Resonance Structure and Absolute Cross Sections in Near-Threshold Electron-Impact Excitation of the $4s^2\,{}^1S \rightarrow 4s4p\,{}^3P$ Intercombination Transition in Kr^{6+}

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First measurements of absolute total cross sections for electron-impact excitation of an intercombination transition to a nonradiating state of an ion are reported. The cross sections for near-threshold excitation of the $4s^2\,{}^1S \rightarrow 4s4p\,{}^3P$ transition of Kr^{6+} are dominated by dielectronic resonances. The measurements can serve as a benchmark for theoretical predictions of dielectronic resonance structure in the excitation of multicharged ions.

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Experimental measurements of total cross sections for electron-impact excitation of a nonradiating state involving a change of spin are a rarity in atomic physics, and when the target is an ion, experimental data are nonexistent. In this Letter we present measured data for just such a collision. Specifically, we report the experimental observation of resonance structure in the near-threshold electron-impact excitation of the Kr^{6+} ($4s^2\,{}^1S \rightarrow 4s4p\,{}^3P$) intercombination transition. The absolute total cross sections, the first reported for a spin-changing transition in a multicharged ion, were measured using a merged-beam electron-energy-loss technique [1] and are clearly dominated by resonant processes near threshold.

Electron collisions with multiply charged ions are important in laboratory and astrophysical plasmas. Because the quantity of data needed is so enormous, theoretical calculations must provide most of the data needed for modeling these systems. The role of experiment is to provide "reality" in enough test cases that the level of confidence in the theoretical data is well established. Compared with other electron-impact processes, there is a marked dearth of experimental data on excitation [2] which can test the theory.

Krypton is an important constituent in high-temperature tokamak plasmas where it is introduced to facilitate spectroscopic ion temperature measurements in the core [3]. Electron-impact excitation of krypton ions is also significant in other laboratory plasmas [4].

Absolute cross sections have been measured [5] for only a handful of multicharged ions using the cross-beam radiation detection or the present merged-beam electron-energy-loss methods. Also, some cross sections, made absolute by normalization to theoretical radiative recombination cross sections, have been measured for very highly charged ions using the electron beam ion trap (EBIT) technique. These existing measurements are generally for radiating states with large oscillator strengths connecting to the ground state. Total absolute cross sections for electron-impact excitation of intercombination transitions of an ion have been reported only for Li^+ ($1s^2\,{}^1S \rightarrow 1s2p\,{}^3P$) [6].

Since the present method relies on detection of electrons which have lost the appropriate amount of energy instead of photons emitted from an excited state, absolute total cross sections for transitions to both radiating and nonradiating states can be measured. The distinction with more traditional energy-loss methods lies in the fact that 100% of the inelastically scattered electrons are collected, giving a total cross section, whereas the traditional approach incorporates angular dispersion and is generally involved with relative differential cross section measurements.

Details of the merged-beam electron-energy-loss apparatus have been given elsewhere [1,7], so only a brief summary is included here. A closely related technique has been used and described by Smith *et al.* [8] for singly charged ions. Electrons are merged with ions using a trichoidal analyzer (crossed magnetic and electric fields) and demerged with a similar analyzer after traversing a 96.5 mm electric-field-free interaction region. A schematic of our apparatus is shown in Fig. 1. The apparatus is immersed in a uniform solenoidal magnetic field (≈ 3

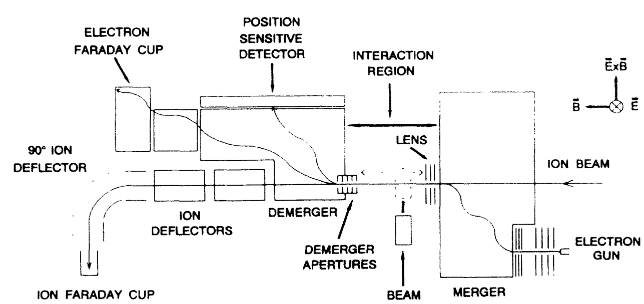

FIG. 1. Schematic view of the electron-ion merged-beam apparatus.

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mT) parallel to the ion beam. Electrons from the gun enter the crossed-field region of the first analyzer and undergo trochoidal motion, exiting the crossed-field region after two cyclotron gyrations and an appropriate drift perpendicular to the two fields. The electrons then become collinear (merged) with the ions, which originate from an electron-cyclotron-resonance (ECR) ion source. After traversing the 96.5 mm long electric-field-free interaction region, the beams enter the second trochoidal analyzer (called the demerger). The demerger disperses the primary electrons through a relatively small angle into a Faraday cup. The inelastically scattered electrons are dispersed through a larger angle onto a position-sensitive detector (PSD). The ions are not significantly deflected in the demerger, but are subsequently bent through 90° and collected in another Faraday cup. Electrons scattered elastically at large angles by ions in the merge path could in principle also reach the detector, but are blocked from entering the demerger by a series of demerger apertures.

A movable beam probe [9] using fluorescent screen and digitized video techniques enables the measurement of the amount of electron- and ion-beam overlap (form factor) along the interaction path. The overlap of the beams is maximized in the "upstream" part of the merge path and minimized near the entrance to the demerger to obviate the possible problem of electron-ion elastic scattering past the demerger apertures mentioned above.

The signal on the PSD is accompanied by large background count rates due to both electron and ion scattering on residual gas ($P \approx 1.5\times10^{-8}$ Pa) and surfaces. Because of the low signal-to-noise ratio (less than 10^{-2}), both beams are chopped at 2 kHz in a phased four-way chopping scheme [1,7], and the detector output is accumulated in four histogramming memories according to position and temporal block. The four temporally distinguished memories correspond to different combinations of the beams' being on and off so that (after correction for detection-system dead times) the memory contents can be appropriately added and subtracted to obtain the signal as a function of position.

