The Abdus Salam
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"Workshop on Ion Beam Studies of Nanomaterials:
Synthesis, Modification and Characterization"

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Ion Channeling through Carbon Nanotubes

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Support: NSERC & PREA

NSERC CRSNG

Outline

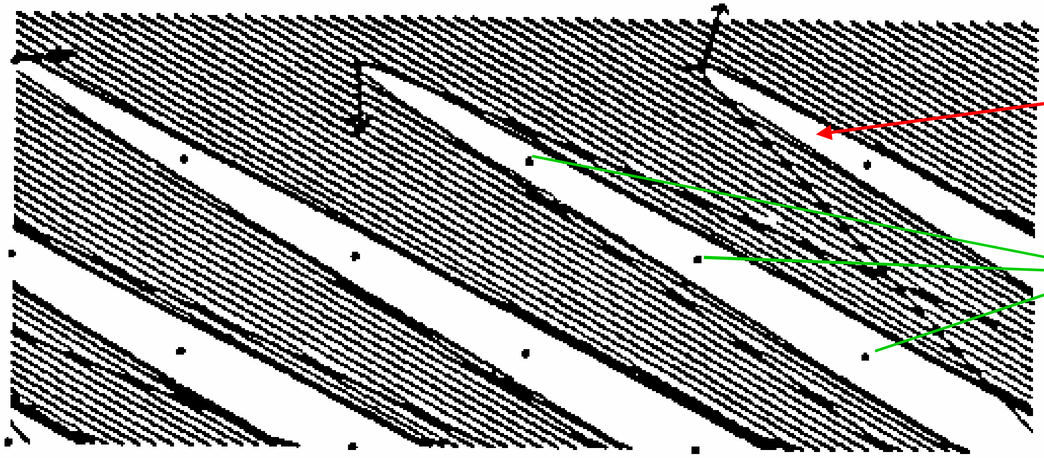
- **Reminder: Channeling in single crystals**
- **Ion interactions with carbon nanotubes**
- **High-energy channeling** (~GeV)
  - Potentials and beam deflection
  - Rainbow effect in short ropes
- **Medium-energy channeling** (~MeV)
  - Modeling the dynamic response
  - Simulations of ion distributions
  - New developments
- **Low-energy channeling** (~keV)
  - MD simulations
  - Related problems
- **Outlook**

Ion channeling in crystals

- "Accidental" discovery in computer simulation (1963)
- Theory:
  - Continuum-potential models
  - Binary collision approximation
  - De-channeling, …
- Applications:
  - Medium energies:
    - ion implantation
    - probing impurities in crystals
    - thin films & interface analysis
  - High-energy physics:
    - using bent crystals for beam extraction & collimation at particle accelerators (CERN, JINR, FNAL, BNAL, IHEP, INFN-LNF)

Channeling of fast ions in single crystals

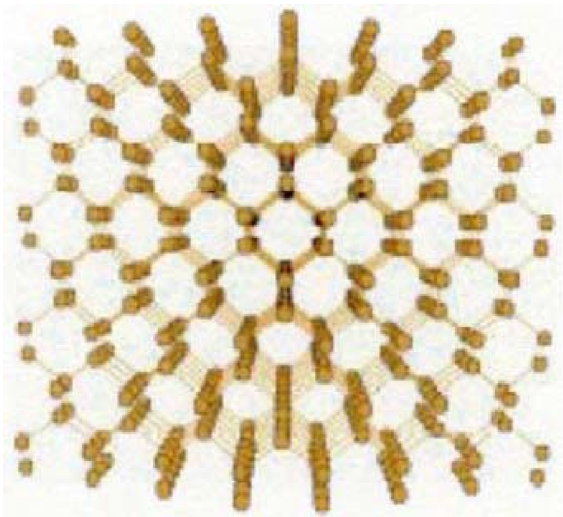
Side view of ion beam channeling



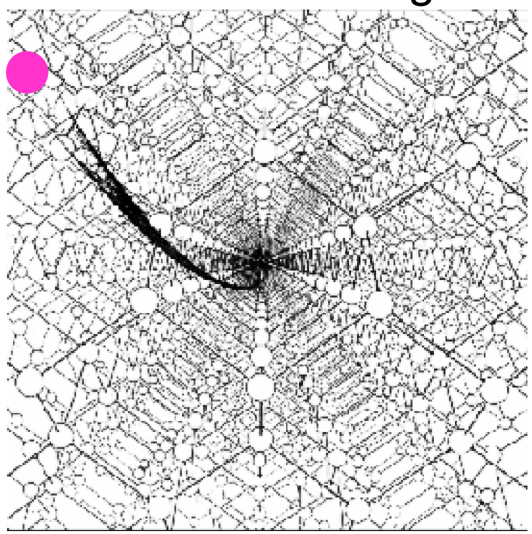
Shadow cone

Average potential along atomic rows

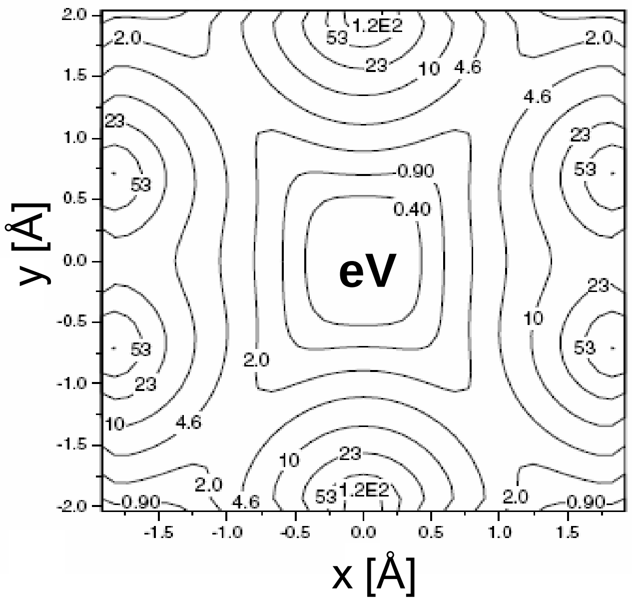
Front view of Si channels



Axial channeling



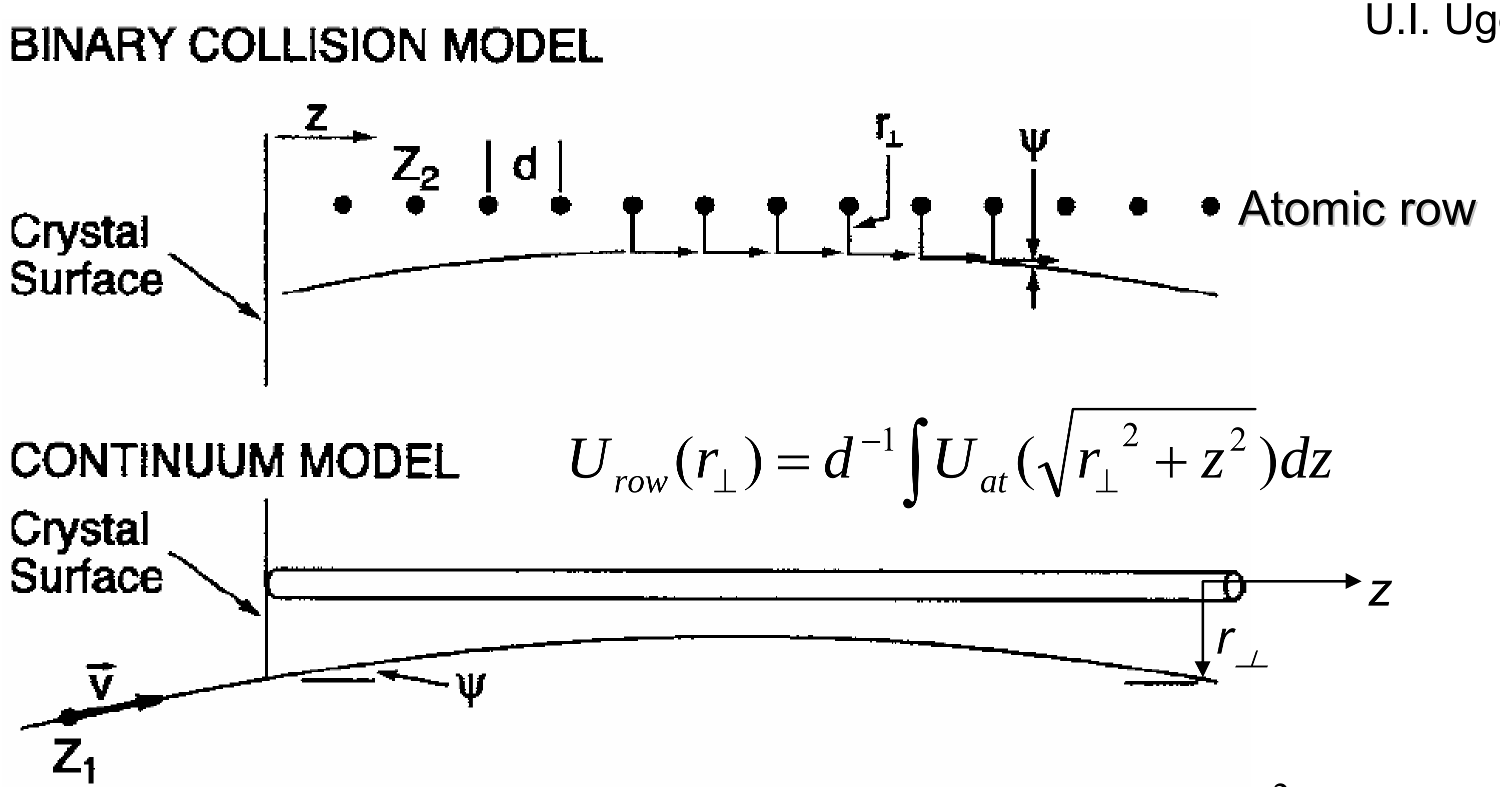
Equipotential curves



Axial channeling through single crystal

L.C. Feldman *et al.*, *Materials Analysis by Ion Channeling* (1982)

U.I. Uggerhoj



$$U_{row}(r_\perp) = d^{-1}\int U_{at}(\sqrt{r_\perp^{\ 2} + z^2})dz$$

Ion trajectory in transversal plane $$E_\perp = \frac{pv}{2}\psi^2 + U_{row}(r_\perp) + \frac{L_0^{\ 2}}{2m\gamma r_\perp^{\ 2}} = const$$

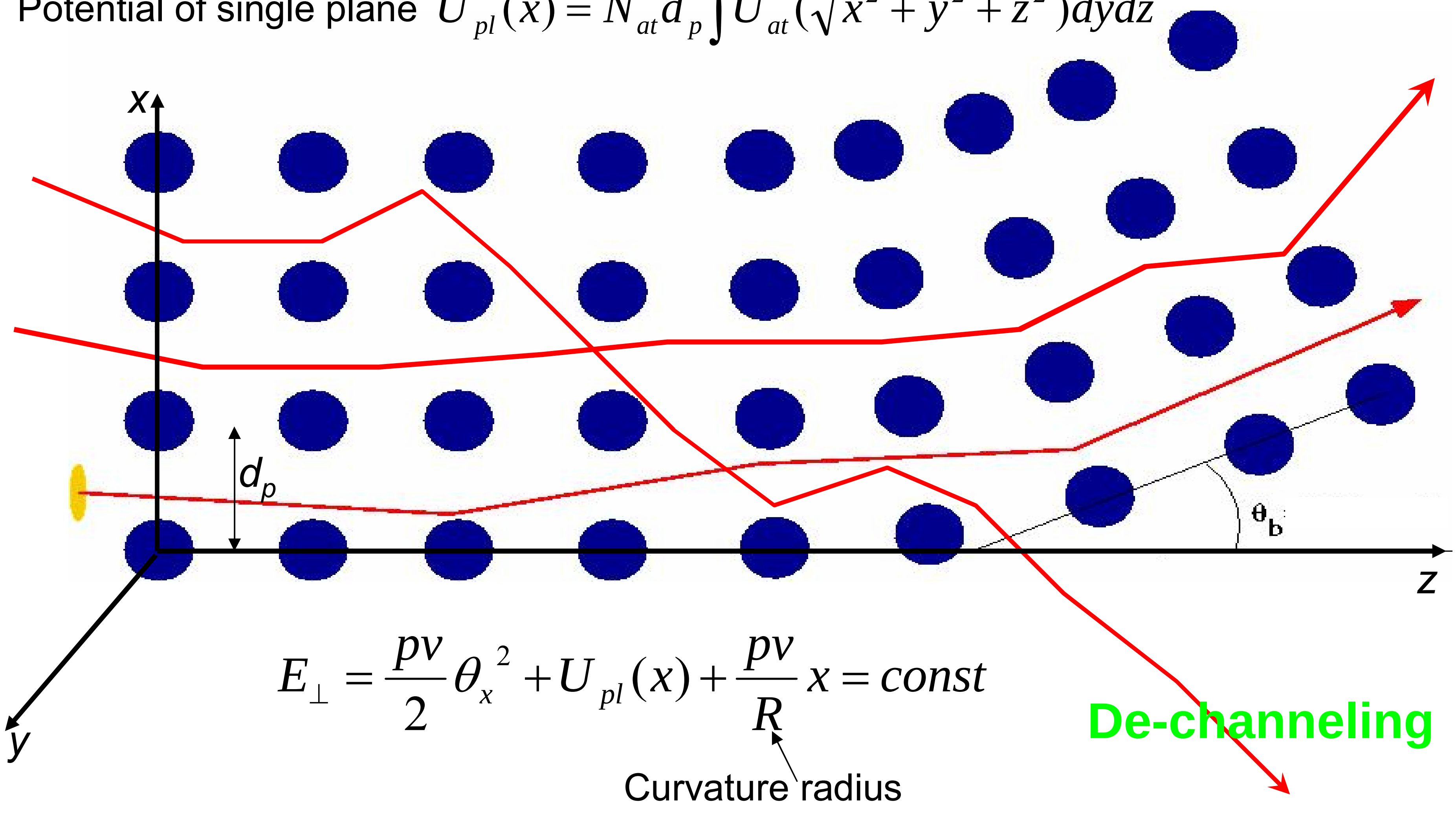
Critical angle for channeling $$\psi_c = \sqrt{\frac{4Z_1Z_2e^2}{pvd}}$$

Planar channeling through crystal bent in *x* direction

V.M. Biryukov *et al.*, *Crystal Channeling and Its Applications at High-energy Accelerators* (1997)

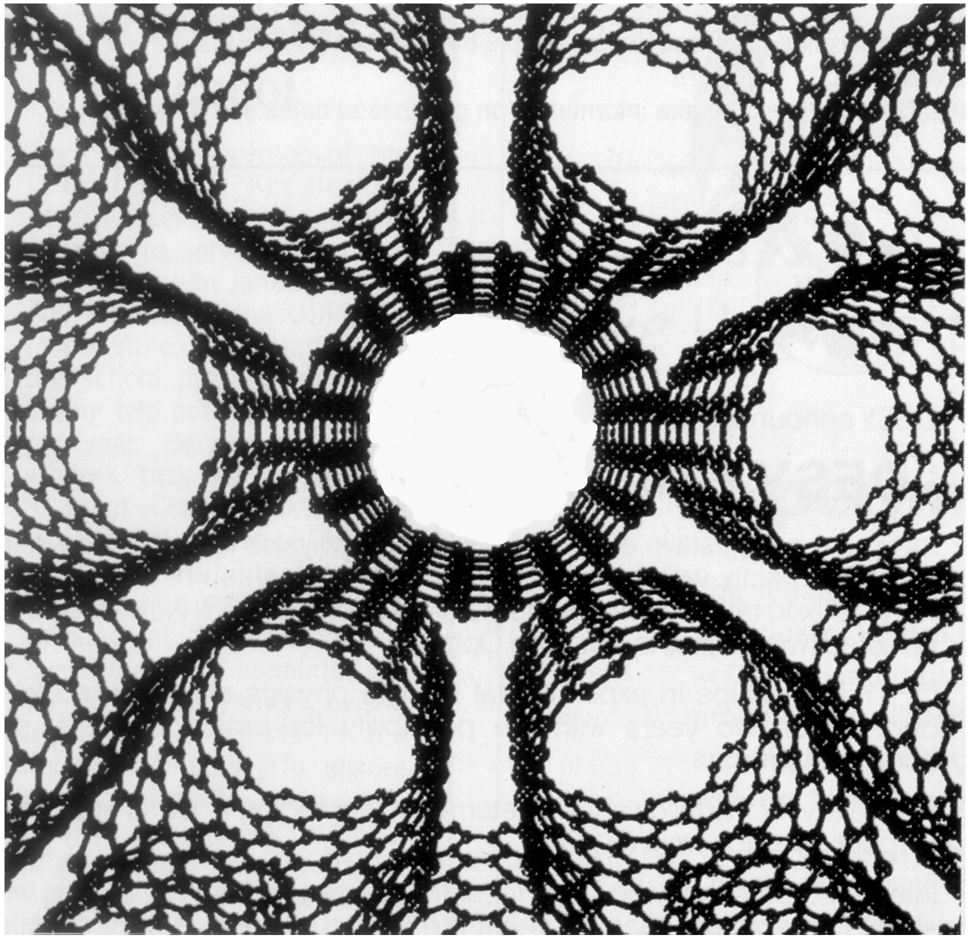
R. Fliller III

Potential of single plane $U_{pl}(x) = N_{at} d_p \int U_{at}(\sqrt{x^2 + y^2 + z^2}) dydz$



$$E_\perp = \frac{pv}{2}\theta_x^{\ 2} + U_{pl}(x) + \frac{pv}{R} x = const$$

Ion channeling through carbon nanotubes?
Dream vs. reality



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Carbon nanotubes

❑ Properties:

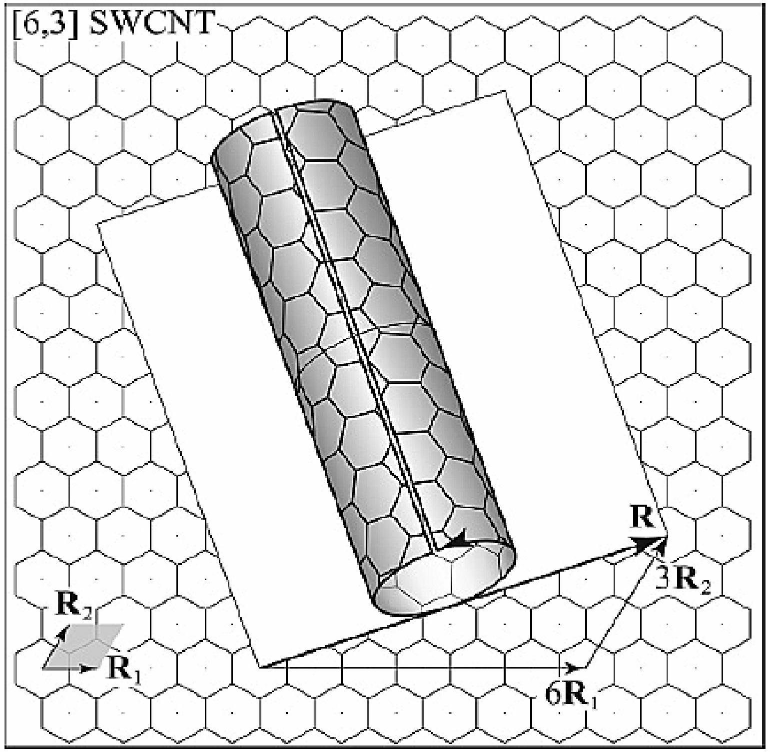
- Electrical, mechanical, thermal
- Dependent on: molecular structure,
  geometric confinement, local modification

❑ Applications:

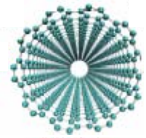
- Nanoelectronic devices
- New composite materials
- Sensitive chemical detectors
- Ion storage (H, Li)
- Field emission displays
- Nanoelectromechanical systems (NEMS)

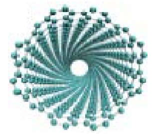
Formation of single-wall carbon nanotube (SWNT)

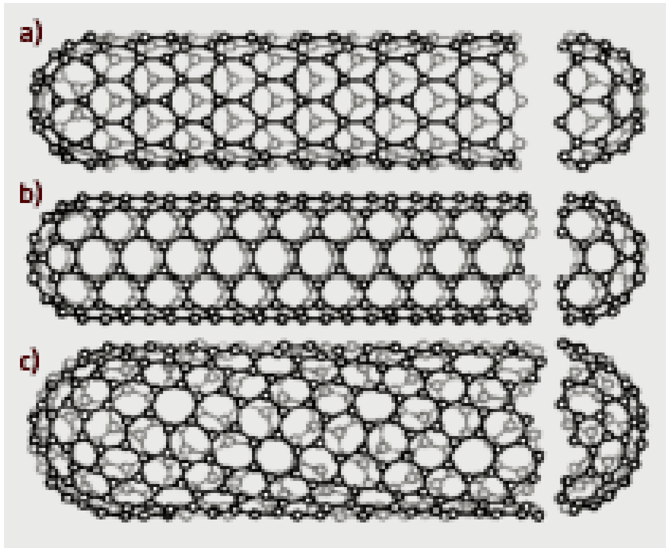
Rolling single graphene sheet:
hexagonal lattice (d=0.14 nm)
of covalently bonded C atoms



a) zig-zag 

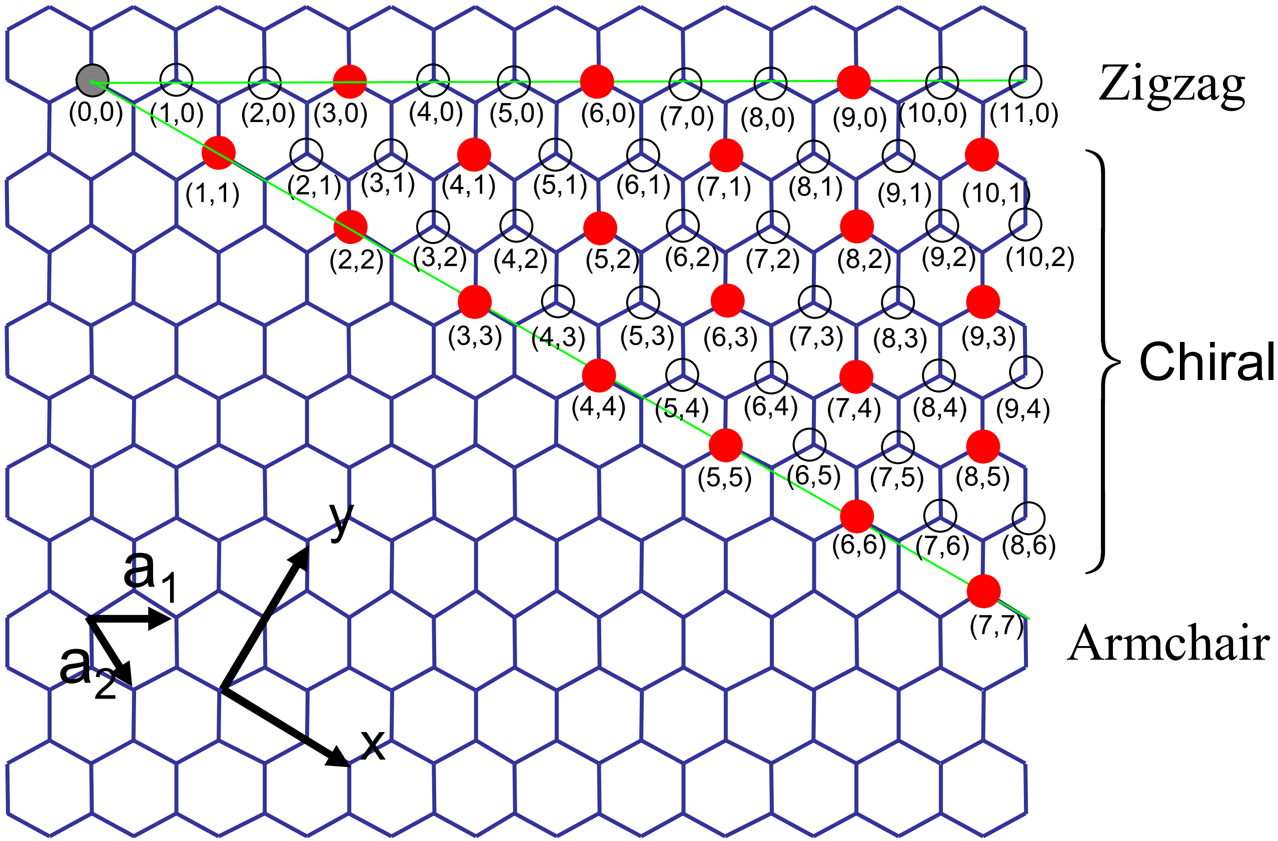
b) armchair 

a) chiral 



Diameter ~ 1 – 2 nm, Length ~ 1 mm

(n,m) nomenclature of SWNTs

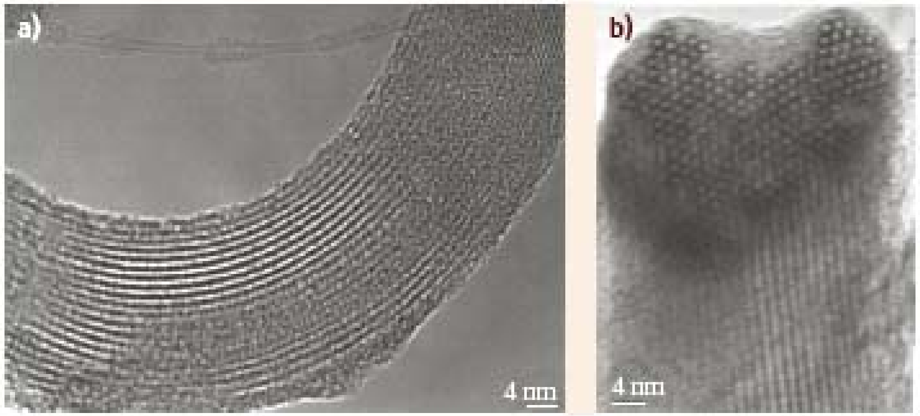


n - m = 3q (q: integer): metallic

n - m ≠ 3q (q: integer): semiconductor

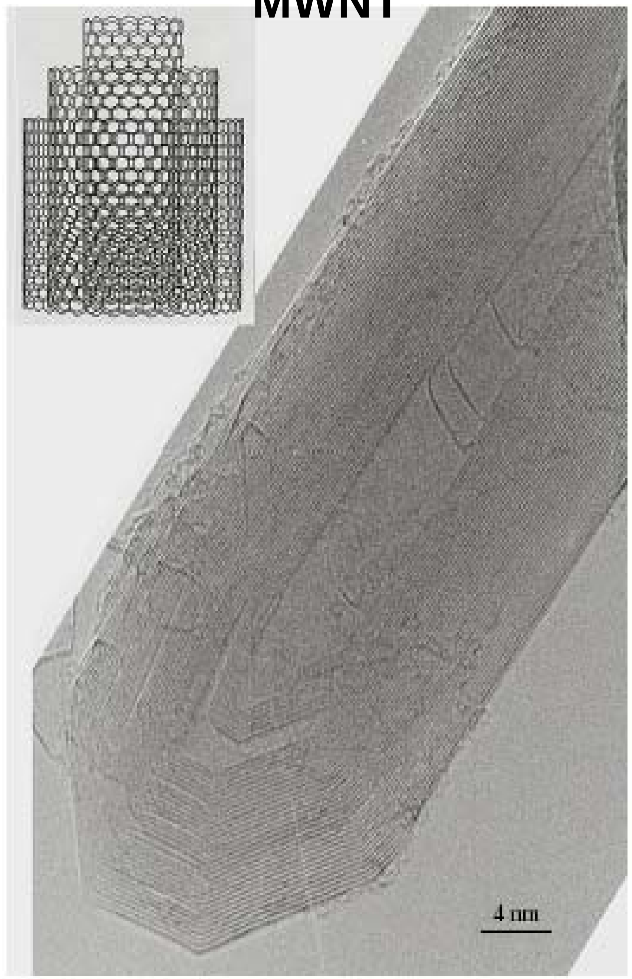
Stacking of nanotubes by van der Waals forces with inter-wall separations ~ 0.34 nm

