Invited Survey

CENBG 9012

4th WORKSHOP ON HIGH-ENERGY ION-ATOM COLLISION PROCESSES - DEBRECEN, 17-19 September 1990

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ABSTRACT

The interaction of moving ions with single crystals is very sensitive to the orientation of the incident beam with respect to the crystalline directions of the target. The experiments show that high energy heavy ion channeling deeply modifies the slowing down and charge exchange processes. In this review, we describe the opportunity offered by channeling conditions to study the charge exchange processes. Some aspects of the charge exchange processes with high energy channeled heavy ions are selected from the extensive literature published over the past few years on this subject. Special attention is given to the work performed at the GANIL facility on the study of Radiative Electron Capture (REC), Electron Impact Ionisation (EII), and convoy electron emission. Finally we emphasize the interest of studying resonant charge exchange processes such as Resonant Coherent Excitation (RCE), Resonant Transfer and Excitation (RTE) or Dielectronic Recombination (DR) and the recently proposed Nuclear Excitation by Electron Capture (NEEC).

I - INTRODUCTION

Channeling phenomena have been extensively studied in the last twenty five years and have shown to be very helpful for the more general study of ion-matter interaction. However, most of experimental studies have been performed with light projectiles. Channeling investigations with heavy ions have been mainly performed with moderately heavy ions at Tandem energies, particularly by the Oak Ridge group in successful experiments [1]. It can be expected that channeling studies of very fast heavy ions, then in high charge states, will reveal specific aspects of their interaction with matter.

The recent availability of high energy heavy ion beams at GANIL (Caen), BEVALAC (Berkeley), GSI-Darmstadt (UNILAC and SIS) makes it possible to undertake such studies. The feasibility of such experiments has been first demonstrated at GANIL, where $Ar^{(16+)}$ ions of 60 MeV/u have been channeled in a 100 μm thick Ge crystal [2]. This experiment has shown that it is possible to study new aspects of charge exchange processes when high energy heavy ions interact with solids. As a matte of fact, when a swift ion beam passes through a solid target its charge state is continuously changed due to successive electron capture, loss or excitation events. Channeling conditions constrain the incident ions to interact mainly with valence and/or conduction electrons. In this case the interaction of fast heavy ions with solid is strongly modified. Particularly the charge exchange process is found to be completely different from what it is in random conditions or in an amorphous medium.

After a short description of heavy ion channeling we describe channeling effects on:

- the emerging ion charge state distribution for low charge state and high charge state of the incoming ion beam
- electron capture and particularly Radiative Electron Capture (REC)
- electron Impact Ionisation (EII)
- convoy electron production.

At the end we present two resonant processes that allow to capture quasi-free electrons, the Resonant Dielectronic Capture [3], [4] and the recently proposed Nuclear Excitation by Electron Capture (NEEC) [5]. We describe also a resonant excitation effect, the coherent excitation of channeled ions (the so called Okorokov effect), specific of the channeling geometry.

II - ENERGETIC HEAVY-ION CHANNELING IN BRIEF

Channeling of positive ions in a crystal occurs when the direction of the incident beam is close to a planar or axial direction of the crystal [6], [7]. In perfect axial alignement for example, the ions entering the crystal with an impact parameter to an atomic row, p, larger than the thermal vibration amplitude, are repelled by the atomic row as a whole and can be considered as submitted to a continuum potential V(p) which is the periodic ion-atom potential averaged along the axial direction. A complete discription of axial channeling must take more than one atomic string into account. In figure 1 we show the maps in a Silicon crystal of the electron density averaged along the $< 110 >$ direction (a), and of the continuum potential for a single charged projectile (b). The electron density has been calculated by means of the electron wave functions in solid silicon, and the potential deduced from the electron density. The entrance conditions, incidence angle to the axis direction and impact location, define what is called the transverse energy of the incident projectile, that can be considered to be constant, at first approximation, during the passage through a thin crystal. The value of the transverse energy determines the closest distance of approach to the atomic rows. The best channeled particles have the smallest transverse energy and then are maintained quite far from the atomic rows. In particular some particles have such a small transverse energy that they are trapped between the same set of atomic strings all along their pathlength. They are said to be hyperchanneled.

An example of very good channeling conditions is given in figure 2. This figure shows the orientation dependences of the Xe Ly$_\alpha$ yield (resulting from Xe K-shell excitation in close collisions with Si atoms) and of the Xe^{37+} fraction in the transmitted beam when 27 MeV/u Xe^{35+} ions are aligned along the < 110 > direction of thin crystal. Whereas the Xe Ly$_\alpha$ yield presents an ordinary channeling dip, the Xe^{37+} component presents a sharp peak, which spectacularly shows that only the very best channeled ions, i.e. those with a very small transverse energy, are able to lose only two electrons during the traversal of the crystal (instead of about ten for most of the channeled ions).

