Tabletop Nucleosynthesis Driven by Cluster Coulomb Explosion

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Coulomb explosion of completely ionized $(CH_4)_n$, $(NH_3)_n$, and $(H_2O)_n$ clusters will drive tabletop nuclear reactions of protons with $^{12}C^{6+}$, $^{14}N^{7+}$, and $^{16}O^{8+}$ nuclei, extending the realm of nuclear reactions driven by ultraintense laser-heterocluster interaction. The realization for nucleosynthesis in exploding cluster beams requires complete electron stripping from the clusters (at laser intensities $I_M \geq 10^{19}$ W cm^{-2}), the utilization of nanodroplets of radius 300–700 Å for vertical ionization, and the attainment of the highest energies for the nuclei (i.e., ~30 MeV for heavy nuclei and ~3 MeV for protons).

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Cluster dynamics transcends molecular dynamics of large finite systems [1] towards nuclear reactions in ultraintense laser fields [2–9]. The interaction of ultraintense (peak intensity $I_M = 10^{15}$–10^{21} W cm^{-2}), ultrafast (temporal length $\tau = 10$–100 fs) laser pulses with matter drives novel ionization phenomena [2–12] and attosecond electron dynamics [11] in atoms, molecules, clusters, plasmas, and the condensed phase. Extreme multielectron inner and outer ionization of elemental and molecular clusters in ultraintense infrared [2–10] and soft x-ray [13] laser fields led to the production of highly energetic particles, i.e., keV electrons [14], x-ray photons [15], and keV-MeV multicharged ions and nuclei [2–9,16]. Coulomb explosion (CE) of deuterium containing homonuclear clusters [e.g., $(D_2)_n$ [2,6]] and heteroclusters [e.g., $(D_2O)_n$ [3,8], CD_4 [4,5,7], or $(DI)_n$ [9]] drives "cold-hot" *dd* nuclear fusion [2–9]. We propose and demonstrate that CE of completely ionized $(CH_4)_n$, $(H_2O)_n$, and $(NH_3)_n$ molecular clusters will drive the nucleosynthesis reactions [17,18] $^{12}C(p,\gamma)^{13}N$, $^{14}N(p,\gamma)^{15}O$, and $^{16}O(p,\gamma)^{17}F$ of protons with heavier nuclei. These nucleosynthesis reactions are part of the CNO cycle that constitutes the energy source of hot stars [17,18]. We extend the realm of nuclear reactions driven by cluster CE from *dd* fusion [2–9] to nucleosynthesis involving heavy nuclei, driven by ultraintense laser-heterocluster interaction.

The response of elemental and molecular clusters to ultraintense laser fields induces attosecond-femtosecond electron dynamics of sequential-parallel inner ionization, nanoplasma formation, and outer ionization [9,10,19–21], which triggers femtosecond nuclear dynamics of CE [2–10,19–21]. The maximization of the nucleosynthesis yields of protons with $^{12}C^{6+}$, $^{14}N^{7+}$, and $^{16}O^{8+}$ nuclei produced by CE of completely ionized clusters will be attained at the highest energies of the nuclei, requiring complete inner [10] and outer [10,19] cluster ionization. The largest cluster size that allows for complete outer ionization at a given intensity is the border radius $R_0^{(I)}$ [20,21] for cluster vertical ionization (CVI), which is realized for an initial cluster radius of $R_0 \leq R_0^{(I)}$. Utilizing an electrostatic model to fit molecular dynamics simulation results for outer ionization for $(D_2)_n$, $(^3He)_n$, $(CD_4)_n$, $(CH_4)_n$, $(DI)_n$, $(CD_3I)_n$, and Xe_n clusters for laser pulse length $\tau = 25$ fs [9,10,19–21] led to an expression for $R_0^{(I)}$ and for the corresponding number $n^{(I)}$ of cluster molecules

$$R_0^{(I)} = 1.2 \times 10^{-8} I_M^{1/2} / \rho_{mol} q_{mol}, \tag{1}$$

$$n^{(I)} = 7.2 \times 10^{-24} I_M^{3/2} / \rho_{mol}^2 q_{mol}^3, \tag{2}$$

where $R_0^{(I)}$ is given in Å, the peak intensity I_M in W cm^{-2}, the cluster initial molecular density ρ_{mol} in Å^{-3}, and the molecular charge q_{mol} in *e* units. Such large cluster (nanodroplet) sizes (Table I) are amenable to experimental preparation [8].

