

КИНЕТИЧЕСКИЕ ЯВЛЕНИЯ В ПОЛУПРОВОДНИКЕ, ВОЗБУЖДАЕМОМ ОРИЕНТИРОВАННЫМ ПУЧКОМ БЫСТРЫХ ЗАРЯЖЕННЫХ ЧАСТИЦ

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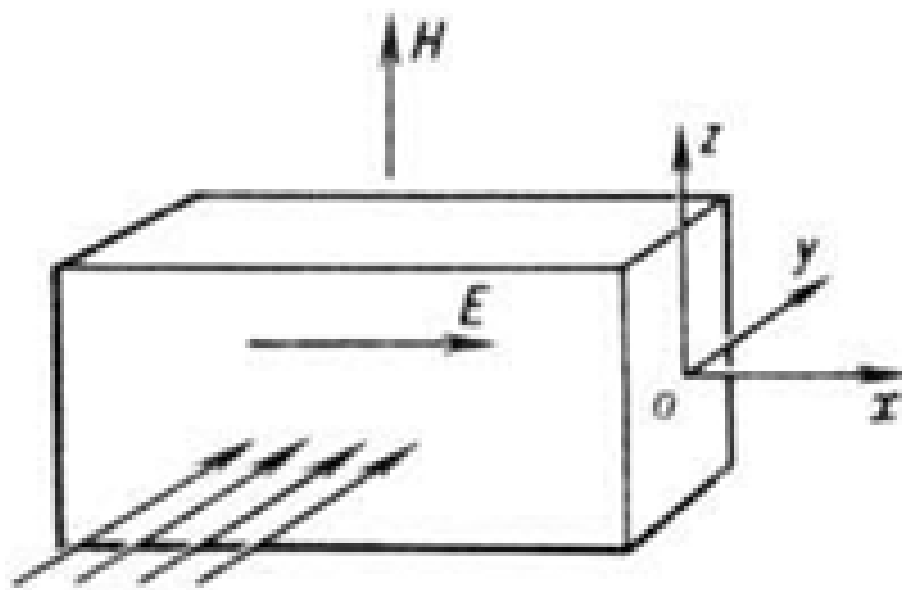
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Показано, что прохождение каналированных частиц в кристалле без центра симметрии или в магнитном поле приводит к появлению тока (квазифотогальванический и квазифотомагнитный эффекты) и построена теория этих явлений. Исследована зависимость эффекта от состояния и квантовых переходов каналированной частицы.

При воздействии на кристалл с центром симметрии импульсом быстрых частиц в магнитном поле также возникает электрический ток (эффект Кикоина-Носкова [1]). В отсутствие магнитного поля такой эффект проявляется в нецентросимметричных кристаллах.

При возбуждении кристалла пучком каналированных частиц эффекты повреждения кристалла быстрой частицей отсутствуют, а изменение энергии быстрых ориентированных заряженных частиц или их угла влета относительно кристаллографических плоскостей приводит к контролируемым изменениям уровня возбуждения кристалла и спектра генерируемых в кристалле возбуждений [2,3].

Воздействие канализированных частиц на кристалл в магнитном поле



Матрица плотности возмущенной каналированными частица электрон-фононной системы кристалла и выражения для ТОКОВ.

Общее выражение для плотности тока в макроскопически пространственно однородной электрон-фононной системе кристалла, описываемой неравновесной матрицей плотности , имеет вид

$$\vec{j} = eSp\left(\hat{V}\hat{\rho}_e\right),$$

\hat{V}

оператор скорости электронов кристалла;

$\hat{\rho}_e$

- матрица плотности электронов

Общее выражение для тока j (1) распадается на вклады диагональных элементов матрицы плотности электронов, т.е. функций распределения $f_p \equiv \rho_{pp}$

$$\vec{j}_{\text{diag}} = e \int d^3 p \left(\hat{V} \right)_{pp} \rho_{pp} \equiv e \int d^3 p f_p \left(\hat{V} \right)_{pp} = \frac{1}{\hbar} \sum_{sk} f_{sk} \frac{\partial \varepsilon_{sk}}{\partial \mathbf{K}},$$

и недиагональных элементов матрицы плотности и скорости электронов

$$\vec{j}_{\text{ndiag}} = e \int d^3 \vec{p} d^3 \vec{p}' \left(\hat{V} \right)_{pp'} \rho_{pp'}; \quad \mathbf{p} \neq \mathbf{p}'$$

Гамильтониан рассматриваемой системы имеет вид

$$\hat{H} = \hat{H}_{Kp} + \hat{H}_{4-Kp} + \hat{H}_4 \equiv \hat{H}_1 + \hat{H}_2,$$

$$\hat{H}_1 = \hat{H}_{Kp} + \hat{H}_{4-Kp}$$

$$\hat{H}_2 \equiv \hat{H}_4$$

$$i \frac{\partial \hat{\rho}}{\partial t} = [\hat{H}, \hat{\rho}],$$

Введем теперь гамильтониан кристалла, эволюционирующего в усредненном строго периодическом потенциале ОЧ (с периодом, совпадающим с периодом кристалла)

$$\hat{H}_0 = Sp_2 \hat{\rho}_2^0 \hat{H}_1 ,$$

$$\hat{\rho}_2^c$$

$$\hat{W} = \hat{H}_1 - \hat{H}_0$$

Оператор W не имеет диагональных по состояниям ОЧ матричных элементов, поскольку

$$Sp_2 \hat{\rho}_2^0 \hat{W} = Sp_2 \rho_2^0 \hat{H}_1 - \hat{H}_2 = 0.$$

$$\hat{\rho}_1 = Sp_2 \hat{\rho}.$$

$$i \frac{\partial \hat{\rho}_1}{\partial t} = \left[\hat{H}_0, \hat{\rho}_1 \right] + Sp_2 \left[\hat{W}, \hat{\rho} \right].$$

Ограничимся квадратичным приближением по оператору неупругого взаимодействия . В случае не очень толстого кристалла, когда можно пренебречь влиянием рассеивающей системы (кристалла) на матрицу плотности ОЧ , полная матрица плотности может быть заменена на

$$\hat{\rho} \ t = \hat{\rho}_2^0 \ \hat{\rho}_1 \ t .$$

кинетическое уравнение для электрон-фононной системы кристалла, возбуждаемой ОЧ

$$\frac{\partial \rho_{1SS'}}{\partial t} + i \ (E_S - E_{S'}) \ \rho_{1SS'} = I_{SS'} ,$$

Интеграл столкновений

$$I_{SS'} = \pi \sum_{S'', S'''} \rho_{2\alpha}^0 W_{SS''}^{\alpha'\alpha} W_{S''S'}^{\alpha\alpha'} \rho_{1S''S'''}^t \left[\delta(E_S + E_{\alpha'} - E_{S''} - E_{\alpha}) + \delta(E_{S'} + E_{\alpha'} - E_{S''} - E_{\alpha}) \right] -$$

$$- \left[W_{SS''}^{\alpha\alpha'} W_{S''S'}^{\alpha'\alpha} \rho_{1S''S'''}^t + W_{S''S'''}^{\alpha\alpha'} W_{S''S'}^{\alpha'\alpha} \rho_{1SS''}^t \right] \delta(E_{S''} + E_{\alpha'} - E_{S''} - E_{\alpha}) .$$

Вклады в ток за счет недиагональных элементов
электронной матрицы плотности $\hat{\rho}_{эл}$

$$\vec{J}_{недиаг} = \vec{J}_{недиаг}^{phot} + \vec{J}_{недиаг}^{phon} + \vec{J}_{недиаг}^{оч},$$

