CRYSTAL EXCITATIONS FEATURES IN THE PHOTON EMISSION SPECTRUM OF THE QUANTUM CHANNELED PARTICLE

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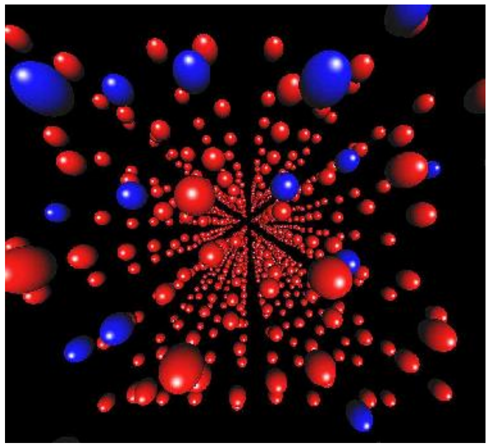


SYSTEM HAMILTONIAN

$$\hat{H} = \hat{H}_{cr} + \hat{H}_{op} + \hat{H}_{\text{int}},$$

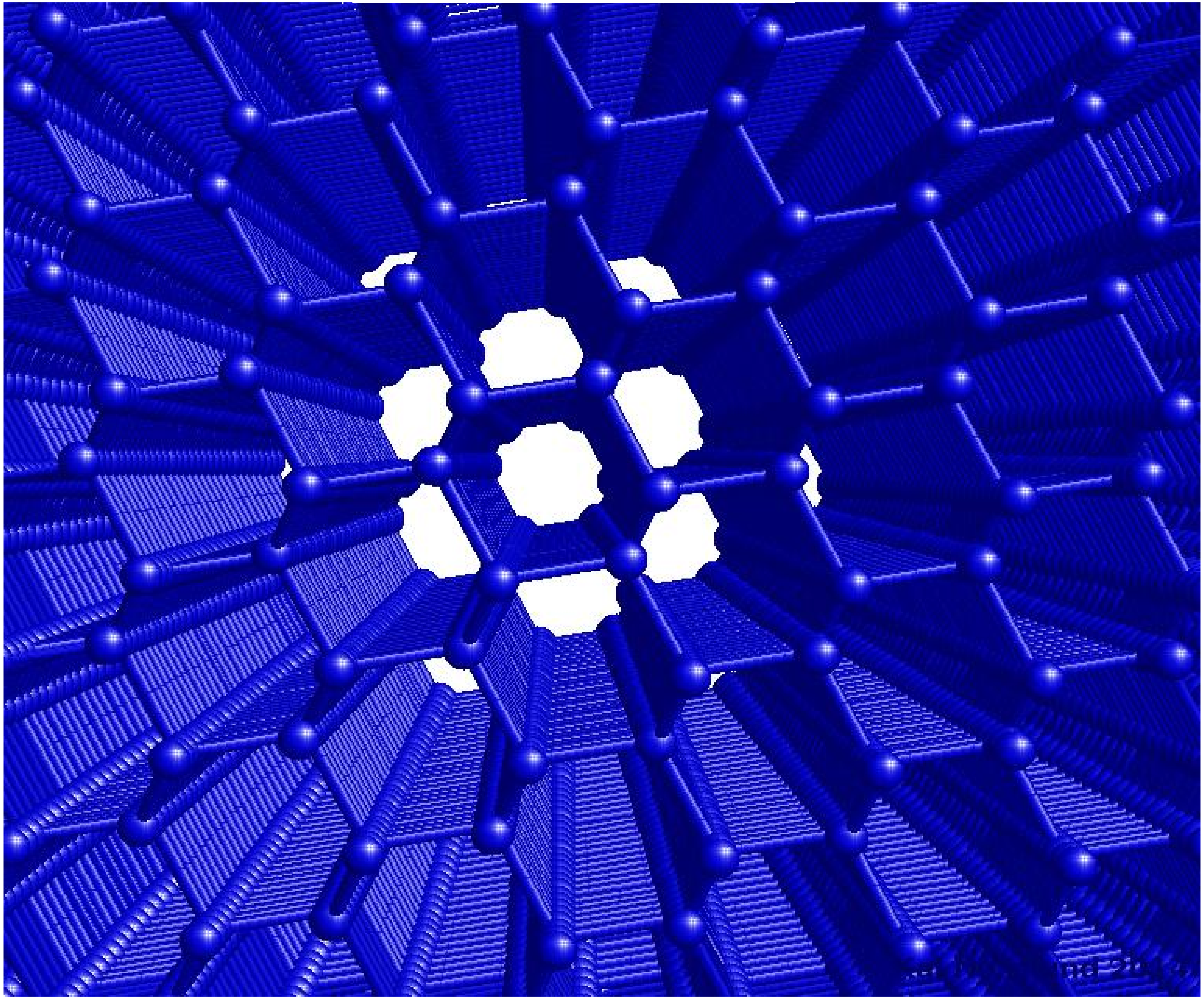
$$\hat{H}_{\text{оч}} = \vec{p}^{\,2} / 2m + eU\left(\vec{r}\right)$$

$$\left[E_{n,p}^{2} / c^{2} - 2eE_{n,\vec{p}}U\left(\vec{r}\right)/c^{2} + e^{2}U^{2}\left(\vec{r}\right)/c^{2} + \hbar^{2}\Delta_{\vec{r}} - \right.$$
$$\left. - m^{2}c^{2} + ie\hbar\vec{\sim}\nabla_{\vec{r}}U\left(\vec{r}\right)/c\right]\cdot{}_{n,\vec{p}}\left(\vec{r}\right) = 0,$$

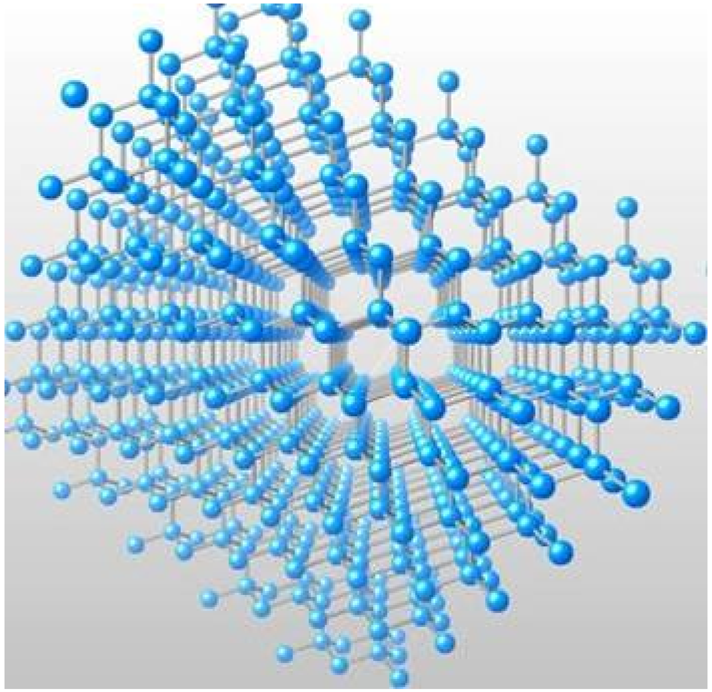
$$\vec{\sim} = ¥^{0}\vec{¥}, \qquad ¥^{«}\left(« = 1,2,3\right)$$

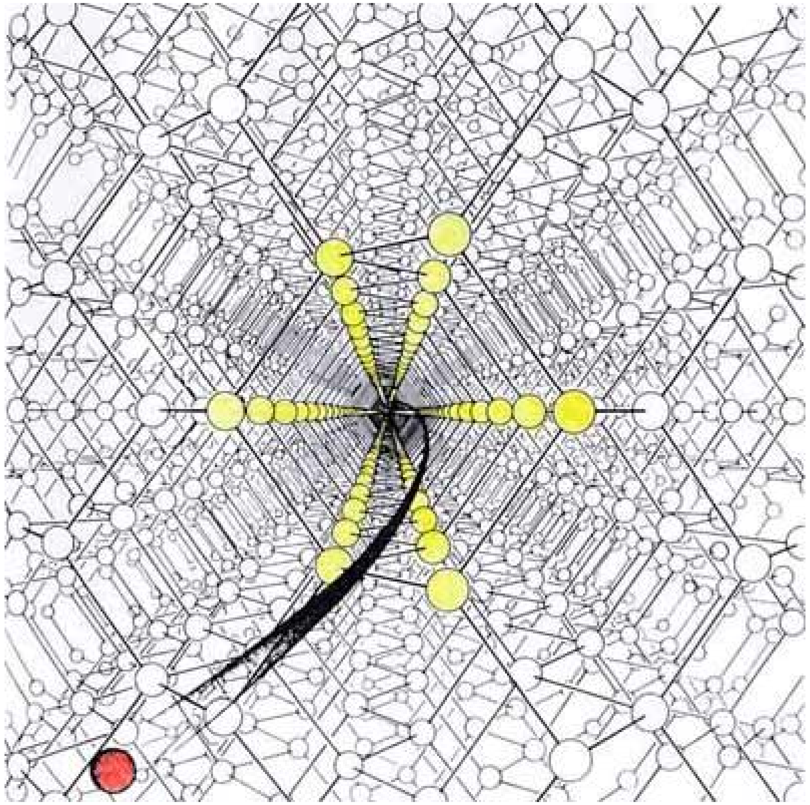
$$\left(\frac{\hbar^{2}}{2m}\Delta_{\vec{r}} + \frac{E_{n,\vec{p}}^{2} - m^{2}c^{4}}{2mc^{2}}\right)\cdot{}_{n,\vec{p}}\left(\vec{r}\right) = \left(eE_{n,\vec{p}}U\left(\vec{r}\right)/mc^{2}\right)\cdot{}_{n,\vec{p}}\left(\vec{r}\right)$$

