RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 47, NUMBER 5 MAY 1993

Absolute low-energy experimental cross sections for $(e,2e)$ processes on helium

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(Received 14 December 1992)

Coincidence experiments for electron-impact ionization of helium in a symmetric coplanar energy-sharing geometry at incident energies from 45 to 500 eV and an angle of 45° are described. Results are put on an absolute scale by normalization to elastic-scattering data and are compared to theoretical calculations in distorted-wave Born and impulse-type approximations. We suggest that an old debate concerning the proper way to evaluate the half-off-shell Coulomb T matrix should be reopened.

PACS number(s): 34.80.Dp

Considerable progress has been made over the last few years in the investigation of $(e,2e)$ phenomena at low incident energy (threshold up to a few hundred eV). Particular interest has been attached to energy-sharing conditions, large ejection and scattering angles in coplanar geometries, perpendicular plane and inclined plane geometries. Such conditions tend to show up dynamical effects in the collision process and are a very stringent test for theory. However, until recently very few experiments have been made which give an absolute scale for the cross sections in such conditions. This is a pity since, while theories like the distorted-wave Born (DWBA) or distorted-wave impulse (DWIA) approximations often give good qualitative agreement with experiment, further refinement of the models requires comparison to be made with absolute cross sections. The different sets of relative experimental data have sufficient points in common that, if the absolute cross section were known accurately as a function of incident energy for any particular convenient type of kinematics, the majority of them could be put on a unique coherent absolute scale.

We are interested in obtaining an absolute scale for $(e,2e)$ measurements made under coplanar energy-sharing conditions with the final-state electrons detected symmetrically at 45° with respect to the incident beam direction. All methods proposed till now to obtain such a scale make appeal to known reference cross sections and are only as accurate as are the latter. The gas-cell measurements of Van Wingerden *et al.* [1] from 200 to 2800 eV final-state energy used the single-differential elastic-scattering cross sections (SDCS's) of Jansen *et al.* [2], whereas the crossed-beam experiments of Gélébart, Defrance, and Peresse [3] at 200 eV incident energy and of Gélébart and Tweed [4] at 100 eV used those of Register, Trajmar, and Srivastava [5]. The near-threshold crossed-beam measurements of Rösel *et al.* [6] depend on normalization to total ionization or to inelastic double-differential cross sections.

In an energy-sharing ionization experiment the energy E_e of the detected electrons is related to the incident energy E_0 by $2E_e = E_0 - V_I$ where V_I is the ionization potential. Gélébart and collaborators, like Van Wingerden *et al.*, normalized to the elastic cross section at energy E_e. Here we prefer to normalize to the elastic cross section at energy E_0. Our measurements cover the range 45 eV $\leq E_0 \leq$ 500 eV. The elastic-scattering data of Jansen *et al.* go from 100 to 3000 eV and those of Register, Trajmar, and Srivastava go from 5 to 200 eV. Very recently, Brunger *et al.* [7] have made a careful investigation of elastic scattering combining theory and experiment in the range 18–50 eV. We have made a graphical interpolation between all three datasets so as to decide on a smoothly varying reference cross section. This is close to Brunger *et al.*'s data below 50 eV and to Jansen *et al.*'s above 100 eV, but is about 10% higher than Register, Trajmar, and Srivastava's data in the region 30 to 200 eV.

Our experimental apparatus is a slightly modified form of that described by Gélébart, Defrance, and Peresse [3]. An incident electron beam having energy width ΔE_0 equal to 480 meV and intensity about 2 μA is crossed at right angles with a target gas jet produced by a capillary tube. The electron gun can be operated in such a way as to maintain the same beam profile at the collision center irrespective of energy E_0 or beam current; the beam stability is very good for $E_0 \geq 30$ eV. A small collector (of the same internal diameter as the capillary tube used to produce the gas jet) can be moved through the incident electron beam just outside and after the collision zone. This makes it possible to determine the beam profile. By applying left-right and up-down deflection potentials in the gun, the beam may be swept through the gas jet while monitoring scattered electron count rates and/or the current from the collector. In this way we can verify that the jet has a very small angular spread and its diameter is basically determined by that of the capillary tube.

