Double ionization of He by electron impact at large momentum transfer

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The double ionization of He by electron impact at 580 eV has been studied in a coplanar symmetric $(e,(3-1)e)$ experiment, in which two fast electrons of 250 eV are detected. In this way a momentum transfer as large as 6 a.u. is achieved. The results are compared with the predictions of a theoretical model based on the impulse (knock-out) approximation. The calculations, which include radial correlation of electrons in the He ground state wave function, better describe the experiment than those with an uncorrelated wave function.

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Double ionization is one of the most interesting and intriguing processes in atomic physics and as such it has attracted a lot of theoretical and experimental interest in the last few years [1–3]. The He atom represents the architypal system for the study of double ionization, because it has only two electrons and the He^{2+} continuum is void of resonances. In order to achieve a complete picture of the process, experiments in which two or three charged particles in photoionization or electron impact, respectively, have to be detected in coincidence are needed. Double-photoionization studies by electron-electron [1] or electron-ion coincidence [4] techniques have covered a large variety of kinematic conditions from the near-threshold region [5] up to about 500 eV incident energy [6]. On the other hand, electron-impact experiments suffer from a more complex final state, where four charged particles are present, and despite the noticeable progress due to the use of multicoincidence techniques [7–9] some kinematical regions have not yet been explored. In particular, experiments involving large momentum transfer are rare [10,11]. The region of large momentum transfer is quite interesting because it is expected that in this condition the cross section for double ionization provides direct information on the electron-electron correlation in the initial state [12]. The recent $(e,3e)$ experiments by El Marji *et al.* [10] and Lahmam-Bennani *et al.* [13] have shown that the angular distribution of the center of mass of the ejected electron pair provides some evidence of an ''initial-state two-electron wave function.'' However the low momentum transfer in the two experiments hampered a definite answer. Popov *et al.* [14] have recently predicted that $(e(3-1)e)$ experiments, i.e., double-ionization experiments by electron impact in which only two of the three electrons in the final state are detected in coincidence after energy and angular selection, can also be used to study electron-electron correlations in the initial atomic bound state provided the experiment is performed in symmetric kinematics and two fast electrons are detected. In symmetric kinematics two electrons of equal energy are detected at the same ejection angle with respect to the incident direction; thus large momentum transfers are involved.

In this work we report on an $(e,(3-1)e)$ experiment performed with coplanar symmetric kinematics at an incident energy $E_0 = 580$ eV. In the experiment two fast electrons with kinetic energies $E_1 = E_2 = 250$ eV are detected in coincidence at the angles $\vartheta_1 = \vartheta_2 = \vartheta$. The third slow electron with a kinetic energy $E_3 \cong 1$ eV (the He double-ionization potential being about 79 eV) remains undetected. The angular distribution has been measured between 25° and 65°; thus the momentum transfer $\mathbf{K} = \mathbf{k}_0 - \mathbf{k}_1$, where $\mathbf{k}_0$ and $\mathbf{k}_1$ are the momenta of the incident and scattered electrons, respectively, varied between 3.2 and 6.1 a.u.

The apparatus used for the present measurements is an electron-impact spectrometer specially designed for electron-electron coincidence experiments. It consists of a vacuum chamber equipped with an electron-beam source, two twin hemispherical electrostatic analyzers, and an effusive gaseous beam. A detailed description of the apparatus is reported elsewhere [15,16]. The home-made electron gun was operated in order to provide an incident beam of 0.8 μA at $E_0 \approx 580$ eV. The two electrons are analyzed in energy by passing through the hemispherical electron spectrometers, rotatable in the scattering plane from $-15°$ to 150° with respect to the direction of the incident beam. The zero of the angular scales was set by determining the symmetry of the scattered electron yield around 0°. The energy resolutions of the analyzers, measured as full width at half maximum

