NUCLEAR SYNTHESIS ON ORDERED CRYSTAL TARGET WITH PARTICIPATION OF MONOCHROMATIC BEAMS OF LIGHT OR MIDDLE ISOTOPES

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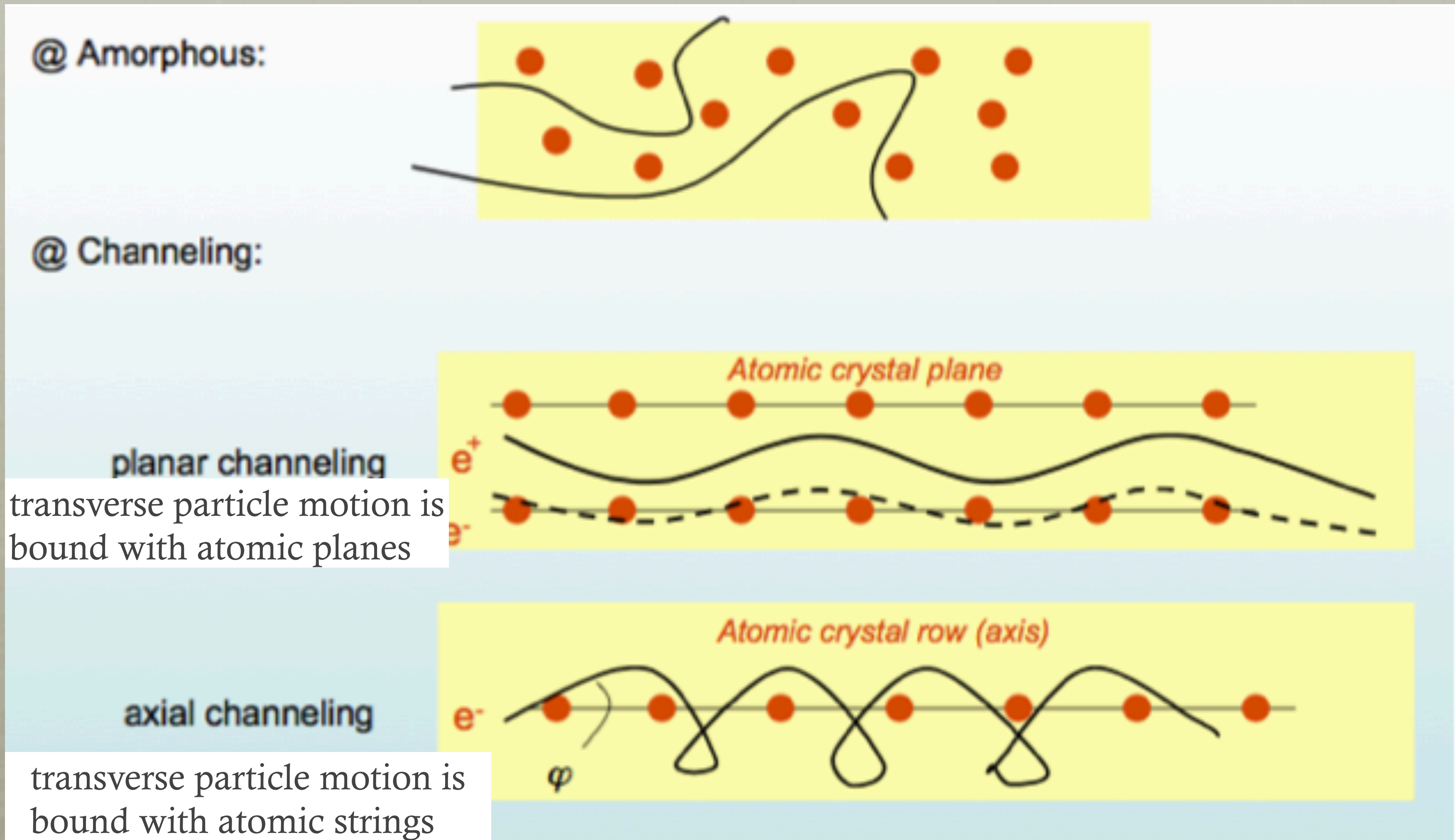
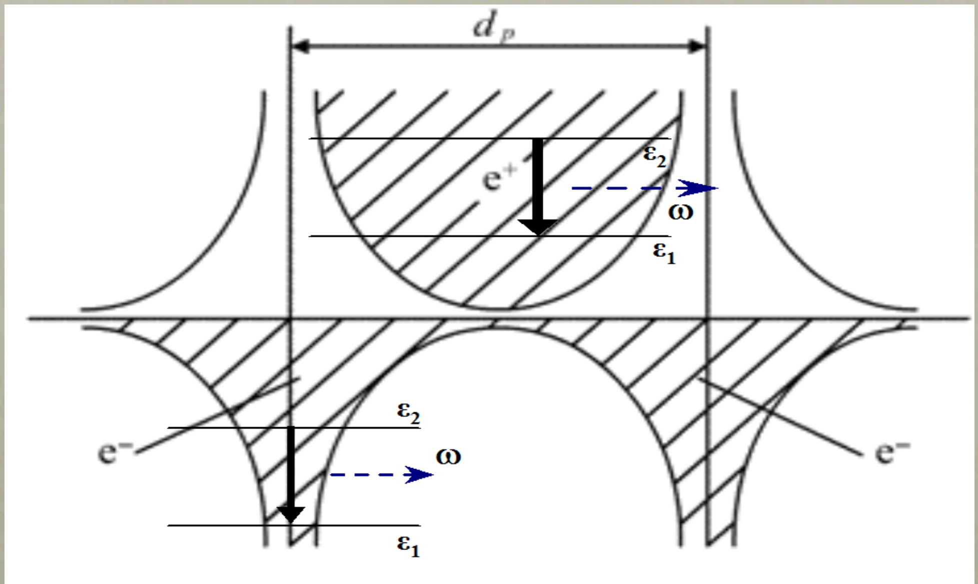
CHANNELING EFFECTS



