Coincidence measurements of electron-impact coherence parameters for *e*-He scattering in the full range of scattering angles

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Electron impact coherence parameters for inelastic *e*-He scattering have been measured for the excitation to the 2 $^1P_1$ state at collision energy of 100 eV. The experiment was conducted using angular correlation electron-photon coincidence technique with a magnetic angle changer allowing measurements in full range of scattering angles. The results are compared with other experimental data and theoretical predictions available for this collisional system.

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I. INTRODUCTION

Coincidence measurements of the electron-impact coherence parameters (EICPs) provide the most detailed data on collisional excitation processes. Such measurements can be very good tests of theoretical models of inelastic scattering problems. Despite development of computational methods of modeling there are still serious discrepancies among theoretical predictions for many target atoms, especially at large scattering angles [1]. Since no experimental data on EICPs have been available for the scattering angles above 130°, the disagreements could not be resolved. The lack of such data is due to geometrical limitations related to finite dimensions of devices such as electron guns and scattered electron detectors.

The possible way of overcoming those difficulties is utilization of magnetic-angle-changer (MAC) devices [2,3], which were successfully applied in variety of scattering experiments, for example in differential cross-section (DCS) measurements [4–8]. It has been shown recently, that MAC devices can be also used to extend measurements of EICPs to large scattering angles both in the electron-photon coincidence technique [9] and the superelastic scattering approach [10,11].

Impact excitation of He atoms has been the most widely studied subject in the field of electron-atom collisions [1]. The system has been investigated both theoretically and experimentally for relatively wide ranges of excitation energies and scattering angles. Moreover, the first experiments involving determination of a quantum mechanically complete set of EICPs were carried out by Kleinpoppen and co-workers for excitation to the first two singlet P states of He [12,13].

The EICPs and the DCS provide complete information on excitation of He to P singlet states. The set of parameters used in this paper includes the alignment angle γ, the shape parameter P_L, and the angular momentum transfer $L_\perp$ [1].

The angular part of charge cloud density distribution for He atom $^1P_1$ state can be expressed as

$$|\Psi(\vartheta,\varphi)|^2 = \frac{3}{8\pi}\sin^2\vartheta[1 + P_L\cos(2\varphi - 2\gamma)], \quad (1)$$

where ϑ and φ are spherical coordinates. Relative width and length of the charge cloud distribution in Fig. 1 are denoted by w and l, respectively. The shape parameter

$$P_L = \frac{l-w}{l+w}, \quad (2)$$

reflects the extent of its linear stretch along the direction determined by the alignment angle γ. Distribution shown in Fig. 1 corresponds to $P_L=0.6$ and $\gamma=30°$.

Despite quite large amount of data accumulated so far, there have been no experimental results for EICPs characterizing this collisional system at large scattering angles. Experimental results covering the full range of scattering angles will be certainly useful for fine tuning the theoretical methods.

II. EXPERIMENT

The experimental setup was described in detail in our recent paper [9]. Briefly, 100 eV electron beam with 2 μA current was cross-fired with an effusive beam of He atoms. The atomic beam was formed by a capillary tube (25 mm length, 1 mm inner diameter). The width of the beam in the interaction region (3 mm over the tube outlet) was about 2 mm (full width at half maximum) and its number density was of the order of 10^{12} cm^{-3}.

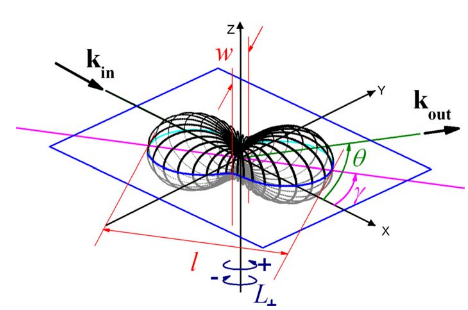

FIG. 1. (Color online) Angular density distribution of electron charge cloud of He atom excited by electron-impact to $^1P_1$ state. Momenta of the projectile before and after the collision are denoted by $\mathbf{k}_{in}$ and $\mathbf{k}_{out}$, respectively. The scattering angle is indicated by θ.

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Measurements at large scattering angles are facilitated by a MAC. The device deflects 100 eV electron beam by more than 50°, sufficiently to extend measurements up to 180°. Additionally, the beam of unscattered electrons is spatially separated from the electrons scattered inelastically at 0° in MAC's field making measurements for 0° scattering angle more feasible [7].

