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Electron Diffraction of Ionic Argon Nanoclusters Embedded in Superfluid Helium Droplets

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Abstract

We report electron diffraction of cationic argon nanoclusters embedded in superfluid helium droplets. Superfluid helium droplets are first doped with neutral argon atoms to form nanoclusters, and then the doped droplets are ionized by electrons. The much lower ionization energy of argon ensures that the positive charge resides on the Ar nanocluster. Using different stagnation temperatures therefore droplets with different sizes, we have been able to preferentially form a small ionic cluster containing 2 – 4 Ar atoms and a larger cluster containing 7 – 11 atoms. The fitting results of the diffraction profiles agree with structures reported from theoretical calculations, containing a cationic trimer core with the remaining atoms largely neutral. This work testifies to the feasibility of performing electron diffraction from ionic species embedded in superfluid helium droplets, dispelling the concern over the particle density in the diffraction region. However, the large number of neutral helium atoms surrounding the cationic nanoclusters poses a challenge for the detection of the helium solvation layer, and the detection of which awaits further technological improvements.

Graphical Abstract

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The crystallization problem in crystallography¹⁻⁵ has spurred intense efforts in recent years in method development for structure determinations of biological macromolecules. The method of using ultrashort and ultra-intense x-ray photons to generate diffraction patterns before the sample is disintegrated has gained tremendous success,^{6,7} and it has been adopted to determine the shape of and detect the vortices in superfluid helium droplets.⁸ Compared with x-ray photons, electrons have much larger diffraction cross sections,⁹ and with the invention of direct electron detectors and advanced data processing algorithms, cryo-electron microscopy (cryoEM) has gained tremendous momentum in recent years.¹⁰⁻¹²

Our group has been developing a method called serial single molecule electron diffraction imaging (SS-EDI) as an alternative approach to solve structures of large biological molecules and nanomaterials.⁵ The procedure starts with electrospray ionization (ESI) to produce ions for doping into superfluid helium droplets, and then the cooled ions are aligned by an elliptically polarized laser field and subjected to radiation by high energy electrons. The collection of images, each from molecules oriented from a chosen projection, is then used to determine the three-dimensional structure.

Our method is advantageous to the existing methods in several aspects, including much reduced requirements on sample purification, radiation intensity, and detector quality. However, the price for these advantages is the need for a molecular goniometer that can orient and reorient single molecules with high precision.¹³⁻¹⁵ Fortunately, with field-induced orientation and alignment, and with superfluid helium droplet cooling, molecular orientation control has been demonstrated by several groups around the world.¹⁶⁻²⁰ In fact, the ease in

aligning a molecule embedded in superfluid helium droplets has further prompted the idea of using Coulomb explosion to obtain structures of small molecules.^{4,21,22}

In our effort of building the prototype for SS-EDI, we have successfully demonstrated the feasibility of doping proteins such as the green fluorescent protein into superfluid helium droplets;²³⁻²⁵ and performed electron diffraction (ED) of neutral molecules and nanoclusters, including carbon tetrabromide (CBr₄), ferrocene (C₁₀H₁₀Fe), iodine (I₂), pyrene (C₁₆H₁₀), and carbon disulfide (CS₂) clusters embedded in superfluid helium droplets, without laser alignment.²⁶⁻³⁰ Some of the species in this list contain no heavy atoms, which shows the efficacy of the method for studies of biological molecules.

In this work, we further venture into the arena of ionic species, to tackle the concern of particle density in the diffraction region. Ionic species suffer from the space charge limit, and hence are intrinsically low in concentration. However, ions can be manipulated electrostatically, hence the background issue from undoped droplets can be partially alleviated. To minimize the technological barrier, we use argon clusters from electron impact ionization (EI) to prepare Ar_N⁺ doped helium droplets, taking advantage of the large diffraction cross section of Ar³¹ and the high yield of electron impact ionization. By varying the doping pressure and the source temperature of the droplet beam, therefore the size of the droplets, we report ED of two different cluster sizes. For reference, we also record the ED of large neutral Ar_N. Although without sample alignment, the surrounding helium – a major issue for background subtraction – seems like a nuisance, they offer a means for cluster growth, enabling the formation of clusters with desirable properties.³²⁻³⁶

Information on structures of Ar_N⁺ is primarily from theoretical calculations,³⁷⁻⁴⁴ while the dissociative nature of the excited state of Ar_N⁺ prevents high resolution spectroscopic investigations.⁴⁵⁻⁴⁸ The translational energy distribution from vibrational dissociation of Ar₃⁺ has confirmed its linear structure.^{37,41,49,50} Based on theoretical calculations and photoabsorption spectroscopy,^{38,40,48} larger clusters are considered to center around the linear trimer cation and form crowns surrounding the cation, while Ar₂⁺ centered structures only start to be more stable with $n > 15$. Our work is therefore the first experimental attempt in solving the atomic structures of Ar_N⁺ with $n > 3$. Unfortunately, due to the presence of a large number of neutral He, signal from the He atoms forming the solvation shell of the cationic cluster is below our detection limit. Hence we do not have information on the helium snowball⁵¹ surrounding the cationic nanocluster.

