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IONIZATION OF HELIUM: ANGULAR CORRELATION OF THE SCATTERED AND EJECTED ELECTRONS

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Ionizing collisions of 114- and 50-eV electrons with helium have been studied by the measurement of the two outgoing electrons in coincidence as a function of the angle between them. At the same time the energies of the two electrons are determined. The results are compared with solutions of the Lippmann-Schwinger equation. Angular correlation distributions are found to be more sensitive for the test of a theory than energy loss and differential cross sections or the total cross section.

Although the single ionization of atoms by slow electrons is one of the most important atomic collision processes, existing theoretical approximations are not yet as accurate as could be wished.[1] Therefore, often one is not in the position to calculate with sufficient accuracy ionization cross sections which are needed (for laboratory and astrophysical plasmas), and which are not measurable now and in the near future. On the other hand, there exists a severe lack of detailed[2] measurements of ionizing collisions of slow electrons with simple atoms, for which the target eigenfunctions are well known, so that the scattering approximations may be tested extensively.

In this paper we describe an experiment by which all collisional parameters for the single ionization of helium by slow electrons can be chosen and measured. These parameters are the energy of the incident electron E_p, and the energy and angle of the scattered electron, E_s, θ_s, and the ejected electron, E_e, ϑ_e. For the time being we are not yet in the position to choose the last parameter, the azimuth φ_e of the ejected electron. The apparatus detects only electrons with $\varphi_e = 0$. In addition, in this paper we present results of a theoretical treatment of the ionization problem and compare it with two experimentally determined angular correlation distributions.

A schematic representation of the experimental arrangement is given in Fig. 1. Electrons from a filament K are collimated by the lens system L_1 and injected into the 127° electrostatic energy selector S. Energy-selected electrons are accelerated by the lens system L_2 and are focused onto the atomic beam. The aperture box AP reduces the number of background electrons from the gun. After collision the two outgoing electrons are collected in collectors A_1 and A_2, respectively. A_1 can be rotated in the angular range from $-70°$ to $+125°$ and A_2 from $+70°$ to $-125°$. The angular resolution of A_1 is $\pm1°$; that of A_2 is $\pm10°$. In the beam collector BC of A_1 the primary electron beam is collected for small values of θ_s. The collector A_2 consists of an einzel lens L_5, a retarding field R (for intensity reasons), and the multiplier M_2. Ionizing collisions are identified by the coincidence signal from M_1 and M_2. The time resolution is 10 nsec.

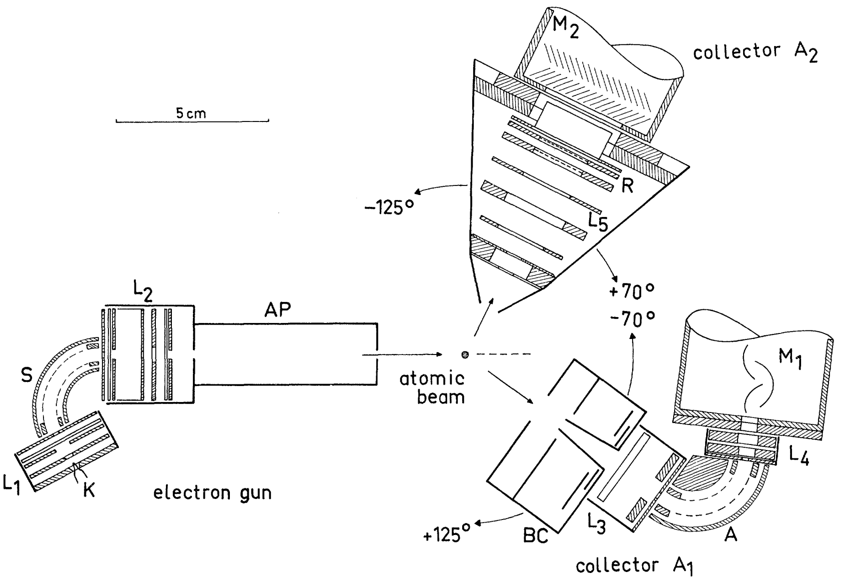

FIG. 1. Schematic diagram of the experimental arrangement. For details see text.

Typically between 0.3 and 20 coincidences per minute are registered in a multichannel analyzer. The channel number is proportional to the angular position of A_2. The parameters E_p, E_s, E_e, θ_s, and φ_e are kept fixed in one experiment and θ_e is varied.

