IL NUOVO CIMENTO Vol. 34 C, N. 4 Luglio-Agosto 2011
DOI 10.1393/ncc/i2011-10930-x

Colloquia: Channeling 2010

Some new processes in the collisions of high energy ions and electrons with amorphous or crystalline target atoms

M. A. Aginian, R. O. Avakian(*), K. A. Ispirian and M. K. Ispiryan

Yerevan Physics Institute - Yerevan, Armenia

(ricevuto il 22 Dicembre 2010; pubblicato online il 22 Agosto 2011)

Summary. — It is shown that taking into account the energy levels of the ions and/or of the crystalline atoms, some energy transfer and excitation processes with consequences similar to the Kossel and Okorokov effects can take place when some additional resonance conditions are satisfied. Such resonance processes can be expected also when microbunched electron beams interact with ions. Since these processes have significant cross-sections and the interaction of projectile ions with atoms of crystals has not been almost studied, it is proposed to begin their study in Kossel- and Okorokov-type experiments.

PACS 41.75.Ak – Positive-ion beams.
PACS 61.85.+p – Channeling phenomena (blocking, energy loss, etc.).
PACS 34.50.Fa – Electronic excitation and ionization of atoms (including beam-foil excitation and ionization).

1. – Introduction

A project on a new complex of multipurpose accelerator of high energy ions is under development at Yerevan Physics Institute (YerPhI), now A. I. Alikhanian National Scientific Laboratory. According to the Conceptual Design the transformation of the 4.5 GeV electron synchrotron into an ion synchrotron together with the other components of the complex will provide ion beams of proton, helium, carbon and other ions up to xenon with intensity from $4 \cdot 10^{10}$ to $4 \cdot 10^{8}$ per pulse and energy from 50 MeV/u up to a few GeV/u. The preliminary scheme of the complex is shown in fig. 1. In brief, the ions from the linear accelerator RFQ-DTL, 1, are injected into the ion synchrotron, 2. After acceleration the ions are focused on target to produce projectile fragments. The separation of the fragments is done by the fragment separator, 3, connected with storage ring, 4, and/or to the beam lines to the experimental halls, 5-7, in some of which it is planned to carry out atomic physics investigations.

(*) E-mail: ravakian@yerphi.am

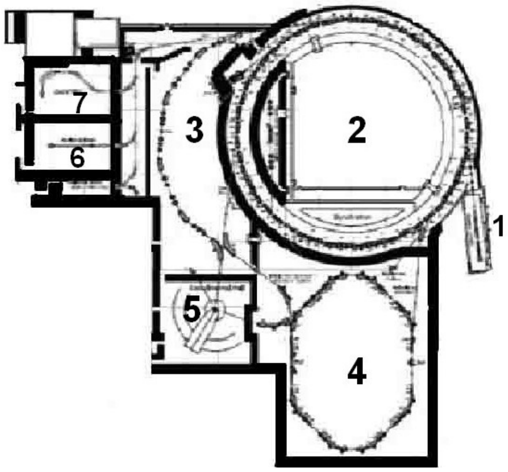

Fig. 1. – The preliminary scheme of the complex. 1 is the linear accelerator RFQ-DTL, 2 is the ion synchrotron, 3 is the fragment separator, 4 is the storage ring, 5-7 are experimental halls.

Taking into account the above said in this work an attempt is made to describe what new types of investigations can be carried out in the field of atomic physics besides those described in programs of existing facilities of relativistic ion beams and in the monographs [1-3].