Most aspects of the experimental setup, as shown in Fig. 1, have been detailed in our previous publications, with the exception of the ionization component located at the exit of the doping chamber.^{26,27,29} The ionization component consists of a tungsten filament for hot electrons biased at 90 V and a grid at 150 V above the filament. The grid has a diameter of 8 mm and the droplet beam passes through the center of the coil, bombarded by the energized hot electrons for ionization. Although upon the first impact, a helium atom can be ionized, when Ar_N resides inside the droplet, and when the droplet is smaller than 10⁶ atoms/droplet,^{52,53} charge transfer results in Ar_N⁺ doped droplets.⁵⁴ The droplet beam then enters the diffraction chamber via a cone of 5 mm in diameter (not shown in the figure) where a pair of electrodes are used to accelerate the charged droplets and steer them into

the diffraction region. For diagnostics of the doping condition of the droplet beam, the repeller electrode is pulsed at 1000 V, and the time-of-flight (TOF) of the charged droplets on the microchannel plate (MCP) detector located downstream in line with the droplet beam provides the size information. For simple diagnostics and monitoring, we also use a small (3 mm in diameter) metal surface attached to an operational amplifier during the experiment to monitor the total ion flux arriving at the diffraction region. The small metal detector can swing out of the path of the MCP via feedthrough actuated from the outside of the vacuum chamber.

The electron diffraction chamber has also been detailed before.^{26,27,29} However, to prevent interference of the biased electrodes on the electron beam, the diffraction region is shielded by a grounded cylinder with openings for the charged droplets (inset of Fig. 1).

FIG. 2 presents the time profiles of the different types of droplets near the diffraction region relative to the trigger of the droplet pulse valve. The arrival time of the neutral droplets (red squares) was obtained from the total diffraction intensity – the integrated diffraction signal across the whole phosphor screen, and the vertical scale is adjusted to be comparable with those of the accelerated ions. Charged droplets are detected on the small area detector right next to the diffraction region. Ionization by the biased grid also accelerates the charged droplets, resulting in an earlier arrival time even without the pulsed voltage on the repeller (dot-dashed line). The kicker pulse further accelerates the droplets, resulting in an arrival time 300 μs ahead of the neutral droplets. As long as the duration of the electron gun is set correspondingly and is shorter than 100 μs , the recorded diffraction pattern should be completely separated from ionized samples.

The arrival times of the doped droplets are also indicative of their sizes. Although consistent with our previous observation,^{52,55,56} two groups of droplets coexist even at source temperatures of 16 and 18 K, they are not well separated in arrival time in the diffraction region, particularly when the response time of the detector is 200 μs . The small shoulder leading to the main peak in the dot-dashed line represents the small size group: its intensity is further reduced by the ionization grid and over-focusing by the Einzel lens. The larger group with sizes on the order of 10^4 atoms/droplet has a higher pickup efficiency and ionization yield, hence it is preferentially observed and optimized for diffraction.

We record diffraction patterns under three different experimental conditions. In the first experiment, neutral droplets with sizes over 10^5 atoms/droplet are used to pick up Ar under an average doping pressure of 4×10^{-6} Torr, corresponding to the formation of Ar_N with $N > 10$ in each droplet. In the second and third experiments, droplets in the size range of 10^4 atoms/droplet pass through the doping chamber with higher doping pressures, preferentially forming Ar_N^+ with $N \approx 3$ and 10. In both cases, we use the Poisson distribution to calculate the average number of pickup events, assuming that each pickup event minimally reduces the droplet size (by 184 atoms for each Ar atom⁵⁷) therefore does not affect future pickup events.

For all three diffraction experiments, the images are recorded with active background subtraction. For diffraction of neutral clusters, the sample pulsed valve and the electron

beam operate at 10 Hz, while the helium droplet beam operates at 5 Hz, and the difference ($I_{diff,Ar}$) between the images obtained with ($I_{He_{on},Ar}$) and without ($I_{He_{off},Ar}$) the droplet beam should eliminate the contribution from bare Ar diffused from the doping chamber into the ionization/diffraction chamber. In addition, a separate diffraction profile of neat neutral helium droplets ($I_{diff,neat}$) is recorded using the same method of active background subtraction without activating the sample pulse valve. For diffraction of ion doped droplets, both the sample and the droplet pulse valves operate at 10 Hz, but the electric pulse on the repeller electrode is at 5 Hz, and the difference (I_{diff,Ar_N^+}) between the images recorded when the repeller is on and off is the net diffraction from the ion doped droplets. The upper limit of the repetition rate is determined by both the data transfer rate of the camera and the pumping speed of the droplet pulse valve, while the exposure time of each pulse is determined by the effective dwell time of the cluster doped droplets in the electron beam, which will be detailed in each diffraction experiment.

