### Single photons in neutrinonucleus scattering: overview and some theory considerations

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## Outline

- history/introduction/motivation
- neutrino oscillation implications (sterile neutrino?)
- other new physics implications (proton decay?)
- astrophysical implications (pulsar kicks?)
- nucleon-level knowledge
- nuclear issues

#### Motivations **FIG. 1: The EQUATE CONCLUDENT CONCLUSION FOR EXAMPLE 2007**



*[MiniBooNE, PRL 102, 211801 (2009)]*

~ irreducible background for  $v<sub>e</sub>$  appearance

**1** MiniBooNE(other) experiments are(will be) sensitive to this cross section

*theoretical:* 

Any fields coupling to anomalous symmetries must have peculiar interactions  $\gamma$ 



 $\partial_{\mu}J^{\mu}_{5} \propto \epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} \Rightarrow \mathcal{L} \sim \epsilon^{\mu\nu\rho\sigma} \pi F_{\mu\nu}F_{\rho\sigma}$ 

Similarly, for any field coupled to baryon number



 $\partial_{\mu}J_{\text{baryon}}^{\mu} \propto \epsilon^{\mu\nu\rho\sigma}\partial_{\mu}Z_{\nu}F_{\rho\sigma} + \ldots \quad \Rightarrow \qquad \mathcal{L} \sim \epsilon^{\mu\nu\rho\sigma}\omega_{\mu}Z_{\nu}F_{\rho\sigma}$  $\Rightarrow$ 

*[Harvey, Hill & Hill, PRL 99, 261601 (2007)]* 

*If Z was much lighter, would see e.g.* ω→*Z*γ *directly.* 

$$
Br(\omega \to \gamma \nu \bar{\nu}) \sim \left(\frac{g_{\text{weak}}^2}{m_W^2}\right)^2 \frac{f_{\pi}^6}{m_{\omega}^2} \sim \frac{G_F^2 f_{\pi}^6}{m_{\omega}^2} \sim \text{tiny}
$$

*But in practice, Z is heavy (weak interactions are weak !)*

*Compare Primakoff effect:*



*scattering off baryon number*

 $\omega$ 

 $\gamma$ 

My My

## Oscillation implications

#### Fig. 2. The normalization assumes an energy- and angletan braductio ton productio **1σ 0.2 0.4 0.6 0.8 1 1.2 1.4 -0.2**  $\blacksquare$  (color online). Single-photon events at  $\blacksquare$  $200$  and the seen from this table that table the seen from this table table table that the seen from this table the direct estimate of the number of single-photon events broguction. simple model for single photon production:





#### $\mathbb{P}_{\mathbb{P}}$  . The effects of a larger incoherent  $\mathbb{P}_{\mathbb{P}}$  $p_{\rm eff}$  and direct estimate (i.e.,  $p_{\rm eff}$  estimate (i.e.,  $p_{\rm eff}$  ) and  $p_{\rm eff}$ **0** *[RJH PRD 84, 017501 (2011)]*





not matter whether the MiniBooNE ! **incoh.** ∆ **coh.** ω **20 incoh.** ∆  $\overline{\mathbf{m}}$ **incoh.** ω **coh.** ∆ *[MiniBooNE, PRL 105, 181801 (2010)]* [MiniBooNE, PRL 102, 211801 (2009)]

 $\mathbf{1}$ incoherent processes. In the latter coherent processes of the latter case, th difference between the !0-constrained background and the direct early in the figure by including 0.5 times the direct estimate for nd chollid ha  $\mathbf H$ ild silould be MiniBooNE data [5] with other backgrounds subtracted in MiniBooNE data [28] with other backgrounds subtracted in icloan/nucloan ucleon/nuclear MiniBooNE !-mode in ranges of EQE. Ranges in square brackets **events 30 50 ix/r neutron Compton proton Compton** that can and should be debated: Within nucleon/nuclear/flux/reconstruction/.. uncertainties

