Geant4 11.2.p01

Physics III:
Decay and Low Energy Processes

Dennis Wright

Geant4 Tutorial at Jefferson Lab

26 March 2024

Outline

- Particle decays
  - decay channels and tables
  - special decays
- Optical photon interactions
- Phonons and electron/hole propagation
  - Lattices
- Crystal channeling

Particle Decays

- For all unstable, long-lived particles
  - not used for radioisotopes (G4RadioactiveDecay)
- Decay can happen in flight or at rest
  - decay process is discrete + at-rest (G4VRestDiscreteProcess)

- Different from other physical processes
  - mean free path (λ) for most processes: $1/\lambda = \Sigma = N\rho\sigma/A$
  - for decay in flight (mean free path): $\lambda = \gamma\beta c\tau$
  - for decay at rest (mean life time): $\lambda \rightarrow \tau$
  - at rest processes like decay and capture compete in time

- Same process used for all eligible particles
  - retrieves branching ratios and decay modes from decay table stored for each particle type

Particle Decay Modes Available

- Phase space
  - two-body: $\pi^0 \rightarrow \gamma\gamma$ (~98.8%)
  - three-body: $K^0_L \rightarrow \pi^0 \pi^+ \pi^-$
- Dalitz
  - $\pi^0 \rightarrow l^+ l^- \gamma$
- Muon and tau decay
  - $\mu^- \rightarrow e^- \overline{\nu_e} \nu_\mu$
  - no radiative corrections , mono-energetic neutrinos
- Semi-leptonic K decay
  - $K \rightarrow \pi\, l\, \nu$

Defining Decay Channels

- Geant4 provides decay modes for long-lived particles
  - user can re-define decay channels if necessary

- But decay modes for short-lived (e.g. heavy flavor) particles not provided by Geant4
  - user must "pre-assign" to particle
    - proper lifetime
    - decay modes
    - decay products
  - process can invoke decay handler from external generator
    - must use G4ExtDecayer interface

- Take care that the pre-assigned decays from generators do not overlap with those defined by Geant4 (e.g. K^0_S , τ)

Specialized Particle Decays

- G4DecayWithSpin
  - produces Michel electron/positron spectrum with first order radiative corrections
  - initial muon spin is required
  - propagates spin in magnetic field (precession) over remainder of muon lifetime

- G4UnknownDecay
  - only for not-yet-discovered particles (SUSY, etc.)
  - discrete process – only in-flight decays allowed
  - pre-assigned decay channels must be supplied by user or generator

Optical Processes

- Propagation of optical photons and their interaction with materials is treated separately from regular electromagnetic processes. Why?
  - wavelengths are much larger than atomic spacing
  - they are treated (partially) as waves; no smooth transition to gammas
  - energy/momentum not generally conserved in G4 optics

- Optical photons produced directly by three processes
  - G4Cerenkov
  - G4Scintillation
  - G4TransitionRadiation

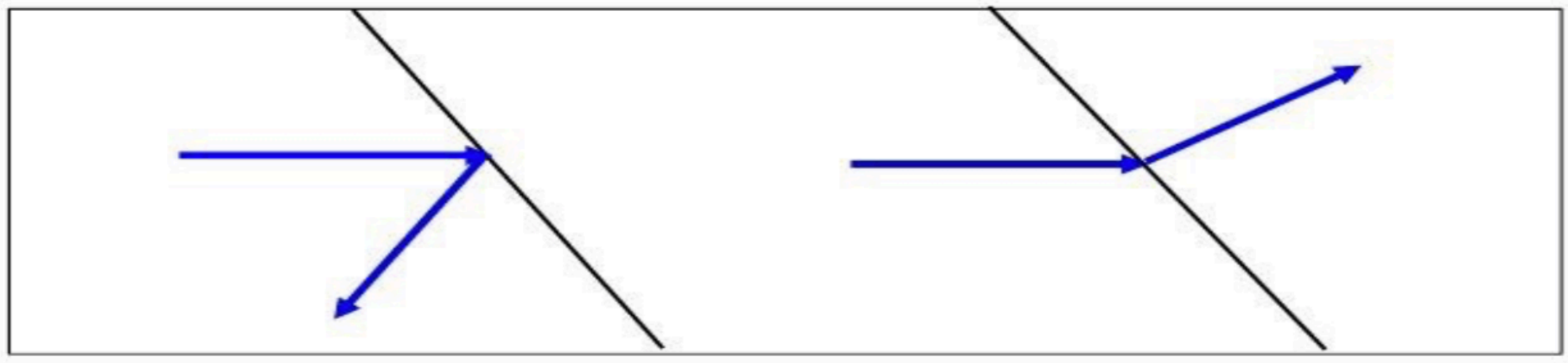
Optical Photon Transport

- Refraction and reflection at boundaries
- Wavelength shifting
- Bulk absorption
- Rayleigh scattering