It is well known that when a projectile ion I^{q+} (q is the number of the electrons pulled out from the atom of the fully or partially stripped ion) collides with amorphous target atom A, it can take place "pure" excitation of A or I^{q+} due to allowed transitions with energies $h\nu_{ik} = \hbar\omega_{ik} = E_k - E_i$ or $h\nu_{lm} = \hbar\omega_{lm} = E_m - E_l$, respectively:

$$I^{q+} + A \rightarrow I^{q+} + (A)^{**}, \quad (1)$$

$$I^{q+} + A \rightarrow (I^{q+})^{**} + A. \quad (2)$$

The excited atom $(A)^{**}$ or ion $(I^{q+})^{**}$ further emits an Auger electron or a characteristic radiation (ChR) photon

$$\begin{aligned} &(A)^{**} \rightarrow A^{1+} + e_{\text{Auger}} \quad &\text{or} \quad &(A)^{**} \rightarrow A + (\hbar\omega)_{\text{ChR}}, \\ &(I^{q+})^{**} \rightarrow I^{(q+1)+} + e_{\text{Auger}} \quad &\text{or} \quad &(I^{q+})^{**} \rightarrow I^{q+} + (\hbar\omega)_{\text{ChR}}. \end{aligned} \quad (3)$$

The Coulomb excitation is the main mechanism of these non-resonance excitation processes (1) and (2). The well-known process of particle-induced X-ray emission, PIXE, which found wide application in material analysis, archeology, gamma astronomy, etc., is described by the process (1). There is a growing interest to the study of (1) and (2) in amorphous targets at high energies [1-3]. Recently, for instance, it has been calculated [4] the cross-section of the reaction of type (2), namely, $U^{90+} + A \rightarrow A + (U^{90+})^{**}$, where A is Kr, Xe or Au atom. At $20\,\text{GeV}/u$ the cross-section of the last reaction is significantly large, $\sigma \sim (1\text{–}8) \cdot 10^{-21}\,\text{cm}^2$ [4].

In crystals the process (1) has been studied at low energies (see the review [5]). It describes also the ion-induced Kossel effect when the characteristic radiation photons give Bragg diffraction producing Kossel patterns (see the review [5]). The Kossel effect was predicted in [6] and observed later in [7]. The projectile ion excitation process (2) in crystals describes the so-called Okorokov effect, predicted and first observed in [8] and [9, 10], respectively. Processes of type (1) and (2) in which the atoms or projectile ions are excited, further will be called "Kossel-type" and "Okorokov-type" processes, respectively. At present special methods [11, 10] for detection of Kossel and Okorokov effects have been developed.

In sect. **2** of this work the other known Kossel- and Okorokov-type processes studied mainly for amorphous targets will be briefly described. Then as in the pioneering works [6, 8] in sect. **3** some new processes taking place in crystals will be qualitatively described. All these old and new processes can be easily studied by the above-mentioned methods.

2. – Kossel- and Okorokov-type processes studied mainly in amorphous targets

Besides the "pure processes" (1) and (2) there are some processes [1-3], induced by I^{q+} and accompanied by transfer of electron and/or excitation, which result in excited ions and/or atoms.

2˙1. *Processes with K-, L-ionization*

$$I^{q+} + A \to I^{q+} + A^{1+}_{K,L} + e^-, \tag{4}$$

$$I^{q+} + A \to I^{(q+1)+}_{K,L} + A + e^-. \tag{5}$$

After a short time, $\sim 10^{-14}$ s, the vacant levels of $A^{1+}_{K,L}$ and $I^{(q+1)+}_{K,L}$ are fulfilled with emission of corresponding characteristic radiation photon. Recently the cross-section of the process, $U^{90+} + A \to A + U^{91+} + \mathrm{e}^-$ where A is Kr, Xe and Au atom has been calculated in [4] at $20\,\mathrm{GeV}/u$ with result $\sigma \sim (0.1\text{–}1) \times 10^{-21}\,\mathrm{cm}^2$ for measurements at GSI.

2˙2. *Non-radiative and radiative electron capture (NEC and REC)*

$$I^{q+} + A \to I^{(q-1)+} + A^{1+}, \tag{6}$$

$$I^{q+} + A \to I^{(q-1)+} + A^{1+} + \hbar\omega, \tag{7}$$

during which the flying ion captures an electron from the target atom, A, without (NEC) or with (REC) photon radiation [1]. NEC and REC are important processes which will be studied at high ion energies. At a few hundred MeV/u the total cross-section of REC becomes larger than that for NEC [1]. The processes (6) and (7) have been studied in amorphous targets (see [1]), while (7) has been also studied unsatisfactorily in crystals [12, 13] and will be studied at high energies at GSI [14].

