Neutrino-atom collisions

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Outline

- Introduction
- Atomic ionization by neutrinos
- Neutrino-nucleus coherent scattering
- Conclusions

Elastic scattering processes

Elastic neutrino-electron scattering

- $\nu + e^- \rightarrow \nu + e^-$

Coherent elastic neutrino-nucleus scattering

- $\nu + N \rightarrow \nu + N$

In typical laboratory experiments, neutrinos scatter in detectors on ***atomic*** electrons and nuclei

Neutrino electromagnetic properties

C. Giunti and A. Studenikin, *Neutrino electromagnetic interactions: A window to new physics*, RMP **87**, 531 (2015) arXiv:1403.6344

- Millicharge δ_Q (from neutrality of matter $|\delta_Q| \lesssim 3 \times 10^{-21}$)

- Mean-square charge radius $\langle r_\nu^2 \rangle$

- In the minimally extended SM with right-handed neutrinos, the magnetic moment is

$$\mu_\nu = 3 \times 10^{-19} \mu_B \left(\frac{m_\nu}{1\mathrm{eV}} \right)$$

Searches for neutrino magnetic moment μ_ν in $\nu + e^- \rightarrow \nu + e^-$

- Based on measurements of

$$\frac{d\sigma}{dT} = \frac{d\sigma_{\mathrm{SM}}}{dT} + \frac{d\sigma_{(\mu)}}{dT}$$

(*T* is the energy transfer)

- When scattering on a free electron at $T \ll E_\nu$:

$$\frac{d\sigma_{\mathrm{SM}}}{dT} \approx 10^{-47}\ \mathrm{cm}^2/\mathrm{keV}$$

$$\frac{d\sigma_{(\mu)}}{dT} \propto \frac{\mu_\nu^2}{T}$$

Current experimental limits on μ_ν

- Accelerator neutrinos:

LSND, Los Alamos (ν_μ-e) $\rightarrow \mu_{\nu_\mu} \leq 6.8\times10^{-10}\mu_B$

DONUT, Fermi Lab (ν_τ-e) $\rightarrow \mu_{\nu_\tau} \leq 3.9\times10^{-7}\mu_B$

- Solar neutrinos:

Super Kamiokande, Japan $\rightarrow \mu_\nu \leq 1.1\times10^{-10}\mu_B$

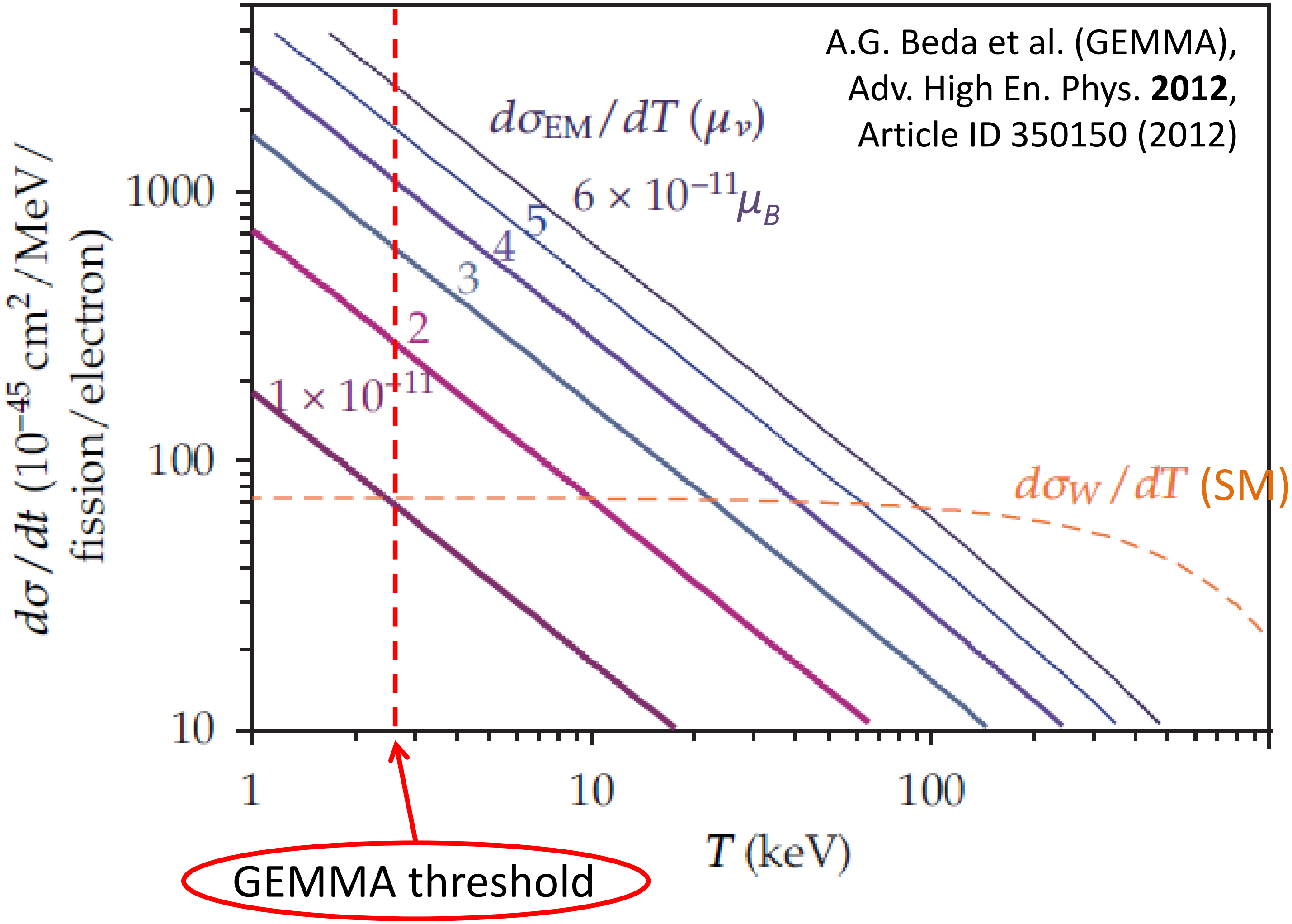
Borexino, Italy $\rightarrow \mu_\nu \leq 5.4\times10^{-11}\mu_B$