Для $\vec{j}_{\text{медиаз}}^{(оч)}$ в результате подстановки решения уравнения, усредненного по $\hat{\rho}_{ph}$, получаем

$$j^{оч} = e \sum_{S,\alpha} \int \left[f_{S\vec{K}_1} f_{S\vec{K}_2} \rho_{2\alpha}^0 - f_{S\vec{K}_2} (1 - f_{S\vec{K}_1}) \right] W_S^{оч}(\vec{K}_2, \vec{K}_1) \vec{R}_S(\vec{K}_2, \vec{K}_1) \delta(\Delta E_{оч}(\vec{K}_1 - \vec{K}_2) - \varepsilon_S(\vec{K}_1) + \varepsilon_S(\vec{K}_2)) d\vec{K}_1 d\vec{K}_2,$$

$$W_S^{оч}(\vec{K}_2, \vec{K}_1) = \frac{a^6}{h^5 2\pi} \left| W_{\vec{K}_2 \vec{K}_1}^{SS} \right|^2.$$

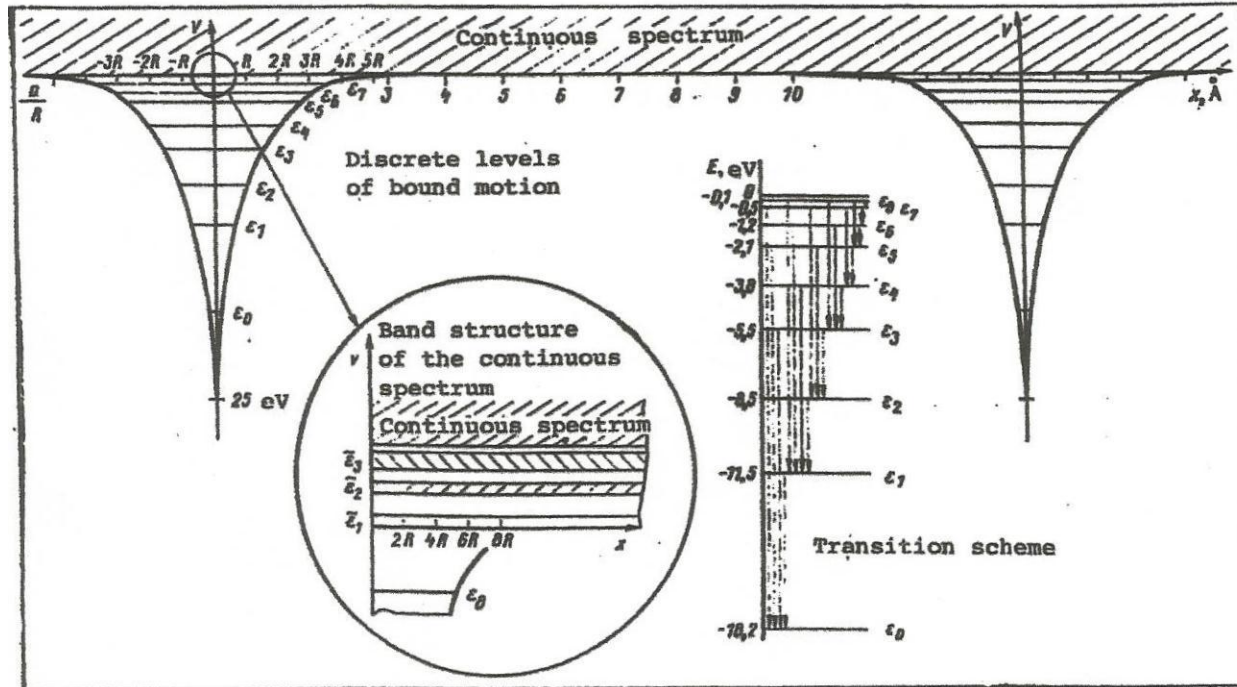
Здесь предполагается, что блоховские периодические амплитуды нормированы на объем элементарной ячейки :

$$\int_{a^3} U_{S\vec{K}}^* U_{S,\vec{K}} d^3 r = \delta_{SS'} a^3 .$$

$$\vec{R}_S \vec{K}_2, \vec{K}_1 = - \left(\frac{\partial}{\partial \vec{K}_1} + \frac{\partial}{\partial \vec{K}_2} \right) \Phi_{S \vec{K}_2, \vec{K}_1} + \Omega_S \vec{K}_2 - \Omega_S \vec{K}_1 ,$$

$$\vec{\Omega}_S \vec{K} = \frac{i}{a^3} \int U_{S\vec{K}}^* \frac{\partial}{\partial \vec{K}} U_{S\vec{K}} d\vec{r} ,$$

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



$$\overline{\Delta E} \sim \frac{U_{acc}}{N} \sim \frac{U_0 \gamma}{\sqrt{\gamma}} \sim U_0 \sqrt{\gamma}$$

$$U_0(\text{Si}) \approx 25 \text{ eV} \quad R \approx 0,2 \text{ \AA}$$

$$\overline{\omega_{12}}(\text{lab}) \sim \gamma^{3/2}$$

$$\omega_{max}(\text{lab}) \sim U_0 \gamma^2$$

EQUATION FOR THE WAVE FUNCTION OF THE ORIENTED PARTICLE

$$\left[E_{n,p}^2 / c^2 - 2eE_{n,\bar{p}} U \vec{r} / c^2 + e^2 U^2 \vec{r} / c^2 + \hbar^2 \Delta_{\vec{r}} - m^2 c^2 + i e \hbar \vec{\alpha} \nabla_{\vec{r}} U \vec{r} / c \right] \psi_{n,\bar{p}} \vec{r} = 0.$$

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

$$\left(-\frac{\hbar^2}{2m} \Delta_x + e U x E_{n,\bar{p}} / mc^2 \right) \psi_{n,\kappa} \vec{r} = \varepsilon_{n,\kappa} \psi_{n,\kappa} \vec{r}.$$

$$\left(-\frac{\hbar^2}{2m} \Delta_x + \frac{E_{n,\bar{p}}}{mc^2} V x \right) \psi_{n,\kappa} \vec{r} = \varepsilon_{n,\kappa} \psi_{n,\kappa} \vec{r}.$$

$$V x = \sum_{G_x} V_{G_x} \exp i G_x x = V_0 + 2 \sum_{G_x > 0} V_{G_x} \cos G_x x, \quad V_0 = -2V_G$$

$$2S = G_x x \quad \left(-\frac{\hbar^2 G_x^2}{4 \cdot 2m} \Delta_S + \frac{E_{n,\bar{p}}}{mc^2} V 2S \right) \psi_{n,\kappa} 2S = \varepsilon_{n,\kappa} \psi_{n,\kappa} 2S, \quad \psi_{n,\kappa} S \equiv U S$$

Quasiclassical condition?

$$\frac{m\hbar|F|}{p^3} \ll 1 \quad F = -\gamma \frac{dU}{dx} \quad \frac{m\hbar\gamma \left| \frac{dU}{dx} \right|}{p^3} \ll 1 \quad ??$$

potential energy as a disturbance?

