Theoretical arguments for polarization and correlation X-ray measurements with channeled highly-charged ions

V.V.Balashov

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Processes:

a) **resonant coherent excitation;**

b) **dielectronic recombination;**

c) **radiative electron capture**.

Theory:

a) **channeled ion as an open quantum system (density matrix approach);**

b) **statistical tensor formalism to describe polarization and correlation phenomena in collisions;**

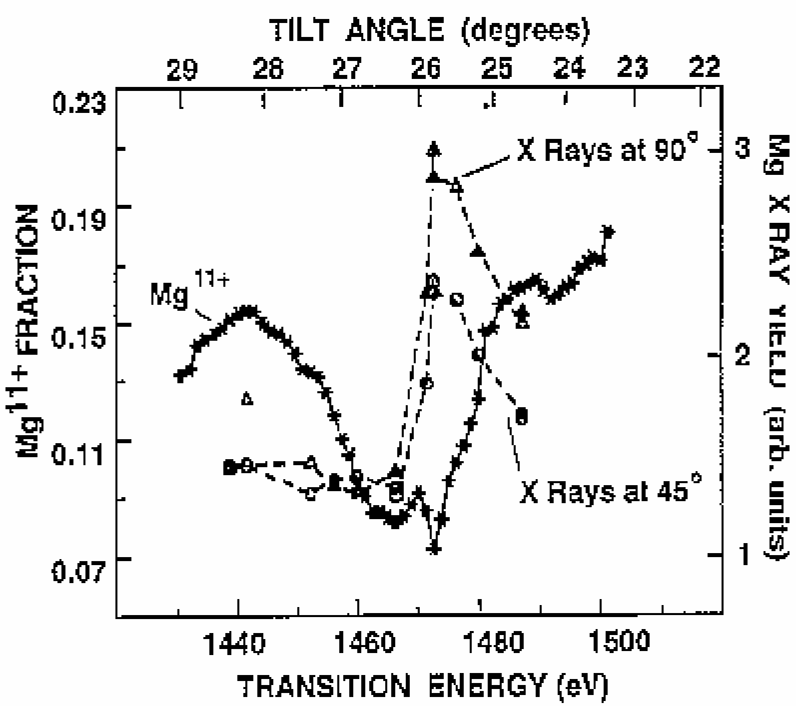
c) **relativism in treating ion movement and transformation of the electromagnetic field of the crystal into the projectile frame.**

Angular anisotropy of the X-ray radiation in the RCE process as an evidence of alignment of resonant coherent excited channeled ions

Nuclear Instruments and Methods in Physics Research B 100 (1995) 272–278

Resonant coherent excitation of N^{6+} and Mg^{11+} in planar channeling: anisotropies in ionization probabilities and X-ray emission

S. Datz [a,*], P.F. Dittner [a], H.F. Krause [a], C.R. Vane [a], O.H. Crawford [a], J.S. Forster [b], G.S. Ball [b], W.G. Davies [b], J.S. Geiger [b]



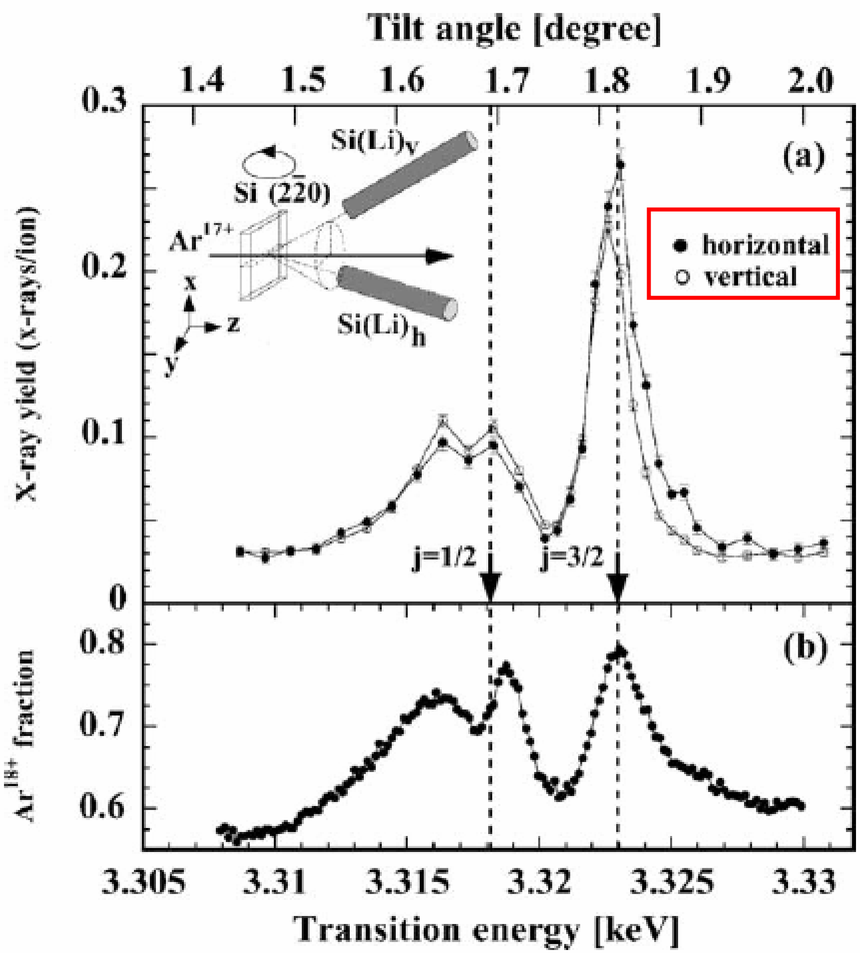
Mg^{11+} (25 MeV/amu) in (100) Ni

Fig. 12. X-ray yields in detectors placed at angles of 45° and 90° to the beam as a function of transition energy (tilt angle) as compared with charge state fraction (i.e., Fig. 11).

Nuclear Instruments and Methods in Physics Research B 205 (2003) 779–783

Angular distribution of X-ray emission from resonant coherently excited highly-charged heavy ions

T. Azuma [a,*], T. Muranaka [a], Y. Takabayashi [b], T. Ito [b], C. Kondo [b], K. Komaki [b], Y. Yamazaki [b,c], S. Datz [d], E. Takada [e], T. Murakami [e]



X-rays emitted from resonant coherently excited $n = 2$ states of 390 MeV/amu hydrogen-like Ar^{17+} ions

Fig. 1. The RCE profiles of $(k, l) = (1, 1)$ transition in $(2\bar{2}0)$ planar channeling through a 21 μm-thick Si crystal as a function of the angle, θ, between the beam direction and the [1 1 0] axis for (a) de-excitation X-rays from Ar ions measured by the Si(Li) detectors at the horizontal position (●), and at the vertical position (○) and (b) the ionized Ar^{18+} fraction in transmitted Ar ions.

Density-matrix approach to describe resonant coherent excitation of highly-charged Ions in crystals

1. V.V.Balashov, I.V.Bodrenko - Angular anisotropy of characteristic electromagnetic radiation of channeled ions in conditions of resonance coherent radiation - Moscow University Physics Bulletin 56 (2001) 33, N1.
2. V.V.Balashov, I.V.Bodrenko - Alignment of resonant coherently excited ions under planar channeling - ICPEAC XXIV, Rosario, Argentina, July 2005; Book of abstracts, Tu 133.
3. V.V.Balashov, I.V.Bodrenko - Characteristic X-ray production in the RCE process - Phys.Lett. A 352 (2006) 129.
4. V.V.Balashov, I.V.Bodrenko - Metastable ion production in the RCE process - NIM B 245 (2006) 52.
5. V.V.Balashov, A.A.Sokolik – Resonant coherent excitation of channeled 94 Mev/u ions Ar^{17+} in oriented Si crystal – Optics and Spectroscopy (submitted).

Density matrix approach; the generalized Master equation

$$i\frac{\partial\hat{\rho}}{\partial t} = \left[\hat{H}, \hat{\rho}\right] + \hat{R}\,\hat{\rho};$$

$$\hat{H} = \hat{H}_0 + \hat{V}(t); \quad \hat{V}(t) = \hat{V}^{(lattice)}(t) + \hat{V}^{(wake)}(t).$$

A system of coupled equations to solve:

$$\frac{\partial\rho_{pp}(t)}{\partial t} = 2 \cdot \sum_{q=1}^{N} Im\left[V_{pq}(t) \cdot \rho_{qp}(t)\right] - \lambda_p(t)\rho_{pp}(t) + \sum_{q \neq p} \lambda_{qp}(t)\rho_{qq}(t);$$

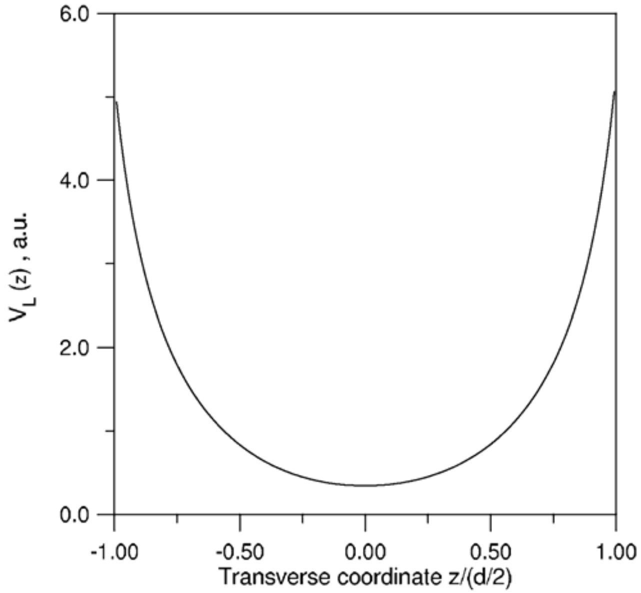
$$\frac{\partial\rho_{pq}(t)}{\partial t} = -i \cdot \sum_{r=1}^{N}\left[V_{pr}(t)\rho_{rq}(t) - \rho_{pr}(t)V_{rq}(t)\right] - $$