Two 127° cylindrical electrostatic analyzers, a and b, are placed in the plane perpendicular to the gas jet, on either side of the incident beam at 45° angles with respect to its direction. Their entrance optics are set in such a way that the whole region of intersection of the incident electron beam and target gas jet is included in their cones of view. Thus the source volume for each detector is determined by the beam overlap volume, *not* by the real solid angle of view. The *effective* solid angles of view $\Delta\Omega_i$ ($i=a,b$) of the analyzers are then determined by basically geometrical considerations; they are 3×10^{-4} sr. This practice has the advantage that the source volumes for coincidence measurements and for each detector individually in noncoincidence measurements are all the same. Moreover, they are independent of the angular positions of the detectors with respect to the electron beam and with respect to the target gas jet. The global transmission efficiencies $\epsilon_i(E)$ of the analyzers and their effective energy windows $\Delta E_i(E)$ are obtained as a function of detected energy E from observations of elastic scattering. Below 30 eV it was necessary to use downwards extrapolation to get the ϵ_i, but they were then so slowly varying as to be practically constant. To confirm our estimates of them, we made observations of the double-differential ionization cross section (DDCS). For an incident energy E_0 and an ejected electron energy E, the count rate $N_{\mathrm{DDCS}}(E_0,E)$ is related to the cross section $\sigma_{\mathrm{DDCS}}(E_0,E)$ by

$$N_{\mathrm{DDCS}}(E_0,E)=\sigma_{\mathrm{DDCS}}(E_0,E)\mathcal{L}(E_0)\Delta\Omega_i\epsilon_i(E)\Delta E_{\mathrm{DDCS}}(E)\ , \tag{1}$$

where $\mathcal{L}(E_0)=nN_el$ is a quantity related to the gas jet density n atoms/sec, the incident beam current N_e electrons/sec, and the effective length l of the collision zone. This is energy dependent but, for the reasons given above, it is the same for coincidence and for noncoincidence measurements and is independent of detector positions. The effective energy width ΔE_{DDCS} is obtained from the known ΔE_0 and from $\Delta E_i(E)$ determined by observations of the apparent width of the elastic-scattering peak. The latter do not require a particularly long stability in time of the electron beam current provided that the beam profile is stable. From our count rates N_{DDCS} and our estimated ϵ_i, we obtained relative cross sections $\sigma(E_0,E)$ for $E_0=500$ eV. We compared these to the absolute DDCS of Müller-Fiedler, Jung, and Ehrhardt [8] for E from 10 to 40 eV, and of Opal, Beaty, and Peterson [9] for E up to 200 eV and obtained good agreement with them as to shape over the whole energy range. The lower limit of 10 eV corresponds to an incident energy of 44.58 eV under energy-sharing conditions, which imposes the lower energy limit in our present experiments.

We were able to determine apparatus settings such that ΔE_a and ΔE_b remain unchanged as a function of energy: they had values of 1180 and 1140 meV, respectively, in the present experiments. The energy dependence of the ϵ_i results only from the deceleration of the detected electrons in the entrance optics since the potentials on the cylindrical analyzers are not varied. Insofar as possible, our coincidence measurements of ionization and the parallel observations of elastic scattering (both to determine analyzer parameters and to provide an absolute scale) were carried out under similar conditions so as to minimize possible sources of error. This usually meant accepting low coincidence count rates and long accumulation times, so for measurements of triple-differential cross sections (TDCS's) the long-term stability in time of our apparatus was of prime importance. Under energy-sharing conditions, the cross section $\sigma_{\mathrm{TDCS}}(E_0)$ is related to the coincidence count rate $N_{\mathrm{TDCS}}(E_0)$ by