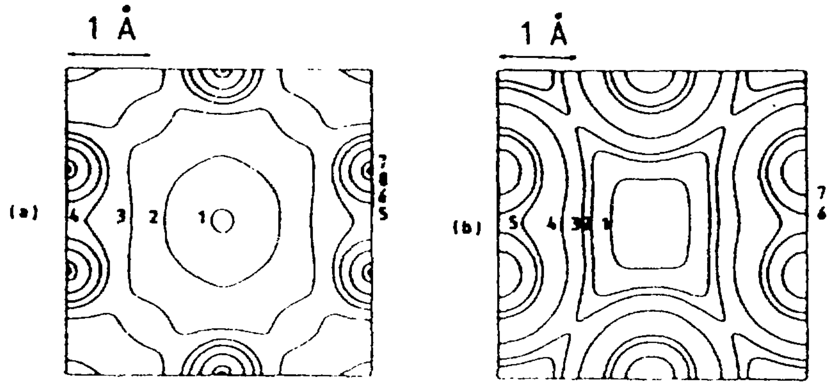

Figure 1 : (a) Map of the electron density in a silicon crystal, averaged along the < 110 > *direction. Contour line 1 to 8 : 0.032, 0.1, 0.24, 0.5, 1, 3, 10 and 30 (electrons per* Å^3*) (b) Map of the continuum potential for a unit charge along the* < 110 > *direction of Si. Contour line 1 to 7 : 0.5, 1.5, 2.25, 5, 15, 21, 50(eV) (from Ref. [20])*

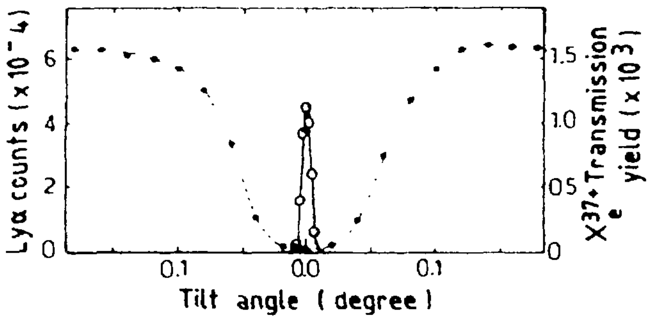

Figure 2 : Angular scans across the [110]-axis. Full circles: Xe Lyman α photon yield. Open circles: fraction of emerging Xe^{37+}*. The solid line through the open circles is the result of a Monte Carlo simulation (from Ref. [20]).*

III - EXPERIMENTAL SET-UP

A typical experimental set up, for the study of charge exchange processes in channeling conditions, is essentially constituted by :

- a beam monitor for dose determination
- a very good single crystal placed in a high resolution goniometer
- one (or several) X ray detector viewing the crystal
- an electron spectrometer

- a charge state analyser placed after the target chamber for measurements of the charge state distribution and energy loss of emergent ions, associated with a wire chamber or position sensitive detector

- a microchannel plate (or channeltron) or a position sensitive detector for single (or multiple [8]) coincidence measurements between X ray/or electron emitted at 0° and transmitted ions of a given (or various) charge state.

And finally a high quality incident beam of the appropriate charge state with very low energy and angular dispersion.

IV - CHARGE STATE DISTRIBUTIONS

It is well known, for random orientation of the crystal, that electron loss and capture leads into an equilibrium charge state distribution of the emerging beam if the target is thick enough. This distribution depends on the nature and velocity of the ion but is independent of the initial charge state.

In channeling conditions the situation is very different. That effect was observed, for the first time, by the Oak Ridge group [1] in the study of the emerging charge state distribution of oxygen ions, at Tandem energies (4.45 to 40 MeV) in a gold crystal. An example of their results [1], [16] is reported in figure 3.