- Geant4 keeps track of polarization
  - but not overall phase, so no interference
- Optical properties attached to G4Material (by user code)
  - reflectivity, transmission efficiency, dielectric constants, surface properties, including binned wavelength/energy dependences
- Photon spectrum attached to G4Material (by user code)
  - scintillation yield, time structure (fast, slow components)

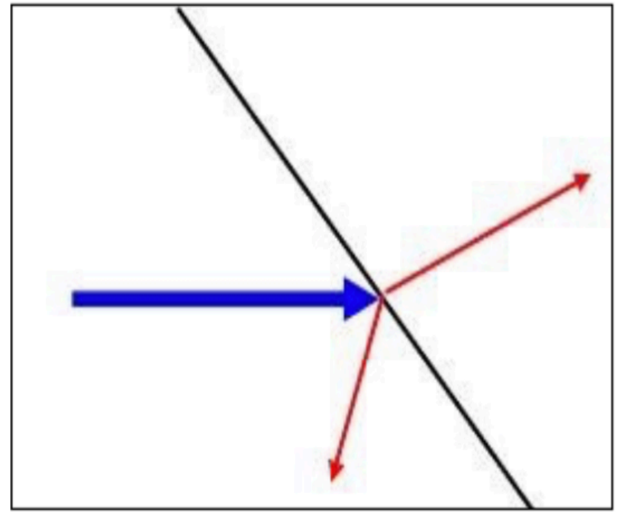
Optical Boundary Processes

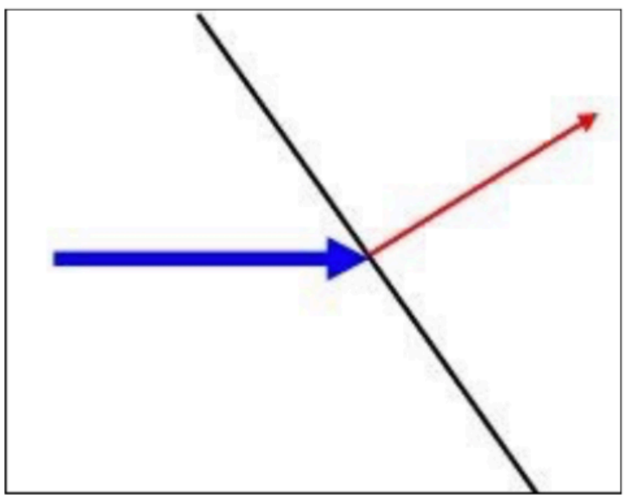
- G4OpBoundaryProcess
  - refraction
  - reflection
- User must supply surface properties using G4OpticalSurfaceModel
- Boundary properties
  - dielectric-dielectric
  - dielectric-metal
  - ...
- Surface properties
  - polished
  - ground
  - front- or back-painted
  - ...



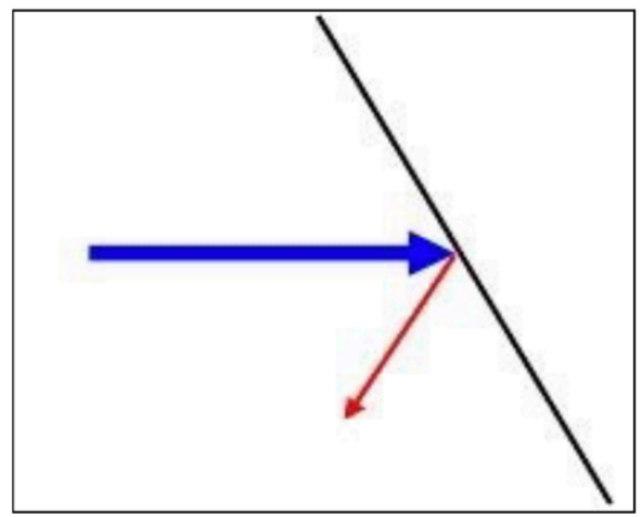
Reflection or Refraction

- Geant4 events support "particle-like" behavior – no "splitting" of tracks
- Each event has either a reflected or refracted photon, chosen randomly from user-input efficiencies