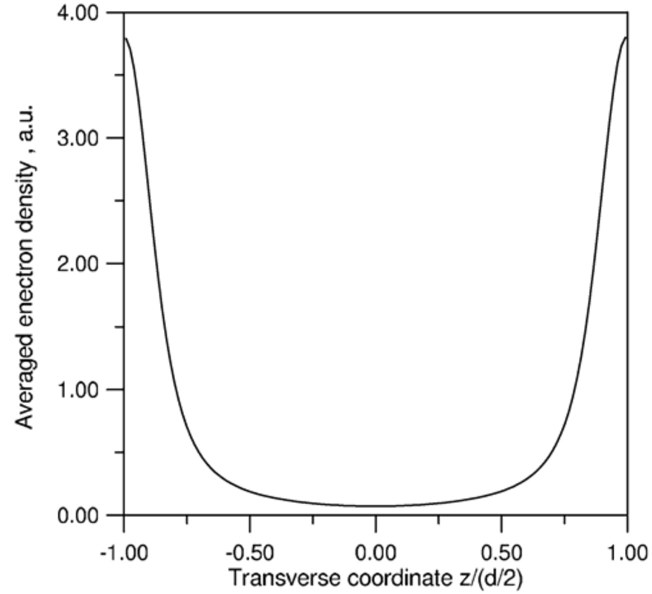
$$-\frac{1}{2}\left[\lambda_p(t) + \lambda_q(t) + \lambda_{pq}^{(elastic)}(t)\right]\rho_{pq}(t);$$

$$\rho_{pq}(t=0) = \delta_{p1}\delta_{q1}.$$

The Lindhard continuous potential $V_L(z)$ for a planar channel is derived by averaging the lattice potential over the (x, y) plane:

$$V_L(z) = \left\langle V^{(lattice)}(\vec{r}) \right\rangle =$$
$$= \sum_h \Phi_{h00} e^{i\vec{G}_{h00}\vec{r}} = \frac{16\pi Z_2}{a^3} \sum_{j=1}^{3} a_j \sum_{q=-\infty}^{+\infty} e^{-\frac{8\pi^2 q^2}{3}\frac{1}{a^2}<r^2>} \frac{e^{-i4\pi\frac{qz}{a}}}{\left(\frac{b_j}{a_{TF}}\right)^2 + \left(\frac{4\pi q}{a}\right)^2}$$

