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# Effect of Polarization Phenomena on Interaction of Projectile with a Solid Target – I

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**Abstract.** The change in the size of projectiles wave field in interaction with the the solid is analysed. The creation of resonance states of projectile during the time of flight across the solid film is found. There are conditions when the ptojectile is captured in own polarization field created in the environment.

## 1 Introduction

In a number of current investigations within the scope of modern physics the time-resolved experiments and consequence theories play a central role in understanding of physical phenomena. As an important example consider the detailed information about the particle-solid and particle-nucleus interaction physics. Although the standard scattering theory in principal can give us estimations of probabilities of transitions of the system to different conceivable final states, it cannot explain some important intermediate processes which can effectively change the expected results. The scattering theory which is published in fundamental monographs (see, e.g., [1, 2]), based on the representation on scattering matrix which elements define the probabilities of transitions the quantum system from any initial quantum state to different final stationary states at infinite large future time. Note, in this approach the possibilities to transition in different non-stationary but considerably short lived and nevertheless important states are totally dropped. The investigation of those states is main goal in nuclear physics as well as in biology. They are as a rule, mixed states. The appropriate tool for mathematical investigation of such a states are the density matrixes of different types. But the mathematical expression for the density matrix (DM) doesn't yet give the clear understanding the phenomenon under investigation. There is often lack of algorithms of election of right decision among a series of other appropriate conclusions.

As an effect that requests new explanations consider the particle-atomic chain interaction phenomenon. Consider the passage of hydrogen atom parallel to the chain of seven carbon atoms [3]. Interaction between the electron and atoms has described with the help of convenient potential coupling in the electron affinity well for each carbon atom. We observe a possible splitting the electrons wave packet during the passage of the hydrogen atom parallel to the chain of seven carbon atoms. We observe the non-uniform distribution of probabilities of localization the electron in the chain. The result was obtained with the help of direct numerical solution of the non-stationary 3-d Schroedinger equation. The resulting state it was now expanding the spatial and structured. Note, experimental investigation of polarization effects in nanotubes was undertaken in [4].

In above calculation all the non-elastic collisions with free electrons are dropped. If we take into account this interaction (assume that the event is take place in the carbon nano-tube), then the property of an electrons wave packet significantly changes [5]. When the coherence length becomes less the interatomic distance we come to conclusion that among several points of electron localization must survive only one (including the hydrogen atom conservation). How we can estimate the probabilities of each of outcomes? How we can understand the detailed mechanism of such a transition? That problems tightly connected to famous wave function reduction problem and in principal can be solved with the help of estimating the time-evolution of density matrix.

The effect of projectiles spatial localization can found a more usual interptretation based on the famous phenomenon of the polarization well described by the wake potential of such a size that can capture the projectile in the some quantum-mechanical coupling state. The new developments of nanotechnology and its subsections as photonics and plasmonics can bring an additional sharpness in the discussions. In the present work the corresponding polarization phenomena together with the above mentioned correlation length are considered and some feasible quantum-mechanical problems are solved. In the article, as a rule, all quantities are presented in Hartree atomic units.

## 2 Semiclassical Approximation

Consider the interaction of the projectile with the homogeneous condensed medium which elementary excitations are known and their Bose-type creation and annihilation operators are $b^{+}_{\beta\vec{k}}$ $b_{\beta\vec{k}}$ (here $\beta$ denotes the type of the excitation, $\vec{k}$ – its momentum). The Hamiltonian of the system has the usual form $\hat{H} = \hat{H}_0 + \hat{H}_{\text{int}}$, where (in the Schrödinger representation) $\beta$ denotes the type of the excitation

$$\begin{aligned} \hat{H}_0 &= \int \hat{\psi}^{+}(\vec{x})\Big(-\frac{\nabla^2}{2M}\Big)\hat{\psi}(\vec{x})dV + \sum \omega_\alpha(\vec{q})\hat{b}^{+}_{\alpha\vec{q}}\hat{b}_{\alpha\vec{q}}\,; \\ \hat{\psi}(\vec{x}) &= \sum_{\vec{k}} \frac{1}{\sqrt{\Omega}} \exp(i\vec{k}\vec{x})\hat{a}_{\vec{k}}\,, \\ \hat{H}_{int} &= Z\int \hat{\rho}(\vec{x})\hat{\varphi}(\vec{x})dV\,; \quad \hat{\rho}(\vec{x}) = \hat{\psi}^{+}(\vec{x})\hat{\psi}(\vec{x})\,. \end{aligned} \tag{1}$$

