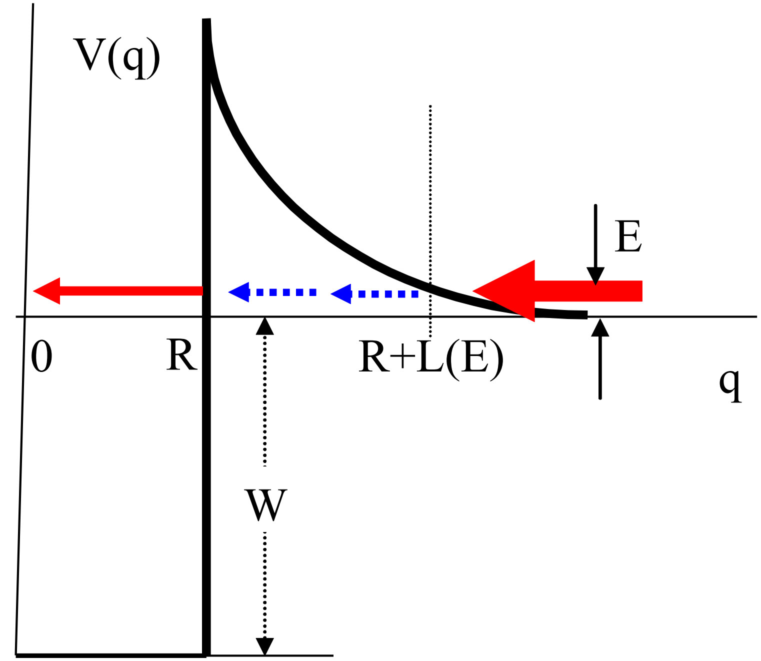
Efficient space-selective and space-scanning nuclear fusion based on channeling low-energy particles in crystals

Vladimir Vysotskii , Mykhaylo Vysotskyy,
Taras Shevchenko National University of Kyiv, Ukraine

Sergio Bartalucci[2]
LNF-INFN Research Division, Frascati, Italy

The well-known and very significant problems of implementing controlled thermonuclear fusion have been solved (without significant success and at very high financial costs) for more than 70 years.
The analysis shows that many of these problems can be successfully solved using models and methods of low energy nuclear physics and the physics of channeling particles into crystals

The problem of "standard" nuclear fusion fo free particles at low energy



$$D = e^{-W(E)};$$ *Fusion without screening*

$$V_{\max} = \frac{Z_1 Z_2 e^2}{R} \approx \begin{cases} 0.5\,MeV \;\; for\, d + d \;\; fusion \\ 1.5\,MeV \;\; for\; Li + p \;\; fusion \\ 6\,MeV \;\; for\, Ni + p \; fusion \end{cases}$$

$$W(E) = (2/\hbar) \int_{R}^{R+L(E)} \sqrt{2M[V(q) - E]}dq =$$

$$\exp\{-2\pi Z_1 Z_2 e^2 / v\} = \exp\{-2\pi Z_1 Z_2 / 137\beta\},\; \beta = v/c$$

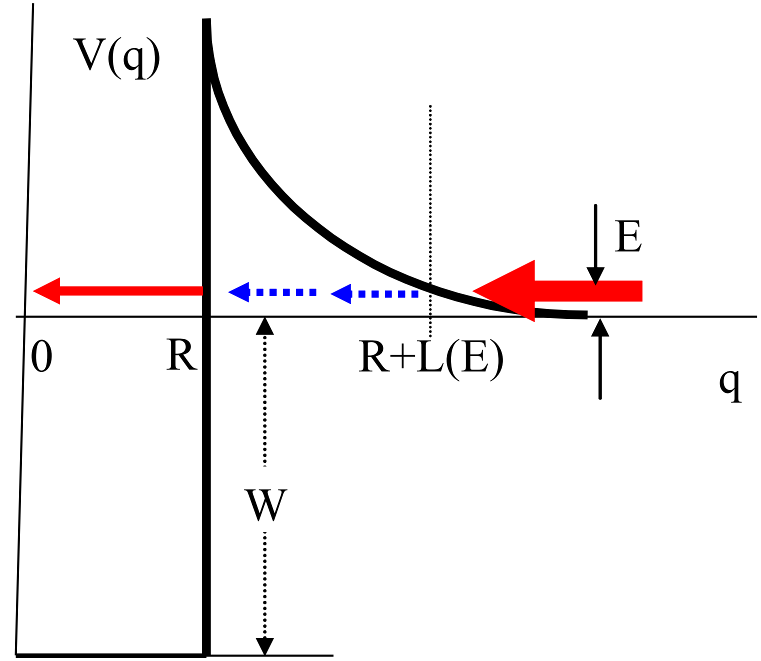
Thermonuclear fusion

$$d + d : T = 300K,\; \bar{v}/c \approx 3*10^{-6},\; Z_1 = 1,\;\; Z_2 = 1,\; D \approx 10^{-2500}$$

$$Li + p : T = 1000K,\; \bar{v}/c \approx 7*10^{-6},\; Z_1 = 1,\;\; Z_2 = 3,\; D \approx 10^{-3200}$$

$$Ni + d : T = 1500K,\; \bar{v}/c \approx 7.10^{-6},\; Z_1 = 28,\;\; Z_2 = 1,\; D \approx 10^{-30000}$$

Nuclear fusion at low energy at the presence of screening



$$E_{eff} \approx kT + Z_1 Z_2 e^2 / R_{screen} \equiv kT + E_{screen}$$

$$D = \exp\left(-2\pi Z_1 Z_2 e^2 \sqrt{\mu / 2\hbar^2 E_{eff}}\right);$$

$$T = 300K : d + d \to He^3 + n; \quad t + p; He^4 \quad reactions:$$

$$E_{eff} \approx E_{screen}^{(d+d)} \approx 27\ eV,\ D^{(d+d)} \approx 10^{-80};$$

$$T = 1000K : Li^7 + p \to 2He^4 \quad reaction:$$

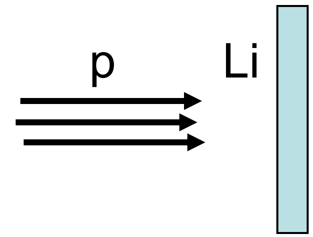
$$E_{eff} \approx E_{screen}^{(Li+p)} \approx 50\ eV,\ D^{(Li+p)} \approx 10^{-200};$$

$$T = 1500K, Ni + p,$$

$$E_{screen}^{Ni+p} \approx 250\, eV; D^{(Ni+p)} \approx 10^{-600}$$

Accelerator fusion

Alternative method for realization of nuclear fusion is the use of interaction of accelerated particles with a solid target



$$At\ E_p = 25\,KeV \quad (v_p / c \approx 7*10^{-3})\ we\ have \quad D(E) = e^{-2\pi Z_1 Z_2 c/137 v} \approx 10^{-8}$$

At i_p =1 mA the total number of Li+p reactions is the following

$$J = \sigma i_p n_{Li} L \approx 10^{7}\ counts / \sec$$

$$Here\ \sigma \approx (\lambda^2 / 2\pi) W \approx 10^{-29}\, cm^2,\ n_{Li} \approx 10^{22}\, cm^{-3},\ L \approx 0.01 cm.$$

It is well known that such reaction is impossible at low energy of protons:

$$At\ E = 500\,eV \quad (v/c = 6.2*10^{-3}\ \ for\ Li + p = 2He^4\ \ reaction)\ we\ have$$

$$W(E) = (2/\hbar) \int_R^{R+L(E)} \sqrt{2M[V(q) - E]}\,dq,\ D = \exp\{-2\pi Z_1 Z_2 c / 137 v\} \approx 10^{-45}$$

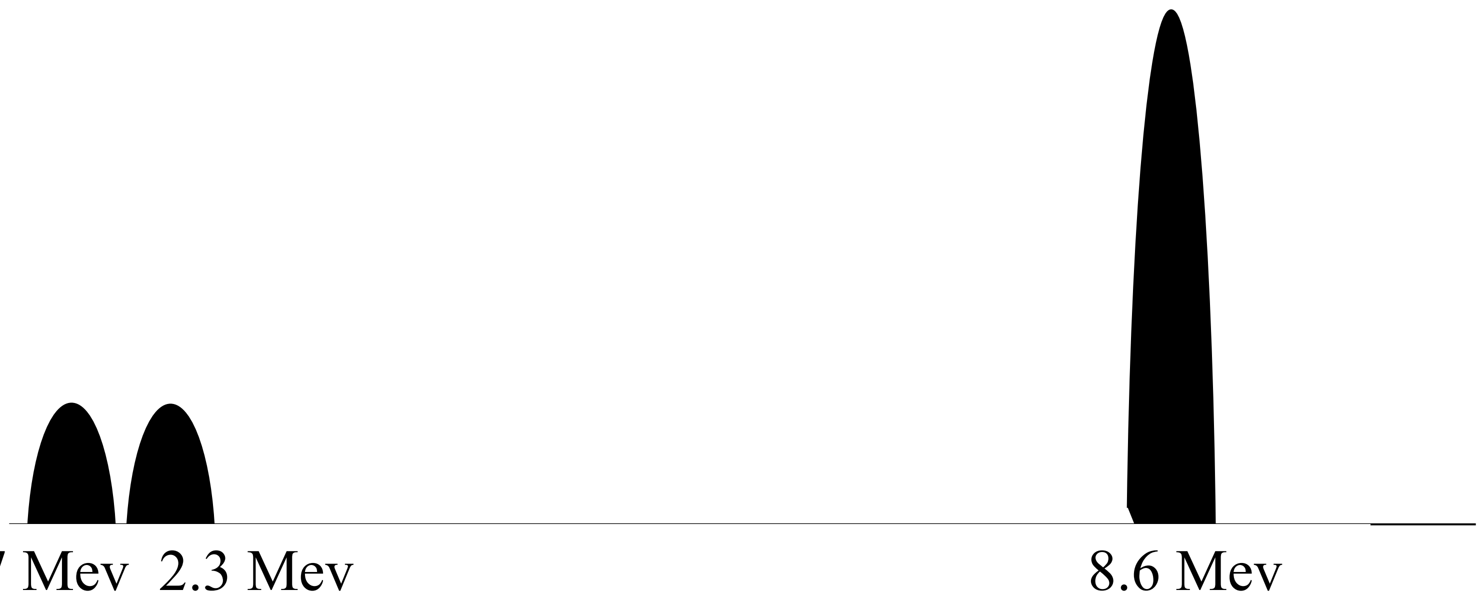
At the same current of protons I_p =1 mA the total number of reactions is

$$J = \sigma i_p n_{Li} L \approx 10^{-31}\ counts / \sec$$

$$Here\ \sigma \approx (\lambda^2 / 2\pi) D \approx 10^{-67}\, cm^2,\ n_{Li} \approx 10^{22}\, cm^{-3},\ L \approx 0.01 cm.$$

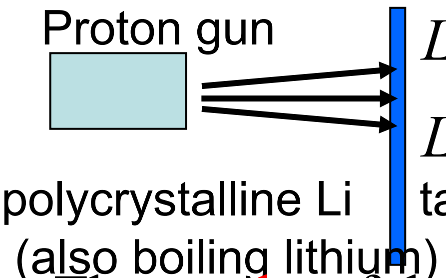
Expected spectrum of reaction products in accelerating Li+p fusion

$$Li = \begin{cases} Li^6 (7.6\%) \Rightarrow Li^6 + p = He^3 (1.7\,MeV) + He^4 (2.3\,MeV) \\ Li^7 (92.4\%) \Rightarrow Li^7 + p = 2He^4 (8.6\,MeV + 8.6\,MeV) \end{cases}$$



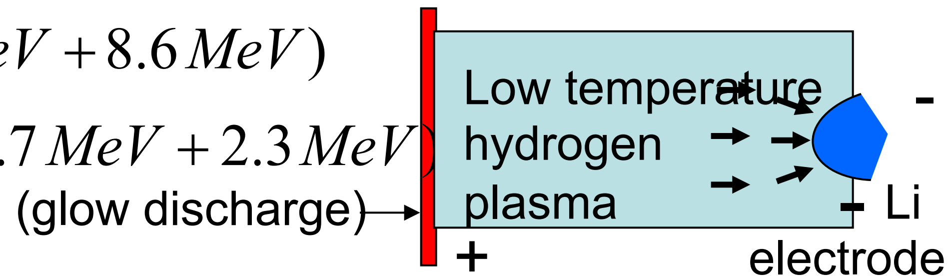
Experimental paradoxes of accelerator fusion at low energy

Usually experiments on accelerator fusion are conducted at high energy. A lot of experiments with low energy of proton beam was conducted in the work [S.Lipinski, H.Lipinski. Patent WO 2014/189799 A9]

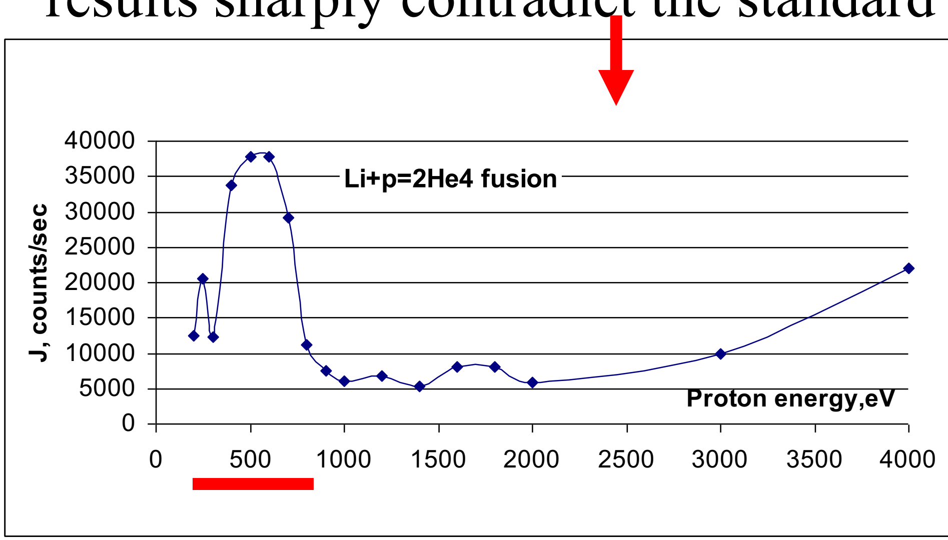


$$Li^7 + p = 2He^4(8.6\,MeV + 8.6\,MeV)$$

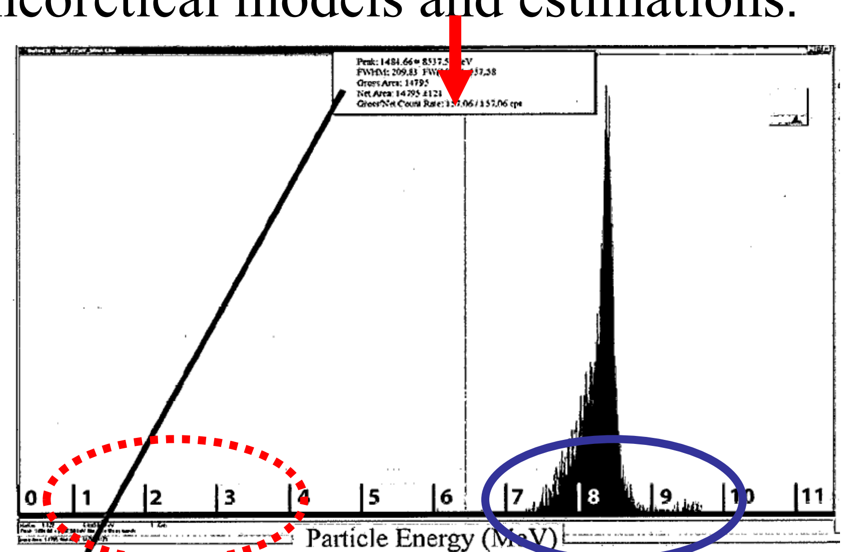
$$Li^6 + p = He^3 + He^4(1.7\,MeV + 2.3\,MeV)$$



The results of these experiments are very paradoxical and anomalous. These results sharply contradict the standard theoretical models and estimations.

