

Mechanism for the efficient homogeneous nucleation of ice in a weakly-ionized, ultra-cold plasma

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ABSTRACT

It is proposed that the rapid observed homogeneous nucleation of ice dust in a cold, weakly-ionized plasma depends on the formation of negative hydroxyl ions by fast electrons impacting water molecules. These OH⁻ ions attract neutral water molecules because of the high dipole moment of the water molecules and so hydrates of the form (OH)⁻(H₂O)_n are formed. The hydrates continuously grow in the cold environment to become macroscopic ice grains. These ice grains are negatively charged as a result of electron impact and so continue to attract water molecules. Because the hydroxyl ions are negative, unlike positive ions they do not suffer recombination loss from collision with plasma electrons. Recombination with positive ions is minimal because positive ions are few in number (weak ionization) and slow-moving as result of being in thermal equilibrium with the cold background gas.

1. INTRODUCTION

Grains of water ice occur in many terrestrial and extra-terrestrial contexts. Examples include noctilucent clouds (Vaste 1993), comet tails (Protopapa et al. 2014), Saturn's diffuse rings (Vahidinia et al. 2011), plumes ejected by Enceladus (Dong et al. 2015), protoplanetary disks (Terada et al. 2007), and matter orbiting black holes (Moultaka et al. 2015). In order for these grains to nucleate, there must be pre-existing water vapor or hydrogen and oxygen that make water. Mechanisms for ice nucleation are categorized as being either inhomogeneous or inhomogeneous: inhomogeneous nucleation involves ice forming as a cover or mantle on a pre-existing non-ice solid material such as silicate or carbon whereas homogeneous nucleation is the situation where ice forms with no non-ice substrate. Studies of tropospheric (lower atmosphere) ice formation have shown that inhomogeneous nucleation dominates homogeneous nucleation by orders of magnitude (Pruppacher & Klett 2010). This tropospheric domination of inhomogeneous nucleation has generally been presumed to extend to noctilucent clouds (mesosphere) (Gumbel & Megner 2009) and to extra-terrestrial contexts (Jones & Williams 1984; Seki & Hasegawa 1983). However, these non-tropospheric contexts differ by being ultra-cold (gas temperature 150 K or less) and weakly ionized.

The paradigm that homogeneous nucleation is negligible compared to inhomogeneous nucleation requires pre-existence of non-ice solid material. It is generally presumed that this solid material is silicate (Seki & Hasegawa 1983) in the context of protoplanetary disks while for noctilucent clouds it is generally presumed that the solid material is carbon smoke from ablating micrometeoroids (Gumbel & Megner 2009). However, various observations cast doubt on this paradigm:

1. The presumption that extra-terrestrial water ice can exist only as a coating on silicate cores is clearly invalid for Saturn's rings where in-situ mass spectrometry of ring ice grains by the Cassini spacecraft Cosmic Dust Analyzer (CDA) showed that dust grains were composed of either water ice or silicate (Hsu et al. 2018), but not of both.
2. The spectra of Saturn's rings show water ice but no evidence of silicates (Spilker et al. 2003).
3. Potapov et al. (2021) showed that fits to certain protoplanetary disk infrared absorption spectra were best explained using pure water ice rather than a combination of ice and silicates.
4. There is minimal observational evidence for the existence of carbon smoke particles at the location where noctilucent clouds form and there is minimal evidence that micrometeoroids deposit this carbon smoke (Rapp & Thomas 2006).

5. Murray & Jensen (2010) and Zsazetsky et al. (2009) have postulated that homogeneous nucleation can occur in noctilucent clouds. An important feature of the Murray/Jensen and Zsazetsky et al. papers is the realization that at the very low temperatures and pressures of interest, nucleation likely occurs in a quite different manner from nucleation in the tropospheric terrestrial atmosphere.
6. An ice dusty plasma experiment by Shimizu et al. (2010) at the Max Planck Institute for Extraterrestrial Physics showed that water ice grains would spontaneously nucleate in a weakly ionized plasma formed from a mixture of D₂ and O₂ if the electrodes were cooled by liquid nitrogen so that the background gas would be at a low temperature. Shimizu et al. modeled their experiment assuming that the nucleation was inhomogeneous (ice nucleated about non-ice seed particles) but noted that there was no experimental evidence for the existence of the assumed seed particles.
7. An ice dusty plasma experiment at Caltech (Chai & Bellan 2013, 2015a,b; Marshall et al. 2017) has shown that ice spontaneously nucleates when a small amount of water vapor is injected into a weakly ionized plasma if the plasma background gas is cold (<200 K) and above a critical pressure. Once nucleation has occurred, the pressure can be lowered at which point the ice grains grow quickly to a large size within 10-100 seconds. The ice grains are long, slightly dendritic spindles that are highly charged. The system behaves as a classic dusty plasma with the additional feature that the spindles self-align so as to be mutually parallel. The experimental parameters are similar to the presumed parameters of protoplanetary disks, noctilucent clouds, and Saturn's rings. Specifically, the background gas density of the lab experiment is within one or two orders of magnitude of these naturally occurring situations, the background gas temperature is similarly cold, the degree of ionization is similarly small, and water molecules are similarly present. Since protoplanetary disk parameters vary considerably depending on the distance from the star and the altitude above the midplane, it is quite plausible that the lab experiment exactly duplicates some specific localized protoplanetary disk region.