Rope of SWNTs in hexaginal lattice

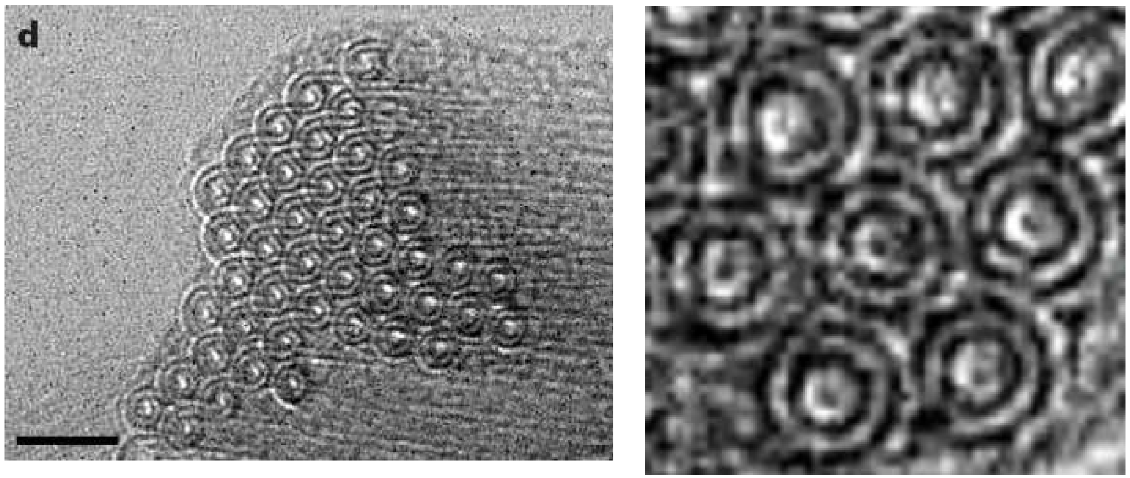


Multi-walled carbon nanotube

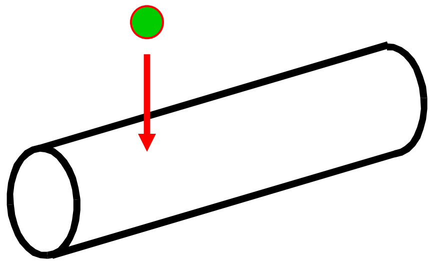
MWNT



Rope of DWNTs in hexaginal lattice

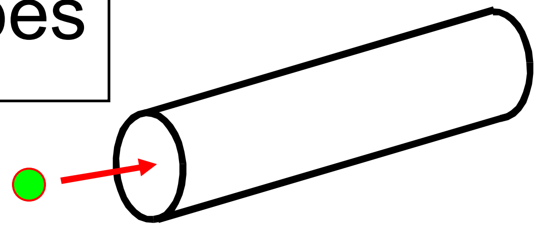


Ion irradiation of carbon nanotubes



- **Beam characteristics:**
  - Directions oblique or perpendicular to nanotube
  - Energies from ~ 100 eV to ~ 100 MeV
  - Heavy and light ions
  - Strong dependence on irradiation dose
  - Beam diameter for local modifications (FIB)
- **Effects on nanotubes:**
  - Creation of local defects (~ 20 eV per atom)
  - Doping, functionalization
  - Inter-tube junctions (with high-T annealing)
  - Amorphization, welding
  - Stiffening, bending, buckling
  - Observed by: SEM, TEM, RS, FEM, AFM, STM, …

Ion channeling through carbon nanotubes

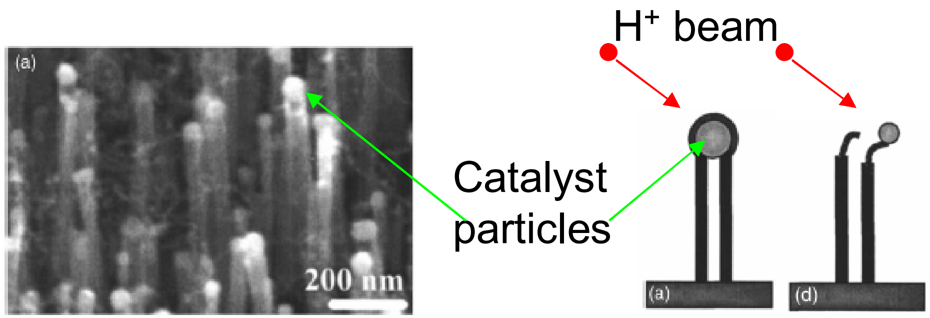


- Advantages over single crystals
  - Wider channels: weaker dechannelling
  - Broader beams (using nanotube ropes)
  - Wider acceptance angles (~ 0.1 rad)
  - Lower minimum ion energies (< 100 eV)
  - 3-D control of beam bending over greater lengths
- Applications
  - Creating and transporting highly focused nano-beams
  - Nano-implantation in electronics, biology & medicine
  - Beam extraction, steering & collimation at accelerators
  - Manipulate plasma deposition, molecule transmission
  - Sources of hard X- and gamma-rays

Some issues regarding realization of channeling

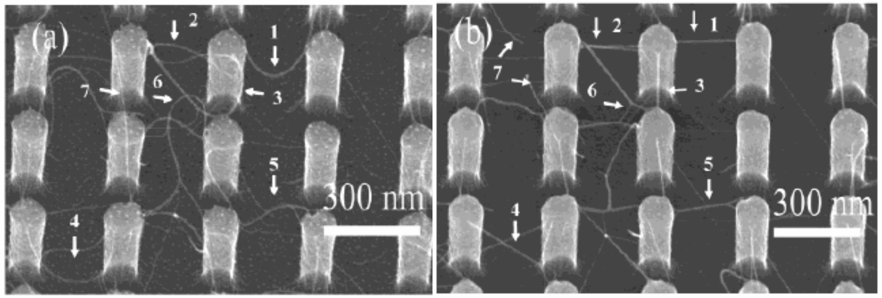
- **Open ends** (sputter etching)

  J.F. AuBuchon *et al.*,
  J. Appl. Phys. 97 (2005) 124310



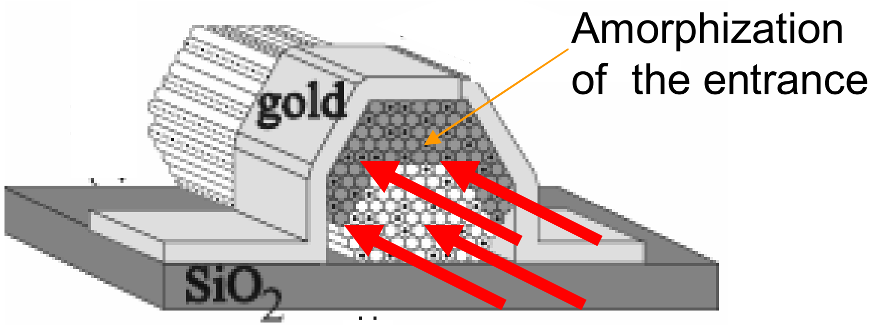
- **Straightening** (using Ga^+ beam)

  Y.J. Jung *et al.*,
  Nano Letters 4 (2004) 1109



- **Clamping** by metal wires

  H. Stahl *et al.*,
  Phys. Rev. Lett. 85 (2000) 5186



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Continuum approximation for nanotube wall potential

- Repulsive potential of a C atom, $U_{at}(R)$ (Lindhrad, Molière, Doyle-Turner)
- Atomic row potential from longitudinal average

$$U_{row}(r) = \frac{1}{d_{at}} \int_{-\infty}^{\infty} U_{at}\left(\sqrt{r^2 + z^2}\right) dz$$

- Wall potential for zig-zag and armchair nanotubes with radius $|r_j| = a$

$$U_{z,a}(r, \varphi) = \sum_{j=1}^{N} U_{row}\left(\sqrt{r^2 + a^2 - 2ra\cos(\varphi - \varphi_j)}\right)$$

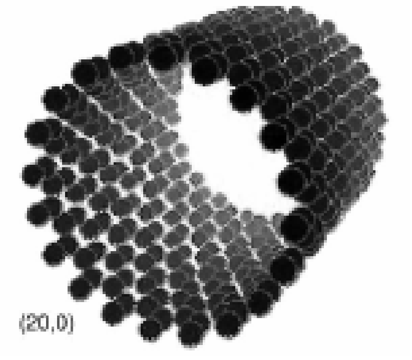
- Wall potential for chiral nanotubes with radius a from averaging over circumference

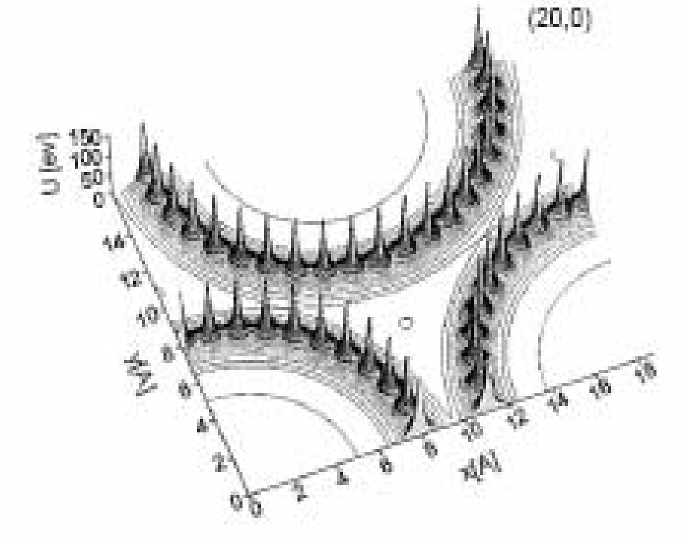
$$U_{chi}(r) = a\sigma_{at} \int_0^{2\pi} \int_{-\infty}^{\infty} U_{at}\left(\sqrt{z^2 + r^2 + a^2 - 2ra\cos\varphi}\right) dz\, d\varphi$$

Continuum approximations for the repulsive atomic potential in SWNTs

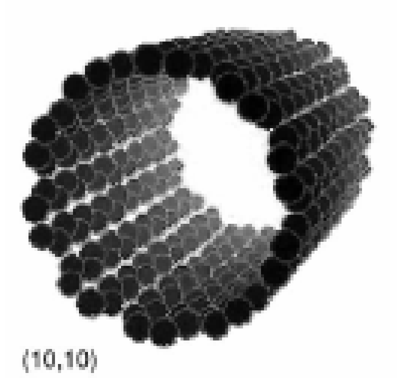
X. Artru *et al.*, *Phys. Reports* 412 (2005) 89

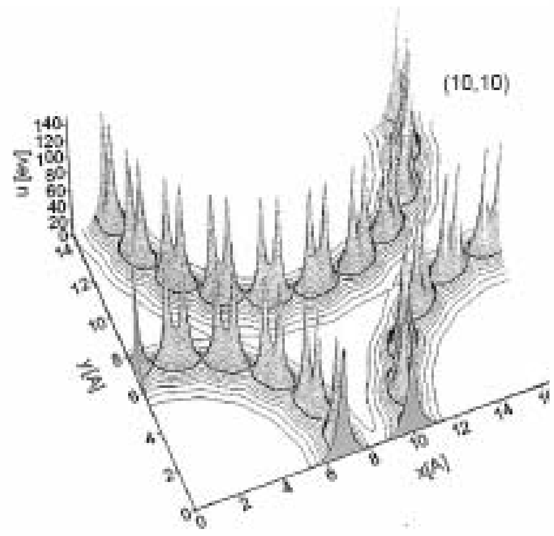
Zig-zag



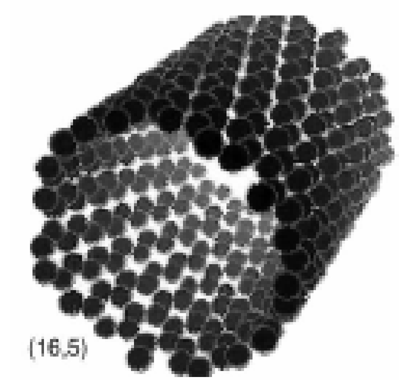


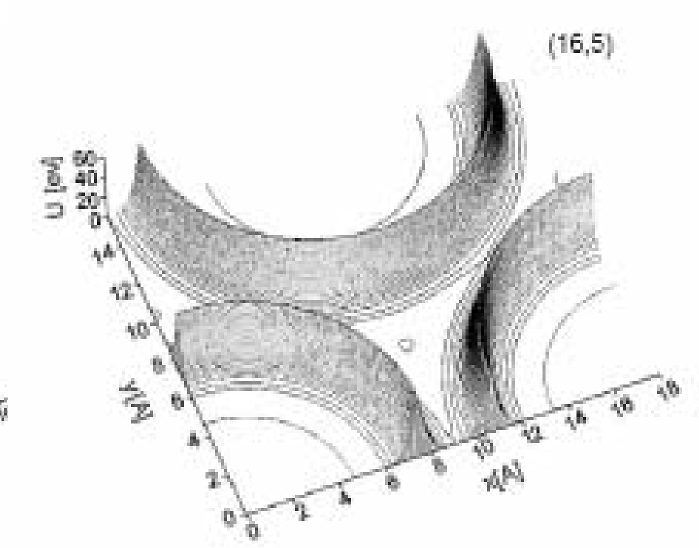
Armchair





Chiral

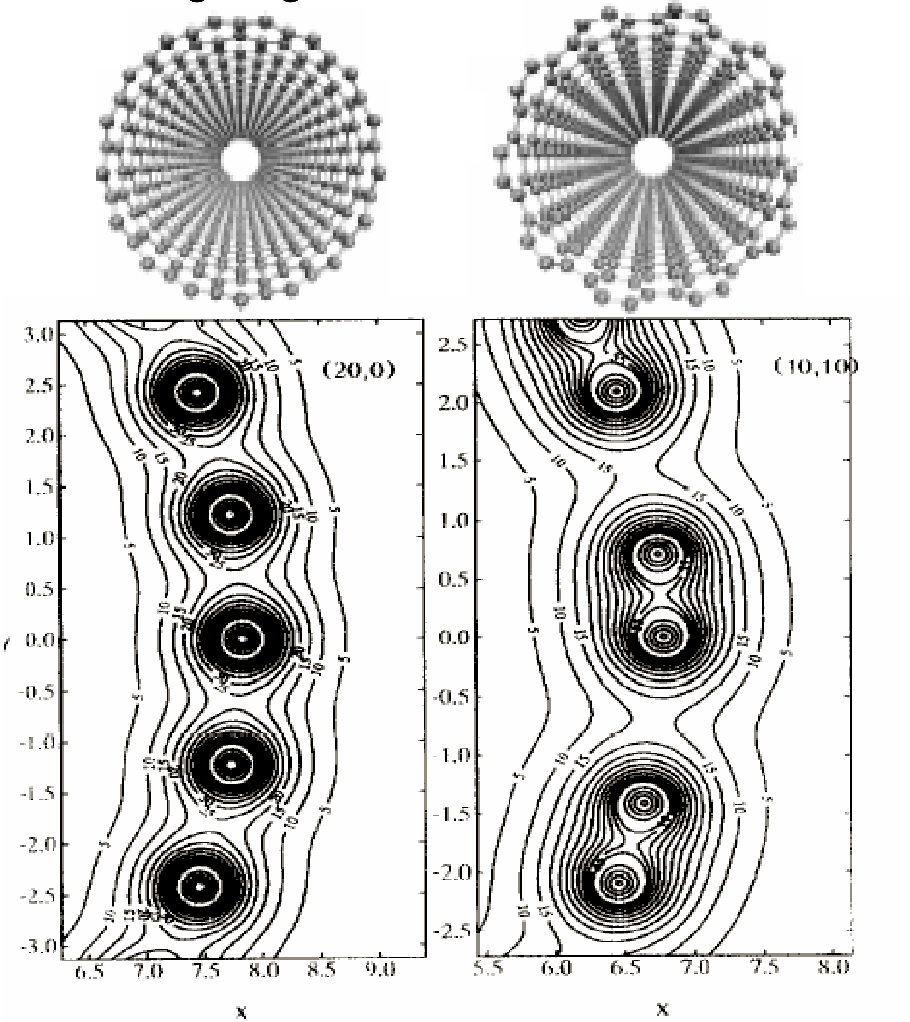




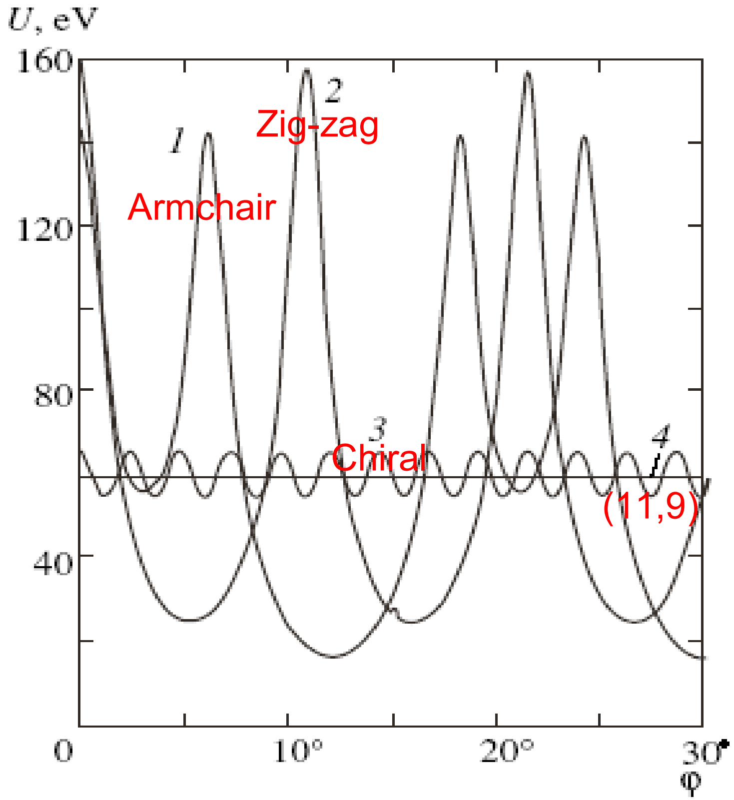
Continuum potential due to atomic rows in achiral SWNTs

N.K. Zhevago and V.I. Glebov, *J.E.T.P.* 91 (2000) 579

Zig-zag Armchair

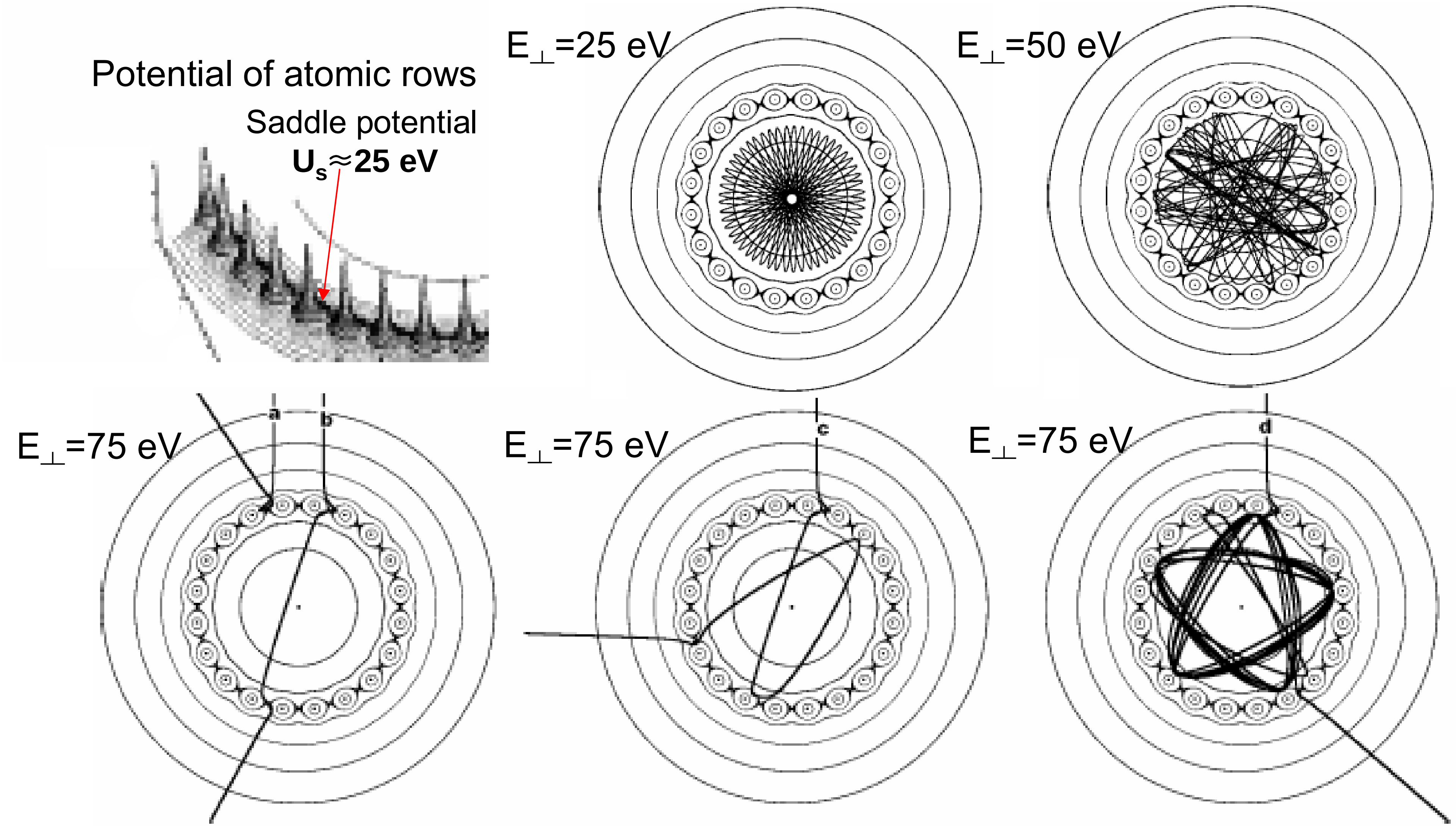


Angular variation of potential barrier at the nanotube wall



Trajectories for ion channeling in a zig-zag SWNT(10,0) at several transverse energies $E_\perp$ relative to saddle U_s