$$\gamma U \ll \frac{\hbar^2}{ma^2} \quad ?? \quad \text{at } ka \leq 1$$

DIMENSIONLESS EQUATION FOR THE WAVE FUNCTION OF THE FAST PARTICLE

$$\frac{\partial^2 U}{\partial S^2} + \tilde{a} - 2q \cos 2S \quad U \quad S = 0, \quad V_0 = -2V_{G_x}, \quad n=4$$

$$\tilde{a} = \frac{8m\varepsilon_{n,\kappa}}{G_x^2 \hbar^2} - \frac{8E V_0}{\hbar^2 c^2 G_x^2}; \quad q = \frac{8E V_{G_x}}{\hbar^2 c^2 G_x^2}; \quad S = G_x x / 2; \quad G_x \equiv nG_{\text{мин}} = nG = n2\pi / d; \quad E_{\perp} \equiv \varepsilon_{n,\kappa}$$

$$\tilde{a} = \frac{8m\varepsilon_{n,\kappa}}{n^2 G^2 \hbar^2} + \frac{2 \cdot 8E V_{G_x}}{\hbar^2 n^2 c^2 G^2} = \frac{8m\varepsilon_{n,\kappa}}{n^2 G^2 \hbar^2} + \frac{16E V_{G_x}}{\hbar^2 n^2 c^2 G^2}; \quad q = \frac{8E V_{G_x}}{\hbar^2 c^2 n^2 G^2};$$

n=4

$$\tilde{a} = \frac{m\varepsilon_{n,\kappa}}{2G^2 \hbar^2} + \frac{E V_{G_x}}{\hbar^2 c^2 G^2} = \frac{m\varepsilon_{n,\kappa}}{2G^2 \hbar^2} + \frac{E V_{G_x}}{\hbar^2 c^2 G^2}; \quad q = \frac{E V_{G_x}}{2\hbar^2 c^2 G^2};$$

$$2S = G_x x; \quad G_x \equiv nG_{\text{мин}} = nG = n2\pi / d; \quad E_{\perp} \equiv \varepsilon_{n,\kappa}$$

ESTIMATION OF THE DIMENSIONLESS CONSTANTS FOR THE LEPTON IN Si

$$\frac{2\hbar^2 G^2}{m} = \frac{2 \cdot 10^{-68} 10^{-20}}{10^{-30}} = 2 \cdot 10^{-18} \text{ J} = \frac{2 \cdot 10^{-18}}{1.6 \cdot 10^{-19}} \text{ J} = 12.5 \text{ eV}$$

$$\frac{EV_G}{\hbar^2 c^2 G^2} \rightarrow \frac{EV_G}{\hbar^2 c^2 G^2} = \frac{mEV_G}{\hbar^2 mc^2 G^2} = \gamma \frac{2mV_G}{2\hbar^2 G^2} = 2\gamma V_G / \frac{2\hbar^2 G^2}{m} \approx \gamma 30 \text{ eV} / 12.5 \text{ eV} \approx 2.4\gamma$$

$$\tilde{a} = \frac{\varepsilon_{n,\kappa}}{12.5 \text{ eV}} \frac{16}{n^2} - 2.4\gamma \frac{16}{n^2}; \quad q = 2.4\gamma \frac{8}{n^2}; \quad S = G_x x; \quad G_x \equiv nG_{\text{мин}} = nG = n2\pi / d; \quad E_{\perp} \equiv \varepsilon_{n,\kappa}$$

$$\tilde{a} = \varepsilon_{n,\kappa} / 12.5 \text{ eV} + 2.4\gamma; \quad q = 1.2\gamma; \quad 2S = G_x x; \quad G_x \equiv 4G_{\text{мин}} = 4G = 4 \cdot 2\pi / d; \quad E_{\perp} \equiv \varepsilon_{n,\kappa}$$

$$\varepsilon_{n,\kappa} = 12.5 \text{ eV} \tilde{a} - 2.4\gamma$$

$$q = 1.2\gamma;$$

$$\varepsilon_{n,\kappa} = \tilde{a} - 2.4\gamma, \quad q = 1.2\gamma;$$

Probability of nondipole radiation of photons

$$\frac{d^2 w}{d\omega d\Omega}(\omega, \theta) = \frac{e^2 \omega}{2\pi} \sum_f \left(1 + u + \frac{u^2}{2} \times \left[\left| I_{if}^1(k_x) \right|^2 \theta^2 + \left| I_{if}^2(k_x) \right|^2 - 2 \operatorname{Re} \left[I_{if}^1(k_x) I_{if}^{2*}(k_x) \theta \cos \varphi \right] \right] + \frac{u^2}{2E^2} \left| I_{if}^1(k_x) \right|^2 \times \delta \left\{ 2 \frac{\omega}{E - \omega} \left[\theta^2 + E^{-2} E - \omega \theta^2 \cos^2 \varphi \right] - \varepsilon_i E + \varepsilon_f E - \omega \right\} \right)$$

$$u_{if} = \omega_{if} / E - \omega_{if}$$

$$\omega / E = x$$

$$I^1 = \langle \psi_n \exp ikx \psi_{n'} \rangle$$

$$I^2 = \langle \psi_n \exp ikx \frac{\partial}{\partial x} \psi_{n'} \rangle$$

FORMALISM

Emission of γ rays by channeled particles

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Zh. Eksp. Teor. Fiz. 75, 1389-1401 (October 1978)

$$\frac{d^2w}{d\omega d\Omega} = \frac{e^2\omega}{2\pi} \sum_f |M_{if}|^2 \delta[\omega - \omega_{if} - (E_p^{\parallel} - E_{p-k}^{\parallel})].$$

$$E_p^{\parallel} - E_{p-k}^{\parallel} \approx \omega - \frac{\omega}{2(E_i - \omega)} [(\theta^2 + E_i^{-2})E_i - \omega\theta^2 \cos^2 \varphi].$$

$$\delta\left(\frac{\omega}{2(E - \omega)} \left[\left(\theta^2 + \frac{1}{\gamma^2} \right) E - \omega\theta^2 \cos^2 \varphi \right] - \omega_{if}\right) =$$

$$= \delta\left(\varepsilon_i - \varepsilon_f - \frac{\omega}{2(E - \omega)} \left[\left(\theta^2 + \frac{1}{\gamma^2} \right) E - \omega\theta^2 \cos^2 \varphi \right]\right).$$

$$\delta\left(\varepsilon_i - \varepsilon_f - \frac{\omega}{2(E - \omega)} \left[\left(\frac{1}{\gamma^2} \right) E \right]\right) =$$

$$= \delta\left(A_i q - A_f q' - 2q + 2q' - \frac{\omega}{2(E - \omega)} \frac{1.44E}{q^2}\right)$$

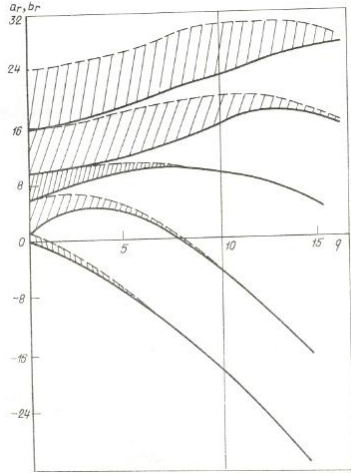
$$\delta\left(12.5A_i q - 12.5A_f q' - 25q + 25q' - \frac{x}{1-x} \frac{300000}{q}\right) =$$

$$= \frac{1}{12.5} \delta\left(A_i q - A_f q' - 2q + 2q' - \frac{x}{1-x} \frac{24000}{q}\right)$$

$$0.72 \frac{E}{1.2\gamma} = 0.6 \frac{E}{\gamma} = 0.6 \cdot 0.5 \text{ MeV} = 300000 \text{ eV}$$

Orientation dependence of the band structure of relativistic positrons in single crystal

The transverse motion band spectrum of a oriented fast particle in the approximation of a sinusoidal crystal potential (band spectrum allocated to 25MeV energy particles). The lower band border and the upper band border vs pulse (in dimensionless units) for the crystallographic plane (110) in silicon Si.