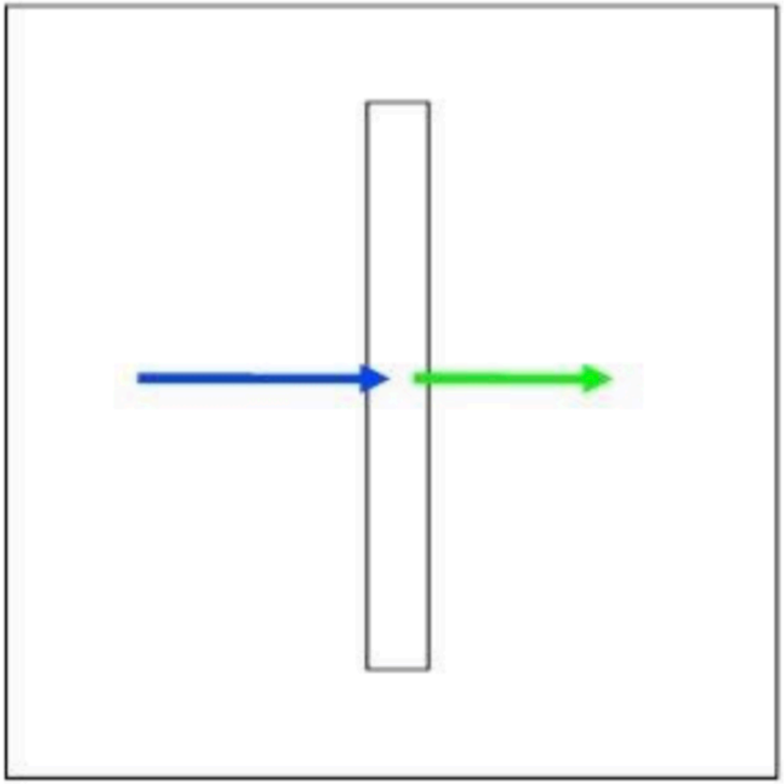


OR



Optical Processes: Wavelength Shifting

- Handled by G4OpWLS
  - initial photon is killed, one with new wavelength is created
  - gets mean free path from physics table
- User must supply:
  - absorption length as function of photon energy
  - emission spectra parameters as function of energy
  - time delay between absorption and re-emission



Optical Bulk Processes

- G4OpAbsorption
  - uses photon attenuation length from material properties to get mean free path
  - photon is simply killed after a selected path length

- G4OpRayleigh
  - elastic scattering including polarization of initial and final photons
  - builds its own physics table (for mean free path) using G4MaterialTable
  - may only be used for optical photons (a different process provided for gammas)

Solid State Physics Developments

- Tools to support some solid-state physics processes
  - phonon propagation and scattering
  - electron/hole production and drift
  - crystal channeling of charged particles

- A common feature for these processes is the need to define a “lattice structure” (numerical parameters) for a volume

- Some of these tools (phonon propagation) were released in Geant4 10. 1

Lattices

- Geant4 treats materials as uniform, amorphous collections of atoms. Steps may be of any length, in any direction and it is assumed that some atom will be at the location of the interaction
  - actual lattices are not constructed in Geant4

- G4LatticeLogical has been introduced as a container to hold parameters and look-up tables for use with the phonon handling processes

- There is a singleton, G4LatticeManager, which keeps track of lattices and how they are associated with materials and volumes

Phonons in Geant4

- See examples/extended/exoticphysics/phonon
- For cryogenic detectors in dark matter searches
  - Ge crystals at 40-60 mK
  - observation of dark matter candidates through recoil with Ge nucleus in lattice and subsequent phonon and electron/hole pair creation
  - transport must be modeled in cryogenic environment
- Processes developed so far support acoustic phonons, which are relevant for low temperature detectors
- Phonon is described by its wave vector k, frequency ω and polarization e. Three polarization states are recognized:
  - Longitudinal (L) (G4PhononLong)
  - Transverse "slow speed" (ST) (G4PhononTransSlow)
  - Transverse "fast speed" (FT) (G4PhononTransFast)