transverse particle motion is bound with atomic planes

transverse particle motion is bound with atomic strings

Positive particles (positrons, protons)



Negative particles (electrons)

Negatively-charged particles like antiprotons and electrons are attracted towards the positively-charged nuclei of the plane, and after passing the center of the plane, they will be attracted again, so negatively-charged particles tend to follow the direction of one crystalline plane.

- Positively-charged particles like protons and positrons are repulsed from the nuclei of the plane, so they tend to follow the direction between two neighboring crystalline planes, at the largest possible distance from each of them.
- The positively-charged particles have a smaller probability of interacting with the nuclei and electrons of the planes.

Vexata Quaestio: Is it possible to increase the rate of nuclear reactions inside crystals?

for the optimization of nuclear reactions such as $^{2}H(d,p)T$ and $^{2}H(d,n)^{3}He$ based on a beam of accelerated particles, incident on various crystals.

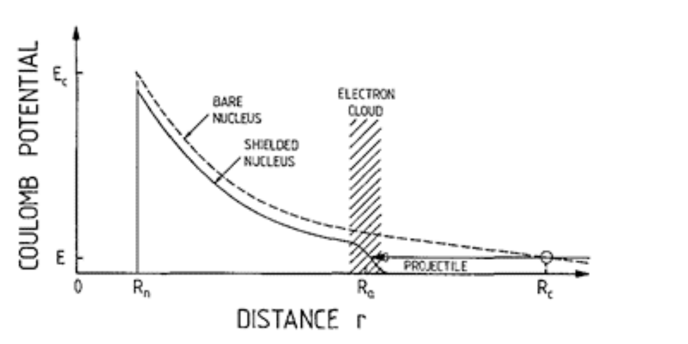
Several expts with D-implanted solid targets (Li, Ta, C, Zr, Ti etc) have shown strong enhancement of fusion rates as compared to gas target, probably due to electron screening effect and changes in deuteron density profile.

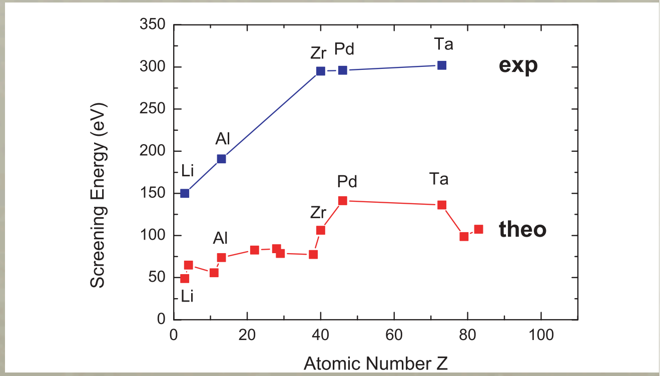
No simple model works fine, very time consuming simulations!

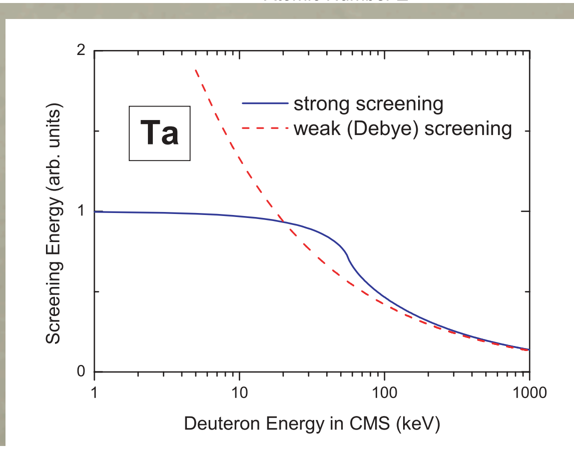
More recent data[2] seem not justifiable within known models (Debye-Hückel)!