- Reactor antineutrinos:

TEXONO, Taiwan $\rightarrow \mu_{\nu_e} \leq 7.4\times10^{-11}\mu_B$

GEMMA, Russia $\rightarrow \mu_{\nu_e} \leq 2.9\times10^{-11}\mu_B$

Weak and electromagnetic cross sections for scattering of reactor $\bar{\nu}_e$ on electrons in Ge



A.G. Beda et al. (GEMMA),
Adv. High En. Phys. **2012**,
Article ID 350150 (2012)

GEMMA threshold

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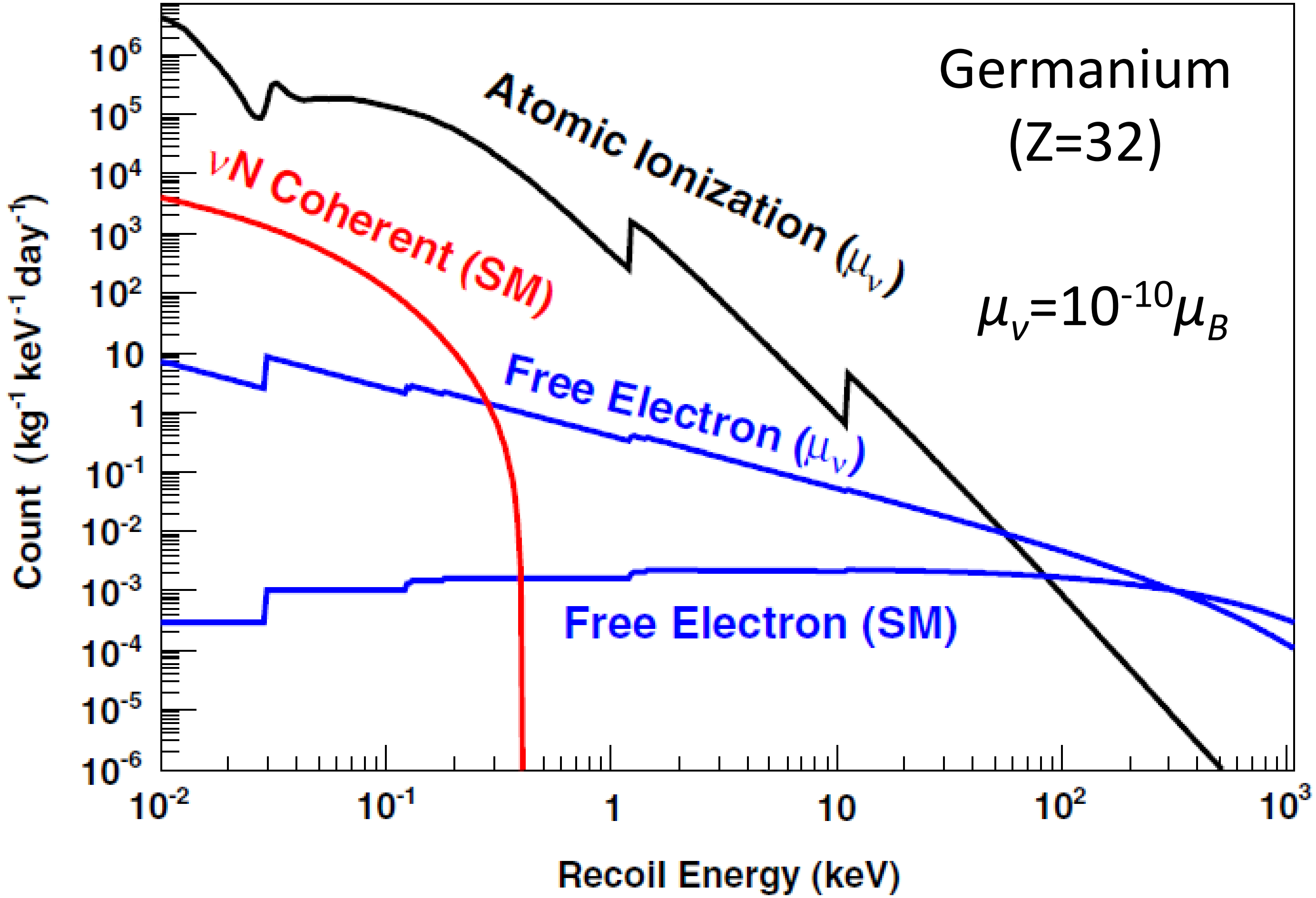
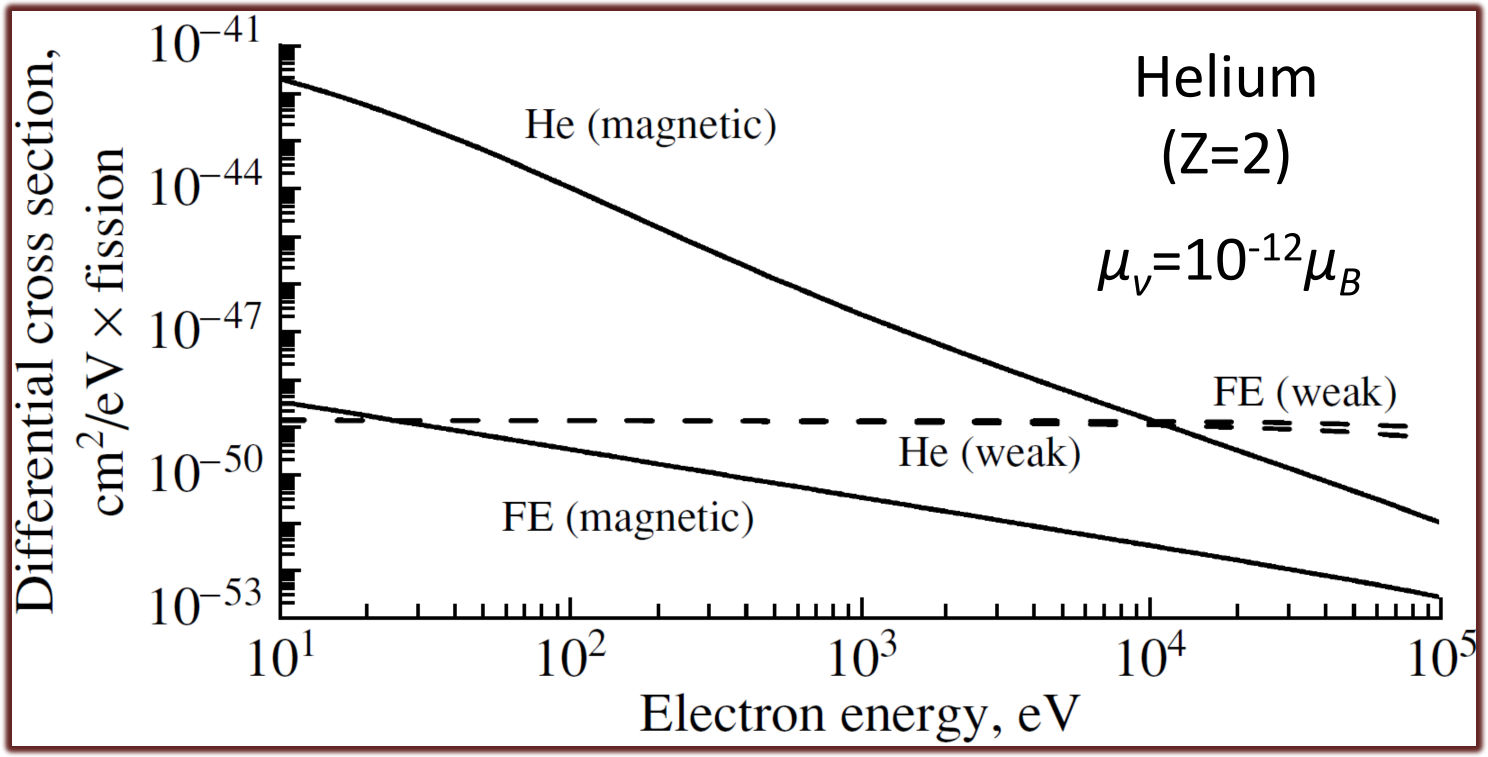
Atomic ionization effect

