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# STUDY OF THE CONVOY ELECTRON PRODUCTION FROM SOLIDS WITH HYDROGENIC Ni-IONS*

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We have measured the target thickness dependent convoy electron yields $Y_e$ from hydrogenic $Ni^{27+}$, $Ni^{28+}$ (15.6 MeV/u) which is discussed in the framework of an extended model for ELC and ECC in solids considering also contributions from excited states. To understand the target thickness dependent evolution in the case of incident $Ni^{27+}$ it must be assumed that convoy electrons produced by ELC arise mainly from excited states. The mean transport length $\lambda_c$ for convoy electrons for light projectile ions is equal to the attenuation length of isotachic free electrons $\lambda_e$, whereas for the heavy ions an enhanced transport length $\lambda_c >> \lambda_e$ must be introduced.

The understanding of electron production in ion–atom and ion–solid collisions in general is based on the same conceptions. Differences arise from the high collision rate for ions penetrating a thin solid, whereas in an ion–atom interaction normally single collision conditions are assumed. As a consequence of this high collision rate the population of excited states for ions penetrating solids is shifted towards higher $n$ and $\ell$ states in [1]. This atomic charge cloud around a fast highly charged ion inside the solid can be a source for the formation of electrons in low-energy continuum states, i.e. "convoy" electrons accompanying the projectile just above the ionization threshold with direction and velocity close to those of the ion [1].

To understand the mechanism for the production of convoy electrons induced by heavy projectile ions penetrating solid targets we measured the target thickness

*Dedicated to Academician D. Berényi on his 60th birthday.

dependence of the convoy electron production $Y_e(\rho x)$ and the evolution of the outgoing charge states $F(q_f)$ for hydrogen like $Ni^{27+}$ and $Ni^{28+}$ ions. The resulting equilibrium charge fractions are given in Table I.

**Table I**

Equilibrium charge state fraction $F_\infty(q_f)$ for $Ni^{27+}$ and $Ni^{28+}$ (15.6 MeV/u) on carbon foil

| Outgoing charge $q_f$ | Fraction $F_\infty(q_f)$[%] |
|---|---|
| 28 | 40 |
| 27 | 44 |
| 26 | 12 |
| 25 | $\leq 3$ |

It was attempted to describe the yield $Y_e(\rho x)$ for these heavy hydrogen like ions in the framework of model for ELC (*e*lectron *l*oss to the *c*ontinuum) and ECC (*e*lectron *c*apture to the *c*ontinuum) in solids introduced earlier for the case of light hydrogen projectiles [2] which has later been extended to the case of heavy projectile ions [3].

The essential concept of this model is based on the assumption that convoy electron production is closely related to the charge exchange processes. The number of convoy electrons $Y_{\mathrm{ECC}}(q_f)$ produced by the ECC mechanism and detected in correlation with the outgoing charge state $q_f$ is supposed to be proportional to the number of projectiles $N(q_f)$ with charge $q_f$ (see Eq. (1)). In the same way the number of convoy electrons $Y_{\mathrm{ELC}}(q_f)$ produced by an ELC event is proportional to the number of projectiles $N(q_{f-1})$ with charge $q_{f-1}$. To account for the different probabilities for electron loss from excited and ground states the number of projectiles with one electron has to be divided into the ground state fraction and the number of ions in excited states $N^*(q_{f-1})$. For a complete understanding of the relations between charge exchange and convoy electron production therefore a knowledge of the charge and excited state distribution is necessary.

Beside the terms which describe the production of convoy electrons an additional term accounts for the transport of these electrons through the bulk of the solid. In Eq. (1) this has been included by the exponential factor with the characteristic leghth $\lambda_c$ which describes the inelastic and elastic scattering of convoy electrons by the atoms and electrons of the solid.

$$Y_e(q_f) = \int dx' \exp[(x-x')/\lambda_c] \{ F(q,x')\, \alpha_c\, \sigma_{q,q-1} + \\ + F(q-1,x')\, \alpha_L\, \sigma_{q-1,q} \}. \quad (1)$$

To evaluate the charge exchange cross sections we apply here the model of charge exchange introduced by Allison [4] for gas-targets. When in a first approach the excited state contribution (otherwise associated with $\lambda_{ce}$ [3, 6]) is neglected we can determine values for the single electron loss and capture cross section for the studied collision system (Table II).

