ՀԱՅԱՍՏԱՆԻ ԳԻՏՈՒԹՅՈՒՆՆԵՐԻ ԱԶԳԱՅԻՆ ԱԿԱԴԵՄԻԱ
НАЦИОНАЛЬНАЯ АКАДЕМИЯ НАУК АРМЕНИИ
NATIONAL ACADEMY OF SCIENCES OF ARMENIA
ДОКЛАДЫ ԶԵԿՈՒՅՑՆԵՐ REPORTS

Հատոր Том Volume 111 2011 № 1

PHYSICS

УДК 537.534+539.186

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Kossel and Okorokov Effects Like Processes Produced by Ions in Crystalline Targets

(Submitted by academician R.H. Avagyan 29/VI 2010)

Keywords: *Ion beams, Channeling, Electronic excitations and ionization of atoms*

1. Introduction. It is well-known that the characteristic radiation photon produced in an atom A inside the crystal by any particle, in particular, by a projectile ion I^{q+} (q-is the number of the pulled out electrons), can undergo Bragg diffraction, and produce Kossel paterns [1-4]. This effect has been predicted in [1] qualitatively and observed after 11 years (see [2-4]). On the other hand, when a projectile ion passes through the crystallographic planes under certain condition it can take place resonance coherent excitation (RCE) or Okorokov effect predicted qualitatively in [5] and observed later in [6,7]. Let us note that in theoretical and experimental works on coherent bremsstrahlung (CB) [8] and of parametric X-ray radiation (PXR) [9] no energy levels are taken into account. In the works devoted to Kossel and Okorokov effects, it is taken into account only the possible energy levels of the crystal atoms, $\sim\omega_{lm}$ and of the projectile ions $\sim\omega_{ik}$, respectively. Especial methods have been developed for detection of both effects [4,7].

However there are some other processes studied for amorphous targets (see, [10]), during which also it takes place the excitation of A or I^{q+}. If these known processes of excitation take place in crystals further they will be called as "Kossel type" and "Okorokov type" processes. Naturally, they can be detected by the same methods developed for Kossel and Okorokov effects.

In section 2 of this work it will be described these known processes. Then in section 3 it will be shown that in the case of crystalline targets there are some other new processes which also can be observed by the above mentioned methods.

2. Known Kossel and Okorokov type processes. *2a. Processes without electron and photon production* have the form

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

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

The excited atom $(A)^{**}$or ion $(I^{q+})^{**}$ further return to their main state emitting an Auger electron or a characteristic radiation (ChR) photon

$$\begin{array}{lll} (A)^{**} \rightarrow A^{1+} + e_{Auger} & or & (A)^{**} \rightarrow A + (\hbar\omega)_{ChR} \\ (I^{q+})^{**} \rightarrow I^{(q+1)+} + e_{Auger} & or & (I^{q+})^{**} \rightarrow I^{q+} + (\hbar\omega)_{ChR}. \end{array} \tag{3}$$

The well-known process of particle induced X-ray emission, PIXE, [11] which found wide application in material analysis, archeology, gamma astronomy, etc, is based on the process (1). Less attention has been paid to the projectile "pure" (without electron exchange) excitation process (2). Recently it has been shown [12] that the cross section of the reaction of the type (2), namely, $U^{90+} + A \rightarrow A + (U^{90+})^{**}$, where A is Kr, Xe or Au atom, at 20 GeV/u, is equal to $\sigma \sim (1-8)10^{-21}$ cm^2.

2b. Resonant transfer of energy (RTE) processes are of the type

$$(Don)^{**} + Acc \rightarrow Don + (Acc)^{**}, \tag{4}$$

where the object (molecule, atom etc) donor, Don, gives its excitation to the acceptor, Acc. I^{q+} or A can be Don or Acc in (4), and the excited $(Don)^{**}$ or $(Acc)^{**}$ return to their main state according to (3). In the work [13] a general expression is derived for the matrix element 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 rate of RTE is proportional to R^{-6} according to Forster's prediction [14]. The process (4) occurs 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 velocities greater than thermal ones have been carried out. Nevertheless, one can expect that in the case of Don moving with higher or even with relativistic velocities the cross sections for RTE may be large, because shorter R can occur.

