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

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

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

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

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**

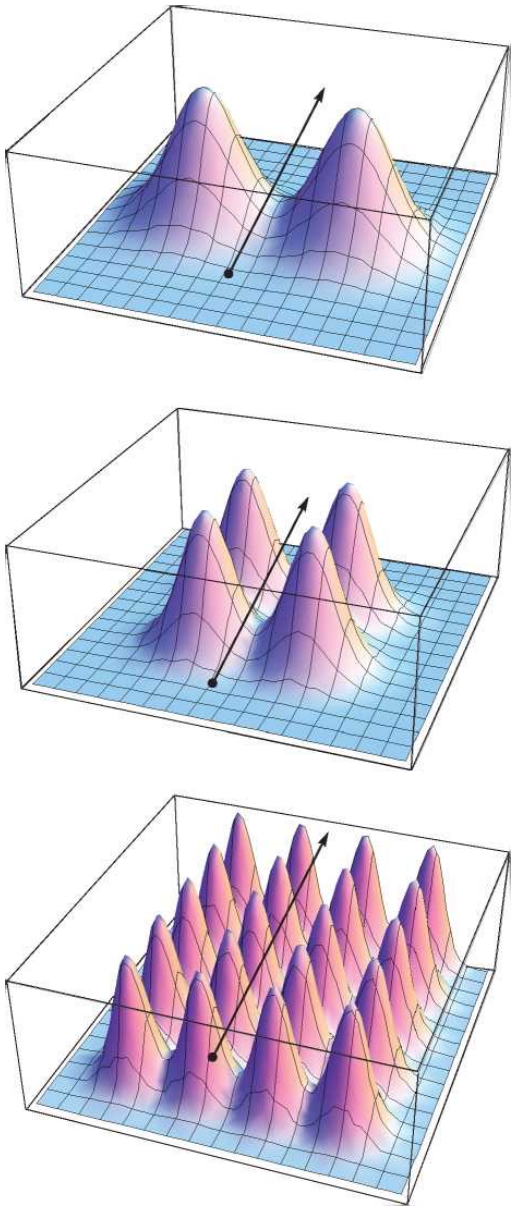
•such an ideal **perfect single crystal target** must be replaced after a short operating time due to its destruction in the process of nuclear reactions.

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

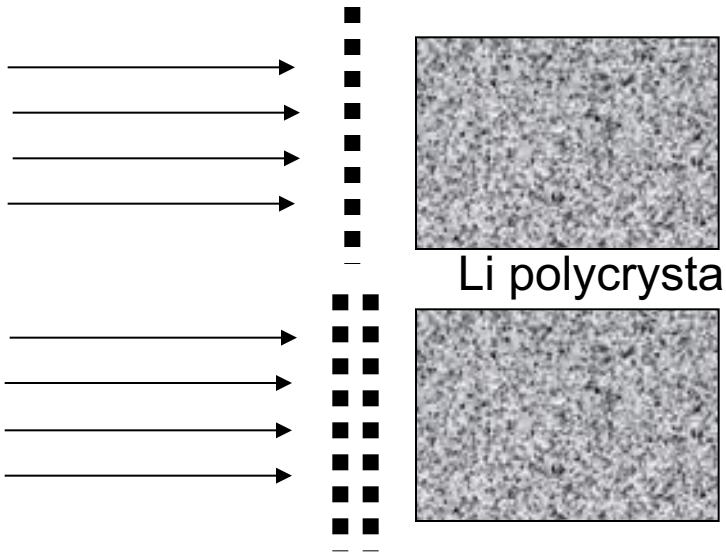
•short-distance adaptive channeling of low-energy particles in a thin single crystal above-target film (e.g. graphene) with the optimal longitudinal velocity which leads to the formation of a correlated package in the transverse direction;

•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

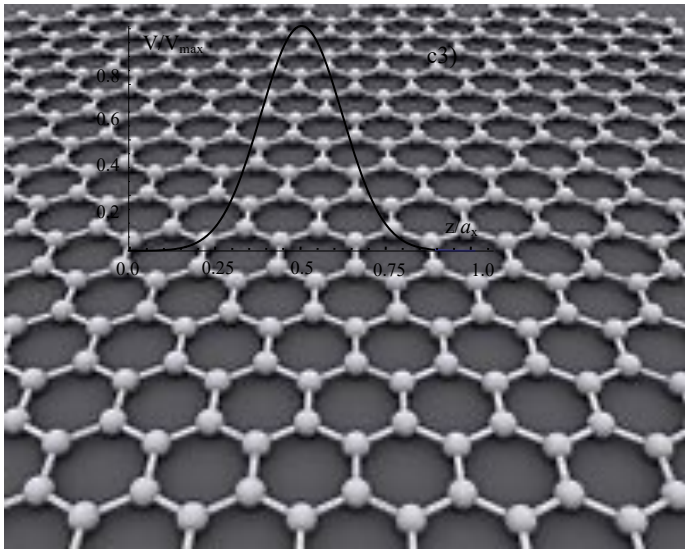


$Li^7+p=2He^4$



Li polycrystalline targets

Single-layer graphene



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

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

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

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

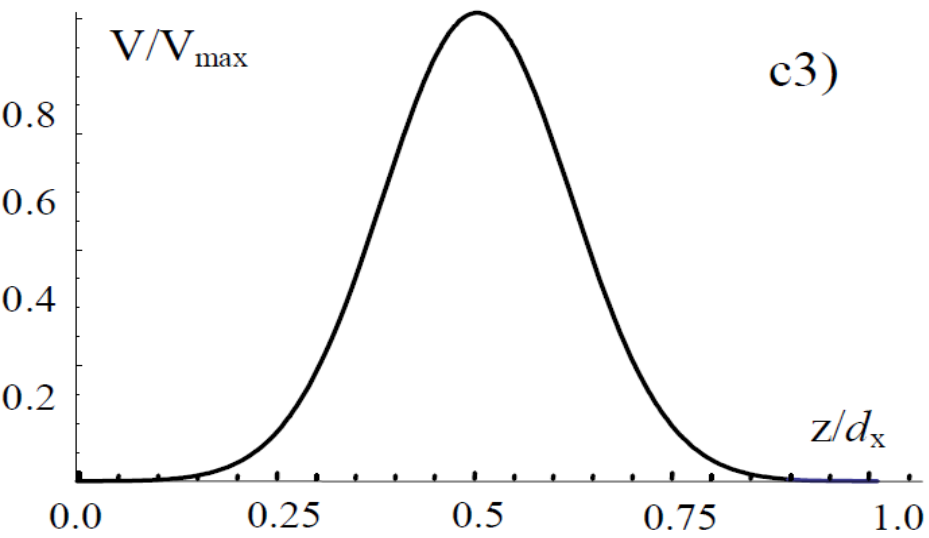
Here a_x and a_z are, respectively, the distance between atoms in the transverse and longitudinal directions, u is the screening radius of the potential near each atom, ω_{msx} is the local frequency of particle oscillations at points with the longitudinal coordinate $z_n=(n-1/2)d_z, n=1,2,...,N$.

