PHYSICAL REVIEW A VOLUME 53, NUMBER 6 JUNE 1996

Compton double-to-single ionization ratio of helium at 57 keV

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(Received 5 February 1996)

We have measured the Compton double-to-single ionization ratio of helium using an ion time-of-flight spectrometer along with monochromatized synchrotron radiation of 57 keV. This photon energy is high and probes the Compton ionization alone, since the photoionization makes only a negligible contribution to the total cross section. Comparing our result, which is $(1.25 \pm 0.3)\%$, with theoretical calculations and measurements at lower energies shows that this energy is most likely still not high enough to confirm the value of the asymptotic high-energy limit experimentally. [S1050-2947(96)50706-7]

PACS number(s): 32.80.Cy, 32.80.Fb

The many-body problem is pervasive in all fields of physics. Even the three-body problem is still not well characterized by theoretical models so that experimental data are still needed in order to test the different theoretical appoaches to this general problem. Helium is a simple three-body system, and with only two electrons the simplest atom to exhibit electron-electron correlation.

The coupling between the electrons and the incoming photon is a single-particle operator. Thus, the simultaneous ejection of two electrons is caused purely by the electron-electron interactions in the initial and final states, called ground-state correlation and final-state correlation, respectively. Therefore, the photoionization of helium has long been used as a testing ground for understanding correlation phenomena, such as autoionization, ionization with excitation, and double photoionization [1].

At high photon energies above several keV, Compton scattering can produce singly or doubly charged helium ions with a cross section that dominates that of photoionization. Theoretical prediction of the photon energy dependence of the double photo- or Compton ionization of helium probes one of the most challenging problems in atomic physics, namely, the proper description of the two continuum-electron wave functions [2].

Despite the importance of the problem, theoretical predictions of the double-to-single ionization ratio at high photon energies have not converged. Nonrelativistic predictions of the high-energy asymptotic ratio vary by a factor of 2 [3–7]. They also show significantly different behavior before they approach their asymptotic limit. Recent measurements, similar to the one described here, have been performed at photon energies up to 20 keV [8–14]. However, this energy has proved to be still not high enough to resolve the large theoretical differences at high photon energies.

The present experiment was thus a logical next step in a continuing series of experiments, which became feasible only through high-energy, third-generation synchrotron radiation facilities. The photon energy of 57 keV was chosen to decide among the theoretical predictions and seemed to be high enough [4] for this purpose.

The experiment was performed at the new high-energy beam line BL25 at the European Synchrotron Radiation Facility (ESRF) operated in a 16-bunch mode. The photons coming from the seven-period wiggler ID15 were monochromatized by a focusing Bragg-type monochromator and collimated by lead slits. The monochromator crystal is bent and can, therefore, provide a focused beam of high photon flux, which is important for this experiment because of the very low cross section of the processes. The photon energy is tunable in the range from 30 keV to about 170 keV [15], with the highest photon flux around 57 keV. For higher energies the number of photons decreases rapidly and would make this experiment even more difficult to perform. The photon energy resolution is about 0.1%; further details of the beam line are described elsewhere [16]. The photon beam entered the experimental chamber through a beryllium window mounted on a long narrow tube (~ 0.6 m long) that was wrapped with lead sheets in order to reduce the scattered photon flux striking the spectrometer. (Note that at a photon energy of 57-keV photons are not efficiently blocked by conventional stainless steel vacuum fittings.) The chamber was terminated by another beryllium window mounted on a narrow, lead-wrapped tube (~ 1 m long) to suppress photons backscattered off-axis from the downstream beryllium window. The emerging photon beam was stopped in a lead brick.

The helium ions, which were produced in the interaction region defined by the intersection of photon beam and an effusive gas beam, were detected with an ion time-of-flight (TOF) spectrometer. The complete experimental setup is described elsewhere [8,9]. Great care was taken that the photon beam did not hit any part of the spectrometer, which might result in secondary electrons that could collide with the helium atoms and influence the double-to-single ionization ratio. Backscattered photons along the photon beam axis from the beryllium exit window of the vacuum chamber would have resulted in a 6-ns time-delayed interaction with the he-

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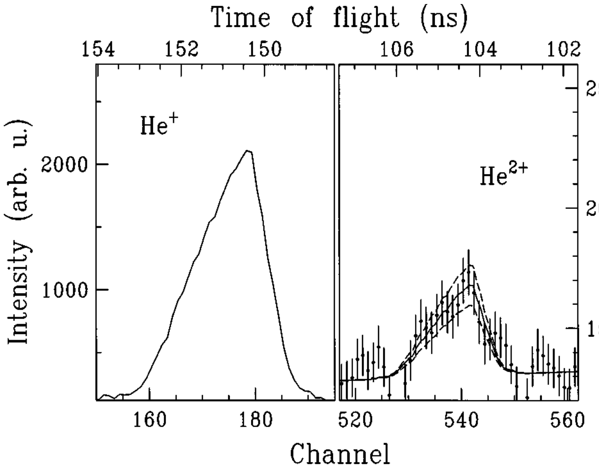

FIG. 1. Helium time-of-flight spectrum at a photon energy of 57 keV. The He^{2+} peak is shown together with the corresponding least-squares fit curve. The peak shape used to fit the He^{2+} data was derived from the shape of the He$^+$ peak. The dashed curves are derived from our upper and lower error bars for the double-to-single ionization ratio.

