Low Energy Geant4
(for Dark Matter and Neutrino Experiments)

Dennis Wright (SLAC)

DANCE Workshop

29 October 2019

Outline

- Introduction
- High energy

- Geant4 features useful for DM + ν experiments
  - RDM (activation) + gamma de-excitation
  - biasing
  - HP neutrons
  - optical photons, scintillation, Cerenkov

- Future developments
  - neutrino interactions
  - phonons
  - better atomic relaxation
  - rare decays

Geant4

- A C++, open source, multithreaded, Monte Carlo simulation toolkit
  - NOT an application: user decides at programming level which physics to use and how to build the geometry

- Contains the physics, geometry and tracking components necessary to build detailed simulations
  - used both in design and analysis phases of an experiment

- Developed and supported by the Geant4 collaboration
  - CERN, KEK, SLAC, ….
  - originally developed for HEP, now expanding to nuclear physics, DM and neutrino communities

High Energy Models

Geant4 High Energy Models

- Most DM, ν and HE experiments use generators for high energy events
  - Geant4 typically used to propagate the generated tracks through the detector

- However, Geant4 does have two high energy hadronic models
  - Fritiof (FTF) parameterized QCD string model good from 2-3 GeV up to ~TeV
    - can do nucleus-nucleus with some restrictions
    - can do anti-light nucleus – nucleus
  - Quark Gluon String model (QGS) QCD string model good from 15 GeV up to ~ TeV

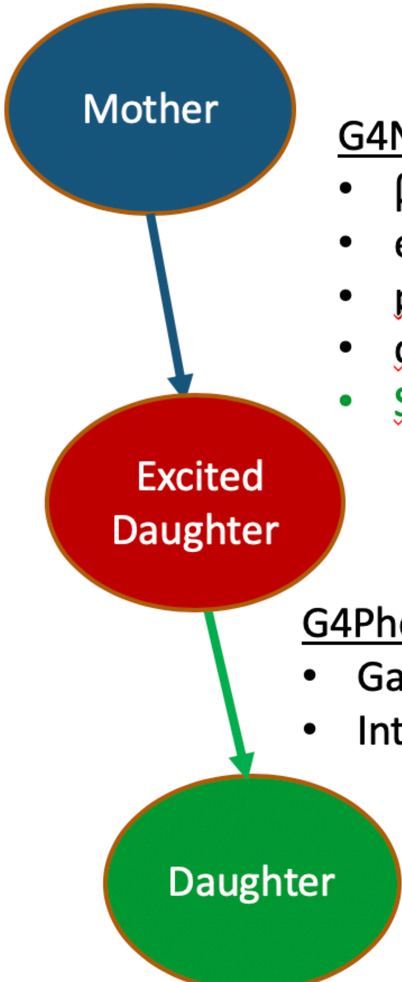
- Cascade models (Bertini, Binary, INCLXX) are used for intermediate to low energies (0 – 10 GeV)

Geant4 High Energy Models

- Geant4 electromagnetic models cover all energies
  - 0 to ~PeV
  - several options which allow user to choose better precision or greater speed
- Electro-nuclear and photo-nuclear
  - for incident γ, e, μ
  - up to ~TeV

Models for Neutrino and Dark Matter Experiments

Radioactive Decay



G4NuclearDecay

- β^-,β^+, α
- e^- capture K,L, M, + N
- p,n emission
- discrete β^- n delayed
- Spontaneous Fission

G4PhotoEvaporation

- Gamma transition
- Internal conversion

G4AtomicRelaxation

- Xrays emission
- Auger emission

- Database-driven model for decay of nuclides
  - both at rest and in flight
- Geant4 database RadioactiveDecay5.3 takes its values from ENSDF
  - with some local additions
  - updated once per year
- All decay channels compete based on their branching ratios
  - decay chains continue down to stability

Radioactive Decay

- Beta decay
  - uses high precision Fermi function approximation (< 0.5 %)
  - first, second and third unique forbidden spectrum shapes used where available - all other transitions have ”allowed” shape

- Electron capture
  - N-shell capture recently added, but only for a few nuclides so far
  - capture to sub-shells (p, d, …)

- Beta-delayed neutrons
  - only n-emission from discrete levels so far
  - emission from continuum in progress

Activation in Radioactive Decay

- Variance reduction mode
  - allows the decay chain to be altered by user commands
    - emphasize rare branches
    - integrate over time profile of source and/or detector
    - collect all decay products of complete decay chain

- Activation
  - radioactive decay process can be assigned to nuclides which are products of some initial reaction (proton, neutron induced, etc.)
  - but, most Geant4 hadronic models may not produce exactly the initial nuclide you want
    - for that you need to use G4ParticleGun