Phonon Interactions

- Currently no production process. Use G4ParticleGun to insert a phonon, which then propagates through volume

- Two phonon processes important in cryogenic crystals:
  - isotope scattering
  - anharmonic down-conversion

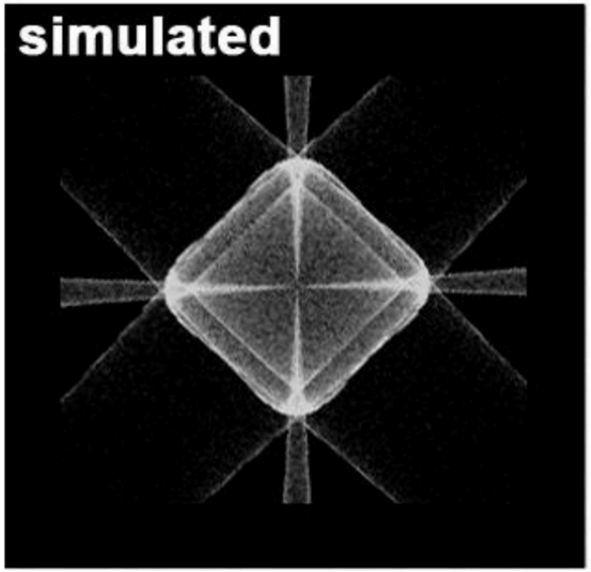
- G4PhononScattering: elastic scattering of phonon from isotopic impurities or lattice defects, during which the phonon momentum vector is randomized and the polarization state can change freely between the L, ST and FT states

- G4PhononDownConversion: a single longitudinal phonon can split into two (L + T) or (T + T) phonons with reduced energy. Energy conserved, but not momentum (exchanged with crystal)

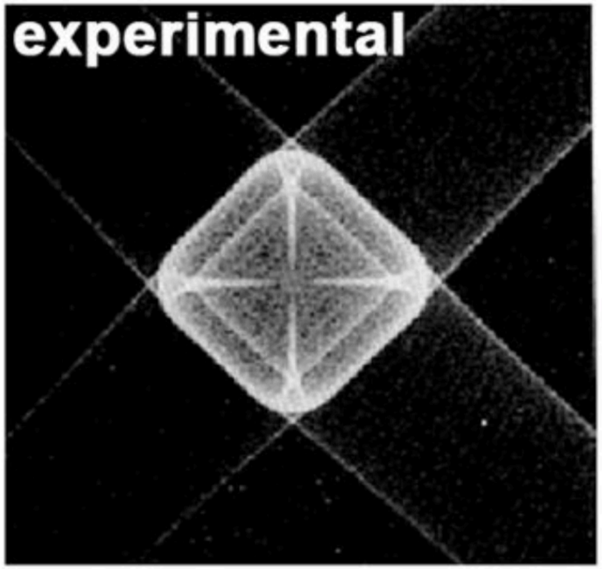
Phonon Caustics in Germanium

- Anisotropic elasticity of crystal leads to phonon transport being focused along preferred directions in the crystal
  - resulting intensity patterns called caustics

- Generate phonons at center of one face of Ge crystal, measure phonon distribution at opposite face



Caustics in Ge collected by `phonons` example



Caustics in Ge observed by Northrop and Wolfe PRL 19, 1424 (1979)