Concurrently, the laser intensity has to be sufficiently high to allow for the formation of bare nuclei by complete inner ionization of the constituents at this large cluster size. The intensity thresholds for the removal of the last 1*s* electron from single C, N, and O atoms were calculated from the barrier suppression ionization (BSI) mechanism [22] and by the quantum mechanical Ammosov-Delone-Krainov (ADK) model [23], with the ionization probability being determined by single cycle averaging. The BSI and ADK results (Fig. 1) are very close, revealing complete ionization of the C, N, and O single atoms at $I_M \geq 4 \times 10^{19}$ W cm^{-2}. For large clusters, with $R_0 = R_0^{(I)}$, the atom stripping intensity thresholds are considerably reduced as compared to the single atom, due to ignition effects [10] induced by the inner field of the ions (Fig. 1), assuming the values $I_M = 4 \times 10^{17}$ W cm^{-2} for $(CH_4)_{n^{(I)}}$, $I_M = 10^{18}$ W cm^{-2} for $(NH_3)_{n^{(I)}}$, and $I_M = 3 \times 10^{18}$ W cm^{-2} for $(H_2O)_{n^{(I)}}$. Accordingly, for $I_M \geq 3 \times 10^{18}$ W cm^{-2}, cluster CE generates high-energy nuclei (C^{6+}, N^{7+}, O^{8+}) and protons (H^+) for nucleosynthesis.

The energies of the nuclei driven by CE of molecular heteroclusters manifest an energy maximum E_M at the

TABLE I. Parameters and estimates of nucleosynthesis yields driven by CE induced by an ultraintense laser ($I_M = 10^{20}$ W cm^{-2} and $\tau = 25$ fs).

Reaction	Cluster	$R_0^{(I)}$ (Å)[a]	$n^{(I)}$[b]	$E_{\rm MAX}^{(I)}$ (keV)[c]		$\eta(E_{\rm MAX}^{(I)})$[d]		Y[e]	
				IF	OF	IF	OF	IF	OF
$^{12}C(p,\gamma)^{13}N$	$(CH_4)_{n^{(I)}}$	750	2.2×10^7	5930	3960	...	...	(3.0)	(80)
$^{14}N(p,\gamma)^{15}O$	$(NH_3)_{n^{(I)}}$	500	1.3×10^7	3990	2680	3.40	4.16	3.6(3.0)	79(50)
$^{16}O(p,\gamma)^{17}F$	$(H_2O)_{n^{(I)}}$	360	6.3×10^6	2880	1920	4.60	5.62	4.9(3.0)	81(60)

[a]Border radius, Eq. (1).
[b]Equation (2).
[c]Center of mass energies for the IF and OF mechanisms, Eqs. (4) and (6).
[d]The Gamov parameters at $E_{\rm MAX}^{(I)}$, Eqs. (5) and (7).
[e]Data for $(NH_3)_{n^{(I)}}$ and $(H_2O)_{n^{(I)}}$. Data in brackets were calculated from the experimental cross sections [17,18] for $(NH_3)_{n^{(I)}}$ and $(H_2O)_{n^{(I)}}$ and for $(CH_4)_n$ at resonance, with $n = 1.2 \times 10^6$ (see text).