2. CLASSIC NUCLEATION THEORY SUMMARIZED

Gas phase ice nucleation is conventionally assumed to occur in accordance with classic nucleation theory (CNT) which postulates that nucleation is inhomogeneous and results from the interplay between the thermodynamic concepts of Gibbs free energy and surface tension. CNT was originally formulated for liquid drops but has been proposed to extrapolate to ice nucleation. CNT assumes that a new-born liquid drop (in the ice extrapolation, new-born ice grain) is spherical and has a radius r that relates to the surface tension. This model was reviewed by Rapp & Thomas (2006) and by Gumbel & Megner (2009) in the context of noctilucent cloud ice grains and the process was that of water nucleating on charged meteoric smoke particles. A critical assumption in CNT is that nucleation can be described using bulk matter properties. CNT shows using considerations of surface tension that there is an energy barrier preventing nucleation at small radius; this is because the force associated with surface tension is inversely proportional to the radius of curvature of the surface so this force becomes infinite as the radius approaches zero.

Gumbel and Megner noted that ionic nucleation could be an alternate to meteoric smoke nucleation. This alternate had been proposed by Witt (1969) and studied further by Sugiyama (1994); Goldberg and Witt measured mesospheric ionic content with a sounding rocket. Gumbel and Megner considered $H^+(H_2O)_n$ as the embryonic core nucleus and this ionic process was deemed more favorable than nucleation on a neutral substrate because of the attraction of the dipole moment of a water molecule to the charge of a proton. The Gumbel and Megner model was based on CNT and proposed that the critical nucleus radius at which growth can overcome surface tension is a ~ 1 nm. The Gumbel and Megner model also proposed that the critical radius becomes zero for the case of ionic nucleation at sufficiently low temperatures. Although Gumbel and Megner suggested that the ionic scheme could surpass heterogeneous nucleation, they then dismissed the ionic scheme on the grounds that ambient electrons would quickly neutralize the proton hydrates so that this recombination would eliminate the advantages of charge attracting water molecules. Gumbel and Megner proposed that negatively charged meteor smoke particles would instead provide a more plausible nucleus as these would not suffer recombination via electron collisions and yet would still exploit the attraction of water molecules to a charged nucleus. Hervig et al. (2012) interpreted optical properties of noctilucent clouds as indicating that ice grains contained small amounts of solid material that would be consistent with meteor smoke and so provide support for the negatively charged meteor smoke acting as nuclei.

3. NUCLEATION FROM NEGATIVE IONS

The purpose of this paper is to argue that ice nucleation is indeed ionic as proposed by Gumbel and Megner but on *negative ions* rather than the positive ions considered by Gumbel and Megner. A negative ion would attract a water molecule just like a negatively charged smoke particle and being negative, would similarly be immune to recombination via electron impact. The question then is whether the proposed negative ions exist.

There is substantial evidence for the existence of negative ions in various plasmas but this evidence is generally indirect because direct observation of negative ions is difficult. The difficulty arises because negative ions have negligible spectroscopic footprint so their existence cannot be easily demonstrated by remote spectroscopic observation. Two types of indirect measurement have been used. The first is to make precise measurements of the electron and the positive ion densities. Since the plasma is expected to be quasi-neutral, if measurements indicate an electron density lower than the positive ion density, then there must be negative ions to provide the overall quasi-neutrality. The second method is to transiently detach electrons from the negative ions using energetic photons and then measure a transient increase in the electron density using probes or microwaves. The problem with indirect methods is that their interpretation is complex and requires numerous assumptions and models. Direct measurement would clearly be preferable. The most obvious direct measurement method is direct collection of negative ions but this is impossible for astrophysical situations and difficult for laboratory situations. On the other hand, negative ions are routinely observed in the low-altitude atmosphere (troposphere). There is little observational information at mesospheric altitudes where any depletion of electrons relative to ions has generally been attributed to dust rather than ions capturing electrons.