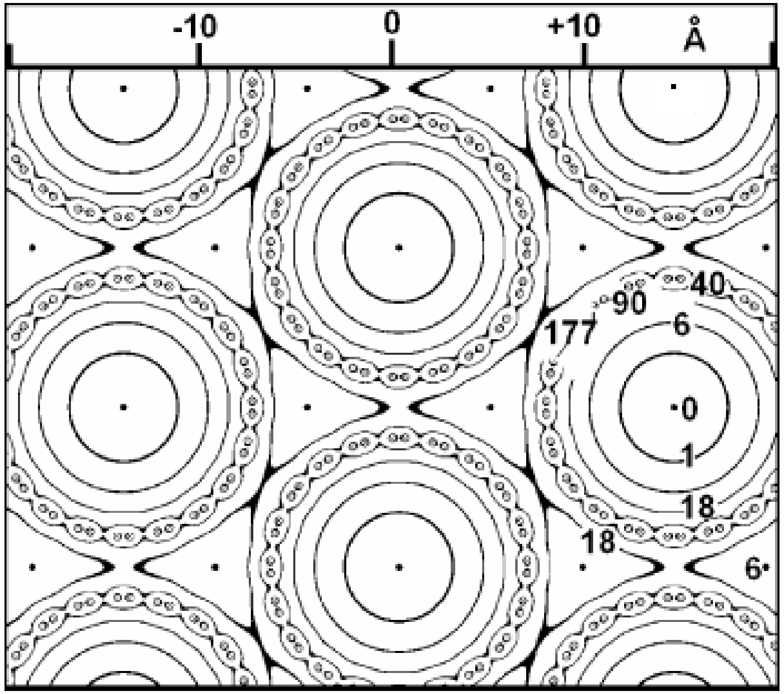
X. Artru *et al., Phys. Reports* 412 (2005) 89



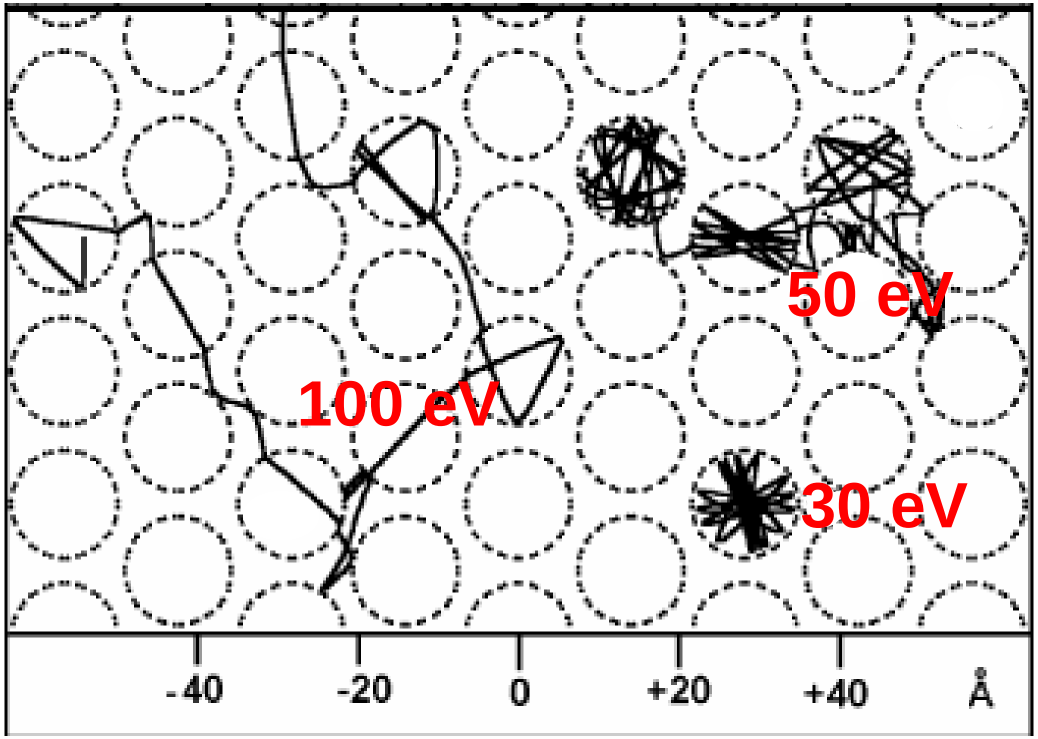
Ion channelling through rope of armchair SWNTs(10,10)

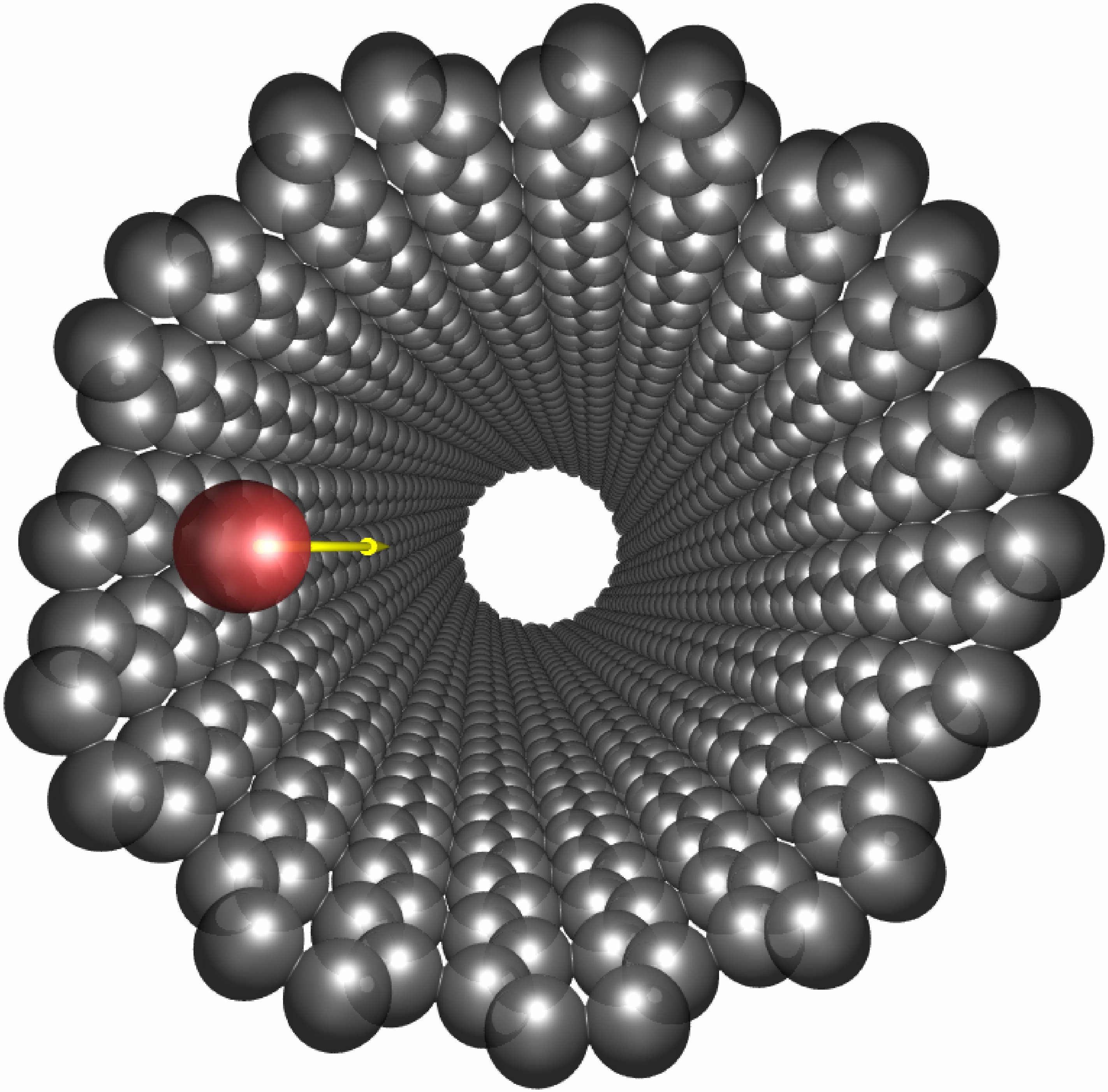
A.A. Greenenko and N.F. Shulga, *Nucl. Instr. Meth.* B 205 (2003) 767

Equi-potential surfaces (eV)



Ion trajectories with beam momentum 10 GeV/c and perpendicular energies 30, 50, and 100 eV

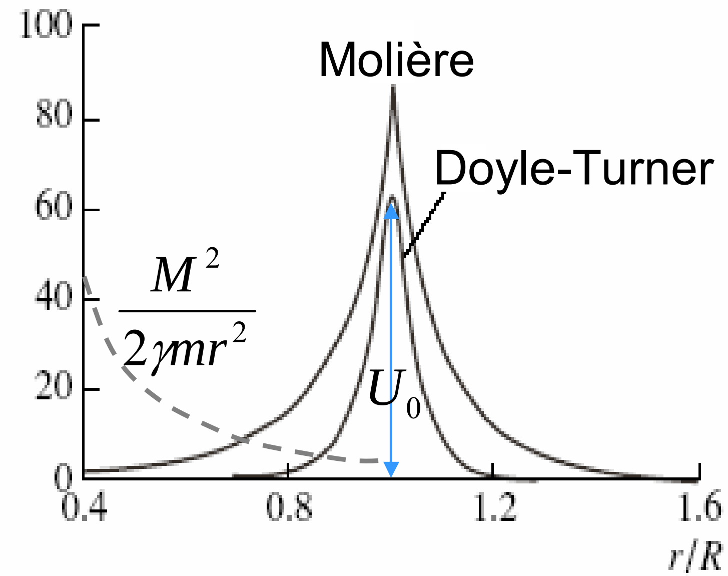




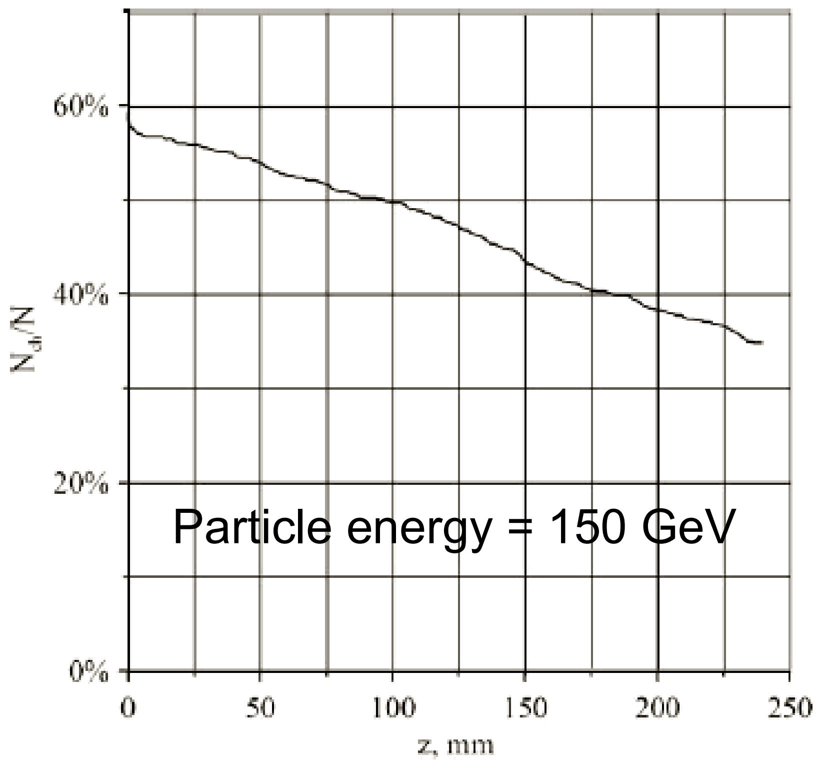
Ion channelling through a straight chiral SWNT(11,9)

N.K. Zhevago and V.I. Glebov, *Phys. Lett.* A 250 (1998) 360 & 310 (2003) 301

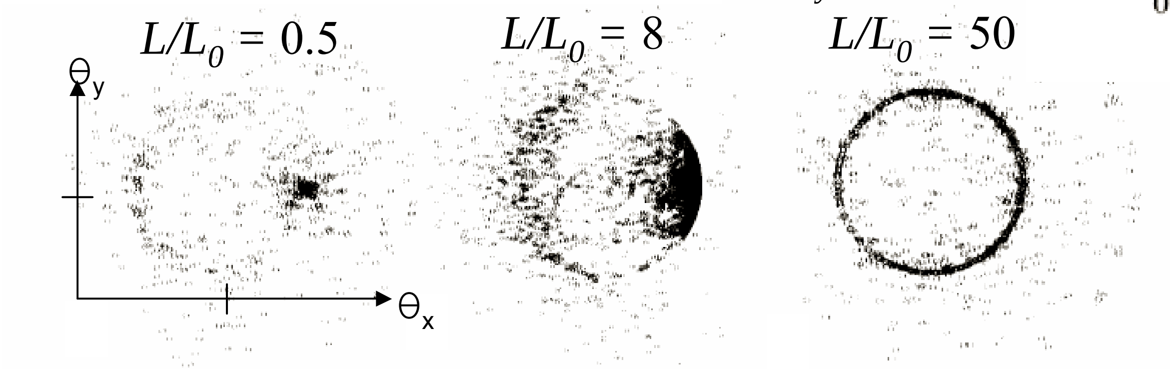
Axially symmetric potential



Removal of ions due to dechanneling



Angular distributions of GeV ions for incident angles: $\theta_{0x} = \theta_L/2$, $\theta_{0y} = 0$



$$\theta_L = \sqrt{2U_0/E}$$

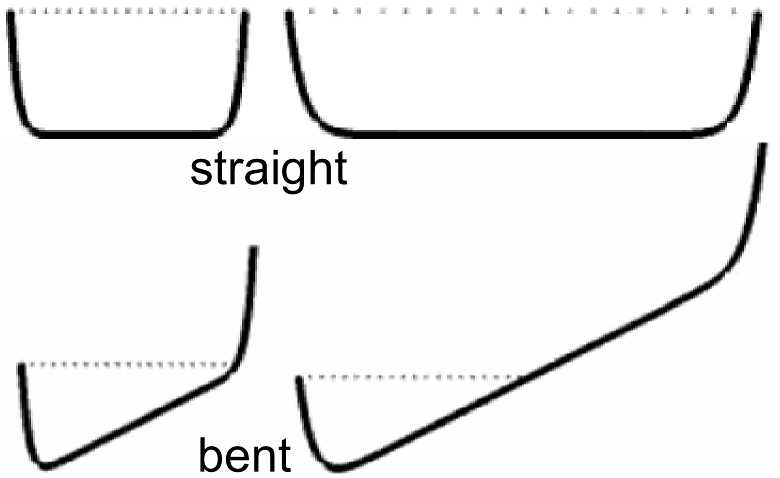
$$L_0 \equiv d/2\theta_L$$

Optimal nanotube diameter for GeV proton beam steering in bent chiral SWNTs

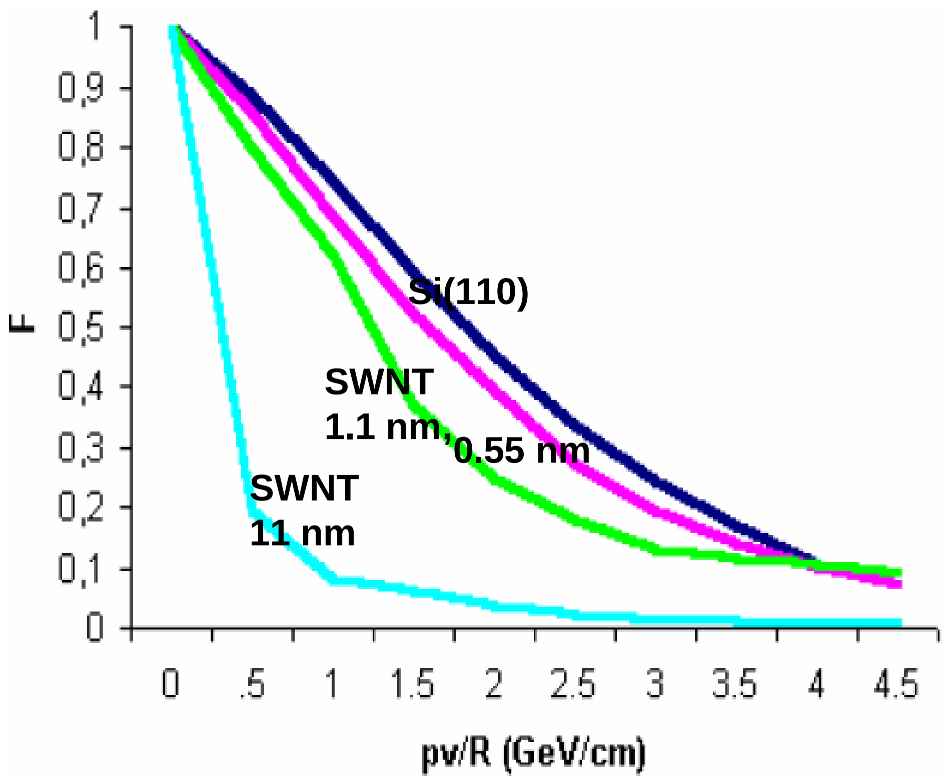
V.M. Biryukov and S. Bellucci, *Phys. Lett.* B 542 (2002) 111

Effective potentials inside narrow and wide SWNTs

$$U_{eff}(x) = U(x) + \frac{pv}{R}x$$



Fractions of channelled protons vs nanotube curvature ***pv* / *R*** for: Si(110) crystal channel and three SWNTs with different diameters

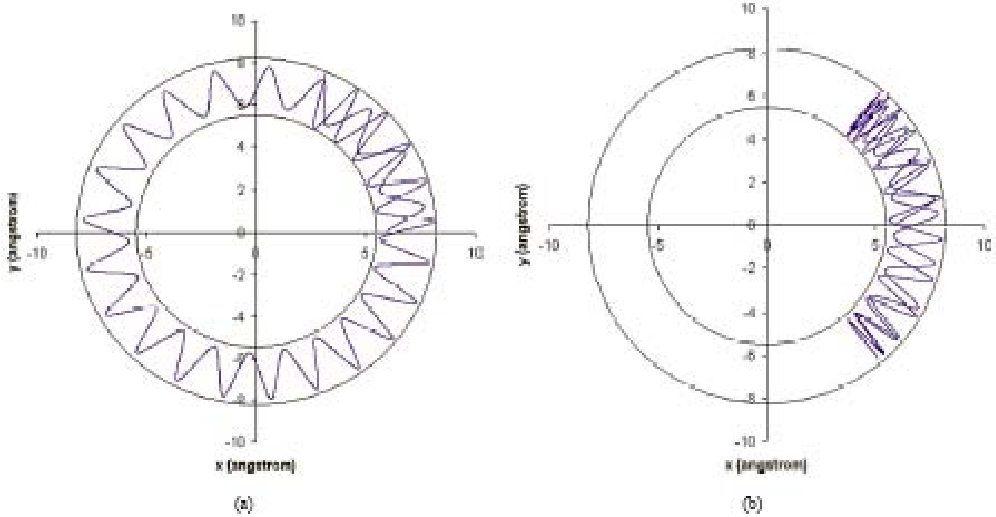


Conclusion: wide SWNTs are not more effective for beam steering

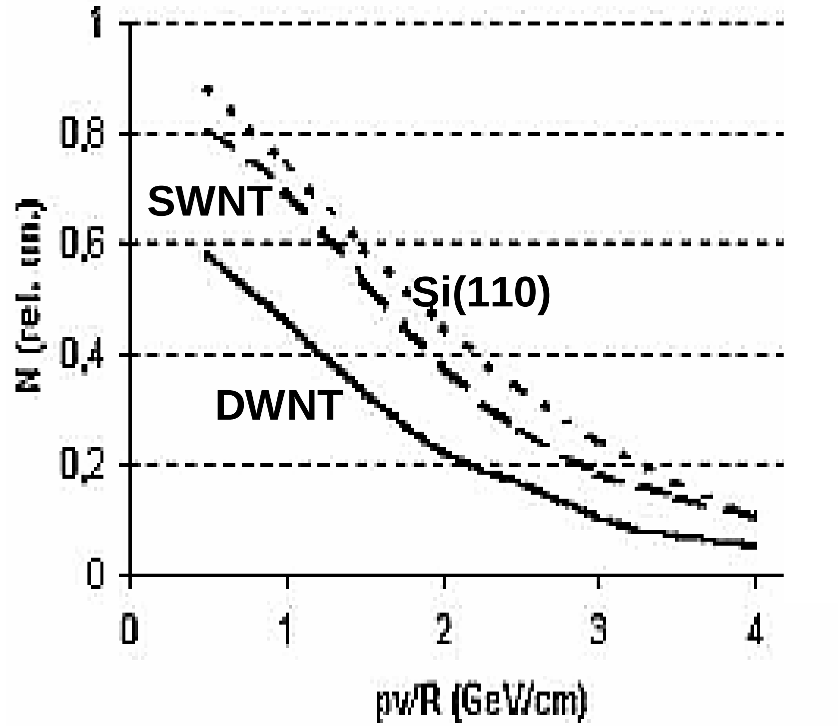
GeV proton beam steering in bent <u>chiral</u> DWNTs

S. Bellucci *et al.*, *Phys. Lett.* B 608 (2005) 53

Proton trajectories between the walls in (a) straight and (b) bent DWNT

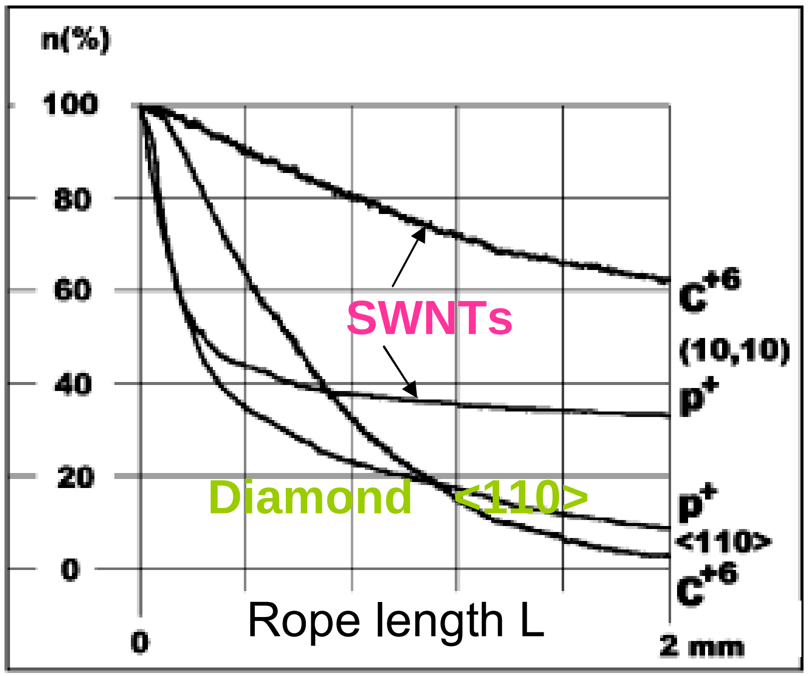


Fractions of protons channelled through: Si(110) crystal channel, SWNT with diameter 0.55 nm, and a DWNT



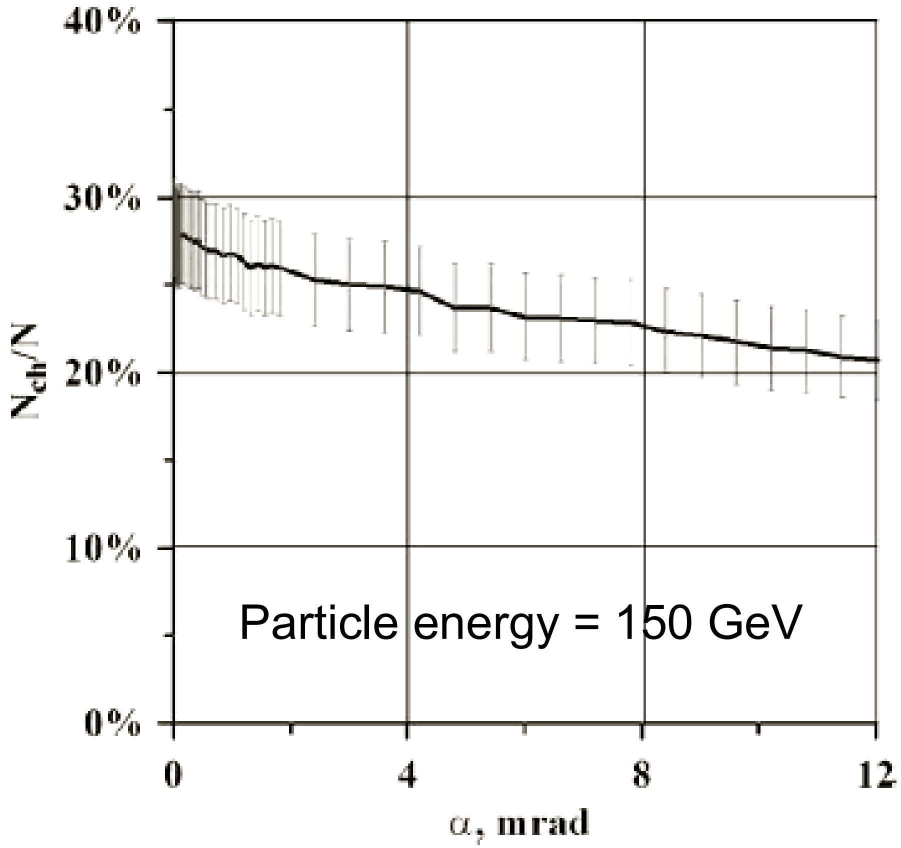
Deflected beam fractions in bent ropes of SWNTs