Oriented thin crystal

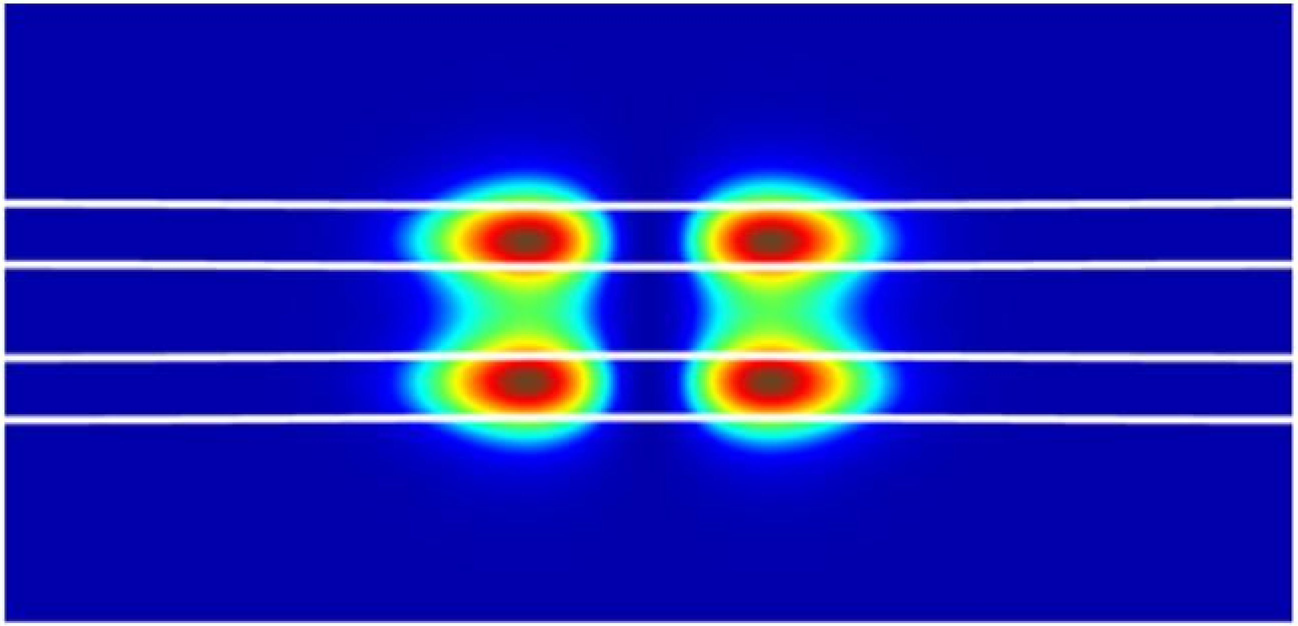


CHANNELED PARTICLE IN THE CRYSTAL

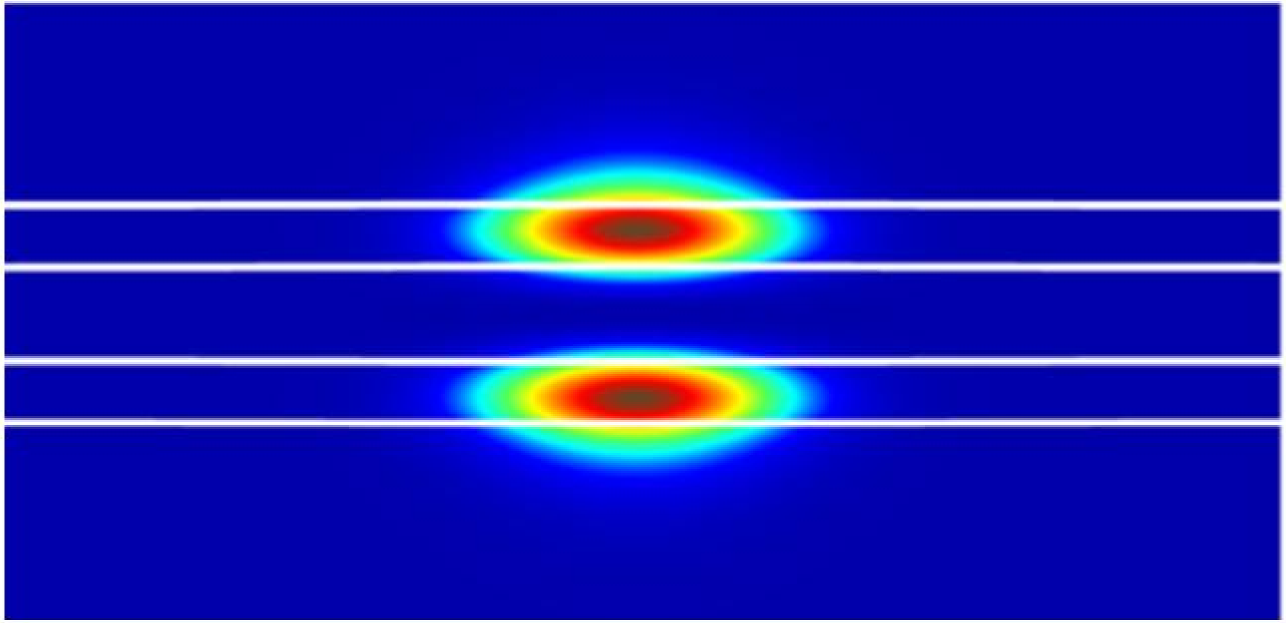


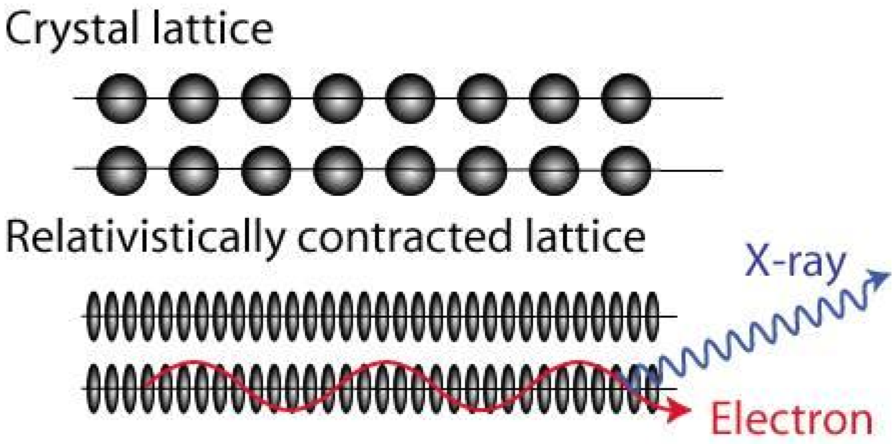


CHANNELING WITH QUASIBLOCH BEHAVIOUR OF THE CHANNELED PARTICLE



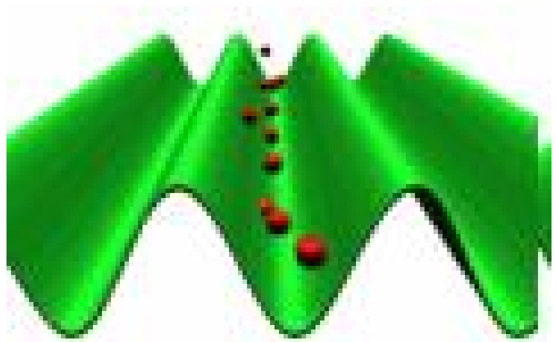
CHANNELING WITHIN THE DISTINCT CHANNELS

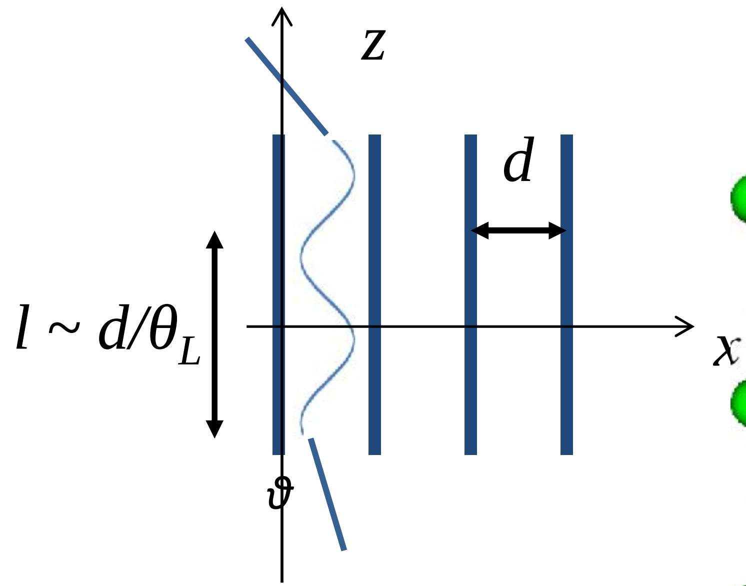


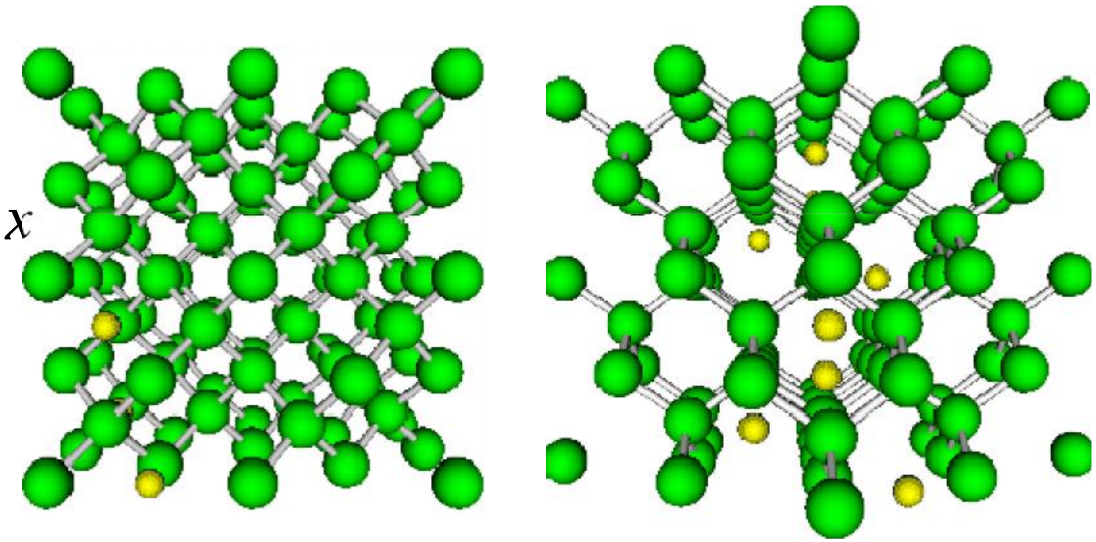


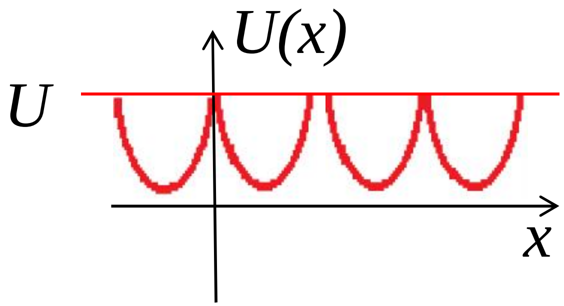
CHANNELED PARTICLE IN THE CRYSTAL

Planar channeling - thick crystal









$\theta < \theta_L = \sqrt{2U / E}$ Lindhard angle

E >> mc²; U ~ 20 - 100 eV

d – interplane distance;

S-MATRIX

$$V = Ze\int\left(jA\right)d^3x, \qquad j = \left\{j_0, \vec{j}\right\} \qquad A = \left\{\ddot{}\ , \vec{A}\right\}$$

$$\cdot\left(\vec{r}, t = 0\right) = \cdot_{\,i}\left(\vec{r}\right) \qquad \cdot\left(\vec{r}, t\right) = \sum_{n,\vec{p}} C_{n,\vec{p}}\left(t\right)\cdot_{\,n.\vec{p}}\left(\vec{r}, t\right)$$

$$M_{if}\left(t\right) = \int d^3\vec{x}\cdot^{*}_{f}\left(\vec{r}\right)\cdot\left(\vec{r}, t\right) = \int d^3\vec{r}\cdot^{*}_{f}\left(\vec{r}\right)T\exp\left\{-\int_{-\infty}^{t} V\left(t\right)dt\right\}\cdot_{\,i}\left(\vec{r}\right).$$

$$M_{if} = \left\langle i\left|S\right|f\right\rangle = \int d^3\vec{x}\cdot^{*}_{f}\left(\vec{r}\right)T\exp\left\{-iZe\int_{-\infty}^{+\infty}\left(jA\right)d^4x\right\}\cdot_{\,i}\left(\vec{r}\right).$$

$$W_{if} = \overline{\left|M_{if}\right|^2}\,¢\left(E_i - E_f - \hbar\mu\right). \qquad S = S^{(1)} + S^{(2)}$$

$$S^{(1)} = -iZe\int j\left(x\right)A\left(x\right)d^4x, \; S^{(2)} = -\frac{Z^2e^2}{2}\int\int d^4x d^4x' T\left(j^{«}\left(x\right)A_{«}\left(x\right)j^{¬}\left(x'\right)A_{¬}\left(x'\right)\right).$$

THE PROCESSES OF THE FIRST ORDER

$$dW_{if}^{(1)} = \int j_{if}^{*(0)}(x) j_{if}^{(0)}(x') \langle \Phi(x)\Phi(x')\rangle d^4x d^4x' d\neg +$$

$$+\int j_{if}^{*(\sim)}(x) j_{if}^{(\ )}(x') \langle A_{\sim}(x) A\ (x')\rangle d^4(x) d^4x' d\neg +$$

$$+\int j_{if}^{*(0)}(x) j_{if}^{(\sim)}(x') \langle [\Phi(x) A_{\sim}(x')]_+ \rangle d^4x d^4x' d\neg .$$

$$D_{\text{«}\neg}(x,x') = i\langle T A_{\text{«}}(x) A_{\neg}(x')\rangle, \qquad \vec{j}_{if} = \overline{\ddot{\ }_i(x)}\vec{\sim}\cdot{}_f(\vec{x})$$

$$\vec{A} = \sum_{K\sim}\left(\hat{C}_{K\sim}\vec{A}_{K\sim} + \hat{C}^{+}_{K\sim}\vec{A}^{*}_{K\sim}\right), \qquad \vec{A}_{\vec{K}\sim} = \sqrt{4\text{®}}\,\frac{\vec{e}^{(\sim)}}{\sqrt{2\text{µ}}}\exp\left(i\vec{K}\vec{r}\right)$$

$$dW_{if} = \sum_{\vec{G}} \frac{\mathrm{Im}\,\text{£}^{-1}\left(\vec{q},\vec{q}+\vec{G},\text{µ}\right)}{q^2\left[1-\exp\left(-\hbar\text{µ}/T\right)\right]} \langle f|e^{i\vec{q}\vec{r}}|i\rangle\langle i|e^{-i(\vec{q}+\vec{G})\vec{r}}|f\rangle\,\text{¢}\left(E_i - E_f - \hbar\text{µ}\right),$$