Experiments were conducted using the angular correlation electron-photon coincidence method. The coincidence signal N_{coin} is proportional to the probability of photon emission $I(\varphi)$ in a given direction by atoms excited by the collision act of interest. The distribution of photon emission in the scattering plane by the atoms excited to $^1P_1$ state is related to EICPs:

$$I(\varphi) \sim 1 - P_L \cos(2\varphi - 2\gamma), \quad (3)$$

where φ denotes the angle between the direction of photon emission and direction of the incoming electron beam. P_L and γ values can be determined by fitting the angular correlation curve (3) to values of the coincidence signal $N_{coin}(\varphi) \sim I(\varphi)$ measured at several positions of the photon detector φ.

Experimental uncertainties related directly to MAC field were analyzed thoroughly in [9]. Therefore, we restrict the discussion to possible influence of the uncompensated magnetic field on the experimentally determined values of EICPs.

Regardless of experimental method used (angular correlation technique, coherence analysis or superelastic scattering), the presence of the magnetic field affects results of EICP measurements. The charge cloud of the excited atom rotates in the magnetic field. Since the excited atoms relax spontaneously to the ground state at various times after the excitation, measurements yield results averaged over different angular positions of the charge cloud. It can be easily shown [9] that the influence of a homogenous magnetic field perpendicular to the scattering plane results in a shift $\Delta\gamma$ in the alignment angle γ

$$\Delta\gamma = \frac{1}{2}\arctan 2\eta B \approx \eta B. \quad (4)$$

B is the magnetic field and η is a coefficient dependent on the lifetime of the atomic excited state. For $2\,^1P_1$ state of helium atom $\eta = 2.8\frac{\text{deg}}{\text{mT}}$ [9]. The approximation in expression (4) is justified if the precession of the charge cloud is sufficiently slow compared to the decay rate.

The rotation of the charge cloud additionally reduces measured P_L to the apparent value:

$$\widetilde{P_L} = \frac{P_L}{\sqrt{1 + 4\eta^2 B^2}}. \quad (5)$$

Accounting for the effect is necessary in both coincidence measurements [9] and in superelastic scattering experiments [14]. However, if the strength of the magnetic field in the interaction region is sufficiently low, its effects can be accounted for as contributions to the experimental uncertainties.

TABLE I. Results and statistical uncertainties of measurements of EICPs for excitation of helium atoms to $2\,^1P_1$ state by 100 eV electrons.

θ (deg)	MAC	P_L	γ (deg)
0	on	0.968 ± 0.058	-5.8 ± 1.2
23	off	0.798 ± 0.026	-67.1 ± 1.7
23	on	0.804 ± 0.020	-65.9 ± 0.6
33	off	0.600 ± 0.047	-44.9 ± 4.0
33	on	0.600 ± 0.075	-46.2 ± 3.1
45	off	0.529 ± 0.070	-12.9 ± 4.6
60	off	0.94 ± 0.18	10.3 ± 5.9
85	on	0.606 ± 0.088	57.1 ± 3.8
100	on	0.12 ± 0.13	70[a]
120	off	0.20 ± 0.15	90[a]
135	on	0.35 ± 0.14	-63 ± 11
150	on	0.75 ± 0.17	-61.2 ± 5.8
176	on	1.11 ± 0.37	-13 ± 11
180	on	1.01 ± 0.23	-6.9 ± 8.6

[a]Estimated value, explanation in text.

Our MAC device has been designed in a way ensuring almost total cancellation of magnetic field within the interaction region [9]. The residual magnetic field is estimated to be lower than 0.06 mT in the central region (approximately 2 mm in diameter) for 3 A of MAC's current. The shift in apparent alignment angle estimated for this value of the mag-