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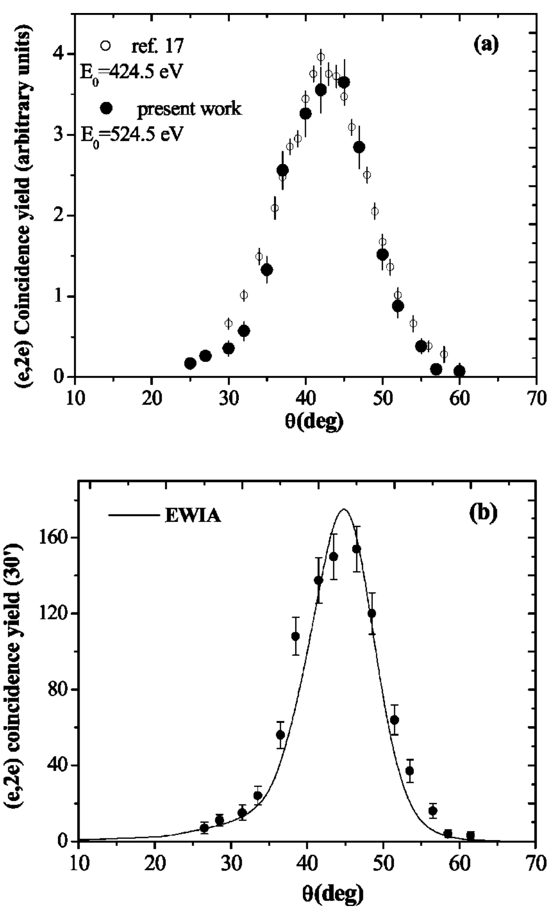

FIG. 1. Comparison of the $(e,2e)$ angular distributions in coplanar symmetric conditions measured at 524.5 eV (closed circles) in this work with (a) the one measured at 424.5 eV (open circles) in Ref. [17] and (b) calculations within the EWIA using the Silverman-Platas-Matsen wave function [22].

(FWHM), were $\Delta E \cong 2.2$ eV. The angular acceptances of the two analyzers were $\pm 0.5°$ and $\pm 2°$, respectively. The overlap of the fields of view of the analyzers was checked at several ϑ values by sweeping the electron beam through the gas target and detecting the ejected electrons. These noncoincidence angular distribution measurements showed that the interaction region, defined by the intersection of the incident electron and gaseous beams, is well inside the field of view of the two analyzers and that their overlap does not vary appreciably with ϑ. Finally the angular efficiency was verified via an $(e,2e)$ measurement on He in symmetric kinematics at $E_0 = 524.5$ eV and $E_1 = E_2 = 250$ eV. The results of this measurement are compared in Fig. 1(a) with previous measurements [17] at 424.5 eV and in Fig. 1(b) with the predictions of the eikonal wave impulse approximation (EWIA) model described below [20]. The small differences between the two sets of experimental data (the angular distribution measured at 524.5 eV is slightly narrower and its center of gravity is shifted about 1° toward larger ϑ) are consistent with the difference in incident energy of the two experiments according to previous findings in $(e,2e)$ studies [18]. The agreement with theory is satisfactory once the theory is shifted by about 1.5°. As an outcome of all these checks we exclude major changes in the angular efficiency of the apparatus when collecting coincidence data in the range 25°–70°.

The typical count rate for the $(e,(3-1)e)$ experiment was about 0.2 mHz. Thus accumulation times on the order of a few hundred hours per point were needed to achieve statistics of about $\pm 20\%$. During the measurements the stability of the apparatus was monitored by periodically measuring the noncoincidence angular distribution of the scattered/ejected electrons with both analyzers and the point at $\vartheta = 40°$ of the $(e,2e)$ angular distribution. These measurements proved the overall stability of the setup throughout the six months needed to measure the $(e,(3-1)e)$ angular distribution. Indeed the count rates of the $(e,2e)$ measurements, once normalized to the count rate of one analyzer, used to monitor any variation of target density and flux of the incident beam, oscillated in a band of about $\pm 10\%$.