H.T. Wong et al. PRL **105**, 0161801 (2010)



The spectra due to neutrino interactions on the Ge target with reactor antineutrinos.

Atomic ionization effect for He



Helium
(Z=2)

$\mu_\nu=10^{-12}\mu_B$

V. P. Martemyanov and V. G. Tsinoev, Phys. At. Nucl. **74**, 1671 (2011)

Theoretical analysis of atomic ionization by neutrino impact

$$\frac{d\sigma_{\mathrm{SM}}}{dT}=\left(\frac{d\sigma_{\mathrm{SM}}}{dT}\right)_{\mathrm{FE}} f_{\mathrm{SM}}(T), \qquad f_{\mathrm{SM}}(T)=\frac{1}{2m_e}\int_0^{\infty} S\left(T,q^2\right)dq^2,$$

$$\frac{d\sigma_{(\mu)}}{dT}=\left(\frac{d\sigma_{(\mu)}}{dT}\right)_{\mathrm{FE}} f_{(\mu)}(T), \qquad f_{(\mu)}(T)=T\int_0^{\infty} S\left(T,q^2\right)\frac{dq^2}{q^2}.$$

The key quantity is the dynamical structure factor

$$S\left(T,\vec{q}^{\,2}\right)=\sum_n \left|\langle n|\rho(\vec{q})|0\rangle\right|^2 \delta(T-E_{n0}),$$

$$\rho(\vec{q})=\sum_{j=1}^{Z}\exp\left(i\vec{q}\cdot\vec{r}_j\right).$$

Ionization from hydrogen-like states at $T=I_{nl}$

$$1s: \quad f_{\mathrm{SM}}\left(I_{1s}\right)= f_{(\mu)}\left(I_{1s}\right)=1-\frac{7}{3}e^{-4}=0.957,$$