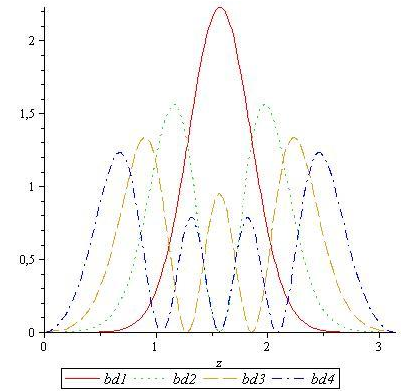
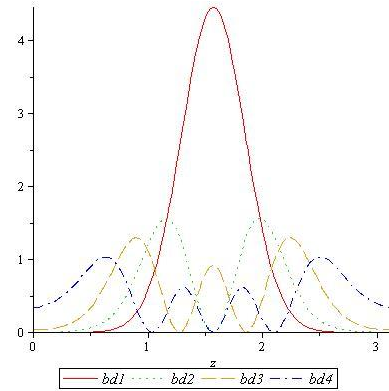


$$V(x) = \bar{V} + 2 \sum_{n=1,2} V_{4n,0,0} \cos 4Gx .$$

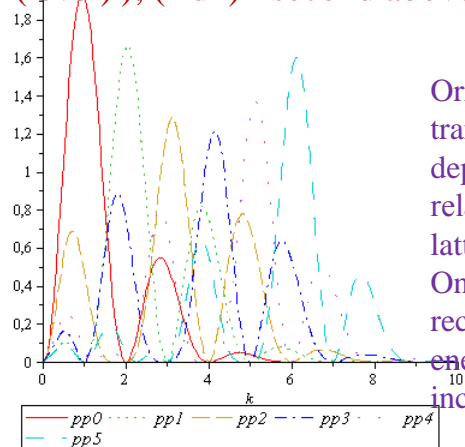
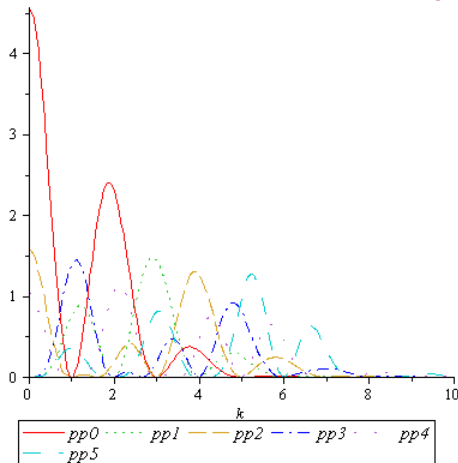
$$\frac{\partial^2 U}{\partial S^2} + \tilde{a} - 2q \cos 2S U S = 0,$$

$$\tilde{a} = E_{\perp}^2 / 4G^2 \hbar^2 c^2 - \frac{8EV_0}{2\hbar^2 c^2 G^2};$$

$$l = \frac{EV_G}{2\hbar^2 c^2 G^2}; \quad S = 2Gx; \quad G \equiv G_{min} = 2\pi / d;$$

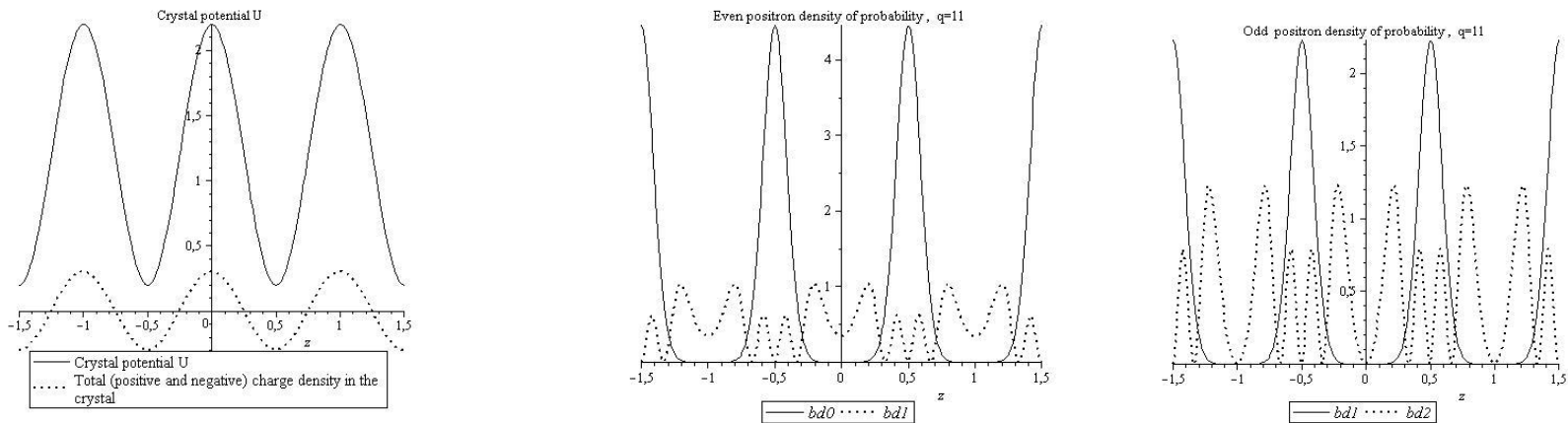


Squares module of the even (a) and odd (b) wave functions of positrons with an energy of 28 MeV in the planar channel (110) in a single crystal Si. (BD1) - first deep sub-barrier level; (Bd2) - the second level in the middle of the channel; (BD3) - the first above- barrier zone (level)); (Bd4) - second above- barrier zone



Orientation dependence of the probability of the population of the transverse motion positron levels for the even and odd levels depending on the angle of incidence of the positron in a crystal relative to the plane (110) in the Si. Angle θ is measured in reciprocal lattice vectors. Levels of oriented particles are numbered by index bd. On the x-axis the wave vector is specified as a fraction of the reciprocal lattice vector, with five of the reciprocal lattice vectors at energy 28 MeV correspond approximately to an Lindhardt angle of incidence of the positron

Along the x-axis of the graph the planar potential U is shown (solid line) and a graph of the distribution of the total density of positive and negative charges in a crystal (a line consisting of points).



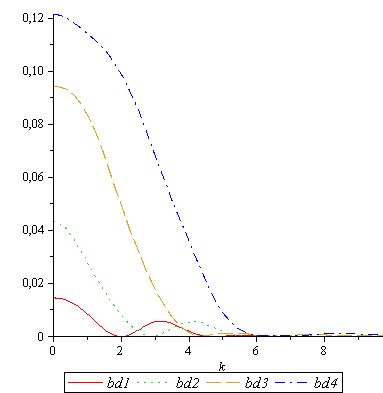
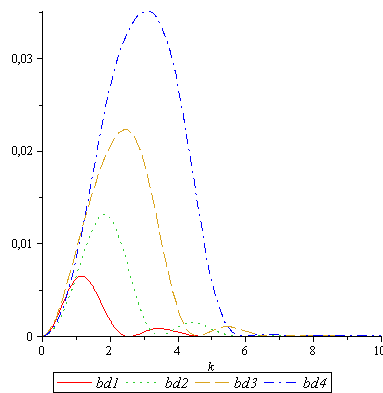
Squares module of the even (a) and odd (b) wave functions of positrons with an energy of 28 MeV in the planar channel (110) in a periodic potential with parameters corresponding to the plane 110 in the silicon single crystal. x-coordinate is listed in dimensionless units as a fraction of the interplanar distance. In Figure A: (bd0) - the first deep sub-barrier zone; (Bd1) - third

