Modeling the energy response of the Daya Bay antineutrino detectors

Goal: establish positron energy scale from inverse beta decay (IBD) interactions in a 1-8 MeV energy range

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on behalf of the Daya Bay collaboration

**Constrained by gamma data**

- Detector targets enclosed by non-scintillating acrylic vessels
- Kinetic energy of positrons near acrylic vessels not fully converted to scintillation light (~13% of all IBD positrons)
- Positron annihilation gammas with longer range can also deposit energy in vessels
- Introduces spectral distortion at around 1 MeV

**Extracted from MC simulation**

- All data consistent with prediction from gamma+boron constrained energy model
- Best fit model stable within 68% CL when including additional data constraints

**Non-linear response from liquid scintillators**

- Decrease in light yield due to ionization quenching
- Emission and absorption/ep-emission of Čerenkov light
- Semi-empirical electron response model based on Birks law

- Energy deposited in scintillating volumes $E_{dep}$

**Particle kinetic energy $E_{true}$**

- Energy converted to visible light $E_{vis}$

- Energy seen by readout electronics $E_{REC}$

**Full IBD positron non-linearity model**

- Ionizing positrons assumed to interact with scintillator in same way as electrons, full response computed from electron curve
- 2 annihilation gammas
- 4 curves numerically selected from 1-sigma phase space to parameterize shape uncertainties
- Sub-percent overall uncertainty from non-linear response model
- Reduced dependency on reactor models in oscillation analysis
- Crucial for measurement of reactor spectrum

**Validation with additional calibration data**

- 53 MeV cutoff in Michel electron spectrum from muon decays
- Continuous beta+gamma spectra from bismuth and thallium decays

**Unconstrained 5-parameter fit to $\gamma + ^{12}$B data:**

- Absolute energy scale
- Birks constant
- Relative contribution from Čerenkov light
- Size and decay constant of electronics model

Gammas connected to electron scintillator model through MC:

$$K_{\gamma} = \int K_{\gamma}(x) \cdot K_{\gamma}(x) \cdot A(x) \cdot B(x) \cdot C(x)$$

**MC gamma propagation**

- Monenergetic gamma lines from various sources
- Radioactive calibration sources employed regularly: $^{14}$C, $^{60}$Co, $^{203}$Hg, $^{137}$Cs
- Sources employed during special calibration periods: $^{14}$C, $^{60}$Co, $^{137}$Cs, $^{241}$Am, $^{63}$Ni, $^{7}$Li, $^{13}$N, $^{20}$Ne, $^{24}$Na, $^{40}$K, $^{23}$Na, $^{22}$Na, $^{35}$Cl, $^{18}$F, $^{18}$O, $^{36}$Cl, $^{36}$Ar, $^{40}$Ca, $^{208}$Tl
- Singles and correlated spectra in regular physics runs: $^{40}$K, $^{208}$Tl, neutron capture on H, C, Gd

**Constrained by gamma data**

- Size and decay constant of electronics model
- Reduced dependency on reactor models in oscillation analysis

**Energy conversion**

- Electronics does not fully capture late secondary PMT hits
- Charge collection efficiency decreases with visible light
- Cannot be easily calibrated out on single channel level
- Use effective exponential model as a function of total visible energy

**Energy of primary $\gamma$ / $\beta$**

- Continuous spectrum from $^{12}$B produced by muon spallation inside scintillating volumes

**Constrained by readout electronics model parameters constrained by fit to gamma+boron calibration data**

- Ionizing energy scale from inverse beta decay (IBD) interactions in a 1-8 MeV energy range
- 5-parameter fit to $\gamma + ^{12}$B data
- Absolute energy scale
- Birks constant
- Relative contribution from Čerenkov light
- Size and decay constant of electronics model

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$$K_{\gamma} = \int K_{\gamma}(x) \cdot K_{\gamma}(x) \cdot A(x) \cdot B(x) \cdot C(x)$$

**Data**

- Benchmark experiment using uncalibrated electronics
- Calibration of readout electronics response using flash ADC

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