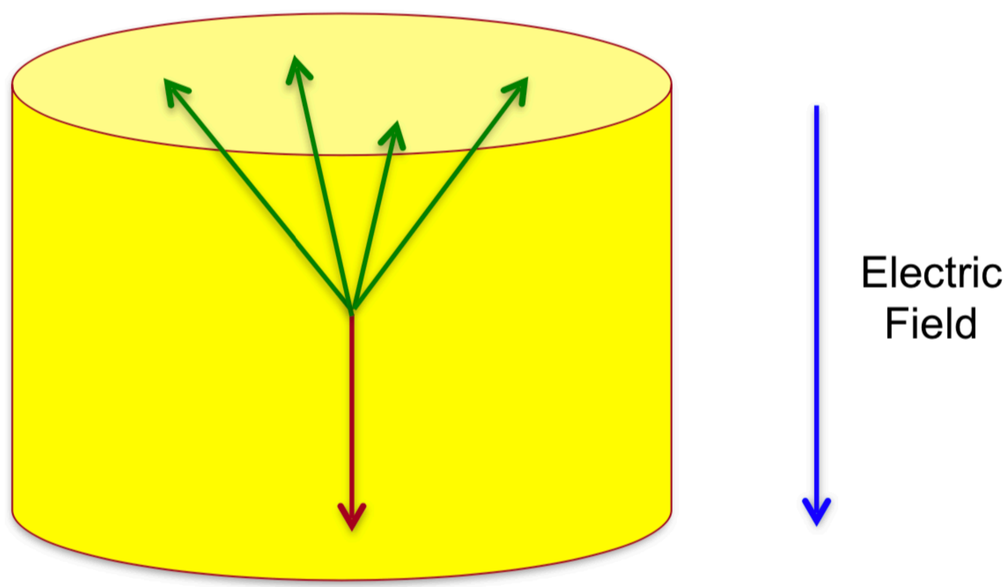
Electron Hole Propagation in E Field

- Hole has a scalar effective mass in Ge
  - propagates as a charged particle in vacuum with an applied electric field

- Electron has a tensor effective mass
  - propagates along valleys in momentum space (band structure)
  - inter-valley scattering from lattice or impurity is possible