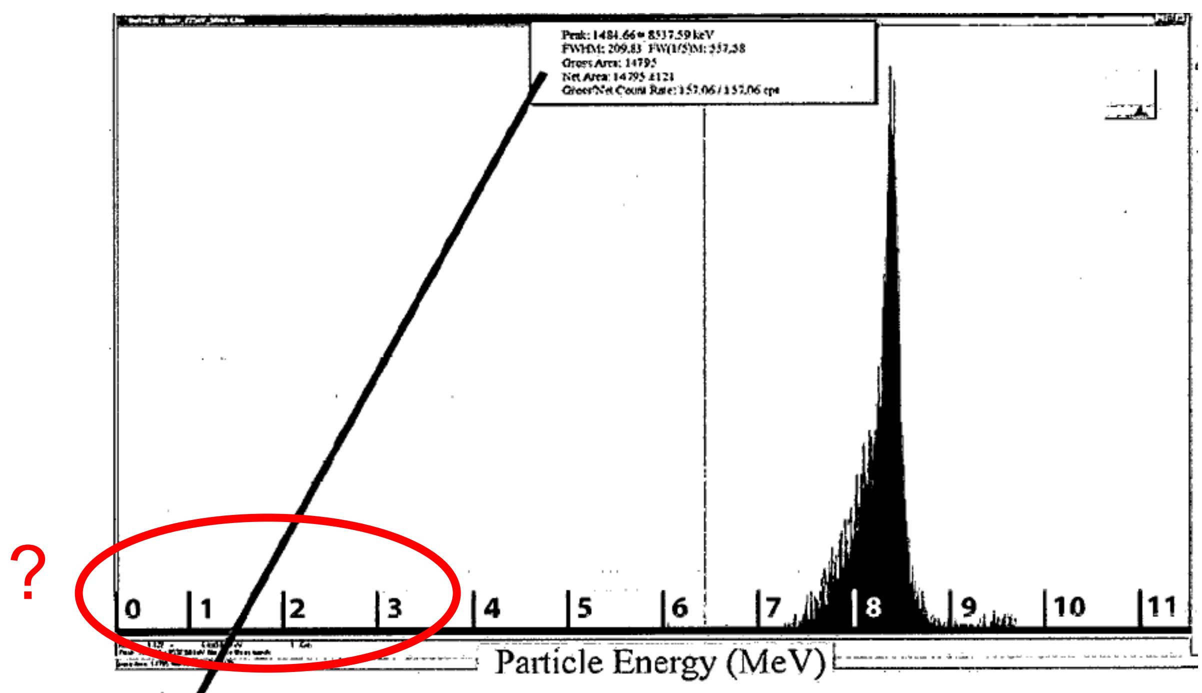


Dependence of the rate of generated fast He^4 nuclei versus proton energy



Energy spectrum of generated alpha particles He^4 at proton energy E≈300-500eV

Expected and observed spectrum of alpha particles



There are a lot of main questions for understanding of these experiments:

1. **Why the maximum of Li+p reaction is at low energy of ~500 eV?**

2. **Why in alpha-spectrum of Li+p reaction there are no alpha particles with energies 1.7 and 2.3 MeV?**

Similar fundamental problems occur in the analysis of any other LENR experiments involving particles with low energy:

3. **Abnormally high probability of any LENR reactions**

4. **Total absence of radioactive daughter isotopes in any LENR reactions and very strong suppresion of gamma-radiation**

Acording to our analysis, these processes are fully justified in the self-similar formation of coherent correlated states of interacting particles during adaptive (not averaged) channeling in crystals or quasi-crystals

The traditional approach to the physics of charged particles tunnelling is based on the assumption of mutual independence of the particle states corresponding to each energy level of quantized states. For such systems the **tunnelling processes** for each state are also **mutual independent.**

The conceptual basis of the tunneling effect is connected with the wave-particle duality **and Heisenberg -Robertson uncertainty relations (1927-1929)**

$$\sigma_A \sigma_B \geq |< [\widehat{A}\widehat{B}] >|^2 /4;$$

$$\sigma_p \sigma_q \geq \hbar^2 / 4, \; \delta p \delta q \geq \hbar / 2; \; \sigma_p =< (p - < p >)^2 >,$$

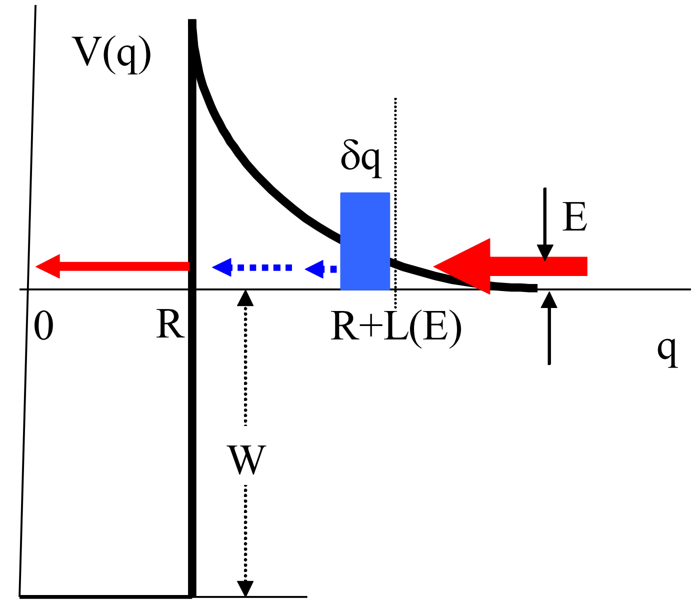
$$\sigma_q =< (q - < q >)^2 >, \delta p = \sqrt{\sigma_p}, \delta q = \sqrt{\sigma_q}$$

which connects the dispersions and mean square errors of the coordinate q and the corresponding component of the momentum of a particle p.

Relation $\delta p \delta q \approx \hbar / 2$ can be used for the estimation of barrier transparency

$$D(E) = \exp(-2 \int_R^{R+L(E)} \sqrt{2M[V(q) - E]} dq / \hbar\} = \exp\{-2L\delta p / \hbar\} \approx \exp\{-L / \delta q\}$$

L(E) – **width of the barrier** *V(q);*



$\delta q \approx \hbar / 2\delta p$ – **quantum-mechanical skin layer;**

$$\delta p \equiv \int_R^{R+L(E)} |p(q)| dq / L(E) =$$

$$\sqrt{2M} < \left| \sqrt{V(q) - E} \right| >;$$

$|p(q)| = \sqrt{2M[V(q) - E]}$ - mean square

effective radial momentum of a particle with energy $E \leq V(q)$ in the subbarrier region $V(q) \geq E,\ 0 \leq q \leq L(E)$.

In the case of low energy $E << \bar{V}$ the condition $L(E) / \delta q >> 1$ is satisfied, then the transparency coefficient of the Coulomb barrier will be extremely small:

.

$$D(E) = \exp\{-L(E) / \delta q\} << 1$$

Correlated coherent states of particles and Schrödinger-Robertson uncertainty relation (1930)

In 1930, Schrödinger and Robertson independently generalized the Heisenberg idea of the quantum-mechanical uncertainty of different dynamical quantities A and B for the case of mutual coherence of the particle states corresponding to each energy level of quantized states and received the more universal condition called the Schrödinger--Robertson uncertainty relation

$$\sigma_A \sigma_B \geq \frac{|<[\widehat{A}\widehat{B}]>|^2}{4(1-r^2)}; \ |r| \leq 1, \ r = \frac{\sigma_{AB}}{\sqrt{\sigma_A \sigma_B}}$$ - coefficient of correlation

$$\sigma_{AB} = \frac{<\{\Delta\widehat{A}, \Delta\widehat{B}\}>}{2} = \frac{(<\widehat{A}\widehat{B}> + <\widehat{B}\widehat{A}>)}{2} - <A><B>$$ - cross dispersion of A and B

$$\delta p \delta q \geq \frac{\hbar}{2\sqrt{1-r^2}} \equiv \hbar_{eff}/2, \quad \hbar_{eff} = \frac{\hbar}{\sqrt{1-r^2}} \equiv G\hbar$$ - **effective Planck constant**

$$r = \frac{\{<qp> + <pq>\}}{2\sqrt{<p^2><q^2>}}; \quad \delta E \delta t \geq \hbar_{eff}/2, \quad G = \frac{1}{\sqrt{1-r^2}}$$ - **coefficient of correlation efficiency**

The physical reason for the increase of the probability of tunneling effect is related to the fact that the formation of a coherent correlated state leads to the cophasing and coherent summation of all fluctuations of the momentum $\Delta\vec{p}(t)=\sum_{n}^{N}\Delta\vec{p}_n(t)$

for various eigenstates the superpositional correlated state $\sum_{n}^{N}c_n(t)\Psi_n(r)e^{-iE_nt/\hbar}$

This leads to a very great dispersion of the momentum

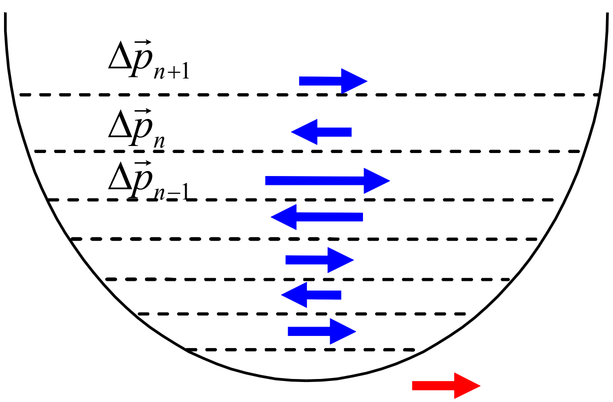
$$\sigma_p \equiv <\{\vec{p}(t)-<\vec{p}(t)>\}^2>=<\left\{\sum_{n}^{N}\Delta\vec{p}_n(t)\right\}^2>=N\left\langle(\Delta\vec{p}_n)^2\right\rangle+N^2\left\langle\Delta\vec{p}_n\Delta\vec{p}_m\right\rangle$$

and very great fluctuations of kinetic energy

$$<\Delta T>=<\Delta\vec{p}(t)^2>/2M=N^2\left\langle\Delta\vec{p}_n\Delta\vec{p}_m\right\rangle/2M+N\left\langle(\Delta\vec{p}_n)^2\right\rangle/2M\sim N^2$$

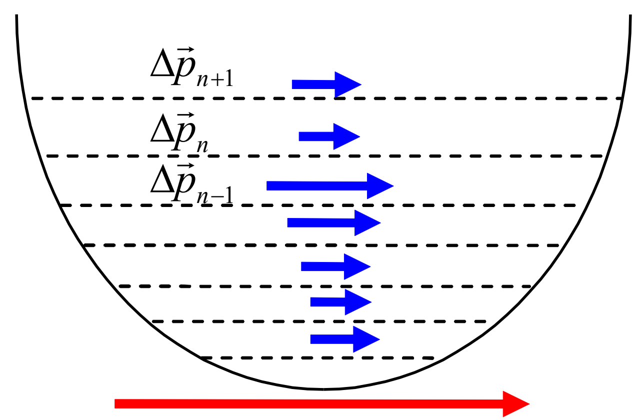
of the particle in the potential well and **increasing of potential barrier penetrability**.

Uncorrelated state



$$\delta p_{uncorr}=\sqrt{\sum_n(\Delta\vec{p}_n)^2}=\sqrt{N}\sqrt{<(\Delta\vec{p}_n)^2}$$

Correlated state

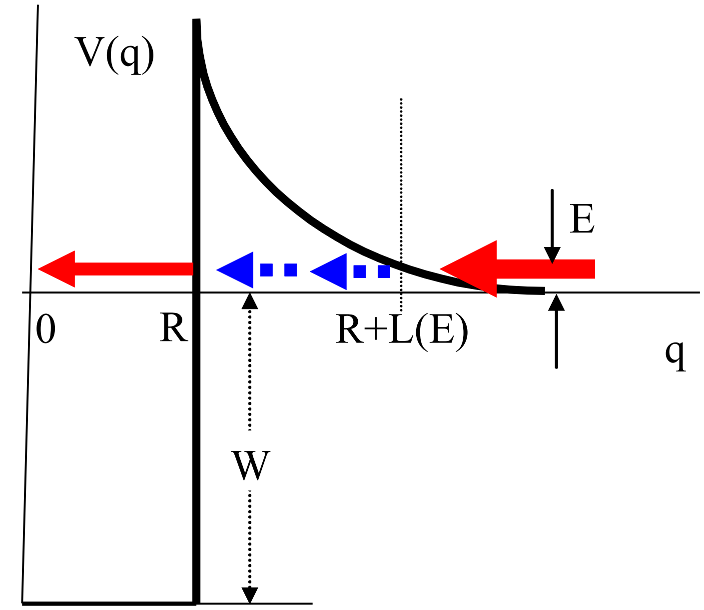


$$\delta p_{corr}=\sqrt{\sum_n(\Delta\vec{p}_n)^2}=N\sqrt{<(\Delta\vec{p}_n\Delta\vec{p}_m)^2}+\sqrt{N}\sqrt{<(\Delta\vec{p}_n)^2}$$

For Coulomb potential barrier the modified uncertainty relation is

$$\delta q \approx \frac{\hbar}{2\sqrt{1-r^2}\,\delta p} \equiv \frac{\hbar_{eff}}{2\delta p} =$$

$$= \frac{\hbar}{2\sqrt{1-r^2}\sqrt{8M} < \sqrt{V(q)-E} >}$$

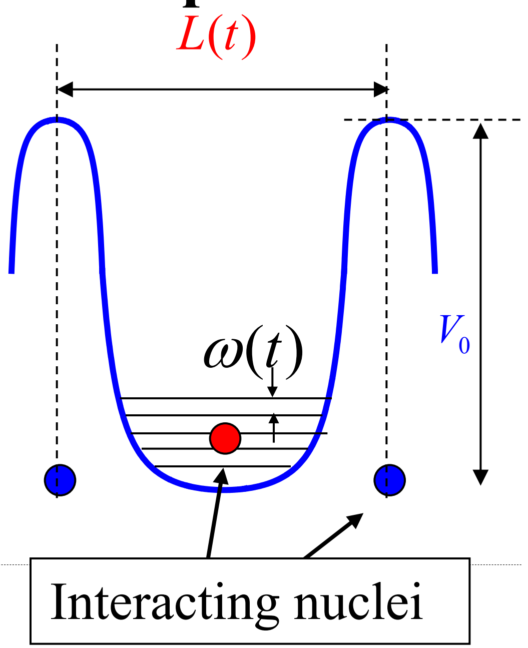


At full correlation $|r| \to 1$ the mean square effective coordinate of a particle will be unlimited ($\delta q \to \infty$) at any energy!

