Measurement of electron-impact single-ionization cross sections of Ar^{8+}

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(Received 10 June 1991)

A crossed-electron-ion-beam experiment was used to measure the total ionization cross section for Ar^{8+} in the energy range from 50 to 600 eV. The present results are roughly in agreement with the previous measurements of Defrance *et al.* [Nucl. Instrum. Methods Phys. Res. B **23**, 256 (1987)] above 450 eV. However, the present measurements show a significant contribution below the threshold for direct ionization. The present measurements agree with the distorted-wave calculations of Pindzola *et al.* [Phys. Rev. A **41**, 1375 (1990)] when 3% of the incident ion beam is assumed to be in metastable states and excitation autoionization from metastable states is included.

PACS number(s): 34.80.Kw, 32.80.Cy, 32.80.Dz

Electron-impact ionization of highly charged ions is of great importance in understanding the atomic processes in laboratory and astrophysical plasmas. The approximations used in such calculations impose serious limitations on their accuracy, and experimental measurements of the cross sections are necessary to ensure understanding of the basic physical processes.

In the present work, the existence of metastable-state ions and enhancement in the ionization cross sections due to excitation autoionization from such metastable states has been observed. Ne-like ions are of fundamental interest in that the physics of ionization from a neonlike metastable ion is quite different from that of a ground-state ion.

Extensive work has been done on Ar ions. Experimental measurements of Meng *et al.* for several Ar ions show an ionization rate coefficient that is almost a factor of 2 lower than any of the available calculations for ground-state ions [1]. This discrepancy should be resolved, especially since the calculations for ground-state ions have almost always been found to underestimate the actual rates. It is well known that, near the direct-ionization threshold, indirect ionization involving excitation autoionization can make a significant contribution to the total ionization cross section [2]. Although excitation autoionization does not contribute significantly to the ionization of the ground state of neonlike ions [3], calculations by Pindzola *et al.* show significant contributions to the ionization cross sections from metastable states of these ions [4]. Such metastable Ar^{8+} ions have been reported by several groups in different experimental setups. In an ion-atom collision experiment, Bordenave-Montesquieu *et al.* postulated one-electron capture and other processes by $Ar^{8+}(2p^5 3s)^3P_{0,2}$ metastable states [5] based on calculations by Fielder *et al.* [6]. A spectroscopic study by Bliman *et al.* reported the production of doubly excited Ar^{7+} following charge transfer by $Ar^{8+}(2p^5 3s)^3P_{0,2}$ colliding with H_2[7]. (The configuration is also based on calculations by Fielder [6].) Recently, a small percentage of metastable Ar^{8+} ions was found by Meyer in scattering from metal surfaces using the Oak Ridge National Laboratory (ORNL) electron-cyclotron-resonance (ECR) ion source [8]. However, crossed-beam measurements by Defrance *et al.* with another ECR source did not indicate the presence of metastable ions [9]. In an earlier attempt at ORNL to measure the Ar^{8+} ionization cross section, a considerable metastable content to the beam was indicated [10]. The present experimental measurements of electron-impact ionization in the near-threshold region were made in an attempt to resolve the discrepancies involving the production of Ar^{8+} metastable ions.

The experimental setup [11–14] and general method [15] have been described in detail elsewhere. Briefly, Ar^{8+} ions produced by the ORNL ECR ion source were accelerated to 80 keV and mass-selected before entering the interaction region where they crossed a magnetically confined electron beam at 90°. Previously, the energy spread of the electrons was estimated to be 2 eV or less [16]. The ions were charge-selected by a magnetic analyzer after the interaction region and the Ar^{9+} signal ions were counted using a channeltron detector. The electron beam was modulated, and the Ar^{9+} signal with the electron beam turned off was subtracted from that with the electron beam turned on. All the measured cross sections are reported with the equivalent of one standard deviation, with the total uncertainty being reported for each point.

