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Interference Effect in the Relativistic Inner Shell Ionization of Atoms by Electron Impact

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Abstract

We present in this paper, the results of our calculation of right-left asymmetry in the relativistic (e, 2e) processes for inner K-shell ionization of atoms. The calculation has been performed in plane wave Born approximation (PWBA) using one photon exchange approximation. The triple differential cross section (TDCS), in plane wave Born approximation (PWBA) can be factorized into products of electron kinematic factors and atomic structure functions [Donnely (1984)]. The right left asymmetry in the relativistic (e, 2e) process on the K-shell of the atoms has been shown to depend on the interference between the transition charge and component of the transition current in the scattering plane. Further, we discuss the dependence of right-left asymmetry on the incident electron energy, atomic number of the target and scattering angle.

Keywords:

(e, 2e) process, TDCS, right-left asymmetry, PWBA

1. Introduction

The ionization of atoms by electron impact is one of the basic processes of atomic physics, with fundamental applications in different areas as astrophysics, plasma physics, fusion physics, surface science etc. The complex interactions involved in electron impact ionization of atoms, is a challenging problem to understand. Fundamentally an (e, 2e) process is one where an electron, of well defined energy and momentum, is incident on a target, ionizes it and the outgoing electrons are detected in coincidence with their energies and angles resolved. Electron-impact ionization is a subtle process of atomic physics, which elucidates different features of the collision dynamics and is also used as a technique to probe target wave functions. The study of ionization process in different geometrical arrangements provides a technique to understand the reaction mechanism better. Through the careful choice of geometrical arrangement and the energies of the incoming and exiting electrons, one can predict the physics which will dominate the shape and magnitude of the triple differential cross section. The calculation of triple differential cross section opens up a whole new area of theoretical study and offers a direct insight into the subtleties of spin-dependence and other purely relativistic effects. Further, the calculation of spin asymmetry in the TDCS of the (e, 2e) processes on atoms enables us to understand the reaction mechanism in terms of spin of atoms.

The study of (e, 2e) processes on atoms by polarized electrons has become a powerful tool to investigate the elementary processes involved in electron impact ionization of atoms. The spin asymmetry (A) provides information about the spin dependence of the TDCS. It is defined as a relative difference between the TDCS for antiparallel and parallel spin combinations of the colliding particles $A = (\sigma\uparrow\downarrow - \sigma\uparrow\uparrow)/(\sigma\uparrow\downarrow + \sigma\uparrow\uparrow)$. Various workers (see Nakel and Whelan [1] and references cited therein) studied the spin asymmetry in (e, 2e) processes for different high Z targets (such as Cu, Ag, Au, U etc.) using transversely polarized electron beam in the relativistic energy regime. Satisfactory studies have been done for the relativistic (e, 2e) processes on atoms using transversely polarized electron beam but very few studies have been done using longitudinal electrons as incident beam. The investigation of *chiral* and *handedness* effects i.e. dichroism, in different collision problems (γ, 2e), (e, 2e) and positronium formation etc with the atomic and molecular targets, holds a particular fascination and is of great importance in understanding the dynamics of the processes. Recently Purohit [2] and Purohit *et al*. [3] have theoretically demonstrated up-down asymmetry in the relativistic (e, 2e) processes for

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the K-shell ionization of atoms. Bhullar and Sud [4] and Sud [5] have theoretically demonstrated spin asymmetry in triple differential K-shell ionization (TDCS) of atoms by longitudinally polarized relativistic electrons in coplanar asymmetric geometry and Sud and Purohit [6] in non-coplanar asymmetric geometry in the relativistic (e, 2e) process for K-shell ionization of Cu, Ag and Au atoms. They have shown that the longitudinal spin asymmetry in (e, 2e) reaction depends on electron impact energy, atomic numbers of the target and scattered electron angle.

In this communication we present the formalism to evaluate the right-left asymmetry in relativistic (e, 2e) process on atom in plane wave Born approximation (PWBA). The continuum electrons are represented by plane waves and the cross section for the (e, 2e) process can be expressed in terms of atomic structure functions, which in turn can be related to bilinear combination of the four-current components in momentum space. Donnelly [7] have given detailed formalism for decomposition of the PWBA cross section into sum of the products of the kinematical factors and structure functions using the fact that the potential generated by the plane waves electron can be separated into so called longitudinal and transverse parts with respect to the momentum transfer direction. It may be mentioned here that the formalism presented in this communication to evaluate the right-left asymmetry in relativistic (e, 2e) process on atoms is in one photon exchange approximation and in the high energy approximation used here, the TDCS for the (e, 2e) process on K-shell of atom is expressible in terms of the atomic structure functions.