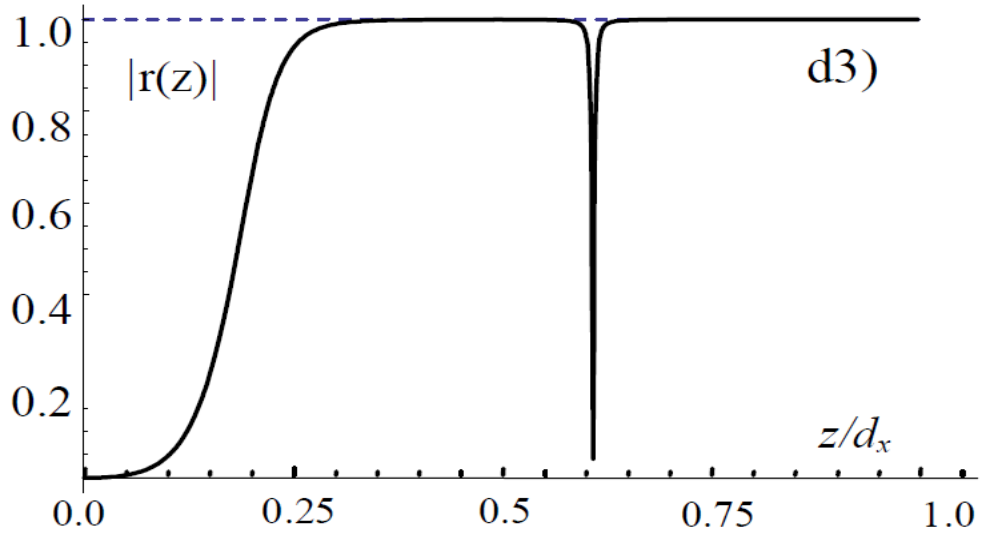
Numbers N corresponding to the maximum value of the model parabolic potential.

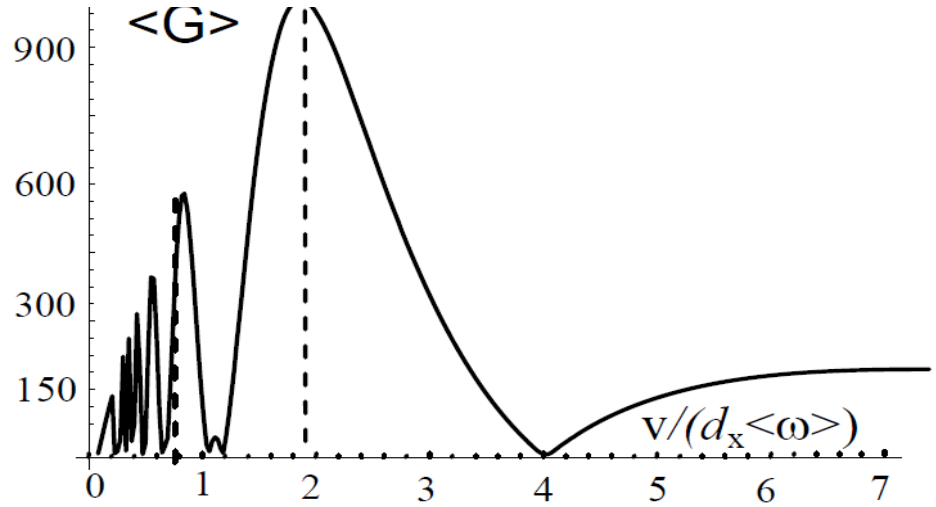
For the case of single-layer graphene N=1 and

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

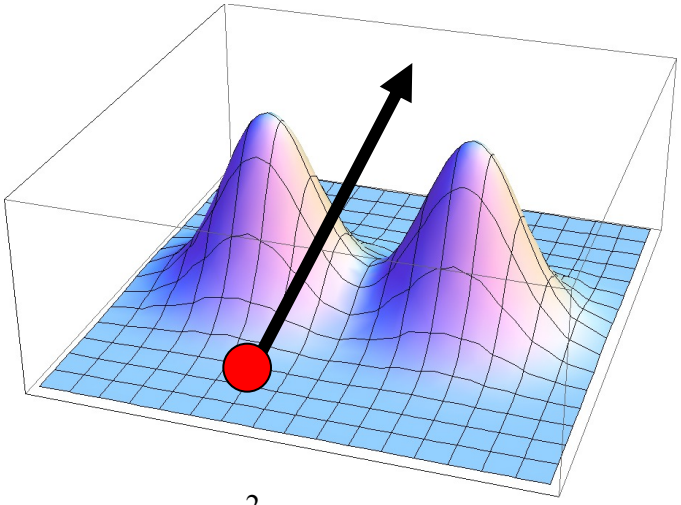
For single-layer graphene with a typical ratio of parameters $d_x/a=6$ we have the following parameters of the wave superposition at the output of the channel