 $\overline{\phantom{a}}$  so which  $\overline{\phantom{a}}$  so which  $\overline{\phantom{a}}$  so  $\overline{\phantom{a}}$  $\sim$  - and under II IJ. GIJLI II  $475-125$  MeV bins, respectively. If no additional incoassured hackgrou easul eu *D*al  $M:$ ... Neglected single-photon events give a significant con-1\$, non-! 85[17–26] 151[30, 45] 159[32, 48] **ASSUPAD hackord** casul cu *b*achgi c **LASSER CO DUCKS** CATE WICH APPT OAT  $\mathcal{L}_{\text{max}}$   $\mathcal{L}_{\text{M}}$ : $\mathcal{D}_{\text{max}}$ ION OT MINIBOOI MB !"e ! !"e 6.1 4.3 6.4 **0** - an unmeasured background with approximate size and kinematic distribution of MiniBooNE's excess

 $\overline{\phantom{a}}$   $\overline{\$  $\blacksquare$  = 2DDCO)  $\mathbf{u} \mathbf{v}$   $\mathbf{v}$ been assumed, in accordance with a comparison to MAC BACKGROUNDS IN TABLE IN THE BACKGROUNDS IN THE BACKGROUNDS IN THE BACKGROUNDS IN THE BACKGROUNDS IN THE BA direct estimate of  $\alpha$ mate agreement  $m$ induction agriculture based on  $R$ - approximate agreement between neutrino and antineutrino modes for paper, and is consistent with the absence of a significant ennancement re required enhancement relative to MC

# Astrophysical implications?

An enhanced coherent single-photon cross section has interesting implications



may also play a significant role in neutron star cooling similar dynamics may play a role in pulsar kicks - large velocities of important applications in various other physical regimes. supernova remnants, generated by asymmetric neutrino emission

effective electron magnetic moment (large)

elsewhere, including the detailed derivation of pCS and  $\alpha\beta B$  *[Vilenkin ApJ 451, 700 (1995), ...]*

[1] J. S. Bell and R. Jackiw, Nuovo Cim. A 60, 47 (1969). **Example 2. Linuxerse mean fr Example 20** The case of the c  $\overline{\mathbf{r}}$ inverse mean free path (small)  $\overline{\phantom{a}}$ contribution of electron to

parity violation and significant Interaction that has both significant parity violation *and* significant o. Generate observed kick contribution to scattering required to generate observed kick

 $j_{pv}/j_0 \sim \alpha \beta B$ 

# Implications for proton decay



Experimental reach limited by atmospheric backgrounds

These backgrounds differ in the hadronic final state, in particular neutron content

Significant overlap with neutrino cross section problem: energy range, need to understand final state interactions

Could imagine a situation where a few signal-like events are detected, but proton decay interpretation relies on O(1) factors in predicted neutron fraction of neutrino backgrounds

Any new experimental handles are useful

## Nucleon level knowledge

#### Why is it so #?! hard to calculate?

- what are the errors ?  $\approx$  what is the expansion ?
- need to get creative:  $1/N_c$ ,  $z$  (dispersive),  $1/A$  (nucleus), ...
- model independent approach: decompose into helicity amplitudes. but 12 of them, depending on multiple kinematic invariants - need dynamical model/small parameter expansion

Caution is warranted. E.g., in the case of axial-vector form factor entering CCQE. Only one poorly constrained invariant amplitude F<sub>A</sub> a function of only *one* kinematic variable Q2, yet significant (~40%) cross section uncertainty 13