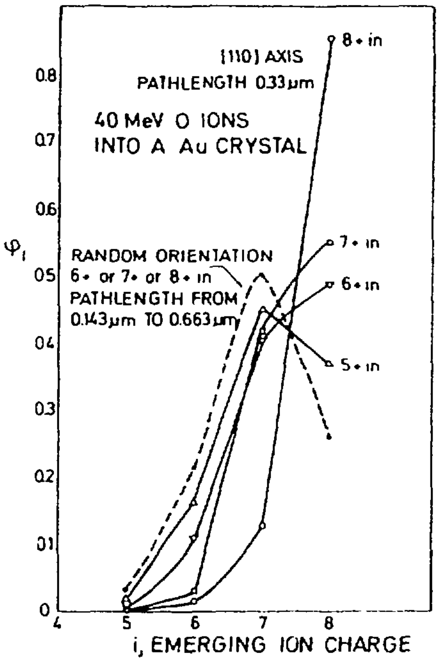

Figure 3 : Emergent charge state distributions obtained for random and [110] channeled oxygen ions with an input energy of 40 MeV. Input charges and pathlengths indicated. (from ref. [1])

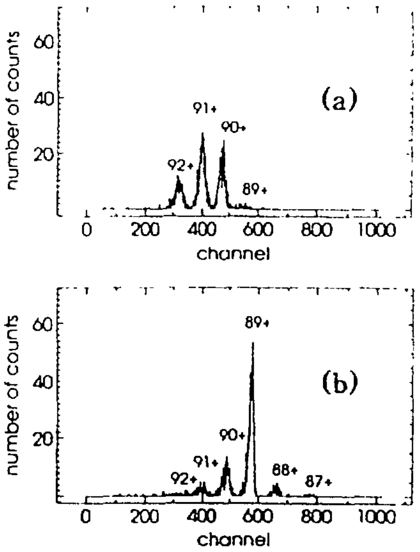

Figure 4 : Observed charge state distributions from 405 MeV/u U^{89+} exiting the 0.37 mm thick Si single crystal. (a) The ions pass through a random direction of the crystal. (b) The ions are aligned with the < 110 > axis of the crystal (from ref. [17])

This work has been extended by the GANIL group for 25 MeV/u and 44 MeV/u Xenon ions with different incoming charge states channeled in a Si crystal, and also by Claytor et al [17] at BEVALAC for 405 MeV/u Uranium ions channeled in a Si crystal (cf. figure 4).

The emerging charge-state distribution extracted from works performed recently at GANIL [9, 10, 18] are reported in figure 5 : 27 MeV/u Xe^{35+} incident ions (a), 25 MeV/u Xe^{50+} to Xe^{54+} incident ions (b) and 44 MeV/u Xe^{54+} incident ions (c) in random conditions and for < 110 > alignment after a pathlength of 21 μm through a Si crystal.

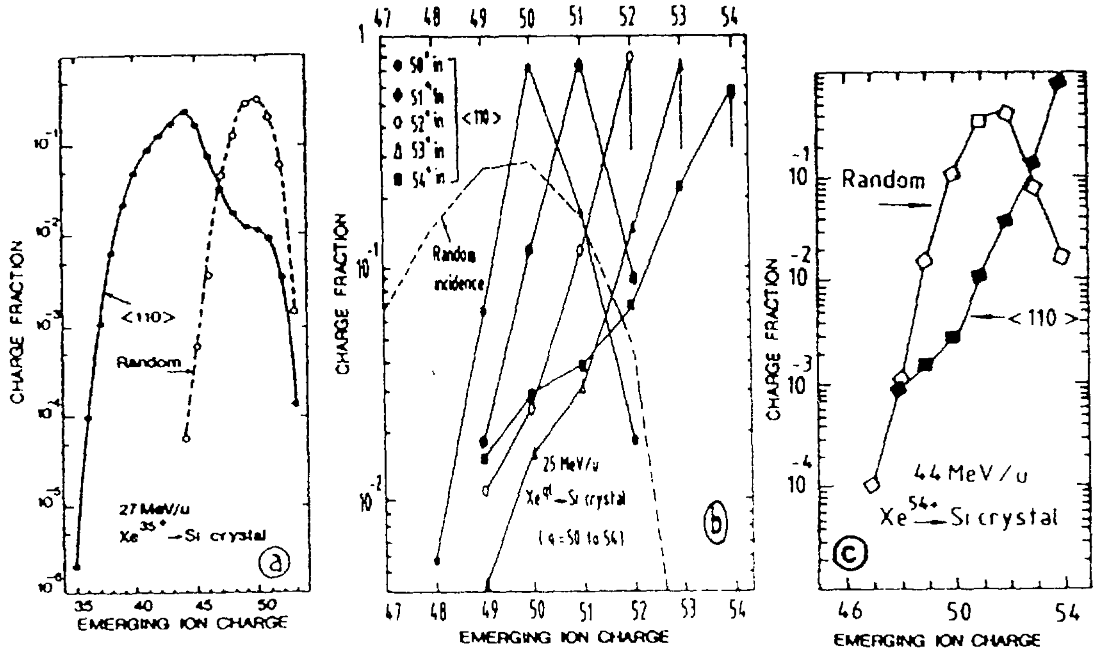

Figure 5 : Charge state distributions after the passage of incident (a) 27 MeV/u Xe^{35+} *(b), 25 MeV/u* Xe^{q+} *(q = 50 to 54) (c), 44 MeV/u* Xe^{54+} *ions through a 21* μm *Si crystal in random and in < 110 > alignment conditions, respectively*