Rope of armchair SWNTs(10,10)
A.A. Greenenko and N.F. Shulga,
Nucl. Instr. Meth. B 205 (2003) 767



Curvature radius R = 20 cm
Beam momentum=10 GeV/c

Rope of chiral SWNTs(11,9)
N.K. Zhevago and V.I. Glebov,
Phys. Lett. A 310 (2003) 301



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Theory of rainbows in short ropes of SWNTs

- Scattering angles depend on impact parameters (x_0, y_0) and length L

$$\Theta_x = \Theta_x(x_0, y_0 ; L), \quad \Theta_y = \Theta_y(x_0, y_0 ; L)$$

- In the small-angle approximation for short nanotubes, the differential cross section for ion transmission

$$\sigma = 1/|J|$$

- $J = \partial_x \Theta_x \partial_y \Theta_y - \partial_x \Theta_y \partial_y \Theta_x$ is the Jacobian of the mapping

$$(x_0, y_0) \rightarrow (\Theta_x, \Theta_y)$$

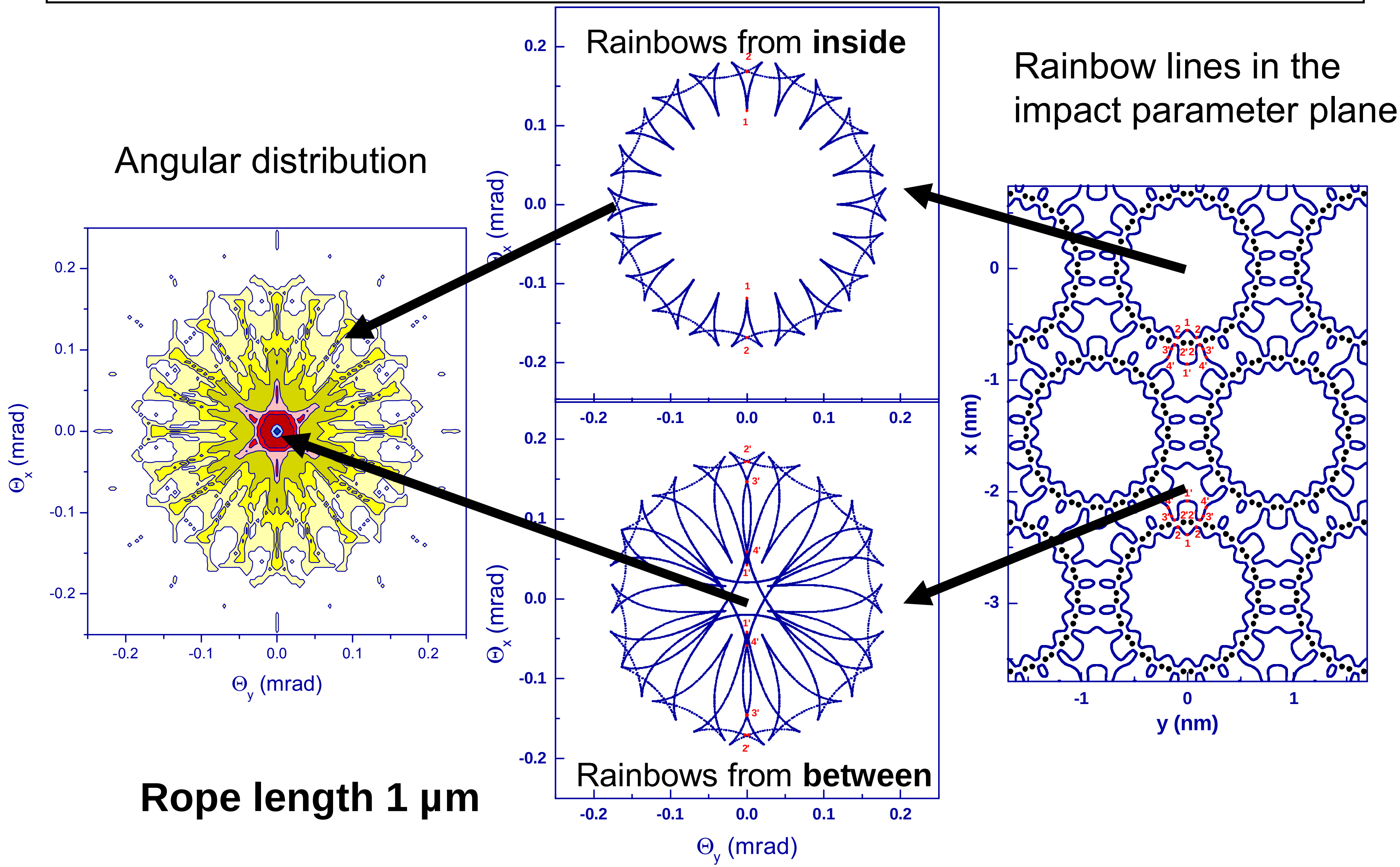
- Rainbow lines in the impact parameter plane are defined by

$$J(x_0, y_0 ; L) = 0$$

- Total potential is sum over all atomic rows on all nanotubes in the rope
- Could be used for precise measurement of electron density in nanotubes

Rainbow effect after 1GeV proton channelling through a <u>short</u> rope of <u>armchair</u> SWNTs(10,10)

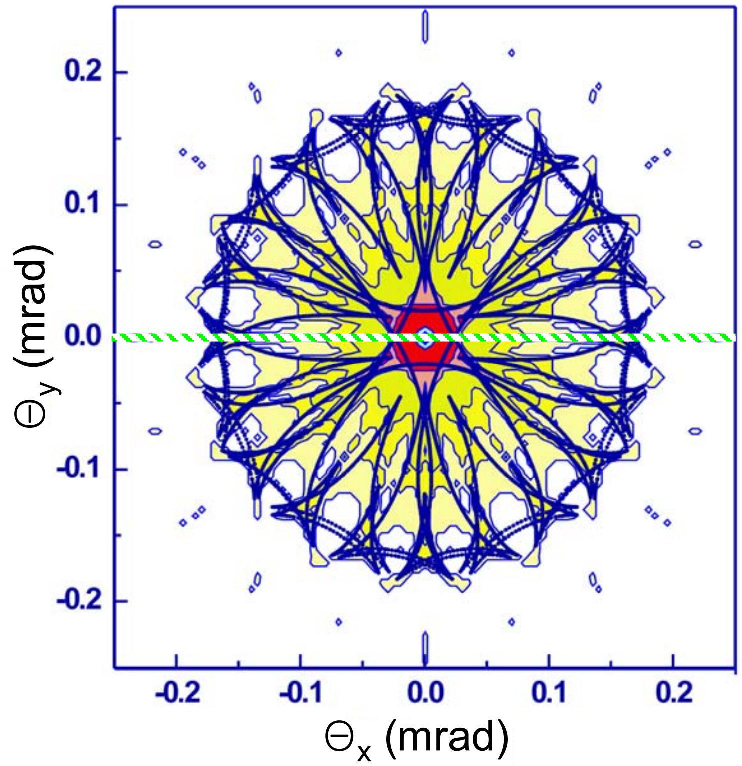
S. Petrovic *et al.*, *Eur. Phys. J.* B 44 (2005) 41



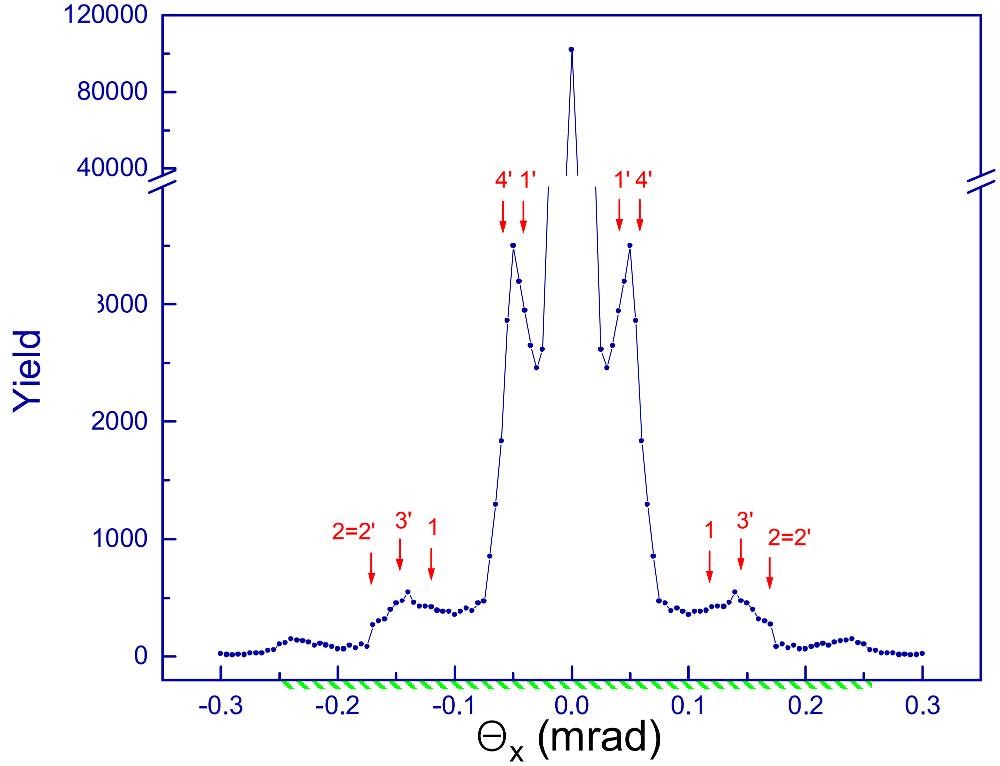
Rainbow effect after 1GeV proton channelling through a <u>short</u> rope of <u>armchair</u> SWNTs(10,10)

S. Petrovic *et al.*, *Eur. Phys. J.* B 44 (2005) 41

Angular distribution with rainbow lines



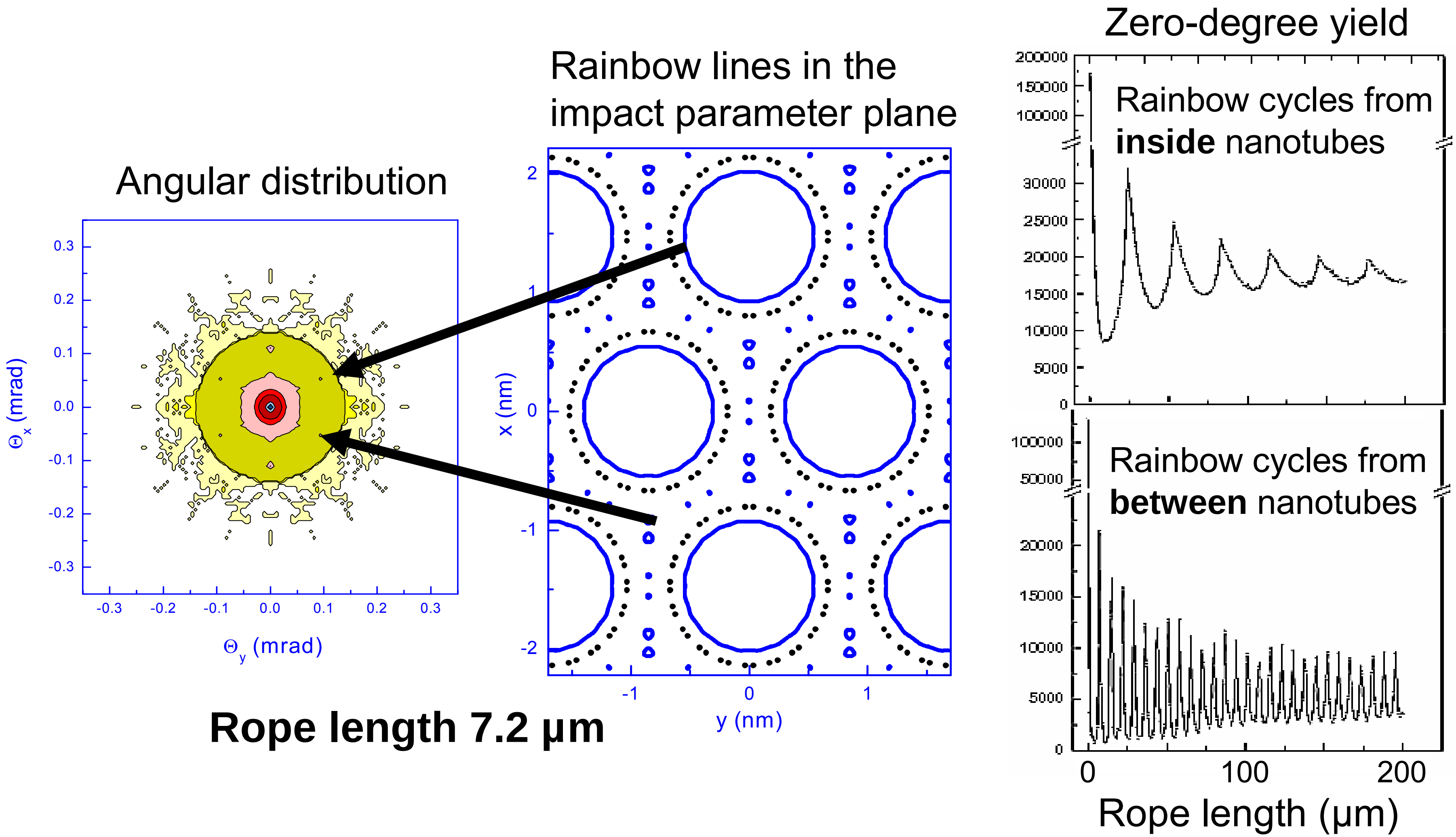
Yield of protons along Θ_x line



Rope length 1 μm

Rainbow effect after 1GeV proton channelling through <u>longer</u> ropes of <u>armchair</u> SWNTs(10,10)

S. Petrovic *et al.*, *Nucl. Instr. Meth* B 234 (2005) 78

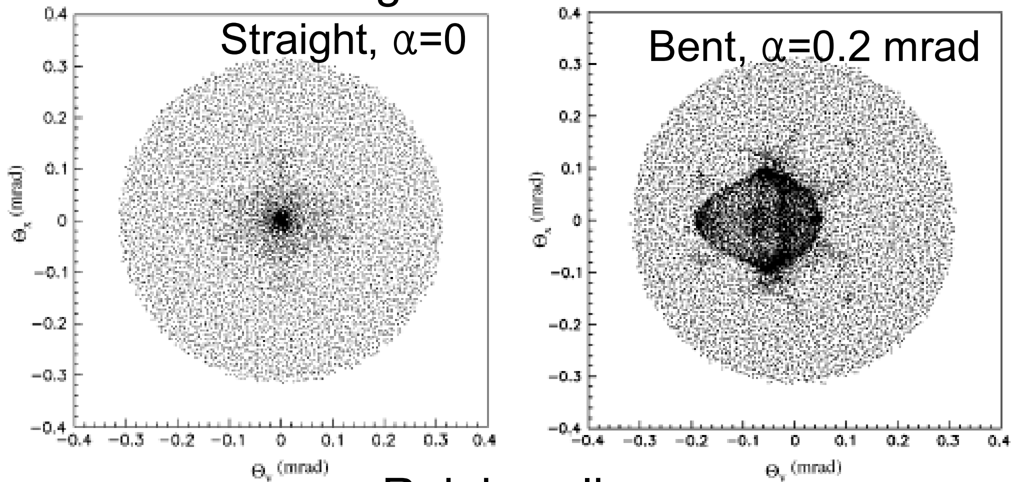


Rope length 7.2 μm

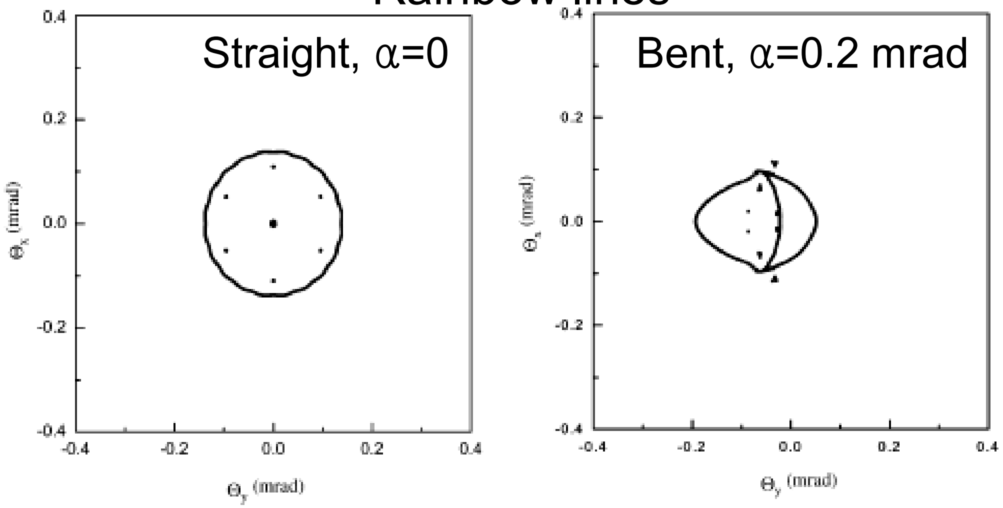
Channeling of 1 GeV protons through a bent rope of <u>armchair</u> SWNTs (10,10)

N. Neskovic *et al., Nucl. Instr. Meth.* B 230 (2005) 106

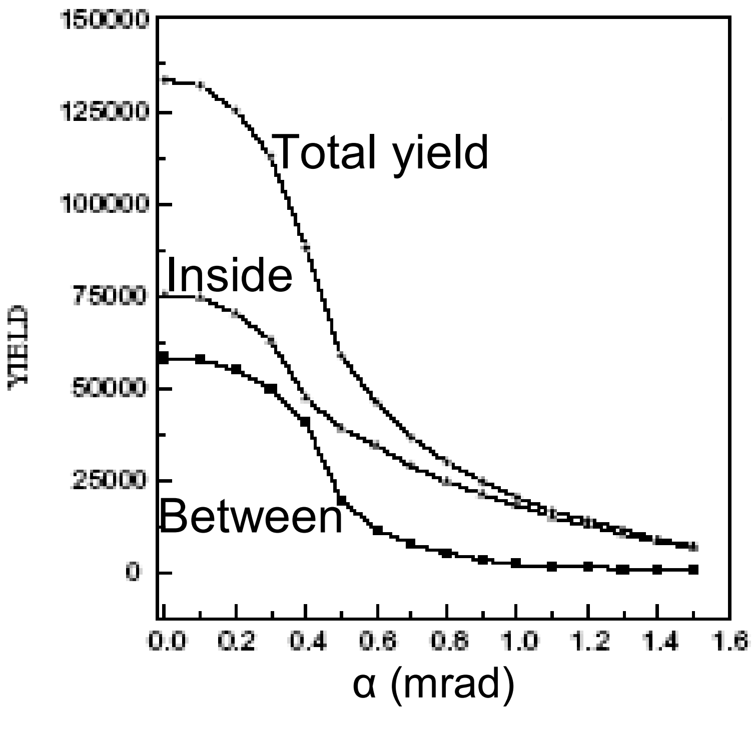
Angular distributions



Rainbow lines



Yields of protons transmitted inside and between nanotubes vs bending angle in 7 μm rope



Outline

- ❑ **Reminder: Channeling in single crystals**
- ❑ **Ion interactions with carbon nanotubes**
- ❑ **High-energy channeling** (~GeV)
  - Potentials and beam deflection
  - Rainbow effect in short ropes
- ❑ **Medium-energy channeling** (~MeV)
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  - New developments
- ❑ **Low-energy channeling** (~keV)
  - MD simulations
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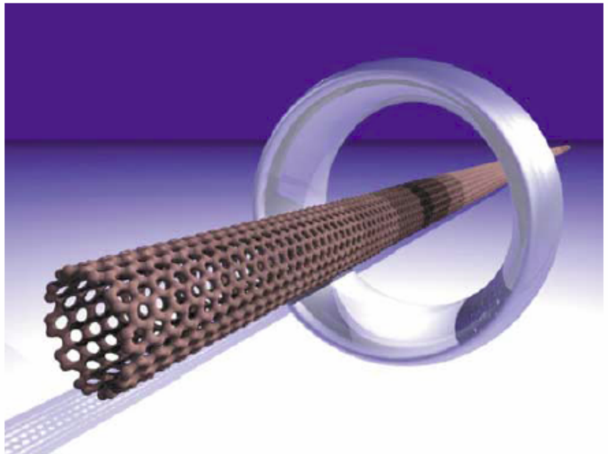
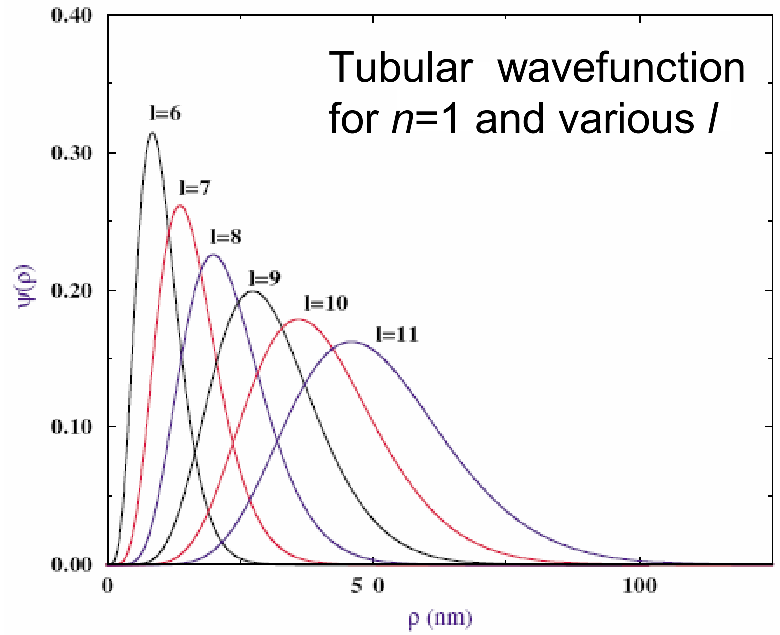
- ❑ **Outlook**

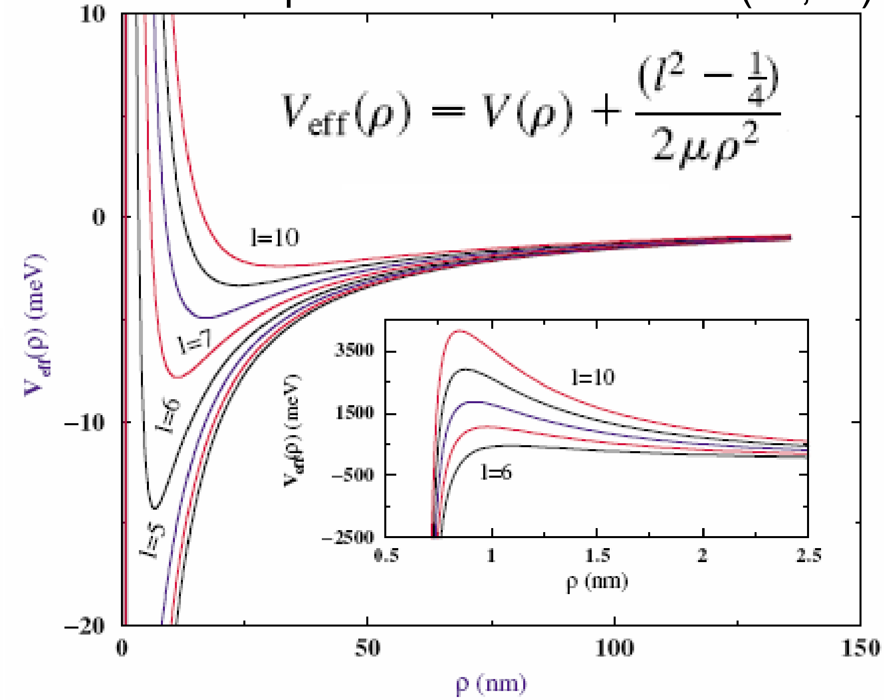
Electron image states around carbon nanotubes

Theoretical prediction: B.E. Granger *et al.*, *Phys. Rev. Lett.* 89 (2002) 135506





Effective potential around SWNT (10,10)