The results of the $(e,(3-1)e)$ measurements are shown in Figs. 2(a) and 2(b). In Fig. 2(a) the $(e,(3-1)e)$ and $(e,2e)$ angular distributions are compared. The lines between the experimental points are only meant to guide the eyes. The $(e,(3-1)e)$ angular distribution is shifted toward larger ϑ and is broader than that for $(e,2e)$. The shift can be attributed to the different short- and long-range distortions suffered by the two fast electrons. Despite the fact that in both cases the two fast electrons have the same kinetic energy, in the $(e,(3-1)e)$ process they are moving in the field of the $[\mathrm{He}^{2+} + e(E_c = 1\ \mathrm{eV})]$ system, while in the other case they are moving in the He^{+} field. The shape of the $(e,2e)$ angular distribution in symmetric kinematics as well as that of the binary peak in asymmetric kinematics are mainly determined by the momentum distribution of the ejected electron in the initial bound state of the target. The different widths observed in the two angular distributions of Fig. 2(a) lead to the consideration that the one-electron momentum distribution is not the main factor that determines the shape of the $(e,(3-1)e)$ angular distribution.

In Fig. 2(b) the experimental results are compared with the predictions of a theoretical model [19] recently proposed for the study of double ionization by electron impact at intermediate energies in the regime of large momentum transfer. In this model the four-body system is separated into two subsystems; one formed by the two fast electrons taking part in the knock-out electron-electron collision, and the second by the residual He^{2+} ion and the slow electron. The momenta of the fast electrons in the first subsystem are modified due to the interaction with the second subsystem treated in the frozen-core approximation, using the EWIA [20]. In the present calculations the EWIA with shell-averaged potential has been used in order to take into account the distortion of the momenta in the atomic region where the knock-out collision takes place. The model of the distorting potential as well as its dependence on the model of the He ground state are discussed in detail elsewhere [19].

In the calculations the following form for the He ground-state wave function was used:

$$\Phi_0(r_1,r_2) = \frac{1}{\sqrt{N}}\{\exp(-ar_1 - br_2) + \exp(-br_1 - ar_2)\}, \tag{1}$$