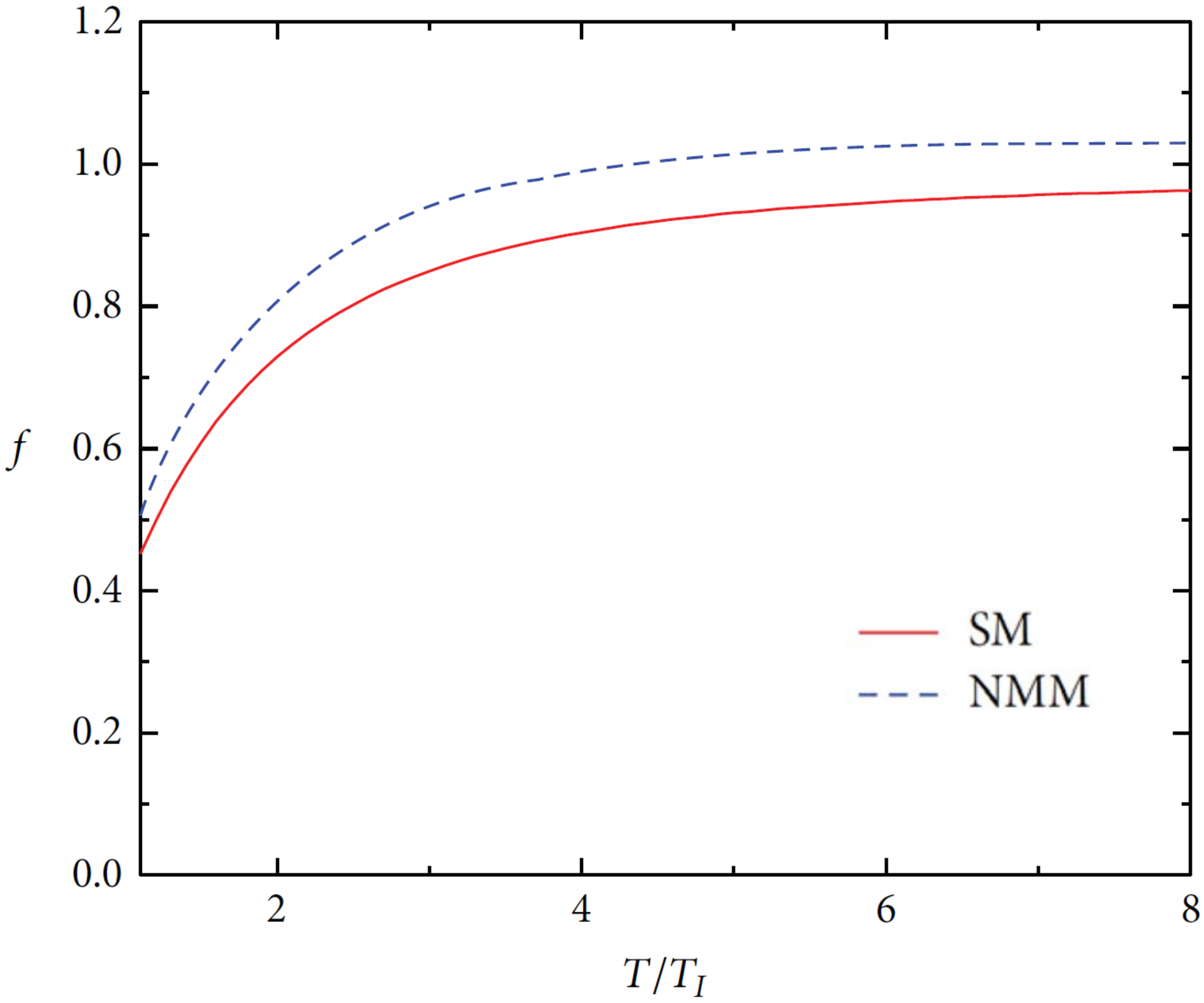
$$2s: \quad f_{\mathrm{SM}}\left(I_{2s}\right)=1-\frac{1639}{15}e^{-8}=0.963,$$

