Comparative study of energy of particles ejected from
coulomb explosion of rare gas and metallic clusters irradiated
by intense femtosecond laser field

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Abstract. We present our study of high intensity femtosecond laser field interaction with large
cluster of Kr and Na (contained 2.10^3 to 2.10^7 atoms). When laser intensity is above a critical
value, it blows off all of electrons from the cluster and forms a non neutral ion cloud. The
irradiation of these clusters by the intense laser field leads to highly excitation energy which
can be the source of energetic electrons, electronic emission, highly charge, energetic ions and
fragmentation process. During the Coulomb explosion of the resulting highly ionized, high
temperature nanoplasma, ions acquire again their energy. It is shown that ultra fast ions are
produced. The goal of our study is to investigate in detail a comparative study of the expansion
and explosion then the ion energy of metallic and rare gas clusters irradiated by an intense
femtosecond laser field. We have found that ions have a kinetic energy up to 10^5 eV and the
Coulomb pressure is little than the hydrodynamic pressure. The Coulomb explosion of a cluster
may provide a new high energy ion source.

1. Introduction
High power femtosecond lasers are capable of achieving a light intensity up to 10^{21}-10^{22} W/m^2. In this
regime, a novel physics comes in our grasp of modern physics. The production of high temperature
plasmas with small scale, short pulse, and high intensity lasers has been actively pursued during the
last years. The interaction of clusters with high intensity laser fields has been studied by several
numbers of groups [1, 2, 3]. Energetic ions and electrons up to 1 keV are produced as noble gas
clusters explode [4, 5]. The ions are stripped to very high charge state [6, 7, 8], and X-ray yield is
comparable to that from solid targets [9]. The observation of neutrons from deuterium clusters
demonstrated that nuclear fusion can occur in the plasma formed after the explosion of the clusters
[10]. Of particular interest, the measurement of the energy absorption efficiency of high density
plasma created by intense irradiation of a solid target, have shown that the plasma typically absorbs a
large fraction of the laser energy depending upon intensity and laser wavelength [11]. When the laser
interacts with clusters it changes the regime of electromagnetic wave propagation and very efficient
absorption of radiation has been demonstrated with a formation of very high temperature under dense

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plasma [12, 13]. It has been noticed that for small diameter clusters, the coulomb explosion plays an important role [14].

Recent studies of individual clusters interaction with intense laser have confirmed that hot electrons (up to 3 keV) are produced during the laser cluster interactions and a greater energy can be deposited in the ions when these hot, highly ionized clusters explode. These studies indicated that the clusters are rapidly heated by the laser, to non-equilibrium, superheated state, due to the passage of free electron density in the cluster through a Mie resonance with the laser field during the cluster expansion [15, 16]. These superheated cluster nanoplasma eject electrons with many keV of energy [17, 18]. After the cluster are heated, charge separation of the hot electrons leads the cluster to explode, and ions acquired energy by the conversion of the energy deposited by the laser in the cluster to ion kinetic energy.

The goal of our paper is to study the comparative behaviour of coulomb explosion and ion energies ejected from the exploding metallic and noble large gas clusters (Na and Kr) respectively irradiated by intense femtosecond laser fields. We further study the temporal comparison between the different parameters of the formed nanoplasma of Na and Kr clusters within the framework of the modified nanoplasma model. After a general introduction on intense laser cluster interaction, we show in section 2 a brief description of the nanoplasma model. In section 3, we discuss the obtained results and finally, we draw our conclusion.

2. Nanoplasma model

In The nanoplasma model developed firstly by T. Ditmire et al [8], and reformulated by F. Megi et al [15] by adding the term of electron collisions with surface in the expression of the electron ion collision frequency, has proved a quite successful in reproducing most of the experimental results concerning expansion, ion and electron emissions from single clusters [16]. This model treats the expanding cluster as a spherical nanoplasma, subjected to the standard processes of a laser heated nanoplasma such as collisional heating, as well as collisional and tunnel ionization. The model suggests that the cluster explosion is driven by an enhancement in the electron heating in the cluster; also treats the formation of high density nanoplasma, ionization and heating in the laser field and its rapid expansion then explosion of the cluster leading to the ejection of energetic electrons and ions. A key aspect was the inclusion of shielding and enhancement of the laser field inside the cluster; which gives rise to a resonance in collisional heating rate. This model relies on three main assumptions: first, the laser field is described within the dipolar approximation; this is valid as long as $\lambda >> R_0$ where $\lambda$ and $R_0$ are the laser wavelength and the initial cluster radius respectively. Second, the electronic and ionic densities are supported to be uniformly distributed within the cluster throughout the interaction and the third assumption is that the electrons are assumed to be instantaneously thermalized so their energy distribution is Maxwellian. The nanoplasma model is reduced to a set of differential coupled equations describing the time evolution of the electronic density $n_e$ inside the cluster, which vary due to ionization processes and free streaming, of the populations of the different charge states that evolve through field and collisional ionization, of the net cluster charge, which increases due to free streaming, of the cluster radius, subjected to Coulombian and hydrodynamic pressures, and of the electronic temperature $T_e$; which results from balancing between energy gains and losses within the cluster volume.