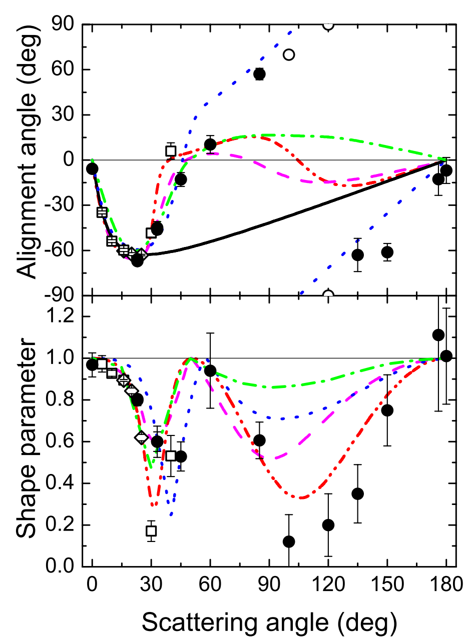

FIG. 2. (Color online) Results of measurements of EICPs for *e*-He inelastic scattering (excitation to $2\,^1P_1$ state by electrons of energy of 100 eV) compared to selected reference data. Circles, present results; diamonds, Eminyan *et al.* [13] experiment; squares, Steph and Golden [15], experiment; solid line, FBA; dotted line, PODWA [16]; dash-dot line, SODWA [17]; dashed line, *R*-matrix CC [18]; dash-dot-dot line, CCC [19].

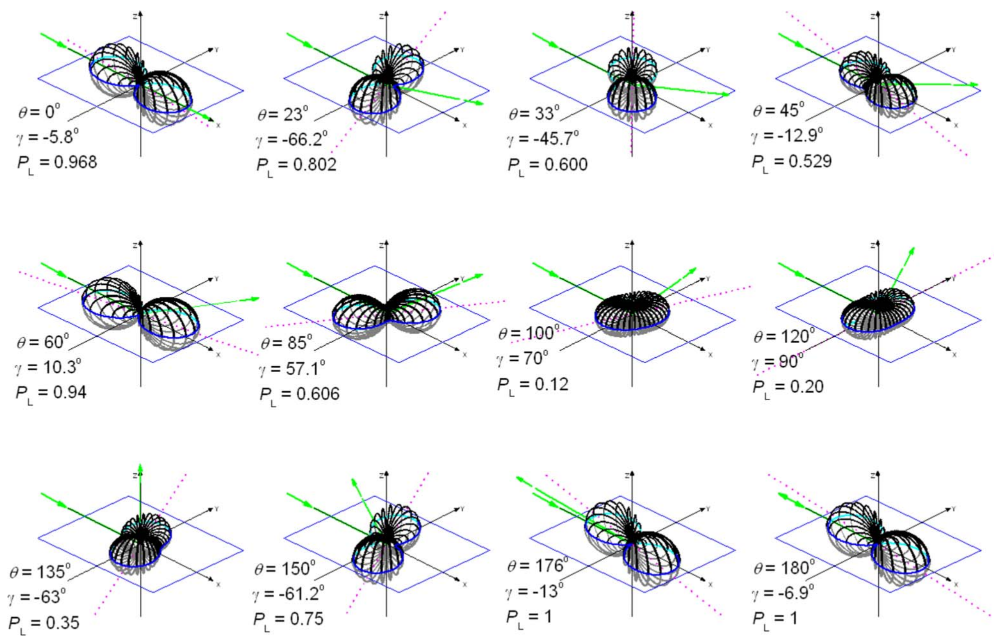

FIG. 3. (Color online) Graphical representations of angular distribution of excited atom's electron charge cloud corresponding to P_L and γ determined for various scattering angles. (Excitation of He atom to the $2\,^1P_1$ state for electron-impact energy of 100 eV).

netic field is $\Delta\gamma_{max}=0.17°$. Corresponding reduction of the measured shape parameter P_L is 1.7×10^{-5}.

We estimate that the accuracy of alignment of components of the experimental setup combined with finite angular resolution of both photon and electron detectors, and the residual resonance photon trapping sum up to 3% uncertainty for P_L. The maximum error of γ determination is 0.6° without MAC's field and when MAC is turned on, it increases up to 1.4° due to low uncompensated magnetic field present in the interaction region and the inaccuracy of determination of electron beam deflection angle.

The scattering angle is determined with accuracy of 0.5° without MAC's field and up to 1.0° when the MAC is turned on.

The statistical uncertainties vary with the scattering angle, so they are presented together with the results in the next section.

III. RESULTS AND DISCUSSION

EICPs were measured for electron-impact excitation of helium atoms to the $2\,^1P_1$ state at collision energy of 100 eV for 12 scattering angles in the range from 0° to 180°. Where possible, the measurements were carried out with MAC switched off. For selected scattering angles the experimental runs were repeated twice—with and without MAC's magnetic field. The time of signal accumulation depended strongly on the scattering angle and varied from 36 h at 0° to 1700 h (10 weeks) at the largest scattering angles.