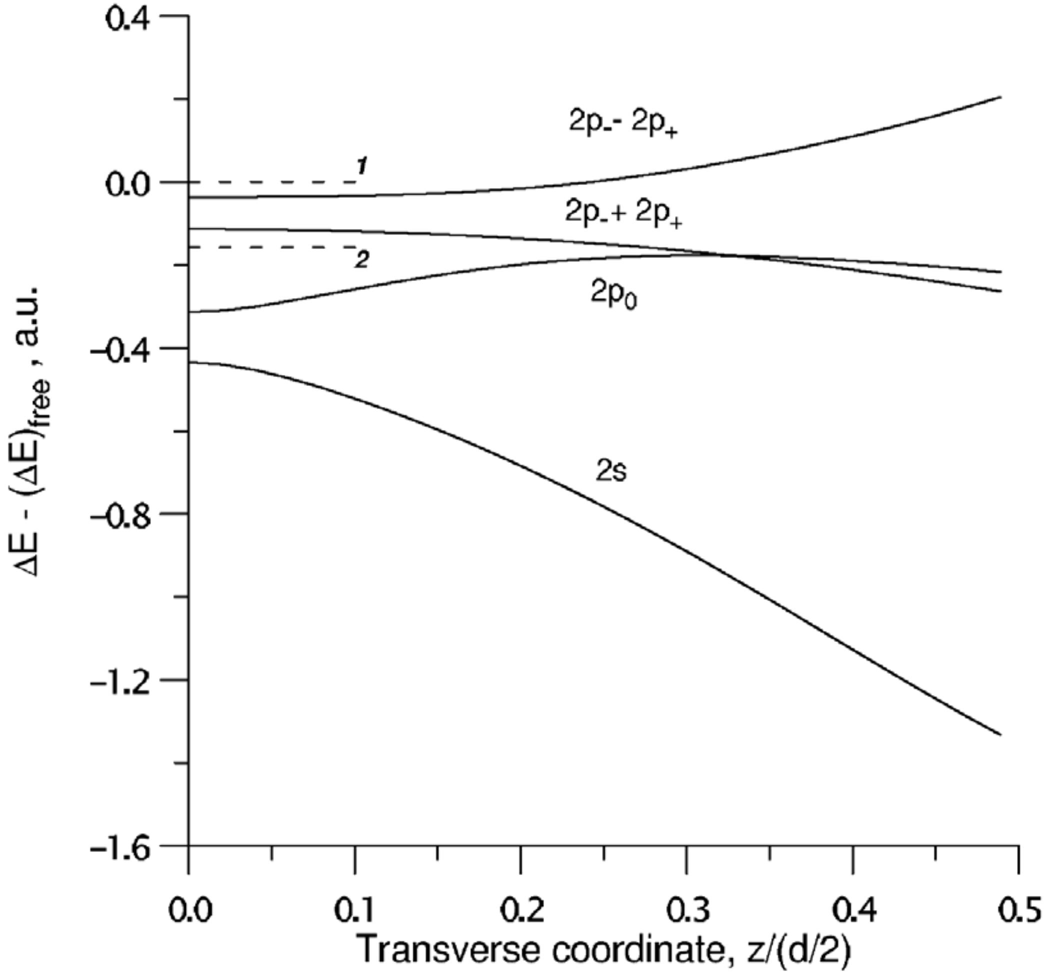




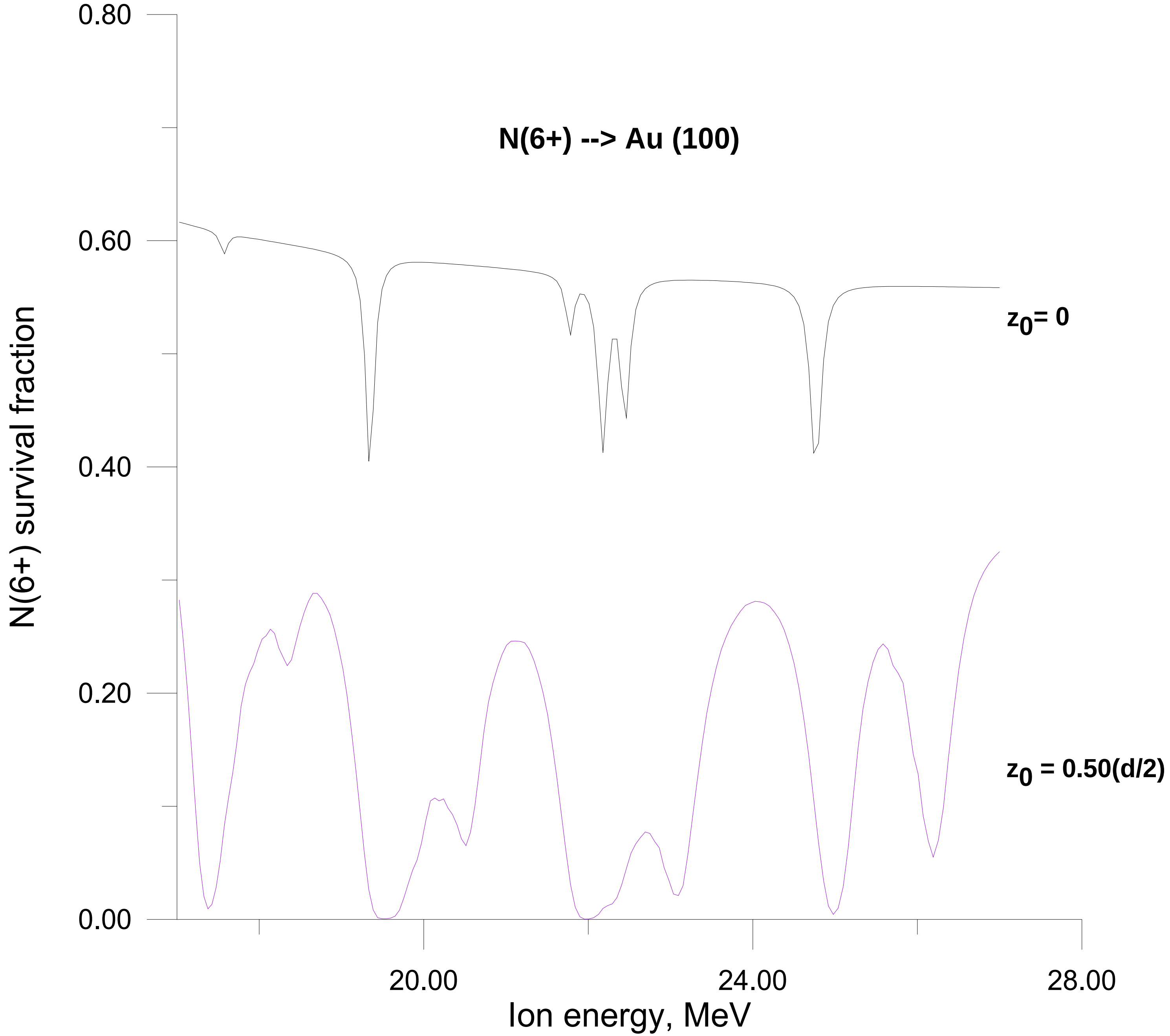
and is linked by the Poisson equation

$$\frac{d^2 V_L(z)}{dz^2} = 4\pi n_e(z)$$

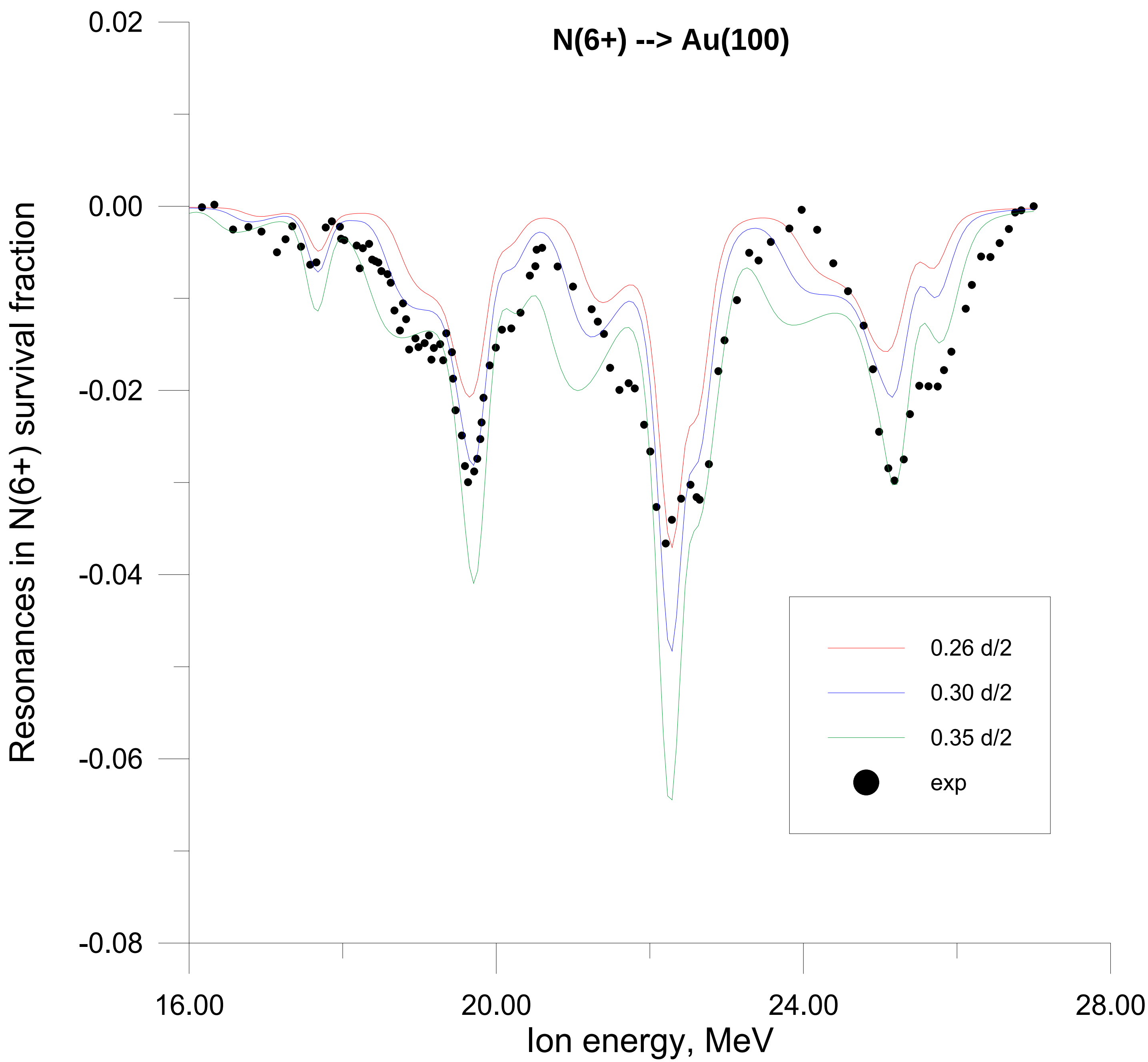
with the in-channel electron density $n_e(z)$ of the target.



Calculated splitting of the $1s^2 \to 1s2l$ transition energy in N^{5+} ions with kinetic energy E=17.5 MeV in planar channel (100) of gold crystal as a function of the ion displacement from the central plane of the channel.



0.80
0.60
0.40
0.20
0.00
N(6+) survival fraction
N(6+) --> Au (100)
z0= 0
z0 = 0.50(d/2)
20.00
24.00
28.00
Ion energy, MeV



N(6+) --> Au(100)
Resonances in N(6+) survival fraction
Ion energy, MeV
0.02
0.00
-0.02
-0.04
-0.06
-0.08
16.00
20.00
24.00
28.00
0.26 d/2
0.30 d/2
0.35 d/2
exp

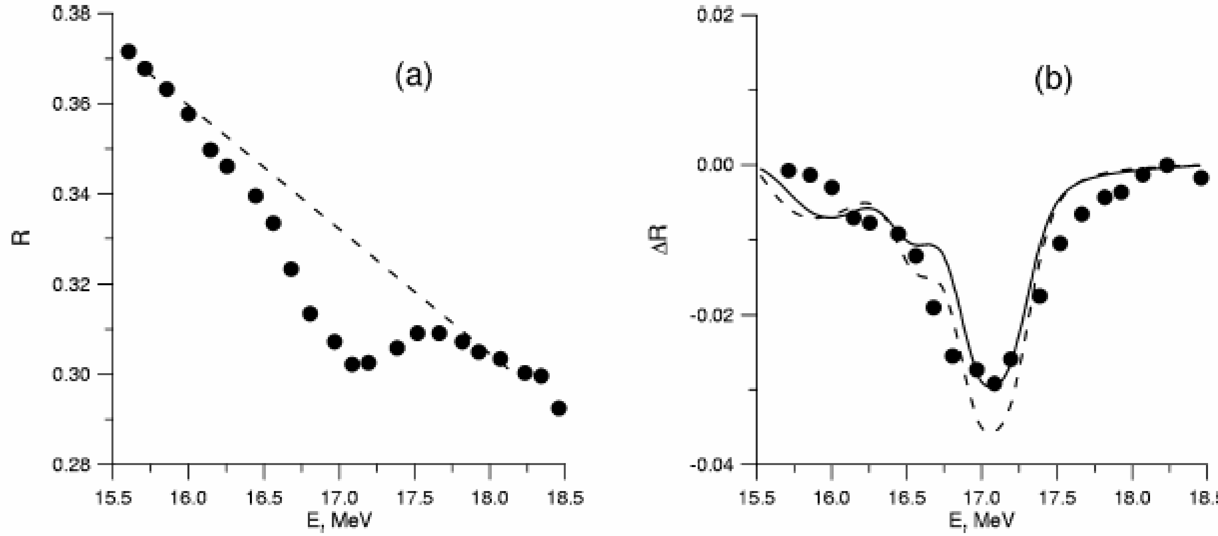


Fig. 1. Survival fraction of N^{5+} ions after passing (100) planar channel in gold crystal; (a) measurements [11], dashed line—the background contribution from non-resonant processes; (b) the resonance contribution; points—extraction from the experimental data as explained in the text; curves—calculations with $z_0^{(\max)} = 0.20(d/2)$ (solid line) and $z_0^{(\max)} = 0.24(d/2)$ (dashed line).

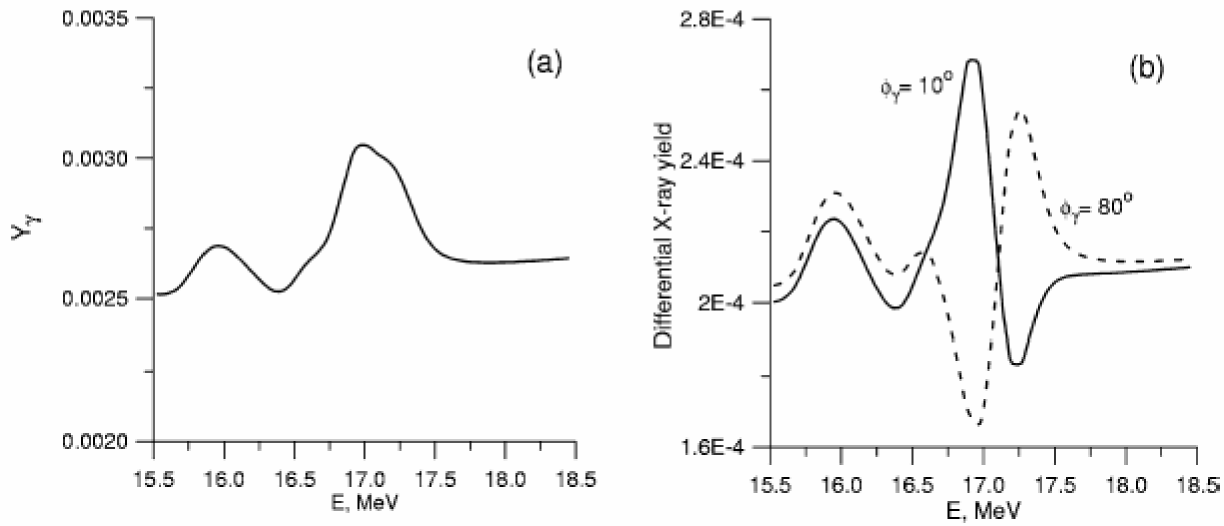


Fig. 2. Contribution to the yield of $1s2p \to 1s^2$ photons from N^{5+} ions entering the channel within the coherence zone (1) calculated with $z_0^{(\max)} = 0.22(d/2)$; (a) the integral yield Y_γ; (b) the differential yield $d(Y^{(\gamma)})/d\Omega_\gamma$ at $\theta_\gamma = 10^\circ$ and 80°.