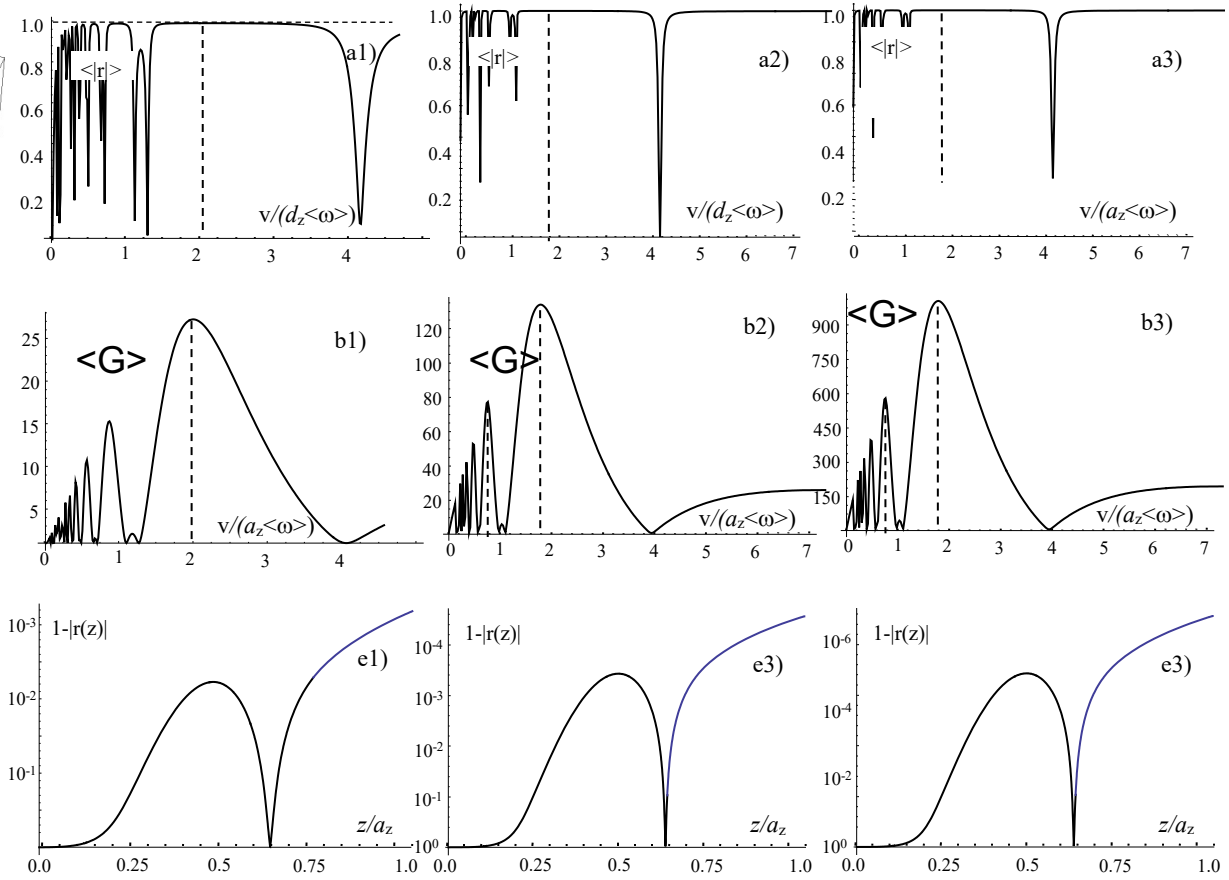


Features of the formation of CCS and nuclear reactions in the interaction of slow protons with molecules and clusters in lithium vapor



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

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



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.

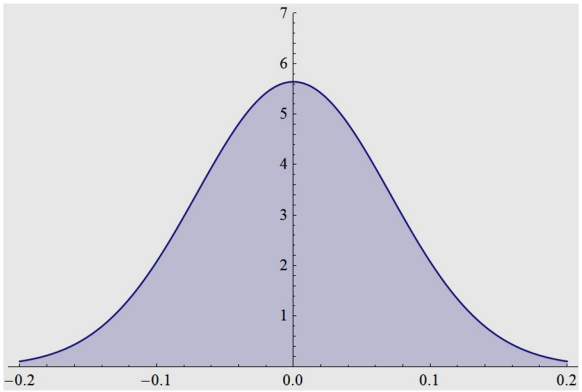
This provides a high efficiency of the synthesis reaction even on a single-atom crystalline film of the graphene type.

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] .

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

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



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

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

$$\sqrt{\frac{up_0}{4\hbar\pi^{1.2}\left(p_0 u^2 + iz\hbar g\right)}} \exp\left\{-x^2 / 2\left(\frac{p_0 u^2 + iz\hbar g}{p_0 g}\right)\right\} e^{ip_0 z/\hbar} e^{-i(p_0^2/2m\hbar)t}$$

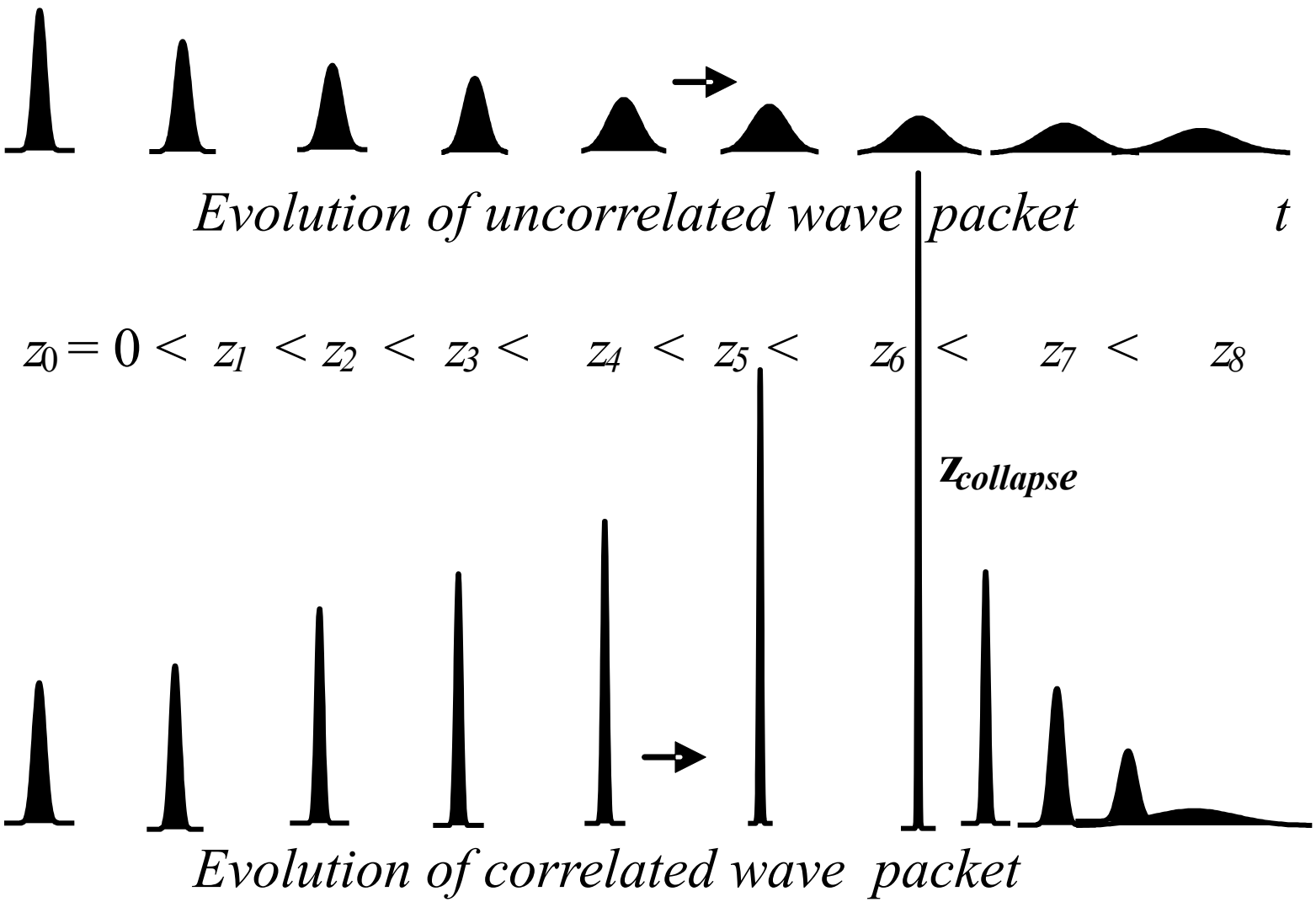
The spatial localization density of a **moving correlated packet** in the space behind the crystal is described by the function

