Constraining Neutrino Electromagnetic Properties by Atomic Ionization [1]

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Outline

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EM Form Factors of Spin-1/2 Particles

The general EM current matrix element:

$$\langle p'|j_\mu^{(\gamma)}(0)|p\rangle = \bar{u}(p')\Big[F_1(q^2)\gamma_\mu - iF_2(q^2)\sigma_{\mu\nu}q^\nu + F_A(q^2)\left(q^2\gamma_\mu - \not{q}q_\mu\right)\gamma_5 + F_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5\Big]u(p)$$

- $\mathbb{q} \equiv F_1(0)$: charge (P,T-even)
- $\langle \mathbb{r}^2 \rangle \equiv 6\frac{d}{dq^2}F_1(q^2)|_{q^2=0}$: charge radius squared (P,T-even)
- $\mathbb{\kappa} \equiv F_2(0)$: anomalous magnetic dipole moment (P,T-even)
- $\mathbb{d} \equiv F_E(0)$: electric dipole moment (P,T-odd)
- $\mathbb{a} \equiv F_A(0)$: anapole moment (P-odd,T-even)

$\mathbb{q}_\nu$ in the Standard Model (and Beyond)

Trivial Answer

Zero, by construct.

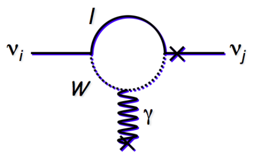
Non-trivial Answer

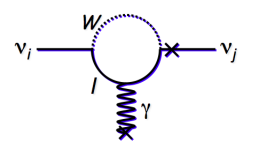
Consider: (i) gauge symmetry and (ii) anomaly cancellation

- SM with only ν_L: charge quantization and $\mathbb{q}_\nu = 0$
- Extended SM with ν_R and Majorana masses: same conclusion
- Extended SM with ν_R and Dirac masses:
  - charge quantization loss (unbroken $B - L$ symmetry)
  - $\mathbb{q}_\nu = \epsilon$, $\mathbb{q}_e = \epsilon$, $\mathbb{q}_p = 1 - \epsilon$, $\mathbb{q}_n = -\epsilon$
  - by charge neutrality of H and n: $|\mathbb{q}_\nu| \lesssim 10^{-21}\ e$

κ_ν and $\mathbb{d}_\nu$, in the Standard Model

- If massless: $\kappa_\nu = 0$, $\mathbb{d}_\nu = 0$ (no chirality flip)
- Now known $m_\nu \neq 0$, non-zero κ_ν and $\mathbb{d}_\nu$ arise from radiative corrections with mass-term insertion, e.g.:





- Naive dimensional analysis with $m_\nu \sim 1\text{eV}$

$$\begin{matrix} \kappa_\nu \\ \mathbb{d}_\nu \end{matrix} \sim \frac{e}{4\pi} \frac{G_F}{\sqrt{2}} m_\nu \sim \begin{matrix} 5 \times 10^{-19}\, \mu_{\rm B} \\ 5 \times 10^{-30}\, e\,\text{cm} \end{matrix}$$

- One-loop results for $i = j$:
  $\kappa_\nu = 3.20 \times 10^{-19} (\frac{m_\nu}{\text{eV}}) \mu_{\rm B}$, $\mathbb{d}_\nu = 0$ (Marciano; Lee & Shrock, '77)
- In ultrarelativistic scattering ($m_\nu \approx 0$), EM scattering amplitude depends on
  $\mu_\nu = \kappa_\nu - i\mathbb{d}_\nu$