$$W = \sum_q W_{if} E_i / pv$$

PHONON AND PLASMON GENERATION WITH THE CHANNELED PARTICLE

$$\hat{H}_{\text{int}\,fi} = e\int \hat{j}_{fi}\hat{A}d^4x,\qquad j^{\text{«}}_{fi} = \bar{\cdot}_f\,\text{¥}^{\text{«}}\cdot_i = \left(\cdot^*_f\cdot_i,\ \cdot^*_f\tilde{\vec{}}\cdot_i\right),\quad dW_{if} = \left|H_{\text{int}\,fi}\right|^2 d\text{¬},$$

$$dW_{if} = \overline{\int\int \hat{j}^{*(0)}_{if}(x)\, j^{(0)}_{if}(x')}\left\langle \Phi(x)\Phi(x')\right\rangle d^4x d^4x' d\text{¬}.$$

$$\Phi\left(\vec{q}+\vec{G},t\right) = V_c\left(\vec{q}+\vec{G}\right)\text{¢°}_e\left(\vec{q}+\vec{G},t\right) + \sum_p V_p\left(\vec{q}+\vec{G}\right)\text{¢°}_p\left(\vec{q}+\vec{G},t\right).$$

$$W_{if} = \sum_{\vec{G},\vec{G}',\mu}\ \sum_{q'\text{£}BZ}\left\langle \cdot^*_i l^{i\left(\vec{q}+\vec{G}\right)\vec{r}}\cdot_f\right\rangle\left\langle \cdot_i e^{i\left(\vec{q}-\vec{G}\right)\vec{r}'}\cdot^*_f\right\rangle\times$$

$$\times\Big[V_c\left(\vec{q}+\vec{G}\right)V_c\left(\vec{q}+\vec{G}'\right)e^2S_{ee}\left(\vec{q}+\vec{G},\vec{q}+\vec{G}'\mu\right) + \sum_{pp}V_p\left(\vec{q}+\vec{G}\right)V_{p'}\left(\vec{q}+\vec{G}'\right)\times$$

$$\times e^2S_{pp'}\left(\vec{q}+\vec{G},\vec{q}+\vec{G}'\mu\right) + 2\sum_p e^2V_c\left(\vec{q}+\vec{G}\right)V_p\left(\vec{q}+\vec{G}'\right)S_{ep}\left(\vec{q}+\vec{G},\vec{q}+\vec{G}',\mu\right)\Big].$$

GENERATION OF THE PHONONS AND ELECTRON EXCITATIONS WITH THE CHARGED PARTICLE IN THE SOLID

$$\frac{1}{2\text{®}}\int_{-\infty}^{+\infty} dt\, e^{i(\mu+i\text{¢})t}\left\langle \text{¢°}_A\left(\vec{q}+\vec{G},t\right)\text{¢°}_B\left(\vec{q}'+\vec{G}',0\right)\right\rangle_T = S_{AB}\left(\vec{q}+\vec{G},\vec{q}'-\vec{G}',\mu\right).$$

$$W_{if} = W_{if}\left(electron\right)+W_{if}\left(phonon\right)+W_{if}\left(\mathrm{int}\right).$$

$$W_{if} = \sum_{\vec{G},\vec{G}'}\int\int d^3\vec{x}d^3\vec{x}'\left(\cdot_f^{*}\exp\left(i\left(\vec{q}+\vec{G}\right)x\right)\right)\cdot_i\left(\vec{x}\right)\left(\cdot_i^{*}\left(\vec{x}'\right)\exp\left(i\left(\vec{q}+\vec{G}'\right)x'\right)\right)\times$$
$$\times\cdot_f\left(\vec{x}'\right)\sum_{pp'}V_p\left(\vec{q}+\vec{G}\right)V_p\left(\vec{q}+\vec{G}'\right)S_{pp'}\left(\vec{q}+\vec{G},\vec{q}+\vec{G}',\mu\right).$$

$$V_p\left(\vec{q}+\vec{G}\right)=\sum_{G'}V_{cp}\left(\vec{q}+\vec{G}\right)\text{£}^{-1}\left(\vec{q}+\vec{G},\vec{q}+\vec{G}'\right)$$

$$S_{kp}\left(\vec{q}+\vec{G},\vec{q}+\vec{G}',\mu\right)=S_{kp}^{(1)}\left(\vec{q}+\vec{G},\vec{q}+\vec{G}',\mu\right)+$$
$$+S_{kp}^{(2)}\left(\vec{q}+\vec{G},\vec{q}+\vec{G}',\mu\right)+S^{(\mathrm{int})}\left(\vec{q}+\vec{G},\vec{q}+\vec{G}',\mu\right)+\ldots$$