2. Theory

We calculate right-left asymmetry by using the triple differential K-shell ionization cross section computed in first Born approximation. We can express the TDCS of the K-shell ionization cross section for the (e, 2e) process on atoms by longitudinally polarized electron beam following Jin et al [8] as

$$\begin{aligned}\frac{\mathrm{d}^3\sigma(\pm)}{\mathrm{d}E_1\mathrm{d}\Omega_1\mathrm{d}\Omega_2} = \frac{P_2E_2}{(2\pi)^3}\sigma_m \\ [V_LW_L + V_TW_T + V_{TT}W_{TT}\cos 2\phi \\ + V_{LT}W_{LT}\cos\phi \pm V_{LT'}W_{LT'}\sin\phi] \qquad (1)\end{aligned}$$

where σ_m, is the well-known Mott cross section; V_L, V_T, V_{TT}, V_{LT} and $V_{LT'}$, are electron kinematic factors and the quantities W_L, W_T, W_{TT}, W_{LT} and $W_{LT'}$ are the longitudinal, transverse, transverse-transverse, longitudinal- transverse and polarized longitudinal-transverse atomic structure functions, respectively whose explicit expressions are given in [9] and for brevity we are not giving these expressions here. P_2 and E_2 are the momentum and energy of the ejected electrons.

We have used Plane wave Born approximation (PWBA) formalism to calculate right-left asymmetry for the inner K-shell ionization of Cu, Ag and Au atoms. We have given the estimates of right-left asymmetry for the first time by using the form of TDCS as described above (see Eq. 1). Our calculation of TDCS using PWBA approximation [9] explains the shape, position and shifting of the binary peak away from the direction of the momentum transfer and gives an overall good agreement with the available experimental data.

We calculate the TDCS (σ^R) for $\phi = \pi$ and the TDCS (σ^L) for $\phi = 0°$ and by taking the difference of the two, we calculate the Right-Left asymmetry for K-shell ionization of atoms. We can express the right-left asymmetry A_{RL} by using equation (1) as

$$A_{RL} = (\sigma^R - \sigma^L) / (\sigma^R + \sigma^L). \qquad (2)$$

We can express right-left asymmetry using equations (1) and (2) as

$$A_{RL} = -V_{LT}W_{LT} / \sigma_{unpol}, \qquad (3)$$

where σ_{unpol} is the TDCS for unpolarized incident electron beam and W_{LT} is the interference between the transition charge and component of the transition current in the scattering plane. The explicit expression for W_{LT} is given as

$$W_{LT} = -\sqrt{2}\mathrm{Re}\,[\,J_0^*J_x^*\,], \qquad (4)$$

where $J^\mu = (J_0, J^\mu)$ is the Fourier transform of the transition current.

3. Results and discussion

We present in this section our estimates of right-left asymmetry in the relativistic (e, 2e) processes using longitudinally polarized electron beam for the first time. We calculate the TDCS (σ^R) of K-shell ionization of (e, 2e) reaction for $\phi = \pi$ and the TDCS (σ^L) for $\phi = 0°$ using equation (3) and by taking the difference of the two, we calculate the right-left asymmetry for Kshell ionization of atoms. We present the results of our calculation of right-left asymmetry for K-shell ionization of Cu, Ag, Au and U atoms at incident electron energy 300 keV and 500 keV for different values of scattering angles (θ_1) in Figs. 1,2,3 and 4 respectively.

The right-left asymmetry is found to be oscillatory and having peaks in the binary and recoil regions for all the targets investigated. The oscillatory structures in the