Electrons travel along valleys

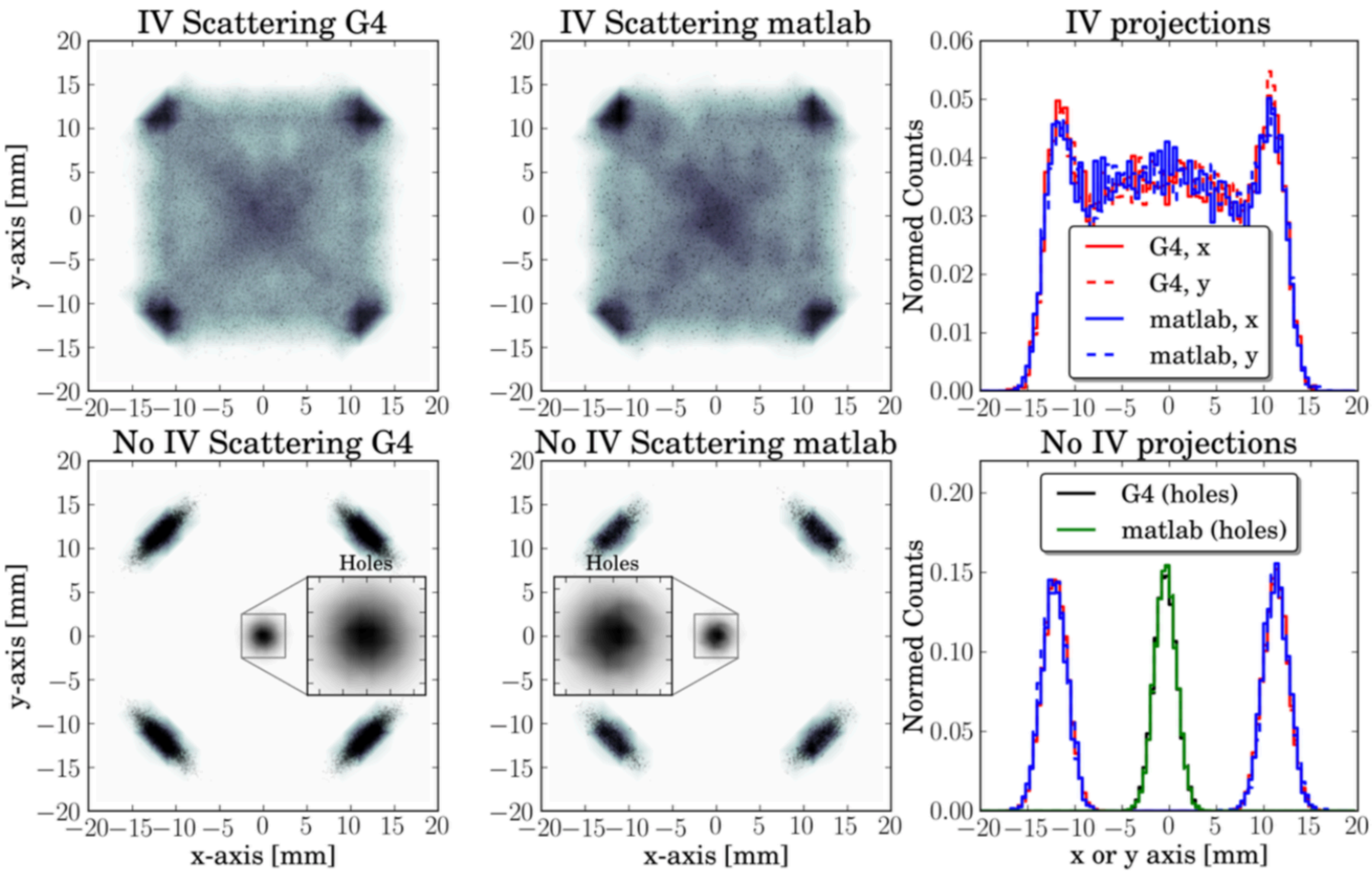
Holes travel along field lines



Luke-Neganov Phonon Production

- Charged particles (including holes) drifting through crystal can generate phonons along their trajectories
  - process analogous to Cerenkov radiation
- “Non-ionizing energy loss” can be calculated and stored by a few standard processes
- Code in development produces phonons which propagate as described previously

Intervalley Scattering



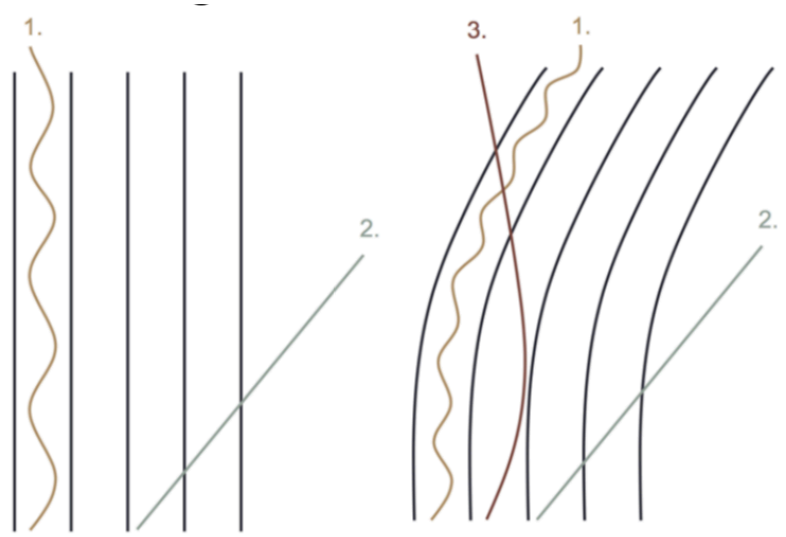
Comparison of G4 and Matlab simulations (w/o inter-valley scattering) of CDMS crystals, R. Agnese, UFL

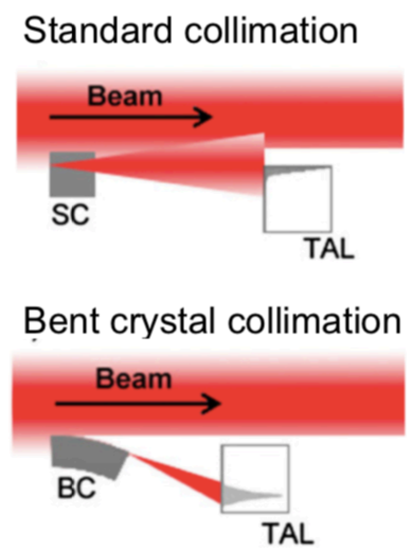
Crystal Collimation or Channeling (developed by Enrico Bagli, U. Ferrara)

- Particles with directions aligned with crystal planes are channeled (1)

- Crystal can be used as primary collimator to deflect halo particles toward secondary collimator