Implications of Abnormally-Large $\mathfrak{q}_\nu$ and μ_ν

- Potential new physics!
- Astrophysical implications
  - Solar neutrino problem ($\nu_e \to \nu_{x \neq e}$ by $B_\odot$)
  - Stellar ($\odot$, W.D., R.G.,) cooling ($\gamma^* \to \nu\bar{\nu}$)
  - Supernovae and neutron stars cooling ($\nu_L \to \nu_R$)
  - Big-Bang nucleosynthesis d.o.f. ($\nu_L \to \nu_R$)
- Cosmological implications
  - What if a primordial magnetic field exists? ($\nu_L \leftrightarrow \nu_R$)
  - What if a neutrino decay radiatively? ($\nu_i \to \nu_f + \gamma$)

Indirect bounds can be inferred from these astro. and cosmo. constraints:

- $\mathfrak{q}_\nu < 10^{-13} - 10^{-15}\, e$
- $\mu_\nu < 10^{-10} - 10^{-13}\, \mu_\mathrm{B}$

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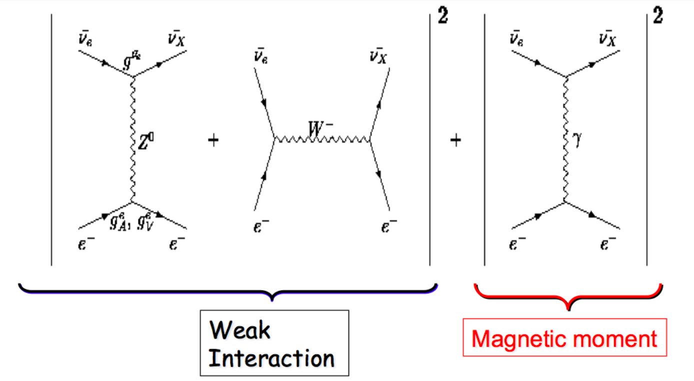
Direct Searches of q_ν and μ_ν

Primary detection channel: the recoil electron in atomic ionization

$$\nu + e^-(\mathrm{A}) \to \nu + e^- + \mathrm{A}^+$$

e.g. a non-zero μ_ν yields:



Current Limits

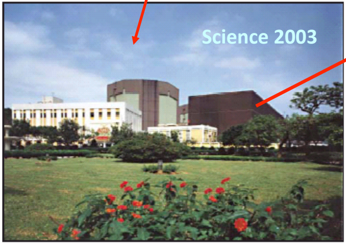
- A few results on μ_ν (in μ_B):

Exp.	ν_l	$\mu_\nu <$	Yr	Place
GEMMA	$\bar{\nu}_e$ (reac.)	2.9×10^{-11}	'13	KNPP, RU
TEXONO	$\bar{\nu}_e$ (reac.)	7.4×10^{-11}	'07	KSNL, TW
Borexino	$\nu_\odot$ (^{7}Be)	5.4×10^{-11}	'08	LNGS, IT
SuperK	$\nu_\odot$ (^{8}B)	3.6×10^{-10}	'04	Kamioka, JP
LSND	ν_μ (acc.)	6.8×10^{-10}	'01	LANL, US
DONUT	ν_τ (acc.)	3.9×10^{-7}	'01	FNAL, US

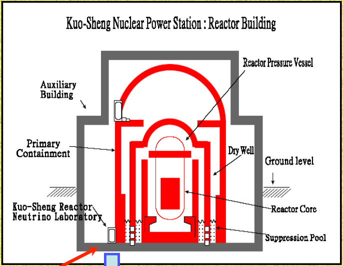
- A few results on q_ν (in e):

Exp.	ν_l	$q_\nu <$	Yr	By
GEMMA	$\bar{\nu}_e$ (reac.)	1.5×10^{-12}	'13	Studenikin
TEXONO	$\bar{\nu}_e$ (reac.)	3.7×10^{-12}	'07	Gninenko et al.

Kuo Sheng Reactor Neutrino Laboratory (KSNL)



Powerful collaboration. Scientists from Taiwan and mainland China are studying neutrino emissions from this nuclear power plant outside Taipei.

