Physics III: Decays and Low Energy Processes

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based on Dennis Wright's lectures

Decay and Low Energy Processes

Geant4 includes processes at low energies to ensure full coverage of interactions with materials

- Particle decays
- Optical photon interactions

Recently added partial support for solid-state (crystal) interactions

- Phonon propagation
- Electron/hole propagation
- 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 a discrete + at-rest process (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): $\lambda \longrightarrow \tau$
  - at-rest processes like decay and capture compete in time e.g. μ^-
- Same process used for all eligible particles
  - retrieves branching ratios and decay modes from decay table stored for each particle type

Particle Decay Models Available

Phase space

- 2-body: $\pi^0 \rightarrow \gamma\, \gamma$ (~98.8 %)
- 3-body: $K^0_L \rightarrow \pi^0\, \pi^+\, \pi^-$
- many body

Dalitz

- $\pi^0 \rightarrow l^+\, l^-\, \gamma$

Muon and tau decay

- e.g. most dominant muon decay: $$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$ $$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
- no radiative corrections, mono-energetic neutrinos

Semi-leptonic K decay

- $K \rightarrow \pi\, l\, \nu$

Decay table:

Possible decay table for K^+

	product	branching ratio [%]	decay mode
$\rightarrow$	$\mu^+\nu_\mu$	63.4	leptonic
$\rightarrow$	$\pi^0 e^+ \nu_e$	8.1	semileptonic
$\rightarrow$	$\pi^0\pi^+$	21.1	hadronic
$\rightarrow$	$\pi^-\pi^+\pi^+$	5.6	hadronic
$\rightarrow$	$\pi^+\pi^0\pi^0$	1.17	hadronic
$\rightarrow$	...	...	...

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 flavour) 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 1st 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
- 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

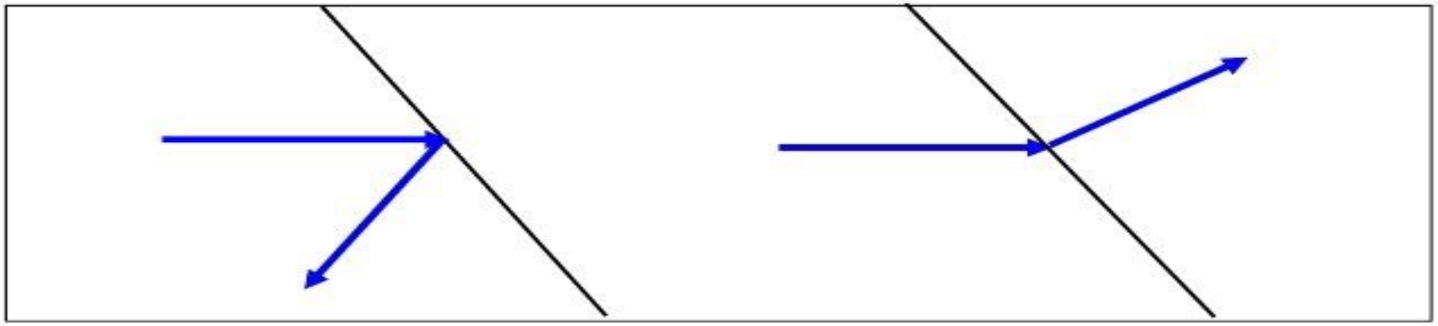
User must supply surface properties using G4OpticalSurfaceModel

