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THE RELATIVE DIFFERENTIAL CROSS SECTION FOR THE EXCITATION OF THE 3^1P ($m_\ell = 0$) STATE IN HELIUM BY 70 eV ELECTRONS

by

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THE RELATIVE DIFFERENTIAL CROSS SECTION FOR THE EXCITATION OF THE 3^1P ($m_\ell = 0$) STATE IN HELIUM BY 70 eV ELECTRONS

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This thesis describes an experiment that measures a relative differential cross section for the excitation of the 3^1P ($m_\ell = 0$) state in helium by 70.0 eV electrons. Since this magnetic substate is degenerate in energy with the other magnetic substates with $m_\ell = +1$ and -1, it is not possible to measure these differential cross sections from an energy loss experiment. However, it is possible to measure these differential cross sections by detecting an inelastically scattered electron in coincidence with the photon that is emitted when a magnetic substate decays. A ratio λ of the differential cross section for the $m_\ell = 0$ substate to a sum of differential cross sections for all the magnetic substates can be found from the polarization of the photon or by varying the position of the photon detector. It is also possible to measure the differential cross section for the $m_\ell = 0$ substate alone by placing the photon detector at a right angle to the electron beam and in the scattering plane which was done here. Therefore, the results of this experiment are fine in detail, in

the sense that the differential cross sections are for a state where all the quantum numbers are given. The results of this experiment agree well with previous experimental results, but are now extended to larger scattering angles where the theories give different results. The present results agree best with theories which include electron exchange effects. However, the present results are still below these theories. This may indicate that electron exchange effects are more prominent than expected or that the distortion of the incident electron wavefunction is not what some of these theories have assumed.

Part of this thesis deals with some problems that were encountered when the experiment was designed. Some of these problems are: space-charge effects in electrostatic lenses, design of the electron optics for an energy monochromator, and an expression for the effective scattering length. Other subjects such as the Hertzog correction, the Abbie-Helmholtz Law, and apertures are also presented.

Dedicated

to my parents

Charles and Irene,

to my sisters

Shirley and Ann Marie,

and to my nephews

Dustin and Gabriel.

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CHAPTER I

INTRODUCTION

In the past, two principal methods were used to study the excitation of an atom by electron impact. The first is electron spectroscopy in which measurements of the electron energy loss spectrum yield level cross sections for those levels which are resolved. The second method involves measurement of the photon emitted from the excited state subsequent to the excitation. Both of these methods provided valuable data and have contributed to the understanding of electron impact excitation of atoms. But the data that these experiments provide are limited. In the energy loss experiments, the excited states are identified by the amount of energy that the electron loses during the collision. Because there are states that have equal or almost equal energies, and because the electron beam has an energy spread, this experiment often measures a sum of the differential cross sections of the unresolved states. If a state has fine-structure or hyperfine-structure, then there may be a number of substates that have an energy difference of .04 meV or less. Thus, the energy spread of the electron beam and the energy resolution of the electron detector must both be less than .04 meV before it is possible to distinguish these substates. Of course, when the substates are degenerate in energy, they cannot be distinguished by the energy loss of the scattered electron alone.

In electron excitation experiments that detect the emitted photon rather than the scattered electron, it is possible to resolve some states that cannot be easily resolved in the energy loss experiments. By measuring the intensity of an emission line, it is possible to infer the total excitation cross section by electron impact for the state. Unfortunately, there are other indirect ways that a state can be populated in addition to direct impact of an electron. For example, another excited state or states can decay or cascade to the state being investigated. Another process is resonant trapping where an atom in the ground state absorbs a photon that was emitted by another atom. This newly excited atom may then decay via the transition for the emission line selected by the experiment. Finally, in collisional energy transfer, an atom in a long lived highly excited state can collide with another atom in the ground state. After the collision, one of these atoms could then be in the state being investigated. Therefore, this type of experiment may not measure directly the emission cross section, but will measure an apparent emission cross section. There are methods to separate out the collisional transfer of excitation and the resonant trapping contributions to the apparent emission cross section. However, it is more difficult to separate out the cascade contribution.