Figures 2 and 3 show two examples of angular correlation distributions plotted in polar coordinates. In Fig. 2 the incident electron has the primary energy $E_p = 114$ eV and is travelling in the 0° direction. After the collision (in the center of the diagram) one of the two outgoing electrons is collected by the collector A_1, which is at $\theta_s = 7°$ and permits only electrons with $E_s = 74.5$ eV to be detected. Correspondingly the second outgoing electron has kinetic energy $E_e = 15.0$ eV. For $\varphi_e = 0°$ it has the freedom to travel in the direction θ_e with a probability which is proportional to the differential cross section

$$d^3\sigma(E_p, E_s, E_e, \theta_s, \varphi_e | \theta_e)$$

and which may be normalized to units of a_0^2 (a_0 = Bohr radius). The distance of each point from the center of the diagram for a given scattering angle θ_e is plotted in these units. The full curve has been calculated (see below) and the measured points have been normalized to fit the calculated curve at $\theta_e = +85°$. Within experimental uncertainty there is a general qualitative agreement between the theoretical curve and the measured data, although a slight systematic deviation (for negative θ_e) is notable. Such a degree of agreement or better seems to be typical for $E_p > 100$ eV and small scattering angles θ_s.

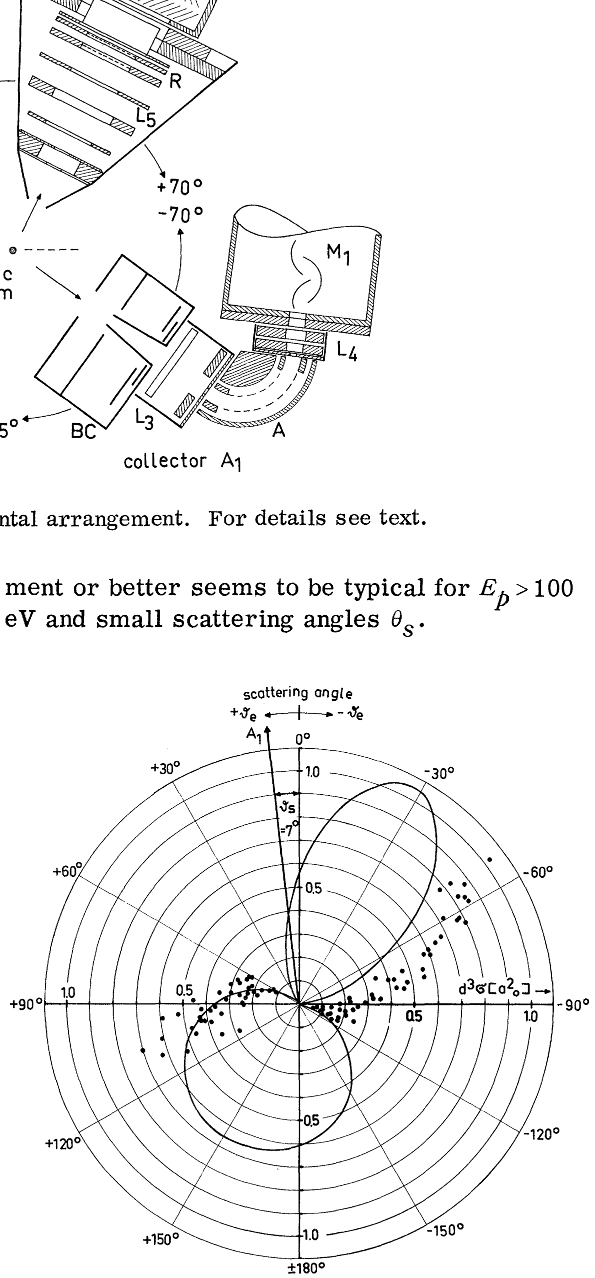

FIG. 2. Measured (dots) and calculated (full line) angular distribution of the ejected (slow) electrons with kinetic energy $E_e = 15$ eV and azimuth $\varphi_e = 0$ after ionizing collisions of 114-eV electrons with helium. This distribution corresponds to scattered (fast) electrons which have kinetic energy 74.5 eV and $\theta_s = 7°$. The intensity maximum ($1.1a_0^2$) of the calculated "binary encounter" peak is at $\theta_e = -28°$, the maximum ($0.65a_0^2$) of the "recoil" peak is near $\theta_e = +150°$. The experimental points are normalized to the calculated curve at $\theta_e = +85°$.

