# Interference between Scattered and Ejected Electrons in *e*-He Collisions: A New Probe for Coherence Studies

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We present a method for the study of coherences between states of different excitation energies. This method is based on the occurrence of interferences between scattered and ejected electrons resulting from the electron impact excitation of autoionizing states. Preliminary measurements are presented which for the first time show such interference effects.

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During the past 15 years the experimental observation of coherences between collisionally excited states has provided an enormous wealth of detailed information on the mechanism and dynamics of various atomic collision processes.

According to the quantum dynamical description of an atomic collision process the final state of the collision partners for a selected scattering direction can be represented as a coherent superposition of the possible final states. For instance, in the case of the electron impact excitation of an atom, which we shall consider here,

$$|\Psi\rangle = \sum_{nLM} a_{nLM} |nLM\rangle , \qquad (1)$$

where the quantum numbers $n$, $L$, and $M$ serve to characterize the possible final states of the atom. The $a_{nML}$ are complex numbers depending on the energy and scattering angle of the projectile electron and represent the excitation amplitudes for the various final states $|nLM\rangle$; their absolute values squared represent the excitation cross sections, whereas their relative phases can only be determined by our measuring the coherences between the various states. It will be clear that a determination of the coherence between any two final states $|nLM\rangle$ and $|n'L'M'\rangle$ involves an analysis of the interference between the excitation of those states, which is determined by terms of the type $a_{nLM}a^*_{n'L'M'}$.

When an experiment is performed, one usually selects a single final state, or a set of degenerate final states, by fixing, for instance, the energy loss of the projectile electrons or the wavelength of emitted photons. If only a single state is selected, then no coherences can be detected. If a set of degenerate substates $|nLM\rangle$ with fixed $n$ and $L$ is selected, then coherences between the substates with different $M$ can in principle be detected. However, if the detection scheme of the experiment has cylindrical symmetry with respect to some axis (e.g., if the direction of the scattered electrons is not observed), then all coherences between different $|LM\rangle$ states will be washed out due to an integration of the observed quantities over all scattering directions. Only if the cylindrical symmetry is lowered to a planar symmetry by fixing the scattering angle of the scattered electrons can the coherences then be observed. This forms the basis for the well-known electron-photon or electron-electron coincidence experiments.[1]

Returning to Eq. (1), it is clear that states with different $n$ and $L$, thus with different excitation energies, are also coherently excited. However, except in the case of quantum beats, these coherences can normally not be observed because of the energy differences between the detected particles (electrons or photons) resulting from different excited states, which excludes interferences between them. Only when the different states can decay to the same final state can interferences and hence coherences between them be observed experimentally. Such a situation occurs, for instance, in the near-threshold excitation of autoionizing states, where the energy distributions of the scattered and ejected electrons are broadened and shifted as a result of postcollision interaction. Because of this effect, the energy distributions of electrons of different states may (partly) overlap, so that coherence studies are possible.[2-4]

In this Letter we present the first experiment where it is possible to study coherences between the excitation of states that are separated in energy by several eV without employing shifting or broadening effects, such as those caused by postcollision interactions. This experiment concerns the excitation of autoionizing states of helium by electrons in the incident-energy domain where the energies of the scattered and ejected electrons are about equal. In this energy region there will be overlappings between scattered- and ejected-electron energies resulting from the excitation of different autoionizing states. This provides the possibility of different autoionizing states decaying to final states (He$^+$ ion+scattered electron+ejected electron) where the roles of the scattered and ejected electrons are interchanged, but which are indistinguishable. We expect that in this situation the scattered electrons from one of the autoionizing states will interfere with the ejected electrons from the other and vice versa, and thus that coherences between the two states can be studied. To illustrate this we consider the excitation of, for instance, the $(2s^2)\,^1S$ and $(2p^2)\,^1D$ autoionizing states of helium:

$$\begin{aligned} &e_0(E_0)+\mathrm{He}\rightarrow \mathrm{He}^{**}(^1S)+e_s(E_s^S)\rightarrow \mathrm{He}^+ + e_s(E_s^S)+e_j(E_j^S)\,,\\ &e_0(E_0)+\mathrm{He}\rightarrow \mathrm{He}^{**}(^1D)+e_s(E_s^D)\rightarrow \mathrm{He}^+ + e_s(E_s^D)+e_j(E_j^D)\,, \end{aligned} \tag{2}$$

