Compton double ionization of helium in the region of the cross-section maximum*

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Introduction

There exist substantial discrepancies between theoretical predictions for the cross section of double ionization in helium by Compton scattering. Consistency between different approaches has been reached for the high-energy asymptotic value of the double-to-single ionization ratio $R_C = \sigma_C^{2+}/\sigma_C^{+}$ (cf. [1] and references therein), but the available theoretical results differ strongly in their predictions for the energy dependence of R_C leading up to this limit. The sparsity and large uncertainty of published experimental results have previously prohibited a conclusive assessment of any of these predictions. The main impediment to experimental determinations of R_C arises from the smallness of the Compton cross section of about 10^{-24} cm^2. The fundamental difficulty for theoretical treatments lies in accounting adequately for electron correlation in the initial bound and final continuum states of the system. In the effort to include final-state correlation, substantial progress has been made for the corresponding case in photoabsorption (cf. [2] and references therein), where, in contrast to Compton scattering, the transfer of energy and angular momentum are well-defined and fixed. We have measured precise experimental results for the ratio R_C in the 8–28 keV x-ray energy range which allow a critical evaluation of theoretical predictions.

Method

The experiment was performed at the Basic Energy Sciences Synchrotron Radiation Center (BESSRC) undulator beam line 12-ID at the Advanced Photon Source (APS). The collimated x-ray beam was intersected with a jet of cold helium atoms in a vacuum chamber. The vacuum chamber held a time-of-flight (TOF) spectrometer in a 160° reflectron geometry with 40-cm flight path. The electrostatic reflector in the flight path of the ions effectively eliminated prompt counts on the detector caused by scattered x-rays and energetic electrons from the interaction region. A two-dimensionally position-sensitive multi-channel plate (MCP) detector was used. Time-of-flight measurements were made relative to the time structure of the storage-ring fill pattern. The combination of a cold and spatially confined target, a TOF spectrometer with a position-sensitive detector, and event-mode data acquisition constitutes a COLTRIMS system (cold target recoil ion momentum spectroscopy [3]). Here, this technique was employed to distinguish Compton ionization events from photoabsorption events by means of their different recoil momenta. Whereas in photoabsorption the ion recoils from the emission of photoelectrons, virtually no momentum is transferred to the residual ion in Compton scattering (cf. [4]).

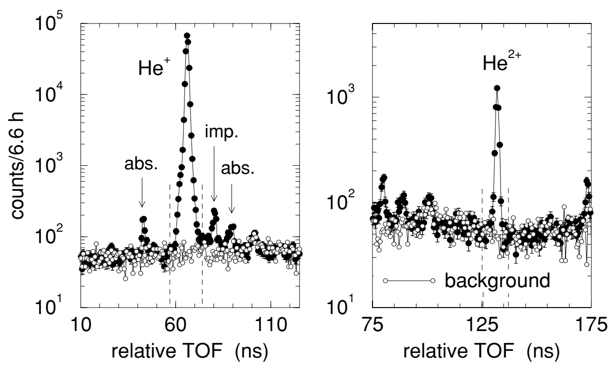

Fig. 1: Compounded TOF spectra for He^+ and He^{2+} ions with small momenta perpendicular to the flight path, measured with 16-keV x rays, points with errorbars; background measurement, open circles; integration limits for Compton events, dashed lines. The arrows indicate the remnants of forward/backward recoiling He^+ from photoabsorption (abs.) and He^+ counts created by a bunch impurity in the storage ring fill pattern (imp.).

Measurements were carried out at energies between 8 and 28 keV during timing mode operation of the storage ring (20 single pulses in 130-ns intervals, 3.7 μs repetition time). The microsecond-timescale ion flight times in conjunction with the short intervals between subsequent x-ray pulses caused the TOF spectrum to multiply overlap itself. Special care was taken in choosing the spectrometer operating parameters to ensure that the He TOF peaks (~2 ns fwhm) were not superimposed on other structures in the spectrum. The portions in the

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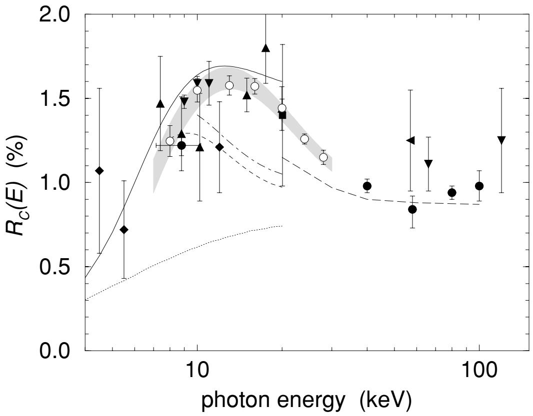