[1]F. Raiola et al., **EPJ A** Vol. 13, N. 2 (2002), 377-382

[2]A Huke et al., **PR C** Vol. 78, 015803 (2008)

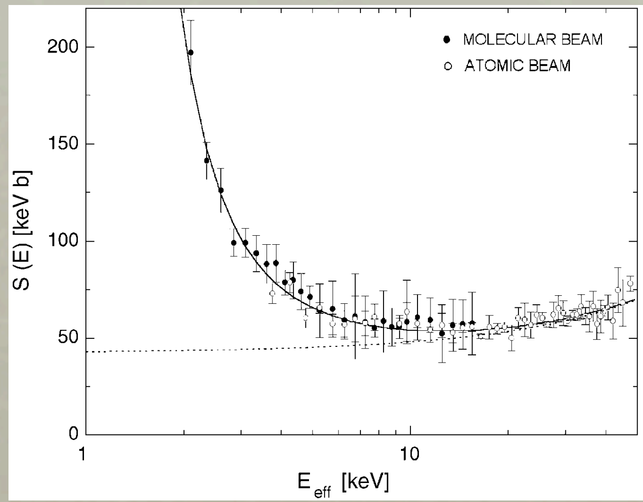






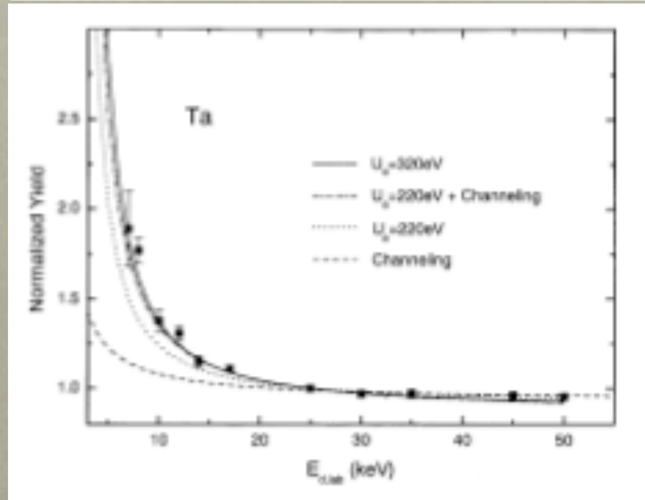
IS CHANNELING AN EXPLANATION?

Channeling should increase the rate by collimating the beam onto interstitial D, but at low energy 4 < E < 100 keV it seems excluded by Bochum[1] experiment on D –Ta target
Ch. Flux $\Phi_{chann} \approx 1/E$ since $\theta_{cr} \sim (E)^{-1/2}$
Channeling is effective only at low energy, and does not show a different behaviour, only the enhancement is steeper when E => 0. But nothing is observed (dechanneling?)



Also TUB expt[3] with 5 < E < 60 keV gets a reduction of e-screening energy in Ta by ~100 eV, to be considered an upper limit. But:

- slope insensitive for E > 20 keV
- Radiation damage in target
- Random orientation of crystal, so no accurate measurements as function of Lindhard angle were made

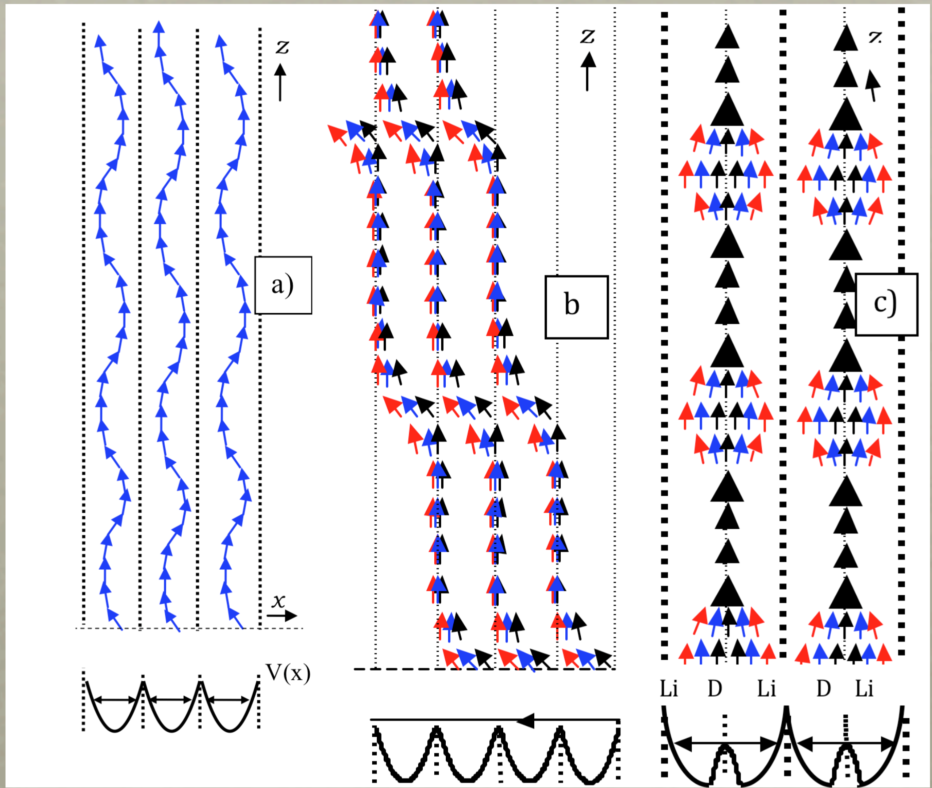


[3]A Huke et al., **NIM B** Vol. 193, 183 (2002)