The results of measurements are shown in Table I and plotted in Fig. 2. The figure also contains other available experimental and selected theoretical data. Both sets of earlier experimental data (Eminyan *et al.* [13] and Steph and Golden [15]) were obtained using angular correlation technique, similar as in our work. Theoretical data shown in Fig. 2 include results of application of the first Born approximation (FBA), polarized orbital distorted wave approximation (PODWA) (Scott and McDowell [16]), second-order distorted wave approximation (SODWA) (Madison and Winters [17]), and two close coupling methods: *R*-matrix (Fon *et al.* [18]) and convergent close coupling (CCC) (Fursa and Bray [19]). Angular distribution of electron charge clouds corresponding to the determined P_L and γ parameters are shown in Fig. 3.

The results obtained for two scattering angles require special comment. For 100° and 120° the measured values of P_L are very low. In such cases the charge cloud distribution has nearly rotational symmetry (Fig. 4). Thus the alignment angle is loosing its meaning and the measured values of γ have unreasonably high statistical uncertainties. Therefore, estimates based on interpolation of nearby data were included instead in Table I and Fig. 2 (indicated as open circles).

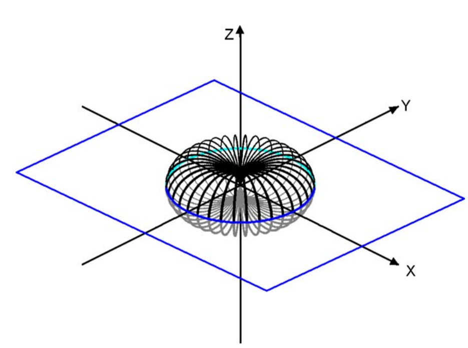

FIG. 4. (Color online) Angular part of the charge cloud density distribution for the shape parameter $P_L=0$. The alignment angle γ is meaningless as the angular distribution has rotational symmetry.

To the contrary, symmetry requirements imply that for scattering angles 0° and 180° $P_L=1$ and $\gamma=0°$. Measurements at these scattering angles can therefore be good tests of data consistency. While the results obtained for $\theta=180°$ are in very good agreement with the predictions, the apparent value of the alignment angle for $\theta=0°$ is considerably different from $\gamma=0°$. The discrepancy can be explained as a consequence of the very steep dependence of γ on the scattering angle in the vicinity of $\theta=0°$ and the finite divergence of the electron beam and the acceptance angle of the electron detection system [20,21].

The present results are in quite good agreement with other experimental data available for low scattering angles and in general qualitative accord with theoretical predictions.

Both minima of P_L have been predicted by all the available theoretical models. The first minimum is also seen in the experimental data of Steph and Golden [15], although its position and depth are different. The depth of the second minimum is reproduced most closely by the CCC method [19].

The minimum of the γ angle found at low scattering angles is in agreement with all sets of data, including FBA. The minimum is followed by a steep rise predicted by all theoretical models except FBA. The experimental results [15] suggest a slightly steeper slope. The dependence of the alignment angle on the scattering angle above 60° is very unexpected. It suggests transition through the value of 90° (which is also equivalent to −90°). Such behavior was predicted only by PODWA [16]. However, the shape parameter P_L anticipated by that method in this scattering angle range is much higher than the present results. At the largest scattering angles the alignment angle tends to zero from the negative values as predicted by most theoretical approaches except SODWA [17].

IV. SUMMARY

The electron-photon coincidence technique enhanced with application of a MAC device was used for measurements of EICPs for 100 eV electron-impact excitation of He atoms to the $2\ ^1P_1$ state. For the first time, the excitation parameters were determined in the full range (0°−180°) of scattering angles.

The results for low scattering angle range reconfirm previous experiments and theoretical calculations qualitatively. However, in the most interesting range of large scattering angles, the same level of consistence is observed only for the shape parameter, while the dependence of γ shows an unexpected behavior.

The data will be certainly useful for fine tuning of methods of theoretical modeling of scattering processes. Conducting similar measurements for other energies or more complex targets might help to explain discrepancies among various theoretical approaches, which are even more significant than in the case of helium.

Although feasibility of coincidence measurements in the full range of scattering angles has been demonstrated, the relatively low true coincidence count rate at large scattering angles still remains the major difficulty of such experiments.

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