Simulating the Gösgen Nuclear Reactor Experiment in Search of a Sterile Neutrino

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Introduction

Neutrinos:

- At least 500,000 times less massive than electrons
- Only interact via the weak force and gravity
- Exist in three known flavors—electron, muon, and tau—which they oscillate between as they travel
- Most studied at nuclear reactors

Figure 1: Nuclear Reactor in Gösgen, Switzerland

The Gösgen Nuclear Reactor Experiment[4]:

- The reactor produced 5 x 10^{20} electron antineutrinos/ second
- Three detectors at 37.9, 45.9, and 64.7 m
- Used a two-neutrino approximation to approximate oscillation probability using the first and third mass eigenstates, and the electron and not-electron neutrino flavors

Reactor Antineutrino Anomaly[3]:

- Nuclear reactor experiments with baselines less than 100 m see a deficit in electron antineutrinos
- The cause: there are not just three neutrinos as the experimentalists assume
- We believe these neutrinos oscillated into a fourth flavor, the sterile neutrino

Motivation

Discovering a fourth neutrino would:

1. Shatter the standard model which only lists three neutrino flavors
2. Change how the evolution of the universe is understood
3. Possibly explain mystery of dark matter[2]

Outline

Our big question: **Does the Gösgen experimental data favor a fourth neutrino?** We had two steps to answer this:

1. Perfect a model that reproduces Gösgen's χ^2 90% exclusion region
   - ➢ χ^2 tells us how well the model fits the data by comparing experimental to theoretical
   - ➢ A smaller χ^2 implies a better fit
   - ➢ The χ^2 depends on Δm^2, the mass squared difference, and $sin^2 2\theta$, the mixing angle
   - ➢ The exclusion region excludes values for $\Delta m^2$and $sin^2 2\theta$ at a 90% confidence level
2. Update the model to see what the data tells us about the fourth neutrino

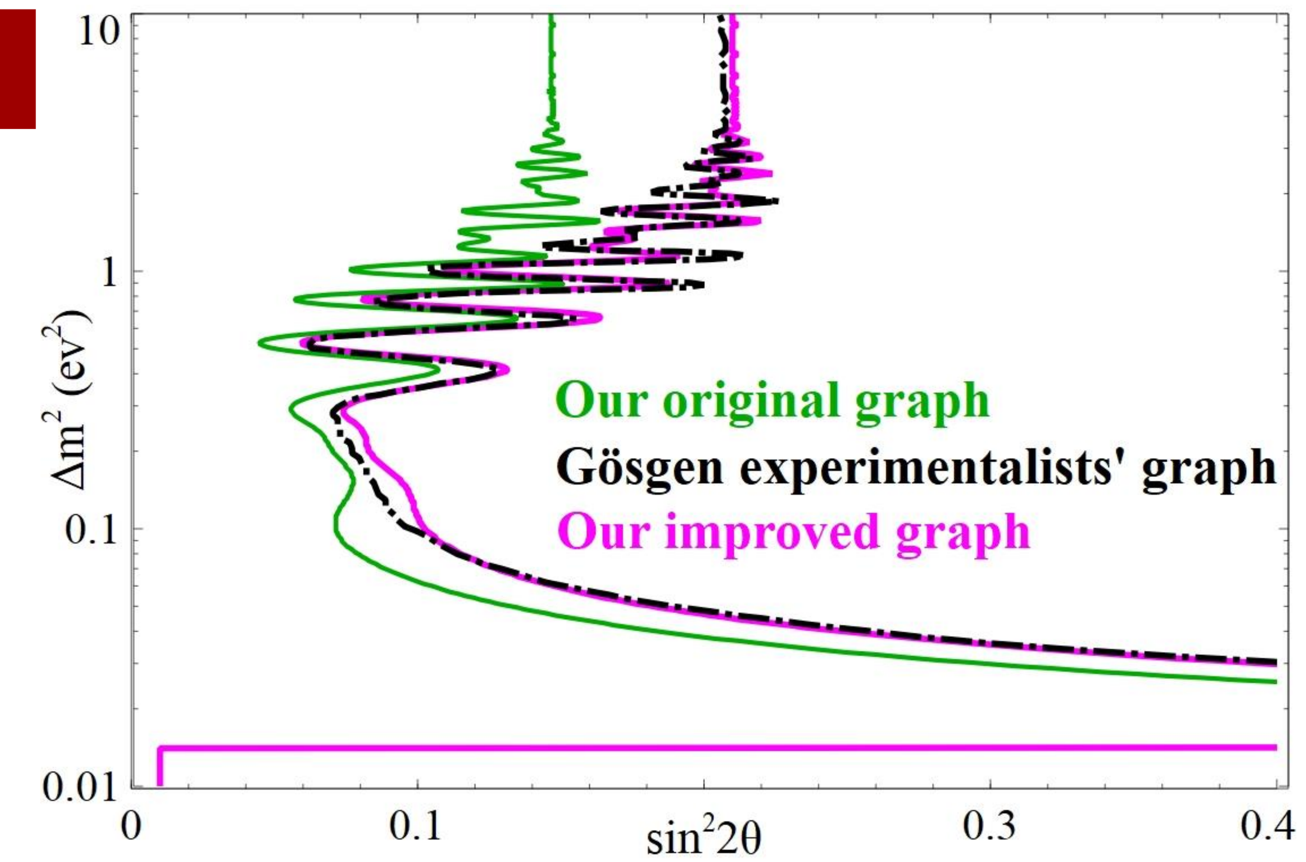
Method

To perfect our model:

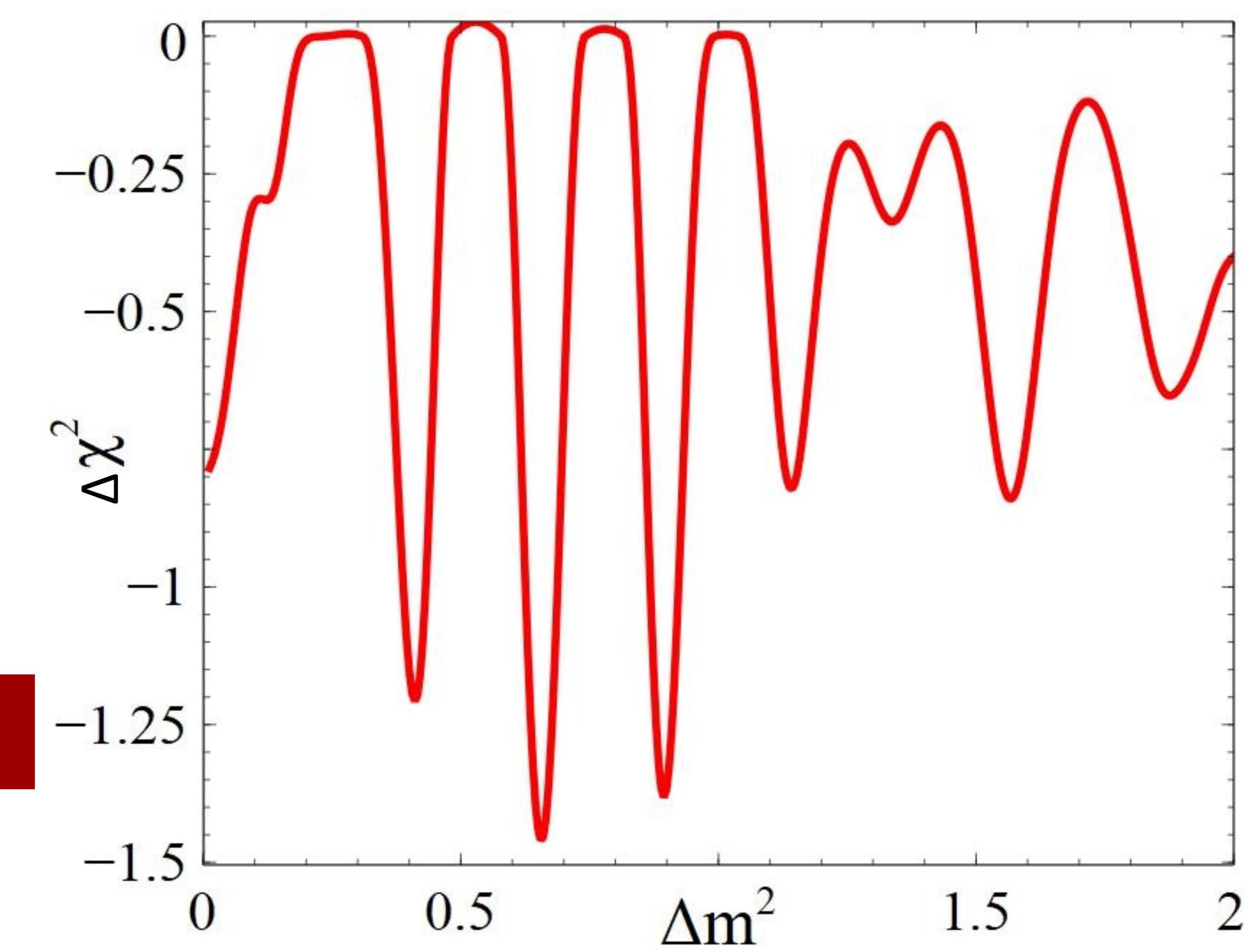
- I added two calibration parameters to the χ^2 equation
- These scaled the statistical error and the theoretical spectrum
- Our model then produced a graph that matched that of the experimentalists (*Graph 1*)

To compare the χ^2 analyses:

- I added a routine that produced a graph of $\Delta\chi^2$ (*Graph 2*)
- $\Delta\chi^2$ is the χ^2 of the four-neutrino analysis subtracted by the χ^2 of three-neutrino analysis
- The dips show which values the four-neutrino analysis favors for Δm^2



Graph 1:The 90% exclusion region for the oscillation parameters , Δm^2 and $sin^2 2\theta$



Graph 2: The $\Delta\chi^2$ minimized with respect to $sin^2 2\theta$, showing which Δm^2 are most probable

Δm^2 (eV^2)	$Sin^2(2\theta)$	$\Delta\chi^2$
0.411	0.047	-1.207
0.655	0.061	-1.460
0.894	0.071	-1.382
1.143	0.063	-0.822

Table 1: The most likely Δm^2 & $Sin^2(2\theta)$ values and their corresponding $\Delta\chi^2$ values

Results & Conclusion

- We accurately reproduced the experimentalists' results (*Graph 1*)
- Found four favored values for Δm^2 of oscillations including the fourth neutrino (*Table 1*)
- These Δm^2 values are 100+ times larger than Δm^2_{31}.[1] So these must be for the fourth neutrino.

Next Steps

- We currently use the accepted two neutrino approximation for the four-neutrino oscillation probability:

$$P_{ee} = 1 - sin^2(2\theta_{13})\, sin^2(\frac{1.27\Delta m^2_{31} L}{E})$$

- We will look into using a non-approximated four-neutrino probability
- Apply the method used here (calibration parameters) to other experiments in order to reproduce their results
- Combine results from this experiment with 17 others to make a statistically more significant statement for the fourth neutrino

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