In this ideal case the tunnel transparency of arbitrary potential barrier will be close to 1 at any low energy E of the particle (!):

$$D_{r\neq 0} = \mathrm{e}^{-W(E)} \approx e^{-\sqrt{1-r^2}\,L(E)/\delta q} = (D_{r=0})^{\sqrt{1-r^2}} \to 1 \; at \; |r| \to 1$$

The simple estimation of efficiency the effect of correlated state



$$\delta q \delta p \geq \frac{\hbar}{2\sqrt{1-r^2}}; \qquad \delta T \equiv \frac{(\delta p)^2}{2m} \geq \frac{\hbar^2}{8(\delta q)^2(1-r^2)} - \textit{fluctuation of energy};$$

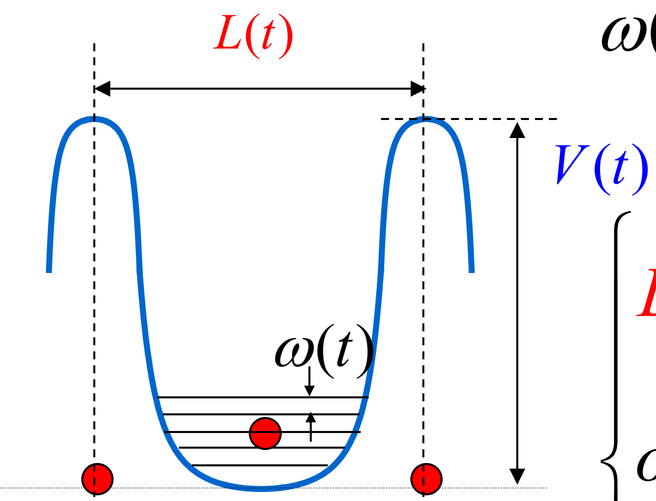
$$If\ \delta q \approx \frac{a}{2} \approx 1\,A \ \ than: \begin{cases} \delta T_{r=0} \geq \dfrac{\hbar^2}{2m_p a^2} \approx 0.05\,eV \quad at\, r = 0 \\ \delta T_r \geq \dfrac{\hbar^2}{2m_p a^2(1-r^2)} \approx 25\,keV\ (!!!) \quad at\, r = 0.999999 \end{cases}$$

(crystal channel)

Formation of the correlated state of a particle at limited periodical deformation of potential well

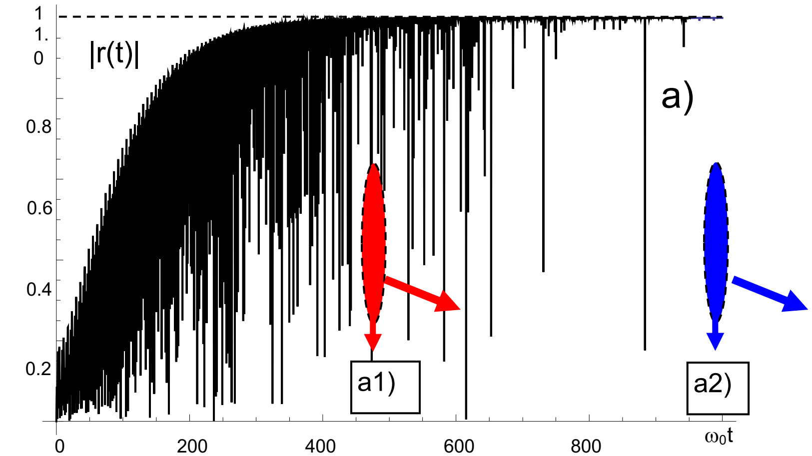
$$V(x,t)=\frac{M\{\omega(t)\}^2x^2}{2};\;\; \omega(t)=\sqrt{8V_{\max}(t)/L(t)};$$

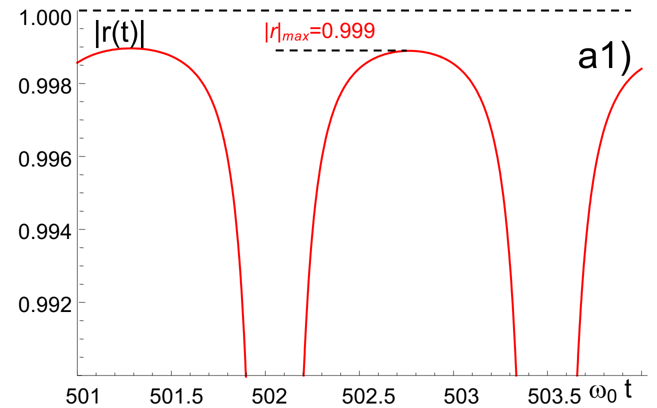
$$\omega(t)=\omega_0\,(1+g\cos\Omega t),\;|\,g\,|<<1$$

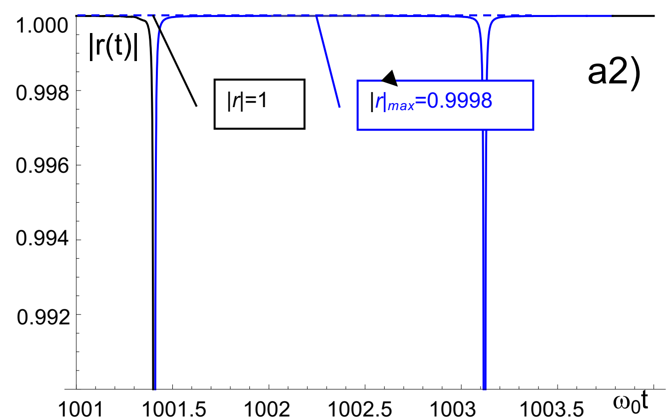


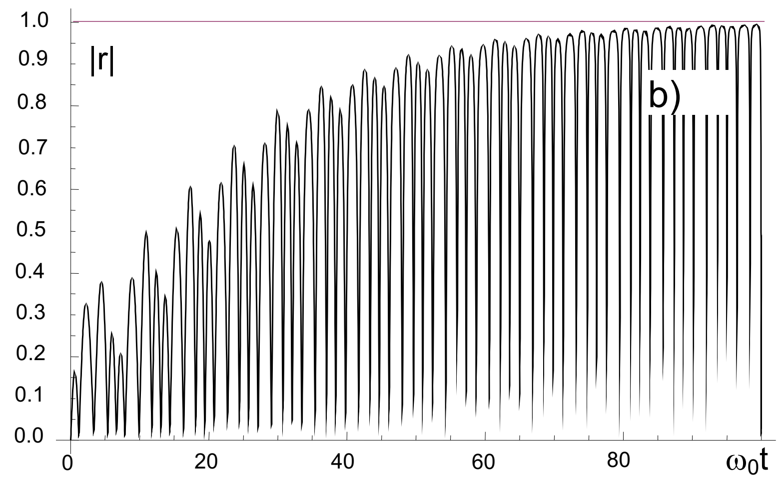
$$\begin{cases} L(t)=L_0\{1+2\dfrac{\Delta L}{L_0}\cos\Omega t\};\; g=\dfrac{\Delta L}{L_0} \\ or \\ V(t)=V_0\{1+\dfrac{\Delta V}{V_0}\cos\Omega t\};\; g=\dfrac{\Delta V}{V_0} \end{cases}$$

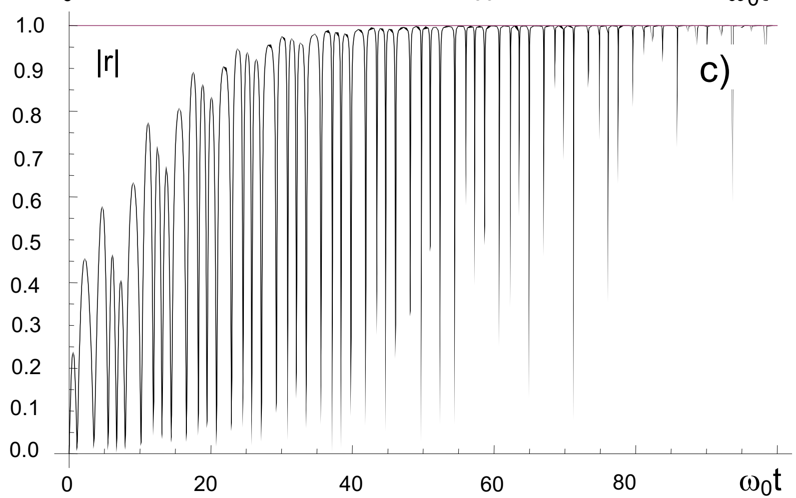
Limited pumping at $\omega_0 = \Omega$











Time dependences of the correlation coefficient r for limited change in the oscillator frequency

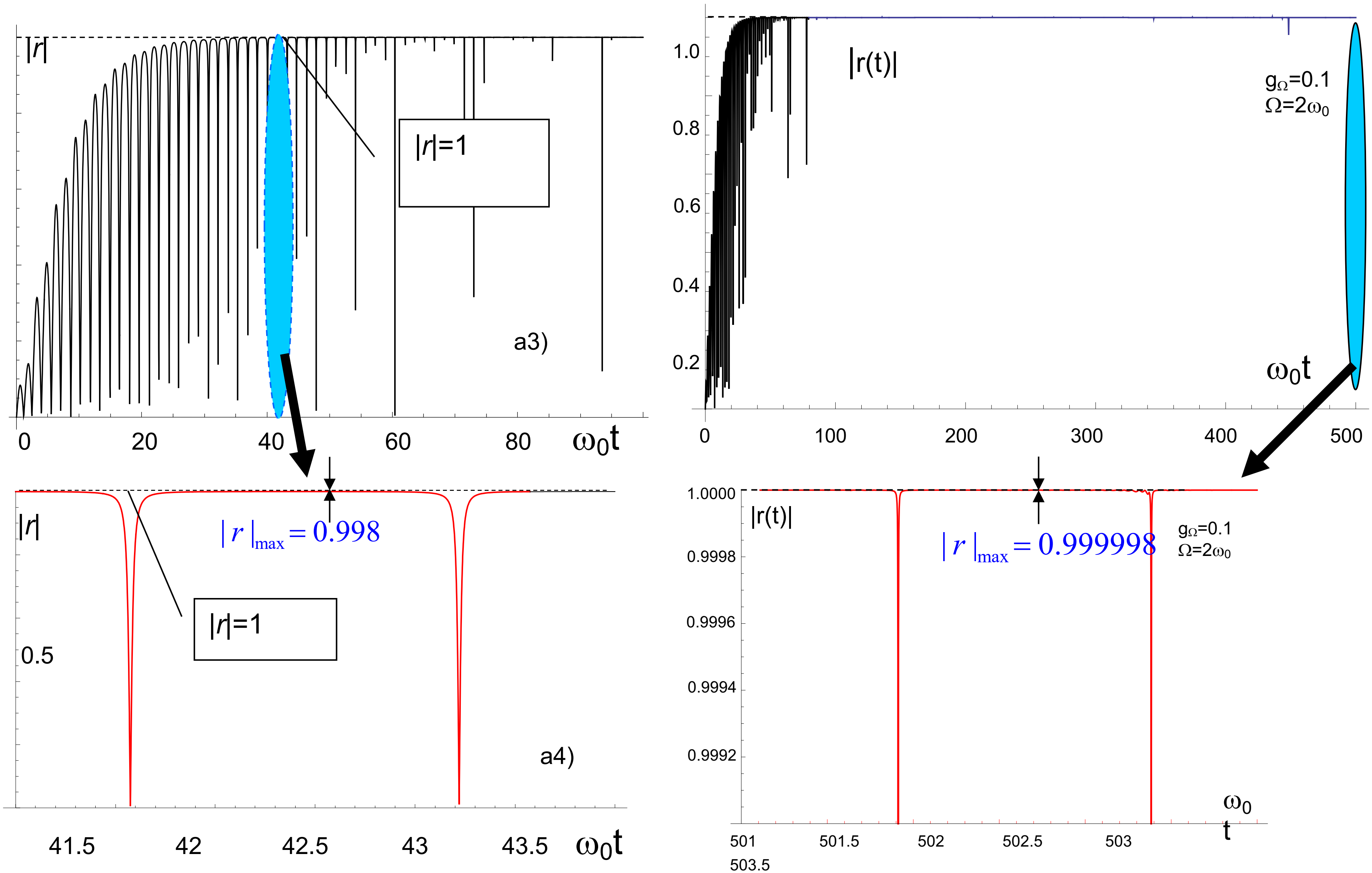
$$\omega(t) = \omega_0 \left(1 + g\cos\Omega t\right)$$

at $\omega_0 = \Omega$ for various frequency modulation depths:

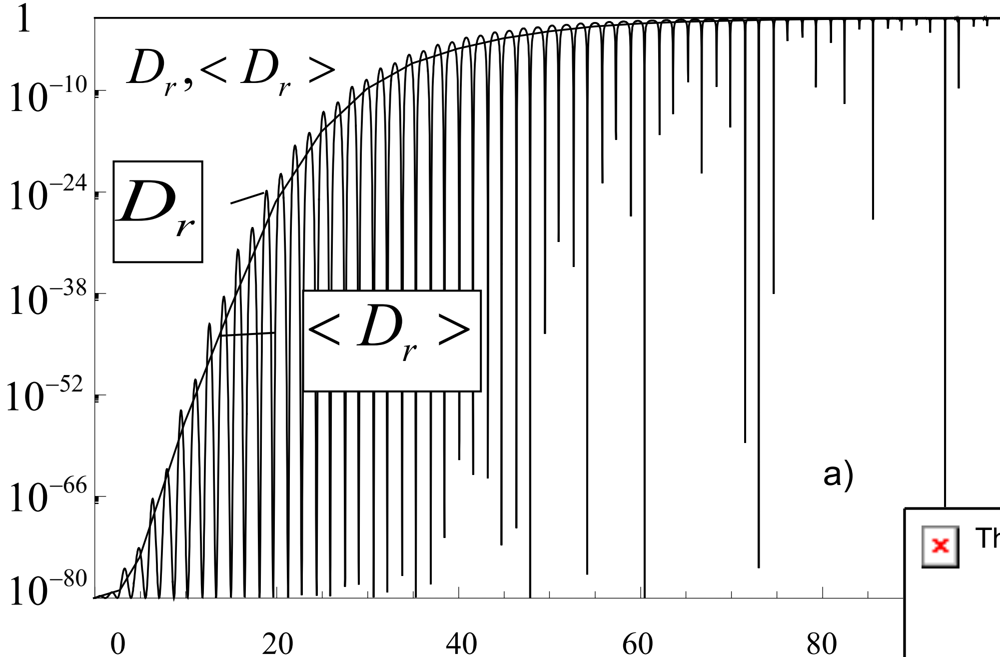
$a)\quad g = 0.1;\ b)\quad g = 0.2\ \ c)\ \ g = 0.3$

Limited pumping at $\Omega = 2\omega_0$

$$\omega(t) = \omega_0\,(1 + g_\Omega \cos\Omega t),\ \Omega = 2\omega_0,\ g_\Omega = 0.1$$



$$< D_{r\neq 0} >_t = < e^{-W(E)\sqrt{1-r^2}} >, \quad Li^{6,7} + p$$



Time dependences of real and averaged coefficient of **transparency** for the case of oscillator frequency

$$\omega(t) = \omega_0 \left(1 + g_\Omega \cos \Omega t\right)$$

at

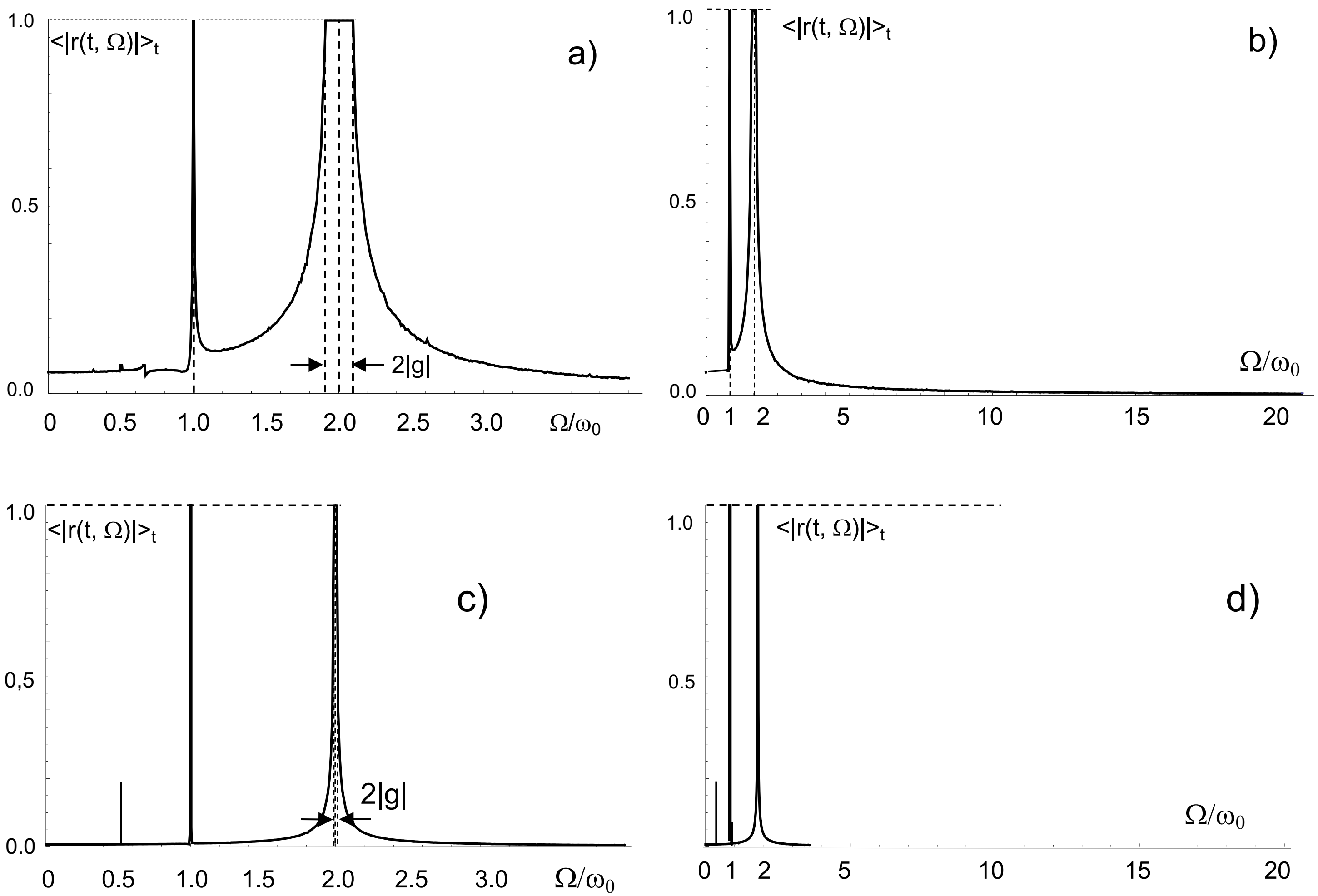
The picture can't be displayed.