Below is a list of several relevant situations showing that plasmas can contain electronegative atoms or molecules. These examples show that plasmas can contain negative ions of oxygen, hydrogen, hydroxyl, and sulfur hexafluoride.

Nguyen et al. (2009) measured electron and ion densities in an argon-water plasma and found that the free electron density was suppressed compared to that of a pure argon plasma. This was attributed to electrons attaching to electronegative atoms or molecules such as hydroxyl and oxygen.

Howling et al. (1994) observed growth of highly polymerized negative polysilicon hydride molecules in a silane (SiH_4) plasma and suggested that negative ions are the precursors to particle formation. Because electrons move faster than ions, electrons leave the bulk plasma faster giving the bulk plasma a positive potential. This constitutes a potential well for negative ions and so negative ions have near perfect confinement which provides ample time for negative ions to interact with other species. The negative ions are presumed to induce a dipole moment in silane molecules so that there is then an attraction between the negative ion and the silane. This continues to attract other silane molecules so a large well-confined negative structure is developed. This process has been reviewed by Girshick (2020).

Using a Wien $\text{E} \times \text{B}$ filter, Renaud et al. (2015) observed negative fluorine atoms in a SF_6 discharge ion thruster.

Millar et al. (2017) reviewed negative ions in astrophysical environments and noted that the ratios of negative hydrogen atoms and negative hydrocarbon molecules (C_4H^- , C_6H^- , etc.) to neutrals can be as high as 10%.

Coates et al. (2010) detected negative ions in the plume of Enceladus and interpreted these as negative water clusters.

Arshadi & Kebarle (1970) observed gas phase hydrates of OH^- , i.e., $\text{OH}^-(\text{H}_2\text{O})_n$ in water vapor containing traces of hydrogen peroxide and in pure water. They also observed gas phase hydrates of O_2^- , i.e., $\text{O}_2^-(\text{H}_2\text{O})_n$. Kebarle et al. (1968) observed gas phase hydration of F^- , Cl^- , Br^- , I^- , O_2^- , and NO_2^- . Meot-Ner & Speller (1986) also measured production of $\text{OH}^-(\text{H}_2\text{O})_n$. Newton & Ehrenson (1971) reported ab initio calculations of the formation of $\text{OH}^-(\text{H}_2\text{O})_n$.

Sirse et al. (2017) observed O^- , F^- , and CF_3^- in an $\text{Ar}/\text{O}_2/\text{C}_4\text{F}_8$ capacitively coupled rf discharge using a diagnostic involving laser photo-emission and resonance shift of a hair-pin probe.

Gregory et al. (2019) made ab initio molecular dynamics studies of the formation of $\text{O}_2^-(\text{H}_2\text{O})_n$ and found very stable structures.

Witt (1969) considered ion hydrates forming noctilucent clouds and mainly considered positive ions although mentioned the possibility of a NO_2^- hydrate.

Jungen et al. (1979) presented experimental data showing that electrons with energy exceeding approximately 4.5 eV would dissociate water to produce negative hydroxyl ions; thus tail electrons in an approximately 2 eV plasma could produce negative hydroxyl ions.

Shimizu et al. (2010) observed using mass spectrometry an increase in DO (hydroxyl ion with deuterium) from background level in their $\text{D}_2\text{-H}_2$ weakly ionized plasma when the electrodes were not cooled so no ice dust was formed. However, they saw a very slight decrease in DO if the electrodes were cooled so that ice dust was formed.