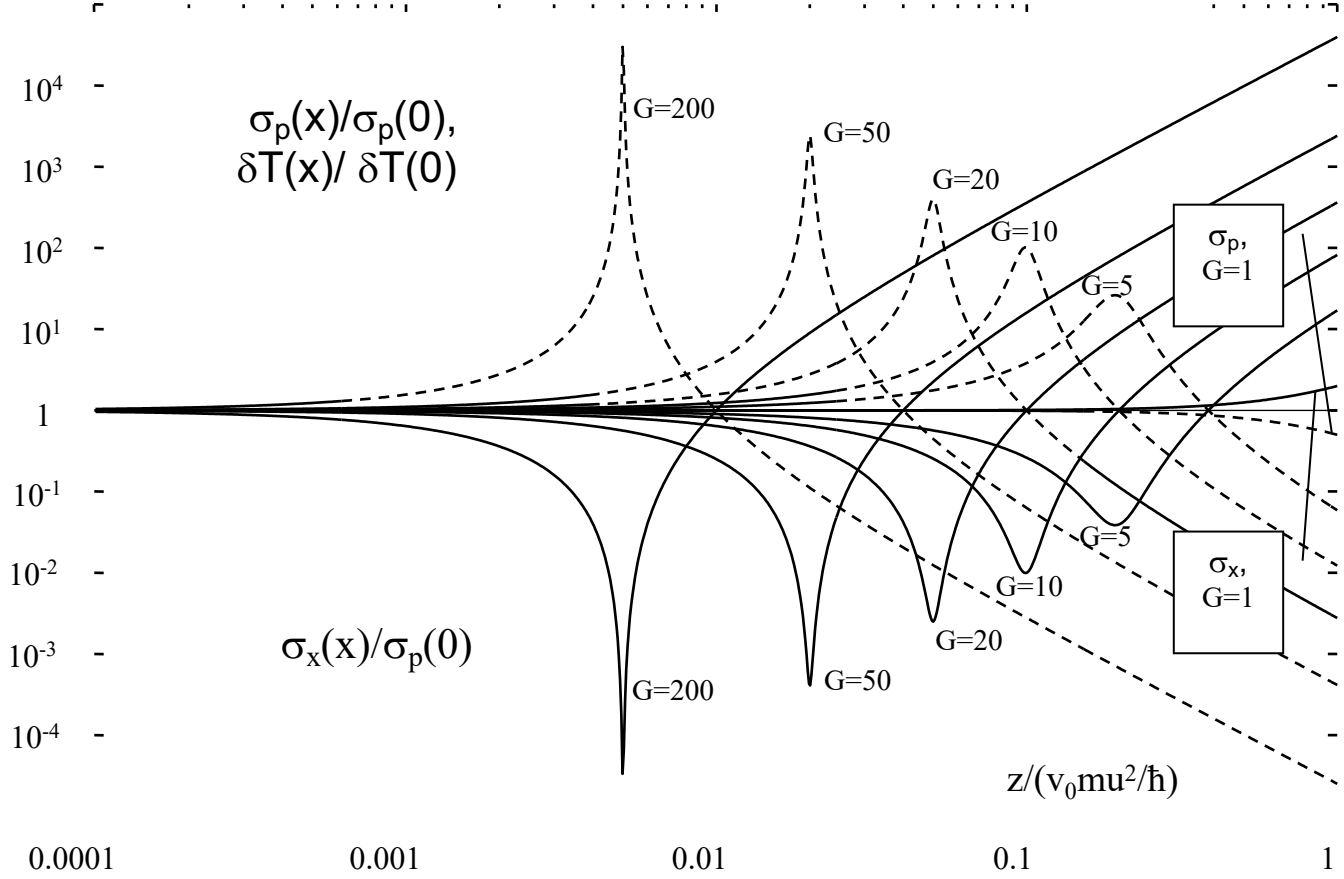
$$|\Psi_{corr}(x, z \geq 0, t \geq 0)|^2 =$$

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

Packet width u(z) change with increasing distance

$$u(z) = u_0 \left\{(1 - \frac{z\rho\hbar}{u_0^2 p_0})^2 + \frac{z^2\hbar^2}{p_0^2 u_0^4}\right\}^{1/2}, z_{collapse} = \frac{G p_0 u_0^2}{(G^2 - 1)\hbar} \approx \frac{m v_0 u_0^2}{G\hbar}$$

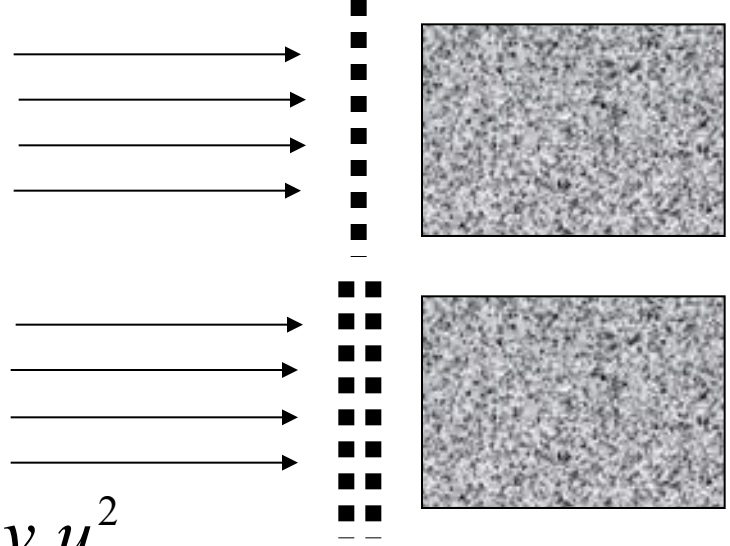

Evolution of uncorrelated wave packet
t
$z_0 = 0 < z_1 < z_2 < z_3 < z_4 < z_5 < z_6 < z_7 < z_8$
$z_{collapse}$
Evolution of correlated wave packet
t