2c. K- and L-shell ionization processes with emission of electron are described by

$$I^{q+} + A \rightarrow I^{q^+} + A^{1+}_{K,L} + e^-, \tag{5}$$

$$I^{q+} + A \rightarrow I^{(q^+1)}_{K,L} + A + e^-, \tag{6}$$

After a short time, $\sim 10^{-14}s$, the vacant levels of $(A)^{1+}_{K,L}$ and $(I^{q+})^{ion}_{K,L}$ are fulfilled, and with a probability proportional to the fluorescence coefficient a characteristic radiation photon is emitted. Recently the cross section of the process, $U^{90+} + A \rightarrow A + (U^{91+})^{**} + e^{-}$, where A is Kr, Xe and Au atom, has been calculated in [12] at 20 GeV/u with result $\sigma \sim (0.1 - 1)10^{-21}$ cm^2 for measurements at GSI.

2d. Non-radiative and radiative electron capture (NEC and REC) have the form

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

$$I^{q+} + A \rightarrow I^{(q-1)+} + A^{1+} + \hbar\omega, \tag{8}$$

during which the flying ion captures an electron from the target atom, A, without (NEC) or with (REC) photon radiation [10]. NEC and REC are important processes which will be studied at high ion energies, and at a few hundred MeV the total cross section of REC becomes larger than that for NEC [10].

2e. Resonance transfer of electron and excitation (RTEE)

$$I^{q+} + A \rightarrow (I^{(q-1)+})^{**} + A^{1+} \tag{9}$$

occurs at a few hundreds MeV when the velocity of I^{q+} equals to that of one of Auger electrons (see the review [15]).

3. New Kossel and Okorokov type processes. Just as in the case of the Kossel and Okorokov effects, all the above discussed Kossel and Okorokov type processes with photon emission can take place also when an ion I^{q+} passes through crystallographic planes under an incidence angle θ_{inc} with respect to them and be detected with the help of characteristic radiation photons. Below it will be shown that taking into account more accurately $\hbar\omega_{lm}$ and $\hbar\omega_{ik}$ some new type of resonance excitation and radiation processes can take place.

3a. Projectile Ion Excitation due to NEC, REC and RTEE. Now let us take into account only the levels $h\nu_{ik}$ of I^{q+}.

In crystals the projectile ion can be excited not only due to RCE, but also due NEC and REC, (7) and (8), respectively, when the RCE condition is not fulfilled. Eventually the excited ion can be undergone resonance de-excitation, and a photon detected. Unfortunately, there are only a few experimental works devoted to REC of ions channeled in crystals at low energies [16], using 17-40 MeV oxygen ions in Si, and [17], using 10-20 MeV/u U^{91+}, Pb^{81+} in Si, as well as a theoretical study [18]. There are plans to study them at high energies, of the order of tens GeV/u, for instance, at GSI [19].

The theoretical cross sections for RTEE at resonant energies, ∼(50-300) MeV, are in satisfactory agreement with the experimental results $\sim (10^{-21} - 10^{-20})$ cm^2 (see [15]), measured, mainly in H_2 and He gas targets. The experimental study of the processes 3a) in crystals when there is no channeling is realistic, since the cross sections are large.

3b. Resonant Excitation of the Channeled Ions (RECI). Now let us again take into account $h\nu_{ik}$ and assume that the projectile ions are channeled between the crystallographic planes with distance between each other d. As it is well known in contrast to channeling of light particles, e or e^+, the channeling of ions, I^{q+} is a classical phenomenum: I^{q+} make oscillations 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. Just as in the case of RCE, one can expect that RECI will occur if this frequency in the mean rest frame of the ion is qual to $h\nu_{ik}$, i.e. 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 $T_K = MV^2/2 \ll E \approx N_{nucl}M_{nucl}c^2 = N_{nucl}10^9 eV$ where N_{nucl} is the number of nucleons (11) gives

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

Numerically taking $d \approx 2A^o$, $T_K \approx 400$ MeV and $N_{nucl} \approx 10$, one obtains $h\nu_{ik} \approx 1.2$ keV. Therefore, the RECI experiments are possible.

RECI is an Okorokov type effect, and due to resonance or non-resonance de-excitation of the excited ions it will be produced a Doppler shifted RECI photon, 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 channeling radiation [9, 21, 22] which occur under quite other resonance conditions.