Orientation dependence

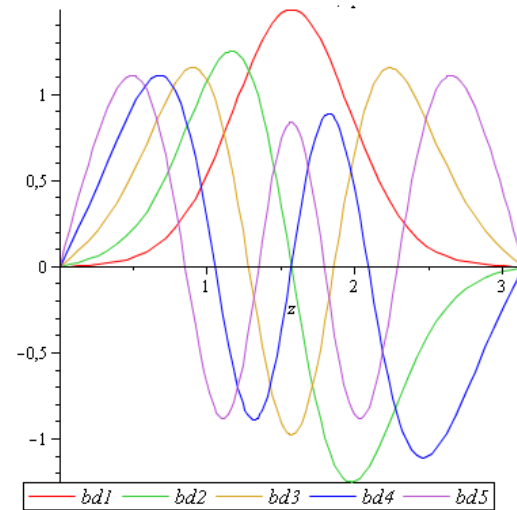
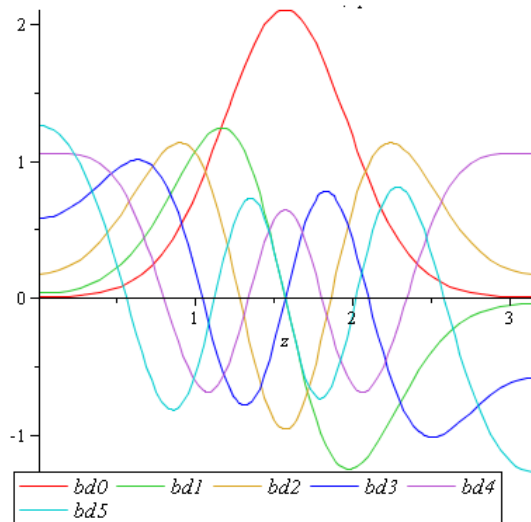
Squared modulus of the matrix element of the transition positron for the even and odd levels depending on the angle of incidence of the positron in a crystal.

Angle θ is measured in reciprocal lattice vectors.

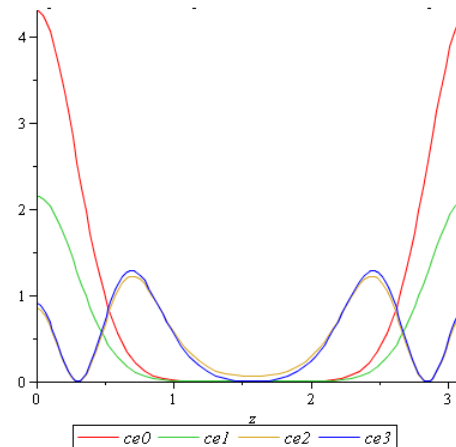
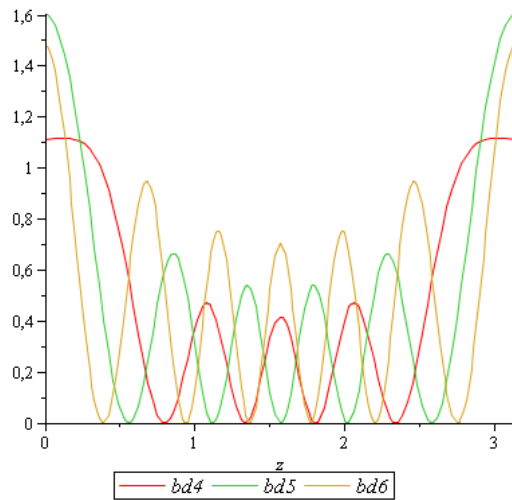
Levels of oriented particles are numbered with index bd . On the x-axis the wave vector is specified as a fraction of the reciprocal lattice vector, with five of the reciprocal lattice vectors at energy 28 MeV correspond approximately to an Lindhard angle of incidence of the positron



a. First six even and b. first six odd wave functions of the positron with the energy corresponding to the parameter $q = 11.3$ (about 50 MeV). It shows part of the wave functions corresponding to only the right half of the corresponding channel



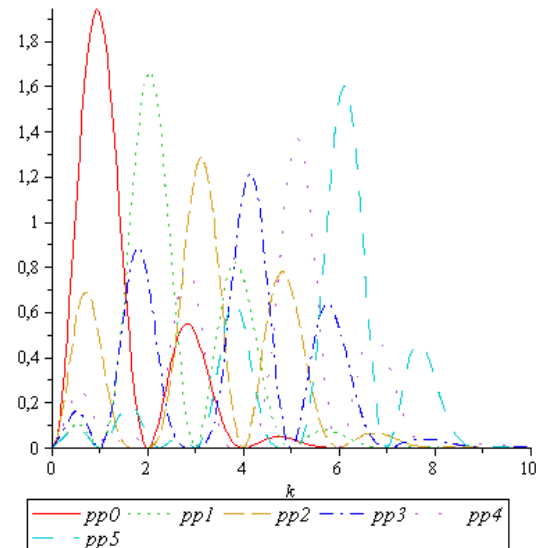
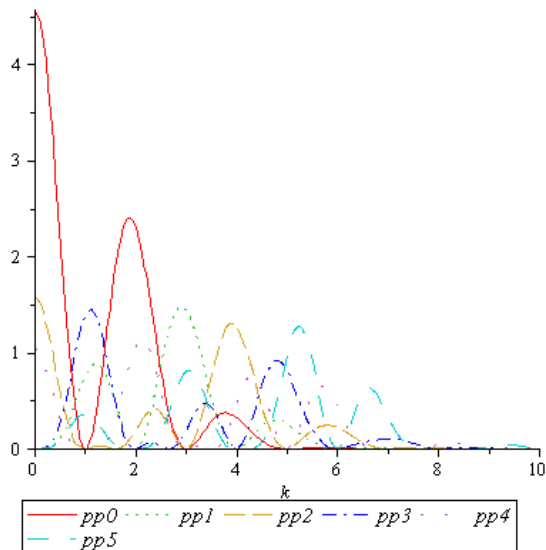
- a. - The square modulus of the wave function of the positron over barrier three zones of the transverse motion at $q = 11$
- b. - Squared modulus of the electron wave functions for the four zones of the sub barrier transverse motion at $q = -10$



Orientation dependence of the probability of the population of the lower boundary of the zone of the cross-traffic for positron in the even and odd states, respectively, depending on the angle of incidence of the positron in a crystal relative to the plane (110) in the Si.

The angle θ is measured as the number of reciprocal lattice vectors corresponding to the projection of the momentum of the positron channeling across the planes, divided by the total momentum of the positron. Levels of oriented particles are numbered with Indexes bd .

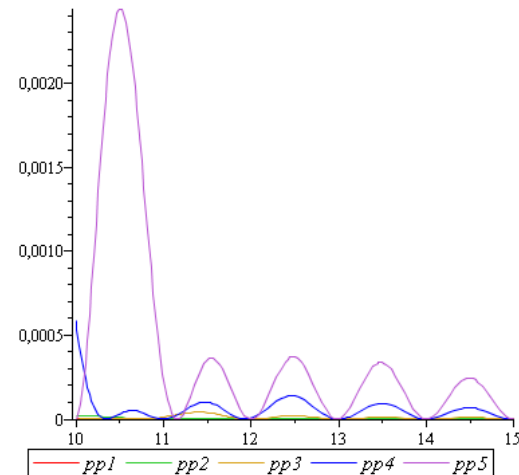
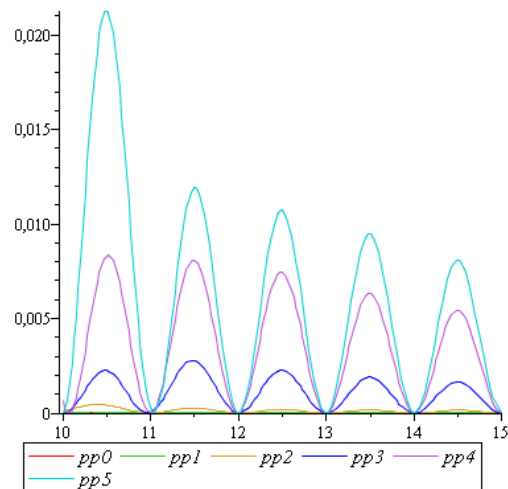
On the x-axis the wave vector is specified as a fraction of the reciprocal lattice vector. The four vectors of the reciprocal lattice at energy 28 MeV correspond approximately to an Lindhardt angle of incidence of the positron, so that the value of the argument along the x-axis, approximately equal to four, shares sub barrier and over barrier states.



