

Conclusions

Photodiode arrays provide the experimentalist with an x-ray detection medium that is more sensitive than film and has a larger dynamic range than film. They are appropriate for use in imaging or spectroscopic diagnostics of laser-plasma x rays. This has been demonstrated with the Hughes PDA attached to an x-ray pinhole camera deployed on the University of Rochester's OMEGA laser target chamber.

ACKNOWLEDGMENT

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1.D Ionization of Atoms with Intense, Linearly and Circularly Polarized, Picosecond Laser Pulses

Current high-power lasers can produce focused intensities in which the electric field is comparable to that which binds an atomic electron ($\sim 10^9$ V/cm). Under these conditions, the externally applied field cannot be treated as a small perturbation of the atomic system. The atomic- and laser-field systems must be considered together, opening an interesting new regime of atomic-physics research. An atom exposed to these strong fields becomes severely distorted and can undergo rapid ionization. The goal of this research is to study the response of atoms and ions to these extreme conditions.

A difficulty with experiments measuring the ionization of atoms and ions with high-intensity lasers has been the uncertainty in the absolute intensity, which is often a factor of 2. This makes a comparison between theoretical predictions and experimental results somewhat imprecise and can make it difficult to distinguish different ionization mechanisms. On the other hand, the relative (shot-to-shot) laser intensity can be measured with significantly higher precision, perhaps $\pm 20\%$ or better. Thus, comparisons between experimental results and theoretical predictions are facilitated by dependence upon the relative rather than absolute measurements of the laser intensity.

This article presents results of experiments comparing the intense field ionization of Xe and Ne atoms with linearly and circularly polarized, picosecond laser pulses. In a previously reported work, the ionization of noble gases was measured using a 1-ps, 1- μm wavelength laser with intensities up to mid- 10^{16} W/cm² with linear polarization.^{1,2} It was found that the ionization threshold intensity of different charge states scaled as E_{ion}^4/Z^2 and that classical, field-induced ionization [barrier suppression ionization (BSI)] could best explain the experimental results over the large range of ion species measured. It was also found that a complex-atom, tunneling-ionization model of Ammosov, Delone, and Krainov (ADK)³ could also explain the ionization of Xe and Kr, though it did not work quite as well for the lighter noble gases. By comparing the ionization with linearly and circularly polarized laser light, we are able to distinguish between the two theories and find that the tunneling theory (ADK) provides a more accurate description of the relative ion production for the two polarizations.

Experimental Observations

The laser used for these experiments is based on the chirped-pulse-amplification technique and has been described in detail elsewhere.^{4,5} CPA laser systems allow the production of high-power, ultrashort pulses in solid-state lasing media.⁶ A laser pulse from a mode-locked oscillator is frequency chirped, temporally expanded in a fiber, and further stretched in time by an expansion grating pair. The longer pulse allows more energy to be extracted from the subsequent amplifier system than would be by a short pulse. After amplification, the pulse is compressed by a grating pair to picosecond or subpicosecond duration. There is a resulting increase in power by a factor equal to the chirp ratio (i.e., the stretched-pulse duration divided by the compressed-pulse duration). The chirping in the fiber, the compression and expansion grating pairs, and the chirp ratio are well described in Refs. 7–10.

For these experiments the compressed pulse was focused to a maximum intensity of approximately 1×10^{15} W/cm² by a 20-cm focal-length lens located inside a vacuum chamber. The chamber was backfilled with either xenon or neon to a known pressure between 5×10^{-8} and 5×10^{-5} Torr. A time-of-flight ion spectrometer was used to separate the ion species. The spectrometer has an extraction voltage of 800 V/cm and a drift tube length of 60 cm. The ion detector is a dual microchannel plate typically operated at 2 keV for maximum gain. The ion signal is digitized with a 100-MHz transient digitizer (Kinetic Systems 4030) and the signals are stored digitally. Analysis of the spectra consists of integrating the various ion peaks to find the number of ions in each peak. The ion number for each laser shot is then plotted versus the incident laser intensity. A data run consists of taking approximately 150 laser shots at each of three different backfill pressures. The data taken at the highest intensities for linear polarization were taken with extra wire grids placed in the spectrometer to reduce the transmission efficiency. The use of different backfill pressures and the addition of the wire grids are necessary to avoid detector saturation for large ion number. Since the spectrometer efficiency is known, the data can be scaled to account for these changes.