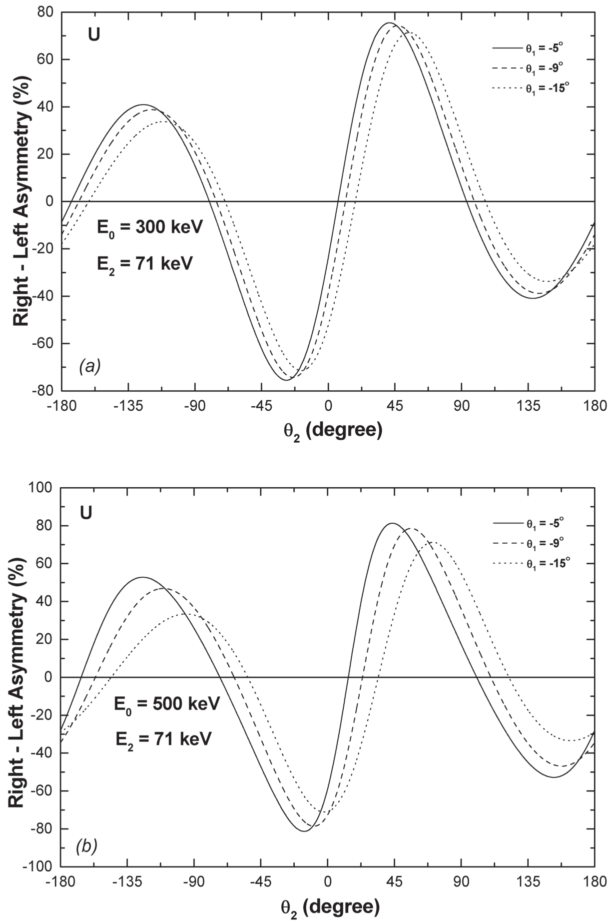

Fig. 1 Right-Left asymmetry for Cu atom as a function of ejected electron angle (θ_2) for kinematical conditions shown in the frame.

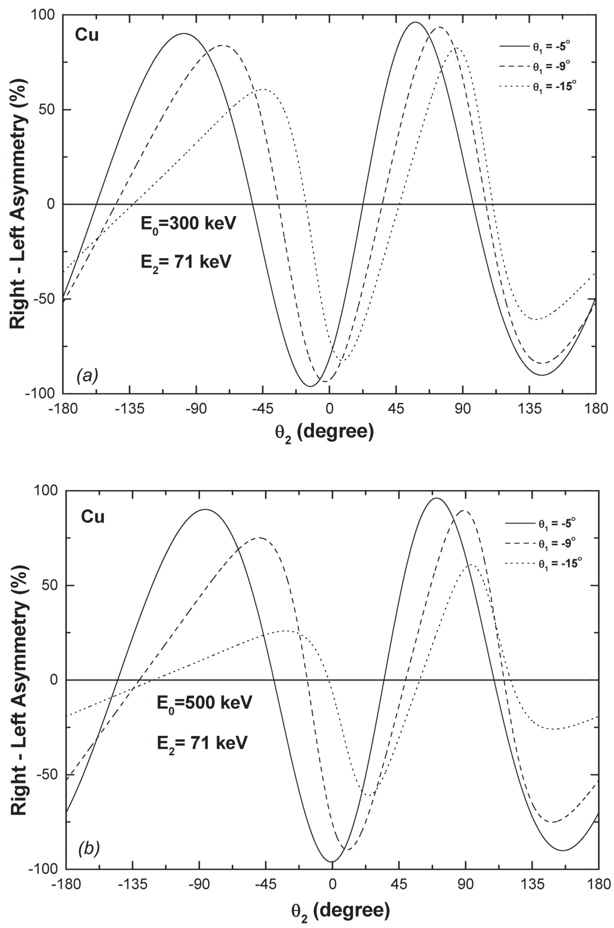

Fig. 2 Same as in Fig. 1 but for Ag atom.

right-left asymmetry shows its dependence on the direction of momentum transfer and direction of recoil momentum, which can be observed by changing the value of scattered electron direction (θ_1). The right-left asymmetry is found to depend on the ejected electron angle θ_2. It is also observed that the right-left asymmetry is zero at certain values of ejected electron angles (θ_2). At these points the TDCS for the process with the ejected electron direction $\phi = 0°$ and $\phi = \pi$ is equal. The position of the each zero depends on the atomic number, energy of the target as well as the electron impact energies. More sophisticated calculation and experiments will help us to understand the spin polarized electron ionization process better. The right-left asymmetry is also found to depend on the electron impact energy and is large for higher scattering angles at lower electron impact energy. The right-left asymmetry has been computed by evaluating the interference term between the transition charge and the component of the transition current in the direction of the scattering plane. Thus, the present investigation of the (e, 2e) process on atoms shows that the observed right-left asymmetry is large, measurable and oscillatory in nature and it depends on incident electron energy, atomic number of the target and scattering angle. Further, our study has shown that the right-left asymmetry studies of the (e, 2e) process on atom provides a tool to probe the interference between the transition charge and component of transition current in the scattering plane. The magnitude of the right-left asymmetry decreases as nuclear charge is increased from Cu to U for both incident electron energies $E_0 = 300\,\text{keV}$ and $500\,\text{keV}$. The magnitude of asymmetry also decreases with the increase of scattering angle at both incident electron energies however the decrement is less as nuclear charge is increased.