Boundary properties

- dielectric-dielectric
- dielectric-metal
- …

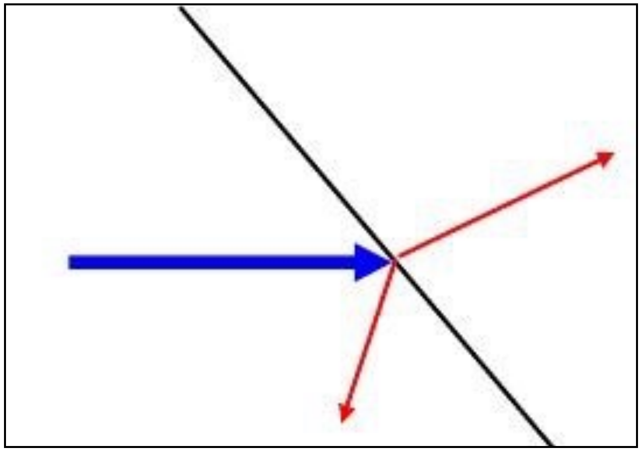
Surface properties

- polished
- ground
- front- or back-painted
- …

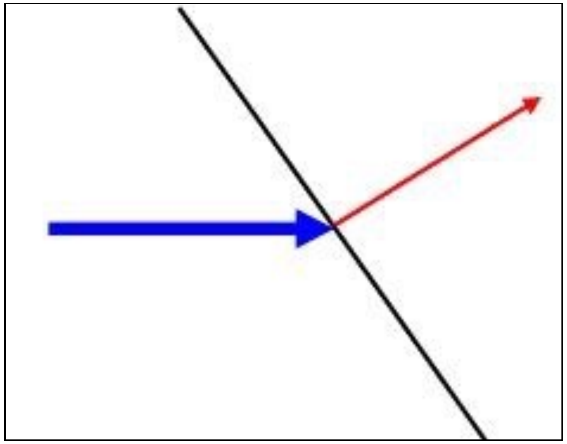


Reflection or Refraction?

Geant4 events reflect “particle-like” behavior – no “splitting” of tracks



Each event has either a reflected or refracted photon, chosen randomly from user-input efficiencies



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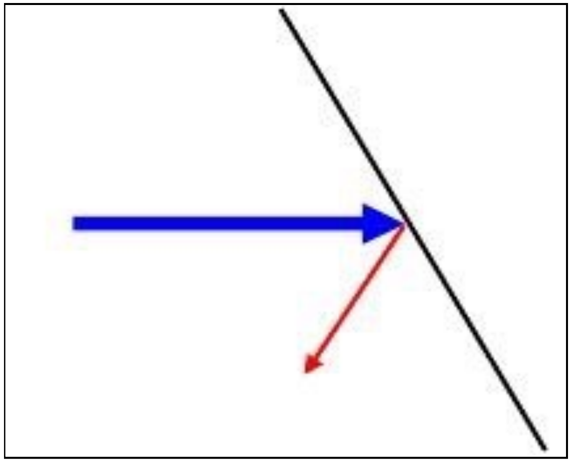


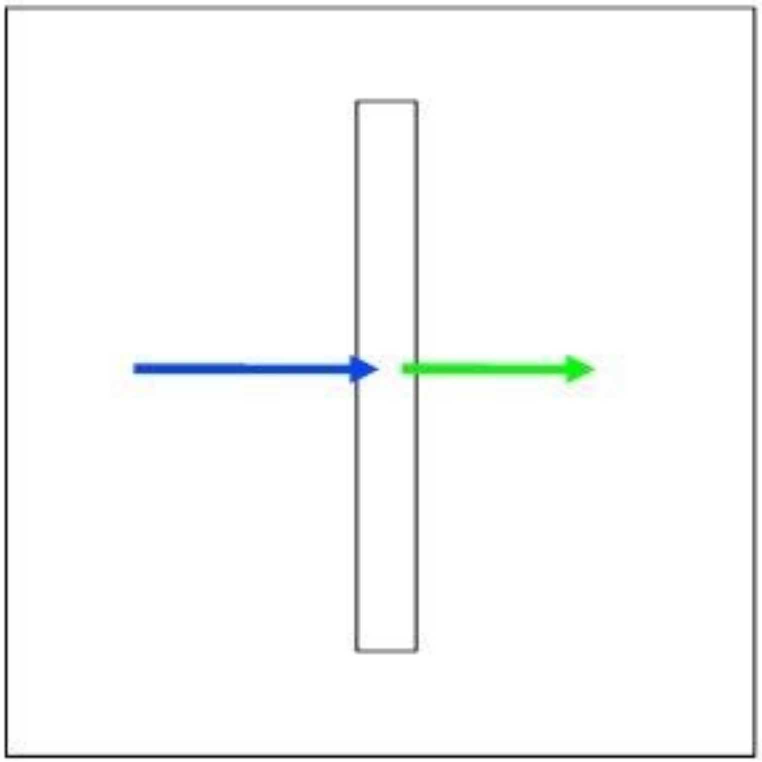
Optical Processes: Wavelength Shifting

Handled by G4OpWLS

- initial photon is killed, one with new wavelength is created
- builds its own physics table for mean free path

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

A group of Geant4 collaborators has been developing 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 10.1

Lattices

Geant4 treats materials as uniform, amorphous collections of atoms. Steps may be of any length, in any direction, and some atom will be at the destination for interaction.

`G4LatticeLogical` have been introduced as a container to carry around parameters and lookup tables for use with the phonon handling processes.

There is a singleton `G4LatticeManager` which keeps track of lattices, and how they're associated with materials and volumes.

Phonons in Geant4

See `examples/extended/exoticphysics/phonon`

FOR: cryogenic detectors for Dark Matter Search are Ge crystals; operates at 40-60 mK; observation of dark matter particles through recoil from Ge nuclei -> phonon and electron-hole pair creation; phonons, electrons and holes transport needs to be modelled in cryogenic environment.