upper edge of the energy distribution [3–9,20,21]. Under CVI conditions, which are applicable for $R_0 \le R_0^{(I)}$, the energy of the majority of the ions from CE of heteroclusters lies in the vicinity of the maximal energy of E_M [3,4,7,9,20,21], due to kinematic effects [3,4,7]. The maximal energy $E_{\rm Mj}$ for the jth ion with charge q_j is then given by [4,10,20,21]

$$E_{\rm Mj} = \alpha(4\pi\rho_{\rm mol}/3)^{1/3}\bar{B}q_{\rm mol}q_j k_{\rm mol}^{-2/3} n_A^{2/3}, \qquad (3)$$

where $\bar{B} = 14.4$ eV Å, $n_A = nk_{\rm mol}$ is the total number of cluster ions (with $k_{\rm mol}$ ions in each molecule), and the charges q_j are $q_Z = Z$ for the heavy nuclei and $q_{H^+} = 1$ for the protons. The numerical parameter is $\alpha = 0.65$–0.93 (with an average value of $\alpha = 0.80$) and accounts for the laser pulse shape [20] and for kinematic [3,4] effects.

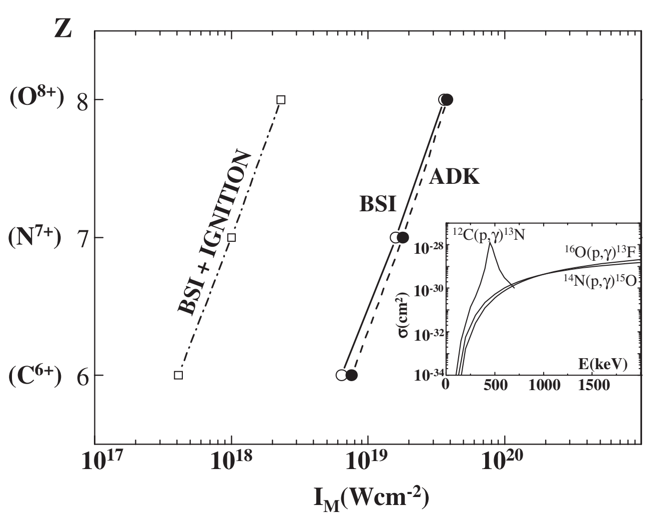

FIG. 1. Extreme multielectron ionization of C, N, and O atoms in ultraintense laser fields. The intensity thresholds required for complete ionization of single atoms were calculated by the BSI model (○) and by the ADK model (●). The inner ionization of clusters with radius $R_0^{(I)}$ was calculated from the BSI model with an inner field [10] (□) and marked BSI + IGNITION. The inset shows the energy dependent cross sections for nucleosynthesis reactions [17,18].

The scaling law $E_{\rm Mj} \propto n_A^{2/3}$ [Eq. (3)] is given for the energies of the heavy nuclei and of the protons obtained from CE of $(CH_4)_n$ ($k_{\rm mol} = 5$), $(NH_3)_n$ ($k_{\rm mol} = 4$), and $(H_2O)_n$ ($k_{\rm mol} = 3$) clusters (Fig. 2). The dependence $E_{\rm Mj} \propto q_{\rm mol}q_j$ manifests energy boosting effects [3,4], while $E_{\rm Mj}$ for the heavy nuclei is roughly higher by a numerical factor of Z relative to the value for H^+. The scaling law [Eq. (3)] breaks down for $R_0 \ge R_0^{(I)}$, where a much weaker increase of $E_{\rm Mj}$ with increasing n_A is exhibited [19,20]. The energies $E_{\rm Mj}^{(I)}$ of the nuclei from CE of clusters with radii $R_0^{(I)}$ and size $n^{(I)}$ fall in the range $E_{\rm Mj} \simeq 3$ MeV for protons to $E_{\rm Mj} \simeq 30$ MeV for the heavy nuclei (Fig. 2) that are high enough to trigger nucleosynthesis.