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



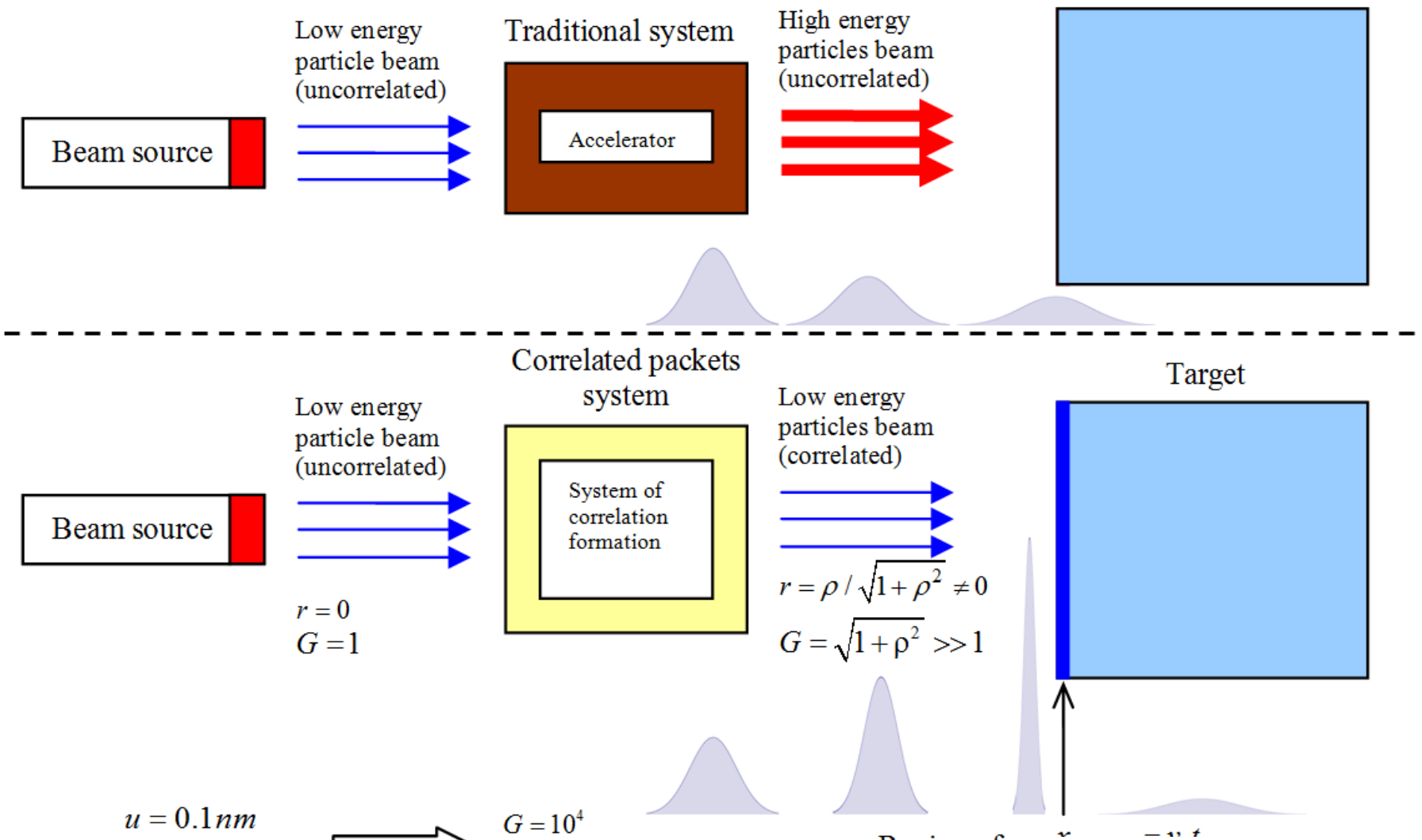
Li polycrystalline targets

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

$$proton, u_0 \approx 2\,\AA, z_{collapse} \approx 10-50\,\AA$$

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
High energy
particles beam
(uncorrelated)
Beam source
Accelerator
Correlated packets
system
Target
Low energy
particle beam
(uncorrelated)
Low energy
particles beam
(correlated)
Beam source
System of
correlation
formation
$r = 0$
$G = 1$
$r = \rho / \sqrt{1+\rho^2} \neq 0$
$G = \sqrt{1+\rho^2} >> 1$
$u = 0.1nm$
$\delta T_{uncorr} \approx 10^{-3} eV$
$G = 10^4$
$\delta T_{corr} \approx 100\, keV$
Region of
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

The initial form of the particle in the correlated state (after leaving the adaptive short channel (one grating period) corresponds to the transverse correlated wave packet

$$\Psi(x,0)=\frac{1}{\sqrt[4]{\pi u^2}}\exp\left\{-\frac{x^2 g}{2u^2}+ipx/\hbar+i\sqrt{p_0^2-p^2}\,z/\hbar\right\}$$

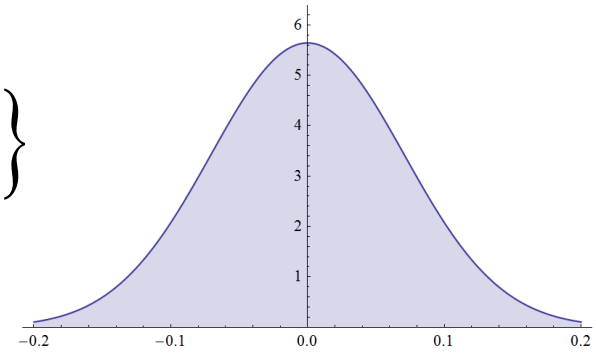
$$g=1+i\rho;\quad \rho=r/\sqrt{1-r^2}$$

$$-\infty<\rho<\infty$$

r – correlation coefficient

Such packets are characterized by correlation coefficient $r=\rho/\sqrt{1+\rho^2}$ and they have identical to $|\Psi_{uncorr}(x,0)|^2$ initial space structure

$$|\Psi(x,0)_{uncorr,corr}|^2=\frac{1}{\sqrt{\pi u^2}}\exp\left\{-x^2/u^2\right\}$$