The processes developed so far support acoustic phonons, which are relevant for these low-temperature detectors.

The phonon is described by its wave vector $\vec{k}$, frequency ω, and polarization $\vec{e}$. Three polarization states are recognized (corresponds to the 3 eigenvalue/vector of the phonon propagation wave equition):

- 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.

The two phonon processes important at cryogenic crystal: **isotope scattering**, **anharmonic downconversion**

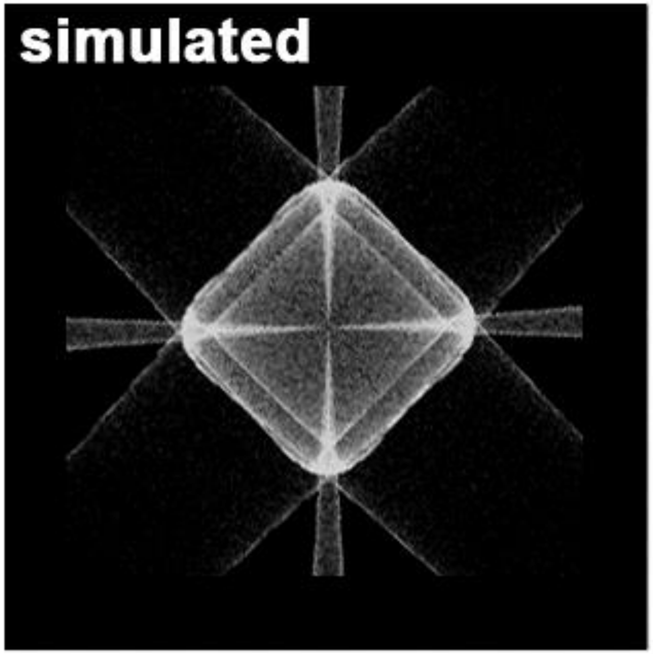
`G4PhononScattering:` an elastic scattering of phonons off of isotopic impurities or lattice defects, during which the phonon momentum vector is randomized, and the phonon polarization state can change freely between the three states L, S T , F TT (mode mixing)

`G4PhononDownconversion:` A single longitudinal (L) phonon split into two L'T or TT phonons with reduced energy. Energy is conserved but not the momentum (momentum exchange with the crystal).

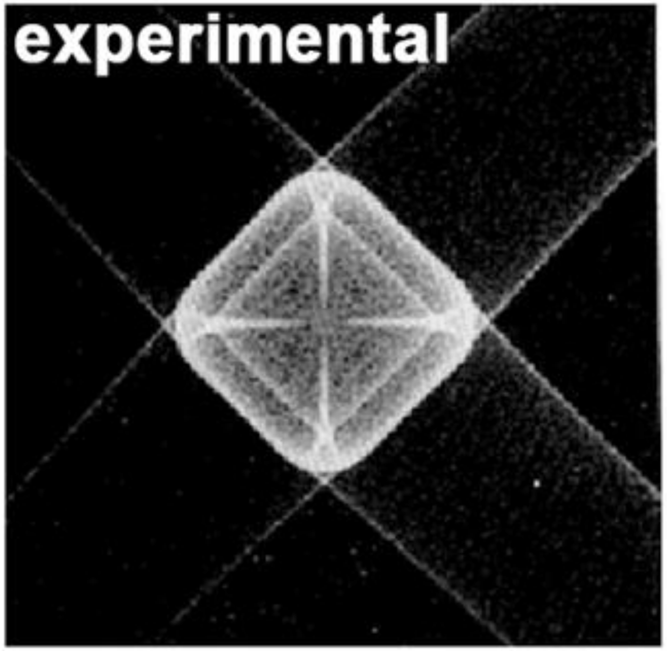
Phonon Caustics In Germanium

A scattering event randomizes a phonon's wave vector. The anisotropic elasticity of crystals leads to phonon transport being **focused along preferred directions in the crystal**. The resulting intensity patterns are called *caustics*.

Generate phonons at the center of one face of a germanium crystal, and measuring the distribution of phonons on the opposite face. Focusing produces a pattern of *caustics*.