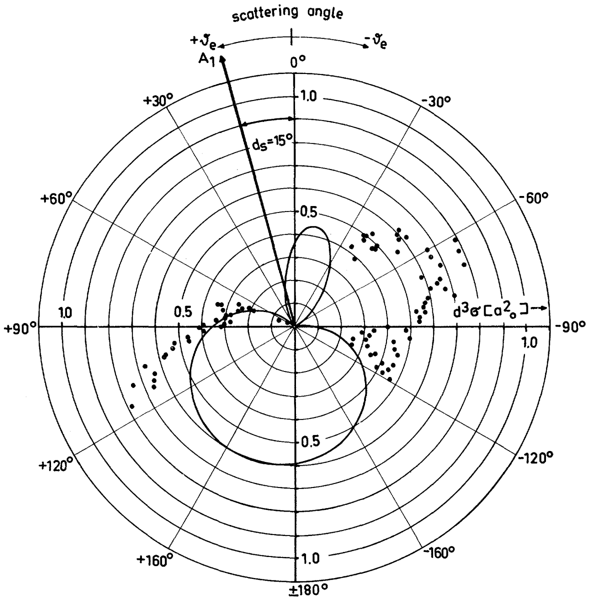

FIG. 3. Measured and calculated angular distribution of the ejected electrons with kinetic energy $E_e = 10.5$-eV and azimuth $\varphi_e = 0$ after ionizing collisions of 50-eV electrons with helium. The other collisions parameters are $E_s = 15$ eV and $\theta_s = 15°$. See also Fig. 2.

Below $E_p = 100$ eV the discrepancies increase. Figure 3 gives an example. Here $E_p = 50$ eV, $E_s = 15$ eV, $E_e = 10.5$ eV, $\theta_s = 15°$, and again $\varphi_e = 0$. The normalization of the experimental points to the theoretical curve has also been made at $\theta_e = +85°$. Here, the experimental maximum coincides with the theoretical minimum, i.e., the angular correlation cross section $d^3\sigma$ clearly shows the weakness of the theoretical treatment. The total ionization cross section as a function of the energy E_p, namely

$$\sigma(E_p) = \int\int\int d^3\sigma(E_p; E_s, E_e, \theta_s, \varphi_s, \theta_e, \varphi_e) \times dE_s\, d\Omega_s\, d\Omega_e$$

would not be as sensitive for the comparison between theory and experiment.

The theoretical angular correlation distributions $d^3\sigma$ have been calculated, since in the literature no such detailed cross sections are available. Taking into account the spin orientations of the incident and outgoing electrons, for helium we derive the expression (in atomic units)

$$d^3\sigma = (2\pi)^{-5}(k_s k_e/k_p)2\{\tfrac{1}{4}|f+g-2h|^2 + \tfrac{3}{4}|f-g|^2\},$$

where $k_j = (2mE_j/\hbar^2)^{1/2}$ with $j = p, s, e$; f is the direct scattering amplitude, and the exchange amplitude $g(\vec{k}_e, \vec{k}_s)$ is assumed to be equal to $f(\vec{k}_s, \vec{k}_e)$. g describes the scattering events for which the incident electron (denoted by index 1) transfers most of its momentum to one of the atomic electrons (index 2), which then is ejected as a fast particle. h represents the amplitude which describes the capture of the incident electron by the ion, and as a consequence, both atomic electrons (2 and 3) are ejected.

In our calculations we neglect h and set

$$f(\vec{k}_s, \vec{k}_e) = \int d\tau_{123} W_f(3) \exp(-\vec{k}_s\cdot\vec{r}_1 - i\vec{k}_e\cdot\vec{r}_2) \times (V_{\rm tot} + 2/r_3) \exp(i\vec{k}_p\cdot\vec{r}_1)\eta(2)\eta(3),$$

where $W_f(3)$ is the hydrogenic wave function for the He^+ ion, i.e.,

$$W_f(3) = 2(2/\pi)^{\frac{1}{2}} e^{-2r_3}$$

and

$$V_{\rm tot} = -\frac{2}{r_1} - \frac{2}{r_2} - \frac{2}{r_3} + \frac{1}{r_{12}} + \frac{1}{r_{31}} + \frac{1}{r_{23}},$$

$$\eta(r) = N_0(e^{-\gamma r} + Ce^{-2\gamma r}),$$

with $N_0 = 0.837$, $\gamma = 1.456$, and $C = 0.6$.[3] The functions $\eta(r)$ are solutions of a Hartree-Fock approximation. With these functions the integrals for the scattering amplitudes f and g can be evaluated. They depend only on the wave vectors and therefore on the energies and scattering angles of the electrons.