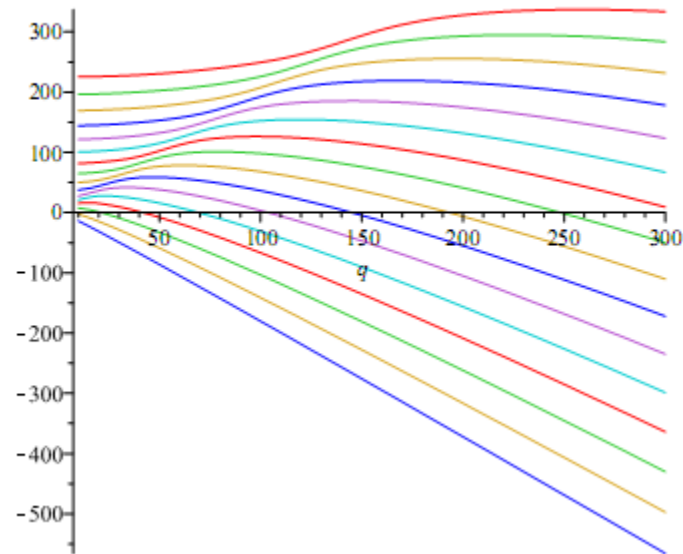
Orientation dependence of the probability of the population of the transverse motion of the positron levels for the even and odd levels depending on the angle of incidence of the positron in a crystal relative to the plane (110) in the Si.

Angle θ is measured in reciprocal lattice vectors. Levels of oriented particles are numbered with index bd .

On the x-axis the wave vector is specified as a fraction of the reciprocal lattice vector. Five of the reciprocal lattice vectors at the energy 28 MeV correspond approximately to an Lindhardt angle of incidence of the positron



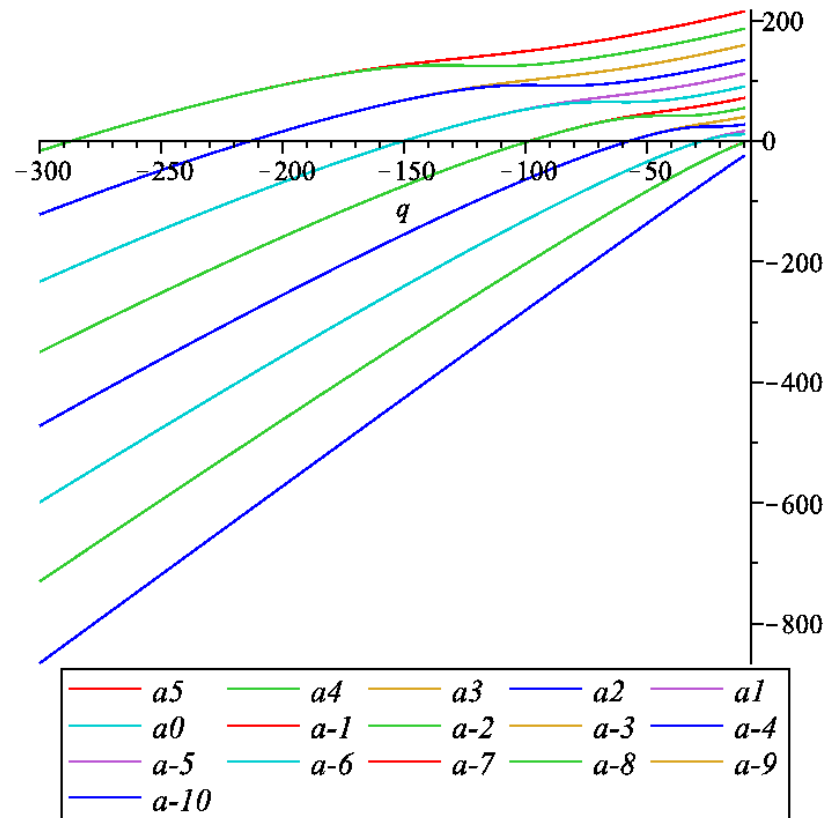
The lower border of 15 bands of low transverse-motion for channeled positrons with the energy corresponding to a range of dimensionless parameter q from zero to 300



$$\Delta E_{\perp}^2 = 4\hbar G^2 c^2 \cdot 2^{4r+5} \sqrt{2\pi q}^{r/2+3/4} e^{-4\sqrt{q}} / r.$$

BAND STRUCTURE FOR THE ELECTRON

```
plot( [ (MathieuA(15 - n, q) + q)$(n = 0 ..15) ], q = -300 .. -10, legend = [
'a || (5 - n) '$(n = 0 ..15) ])
```



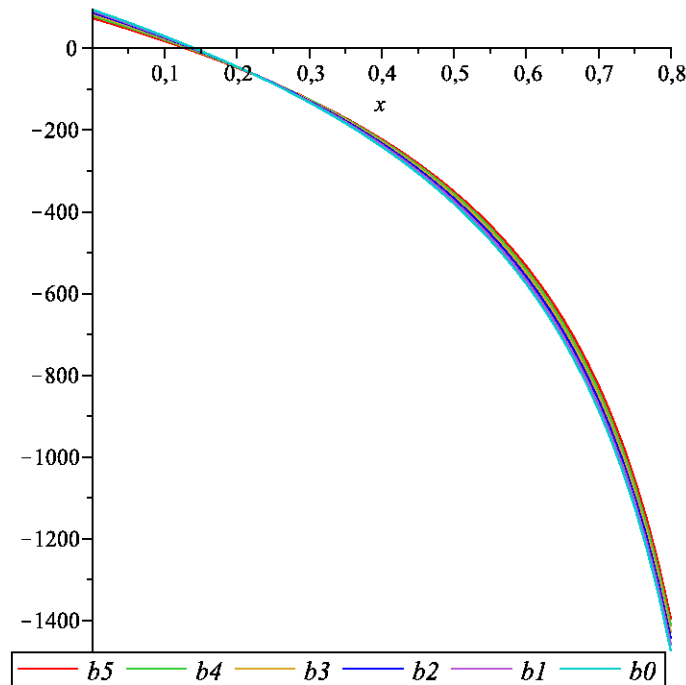
INDEPENDENCE OF THE PHOTON ENERGY ON THE BAND NUMBER

EMISSION OF THE HIGH ENERGY PHOTONS IN NON DIPOLE TRANSITIONS

BETWEEN NON ADJACENT BANDS OF THE ABOVE BARRIER PARTICLE

INITIAL SET OF BANDS AND FINAL SET OF BAND CORRESPOND TO DIFFERENT ENERGIES

```
plot( [ [ ( -2*71*x - 24000*x / (71*(1-x)) + MathieuA(6-n+3, 71) - MathieuA(6-n, 71*(1-x)) ) ] (n=1..6) ], x=0..0.8, legend=['b' || (6-n)] (n=1..6) ] )
```

