

Constraining Neutrino Magnetic Moments with Sub-keV Detectors

C.-P. Liu

National Dong Hwa University, Taiwan

MITP Workshop on Low-Energy Precision Physics
Mainz, Germany
Oct. 11, 2013



Outline

- 1 Introduction
 - Motivation
 - Current Status
- 2 ν -Atom Ionization
 - Formalism
 - Approximations
 - ab initio Calculations
- 3 Summary



Outline

- 1 Introduction
 - Motivation
 - Current Status
- 2 ν -Atom Ionization
 - Formalism
 - Approximations
 - ab initio Calculations
- 3 Summary



EM Moments of Spin-1/2 Particles

The EM current matrix elements:

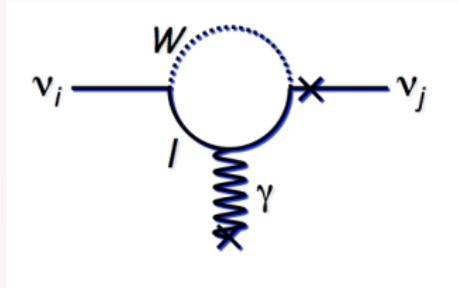
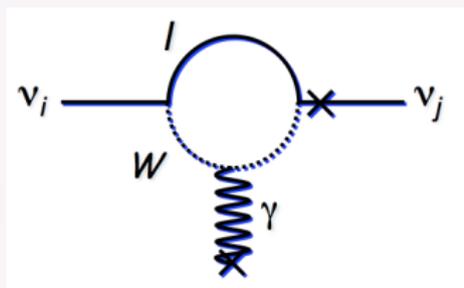
$$\begin{aligned} \langle p' | j_\mu(0) | p \rangle = & \bar{u}(p') \left[F_1(q^2) \gamma_\mu - i F_2(q^2) \sigma_{\mu\nu} q^\nu \right. \\ & \left. + F_A(q^2) (q^2 \gamma_\mu - \not{q} q_\mu) \gamma_5 - i F_E(q^2) \sigma_{\mu\nu} q^\nu \gamma_5 \right] u(p) \end{aligned}$$

- $F_1(0)$: charge (P,T-even)
- $F_2(0)$: anomalous magnetic dipole moment (P,T-even)
- $F_E(0)$: electric dipole moment (P,T-odd)
- $F_A(0)$: anapole moment (P-odd,T-even)
 - gauge-dependent, not observable (Musolf & Holstein, '91)



EM Moments of Neutrinos in the Standard Model

- **Neutral:** $F_1(0) = 0$ (μ_ν purely anomalous)
- If **massless:** $\mu_\nu \equiv F_2(0) = 0$, $d_\nu \equiv F_E(0) = 0$ (no **chirality flip**)
- Now known $m_\nu \neq 0$, non-zero μ_ν and d_ν arise from radiative corrections with **mass-term insertion**, e.g.:



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

$$\mu_\nu \sim \frac{e}{4\pi} \frac{G_F}{\sqrt{2}} m_\nu \sim 5 \times 10^{-19} \mu_B$$

$$d_\nu \sim 5 \times 10^{-30} \text{e cm}$$

- One-loop results:

$$\mu_\nu = 3.20 \times 10^{-19} \left(\frac{m_\nu}{\text{eV}}\right) \mu_B, \quad d_\nu = 0 \text{ (Marciano; Lee & Shrock, '77)}$$

Some Subtleties

1. Neutrinos mix (misalignment of mass and flavor eigenstates)

- static moments μ_{ν_i} (static d_{ν_i} vanish at one-loop)
- transition moments $\mu_{\nu_{fi}}$ and $d_{\nu_{fi}}$

2. Dirac / Majorana Neutrinos?

- If Majorana, only transition moments exist (static ones violate CPT)
- A potential channel to differentiate ν_D/ν_M



Implications of Large μ_ν

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

Indirect bounds can be inferred from these astro. and cosmo. constraints: $\mu_\nu < 10^{-10} - 10^{-13} \mu_B$



Constraints by Naturalness (Bell et al., '05; '07)

- High-scale Λ physics generates m_ν and μ_ν through similar diagrams
 $\implies m_\nu$ and μ_ν are **correlated**
- Because m_ν is severely constrained ($< 2\text{eV}$), so is μ_ν
- By **naturalness** (no fine-tuning), at $\Lambda = 1\text{ TeV}$:

$$\mu_\nu \lesssim 10^{-14} \mu_B, (\text{Dirac})$$

$$\mu_{\tau\mu, \tau e} \lesssim 10^{-9} \mu_B, \mu_{\mu e} \lesssim 10^{-7} \mu_B, (\text{Majorana})$$

- Larger Λ , tighter bound
- The bound for ν_D is quite stringent; for ν_M is less so.