Fig. 2: Experimental and theoretical results for $R_C(E)$. This work, open circles; the shaded band is a smooth curve fitted to the data and broadened by the experimental uncertainty. Other experiments: Spielberger *et al.* [4, 12, 13], solid circles; Levin *et al.* [8], triangles up; Morgan and Bartlett [9], diamonds; Samson *et al.* [10], square; Becker *et al.* [11], triangles down; Wehlitz *et al.* [14], triangle left. Theory: Bergstrom *et al.* [17], solid curve; Andersson and Burgdörfer [15], short-dashed and dot-dashed curves; Spielberger *et al.* [13], long-dashed curve; Surić *et al.* [16], dotted curve.

total TOF spectrum resulting from the 20 single pulses were added up in the analysis into single TOF spectra for the two He charge states (see Fig. 1). Typical accumulation times were 6–8 hours per energy with target gas and a comparable period without gas to determine the background TOF spectrum at each energy.

Results and Discussion

Fig. 2 shows a comparison of our measured values for the ratio $R_C = \sigma_C^{2+}/\sigma_C^{+}$ in helium (open circles) with published experimental [4, 8, 9, 10, 11, 12, 13] and theoretical [15, 16, 17, 13] results. The present data are highlighted by the shaded band, which is a smooth curve fitted to the data points and broadened by the experimental uncertainty. It traverses the considerable scatter of prior experimental data in this region and suggests a smooth connection with the recent high-energy data of Spielberger *et al.* (solid circles, [12, 13]) which indicate a very flat behavior of $R_C(E)$ above 40 keV x-ray energy.

Among the theoretical predictions of $R_C(E)$ the present experiment favors most the result of the many-body perturbation theory (MBPT) calculation by Bergstrom *et al.* (solid curve, [17]), which lies 5–10% higher than the shaded band. At 20 keV the discrepancy is greater and the experimental result decreases more rapidly with energy than the apparent trend in the MBPT results. From about 10 keV upwards our R_C values lie higher than the results of Andersson and Burgdörfer [15], who performed their calculation with two different choices of correlated final-state wave functions (short dashed and dot-dashed curves). This underestimation persists, to a lesser degree, in the improved extension of that work above 20 keV (long dashed curve, [13]). In the calculation based on the impulse approximation (IA) the maximum in $R_C(E)$ is absent (dotted curve, [16]). This calculation clearly fails to describe $R_C(E)$ in the energy range of the present experiment. It was recently estimated that use of the IA for the calculation of the helium double-ionization cross section should be adequate only above about 50 keV [18].

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References

[1] T. Surić, K. Pisk, R. H. Pratt, Phys. Lett. A **211**, 289 (1996).
[2] J. A. R. Samson *et al.*, Phys. Rev. A **57**, 1906 (1998).
[3] J. Ullrich *et al.*, J. Phys. B: At. Mol. Opt. Physics **30**, 2917 (1997).
[4] L. Spielberger *et al.*, Phys. Rev. Lett. **74**, 4615 (1995).
[5] Ken-ichi Hino *et al.*, Phys. Rev. A **48**, 1271 (1993).
[6] E. G. Drukarev, Phys. Rev. A **51**, R2684 (1995).
[7] B. Brehm, J. Grosser, T. Ruscheinski, and M. Zimmer, Meas. Sci. Technol. **6**, 953 (1995).
[8] J. C. Levin, G. B. Armen, and I. A. Sellin, Phys. Rev. Lett. **76**, 1220 (1996).
[9] D. V. Morgan and R. J. Bartlett, Phys. Rev. A **59**, 4075 (1999).
[10] J. A. R. Samson, Z. X. He, W. Stolte, and J. N. Cutler, J. Electr. Spectr. Rel. Phen. **78**, 19 (1996).
[11] U. Becker *et al.*, Aust. J. Phys. **52** (1999). Results shown are weighted means of data points within $E\pm$ 0.3 keV.
[12] L. Spielberger *et al.*, Phys. Rev. Lett. **76**, 4685 (1996).
[13] L. Spielberger *et al.*, Phys. Rev. A **59**, 371 (1999).
[14] R. Wehlitz *et al.*, Phys. Rev. A **53**, 3720 (1996).
[15] L. R. Andersson and J. Burgdörfer, Phys. Rev. A **50**, R2810 (1994).
[16] T. Surić, K. Pisk, B. A. Logan, R. H. Pratt, Phys. Rev. Lett. **73**, 790 (1994).
[17] P. M. Bergstrom, Jr., K. Hino, and J. Macek, Phys. Rev. A **51**, 3044 (1995).
[18] Z. Kaliman, T. Surić, K. Pisk, R. H. Pratt, Phys. Rev. A **57**, 2683 (1998).