Here $b_{\alpha\vec{k}}$ denotes the annihilation operator for the projectile found in the state with the certain momentum $\vec{k}$, $\Omega$ – is the normalization volume, $Z$ - is the charge of projectile. The operator of the polarization field potential which created by the volume elementary excitations in the medium has the commonly used expression

$$\varphi^{(V)}(\vec{x},t) = \sum_{\beta,\vec{q}} g_\beta(\vec{q}) \left(\hat{b}_{\beta\vec{q}}(t)e^{i\vec{q}\vec{x}} + \hat{b}^+_{\beta\vec{q}}(t)e^{-i\vec{q}\vec{x}}\right). \tag{2}$$

Here $g_\beta\left(\vec{q}\right)$ - the binding coefficitnts between the projectile and elementary excitations. They are usually expressed [6] through derivatives of dielectric function Fourier components $\varepsilon_\omega\left(\omega\right)$ on frequency, $g_\beta\left(\vec{q}\right) = \sqrt{4\pi/q^2\varepsilon'_\omega\left(\omega\right)\Omega}$. Evolution of the system is defined by the Schrödinger equation for the vector of state

$$i\left(d/dt\right)|t\rangle = \hat{H}|t\rangle\,. \tag{3}$$

In the semiclassical approach the key statement is the suggestion on the classical nature of the projectile. This approach is interesting not only as any formal example but can be applied to the real physical situations (e.g., in the theory of free electron laser [7] where the electron bunch was considered as one particle). In this case the equation (3) has an exact solution which is expressed through the coherent states

$$|t\rangle = \prod_{\beta,\vec{q}} \exp\left\{-|Q_{\beta\vec{q}}(t)|^2/2 - i\Phi_{\beta\vec{q}}(t)\right\} \times \sum_{n=0}^{\infty} Q^n_{\beta\vec{q}}(t)\left((\hat{b}^+_{\beta\vec{q}})^n/n!\right)|\mathrm{vac}_Q\rangle\,, \tag{4}$$

where $|\mathrm{vac}_Q\rangle$ is the vacuum state of the quasiparticle's field and

$$\begin{aligned} Q_{\beta\vec{q}}(t) &= -iZg_{\beta\vec{q}}\int_0^t \rho_{\vec{q}}(t')e^{i\omega_\beta t'}dt'\,, \\ \Phi_{\beta\vec{q}}(t) &= \int_0^t \mathrm{Im}\left[\dot{Q}^*_{\beta\vec{q}}(t')Q_{\beta\vec{q}}(t')\right]dt' \end{aligned} \tag{5}$$

Here $|vac_Q)$ is assumed the projectile obeys the charge distribution (not the point charge) of time-depended Gauss shape

$$\begin{aligned} &\rho(\vec{x},t) = (2\pi\delta^2(t))^{-3/2}\exp\left(-\left(\vec{x}-\vec{x}_0(t)\right)^2/2\delta^2(t)\right)\,, \\ &\rho_{\vec{q}}(t) = \exp\left(-i\vec{q}\,\vec{x}_0(t) - q^2\delta^2(t)/2\right) \end{aligned} \tag{6}$$

Here the quantity $\delta(t)$ is the mean-square width of the projectiles density distribution. The width can change during the motion and it the cause why the additional factor is placed in integrand. As it follows, the more delocalized the projectile the less number of quasiparticles it generates in the target. For the further consideration it is desirable to understand the physical meaning of the quantity $|Q_{\beta\vec{q}}(t)|^2$, which is the measure of the mean number of quasiparticle generated by the projectile in the medium to the current time $t$.

With usage of formulae (3–6) one can calculate the potential of the mean polarization field generated by the projectile in the medium to the time $t$,

$$\left\langle \varphi^{(V)}(\vec{x},t) \right\rangle = \sum_{\beta,\vec{q}} g_\beta(\vec{q}) \left( Q_{\beta\vec{q}}(t) e^{i\vec{q}\vec{x}-i\omega_\beta t} + Q^*_{\beta\vec{q}}(t) e^{-i\vec{q}\vec{x}+i\omega^*_\beta t} \right). \tag{7}$$

The strength of the field is the less the greater the delocalization of the projectile. The projectile can be captured in its own polarization well only in the case of sufficiently great localization.