Resonant coherent excitation of channeled 94 Mev/u ions Ar^{17+} in oriented Si crystal

Measurements:

Y.Nakai, T.Ikeda et al. - NIM B 205 (2003) 779

Theory:

V.V.Balashov, A.A.Sokolik – Optics and Spectroscopy (2006).

Time oscillating lattice potential in the projectile frame:

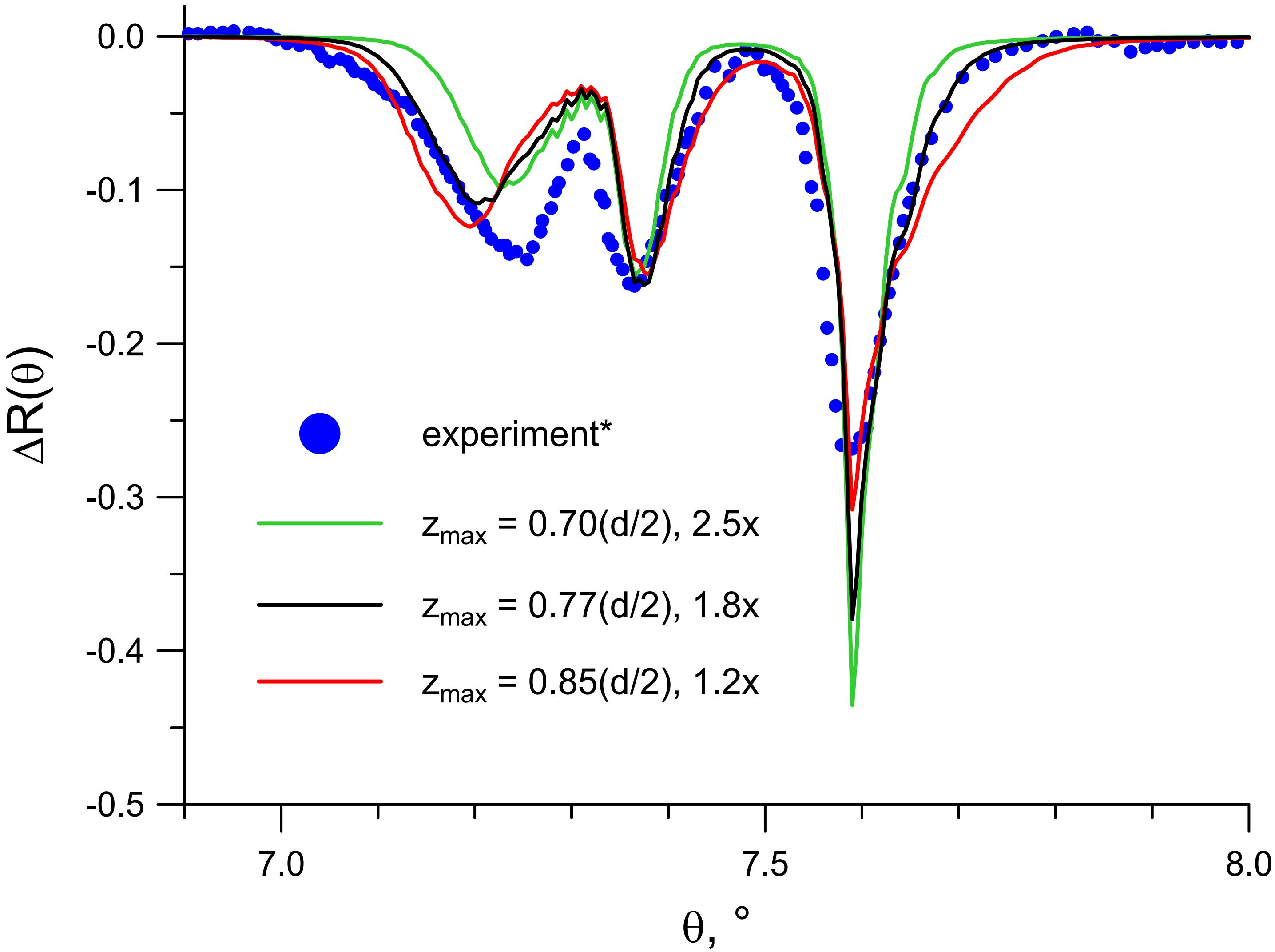
$$V'^{(lattice)}(\vec{r}\,',t') = \sum_{kln} \gamma \cdot \Phi_{kln} e^{i\vec{G}'_{kln}\vec{r}} e^{i(\vec{G}_{kln})_z (z_{ion} + d/2)} e^{i(\vec{G}_{kln})_x \gamma v_{ion} t'}$$

$$\gamma = (1 - v_{ion}^2 / c^2)^{-\frac{1}{2}}$$

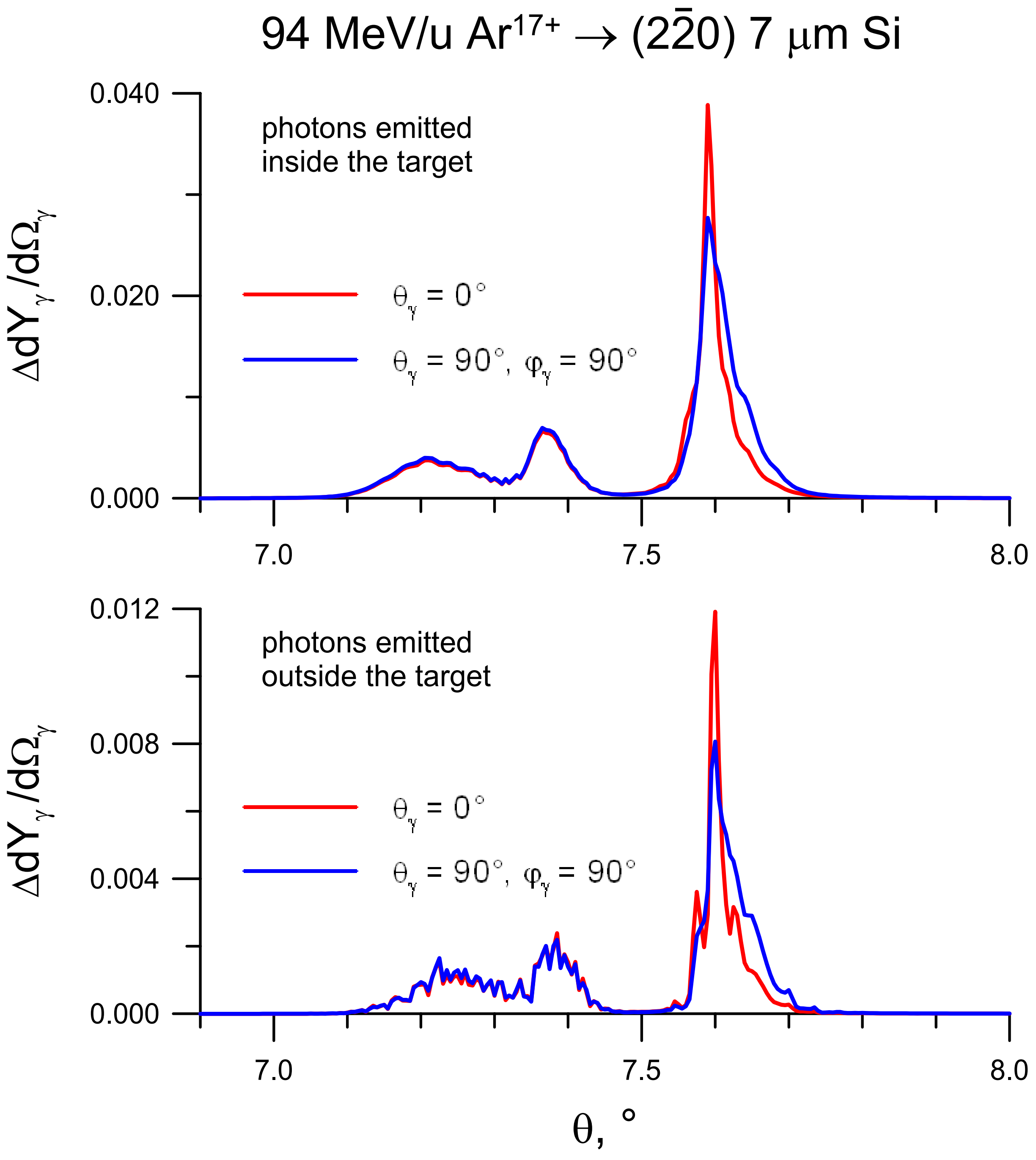
$$k \cos\theta + l\sqrt{2}\sin\theta = \frac{E_{trans}\, a}{h \cdot v_{ion}\gamma}$$