PLASMON DISPERSION

$$\mathrm{Im}\left[-\frac{1}{\text{£}\left(\vec{q},\text{µ}\right)}\right]=\frac{\text{®µ}_p^2}{2\text{µ}^2\left(\vec{q}\right)}\text{¢}\left(\text{µ}-\text{µ}\left(\vec{q}\right)\right);$$

$$\text{µ}^2\left(\vec{q}\right)=\text{µ}_p^2+\left(\frac{\vec{q}^{\,2}}{2m}\right)^2.$$

ONE PHONON DYNAMICAL STRUCTURE FACTOR AND THE DEBYE-WALLER FACTOR

one-phonon dynamical structure factor

$$S_{kp}^{(1)}\left(\vec{q}+\vec{G},\vec{q}+\vec{G}',\mu\right)=\exp\left[-Y_k\left(\vec{q}+\vec{G}'-\vec{G}'\right)-Y_p\left(\vec{q}+\vec{G}'-\vec{G}'\right)\right]\sum_{n}F_k^{(1)}\left(\mathrm{a}\right)F_p^{*(1)}\left(\mathrm{a}\right)\times$$

$$\times\; exp\left[-i\left(\vec{q}+\vec{G}'-\vec{G}''\right)\vec{R}_{kp}^{(0)}\right]\sum_{\pm}\Delta\left(\vec{q}_{\mathrm{a}}\pm q\right)\left[n\left(2\right)+\frac{1}{2}\mp\frac{1}{2}\right]\text{¢}\left(\mu\pm\mu\left(\mathrm{a}\right)\right).$$

RADIUS-VECTORS OF THE IONS IN THE CRYSTAL

$$\vec{R}_{kp}^{(0)}=\vec{R}^{(0)}\left(0,k\right)-\vec{R}^{(0)}\left(0,p\right)$$

$$F_k^{(1)}\left(\mathrm{a}\right)=\left(\hbar/2M_kN\mu\left(\mathrm{a}\right)\right)^{1/2}\left[\left(\vec{q}+\vec{G}'\right)\vec{e}\left(k\right)\mathrm{a}\right].$$

DEBYE-WALLER FACTOR

$$Y_k\left(\vec{q}+\vec{G}'-\vec{G}''\right)=\left(\hbar/2M_kN\right)\sum_{\mathrm{a}}\frac{\left|e\left(k\middle|\mathrm{a}\right)\left(\vec{q}+\vec{G}'-\vec{G}''\right)\right|^2}{\mu\left(\mathrm{a}\right)}\left[2n\left(\mathrm{a}\right)+1\right].$$

TWO-PHONON AND MULTIPHONON DYNAMICAL STRUCTURE FACTORS

$$S_{kp}^{(2)}\left(\vec{q}+\vec{G}',\vec{q}+\vec{G}'',\mu\right)=\exp\left[-Y_k\left(\vec{q}+\vec{G}'-\vec{G}''\right)-Y_p\left(\vec{q}+\vec{G}'-\vec{G}''\right)\right]\times$$

$$\times\exp\left[-i\left(\vec{q}+\vec{G}'-\vec{G}''\right)\vec{R}_{kp}^{(0)}\right]\sum_{\text{a}_1\text{a}_2}F_k^{(1)}\left(\text{a}_1\right)F_k^{(1)}\left(\text{a}_2\right)F_p^{*(1)}\left(\text{a}_1\right)F_p^{*(1)}\left(\text{a}_2\right)\times$$

$$\times\sum_{t,t'=\pm 1}\Delta\left(\vec{q}+t\vec{q}_{\text{a}_1}+t'\vec{q}_{\text{a}\,2}\right)¢\left(\mu+t\mu\left(\text{a}_1\right)+t'\mu\left(\text{a}_2\right)\right)\left[n\left(\text{a}_1\right)+\frac{1}{2}+\frac{t}{2}\right]\left[n\left(\text{a}_2\right)+\frac{1}{2}+\frac{t'}{2}\right].$$

ENERGY-MOMENTUM CONSERVATION LAWS FOR THE QUANTUM CHANNELED PARTICLE

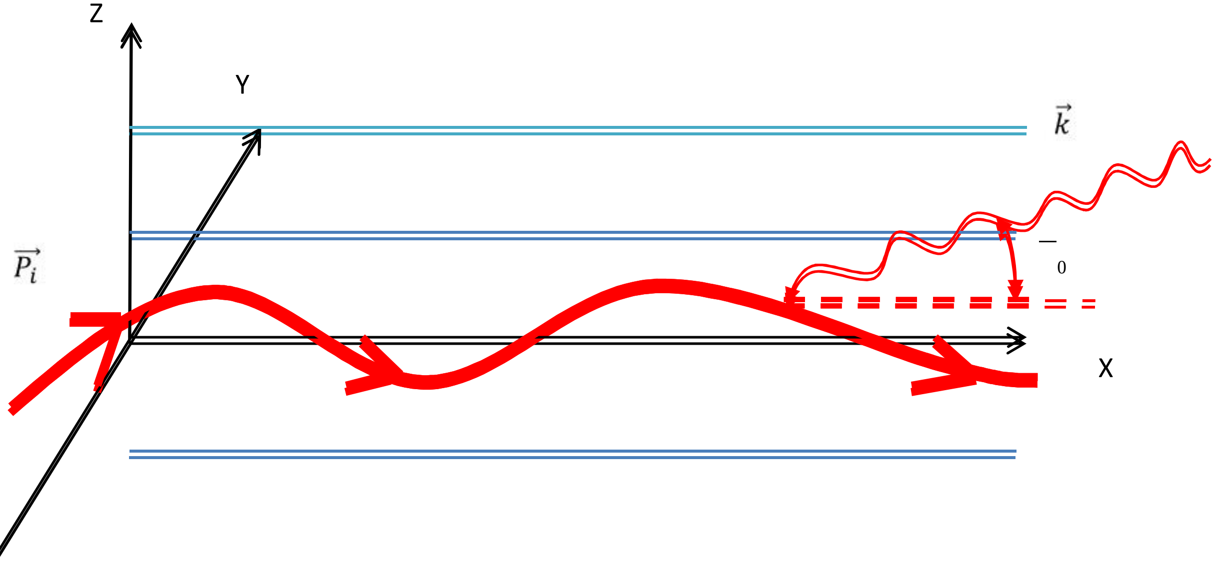
$\hbar\vec{K}:\ \ E_n(\vec{q}) = E_{n'}\left(\vec{q}+\vec{K}'\right);$ $\qquad$ $\text{©}_n^2(q_x) = 2EE_n(q_x)$ $\qquad$ $\hbar q_y / m_{\text{рел}} = V_y \ \ \left(V_y\right.$

$q_y\left(q_y \gg K_y\right)$ $\qquad$ $2\hbar K_y q_y c^2 = \text{©}_n^2 - \text{©}_{n'}^2.$ $\qquad$ $\hbar K_y V_y = E_n - E_{n'}$

$$m_0^2c^4 + \hbar q_y^2c^2 + \hbar q_z^2c^2 + \text{©}_n^2(q_x)c^2 =$$
$$= m_0^2c^4 + \hbar^2\left(q_y + K_y\right)^2 + \hbar q_z^2c^2 + \text{©}_{n'}^2(q_x)c^2.$$

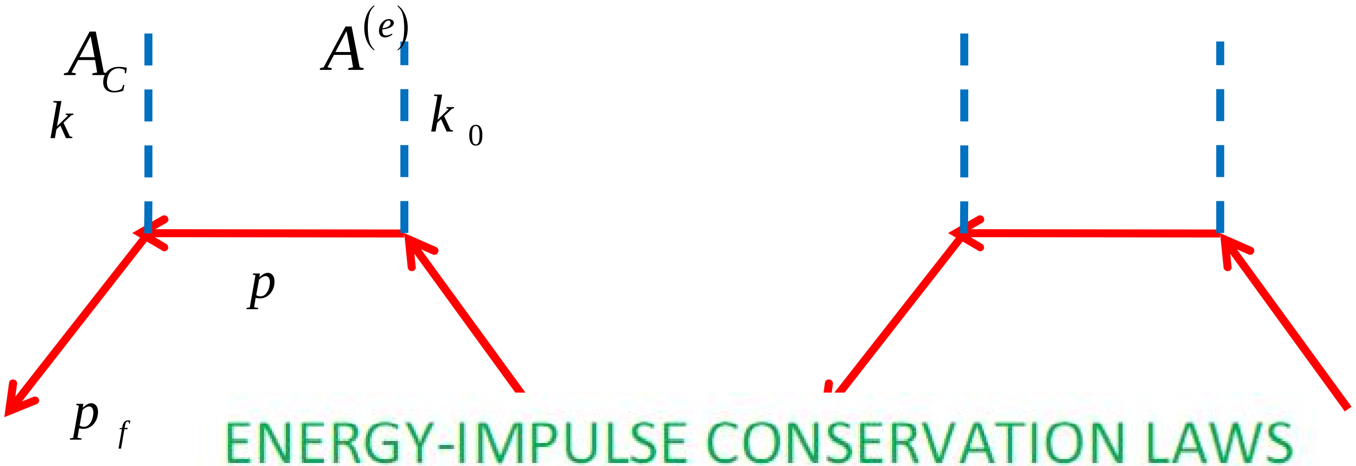
$$\hbar\mu = \left(\Delta E'_\perp\sqrt{1-\left(v_\parallel / c\right)^2} - \hbar\mu_{pe}\right) / \left(1-\left(v_\parallel / c\right)n(\mu)\cos^{-}\right).$$

