Physics of $\nu$-A Interactions

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Oscillation Signals as $F(E_\nu)$


DUNE, 1300 km
HyperK (T2K) 295 km

Energies have to be known within 100 MeV (DUNE) or 50 MeV (T2K)

Ratios of event rates to about 10%

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What is (not) measured in a LBL exp?

- The neutrino energy on this plot is not measured
- LBL experiments measure only flux-averaged cross sections

BUT:

- Extraction of neutrino oscillation parameters requires neutrino energy event by event
  ➔ needs nuclear theory and modeling
Oscillation signal in T2K
\( \delta_{CP} \) sensitivity of appearance exps

Reconstruction error as large as \( \delta_{CP} \) dependence


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First Take-Home Message

- Whenever you see a plot with the neutrino-energy on an axis: ask yourself where this energy comes from!
Problem: Neutrino Energy

- The incoming neutrino energy on the abscissa of all such plots is not known, but must be reconstructed from an only partially observed final state (detector limitations!), backwards‘ to the initial state.

- This reconstruction requires:
  1. Knowledge of neutrino-nucleus cross sections
     ⇔ knowledge of neutrino-nucleon cross sections
  2. Transport of initially produced hadrons through the nuclear volume, needs good knowledge of hadron-hadron FSI cross sections
Neutrino Parameter Uncertainties

From J. Wolcott, NUINT2018
Neutrino-Nucleon Cross Sections

Experimental error-bars directly enter into neutrino-nuclear cross sections and limit accuracy of energy Reconstruction, most of these data ~ 35 years old

BUT: this is only part of the problem, The other part is FSI, since experiments use nuclear targets

All modern long-baseline experiments

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First Conclusion

- The elementary cross sections for *neutrino + nucleon* can only be improved by new measurements on *H* and *D* targets.
- Theory cannot deliver these observables (within the next 10 years) not even in LQCD.
Neutrino Cross Sections: Nucleus

- All targets in long-baseline experiments are nuclei: C, O, Ar, Fe

- Cross sections on the nucleus:
  - QE + final state interactions (fsi)
  - Resonance-Pion Production + fsi
  - Deep Inelastic Scattering $\rightarrow$ Pions + fsi

- Additional cross section on the nucleus:
  - Many-body effects, e.g., 2p-2h excitations
  - Coherent neutrino scattering and coh. pion production
A wake-up call for the high-energy physics community:

Nuclear Physics determines response of nuclei to neutrinos

Wake up, Dr. ......, you're being transferred to low energy physics
All targets in long-baseline experiments are nuclei: C, O, Ar, Fe

Cross sections on the *nucleus*:
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Generators describe $\nu A$ interactions?

- Take your favorite neutrino generator (GENIE, ...):
  
  „*a good generator does not have to be right, provided it can be made to fit the data*“

- All of these ‘standard‘ generators neglect from the outset:
  - Nuclear binding
  - Final state interactions in nuclear potential
  - Same ground states for different processes

- Generators use outdated physics: e.g. Rein-Sehgal for resonances

- Time to build new, consistent generators, based on present day’s nuclear physics, both for initial interaction and the final state interactions

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Proto-Dune Generator

- Quantum-kinetic Transport is the state-of-the-art method to describe non-equilibrium nuclear processes (e.g. QGP ALICE physics)

- Transport can also be used to describe vA reactions: it evolves an 8-dimensional phase-space distribution $F(x,p)$ in time.

- Theoretical Basis: Kadanoff-Baym equations in the gradient approximation, Botermans-Malfliet off-shell handling
Quantum-kinetic Transport Theory

Describes the time-evolution of $F(x,p)$

\[
D F(x,p) - \text{tr} \left\{ \Gamma f, \text{Re} S^{\text{ret}}(x,p) \right\}_{PB} = C(x,p).
\]

For each particle species one such equation, all coupled by the collision term $C$.

Wigner-distribution of the one-body density matrix = spectral function

Kadanoff-Baym equations

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GiBUU : Quantum-Kinetic Theory and Event Generator based on a BM solution of Kadanoff-Baym equations

- GiBUU propagates phase-space distributions, not particles

- Code from gibuu.hepforge.org, new version GiBUU 2019
**GiBUU** describes: (within the same unified theory and code)

- heavy ion reactions, particle production and flow
- pion and proton induced reactions on nuclei
- photon and electron induced reactions on nuclei
- neutrino induced reactions on nuclei

using the same physics input! And the same code!

**NO TUNING!**
The GiBUU Generator

- Code written in modern Fortran 2003, open source, well commented throughout
- Produces millions of events on 'normal' PC, within a day of running time
- Gives result file with four-vectors of all final state particles on event-by-event basis, plus other relevant information, such as history-info on primary reaction mechanism (QE, DIS, Res,…)
- Allows for reweighting of events because of history info
- Applicable for quasiclassical regime: energy transfer >~ 50 MeV

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Inclusive QE Electron Scattering

- a necessary check for any generator development

**2.2 GeV, 15 deg, Q^2 = 0.3 GeV^2**

Target: C

**0.56 GeV, 60 deg, Q^2 = 0.24 GeV^2**

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T2K Inclusive Cross Section


GiBUU curves differ by factor 2 in 2p2h

Target: CH

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ArgoNeUT inclusive

Data: ArgoNeuT


ArgoNeUT used a high-energy beam close to DUNE
Pion Production on LAr

ArgoNeut
arXiv:1804.10294
Antineutrinos

Excellent agreement of GiBUU with Ar data
NO Tune
DUNE Challenge: $^{40}\text{Ar}$

- $^{40}\text{Ar}$ not isospin symmetric, $N > Z$: isospin $T = 2$
- Isospin dependence of nuclear processes?
- Relation to electron scattering process?
  - Wigner-Eckart theorem gives factor $T + I = 3$ for neutrino/electron
- CHECK: how well does GiBUU do on ArgoNeut data?
Event Distributions in DUNE ND

2p2h contributes with < 5%

Pion channels (Res + DIS) are dominant
At MB $n < p$, at DUNE $n \sim p$:

$n$ not suppressed at DUNE because of pi-production channels
Dramatic improvement in $0\pi + 1p + Xn$ sample, down by only factor 3

$\Rightarrow$ Kinematic reconstruction useful also at DUNE energies

Mosel et al.,
Summary I

- Energy reconstruction is essential for precision determination of neutrino oscillation parameters (and nu-hadron cross sections)
- Neutrino energy must be known within at least about 50 (T2K) or 100 (DUNE) MeV
- Uncertainties in elementary $\nu N$ cross sections limit any reconstruction
- Nuclear effects complicate the energy reconstruction even further
- Need generators for E-reconstruction, based on up-to-date Nuclear Theory with predictive power and no artificial degrees of freedom

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Summary II

- GiBUU is a first step into that direction (ProtoDUNE generator), gives good description of all cross sections, both for electrons and neutrinos, without tune.
- Experiments at the DUNE ND are essential because they allow to test generators on an unexplored target (Ar) in an unoscillated beam.
- Until DUNE operates: have an Ar target (ProtoDUNE ?) in a higher energy beam (at CERN?).
- Theory and Generator Development should be an integral part of any such experiment (and its funding!)
Essential References:

   contains both the theory and the practical implementation of transport theory

   contains the latest changes in GiBUU2016

   short review, contains some discussion of generators

   https://dx.doi.org/10.1088/1361-6471/ab3830
   general review of neutrino generators

Most of the work reported here was done in collaboration with Kai Gallmeister