For incoming Xe^{35+} ions (figure 5a) the distribution obtained in axial alignment extends from q = 35 to q = 53 which reveals a large dispersion in the charge changing process of aligned projectiles. As it will be confirmed by the analysis of energy losses, this broad distribution results from the transverse energy distribution of the aligned particles. It is clear in particular that the small fraction of ions which have kept their initial charge state are the best channeled ones, with a very small transverse energy, that have travelled through regions of very low electron density. The only part of the distribution that is charge equilibrated is the highest charge side, which contains the unchanneled component (~ 2 %) of the beam.

For the incoming highly stripped Xe ions (q = 50 to 54) represented in figure 5b, the charge distributions obtained for random incidence of the various charge states are nearly identical and this distribution is equilibrated around the mean value 49.5 (the same value is also found for 27 MeV/u incident Xe^{35+}). On the contrary the distributions obtained for axial alignment are quite different from each other and then quite far from being equilibrated.

They exhibit the same essential feature, which is the "freezing" of the incident charge state : in the five cases, 60 to 85 % of the incident ions have kept their initial charge state. Moreover the detailed observation of the energy distribution of the transmitted ions shows that "frozen" ions were channeled in the crystal, as revealed by their reduced energy loss.

The distributions obtained with 52^+ and 53^+ incident ions (figure 5b), i.e He-like and H-like species, show that these two species cannot lose their K-shell electron(s) if they are channeled, which is easily understood since collisions with quasi-free target electrons, the only collisions allowed to channeled particles, cannot transfer enough energy to ionize K electrons. In both cases a fraction of the incident ions have been able to capture one electron, and again the energy distribution of these ions shows that most of them are well channeled. The simultaneous measurements of the charge state distribution and X ray emission show that the capture process which is involved here is Radiative Electron Capture (REC) [9] (cf. below).

The channeling charge state distributions obtained with 50^+ and 51^+ incident ions (figure 5b) are different from the previous ones because the loss of L-shell electrons becomes possible for these channeled ions. The electron loss probability is of course higher for 50^+ ions than for 51^+ ions. They also may capture electrons by means of REC. The capture probability is seen on figure 5b to be higher for 51^+ ions than for 50^+ ions. Even though these two charge distributions are not equilibrated, the balance between electron loss and electron capture for each of the two incident species indicates that the mean charge state of the equilibrated distribution for channeled ions would be about 50.5, since a mean charge state at equilibrium corresponds to the charge state for which electron loss and capture have the same probability to occur. These results are explained in details by Poizat et al [18]. We comment only here the still unpublished results for 44 MeV/u reported in figure 5c. For incident Xe^{54+}, 95 % of the ions are in a "frozen" state, this result can be compared with the result obtained for the same incident charge state at 25 MeV/u where only 60 % are "frozen" (figure 5b). For that channeled ions the capture process involved is also Radiative Electron Capture and REC cross sections are proportional to v^{-5}, where v is the projectile velocity.

V - RADIATIVE ELECTRON CAPTURE

Two mechanisms are usually responsible for charge tranfer in the interaction between swift ions and solid targets : Mechanical Electron Capture (MEC) and Radiative Electron Capture (REC).

The MEC process is radiationless : three particles (the projectile, the captured electron and the target-core) share out the initial energy [8], [11]. In the REC process, the electron-projectile dipole allows the emission of a photon which takes away the excess energy and momentum [12], [13]. MEC is dominant for impact parameters of the order of the radius of the initial electronic orbital in the target atom. On the other hand a much larger range of impact parameters contributes to REC [14]. And for relativistic ions in low-atomic number targets, REC has been shown to be the dominant process for charge transfer [15].

When ions are channeled through single crystals the MEC process is strongly inhibited and a detailed study of REC is possible. The first experiment designed for the study of REC using channeling conditions was performed at Oak Ridge [16] using medium heavy ions at Tandem energies. A sample of these results for 27.78 MeV 0^{7+} ions channeled along the < 110 > axis of an Ag single crystal is reported in figure 6.