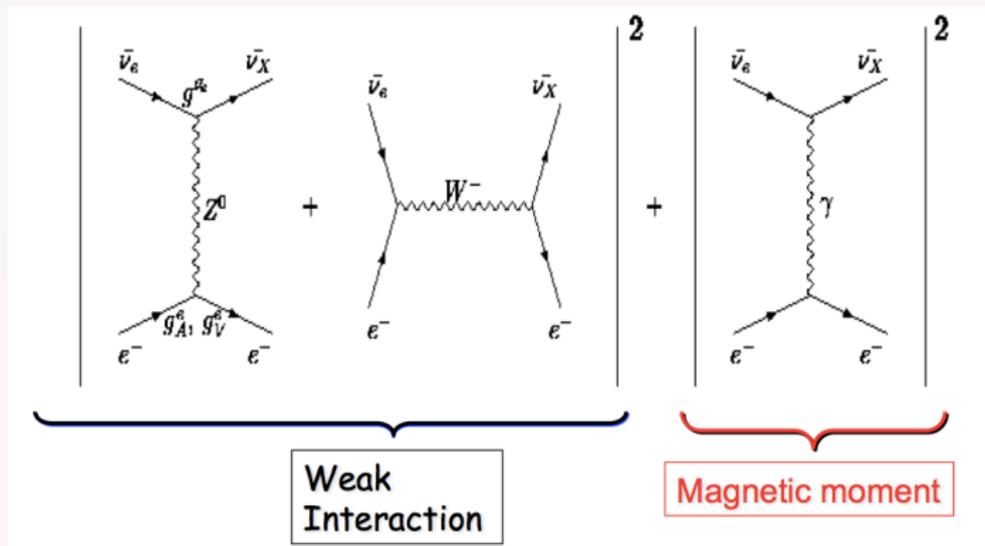
Outline

- 1 Introduction
 - Motivation
 - Current Status
- 2 ν -Atom Ionization
 - Formalism
 - Approximations
 - ab initio Calculations
- 3 Summary



Direct Searches

- Main detection channel: the recoil electron in $\nu + e^-(A) \rightarrow \nu + e^- + A^+$ (primary)



- Weak: helicity-conserving, Magnetic: helicity-flipping



Current Upper Limits

- The observed μ_ν^2 :

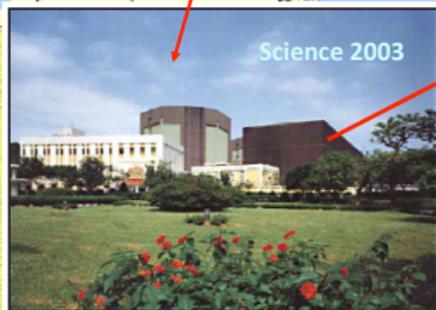
$$\mu_\nu^2(\nu_l, L, E_\nu) = \sum_j \left| \sum_i U_{ij} e^{-iE_\nu L} (\mu_{ij} - d_{ij}) \right|^2$$

- A few results:

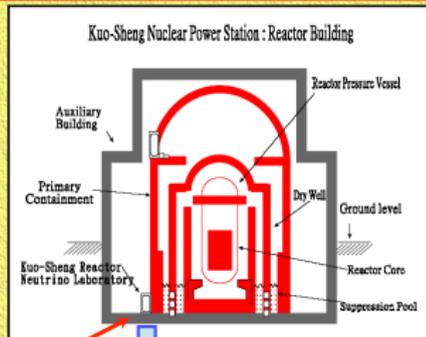
Exp.	ν_l	$\mu_\nu <$	Yr	Place
GEMMA	$\bar{\nu}_e$ (reac.)	2.9×10^{-11}	'13	KNPP, RU
TEXONO	$\bar{\nu}_e$ (reac.)	7.4×10^{-11}	'07	KSNL, TW
MUNU	$\bar{\nu}_e$ (reac.)	1.0×10^{-10}	'03	Bugey, FR
Borexino	ν_\odot (^7Be)	5.8×10^{-11}	'08	LNGS, IT
SuperK	ν_\odot (^8B)	3.6×10^{-10}	'04	Kamioka, JP
LSND	ν_μ (acc.)	6.8×10^{-10}	'01	LANL, US
DONUT	ν_τ (acc.)	3.9×10^{-7}	'01	FNAL, US