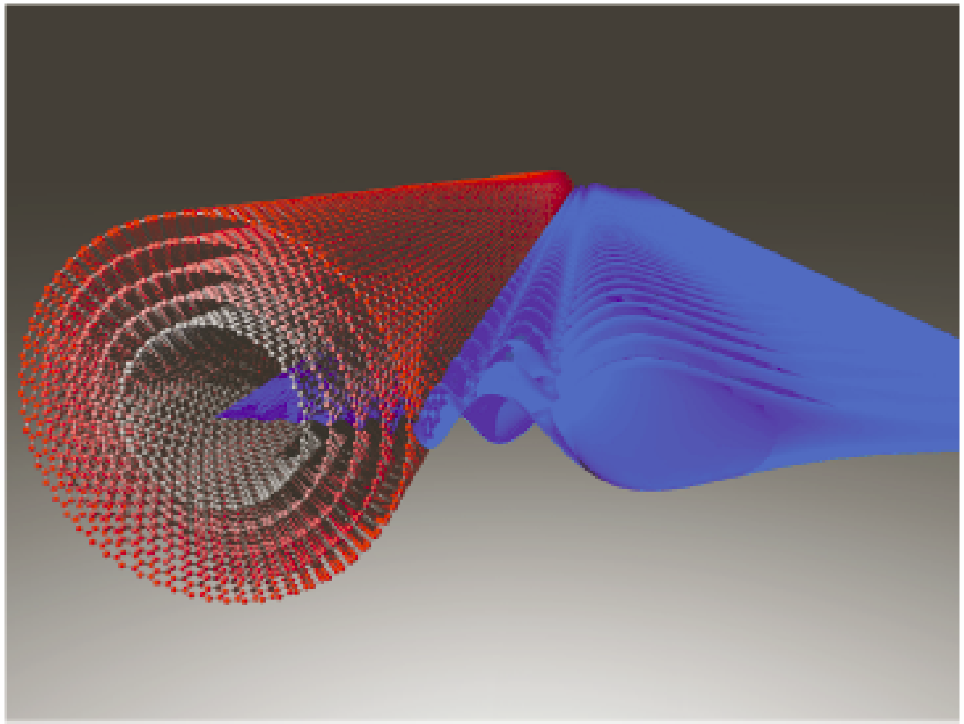
Approximate image potential

$$V(\rho_0) \approx \frac{2}{\pi}\frac{q^2}{a} \sum_{n=1,3,5,\ldots} \mathrm{li}[(a/\rho_0)^n]$$

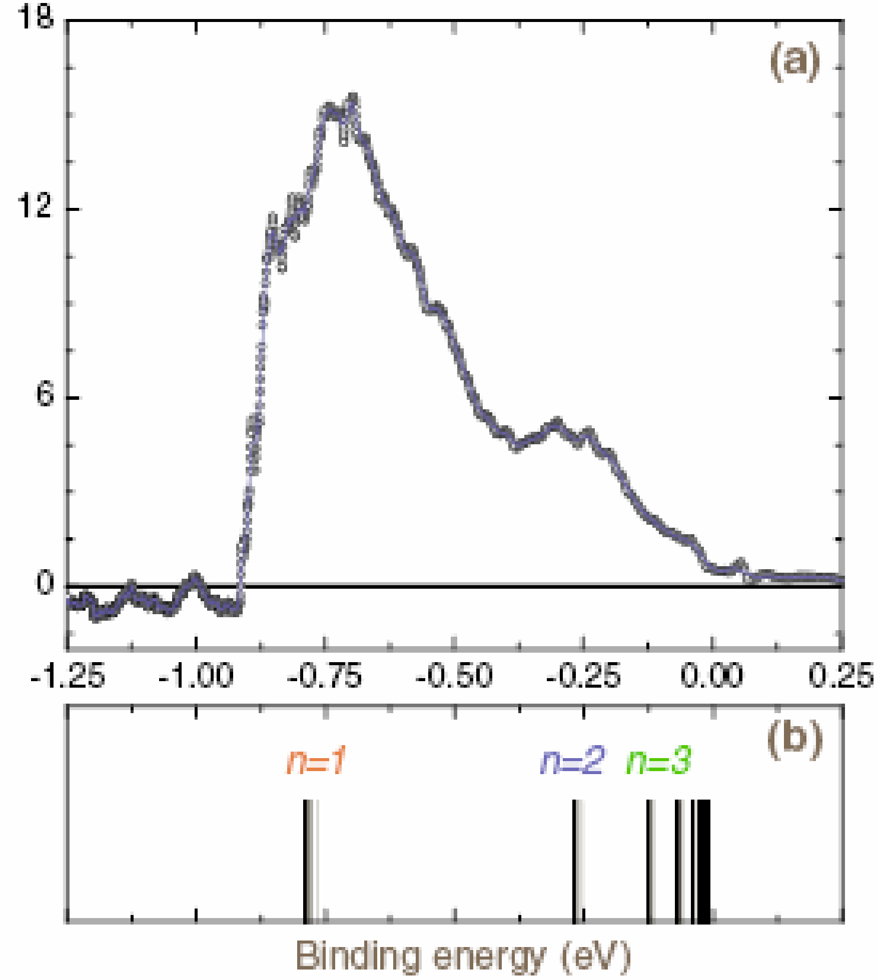
Electron image states around carbon nanotubes

Experimental confirmation: M. Zamkov *et al.*, *Phys. Rev. Lett.* 93 (2004) 156803

Visualization of electron wavefunction with n=3, l=1

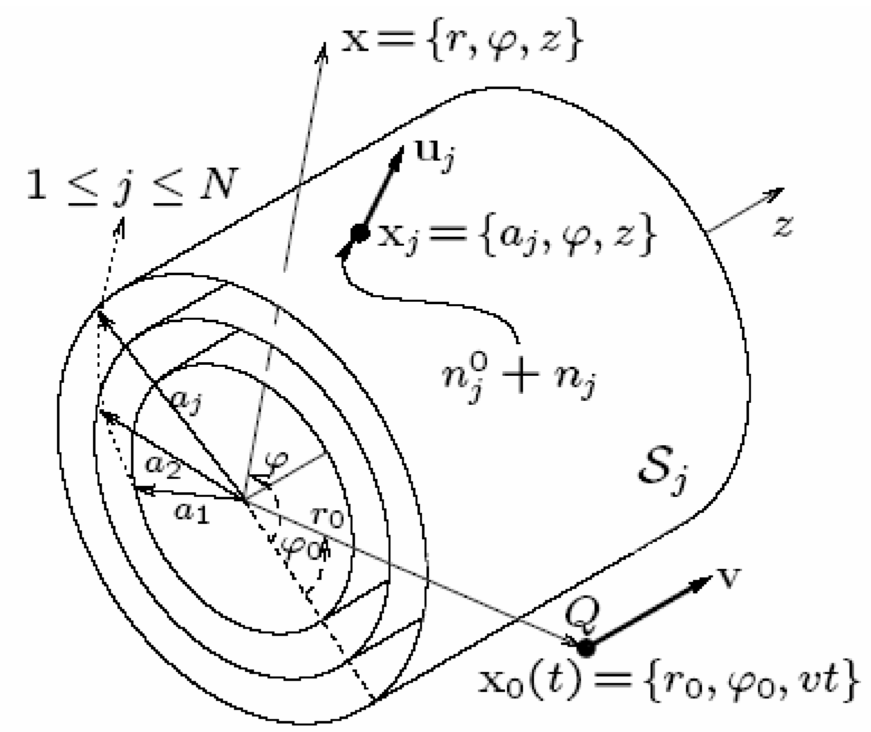


Photoelectron signal from image state



2D hydrodynamic model of electron response

D.J. Mowbray *et al., Phys. Rev.* B 70 (2004) 195418



$$\frac{\partial n_j(\mathbf{x}_j, t)}{\partial t} = -n_j^0 \nabla_j \cdot \mathbf{u}_j(\mathbf{x}_j, t)$$

$$\frac{\partial \mathbf{u}_j(\mathbf{x}_j, t)}{\partial t} = \nabla_j \Phi(\mathbf{x}, t)|_{r=a_j} - \frac{\alpha_j}{n_j^0} \nabla_j n_j(\mathbf{x}_j, t) + \frac{\beta}{n_j^0} \nabla_j \left[\nabla_j^2 n_j(\mathbf{x}_j, t) \right] - \gamma_j \mathbf{u}_j(\mathbf{x}_j, t)$$

$$\Phi(\mathbf{x}, t) = \frac{Q}{\|\mathbf{x} - \mathbf{x}_0(t)\|} - \sum_j \int_{\mathcal{S}_j} d^2 \mathbf{x}'_j \frac{n_j(\mathbf{x}'_j, t)}{\|\mathbf{x} - \mathbf{x}'_j\|}$$

Stopping power

$$S = Q \frac{\partial \Phi_{ind}}{\partial z} \Big|_{\mathbf{x} = \mathbf{x}_0(t)}$$

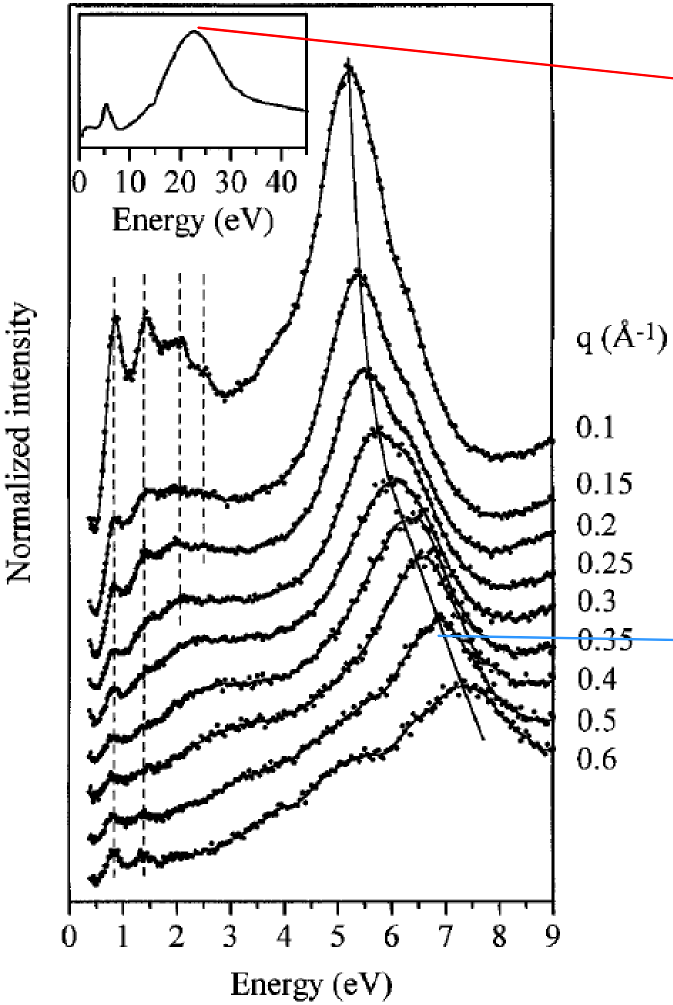
Self-energy (image potential)

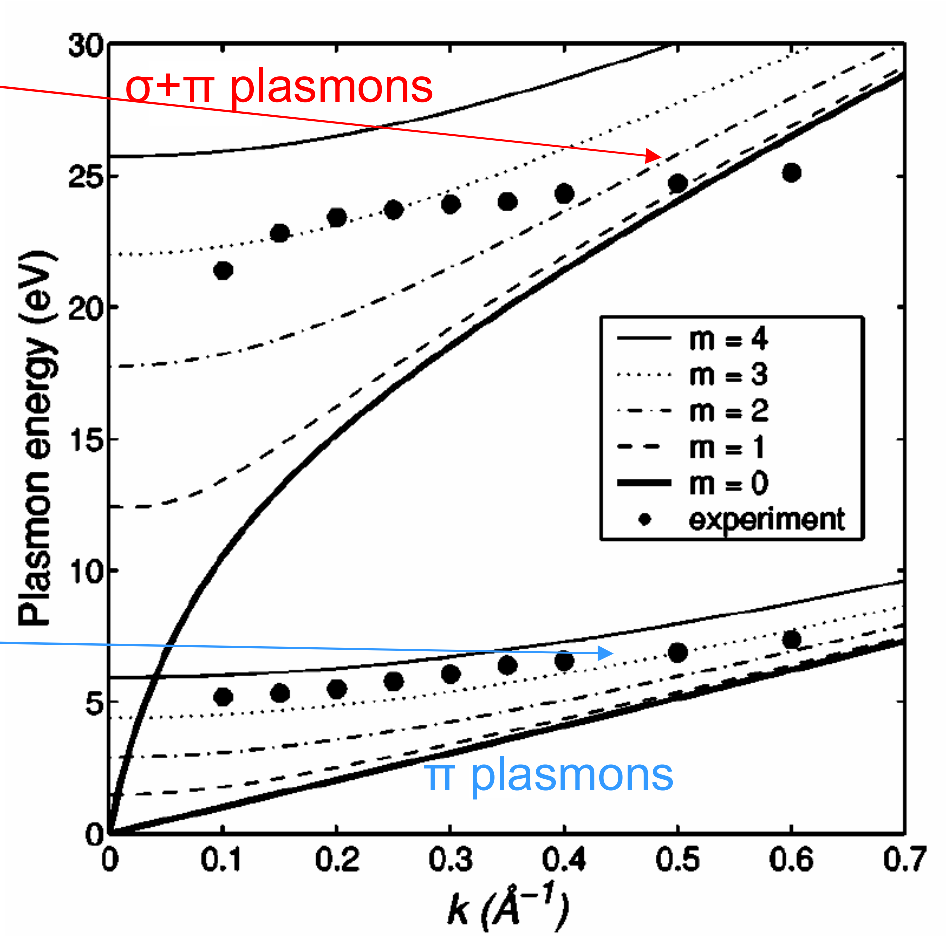
$$E_s = -\frac{Q}{2} \Phi_{ind} \Big|_{\mathbf{x} = \mathbf{x}_0(t)}$$

Plasmon spectra: σ and π electrons on SWNT

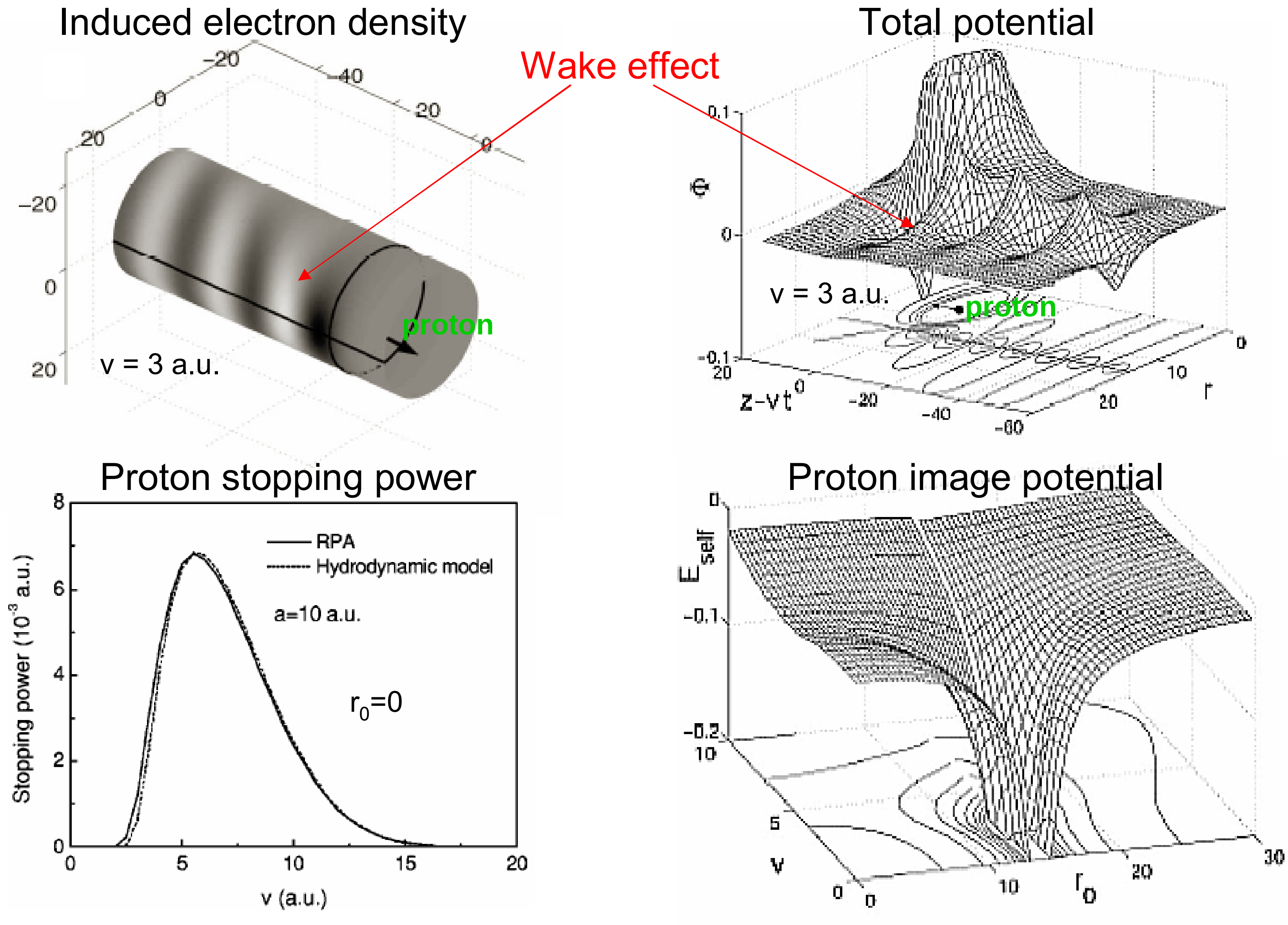
EELS experiment: T. Pichler *et al.*, *Phys. Rev. Lett.* 80 (1998) 4729

Theoretical plasmon dispersion: **Two-fluid model**

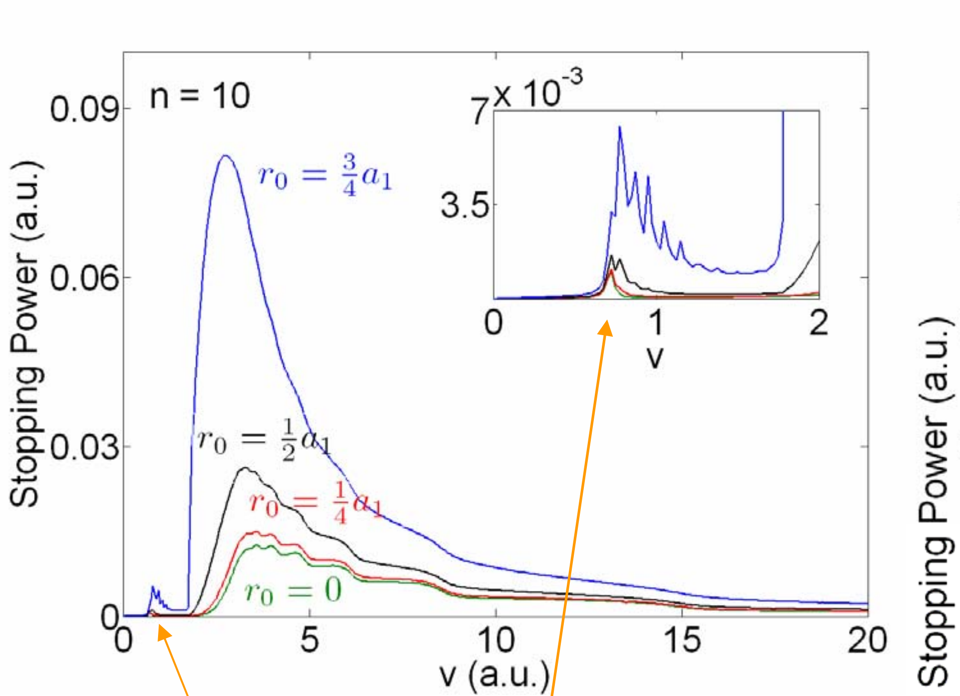


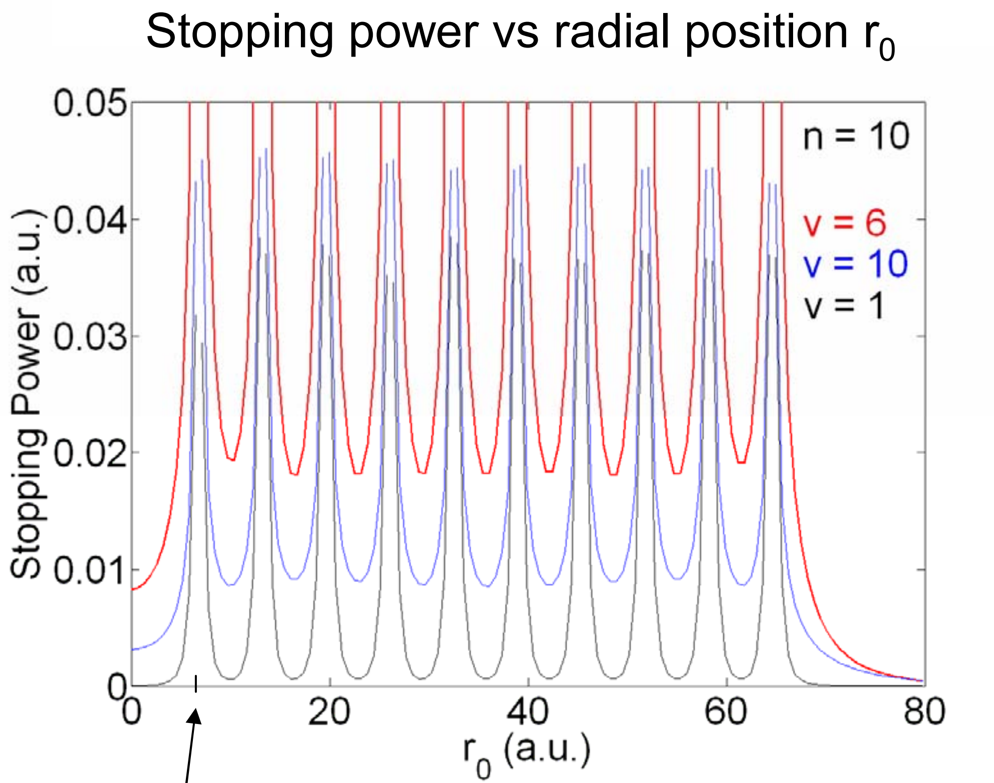


Dynamic polarization of electrons on SWNT by proton



Proton stopping power for MWNT with n = 10 walls

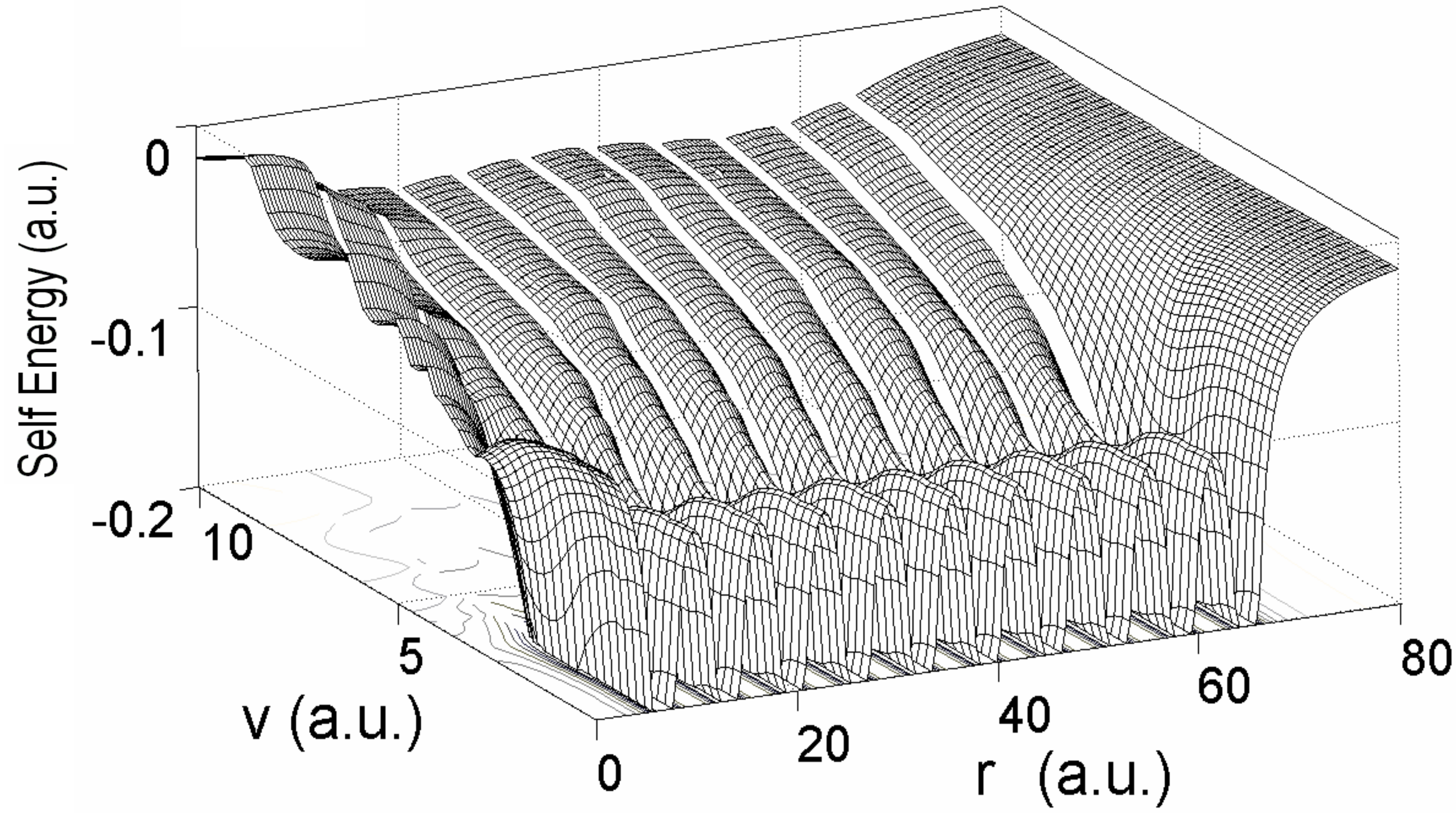




$a_1 \approx 6.8$ a.u.

Calculations done with **two-fluid model**: notice low-speed features due to quasi - acoustic π plasmons having dispersion $\omega_\pi \approx v_a k$ with acoustic speed $v_a = (3\pi\sigma_0/8)^{1/2} \approx 0.7$ a.u.. Is there a drift instability?