0.1

$$< D_r > = \frac{1}{2\pi} \int_{t-\pi}^{t+\pi} (D_{r=o})^{\sqrt{1-r^2(t)}}$$

From the detailed analysis follows that the process of correlated states formation at the action of limited periodic modulation $\omega(t) = \omega_0 (1 + g\cos\Omega t)$ is possible only at any of two conditions: $\Omega = \omega_0$

or Ω is close to $2\omega_0$ and lies inside the interval $|\Omega - 2\omega_0| \le g$



Dependences of averaged correlation coefficient $\langle|r|\rangle_t$ on frequency of modulation Ω at:

$|g|=0.1$, $\omega_0 t \approx 1000$ (a,b) and

$|g|=0.01$, $\omega_0 t \approx 10000$ (c,d).

The same process of self-similar formation of correlated state can be realized at channeling of particles

Self-similar formation of coherent correlated states at proton channeling in crystals

The actual periodical longitudinal structure of parabolic crystal interplanar channel can be approximated by the simple function with nonuniform frequency

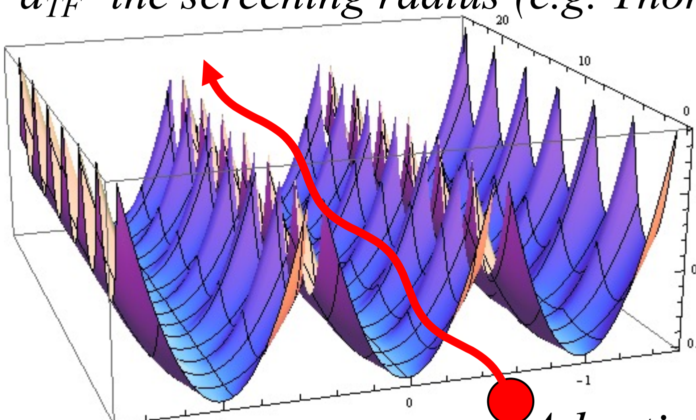
$$V(x,z)=\frac{mx^2\omega^2(z)}{2};\ \omega^2(z)\approx\omega_{\max}^2\sum_{n=0}^{N}\exp\left\{-\frac{|z-d_z n|}{a_{TF}}\right\},n=0,1,2...$$

$$<V(x,z)>_{d_z}\equiv\frac{1}{d_z}\int_{-a_z/2}^{a_z/2}V(x,z)dz\approx\frac{mx^2\omega_0^2}{2};$$

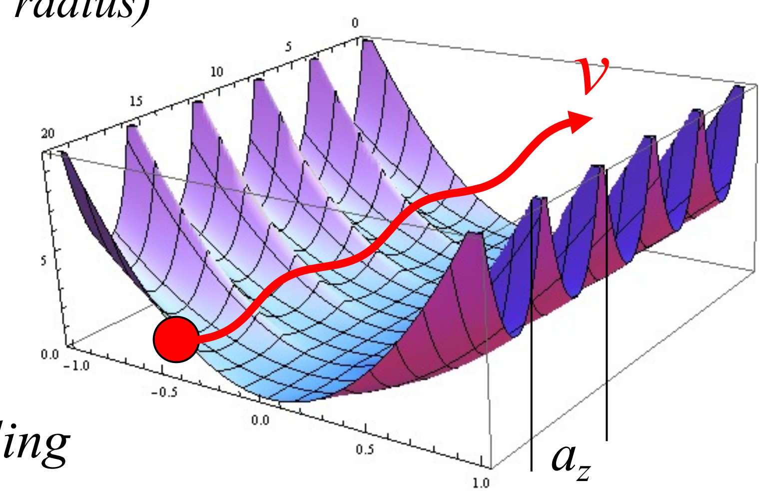
$$\omega_0=\sqrt{<\omega^2(z)>}=\omega_{\max}\sqrt{2a_{TF}/a_z}$$

d_z -longitudinal period of the crystal lattice;

a_{TF}- *the screening radius (e.g. Thomas-Fermi radius)*



Adaptive channeling



In the coordinate system moving with the particle with velocity v, **the potential energy corresponds to a nonstationary potential well of interplanar channeling**

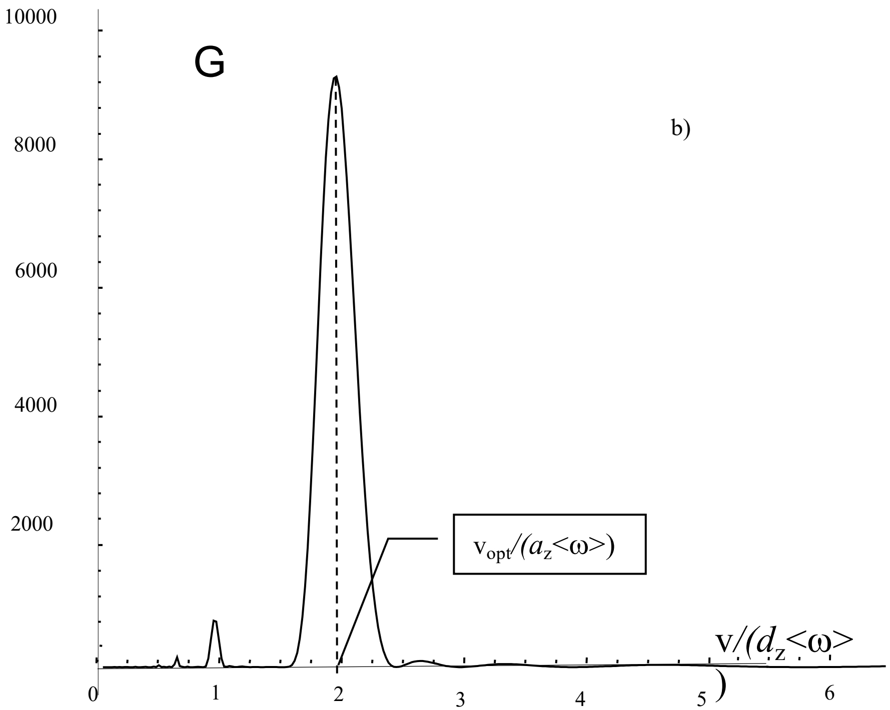
$$V(x,t) \approx \frac{mx^2(\omega(t))^2}{2} \equiv \frac{mx^2\omega_{\max}^2}{2}\sum_{n=0}^{N}\exp\left\{-\frac{|vt-d_z n|}{a_{TF}}\right\}$$

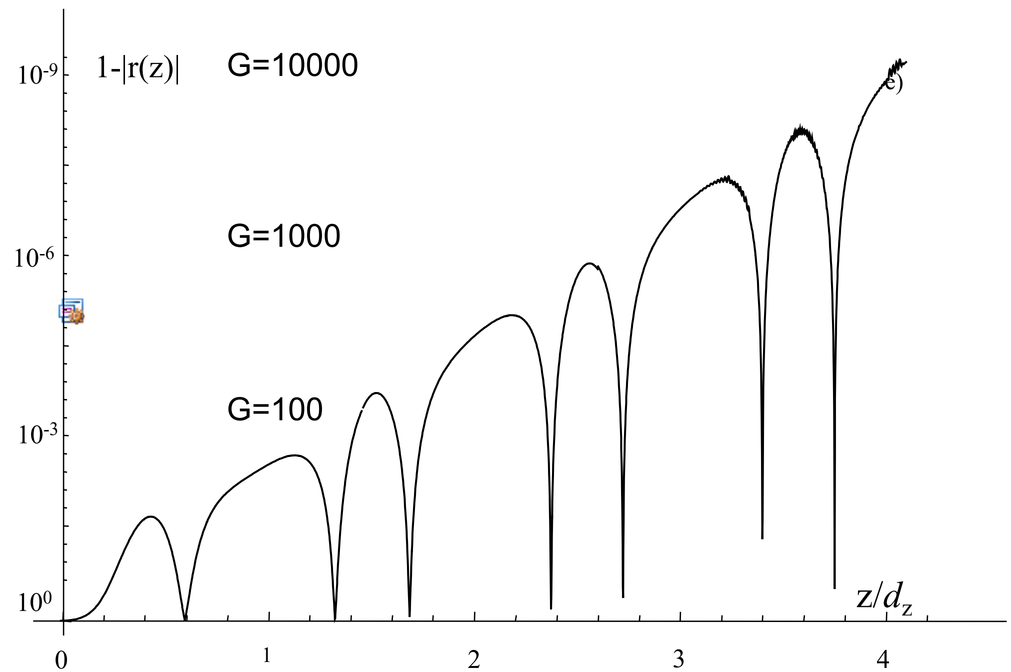
$$\omega(t) = \omega_{\max}\left\{\sum_{n=0}^{N}\exp\left[-\frac{|(v/d_z)t-n|}{a_{TF}/d_z}\right]\right\}^{1/2} = \omega_{\max}\left\{\sum_{n=0}^{N}\exp\left[-\frac{|\Omega t-n|}{a_{TF}/d_z}\right]\right\}^{1/2};$$

$$\omega_{\max} \equiv \omega_0\sqrt{d_z/2a_{TF}},\ \ \Omega = v/a_z;$$

$$\omega_0 = \sqrt{8<V>/m_p d_x^2} \approx (0,5...1)*10^{15}\,s^{-1} - \text{"}usual\text{"}\ frequency\ of\ proton$$

$$channeling\ in\ averaged\ potential\ of\ the\ planar\ crystal\ channel$$





The dependence of the averaged (over the spatial interval a_Z) the coefficient of correlation efficiency <G> (b) on the velocity of the particle v; c) dependence on the coordinate of the potential energy of a particle moving in a crystal; d) dependence on the coordinate (in logarithmic scale) of the correlation coefficient of a particle moving at the optimum velocity. All the values correspond to a crystal with a parameter ratio $K=d_z/u=5$.

Taking into account the condition for the optimal formation of a correlated state $v_{opt} = 2d_z \langle\omega\rangle$ we can calculate the optimal kinetic energy of the protons ensuring the most effective increase in the correlation coefficient

$$T_{opt} = \frac{m_p v_{opt}^2}{2} = 2m_p d_z^2 < \omega >^2 \approx 400...600\, eV$$

which agrees very well with the data of the experiments discussed above!

If we use the exact formula for estimating the lower limit of the energy of fluctuations of a particle localized in the potential well by width $L \le d_x = (2,5...3,5)\mathring{A}$, then in the case of the proton with $G=10^3$ we can find

$$\delta T^{(\min)} \ge G^2\hbar^2 / 8M(\delta q)^2 = G^2\hbar^2 / 2m_p d_x^2 \approx 40...50\ keV$$

At this energy, the probability of the tunnel effect and the cross sections of Li+p nuclear reaction increase sharply to the values

$$D(\delta T^{(\min)}) \geq 10^{-4}, \sigma_{Li+p}^{(\min)} = \sigma_0(\delta T^{(\min)}) \geq 10^{-30}\, cm^2,$$

$$\sigma_0 = S(E)/E,\ S(E) = 0.5\, keVbn - astrophysical\ factor\ \ for$$

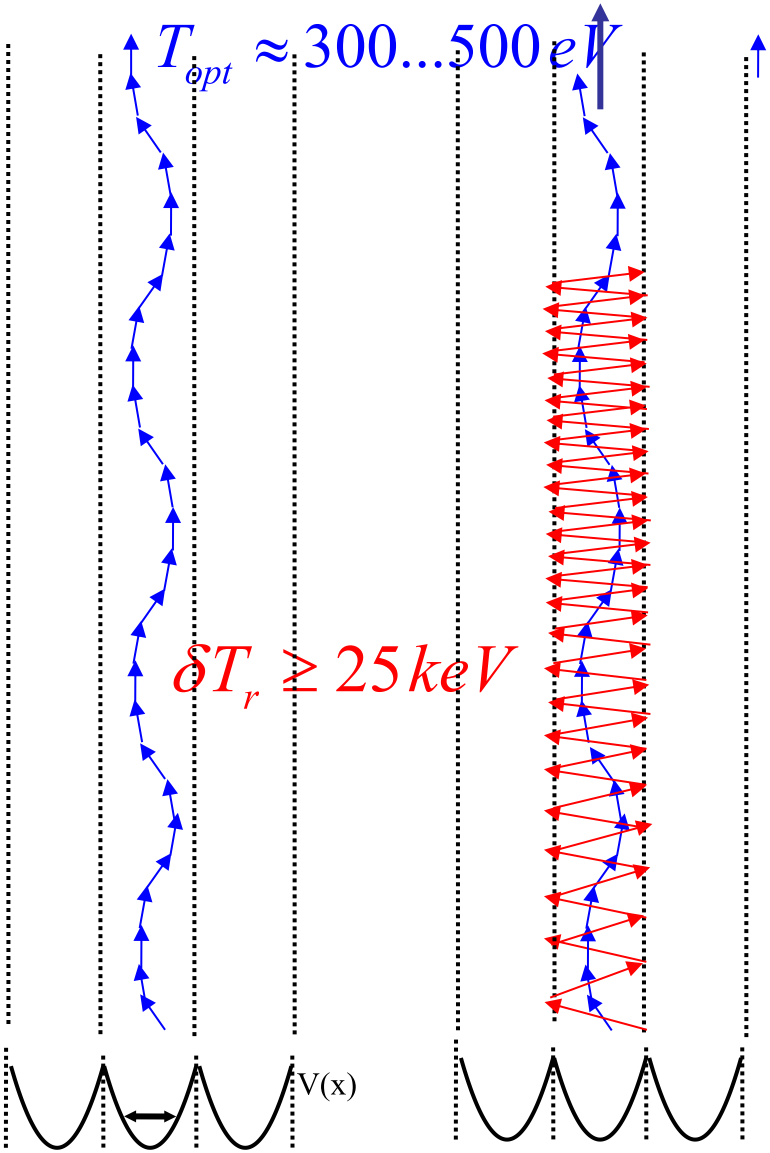
$$(Li^7, p)\ reaction\, at\ \ E \leq 500\, keV$$

At such reaction cross section, the **specific probability of a synthesis reaction for a single proton**, as well as **the total intensity** of reactions of a proton beam with surface atoms at a current, are determined by the quantities (I =50mkA)

$$dW_f / dz = \sigma < n_{Li} > \approx 3.10^{-6}\, cm^{-1},$$

$$J = \sigma_{Li+p} i_p < n_{Li} >< L > \approx 1000\, reactions / \sec$$

close to the data in discussed above experiments.