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.



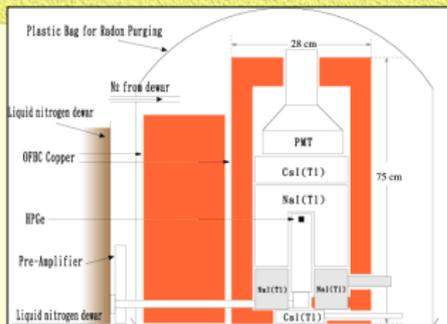
- ✓ 28 m from core#1 @ 2.9 GW
- ✓ ~30 mwe overburden
- ✓ ~10 m below ground level

(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 : $\sim 1 \text{ day}^{-1}\text{keV}^{-1}\text{kg}^{-1} \text{ (cpd)}$
 - ↳ **DAQ threshold 5 keV**
analysis threshold 12 keV



(courtesy of H. Wong)



The Ways of Improvement

- **The 4 basics**: bigger target mass, longer detecting time, smaller background, and more intense beam
- Consider neutrinos scattering off free electrons (Vogel & Engel, '89):

$$\frac{d\sigma_w^{(\text{FE})}}{dT} = \frac{G_F^2 m_e}{2\pi} \left[g_v^2 + g_v'^2 \left(1 - \frac{T}{E_\nu} \right)^2 - g_v g_v' \frac{m_e T}{E_\nu^2} \right],$$

$$\frac{d\sigma_\mu^{(\text{FE})}}{dT} = 4\pi\alpha\mu_\nu^2 \left(\frac{1}{T} - \frac{1}{E_\nu} \right),$$

- At low T , weak scattering stays constant, while magnetic scattering diverges as $1/T$
- Need **low-threshold detectors**
 - GEMMA: Ge @ 1.5 keV; TEXONO: Ge @ 5 keV (now 500 eV!)

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



Outline

- 1 Introduction
 - Motivation
 - Current Status
- 2 ν -Atom Ionization
 - **Formalism**
 - Approximations
 - ab initio Calculations
- 3 Summary



Differential Cross Section $d\sigma/dT d\Omega$

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

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

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

- 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.



Outline

- 1 Introduction
 - Motivation
 - Current Status
- 2 ν -Atom Ionization
 - Formalism
 - **Approximations**
 - ab initio Calculations
- 3 Summary



Stepping Approximation (Kopeikin et al., '97; Fayans et al., '01)

- Ionization of an atomic shell i only happens when $T \geq B_i$.
- Treating the open-channel electrons as free leads to the SA:

$$\frac{d\sigma_{w,\mu}^{(\text{SA})}}{dT} = \sum_{i=1}^Z \frac{d\sigma_{w,\mu}^{(\text{FE})}}{dT} \theta(T - B_i).$$

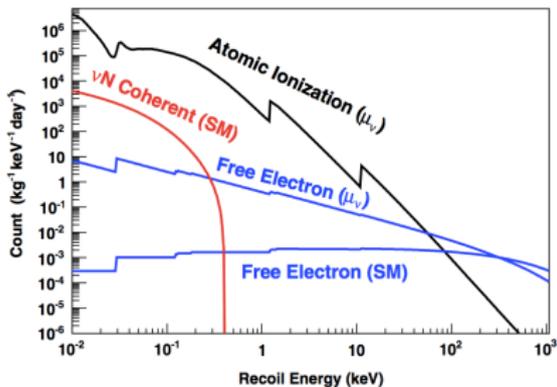
- Easy to implement, and should work well when $T \gg B_j$.
- Overestimate near ionization thresholds $T \sim B_j$.