IN CLASSICAL APPROXIMATION



$$\vec{p}_{i\perp}^{\,2} \big/ 2m \ll \langle U \rangle, \qquad \frac{p_0^2 - {}_0^2}{2m} \ll \langle U \rangle, \qquad \bar{}_0 \le \frac{2mU}{p_0^2} \approx \bar{}_L$$

Plasmon excitation (or absorption) and photon excitations by “bound” electrons



ENERGY-IMPULSE CONSERVATION LAWS

$$\boldsymbol{p}_i + \boldsymbol{k}_0 = \boldsymbol{p}_f + \boldsymbol{k},$$

$$\left|\vec{\boldsymbol{p}}_i\right| \cos{}^{-}{}_i + \frac{\hbar\mu_0}{\boldsymbol{c}} \cos\cdot{}_i = \left|\vec{\boldsymbol{p}}_f\right| \cos{}^{-}{}_f + \frac{\hbar\mu}{\boldsymbol{c}} \cos\cdot{}_f,$$

$$\boldsymbol{E}_i + \hbar\mu_0 = \boldsymbol{E}_f + \hbar\mu,$$

$$\hbar\mu = \boldsymbol{E}_i - \boldsymbol{E}_f + \hbar\mu_0.$$

Related coordinate system

$$p_x = \frac{p'_x + \left(\frac{E'}{c}\right)}{\sqrt{1- \quad ^2}} = 0, \qquad = -\frac{p'_x c}{E'},$$

Impulse and energy in the

related coordinate system

$$p_y = p'_y,$$

$$p_z = p'_z, \qquad \left(p_\perp = p'_\perp\right)$$

$$¥ = \frac{1}{\sqrt{1- \quad ^2}}$$

$$\left(\frac{E}{c}\right) = \frac{\left(\frac{E'}{c}\right) + \quad p'_x}{\sqrt{1- \quad ^2}} \approx \frac{¥}{c}\left(m_0 c^2 + \frac{p_\perp^2}{2m}\right).$$

In related system

$$\mu = \mu_0 \frac{\sqrt{1-\frac{v^2}{c^2}}}{1+\frac{\vec{v}\vec{k}}{\mu_0}} = \mu_0 \frac{\sqrt{1-\frac{v^2}{c^2}}}{1+\frac{v\cos\left(® - ^-\right)}{c}} \approx \mu_0 \frac{\sqrt{1-\frac{v^2}{c^2}}}{1-\frac{v}{c}+\frac{v}{c}-{}^2}.$$

MATRIX ELEMENTS

$$S_{i\to f} = -2\text{®}\, iU_{if}\,\text{¢}\left(E_i + \text{µ}_i - E_f - \text{µ}_f\right)$$

$$U_{i\to f} = -2\text{®}\sim e^{i\left(\vec{k}_i - \vec{k}_f\right)\vec{R}}\sqrt{\text{µ}_i \text{µ}_f}\sum_n \left\{ \frac{\left(\vec{r}\vec{e}_f\right)_{fn}\left(\vec{r}\vec{e}_i\right)_{ni}}{E_i - E_n + \text{µ}_i} + \frac{\left(\vec{r}\vec{e}_i\right)_{fn}\left(\vec{r}\vec{e}_f\right)_{ni}}{E_i - E_n - \text{µ}_f} \right\}\text{¢}\left(E_i + \text{µ}_i - E_f - \text{µ}_f\right)$$

$$d\text{±} = 2\text{®}\left|U_{if}\right|^2 \text{¢}\left(E_i + \text{µ}_i - E_f - \text{µ}_f\right)\frac{d^3\vec{k}_f}{\left(2\text{®}\right)^3}$$

$$d\text{±} = \left|\sum_n \left\{ \frac{\left(\vec{Q}\vec{e}_f\right)_{fn}\left(\vec{Q}\vec{e}_i\right)_{ni}}{E_i - E_n + \text{µ}_i} + \frac{\left(\vec{Q}\vec{e}_i\right)_{fn}\left(\vec{Q}\vec{e}_f\right)_{ni}}{E_i - E_n - \text{µ}_f} \right\}\right|^2 \text{µ}_i \text{µ}_f^2\, d\Omega_f$$

MATRIX ELEMENTS

$$\omega_1 = E_s - E_1 \qquad\qquad (\omega_1{=}\omega_2)$$

$$\psi_{\,s} \sim e^{-i(E_s - \frac{i}{2} r_s)t}$$

$$U_{i\to f} = -\frac{\text{2®~}}{\sqrt{\mu_i \mu_f}} \sum_n \left\{ \frac{\left(f \left| \hat{e}_f e^{-\vec{k}_f \vec{r}} \right| n \right) \left(n \left| \hat{e}_i e^{\vec{k}_i \vec{r}} \right| i \right)}{E_i - E_n + \mu_i} + \frac{\left(f \left| \hat{e}_f e^{\vec{k}_i \vec{r}} \right| n \right) \left(n \left| \hat{e}_f e^{-\vec{k}_f \vec{r}} \right| i \right)}{E_f - E_n + \mu_f} \right\}$$

$$d\sigma = \omega_1 \omega_2{}^3 d\Omega_2 \sum \frac{\langle 2 | \vec{Q}\widehat{\vec{e_2}} | s \rangle \langle s | \vec{Q}\widehat{\vec{e_1}} | 1 \rangle}{(E_s - E_1 - \omega_1)^2 + \frac{1}{4} r_s{}^2)}$$

PHOTON ENERGY

$$\hbar\mu = \frac{\Delta E'_{\perp}\sqrt{1-\left(v_{\parallel}/c\right)^{2}} \pm \hbar\mu_{pe}}{1-\left(v_{\parallel}/c\right)n\left(\mu\right)\cos^{-}}$$

$$\hbar\mu = \frac{\Delta E'_{\perp}\sqrt{1-\left(v_{\parallel}/c\right)^{2}} \pm m\hbar\mu_{phonon}}{1-\left(v_{\parallel}/c\right)n\left(\mu\right)\cos^{-}}$$

$$\hbar\mu = \frac{\hbar\mu_{pe}}{1-\left(v_{\parallel}/c\right)n\left(\mu\right)\cos^{-}};\quad \hbar\mu = \frac{m\hbar\mu_{transv1,phonon} \pm s\hbar\mu_{transv2,phonon}}{1-\left(v_{\parallel}/c\right)n\left(\mu\right)\cos^{-}}$$

COHERENT PROCESSES

$$\left[\left(\frac{i\hbar}{c}\frac{\partial}{\partial t}-\frac{e}{c}U\left(\text{£}\right)\right)^{2}+\hbar^{2}\Delta-m^{2}c^{2}-i\frac{e\hbar}{c}\overline{\sim}\frac{\partial U}{\partial\Sigma}\right]\text{¨}=0.$$

$$i\hbar\frac{\partial\text{¨}\left(x,t\right)}{\partial t}=\left\{\left[\hbar^{2}c^{2}\Delta_{xx}+E^{2}-m^{2}c^{4}-\hbar^{2}P_{z}^{2}c^{2}-\hbar^{2}P_{y}^{2}c^{2}-2EeU\left(x\right)\right]/E+Ve^{i\mu_{1}t}\right\}\text{¨}\left(x,t\right).$$

$$T=\text{®}\hbar/V_{mn}\qquad 2\hbar K_{y}q_{y}c^{2}=\text{©}_{n}^{2}-\text{©}_{n'}^{2}.\qquad \hbar K_{y}V_{y}=E_{n}-E_{n'}$$

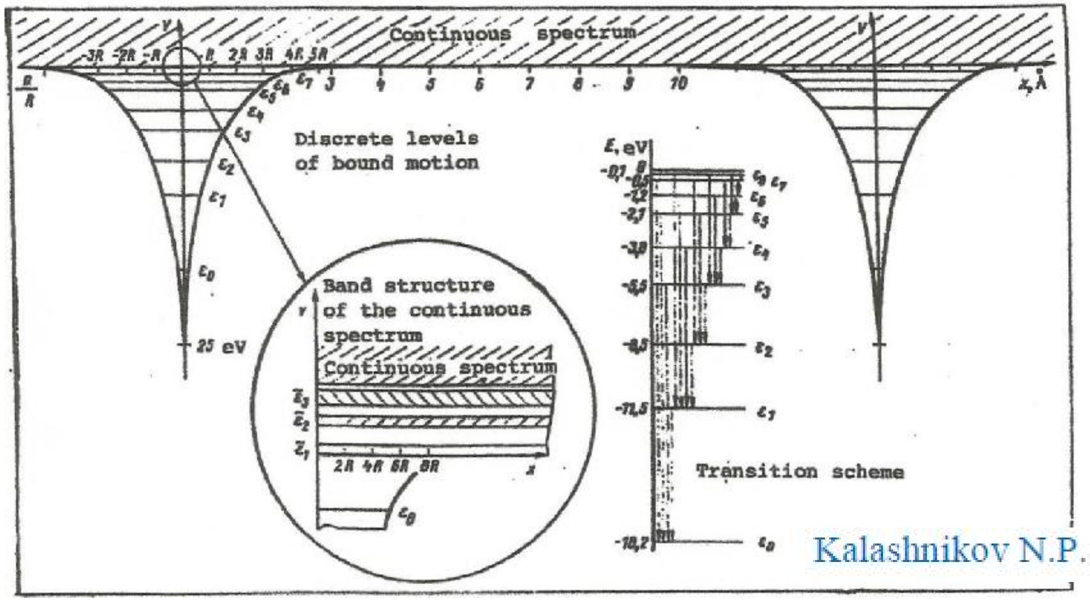
Structure of energy bands, ratio of initial population and radiative transitions of 56-MeV electrons channeled along the (110) plane in Si