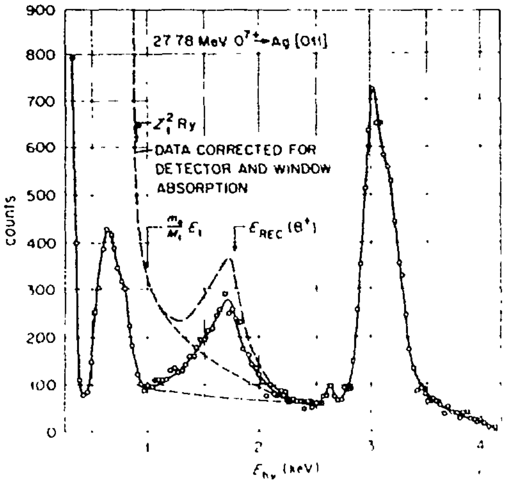

Figure 6 : Measured and absorption corrected photon spectrum resulting from 27.78 MeV 0^{7+} ions transmitted parallel to the [011] axial channels of a thin Ag single crystal (from ref. [16])

This work has been extended at GANIL for higher energies and for heavier ions [9]. Using 25 MeV/u Xe ions (with incident charges 52^+, 53^+, 54^+) in a Silicon crystal we have shown that channeling measurements with fast stripped heavy ions incident on thin crystals allow not only an observation of REC into K, L and M shells but also a detailed study of the process.

The study of X-ray spectra obtained with the three incident charge states of the Xe ions have been published in references [9] and [10].

An example is presented in figure 7, where is shown the X-ray spectra obtained from the interaction between 25 MeV/u Xe^{53+} ions and a Silicon crystal. The photons are detected by a solid state Ge detector viewing the crystal. Two spectra are given in figure 7a, for random and < 110 > incidence, respectively and for the same number of incident ions. Three peaks corresponding to K, L and M-REC respectively have been observed. They are located at energy : $E^i_{REC} \simeq E^i_B + (m/M)E_o$ where E^i_B is the electron binding energy in shell i(= K, L, M) after capture, m and M are the electron and projectiles masses, respectively, and E_0 the Kinetic energy of the projectile.

The L and M-REC intensities are observed to be about the same in channeling and in random conditions although they appear more clearly in the channeling spectrum as a result of the decrease of bremsstrahlung in channeling conditions. On the other hand, in random conditions, the K-REC contribution is small because the first capture that fills the (single) K hole is most often a non radiative event, and also because, at equilibrium the K-shell is almost always filled. For < 110 > alignment, the K-REC intensity is markedly larger, due to the fact that most of the incident 53^+ ions are "frozen" and a target electron capture into their K-shell is possible.

In brief the use of channeled swift heavy ions permit a fine study of REC. The cross sections can be measured [9], the line shapes appear very clearly and can be analyzed in great detail. As it can be seen in figure 7a, the REC lines are wider than Lyman lines, and this is due to the fact that the target electrons captured by the REC process are not at rest, but have a momentum distribution, usually called the Compton profile. The study of orientation dependence around the target axial direction permit to measure this effect with good precision.

The first measurement has been published in reference [9] where is shown the increase of the K-REC line width as a function of the tilt angle around the Si < 110 > direction. The particles with very low transverse energy can only capture valence electrons, since these electrons have small momenta the line associated to this process is small. When increasing the tilt angle, the transverse energy of the particles increases and the capture of L shell target electrons (with much higher momenta) becomes more and more probable leading to broader line widths.

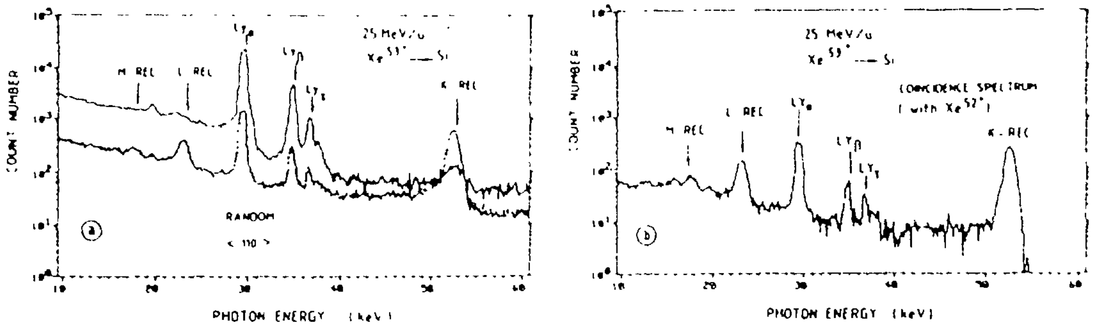

Figure 7: X-ray spectrum for 25 MeV/u Xe^{53+} *incident ions a) for* < 110 > *axial alignment and random orientation b) for* < 110 > *alignment, in coincidence with* 52^+ *well channeled ions (from ref. [18])*

