Some New Processes in the Collisions of High Energy Ions and Electrons with Amorpous or Crystalline Target Atoms

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(Channeling 2010, Ferrara, October 3-8, 2010)

Introduction

Taking into account that soon ion beams with various energies and charges will be available at YerPhI, 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 GSI, CHIBA, USA and other FRIBs and in the monographs [1-3].

1. J. Eichler, Lectures on Ion-Atom Collisions from Nonrelativistic to Relativistic Velocities, Elsevier, Amsterdam, 2005.
2. A.B. Voitkiv and J. Ullrich, Relativistic Collisions of Structured Atomic Particles, Springer-Verlag, Berlin, 2008.
3. D. Belkic, Quantum Theory of High-Energy ion-Atom Collissions, CRC Press, 2008.

It will be considered interaction of “pure” resonant (Coulomb) excitations of the types

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

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

Followed after time ~10^{-14} s by de-excitation

$$(A)^{**} \rightarrow A^{1+} + e_{Auger} \quad or \quad (A)^{**} \rightarrow A + (\hbar\omega)_{ChR}$$

$$(I^{q+})^{**} \rightarrow I^{(q+1)+} + e_{Auger} \quad or \quad (I^{q+})^{**} \rightarrow I^{q+} + (\hbar\omega)_{ChR} \qquad (3)$$

Type (1) (A-A)will be called “Kossel type”,e.g the well known Particle Induced X-ray Emission (PIXE) processes [6],**
Type (2) (I^{q+} -I^{q+**}) will be called Okorokov type process, e.g, $U^{90+}+A \rightarrow A+(U^{90+})^{**}$, where A is Kr, Xe or Au, has been calculated recently at E=20 GeV/u in [7] with σ~(1-8)10^{-21} cm^2.

6. Particle Induced X-Ray Emission Spectroscopy (PIXE), Eds. S.A.E. Johansson, J.L. Campbell and K.G. Malmqwist, J. Willey & Sons, New York 1998.
7. A. Voitkiv, B. Najjari and V.P. Shevelko, ArXive-nucl.phys.atom/ph/1004.0630, 2010.

Besides pure excitation processes there are processes with electron, etc. [1-3] which have been studied with gas targets

Processes with K-, L- ionization

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

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

Nonradiative and Radiative Electron Capture (NEC and REC)

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

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

Resonant Transfer of Eleectron and Energy

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

The experimental study of (1)-(8), especially of REC (7) in gas targets is in atomic program of GSI etc, while we plan to study (1)-(8) also in crystalline targets.

To finish Introduction we need to remind Forster process, and Kossel and Okorokov effect following [8,9]

8. E.Lanber, S. Dabritz, Mat. Sci. &Eng. 7, 012015, 2010.

9. Yu.Pivovarov, To be printed in Proc. of Channeling2010

Kossel Effect

W. Kossel in 1924 predicted [13] that the characteristic radiation (Ch.R) Photons produce Bragg diffraction (see Fig.3) discovered in [14]

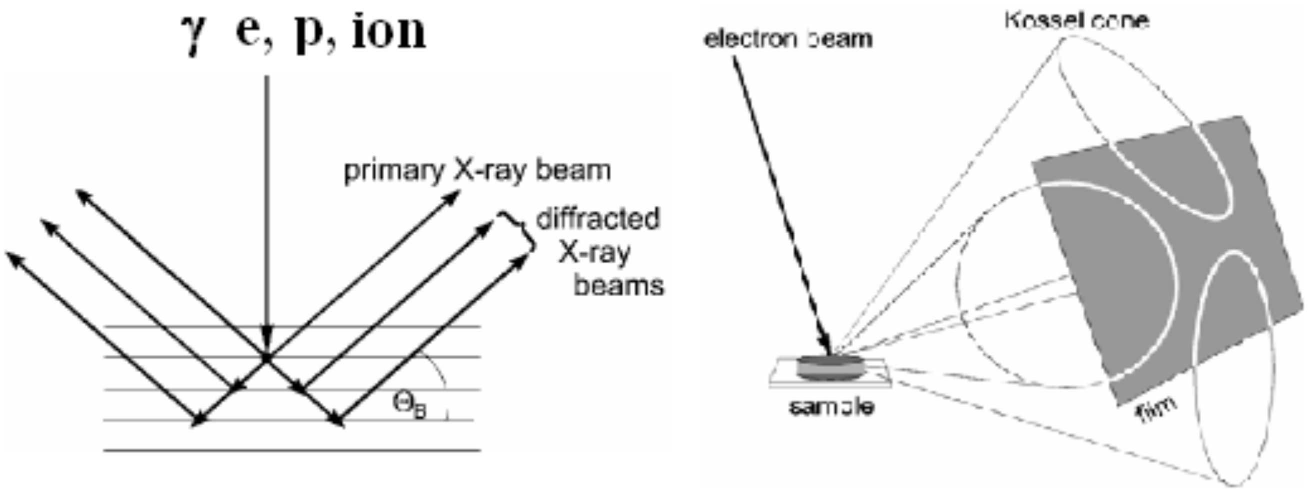

Fig.3 Excitation of ChR, diffraction a) and observation b) of Kossel effect.