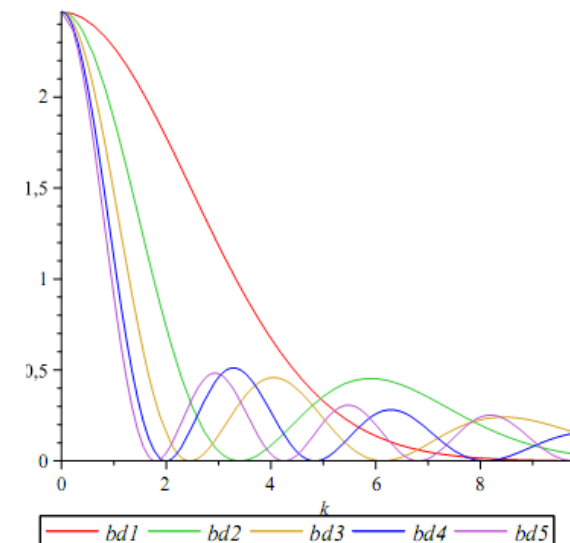
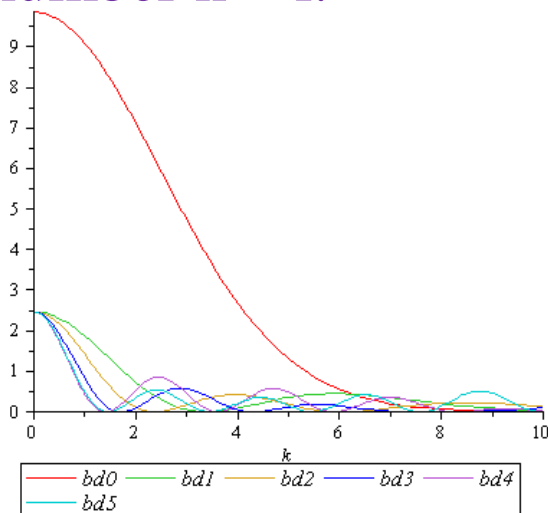


NON_DIPOLE MATRIX ELEMENTS

The square modulus of the matrix elements of the transition energy of the positrons corresponding to $q = 11$, even, from state n zone sub barrier movement in an even state of the sub barrier movement zone n .

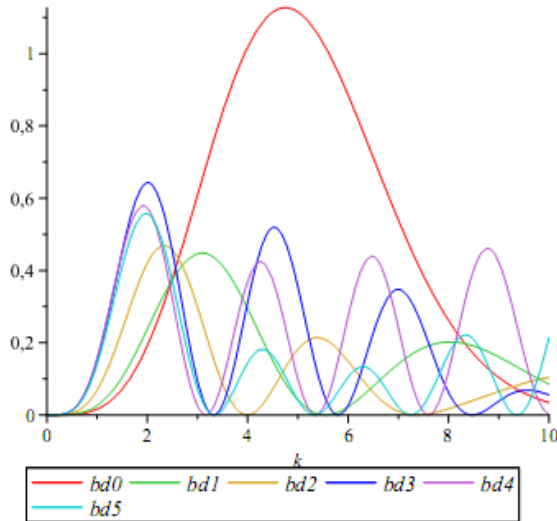
Designation: bd_i $i = 1, \dots, 5$ zones meet the number $n = i$

The square modulus of the matrix elements of the transition energy positrons with corresponding $q = 11$, an n - zone odd state sub barrier movement in an odd state sub barrier movement zone with the number $n + 1$. Designation bd_i with $i = 1, \dots, 5$ zones meets the number $n = i$.

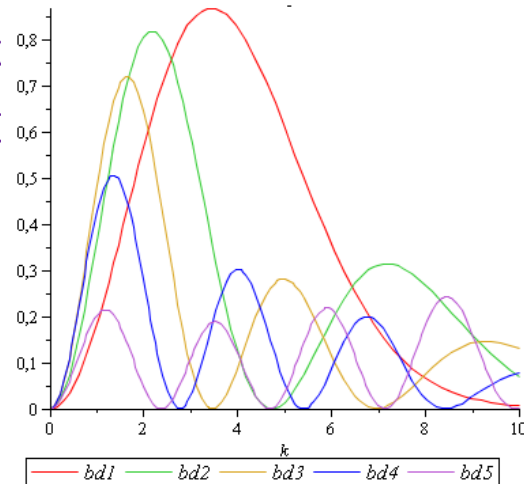


The square modulus of the matrix elements of the positron transition with the energy corresponding to $q = 11$, from n zone even state of sub barrier movement in an even state sub barrier movement with zone number $n + 2$. Designation $bd_i, i = 1, \dots, 5$ answers $n = i$ Zone number.

$$\text{plot} \left(\left[\left(\int_0^\pi \text{MathieuCE}(n, 11, z) \cos(k \cdot z) \text{MathieuCE}(n + 2, 11, z) dz \right)^2 + \left(\int_0^\pi \text{MathieuCE}(n, 11, z) \sin(k \cdot z) \text{MathieuCE}(n + 2, 11, z) dz \right)^2 \right] \right) \text{ for } n = 0 \dots 5, k = 0 \dots 10, \text{ title}$$



The square modulus of the matrix elements of the positron transition with the energy corresponding to $q = 11$, from even state of n zone sub barrier movement in an n odd state sub barrier movement. Designation $bd_i, i = 1, \dots, 5$ answers $n = i$ Zone

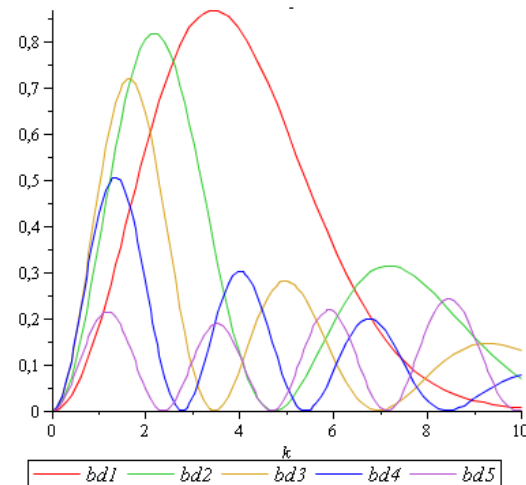
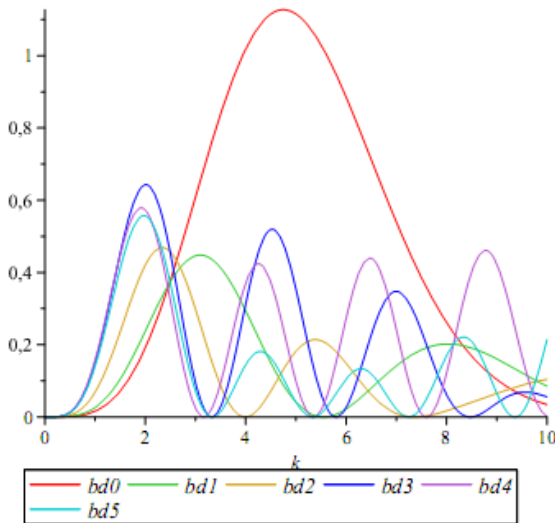


swers

The square modulus of the matrix elements of the positron transition with the energy corresponding to $q = 11$, from n zone even state of sub barrier movement in an even state sub barrier movement with zone number $n + 2$. Designation bd_i $i = 1, \dots, 5$ answers $n = i$ Zone number.

$$plot \left(\left[\left(\int_0^\pi \text{MathieuCE}(n, 11, z) \cos(k \cdot z) \text{MathieuCE}(n + 2, 11, z) dz \right)^2 + \left(\int_0^\pi \text{MathieuCE}(n, 11, z) \sin(k \cdot z) \text{MathieuCE}(n + 2, 11, z) dz \right)^2 \right] \right)_{k=0..10, title}$$

The square modulus of the matrix elements of the positron transition with the energy corresponding to $q = 11$, from even state of n zone sub barrier movement in an n odd state sub barrier movement zone. Designation bd_i $i = 1, \dots, 5$ answers $n = i$ Zone number.