2˙3. *Resonance transfer of electron and excitation (RTEE)*

$$I^{q+} + A \to (I^{(q-1)+})^{**} + A^{1+} \tag{8}$$

occurs at a few hundreds MeV when the velocity of I^{q+} equals that of one of Auger electrons (see the review [15]). The process (8) has been studied unsatisfactorily also in crystal [16].

2˙4. *The resonant transfer of energy (RTE)*

$$(Don)^{**} + Acc \rightarrow Don + (Acc)^{**} \tag{9}$$

takes place between two objects, called donor (Don) and acceptor (Acc) (see [17]). During RTE I^{q+} or A can be Don or Acc, and the excited $(Don)^{**}$ or $(Acc)^{**}$ return to their unexcited states according to (3). The virtual photon exchange between Don and Acc is the mechanism of RTE [17]. In old times the processes (9) had the names of first kind blow. In the work [17] a general expression is derived for the matrix elements for RTE, and it is shown that when Don and Acc are almost in rest for some values of distance R between Don and Acc the cross-section of RTE is proportional to R^{-6} according to Forster's prediction [18]. The processes (9) occur in biological systems, in gas lasers, etc. Unfortunately, up to now no theoretical and experimental studies of RTE when Acc and/or Don move with significant velocities have been carried out. Nevertheless, one can expect that in the case of moving Acc or Don the cross-sections for RTE remain significantly large. The processes (9) have not been studied at high energies.

We propose to carry out complete, comprehensive experimental investigation of the processes (4)-(9) in crystalline targets after quantitative theoretical studies.

3. – New Kossel- and Okorokov-type processes in crystalline targets

When an ion I^{q+} with velocity V passes through crystallograpic planes under an incidence angle θ_{inc}, besides the well-known types of Kossel [6, 7], Okorokov [8, 9] and PXR [19] radiation, it can be produced and detected Kossel-type radiation due to processes (1), (4) and (9) as well as Okorokov-type radiation due to processes (2), (5), (7) and (9). However, as will be considered below, new Kossel- and Okorokov-type radiation can be produced at certain conditions and detected by the methods developed for Kossel and Okorokov effects.

3˙1. *Resonant excitation of channeled ions (RECI).* – Now let us take into account only the transition energy $h\nu_{ik}$ between the levels of the projectile ions. Let the ions be channeled between the crystallographic planes with distance between each other d. As is well known, in contrast to channeling of light particles, electrons and positrons, the channeling of ions, I^{q+}, is a classical phenomenon: I^{q+} make oscillatory motion with frequency, which in the case of harmonic potential $U(x) = U_0(2x/d)^2$ is equal to [20]

$$f = \frac{V}{\pi d}\sqrt{\frac{2U_0}{E}}\,, \tag{10}$$

where U_0 is the depth of the crystal potential. In the frame in which the ion makes only transversal oscillations the frequency (10) becomes γf. Just as in the case of RCE [8, 9], one can expect that RECI will occur if γf is equal to ν_{ik}. Hence, the resonance condition of RECI is

$$h\nu_{ik} = \frac{2\hbar c\beta\gamma}{d}\sqrt{\frac{2U_0}{E}}\,. \tag{11}$$

For non-relativistic ions with kinetic energy $T_K = MV^2/2$ much less than the total energy $E \approx N_{\text{nucl}} \cdot M_{\text{nucl}} \cdot c^2 = N_{\text{nucl}} \cdot 10^9$ eV, where N_{nucl} is the number of nucleons, (11) gives

$$h\nu_{ik} \approx \frac{4\hbar c}{d}\frac{1}{N_{\rm nucl}}\sqrt{\frac{T_K U_0}{(M_{\rm nucl}c^2)^2}}\,. \tag{12}$$

Numerically, taking $d \approx 2\,\text{Å}$, $T_K \approx 400\,\text{MeV}$ and $N_{\rm nucl} \approx 10$, one obtains $h\nu_{ik} \approx 1.2\,\text{keV}$. Therefore, one can be convinced that RECI experiments are possible.