The cross sections $\sigma(E)$ for reactions $^{14}N(p,\gamma)^{15}O$ and $^{16}O(p,\gamma)^{17}F$ (inset in Fig. 1) [17,18] do not manifest resonances and can be expressed by the exponential rela-

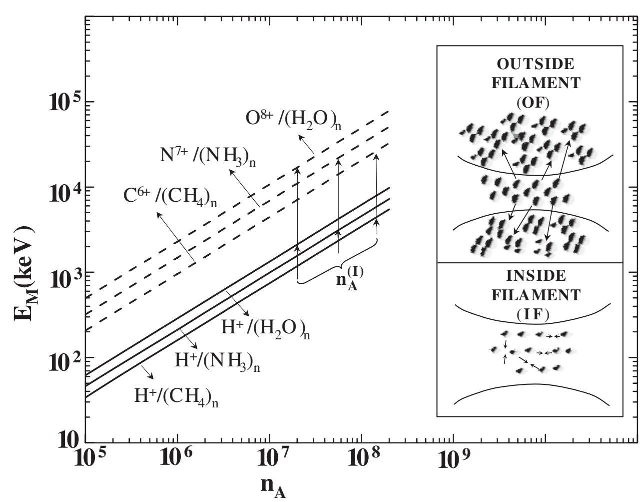

FIG. 2. The cluster size dependence of the maximal energies of protons (solid lines) and of C^{6+}, N^{7+}, and O^{8+} nuclei (dashed lines) produced from CE of $(CH_4)_n$, $(NH_3)_n$, and $(H_2O)_n$ clusters under initial conditions of complete cluster vertical ionization. The values of $n_A^{(I)}$ for $I_M = 10^{20}$ W cm^{-2} and $\tau = 25$ fs are marked by vertical arrows. The insets at the right-hand side of the figure portray the OF reaction and the IF reaction.

tion [17,18] $\sigma(E) = (S(E)/E)\exp(-\eta(E))$, where E is the center of mass energy (in keV), and $S(E)$ is a slowly varying function of E [which is taken as $S(0) = 3.5 \times 10^{-24}$ cm^2 keV for $^{14}N(p,\gamma)^{15}O$ and 9.4×10^{-24} cm^2 keV for $^{16}O(p,\gamma)^{17}F$ [17,18]]. The Gamov parameter is $\eta(E) = 31.3 q_{H^+} q_Z \mu^{1/2}/E^{1/2}$, where the reduced mass is $\mu = m_{H^+} m_Z/(m_{H^+} + m_Z)$, where m_{H^+} and m_Z are the masses of protons and of heavy nuclei, respectively (in amu), and E (in keV) is expressed in terms of the laboratory frame energies of the colliding nuclei.

The nucleosynthesis reactions take place both inside the plasma filament (IF), where collisions between high-energy nuclei occur [2,5,6] (inset in Fig. 2), and outside the plasma filament (OF) [8], where the high-energy nuclei produced inside the filament collide with cluster nuclei in rest outside it (inset in Fig. 2). For nucleosynthesis driven by CE of clusters with radius $R_0^{(I)}$ (at $I_M = 10^{20}$ W cm^{-2}), we evaluated the maximal values of the energies $E_{MAX}^{(I)}$ for the center of mass proton-nuclei collisions and for the value of the Gamov parameter $\eta(E_{MAX}^{(I)})$ at this energy (Table I). Using the standard expression for the center of mass energy, we get for the IF mechanism

$$E_{MAX}^{(I)} = 8.6 \times 10^{-18} \alpha \mu [(q_j/m_j) + (q_{j'}/m_{j'})] I_M/\rho_{mol} q_{mol} \quad (4)$$

and

$$\eta(E_{MAX}^{(I)}) = 1.07 \times 10^{10} q_j q_{j'} (\rho_{mol} q_{mol}/[(q_j/m_j) + (q_{j'}/m_{j'})]\alpha I_M)^{1/2}, \quad (5)$$

while for the OF mechanism

$$E_{MAX}^{(I)} = 8.6 \times 10^{-18} \alpha \mu (q_j/m_j) I_M/\rho_{mol} q_{mol} \quad (6)$$