Fig. 3 shows the diffraction profile of the neutral argon clusters: the exposure time of each pulse was set at 20 μ s/pulse, and the total exposure time was 1.73 s, corresponding to 86,273 shots in less than 5 hours of experiment time. The horizontal axis is the momentum transfer defined as s :⁹

$$s = \frac{4\pi}{\lambda} \sin\left(\frac{\theta_d}{2}\right) \quad (1)$$

in terms of the de Broglie wavelength λ (0.06 Å at 40 keV) and the diffraction angle θ_d . The doping statistics predict a broad size distribution centered at 9 Argons, but the diffraction profiles have a similar shape when more than 7 monomers form a face-centered cubic structure.²⁸⁻³⁰ This is because the contribution from the outer edges of the cluster is dwarfed by the regularly repeated pair distances between neighboring atoms. Exceedingly large clusters, for example, clusters containing more than 10 unit cells, however, would result in sharper features in the diffraction profile, hence the width of the observed features can be used for a rough estimate of the upper size limit. Following the treatment in our previous work,^{28,30} we performed a least-squares fitting of the experimental diffraction profile by adjusting the contribution of helium and using the face-centered cubic packing structure as shown in the inset:

$$I_{diff,Ar} = \beta \cdot I_{diff,neat} + \alpha_0 + \alpha_N \cdot I_N. \quad (2)$$

In the above equation, the coefficients α_N and β are fitting parameters related to the contribution of crystalline argon and neat neutral helium droplets, and α_0 is a baseline correction largely due to leaked light into the camera. The value of β (0.07) represents the fraction of helium atoms remaining in the diffraction region after Ar doping, and in this case, about 93% of helium atoms are lost due to collisions in the doping region, destroyed by the colliding dopant, sent off track and cannot reach the diffraction region, or boiled off due to dopant pickup.

The diffraction profile is dominated by the monotonic decay due to the atomic scattering of both helium and argon. However, interferences among diffraction waves of different atomic pairs are observable from the blue traces. The primary peak near $2.0 \text{ \AA}^{-1}$ is largely related to the nearest neighbor distance between two Ar atoms at $3.72 \text{ \AA}$, i.e. the most repeated pair distance of the nanocrystal. The agreement between experiment and fitting confirms that the nanocluster in superfluid helium droplets forms similarly as bulk solids.²⁹

Fig. 4 shows the radial profiles of the experimental diffraction pattern of ionized small Ar clusters obtained after 1,619,653 shots (90 hours of total experiment time). The exposure time of each pulse is $40 \text{ \mu s}$, and the total exposure time is 64.8 s . The droplet source temperature was at 18 K , with an average droplet size of 6×10^4 helium atoms (only the larger group survives and is used in this experiment, see Section on “Experimental setup”).^{52,55,56} After passing through a region of argon gas with a distance of 1 cm and a doping pressure of $4 \times 10^{-5} \text{ Torr}$, the most probable Ar_N^+ is with $N = 3$, but Ar_2 and Ar_4 are also probable. Based on the doping statistics, the fitting equation thus includes contributions from monomers to tetramers of ionized argon:

$$I_{diff, \text{Ar}_N^+} = \beta \cdot I_{diff, \text{neat}} + \alpha_0 + \alpha_1 \cdot I_1 + \alpha_2 \cdot I_2 + \alpha_3 \cdot I_3 + \alpha_4 \cdot I_4. \quad (3)$$

The structures of Ar_N^+ are obtained from the literature,³⁸ and the diffraction profiles of monomers to tetramers are represented by I_1 to I_4 . The tetramer ion contains a trimeric core with a linear Ar_3^+ , and the 4th atom forms an angle of 71.6° from the axis of Ar_3^+ , as shown in the inset. Although an intriguing possibility of the current system is the presence of the Ar_N^+ -He snowball,⁵¹ limited by the low scattering amplitude of He and the small number of helium atoms in the snowball (on the order of tens), compared with the neutral atoms in the droplet (on the order of hundreds or more), any signature of the snowball would be buried by the diffraction of Ar_N^+ and neutral He. Attempts to obtain monomeric Ar^+ doped small droplets were unsuccessful with the current experimental setup.

For the fitting procedure, we used the same profile of $I_{diff, \text{neat}}$ in Eq. (3) as that in Eq. (2), i.e. the diffraction profile of neutral neat helium droplets as illustrated in Fig. 3 (green trace). This choice is partly because of the low number of ionized helium droplets and hence the necessary long data accumulation time, but more importantly it is based on the consideration that when only one charge resides on a droplet containing thousands of neutral He, the diffraction pattern should be largely similar to that of a neutral droplet. However, this choice results in a value of $(6.34 \pm 0.07) \times 10^{-3}$ for β , alluding to a very small fraction of remaining helium atoms after doping and ionization, compared to the neat neutral droplet beam.

A direct fitting of Eq. (3) encounters another problem: the values of α_2 and α_4 have uncertainties larger than the actual value of the fitting coefficient. This is due to the high correlation in the structures of the cluster ions: a trimer is essentially a composition of two dimers, while a tetramer contains a trimer and an additional atom. By setting $\alpha_4 = 0$, the fitting results in $\alpha_2 = 0$, and $\alpha_3 = (4.22 \pm 0.94) \times 10^{-4}$. The two fitting procedures are then compared using the Akaike information criterion (AIC) defined as

$$AIC = m \cdot \ln(\hat{\sigma}^2) + 2k, \quad (4)$$

where m is the number of data points (sample size), $\hat{\sigma}^2$ is the Sum of Squared Residuals (SSR) over m , and k is the number of fitting parameters.⁵⁸ Models are considered equivalent when their AIC difference is < 2 ,⁵⁹ while a model is strongly preferred when its AIC is lower by more than 10 than the AICs of other models. The difference in AIC values with or without setting $\alpha_4 = 0$ is 1.8, hence the two fitting results are statistically the same. We therefore cannot conclude on a definitive size or size distribution of Ar_N^+ for this group of small nanocluster ions embedded in helium droplets. However, we can conclude that a linear trimeric structure is consistent with the experimental diffraction profile.