where $e_0$, $e_s$, and $e_j$ denote the incident, the scattered, and the ejected electrons with energies $E_0$, $E_s$, and $E_j$, respectively. The labels $S$ and $D$ refer to the two autoionizing states. If now the incident energy is chosen such that $E_s^D=E_j^S$ and $E_s^S=E_j^D$ and if a fixed detection direction is chosen, the two final states are identical and we expect interferences to occur between scattered electrons from the $^1D$ state and ejected electrons from the $^1S$ state and vice versa. Of course, there is also the interfering contribution as a result of the direct ionization process.

We have performed a series of experiments to demonstrate the expected interference effects. Using a conventional electron spectrometer,[5,6] we have measured ejected-electron spectra in the incident-energy range where the effects are expected to occur. The apparatus is operated in the so-called constant-energy-loss mode. That is, the energy loss $E_L=E_0-E_t$ is kept constant, while the energy $E_t$ of the electrons that will be transmitted by the analyzer is varied along with $E_0$. If now the energy loss is fixed at the excitation energy of one of the autoionizing states and we vary $E_t$ (and $E_0$), we will detect at $E_t=E_j^L$ ($L$ indicates any autoionizing state) ejected electrons together with the scattered electrons resulting from the selected autoionizing state. This is shown schematically in Fig. 1, where the two sloping lines indicate the energies of the detected scattered electrons from the $^1S$ and $^1D$ states, whereas the horizontal lines represent the energies of the ejected electrons from these states. At each of the four intersection points interferences between scattered and ejected electrons may occur. Note that at the points A and D interferences between scattered and ejected electrons from the same state may occur.

Figure 2 shows our first measurements on interferences between scattered and ejected electrons. The spectra, which have been taken in the constant-energy-loss mode and at a detection angle of 10° with respect to the incident beam direction, exhibit ejected-electron structures due to the $(2s^2)\,^1S$, $(2s2p)\,^3P$, $(2p^2)\,^1D$, and $(2s2p)\,^1P$ autoionizing states at 57.82, 58.30, 59.90, and 60.13 eV, respectively. In spectra 2(a) and 2(b) the energy loss was fixed at values which do not correspond to the excitation energy of any of the autoionizing states. So the structures in these spectra are caused by interference between ejected autoionization electrons and the direct ionization continuum only. It is seen that the two spectra look quite similar. This is understandable since one would not expect the relative phases between the different autoionization processes and the direct ioniza-

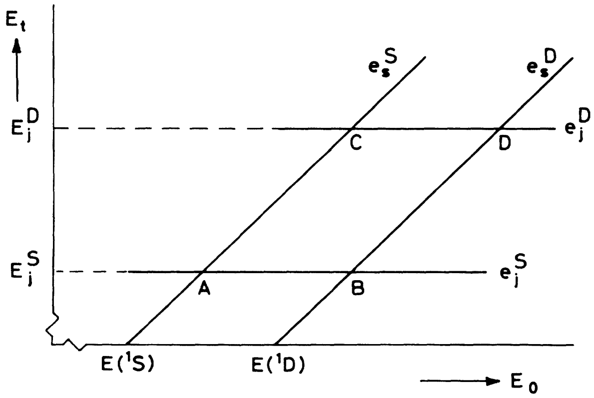

FIG. 1. Schematic diagram of the energies of the scattered and ejected electrons [resulting from excitation and subsequent decay of the $(2s^2)\,^1S$ and $(2p^2)\,^1D$ autoionizing states of helium] as a function of the incident-electron energy $E_0$.