Proton self energy (image potential) for MWNT with n = 10 walls (single-fluid model)



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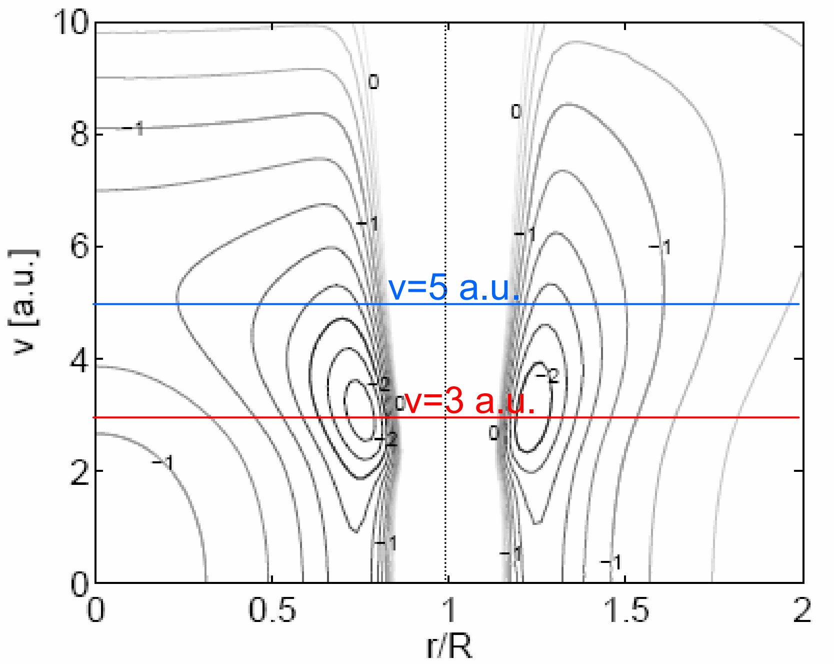
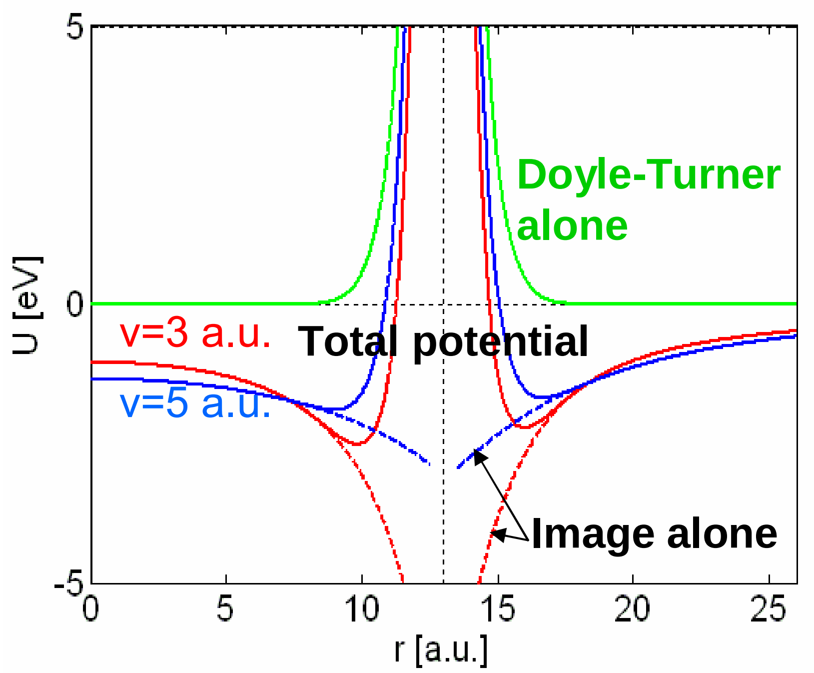
Total potential for proton moving parallel to a chiral SWNT(11,9) with image and Doyle-Turner potentials

Contour plot of total potential



Nanotube radius ≈ 13 a.u.



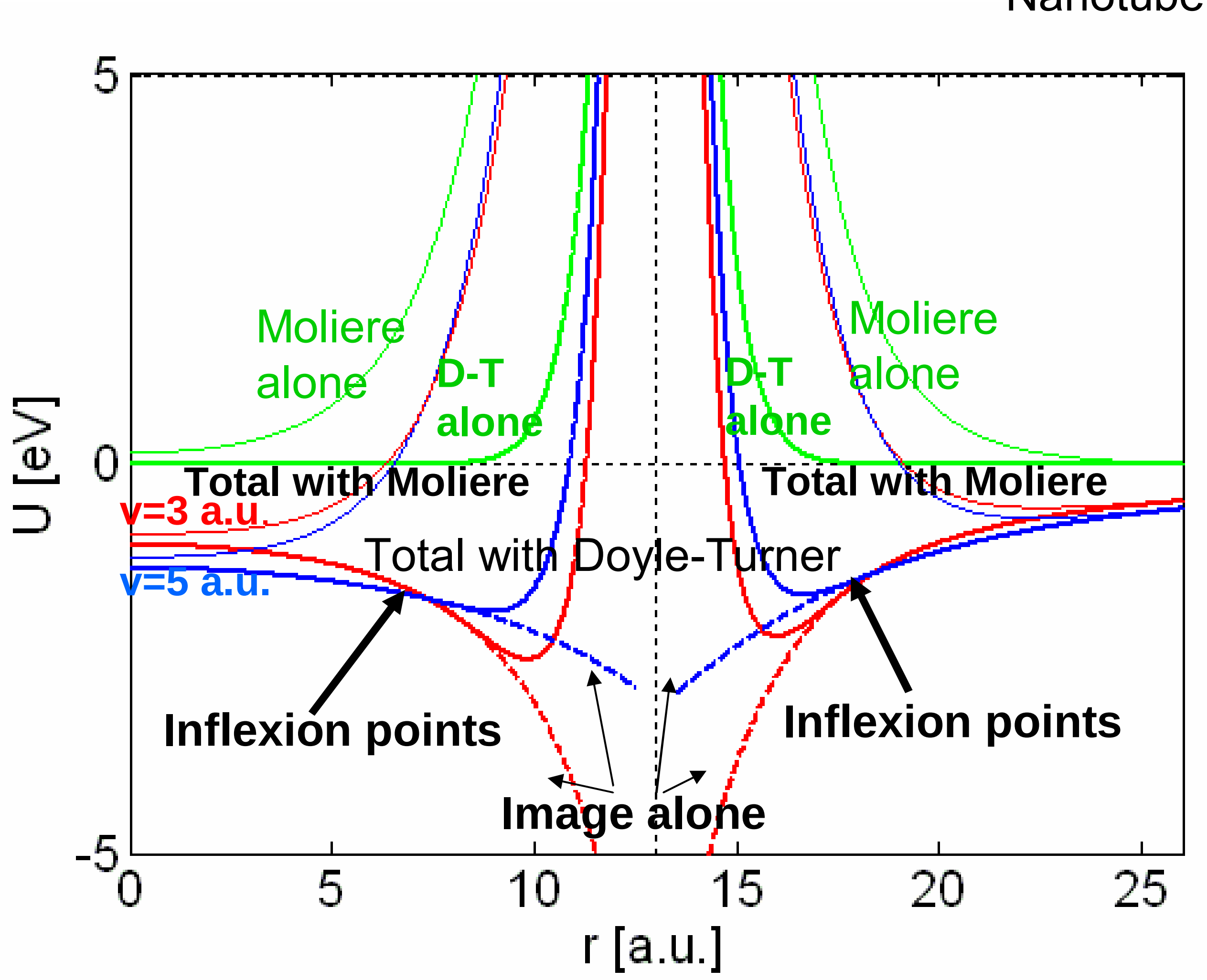
$$U_{im}(r) = \frac{Z_1^2}{\pi} \sum_{m=-\infty}^{\infty} \mathrm{P} \int_0^{\infty} dk\, I_m^2(kr_<) K_m^2(kr_>) \frac{4\pi n_0 R(k^2 + m^2/R^2)}{(kv)^2 - \omega_m^2(k)}$$

$$\omega_m^2(k) = (k^2 + m^2/R^2)\left[v_s^2 + 4\pi n_0 R\, I_m(kR) K_m(kR)\right], \quad r_< = \min(r, R),\; r_> = \max(r, R)$$

$$U_{DT}(r) = 4\pi n_0 R Z_1 Z_2 \sum_{j=1}^{4} a_j b_j^2\, I_0(2b_j^2 Rr) \exp\left[-b_j^2\left(r^2 + R^2\right)\right]$$

Comparison of Doyle-Turner and Moliere potentials for proton moving parallel to SWNT(11,9) at v = 3 and 5 a.u.

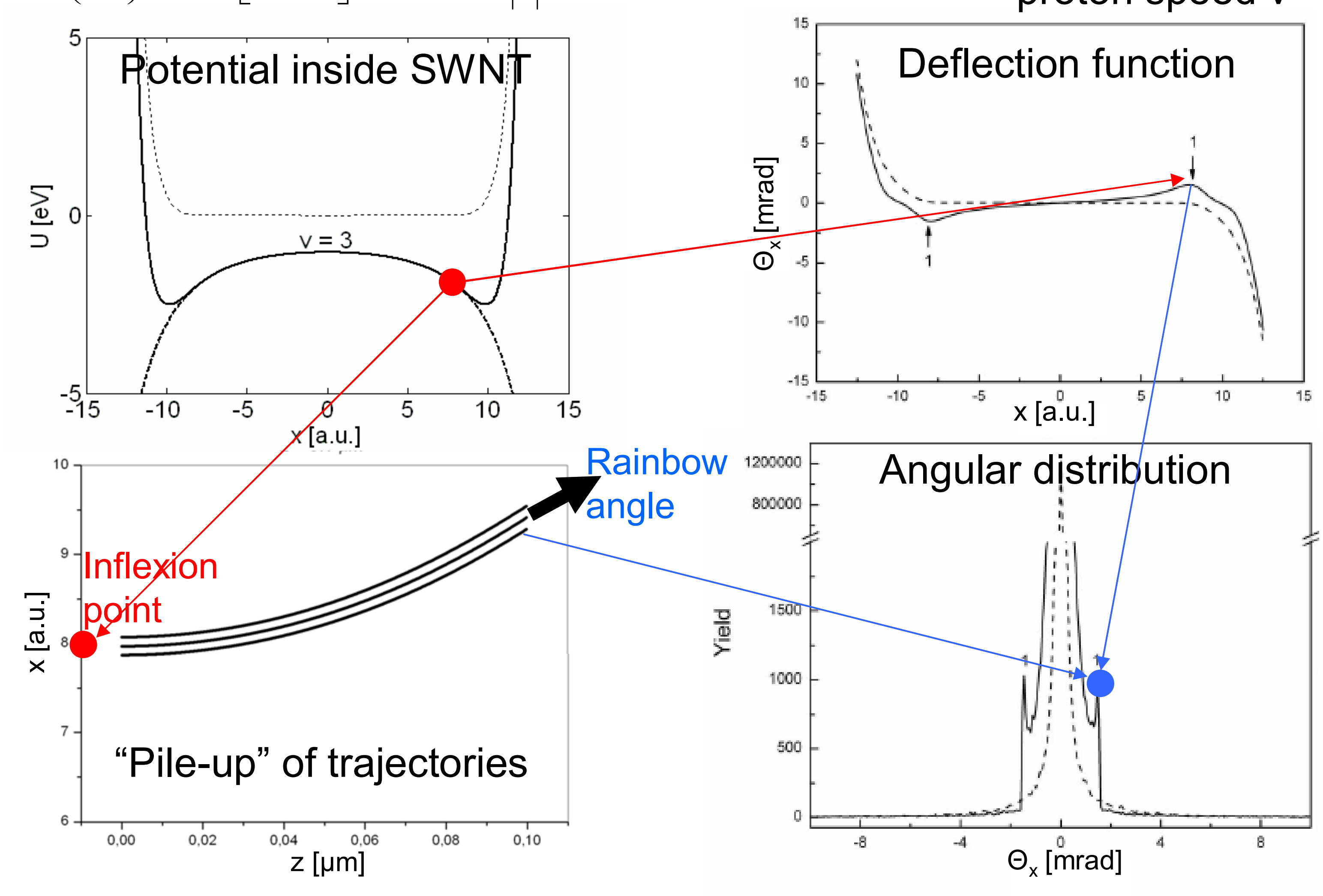
Nanotube radius ≈ 13 a.u.



Rainbow effect for proton channelling in short chiral SWNT(11,9) with image & Doyle-Turner potentials

$$J = \left(\frac{L}{2E}\right)^2 \frac{1}{2r}\frac{d}{dr}\left[\frac{dU(r)}{dr}\right]^2 = 0 \Rightarrow \sigma = \frac{1}{|J|} \to \infty$$

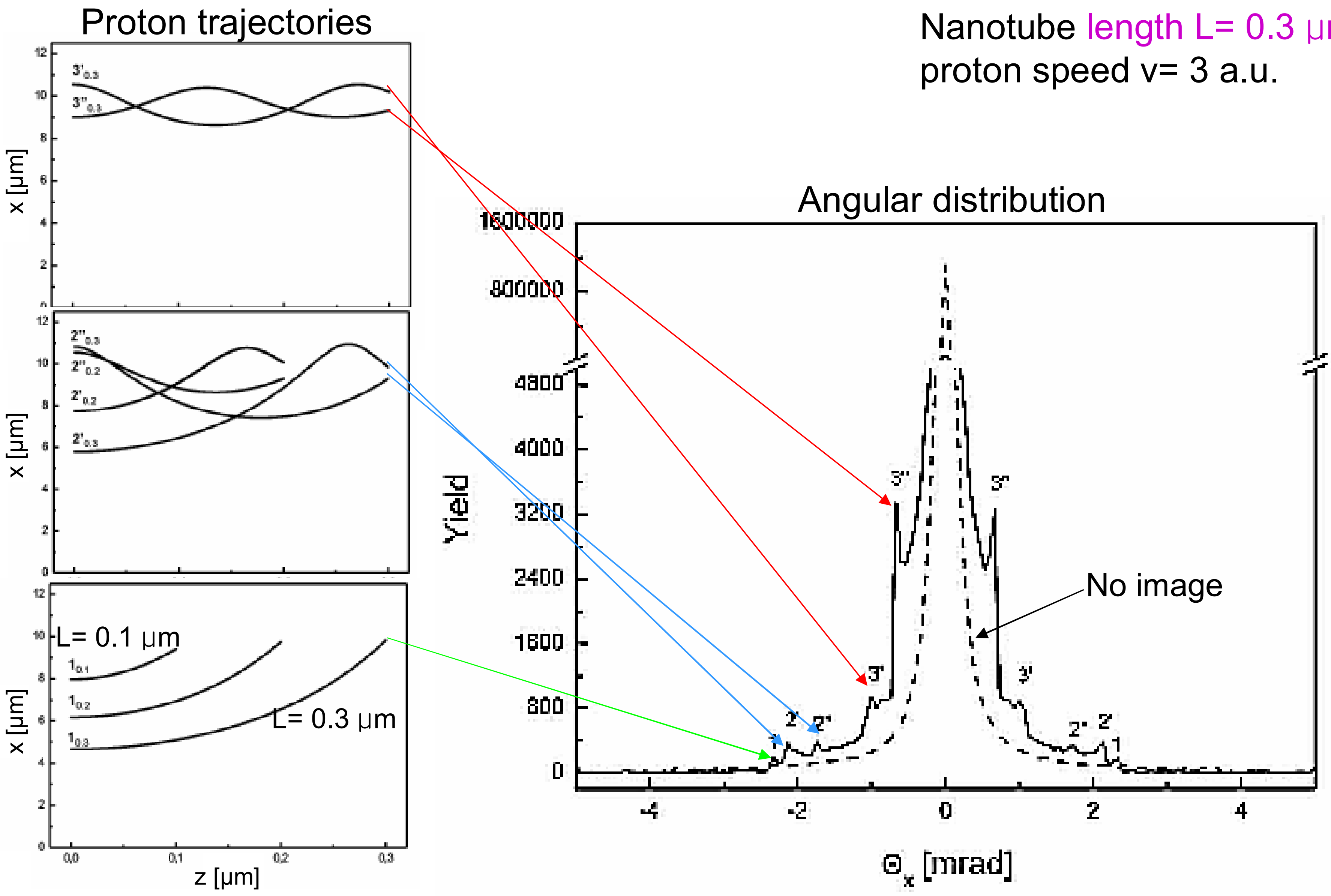
Nanotube length L= 0.1 μm
proton speed v = 3 a.u.



Formation of multiple rainbows in chiral SWNT(11,9)

D. Borka *et al., Phys. Rev.* A, in press (2006)

Nanotube length L= 0.3 µm
proton speed v= 3 a.u.



Proton channelling through a wider & longer chiral SWNT with image and Moliere potentials

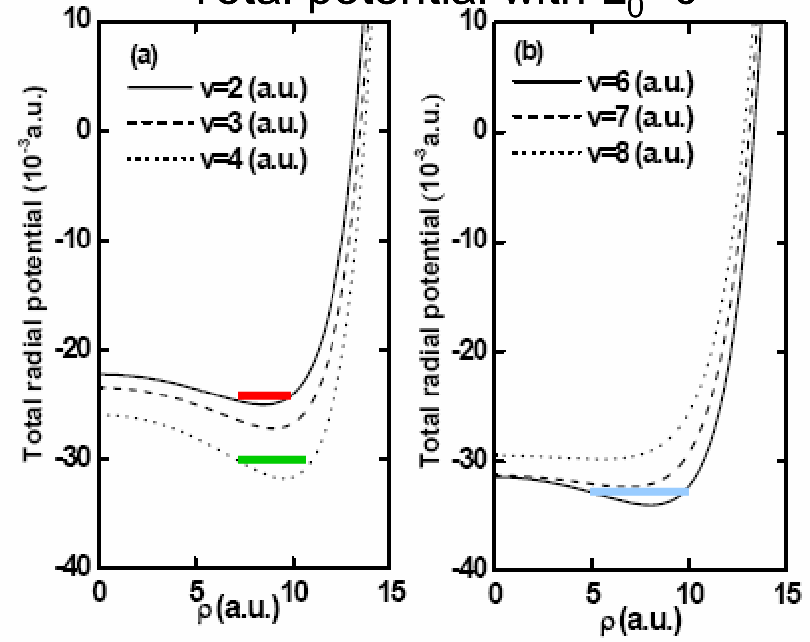
D.P. Zhou *et al.*, *Phys. Rev.* A 72 (2005) 23202

Nanotube radius =20 a.u.

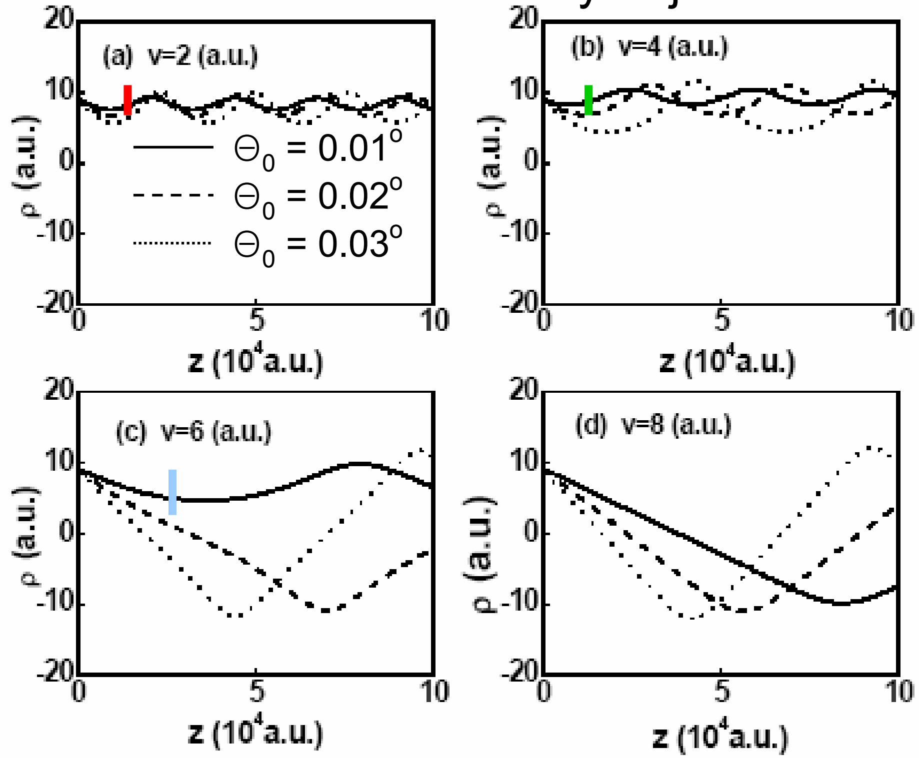
$$M\ddot{\rho} = F_\rho^{(n)} + F_\rho^{(p)} + \frac{L_0^2}{M\rho^3}, \qquad M\ddot{z} = F_z^{(p)}, \qquad M\rho^2\dot{\phi} = L_0,$$

Moliere & image forces, stopping force; angular momentum

Total potential with L_0=0



Two kinds of oscillatory trajectories

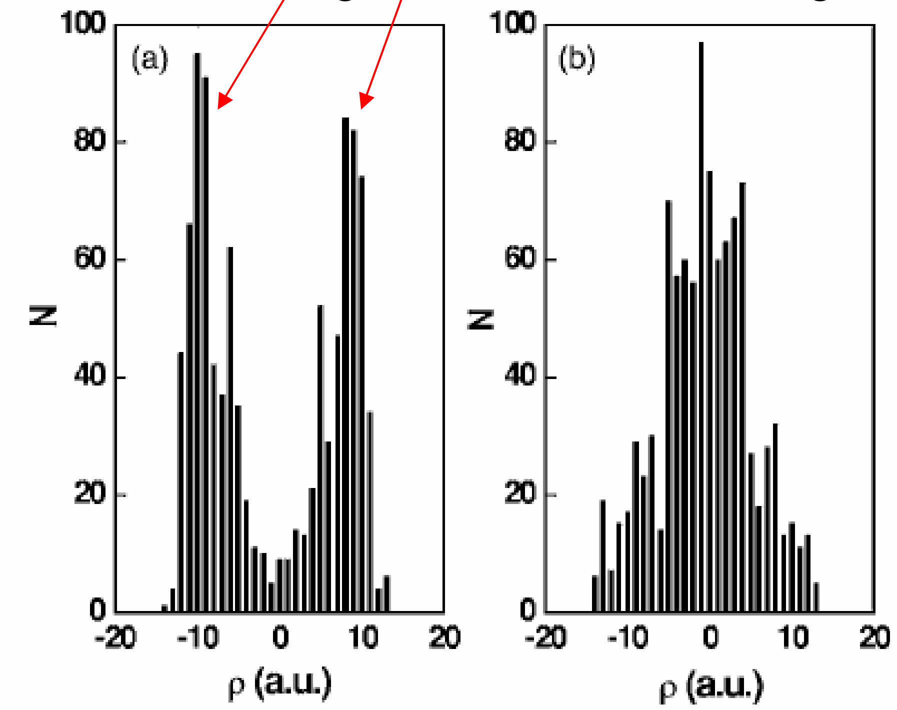


Creation of hollow nano-beam of protons after channelling through a SWNT due to image force

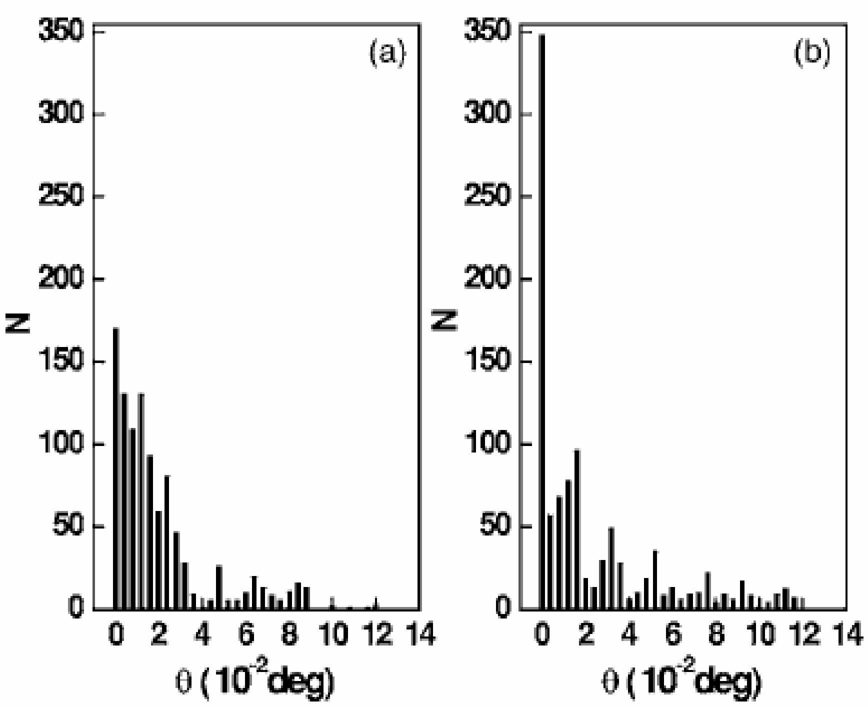
D.P. Zhou *et al.*, *Phys. Rev.* A 72 (2005) 23202

Proton speed = 4 a.u., NT radius = 20 a.u., NT length = 10^5 a.u.