The dominant processes that contribute to the ionization cross section are the following: direct ionization from the ground state,

$$Ar^{8+}(2p^6)+e \rightarrow Ar^{9+}+2e \ ; \tag{1}$$

direct ionization from the metastable states,

$$Ar^{8+}(2p^5 nl)+e \rightarrow Ar^{9+}+2e \ ; \tag{2}$$

excitation autoionization from the metastable states,

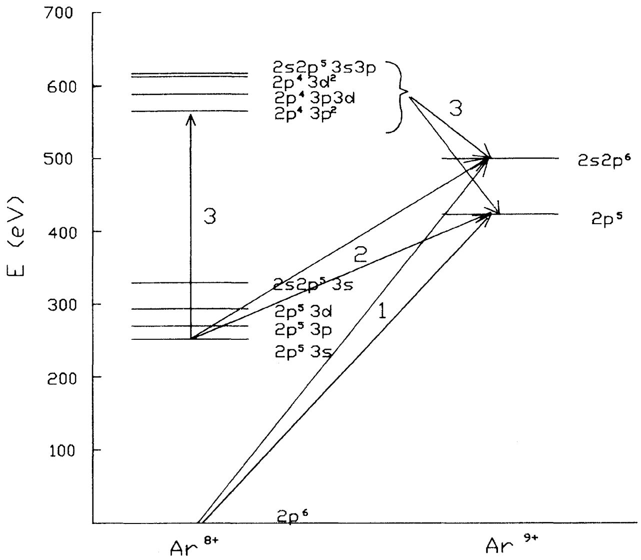

FIG. 1. Energy levels of Ar^{8+} and Ar^{9+} and the main channels of transitions considered. 1, direct ionization from the ground state Ar^{8+} to Ar^{9+}; 2, direct ionization from $Ar^{8+}(2p^53s)$ to Ar^{9+}; 3, excitation autoionization from $Ar^{8+}(2p^53s)$.

$$\begin{aligned} Ar^{8+}(2p^5nl)+e &\rightarrow Ar^{8+}(A)+e \\ &\rightarrow Ar^{9+}+2e\ ; \end{aligned} \tag{3}$$

and excitation autoionization from the ground state,

$$\begin{aligned} Ar^{8+}(2p^6)+e &\rightarrow Ar^{8+}(A)+e \\ &\rightarrow Ar^{9+}+2e\ , \end{aligned} \tag{4}$$

where A represents the autoionizing states. The contribution from process (4) is small due to the large energy difference between the ground state and the autoionizing states and has been neglected in the calculated results referenced here [3,4].

Multiconfiguration atomic-structure calculations employing Cowan's relativistic Hartree-Fock code were used to obtain the configuration-average energy levels for different electronic configurations of Ar^{8+}: $2p^6$, $2p^53s$, $2p^53p$, etc., and for the lowest-energy levels of $Ar^{9+}(2p^5,2s2p^6)$ [17]. Figure 1 shows the energy levels of the different electronic configurations and the main transition channels involved. Pindzola *et al.* [4] have employed a configuration-average method and used a distorted-wave approximation [18] to calculate the direct- and indirect-ionization cross sections from the $Ar^{8+}(2p^53s)$ manifold. They found that over a large energy range the cross section from excitation autoionization from metastable states was twice that of direct ionization from either the ground state or metastable configurations.

Experimental errors due to different sources in the measurements are listed in Table I. In the course of the experiment the detection efficiency of the microchannel plate detector was found to have changed. After checking the stability of the efficiency of the old detector, a new detector was installed. The cross section was remeasured at a number of energies, and the previously measured cross section was corrected for the appropriate detector efficiency. The uncertainty of the detector efficiency was increased to take this correction into account. The data listed in column 2 of Table II are corrected for this effect. A further correction has been made for an apparent space-charge modulation which manifests itself as a nonzero section below threshold, with the cross section increasing with decreasing energy. This modulation is assumed to be of the form $A/\sqrt{E}$, where E is the electron-impact energy and A is the correction coefficient [19]. A least-squares fit to the data below 150 eV gives $A=0.30\pm0.05$ $cm^2\,eV^{1/2}$ and the data with this contribution subtracted are presented in column 3 of Table II. The corrected data are plotted in Fig. 2 and compared with the measurements of Defrance *et al.* [9]. For energies above about 450 eV, the two sets of measurements are consistent within the uncertainties of the two experiments.