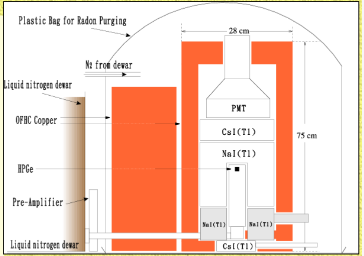


- ☑ 28 m from core#1 @ 2.9 GW
- ☑ ~30 mwe overburden
- ☑ ~10 m below ground level

(courtesy of H. Wong)

TEXONO Magnetic Moment Searches @ KSNL

- simple compact *all-solid* design : HPGe (mass 1 kg) enclosed by active NaI/CsI anti-Compton, further by passive shieldings & cosmic veto
- selection: single-event after cosmic-veto, anti-Comp., PSD
- TEXONO data (571/128 days) ON/OFF) *[PRL2003; PRD 2007]*
  - background comparable to underground CDM experiment : ~ 1 $\text{day}^{-1}\text{keV}^{-1}\text{kg}^{-1}$ (cpd)
  - DAQ threshold 5 keV
    analysis threshold 12 keV



(courtesy of H. Wong)

The Ways of Improvement

- The 4 basics: bigger target mass, longer detection time, smaller background, and more intense beam
- A less trivial sensitivity gain: Consider $\nu + e^- \to \nu + e^-$ at low recoil energies (Vogel & Engel, '89):

$$\frac{d\sigma_w^{(0)}}{dT} \propto T^0 \,,$$

$$\frac{d\sigma_{\mu_\nu}^{(0)}}{dT} \propto \frac{1}{T} \,,$$

$$\frac{d\sigma_{q_\nu}^{(0)}}{dT} \propto \frac{1}{T^2} \,,$$

- Need low-threshold detectors
  - GEMMA: Ge @ 1.5 keV; TEXONO: Ge @ 5 keV (now @ sub-keV!)

At low energies, atomic effects need to be taken into account!

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$\frac{d\sigma}{dT}$: Where Atomic Many-Body Physics Enters

For $\nu + A \to \nu + A^+ + e^-$:

$$\frac{d\sigma_w}{dT d\Omega} = \frac{G_F^2}{2\pi^2}(E_\nu - T)^2 \cos^2\frac{\theta}{2}\Big[R_{00}^{(w)} - \frac{T}{q}R_{03+30}^{(w)} + \frac{T^2}{q^2}R_{33}^{(w)} + (\tan^2\frac{\theta}{2} + \frac{Q^2}{2q^2})R_{11+22}^{(w)} + \tan\frac{\theta}{2}\sqrt{\tan^2\frac{\theta}{2} + \frac{Q^2}{q^2}}R_{12+21}^{(w)}\Big]$$

$$\frac{d\sigma_\mu}{dT d\Omega} = \alpha\mu_\nu^2(1 - \frac{T}{E_\nu})\Big[\frac{(2E_\nu - T)^2 Q^2}{q^4}R_{00}^{(\gamma)} + \frac{4E_\nu(E_\nu - T) - Q^2}{2q^2}R_{11+22}^{(\gamma)}\Big]$$

- The response functions $R_{\mu\nu}^{(w,\gamma)}$ depend on T and $Q^2 = \vec{q}^2 - T^2$.
- Need transition matrix elements $\langle f | j_\mu^{(w,\gamma)} | i \rangle$ of weak $(V - A)$ and EM (V) currents.