V.V. Balashov, A.A. Sokolik, Optics and Spectroscopy (to be published)

94 MeV/u $Ar^{17+} \rightarrow (2\bar{2}0)$ 7 μm Si

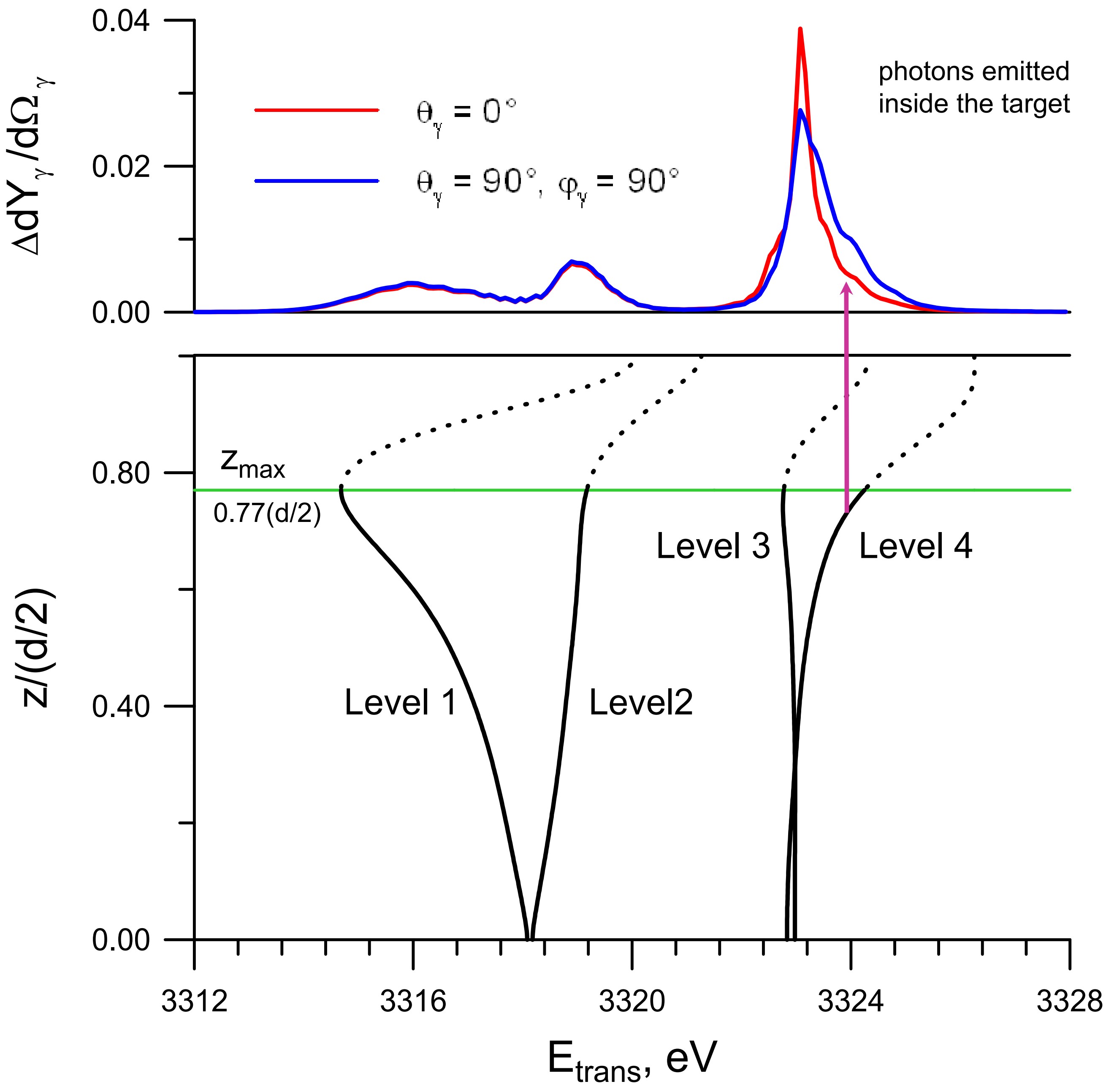


*Y. Nakai, T. Ikeda et al, Nucl. Instr. and Meth. in Phys. Res. B 205 (2003) 784



94 MeV/u $Ar^{17+} \rightarrow (2\bar{2}0)$ 7 μm Si
photons emitted inside the target
$\theta_\gamma = 0°$
$\theta_\gamma = 90°, \varphi_\gamma = 90°$
$\Delta dY_\gamma / d\Omega_\gamma$
0.040
0.020
0.000
7.0
7.5
8.0
photons emitted outside the target
$\theta_\gamma = 0°$
$\theta_\gamma = 90°, \varphi_\gamma = 90°$
$\Delta dY_\gamma / d\Omega_\gamma$
0.012
0.008
0.004
0.000
7.0
7.5
8.0
θ, °

$94\ \mathrm{MeV/u}\ Ar^{17+} \rightarrow (2\bar{2}0)\ 7\ \mu m$ Si



Anisotropic X-Ray Emission from Heliumlike Fe^{24+} Ions Aligned by Resonant Coherent Excitation with a Periodic Crystal Potential

T. Azuma,[1] Y. Takabayashi,[2] C. Kondo,[2] T. Muranaka,[1] K. Komaki,[2] Y. Yamazaki,[2,3] E. Takada,[4] and T. Murakami[4]

Fe^{24+} ions of 423 MeV/amu

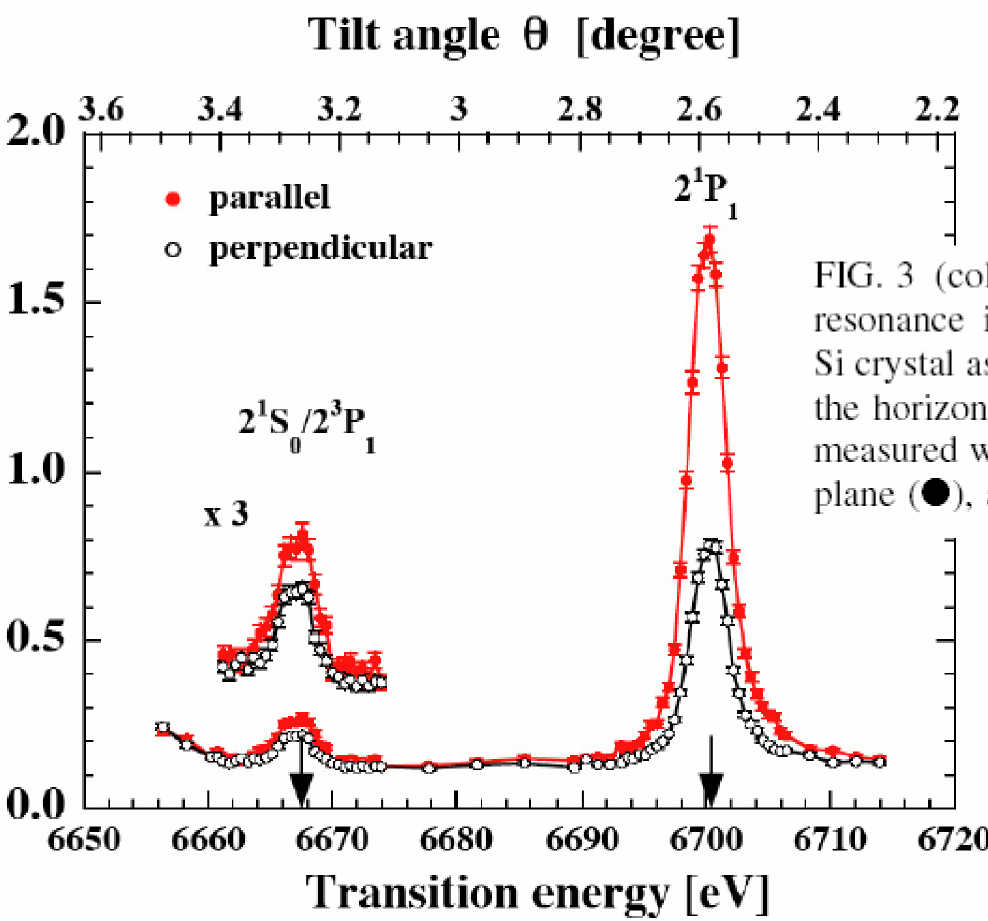


FIG. 3 (color online). The RCE profiles of $(k, l) = (2, -1)$ resonance in $(2\bar{2}0)$ planar channeling through a 21 μm-thick Si crystal as a function of the tilt angle, θ, from the [110] axis in the horizontal $(2\bar{2}0)$ plane for deexcitation x rays from Fe ions measured with the Si(Li) detectors at the parallel position to the plane (●), and at the perpendicular position (○).

