Clusters. Chem. Phys. Lett. 221, 156.
[17] I. Schek and J. Jortner (1996). Micro Shock Wave Propagation in Molecular Clusters. J. Chem. Phys. 104, 4337.
[18] A. Heidenreich, U. Even and J. Jortner (2001). Nonrigidity, Delocalization, Spatial Confinement and Electronic-Vibrational Spectroscopy of Anthracene-Helium Clusters. J. Chem. Phys. 115, 10175.
[19] U. Even, I. Al-Hroub and J. Jortner (2001). Small Helium Clusters with Aromatic Molecules. J. Chem. Phys. 115, 2069.
[20] A. Heidenreich and J. Jortner (2003). Permutational Symmetry, Isotope Effects, Side Crossing and Singlet-Triplet Splitting in Anthracene·$(He)_N$ (N = 1,2) Clusters. J. Chem. Phys. 118, 10101.
[21] A. Heidenreich, I. Last, U. Even and J. Jortner (2001). Nuclear Dynamics in Quantum Clusters. Phys. Chem. Chem. Phys. 3, 2325.
[22] J. Jortner (2004). The Superfluid Transition in Helium Clusters. J. Chem. Phys. 119, 11335.
[23] I. Last, I. Schek and J. Jortner (1997). Energetics and Dynamics of Coulomb Explosion of Highly Charged Clusters. J. Chem. Phys. 107, 6685.
[24] I. Last and J. Jortner (2000). Dynamics of Coulomb Explosion of Large Clusters in a Strong Laser Field. Phys. Rev. A62, 13201.
[25] I. Last and J. Jortner (2001). Nuclear Fusion Induced by Coulomb Explosion of Heteronuclear Clusters. Phys. Rev. Lett. 87, 033401.

[26] I. Last and J. Jortner (2001). Nuclear Fusion Driven by Coulomb Explosion of Homonuclear and Heteronuclear Deuterium and Tritium Containing Clusters. Phys. Rev. A64, 063201.
[27] I. Last and J. Jortner (2002). Nuclear Fusion Driven by Coulomb Explosion of Methane Clusters. J. Phys. Chem. A106, 10877.
[28] I. Last, K. Levy and J. Jortner (2002). Beyond the Rayleigh Instability Limit for Multicharged Finite Systems. Proceed. Natl. Acad. Sci. USA 99, 9107.
[29] J. Jortner and I. Last (2002). Nuclear Fusion Driven by Coulomb Explosion of Molecular Clusters. ChemPhysChem 3, 845.
[30] I. Last and J. Jortner (2004). Electron and Nuclear Dynamics of Molecular Clusters in Ultraintense Laser Fields. I. Extreme Multielectron Ionization. J. Chem. Phys. 120, 1336.
[31] I. Last and J. Jortner (2004). Electron and Nuclear Dynamics of Molecular Clusters in Ultraintense Laser Fields. II. Electron Dynamics of Outer Ionization of the Nanoplasma. J. Chem. Phys. 120, 1348.
[32] I. Last and J. Jortner (2004). Electron and Nuclear Dynamics of Molecular Clusters in Ultraintense Laser Fields. III. Coulomb Explosion of Deuterium Clusters. J. Chem. Phys. 121, 3030.
[33] I. Last and J. Jortner (2004). Electron and Nuclear Dynamics of Molecular Clusters in Ultraintense Laser Fields. IV. Coulomb Explosion of Molecular Heteroclusters. J. Chem. Phys. 121, 8329.
[34] I. Last and J. Jortner (2005). Regular Multicharged Transient Soft Matter in Coulomb Explosion of Heteroclusters. Proceed. Natl. Acad. Sci. USA 102, 1291.
[35] L. Pruvost, I. Serre, H.T. Duong and J. Jortner (2000). Expansion of Cooling of a Rubidium 3D Optical Molasses. Phys. Rev. A61, 053408.
[36] J. Jortner and M. Rosenblit (2005). Dynamics of Ultracold Finite Systems. Adv. Chem. Phys. 132, 247.
[37] J. Jortner and N.C.R. Rao (2002). Advanced Materials: Perspectives and Directions. Pure Appl. Chem. 74, 1491.
[38] N. Bohr and J.A. Wheeler (1939). The Mechanism of Fission. Phys. Rev. 56, 426.
[39] C. Bréchignac, Ph. Cahuzac, F. Carliez and M. de Frutos (1990). Asymmetric Fission of N_n^{++} Around the Critical Size of Stability. Phys. Rev. Lett. 64, 2893.
[40] F. Chandezon, C. Guet, B.A. Huber, M. Jalabert, E. Maurel, E. Monnand, C. Ristori and J.C. Rocco (1995). Critical Size Against Coulomb Dissociation of Highly Charged Sodium Clusters Obtained by Ion Impact. Phys. Rev. Lett. 74, 3784.
[41] E. Springate, N. Hay, J.W.G. Tisch, M.B. Mason, G. Ditmire, M.H.R. Hutchinson and J.P. Marangos (2000). Explosion of Atomic Clusters Irradiated by High Intensity Laser Pulses: Scaling of Ion Energies with Cluster and Laser Parameters. Phys. Rev. A61, 063201
[42] F. Chandezon, S. Tomita, D. Cornier, P. Grubling, C. Guet, H. Lebius, A. Pesnelle and B.A. Huber (2001). Rayleigh Instabilities in Multiply Charged Sodium Clusters. Phys. Rev. Lett. 87, 153402-1.
[43] D. Duft, H. Lebius, B.A. Huber, C. Guet and T. Leisner (2002). Shape Oscillations and Stability of Charged Microdroplets. Phys. Rev. Lett. 89, 084503-1.
[44] Lord Rayleigh (1882). On the Equilibrium of Liquid Conducting Masses Charged with Electricity. Phil. Mag. 14, 184.
[45] Yu. Ts. Oganessian et al (1999). Synthesis of Nuclei of the Superheavy Element 114 in Reactions Induced by ^{48}Ca. Nature (London) 400, 242.
[46] H. Ihee, V. Lostov, U.M. Gomez, B.M. Goodson, R. Srinivasan, C.Y. Ruan and A.H. Zewail (2001).