The Conventional Approach: Free Electron Approximation

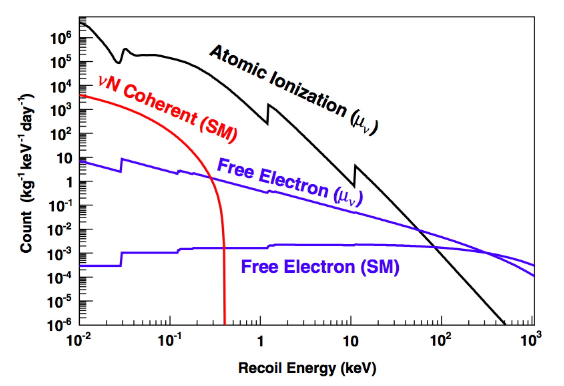
- Suppose E_ν and T much larger than atomic scales, electrons can be treated as free
- An atomic ith electron is not scattered if $T < B_i$
- FEA scattering formula

$$\left.\frac{d\sigma}{dT}\right|_{\mathrm{FEA}} = \sum_{i=1}^{Z} \theta(T - B_i) \frac{d\sigma}{dT}^{(0)}$$

- No atomic calculation needed
- Validity at sub-keV regimes need justification

Can Atomic Effects Change the Traditional Wisdom?

A huge sensitivity gain in μ_ν reported: (Wong et al., PRL '10)



- In contradiction to previous and latter works
- Inadequate equivalent photon approximation being applied (Chen, CPL, et al., '13)

Our Approach: Do the Many-Body Problem

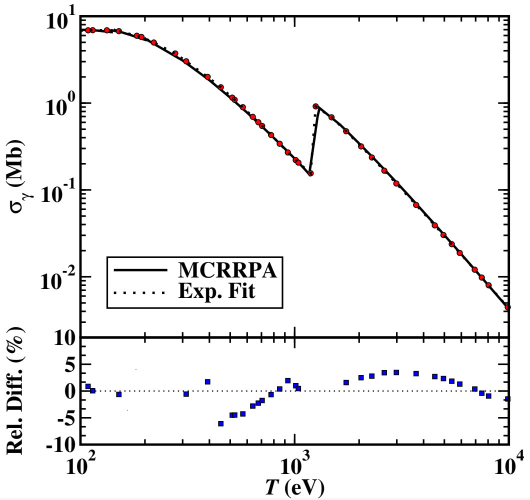
Multi-Configuration Relativistic Random Phase Approximation

- An *ab initio* method based on Hatree-Fock (HF) Approximation
- MC: For open-shell atoms, ground states often contain more than one configuration.
- R: Include leading relativistic effects by solving the Dirac, instead of Schrödinger, equation. [MCDF]
- RPA: Build in (part of) two-body correlations which are important for excited states and transitions.

Specifics for Ge:

- Ground state $|{}^3P_0\rangle = c_1\ |[\mathrm{Zn}]4p^2_{1/2}\rangle + c_2\ |[\mathrm{Zn}]4p^2_{3/2}\rangle$
- $Z\alpha \sim 1/4$, not small
- Need continuum states $|\mathrm{Ge}^+, e^-\rangle$

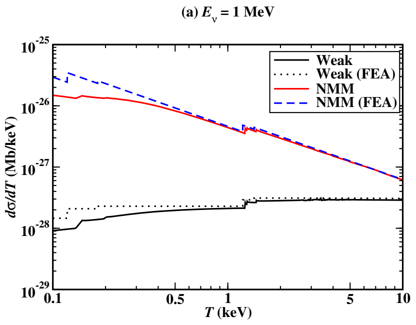
Benchmark: $\gamma + \mathrm{Ge} \to \mathrm{Ge}^+ + e^-$ (Chen, Chi, Huang, CPL, et al., '14)

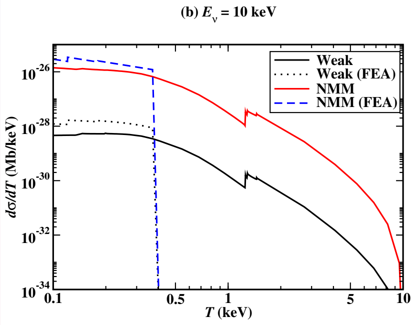


- Exp. data taken from "Atomic Data and Nuclear Data Tables 54, 181-342 (1993)"
- For $T \geq 100\,\mathrm{eV}$, data are well reproduced, with discrepancy $\lesssim 5\%$
- Caution: photoabsorption only benchmarks the on-shell transverse response (best one can do so far)