$$f_{(\mu)}\left(I_{2s}\right)=1-\frac{871}{15}e^{-8}=0.981,$$

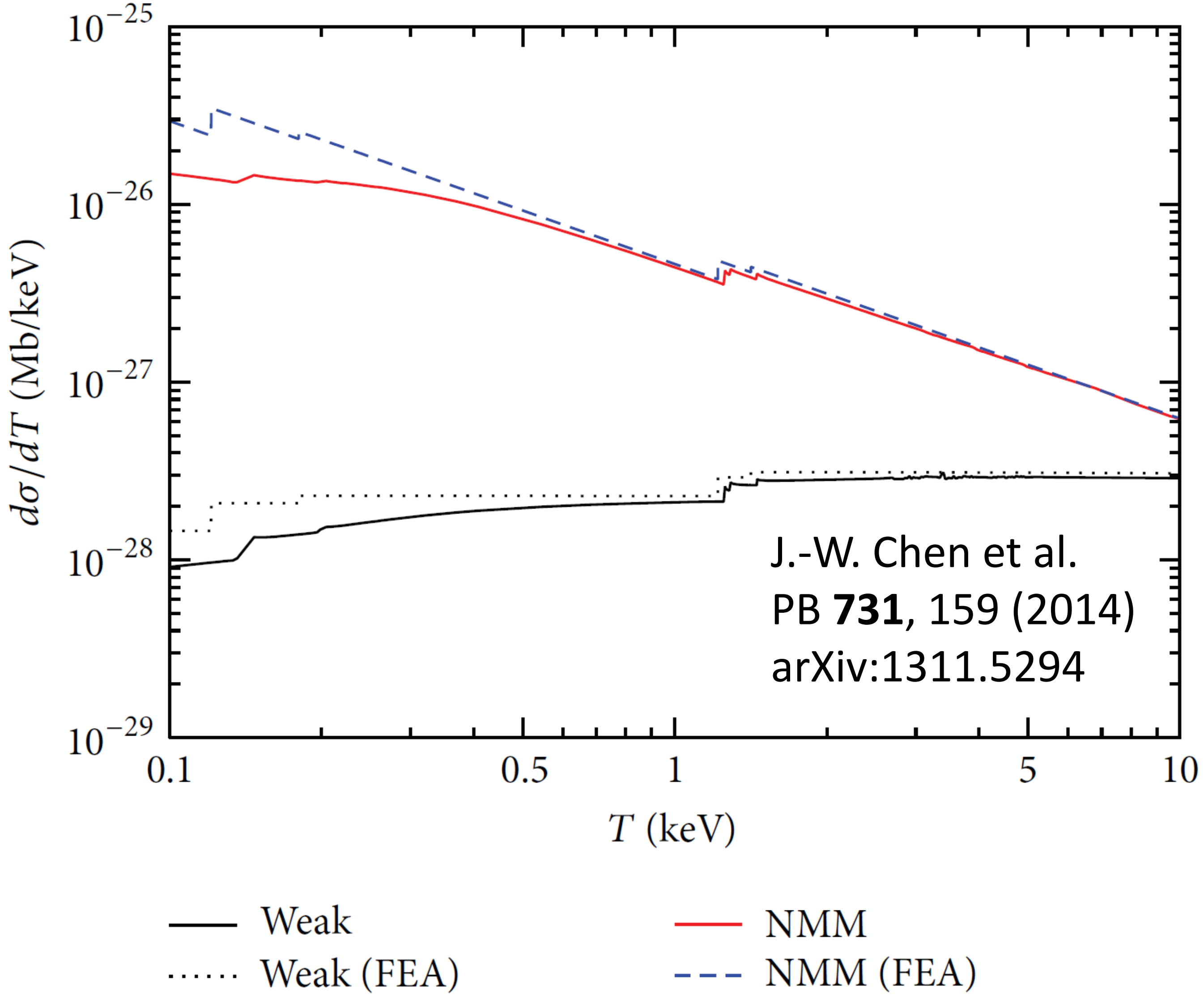
$$2p: \quad f_{\mathrm{SM}}\left(I_{2p}\right)=1-\frac{2101}{45}e^{-8}=0.984,$$