For correlated packet wave function can be calculated:

$$\Psi(x,z,t)_{corr} = \int c(p)_{corr}\, \Psi_p(x,z,0) \exp\left\{-iE_p t/\hbar\right\} dp,\ E_p = p^2/2m$$

$$c(p)_{corr} = \int_{-\infty}^{-\infty} \Psi(x,0)\Psi_p^*(x)dx = \frac{1}{\sqrt[4]{4\pi^3\hbar^2u^2}} \int_{-\infty}^{+\infty} \exp\left\{-\frac{x^2 g}{2u^2} + ipx/\hbar\right\} dx =$$

$$\sqrt{\frac{u}{g\hbar\sqrt{\pi}}} \exp\left\{-\frac{p^2u^2}{2\hbar^2 g}\right\}$$

$$c(p,t)_{corr} = c(p)_{corr}\, e^{-ip^2t/2m\hbar} = \sqrt{\frac{u}{g\hbar\sqrt{\pi}}} \exp\left\{-\frac{(p_0-p)^2u^2}{2\hbar^2 g} - \frac{ip^2t}{2m\hbar}\right\}$$

$$\Psi(x,z,t)_{corr} \approx \frac{1}{\sqrt{(1+itg\hbar/mu^2)u\sqrt{\pi}}} \exp\left\{-\frac{x^2}{2u^2(1+i\hbar tg/mu^2)/g}\right\} e^{ip_0 z} =$$

$$\frac{1}{\sqrt{[(1-\rho t\hbar/mu^2)+it\hbar/mu^2]u\sqrt{\pi}}} \exp\left\{-\frac{x^2(1+i\rho)}{2u^2[(1-\rho t\hbar/mu^2)+it\hbar/mu^2]}\right\} e^{ip_0 z}$$

$$|\Psi(x,z,t)|_{corr}^{\ 2} = \frac{1}{u\sqrt{\pi}\sqrt{\left\{1-\rho\frac{t\hbar}{mu^2}\right\}^2+\left\{\frac{t\hbar}{mu^2}\right\}^2}} \exp\left\{-\frac{x^2}{u^2[(1-\rho\hbar t/mu^2)^2+(\hbar t/mu^2)^2]}\right\}$$

From the analysis of this expression follows that during the movement of the correlated packet significant evolution of its structure takes place
It differs correlated packet evolution from the monotonic spreading of the uncorrelated packet

Spatial width of the correlated packet:

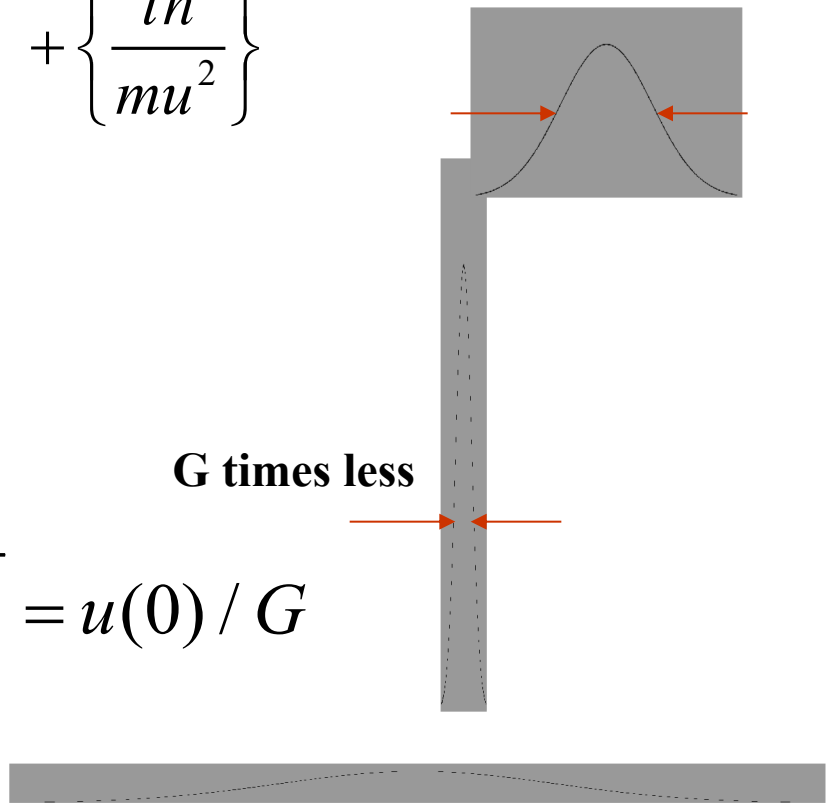
$$u(t) = u(0)\sqrt{\left\{1-\rho\frac{t\hbar}{mu^2}\right\}^2 + \left\{\frac{t\hbar}{mu^2}\right\}^2}$$