This theory allows for exchange and interaction of the electrons with the nucleus; it therefore reproduces both the "binary encounter" peak (values of θ_e almost all negative) and the "recoil" peak (θ_e almost all positive values; both electrons being scattered into the same θ half-plane). The wave functions used in the calculation are too simple (for the intermediate energy range) to reproduce all experimental details of the angular correlation distributions, namely angular positions of maxima or minima, intensity ratios, slopes, etc.

Recently Glassgold and Ialongo[4] have calculated the angular distributions of the outgoing electrons in electronic ionization for H and He and for atoms with similar valence shells. These authors concentrate on high kinetic energies of the incoming electron and the symmetrical situation, i.e., processes in which the outgoing electrons have the same energy and make the same angle with the incident beam. Unfortunately, we are not yet in the position to measure the symmetrical case, since the cross section is too low. A detailed discussion of our theoretical approach and a summary of all our experimental results to date are being prepared for publication.

The character of our measurements aims towards a thorough comparison with theory. From each ab initio calculation the theoretician should be able to extract differential and angular-correlation cross sections. Comparison of these data with experiments may be regarded as a test of the theory of higher order than the comparison with total cross sections. In addition,[4] measurements of this kind can be expected to provide new information on the momentum distribution and on the self-consistent field of the atomic electrons.

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[1] The latest review on the theory of the ionization of atoms by electron impact has been published by M. R. H. Rudge, Rev. Mod. Phys. 40, 564 (1968).

[2] For example, energy loss or differential cross sections. Up to now nearly exclusively the energy dependence of the total cross section has been measured, which represents an integration over several collision parameters.

[3] N. F. Mott and H. S. W. Massey, The Theory of Atomic Collisions (Clarendon Press, Oxford, England 1965), 3rd ed.

[4] A. E. Glassgold and G. Ialongo, Phys. Rev. 175, 151 (1968).

DEPENDENCE OF PITCH ON COMPOSITION IN CHOLESTERIC LIQUID CRYSTALS

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Two-component cholesteric liquid crystal films have been observed to exhibit a remarkable structural dependence on composition. There is evidence that the relationship of color and temperature in these films is connected with this dependence.

Dispersive scattering, and other anomalous optical properties of cholesteric liquid crystal films, can be explained in terms of Bragg-like scattering[1] from regions of local order which have an internal helical structure.[2] The basic optical parameters which characterize these films are the index of refraction n, and the pitch p of the helical arrangement. It is well known that the pitch is sensitive to temperature,[3] shear,[4] and organic vapors.[5] It is the purpose of this Letter to report the unusual effect of chemical composition on pitch in two-component mixtures.

The liquid crystal sample was mounted on a spectrometer stage. A monochromator was used as a source and a photodiode as a detector. The pitch was determined by measuring the angle of incidence φ_i and the angle of reflection φ_s as a function of scattered wavelength λ, according to

$$\lambda = 2np\cos\tfrac{1}{2}\left\{\sin^{-1}\left(\frac{\sin\varphi_i}{n}\right)+\sin^{-1}\left(\frac{\sin\varphi_s}{n}\right)\right\}. \quad (1)$$

This formula was derived by Fergason on the basis of a model of regions of local order imbedded in a material with refractive index n. These regions exhibit Bragg-like scattering in the optical regime. The appropriate geometry and definition of symbols are shown in Fig. 1.

The liquid crystal ingredients, all of which were crystalline at room temperature, were first weighed and dissolved in petroleum ether.

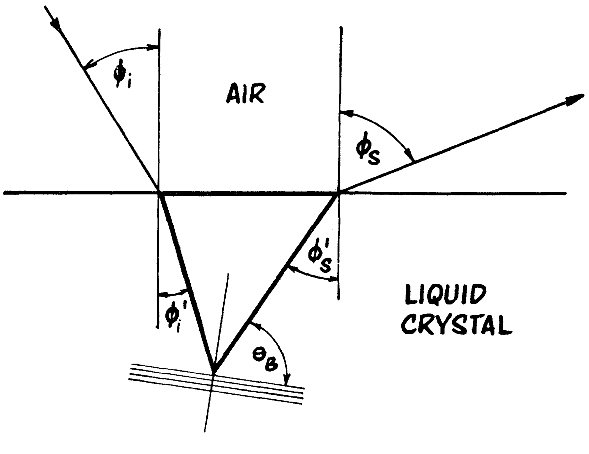

FIG. 1. Details of scattering geometry.