$$N_{\mathrm{TDCS}}(E_0)=\sigma_{\mathrm{TDCS}}(E_0)\mathcal{L}(E_0)\epsilon_a(E_e)\Delta\Omega_a\epsilon_b(E_e)\Delta\Omega_b \times\Delta E_{\mathrm{TDCS}}\ , \tag{2}$$

where ΔE_{TDCS} is the coincidence energy window given by Lahmam-Bennani, Cherid, and Duguet [10]:

$$\Delta E_{\mathrm{TDCS}}^2=\Delta E_0^2+(\Delta E_a^{-2}+\Delta E_b^{-2})^{-1}\ .$$

As discussed by Cherid *et al.* [11], the latter window was probably defined incorrectly by Gélébart, Defrance, and Peresse [3] and by Gélébart and Tweed [4]. An *a posteriori* correction would reduce their scale factors by 18%.

The only quantity in Eq. (2) which is unmeasurable in a crossed-beam experiment is $\mathcal{L}(E_0)$. It may, however, be gotten by comparing the single-differential elastic cross section $\sigma_{\mathrm{SDCS}}(E_e)$ with the corresponding count rate $N_{\mathrm{SDCS}}^i(E_e)$ on either of the analyzers:

$$N_{\mathrm{SDCS}}^i(E_e)=\sigma_{\mathrm{SDCS}}(E_e)\mathcal{L}(E_e)\epsilon_i(E_e)\Delta\Omega_i\ .$$

We found the energy dependence of the elastic-scattering count rate to be the same on both analyzers to within an experimental uncertainty of 3%. At low energies it was only slightly different from that of the reference SDCS and at high energies it was identical to theirs. We could therefore conclude that the effective collision length l in our apparatus is essentially constant above 75 eV and does not change greatly with decreasing energy below. Gélébart, Defrance, and Peresse [3] assumed that the variation of $\mathcal{L}$ with energy was negligible, which is correct at *their* incident energies. Then the elastic SDCS at energy E_e may be used to normalize the ionization TDCS at energy E_0:

$$\sigma_{\mathrm{TDCS}}(E_0)=N_{\mathrm{TDCS}}(E_0)\frac{\sigma_{\mathrm{SDCS}}(E_e)}{N^a_{\mathrm{SDCS}}(E_e)}\frac{1}{\Delta\Omega_b\epsilon_b(E_e)\Delta E_{\mathrm{TDCS}}}\ . \tag{3}$$

In the present work we consider energies below 75 eV for which the variation of $\mathcal{L}(E_0)$, although slow, cannot be neglected. We therefore introduce the ratio of transmission efficiencies $\rho_a=\epsilon_a(E_0)/\epsilon_a(E_e)$ and normalize to the elastic SDCS at energy E_0:

$$\sigma_{\mathrm{TDCS}}(E_0)=N_{\mathrm{TDCS}}(E_0)\frac{\sigma_{\mathrm{SDCS}}(E_0)}{N^a_{\mathrm{SDCS}}(E_0)}\frac{\rho_a}{\Delta\Omega_b\epsilon_b(E_e)\Delta E_{\mathrm{TDCS}}}\ . \tag{4}$$

This has the additional advantage that the elastic cross sections used for reference, being at a higher energy than those required by Eq. (3) for the same E_0, generally have a smaller uncertainty. For an investigation of the energy dependence of the TDCS we are in any case obliged to determine the ϵ_i as a function of energy. Two further expressions may be obtained from Eqs. (3) and (4) by inverting the roles of the analyzers a and b: as a cross-check the scale factors are evaluated using both alternative forms.