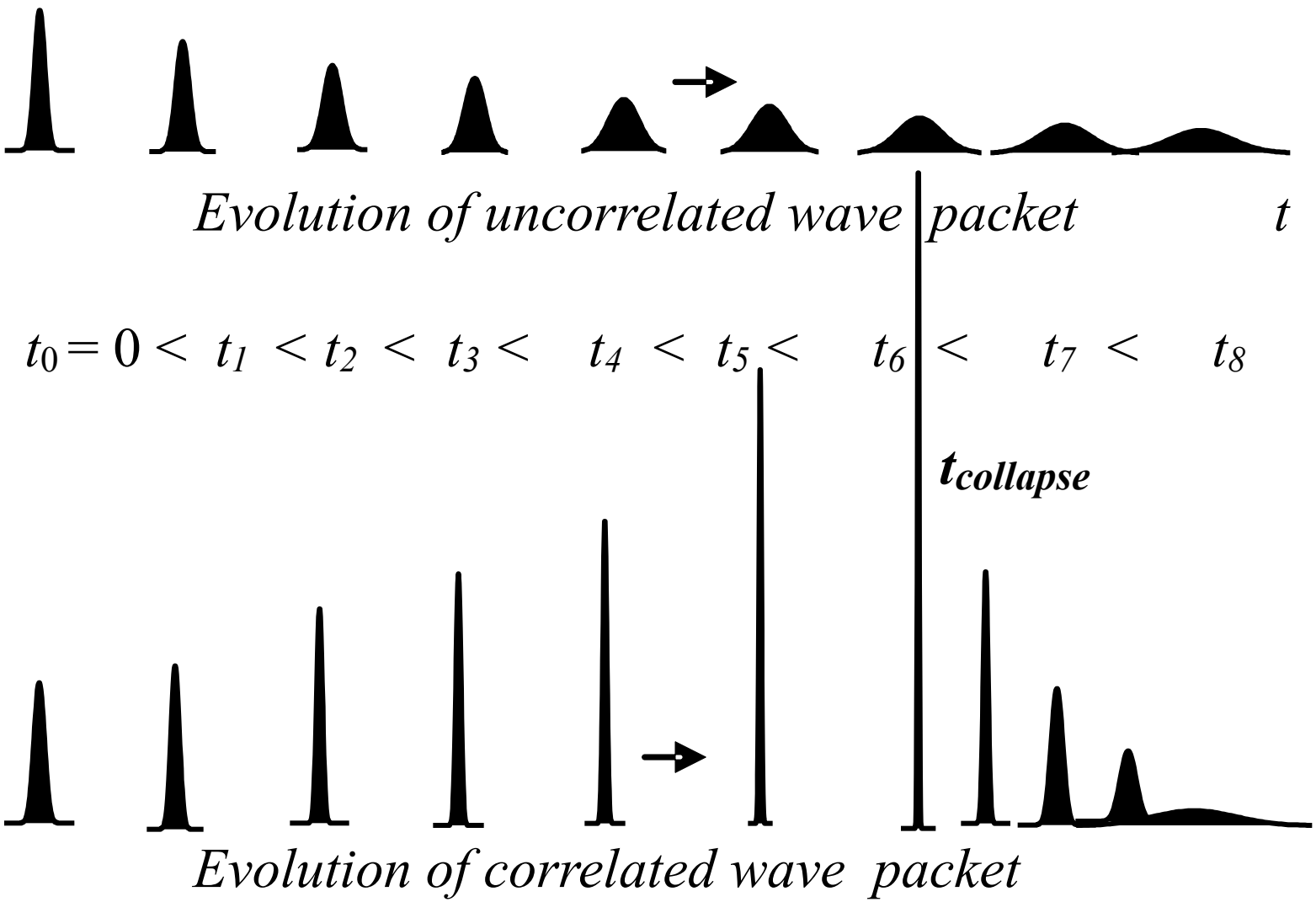
$$t_{\text{collapse}} = \frac{\rho m u^2}{(1+\rho^2)\hbar}$$

$$u_{\min} = u(0)/\sqrt{1+\rho^2} = u(0)/G$$

$$u(t > t_{\text{collapse}}) \approx u(0)\hbar t G / mu^2$$

$$u(t > t_{\text{collapse}}) \approx u(0)\hbar t / mu^2 \quad \text{for uncorrelated}$$

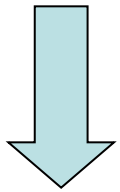



Evolution of uncorrelated wave packet
t
$t_0 = 0 < t_1 < t_2 < t_3 < t_4 < t_5 < t_6 < t_7 < t_8$
$t_{collapse}$
Evolution of correlated wave packet
t

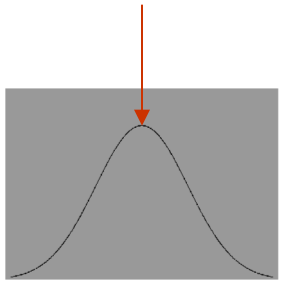
Synchronously with a decrease in the packet width up to the collapse region, its amplitude sharply increases

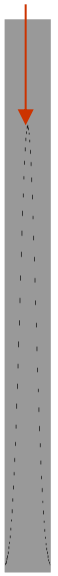
$$z_{\text{collapse}} = v_0 t_{\text{collapse}} = \frac{v_0 \rho m u^2}{(1+\rho^2)\hbar} \approx v_0 m u^2 / G\hbar$$

$$|\Psi(x,0)|^2_{\max} = 1/u\sqrt{\pi}$$



$$|\Psi(z_{\text{collapse}}, t_{\text{collapse}})|^2_{\max} = \sqrt{1+\rho^2}/u\sqrt{\pi} \approx G/u\sqrt{\pi}$$





G times more

$$|\Psi(z > z_{\text{collapse}}, t > t_{\text{collapse}})|^2_{\max} \approx \frac{mu}{t\hbar\sqrt{\pi(1+\rho^2)}} \approx \frac{mu}{tG\hbar\sqrt{\pi}}$$

Average particle momentum and energy fluctuation

$$\sigma_p =< p^2 >= \frac{u}{\hbar\sqrt{\pi \mid g \mid^2}} \int_{-\infty}^{+\infty} p^2 \exp\left\{-\frac{p^2 u^2 (g+g^*)}{2\hbar^2 \mid g \mid^2}\right\} dp = \frac{\hbar^2 \mid g \mid^2}{2u^2} \approx \frac{G^2\hbar^2}{2u^2}$$

The momentum dispersion σ_p and the corresponding root-mean-square fluctuation of the kinetic energy of the correlated increase with the increase of correlation coefficient and correlation efficiency coefficient:

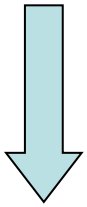
$$\delta T = \frac{\sigma_p}{2m} = \frac{\hbar^2 \mid g \mid^2}{4mu^2} \approx \frac{\hbar^2}{4mu^2(1-r^2)} \equiv \frac{G^2\hbar^2}{4mu^2}$$

- Proton

Uncorrelated proton beam

u = 0.1 nm

$\delta T = \sigma_p/2m = h^2/4mu^2 \sim 10^{-3}$ **eV**



$G = 10^3$

Correlated proton beam

$\delta T = \hbar^2 G^2/4mu^2 \geq 10$ **keV**

•Considered above features of the correlated wave packet make it possible to predict the possibility of its use for a number of applied and fundamental problems.

Along with the collapse on a specific distance, the creation of such a packet is accompanied by a significant increase of its kinetic energy fluctuations, which can be many orders of magnitude higher than the average motion energy of the packet itself. This may allow them to be used for nuclear reactions even at low particle energies.

•

The importance of correlated states and their fundamental difference from uncorrelated superpositional states:

•such states may have great fluctuations of energy that can exist for a long time without violating the law of conservation of energy.