"Standard" channeling

"Channeling in coherent correlated state

$$v_{opt} \approx k\omega_0 \sqrt{d_z^3 / 2a_{TF}} = k\sqrt{4(d_z^3 / d_x^2 a_{TF}) < V > / m_p};$$

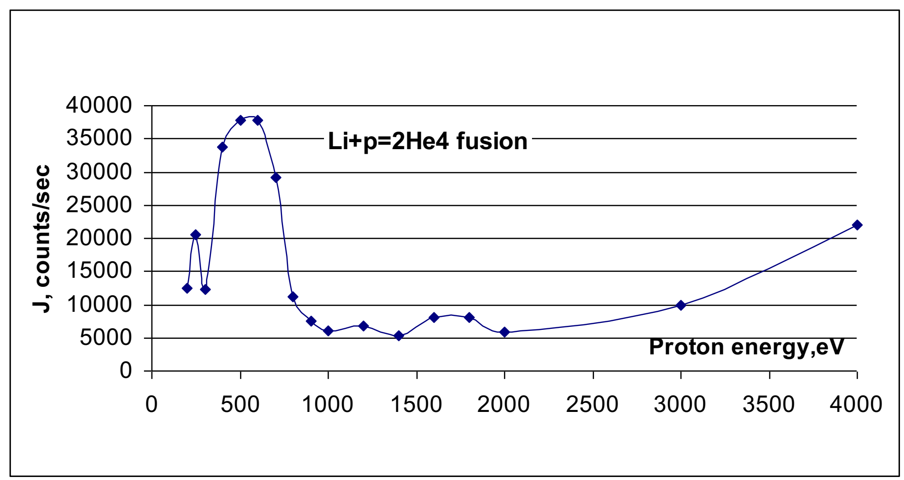
$$T_{opt} = \frac{m_p v_{opt}^2}{2} = 4k^2 \frac{d_z^3}{d_x^2 a_{TF}} < V >,\ k \approx 0.2...0.25$$

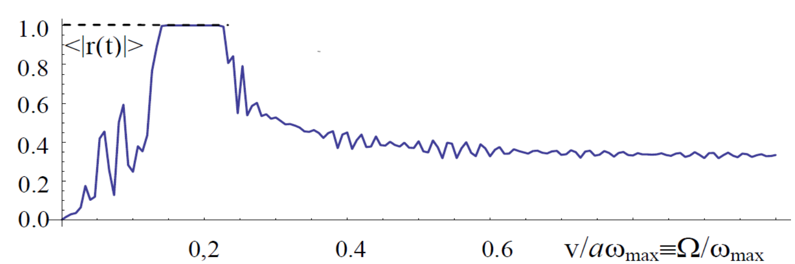
For crystal with

$$a_z = 2a_x,\ a_x \approx 2A,\ a_{TF} \approx 0.3A, < V >= 20...40\, eV$$

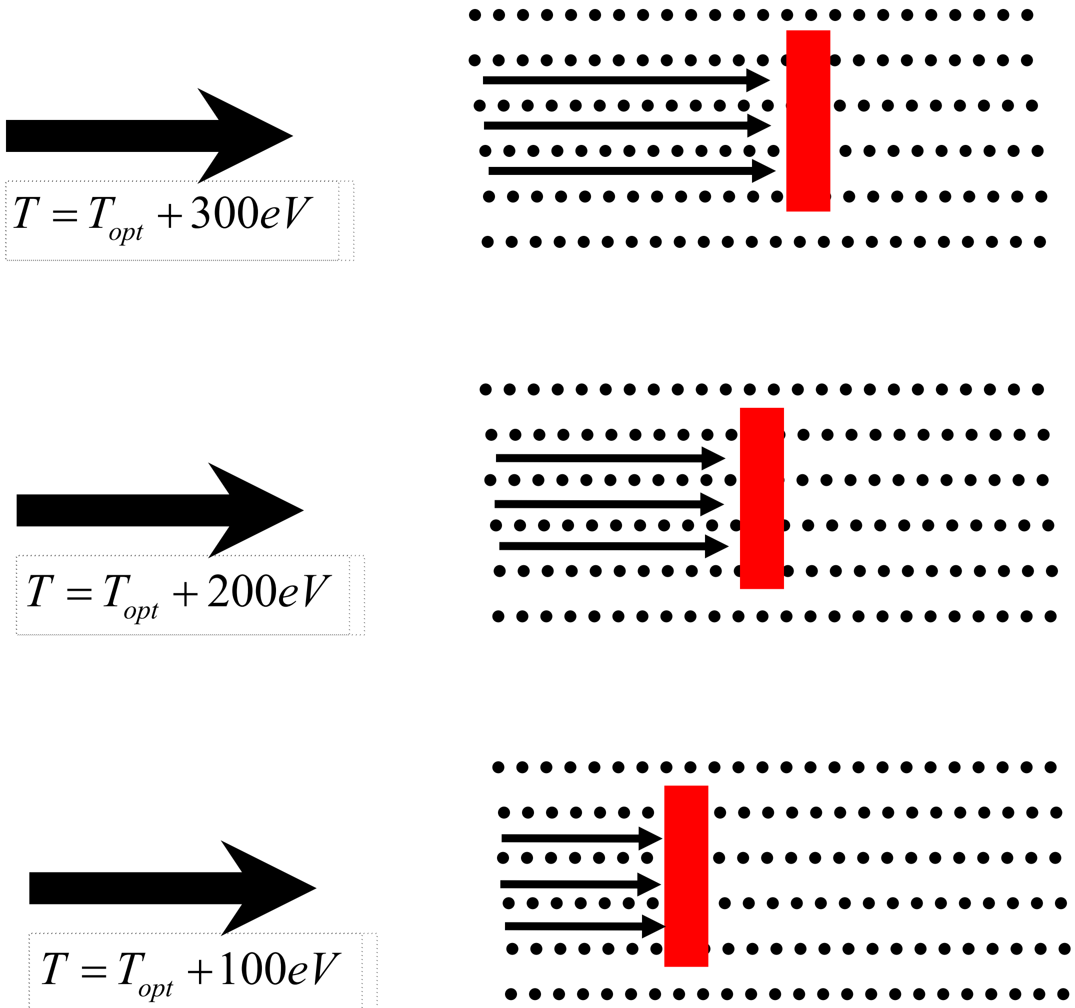
we have $T_{opt} \approx 300...400\ eV$;

$$\delta T_r \geq \frac{\hbar^2}{8Ma^2(1-r^2)} \approx 10...25\, keV\ (!!!)$$

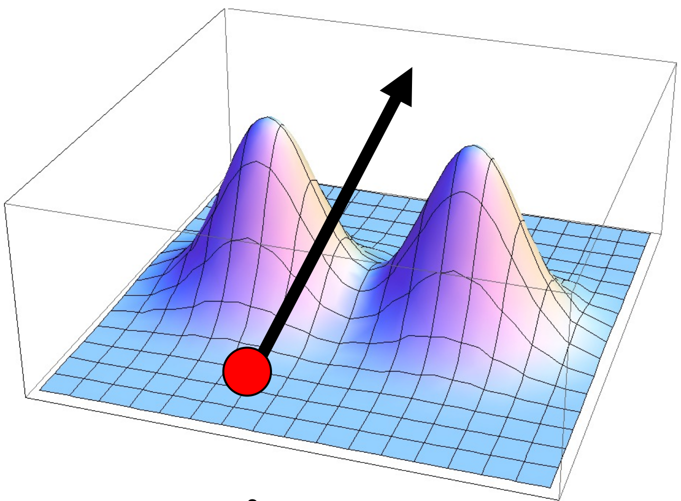




Space-scanning nuclear fusion

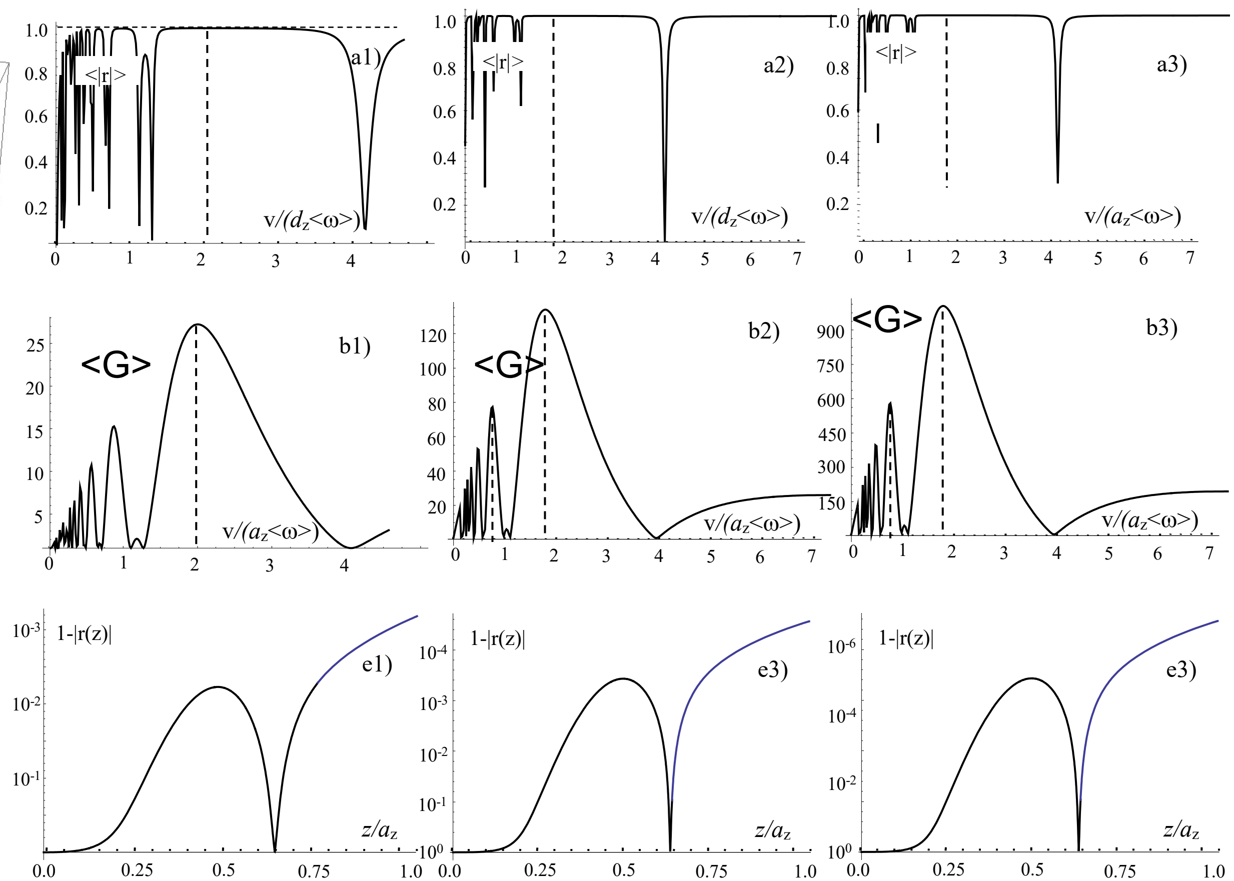


Features of the formation of CCS and nuclear reactions in the interaction of slow protons with molecules and clusters in lithium vapor



$$T_{opt} = \frac{m_p v_{opt}^2}{2} = 2 m_p d_z^2 < \omega >^2 \approx$$

$$\approx 400...600\, eV$$



The dependence of the averaged <| r |> (a) and <G> (b) on the velocity of the particle v; d) the dependence on the coordinate of the correlation coefficient of a particle moving with the optimal velocity. All quantities correspond to diatomic molecules with the following parameters: a1) – e1) - d */ u* = 4; a2) – e2) - d*/ u* = 5; a3) - e3 – *d / u*= 6

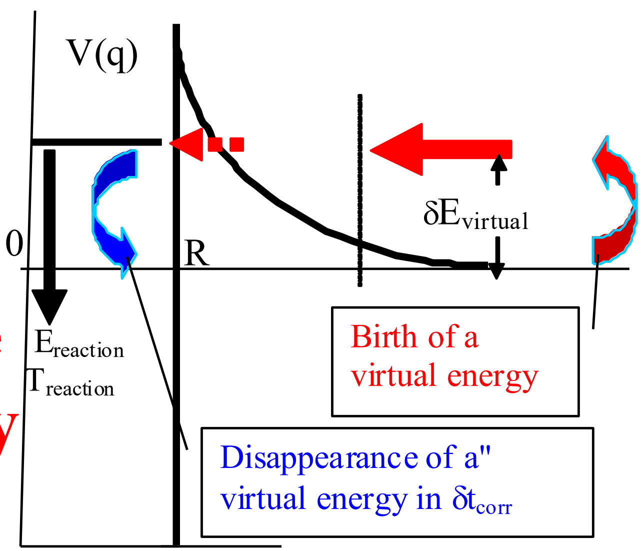
Reasons of total suppression of long-term and "radioactive" channels of LENR and total absence of radioactive ash

The main difference of nuclear fusion on the basis of correlated states is to **use a very large virtual energy, existing a relatively long time**

$$\delta E \delta t \geq \hbar / 2\sqrt{1-r^2} \Rightarrow \delta t_{corr} \geq \hbar / 2\delta E_{virtual}\sqrt{1-r^2}$$

Any nuclear reaction with participation the particle (**that "get" this virtual energy $\delta E_{virtual}$ for a short time δt_{corr} to effectively pass the potential barrier V(r)), will be possible only when the duration of the reaction $T_{reaction}$ (with "return" of the virtual** energy $\delta E_{virtual}$) **will not exceed this time ($T_{reaction} \leq \delta t_{corr}$ and $E_{reaction} \geq \delta E_{virtual}$**)

If this condition is not met, then such a reaction becomes impossible due to violation of the law of energy conservation



Coherent correlated state at low energy for Li + p reaction

$$Li^7 + p = Be^8{*} : \left\{ Be^8{*} : Q \approx 17,255\, MeV, T \approx 10^{-20}\, s \right\} \to 2He^4 + 17,255\, MeV$$

In correlated state we have $\delta E \delta t_{correlated} \geq \hbar / 2\sqrt{1-r^2}$,

$$\delta t_{correlated}^{\min} = \hbar / 2\delta E \sqrt{1-r^2} >> \delta t_{uncorrelated}^{\min} = \hbar / 2\delta E;$$

We need $\delta t_{correlated} > \tau_{tot} = T_{reaction} + \tau_{"trip"} \approx 10^{-20}\sec$

At $\delta E = 10...100\, keV$ and $r = 0.999999$ we have $\delta t_{correlated} \approx (20...2)10^{-19}\, s$

In the result we have $\delta t_{correlated} > \tau_{tot} = T_{reaction} + \tau_{"trip"}$ and LENR is possible!

For alternative reaction

$$Li^6 + p = Be^{7*} \left\{ Be^{7*} : Q = 4\, MeV, T_{reaction} \approx 1.3 * 10^{-13}\, s \right\} \to He^4 + He^3$$

the opposity relation takes place $\delta t_{correlated} << \tau_{tot} = T_{reaction} + \tau_{"trip"} \approx 10^{-13}\, s$

and LENR in this case is inpossible!