Caustics in Ge collected by `phonons` example

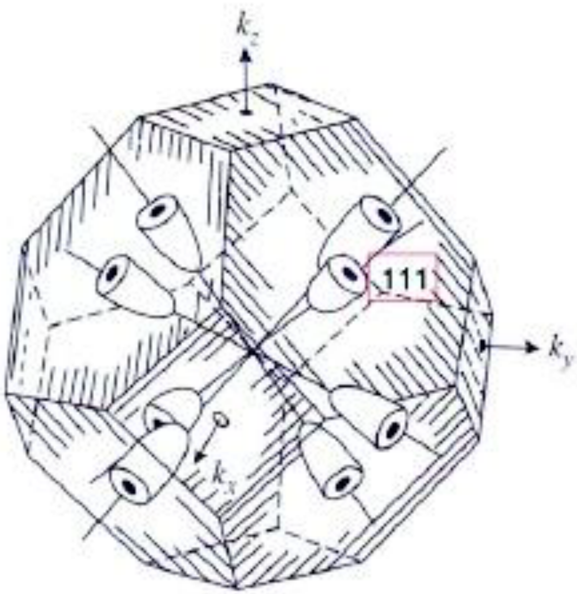


Caustics in Ge observed by Northrop and Wolfe PRL 19, 1424 (1979)

Electron/hole Transport

Energy-momentum relation (band structure) in Ge is highly anisotropic

- Eight equivalent minima (right)
- Electron develops a mass tensor
- Mass tensor diagonalizes in coordinate system aligned with symmetry axis
- Two components, $m_{||}$ and $m_{\perp}$, remain



L valleys of Ge

Electrons travel along, scatter between valleys (minima)

Holes drift along electric field lines

Electron vs. Hole Propagation in E Field

Hole has a scalar effective mass in Ge:

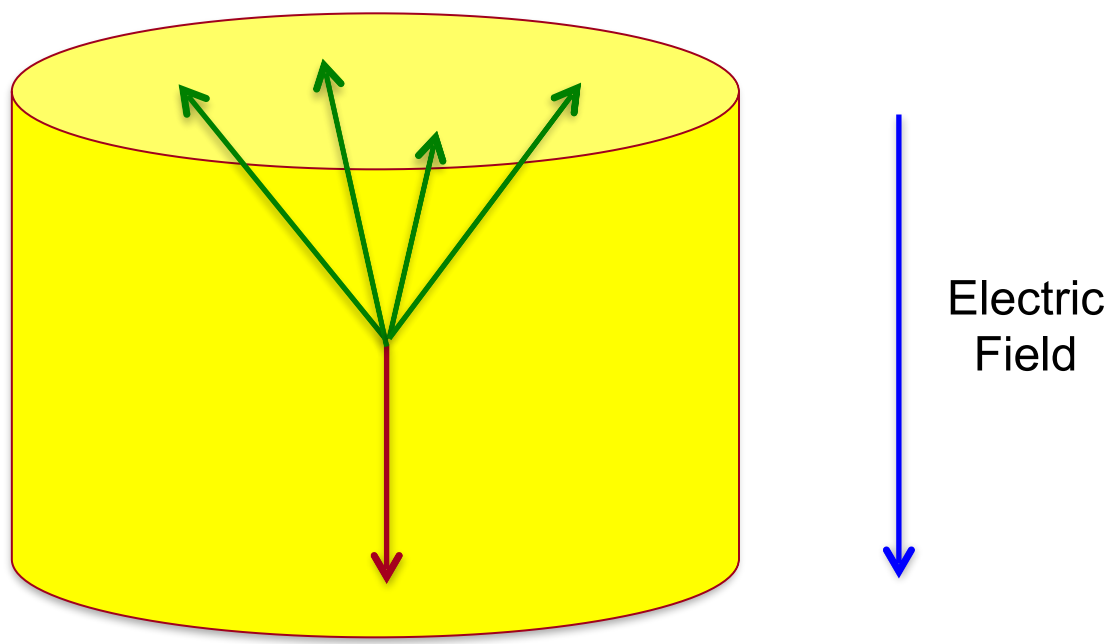
- propagates as a charged particle in vacuum with an applied electric field

Electron has a tensor effective mass in Ge:

- propagates along valleys (band structure); inter-valley scattering (off the lattice or off an impurity)

Electrons travel along valleys

Holes travel along field lines



Neganov-Luke Phonon Production

Charged particles (including holes) drifting through crystal can generate phonons along their trajectories