and

$$\eta(E_{MAX}^{(I)}) = 1.07 \times 10^{10} q_{j'} (\rho_{mol} q_{mol} q_j m_j/\alpha I_M)^{1/2}, \quad (7)$$

where q_j and/or $q_{j'}$ represent q_{H^+} and/or q_Z given in e units, q_{mol} is given in e units, m_{H^+} and m_Z in amu, ρ_{mol} in Å^{-3}, I_M in W cm^{-2}, and $E_{MAX}^{(I)}$ in keV. The prediction of effective nucleosynthesis emerges from the relatively small values of the $\eta(E_{MAX}^{(I)})$ parameters (Table I), which do not significantly diminish $\sigma(E_{MAX}^{(I)})$. Accordingly, the nucleosynthesis reactions are amenable to experimental observation. The reaction yields Y for the $H^+ + j$ ($j = C^{6+}, N^{7+}, O^{8+}$) nucleosynthesis reactions (per laser pulse) are [4,21]

$$Y = [\kappa_{H^+}\kappa_Z/(\kappa_{H^+} + \kappa_Z)^2]\rho_P^2 V_f \ell \langle\sigma\rangle, \quad (8)$$

where $\langle\sigma\rangle$ is the energy averaged cross section, κ_Z and κ_{H^+} are the numbers of heavy nuclei and of protons per molecule, respectively, and $\rho_P = 2 \times 10^{19}$ cm^{-3} is the filament ion density [2,6] (taken to be equal for the IF and OF modes). The volume $V_f = \pi r^2 h$ of the plasma filament is described as a cylinder with radius r and length h [2] being inversely proportional to the laser peak intensity. At $I_M = 5 \times 10^{17}$ W cm^{-2}, $r = 0.01$ cm and $h = 0.2$ cm [2], resulting in $V_f = 6 \times 10^{-5}$ cm^3, while at $I_M = 10^{20}$ W cm^{-2}, we estimate $V_f = 5 \times 10^{-7}$ cm^3, which is larger than in Ref. [8]. The path length l for the nuclei depends on the (OF or IF) reaction mode. For OF, $l \simeq 0.1$ cm, corresponding to the size of the cluster beam radius [8], while for IF, $l \simeq \pi r/2$, resulting in $l = 2.5 \times 10^{-3}$ cm at $I_M = 10^{20}$ W cm^{-2}. The yields [Eq. (8)] for $^{14}N(p,\gamma)^{15}O$ driven by CE of $(NH_3)_{n^{(I)}}$ ($n^{(I)} = 5 \times 10^7$) and $^{16}O(p,\gamma)^{17}F$ driven by CE of $(H_2O)_{n^{(I)}}$ ($n^{(I)} = 2 \times 10^7$) were calculated with $\langle\sigma\rangle = \sigma(E_{MAX}^{(I)})$ and involve ~50–100γ particles per laser pulse (Table I).

The cluster size dependence of the yields for nucleosynthesis driven by CE of $(CH_4)_n$, $(NH_3)_n$, and $(H_2O)_n$ clusters for the OF and IF mechanisms, as calculated from Eq. (8), with the maximal E_{Mj} energies [Eq. (3)] of the nuclei, together with the experimental cross sections (inset in Fig. 1), are portrayed in Fig. 3 and reveal the following features: (A) The yields are dominated in all cases by the OF mechanism (Table I and Fig. 3). This is due to the low value of l for IF at the high intensity. (B) γ-ray pulses ($Y \simeq$ 50–100) can be generated with a temporal pulse length of $\simeq$ 20–100 fs. (C) For the $^{14}N(p,\gamma)^{15}O$ and $^{16}O(p,\gamma)^{17}F$ reactions without resonance in $\sigma(E)$, a smooth increase of Y with increasing n_A is exhibited (Fig. 3). (D) For the $^{12}C(p,\gamma)^{13}N$ reaction, the yield (for the dominating OF mode) exhibits two peaks (Fig. 3). These are due to the