Coincidence measurements on X-ray radiation from swift highly-charged ions in matter

- "…**Future experiments are desirable such as coincidence measurements of X-rays and exit ions tagged with the charge state and the deflection angle**…" **:**

  Y.Iwata et al., *K_α X-ray emission from resonant coherently excited F^{8}+ ions ..;* NIM B48 (**1990**)163.

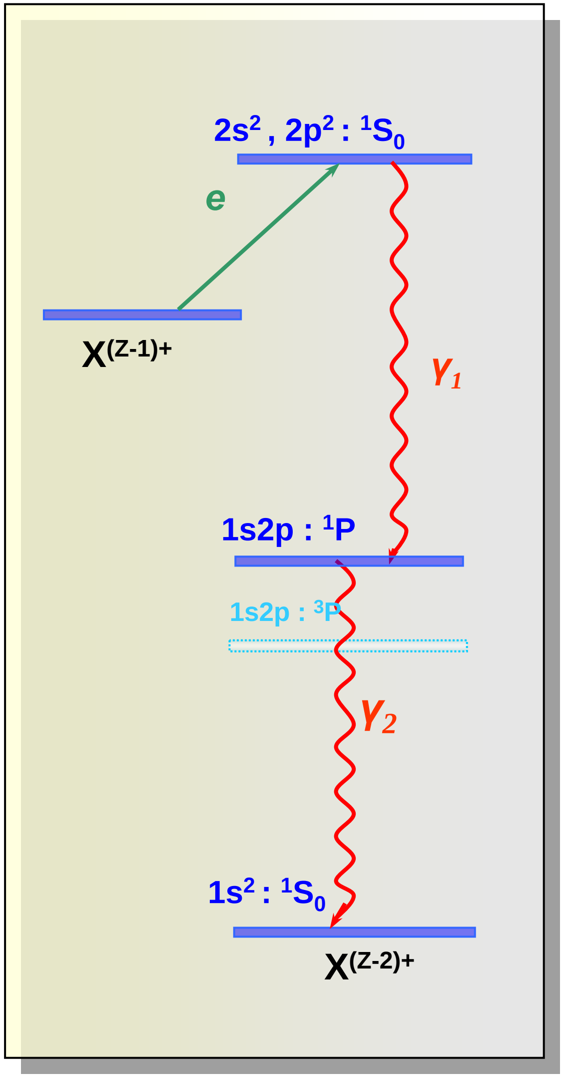
- **A series of measurements of X-ray spectra in coincidence with transmitted channeled ions of various charge states:**

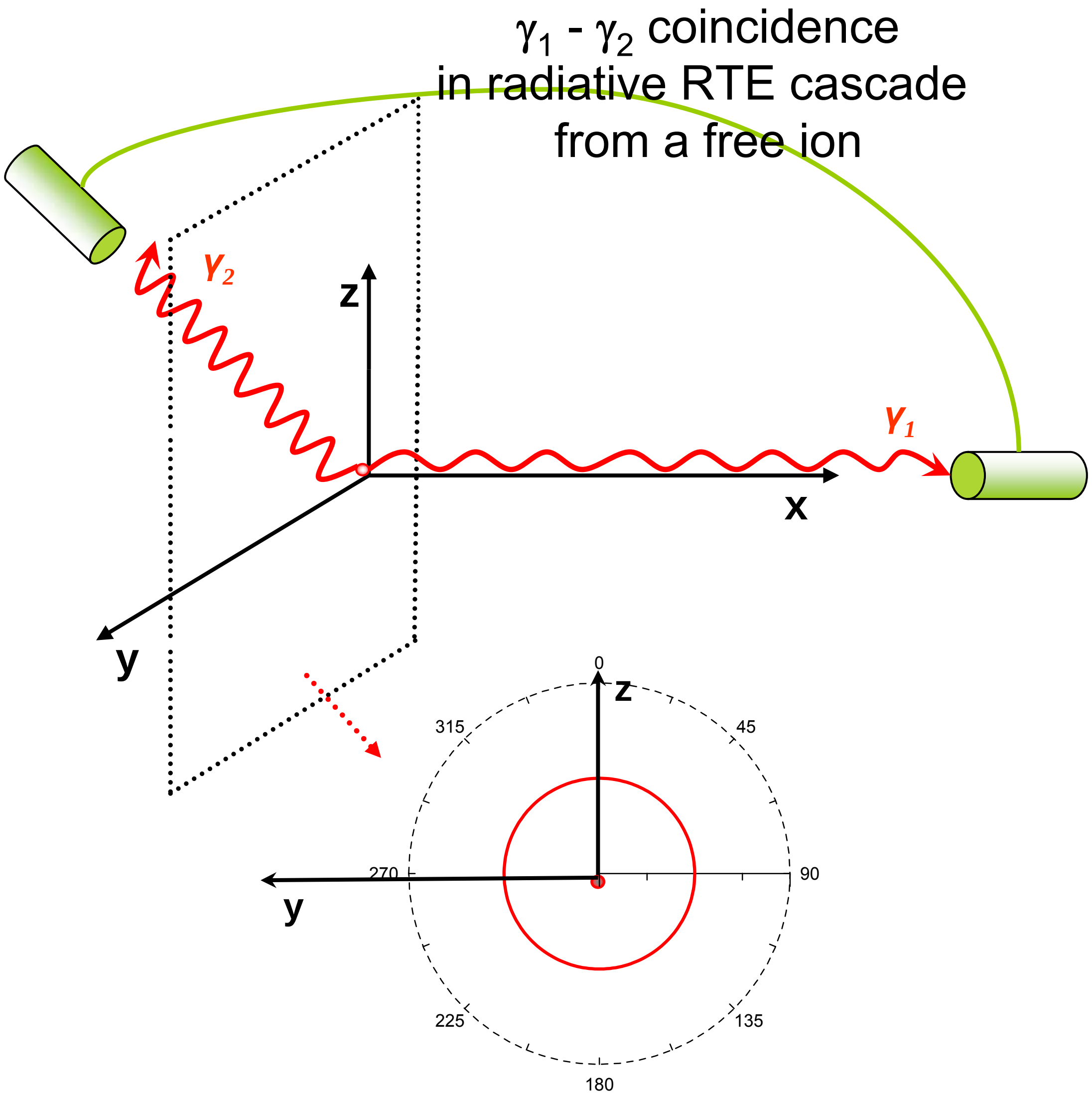
  S.Andriamonje et l., NIM B 87 (**1994**) 116;
  S.Andriamonje et al., Phys.Rev. 54 (**1996**)1404;
  D.Dauvergne et al., NIM B 205 (**2003**) 773.

- **Unified density matrix (statistical tensor) formalism to describe angular anisotropy and angular correlations of cascade photons in dielectronic recombination (RTE) and radiative electron capture (REC) processes:**

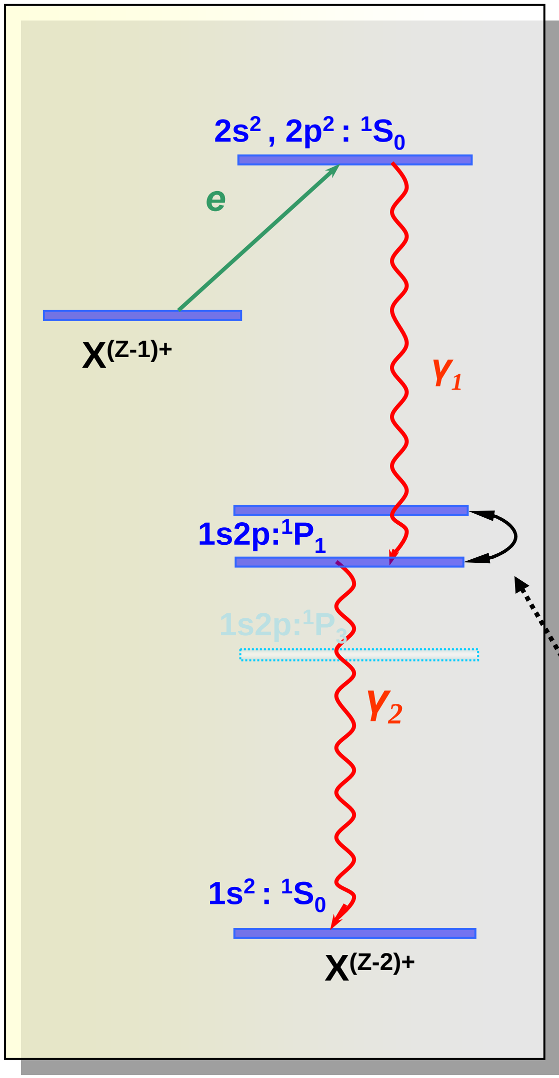
  V.V.Balashov et al.,- Optics and spectroscopy, 77 (**1994**) 801;
  S. Zakowicz, Z. Harman, N. Grün, and W. Scheid, - Phys. Rev. A 68 (**2003**) 042711;
  A.Surzhikov et al. - Phys.Rev. A73 (**2006**) 032716.