Neither of these types of experiments can determine the differential cross sections for the substates. The energy loss experiment cannot be used, because the energy splitting of the substates are much smaller than the energy spread of the electron

beam. The emission experiment cannot be used because they measure the total level cross sections. This is unfortunate, because these differential cross sections for the substates can be a strict test for theories. As stated before, the differential cross sections from energy loss experiments are a sum of these differential cross sections. This means that the theories must also sum their substate differential cross sections in order to describe the data from these experiments. Thus a theory would be judged successful if this sum agreed with this experimental data. However, this does not guarantee that the individual substate differential cross sections are accurate.

Overview of Correlation Experiments

Percival and Seaton (1958), in their extension of earlier theories, showed that it is possible to get some information on the total cross section for the substates by measuring the percentage of optical polarization of the emission line. In other words, the relative population of the substates determine the relative polarization of the emission line. Macek and Jaecks (1971) then stated that by detecting the scattered electron in coincidence with the photon that is emitted when the state decays, it is possible to determine the differential cross sections for the substates in a practical experiment, and gave an expression for the coincidence counting rate. In general, this expression is a summation of several terms. Each of these terms has a factor that is given by the position of the photon detector,

the orientation of the scattering plane, and the angle of polarization of the polarizing filter. These terms have coefficients that are given by a linear combination of the differential cross sections for the substates and their relative phases for their wavefunctions. Thus by changing the position of the photon detector or the angle of polarization of the filter, it is possible to determine the coefficients. It is then possible to find the differential cross section for each substate and their relative phases for their wavefunctions in some cases. The relative phases of the wavefunctions are now an experimentally measurable quantity which must also be described by theory.

There are typically two ways that the substate differential cross sections and the relative phases of the wavefunctions are found by experiment. One is to keep the position of the photon detector fixed but vary the polarizing angle of the filter. The other is not to use the polarizing filter at all but vary the position of the photon detector. The choice between these two ways depends on the state that is being studied and other experimental considerations. This subject will be given in more detail in a later section on past experiments.

Therefore an electron-photon coincidence experiment should have features that are diagrammed in Fig. (1.1). The first feature is an electron beam that has a reasonably small energy spread. The direction of the electron beam defines the positive z-axis by convention. The next feature is the electron detector. Its position defines the scattering plane (the plane that