There are no experimental data available for right-left asymmetry so we suggest that the experimental measurements of the right-left asymmetry using longitudinally polarized electron beam be undertaken to understand the role and importance of the spin polarized studies in the relativistic (e, 2e) process on K-shell ionization of atoms. So in conclusion, in this paper we have given our first estimates for right left asymmetry in the relativistic (e, 2e) processes and we have shown that the (e, 2e) process on atom in right-left geometry provides a tool to probe the interference between the transition charge and component of transition current in the scat-

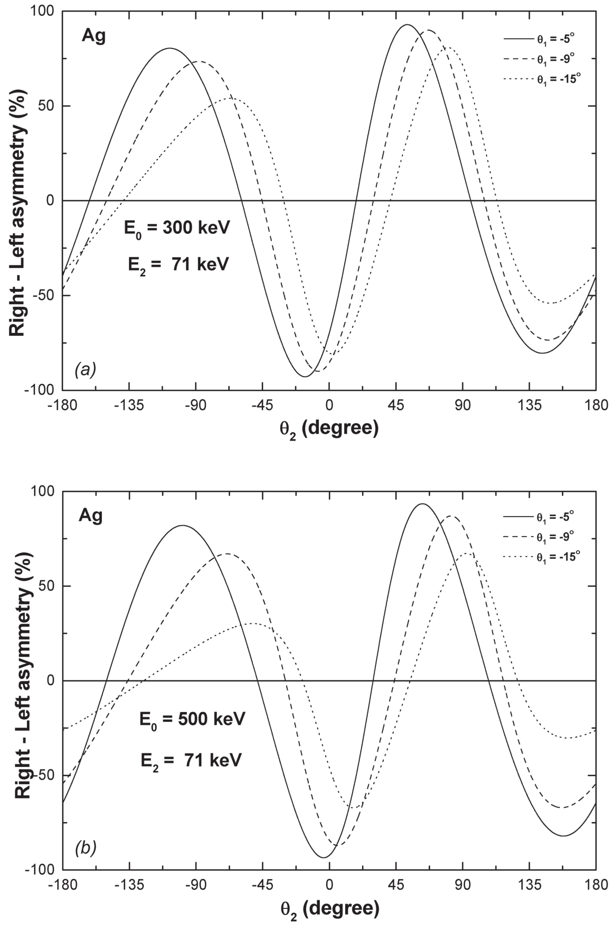

Fig. 3 Same as in Fig. 1 but for Au atom.

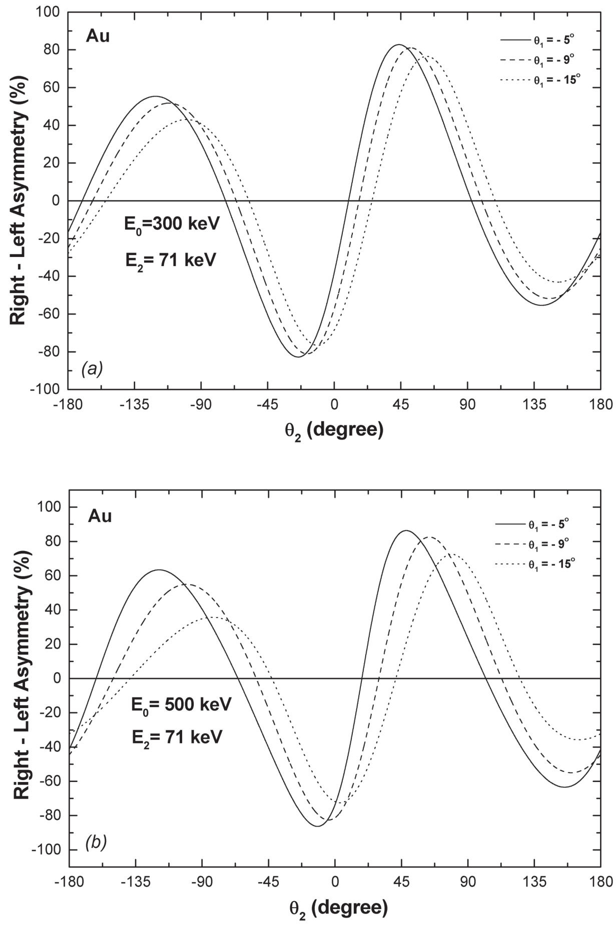

Fig. 4 Same as in Figure 1 but for U atom

tering plane. It would be interesting to have more theoretical and experimental investigations of the right left asymmetry using longitudinally polarized electrons in the relativistic (e, 2e) process as this will help us to understand the process better.

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