The contribution of Ar^+ is negligibly small in the fitting of Eq. (3), in agreement with the low probability of doping based on the Poisson statistics. We then tested the significance of α_1 by comparing the AIC values between the two models, with and without Ar^+ , and the difference is 1.5. Once again this means that the two models are statistically equivalent, in which case, the model with fewer parameters should be adopted. We note here that the effect of the +1 charge on the diffraction profile of Ar is mostly in the very small s range covered by the faraday cup on the phosphor screen,⁶⁰ hence the neutral profile is used in the calculation of Ar_N^+ with $N = 1$ to 4.

Compared with Fig. 3, the primary contribution to the modulation in the diffraction profile is shifted from 2.0 to 2.7 $\text{\AA}^{-1}$, largely due to the much shorter distance of 2.56 $\text{\AA}$ between two adjacent argon atoms, from the van der Waals distance of 3.72 $\text{\AA}$. The small amplitude modulation in the residue is non-periodic, and we do not have any explanation for its physical meaning. As will be shown in the diffraction profile of the larger ionic clusters, this modulation is unique to the small ionic cluster, hence it is not a system artifact.

Fig. 5 shows the diffraction profiles of larger Ar_N^+ , fitted using Eq. (2), since the exact number of atoms does not affect the theoretical profile for the large value of N . The number of exposures is 105,338, and the total exposure time is 12.37 s (6 hours of experiment time). The droplet source temperature was at 16 K, with an average droplet size of 7×10^4 helium atoms. At a doping pressure of 1.1×10^{-4} Torr, the most probable Ar_N is with $N = 7$ to 10.

Two different views of Ar_{10}^+ are presented in the inset of Fig. 5, consisting of a pseudo linear cationic trimer core and 7 neutral atoms. Five of the seven Ar atoms form a ring surrounding one end of the linear trimer, while the other two stagger from the atoms of the 5-member ring and surround the other end of the trimer. The distances between the neutral Ar to the charged Ar_3^+ ranges from 3.42 to 3.87 $\text{\AA}$. Other potential structures, for example a structure with a cationic dimer core, are substantially higher in energy or disagree with the absorption feature and are therefore not considered here.^{38,40,48} The high quality of the final fitting, as indicated by the residue, confirms this choice for the structure.

In addition to the cationic trimer core structure, we also tried to fit the diffraction profile using the structure of the neutral cluster as illustrated in the inset of Fig. 3. The difference between the ionic structure and the neutral structure diminishes with increasing cluster sizes,

since the charge is localized on just 3 Ar atoms. The dashed line and dotted line in figure 5 are the theoretical contributions from Ar_{10}^+ and Ar_9 . The peak positions in the two profiles are shifted from 2.00 (neutral) to 2.15 $\text{\AA}^{-1}$ (cation), implying a generally more compact structure for the cationic cluster. However, compared with Fig. 4 with a primary peak at 2.7 $\text{\AA}^{-1}$, this larger cluster of Ar_{10}^+ contains many more longer pair distances such as those between neutral atoms, hence the collective effect is to shift the primary peak to a smaller value of s . To compare the relative quality of the two different structures of Ar_{10}^+ and Ar_9 , we list the AIC values in Table I, and as expected, a strong preference for the ionic model is confirmed.

Based on the diffraction cross sections of He and Ar and values of the fitting coefficients,³¹ we can estimate the amount of remaining He attached to Ar_N^+ . In Figs 4 and 5, the numbers are between 400 and 1000. These values are substantially smaller than the initial neutral droplet size (over 10^4), and the reduction in the number of He atoms is caused by doping of Ar and ionization by energetic electrons. In addition, the ionized droplets are “kicked” by a pulsed electrode into the diffraction region, and the timing of the pulsed electron beam further has a selection effect.

Electron diffraction of bare ionic clusters has been attempted using trapped ions generated from magnetron sputtering, electron impact, or discharge.⁶¹⁻⁶⁵ Structures of heavy metal ions and even cationic buckminsterfullerene have been determined. More recently, phase or structure changes of Ru_{14}^- and Ru_{14}^- upon hydrogen adsorption have been revealed from trapped ion ED.^{61,66} In these experiments, ions are first stored in a Paul trap, but just prior to the arrival of electrons, the cooling gas of the ion trap is pumped out. Without the cooling gas, ions can only stay in the trap for a few seconds of diffraction time, after which, the trap has to be refilled with ions and cooling gas until the next cycle.