Data were taken using both linearly and circularly polarized light. The experiments with linear polarization were performed with a quarter-wave plate in the beam that was set for zero retardation. When circular polarization was required, the wave plate was rotated by 45° . This ensures that any distortion in the wavefront or energy attenuation that might be introduced by the wave plate is present for both polarizations.

A comparison of the production of singly ionized xenon and neon for linearly and circularly polarized light is shown in Fig. 50.22. In the case of circular polarization an intensity increase of about 1.7 ± 0.1 is required to produce the same number of xenon ions as in the linear polarization case, and a factor of 1.5 ± 0.1 is required for neon.

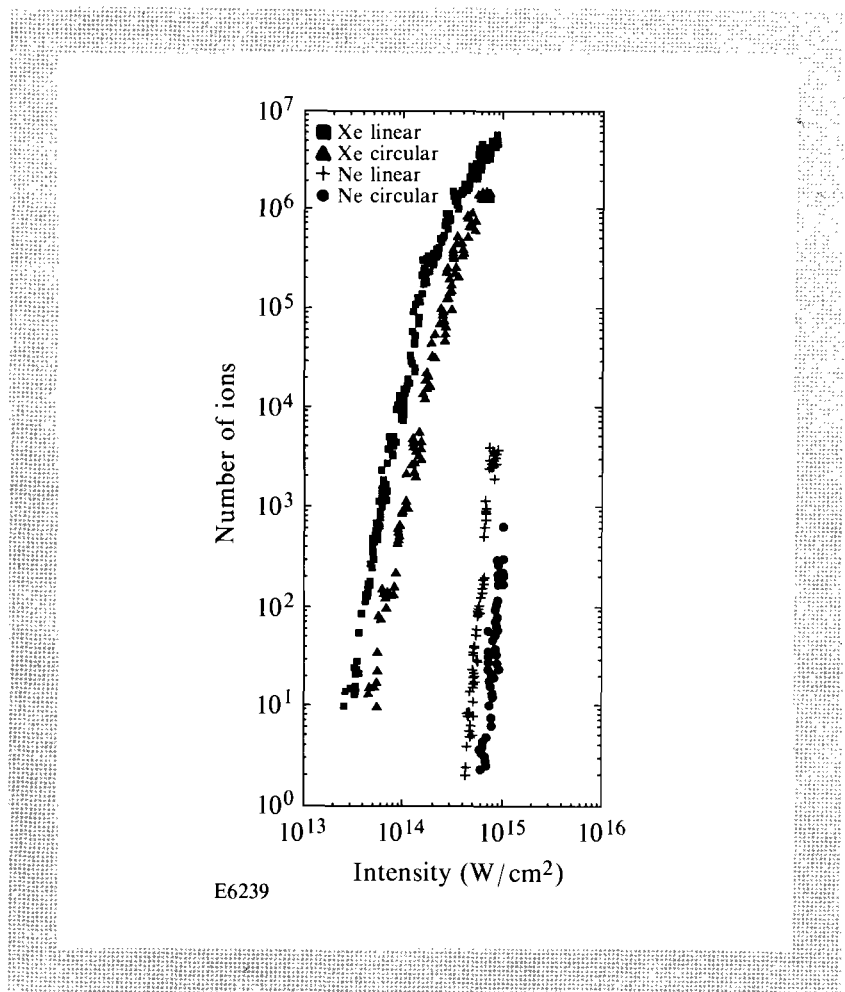


Fig. 50.22
Comparison of the production of Xe⁺ and Ne⁺ ions for linearly and circularly polarized light. The laser pulse length is 1.9 ps.

Theoretical Predictions

Experiments involving the interaction of atoms with intense laser fields have traditionally been divided into two regimes: multiphoton and tunneling. In the former, laser ionization can be described by perturbation theory, while in the latter, ionization can be described as an ac-tunneling process. These regimes can be quantitatively differentiated by introducing the Keldysh γ parameter¹¹

$$\gamma = \sqrt{\frac{E}{2\Phi}}, \tag{1}$$

where E is the ionization potential of the atom or ion and Φ is the ponderomotive potential of the laser. The ponderomotive potential is equal to the average kinetic energy of an electron oscillating in a laser field. The multiphoton regime has traditionally corresponded to $\gamma \gg 1$ with $\gamma \ll 1$ corresponding to the tunneling regime. In the tunneling regime, the electric field can be treated with a quasi-static approximation.