Motion modes of positive ions

Transverse motion is quantized: quasiclassical approach; $E_x = (p \sin\theta)^2 / 2m$;V(x) transverse potential
$p_x(x) = \sqrt{2m(E_x - V(x))}$
The trajectory of the particle is periodic function *sin(kz).* The bigger the entrance angle θ the bigger the transverse osc. amplitude.
Transverse motion overcomes potential barrier => Quasichanneling $p_{xmin} = \sqrt{2m(E_x - V_0)}$
If $\theta = \theta_{Lindhard}$ we have $p_{xmin} = 0$ here $(p \sin\theta_{Lindhard})^2/2m = V_0$

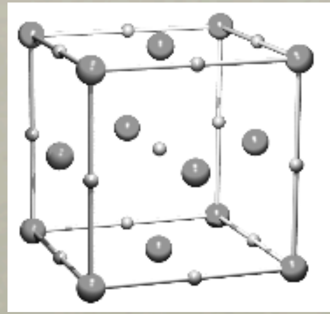
a) channeling in the system of crystal planes
b) overbarrier quasi-channeling in crystals consisting of identical atoms at initial Lindhard angle
c) overbarrier quasi-channeling in crystals, consisting of atoms of different types (for example *LiD*)



Periodical beam self-focusing onto ions which are present on the planes is typical of overbarrier quantized motion, where p_x is very small

A DIFFERENT APPROACH

- Controlled fusion by ion bombardment of a target not energetically favourable because $\sigma_n / \sigma_e = 10^{-8}$ where $= \sigma_e = \sigma_{exc} + \sigma_{ion}$



- Energy > 100 keV

- No ion implant, use of monocrystalline target LiD bombarded by D, T beams

- Increase $\sigma_{\mathbf{n}}$ ➔ $\sigma_{\mathbf{n}}^* >> \sigma_{\mathbf{n}}$ and decrease $\sigma_{\mathbf{e}}$ $\mathbf{k} = \sigma_{\mathbf{n}}^* \sigma_{\mathbf{e}}^* / \sigma_{\mathbf{n}} \sigma_{\mathbf{e}} \approx 100$ is achievable!

$$\sigma_n^* \cong \sigma_n a \int_{-a/2}^{a/2} \left|\psi_{1,2}\right|^2 f_n(x)dx \qquad f_n(x) = \exp(-x^2/2u^2)\big/\sqrt{2\pi}\,u$$

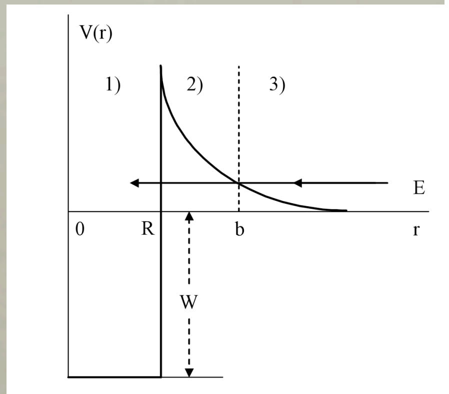
- Motion near the top of a barrier: incident particles move in a small region where nuclei are more dense. It can be shown that $\sigma_{\mathbf{n}}^* = \sigma_{\mathbf{n}}\, \mathbf{a}/(\sqrt{2\pi})\mathbf{u}$ and similarly, if $\Delta \mathbf{x} << \mathbf{u} << \mathbf{R}$, we find $\sigma_{\mathbf{e}}^* = \sigma_{\mathbf{e}}\, \mathbf{a}/2\mathbf{R}$ with $\mathbf{k} = \sqrt{(2/\pi)}\, \mathbf{R}/\mathbf{u} \approx \mathbf{10}$ for T target

- Motion near atomic plane: axial quasi-channeling at small angles may increase the ratio σ_n / σ_e by a factor $k^2 \approx 100$, using the 3-dim semiclassical solution of Schrödinger equation and if $\Delta x, \Delta y < u$, which limits the incident angle to $\Delta \theta \approx \theta\, u/(\sqrt{2\pi}\mathbf{R})$, $\theta \approx \sqrt{(\mathbf{U_0}/\mathbf{E_0})}$