Our work is the first that uses directly ionized ions for diffraction without an ion trap. Compared with imaging, diffraction is independent of the location of the atoms in the interaction region, hence the motion of the ions does not substantially affect the diffraction pattern of a parallel electron beam. This feature makes it ideal to use a focused slow-traveling ion beam for structure determination. Ionized samples are advantageous in that they can be separated from neutrals via electrostatic manipulation, but in the meantime, the field from the ion optics can also affect the motion of the diffracted electrons, hence shielding of the electron path is necessary.

In our previous work on neutral nanocluster doped droplets, a substantial effort was devoted to the removal of neat droplets that contain no diffraction sample, including the use of extreme doping conditions leading to the sacrifice of small droplets.²⁶⁻³⁰ In this experiment of ionic samples, this problem is partially alleviated by the acceleration electrodes. However, for effective doping and ionization, larger droplets are still preferred, and the strong helium background from helium atoms still remains. Additional technological improvements are needed to further minimize the contribution from the remaining helium atoms and maximize the ion count.

In conclusion, we have demonstrated the feasibility of electron diffraction of cationic argon nanoclusters embedded in superfluid helium droplets. Contributions from Ar_N^+ containing hundreds to thousands of He can be clearly identified and fitted using model structures. Our results confirm the linear trimeric core of Ar_N^+ , surrounded by neutral argon atoms. As a direct structure tool, ED is promising in solving structures of clusters, including ionic clusters with applications in biological and material sciences.

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REFERENCE

- (1). Neutze R; Wouts R; van d. S. D.; Weckert E; Hajdu J Potential for Biomolecular Imaging with Femtosecond X-Ray Pulses, *Nature* 2000, 406, 752–757. [PubMed: 10963603]
- (2). Yang J; Centurion M Gas-Phase Electron Diffraction from Laser-Aligned Molecules, *Struct. Chem* 2015, 26, 1513–1520.
- (3). Karamatskos ET; Raabe S; Mullins T; Trabattoni A; Stammer P; Goldsztejn G; Johansen RR; Długolecki K; Stapelfeldt H; Vrakking MJJ; Trippel S; Rouzée A; Küpper J Molecular Movie of Ultrafast Coherent Rotational Dynamics of Ocs, *Nat. Commun* 2019, 10, 3364. [PubMed: 31358749]
- (4). Schouder C; Chatterley AS; Calvo F; Christiansen L; Stapelfeldt H Structure Determination of the Tetracene Dimer in Helium Nanodroplets Using Femtosecond Strong-Field Ionization, *Struct. Dyn* 2019, 6, 044301. [PubMed: 31463336]
- (5). Beckman J; Kong W; Voinov VG; Freund WM, USA Patent No. US20150168318A1 (3 8, 2016).
- (6). Johansson LC; Stauch B; Ishchenko A; Cherezov V A Bright Future for Serial Femtosecond Crystallography with Xfels, *Trends Biochem. Sci* 2017, 42, 749–762. [PubMed: 28733116]
- (7). Neutze R Opportunities and Challenges for Time-Resolved Studies of Protein Structural Dynamics at X-Ray Free-Electron Lasers, *Philos. Trans. R. Soc. Lond. B Biol Sci* 2014, 369, 20130318. [PubMed: 24914150]
- (8). Gessner O; Vilesov AF Imaging Quantum Vortices in Superfluid Helium Droplets, *Annu. Rev. Phys. Chem* 2019, 70, 173–198. [PubMed: 31174460]
- (9). Brockway LO Electron Diffraction by Gas Molecules, *Rev. Mod. Phys* 1936, 8, 231–266.
- (10). Lawson CL; Kryzhtafovich A; Adams PD; Afonine PV; Baker ML; Barad BA; Bond P; Burnley T; Cao R; Cheng J; Chojnowski G; Cowtan K; Dill KA; DiMaio F; Farrell DP; Fraser JS; Herzik MA Jr; Hoh SW; Hou J; Hung L-W; Igaev M; Joseph AP; Kihara D; Kumar D; Mittal S; Monastyrskyy B; Olek M; Palmer CM; Patwardhan A; Perez A; Pfab J; Pintilie GD; Richardson JS; Rosenthal PB; Sarkar D; Schafer LU; Schmid MF; Schroder GF; Shekhar M; Si D; Singharoy A; Terashi G; Terwilliger TC; Vaiana A; Wang L; Wang Z; Wankowicz SA; Williams CJ; Winn M; Wu T; Yu X; Zhang K; Berman HM; Chiu W Cryo-Em Model Validation Recommendations Based on Outcomes of the 2019 Emdataresource Challenge, *Nat. Methods* 2021, 18, 156–164. [PubMed: 33542514]
- (11). Taheri ML; Stach EA; Arslan I; Crozier PA; Kabius BC; LaGrange T; Minor AM; Takeda S; Tanase M; Wagner JB; Sharma R Current Status and Future Directions for in Situ Transmission Electron Microscopy, *Ultramicroscopy* 2016, 170, 86–95. [PubMed: 27566048]
- (12). Elmlund D; Elmlund H Cryogenic Electron Microscopy and Single-Particle Analysis, *Annu. Rev. Biochem* 2015, 84, 499–517. [PubMed: 25747402]
- (13). Starodub D; Rez P; Hembree G; Howells M; Shapiro D; Chapman HN; Fromme P; Schmidt K; Weierstall U; Doak RB; Spence JCH Dose, Exposure Time and Resolution in Serial X-Ray Crystallography, *J. Synchrotron Radiat* 2008, 15, 62–73. [PubMed: 18097080]