For the same reason (the duration of the existence of energy fluctuations is much less than the time of spontaneous gamma-decay) are strong **suppressed gamma-decay channels and creation of radioactive daughter isotopes**

ISSN 1063-7761, Journal of Experimental and Theoretical Physics, 2019, Vol. 128, No. 6, pp. 856–864. © Pleiades Publishing, Inc., 2019.
Russian Text © The Author(s), 2019, published in Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2019, Vol. 155, No. 6, pp. 1009–1020.

NUCLEI, PARTICLES, FIELDS, GRAVITATION, AND ASTROPHYSICS

Features of Correlated States and a Mechanism of Self-Similar Selection of Nuclear Reaction Channels Involving Low-Energy Charged Particles

V. I. Vysotskii[a,]* and M. V. Vysotskyy[a]

[a] *Taras Shevchenko National University of Kyiv, Kyiv, 01601 Ukraine*

* *e-mail: vivysotskii@gmail.com*

Received August 14, 2018; revised December 6, 2018; accepted December 20, 2018

Abstract—Features of the Robertson–Schrödinger coordinate–momentum and energy–time uncertainty relations and connection between them have been considered. A method has been proposed to determine the duration of giant energy fluctuations of particles in a correlated coherent state. This method makes it possible to justify both a huge (many orders of magnitude) increase in the probability of the tunnel effect with the subsequent low-energy nuclear reaction and the automatic selection of low-energy reaction channels involving charged particles and the exclusion of the production of radioactive daughter isotopes. It has been shown that the same mechanism of formation of correlated coherent states explains a very significant suppression of gamma radiation observed in such reactions stimulated by the virtual energy as compared to similar reactions proceeding at a high "real" energy of particles.

DOI: 10.1134/S1063776119040125

1. INTRODUCTION

The quantum-mechanical tunnel effect is among

topes in reaction products, and very strong suppression of gamma radiation, which should inevitably

For the same reason (the duration of the existence of energy fluctuations is much less than the time of spontaneous gamma-decay or decay of compond nucleus) are:

strong **suppressed gamma-decay channels**

and

completely prohibited nuclear fusion channels that lead to the formation of radioactive daughter isotopes

Conclusions

*The method of coherent correlated states allows to realize huge fluctuation of pulse and energy that can exceed by many orders of low energy of longitudinal motion of channeling particles.

*The excitation of such states is associated with the parametric action of the natural periodic crystal structure on the phase characteristics of the particle's own states in the channel.

*Presented results clearly demonstrate the "giant" increases (by many order of magnitude) of localization density under the potential barrier and also the possibility of very effective under the barrier penetrations of particles connected with self-similar formation of correlation coefficient at resonant velocity of channeling particle.

*The theoretical results are in good agreement with the paradoxical data of earlier experiments on nuclear fusion at low energy

* With a controlled decrease in the initial energy of particles, the region of CCS formation and nuclear fusion is shifted towards the channel entrance. In this mode it is possible to gradually shift the fusion region over the entire crystal volume to its front and implement spatially scanning low-energy nuclear fusion.

Thank you for attention

Application of short-distance adaptive channeling of low energy particles in above-target graphene film to optimize nuclear fusion in unstructured target

Vladimir Vysotskii , Mykhaylo Vysotskyy,
Taras Shevchenko National University of Kyiv, Ukraine

Sergio Bartalucci
LNF-INFN Research Division, Frascati, Italy

In our previous works

V.I.Vysotskii, M.V. Vysotskyy, S. Bartalucci. Jour.Exper. Theor. Phys, **127**(3), 479 (2018).
S. Bartalucci. V.I.Vysotskii, M.V. Vysotskyy. Phys. Rev. AB, **22** (5), 054503 (2019).

it was shown that the motion of charged particles with optimal longitudinal velocity $v_z^{opt} = 2d_z < \omega(z) >_z$ in a periodic (d_z) interplanar potential well V(x,z) leads to the formation of coherent correlated states of these particles and to the generation of giant fluctuations of the transverse kinetic energy $\delta T_x \geq$ 30-50 keV. Such an effect is associated with the formation of an optimal coherent superposition of particle eigenfunctions and the condition for the implementation of the Schrödinger-Robertson uncertainty relation

$$q_\perp = x, q_\| = z$$

$$\delta p_\perp \delta q_\perp \geq \frac{\hbar}{2\sqrt{1-r^2}} \equiv \hbar_{eff}/2, \quad \hbar_{eff} = \frac{\hbar}{\sqrt{1-r^2}} \equiv G\hbar, G = \frac{1}{\sqrt{1-r^2}}$$

$$r = \frac{\{< q_\perp p_\perp > + < p_\perp q_\perp > \}}{2\sqrt{< p_\perp^2 >< q_\perp^2 >}}; \quad \delta T_\perp = \frac{(\delta p_\perp)^2}{2M} \geq \frac{\hbar^2 G^2}{8M(\delta q_\perp)^2}$$

To implement this method, very special conditions are required:

• the target for nuclear fusion must be in the form of a **perfect single crystal** for realization of adaptive (at low energy) channeling

•this target must be composed of **isotopes necessary for the implementation of the optimal nuclear reaction**

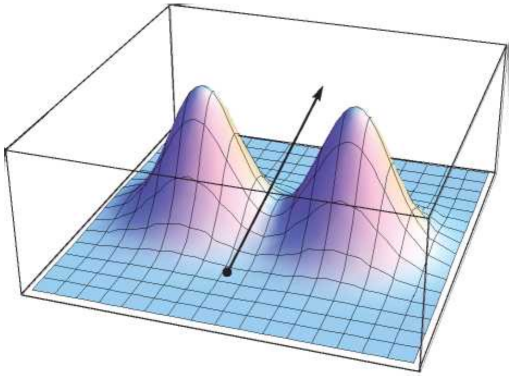
•such an ideal **perfect single crystal target** must be replaced after a short operating time due to its destruction in the process of nuclear reactions.

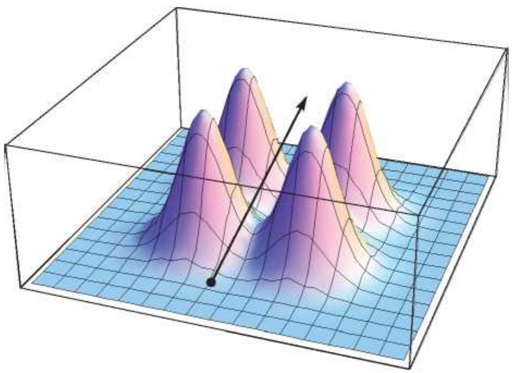
These problems may be solved by using two-stage mode of particle motion, which combines:

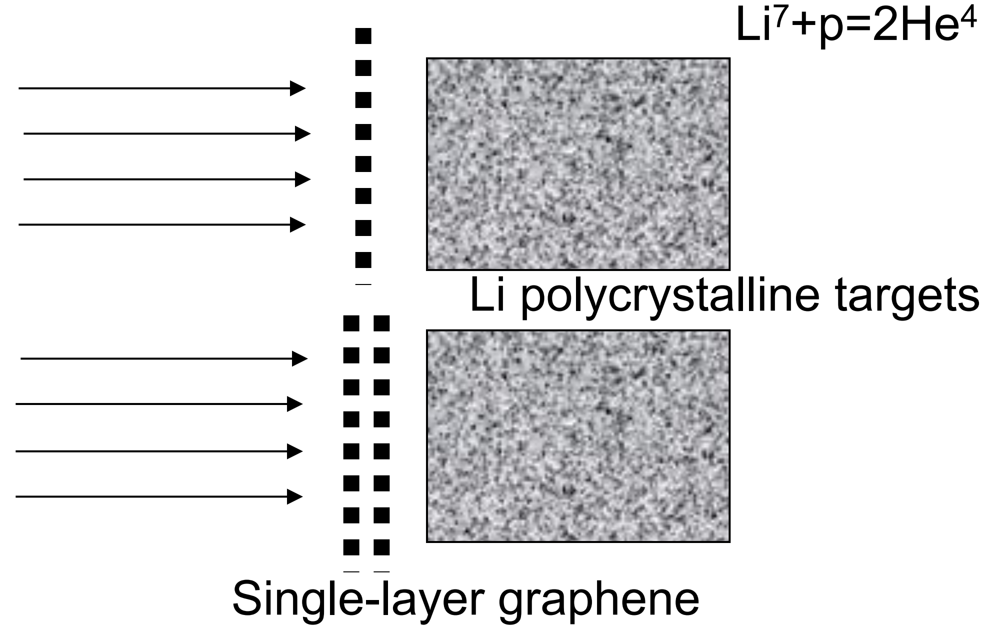
•**short-distance adaptive channeling of low-energy particles in a thin single crystal above-target film** (e.g. graphene) with the optimal longitudinal velocity which leads to the formation of a correlated package in the transverse direction;

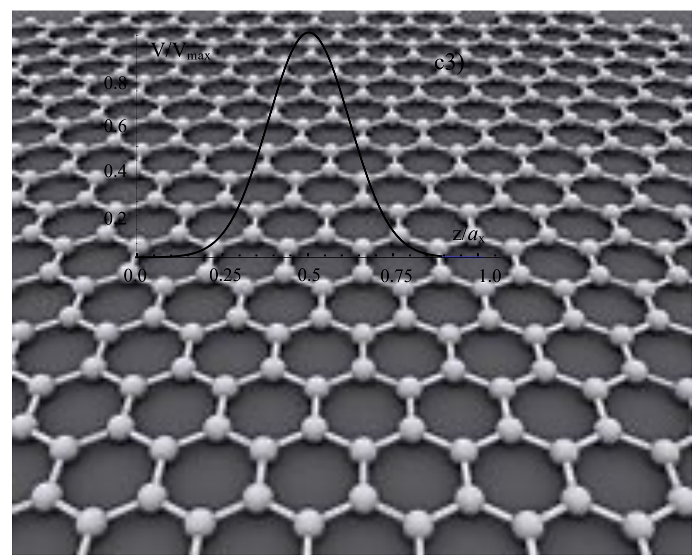
•**subsequent distant interaction of this package with an unstructured target with optimal isotope composition**.

Scheme for the use of adaptive channeling in short channels for the implementation of nuclear fusion at low energy in an unstructured targets









The mode of motion of relatively slow particles (protons) in the space between atoms of N-layer graphene corresponds to periodical inhomogeneous harmonic oscillator, the potential energy of which can be approximated by the

$$V(x,z)=\frac{m_p x^2\omega^2(z)}{2}\equiv\frac{m_p x^2\omega_{\max}^2}{2}\sum_{n=1}^{N}\exp\{-|z-(n-1/2)d_z|/a\},\ |x|\leq d_x, z\geq 0$$

Upon transition to the comoving coordinate system, the motion of a particle in such a field corresponds to a **non-stationary harmonic oscillator** with a variable frequency

$$\omega(t)=\omega_{\max}\left\{\sum_{n=1}^{N}\exp\left[-|(v/d_z)t+1/2-n|K\right]\right\}^{1/2},K=d_z/a,\ t\geq 0$$

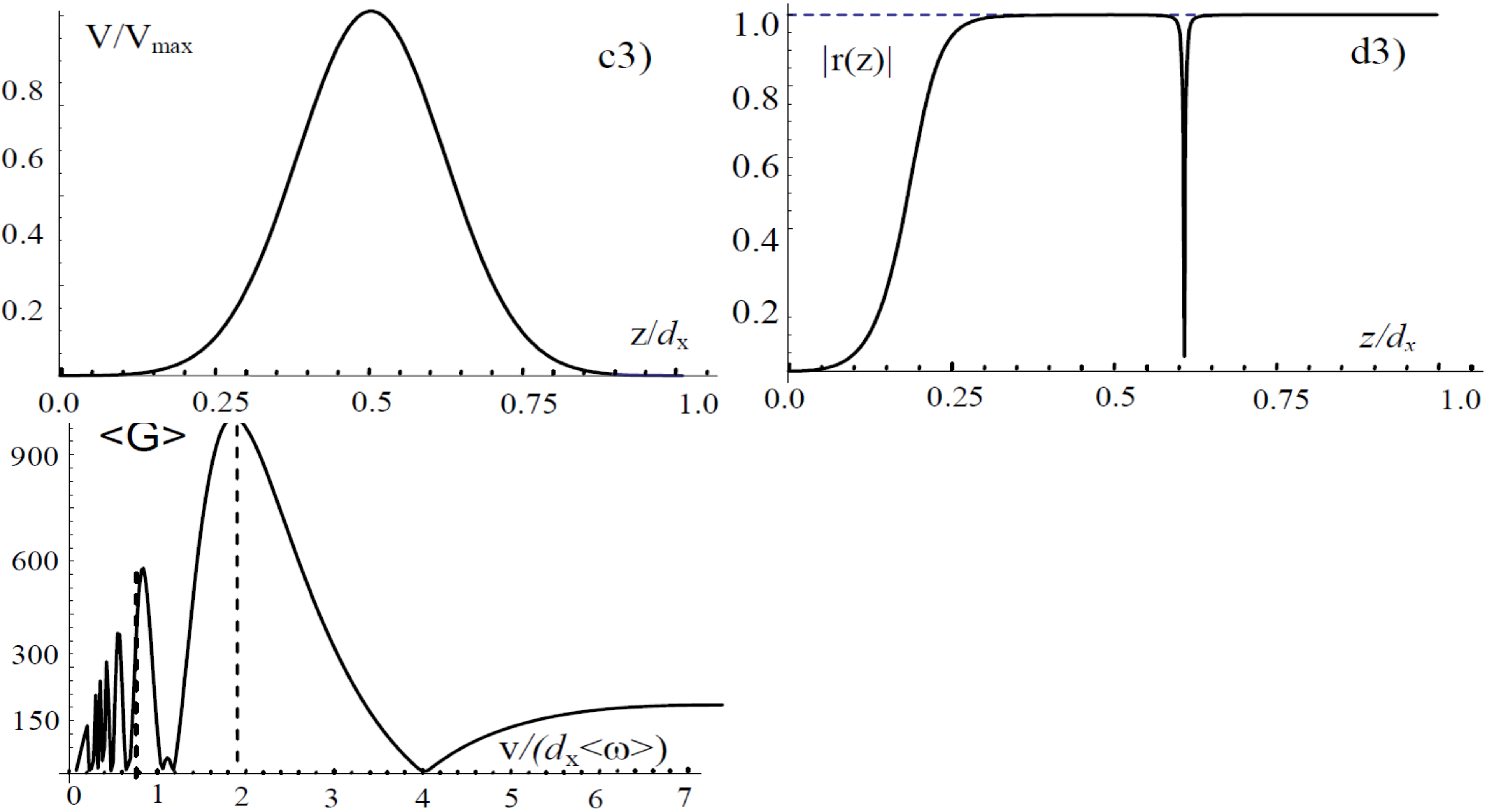
Here a_x and a_z are, respectively, the distance between atoms in the transverse and longitudinal directions, u is the screening radius of the potential near each atom, ω_{msx} is the local frequency of particle oscillations at points with the longitudinal coordinate $z_n=(n-1/2)d_z, n=1,2,...,N$.

Numbers N corresponding to the maximum value of the model parabolic potential.

