Detectors for Super-Beams and Neutrino Factories

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Acknowledgements

• This summary is greatly informed by:
  – The recent FNAL study on neutrino detectors for super-beams (M. Goodman and D. Harris, chairs)
  – J-PARC ν studies
  – BNL oscillation LOI
  – Recent Annual Review on Oscillation Physics at Neutrino Factories (J.J. Gomez-Cadenas, D. Harris)

• Thank you!
Organizational Preamble...

- This is the first of two talks reviewing detectors
  - André Rubbia will cover liquid Argon

- The rationale, courtesy of Hugh Montgomery:

  “Should we hold off for liquid Argon, or should we proceed with the *miserable technologies* we have in hand?”
Miserable Technologies for Super-Beams and Neutrino Factories

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The Catalog of Misery 😞

- Large черенков (Čerenkov) detectors
- Low Z Sampling Calorimeters
- Magnetized Fe Sampling Calorimeters
- And their “issues”...
  - efficiencies and backgrounds
  - construction and funding realities

\[
\begin{align*}
\nu_\mu &\rightarrow \nu_e, \\
\text{accept } &\nu_e \text{ CC.} \\
\text{Reject } &\pi^0
\end{align*}
\]

for superbeams, \( \nu_\mu \rightarrow \nu_e \), accept \( \nu_e \) CC. Reject \( \pi^0 \)

\[
\begin{align*}
\nu_e &\rightarrow \nu_\mu \text{ (gold), } \\
\nu_\tau &\text{ (silver)} \\
\text{accept “wrong-sign” } &\text{CC.}
\end{align*}
\]

for neutrino factories, \( \nu_e \rightarrow \nu_\mu \) (gold), \( \nu_\tau \) (silver) accept “wrong-sign” CC.
The Ground Rules

• After the present generation of superbeams (NUMI, CNGS), order of magnitude increases in flux appear difficult
  – corollary: also difficult to increase the number of facilities by an order of magnitude

• To reach sensitivity to CP violation in oscillations, we must improve detectors
  – size ↑, signal efficiency ↑, backgrounds ↓
  – or add new capabilities, e.g., electron charge (André)
Teragram$^\S$-Class Water Čerenkov

- Perceived widely as a “straightforward” extension of existing engineering
- No shortage of proposals, e.g., Hyper-K, UNO
- No shortage of sites, e.g., DUSEL, Frejus, Kamioka, etc.
- Physics case is “broad”
  - proton decay, neutrino astrophysics

$^\S$Labeling this a “Megaton” detector would be an enormous public relations mistake. We need to expunge this unfortunate jargon ASAP before someone overhears us...
Teragram $\text{H}_2\text{O} \checkmark : \text{Signatures I}$

- Elegant proof of $e/\mu$ separation from Super-Kamiokande atmospheric neutrino results
  - Sub-GeV single-ring dominated: “Sharpness!”

Figures courtesy M. Messier
Teragram $\text{H}_2\text{O}$ Č : Signatures II (cont’d)

- $e/\pi^0$ separation is a more subtle business
  - Multi-ring topologies more difficult
  - At high energies, $\pi^0 \rightarrow \gamma\gamma$ more “closed”

Figures courtesy M. Messier
Teragram $\text{H}_2\text{O} \, \checkmark \, \text{Signatures II} \, (\text{cont'd})$

- Also, many processes contribute to single-ring
  - Example: K2K (broadband) beam at Super-K
  - At $E_\nu \sim 3$ GeV, FC 1-ring $\mu$ candidates are $1/3$ QE, $1/3$ single $\pi$, $1/3$ "DIS"

Figures courtesy T. Kajita
Teragram $H_2O$ Č: Signatures II (cont’d)

- Can avoid problems by sticking to low energy, quasi-elastic regime (and paying a rate price!)

**Flux (not rate) on and off-axis**

Figure courtesy A. Konaka
Teragram $\text{H}_2\text{O}$ Č: Signatures II (cont’d)

- $e/\pi^0$ separation demonstrated (in low $E_\nu$ OA beam)
  - but it will be a complicated multi-variate business

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Kevin McFarland: Detectors

Figures courtesy T. Kajita
Editorial comment: e/$\pi^0$ separation is much tougher at high energies

- BNL proposal (in my view) needs more to demonstrate feasibility of this rejection
- Background control relies on rarity of single pions at high $E_{\pi^0}$
- Note that single-ring events in this region are mostly inelastic!

Single $\pi^0$ background vs $E_{\pi^0}$ (M. Diwan)
Teragram H$_2$O Č : Technology

- Contained detector with instrumented wall has been extensively studied at engineering level
- “Open” technology (CNGT) historically risky
- Photosensors
  - figure of merit at low E: (coverage)×(quantum eff.)
  - is this figure of merit identical for use of H$_2$O Č as a neutrino target?
Some UNO details:
- depth reduced by “sideways” topology
- two photocathode density zones to lower sensor costs
  - middle zone is high density for nucleon decay and solar $\nu$
  - edge zones lower density: suitable for atmospheric and beam $\nu$
Teragram H₂O Č : Technology (cont’d)

- Some Hyper-K details:
  - sideways cylinder limits depth, simplifies geometry with beam
  - copious segmentation (10 modules)
Teragram H$_2$O Č : Technology (cont’d)

- Photosensor R&D: can one drive down cost?