We have recently reported studies of ionization in the tunneling regime of five noble gases using the T³ laser,^{1,2} where a comparison between our data and various theoretical models for photoionization was made. Two theories agreed well with the experimental data. Both of these are explicitly based on a quasi-static model of the laser field.

BSI is a simple, one-dimensional model of ionization^{1,12} based on the superposition of the Coulomb potential and a quasi-static laser field. The threshold intensity for ionization (I_{th}) is defined as the intensity at which the peak electric field allows the bound electron to escape without tunneling and is $I_{th} = E^4/(16 Z^2)$ in atomic units, where Z is the charge state of the atom or ion after ionization.

We have defined an experimental threshold intensity for ionization to be that intensity at which the ionization probability in the pulse is approximately 1%. Figure 50.23 shows a comparison of the experimental and BSI ionization threshold intensities. As can be seen, there is good agreement between the model and the experiment over three orders of magnitude in laser intensity.

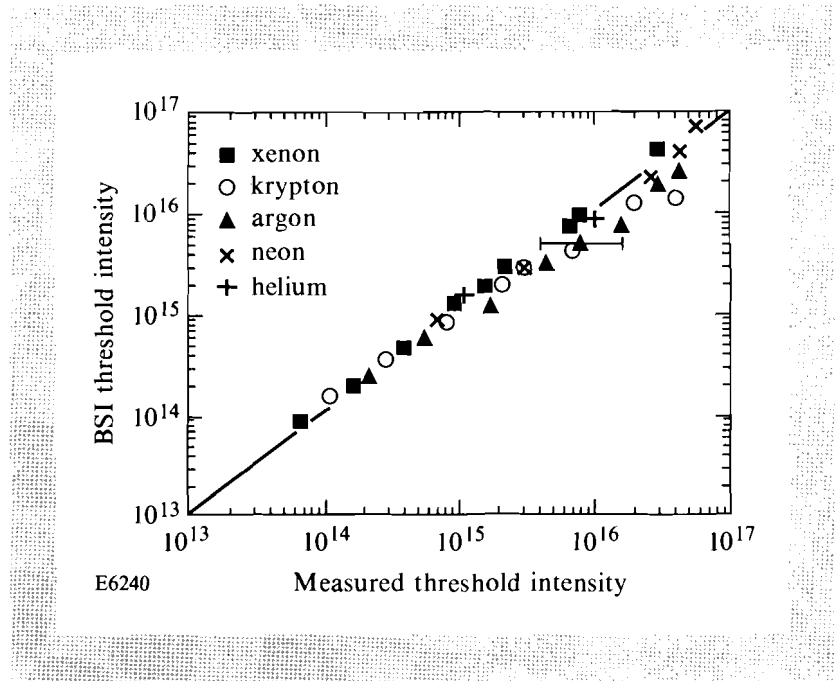


Fig. 50.23 Comparison of the measured threshold intensity for ionization of various charge states of a noble gas with the BSI predictions (from Ref. 1).

The ADK model³ is an extension of the 3-dimensional (3-D) dc-tunneling model. The 3-D, dc-tunneling model supplies the tunneling ionization rate for a hydrogen atom in a static electric field and is given by^{13,14}

$$W_i = 4\omega_A \frac{(2E_i)^{5/2}}{\epsilon} \exp\left[-\frac{2(2E_i)^{3/2}}{3\epsilon}\right]. \quad (2)$$

Perelomov *et al.*¹⁵ introduced an atomic shell dependence and an oscillatory electric field to this model, resulting in an ionization rate of

$$W_{\text{linear}} = \omega_A C_{n^*l}^2 f_i(l, m) E_i \left[\frac{3\epsilon}{\pi(2E_i)^{3/2}} \right]^{1/2} \left[\frac{2}{\epsilon} (2E_i)^{3/2} \right]^{2n^* - |m| - 1} \times \exp\left[-\frac{2}{3\epsilon} (2E_i)^{3/2}\right], \quad (3)$$