In this model, the external electric field is given by

$$\vec{E}_{ext}(t) = E_0 \exp\left(-2\ln2\left(\frac{t}{\tau}\right)^2\right)\vec{e}_z$$

(1)

Where $\tau$ is the full width at half maximum (FWHM) and $E_0$ is the amplitude of the laser field. The internal field is given by
\[ E_{in}(t) = \frac{3}{|\epsilon + 2|} E_{exc}(t). \] (2)

\( f(t) \) is a Gaussian shape and \( \epsilon \) is a dielectric constant given by

\[ \epsilon = 1 - \frac{\omega_p^2}{\omega(\omega + i\nu)}, \] (2a)

where

\[ \omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m}}. \] (2b)

is the electronic plasma frequency, \( n_e \) the electron density and \( \nu \) is the total electron ion collision frequency with the inclusion of the term of electron surface collisions

\[ \nu = \nu_{ei} + \nu_s = \nu_{ei} + \frac{\nu}{R}. \] (3)

Where \( \nu_{ei} \) is the electron-ion collision frequency given by [19, 20]

\[ \nu_{ei} = \frac{1}{2} \left( \frac{Z^2}{\pi \epsilon_0 m_e^2} \right)^{\frac{1}{2}} \ln \Lambda. \] (4)

And the velocity \( v \) is given by

\[ v = \sqrt{v_{th}^2 + v_{osc}^2}. \] (4a)

\( v_{th} \) is the thermal velocity and \( v_{osc} \) is the oscillation velocity of the electron in the field. \( R \) is the cluster radius, \( <Z> \) is the mean ion charge and \( \ln \Lambda \) the modified coulomb logarithm given by the expression

\[ \ln \Lambda = \begin{cases} \frac{1}{4} \ln^2 \left( \frac{1 + m_e v_{osc}^2}{\hbar w} \right), & \text{for } \hbar w \gg k_B T_e \\ \frac{1}{4} \ln^2 \left( 1 + \frac{v_{osc}^2}{v_{th}^2} \right) + \ln \left( \frac{\sqrt{v_{osc}^2 + \exp(\frac{1}{3}\sqrt{\pi/2})}}{v_{th}} \right) \ln \Lambda & \text{for } \hbar w \ll k_B T_e \end{cases} \]. (5)

And \( \ln \Lambda \) is the classical coulomb logarithm [21].

3. Results and discussion
In the following, we are used a Kr and Na clusters (2\( \times \)10\(^7\) atoms per cluster) irradiated by a Gaussian laser pulse, pulse duration 200fs (Full width at half maximum), and peak intensity of 10\(^{17}\) W/cm\(^2\). We assume no temperature nor density gradients and the electric field inside the cluster is uniform. To explore the aspect of the cluster explosion; we have used the nanoplasma model for numerical calculation of the cluster explosion during the irradiation by the intense femtosecond laser pulse. In the cluster, the high electron temperature created through laser driven heating rapidly strip the ions by collisional ionization to high charge state.

In figure1, we show the temporal evolutions of the cluster radius \( R \) for the rare gas Kr and metallic Na clusters. The cluster expands rapidly in the case of Na cluster than the Kr cluster during the pulse once
heating of the electrons in the cluster has begun. In the case of the metallic cluster, it expands rapidly due to the rapid ionization of the cluster.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Temporal evolution of the radius of the cluster $R$ for $2.10^7$ atoms Kr and Na clusters irradiated by 200 fs pulse with peak intensity of $10^{21}$ W/m$^2$ and 390nm wavelength.

The cluster explosion is driven by an enhancement in the electron heating in the cluster; this enhancement occurs when the electron density in the cluster drops to three times the critical density $n_{crit}$, where the critical electron density is given by:

$$n_{crit} = \frac{\epsilon_0 m_e \omega^2}{e^2}.$$  \hspace{1cm} (6)

Where $\epsilon_0$ is the vacuum permittivity and $\omega$ is the laser frequency.

During the laser interaction, free electrons are produced by photo ionization early in the laser pulse. The laser collisionally heats these electrons which further ionize the atoms of the cluster through collisional ionization. At around $t \approx -289.52$ fs, the first resonance occur in the Na cluster but at $-277.92$ fs it occurs in Kr cluster when electron density rises to reach $3n_{crit}$ (figure2); also the times of the second resonance are different, $-94.54$ fs and $-148.39$ fs for both clusters Na and Kr respectively.

The maximum value of the ratio $\frac{n_e}{n_{crit}}$ is about 14.54 for Na cluster than 7.32 for Kr cluster; this difference in the time of resonances and the maximum values of the ratio $\frac{n_e}{n_{crit}}$ is caused by the number of electrons in such cluster.
Figure 2. Electron density $n_e$ normalized by the critical one $n_{\text{crit}}$ as a function of time for $2 \times 10^7$ atoms Kr and Na nanoplasma for 200 fs (FWHM) pulse, 300 nm wavelength and peak intensity of $10^{21}$ W/m$^2$.