For the crude quantitative estimations take the one-mode model dielectric fuction for describing the polarization properties of the target,

$$\varepsilon(\vec{q},\omega) = 1 - \omega_0^2 / \left(\omega^2 + \omega_0^2 - \omega_{\vec{q}}^2 + i0_\omega\right), \tag{8}$$

where $0_\omega \to +0 \cdot \mathrm{sign}(\omega)$ defines the bypass of poles, $\omega_q = \omega_0 + q^2/2$. The quantity $\omega_q$ let equal to frequency of eigen excitation in the target. At the particular estimations for $\omega_0$ take the plasma frequency of Al. In the model under consideration exists only one mode of eigen excitations (quasuparticles). This mode has the energy of free volume plasmon at low momenta and asymptotically at $q \to \infty$ coincides with the energy of the free electron. The eigen excitations occur only at sufficiently great velocity of the projectile, when $q \cdot v > \omega_q$, within the interval $q_- \le q \le q_+$, $q_\pm = v \pm \sqrt{v^2 - 2\omega_0}$.

The wave field of the projectile can be stabilized in its quantum state after been captured in its own polarization well. With usage (7) it is possible to estimate when the capture of the projectile in the own polarization field can occur and which number of coupling states in this case generally exist. The corresponding wave equation for the projectiles wave function $\varphi(\vec{x},t)$ which can be obtained starting from the equation for the DM [8], has the next form:

$$\begin{aligned} i\partial\varphi(\vec{x},t)/\partial t = \Big\{ &-\nabla^2/2m \\ &+ 2Z^2 \sum_{\vec{q}} g_{\vec{q}}^2 \int d^3\xi \int_{t_0}^{t} d\tau \sin(\vec{q}(\vec{x}-\tilde{\xi}))\varphi*(\tilde{\xi},\tau)\varphi(\tilde{\xi},\tau) \Big\} \varphi(\vec{x},t) \end{aligned} \tag{9}$$

Here $m$ is the mass of the projectile. The non-linearity in this equation reflects the feedback effect of exited environment on motion of the projectile.

## 2.1 The extended coherent state approach

Now represent a variant of quantum theory of the event when the quantum projectile is impigned in the solid target been previously accelerated and passed in vacuum a certain macroscopic distance $L$. According to quantum theory the minimal spatial size of its wave packet has the order of $\delta_0 \sim \sqrt{L\lambda}$ where $\lambda$

is the wave length. As a rule consider the case when the wave packet size is much longer compared to the interatomic distance in the target. Let the vector $|0)$ correspond to the initial state of the whole system at the beginning of the interaction at the time $t = 0$. Let consider elementary excitations of the environment as quasiparticles of Bose type, the vacuum state of the quasiparticle field is assumed to be before the interaction begins. Let start with the next expression for the density matrix of projectile obtained early in the work [9] within the modified perturbation theory (MPT)

$$\begin{aligned}\Gamma(\vec{x}_1, \vec{x}_2, t) &= (m/2\pi r)^3 \\ &\times \iint d^3 s_1 d^3 s_2 \exp\left(-imt(s_1^2 - s_2^2)\right) \chi_0^*(\vec{x}_1 + \vec{s}_1, 0)\chi_0(\vec{x}_2 + \vec{s}_2, 0) \\ &\times \exp\Big\{-\sum_{\beta,\vec{q}} \left|Q_{\beta\vec{q}}(t)\right|^2 \left(1 - \exp\left(i\vec{q}(\vec{x}_1 + \vec{s}_1 - \vec{x}_2 - \vec{s}_2)\right)\right)\Big\} \end{aligned} \quad (10)$$

Here $\chi_0(\vec{x}, t)$ - is the wave function of the projectile befor the interaction. Assume it has the Gauss form. After introducing the new variables $y_{1,2} = \vec{s}_{1,2} - \vec{x}_{1,2}$, $\vec{Y} = (\vec{y}_1 + \vec{y}_2)/2$, $\vec{y} = \vec{y}_1 - \vec{y}_2$, some simple transformations and integrating on $\vec{Y}$ this formula been applied to the above one-mode model gives

$$\begin{aligned}\Gamma(\vec{x}_1, \vec{x}_2, t) &= (m/2\pi t)^3 \exp\Big\{-2\delta_0^2 \left(m/2t\right)^2 x^2\Big\} \\ &\times \int d^3 y \exp\Big\{-\left(y^2/8\delta_0^2\right) - 2\delta_0^2 \left(m/2t\right)^2 \left(y^2 - 2\vec{y}\vec{x}\right)\Big\} \\ &\times \exp\Big\{-i\left(m/t\right)\vec{x}\vec{X} + i\left(m/t\right)\vec{y}(\vec{X} - \vec{v}t) \\ &- \sum_{\beta,\vec{q}} |Q_{\beta\vec{q}}(t)|^2 (1 - J_0(q_\perp y_\perp) e^{iq_z y_z})\Big\}. \end{aligned} \quad (11)$$