species	electron affinity energy E_a (eV)
O	1.43
O ₂	0.45
H	0.76
OH	1.82

Table 1. Electron affinities of atoms and molecules obtainable from water

Based on the observations listed above, it is proposed here that negative ions exist in a weakly ionized plasma containing some combination of water molecules, hydrogen molecules, and oxygen molecules. Since a water molecule has a very large dipole moment, it will be attracted to a region of strong electric field; this has been demonstrated by Libbrecht & Tanusheva (1999) and by Bartlett et al. (1963). Thus, there will be an attractive force between a neutral water molecule and a negative ion such as O₂⁻ or OH⁻. The result of this attraction will be formation of a hydrate such as the OH⁻(H₂O)_{*n*} observed by Arshadi & Kebarle (1970). The number *n* of water molecules in the hydrate will increase with time because the hydrate will remain charged. Discharging would require collision with a positive ion but this will rarely happen because, relative to electrons, ions are very slow moving. If the temperature is low, the growing hydrate will become an ice grain rather than a liquid water drop. Thus, the critical ingredients are a cold, weakly-ionized plasma containing electronegative molecules/atoms so that some plasma electrons can attach to the electronegative species and create negative hydrates. These ingredients exist in a weakly ionized plasma containing some combination of water molecules, hydrogen molecules, and oxygen molecules. It is thus highly likely that the rapid homogeneous nucleation observed in the Caltech water ice experiment occurs in the sequence: formation of weakly ionized plasma (free electrons and ions in a sea of neutrals), dissociation of water into hydroxyl and hydrogen atoms, negative ion formation, hydrate on negative ion, growth of hydrate to macroscopic ice grain. Because of continuous electron and ion bombardment with electron flux exceeding ion flux, the ice grain will become increasingly negatively charged in the usual dusty plasma sense (Bellan 2020) as it becomes larger and so will continue to attract water molecules and grow.

An observed feature of the Caltech ice dusty plasma experiment is that initiation of nucleation requires operation above a threshold pressure but once nucleation has begun, it proceeds faster and yields larger particles at pressures lower than this threshold; this feature is seen no matter what species of background gas is used. For example, Marshall et al. (2017) observed that the threshold for nucleation of ice grains in an argon plasma containing a small amount of water vapor was 600 mT but, once nucleated, the ice grains would grow quickly at lower pressures. The main plasma parameters that change with neutral pressure are electron temperature and ion density. The electron temperature decreases with increased pressure while the density has a non-monotonic behavior, first increasing and then decreasing. The production of negative ions is likely strongly affected by electron temperature because the electron affinity is comparable to electron temperatures whereas the effect of electron density is expected to be less because, unlike electron affinity, there is no resonance-like condition.

A related observed feature of the Caltech ice dusty plasma is that nucleation does not occur if there is too much rf power. Specifically, Chai & Bellan (2015a) reported that rf power must not be higher than a certain value (0.5 W) but then once nucleation occurred the rf power could be increased and then the ice grains would grow to a large size. Operation above a critical rf power likely corresponds to operating above a critical electron temperature suggesting that nucleation is inhibited if the temperature of bulk electrons exceeds some critical value.

This suggests that the bulk electron temperature should not be so high as to knock electrons off from electronegative ions. The most likely candidates for forming negative ions in a plasma containing water molecules are atomic hydrogen, atomic or molecular oxygen, and hydroxyl radicals; electron affinities E_a for these species are listed in Table 1.

Table I suggests that the most likely candidate for dominant negative ion in a water-containing capacitive discharge plasma is the hydroxyl radical as the electron temperature in such a plasma is ~ 2 eV (Bora et al. 2013). Plasma electrons at 2 eV would thus have more than enough energy to knock electrons off from O₂ molecules or H atoms, but 2 eV electron energy would be marginal or insufficient for detaching bound electrons from O atoms or OH radicals. While O has an electron affinity similar to OH, as will be seen below, generation of O from water requires more energy than generation of OH so the O path is less favorable. As support for the contention that OH⁻ is likely the predominant negative ion, it is noted that Nguyen et al. (2009) saw evidence of strong OH peaks in both the optical and mass spectra of a water plasma but only a small O₂ peak in the mass spectrum and an even smaller

Ion	Appearance (eV)	Peak production E_p (eV)	Formation mechanism
H ⁻	4.8	6.0, 8.0 (weak)	H ₂ O + e → H ⁻ + OH
OH ⁻	4.7	6.1, 8.5, 11.2	H ⁻ + H ₂ O → OH ⁻ + H ₂
O ⁻	7.4	9.2, 11.2	H ₂ O + e → O ⁻ + 2H (or H ₂)

Table 2. Electron energy in eV at which negative ions first appears when water vapor is bombarded with electrons, electron energy at which negative ion yield has peak and presumed reaction. Date is from Cottin and uncertainties in potential are typically +/- 0.2 volts

O peak. [Sturm et al. \(2010\)](#) observed simultaneous existence of H₂O, O, and OH in a protoplanetary disk so the necessary ingredients for forming negative ion hydrates exist in a protoplanetary disk, namely cold background gas, weak ionization, H₂O, O, and OH. It is thus expected based on the energy arguments from the lab plasma context that in a protoplanetary disk negative hydroxyl ions would also be the most likely candidate for forming hydrates.