- (14). Starodub D; Doak RB; Schmidt K; Weierstall U; Wu JS; Spence JCH; Howells M; Marcus M; Shapiro D; Barty A; Chapman HN Damped and Thermal Motion of Laser-Aligned Hydrated Macromolecule Beams for Diffraction, *J. Chem. Phys* 2005, 123, 244304. [PubMed: 16396534]
- (15). Spence JCH; Doak RB Single Molecule Diffraction, *Phys. Rev. Lett* 2004, 92, 198102. [PubMed: 15169448]
- (16). Pentlechner D; Nielsen JH; Slenczka A; Molmer K; Stapelfeldt H Impulsive Laser Induced Alignment of Molecules Dissolved in Helium Nanodroplets, *Phys. Rev. Lett* 2013, 110, 093002. [PubMed: 23496707]
- (17). Hansen JL; Stapelfeldt H; Dimitrovski D; Abu-Samha M; Martiny CPJ; Madsen LB Time-Resolved Photoelectron Angular Distributions from Strong-Field Ionization of Rotating Naphthalene Molecules, *Phys. Rev. Lett* 2011, 106, 073001. [PubMed: 21405510]
- (18). Kong W; Pei L; Zhang J Linear Dichroism Spectroscopy of Gas Phase Biological Molecules Embedded in Superfluid Helium Droplets, *Int. Rev. Phys. Chem* 2009, 28, 33–52.
- (19). Larsen JJ; Hald K; Bjerre N; Stapelfeldt H; Seideman T Three Dimensional Alignment of Molecules Using Elliptically Polarized Laser Fields, *Phys. Rev. Lett* 2000, 85, 2470–2473. [PubMed: 10978084]
- (20). Friedrich B; Herschbach D Polarization of Molecules Induced by Intense Nonresonant Laser Fields, *J. Phys. Chem* 1995, 99, 15686–15693.
- (21). Pickering JD; Shepperson B; Hübschmann BAK; Thorning F; Stapelfeldt H Alignment and Imaging of the Cs₂ Dimer inside Helium Nanodroplets, *Phys. Rev. Lett* 2018, 120, 113202. [PubMed: 29601737]
- (22). Pickering JD; Shepperson B; Christiansen L; Stapelfeldt H Femtosecond Laser Induced Coulomb Explosion Imaging of Aligned Ocs Oligomers inside Helium Nanodroplets, *J. Chem. Phys* 2018, 149, 154306. [PubMed: 30342461]
- (23). Zhang J; Chen L; Freund WM; Kong W Effective Doping of Low Energy Ions into Superfluid Helium Droplets, *J. Chem. Phys* 2015, 143, 074201. [PubMed: 26298127]
- (24). Chen L; Zhang J; Freund WM; Kong W Effect of Kinetic Energy on the Doping Efficiency of Cesium Cations into Superfluid Helium Droplets, *J. Chem. Phys* 2015, 143, 044310. [PubMed: 26233132]
- (25). Alghamdi M; Zhang J; Oswalt A; Porter JJ; Mehl RA; Kong W Doping of Green Fluorescent Protein into Superfluid Helium Droplets: Size and Velocity of Doped Droplets, *J. Phys. Chem. A* 2017, 121, 6671–6678. [PubMed: 28825305]
- (26). He Y; Zhang J; Kong W Electron Diffraction of CBr₄ in Superfluid Helium Droplets: A Step Towards Single Molecule Diffraction, *J. Chem. Phys* 2016, 145, 034307. [PubMed: 27448887]
- (27). Zhang J; He Y; Kong W Communication: Electron Diffraction of Ferrocene in Superfluid Helium Droplets, *J. Chem. Phys* 2016, 144, 221101. [PubMed: 27305988]
- (28). Zhang J; Bradford S; Kong W Electron Diffraction of Cs₂ Nanoclusters Embedded in Superfluid Helium Droplets, *J. Chem. Phys* 2020, 152, 224306. [PubMed: 32534524]
- (29). He Y; Zhang J; Lei L; Kong W Self-Assembly of Iodine in Superfluid Helium Droplets: Halogen Bonds and Nanocrystals, *Angew. Chem., Int. Ed* 2017, 56, 3541–3545.
- (30). Lei L; Yao Y; Zhang J; Tronrud D; Kong W; Zhang C; Xue L; Dontot L; Rapacioli M Electron Diffraction of Pyrene Nanoclusters Embedded in Superfluid Helium Droplets, *J. Phys. Chem. Lett* 2020, 11, 724–729. [PubMed: 31884792]
- (31). Jablonski AS,F; Powell CJ Nist Electron Elastic-Scattering Cross-Section, Database, Version 3.2, Srd 64; National Institute of Standards and Technology: Gaithersburg, MD, 2010.
- (32). Loginov E; Gomez LF; Vilesov AF Surface Deposition and Imaging of Large Ag Clusters Formed in He Droplets, *J. Phys. Chem. A* 2011, 115, 7199–7204. [PubMed: 21486053]
- (33). Latimer E; Spence D; Feng C; Boatwright A; Ellis AM; Yang S Preparation of Ultrathin Nanowires Using Superfluid Helium Droplets, *Nano Lett.* 2014, 14, 2902–2906. [PubMed: 24742117]
- (34). Thaler P; Volk A; Knez D; Lackner F; Haberfehlner G; Steurer J; Schnedlitz M; Ernst WE Synthesis of Nanoparticles in Helium Droplets-a Characterization Comparing Mass-Spectra and Electron Microscopy Data, *J. Chem. Phys* 2015, 143, 134201. [PubMed: 26450307]