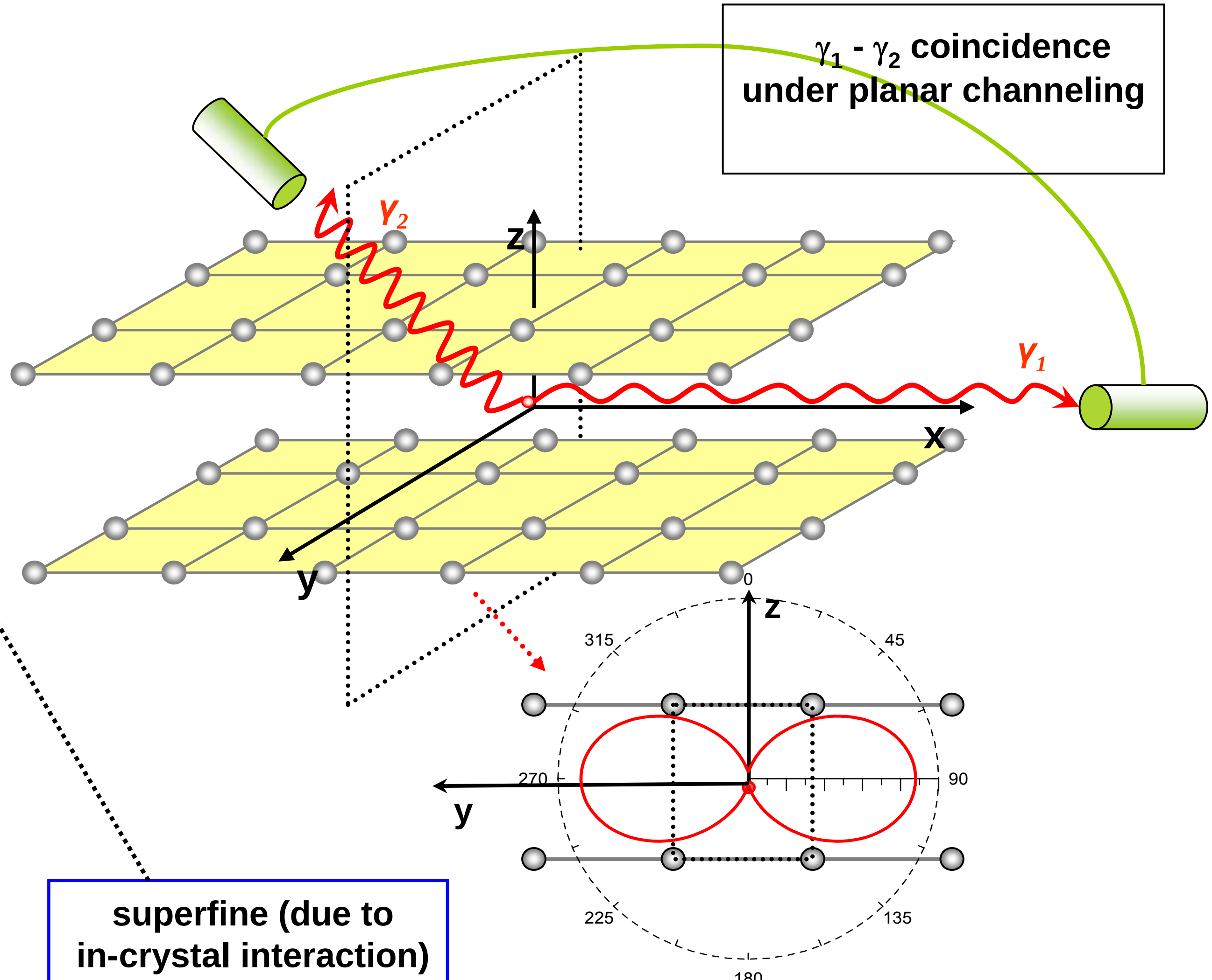
Angular correlations of cascade photons in dielectronic recombination (RTE) and radiative electron capture (REC) processes:





Angular correlations of cascade photons in dielectronic recombination (RTE) of channeled ions





superfine (due to in-crystal interaction) level splitting

Stark mixing of ionic intermediate states in radiative recombination of channeled ions

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Abstract. Stark mixing of intermediate excited ionic states due to combined action of crystal lattice, polarization wake potential and collisions with electrons is considered theoretically. Calculations for radiative recombination of well-channeled Ar and Kr ions under planar channeling in Si crystal show significant influence of the mixing of $[n = 2]$ states on formation of the X-ray spectra and angular correlation between L-REC and $K_{\alpha 1}$ photons.

Int. Conf. HCI2006
North Ireland, Belfast,
Aug.28-Sep.01,
J.Phys. Conf. Series, 2006

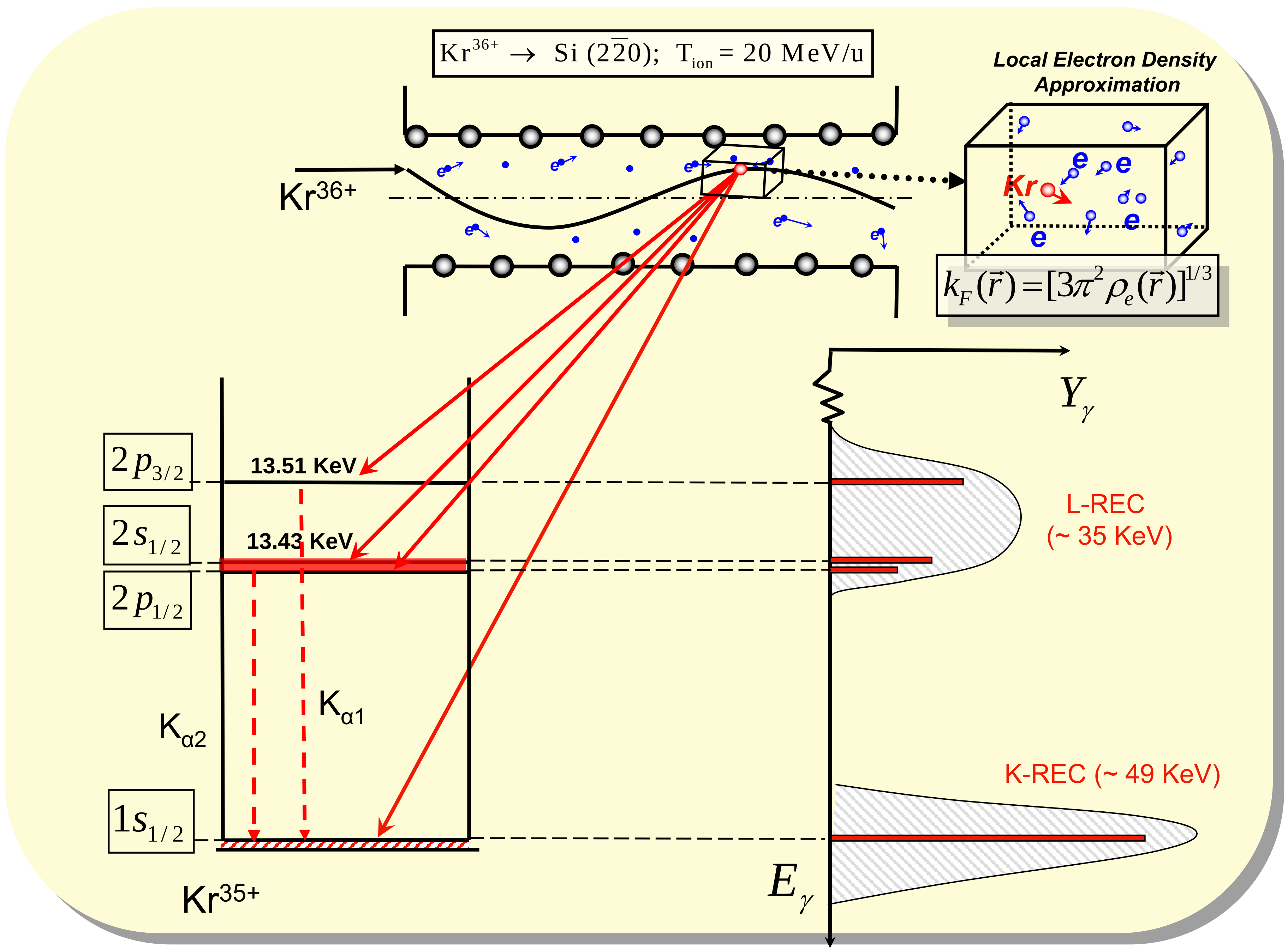
1. Introduction

Radiative electron capture (REC) by channeled ions [1, 2] takes place under non-central ion-target interactions inducing specific processes in the electron shell of the propagating ion via Stark mixing of its excited states. We suggest a unified approach to investigate theoretically both aspects of this mixing: a) due to the combined crystal lattice and polarization wake potential (the *field mixing*); b) due to ion collisions with free electrons in the channel, leading, in parallel with electron loss and electron capture processes, to state-to-state transitions in the ion electron shell (the *collisional mixing*). Our goal is to reveal relation of these mechanisms to REC observables, known according to recent experimental studies in the field or suggested on the base of calculations for future experiments. Our special interest concerns theoretical grounds for coincident REC measurements with channeled ions. As a whole, the present work is based on the density matrix approach [3, 4] to treat the channeled ion as an open quantum system involved into coherent and incoherent interactions with its surrounding and, on the other hand, on formalism [5, 6] describing polarization and correlation phenomena in recombination processes. Our approach is pure nonrelativistic.

Throughout the paper we consider a case of planar channeling of hydrogen-like ions produced in radiative electron capture by incoming bare nuclei. REC studies with planar channeled ions may be of special interest for theoreticians and experimentalists as the breakdown of axial symmetry of interaction of ion beam with matter is here much more pronounced than in case of axial channeling.

