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Study of electron impact excitation of atoms through lasers

Rajesh Srivastava*, Sachin Saxena

Physics Department, Indian Institute of Technology, Roorkee 247667, India

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Abstract

We discuss three different experiments for studying electron-excitation of atoms where lasers have been used in combination. These are stepwise electron–photon excitation, superelastic electron scattering from laser excited atoms and excitation of atoms using spin polarized electrons produced by lasers. We present distorted wave calculations and compare our results with the recently reported such experimental measurements. In particular, the results for the alignment and orientation of the excited $n\,^2P$ states of K ($n=4$) and Rb ($n=5$) atoms and the spin parameters for the lowest excited $^1P_1$ and $^3P_{0,1,2}$ states of argon by polarized electrons are presented and discussed.

Keywords: Electrons; Lasers; Excitation; Atom; Superelastic scattering; Electron spin; Alignment and orientation

1. Introduction

In recent years substantial progress in the study of electron impact excitation of atoms has been made both theoretically and experimentally. This can be attributed to developments in the quality of experimental technology through which one can prepare almost pure initial state of both the projectile and target in any collision process. The knowledge of the techniques to prepare initially an excited state of atom has enabled us to probe its anisotropy. Similarly, the techniques of the production and detection of spin-polarized electrons allow us to explore the spin-dependent forces such as electron exchange and electron spin–orbit interaction (Kessler, 1991). Several new types of atomic physics experiments are currently being performed which provide more detailed information than the traditional cross section measurements (Andersen and Bartschat, 1996). Such experiments have also direct impact on the improvement and development of the theoretical methods. There are number of review articles which give details of the theoretical and experimental work related to the electron-atom scattering (Andersen et al., 1988, 1997). In this paper, we address to some recent experiments and our coupled theoretical calculations for electron impact excitation of atoms where laser has been used in combination to study the process. We discuss here only electron excitation of the P states of some atoms for which measurements have been reported.

A beam of electrons is used to excite the atom from its ground S state to a P state which after the excitation, decays back by photon emission and the emitted photons are detected and analyzed to get the information about the alignment of the excited P state. Unfortunately, electron -impact excitation of the metastable states cannot be investigated by such optical emission measurements that use direct fluorescence, because optical decay is suppressed/forbidden. It is possible, however, to use the *stepwise electron-photon-excitation* method using suitable laser. The wavelength of a laser is tuned to a transition from the metastable state to another upper state, which may then decay via

*Corresponding author. Tel.: +91 1332 270155; fax: +91 1332 273560.
E-mail address: rajsrfph@iitr.ernet.in (R. Srivastava).

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an allowed transition (i.e. laser -induced fluorescence). Such experiment involving stepwise electron-photon excitation has been suggested in the past to study electron-impact excitation of Hg. Using this technique we (Fischer et al., 1999) recently studied Ne atoms, where $2p^6\ ^1S_0$ ground state was excited by electrons to the excited metastable $2p^53s\ ^3P_2$ state which cannot decay back by photons. With laser photons tuned to the $2p^53s\ ^3P_2 \rightarrow 2p^53p\ ^3P_1$ transition (wavelength = 588.2 nm), laser-induced fluorescence of 616.4 nm photons is obtained. The final state ($2p^53s\ ^3P_0$) of this excitation scheme has total angular momentum $J = 0$ and thus the entire information about the alignment of the electron excited state $2p^53s\ ^3P_2$ can be determined when polarized laser light is used and the polarization of the laser induced fluorescence is measured. In this paper (Fischer et al., 1999), we published jointly the experimental measurements of the Munster Group and the relativistic distorted wave calculations from our group and compared both the experimental and theoretical results. Since this work is already published recently we refer reader to this publication for greater details of the theoretical calculation and the experimental measurement as well as their comparison.

Another experimental technique that has been employed recently with considerable success to study the alignment and orientation of the electron impact excited P state is by the *superelastic scattering of electrons*. In this technique, the time reversal arguments are employed to extract the alignment and orientation parameters. For example, for the case of excitation of an atom from its S state to P state, photons are initially directed on to the target from a tunable, polarized, single mode laser beam whose energy is made resonant between the ground S-state and the excited P-state. The target atom absorbs the photon, and is excited coherently to a specific magnetic sub-state of the P state. Following laser excitation the target atom is then subjected to the incident electron beam where electrons are scattered after gaining the energy by de-exciting the atom to a lower state (usually the ground state). Such *superelastically scattered electrons* are then detected and analyzed as a function scattering angles with different state of the laser polarization. By invoking time reversal invariance arguments, atomic alignment and orientation of the excited P state can be deduced from the measurements of the intensity of the super-elastically scattered electrons. In the last couple of years many superelastic scattering experiments have been performed for studying excitation of the P states of the different alkali (Stockman et al., 2001; Hall et al., 2004; Saxena and Srivastava, 2004) and alkaline earth atoms (Murray and Cvejanovoic, 2003; Crowe et al., 2001). In the light of such experiments, in this paper, we present our nonrelativistic distorted wave calculations for the resonance $n\ ^2P$-state excitation of the K ($n = 4$) and Rb ($n = 5$) alkali atoms and compare with the recently reported measurements (Stockman et al., 2001; Hall et al., 2004).

Finally, we describe an experiment where unlike previously described two experiments, the polarized electrons have been utilized to study the electron excitation of atoms. The physics of polarized electrons has been of great fundamental interest for many years (Kessler, 1991; Andersen et al., 1997; Herting et al., 2002, 2003). With the advent of lasers it has become possible to easily prepare a beam of polarized electrons and use it as a probe for studying nature of spin forces. When GaAs photo-cathode is irradiated by circularly polarized laser the polarized electrons are ejected from its surface. These electrons can then be accelerated to the desired impact energy and focussed onto the scattering chamber after suitably deflected by magnetic field. During the recent years, this set-up has been adopted in various electron-atom scattering experiments (Andersen et al., 1997). We discuss here one of such experiments and also report our calculation. On the basis of spin analysis of the scattered electron and using the framework of density matrix formulation Bartschat and Madison (1988) derived seven independent parameters called the generalized STU parameters, which can be measured in such experiments. The experimental determination of the generalized STU parameters requires the knowledge of the incident electron beam spin polarization and the detection of spin polarization of the scattered electrons. In this paper, we give briefly the experimental and theoretical evaluation of only two such spin parameters. We consider the excitation of the lowest lying fine structure P states of Ar from the ground S state by polarized electrons. We obtain theoretical results for the spin parameters using fully relativistic distorted wave theory and compare with the available recent measurements (Dummler et al., 1995; Khakoo et al., 2004).

In Section 2 we briefly describe the theoretical aspects of the superelastic electron scattering experiment and the calculation of the reduced Stokes parameters for the excitation of the unresolved $4\,^2P$ and $5\,^2P$ states of K and Rb atoms, respectively. We also outline our nonrelativistic distorted wave (NRDW) theory used to calculate such results for comparison with the experimental measurements. Section 3 describes the theory of the measurements of the two spin parameters viz. *spin asymmetry* S_A and *spin polarization* function S_P and their relations with the scattering amplitudes of the excitation process initiated by spin polarized electrons. Relativistic distorted wave (RDW) theory used for the calculation of the scattering amplitudes of the excitation of the lowest lying fine-structure resolved P states of argon atom by polarized electrons is also described. Finally in Section 4 we present our various results and their comparison with other theories and recent experiments.