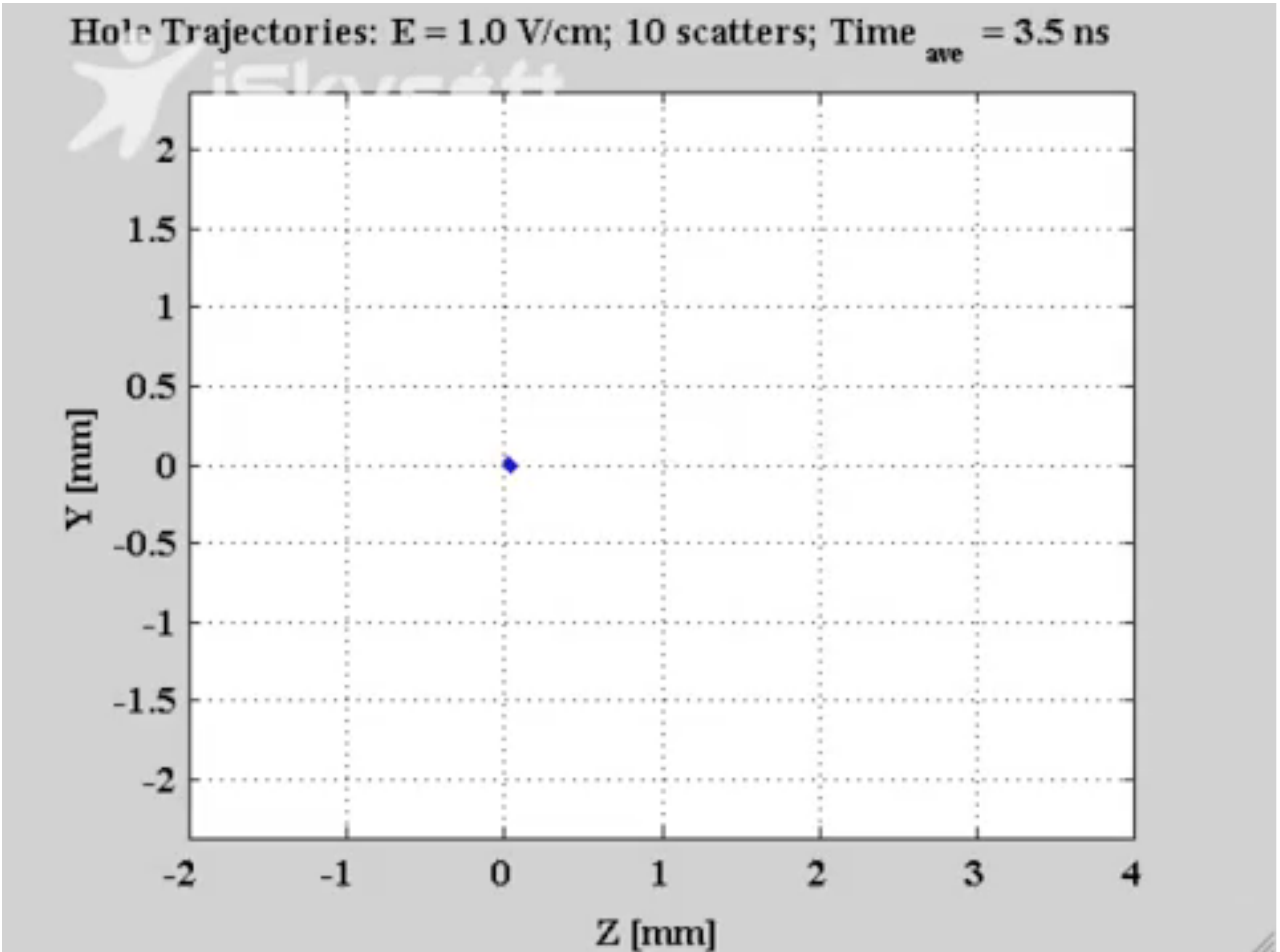
- a process analogous to Cerenkov radiation

“Non-ionizing energy loss” can be calculated and stored by a few standard processes