2. The density matrix approach and REC observables

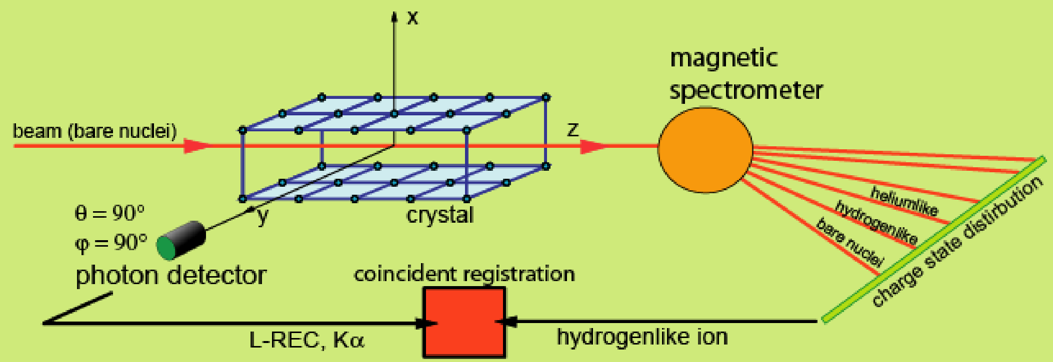
We consider the ion density matrix $\rho_{pq}(t)$ in the representation of $[n = 1]$ and $[n = 2]$ eigenstates



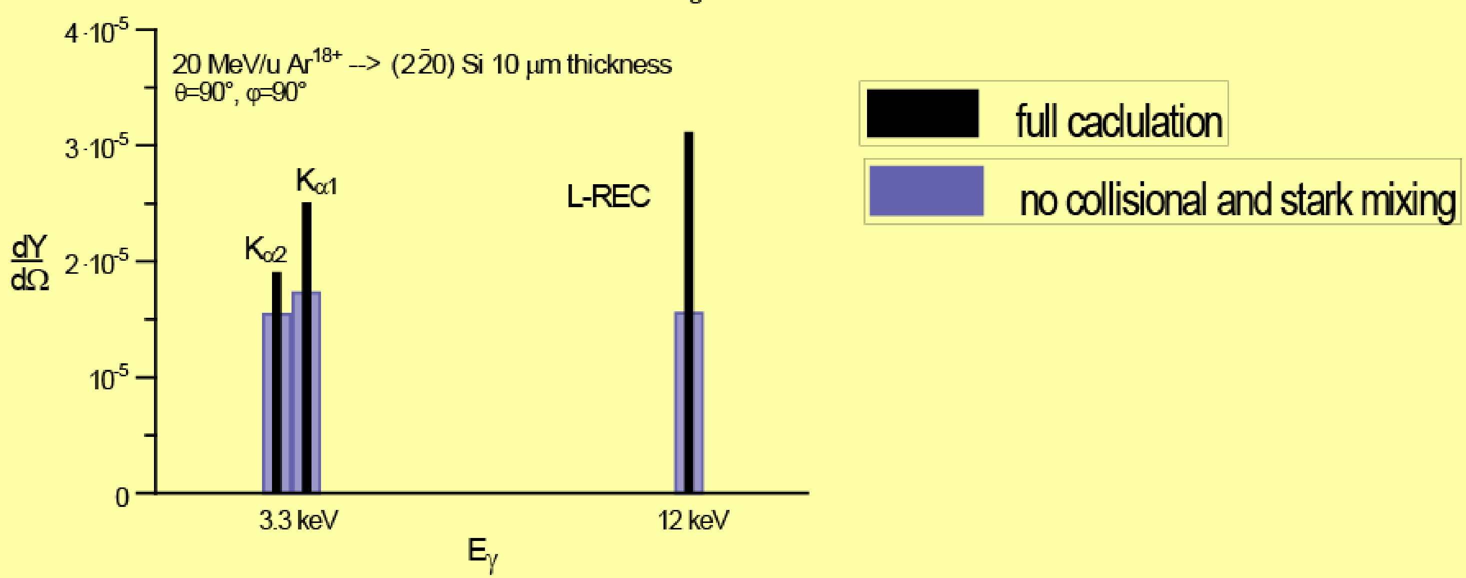
Kr^36+ → Si (2 2̄ 0); T_ion = 20 MeV/u
Local Electron Density Approximation
Kr^36+
Kr
e
$k_F(\vec{r}) = [3\pi^2 \rho_e(\vec{r})]^{1/3}$
Y_γ
$2p_{3/2}$
13.51 KeV
$2s_{1/2}$
13.43 KeV
$2p_{1/2}$
L-REC
(~ 35 KeV)
$K_{\alpha 1}$
$K_{\alpha 2}$
K-REC (~ 49 KeV)
$1s_{1/2}$
Kr^35+
E_γ

Yield of L-REC photons and K_α photons in coincidence with H-like ions

Registration of L-REC, $K_{\alpha 1}$ and $K_{\alpha 2}$ photons in coincidence with H-like ions at the exit of the target gives the spectrum corresponding to well-channeled ions. Stark and collisional mixing are key factors of this spectrum formation in channeling conditions.



Differential yields of K and L-REC photons in coincidence with Ar^{17+} ions at the exit of the target



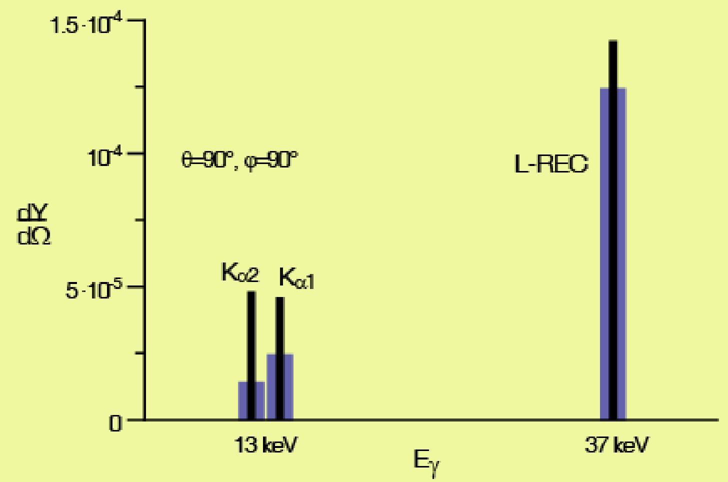
Results of the calculations for incident Kr ions

60 MeV/u Kr^{36+} --> (2-20) Si 10 μm thickness

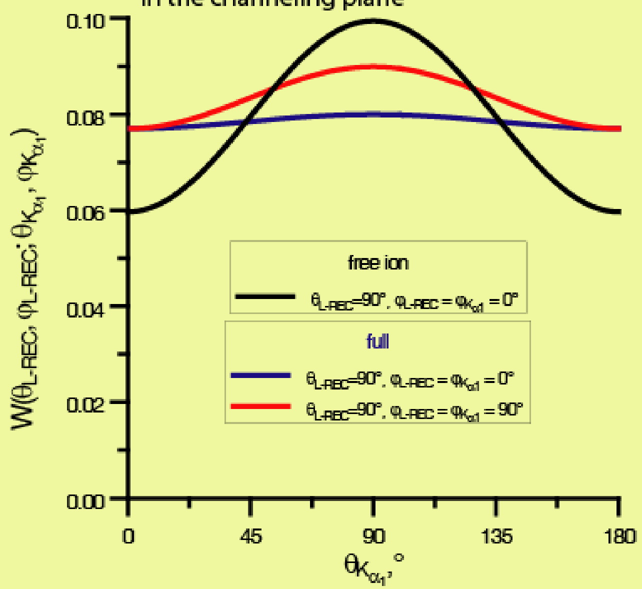
in coincidence with Kr^{35+}

- full caclulation
- no collisional and stark mixing

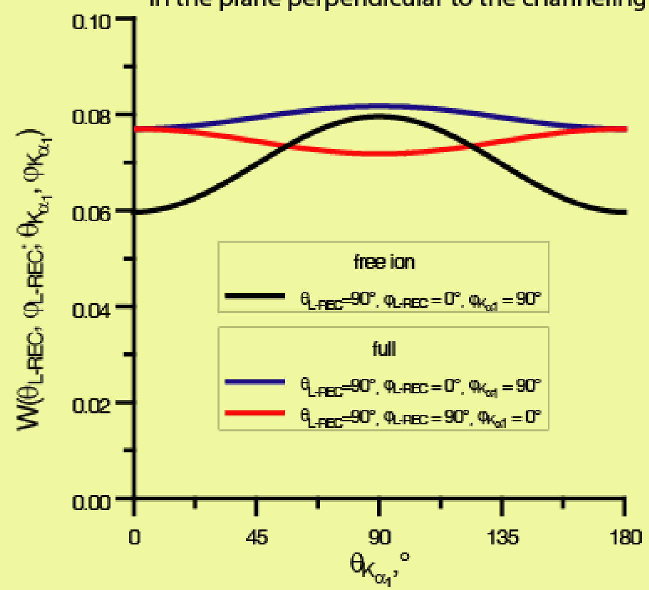
Differential yield of L-REC and K lines



Angular correlation of L-REC and K photons in the channeling plane



Angular correlation of L-REC and K photons in the plane perpendicular to the channeling plane



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Thanks to co-authors:

I.Bodrenko
A.Stysin
A.Sokolik
K.Bahmina

Thanks to GSI (grant INTAS-GSI) for the support

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Thank you !