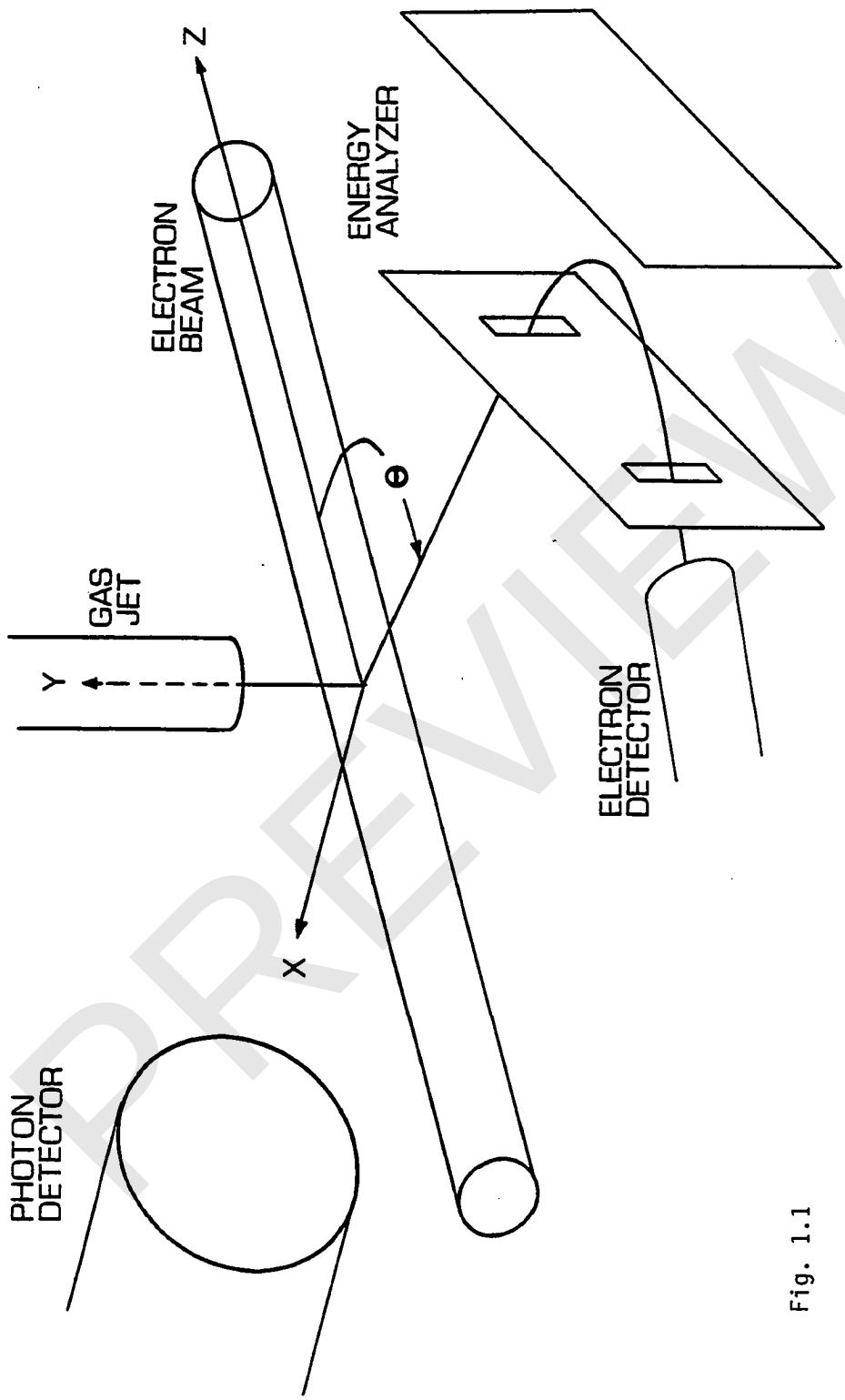

Fig. 1.1

includes the electron beam axis and the central axis of the detector's solid angle), and the scattering angle θ (the angle between the beam axis and the central axis of the detector's solid angle). It is at this scattering angle that the substate differential cross sections will be determined by the experiment. Thus by changing this angle, the substate differential cross section for different scattering angles can be measured. Because the scattered electrons may have a wide range of energies that is caused by elastic scattering, inelastic scattering and ionization, the electrons that have lost a certain amount of energy must be selected before they are detected. This energy selection is done by an electrostatic energy analyzer of some geometry, such as a parallel plate analyzer shown in Fig. 1.1 or a hemispherical analyzer which is used in the present experiment. The energy resolution of the electrostatic energy analyzer should be sufficient to resolve the state that is being studied, or at least sufficient to resolve this state and a few neighboring states from all the rest. The next feature of an electron-photon coincidence experiment is the photon detector. The position of the photon detector axis may or may not be fixed. When the position of the photon detector is fixed, then it should have a polarizing filter in most cases. If the position of the photon detector can be changed, then a polarizing filter is not needed. The position of the photon detector, if its position is to be fixed, or how its position should be varied is decided by the coincidence counting rate function of Macek and Jaecks for the transition that is being

studied and by some experimental requirements. Examples for these different choices and the experimental requirements are given in a discussion of past experiments and the present experiment in the latter part of this chapter.