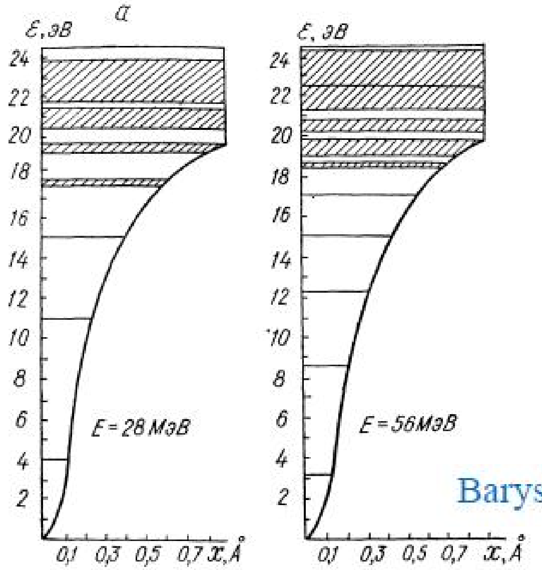
$$\langle \Delta E \rangle \sim \frac{U_{related}}{N} \sim \frac{U_0 \gamma}{\sqrt{\gamma}} \sim U_0 \sqrt{\gamma},$$

$$U_0(W) \approx 100eV, \quad R \approx 0{,}2\,\mathring{A},$$

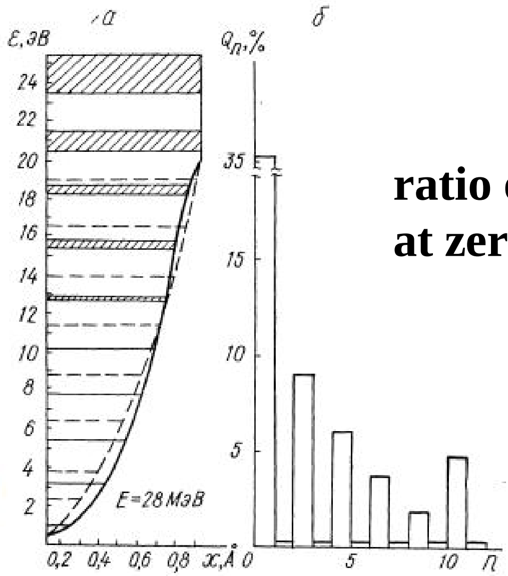
$$\langle \mu_{12} \rangle (lab) \sim U_0 \gamma^{\frac{3}{2}},$$

$$\langle \mu_{max} \rangle (lab) \sim U_0 \gamma^{2}.$$





Baryshevsky V.G.



ratio of initial population at zero angle of incidence

MATRIX ELEMENTS

$$V\left(x,y,z\right)=\begin{cases}-V_{\circ} & |x|<R_{\circ};\\ 0 & |x|>R_{\circ}.\end{cases}$$

$$\cdot_{©P_yP_z}=\cdot_{©}\left(x\right)\exp\left\{iP_yY+iZ\sqrt{P^2-P_y^2+©^2}\right\},$$

$$\cdot_{©}\left(x\right)=D_{©}\left(P_x\right)¨_{©}\left(x\right);\quad \frac{1}{L_x}\int\cdot_{©}^{*}\cdot_{©'}dx=¢_{©©'};$$

$$¨_{©}^{(even)}\left(x\right)=\begin{cases}\exp\left(-©|x|\right) & |x|>R_{\circ};\\ \exp\left(-©R_{\circ}\right)\dfrac{\cos\ ¦x}{\cos\ ¦R_{\circ}} & |x|<R_{\circ};\end{cases}$$

$$\left(©=¦\ \mathrm{tg}\ ¦\ R_{\circ}\right);$$

$$¨_{©}^{(odd)}\left(x\right)=\begin{cases}\exp\left(-©|x|\right)\mathrm{sgn}\,x & |x|>R_{\circ};\\ \exp\left(-©R_{\circ}\right)\dfrac{\sin ¦x}{\sin ¦R_{\circ}} & |x|<R_{\circ};\end{cases}$$

$$\left(©=-¦\ \mathrm{tg}\ ¦R_{\circ}\right),\ \ \mathrm{sgn}\,x=\begin{cases}1 & x>0\\ 0 & x=0,\\ -1 & x<0\end{cases}$$

$$©^2=-2EE_{\perp};\quad ¦^2=2E\left(V_0+E_{\perp}\right);\quad E_{\perp}<0;$$

$$D_{©}^2=\frac{©¦^2L_x}{©_{\circ}^2\left(1+©R_{\circ}\right)}\exp\left(2©R_{\circ}\right);\qquad \left(©_{\circ}^2=2EV_{\circ}\right),$$

$$R_{\circ}\sqrt{©_{\circ}^2-©^2}=\frac{®}{2}n+\arcsin\frac{©}{©_{\circ}},\quad \mathrm{n}=0,1,2,\ldots N;\quad \left(N>\frac{2}{®}R_{\circ}\sqrt{2E_{\circ}V_{\circ}}>N-1\right).$$

MATRIX ELEMENTS

$$\int \cdot_{\copyright'}^{*(even)}(x)\exp\left(-iq_x x\right)\cdot_{\copyright}^{(even)}(x)\,dx = D_{\copyright}D_{\copyright'}\exp\left[-\left(\copyright+\copyright'\right)R_{\circ}\right].$$

$$\left\{\frac{-2\left[-\left(\copyright+\copyright'\right)\cos\left(q_x R_{\circ}\right)+q_x\sin\left(q_x R_{\circ}\right)\right]}{q_x^2+\left(\copyright+\copyright'\right)^2}+\left[\frac{1}{\left(\text{¦}+q_x\right)^2-\text{¦}'^2}+\frac{1}{\left(\text{¦}-q_x\right)^2-\text{¦}'^2}\right]\times\right.$$

$$\times\left[\cos\left(q_x R_{\circ}\right)\left(\copyright-\copyright'\right)+q_x\sin\left(q_x R_{\circ}\right)\right]+\left[\frac{1}{\left(\text{¦}+q_x\right)^2-\text{¦}'^2}-\frac{1}{\left(\text{¦}-q_x\right)^2-\text{¦}'^2}\right]\times$$

$$\left.\times\left[\sin\left(q_x R_{\circ}\right)\frac{\text{¦}^2+\copyright\copyright'}{\text{¦}}+\frac{\copyright}{\text{¦}}\cos\left(q_x R_{\circ}\right)q_x\right]\right\}.$$

MATRIX ELEMENTS

$$1/\left[\left(\text{¦}-q_x\right)^2-\text{¦}'^2\right],\ 1/\left[q_x^2+\left(\text{©}+\text{©}'\right)^2\right]$$

$$\int \cdot_{\text{©}'}^{*(even)}\left(x\right)\exp\left(-iq_x x\right)\cdot_{\text{©}}^{(even)}\left(x\right)dx=-D_{\text{©}}D_{\text{©}'}\exp\left[-\left(\text{©}+\text{©}'\right)R_\circ\right]\times$$

$$\times\frac{4\text{©}_\circ^2}{\left(\text{©}-\text{©}'\right)^2}\frac{q_x\sin q_x R_\circ}{\left(\text{©}+\text{©}'\right)^2}.$$

$$-AA'\exp\left[-\left(\text{©}+\text{©}'\right)R_\circ\right]2\cos\left(q_x R_\circ\right)q_x^2\left[\frac{1}{\left(\text{©}+\text{©}'\right)^3}+\frac{\text{©}'}{\left(\text{¦}^2-\text{¦}'^2\right)^2}\right].$$

MATRIX ELEMENTS

$$\cdot\, {}_{\copyright'}^{*(even)}\left(x\right)\exp\left(iq_x x\right)\cdot\, {}_{\copyright}^{(odd)}\left(x\right)$$

$$q_x /\left(\copyright - \copyright'\right),\ q_x /\left(\copyright + \copyright'\right)$$

$$\int \cdot\, {}_{\copyright'}^{*(even)}\left(x\right)\exp\left(-iq_x x\right)\cdot\, {}_{\copyright}^{(odd)}\left(x\right)dx \sim q_x^2 /\left(\copyright - \copyright'\right)^2 .$$

$$\int \cdot\, {}_{\copyright'}^{*(odd)}\left(x\right)\exp\left(-iq_x x\right)\cdot\, {}_{\copyright}^{(odd)}\left(x\right)dx = -D_{\copyright} D_{\copyright'} \times$$

$$\times \exp\left[-\left(\copyright + \copyright'\right)R_{\circ}\right]\frac{4\copyright_{\circ}^2}{\left(\copyright - \copyright'\right)^2}\frac{q_x \sin q_x R_{\circ}}{\left(\copyright + \copyright'\right)^2} .$$

