Snowmass2021 - Letter of Interest

The RAT(-PAC) simulation and analysis code base

NF Topical Groups: (check all that apply □/■)

■ (CF2) Theoretical calculations and simulation
■ (CF5) End user analysis
■ (NF10) Neutrino detectors

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On behalf of the SNO+, THEIA, *ANNIE, NuDot, and other collaborations, who make use of RAT, RATPAC, and derivatives*

Abstract: RAT-PAC is an open-source GEANT4-based toolkit that offers both micro-physical simulation capabilities and analysis tools for high-precision event modeling, evaluation, and characterization, from benchtop test stands to large-scale detectors.

The RAT-PAC Monte Carlo simulation and analysis suite [1] is a free and open-source version of the RAT toolkit. RAT was first written for the Braidwood reactor experiment [2], and is now the official simulation and analysis package for SNO+ [3], DEAP, and MiniCLEAN [4] experiments, thus benefiting from shared efforts in development and verification. A GEANT4-based package [5], RAT-PAC (standing for "RAT Plus Additional Code") was branched off from the core RAT development some years ago, to form an open-source version of the code, available for public use. RAT-PAC forms the basis of the official software for the THEIA collaboration [6], the proposed third phase of ANNIE [7], and for the WATCHMAN collaboration, who are developing a design for the NEO detector to be located at the AIT facility in the UK [8].

One of the great advantages of the RAT-PAC approach is that its procedural geometry description allows the same code to be used to simulate or analyze data from a large-scale experiment and a small benchtop test-stand. Figure 1 shows the detailed geometry of the full ktonne-scale SNO+ detector, and the even larger THEIA detector, and Fig. 2 shows the much smaller CHESS detector at UC Berkeley/LBNL [9–11]. In addition to the flexible geometry descriptions, RAT-PAC takes a micro-physical approach, relying on physical, rather than phenomenological models. For example, individual photons are simulated hitting photon sensors and the resulting timing and charge are evaluated photon-by-photon, rather than by application of a phenomenological risetime correction. Therefore, simulating both benchtop test stands and large-scale detectors with the same micro-physical detail and the same code means that parameter measurements made by the benchtop are more easily translated into the larger-scale detector. A measurement of, for example, the light yield of a scintillator cocktail performed in a small-scale setup can be straightforwardly propagated to predict performance in large detectors, complete with systematics associated with optical models or even data acquisition approaches. Comparisons between simulations of Cherenkov and scintillation light generated using RAT-PAC and data from test stands, such as at Penn, CHESS at LBNL, and FlatDot at MIT, show good agreement. An example from FlatDot is shown in Fig. 2 [12].

RAT(-PAC) is based on GEANT4.10 [5] and the GLG4Sim package written by Glenn Horton-Smith, with custom code for scintillation and neutron absorption processes as well as a complete model of PMT optics. RAT(-PAC) handles all stages of event simulation: from the propagation of primary particles; production of optical photons via Cherenkov and scintillation processes; individual photon propagation, including a full optical model of all detector materials; photon detection at the single PE level, including individual photon detector charge and timing response; and data acquisition including full customisable simulation of front end electronics, trigger systems, and event builders. It also allows root-formatted data to be used as input, and provides simple analysis tools and ways to include many more, as well as a macro command structure for control. Lastly, RAT-PAC also includes the ability to dynamically generate detector configurations via an external database. Thus, RAT-PAC is a complete package that can be used with small modifications for entire experiments.

As experiments grow in scale and use increasing numbers of photodetectors, RAT-PAC will need to progress to reflect these needs. Planned improvements include:

- Updating dependencies to reflect currently-used versions (Python3, ROOT6, and Geant4.10.6)
- Adding generators for rare physics processes, such as the addition of a neutrinoless ^{124}Xe positron-emission/electron-capture ($0\nu\beta + /EC$) decay generator [13], and double-beta decays to excited states.

- Incorporating new photodetector types in the public code, such as the Large-Area Picosecond Photodetectors (LAPPDs) implemented in the ANNIE and CHESS branches.
- Improvements to simulation efficiency, which will be needed to speed up simulations of experiments with $\mathcal{O}(10^5)$ channels, including the ability to parallelize aspects of the simulation.

These improvements will ensure that RAT-PAC continues to meet the needs of the liquid scintillator and water Cherenkov community.