Equivalent Photon Approximation (for $d\sigma_{\mu}/dT$)

- Two main ingredients of EPA (Weizsacker; Williams '34):
 - Transverse responses dominate (longitudinal ones are ignored)
 - Response functions are on-shell, i.e., $Q^2 = 0$.
- The good thing: $R_{11+22}^{(\gamma)}(Q^2 = 0)$ can be directly obtained from photoionization data.
- Successful for rel. muon stopping power etc.

A big gain? (Wong et al., PRL '10)



Not really:

- R_L sum rule (Voloshin, PRL '10):
 $R_L \gg R_T$, bounded by $R_L^{(FE)}$
- General features (Chen, CPL, et al., PRD '13):
 - (i) no enhancement for R_T
 - (ii) EP spectrum $N(E_{\gamma^*})$ crucial



Outline

- 1 Introduction
 - Motivation
 - Current Status
- 2 ν -Atom Ionization
 - Formalism
 - Approximations
 - ab initio Calculations
- 3 Summary



$\bar{\nu}_e$ Scattering off H-like atoms (Chen, CPL, et al., PRD '13)

- For H-like atoms, the response functions R_L and R_T can be analytically calculated (Nordsieck integrals)

$$R_L^{(1s)} = \frac{2^8 Z^6 \bar{q}^2 (3\bar{q}^2 + \bar{p}_e^2 + Z^2) \exp\left[-\frac{2Z}{\bar{p}_e} \tan^{-1}\left(\frac{2Z\bar{p}_e}{\bar{q}^2 - \bar{p}_e^2 + Z^2}\right)\right]}{3((\bar{q} + \bar{p}_e)^2 + Z^2)^3 ((\bar{q} - \bar{p}_e)^2 + Z^2)^3 (1 - e^{-2\pi Z/\bar{p}_e})}$$

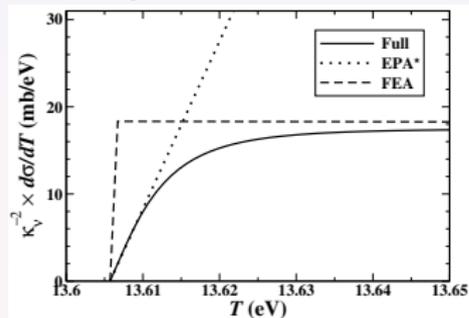
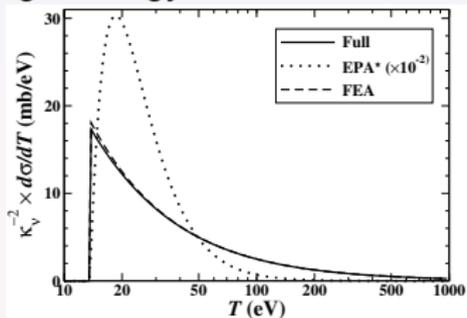
$$R_T^{(1s)} = \frac{2^7 \alpha^2 Z^6 (\bar{p}_e^2 + Z^2) \exp\left[-\frac{2Z}{\bar{p}_e} \tan^{-1}\left(\frac{2Z\bar{p}_e}{\bar{q}^2 - \bar{p}_e^2 + Z^2}\right)\right]}{3((\bar{q} + \bar{p}_e)^2 + Z^2)^2 ((\bar{q} - \bar{p}_e)^2 + Z^2)^2 (1 - e^{-2\pi Z/\bar{p}_e})} + \frac{1}{2} \mu_e^2 \alpha^2 \bar{q}^2 R_L^{(1s)}$$

- The relevant scales: q , p_e , and $Zm_e\alpha$ (binding momentum)
- $Zm_e\alpha$ roughly set the scale below which the free electron picture breaks down