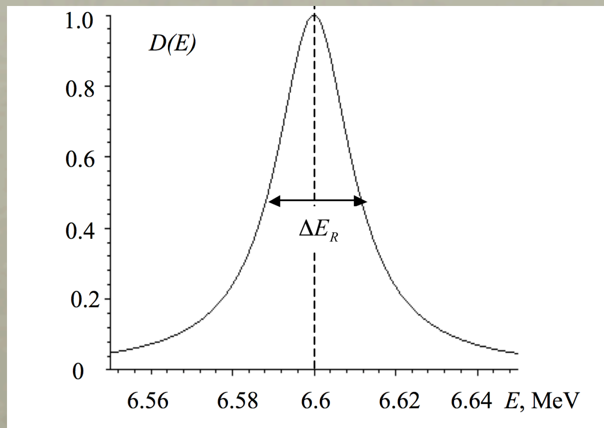
Resonant tunneling of light and mid-mass nuclei

The presence of internal nuclear resonances may increase cross-section by several orders of magnitude

$$\sigma_f = \sigma_{f0} D(E), \quad D(E) = \exp(-2\pi\eta),$$



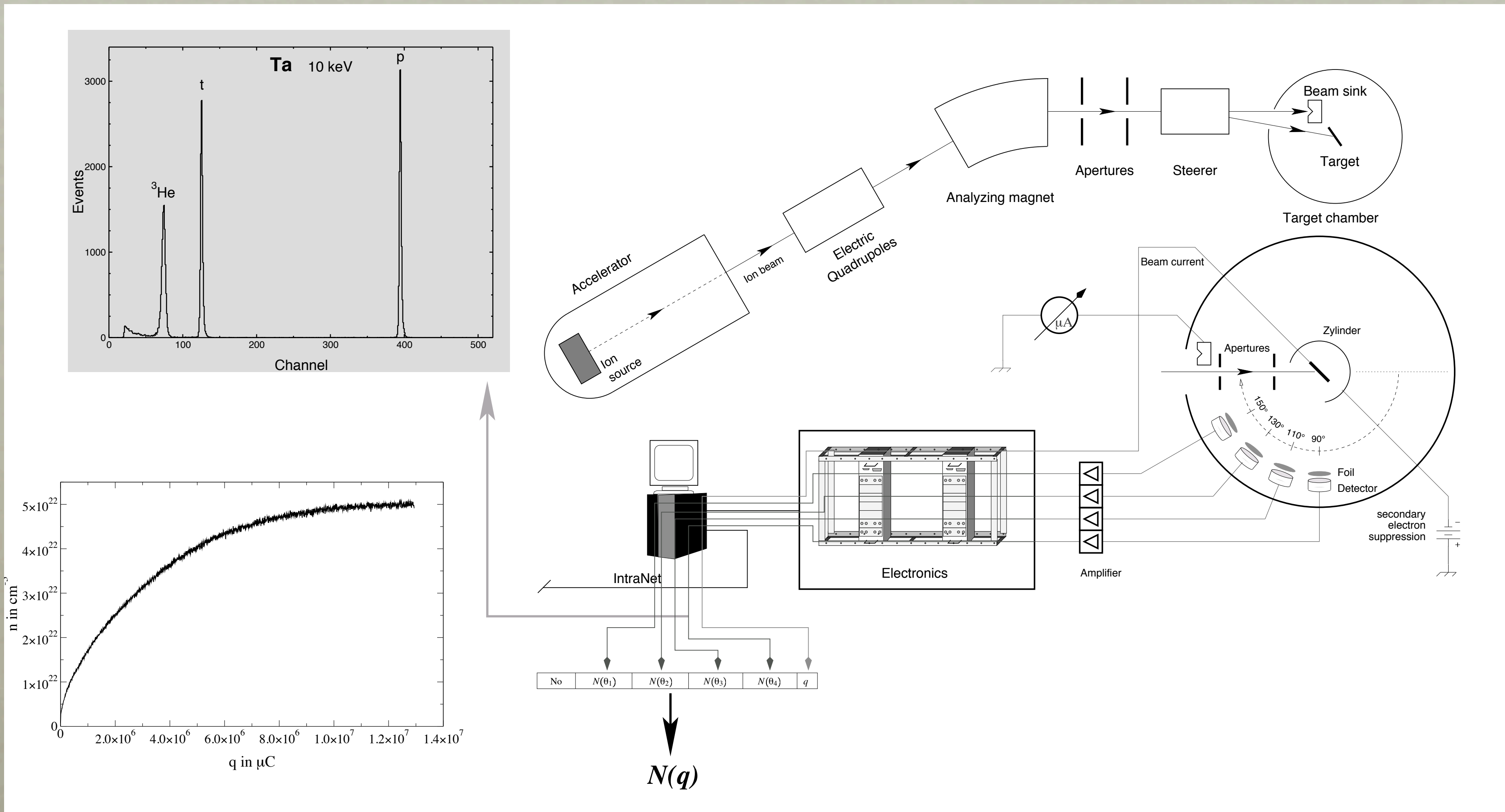
Earlier calculations were done only for s-waves but also resonances with $l > 0$ are present.
Solutions of Schrödinger eqn. for the 3 regions allow to estimate positions and widths of resonant states for moving ions and to satisfy the conditions for resonant tunneling. Screened Coulomb potential is used