Initial probability of level population

$$C_{\copyright}\left(P_x\right)=\int_{-\infty}^{+\infty} dx\cdot\ {}_{\copyright}\left(x\right)\exp\left(iP_x x\right)$$

$$C_{\copyright}\left(P_x\right)=\frac{2\copyright}{\copyright^{2}+P_x^2}\left(\frac{\copyright\left(\copyright_0^2-\copyright^{2}\right)L_x}{1+\copyright R_0}\right)^{1/2}\begin{cases}\dfrac{P_x\sin P_xR_0-\copyright\cos P_xR_0}{P_x^2-\left(\copyright_0^2-\copyright^{2}\right)};_{(n-even)}\\ i\dfrac{P_x\cos P_xR_0+\copyright\sin P_xR_0}{P_x^2-\left(\copyright_0^2-\copyright^{2}\right)}.\left(n-odd\right)\end{cases}$$

Positrons and protons

$$V=\begin{cases} 0 & |x|\le \frac{a}{2}-R_0; \\ V_0 & \frac{a}{2}-R_0\le |x|\le \frac{a}{2}+R_0. \end{cases}$$

$$\left(R_0 \ll a\right)$$

$$E_\perp > 0,\quad \text{©}^2 = 2EE_\perp, \qquad \text{¦}^2 = 2E\left(V_0 - E_\perp\right) \qquad \text{©} \leftrightarrow \text{¦},\ \ R_0 \leftrightarrow a/2$$

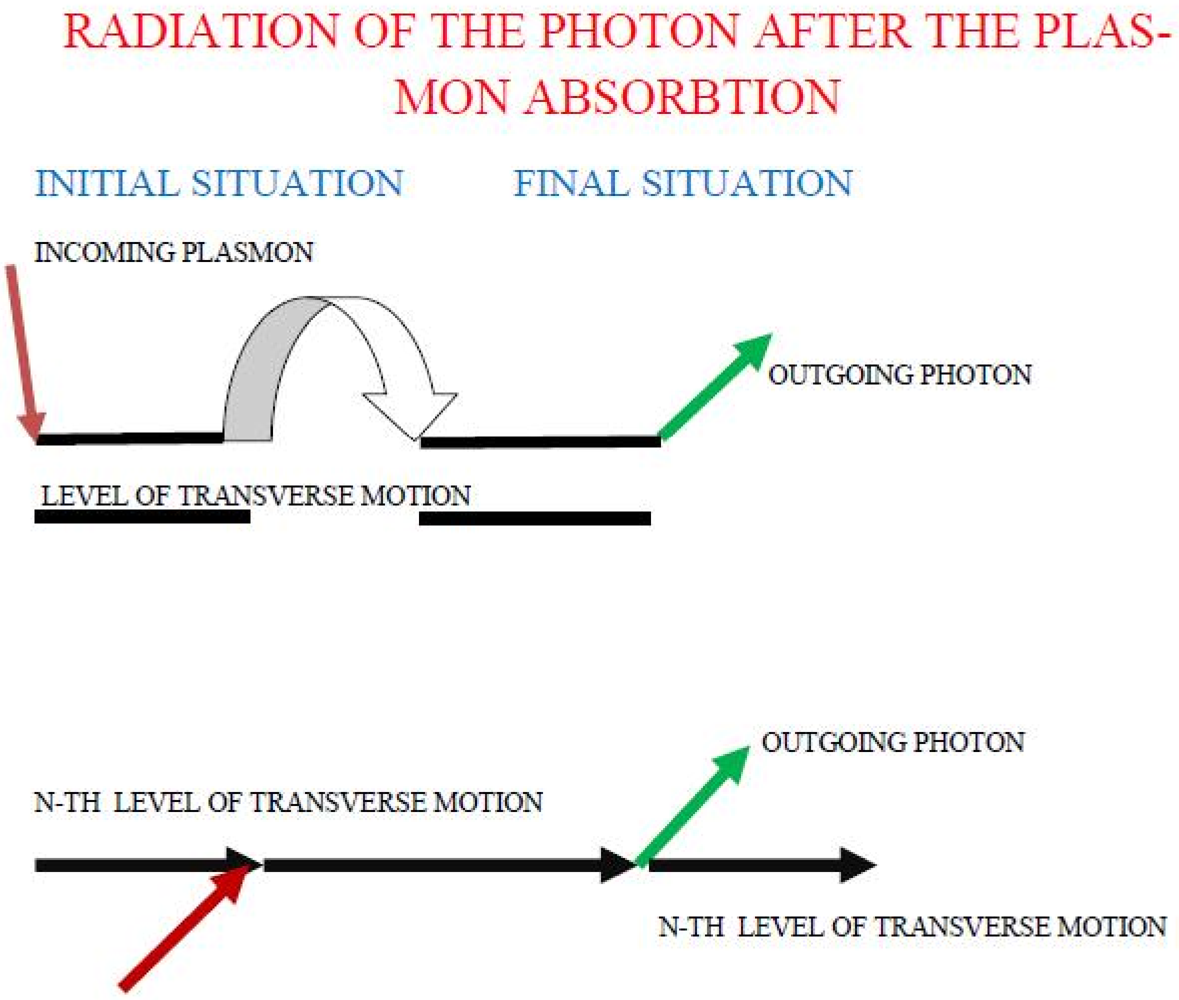
$$\int \cdot\, {}^{*(четн)}_{\text{©}'}(x)\exp\left(-iq_x x\right)\cdot\, {}^{(четн)}_{\text{©}}(x)\,dx = \frac{L_x \text{©©}'\left(\text{¦¦}'\right)^{1/2}}{\text{©}_0^2\left(\left(1+\text{¦}a/2\right)\left(1+\text{¦}'a/2\right)\right)^{1/2}}\times$$

$$\int$$

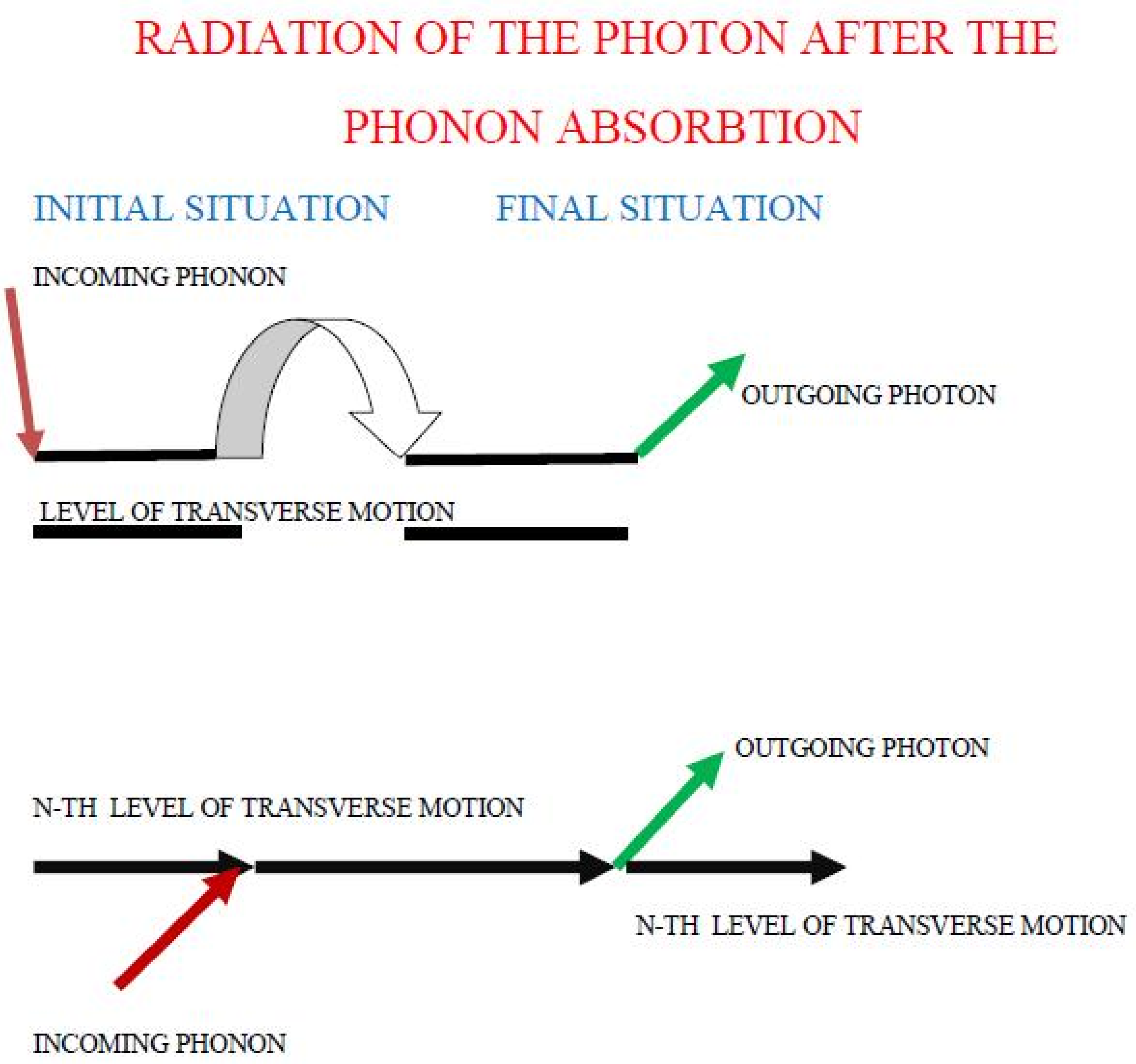
$$\times\frac{2\text{©}_0^2}{\left(\text{©}-\text{©}'\right)^2}\frac{q_x \sin q_x R_0}{\left(\text{©}+\text{©}'\right)^2}.$$

$$C_{\text{©}}\left(P_x\right)=\frac{2\text{©}_0}{\text{¦}^2+P_x^2}\left(\frac{\text{¦}\text{©}^2 L_x}{1+\text{¦}a/2}\right)^{1/2}\begin{cases} \dfrac{P_x\sin\left(P_x a/2\right)-\text{¦}\cos\left(P_x a/2\right)}{P_x^2-\text{©}^2};\left(n-even\right); \\ i\,\dfrac{P_x\cos\left(P_x a/2\right)+\text{¦}\sin\left(P_x a/2\right)}{P_x^2-\text{©}^2};\left(n-odd\right) \end{cases}.$$