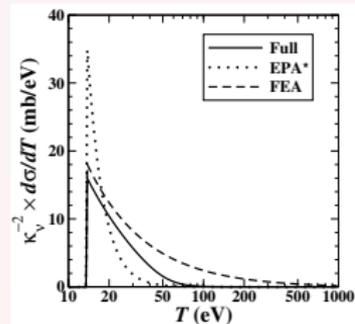
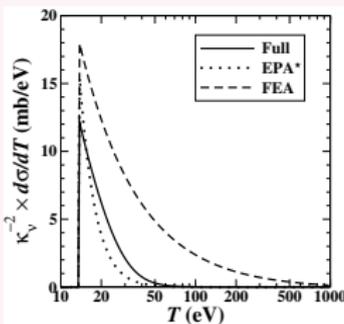
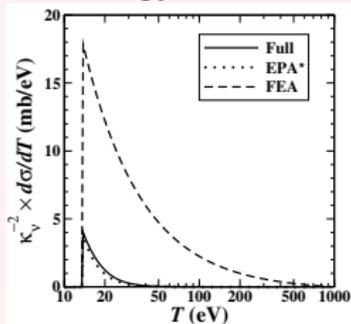


Selected Results for Hydrogen ($Z=1$)

- 1 High energy neutrino: $E_\nu = 1 \text{ MeV} \gg m_e \alpha$



- 2 Low energy neutrino: $E_\nu = 1 - 3 \text{ keV} \approx m_e \alpha$



$\bar{\nu}_e$ Scattering off Ge Atoms

Multi-Configuration Relativistic Random Phase Approximation

- A ab initio method based on **Hartree-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 $|^3P_0\rangle = c_1 |[Zn]4p_{1/2}^2\rangle + c_2 |[Zn]4p_{3/2}^2\rangle$
- $Z\alpha \sim 1/4$, not small
- Need **continuum states** $|\text{Ge}^+, e^-\rangle$



Benchmarks with Ge Structure

- **Single-particle energies** calculated by MCDF vs. **edge energies** extracted from photoabsorption of Ge **solids**¹

	$K(1s_{\frac{1}{2}})$	$L_I(2s_{\frac{1}{2}})$	$L_{II}(2p_{\frac{1}{2}})$	$L_{III}(2p_{\frac{3}{2}})$	$M_I(3s_{\frac{1}{2}})$	$M_{II}(3p_{\frac{1}{2}})$
s.p.	11185.5	1454.4	1287.9	1255.6	201.5	144.8
edge	11103.1	1414.6	1248.1	1217.0	180.1	124.9
	$M_{III}(3p_{\frac{3}{2}})$	$M_{IV}(3d_{\frac{3}{2}})$	$M_V(3d_{\frac{5}{2}})$	$N_I(4s_{\frac{1}{2}})$	$N_{II}(4p_{\frac{3}{2}})$	$N_{III}(4p_{\frac{1}{2}})$
s.p.	140.1	43.8	43.1	15.4	8.0	7.8
edge	120.8	29.9	29.3			

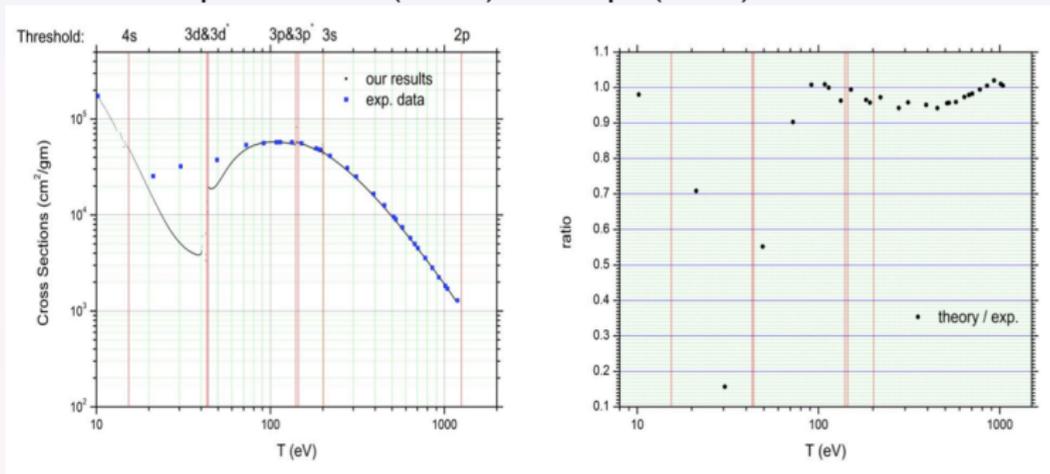
- **Crystal effects** mostly shift outer shells
- **First ionization energy**: 7.856 eV (th.) vs. 7.899 eV (atom. exp.)