Reaction	l	E_0, MeV	$\Delta E/E_0$	E_{opt}, MeV	Q_R, MeV
$^{12}C + ^{16}O$	1	6.6	$3.4.10^{-3}$	11.55	16.9
	3	6.651	$2.4.10^{-3}$	11.639	
	5	6.739	$1.5.10^{-3}$	11.793	
$^{16}O + ^{16}O$	0	8.743	$8.3.10^{-4}$	15.3	16.7
	2	8.759	7.10^{-4}	15.328	
	4	8.796	5.10^{-4}	15.393	
$^{12}C + ^{18}O$	0	3.298	$1.5.10^{-5}$	5.497	22.3
	2	3.322	10^{-5}	5.536	
	4	3.377	$5.4.10^{-5}$	5.628	

Reaction efficiency $\delta = Q_R / E_{opt} \geq 4$
Beams at resonant energy and
high monochromaticity are now feasible!

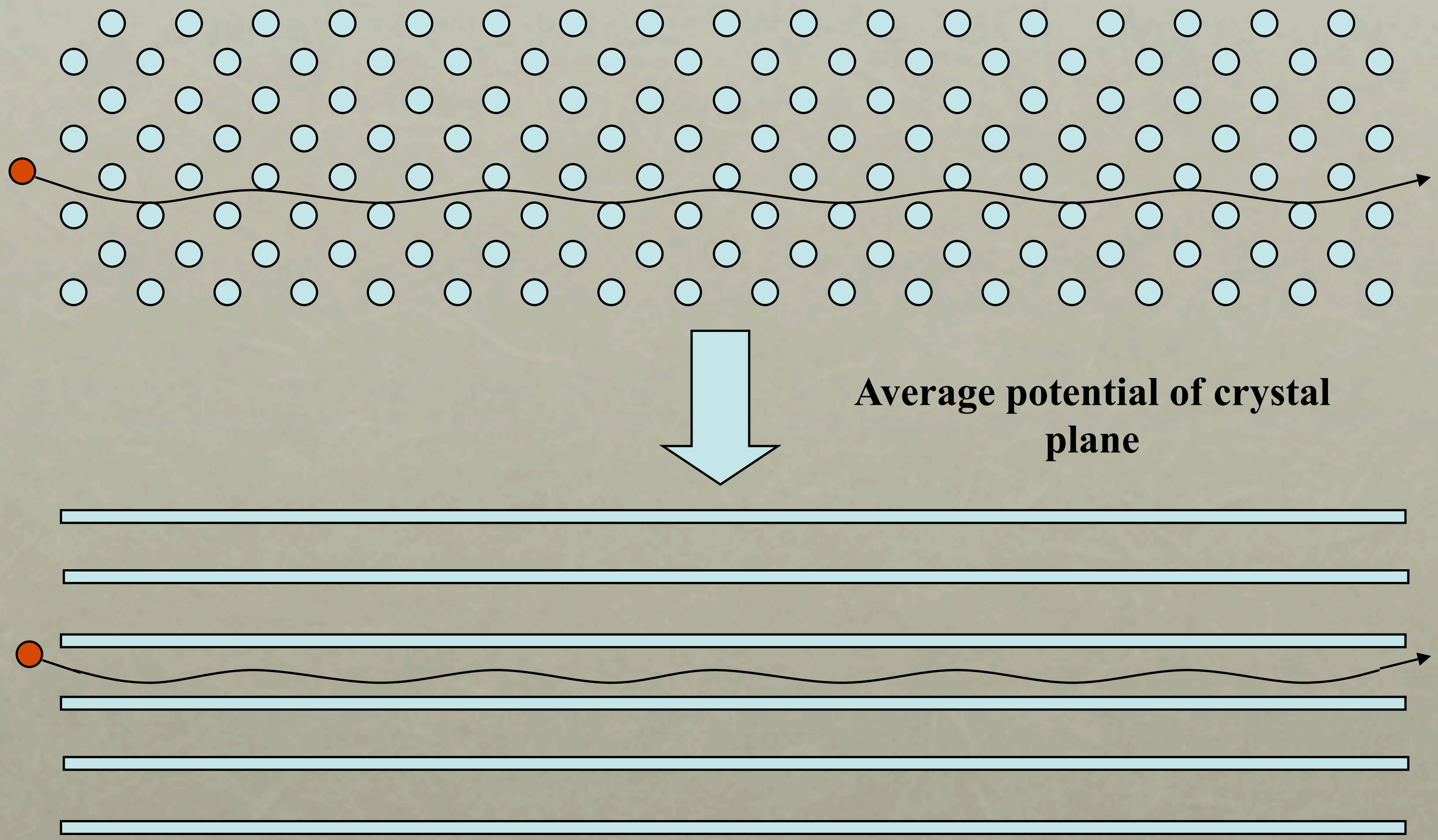
EXPERIMENTAL REQUIREMENTS



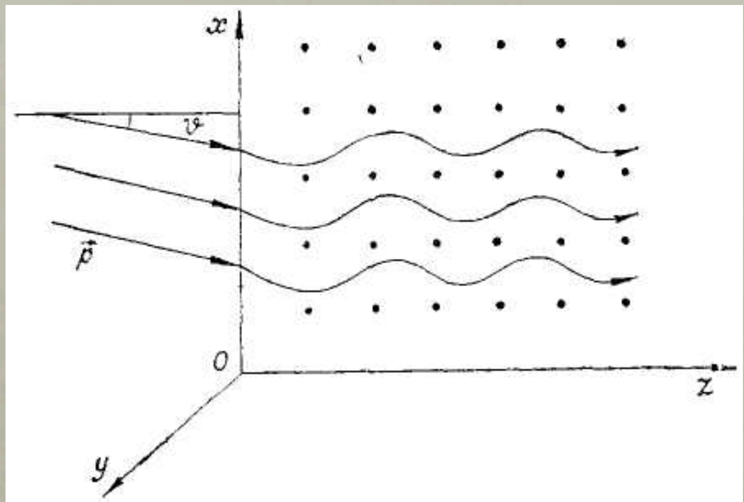
A. Huke et al., JCMNS Vol. 4, P. 194 (2010)