- (35). Lundberg L; Martini P; Goulart M; Gatchell M; Bohme DK; Scheier P Hydrogenated Gold Clusters from Helium Nanodroplets: Cluster Ionization and Affinities for Protons and Hydrogen Molecules, *J. Am. Soc. Mass Spectrom* 2019, 30, 1906–1913. [PubMed: 31168747]
- (36). Schnedlitz M; Fernandez-Perea R; Knez D; Lasserus M; Schiffmann A; Hofer F; Hauser AW; de Lara-Castells MP; Ernst WE Effects of the Core Location on the Structural Stability of Ni-Au Core-Shell Nanoparticles, *J. Phys. Chem. C* 2019, 123, 20037–20043.
- (37). Kalus R; Stachon M; Gadea FX On the Competition between Linear and Perpendicular Isomers in Photodynamics of Cationic Argon Trimers, *J. Chem. Phys* 2012, 137, 234308. [PubMed: 23267487]
- (38). Galindez J; Calvo F; Paska P; Hrivnak D; Kalus R; Gadea FX Dim Modelings for Realistic Simulations of Ionic Rare-Gas Clusters, Test on Structures and Photoabsorption Spectra of Ar_n^+ ($N=3-8$), *Comput. Phys. Commun* 2002, 145, 126–140.
- (39). Hrivnak D; Kalus R Intra-Cluster Transitions in Small Ar_n^+ Cations, *Chem. Phys* 2001, 264, 319–331.
- (40). Doltsinis NL; Knowles PJ; Naumkin FY Induced Dipole-Induced Dipole Interactions in Ar_n^+ Clusters, *Mol. Phys* 1999, 96, 749–755.
- (41). Hsu YT; Mason B; Von Nagy-Felsobuki EI Analysis of Fragmentation Data and Molecular Orbital Calculations of Small Argon Ion Clusters, *J. Cluster Sci* 1997, 8, 59–85.
- (42). Ikegami T; Kondow T; Iwata S The Geometric and Electronic Structures of Argon Cluster Ions($1+$) (Ar_n^+ ($N = 3-27$)), *J. Chem. Phys* 1993, 98, 3038–3048.
- (43). Last I; George TF Semiempirical Study of Rare Gas and Rare Gas-Hydrogen Ionic Clusters: R_n^+ , R_nh^+ , and R_nh_2^+ for $\text{R}=\text{Ar}, \text{Xe}$, *J. Chem. Phys* 1990, 93, 8925–8938.
- (44). Lethbridge PG; Del Mistro G; Stace AJ Hard-Sphere Cluster-Ion Structures, *J. Chem. Phys* 1990, 93, 1995–2003.
- (45). Kalus R; Janecek I; Gadea FX Non-Adiabatic Dynamics Combining Ehrenfest, Decoherence, and Multiscale Approaches Applied to Ionic Rare-Gas Clusters Photodissociation, Post-Ionization Fragmentation, and Collisions, *Comput. Theor. Chem* 2019, 1153, 54–64.
- (46). Pukowiecova P; Gadea FX; Kalus R Photodissociation Dynamics of Ionic Argon Pentamer, *J. Chem. Phys* 2010, 133, 214302. [PubMed: 21142299]
- (47). Haberland; von IB; Kolar; Kornmeier; Ludewigt; Risch. Electronic and Geometric Structure of Ar_n^+ and Xe_n^+ Clusters: The Solvation of Rare-Gas Ions by Their Parent Atoms, *Phys. Rev. Lett* 1991, 67, 3290–3293. [PubMed: 10044695]
- (48). Lvinger NE; Ray D; Alexander ML; Lineberger WC Photoabsorption and Photofragmentation Studies of Argon (Ar_n^+) Cluster Ions, *J. Chem. Phys* 1988, 89, 5654–5662.
- (49). Karlicky F; Lepetit B; Kalus R; Gadea FX Vibrational Spectrum of Ar_3^+ and Relative Importance of Linear and Perpendicular Isomers in Its Photodissociation, *J. Chem. Phys* 2011, 134, 084305. [PubMed: 21361537]
- (50). Lepere V; Picard YJ; Barat M; Fayeton JA; Lucas B; Beroff K Photodissociation Dynamics of Ar_2^+ and Ar_3^+ Excited by 527 Nm Photons, *J. Chem. Phys* 2009, 130, 194301. [PubMed: 19466830]
- (51). Atkins KR Ions in Liquid Helium, *Phys. Rev* 1959, 116, 1339–1343.
- (52). Alghamdi M; Zhang J; Kong W Doping with Multiple Cations and Failure of Charge Transfer in Large Ionized Helium Droplets, *J. Chem. Phys* 2019, 151, 134307. [PubMed: 31594345]
- (53). Ellis AM; Yang S Model for the Charge-Transfer Probability in Helium Nanodroplets Following Electron-Impact Ionization, *Phys. Rev. A: At., Mol., Opt. Phys* 2007, 76, 032714.
- (54). Ferreira da Silva F; Bartl P; Denifl S; Echt O; Maerk TD; Scheier P Argon Clusters Embedded in Helium Nanodroplets, *Phys. Chem. Chem. Phys* 2009, 11, 9791–9797. [PubMed: 19851558]
- (55). Pandey R; Tran S; Zhang J; Yao Y; Kong W Bimodal Velocity and Size Distributions of Pulsed Superfluid Helium Droplet Beams, *J. Chem. Phys* 2021, 154, 134303. [PubMed: 33832230]
- (56). Alghamdi M; Zhang J; Bradford SD; Kong W Suppression of Multiphoton Ionization of Aniline in Large Superfluid Helium Droplets, *Chem. Phys. Lett* 2019, 735, 136752. [PubMed: 32863396]