In order to clean up the X-ray spectrum and to isolate the photon emission due to the channeled ions, coincidence measurements with Xe^{53+} incident ions have been performed. The X-ray spectrum of figure 7b is made of photons detected in coincidence with the part of the transmitted Xe^{52+} ions which have suffered low energy loss, i.e. with the well channeled ions that have captured one electron. When compared to the spectrum of figure 7a obtained simultaneously without coincidence, the REC lines of these spectrum are narrower and less asymmetric (the width of the K-REC line is 1.05 keV), which is due to the narrower Compton profile of target electrons that can be captured by well channeled ions. The Lyman lines are here entirely due to deexcitation after radiative capture into excited states. In particular the L-REC and Ly_α peaks correspond to the same process and the difference of the peak areas probably shows that the angular distributions of L-REC and Ly_α emissions are different.

VI - ELECTRON IMPACT IONIZATION

An other interesting feature given by energetic heavy ions channeled in a single crystal is the study of Electron Impact Ionization (EII). For well channeled ions the only available mechanisms for charge exchange are Radiative Electron Capture and Electron Impact Ionization induced by close collisions with target electrons. In the case of ions entering the crystal with a charge state much lower than the mean charge at equilibrum, REC cross sections are vanishingly small with respect to EII. Then the latter can be examined in detail and EII cross sections can be deduced from the experimental charge-state distribution recorded in channeling conditions through a thin crystal.

The first measurement has been performed by Claytor et al [17] at Lawrence Berkeley Laboratory BEVALAC, with 405-MeV/u Uranium ions channeled along the < 110 > axis of 0.11 and 0.37 mm Si crystals. In the rest frame of the Uranium ions, the target electrons have an energy of 222 keV, whereas the binding energy of H-like Uranium electrons is about 133 keV. Then 1s to $2s^2$ electrons of U^{91+} to U^{88+} ions can be ionized. The electron density along the path of the channeled ions has been measured by comparing the cross sections for electron capture by the channeled ions with the capture cross sections for ions in random directions. The least-squares fit of the charge state yields versus target thickness was used to determine EII cross sections for Be-like to H-like Uranium ions by 222 keV electrons. The results are compared with avalaible theories (references cited in ref. [17]). For K-shell electrons of U^{90+} and U^{92+} ions a large difference is found between EII theories and the experimental results. And for L-shell of the U^{88+} and U^{89+} Claytor et al conclude that their results are not accurate enough to distinguish between the various calculations.

Another study of EII has been performed at GANIL [19] at lower energies and ion charge state. A beam of 27 MeV/u Xe^{35+} ions has been channeled along the < 110 > axis of a Si crystal (17 μm pathlength). In this case the kinetic energy of Si valence electrons in the rest frame of the ion is equal to 14.7 keV. The binding energies of the 2p electrons and all M-shell electrons of these $19e^-$-Xenon ions are such that ionization by 14.7 keV electrons is possible. The electron loss cross sections for collisions with target electrons have been extracted from the emerging channeled charge state distribution (as reported in figure 5a). This charge state distribution in the [110] geometry has been fitted using a Monte Carlo simulation. This method is explained in detail by L'Hoir et al [20].The result is reported in figure 8. The Donets's results obtained by Electron Beam Ionization Method (EBIM) [21] are also reported in this figure. Experimental results are compared with predictions of the Lotz empirical formula [22]. The figure 8 shows that cross sections obtained by the channeling method are 2 to 4 times larger than predicted [22] and 1 to 2 times greater than those measured by Donets. This difference is probably due to the fact that in the crossed-beams experiment of reference [21] the electron flux is obviously too low to induce multistep ionization ; on the contrary, in the channeling method indirect ionization, via excitation, is not negligible.

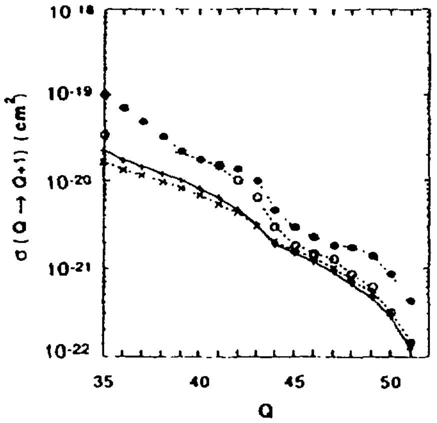

Figure 8: Electron Impact Ionization cross sections $\sigma(Q \to Q+1)$*of* Xe^{Q+} *(*$35 \leq Q \leq 51$*) by 14.7 keV electrons. Full circles : results from ref. [20]; open circles : results from Donets [21]; solid curves : calculation from the Lotz formula [22]; dotted curve : calculation from the Thomson formula (see text in ref. [20])*

VII - CONVOY ELECTRON PRODUCTION

In the foregoing paragraphs the different aspects of electron capture and loss processes under channeling conditions have been discussed. The methods at disposal to study this phenomena are the measurements of the charge state distributions and the measurement of photons arising from the decay of excited projectile ion states. These methods give access to the behaviour of the manifold of bound states in the projectile ion system, and for the study of primary bremsstrahlung one can also learn about free-free transitions in the continuum [23].