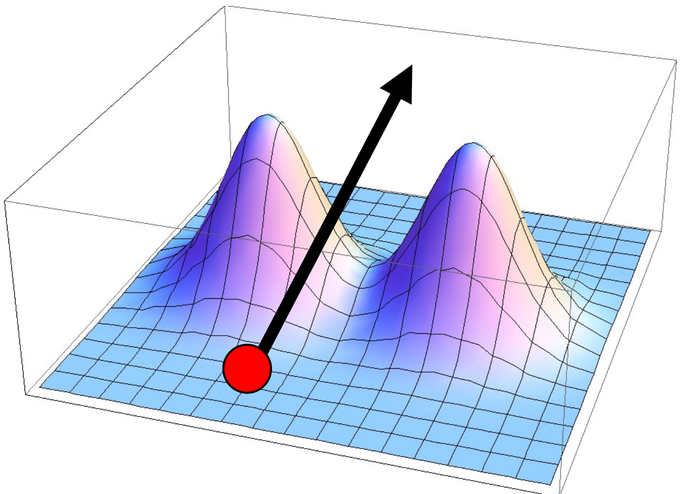
For the case of single-layer graphene N=1 and

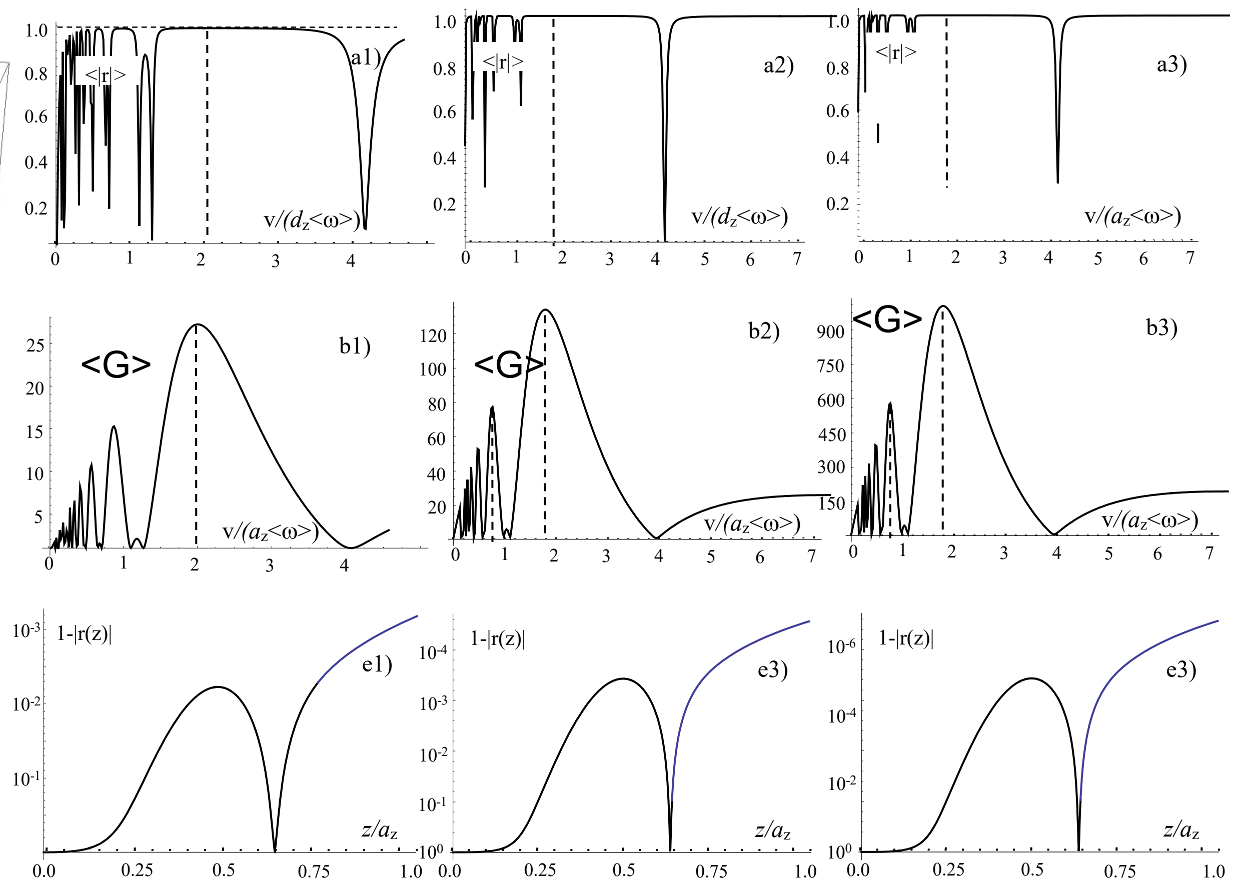
$$\omega(z)=\omega_{\max}\exp\{-|z/2a|\},\ \omega(t)=\omega_{\max}\exp\{-|vt/2a|\}$$

For single-layer graphene with a typical ratio of parameters $d_x/a=6$ we have the following parameters of the wave superposition at the output of the channel



Features of the formation of CCS and nuclear reactions in the interaction of slow protons with molecules and clusters in lithium vapor





$$T_{opt} = \frac{m_p v_{opt}^2}{2} = 2 m_p d_z^2 < \omega >^2 \approx$$

$$\approx 400 \ldots 600\, eV$$

The dependence of the averaged <| r |> (a) and <G> (b) on the velocity of the particle v; d) the dependence on the coordinate of the correlation coefficient of a particle moving with the optimal velocity. All quantities correspond to diatomic molecules with the following parameters: a1) – e1) - $d_z / u = 4$; a2) – e2) - $d_z / u = 5$; a3) - e3 – $d_z / u = 6$

The considered process of effective quantization of a moving proton in a nonstationary potential well refers only to the transverse component of the momentum $p_x = p\sin\theta$, which depends on the angle θ of entry of the particle into the space between atoms and, accordingly, to the transverse energy associated with this component. It should also be recalled that it is these transverse components of momentum and kinetic energy that the process of CCS formation refers to. If the initial transverse component of the total kinetic energy $T_{opt} \approx 400...600$ eV is equal, for example, to $T_x = p_x^2 / 2m_p = 1...10$ eV (for this, the proton must fall at an angle of $\theta \approx 2...10$ degrees to the axis of symmetry), then the effective fluctuations of this energy formed during the formation of the CCS corresponds to $\delta T \approx G^2 T_x \approx 10...100$ keV and more.

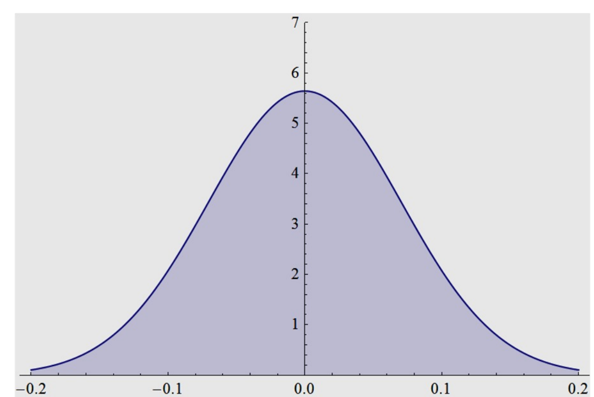
This provides a high efficiency of the synthesis reaction even on a single-atom crystalline film of the graphene type.

The passage of a particle along a crystal channel leads to the formation of a CCS of this particle. This state corresponds to a coherent superposition state with optimal phasing of the eigenfunctions. At the channel output (e.g. at z=0) **this supposition corresponds to a transverse correlated wave packet which describes the state of the particle**

[V. V. Dodonov and A. V. Dodonov, *J. Russ. Laser Res.*, **35(1)**, (2014), 39-46
V.I.Vysotskii, M.V.Vysotskyy. *Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques*, 2019, Vol. 13(6), 1116–1121] .

$$\Psi_{corr}(x, z=0, t=0) = \frac{1}{\sqrt[4]{\pi u^2}} \exp\left\{-\frac{x^2 g}{2u^2}\right\}, \quad g = 1 + iG$$

$$|\Psi_{corr}(x,0,0)|^2 = \frac{1}{\sqrt[2]{\pi u_0^2}} \exp\left\{-\frac{x^2}{u_0^2}\right\}$$



The wave field **in space outside the channel** can be calculated based on the standard procedure for any coherent superposition in quantum mechanics

$$\Psi_{corr}(x,z,t) = \int c(p)\Psi_p(\vec{r})e^{-iE_p t/\hbar}dp =$$

$$\frac{1}{\sqrt{2\pi\hbar}}\int c(p)e^{ipx+\sqrt{p_0^2-p^2}z)/\hbar/\hbar}e^{-i(p_0^2/2m\hbar)t}dp;$$

$$c(p) = \frac{1}{\sqrt{2\pi\hbar}}\int \Psi_{corr}(x,0,0)e^{-ipx/\hbar}dx =$$

$$\frac{1}{\sqrt[4]{4\pi^3 u_o^2\hbar^2}}\int_{-\infty}^{\infty}\exp\left\{-\frac{x^2 g}{2u_o^2}\right\}e^{-ipx/\hbar}dx = \sqrt{\frac{u_0}{g\hbar\sqrt{\pi}}}\exp\left\{-\frac{p^2u_o^2}{2\hbar^2 g}\right\};$$

It is well known in quantum mechanics that the set of coefficients c(p) of the expansion of a general wave function $\Psi_{corr}(x,z,t)$ in terms of partial plane waves $\Psi_p(r)$ in free space is the wave function of the same general wave function in the momentum representation

$$\Psi_{corr}(x, z \geq 0, t \geq 0) = \sqrt{\frac{u}{2\pi g\hbar^2\sqrt{\pi}}} \int_{-\infty}^{\infty} \exp\left\{-\frac{p^2u^2}{2\hbar^2 g}\right\} e^{ipx/\hbar} e^{i\sqrt{p_0^2-p^2}\,z/\hbar} e^{-i(p_0^2/2m\hbar)t}\, dp =$$

$$\sqrt{\frac{up_0}{4\hbar\pi^{1.2}\left(p_0u^2 + iz\hbar g\right)}} \exp\left\{-x^2 / 2\left(\frac{p_0u^2 + iz\hbar g}{p_0 g}\right)\right\} e^{ip_0z/\hbar} e^{-i(p_0^2/2m\hbar)t}$$

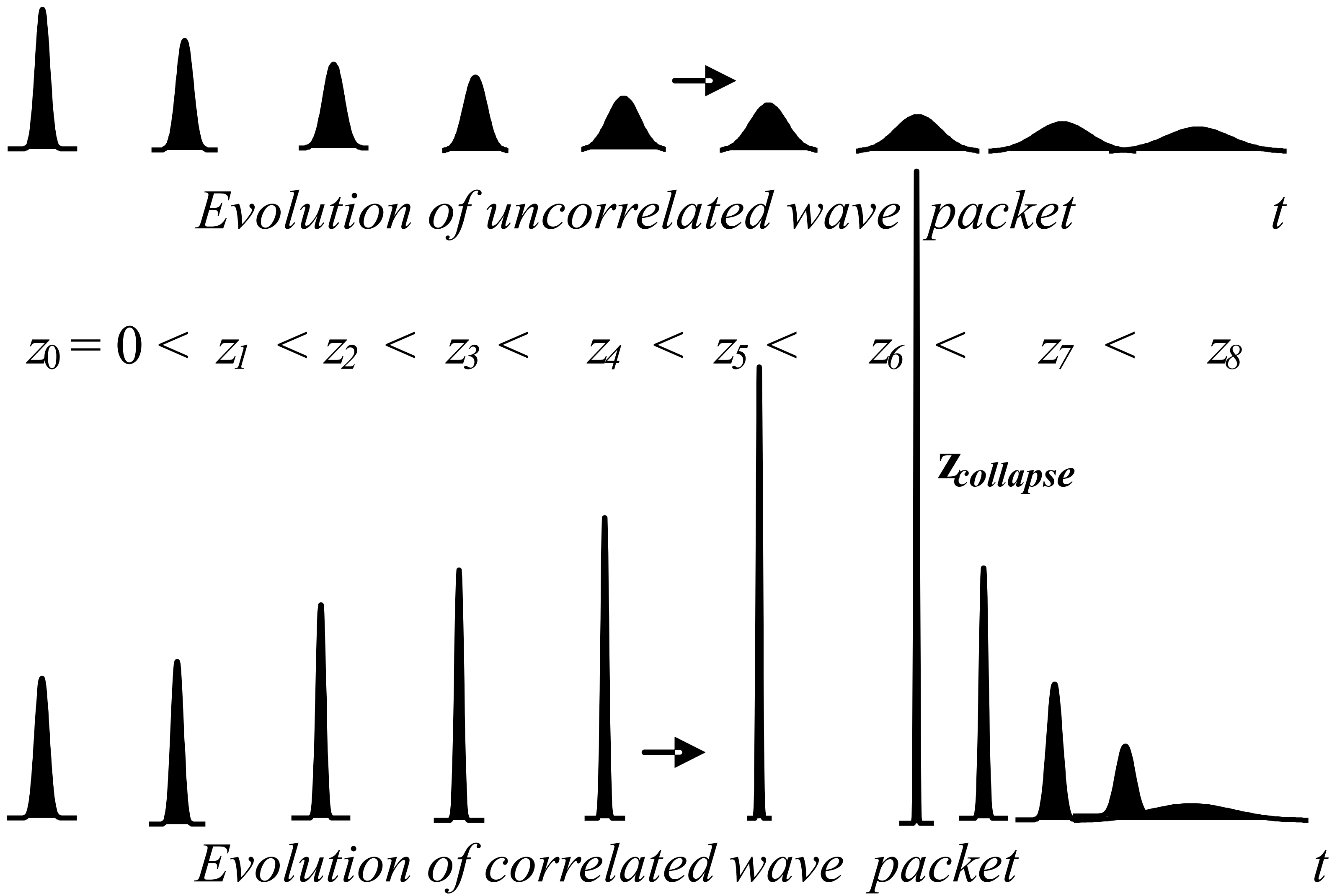
The spatial localization density of a **moving correlated packet** in the space behind the crystal is described by the function

$$|\Psi_{corr}(x, z \geq 0, t \geq 0)|^2 =$$

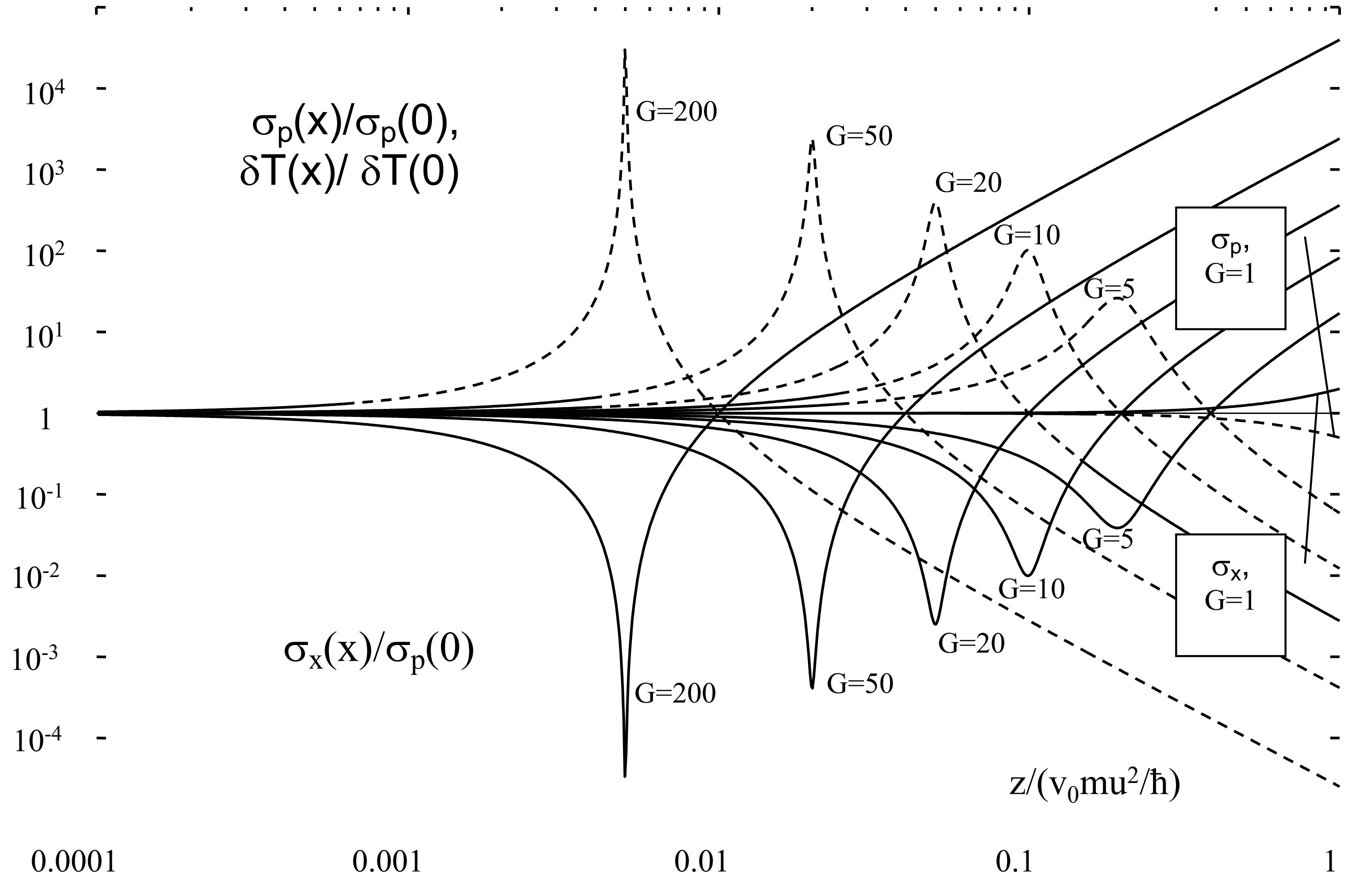
$$\frac{u_0 p_0}{4\hbar\pi^{1/2}\sqrt{(p_0u_0^2 - z\hbar\rho)^2 + (z\hbar)^2}} \exp\left\{-\frac{x^2}{u_0^2\left\{(1 - z\rho\hbar / u_0^2 p_0)^2 + (z\hbar / p_0u_0^2)^2\right\}}\right\}$$