Radial distributions of ion flux after channelling with and without image



Angular distributions after channelling with and without image interaction



Coulomb explosions during H_2^+ channelling in SWNT

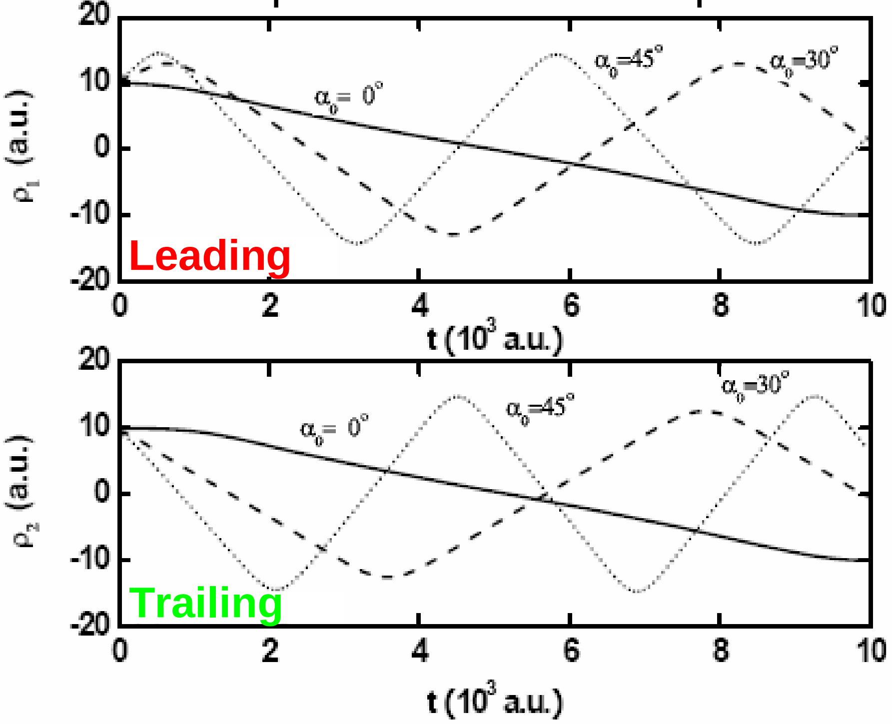
D.P. Zhou *et al., Phys. Rev.* A *73* (2006) 33202

Solve classical equations of motion: $\frac{d\mathbf{r}_i}{dt} = \mathbf{u}_i, \quad M_i \frac{d\mathbf{u}_i}{dt} = \sum_{j(\neq i)=1}^{2} \mathbf{F}_{ij}^{(c)} + \sum_{j=1}^{2} \mathbf{F}_{ij}^{(p)} + \mathbf{F}_i^{(n)}$

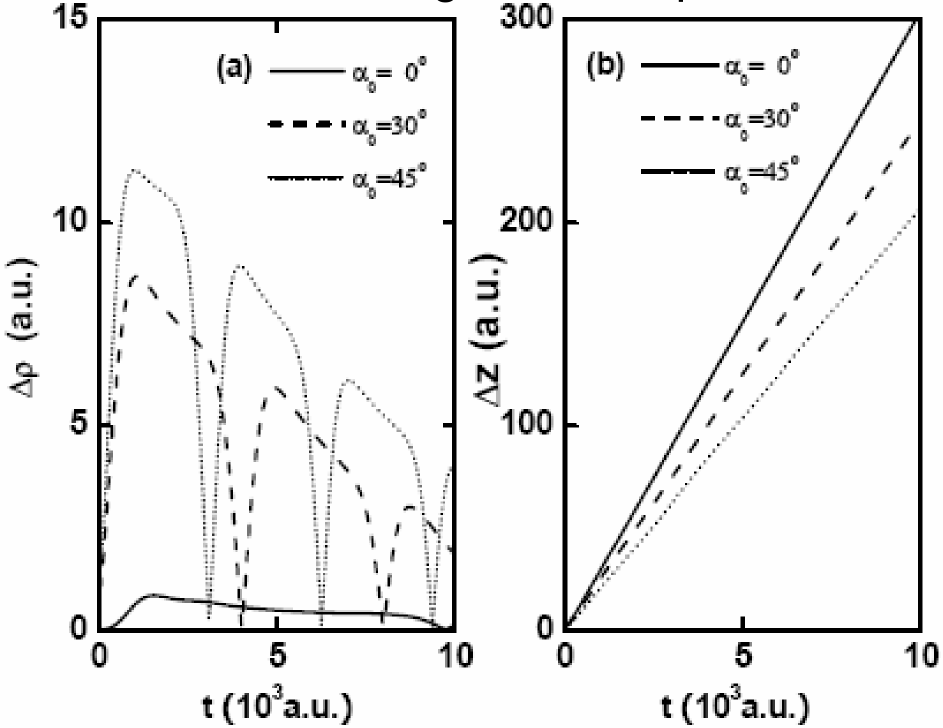
Molecule speed = 5 a.u. and
alignment angles = 0°, 30°, 45°

Forces: Coulomb, polarization, Moliere

Radial positions of the two protons



Radial and longitudinal separations



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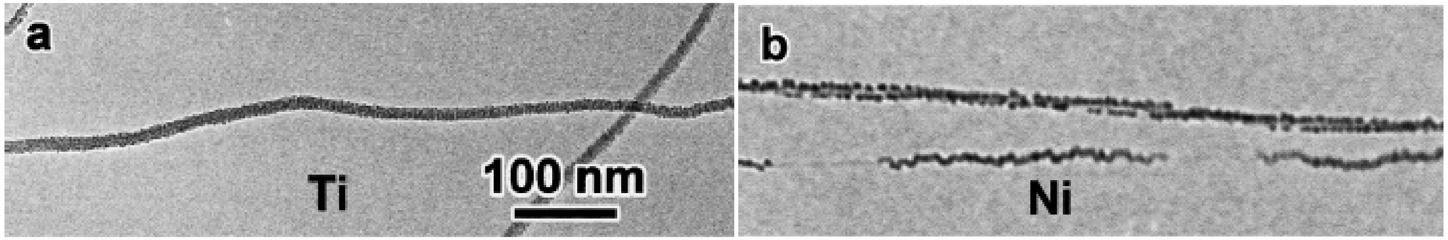
Dynamic polarization of SWNT coated by metal

D.J. Mowbray *et al., Phys. Rev.* B (2006) submitted

TEM images of a=5 nm SWNT: Y. Zhang *et al., Chem. Phys. Lett.* 331 (2000) 35



Stopping power in SWNT with a=7Å

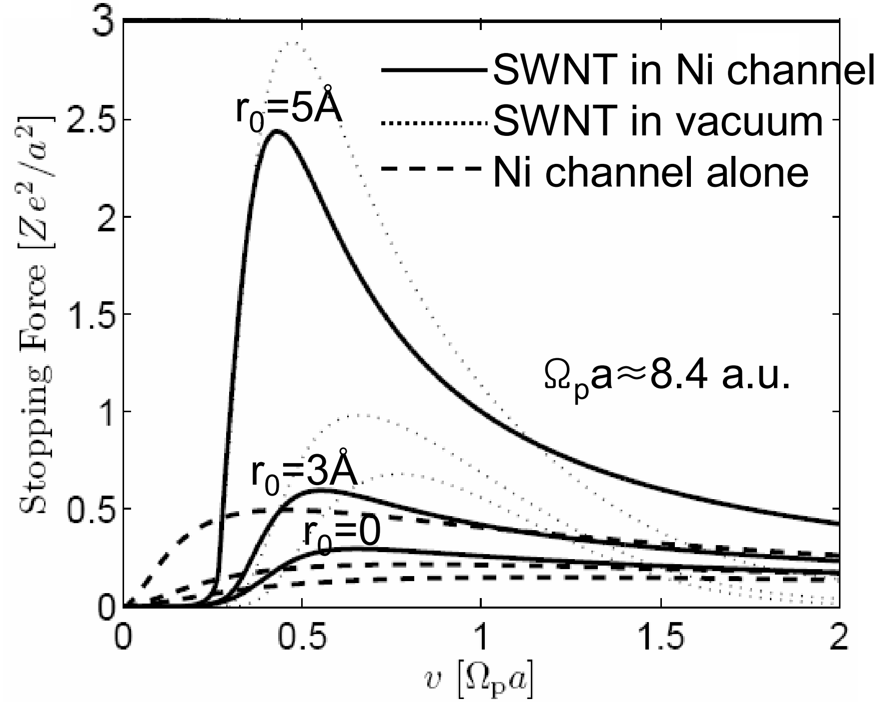
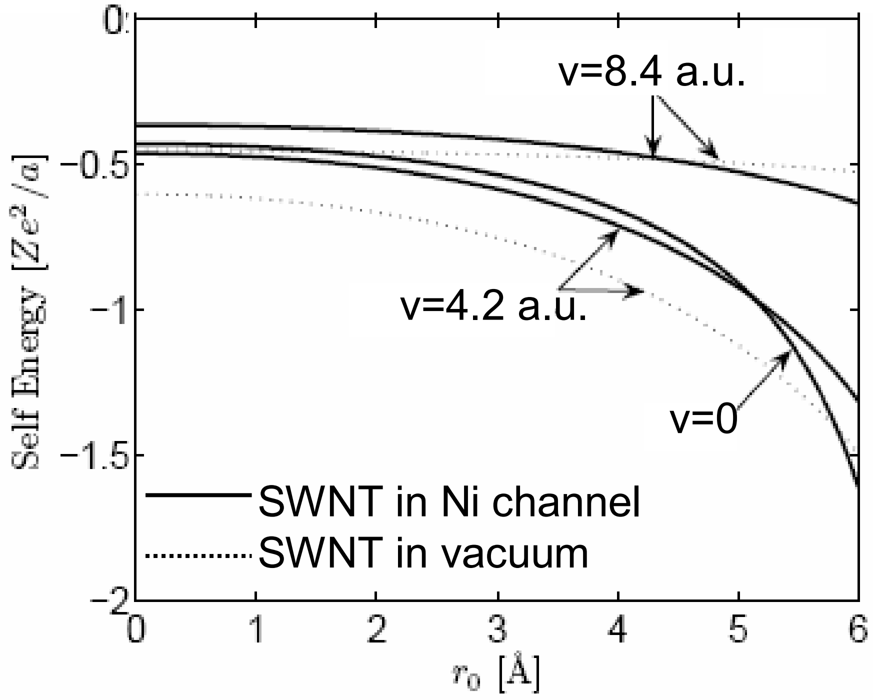


Image potential in SWNT with a=7Å

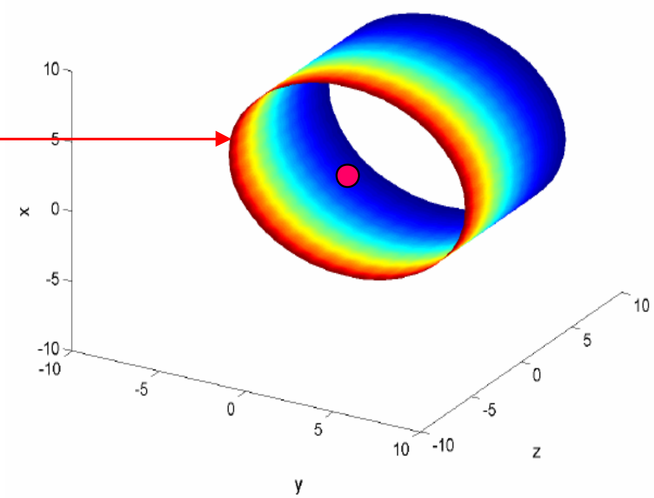


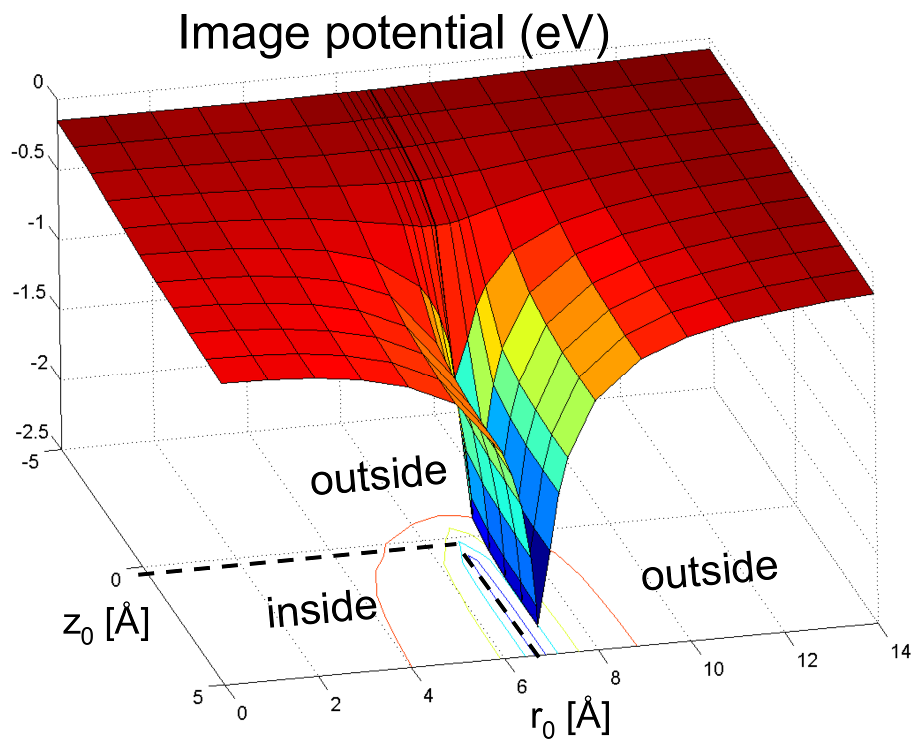
Static image interaction near an open end of a SWNT

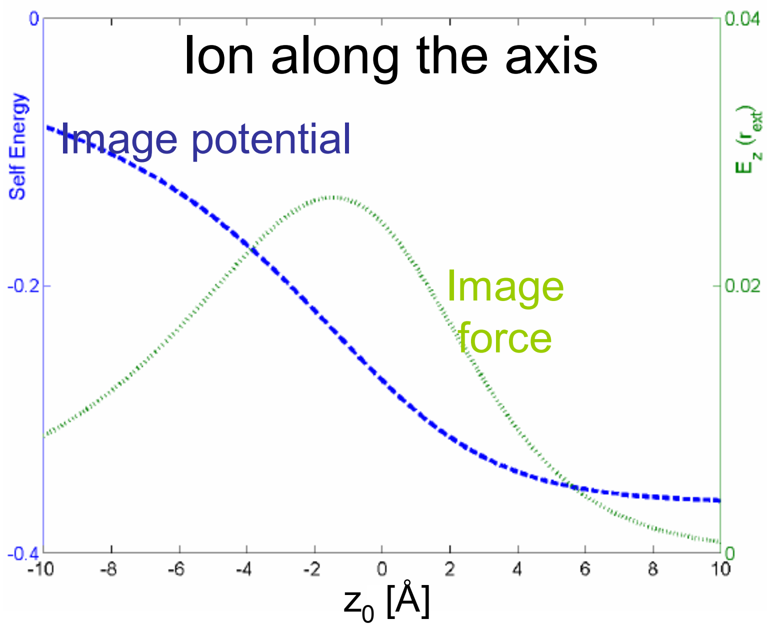
K. Whyte and Z.L. Miskovic, in preparation

Solve integral equation for induced electron density ***n***

$$\frac{\alpha}{n_0} n(\mathbf{r}) + \iint \frac{n(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} \mathrm{d}^2\mathbf{r}' = \Phi_{ext}(\mathbf{r})$$



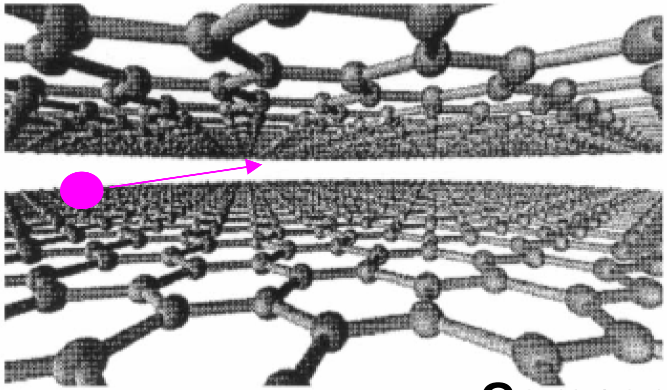




Planar channeling in Highly Oriented Pyrolytic Graphite

J. Zuloaga *et al.*, ICACS 2006, to be published

Graphene planes in HOPG

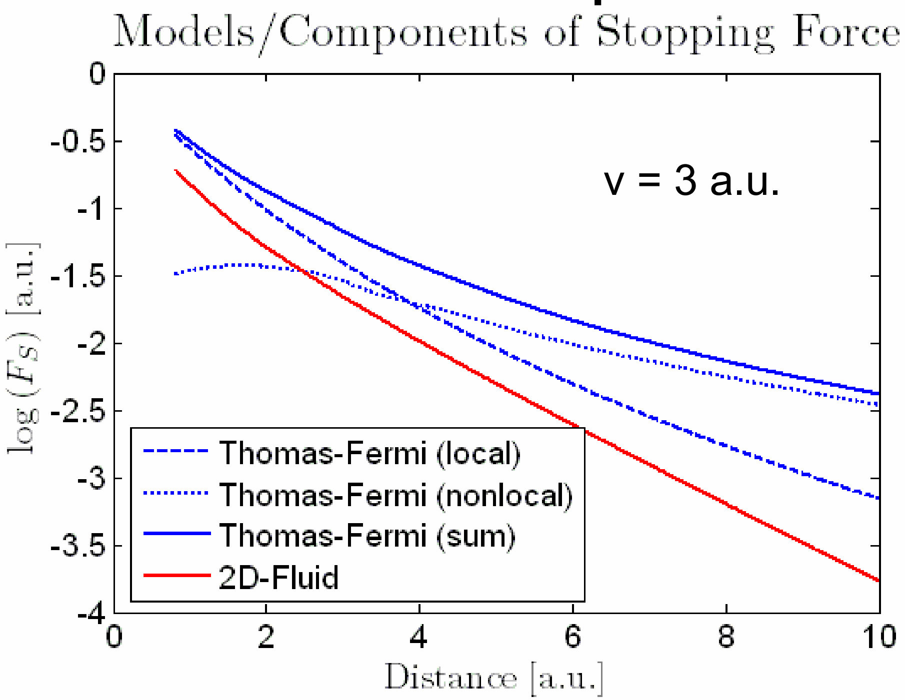


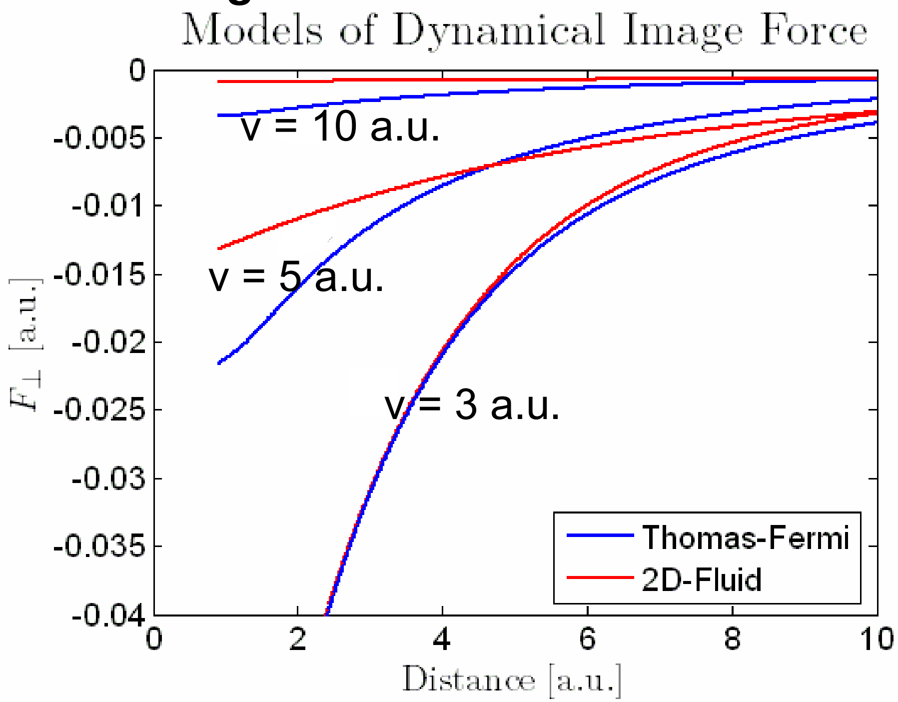
For **single** graphene sheet, calculate stopping power and image force using Kitagawa's dielectric function:

$$\epsilon^{-1}(\mathbf{r}_1, \mathbf{r}_2, \omega) \cong \frac{\omega^2}{\omega^2 - \omega_p^2(\mathbf{r}_1)} \left[\delta(\mathbf{r}_1 - \mathbf{r}_2) - \frac{1}{\omega^2 - \omega_p^2(\mathbf{r}_2)} \frac{(\mathbf{r}_2 - \mathbf{r}_1)}{|\mathbf{r}_2 - \mathbf{r}_1|^3} \cdot \vec{\nabla} n(\mathbf{r}_1) \right]$$

(High-frequency approx. ≈ Local + Non-local terms)

Compare 3D and 2D electron-gas models





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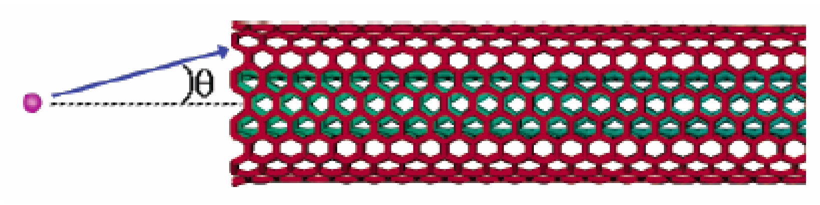
Molecular Dynamics (MD) simulations of ion irradiation effects on carbon nanotubes

- ❑ Atomistic simulations, solving Newton's equations
- ❑ Low impact energies, nuclear stopping dominates
- ❑ Empirical potentials (Tersoff/Brenner, van der Waals, and ZBL or Lennard-Jones), truncation issues, no charging
- ❑ Ab-initio (DFT) potentials, limited number of C atoms
- ❑ Dynamic structure evolution, but limited simulated time
- ❑ Finite length of nanotubes (~ 10 nm), energy dissipation
- ❑ Simulate temperature effects (annealing of defects)
- ❑ Simulate chemical reactions and mechanical response

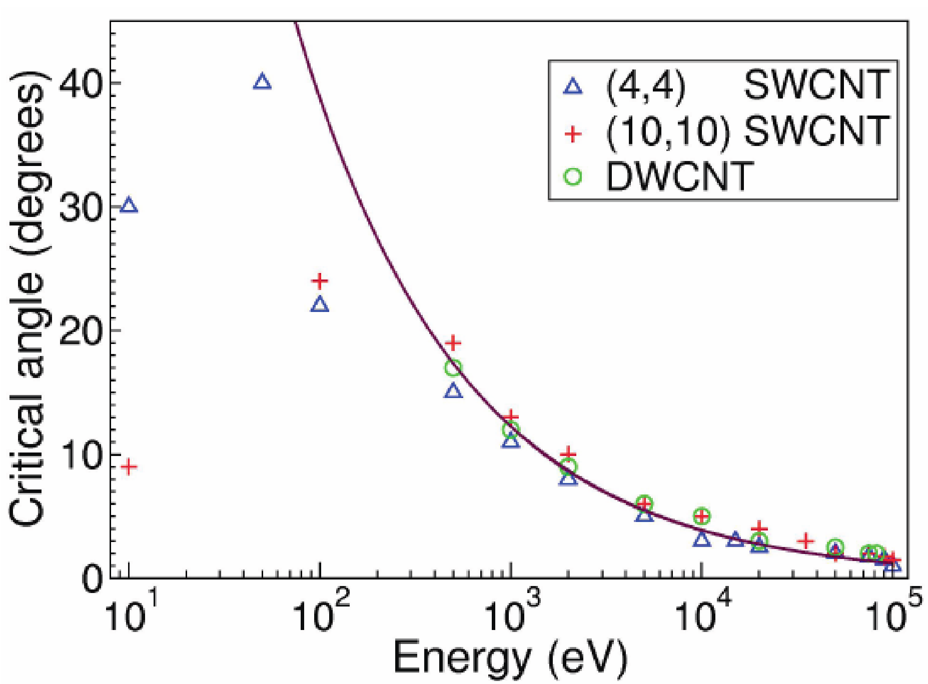
MD sim. of channelling of C^+ ions in SWNT & DWNT