The electron density rises to reach $3n_{\text{crit}}$ at time $t \approx -277.92$ fs and $289.52$ fs for Kr and Na clusters respectively. At this point, the field inside the cluster is enhanced (figure 3), the cluster expansion velocity increases dramatically; and more electrons are liberated through tunnel, laser driven and thermal ionization. The hot electrons can leave the cluster to the $3n_{\text{crit}}$ resonance.
The combined effect of the free streaming of electrons out of the cluster and the hydrodynamic expansion of the cluster is that the electron density starts to fall, after peaking at over 7.32 and 14.54 for both clusters (Kr and Na respectively). The expansion of the cluster lowers the electron density to bring the system into resonance with laser field. The electron density in the cluster drops to $3n_{\text{crit}}$ (figure 2); and the field inside the cluster is strongly enhanced and reach the value $1.65 \times 10^{12} \text{ V/m}$ and $1.58 \times 10^{12} \text{ V/m}$ for Kr and Na clusters respectively (figure 3); then we have a very rapid deposition of the energy into the electrons; at this point, the ions are very rapidly stripped the hot electrons. The inner field $E_{\text{int}}(t)$ (which is almost equal to the external field since the electron density $n_e$ is very low.

Figure 3. Time variation of the amplitudes of the internal and external electric fields for Na and Kr clusters. The laser and cluster parameters are the same as those in Figure 2.
The contributions of the hydrodynamic pressure and the coulomb one are shown in figure 4 for the two clusters. The total charge on the cluster increases, then the coulomb pressure increase to $3.73 \times 10^{12}$ Bar and $2.92 \times 10^{12}$ Bar for Kr and Na clusters respectively; However this is small compared to the hydrodynamic pressure due to the hot electrons of $2.54 \times 10^{13}$ Bar and $1.78 \times 10^{13}$ Bar for the rare gas (Kr) and metallic (Na) clusters respectively. This pressure causes a sharp increase in the cluster expansion velocity. During the majority of time, the dominant pressure is the hydrodynamic pressure with a little contribution of the coulomb explosion force; then the hydrodynamic pressure is dominant in driving the explosion. It has been noticed that for small diameter clusters, the coulomb explosion force plays a key role [4]. Our investigation of the coulomb explosion of large Kr and Na clusters shows that the hydrodynamic pressure plays an important role than the coulomb one which is in good agreement with previous results [22].

**Figure 4.** Variation of the Coulomb and hydrodynamic pressures as a function of time in the Kr and Na clusters for $2.10^7$ atoms irradiated by 200 fs laser pulse, 390 nm wavelength and peak intensity of $10^{21}$ W/m$^2$. 

The contributions of the hydrodynamic pressure and the coulomb one are shown in figure 4 for the two clusters. The total charge on the cluster increases, then the coulomb pressure increase to $3.73 \times 10^{12}$ Bar and $2.92 \times 10^{12}$ Bar for Kr and Na clusters respectively; However this is small compared to the hydrodynamic pressure due to the hot electrons of $2.54 \times 10^{13}$ Bar and $1.78 \times 10^{13}$ Bar for the rare gas (Kr) and metallic (Na) clusters respectively. This pressure causes a sharp increase in the cluster expansion velocity. During the majority of time, the dominant pressure is the hydrodynamic pressure with a little contribution of the coulomb explosion force; then the hydrodynamic pressure is dominant in driving the explosion. It has been noticed that for small diameter clusters, the coulomb explosion force plays a key role [4]. Our investigation of the coulomb explosion of large Kr and Na clusters shows that the hydrodynamic pressure plays an important role than the coulomb one which is in good agreement with previous results [22].
When the electrons mainly gain energy through inverse bremsstrahlung, the ion energy (figure 5) roughly follows the evolution of the internal field. The increase of the electronic temperature leads to higher ionized states, and then electrons with high energy can leave the cluster. The coulomb pressure induced by this loss of the plasma neutrality combined with the hydrodynamic pressure induces the expansion of the nanoplasma. The electron density $n_e$ also decreases to reach the $3n_{\text{crit}}$ resonance condition at different time (second resonance) mentioned above. The enhancement of the internal field (figure3) then leads to a very efficient absorption of the laser energy, resulting to the production of high charge states and high energetic ions 7.5 keV for Kr cluster and 22.03keV for Na cluster three times than ion energy of Kr cluster. Then the combined effect of free streaming and the coulombian and hydrodynamic pressures leads to the final explosion of the cluster.

### 4. Conclusion

We have studied the comparison behaviour of the different physics parameters between rare gas and metallic clusters (Kr and Na) using the modified nanoplasma model to examine the cluster explosion dynamics and scaling of ion energies; similar behaviour was found for the two cases metallic and rare gas clusters. We have found that ions have energy up to $10^3$eV, ions of Na cluster have energy up to three times than the ion energy of Kr cluster, rapid ionization and expansion of Na metallic cluster than Kr rare gas cluster. The coulomb pressure is little than the hydrodynamic one for both cases (metallic and rare gas clusters); then we conclude that the hydrodynamic pressure is responsible for the dynamic of ionization, expansion and explosion of the clusters.
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