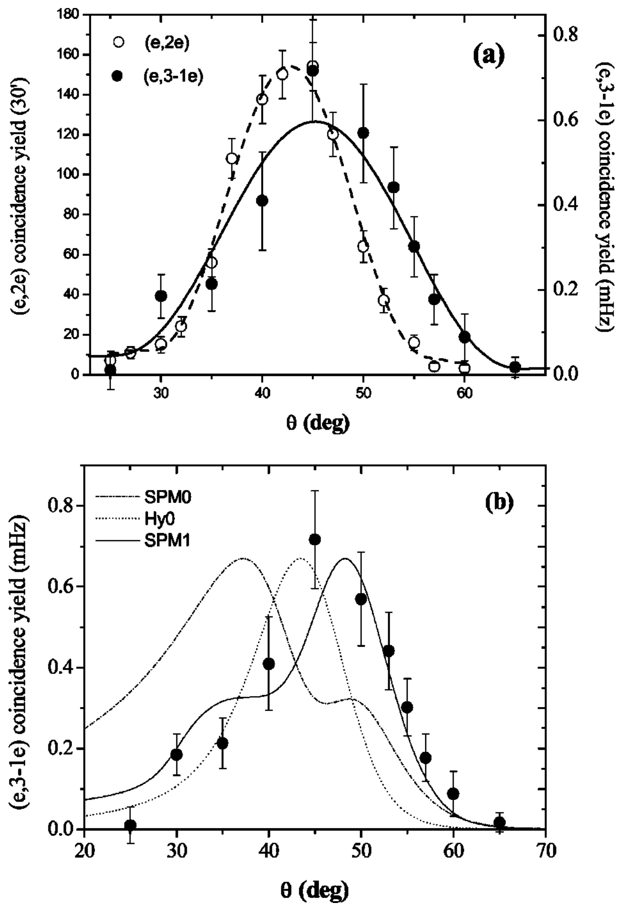

FIG. 2. (a) Comparison between the $(e,(3\text{-}1)e)$ angular distribution (closed circles) at $E_0=580$ eV and $E_1=E_2=250$ eV and the $(e,2e)$ angular distribution (open circles) in coplanar symmetric conditions at 524.5 eV. The lines through the points are only meant to guide the eyes. (b) Comparison of the experimental $(e,(3\text{-}1)e)$ angular distribution with the predictions of the EWIA. The calculations using the shell-averaged potential with Hylleraas and SPM initial state wave functions are represented by the dotted and dash-dotted lines, respectively. The full line represents a calculation using the orbital-averaged potential and SPM initial-state wave function.

with

$$N=128\pi^2\left\{\frac{1}{(4ab)^3}+\frac{1}{(a+b)^6}\right\}. \qquad (2)$$

When $a=b$, $\Phi_0(\mathbf{r}_1,\mathbf{r}_2)$ corresponds to the Hylleraas wave function [21] without correlations, while when $a\neq b$ then $\Phi_0(\mathbf{r}_1,\mathbf{r}_2)$ becomes the Silverman-Platas-Matsen (SPM) wave function [22] with radial correlations. The theoretical predictions have been all rescaled to a common value. The calculation with the Hylleraas wave function [dotted line in Fig. 2(b)] produces a peak centered at about 40°, whose width underestimates the experimental one. The one with the SPM wave function [dash-dotted line, labeled SPM0, in Fig. 2(b)] predicts an angular distribution with two features: one centered at approximately 35° and the other one at about 50°. This is explained in Ref. [19] by the interference of the amplitudes corresponding to the knock-out of the electrons from different 1s orbitals. The calculated shape in this case is quite far from the experimental one. It should be mentioned here that the inclusion of the semiclassical postcollision interaction model [23], which treats the long-range distortion of the fast electrons on their way to the detectors, only slightly shifts the curves toward larger angles without changing the overall agreement with the experiment. However, as noted in Ref. [19], in the case of the SPM wave function with radial correlations the electrons are supposed to occupy different 1s orbitals, characterized by different mean radii ($r_0=a^{-1}$ or b^{-1}). Therefore the shell-averaged potential, which is justified in the case of the Hylleraas wave function, should be replaced in the case of the SPM wave function by the orbital-averaged potential in order to calculate the distortion of momenta. This fact has the consequence that the cross section does not factorize [19]. Therefore it is not usable in a direct way to extract information about the quality of the initial-state wave function as far as the description of electron-electron correlation is concerned. The results of the calculation using an orbital-averaged distorting potential are represented by the full curve, labeled SPM1, in Fig. 2(b). This last calculation correctly describes the width of the measured angular distribution and is definitely in better agreement with the experiment than the EWIA model without a correlated initial-state wave function.

The comparison between theory and experiment in this work has been done on a relative scale; thus only the shape of the angular distribution predicted by the model depending on the different initial-state wave functions has been considered. However, it is interesting to note that on the absolute scale the cross section predicted by the model with the Hylleraas initial-state wave function is four times larger than the one predicted for the SPM initial-state wave function. Therefore an absolute $(e,(3-1)e)$ measurement could be used to better discriminate between different initial-state wave functions.

In summary, the He double ionization by electron impact at large momentum transfer has been studied by an $(e,(3-1)e)$ experiment. Comparison with a theory based on the impulse approximation shows, on one hand, that a correlated initial-state wave function is needed in order to represent the experimental results. On the other hand, it also shows the crucial role of the short-range distortion of momenta in determining the shape of the angular distribution, due to the relatively low energy of the incident beam. This prevents the extraction of direct information about the initial-state wave function from the measured angular distribution. However, the present results provide strong evidence that $(e,(3-1)e)$ measurements at higher incident energy and preferably measured on an absolute scale may allow this goal to be achieved.