Photon Evaporation

- Also a radioactive decay channel, but used as well for other hadronic processes requiring nuclear de-excitation
  - Geant4 database PhotonEvaporation5.3
  - also based on ENSDF data
  - currently about 2800 gamma levels included
  - updated once per year

- Not only discrete gamma emission, but also continuous spectra if required
- Recently added correlation between transitions → angular distributions no longer isotropic
  - time-consuming → off by default

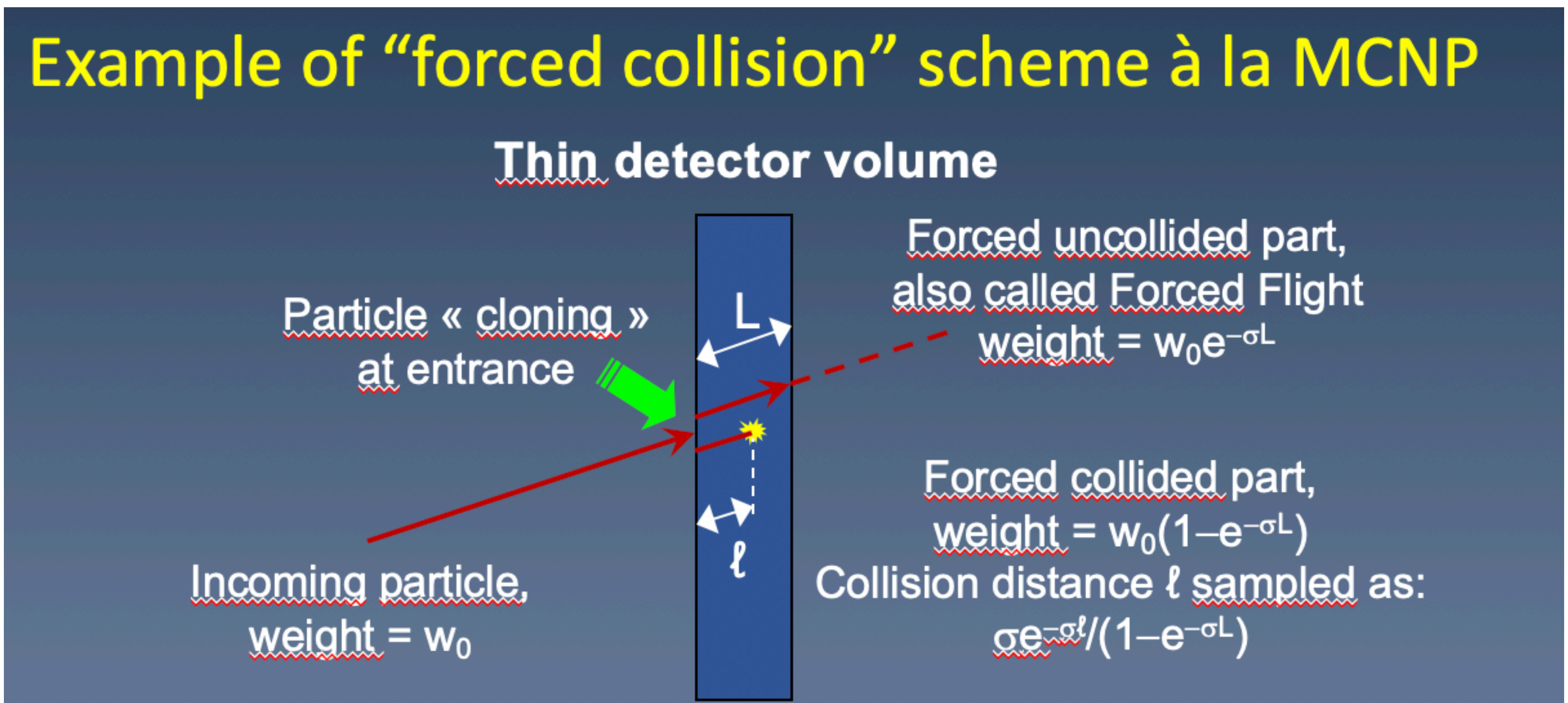
Atomic Relaxation

- If atomic shell is vacated by decay, do electron and gamma cascades as necessary to de-excite
  - X-ray emission
  - Auger emission

- Currently do not add or eject electron if nucleus changes charge – see Future Developments

Biasing

- General biasing functionality added two years ago
  - many different and customizable biasing schemes
  - “forced collision” option perhaps most useful to neutrino detectors
    - can then track neutrinos like any other particle