A piece of complementary information in the energy region close to the ionization threshold can be provided by the study of the induced electron emission in these ion-solid interactions.

In the corresponding electron spectrum these electrons, arising from various production processes, are emitted along the beam direction. In the electron velocity spectrum these "convoy electrons" form a cusp shaped peak with a maximum located at the projectile velocity $\vec{v}_e = \vec{v}_p$.

Recent experimental works have shown the close relation between charge exchange and convoy electron production in solids [24]. It has been found also that the two possible processes for convoy electron production in the case of nearly bare ions, the electron loss to the continuum (ELC) and the electron capture to the continuum (ECC) are important. The first observation of convoy electrons in channeling condition is due to the Oak Ridge group [25], with 2.4 MeV/u oxygen ions channeled along the $< 110 >$ and $< 100 >$ axis of a gold crystal. Similar study have been performed very recently at GANIL with Xe^{q+} (q = 37, 44 and 54) ions at two energies 27 and 44 MeV/u. The forward electron emission was observed with a magnetic sector spectrometer [26]. In figure 9 is shown the velocity spectrum of electrons emitted at 0° when 27 MeV/u Xe^{37+} ions are incident on a non-orientated Si crystal. The convoy electron peak, located at $v_e = v_p = 32.8$ a.u., is on a large background. The origin of these broad electron distribution is the direct ionization of target atoms and the inelastically scattered binary encounter electrons. The spectrum under channeling conditions is also shown in figure 9. The main difference consists in the dramatically changed yield of convoy electrons (a factor 13 less than in the random case), whereas the yield for the binary encounter electrons varies only by a factor of 3.2. For the incident projectile ion Xe^{54+} (44 MeV/u) in figure 10 are shown the electron spectra for aligned and nonaligned situations. Under random incidence the convoy electron peak is clearly observed and it disappears under channeling conditions. This result is not surprising because under channeling condition the charge state of the incoming Xe^{54+} ions is "frozen" (95 %). The only process available for convoy electron production is the radiative electron capture into the continuum or target electron ionization. This figure shows clearly that cross sections for these two processes is very small for 44 MeV/u Xe^{54+} ions channeled in the crystal.

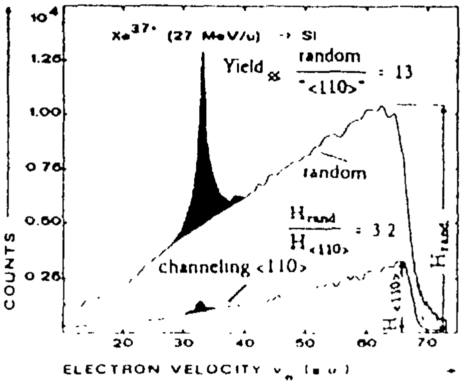

Figure 9: Forward electron spectra obtained with 27 MeV/u Xe^{37+} ions incident on a Silicon crystal (< 110 > axial alignment and random orientation)

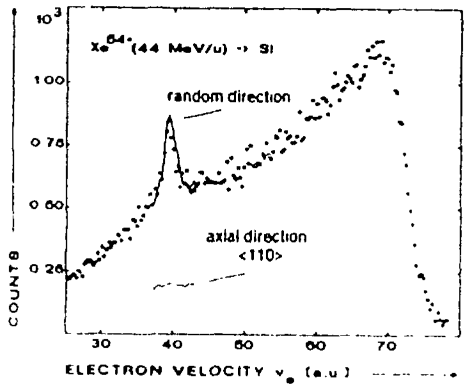

Figure 10: Forward electron spectra obtained with 44 MeV/u Xe^{54+} ions incident on Silicon crystal (< 110 > axial alignment and random orientation)