[Cottin \(1959\)](#) provided extensive measurements of how the production of positive and negative ions from electron bombardment of water vapor depends on electron kinetic energy E . These measurements showed that ion production peaks at specific values of E ; more recent data has been provided by [Fedor et al. \(2006\)](#). Table II lists Cottin's results for the lowest electron energy E that produce negative ions from water molecules and also the kinetic energies denoted as E_p at which this negative ion production is at a peak. The energies reported by Cottin for production of positive ions by electron bombardment of water molecules are ≥ 12.6 V so in a plasma where $T_e \ll 12.6$ eV negative ions should be the dominant type of ion produced by electron bombardment of water molecules.

[Cottin \(1959\)](#) observed that the production of OH⁻ was proportional to the square of the water vapor pressure whereas the production of H⁻ and O⁻ was linearly proportional and concluded from this observation that OH⁻ production is a two-step process where the first step is either



or



that would then be followed by a second step of either



or



The need for two steps, each involving H₂O, would lead to the quadratic dependence on water vapor pressure. [Fedor et al. \(2006\)](#) observed a linear dependence of OH⁻ formation on water vapor pressure but the Fedor et al. measurements were made at a much lower water vapor pressure so the quadratic path might have become insignificant relative to some linear single step path. Also, Fedor et al. noted theoretical arguments against a linear dependence. The path involving H⁻ in the second step (i.e., Eq.3) seems more likely than the path involving O⁻ (i.e., Eq.4) because, as listed in Table I, the electron energy required to form O⁻ is substantially higher than that required to form H⁻. Cottin's plot of OH⁻ production as a function of electron energy shows three maxima where the lowest of the three peaks (6 volts) corresponds to a peak for the production of H⁻ and the highest of the three peaks (11.2 V) corresponds to a peak for the production of oxygen.

It is proposed here that in order to produce negative hydrates in a weakly ionized plasma containing water vapor, a low T_e is desirable to avoid knocking electrons off of electronegative ions while a high T_e is desirable to create these electronegative ions. Because these requirements are conflicting, the optimum T_e should have a value intermediate between the affinity energy of a negative ion and the lowest electron energy peak for creating the negative ion. For hydroxyl negative ions, the lowest electron energy peak is 6 eV.

By expressing the electron Maxwell-Boltzmann distribution in terms of energy, the probability that an electron has a kinetic energy between E and $E + dE$ is

$$f(E)dE = 2\sqrt{\frac{E}{\pi}} \frac{1}{(T_e)^{3/2}} \exp\left(-\frac{E}{T_e}\right) dE \quad (5)$$

where the electron kinetic energy E and the electron temperature T_e are both measured in electron volts. Electrons that have kinetic energy E exceeding the affinity energy E_a of an electron attached to a negative ion will detach the bound electron, in a manner similar to an energetic electron ionizing a neutral atom or molecule. This is analogous to laser photo-detachment (Sirse et al. 2017) where a photon with energy exceeding E_a detaches the bound electron from a negative ion. The flux F_d of "detaching" electrons having $E > E_a$ is

$$F_d = n_e \int_{E_a}^{\infty} \left(\frac{2E}{m_e}\right)^{1/2} f(E) dE = n_e \left(\frac{8T_e}{\pi m}\right)^{1/2} \left(\frac{E_a}{T_e} + 1\right) \exp\left(-\frac{E_a}{T_e}\right). \quad (6)$$

The flux of attaching electrons, i.e., electrons having energy at the energy E_p as listed in the third column of Table I, is found by multiplying Eq.5 by the electron velocity $v \propto \sqrt{E_p}$ and density n_e to obtain

$$F_a = \lambda n_e \frac{E_p}{(T_e)^{3/2}} \exp\left(-\frac{E_p}{T_e}\right) \quad (7)$$

where λ is a coefficient proportional to the width of the peak.

