Model for the capture of secondary electrons by a fast ion

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A capture process is discussed which is strongly assisted by the relaxation of energetic secondary electrons inside a solid target. The following processes are incorporated into the model (in a simplified form): – the production of secondary electrons by a fast projectile inside the target (in binary encounter approximation of the projectile with free target electrons), – the dynamics of the secondary electrons (in continuously slowing down approximation without elastic scattering), – the reduction of the screening of the projectile charge at the exit surface (in sudden approximation and neglecting the image charge). The capture efficiently populates Rydberg states with high angular momenta and gives high coherences between Rydberg states. The application to convoy electrons gives contributions only to the innermost part of the cusp shaped velocity spectra which is possibly caused by the neglect of elastic scattering of the secondary electrons.

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1. Introduction

A fast projectile, traversing a thick foil undergoes a lot of interactions as e.g. capture and loss of electrons inside the solid. For strongly bound projectile electrons these interactions may be treated in good approximation as for a dense gas target [1]. For highly excited states of the projectile, as Rydberg electrons or convoy electrons, which accompany the projectile after the exit from the target with nearly equal velocity, the formation processes are not fully understood [2, 3] but it is generally agreed that they are formed near the exit surface. This is immediately clear by looking at the time reversed path, where the fragile electronic state is destroyed within the characteristic length \( \lambda_{esc} \) for the scattering of the Rydberg or convoy electron. The cross section for the destruction of convoy electrons and high lying Rydberg states can be approximated [4] by the total scattering cross section for free electrons, which means the escape depth \( \lambda_{esc} \) is approximated by the mean free path \( \lambda_e \) of an electron in the solid.

The theoretical investigation of the formation of the highly excited states suffers from the complexity of the solid, from the difficulty of the collision process itself (even for simple system), and from the fact that the detected states outside the solid are not stationary states inside the bulk.

The last problem is sometimes exaggerated for the case of Rydberg electrons where it is assumed that the formation of the Rydberg state can take place only at the exit layer of the target because the radius of the Rydberg orbit is greater than the lattice spacing. This argument must be modified in two respects: 1) The important parameter for the existence of a stationary excited state around the moving projectile is the dynamical screening length [5] \( \lambda_{esc} = \frac{2 \pi v_p}{\omega_{pl}} \) where \( \omega_{pl} \) is the plasma frequency of the target and \( v_p \) is the velocity of the projectile. 2) For high velocities \( v_p \approx 1 \) (atomic units are used) the considered time of the excited state in the solid is so short that the evolution even of a totally screened projectile electron is dominated by the collision with target particles and not by energy phase factors [6]. Experimental evidence for this is given by the transmission of 800 keV H\(^+\) projectiles through thin carbon foils [7], where a fraction of H\(^-\) survives the passage.

Integrating the capture cross section of Rydberg
states over a larger surface layer \( (2_{\text{esc}}) \) brings theoretical and experimental Rydberg yields closer together [4] but cannot explain the abundance of high angular momenta found in high Rydberg states after foil excitation [8]. This discrepancy can probably not be resolved by a model which relies on only one collision inside the solid. Instead it is expected now [8-10] that the solid target opens up additional interaction channels between Rydberg-, convoy- and secondary electrons.

Indeed, fast projectile target interactions, characteristic for a solid, have only been scarcely investigated e.g.: - capture at the surface, including resonant neutralization and capture and the image potential \([11]\) - resonant excitation during channelling \([12]\) - capture into wake riding states \([13]\) - ionization via excited projectile states \([14]\) - and simultaneous excitation by several target cores \([15]\). Especially for the formation of Rydberg states with high principal quantum number \( n \) and high angular momentum values \( l \) in atomic collisions it has been shown that a higher order process as the 2. Born approximation \((B2)\) is favourable already at much lower velocities than for ground state capture \([16]\). Thus one may expect that a solid with many target atoms in close vicinity to the projectile can accomplish a Thomas-type process as in \(B2\) much more efficiently and can use even higher order processes without decreasing the cross sections to zero. In addition to the elastic scattering at different centers the solid offers the possibilities to effectively reduce the kinetic energy of a fast electron which opens a new way to bridge the velocity mismatch between a fast projectile and a slow target electron. Therefore we investigate a model in which we follow the fate of an energetic electron which has been accelerated in a collision process and may either get. If this electron moves in the forward direction it may become captured when the projectile leaves the surface. So the potential step at the surface but then keeps its velocity and because the slowing down force will in general not be exactly parallel to the momentary radius vector between electron and projectile, large angular momenta of the captured electron are possible.

This model is investigated in Sect. 2, some results for Rydberg capture and convoy electrons are given in Sects. 3 and 4 and some discussion is given in Sect. 5.

2. Model

The projectile with charge \( q_1 \) inside the target is assumed to move with constant velocity \( \mathbf{v}_{p,t} = v_p \mathbf{e}_t (v_p \gg 1) \) along the \( z_t \) axis of the laboratory coordinate system \( x_t, y_t, z_t \) where the subscript \( t \) denotes the laboratory system and the superscript \( t \) denotes normalized vectors. The target fills the halfspace \( z_t < 0 \). The passage of the projectile through the surface is chosen as zero of the time. The projectile path is then given by

\[
\mathbf{r}_{p,t} = \mathbf{v}_{p,t} t, \tag{1}
\]

because the slowing down and scattering of the projectile is neglected. The dynamics of the secondary electrons will be treated classically too, as it is often done in Monte Carlo computation of energetic secondary electrons \([17]\), where only some scattering cross sections are taken from quantum mechanical calculations. In our case also the capture into Rydberg states will be treated classically, which appears tolerable as mainly high quantum numbers \( n, l \) of the final state will be involved \([2, 8, 18]\).

Most of the calculation will be done in the coordinate system centered at the projectile, with axes parallel to \( x_t, y_t, z_t \) and characterized by omission of the subscript \( t \). In this system a steady state distribution \( f(\mathbf{r}, \mathbf{v}) \) of secondary electrons will develop around the projectile as long as the boundaries of the target are not involved and as long as the discrete nature of the solid is neglected. This distribution is caused by the stationary flux \( F(\mathbf{v}_e) \) of secondary electrons emitted by the projectile. The flux emitted into a velocity element \( d^3 \mathbf{v}_e \) around \( \mathbf{v}_e \) may be written as if it is scattered with cross section \( d^3 \sigma / d^3 \mathbf{v} \) from an incoming homogeneous flux \( N_e \mathbf{v}_e \) (and this case we will consider explicitly afterwards):

\[
F(\mathbf{v}_e) d^3 \mathbf{v}_e = N_e v_e \frac{d^3 \sigma}{d^3 \mathbf{v}_e} (\mathbf{v}_e) d^3 \mathbf{v}_e. \tag{2}
\]

The motion of the secondary electron will be considered to be deterministic, but fluctuation could be introduced by averaging the dynamics over different