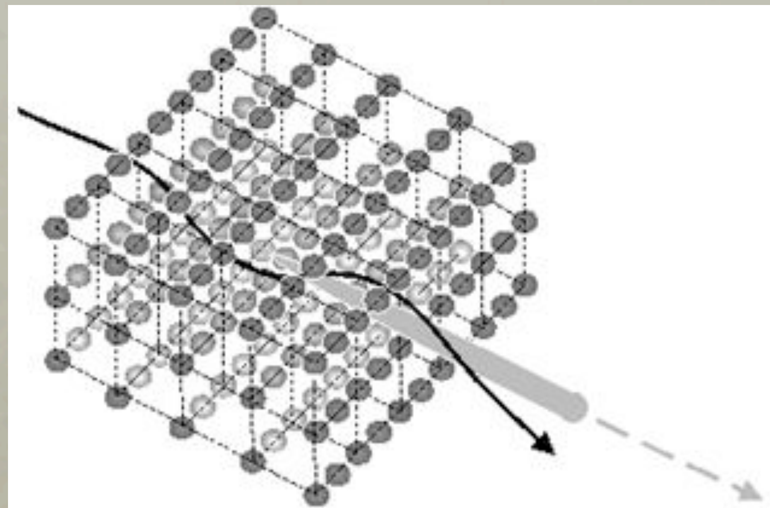
CONCLUSIONS

- Alternative fusion mechanisms highly desirable in the present critical situation of ‘standard’ activities (both magnetic and inertial confinement)
- Interaction mechanisms of light nuclei inside crystals not really understood
- Lack of new experimental data
- Accelerators with required beam characteristics now available (probably)
- Target technology needs improvement!


Average potential of crystal
plane

CHANNELING EFFECTS





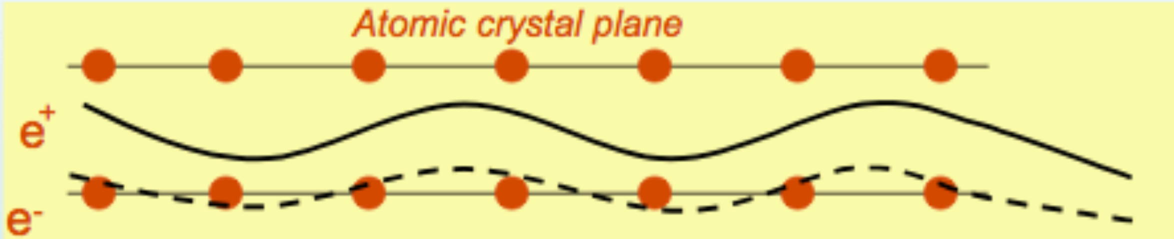
Axial channeling: transverse particle motion is bound with atomic strings (axes)
Planar channeling: transverse particle motion is bound with atomic planes