Packet width u(z) change with increasing distance

$$u(z) = u_0\left\{(1 - \frac{z\rho\hbar}{u_0^2 p_0})^2 + \frac{z^2\hbar^2}{p_0^2u_0^4}\right\}^{1/2}, z_{collapse} = \frac{Gp_0u_0^2}{(G^2 - 1)\hbar} \approx \frac{mv_0u_0^2}{G\hbar}$$



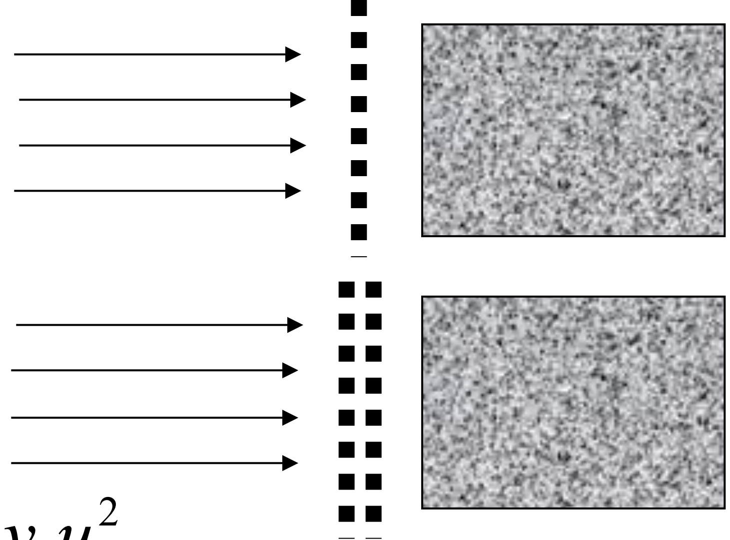
Evolution of uncorrelated wave packet
t
$z_0 = 0 < z_1 < z_2 < z_3 < z_4 < z_5 < z_6 < z_7 < z_8$
$\mathbf{z}_{collapse}$
Evolution of correlated wave packet
t



The maximum (giant) fluctuation of the kinetic energy of a particle

$$\delta T_{\max} = \delta T(z_{collapse}) \approx \frac{\hbar^2 G^4}{4mu_0^2}$$

is generated in the region of the collapse

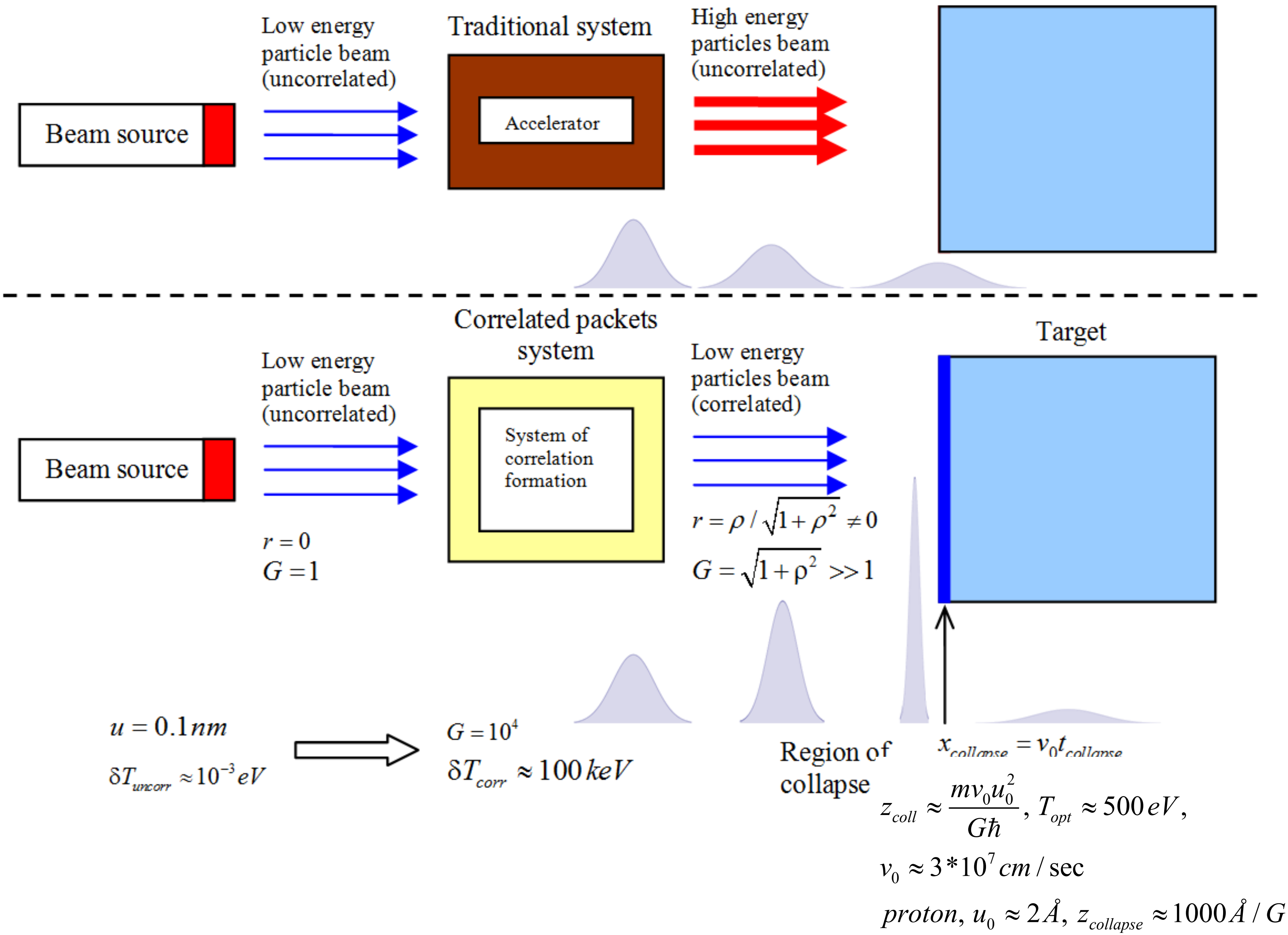


$$z_{coll} \approx \frac{mv_0 u_0^2}{G\hbar}, \; T_{opt} \approx 500\, eV, v_0 \approx 3*10^7\, cm/\sec$$

$$proton,\; u_0 \approx 2\mathring{A},\; z_{collapse} \approx 10-50\mathring{A}$$

The forming crystalline monolayer should be located near the surface of the polycrystalline target.

If a nanostructure with a period of 10 microns of the transverse parabolic potential is used to form a correlated packet , then the distance to the collapse region increases up to 10-100 cm and more.


Low energy particle beam (uncorrelated)
Traditional system
Accelerator
High energy particles beam (uncorrelated)
Beam source
Correlated packets system
System of correlation formation
Target
Low energy particle beam (uncorrelated)
Low energy particles beam (correlated)
Beam source
$r = \rho / \sqrt{1+\rho^2} \neq 0$
$G = \sqrt{1+\rho^2} >> 1$
$r = 0$
$G = 1$
$u = 0.1 nm$
$\delta T_{uncorr} \approx 10^{-3} eV$
$G = 10^4$
$\delta T_{corr} \approx 100\, keV$
Region of collapse
$x_{collapse} = v_0 t_{collapse}$
$z_{coll} \approx \frac{m v_0 u_0^2}{G\hbar}$, $T_{opt} \approx 500\, eV$,
$v_0 \approx 3*10^7\, cm/\sec$
$proton,\ u_0 \approx 2Å,\ z_{collapse} \approx 1000Å/G$

Conclusion

This method (the use of an optimal one- or two-layer single-crystal graphene-type film located in front of an unstructured target) makes it possible to implement efficient nuclear fusion at a low optimal energy in nearby or remote unstructured (or unoriented) nuclear-active targets .

Thank you for attention

Publications 2010-2020 on formation and application of Coherent Correlated States for LENR optimization

- Vysotskii V.I, S.V.Adamenko. Correlated states of interacting particles and problems of the Coulomb barrier transparency at low energies in nonstationary systems. *Journal of Tech. Phys.*, **55**,#5 (2010) 613.
- Vysotskii VI, Vysotskyy MV, Adamenko SV. Formation and application of correlated states in non-stationary systems at low energy of interacting particles. *Journal of Experimental and Theoretical Physics (JETP)*, 2012, **114** (2): 243.
- Vysotskii VI, Adamenko SV, Vysotskyy MV. The formation of correlated states and the increase in barrier transparency at a low particle energy in nonstationary systems with damping and fluctuations. *JETP*, 2012, **115**(4): 551.
- Vysotskii VI, Adamenko SV, Vysotskyy MV. Subbarier interaction of channeling particles under the self-similar excitation correlated states in periodically deformed crystal. *Journal of surface invest.*, 2012, **6**(2): 369.
- Vysotskii VI, Vysotskyy MV. Coherent correlated states and low-energy nuclear reactions in non stationary systems. *European Phys. Jour.**A49***, 2013.

.

- Vysotskii VI, Adamenko SV, Vysotskyy MV Acceleration of low energy nuclear reactions by formation of correlated states of interacting particles in dynamical systems. *Annals of Nuclear energy,* 2013, **62**:618
- Vysotskii VI, Vysotskyy MV. Correlated states and transparency of a barrier for low-energy particles at monotonic deformation of a potential well with dissipation and a stochastic force. *JETP*, 2014, **118**(4): 534.
- Vysotskii VI, Vysotskyy MV. Formation of correlated states and optimization of nuclear reactions for low-energy particles at nonresonant low-frequency modulation of a potential well. *JETP*, 2015, **120**(2): 246.
- Vysotskii VI, Vysotskyy MV. The formation of correlated states and optimization of the tunnel effect for low-energy particles under nonmonochromatic and pulsed action on a potential barrier. *JETP*, 2015, **121**(4): 559.
- Vysotskii VI, Vysotskyy MV. Coherent correlated states of interacting particles – the possible key to paradoxes and features of LENR. *Current Science*, 2015, **108**(4):30.
- Vysotskii VI, Vysotskyy MV. The formation of correlated states and tunneling at low energy at controlled pulse action on particles. *JETP*, 2017, **152**(8):234.
- V.I.Vysotskii, M.V. Vysotskyy, S. Bartalucci. Features of the formation of correlated coherent states and nuclear fusion induced by the interaction of slow particles with crystals and free molecules. *Journal of Experimental and Theoretical Physics (JETP)*, 127 (2018) 479-490.

- Vysotskii VI, Adamenko SV, Vysotskyy MV Acceleration of low energy nuclear reactions by formation of correlated states of interacting particles in dynamical systems. *Annals of Nuclear energy,* 2013, **62**:618
- Vysotskii VI, Vysotskyy MV. Correlated states and transparency of a barrier for low-energy particles at monotonic deformation of a potential well with dissipation and a stochastic force. *JETP*, 2014, **118**(4): 534.
- Vysotskii VI, Vysotskyy MV. Formation of correlated states and optimization of nuclear reactions for low-energy particles at nonresonant low-frequency modulation of a potential well. *JETP*, 2015, **120**(2): 246.
- Vysotskii VI, Vysotskyy MV. The formation of correlated states and optimization of the tunnel effect for low-energy particles under nonmonochromatic and pulsed action on a potential barrier. *JETP*, 2015, **121**(4): 559.
- Vysotskii VI, Vysotskyy MV. Coherent correlated states of interacting particles – the possible key to paradoxes and features of LENR. *Current Science*, 2015, **108**(4):30.
- Vysotskii VI, Vysotskyy MV. The formation of correlated states and tunneling at low energy at controlled pulse action on particles. *JETP*, 2017, **152**(8):234.
- V.I.Vysotskii, M.V. Vysotskyy, S. Bartalucci. Features of the formation of correlated coherent states and nuclear fusion induced by the interaction of slow particles with crystals and free molecules. *Journal of Experimental and Theoretical Physics (JETP)*, 127 (2018) 479-490.

• Vysotskii V.I., Vysotsky M.V. Features of correlated states and a mechanism of self-similar selection of nuclear reaction channels involving low-energy charged particles // *J. of Experim. and Theor. Phys*.- 2019.- **128**. - P. 856–864.

•Bartalucci Sergio, Vysotskii V.I., Vysotsky M.V. Correlated states and nuclear reactions: An experimental test with low energy beams // ***Phys. Rev. Accelerators and Beams***.- 2019.- **22.**- # 5, 054503

•Vysotskii V.I., Vysotsky M.V. Features of the propagation, evolution, and remote collapse of a correlated wave packet // *Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques*, 2019, Vol. 13, No. 6, pp. 1116–1121

•Vysotskii V.I., Vysotsky M.V. Effective LENR in Weakly Ionized Gas Under the Action of Optimal Pulsed Magnetic Fields and Lightning (Theory and Experiments. *Journal of Condensed Matter Nucl. Sci*. v. 29 (2019) ,348-357

• V.I.Vysotskii, M.V. Vysotskyy, S. Bartalucci. Using the Method of Coherent Correlated States for Production of Nuclear Interaction of Slow Particles with Crystals and Molecules. *Journal of Condensed Matter Nucl. Sci.* v. 29 (2019), 358-367.

•V.I.Vysotskii, M.V. Vysotskyy. Universal mechanism of LENR in physical and biological systems on the base of coherent correlated states of interacting particles. **Cold Fusion. Advances in Condensed Matter Nuclear Science** Edited by Jean-Paul Biberian. Elsevier, 2020. CHAPTER 17 pp. 333-370 https://doi.org/10.1016/B978-0-12-815944-6.00017-8\

•V.I.Vysotskii, M.V. Vysotskyy. Application of Correlated wave Packets for Stimulation of LENR in Remote Targets. *Journal Condensed Matter Nucl. Science*, v.33 (2020), pp.305-313

•V.I.Vysotskii, A.A.Kornilova, M.V. Vysotskyy. Features and mechanisms of the generation of neutrons and other particles in first laser fusion experiments. *Journal of Experimental and Theoretical Physics (JETP)*, v.131,N.4, p.566–571(2020), **DOI** 10.1134/S1063776120090101