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[1] J. S. Briggs and V. Schmidt, J. Phys. B **33**, R1 (2000).
[2] G. C. King and L. Avaldi, J. Phys. B **33**, R215 (2000).
[3] J. Berakdar, A. Lahmam-Benanni, and C. Dal Cappello, Phys. Rep. (to be published).
[4] J. Ullrich, R. Moshammer, R. Dörner, O. Jagutzki, V. Mergel, H. Schmidt-Böcking, and L. Spielberger, J. Phys. B **30**, 2917 (1997).
[5] A. Huetz and J. Mazeau, Phys. Rev. Lett. **85**, 530 (2000).
[6] A. Knapp, A. Kheifets, I. Bray, Th. Weber, A. L. Landers, S. Schössler, T. Jahnke, J. Nickles, S. Kammer, O. Jagutzki, L. Ph. H. Schmidt, T. Osipov, J. Rösch, M. H. Prior, H. Schmidt-Böcking, C. L. Cocke, and R. Dörner, Phys. Rev. Lett. **89**, 033004 (2002).
[7] M. J. Ford, J. P. Doering, J. H. Moore, and M. A. Coplan, Rev. Sci. Instrum. **66**, 3137 (1995).
[8] A. Duguet, A. Lahmam-Bennani, M. Lecas, and B. El Marji, Rev. Sci. Instrum. **69**, 3524 (1998).
[9] A. Dörn, R. Moshammer, C. D. Schröter, T. J. M. Zouros, W. Schmitt, H. Kollmus, R. Mann, and J. Ullrich, Phys. Rev. Lett. **82**, 2496 (1999).
[10] B. El Marji, J. P. Doering, J. H. Moore, and M. A. Coplan, Phys. Rev. Lett. **83**, 1574 (1999).
[11] A. Dörn, A. S. Kheifets, C. D. Schröter, B. Najjari, C. Höhr, R. Moshammer, and J. Ullrich, Phys. Rev. A **65**, 032709 (2001).
[12] Yu. F. Smirnov and V. G. Neudatchin, JETP Lett. **3**, 192 (1966); V. G. Neudatchin, G. A. Novoskol'tseva, and Yu. F. Smirnov, Sov. Phys. JETP **28**, 540 (1969).
[13] A. Lahmam-Bennani, C. C. Jia, A. Duguet, and L. Avaldi, J. Phys. B **35**, L215 (2002).
[14] Yu. V. Popov, C. Dal Cappello, and K. Kuzakov, J. Phys. B **29**, 5901 (1996).
[15] E. Fainelli, R. Camilloni, G. Petrocelli, and G. Stefani, Soc. Ital. Fis. D **9**, 33 (1987).
[16] L. Avaldi, R. Camilloni, R. Multari, G. Stefani, X. Zhang, H. R. J. Walters, and C. T. Whelan, Phys. Rev. A **48**, 1195 (1993).
[17] G. Stefani and R. Camilloni, J. Phys. B **18**, 499 (1985).
[18] R. Camilloni, A. Giardini-Guidoni, G. Missoni, G. Stefani, R. Tiribelli, and D. Vinciguerra, in *Momentum Wave Functions—1976*, edited by D. W. Devins, AIP Conf. Proc. No. 36 (AIP, New York, 1976), p. 205.
[19] K. A. Kouzakov and Yu. V. Popov, J. Phys. B **35**, L1 (2002).
[20] R. Camilloni, A. Giardini-Guidoni, I. E. McCarthy, and G. Stefani, J. Phys. B **13**, 397 (1980).
[21] E. A. Hylleraas, Z. Phys. **54**, 347 (1927).
[22] J. N. Silverman, O. Platas, and F. A. Matsen, J. Chem. Phys. **32**, 1402 (1960).
[23] L. Avaldi, R. Camilloni, Yu. V. Popov, and G. Stefani, Phys. Rev. A **33**, 851 (1986).