The photon detector should detect photons emitted from the chosen transition. However, there have been experiments where the photon detector is sensitive to many transitions. This is allowed provided that the intensity of the emission line for the transition that is being studied is much larger than the other emission lines that are also detected. But this approach may cause some problems which will be discussed later.

One of the advantages of an electron-photon experiment is that it is free from some of the problems that plagued the emission experiments. Collisional energy transfer cannot produce a coincidence, because the electron that excited the first atom to a higher state is not detected since it lost too much energy. Cascading cannot produce a coincidence for the same reason, provided that the photon detector is wavelength selected. An example where cascading effects have been observed in an electron-photon coincidence experiment is given in the discussion on past experiments. However, these experiments are not free from resonant trapping effects. It will be shown later that resonant trapping can produce a coincidence, increase the apparent lifetime of the state, and change the polarization of the emitted light. Thus resonant trapping can cause erroneous measurements and should be avoided.

The ^1P-^1S Transitions in Helium

The ^1P-^1S transitions in helium are interesting. Since the nuclear spin of helium is zero, there is no hyperfine-structure. And since the total electron spin of the singlet states is zero, there is no fine-structure. Thus the substates of the ^1P state are degenerate in energy. This leads to a relatively simple function for the coincidence rates. From this function, it is possible to determine all the differential cross sections for the substates and the relative phases for their wavefunctions. It is possible to measure these quantities for ^1P states with different principal quantum numbers. For example, the 2^1P state can be studied by detecting the 583 Å photon from the 2^1P-1^1S transition. Also the 3^1P state can be studied by detecting either the 537 Å photon from the 3^1P-1^1S transition or the 5016 Å photon from the 3^1P-2^1S transition. Thus, there are a number of experiments that can be done on different states. These experiments have already been done, but the results are not complete. Before these experiments are presented, and their advantages and disadvantages are discussed, the function for the coincidence rate is presented. This function is then used to explain how the differential cross sections of the substates and the relative phase of the wavefunctions are extracted from the experimental results.

After Macek and Jaecks, others have also presented theories on electron-photon coincidence experiments that use spherical tensor operators; Fano and Macek (1973), and Blum and Kleinpoppen

(1979). Using the formalism of Macek and Jaecks and using the parameters λ, χ and σ as used by Eminyan et al. (1974), the angular correlation function for a ^1P to ^1S transition in helium is

$$f(\beta,\theta,\phi,\theta_\gamma,\phi_\gamma,\lambda,\chi) = \lambda\cos^2\beta + \frac{1-\lambda}{2}\sin^2\beta + \frac{1-3\lambda}{2}\cos^2\beta\cos^2\theta_\gamma + \sqrt{\lambda(1-\lambda)}\cos\chi * [\sin 2\theta_\gamma\cos^2\beta\cos(\phi-\phi_\gamma)+\sin 2\beta\sin\theta_\gamma \times \sin(\phi-\phi_\gamma)] + \frac{1-\lambda}{2}[(\cos^2\beta\cos\theta_\gamma - \sin^2\beta)\cos 2(\phi-\phi_\gamma)+\sin 2\beta\cos\theta_\gamma \times \sin 2(\phi-\phi_\gamma)]. \quad \text{Eq. (1.1)}$$

β is the angle between the unit axis $\hat{\rho}_\theta$ which is in the direction of increasing angle θ and the direction of the electric vector of the emitted light Fig. (1.2). The position of the photon detector is given by the polar angles θ_γ and ϕ_γ, where the angle ϕ_γ is to an arbitrary x - z plane. The polar angles θ and ϕ give the direction to the electron detector where the angle ϕ is to the same arbitrary x - z plane as ϕ. The parameters λ and χ describe the details of the excitation process and they are related to the excitation amplitudes by