For correlated packet wave function can be calculated:

$$\Psi(x,z,t)_{corr} = \int c(p)_{corr}\, \Psi_p(x,z) \exp\left\{-iE_p t/\hbar\right\} dp,\ E_p = p^2/2m$$

$$c(p)_{corr} = \int_{-\infty}^{-\infty} \Psi(x,0)\Psi_p^*(x)dx = \frac{1}{\sqrt[4]{4\pi^3\hbar^2u^2}} \int_{-\infty}^{+\infty} \exp\left\{-\frac{x^2 g}{2u^2} + ipx/\hbar\right\} dx =$$

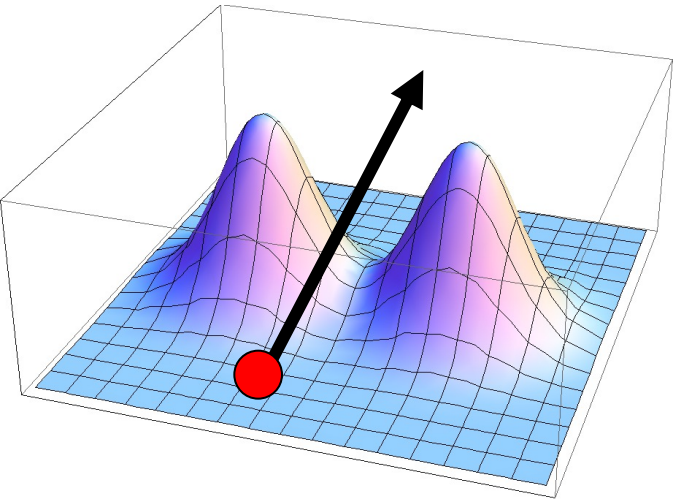
$$\sqrt{\frac{u}{g\hbar\sqrt{\pi}}} \exp\left\{-\frac{p^2u^2}{2\hbar^2 g}\right\}$$

$$c(p,t)_{corr} = c(p)_{corr}\, e^{-ip^2t/2m\hbar} = \sqrt{\frac{u}{g\hbar\sqrt{\pi}}} \exp\left\{-\frac{(p_0-p)^2u^2}{2\hbar^2 g} - \frac{ip^2t}{2m\hbar}\right\}$$

$$\Psi(x,z,0) = \frac{1}{\sqrt[4]{\pi u^2}} \exp\left\{ -\frac{x^2 g}{2u^2} + i p_0 z / \hbar \right\}$$

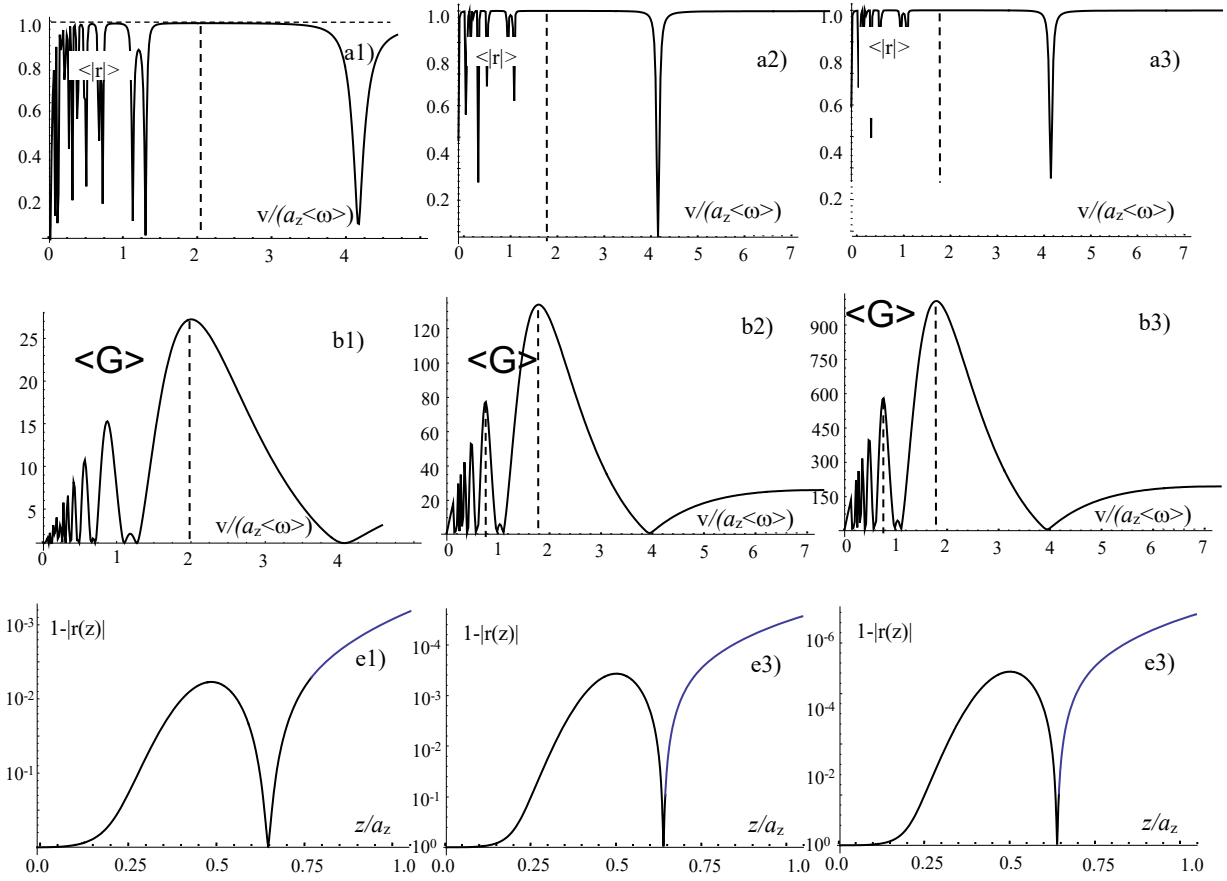
$$g = 1 + i\rho; \quad \rho = r / \sqrt{1 - r^2}$$

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



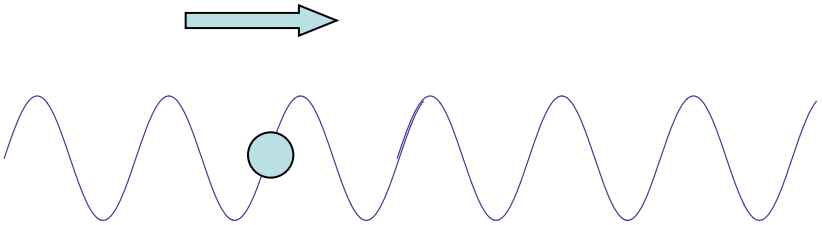
$$T_{opt} = \frac{m_p v_{opt}^2}{2} = 2 m_p a_z^2 < \omega >^2 \approx$$

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



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) - a_z / u = 4; a2) – e2) - a_z / u = 5; a3) - e3 - az / u= 6

The “traditional” method of the analysis of the processes of interaction of slow moving particles (including LENR) is based on their description in the form of unbounded in space plane waves.



Such approach is idealized!