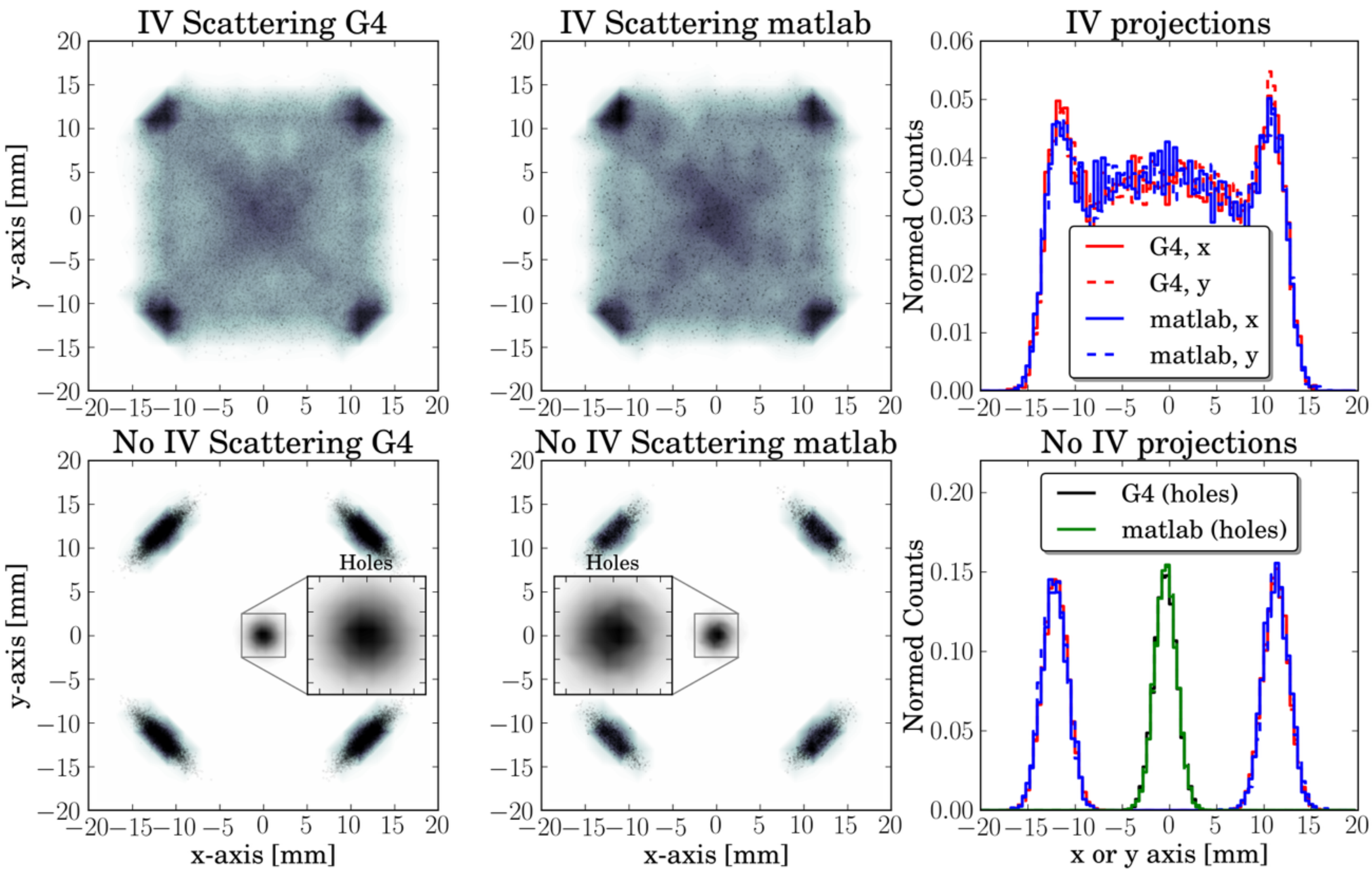
Code in development produces phonons which propagate as described previously.

Neganov-Luke Phonon Production:

The movie shows the transport of charge carriers in a lattice Ge crystal at cryogenic temperatures when an electric field is applied. The electrons (blue) emit phonons (red) that are also transported by Geant4