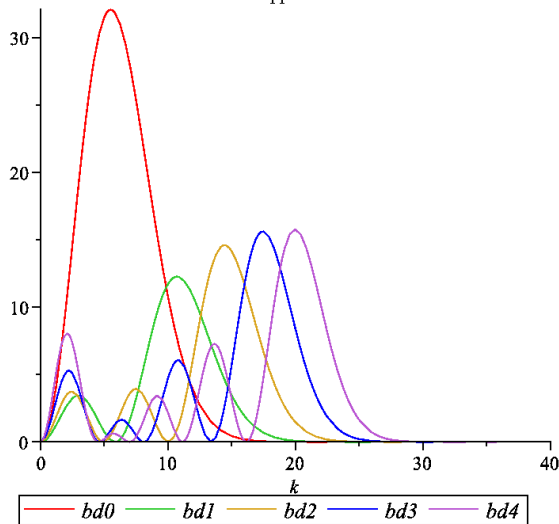


SQUARED MODULO OF THE TWO TYPES OF NON DIPOLE COMPLEX MATRIX ELEMENTS

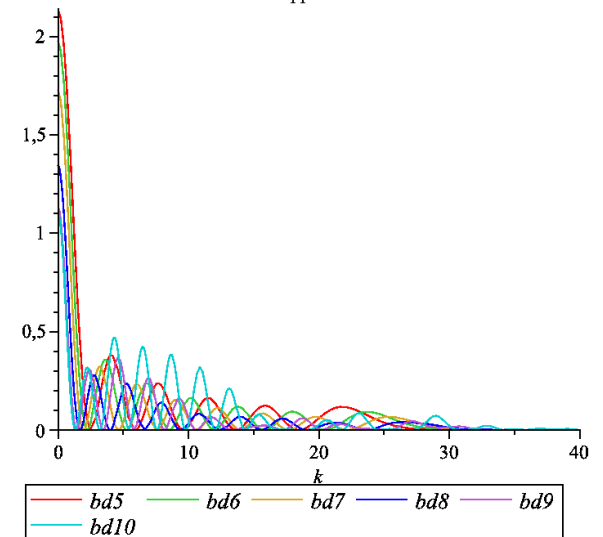
$$\text{plot} \left(\left[\left(\int_0^\pi \text{MathieuCE}(n, 51, z) \cos(k \cdot z) \frac{\partial}{\partial z} \text{MathieuCE}(n, 71, z) dz \right)^2 + \left(\int_0^\pi \text{MathieuCE}(n, 51, z) \sin(k \cdot z) \frac{\partial}{\partial z} \text{MathieuCE}(n, 71, z) dz \right)^2 \right] \right) \$ (n = 0 \dots 4) \Bigg|, k = 0 \dots 40, \text{title}$$

$$\text{plot} \left(\left[\left(\int_0^\pi \text{MathieuCE}(n, 51, z) \cos(k \cdot z) \text{MathieuCE}(n, 71, z) dz \right)^2 + \left(\int_0^\pi \text{MathieuCE}(n, 51, z) \sin(k \cdot z) \text{MathieuCE}(n, 71, z) dz \right)^2 \right] \right) \$ (n = 5 \dots 10) \Bigg|, k = 0 \dots 40, \text{title}$$

Even sub and under barrier positron wave functions matrix elements, q=11



Even sub and under barrier positron wave functions matrix elements, q=11



Calculation of the photon emission probability

$$\omega_{if} = E_i - E_f = \omega_{if} \left[\varepsilon_i - \varepsilon_f \right] / 2$$

$$u_{if} = \omega_{if} / (E_i - E_f)$$

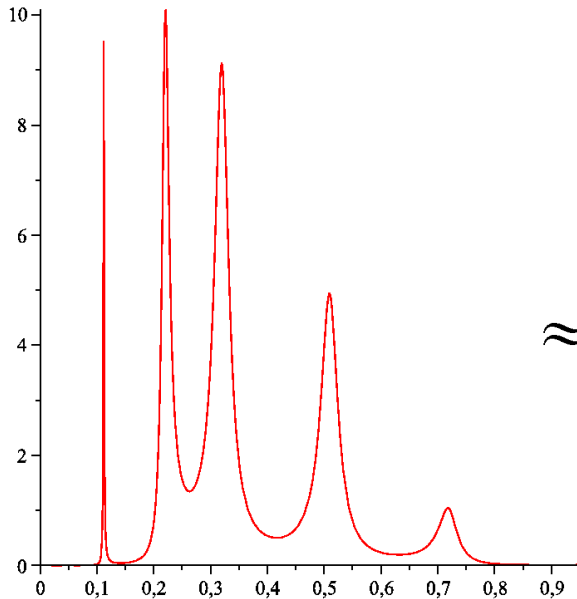
$$\frac{dw_{if}}{d\Omega} = \int d\omega \frac{d^2 w_{if}}{d\omega d\Omega} = \frac{e^2 \omega_{if}}{\pi} \frac{u_{if}^2}{4E^2} \left(1 + u_{if} + \frac{u_{if}^2}{2} \right) \left| I_{if}^1 \right|^2$$

$$w_{if} = \int d\Omega \frac{dw_{if}}{d\Omega} = \frac{e^2}{hc\pi} \frac{\hbar\omega_{if}}{\hbar} \frac{\hbar\omega_{if}^2}{(E_i - \hbar\omega_{if})^2} \frac{mc^2}{E^2} \left(1 + u_{if} + \frac{u_{if}^2}{2} \right) \left| I_{if}^1 \right|^2 d\Omega =$$

$$= 2 \cdot 10^{-3} \cdot 0.6 \cdot 10^{25} \cdot 0.66^2 \cdot 4 \cdot 10^4 \cdot 1.5 \cdot 5 \cdot 3.6 \cdot 10^{-16} \cdot 1/s \approx 0.2 \text{ s}^{-1}.$$

Differential probability for the generation of photons by a channeled particle with $q=71$. On the x-axis dimensionless photon energy x as the part of the energy of the channeled particle is postponed.

$$E = 10 \text{ GeV}$$



$$d\Omega = \sin \theta d\theta d\varphi \approx \theta d\theta d\varphi \approx$$

$$\approx 6 \cdot 10^{-8} \cdot 6 \cdot 10^{-8} \cdot 10^{-1} = 3.6 \cdot 10^{-16} \text{ sr}$$

$$w_{if} \omega_{if} = 0.2 \text{ s}^{-1}$$

RESUME

1. The calculation of the quasi-Bloch energy spectrum of the oriented fast charged particle entering the crystal at an angle substantially greater than the Lindhard angle is performed.
2. It is shown that the band structure with the presence of allowed and forbidden bands has been preserved during the passage of fast charged particles high above the crystal potential.
3. The processes of the photon generation by the quantum crystal-oriented particle entering into the crystal at an angle substantially greater than the Lindhard angle are considered.
4. The probability of the photon excitation by the quantum above-barrier channeled particle is calculated. It is proved that all of the essential features of the above-barrier band structure manifest themselves as the components of the emission spectrum of the crystal-oriented fast charged particle.

Само же уравнение в случае воздействия ультракороткого импульса ОЧ на кристалл описывает динамический отклик электрон-фононной системы кристалла на такое воздействие, вполне аналогичный отклику кристалла на пикосекундные возбуждающие световые импульсы.

В случае прохождения через кристалл ультракороткого (например, пикосекундного) пространственно-модулированного импульса ОЧ, в кристалле будут наблюдаться динамические решетки на неравновесных носителях заряда, аналогичные решеткам, индуцируемым в кристаллах полем двух когерентных интерферирующих электромагнитных волн.

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