Thus F_a characterizes the rate at which negative ions are created while F_d describes the rate at which they are destroyed. The ratio of these two fluxes consequently gives a rough figure of merit for the value of T_e that maximizes creation of negative ions. This ratio is

$$\frac{F_a}{F_d} = \mu \frac{E_p}{(T_e)^2} \frac{\exp\left(\frac{E_a - E_p}{T_e}\right)}{\left(\frac{E_a}{T_e} + 1\right)} \quad (8)$$

where μ is a constant incorporating the factors that do not involve T_e .

Figure 1 plots F_a/F_d for the hydroxyl situation where $E_a = 1.82$ eV and $E_p = 6$ eV. This plot peaks at $T_e = 2.65$ eV which is of the order of the T_e presumed for the Caltech ice dusty plasma. This ratio F_a/F_d is a rough figure of merit because it does not account for additional issues such as stronger detachment of bound electrons by incident electrons with $E \gg E_a$ compared to those with $E \gtrsim E_a$. The peak in Fig.1 at a low but finite electron temperature is consistent with the observation that nucleation in a weakly-ionized plasma occurs at low rf power (Chai & Bellan 2015a) and at high background gas pressure (Marshall et al. 2017), since both of these regimes imply low T_e . Shimizu et al. (2010) observed (Fig. 5 in their paper) an increase of DO upon formation of a weakly ionized deuterium-oxygen plasma when the electrodes were not cooled (no ice nucleation, Fig. 5b) but a slight decrease of DO when the electrodes were cooled (ice dust nucleation seen, Fig. 5a). This observation is consistent with DO being absorbed into negative ion hydrates $\text{DO}^-(\text{D}_2\text{O})_n$ as the initial step in homogeneous ice nucleation in a weakly ionized cold plasma containing D_2O molecules. Shimizu et al.'s observation in their Fig.5c that DO increased when the cooling was removed is consistent with DO no longer being absorbed when ice nucleation stops. This is circumstantial evidence because a conventional mass spectrometer does not observe negative ions since its internal acceleration is arranged for positive ions. Shimizu et al. were thus likely measuring neutral DO but this could be considered a proxy for DO^- .

4. CRITIQUE OF CNT

The plausibility of this negative ion nucleation hypothesis is bolstered by noting that certain aspects of CNT involve using a theory outside its range of validity. CNT is based on thermodynamics but the essential assumption underlying thermodynamics is inappropriate for a dusty plasma because the electrons are much hotter than the ions and neutrals (e.g., electron temperature is of the order of 10^4 K whereas ions and neutral temperature are of the order of $10 - 10^2$ K). The essential assumption of thermodynamics, namely that all constituents are at the same temperature, is thus clearly violated. The Gibbs free energy, an important quantity in CNT, is undefined in a weakly ionized plasma because Gibbs free energy is defined for fixed pressure and fixed temperature. Because a weakly ionized plasma cannot be characterized by a single temperature, the Gibbs free energy is not meaningful in a weakly ionized plasma.

A related aspect that casts doubt on CNT is that application of CNT to ice nucleation presumes that the surface tension of liquid water can be extrapolated to apply to ice, but extrapolating surface tension from liquid to solid is debatable as noted by Makkonen (2012) who showed that solids do not have surface tension in the same sense as