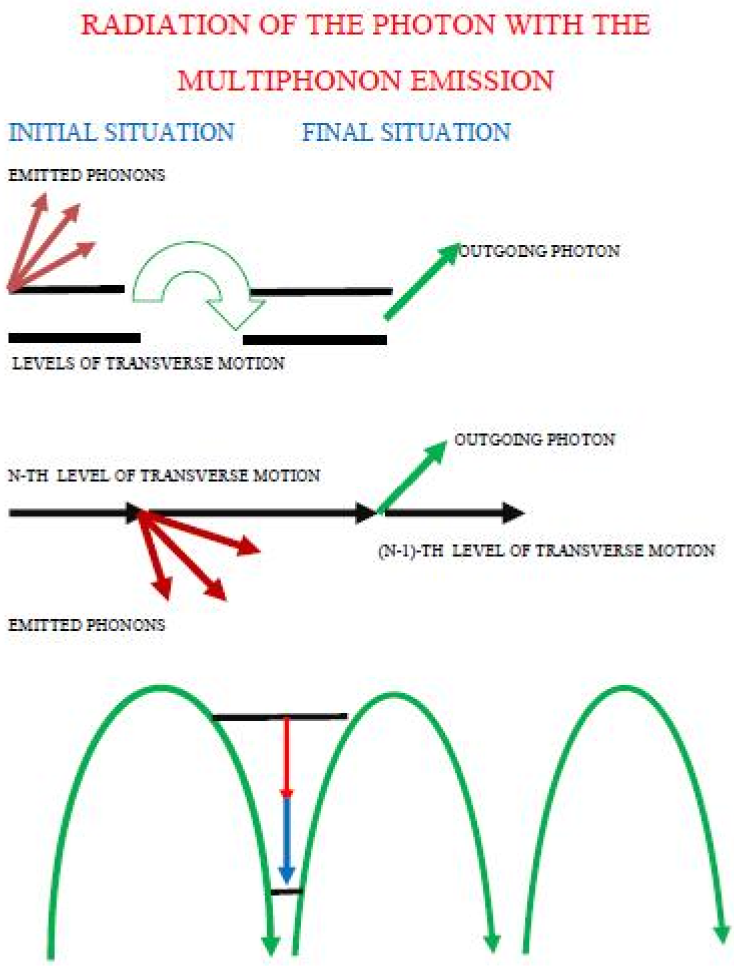
THE RADIATIVE PROCESS WITHOUT ALTERING THE QUANTUM LEVEL OF TRANSVERSE MOTION

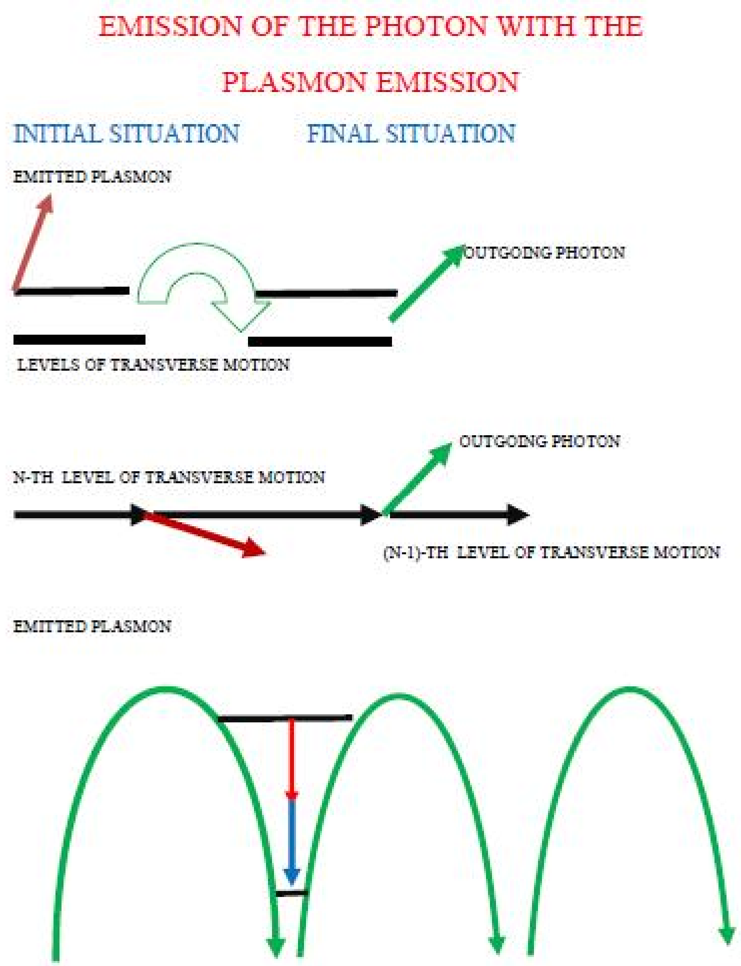


THE RADIATIVE PROCESS WITHOUT ALTERING THE QUANTUM LEVEL OF TRANSVERSE MOTION



THE RADIATIVE PROCESS WITH ALTERING THE QUANTUM LEVEL OF TRANSVERSE MOTION

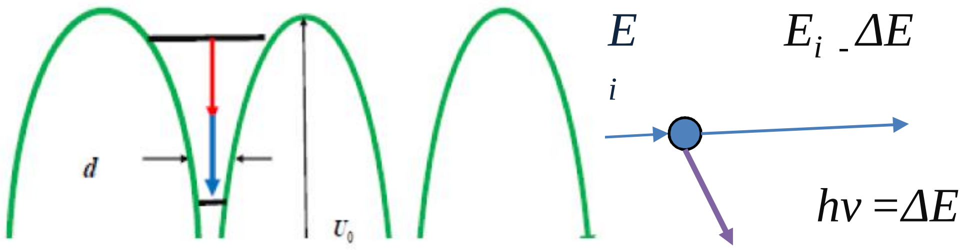


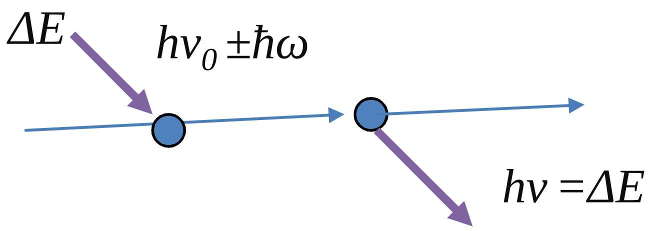


Channeling plasmon-photon or multiphonon-photon radiation conditions

Usual spontaneous radiation

Multiphonon and plasmon processes and “wings” in radiation





1. Potential in lab. system: $U_0 \sim 20eV$; $d \sim 0{,}2\text{-}0{,}3$ Å (Si);
   In related system ($v_x = 0$): $U = U_0\,(E/mc^2)$

2. Number of levels within the potential wall: $N \sim P_{z\,max} d / h \sim (EU_0)^{1/2} d / hc$
3. Distance between levels in related system: $\Delta E \sim U/N \sim (EU_0)^{1/2}(h/mcd)$

4. Multiphonon and plasmon energy in related system:

$$\hbar\mu = 2\boldsymbol{h}\neg_0 / \left(\boldsymbol{mc}^2 / \boldsymbol{E} + \boldsymbol{E}\cdot{}^2 / \boldsymbol{mc}^2\right)$$

5. In resonance conditions quantum fluorescence effect and radiation "wings" will be very noticeable on the phone of the bremsstrahlung :

$$\Delta E \sim (EU_0)^{1/2}(h/mcd) = h\nu < 2h\nu_0 E/mc^2 = 2hE/mc\lambda_0$$

6. Resonance can be reached with adjusting the energy of the channeling particles and correctly orienting laser beam, if:

$$E/U_0 > (\lambda_0/2d)^2 \sim 10^{7\text{-}8}$$

RESUME

1.The mutual influence of the processes of radiation and generation of excitations in the quantum crystal with the channeled particle (electron or positron) is considered.

2.The emergence of new peaks in the emission spectrum of such a channeled particle associated with the processes of simultaneous resonant hard gamma-quantum and plasmon (phonon) excitation during its motion in the crystal is predicted.

3. The distance between the particle transverse motion levels should be equal to the sum of the photon energy and quantum plasmon energy in the coordinate system associated with the moving particle.

4. Plasmon energy in such a system increases with the Lorentz factor , comparing the crystal potential well depth characteristic energy. The energy-momentum conservation laws in the comoving coordinates system are feasible. After the transition to the laboratory coordinate system the plasmon energy is reduced to the values of about 20 eV, while the energy of a photon emitted within a narrow cone of directions, coaxial with the motion direction of a channeled particle is determined in accordance with the energy-momentum conservation laws in this process.

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5.Essentially, this formula represents the record of the Doppler effect for the process of simultaneous emission of a photon and a plasmon with the channeled particle. In this case, however, the resulting emission peaks have a large half-width due to the plasmon (multiphonon) momentum carryover, in contrast to the conventional channeled particle radiation process without plasmon emission. Thus a cone of the emitted photons undergoes blurring.

6.The probability of the discussed process with the transition of fast particles in the virtual state after the emission of the plasmon and with the subsequent emission of photons is calculated .

7. It is found that the photon-plasmon radiation effect probability is of the same order of magnitude with a known standard radiation process probability.

8.The possibility of the experimental observation of the effect is estimated.

9.The comparison with the some theories and effects is elaborated.

THANK YOU FOR THE ATTENTION