13. W. Kossel, Z. Phyzik, 23, 278, 1924.
14. W. Kossel, V. Loeck and H. Voges,, Z. Physik, 94, 139, 1935.

Okorokov Effect or Resonance Coherent Excitation (RCE) of Ions Passing through Crystals

V.V. Okorokov in letters published in 1965 predicted RCE of nuclei [15] and atoms [16] passing crystals qualitatively predicting RCE. Attempts of construction of RCE theory has been made still in [17], nevertheless, the practical theories were created latter beginning [18]. It has been declared that the first observation of RCE has been made in [19], however , many specialists in this field consider the results [20] as first proof of the existence of RCE.

Besides the work [21] all the experiments on RCE have been carried out with channeled ions because this allows to use low ~(1-10) MeV ions and thin crystal targets with thickness ~10 μm.

15. V.V. Okorokov, Yad. Fiz. 2,1009, 1965.
16. V.V. Okorokov, Pisma Zh.Eksp. Teor. Fiz. 2, 175, 1965.
17. N.P. Kalashnikov and S.G. Pankratov, Fiz, Tverd. Tela. 16, 843, 1974
18. S.Shindo and Y.H. Ohtsuki, Phys. Rev. 14, 3929, 1976.
19. V.V. Okorokov et al, Pisma Zh. Eksp. Teor. Fiz. 16, 588, 1972.
20. S. Datz et al, Phys. Rev. Lett. 40, 843, 1978.
21. C.Kondo et al, Phys.Rev. Lett. 97, 135503, 2006.

The Physics

RCE arises when in the ion rest frame (IRF) the frequency $f=V\gamma/d$ of the periodic perturbation field of the crystallographic planes coincides with the transition frequency between two levels of ion with $h\nu_{ik}$. The resonance condition (see Fig. 4) is

$$f = V\gamma / d = \nu_{ik} \qquad \textbf{(10)}$$

Where $\gamma=(1-\beta^2)^{-1/2}=E/Mc^2$

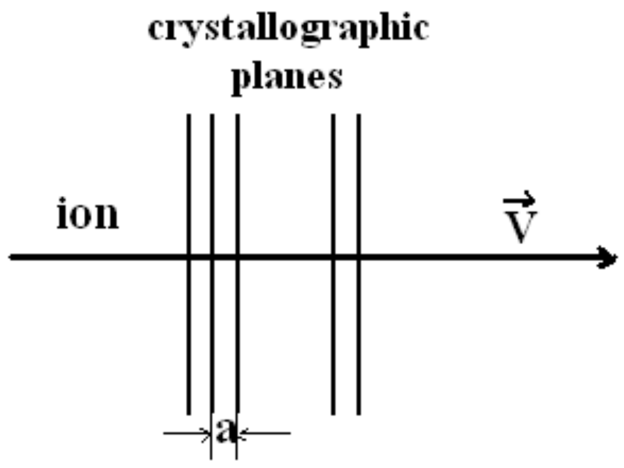

Fig.4

New Processes in I^{q+}+A Collisions in Amorphous and Crystalline targets

Just as in the first works of Kossel [5] and Okorokov [10,11] in this work taking into account both the energy levels of the projectile I^{q+} and atoms A it will be qualitatively discussed some new resonant interactions due to resonant energy excitation and/or transfer processes. It is proposed to study these processes simply by the methods developed for the original Kossel and Okorokov effects.