Channeling of Charged Particles

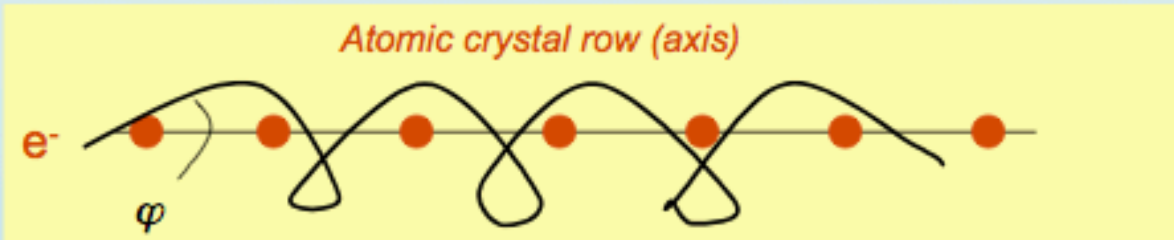
@ Amorphous:

@ Channeling:

planar channeling



axial channeling

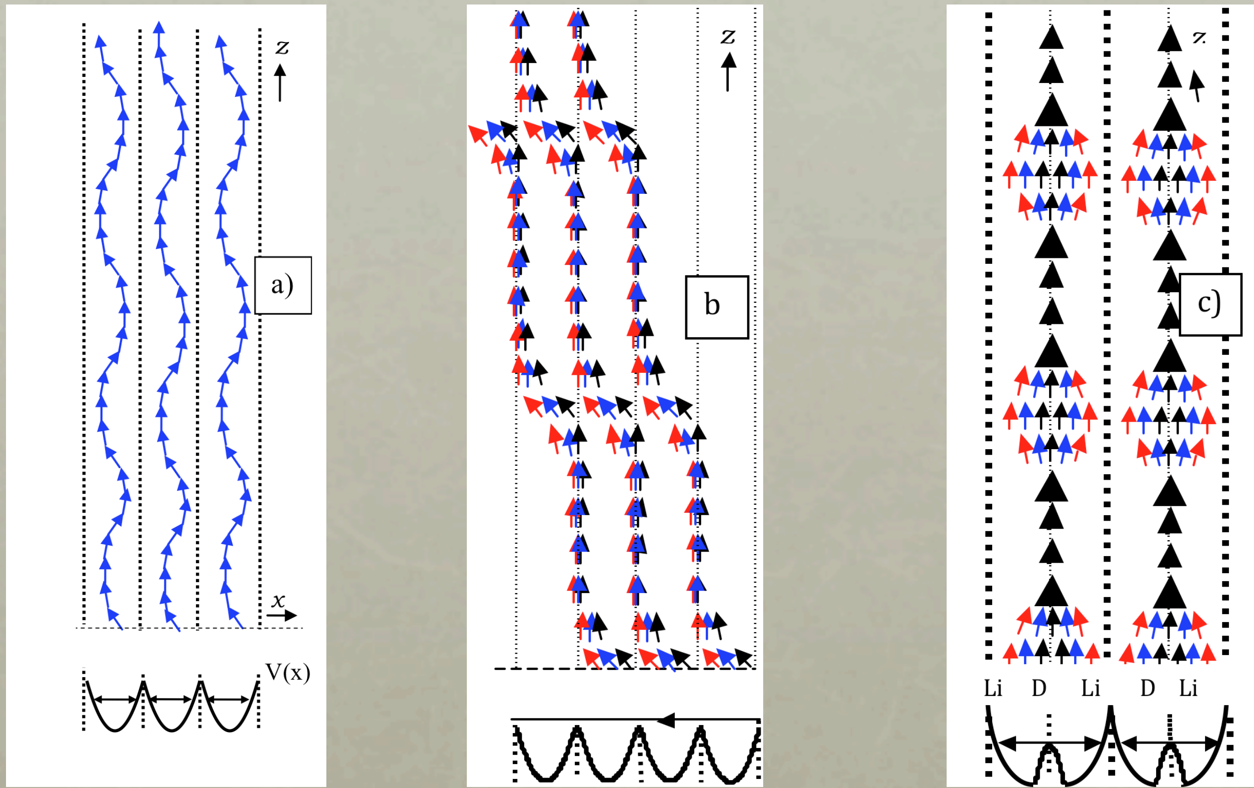


$\varphi << 1 \quad (\varphi < \varphi_L \sim \sqrt{U/E})$ - *the Lindhard angle is the critical angle for the channeling*

Transverse motion is quantized: quasiclassical approach

$E = (p \sin\theta)^2 / 2m$ transverse energy $V(x)$ transvesre potential $p_x(x) = \sqrt{2m(E-V(x))}$

Motion of positive ions in separate channel: the trajectory of the particle is periodic function (like function *sin(kz)* Increasing the entrance angle θ also makes transverse oscillation amplitude increase



Transverse overcomes potential barrier => Quasichanneling $p_{xmin} = \sqrt{2m(E-V_0)}$

If $\theta = \theta_{Lindhard}$ we have $p_{xmin} = 0$ here $(p \sin\theta_{Lindhard})^2/2m = V_0$

Beam self-focusing onto ions which are present on the planes

In case of 2 dim motion (axial channeling) a further increase in reaction rate is possible!