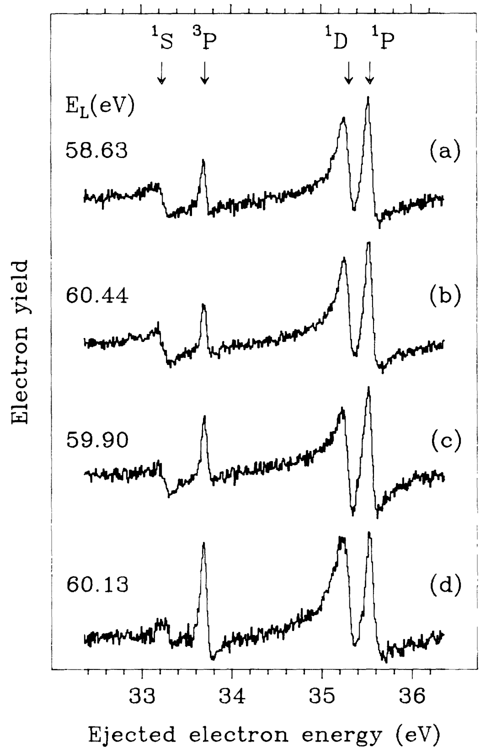

FIG. 2. Ejected-electron spectra, taken in the constant-energy-loss mode at different values of the energy loss $E_L$. The nominal ejected-electron energies of the four observed autoionizing states are indicated by arrows. From all spectra a linear sloping background has been subtracted.

tion process to change very much when the energy loss is changed by a few eV. In spectra 2(c) and 2(d), the chosen energy loss corresponds to the excitation energy of the $(2p^2)^1D$ and $(2s2p)^1P$ states, respectively. In these spectra there is not only the "background" of the direct ionization, but in addition an extra "background" of the scattered electrons resulting from the $^1D$ and $^1P$ excitations, respectively. It is clear that the interference structures in spectra 2(c) and 2(d) differ appreciably from those in spectra 2(a) and 2(b). In particular, the structure as a result of the $^1S$ ejected electrons has changed both in shape and magnitude. Further, the $^3P$ ejected-electron peak, which is about half the size of the $^1P$ peak in spectra 2(a) and 2(b), has about the same height has the $^1P$ peak in spectrum 2(d). Note also the difference of the shape of the $^1D$ and $^1P$ structures in spectrum 2(c) with respect to 2(a) and 2(b), as well as the significant mutual differences between these structures in spectra 2(c) and 2(d).

We attribute all these differences to the fact that in spectra 2(c) and 2(d) interferences occur between scattered and ejected electrons, whereas in spectra 2(a) and 2(b) this is not the case. If it were impossible to observe interference between the excitation of different autoionizing states [reaction scheme (2)], only an extra "background" would have been added incoherently to spectrum 2(a) or 2(b) to obtain 2(c) or 2(d). The interference patterns would still look the same as in spectra 2(a) and 2(b), only the noninterfering background would be larger. This is actually not the case and, since in spectra 2(c) and 2(d) nothing has been changed except for the detection of extra scattered electrons, we conclude that we indeed observe interference between scattered and ejected electrons. In spectra 2(c) and 2(d), interferences occur between the ejected electrons from all four observed states and the $(2p^2)^1D$ and $(2s2p)^1P$ scattered electrons, respectively.

Since our experiment is a noncoincidence experiment, the detection of the ejected electrons of a particular state is integrated over all directions of the corresponding scattered electrons. This implies for the reaction scheme (2) that there is only interference between scattered and ejected electrons if their orbital angular momenta are the same. Therefore, since the ejected electrons have fixed orbital angular momenta, only certain partial waves of the scattered- and of the direct-ionization electrons will contribute to the interference. Thus by our studying the interferences between the scattered electrons from a particular state and ejected electrons from states with different angular momenta, the contributions of different partial waves to the excitation of that state can be probed.

Our present observations open up a whole range of new experiments for coherence studies. As has been shown in the present contribution, our method provides possibilities to study coherences between states of different excitation energies. The method is not restricted to states which are separated by a few eV, such as in the present experiment, but can also be applied to states which lie several hundreds of eV apart, such as, for instance, in inner-shell excitation followed by Auger emission.

Work is in progress to develop the theory needed for the analysis of experiments such as shown in Fig. 2. This will be the subject of a forthcoming publication together with a detailed analysis of the experimental results obtained so far.

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[6] For experimental details such as energy resolution and calibration see J. P. van den Brink, J. van Eck, and H. G. M. Heideman, to be published.