#### It is now straightforward to write down the Lagrangian  $\mathbf{L}$ Systematic expansion at low energy:

$$
\mathcal{L}^{(0)} = -c^{(0)}\bar{N}N, \qquad \mathcal{L}^{(1)} = \bar{N}[c_1^{(1)}i\vec{p} - c_2^{(1)}A\gamma_5]N,
$$
\n
$$
\mathcal{L}^{(2)} = \bar{N}\Big[-c_1^{(2)}\frac{i}{2}\sigma^{\mu\nu}\operatorname{Tr}([iD_{\mu},iD_{\nu}]) - c_2^{(2)}\frac{i}{2}\sigma^{\mu\nu}\tau^a\operatorname{Tr}(\tau^a[iD_{\mu},iD_{\nu}]) + \cdots\Big]N,
$$
\n
$$
\mathcal{L}^{(3)} = \bar{N}[c_1^{(3)}\gamma^{\nu}[iD_{\mu},\operatorname{Tr}([iD^{\mu},iD_{\nu}])] + c_2^{(3)}\gamma^{\nu}[iD_{\mu},\tau^a\operatorname{Tr}(\tau^a[iD^{\mu},iD_{\nu}])] + c_3^{(3)}\gamma^{\nu}\gamma_5[iD_{\mu},[iD^{\mu},A_{\nu}]] + c_4^{(3)}i\epsilon^{\mu\nu\rho\sigma}\gamma_\sigma\operatorname{Tr}(\{A_{\mu},[iD_{\nu},iD_{\rho}]\}) + c_5^{(3)}i\epsilon^{\mu\nu\rho\sigma}\gamma_\sigma\tau^a\operatorname{Tr}(\tau^a\{A_{\mu},[iD_{\nu},iD_{\rho}]\}) + c_6^{(3)}\gamma^{\nu}\gamma_5[[iD_{\mu},iD_{\nu}],A^{\mu}] + c_7^{(3)}\frac{1}{4m}\gamma^{\nu}\gamma_5([[iD_{\mu},iD_{\nu}],A_{\rho}],\{iD^{\mu},iD^{\rho}\} + \cdots]N.
$$

coherent coupling of vector tax where  $\mathbf{w}$  restrictions, the isovector gauge couplings of the set of  $\mathbf{w}$ coherent coupling of vector+axial-vector fields to baryons

cian broake down at energies of sion breaks down at <del>elier gies</del> of  $\tau_{\rm r}$ der f $_{\rm r} \sim 100$  MeV Expansion breaks down at energies of order f<sub>π</sub> ~ 100 MeV  $\qquad \qquad$   $\qquad$ 

del by resonance insertions ("sticking in form i og den større og den stø<br>Nordelsen og den større og s *j* or dispersive analysis to relat udes to observables amplitudes to observables  $\overline{\tilde{f}}$  $z_{\text{p}}$  is neutral gauge fields such as the  $z_{\text{p}}$ factors") or dispersive analysis to relate invariant  $\frac{Z}{\sqrt{N}}$ ⇒ model by resonance insertions ("sticking in form



#### illustrative variations for Delta resonance modeling



## Nuclear issues

#### Why is it so #?! hard to calculate?

- nuclear cross sections at 1 GeV (#?!)
- must translate nucleon-level amplitudes to nuclear cross sections
- final state interactions:  $O(1)$  factors relating nucleonlevel ratio of pi0/gamma to nuclear-level
- experimental handles in electron scattering?

Dipping a toe into the nuclear realm...

$$
\frac{1}{p^2 - m_\Delta^2 + i m_\Delta \Gamma_\Delta} \qquad \qquad \Gamma_\Delta \sim \Gamma_0 (p_\Delta / p_0)^3
$$

$$
m_\Delta \to m_\Delta + \delta \Sigma
$$

 $\delta \Sigma = V(E_\gamma)F(q^2)$ Model self-energy by phenomenological model (calibrated from pion photoproduction on helium, carbon)



Gross features unchanged. This

#### Single photon production in ν-N overview

- ~irreducible background to  $v_e$  appearance searches: must be directly measured (cf. Katori's talk)
- other motivations to measure and constrain neutron content in neutrino nucleus scattering: e.g., important background for proton decay
- potentially interesting astrophysical implications of an enhanced neutral current interaction in presence of e.m. fields and baryons
- difficulties at both nucleon and nuclear levels
- nucleon level: invariant amplitude decomposition and hadronic modeling (cf. talks of Zhang, Nieves and Ruso)
- nuclear level: final state interactions significantly affect pi0/gamma ratio emerging from nucleon-level interactions
- the stakes are large: important backgrounds for sterile neutrinos, proton decay, potential astrophysical implications within SM
- requires dedicated efforts at particle, nucleon, nuclear, detector levels