For each incident energy considered a large number of individual measurements are made and their results combined to obtain the final experimental relative cross sections and the statistical errors on the raw data. These relative cross sections are then placed on an absolute scale, firstly using a point by point normalization from Eq. (4), secondly by taking the normalization so decided at 500 eV as standard and scaling the cross sections at lower energies relative to it. The agreement between the results of the two methods is very good indeed. We estimate the overall error in our *absolute* cross sections (uncertainty of reference cross sections included) to be 18% at $E_0 \geq 150$ eV and 23% at lower energies. In Figs. 1(a) and 1(b) our results are compared with the experimental data of Van Wingerden *et al.* [1], with the data of Gélébart and collaborators [3,4] *scaled down by 18%,* and with various theoretical calculations. Although our present results are compatible with those of Van Wingerden *et al.* in the region of 500 eV, they diverge progressively from theirs as energy decreases. Notably, our cross sections are almost twice theirs for E_0 of the order of 200 eV. However, our values are significantly smaller than those of Gélébart and collaborators, even scaled down.

We compare our experimental results with calculations made in the distorted-wave Born approximation and in various forms of the impulse approximation. These have been reviewed by Weigold and McCarthy [12] and, recently, by McCarthy [13]. In its plane-wave form, the impulse approximation describes the ionization process as a binary collision between an incident electron of fixed momentum and an electron having a momentum distribution characteristic of the target orbital from which it is ejected. In its distorted-wave form it also takes into account (through the wave functions) the interactions of the incident electron with the target and of the scattered and