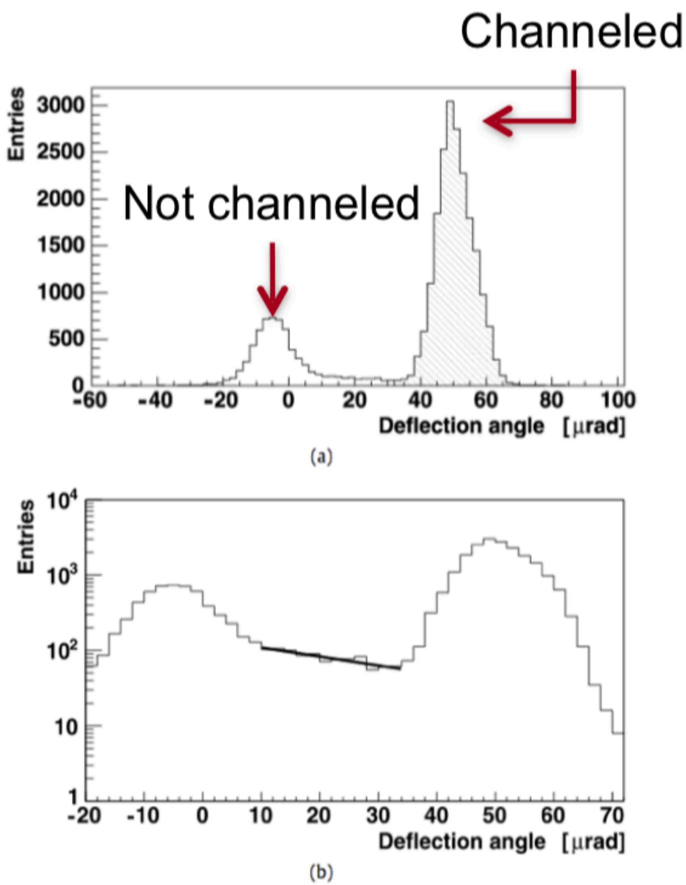
- Main advantage is the possibility of deflecting halo out and reducing losses