High Precision Neutrons

- Geant4's low energy, database-driven neutron transport package
  - uses G4NDL database – based on ENDF-B/VII
  - for neutrons (+ p, d, t, alpha) from 0 to 20 MeV
  - has all the low energy resonances, with thermal broadening

- Necessary for simulating cosmic-induced neutrons in rock
  - other Geant4 neutron propagation models will not get the energies or timing right

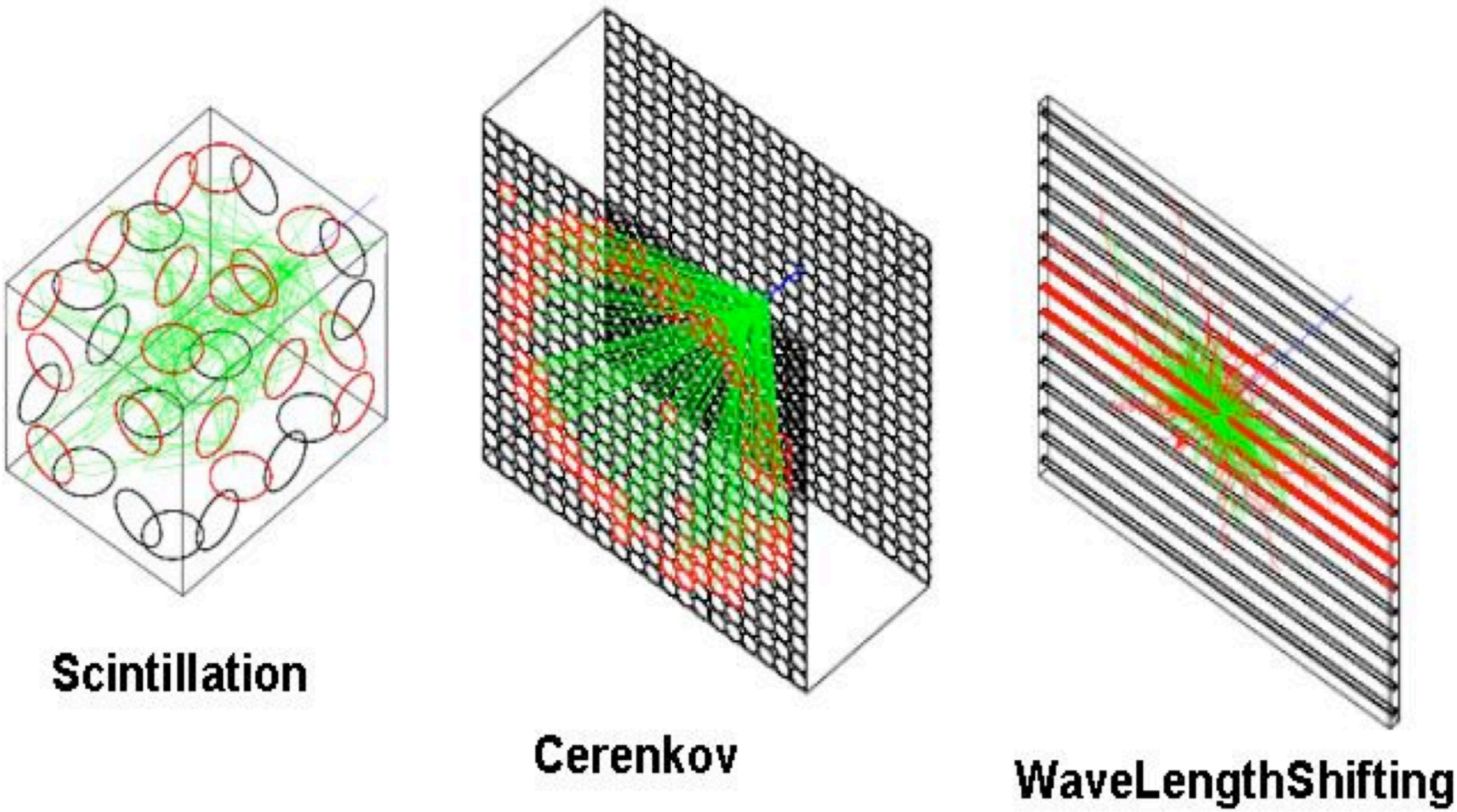
- Probably also necessary for liquid scintillators
  - correct energy deposit and timing may affect light output

Optical Photons

- Package for simulating low energy photons (from visible through X-ray)
  - refraction, reflection, absorption, wavelength shifting, Rayleigh scattering
  - can handle many types of boundary transitions
    - dielectric/non-dielectric
    - liquid/gas interface
    - rough surfaces, smooth surfaces, etc.