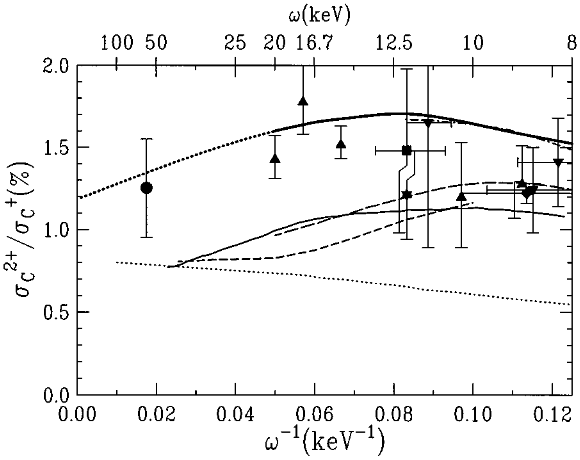

FIG. 2. Comparison of our Compton double-to-single ionization ratio (circle) with other experimental data (square [8], diamond [12], star [13], triangles [10,14]) and theoretical calculations (solid line [3], short dashed line, uncorrelated final state [4], long dashed line, correlated final state [4], dotted line [6], thin dashed-dotted line [5], bold solid line [23]). The extrapolation of the bold solid line [23] using a third-order polynomial curve is depicted as a bold dotted line.

lium atoms, in comparison with the direct photon beam, and were not observed. However, a fast timing signal, provided by ESRF and derived from the storage ring electronics, which served to provide a stop pulse for the time-to-amplitude converter (TAC), was observed to not be perfectly stable. Its double-valued structure and occasional mode hopping caused the corresponding He TOF peaks to exhibit a corresponding double-humped asymmetry, which mirrored the structure of the ESRF stop pulse but could easily be modeled. This electronic defect did not influence the determination of the double-to-single ionization ratio, since this effect modifies the peak shape of both the He$^+$ peak and the He^{2+} peak in the same way. The gas pressure of the helium gas in the chamber was 1×10^{-5} mbar, which is low enough to assure negligible pressure dependence because of inelastic scattering. The background pressure in the chamber was about 5×10^{-8} mbar. The voltages across the microchannel plates of the spectrometer were chosen such that an equal detection efficiency for He$^+$ and He^{2+} ions was assured [17]. The threshold of our constant-fraction discriminator (CFD) was set to a very low level (20 mV) to ensure that there was no discrimination between the He$^+$ ions and He^{2+} ions, as was established in a former experiment [18].

The calibration of the energy and transmitted flux of the monochromator was done with a commercial GeLi detector, which measured the energy distribution of the Compton-scattered photons from a Si(311) crystal mounted upstream of our chamber at a fixed angle using a standard procedure routinely employed on this beam line.

In order to determine the double-to-single ionization ratio we added 28 ion time-of-flight spectra. The resulting spectrum has a total collection time of about 27 h and part of it is shown in Fig. 1. The area of the He$^+$ peak was numerically integrated, whereas the area of the He^{2+} peak was determined by a least-squares fit using the peak profile of the He$^+$ peak, suitably scaled in width and height, thereby accounting for an asymmetric peak shape as described above. The corresponding fit curve of the He^{2+} peak is shown in the panel on the right-hand side of Fig. 1. In addition, we have fitted a Gaussian profile to the He^{2+} peak and we also integrated the peak area numerically. In all three cases the results were very similar (deviations were smaller than the statistical error bar) and we get an average value of He^{2+}-to-He$^+$ ratio of $(1.25\pm0.3)\%$ at a photon energy of 57 keV (±60 eV). This value is displayed along with former results at lower photon energies and theoretical calculations in Fig. 2.

Our data point is lower than the asymptotic value for the double-to-single *photoionization* ratio of about 1.66%, a value which is well established in theory [19–22]. Since the photoabsorption cross section is about three orders of magnitude lower than the cross section for Compton scattering [3], we only probe the *Compton* double-to-single ionization ratio. Nevertheless, according to Amusia and Mikhailov [7] the ratios for both photoionization and Compton ionization have the same asymptotic value, or according to Hino *et al.* [5] have coincidentally the same numerical, but not asymptotic, value. A few theories predict a lower asymptotic value of 0.80% to 0.84% [4,6], in which case our measured ratio is higher. However, another theory predicts that the ratio falls slowly and suggests that the asymptotic value is reached only above 75 keV [23].

Because the new data point at 57 keV is slightly lower than the data points above 12 keV, there is an indication that the ratio is still steadily decreasing with increasing photon energy, as suggested by Refs. [3] and [23]. Therefore, it is more likely that, unless the ratio moves up again, the ratio converges to the lower rather than the higher theoretical values, if indeed any of these values are correct. A tentative extrapolation of the theoretical ratios calculated by Bergstrom *et al.* [23] using a third-order polynomial curve would yield an asymptotic limit of 1.18% (see Fig. 2). Thus, in order to prove the high-energy behavior and to distinguish decisively among the different theoretical predictions, measurements at higher photon energies but also with better accuracy are required.

In conclusion, we have determined the Compton double-to-single ionization ratio of helium at a photon energy of 57 keV using an ion time-of-flight spectrometer. Surprisingly, even at this high photon energy we did not reach one of the theoretically predicted asymptotic values for the high-energy limit.

Note added. Recently we have learned that the double-to-single ionization ratio presented in Ref. [24] has subsequently been refined in a new paper [25] giving a value of 0.84% (+0.08%,−0.11%).

This work was supported by the BMBF, the DFG, the ESRF, the National Science Foundation, under Contract No. PHY9417924, and the Department of Energy, division of Chemical Sciences, under Contract No. DE-FG02-92ER14299. R.W. gratefully acknowledges financial support from the Alexander von Humboldt Foundation.

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