3c. Resonant excitation of the crystal atoms (RECA) by Microbunched Electron Beams. Now let us take into account only $h\nu_{lm}$. Let an electron beam microbunched with frequency f_{MB}, such as are available at the end of the 100 m long undulators of X-ray SASE FELs [23], passes through the crystallographic planes. If the microbunching frequency f_{MB} is equal to $h\nu_{lm}$

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

then the RETA occurs. In (13) γ_e is the electron relativistic factor of the microbunched beam, λ_{MB} and d_{und} are the microbunching 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 RECA in order to study the parameters of microbunching. RECA 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 by the Jaynes-Cummings model [24]. If it takes place a head-on collision of the moving ion with microbunched beam then the resonance condition (13) must be multiplied by the ion's relativistic factor, $2\gamma_{ion}$.

3d. Resonance Transfer of Energy (RTE) from Projectile Ion to Crystal Atoms and vice versa. Now let us consider the process RTE taking into account both the energy levels $h\nu_{ik}$ and $h\nu_{lm}$ when there is no ion channeling. As donors can serve I^{q+} moving with velocity V i) excited due to RCE in a crystal placed upward the RTE target. ii) radio-active ions (RI) from the facilities of RI beams. iii) Another method of obtaining preliminary excited relativistic ions has been proposed in [25, 26]. Before hitting the target the ions undergo head-on collisions with laser beam with photon energy $\hbar\omega_L$ satisfying the resonance condition $\hbar\omega_{ik} = 2\gamma\hbar\omega_L$.

As it has been mentioned above RTE experimentally and theoretically has been studied only at very low energies [27]. Just as in [1, 5] in these short notes we shall consider only some kinematical problems without developing dynamical theory of RTE at higher energies. As in [8] one can show that RTE is a coherent process and has a longitudinal coherence length $L_{coh} = 2\pi\gamma\beta c/\omega_{lm}$. This means that just as in the case of CB [8] at $\gamma \gg 1$, L_{coh} can exceed the distance between the crystallographic planes, and the cross section of the RTE is enhanced. In this case one must observe the ChR photons of crystal atoms in a Kossel type experiment due RTE in crystals.

In principle there may be also other coherent processes, say, the interaction of microbunched beams in crystal when the photons produced on various planes are coherent and can interfere. Using the Hyughens principle, one obtains the following asymmetric Bragg like formula

$$n\lambda = \frac{d}{\sin\theta_{inc}}\left(\frac{1}{\beta} - \cos(\theta_{inc} + \theta)\right), \tag{14}$$

where λ is the wavelength and θ is the angle of the emitted photons with respect to the crystallographic planes. In general, as it follows from (14), $\theta \neq \theta_{inc}$. For $\theta = \theta_{inc}$ and $\beta = 1$, i.e. when the primary particle is ultra-relativistic or photon, one obtains Bragg formula $n\lambda = 2d\sin\theta_{inc}$. One should not mix this new type of radiation with PXR which is produced by charged particles under angles $\sim 1/\gamma$ with respect to the Bragg diffraction angle because the pseudophotons, accompanying the ion, propagate under angles $\sim 1/\gamma$ with respect to the particle direction. In the same way one can consider the RTE in the case when instead of ions the crystal atoms in rest are preliminary excited following the methods for the coherent radiation produced in excited matter [28].

4. Conclusion. Thus, with the help of ions passing through crystals and microbunced electron beams it is possible to look for the above 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 decrease of the effective cross sections.

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Kossel and Okorokov Effect Like Processes Produced by Ions in Crystalline Targets

It is shown that taking into account the energy levels of ions and/or of the crystalline atoms, some new processes with consequences similar to the Kossel and Okorokov effects can take place when certain additional resonance conditions are satisfied.

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Процессы типа эффектов Косселя и Окорокова, вызываемые ионами в кристаллических мишенях

Показано, что с учетом энергетических уровней ионов и/или атомов кристалла при удовлетворении некоторых дополнительных резонансных условий могут иметь место новые процессы, приводящие к явлениям, похожим на эффекты Косселя и Окорокова.

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Իոններից առաջացված Կոսելի եւ Օկորոկովի էֆեկտների տիպի պրոցեսներ՝ բյուրեղային թիրախներում

Ցույց է տրված, որ երբ բավարարված են որոշակի պայմաններ, ապա հաշվի առնելով իոնների եւ (կամ) բյուրեղի ատոմների էներգետիկ մակարդակները, կարող են տեղի ունենալ նոր երեւույթներ, որոնք կբերեն Կոսելի եւ Օկորոկովի էֆեկտների նման հետեւանքների:

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