where the factor f is given by

$$f(l, m) = \frac{(2l+1)(1+|m|)!}{2^{|m|}(|m|)!(l-|m|)!}. \quad (4)$$

The term $\left[3\epsilon / \pi(2E)^{3/2}\right]^{1/2}$ in Eq. (3) results from averaging over one period of the laser, and for the laser parameters discussed here, it is typically of order 10^{-1} . Atomic structure is introduced through the factors $f(l, m)$ and C_{n^*l} , but Perelomov *et al.*¹⁵ did not derive an expression for the C_{n^*l} 's. Ammosov *et al.*³ extended the theory by deriving an approximate expression for the C_{n^*l} 's. This was accomplished by joining the asymptotic wave function of the free electron with the quasiclassical radial wave function of a bound electron.¹³ The initial atomic or ionic state is described by the effective principal quantum number n^* , the orbital angular momentum, and the magnetic quantum numbers l and m . A species-dependent ionization rate results from this inclusion of n^* in the theory. The expression for C_{n^*l} is given by Ammosov as³

$$C_{n^*l} = \left(\frac{2e}{n^*}\right)^{n^*} \frac{1}{(2\pi n^*)^{1/2}}, \quad (5)$$

where $e = 2.71828\dots$. For ionization rate calculations, we have used the ground state values¹⁶ for n^* and l and a summation over the degenerate m states.

Equation (3) is an approximation valid in the limits $n^* \gg 1$, $\epsilon_{\text{laser}} \ll \epsilon_{\text{binding}}$, and $\omega_L \ll E$. The validity of the ADK is expected to improve as n^* increases, and

larger n^* occurs for heavier atoms and higher charge states. Thus, the agreement is expected to be best for xenon and worst for helium.

It was found that ADK and BSI theories both predict the correct spacing for all charge states observed (E^4/Z^2 dependence), but the fit between the ADK theory and the data from the lighter noble gases (helium, neon, and argon) had an absolute error in the threshold intensities of 2 or less.² The agreement with ADK improved for increasing atomic number since n^* is also increasing, and the slope of the ion curve for low ion number agrees with the experiment better than the BSI theory. It should be noted that the absolute error in threshold intensities that ADK predicts for the lighter noble gases is never larger than the experimental uncertainty present in our absolute intensity measurements (a factor of 2), but it is larger than the relative uncertainty.

Circular versus Linear Polarization

Both BSI and ADK models of ionization depend on the strength of the electric field. For linearly polarized light, the electric field oscillates in time, $\epsilon(t) = \epsilon_1 \cos \omega t$, and is related to the intensity as $I_l = \epsilon_1^2$, whereas for circularly polarized light, the electric field has a constant amplitude and is related to the intensity as $I_c = 2 \epsilon_c^2$. In this section, the intensity dependence of the two ionization models is considered by comparing the relative field strengths at which linear and circular polarization give the same ionization rates. At the same ionization rate linear and circular polarization will yield the same number of ions.

Classical field ionization (BSI) depends only on the strength of the electric field and is independent of the oscillatory nature of the field as long as the oscillation frequency is much less than the atomic orbital frequency. Thus for BSI, one expects a factor-of-2 increase in intensity for ionization by circular polarization compared to linear, to produce the same number of ions.

For tunneling ionization, the picture is a little more complicated. At the same intensity, the field strength for circular polarization is $\sqrt{2}$ smaller than that for linear; this reduces the tunneling rate. On the other hand, the circularly polarized field is on continuously; thus, the static field rate

$$W_{\text{circular}} = \omega_A C_{n_i^* l}^2 f_i(l, m) E_i \left[\frac{2}{\epsilon} (2E_i)^{3/2} \right]^{2n_i^* - |m| - 1} \times \exp \left[-\frac{2}{3\epsilon} (2E_i)^{3/2} \right], \quad (6)$$

rather than the time averaged rate (Eq. 3), is applicable. The omission of the averaging term $\left[3\epsilon / \pi (2E)^{3/2} \right]^{1/2}$ decreases the intensity difference to less than a factor of 2. By comparing the linear and circular ionization rates in the intensity ranges of the experiments, we find that the intensity required to ionize Xe atoms should be a factor of 1.6 ± 0.1 times higher for circular polarization than for linear and a factor of 1.5 ± 0.1 for Ne atoms, which is consistent with the experimental results.

Conclusions

In a previous experiment, it was found that both BSI and ADK could be used to explain the high-field ionization of noble gases.² Both theories show a E_{ion}^4/Z^2 dependence in the ionization thresholds of the charge states within the absolute uncertainty in the laser intensity, although ADK systematically underestimated the ionization rate for the lighter noble gases. By comparing ionization with circular and linear polarization, it is found that the ADK tunneling model produces good agreement with the experimental results, while BSI overestimates the required circularly polarized intensity.

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