Direct Imaging of Transient Molecular Structure with Ultrafast Diffraction. Science 291, 458.
[47] J. Jortner (1997). Ultrafast Processes in Chemistry and Biology. Phil. Trans. Roy. Soc. London A356, 477.
[48] L.A. Artsimovich (1964). Controlled Thermonuclear Reactions (Gordon & Breach Science, NY).
[49] J. Zweiback, R.A. Smith, T.E. Cowan, G. Hays, K.B. Wharton, V.P. Yanovsky and T. Ditmire (2000). Nuclear Fusion Driven by Coulomb Explosion of Large Deuterium Clusters. Phys. Rev. Lett. 84, 2634.
[50] J. Zweiback, T.E. Cowan, R.A. Smith, J.H. Hurtlay, R. Howell, C.A. Steinke, G. Hays, K.B. Wharton, J.K. Krane and T. Ditmire (2000). Characterization of Fusion Burn Time in Exploding Deuterium Cluster Plasmas. Phys. Rev. Lett. 85, 3640.
[51] G. Grillon, Ph. Balcou, J.P. Chambaret, D. Hulin, J. Martino, S. Moustaizis, L. Notebaret, M. Pittman, Th. Pussieux, A. Rousse, J.-Ph Rousseau, S. Sebban, O. Sublemonitier and M. Schmidt (2002). Deuterium-Deuterium Fusion Dynamics in Low-Density Molecular Cluster Jets Irradiated by Intense Laser Pulses. Phys. Rev. Lett. 89, 065005.

Joshua Jortner held the position of the Heinemann Professor of Chemistry at Tel-Aviv University (1973-2003). He served as the first Chairman of the Deparment of Chemistry, Deputy Rector, Acting Rector and Vice-President of Tel-Aviv University (1965-1972). He holds honorary doctorates from Universities in Israel, France and Germany and among his awards are the Israel Prize, the Wolf Prize in Chemistry and the Medal of the Israel Chemical Society. He is a member of the Israel Academy of Sciences and Humanities, and a foreign member of 13 Academies of Sciences and Learned Societies in the USA, Europe and Asia. Jortner's scientific work in physical and theoretical chemistry, which contributed to the elucidation of the dynamics of complex systems from large molecules and clusters to biomolecules, is summarized in over 700 scientific articles and 23 books. He contributed to shaping the scientific research and public service in Israel. He served as the President of the Israel Academy of Sciences and Humanities (1986-1995) and as the first Chairman of the Israel National Science Foundation (1986-1995). He acted as science advisor to three Prime Ministers of Israel. On the international level Jortner served as the President of the International Union of Pure and Applied Chemistry (1998-2000). He is currently immersed in scientific research and in international scientific collaborations. His current public service activities span issues of science and public policy.

Isidore Last graduated in 1954 from the physics department of the Gorki State University (modern Nizni Novgorod, Russia). In 1960 he got his Ph.D. degree at the Lebediev Physical Institute (Moscow). From 1974 to 1977 he participated in the Zionist movement in the Soviet Union. In 1977 he immigrated to Israel.
His main work experience: 1954-1957 Lecturer at the Karaganda Mining Institute (Kazakhstan); 1958-1974 Senior Research Fellow at the Institute of Chemistry of the Academy of Science (Ufa, Russia); 1964-1977 part-time Associate Professor at the Bashkirian State University (Ufa); 1974-1977 Senior Research Fellow at the Institute of Geophysics (Ufa); 1979-1996 Research Fellow at the Soreq Nuclear Center; as of 1996 he is at the Tel-Aviv University. His main research activities include: solid dielectrics theory, radiometric chemical analysis, quantum chemistry, chemical reaction dynamics, atmospheric optics, and intense laser light interaction with matter.