RECI is an Okorokov-type effect, and due to resonance or non-resonance de-excitation of the excited ions a Doppler-shifted RECI photon will be produced, which can be detected as the photons of RCE. Let us underline that the resonance condition of RECI, (11) or (12), differs essentially from that of RCE. RECI is similar to the resonance processes due to influence of external fields on ChR [19, 21, 22] which occur under quite other resonance conditions.

3˙2. *Resonant excitation of target atoms (RETA) by microbunched beams.* – Now let us take into account only the transition energy $h\nu_{lm}$ of the crystal atoms. Let an electron beam microbunched with frequency $f_{\rm MB}$, such as those available at the end of the 100 m long undulators of X-ray SASE FELs [23], pass through the crystallographic planes of atoms A with possible energy transition $h\nu_{lm}$. If the microbunching frequency $f_{\rm MB}$ is equal to ν_{lm},

$$f_{\rm MB} = \frac{c}{\lambda_{\rm MB}} = \frac{2\gamma_e^2 c}{d_{\rm und}} = \nu_{lm}, \tag{13}$$

then the RETA will occur. In (13) γ_e is the relativistic factor of the microbunched electrons, $\lambda_{\rm MB}$ and $d_{\rm und}$ are the SASE wavelength and undulator period. Due to resonance or non-resonance de-excitation of the atoms, characteristic radiation photons will be emitted, which one can detect as PIXE or Kossel effect in the presence of other types of radiation. One can use RETA in order to study the parameters of microbunching.

RETA will take place also when a single two-level ion is in the field of microbunched electron beam. The radiation process is similar to that when the ion is trapped in a resonance cavity and emits according to the QED theory described mathematically by the Jaynes-Cummings model [24]. If a head-on collision of the moving ion with microbunched beam takes place, then the resonance condition (13) must be multiplied by the ion's relativistic factor, $2\gamma_{\rm ion}$.

3˙3. *RTE from I^{q+} to target atoms A and vice versa.* – Now let us take into account $h\nu_{ik}$ of I^{q+} and $h\nu_{lm}$ of amorphous or crystalline atoms A. If in the center-of-mass frame the excitation energies of donor and acceptor are each equal to the other, then resonant transfer of energy, RTE (9), can take place [17,18]. As donors can serve: 1) I^{q+} excited due to RCE [8,9] in a crystal upward the RTE target; 2) the radioactive ions (RI) 2a) from the facilities of RI beams as in GSI. These RIs have not only nuclear excited states with very narrow width, but during their production the electron shells undergo sudden reconstruction [25], and RI atomic levels also will be excited. 2b) produced by the method proposed in [26, 27]. Before hitting the target the ions undergo head-on collisions with laser beam of photons with energy $h\nu_L$ which satisfies the resonance condition $h\nu_{ik} = 2\gamma_{\rm Ion}\, h\nu_{L}$.. As has been mentioned above, RTE has been studied only at very low energies [28].

Just as in [6, 8] we do not develop any theory and only note that just as coherent bremstrahlung [29] and RCE [8], RTE can take place at high energies in crystals when both the ion and crystal target energy levels are taken into account. During RTE an Okorokov-type radiation arises due to de-excitation of moving ion or Kossel-type photons are produced by the excited atoms of the crystalline target. One can detect this new type of radiation due to RTE at resonance energies by the known methods on the background other Kossel- and Okorokov-type background. In the same way as the radiation produced in excited matter [30] one can consider the RTE in the case when unexcited ions pass through the preliminary excited crystal atoms.

