MULTIPHOTON IONIZATION OF KRYPTON AND ARGON BY RUBY LASER RADIATION

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We observed multiphoton ionization of krypton and argon atoms by ruby-laser radiation at an electric field intensity ~10^7 V/cm. The ratios of the ionization potentials (I(Kr) = 13.97 eV, I(Ar) = 15.75 eV) to the quantum energy ($\hbar\omega$ = 1.785 eV) show that ionization can occur by absorption of 8 and 9 quanta respectively. For the same photon flux, we measured the ratios of the ion signals of krypton, argon, and xenon, for which measurements were made of the absolute ionization probability [1].

The experimental setup was similar to that used by us for the observation of the multiphoton ionization of the xenon atom [1,2] and the hydrogen molecule [3]. The laser operating mode was thoroughly stabilized. The vacuum chamber was alternately filled with xenon, krypton, and argon to a pressure in the interval 10^{-5} - 10^{-4} mm Hg. The pressure was measured with an ionization manometer, with due allowance for the corrections for its sensitivity to the different gases [4]. The produced ions were analyzed with a time of flight mass spectrometer with resolution better than 20, and registered with an electron multiplier.

The ratios of the ion signals, for equal gas density and for a photon flux intensity $F = 10^{30.6 \pm 0.3}$ $\text{cm}^{-2}\text{sec}^{-1}$ (field intensity $E = 2 \times 10^7$ V/cm) are listed in the table. The error is essentially connected with the uncertainty of the secondary emission coefficient of the first dynode of the electron multiplier for ions of different mass.

Experimental and theoretical results (accuracy of theoretical values corresponds to error of experimentally determined value of F)

	Ratio of ion signals	Ratio of ionization probabilities			
		Experiment	Calculation by formula of Keldysh [8]	Results of Gold and Bebb	
				[6]	[7]
Kr/Xe	$10^{-0.83 \pm 0.1}$	$10^{-0.87 \pm 0.3}$	$10^{-2.8 \pm 0.3}$	$10^{-3.85 \pm 0.3}$	$10^{+3.15 \pm 0.3}$
Ar/Xe	$10^{-2.37 \pm 0.3}$	$10^{-2.06 \pm 0.5}$	$10^{-5.7 \pm 0.6}$	$10^{-2.6 \pm 0.6}$	$10^{+2.2 \pm 0.6}$

From the experimental ratios of the ion signals we can obtain the ratio of the multiphoton ionization probabilities.

The ionization probability is connected with the number N_i of the produced ions by the relation

$$W = N_i/nV_k\tau_k,$$

where n is the density of the neutral atoms, and V_k and τ_k are the effective volume and the time [1]. These values depend on the power in the power-law dependence of the ionization probability on the photon flux intensity ($W = AF^k$). The measurements for xenon [1] have shown that the experimental value of k is smaller by 1 than the number of quanta necessary for the ionization $\langle (I/\hbar\omega) + 1 \rangle$, where $\langle x \rangle$ denotes the integer part of x. This effect can be attributed to the action of the strong electric field of the radiation on the upper energy levels of the atom [8].

Since the upper levels of all the atoms are hydrogenlike, we can expect the action of a strong field on these levels to lead to an analogous effect also in the case of other atoms. We therefore assume that in the case of Ar and Kr the ionization probability is proportional to the intensity of the photon flux raised to a power k in the range

$$\langle (I/\hbar\omega) + 1 \rangle \geq k \geq \langle (I/\hbar\omega) + 1 \rangle - 1.$$

Using this assumption regarding the value of k and the data obtained earlier [1,3] we obtain the following relations:

$$\frac{V_k \tau_k \,(\mathrm{Kr})}{V_k \tau_k \,(\mathrm{Xe})} = 0.7 \pm 0.2; \quad \frac{V_k \tau_k \,(\mathrm{Ar})}{V_k \tau_k \,(\mathrm{Xe})} = 0.3 \pm 0.1.$$

The table lists the probability ratios obtained from the experimental data on the ion signals and their ratios. We see that allowance for the change in the value of $V_k \tau_k$ leads to an insignificant correction, so that the possible difference between the actual and proposed values of k has little effect on the results.

The results of the experiment were compared with the predictions of the theory of L. Keldysh [5] for transitions over the virtual levels of the continuous spectrum, and with the results of the perturbation-theory calculation of Gold and Bebb [6,7], who used an electronic computer and included terms up to fourteenth order.

In the calculations by the Keldysh formula we used the experimentally measured value of k for the Xe atom, and for the Kr and Ar atoms we chose the value of k in accordance with the foregoing assumptions. Calculation yields in this case the ratios $W(\mathrm{Kr})/W(\mathrm{Xe}) \sim F^{-1}$ and $W(\mathrm{Ar})/W(\mathrm{Xe}) \sim F^{-2}$.

Calculation by the Keldysh formula (see Eq. (1) of [8]) and the results obtained by Gold and Bebb in their first paper [6] give qualitatively correct ratios of the ionization probabilities. The quantitative differences between the Keldysh formula and experiment is apparently connected with the fact that in the formula used by us no account is taken of the quasiresonance transitions through the intermediate levels. In their second paper [7] Gold and Bebb refined the wave functions by allowing for the Coulomb interaction in the final state, and also refined the energy differences. However, the calculation of [7] gives a result which does not agree qualitatively with the experiment, for at $F \cong 10^{30}$ $\mathrm{cm^{-2} sec^{-1}}$ the probabilities of the multiphoton ionization of Kr and Ar turn out to be larger than that of Xe. This discrepancy is apparently connected with the fact that the shift and broadening of the levels in a strong field play a significant role, so that perturbation theory is not applicable.

In conclusion it must be noted that in view of the good accuracy with which one can measure the ratio of the multiphoton ionization probabilities of various atoms (compared with the accuracy of measurement of the absolute probability), such results are of great value for checking theoretical assumptions.

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PECULIARITIES OF SHOCK COMPRESSION OF LANTHANIDES

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As is well known, successive rearrangement of the 4f-electron subgroup takes place in rare-earth elements with increasing atomic number.

Inasmuch as the filling of the outer electron shells remains unchanged at the same time, the physico-chemical properties of rare metals are quite similar. In particular, they have space lattices constituting different variants of closest packing.

The appearance of denser phases upon compression of such structures, or a reduction in compressibility, is evidence of a change in the electron distributions.

The rearrangement of the electronic structure has been observed for lanthanides only in the case of cerium [1] at static pressures of 12 kbar. According to Hume-Rothery and Raynor [2], a variant of the transition of 4f-electrons to the 5d-band is realized in this case, and results in the appearance of a strong covalent bond, which increases the density of the metal.

In this communication we report the first results of an investigation of the dynamic compressibility of five lanthanides, La, Ce, Sm, Dy, and Er, up to 3.5 Mbar pressure.

The shock-compression parameters were obtained by the reflection method [2,4] using the experimental apparatus of [5,6], where shock waves of fixed intensity were produced in screens covering the samples.

The directly-measured quantities were the velocities d of the shock waves in the investigated metals. These quantities were used to determine, with the aid of the conservation laws