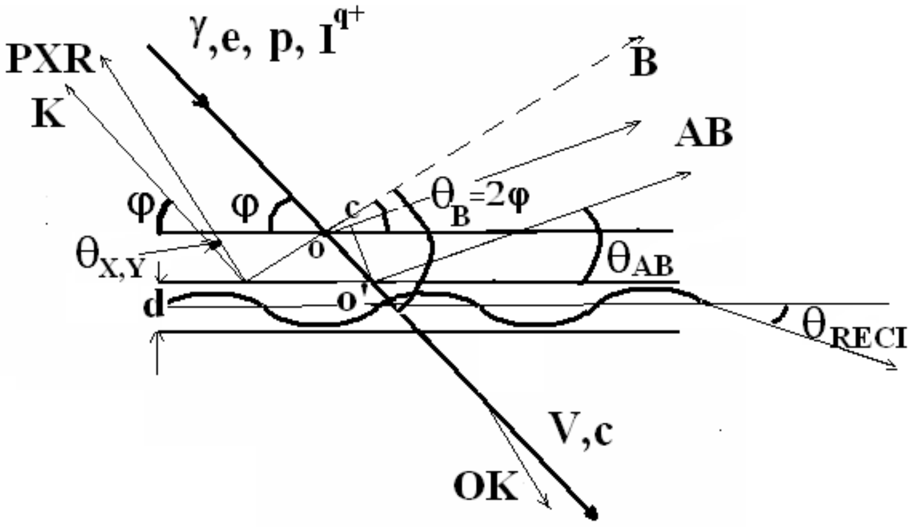

Fig. 5. The production of Bragg diffraction (B), Kossel (K), Okorokov (OK) effects and PXR photons by γ,e, p, I^{q+} in crystals (The orientation 3D RCE [21]).

2a. Resonant Excitation of the Channeled Ions (RECI)

Now let us take into account only the levels $h\nu_{ik}$ of the projectile ions channeled between the crystallographic planes with distance between each other d (see Fig. 5). As it is well known in contrast to channeling of light particles, e or e^{+}, the channeling of ions, I^{q+} is a classical phenomena: I^{q+} make oscillatory motion with frequency, which in the case of harmonic potential $U(x)=U_0(2x/d)^2$ is equal to[24]

$$f = \frac{V}{\pi d}\sqrt{\frac{2U_0}{E}} \qquad (11)$$

where U_0 is the depth of the crystal potential. Just as in the case of RCE [10,11], one can expect that RECI will occur if this frequency in the rest frame of the ion, $f^{IRF}=\gamma f^{LF}$ is qual to $h\nu_{ik}$, i.e

$$h\nu_{ik} = \frac{2\hbar c\beta\gamma}{d}\sqrt{\frac{2U_0}{E}} \qquad (12)$$

24. V.N. Baier, V.M. Katkov, V.M. Strakhovenko, Electromagnetic Processes at High Energies in Oriented Single Crystals, World Scientific, Singapore, 1998/.

For non-relativistic ions $T_K=MV^2/2<<E\approx N_{nucl}M_{nucl}c^2=N_{nucl}10^9$ eV where N_{nucl} is the number of nucleons (12) gives

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

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

Due to resonance or non-resonance de-excitation of the excited ions It will be produced a radiation the Doppler shifted photons of which one can detect as in the case of RCE (see Fig 5) . RECI differs from RCE.

2b. Resonant Excitation of the Target Atoms (RETA) by Microbunched Beams

Let a beam microbunched with frequency f_{MB} such as there are (or will be) available at the end of the 100 m long undulators of SASE FELs [24], passes through an atom A in rest (γ_{ion}=1) with possible energy transition hν_{lm}. If the microbunching frequence f^{LF}_{MB} is equal to ν_{lm},

$$f^{LF}_{MB} = \frac{c}{\lambda} = \frac{2\gamma_e^{2} c}{d_{und}} = \nu_{lm}$$

If the ion is moving with γ_{ion}>>1, then since due to Doppler effect the ion "sees' the frequency multiplied by (2 γ_{ion}) then the RETA resonance condition will be

$$f^{IRF}_{MB} = 2\gamma_{ion} f^{LF}_{MB} = \frac{4\gamma_{ion}\gamma_e^{2} c}{d_{und}} = \nu_{lm}$$

24. P. Emma et al 2009 Proc. of PAC09, p.???; LCLS, Design Study Report, 1998, SLAC-R-521; TESLA Technical Design Report 2001 DESY 011.

the RETA occurs. Due to resonance or non –resonance de-excitation of the excited ions characteristic radiation photons will be emitted, which one can detect as PIXE or Kossel effect in the presence of other types of radiation. This can result in additional background when one according to the proposals [25, 26] will use coherent X-ray transition radiation to study the process of microbunching .

25. E.D. Gazazian, Nucl. Instr. And Meth. B173 (2001) 160.
26 A.H. Lumpkin, W.M. Fawley, D.W. Rule, Proc. FEL 2004, p. 515.

Conclusion

Thus, with the help of ions passing through crystals and microbunced 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 as well as the influence of the multiple scattering, energy losses, crystal thickness, etc.