Ge Ionization by $\mu_{\bar{\nu}_e}$ (Chen, Chi, Huang, CPL, et al., '14)

Setting $\mu_{\bar{\nu}_e} = 2.9 \times 10^{-11}\, \mu_{\mathrm{B}}$:



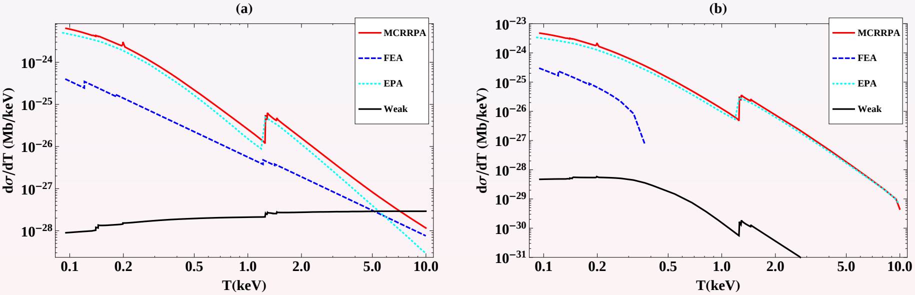


- Typical for reactor $\bar{\nu}_e$
- FEA is good for $T \gtrsim 1\,\mathrm{keV}$
- FEA overestimates at $T \lesssim 1\,\mathrm{keV}$ for both weak and μ_ν interactions

- typical for low-E source, e.g. $^3\mathrm{H}$: $Q \sim 18\,\mathrm{keV}$ (McLaughlin & Volpe, 04)
- FEA has a kinematic cutoff ,i.e., Compton edge (2B vs. 3B final state)

Ge Ionization by $\mathrm{q}_{\bar{\nu}_e}$ (Chen, Chi, Li, CPL, et al., '14)

Setting $\mathrm{q}_{\bar{\nu}_e} = 1 \times 10^{-12}\, e$:



- FEA largely underestimates
- Equivalent Photon Approximation (EPA) works in certain regions

Updated Limits on $q_{\bar{\nu}_e}$ and $\mu_{\bar{\nu}_e}$

- Using MCRRPA instead of FEA, with the GEMMA '13 data set (threshold at 2.8 keV)
  - $q_{\bar{\nu}_e} < 2.1 \times 10^{-12}\ e \rightarrow 1.1 \times 10^{-12}\ e$
  - $\mu_{\bar{\nu}_e} < 2.9 \times 10^{-11}\ \mu_{\mathrm{B}} \rightarrow 2.9 \times 10^{-11}\ \mu_{\mathrm{B}}$
- Projected sensitivities for the future low-threshold germanium detectors (threshold at ~0.1 keV)
  - $q_{\bar{\nu}_e} \sim 0.6 \times 10^{-13}\ e$
  - $\mu_{\bar{\nu}_e} \sim 1.0 \times 10^{-11}\ \mu_{\mathrm{B}}$

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Conclusion

1. Atomic physics starts to be relevant for neutrino detection with detectors at sub-keV thresholds.
2. High-quality atomic calculations substantially reduce the theoretical errors in understanding low-energy detector responses and subsequent physical results.
3. The procedure can be applied to other neutral particle detections, the current shopping list contains
   - Light Dark Matter: $\chi + e^-(\mathrm{A}) \to \chi + \mathrm{A}^- + e^-$ with A = Ge, Xe, Ar, etc.
   - Sterile Neutrino: $\nu_\mathrm{s} + e^-(\mathrm{A}) \to \nu_\mathrm{a} + \mathrm{A}^- + e^-$ (via $\nu_\mathrm{s} \to \nu_\mathrm{a} + \gamma^*$)
   - Suggestions are welcome!

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THANK YOU