In Fig. 3 we present the cross section (corrected for the above effects) at energies below the ground-state ioniza-

TABLE I. Uncertainties of the cross-section measurement: All uncertainties are listed at the equivalent of one standard deviation for statistics.

Source	Uncertainty (%)
Counting statistics (one standard deviation)	
Minimum (at peak of cross section)	±1
Maximum (at $E<100$ eV)	±40
Form factor	±6
Systematic uncertainties	
Particle-counting efficiency	±4
Transmission-to-signal ion detector	±4
Ion current	±2
Electron current	±2
Ion and electron velocities	±1
Space-charge modulation correction	±3
Total uncertainty	$\pm(9–41)$

tion threshold. We also show the calculations of Pindzola *et al.* [4] (solid line) scaled to the measurements by a factor that is consistent with a 3% metastable population in the ion beam. The solid line on the figure includes the configuration-averaged contribution of the excitation-autoionization cross sections, whereas the dashed curve includes only the direct contribution from this configuration. The fact that the ionization cross section lies above the calculation for the direct ionization near 280 eV is attributed to the excitation autoionization from $2p^53s$ with a threshold at 291 eV. The oscillator-strength calculations by Fielder *et al.* [6] predict a 0.3-ms lifetime for the transition from the metastable states to the ground state of $Ar^{8+}(2p^53s, J=2)$. Considering that the flight time of the current experiment is about 15 μs (the beamline distance divided by the ion velocity), there should be no significant difference between the population density in the ion source and that in the interaction volume. Thus, our results shown in Fig. 2 are in good agreement with the distorted-wave calculation of Pindzola *et al.* [4] with the assumption that ions from the ECR ion source include 3% metastable population. The semiempirical formula of Lotz [20], assuming a 3% metastable population, is represented by the dotted line in Fig. 2. The experiment agrees with the distorted-wave results over a large energy range. However, over the entire ener-

TABLE II. Ionization cross-section data: The second column lists the measured data with their absolute uncertainties. The third column gives data reduced by $0.30/\sqrt{E}$ (where E is in eV). Absolute uncertainties in the third column include the contribution from the uncertainties due to correction for space-charge modulation.

	Ionization cross section ($\times 10^{-18}$ cm^2)	
Energy (eV)	Measured data	Data after the correction for space-charge modulation
50.0	0.053±0.018	0.006±0.019
70.3	0.052±0.028	0.012±0.028
74.5	0.039±0.019	0.001±0.019
98.4	0.034±0.002	0.001±0.003
121.1	0.011±0.015	−0.019±0.015
145.1	0.014±0.013	−0.014±0.013
148.1	0.024±0.012	−0.003±0.012
169.1	0.036±0.011	0.010±0.011
193.0	0.035±0.016	0.011±0.017
196.8	0.034±0.011	0.010±0.011
200.0	0.006±0.012	−0.017±0.012
210.8	0.033±0.010	0.010±0.010
221.0	0.050±0.014	0.028±0.014
235.0	0.028±0.012	0.006±0.012
241.0	0.026±0.008	0.004±0.008
245.6	0.046±0.003	0.024±0.003
258.1	0.022±0.011	0.001±0.011
264.9	0.018±0.008	−0.003±0.008
268.3	0.018±0.007	−0.002±0.008
281.8	0.040±0.009	0.020±0.009
289.0	0.041±0.008	0.022±0.008
294.0	0.065±0.004	0.045±0.004
304.5	0.050±0.008	0.031±0.008
313.1	0.052±0.007	0.033±0.007
328.0	0.064±0.008	0.045±0.008
342.3	0.088±0.010	0.070±0.010
351.9	0.068±0.007	0.051±0.007
374.9	0.082±0.006	0.065±0.006
385.6	0.073±0.005	0.056±0.005
391.8	0.089±0.005	0.072±0.005
407.3	0.092±0.010	0.075±0.010
421.6	0.110±0.011	0.094±0.011
441.0	0.174±0.010	0.159±0.011
445.2	0.218±0.016	0.203±0.016
489.0	0.374±0.024	0.359±0.024
492.0	0.354±0.024	0.339±0.024
538.0	0.514±0.032	0.500±0.032
542.0	0.481±0.033	0.466±0.034
588.0	0.597±0.037	0.584±0.037
591.3	0.615±0.038	0.602±0.038