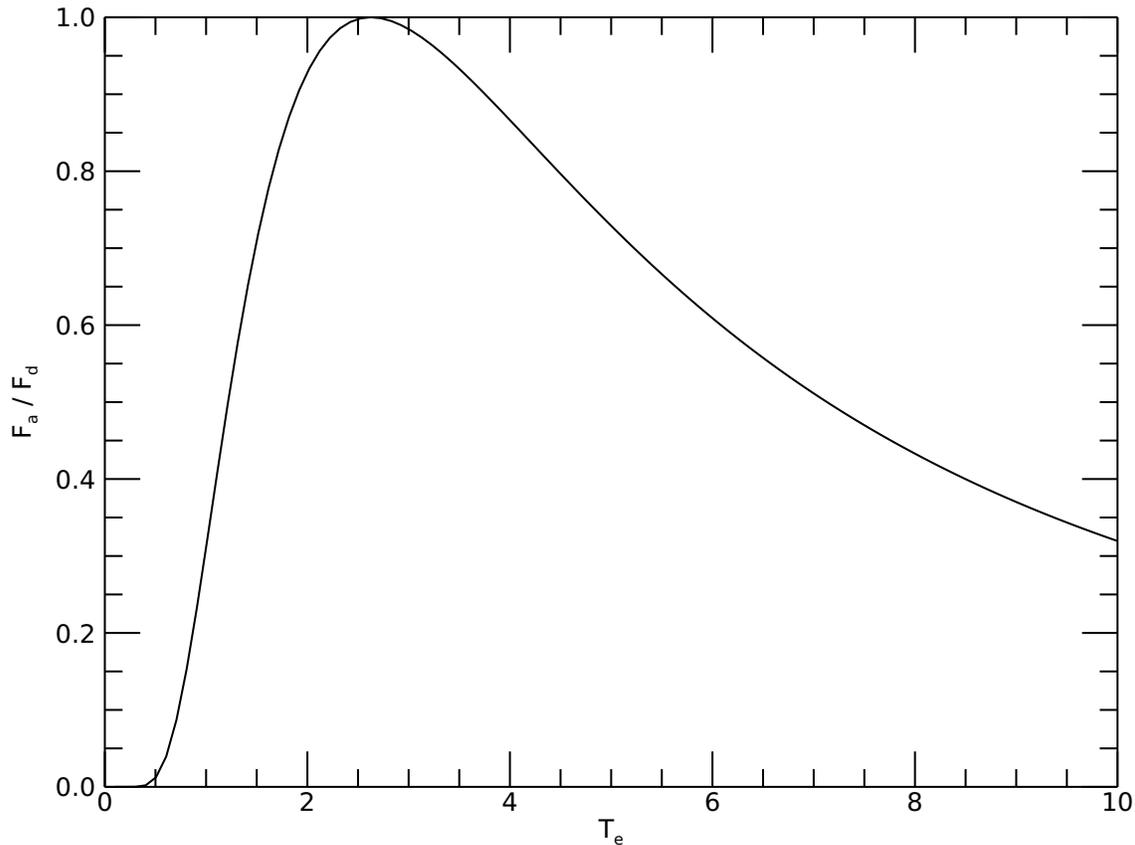


Figure 1. Plot of F_a/F_d normalized to its maximum value versus T_e for hydroxyl negative ion formation using electron affinity energy $E_a = 1.82$ eV and peak electron energy (Cottin 1959) for formation $E_p = 6$ eV.

liquids. The surface of ice in terrestrial conditions is known to be coated by a quasi-liquid layer (QLL) that is a few molecules thick. At first sight, it seems that a QLL could conceivably provide a form of surface tension and so provide a basis for CNT. However, Slater & Michaelides (2019) showed that the QLL vanishes at temperatures < 240 K so ice nucleation models for ordinary terrestrial conditions (i.e., temperature exceeding 240 K) are inapplicable to the much colder astrophysical regime (i.e., $T \ll 240$ K). Concern about invoking surface tension in CNT even for liquid drops was noted by Tolman (1949) who stated “As we consider smaller and smaller droplets of liquid phase, however, the concept of surface tension and the previously satisfactory thermodynamic methods seem less and less appropriate. Indeed, it will ultimately seem more satisfactory to continue the investigation using the concept of forces exerted by individual molecules and the more detailed methods of molecular mechanics.” Homogeneous nucleation must begin by having two molecules bind together but at this stage no surface exists so thermodynamic arguments involving surface tension are inappropriate. Thermodynamics implicitly presumes the presence of a large number of molecules, not two.

In summary, the standard presumption that inhomogeneous nucleation dominates homogeneous nucleation does not apply to the situation of a weakly ionized plasma consisting of a cold background gas with electronegative atoms or molecules. Since OH and H₂O commonly exist in astrophysical situations, since astrophysical situations are typically cold and weakly ionized, and since OH has a large electron affinity, homogeneous nucleation of ice via hydrates based on OH⁻ should be operative in many astrophysical situations.

The semi-quantitative arguments presented here provide guidance for future more precise analysis and measurements to determine which negative ion is indeed dominant and how the process scales to different parameter regimes.

Motivated by these arguments, a diagnostic extending to a water-ice dusty plasma the methods used in Howling et al. (1994) is being constructed. This diagnostic will search for the negative ions predicted to exist as a precursor to the homogeneous nucleation of water ice and will determine how the negative ions depend on plasma parameters such as ion density, electron temperature, and background gas species and whether negative ion formation is the initial step to ice grain nucleation in a cold weakly-ionized plasma containing water vapor.

Acknowledgements: Supported by the NSF/DOE Partnership in Basic Plasma Science and Engineering via USDOE Award DE-SC0020079.

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