- Optical photons generated by G4Cerenkov, G4Scintillation processes
  - can be used to simulate Cerenkov cones for electrons, muons
  - energy not conserved at generation
    - usually too low to worry about

/examples/extended/optical/LXe



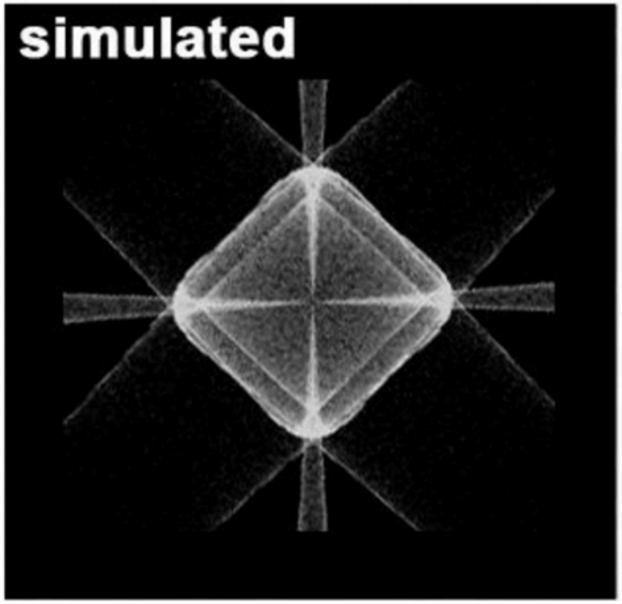
Future Developments

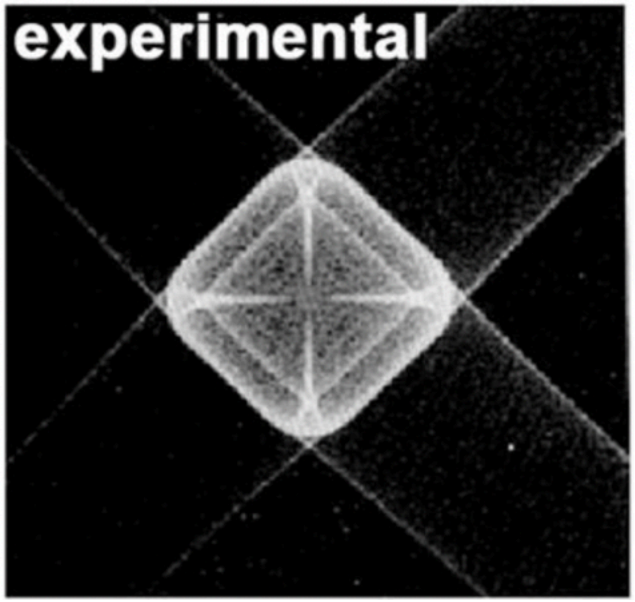
Neutrino Interactions

- Not currently part of Geant4
  - neutrinos generated by the appropriate models
  - no models for interactions
- Low-level effort in Geant4 to develop these
  - not clear if community wants this
  - one person working on this at CERN
- Hadronic interaction in thick targets
  - for beam–based neutrino experiments
  - Geant4 models currently source of significant systematic error → new models, tuning existing models?
- Already developed a GENIE to Geant4 interface to handle final state interactions in neutrino-nucleus
  - GENIE does initial interaction, hands off to Geant4 Bertini cascade to generate hadrons, then give hadrons back to GENIE

Phonons

- Phonon package developed by/for SuperCDMS
  - handles propagation of phonon, electrons, holes in Ge and Si crystals at 0 K
  - not part of Geant4 distribution
  - development ongoing





Improved Atomic Relaxation

- When nucleus increases its charge in radioactive decay, no electrons taken from environment to balance atomic charge
  - leads to small energy non-conservation
  - currently no Geant4 model for this

- When nucleus decreases its charge, no electrons ejected
  - no Geant4 model for this

- Models for both cases exist elsewhere
  - implement?

Rare Decays

- Double β decay (both kinds) could be implemented in Geant4 radioactive decay
  - or is it best to leave this with generators?

- Biasing feature already available in radioactive decay to emphasize rare branches of nuclide decay

- Forbidden, non-unique β decays
  - require up to 10 more parameters per nuclide to get beta decay shape correct
  - currently allowed shape is assumed

Simulation Challenges

- Database development and maintenance
  - radioactive decay, photon evaporation and neutron databases are each taken care of by one person at a low percentage
  - need to keep them up to date and provide for additions

- Neutrino interactions
  - only one person working on this part-time
  - development of neutrino biasing also required
  - tuned or parameterized hadron production models essential to reduce systematic errors in beam-based experiments

- Geant4 support and development is decreasing
  - low energy and nuclear physics development is just beginning
  - US support for Geant4 in these areas is now effectively zero