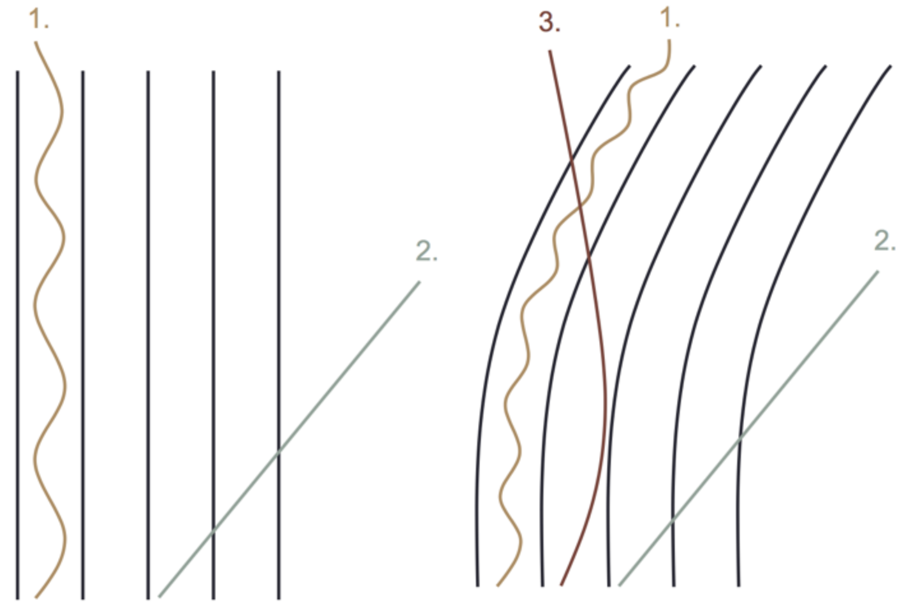
Intervalley Scattering



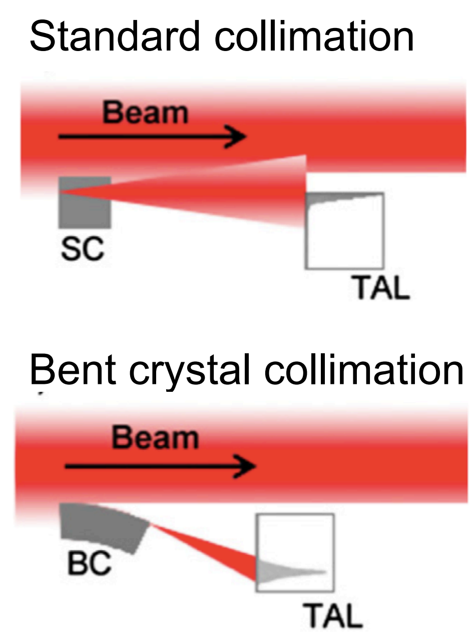
Comparison of G4 and Matlab simulations (w/o inter-valley scattering) of CDMS crystals, R. Agnese, UFL

Crystal Collimation or Channeling

Developed by Enrico Bagli, U. Ferrara

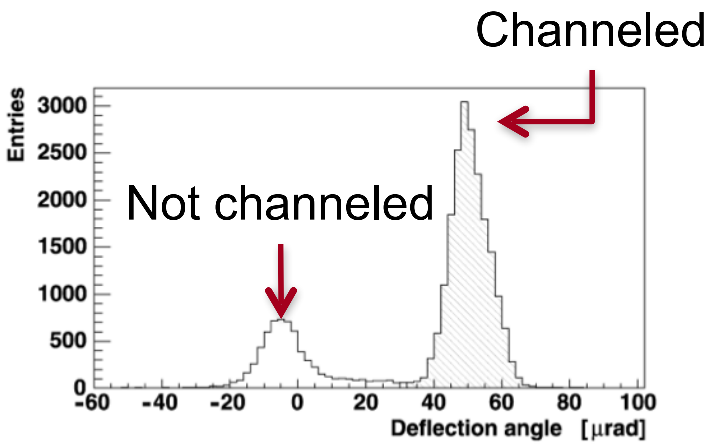


- Particle with directions of motion aligned with crystal planes are captured in channeling (1.).
- Crystal can be used as a primary collimator to deflect particles of the halo toward a secondary collimator.
- Main advantage is the possibility to deflect the beam out and reduce the beam losses.

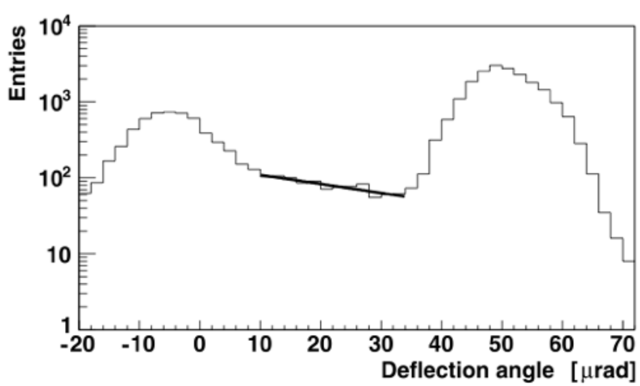


Nuclear Dechanneling Length

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



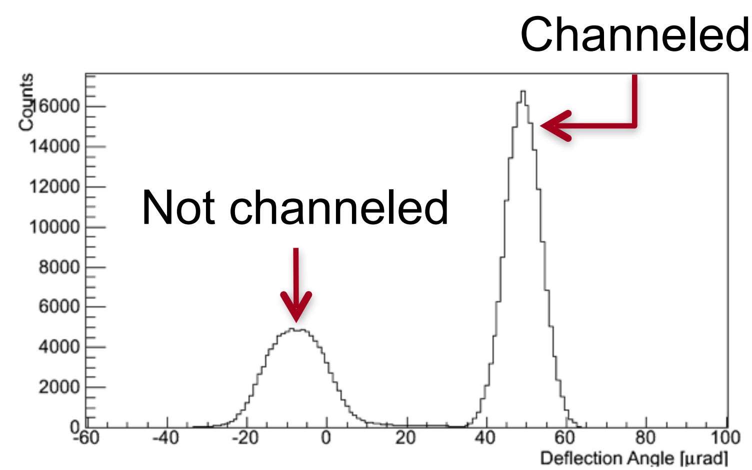
(a)