¹Atomic Data and Nuclear Data Tables 54, 181-342 (1993)



Benchmarks with Ge Photoabsorption

- Photoabsorption of th. (atom) vs. exp. (solid)²



- For $T > 80\text{eV}$, data are well reproduced, with error $< 5\%$
- Current study $T_{\min} = 100\text{eV}$ (crystal effects for future)
- Caution: photoabsorption only benchmark the on-shell $R_{11+22}^{(\gamma)}$ (best one can do so far)

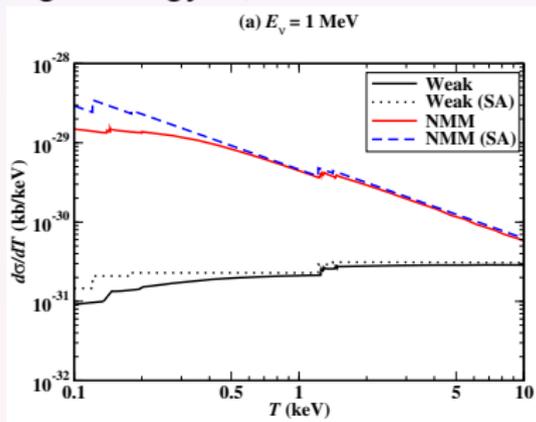
²Atomic Data and Nuclear Data Tables 54, 181-342 (1993)



MCRPPA for $\bar{\nu}_e + \text{Ge} \rightarrow \bar{\nu}_e + \text{Ge}^+ + e^-$

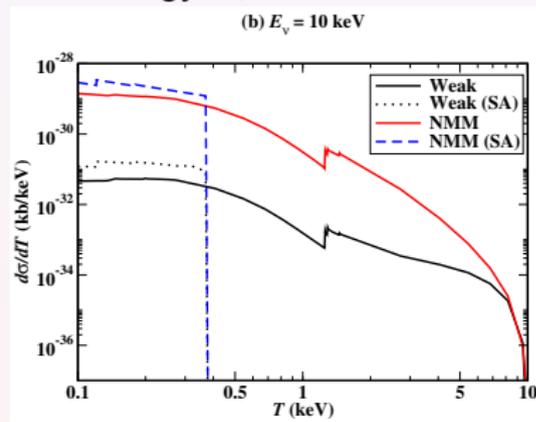
Setting $\mu_{\bar{\nu}_e} = 2.9 \times 10^{-11} \mu_B$:

High energy $E_\nu = 1 \text{ MeV}$:



- relevant for reactor neutrinos
- SA starts to deviate from $T \lesssim 1 \text{ keV}$
- $10^{-12} \mu_B$ possible at $T = 100 \text{ eV}$

Low energy $E_\nu = 10 \text{ keV}$:



- relevant for low E source, e.g. ${}^3\text{H}$: $Q \sim 18 \text{ keV}$ (McLaughlin & Volpe, 04)
- FE kinematics is way off



Conclusion

- 1 Atomic physics starts to be relevant for direct searches of neutrino magnetic moments with low-threshold detectors, which aim at pushing the current limit by another order of magnitude.
- 2 ab initio atomic calculations help to reduce the theoretical errors. Using MCRRPA, the Ge structure and photoabsorption ($E_\gamma \geq 100\text{eV}$) are well described with $\sim 5\%$ uncertainty.



Outlook

- 1 Analysis using new TEXONO data ($T_{\min} = 500\text{eV}$) is going on. A new bound with a tighter theoretical uncertainty hopefully will be out soon.
- 2 Apply to searches of dark matter (WIMP, LDM etc.) with Ge, Xe, and other detectors.
- 3 Study the Ge crystal effect.
- 4 New ideas that could greatly enhance the sensitivity?



Acknowledgement

Collaborators:

- 1 National Taiwan University
Jiunn-Wei Chen, Keh-Ning Huang, Chien-Fu Liu, Hao-Tse Shiao,
Chih-Liang Wu, Chih-Pan Wu
- 2 Academia Sinica / TEXONO
Lakhwinder Singh, Henry T. Wong
- 3 National Dong Hwa University
Hsin-Chang Chi



THANK YOU