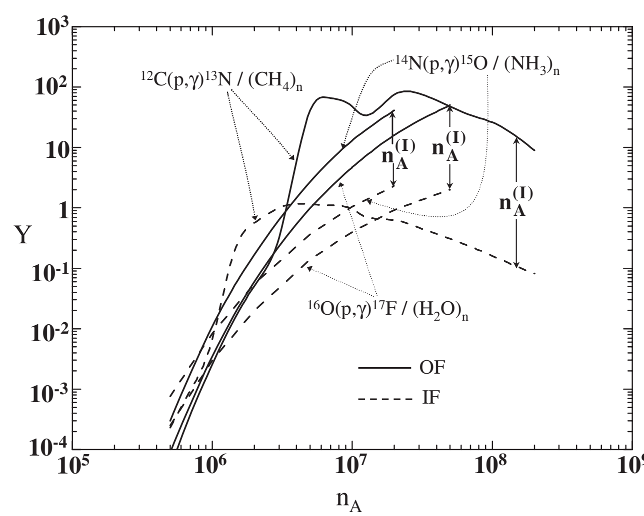

FIG. 3. Cluster size dependence of γ-ray yields (per laser pulse) for the nucleosynthesis reactions $^{12}C(p,\gamma)^{13}N$, $^{14}N(p,\gamma)^{15}O$, and $^{16}O(p,\gamma)^{17}F$, with the H^+, C^{6+}, N^{7+}, and O^{8+} nuclei being produced by CE of completely ionized $(CH_4)_n$, $(NH_3)_n$, and $(H_2O)_n$ clusters. The Y values for the OF reaction mode (solid lines) and for the IF reaction mode (dashed lines) are presented vs n_A. The values of $n_A^{(I)}$ for $I_M = 10^{20}$ W cm^{-2} and $\tau = 25$ fs are marked by vertical arrows.

resonance in $\sigma(E)$, with the protons and the carbon nuclei at resonance energy contributing to the first and to the second peaks, respectively. (E) The highest values of Y for the $^{14}N(p,\gamma)^{15}O$ and $^{16}O(p,\gamma)^{17}F$ reactions ($Y \sim 50$) are attained at $n_A = n_A^{(I)}$ (Fig. 3 and Table I). (F) The maximal values of Y for the $^{12}C(p,\gamma)^{13}N$ reaction (Fig. 3) manifest resonance effects and are attained at the maxima of Y, i.e., $n_A = 7 \times 10^6$ ($Y = 70$) and $n_A = 3 \times 10^7$ ($Y = 80$) for $(CH_4)_n$ cluster sizes that are smaller than the border size, i.e., $n_A < n_A^{(I)} = 1.2 \times 10^8$. With improvement in laser technology, the increase of the larger reaction volumes will be accomplished, further increasing the yields.

We conclude that tabletop nucleosynthesis can be driven by CE of $(CH_4)_n$, $(NH_3)_n$, and $(H_2O)_n$ large molecular heteroclusters (nanodroplets), being amenable to experimental observation. We will explore perspectives for a further increase of the H^+, C^{6+}, N^{7+}, and O^{8+} ion energies and of the nucleosynthesis yields of the $^{12}C(p,\gamma)^{13}N$, $^{14}N(p,\gamma)^{15}O$, and $^{16}O(p,\gamma)^{17}F$ reactions by CE of light-heavy heteroclusters, e.g., $(CH_3I)_n$, $(NH_4I)_n$, or $(H_3OI)_n$, where the highly charged I^{25+} (at $I_M = 10^{19}$ W cm^{-2}) or I^{35+} (at $I_M = 10^{20}$ W cm^{-2}) ions [9] will serve as energetic boosters [3,4,9] for the H^+, C^{6+}, N^{7+}, or O^{8+} nuclei involved in nucleosynthesis driven by CE.

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