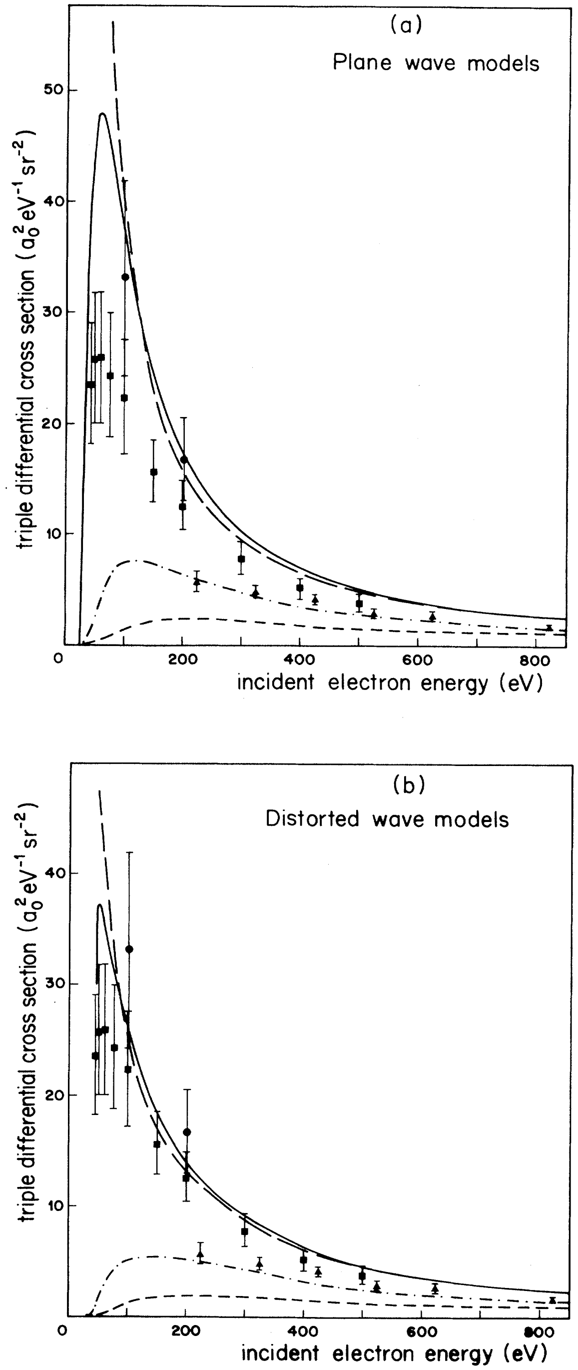

FIG. 1. TDCS in units of $10^{-4}a_0^2$ eV^{-1}sr^{-2} for electron-impact ionization of He in an energy-sharing coplanar symmetric geometry at a 45° angle, as a function of the incident electron energy E_0 in eV. Experimental results: ■, this work; ▲, Van Wingerden *et al.* [1]; ●, Gélébart and collaborators [3,4] reduced by 18%. The error bars combine uncertainties of relative data and scaling method. Theory: (a) PWIA calculations of McCarthy and Roberts [17] and PWBA, (b) present DWIA calculations and DWBA. Impulse approximation with half-off-shell Coulomb T-matrix from the following: ——, regularized; —·—·—·, Ford; and — — —, standard prescriptions. Born 1 approximation: ———.

ejected electron with the residual ion. Description of the binary collision necessitates the evaluation of the half-off-shell Coulomb T matrix, which has been reviewed by Chen and Chen [14]. The standard prescription for obtaining the general Coulomb T matrix gives a form having off-shell singularities which should not be present. This problem was resolved by Ford [15] by paying attention to the order in which limits are taken. His result has a discontinuity in going from on- to off-shell and Roberts [16] proposed an alternative prescription which eliminates this. We will follow McCarthy and Roberts [17] in referring to the three forms of Coulomb T matrix respectively as "standard," "Ford," and "regularized." It is difficult to interpret these in physical terms as the Coulomb T matrix *in itself* is physically meaningful only *on* the energy shell.

In Fig. 1(a) the experimental cross sections are confronted with theoretical calculations in the plane-wave impulse approximation (PWIA) by McCarthy and Roberts, comparing the results obtained with the three different forms of half-off-shell Coulomb T matrix. The Van Wingerden measurements clearly favor the Ford prescription but our measurements lie in between the predictions of the Ford and regularized forms. In addition, we observe a very steep rise near threshold and a subsequent drop which only the regularized prescription gives. Therefore the problem of which form of half-off-shell Coulomb T matrix should be used, which had been thought to be clarified on the basis of experimental evidence, is once again laid wide open. Also shown is the plane-wave Born approximation (PWBA) and it is interesting to note that the regularized prescription agrees with this at energies as low as 500 eV.

The distorted-wave Born approximation [18] has lately been used with considerable success in the interpretation of energy-sharing $(e,2e)$ experiments at incident energies of 100 eV and above, not only in symmetric geometries (Zhang, Whelan, and Walters [19], Rösel *et al.* [20]), but also in asymmetric ones (Cherid *et al.* [11]). It is therefore of interest to consider a distorted-wave form of the impulse approximation (DWIA). The problems then encountered, due to factorization being exact for plane waves but only an approximation for distorted waves, have been discussed by Whelan and Walters [21]. But at 45° in a symmetric geometry factorization should be a good approximation. In Fig. 1(b) we compare the experimental data with our own DWIA calculations made using the standard, Ford, and regularized prescriptions for the half-off-shell Coulomb T matrix and our DWBA calculation. The DWIA results are systematically lower than the equivalent PWIA results and the regularized prescription now gives cross sections which lie only slightly above our experimental data points. The DWBA results agree very well with our experimental data at the higher energies but systematically diverge from them as energy decreases. This is not surprising since the DWBA is essentially a perturbative approach. Like the plane-wave case, the DWBA and the regularized prescription for the DWIA are in agreement for energies above 500 eV.

In conclusion, we first appeal for further experimental work, particularly near to threshold where it would be interesting to see if the steep rise in the cross section predicted by the regularized PWIA and DWIA in fact occurs. Secondly, we feel that if the present experimental data are confirmed there will be a need for the reexamination of the whole philosophy and basis of the impulse approximation. Until an unambiguous way of choosing how to calculate the half-off-shell Coulomb T matrix exists, we can have confidence only in the application of the method at high energy where all prescriptions have the same limit.

Discussions with Dr. Lindsay Frost were very useful. Financial support was received from NATO Contract No. CRG 9201 01, from the SERC, the British Council, the CNRS and from the EEC Sciences program.

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