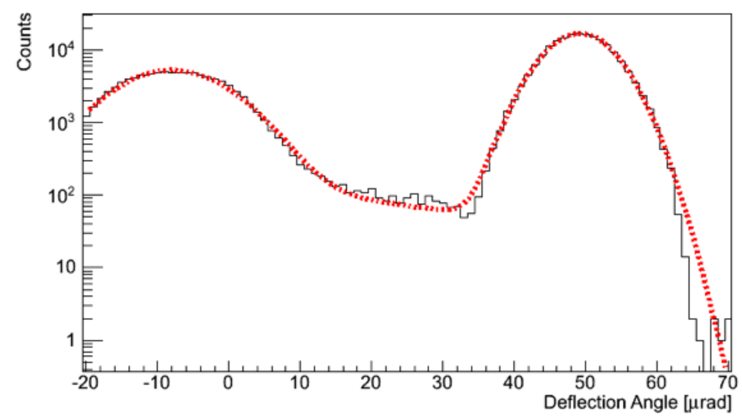


(b)

L_n = (1.53 ± 0.35 ± 0.20) mm

Geant4 Channeling

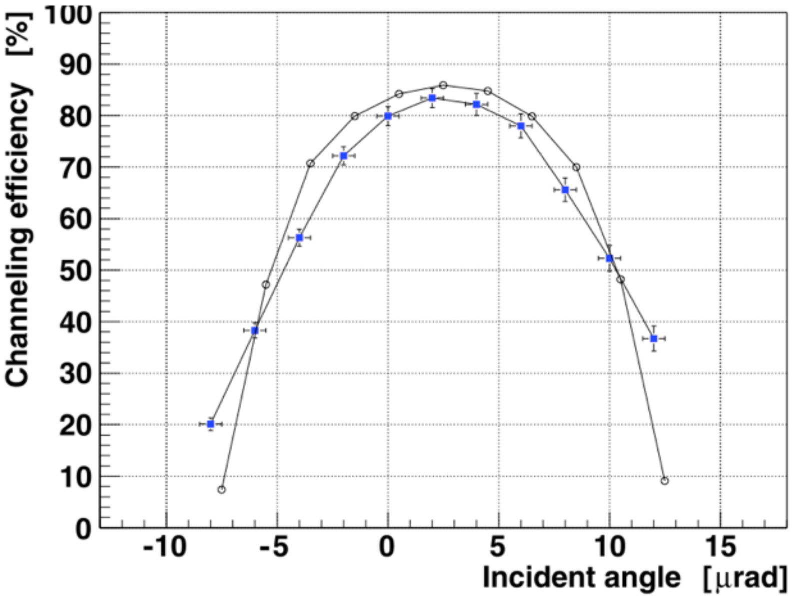




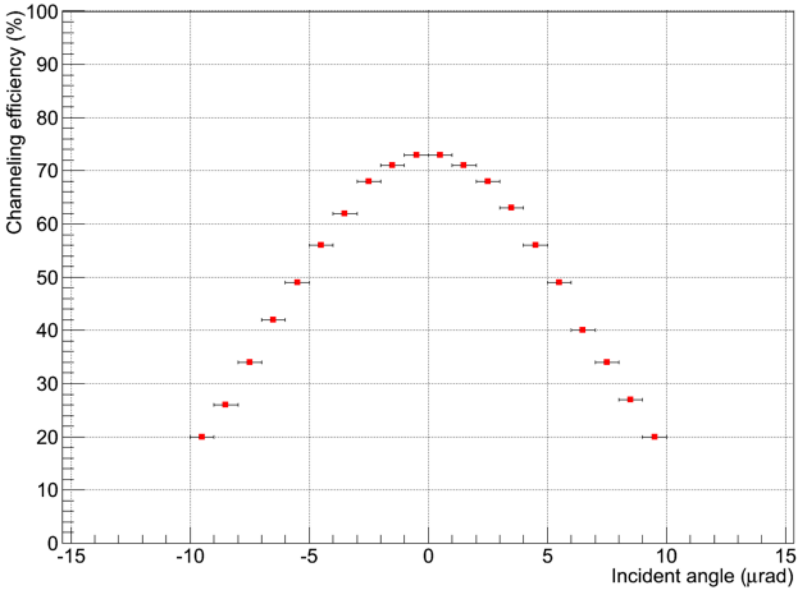
L_n = (1.31 ± 0.05) mm

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 are 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 is now available

- a developing area
- watch for future developments: **http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/PhysicsReferenceManual/html/solidstate/phonon_lattice_interactions/index.html**