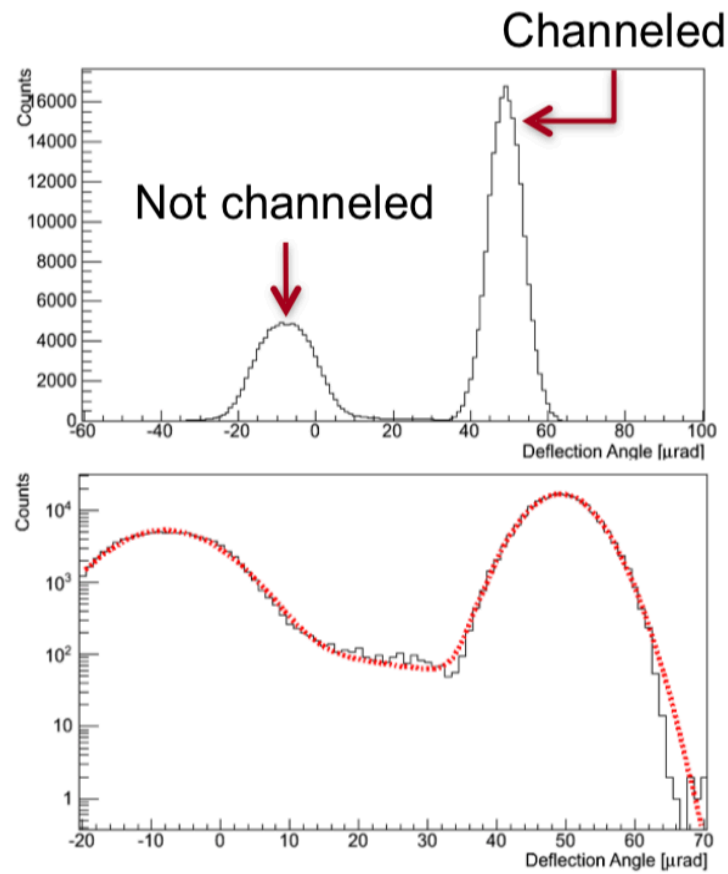
Nuclear De-channeling Length

W. Scandale et al., Phys. Lett. B 680 (2009) 129



$L_n = (1.53 \pm 0.35 \pm 0.20)$ mm

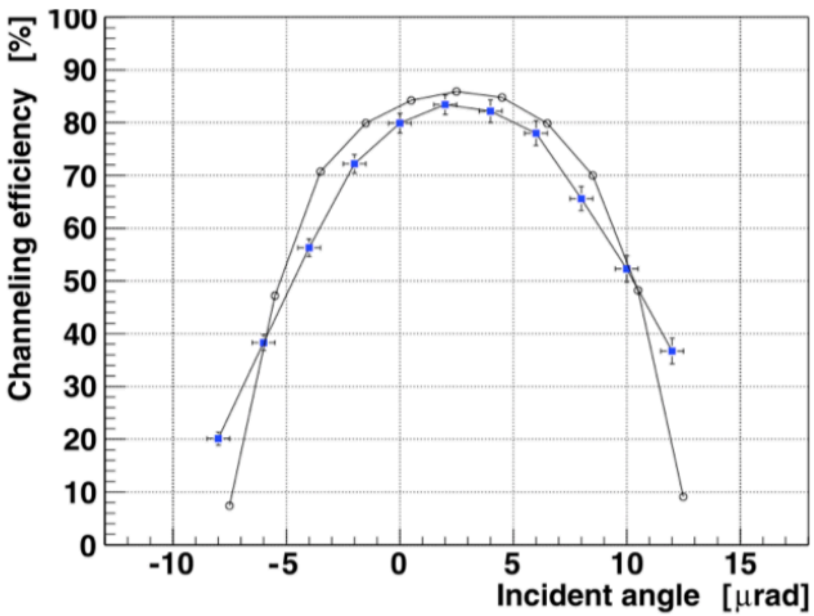
Geant4 Channeling



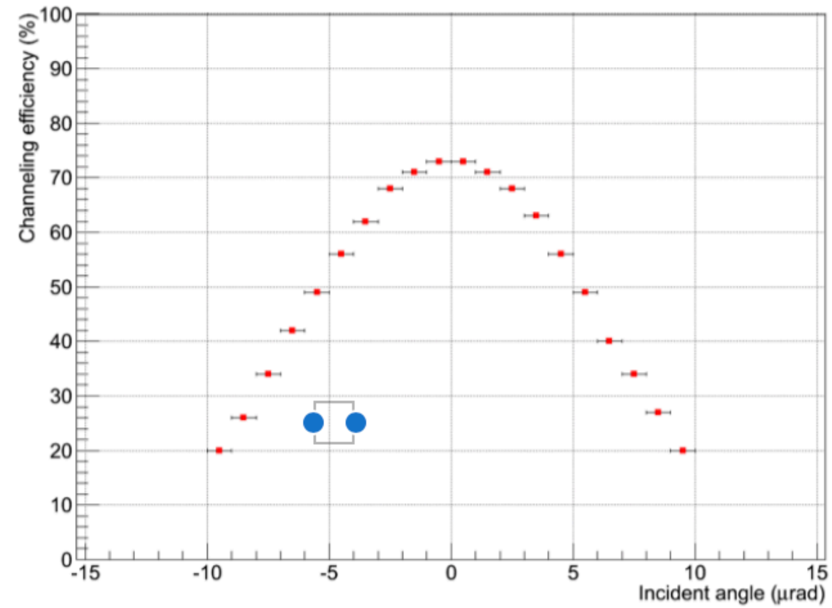
$L_n = (1.31 \pm 0.05)$ mm

Channeling Efficiency vs. Angle

W. Scandale et al., Phys. Lett. B 680 (2009) 129



Geant4 Channeling



- Experimental measurements (a)
- UA9 collaboration simulations (a)
- Geant4 Simulations (b)

Summary

- Geant4 provides decay processes for all long-lived elementary particles
  - short-lived and yet-to-be-discovered particles can also be treated with decay files and special classes

- A versatile optical photon package provides all basic low energy photon interactions with volumes and surfaces
  - particle-like approximation to wave-like physics
  - further details: http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/PhysicsReferenceManual/html/electromagnetic/optical_photons/optical.html

- Phonon propagation in crystals
  - developing area
  - watch for future developments: http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/PhysicsReferenceManual/html/solidstate/phonon_lattice_interactions/index.html