**Table II**

Charge changing cross sections for Ni (15.6 MeV/u) incident on solid carbon according to the model of Allison [4]. Also shown are cross sections from [5] for Ni (17.2 MeV/u)

| Cross section [5] ($10^{-19}$cm$^2$/C-atom) | Ni (15.6 MeV/u) | Ni (17.2 MeV/u) |
|---|---|---|
| $\sigma_{28,27}$ | 0.31 | |
| $\sigma_{27,28}$ | 0.28 | 0.082 |
| $\sigma_{27,26}$ | 0.8 | |
| $\sigma_{26,27}$ | 2.9 | 0.074 |

A comparison to the cross section from [5] shows large differences which could have their origin in the different methods of evaluation of the data. The loss cross sections of [5] shown in Table II can only be compared with some care to our results, because there it was intended to determine single electron loss cross sections from ground states under single collision conditions whereas in the present paper the charge evolution model from Allison was used.

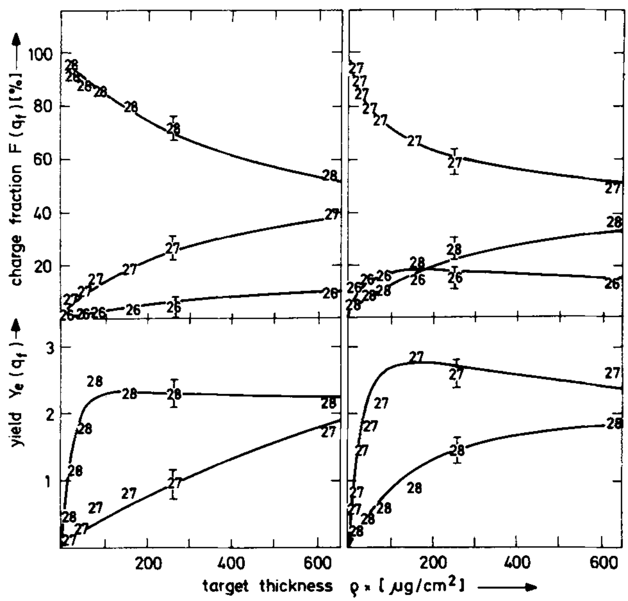


*Fig. 1.* In the top of the target thickness ($\rho x$) dependence of the charge fraction $F(q_f)$ for incoming projectile ions $Ni^{28+}$ (left side) and $Ni^{27+}$ (right side) with energy $E_p = 15.6$ MeV/u is shown. The bottom displays the according convoy electron yield $Y_e(q_f)$, normalized to the sum of projectiles of all charge states, in coincidence with the outgoing projectile ion with charge $q_f$ for incoming charges $Ni^{28+}$ (left side) and $Ni^{27+}$ (right side). The numbers in the figure denote the outgoing charge $q_f$

The fitted charge state evolution $F(q_f)$ was introduced into Eq. (1) and the resulting convoy elctron yield $Y_e(q_i, q_f)$ for different combinations of incident $q_i$ and outgoing charge $q_f$ was determined by fitting $\alpha_L$ and $\alpha_c$ and $\lambda_c$ (see Fig. 1). The result of this procedure is shown in Table III.

**Table III**

Results of the fitting procedure according to Eq. (1). The so-called ECC contribution includes both direct ECC and two step processes as described in the text

| Outgoing charge | Equilibrium contribution | | $\lambda_c$ | $\lambda_{ce}$ |
|---|---|---|---|---|
| $q_f$ | ECC [%] | ELC [%] | [$\mu g/cm^2$] | |
| 28 | 49±8 | 51±8 | 24±5 | 200±20 |
| 27 | 67±14 | 33±14 | 24±5 | – |

The corresponding contribution of ECC and ELC events was determined roughly 50% for each case in the equilibrium of the convoy electron production (Table III). Electrons which are captured into highly excited states and immediately lost into the continuum are also accounted as ECC events. From our measurement this contribution cannot be distinguished from direct ECC events [6].

To give a consistent description of the evolution of the convoy electron yield these parameters must also fit the case of $Y_e$ ($q_i = 27$, $q_f = 28$), because in the equilibrium region the origin of the convoy electrons should be the same. But straightfoward usage of these parameters fails in describing the data. A detailed analysis of the yield $Y_e(\rho x)$ according to this model leads to a consistent description of the $\rho x$ dependence of the yield $Y_e$ when the influence of the excited states is considered [6]. Also the mean transport length $\lambda_c$ for these electrons through the bulk of the solid was found to be enhanced, compared with the value for the isotachic free electrons $\lambda_e$. In a recent paper Burgdörfer [7] showed that the close correlation between an electron and a highly charged ion can persist for path length much longer than a typical mean free path for free electrons. From our measurements we interpreted the specific increase in the convoy electron yield $Y_e$ ($q_i = 28$, $q_f = 28$) as a hint for the existence of the Coulomb focussing effect. One important argument is that in the present work also the evolution of the charge- and excited states were considered to describe the evolution of the convoy electron yield. From the derived cross sections given in Tables II and III no information can be obtained that only these processes can give a satisfactory explanation for the observed evolution of the convoy electron yield.

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