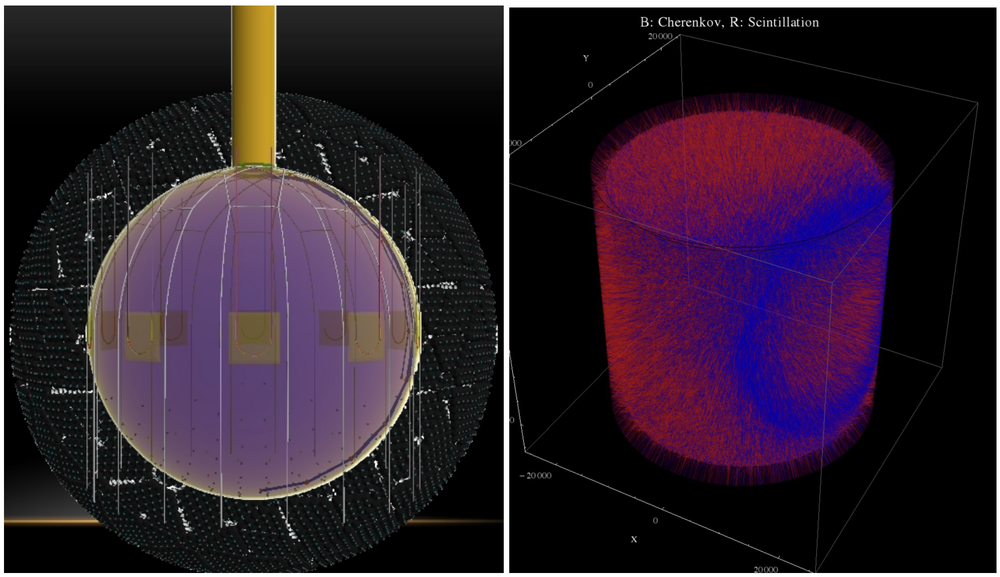

FIG. 1. (Left) RAT-PAC generated image of the ktonne-scale SNO+ detector. (Right) RAT-PAC simulation of a high-energy (GeV) electron in the 50-ktonne THEIA detector, including full photon tracking. Blue shows Cherenkov photon track and red shows scintillation.

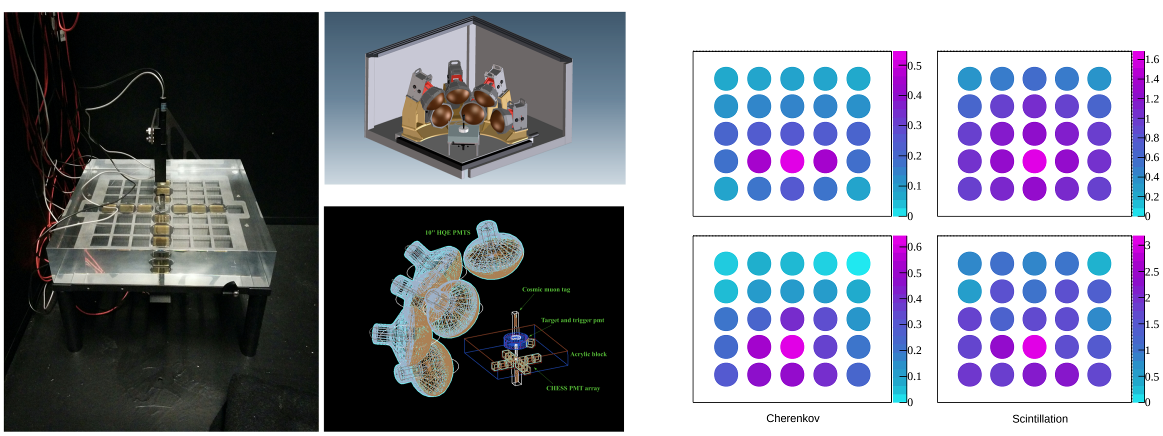

FIG. 2. (Left) Photograph of the CHESS PMT array. (Top centre) CAD image of the full CHESS detector. (Bottom centre) RAT-PAC generated image of the full CHESS detector. (Right) RAT-PAC simulations of both Cherenkov *(left)* and scintillation *(right)* signals show good agreement with data from the FlatDot experiment *(bottom)*, up to a normalization factor reflecting the absolute light yield of the liquid scintillator.

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