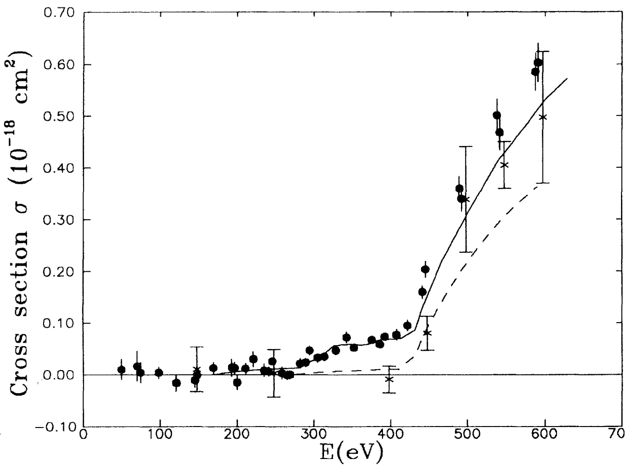

FIG. 2. Total ionization cross sections for Ar^{8+}. Solid circle, present measurements; crosses, measurement by Defrance *et al.* (Ref. [9]); dashed line, calculation using Lotz's formula (Ref. [19]), with 97% contribution from ground state and 3% from $2p^5 3s$; solid line, calculation by Pindzola *et al.*, with 97% contribution from ground state and 3% from $2p^5 3s$ (Ref. [4]).

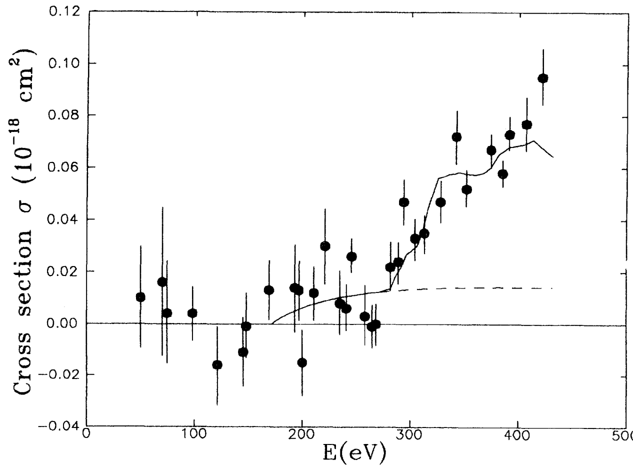

FIG. 3. Ionization cross section below the ground-state direct-transition threshold. Solid circles, present measurements; dashed line, calculated direct ionization from $(2p^5 3s)$ configuration (Ref. [4]); solid line, calculated total ionization cross section from $(2p^5 3s)$ configuration using configuration averaging (Ref. [4]); both calculated results assumed 3% population fraction of metastable ions.

gy range, the data appear slightly higher than the Lotz-formula prediction.

The small percentage of metastable population observed in the present experiment would not have been observed in the measurements of Defrance *et al.* because of the small number of points in this region and the relatively larger uncertainty in their measurements [9]. Depending on source temperatures, operating conditions, the species being observed, and the use of different ion sources, one might expect that the metastable populations for different experiments may differ. These differences could be substantial between beam and plasma measurements. Further measurements in the neonlike isoelectronic sequence are highly desirable.

We wish to thank D. C. Griffin, C. Bottcher, M. S. Pindzola, and R. A. Phaneuf for useful discussions. We are grateful to J. W. Hale for helpful technical assistance. This work was supported by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84-OR21400 with Martin Marietta Energy Systems, Inc. Travel support was provided for the University of North Texas collaborators by the National Science Foundation under Grant No. PHY-88-03562.

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