Requirements for the Final Phase of Project 8

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25 October 2018
The Talk

- Phase IV in the context of Project 8
- A broad description of Phase IV
- Phase IV Demonstrators
  - Atomic tritium production
  - Atomic tritium cooling / purification
  - Atomic tritium trapping
  - Data reduction
  - Simulations
Project 8 Collaboration
Overview by Fertl, DN.00007

- **Phase I — Proof of concept**
  - Active volume: few mm³

- **Phase II — T² spectrum** — Pettus, DN.00008
  - Active volume: few mm³
  - Experimental efforts to end within the year

- **Phase III — Scalability** — Slocum, DN.00009
  - Active volume: 20 cm³
  - Currently in the design stage
  - Demonstrator for Phase IV

- **Phase IV — Ultimate sensitivity goal**
  - Active volume: 10 m³, $10^{12}$ atoms / cm³
  - Ultimate sensitivity to Inverted Ordering

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*Project 8 — Calibrate with krypton, science with tritium*
Why move to atomic tritium?

Molecular tritium smears out the beta endpoint, precludes distinguishing between the Normal and Inverted Ordering.

All tritium-based experiments that want to push beyond KATRIN must use atomic tritium.
Phase IV — Hardware overview

- Tritium molecules are dissociated into atoms
- Atoms are cooled, purified, and transported
- 2-T atom trap contains atoms but allows molecules to escape
- 1-T field from solenoid induces cyclotron motion
- Patch antennas around active volume pick up radio frequency cyclotron waves
- All tritium losses (except from decay) are captured and recycled to dissociator
Simulations
- Mass sensitivity
- Atomic tritium production / transport / injection
- Atomic trap
- Electron trap
- Space / surface charge buildup

Hardware
- Tritium loop / material accountancy
- Vacuum vessel
- Vacuum plumbing
- Magnetic coil tolerances / thermal contraction / engineering
- Cryogenics

Calibration / quantification
- External B field
- Trapping B field
- Electrical potential variations (spatial / temporal)
- Atomic and molecular distributions (velocity / density)
- Backgrounds
- Detector resolution

Atomic tritium
- Production
- Accommodator / immersed source
- Velocity / state selection / transport
- Trap, including loading

Others
- RF, including antenna and transmission lines
- Quantum-limited amplifiers
- Data reduction
- Space and infrastructure
- Slow controls
- Operations
- Shared design repository
- Data acquisition
- Online processing
- Computation
- Analysis

Many aspects of the experimental work have been understood and explored. The **Demonstrators** represent the work that has never been explored, and represents the highest risk to Project 8.
Atomic Tritium Production

Hydrogen cracker test bed
- H₂ supply: MFC / Leak valve
- Thermal cracker
- Main turbo pump
- Skimmer
- Mass spectrometer

Deuterium cracker test bed
- Mass Flow Controller
- Beam Shutter
- Upstream Pressure Gauge
- Residual Gas Analyzer

Exploring alternatives
- Thermal crackers emit electrons
- Tritium ionization and loss
- Incompatible with high B?

Direct current heating of coaxial tungsten capillary

20 sccm ~ 10^{19} atoms/s

m/z 1 Percentage vs Temperature and Flow

RGA Trace beginning Jul 17, 2018 05:26:37 PM

PROJECT 8
Atomic Tritium Cooling / Purification

In final trap injection, atoms climb 1-T step, cooling low-field-seeking states.

PROJECT 8
Atomic Tritium Trapping

- Need high purity, so we trap tritium atoms and allow molecules to escape
- Efforts are focused on Phase IV Demonstrator magnetic trap design
- Require atom-trapping contours that do not intersect the coils themselves
- Associated Demonstrator: What is the interplay between the atom trap (2 T) and the electrons (trapped at $10^{-3}$ T)?

Phase IV Demonstrator Design Concept, trapped volume = 0.6 m$^3$

Phase IV Design Concept, trapped volume = 10 m$^3$
Data Reduction — **Rough** Estimates of P-IV Requirements

- Estimates of P-IV for order of magnitude purposes only
  - $10 \text{ m}^3 \times 10^{12} \text{ atoms / cm}^3 = 10^{19} \text{ atoms, } \tau_{1/2} = 12.3 \text{ years} \rightarrow 25.8 \text{ GBq}$
  - Proportion of events in highest 1.5 keV = $6.66 \times 10^{-4}$
  - Proportion of events emitted within $2^\circ$ of perpendicular to B field = $3.49 \times 10^{-2}$
  - $25.8 \text{ GBq} \times 6.66 \times 10^{-4} \times 3.49 \times 10^{-2} = 600 \text{ kHz event rate}$

- 600 kHz event rate & 5 ms per event $\rightarrow$ **Continual streaming**
- P-II: 200 MB / ch / s, Ph-IV has ~1000 channels $\rightarrow$ 200 GB / s
- Need to process data in hardware (FPGA, FFT on GPUs)
- If we are limited to, e.g., 1 GB / s to disk (300 PB in 10 y, $1M?$) $\rightarrow$ 1.7 kB / event: Start time, $(r, \theta)$, zero-suppressed spectrogram
Simulations—Rough Estimates of P-IV Requirements

Phase III simulations (P-IV Demo)
- 30 channels, 21 patches per channel
- 10 CPU-days / electron for 10-ms trace
  - CPU time split between electron trajectory calculation (depends on trap configuration) and RF propagation (scales with # patches)
- Assume 1-10 million electrons in simulation
- Need 250-2500 speed gain for $10^6$ CPU-hours

Phase IV simulations
- Trajectory calculation time does not change
- 1100 channels, 800 patches per channel, RF wave calculation increases with # patches
- Assume 10-100 million electrons in simulation
- Need *additional* speed gain for $10^7$ CPU-hours

Targeted improvements
- Algorithm development (parametrized trajectory)
- Physics simplification
  - Some questions can be answered with shorter traces
  - Reduced points on patch antenna
- Hardware improvements (GPU)
Wrap up

- Project 8 aims for a 40-meV sensitivity in electron neutrino mass
- Key Phase IV technologies require Demonstrators
- While focusing on shorter-term developments and a methodical, step-by-step approach, we are also keeping in mind the big picture
Thank you!

- This work is supported by:
  - US DOE Office of Nuclear Physics
  - The US NSF
  - The PRISMA Cluster of Excellence at the University of Mainz
  - Internal investments at all institutions