- (57). Lewerenz M; Schilling B; Toennies JP Successive Capture and Coagulation of Atoms and Molecules to Small Clusters in Large Liquid Helium Clusters, *J. Chem. Phys* 1995, 102, 8191–8207.
- (58). Akaike H A New Look at the Statistical Model Identification, *IEEE Trans. Autom. Control* 1974, 19, 716–723.
- (59). Burnham KP; Anderson DR Multimodel Inference: Understanding Aic and Bic in Model Selection, *Sociol. Methods Res* 2004, 33, 261–304.
- (60). Peng L-M Electron Scattering Factors of Ions and Their Parameterization, *Acta Crystallogr., Sect. A: Found. Crystallogr* 1998, A54, 481–485.
- (61). Hehn A-S; Bum Mueller D; Kloppe W; Kappes MM; Schooss D Structural Phase Transition of Ruthenium Cluster Hydrides, *J. Phys. Chem. C* 2020, 124, 14306–14315.
- (62). Kraft M; Flores JR; Kloppe W; Kappes MM; Schooss D Structures of Small Tantalum Cluster Anions: Experiment and Theory, *J. Phys. Chem. A* 2021, 125, 3135–3145. [PubMed: 33830770]
- (63). Schooss D; Weis P; Hampe O; Kappes MM Determining the Size-Dependent Structure of Ligand-Free Gold-Cluster Ions, *Philos. Trans. R. Soc., A* 2010, 368, 1211–1243.
- (64). Parks JH Structure and Dynamics of Trapped Ions. In *Practical Aspects of Trapped Ion Mass Spectrometry*; March RE; Todd JFJ, eds.; CRC Press: 2009, pp. 169–203.
- (65). Maier-Borst M; Cameron DB; Rokni M; Parks JH Electron Diffraction of Trapped Cluster Ions, *Phys. Rev. A: At., Mol., Opt. Phys* 1999, 59, R3162–R3165.
- (66). Bum Mueller D; Hehn A-S; Waldt E; Ahlrichs R; Kappes MM; Schooss D Ruthenium Cluster Structure Change Induced by Hydrogen Adsorption: Ru₁₉, *J. Phys. Chem. C* 2017, 121, 10645–10652.

FIG. 1.

Experimental setup showing the components for electron impact ionization of argon doped droplets and the electrodes for the acceleration of ionized droplets. The arrival time on the MCP detector is used to determine the size of the doped droplets. The detector inside the shield cylinder is removable and is used to monitor the ions during diffraction. The drawing is not to scale.

FIG. 2.

Arrival times of different groups of droplets near the diffraction region. The neutral droplets are determined from the overall diffraction intensity, but the ionic droplets are detected by the detector inside the shield cylinder (Fig. 1). “Ionized droplets” are accelerated by the ionization grid, while the “accelerated ions” are a result of an additional pulsed voltage on the repeller electrode.

FIG. 3. Diffraction profiles of neutral argon clusters containing over 10 Ar embedded in superfluid helium droplets. The structure is shown in the inset.

Fig. 4.

Diffraction profiles of small argon cluster ions. The structures of Ar_3^+ and Ar_4^+ are shown in the inset. The colors represent different charge states: red: +0.5, purple: +0.25, and light blue: neutral.

Fig. 5. Diffraction profiles of large argon cluster ions. Two different profiles from Ar_{10}^+ (dashed line) and Ar_9 (dotted line) are shown for comparison. The total fitting and the residue are based on the profile of Ar_{10}^+ . The inset shows the structure of Ar_{10}^+ from two different observation angles. The color scheme is the same as that of Fig. 4.

Table I.

AIC values of the different fitting models

Model	AIC
Ar_{10}^+	-1451
Ar_9	-1423