Coulomb Explosion of Xenon Clusters irradiated by high-intensity laser pulses of the VUV-FEL


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The interaction of clusters with high intensity optical lasers has been extensively studied in the past decade. Clusters are of special interest in this context because they bridge the gap between molecules and condensed matter physics. While the overall particle density in a cluster beam can be pretty low, the density of each cluster is approximately that of a solid. This high local density leads to strong absorption of laser energy, which is then followed by ionisation and explosion of the cluster. Up to now all experimental work [1] was restricted to high intensity lasers in the infrared to visible optical range. As a consequence the experiment at the VUV-FEL offer the first chance to study the interaction of intense VUV radiation with matter. An overview of experimental set-up and techniques is given in a contribution in the first part of the annual report.

The experiments are performed in the following way. A pulsed beam of clusters is prepared by expanding gas at high pressure through a small nozzle. After passing a skimmer the cluster beam is irradiated by VUV radiation from the FEL. The power density of the VUV radiation in the focal spot reaches up to $10^{14} \text{ W/cm}^2$. Ions produced in the interaction zone are recorded by a time of flight mass spectrometer [2]. As an example, time of flight mass spectra of Xenon clusters are shown, in figure 1. Cluster sizes $N$ are given in the figure and range from a beam of atoms at the bottom to large clusters containing 30000 atoms at the top. The most striking result is that atomic ions are seen although clusters are irradiated. Two distinct changes are visible in figure 1 for increasing cluster size. First, the increase of the maximum ion charge state. At the bottom only singly ionized xenon atoms are seen, while at the top cluster ions up to charge state $6^+$. Second, the intensity of the atomic ions increases with increasing cluster size. This is shown in figure 1 where the intensity of the atomic ion $Xe^+$ is plotted as a function of time of flight.

Figure 1: Time of flight mass spectra recorded after multi-photon ionisation of Xenon atoms and clusters ($h\nu = 12.8eV$). The cluster size $N$ is given in the figure. Vertical lines mark the time of flight, charged Xenon atoms would have without ejection energy from the explosion.
Xenon atoms are present. This changes up to a charge of +8 in the case of the largest clusters at the top. Second, the ions resulting from irradiation of larger clusters are faster. It can be seen that for example the singly charged Xenon atoms resulting from the ionisation of very large Xenon clusters need less time to reach the detector, than Xe\(^+\) ions from small clusters. This behaviour is a fingerprint of a coulomb explosion which accelerates the ions. The straight lines in figure 1 mark the time ions would need to arrive at the detector without initial kinetic energy. By analysing the kinetic energies as a function of the cluster size, one can see in graph a) in figure 2 that for each charge state the kinetic energy increases with increasing cluster size. A similar trend is also observed in high intensity infrared laser experiments and reflects that more energy from the laser field is coupled into the cluster. The slope of the curve is different from that discussed in reference [3] and it may give insight in the explosion dynamics. In figure 2 b) the dependence of the kinetic energy on the ion charge state is shown. The initial radius of the Xenon was \( R \sim 30 \text{Å} \). The quadratic dependence on the ion charge state is a signature of a coulomb explosion. In a Coulomb explosion the first step is multiple ionisation of the cluster followed by a massive loss of electrons. The highly charged cluster then explodes due to Coulomb repulsion between the ions. This means that the accumulated total Coulomb energy is converted into ion kinetic energy. Ion kinetic energies \( E \) are then expected to be proportional to their ion charge \( Q \) squared (\( E_{\text{kin}} \propto Q^2 \)) [1].

Figure 2: Kinetic energies of charged Xenon ions after explosion of Xenon clusters. 

a) With increasing radius of the cluster the Xenon atoms show a higher kinetic energy. This behaviour is shown for three different ion charge states.  
b) Dependence of the kinetic energy on the ion charge state. The initial radius of the Xenon cluster is given in the figure.

References