4. – Conclusion

Thus, with the help of ions passing through crystals and microbunced electron beams it is possible to look for the above 3 new effects. Of course, as in the cases of Kossel and Okorokov effects besides the presented kinematical considerations it is necessary to develop theory of the processes. Designing the experiments it is necessary to take into account that the energy spread $\Delta T/T = \Delta\gamma/\gamma$ of the projectiles results in the decrease of the effective cross-sections.

REFERENCES

[1] Eichler J., *Lectures on Ion-Atom Collisions from Nonrelativistic to Relativistic Velocities* (Elsevier, Amsterdam) 2005.
[2] Voitkiv A. B. and Ullrich J., *Relativistic Collisions of Structured Atomic Particles* (Springer-Verlag, Berlin) 2008.
[3] Belkic D., *Quantum Theory of High-Energy ion-Atom Collissions* (CRC Press) 2008.
[4] Voitkiv A., Najjari B. and Shevelko V. P., ArXiv:1004.0630 (2010).
[5] Gemmel D. S., *Rev. Mod. Phys.*, **46** (1974) 129.
[6] Kossel W., *Z. Phyz.*, **23** (1924) 278.
[7] Kossel W., Loeck V. and Voges H., *Z. Phys.*, **94** (1935) 139.
[8] Okorokov V. V., *Yad. Fiz.*, **2** (1965) 1009; *Pisma Zh. Eksp. Teor. Fiz.*, **2** (1965) 175.
[9] Okorokov V. V. *et al.*, *Pisma Zh. Eksp. Teor. Fiz.*, **16** (1972) 588.
[10] Datz S. *et al.*, *Phys. Rev. Lett.*, **40** (1978) 843.
[11] Lanber E. and Dabritz S., *Mat. Sci. Eng.*, **7** (2010) 012015.
[12] Appleton B. R. *et al.*, *Phys. Rev. B*, **19** (1979) 4347.
[13] Testa E. *et al.*, *Nucl. Instrum. Methods B*, **245** (2006) 476.
[14] Geissel H., *Nucl. Instrum. Methods B*, **67** (1992) 120.
[15] Tanis J. A., *Nucl. Instrum. Methods A*, **262** (1987) 52.
[16] Belkacem A. *et al.*, *Phys. Rev. Lett.*, **64** (1980) 75.
[17] Salam A., *J. Chem. Phys.*, **122** (2005) 044122.
[18] Forster T., *Ann. Phys. (Paris)*, **6** (1948) 55.
[19] Barishevsky V. G., Dubovskaya I. Ya. and Grubich A. O., *Phys. Lett. A*, **77** (1980) 180.
[20] Baier V. N., Katkov V. M. and Strakhovenko V. M., *Electromagnetic Processes at High Energies in Oriented Single Crystals* (World Scientific, Singapore) 1998.
[21] Ikezi H., Lin-Lin Y. R. and Ohkawa T., *Phys. Rev. B*, **30** (1984) 1567.
[22] Mkrtchyan A. R., Gasparyan R. A. and Gabrielyan R. G., *Phys. Lett. A*, **115** (1986) 410.
[23] Emma P. *et al.*, *Proc. FEL2009*, p. 397; *Nature Photon.*, **4** (2010) 641.
[24] Jaynes E. T. and Cummings F. W., *Proc. IEEE*, **51** (1963) 89.
[25] Dykhne A. M. and Yudin G. L., *Vnezapnie Vozmushcheniya i Kvantovaya Evolutsiya* (Usp. Fiz. Nauk, Moscow) 1996.

[26] Ispirian K. A. and Margarian A. T., *Phys. Lett. A*, **44** (1973) 377.
[27] Basov N. G., Oraevsky A. N. and Chichkov B. N., *Zh. Eksp. Teor. Fiz.*, **89** (1985) 66.
[28] Grier A. T. *et al.*, *Phys. Rev. Lett.*, **102** (2009) 223201.
[29] Ter-Mikaelian M. L., *High Energy Electromagnetic Processes in Condensed Media* (Wiley Interscience, New York) 1972.
[30] Ryazanov M. I., *Fiz. Elem. Chastits At. Yadra (JINR)*, **12** (1981) 1035.