C.S. Moura and L. Amaral, *J. Phys. Chem.* B 109 (2005) 13515

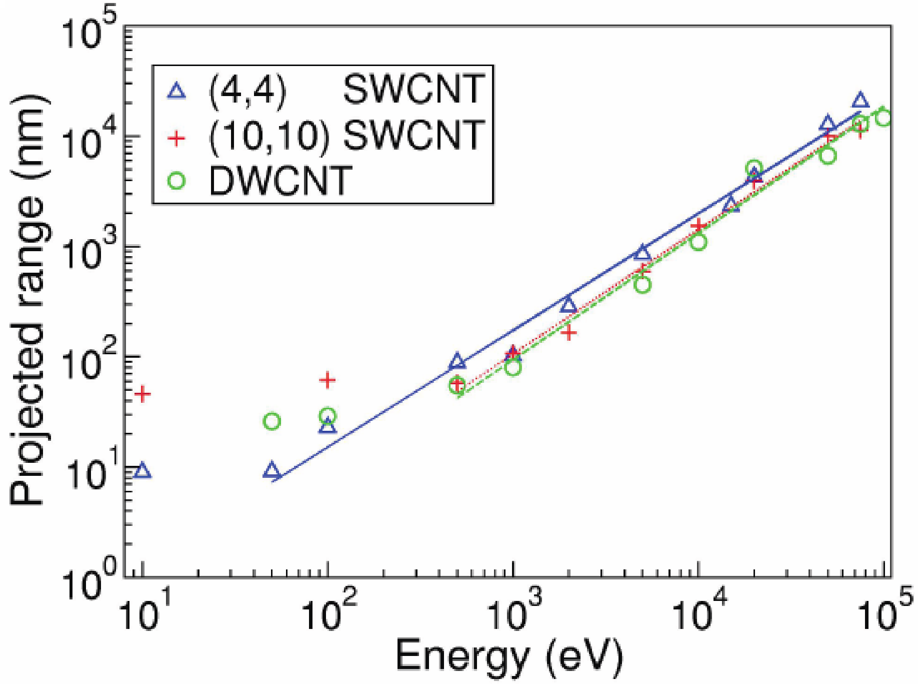


Tersoff potential for C-C in the walls
ZBL potential for projectile - target

Critical angle vs incident energy

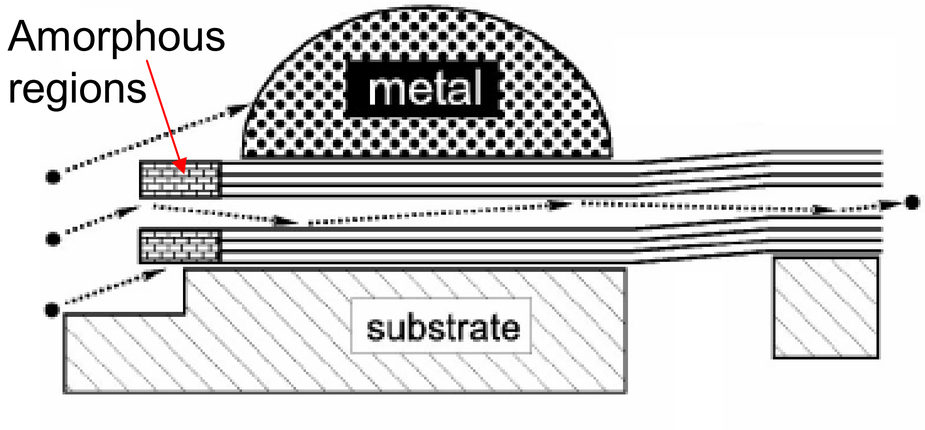


Range vs incident energy



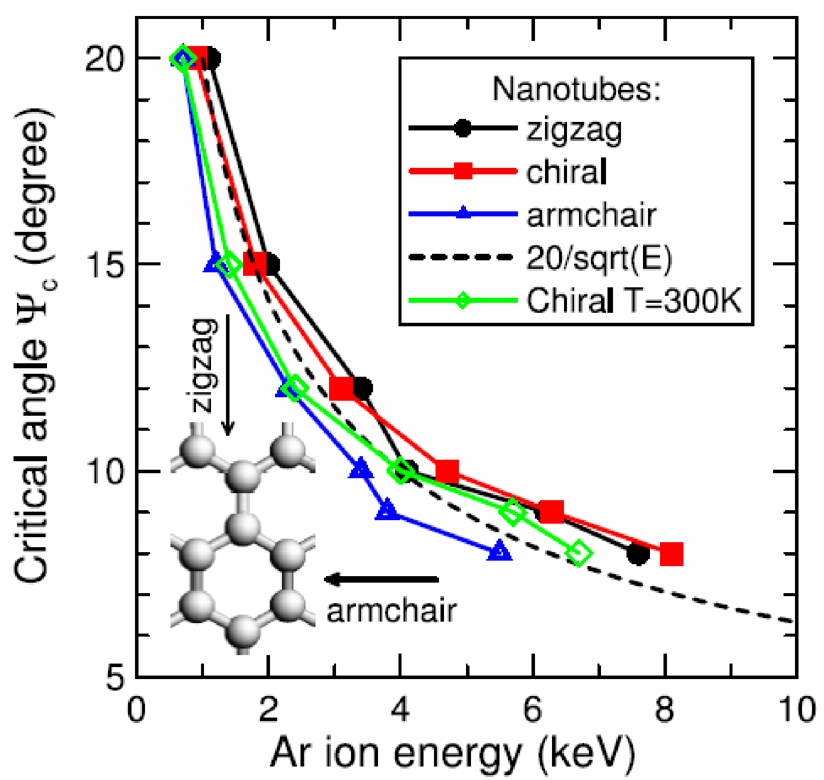
MD sim. of channelling of keV Ar^+ ions in MWNT

A.V. Krasheninnikov and K. Nordlund., *Phys. Rev.* B 71 (2005) 245408



Critical angle for channelling agrees with continuum model

$$\psi_c = \sqrt{U(r_c)/E}$$



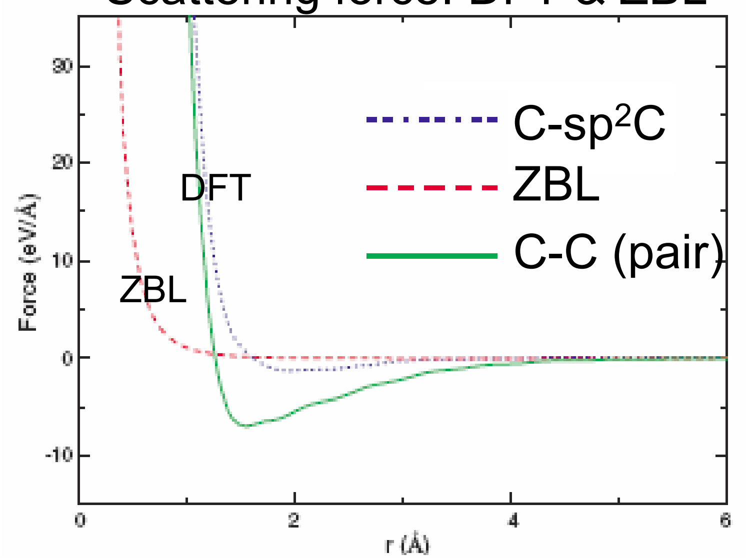
Conclusions:

- channelling dominated by nuclear energy loss (50-100 eV per collision)
- channelling possible even at low energies and large angles (~ 10^o)
- less effective between walls of MWNT
- temperature effects weak
- amorphization of entrance opening for high ion beam doses may be problem but central hollow remains open

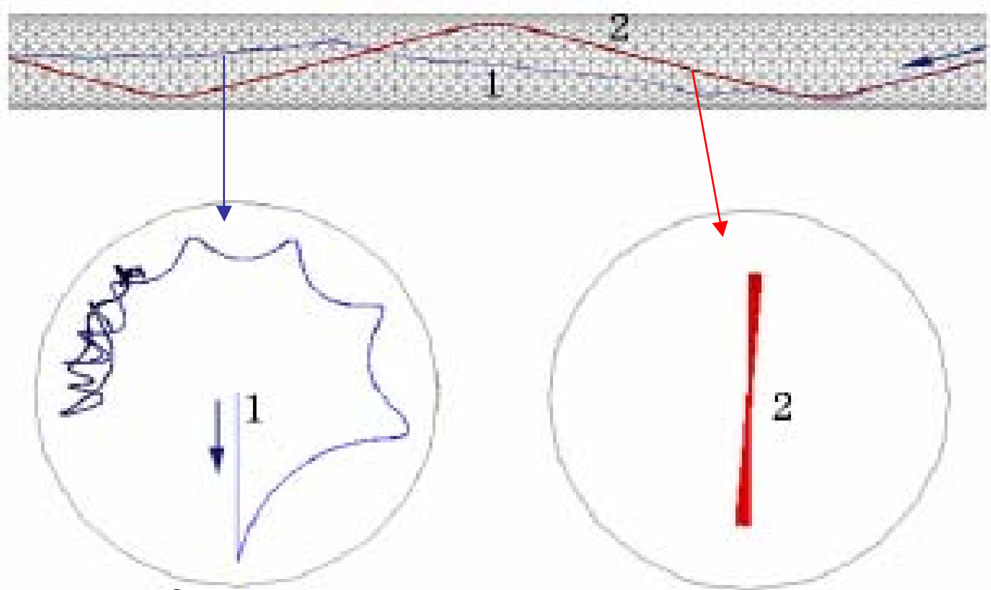
MD sim. of channelling of ~100eV C^+ ions in SWNT

W. Zhang *et al.*, *Nanotechnology* 16 (2005) 2681

Scattering force: DFT & ZBL

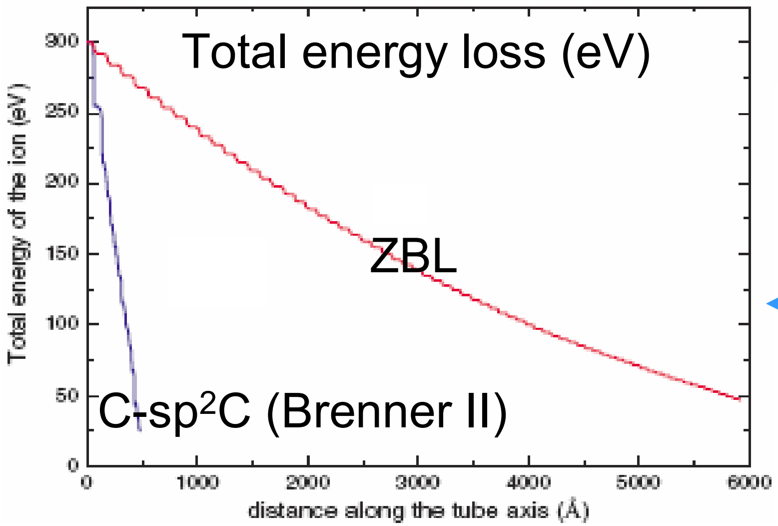


Trajectories for: 1) C-sp²C, 2) ZBL



C-sp²C at 100 eV

ZBL at 100 eV



Electronic energy loss modeled by:
- modified Firsov
- Brandt-Kitagawa

ZBL at 300 eV

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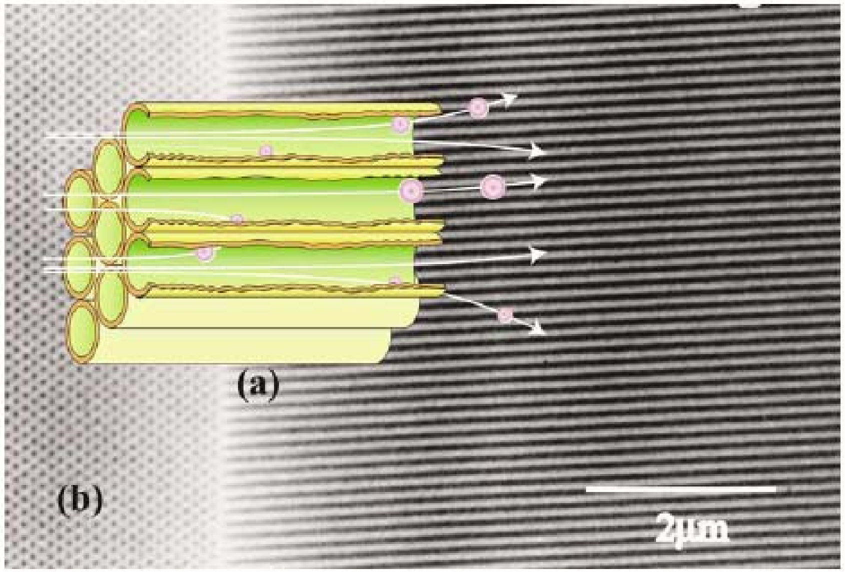
- ❑ **Outlook**

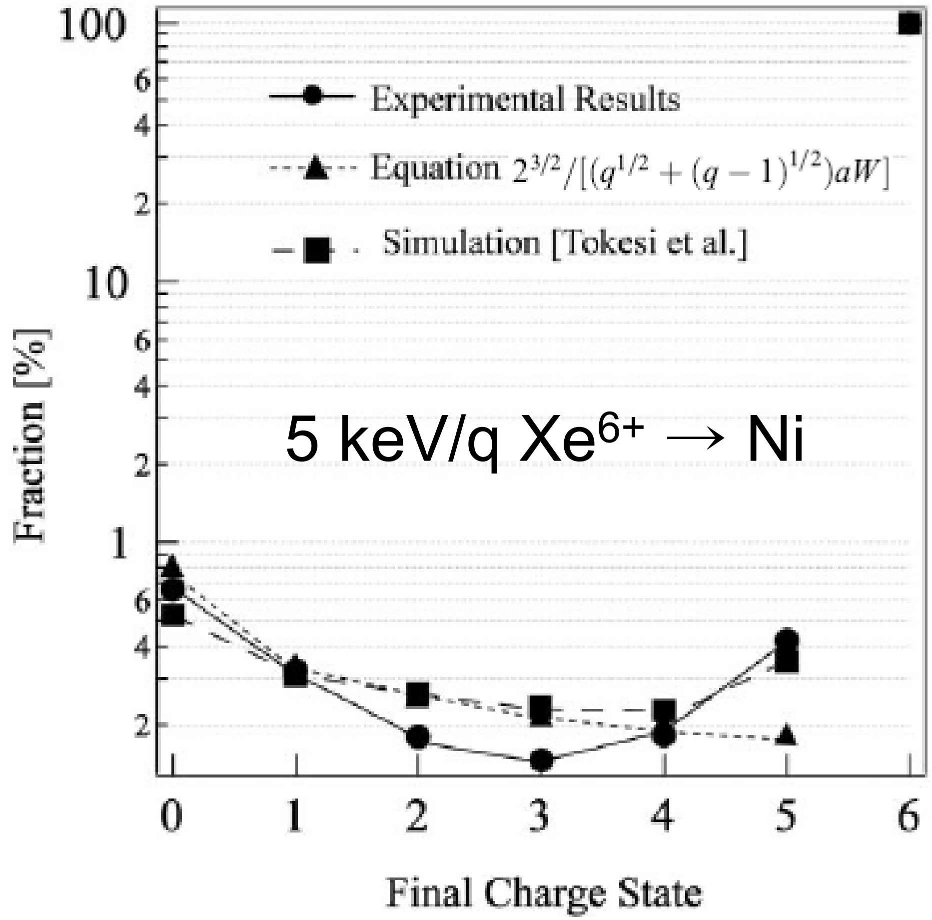
Transmission of highly-charged ions through arrays of metallic capillaries with diamater ~ 100 nm

experiment: Y. Yamazaki, *Nucl. Instr. Meth*. 193 (2002) 516

Schematics of experiment
& SEM image of the array



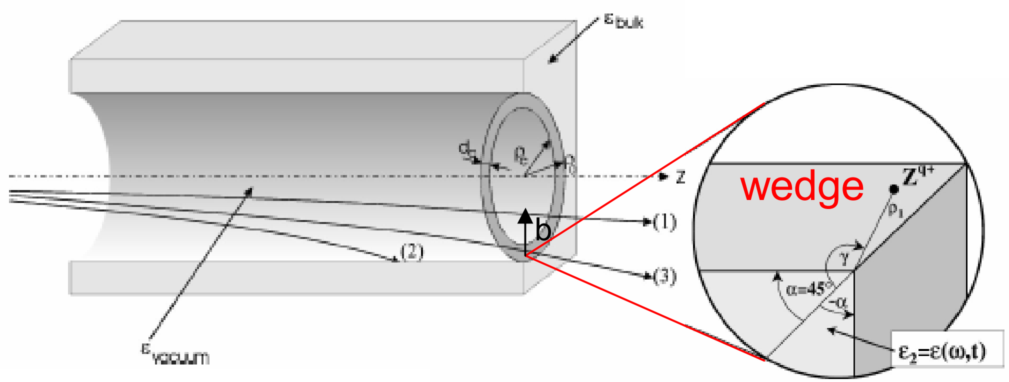
Charge distribution of transmitted ions



Transmission of highly-charged ions through arrays of metallic capillaries with diamater ~ 100 nm

theory: K. Tókési *et al., Phys. Rev*. A 64 (2001) 42902

Use dielectric theory for nano-capillaries to model dynamical image interaction by N.R. Arista, *Phys. Rev*. A 64 (2001) 32901



Distributions of 2 keV N^{6+} →Ni vs closest dist. b and scattering angle

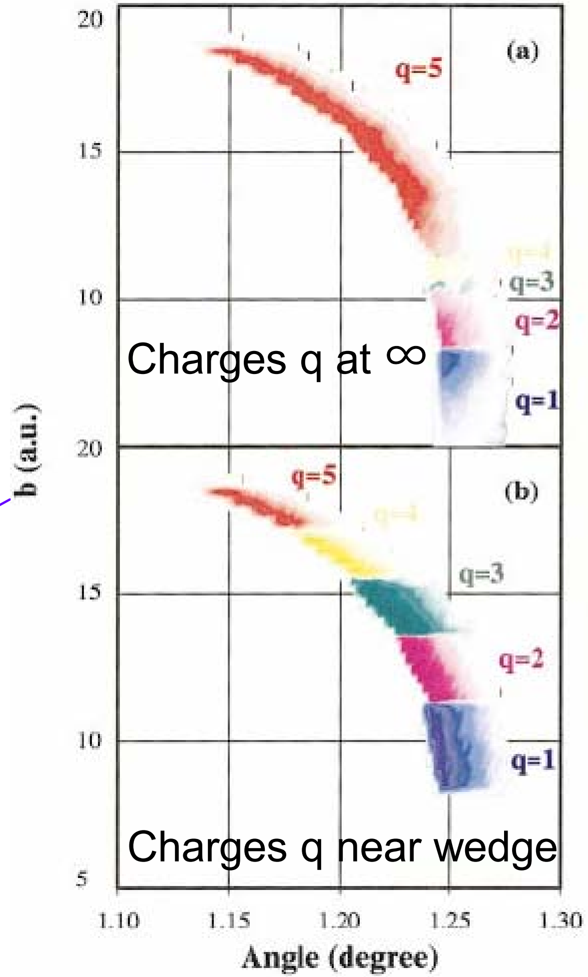
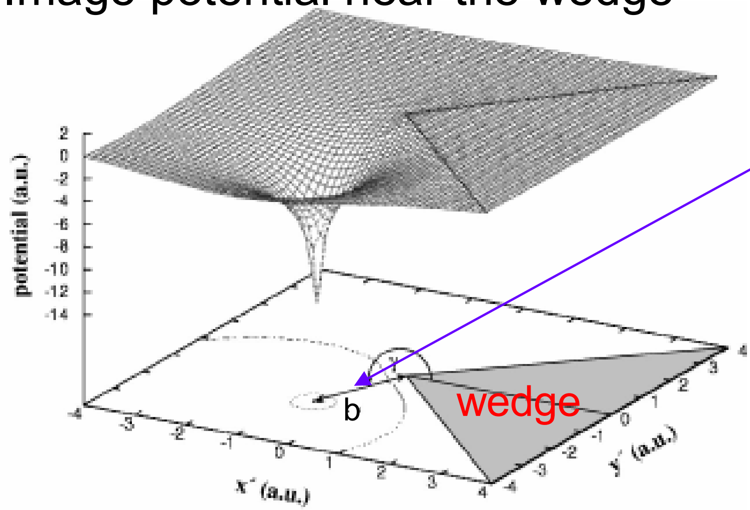
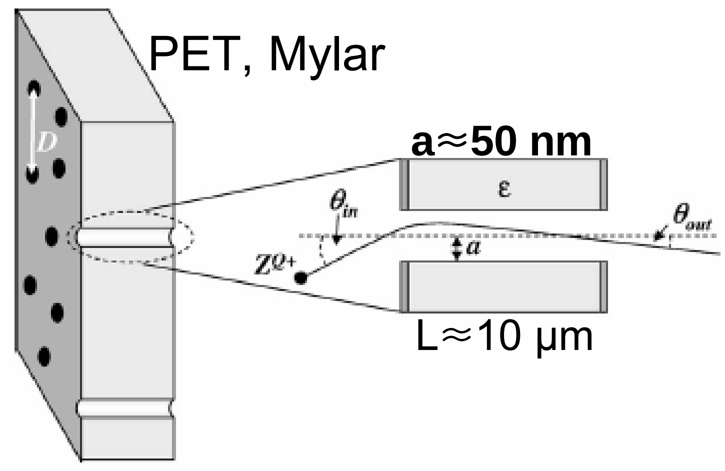


Image potential near the wedge

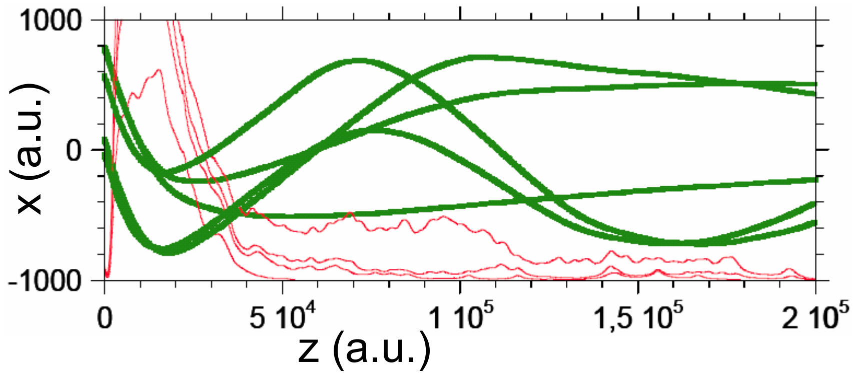


Guiding keV Ne^{7+} ions through insulating capillaries

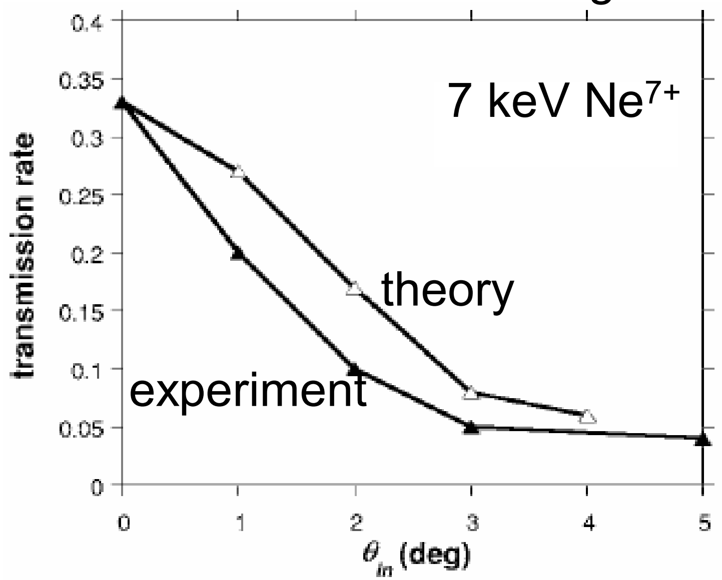
experiment: Gy. Vikor *et al., Nucl. Instr. Meth*. B 233 (2005) 632;
theory: K. Schiessl *et al., Phys. Rev.* A 72 (2005) 62902



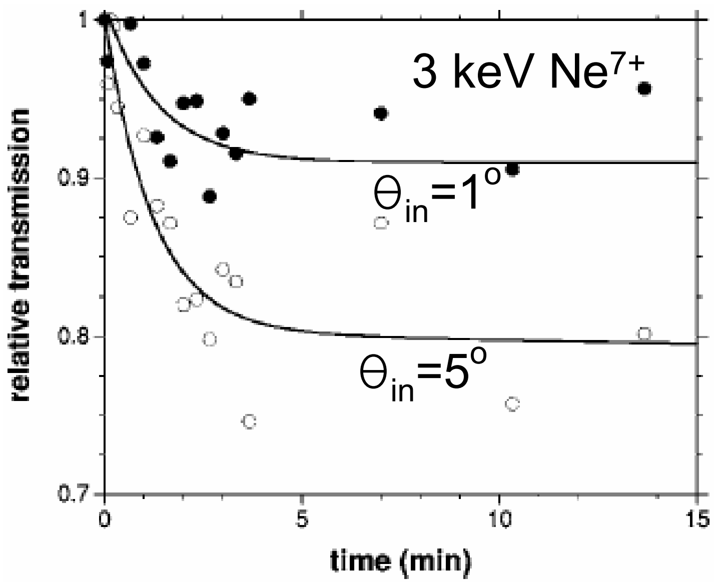
Ion trajectories & deposited charge density



Transmission vs angle



Time dependence of transmission



Outlook

- Simulations of ion channelling through carbon nanotubes predict great advantages in comparison with single crystals & offer new applications
- Theoretical modeling of ion interactions with nanotubes needs improvements at all energies: ab-initio potentials, dynamic response, energy loss, projectile charge states, entrance effects, defects in nanotube structure, …
- Experimental realization of ion channelling still pending, but all major technical issues seem manageable (ongoing activity at INFN-LNF & IHEP)
- Exciting new developments expected in near future for particle channeling through carbon nanotubes, following recent success of ion transport through nano-capillaries