5 inch HPD prototype (Shiozawa, NP02)
Low-Z Sampling Calorimetry

• The concept in a nutshell:
  – Low Z absorber in a calorimeter $\Rightarrow X_0$ increases for fixed mass
  • improved resolution for electromagnetic showers
    – key for $\pi^0/e$ separation
Low-Z Sampling Calorimetry (cont’d)

• Issues: coping with increased size per unit mass
  – Construction/building issues
  – Structural issues of absorber
  – Increased number of ionization sensors

• All lead to a new generation of requirements of industrial capability for detector construction
Low-Z: Signatures (cont’d)

In theory...

- With long \( X_0 \), two photons should rarely be degenerate

- Other final state particles well separated

\[ \pi^+ \quad \text{2GeV } \nu_e \text{ CC} \]
\[ e^- \]
\[ \pi^0 \quad \text{2-3GeV } \nu_e \text{ NC} \]

figures courtesy A. Para
Low-Z: Signatures (cont’d)

• Preliminary efficiency and backgrounds...
  – with realistic detector, see $\varepsilon \sim 10^{-3}$, few$\times 10^{-4}$ for NC, CC, respectively
  – maintain $\sim 40\%$ efficiency for signal

• For $P(\nu_\mu \rightarrow \nu_e)$, see high
  $(S/\sqrt{B}) \sim 40$
  – $\delta m^2 = 2.4 \times 10^{-3}$, $\sin^2 \theta_{13} = 0.1$, 200kTon-yr, $4 \times 10^{20}$ POT/yr NUMI

figures courtesy L. Camilleri
Low-Z: Technologies

• First things first... can we afford absorber?
  – visions of walnut shells, cracked corn, “all liquid”...

• Real question: can we afford structural absorber
  – one idea: Particle board (wood scrap + glue)
    • very strong against compression along board
    • laminations of sheets provide sound 3D structures
  – 50 kT of particle board is two weeks of production at one northern Minnesota plant; cost is ~15 MUSD cut & delivered
Low-Z: Technologies (cont’d)

• “Containerization” and modular construction
  – shipping containers (J. Cooper) appear to be a cost-effective way to house modules
Low-Z: Technologies (cont’d)

- Containing the container...

figures courtesy J. Cooper
Low-Z: Technologies (cont’d)

• Ionization sensors: scintillator+WLS fiber
  – extrapolation from successful MINOS experience
  – new construction facility at FNAL Lab 5:
    continuous inline extrusion process

figures courtesy A. Bross
Low-Z: Technologies (cont’d)

• New and old photosensors:
  - new: VLPCs
    • very high QE
    • success at D0
    • R&D going on now to lower costs. Enough?
  - old: IITs, APDs
    potentially significant cost savings!
    • IITs: noise? timing?
    • APDs: noise (cooling)
    • being revisited in design studies for NUMI

figures courtesy A. Bross, J. Nelson, R. Rusack
Low-Z: Technologies (cont’d)

• Ionization sensors: RPCs
  – inspired by recent use at B-factories
  – reliability problems at BaBar apparently understood
  – gas system, readout under active study for NUMI

![Diagram of Resistive Paint Counter](image)
Magnetized Sampling Calorimeters

- Successful construction of MINOS has bolstered the case that this is an “easy” technology
  - could clearly build a longer MINOS
- Precious (“golden”, “silver”) channels at a neutrino factory requires identifying muon charge in DIS events
- Questions:
  - intrinsic background level
  - \( \tau \) identification? (“silver”)
  - can low cost teragram detector compensate for available flux at “affordable” neutrino factory?
Magnetized Calor.: Signatures

- $\nu_e \rightarrow \nu_\mu, \nu_\tau$ in presence of $\bar{\nu}_\mu, \bar{\nu}_\tau$ (or charge conjugate)
- Wrong-charge background for “golden” channel?

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Cervera et al
Magnetized Calor.: Technology

- $\tau$ appearance ("silver"): OPERA technique
  - topological tau tag to separate from $\mu$+DIS
  - fully tested long before $\nu$ factory beam is available...
Conclusions

• “Teragram-class” detectors will be needed to access CP violation in oscillations

• Superbeams:
  – H$_2$O Č “in the bag” but difficult at higher energies
    • *I look forward to the BNL proponents proving me wrong!*
  – Low-Z calorimeter work (driven by NUMI OA proposal) looks promising

• Neutrino factories:
  – extensions of MINOS (golden), OPERA (silver)

• *Or should we wait for “less miserable technology”? (André)*