$$\lambda = \frac{|a_0|^2}{|a_0|^2 + 2|a_1|^2}, \quad \text{Eq. (1.2)}$$

or

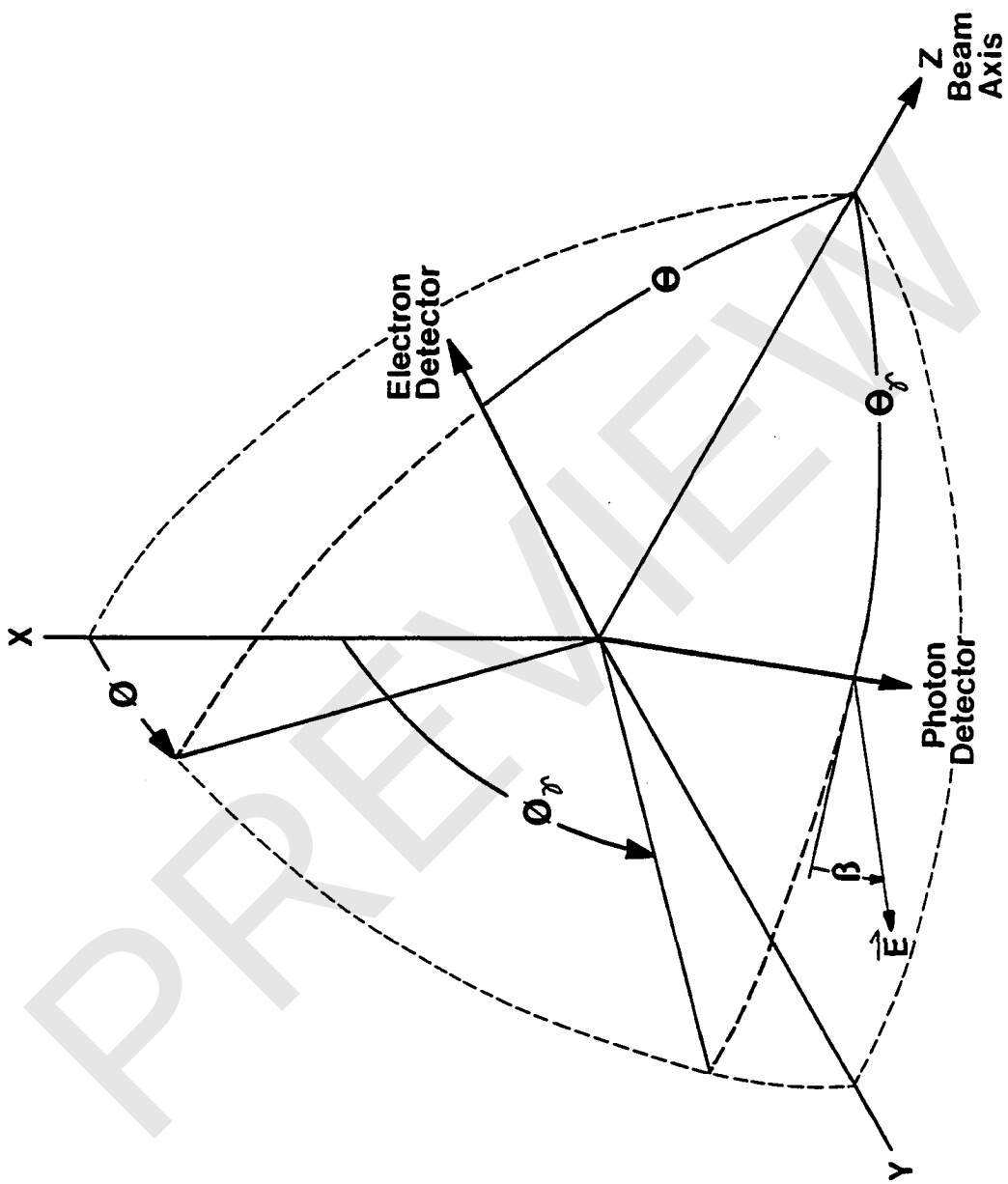

Fig. 1.2