VIII - RESONANCE PHENOMENA IN CHARGE EXCHANGE PROCESS

In the foregoing paragraphs we have only described non resonant phenomena in charge exchange processes, when energetic heavy ions (Xe and U ions of energy larger than 25 MeV/u) are channeled in a single crystal. It is of course of interest to study resonant phenomena but for that measurement it is necessarly to scan the incident beam energy without changing the optical quality of the beam. Such experiments will be probably possible at GSI - Darmstadt [27] and GANIL - Caen. Of particular interest are the studies of Resonant Transfer and Excitation (RTE) and Resonant Coherent Excitation (RCE) with high energy and high charge state incident ions. Simultaneous electron transfer and excitation of the projectile electron is possible when highly stripped ions collide on atom. This effect can be observed using a multiple coincidence method between emitted projectile X ray and various emerging charge state [8]. For nearly bare nucleus the radiationless electron capture process is accompanied by the excitation of a projectile inner shell electron and the requirement of energy and momentum conservation is only satisfied at a "resonant" projectile energy [28], [29]. This process is called Dielectronic Recombination (DR) if the electron captured is free and Resonant Transfer and Excitation (RTE) if the electron captured is bound. At Tandem energies, two experiments have been performed very recently by Datz et al [3] and Belkacem et al [4] for the studies of resonance phenomena in the simultaneus electron transfer and excitation of the projectile electron in channeling condition.

Using a 25 MV Tandem accelerator at ORNL Datz et al [3] have observed dielectronic and direct excitation of H-like S^{15+} and Ca^{19+} and He-like Ti^{20+} ions channeled along the $< 110 >$ axis of a 1.2-μm thick silicon crystal. The same study has been investigated by Belkacem et al [4] at the Argonne Tandem-Linac Accelerator System (ATLAS). Li-like Ti^{19+} and He-like Ti^{20+} having energies between 267 and 320 MeV have been channeled in a thin gold crystal. High-resolution measurements of the energy losses allowed Belkacem et al to show that the measured resonance peak widths for well channeled ions are more than an order of magnitude narrower than any previously observed RTE resonance with hydrogen targets. This result is surprising as it shows that the mean energy of the captured conduction electrons is much lower than one would resonnably expect. Another surprising feature in reference [4] is the large shift in energy between the observed resonance and the predictions. Such a shift can only be interpreted by assuming a very important screening effect of the target electrons on the projectile nucleus.

We present in figure 11, in the projectile rest frame the energy diagram corresponding to the two capture processes that we have already discussed.

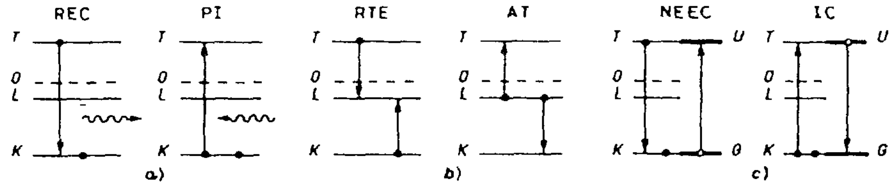

Figure 11 : The processes of target electron capture by a swiftly moving hidrogenic heavy ion (viewed from its rest frame) and their corresponding inverses: T refers to the target electron state, K, L and O to the projectile's atomic orbitals (with O designating the continuum) in the atomic system, while U and G refer to the excited and ground states, respectively, in the nuclear system (from ref. [5]).

One clearly sees that REC is simply the reverse of photo ionization (PI) and that RTE is the reverse of the Auger Transition (AT). We also show in figure 11 the diagram corresponding to another, recently proposed [5], and still never observed, resonant capture process, namely the Nuclear Excitation by Electron Capture (NEEC) which is reverse of Internal Conversion (IC). In RTE the capture leads to excitation of an atomic level while in NEEC a nuclear level is excited. Of course the corresponding cross section is expected to be much smaller than for RTE.

Another resonant process interesting to study with energetic and heavy ion is the Resonant Coherent Excitation (RCE). Channeled ions moving with velocity v along atomic rows experience a coherent periodic perturbation at the string frequency (ν = K(v/d), K = 1, 2, 3,..., where d is the distance between the atoms in the rows). When one of these frequencies coincides with $\nu_r = \Delta E_{ij}/h$, where ΔE_{ij} is the difference between atomic or nuclear states of the ion, a resonant coherent excitation might occur. This effect have been observed for the first time by the Oak Ridge group [30] [31]. Then an important work has been performed with low Z_1 projectiles at Tandem energies. Only resonances corresponding to transitions between n = 1 to n = 2 (or sometimes n = 3), have been observed. The extension of this measurement to high Z_1 ions at higher energies would allow not only to observe the first harmonics of RCE but also stronger resonance effects and resonances for transitions to levels higher than n = 3 [32].

In conclusion we have described here some aspects of charge exchange processes for high energy heavy ions channeled in single crystals. Here it is shown that using high energy heavy ions not only can yield quite novel and detailed information on channeling phenomena but also allows to study the interaction of these ions with a dense electron gas. For well channeled ions, the crystal provides a unique source of high density gas of quasi free electrons.

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