The excitation cross section is determined from the expression

$$\sigma(E_{\text{c.m.}}) = \frac{R}{\varepsilon}\frac{qe^2}{I_e I_i}\left(\frac{v_e v_i}{v_e - v_i}\right)F,$$

where R is the observed signal count rate from detection of inelastically scattered electrons by the PSD, ε the measured PSD detection efficiency (0.60), F the form factor, and v_e, v_i, I_e, and I_i are the velocities and currents of the electrons and ions of charge magnitude e and qe, respectively. For $I_e = 200$ nA, $I_i = 80$ nA, and $F \approx 2.5\times10^{-3}$ cm, $R \approx 10$–$140\ \text{s}^{-1}$ and the backgrounds B_e and B_i are respectively the order of 12 and 8 kHz. Thus, with all beams on, the dead-time correction to the (approximately) 20 kHz rate is about 5% for that time block.

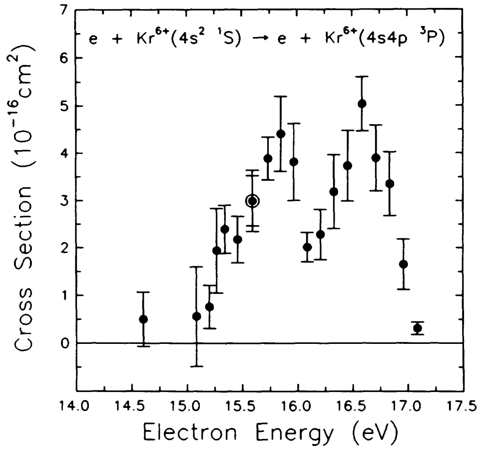

FIG. 2. Absolute total cross sections for electron-impact excitation of the $4s^2\,{}^1S \rightarrow 4s4p\,{}^3P$ transition in Kr^{6+} as a function of the collision energy in the center-of-mass frame. The error bars indicate the total relative uncertainties near the 90% confidence level. The outer error bar on the data point at 15.6 eV indicates the total absolute uncertainty at a high confidence level for that point.

The measured absolute total excitation cross sections for the Kr^{6+} ($4s^2\,{}^1S \rightarrow 4s4p\,{}^3P$) intercombination transition are plotted in Fig. 2 after a contact potential correction of 1.1 eV to force the threshold to agree with the known spectroscopic value [10] of 15.297 eV. The error bars represent an expanded uncertainty with a coverage factor of $k = 1.7$ to represent the total relative uncertainty near the 90% confidence level. They originate from a quadrature sum of contributions of 15% from statistical counting uncertainty, 7% from spatially delimiting the PSD signal, 6% from form factors, 5% from ion-beam metastable content uncertainty, and 10% for uncertainty in the corrections for backscattering and demerger losses. The expanded absolute uncertainty at similar confidence level also includes systematic uncertainties of 12% from the form factors, 2% from the PSD dead-time corrections, 3% from the PSD efficiency, 1% each from the electron and ion currents, and 10% from the ion-beam metastable fraction. The typical total absolute uncertainty at this high confidence level is about 22%, as indicated in Fig. 2 by the double error bars on the data point at 15.60 eV.

To obtain the cross sections plotted in Fig. 2, the measured data were corrected for the presence of metastable ions in the Kr^{6+} ion beam. Results from crossed-beam experiments [11] on the electron-impact ionization of Kr^{5+}, obtained while operating the ECR ion source under the same conditions, yielded an estimate of 0.163 ± 0.037 for the metastable fraction of the Kr^{5+} ion beam. From these data, we were able to estimate the fraction of metastable ions in the Kr^{6+} beam using an analysis similar to that described by Welton, Moran, and Thomas [12]. Using their model, one obtains the relative populations of the ground and metastable levels of an ion based on the rate coefficients for direct ionization of the next lower ionization state, given the relative populations of the ground and metastable levels of that lower state. For ion source plasma electron temperatures in the range of 10 to 5000 eV and using the measured Kr^{5+} metastable fraction, we calculated a metastable fraction of 0.46 ± 0.03 for the Kr^{6+} beam. Measurement of the Kr^{6+} metastable fraction via the ionization cross section measurements using the crossed-beam technique proved infeasible due to extremely high ion backgrounds. For the measurements reported here, other ion-beam impurities were shown to be less than 1%.

The measured data were also corrected for losses due to backscattering in the laboratory frame [1] and for reflection of electrons entering low in the demerger (where the potential is negative). These corrections were made using computer modeling of the trajectories and employing theoretical [13] differential cross sections (DCS). Corrections ranged from zero for high values of the velocity of the center of mass to as much as 37% for the lowest velocities of the center of mass and averaged 20%. Thus, the point at 17.1 eV, taken with the lowest velocity of the center of mass, had to be increased by 37%. Points near 15.75 eV were taken with both low and high velocities of the center of mass, and accordingly some were corrected about 20% and some not at all. Corrections using an isotropic DCS were not significantly different ($<5\%$) from those using ten-state R-matrix calculations [13].

The experimental data clearly show resonance features at 15.9 and 16.6 eV, with perhaps a weaker feature at 15.4 eV. Preliminary calculations [13] using an LS-coupled R-matrix technique indicate dielectronic resonance structures, with order of magnitude and spacing similar to that of the measured resonances, for energies just above the excitation threshold, but the detailed comparison is poor, and further theoretical work is being pursued. The present measurements of the absolute total cross sections for electron-impact excitation of the Kr^{6+} $(4s^2\,{}^1S \rightarrow 4s4p\,{}^3P)$ intercombination transition should serve as a benchmark for future calculations of cross sections for electron-impact excitation of ions including the role of dielectronic resonances.

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