Here is supposed the projectile moves along $z$-axis having the velocity $v$ and instead $\vec{x}_1$, $\vec{x}_2$ the relative and central coordinates are introduced $\vec{x} = \vec{x}_1 - \vec{x}_2$, $\vec{X} = (\vec{x}_1 + \vec{x}_2)/2$. The expression (11) can be applied for numerical calculations in cases when the time of interaction exceeds significantly the time $t_p$ of formatting the polarization field in medium which usually consists several tens of time units. In the simple one-mode model used above, the density matrix (11) can be reduced to the expression, where occurs the possibility of the numerical evaluattion in its simplest form. Here is presented one of the first results of evaluation (Figure 1).

### 2.2 Splitting of the wave field

Show the splitting of the projetiles wave field within the very simplfied approach to the problem (Figure 1). The parameters fixed at the calculation are: The vec-

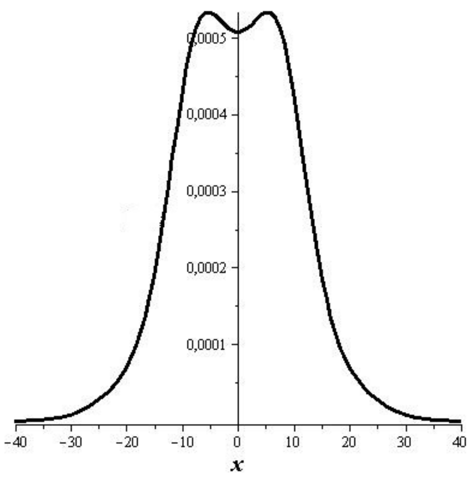


Figure 1. The behavior of DM module $\Gamma(x)$ as a function of the distance x in the direction parallel to the mean velocity of the projectile. Calculation is performed for the parameters: $v = 2, \delta_0 = 5, m = 1836, t_0 = 50, t = 500, X_t = 0, x_t = 0, X_3 = vt, Z = 1$

tors $X_t$, $x_t$ are orthogonal to the mean velocity, $Z = 1$. The time of observation is $t = 500$, the time of interaction $t_0 = 50$.

In the figure is pictured the behavior of DM module as a function of the distance x in the direction parallel to the mean velocity of the projectile. It is evident that at the time $t_0 = 50$ begins the splitting process in the wave field of the projectile (proton). The splitting observed in the direction of velocity. At the increasing time of interaction the splitting increases, but at the small times $t_0 < 40$ the splitting is absent. This example shows that in principal it is possible to observe and control this phenomenon.

## 3 Main Conclusions

Consideration of propagation of accelerated particles through the thin solid films unveils some information on possible resonances which can occur during the interaction of particle with the solid film. Each resonance has the own history: it appears in any time after beginning of the projectile - solid interaction and increases his integral probability to be appear as a real particle during the observation. The resonances can be observed experimentally due to spontaneous breaking of the symmetry in the situation when the coherence length of the projectiles wave field is significantly less compared to the linear size of the total wave field cross section. Resonances reveal comparatively not simple behavior in time with initial appearance and the possible later disappearance. This phenomenon should have an additional investigation. It is possible that in application to the nuclear problems this approach can explain the nature of different resonances which arises in nuclear collisions. Calculation and further analysis of density matrix (DM) for projectile which collides with a solid film reveals some new representations which hard to be anticipated without the calculation. Namely:

1. The coherence properties in the projectiles wave field are describing through the special function of coherence [5].
2. The collision with solid leads to a significant decrease in the total coherence length of projectiles wave field. The coherence length can become much smaller than the initial size of wave field of projectile.
3. During the collision with solid the number of different spatial areas where the mutual coherence in the projectiles wave field is supported, can be multiplied.
4. The process described in the point 3 can be considered as a special form of breaking in quantum mechanics.
5. Knowing the wave packet evolution during the passage through the solid film allows one to explain experimental results on the pore formation during the passage of high charged atomic ions through the thin carbon nanomembranes [10–12].
6. The parts of the wave field considered above can be stabilized in its quantum state after been captured in its own polarization well.

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