$$f_{(\mu)}\left(I_{2p}\right)=1-\frac{103}{15}e^{-8}=0.998.$$

Numerical results for ionization of He by impact of $\bar{\nu}_e$



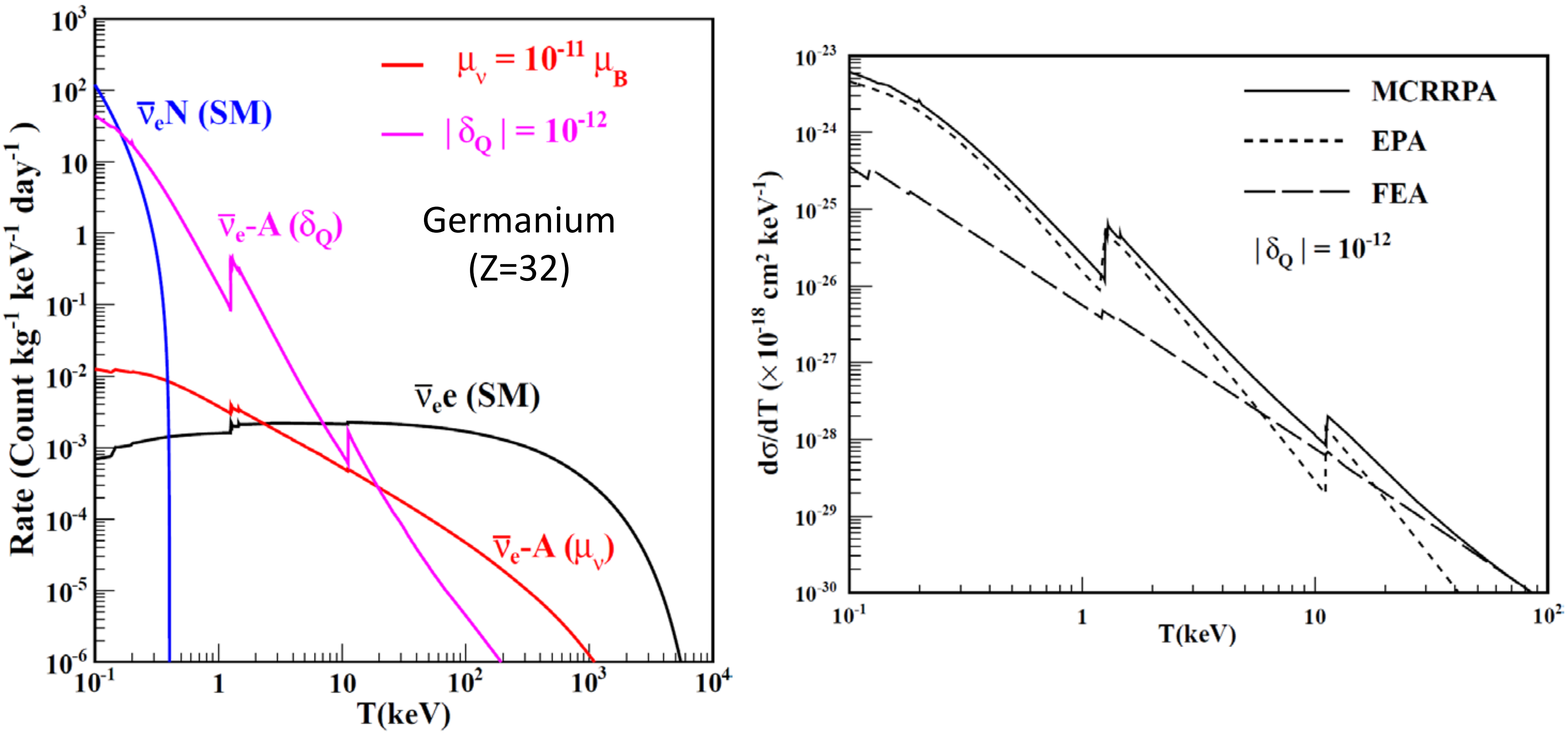
Ab initio calculations for ionization of Ge by impact of $\bar{\nu}_e$



J.-W. Chen et al.
PB **731**, 159 (2014)
arXiv:1311.5294

Atomic ionization effect for neutrino millicharge δ_Q

J.-W. Chen et al. PRD **90**, 011301(R) (2014) [arXiv:1405.7168]



The spectra due to neutrino interactions on the Ge target
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$\nu + N \rightarrow \nu + N$

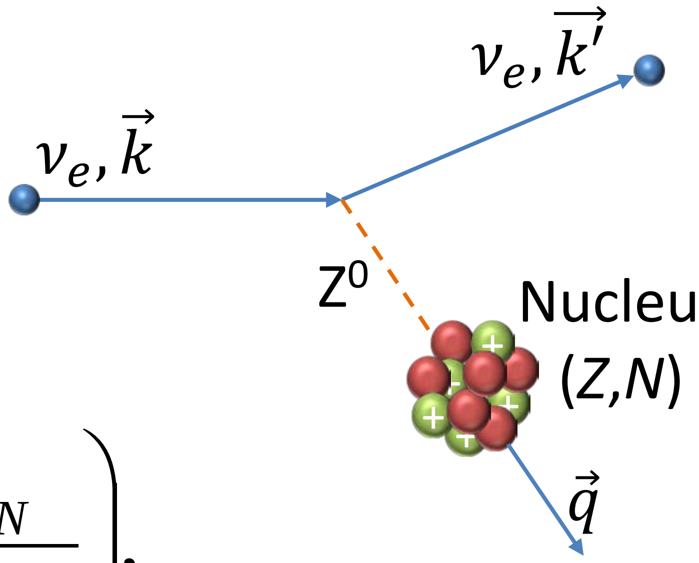
It is a well-predicted SM process that still needs to be observed experimentally.

$$T \leq T_N^{\max} = \frac{2E_\nu^2}{2E_\nu + M_N}$$

- For reactor $\bar{\nu}_e$ on Ge in a HPGe detector $T_N^{\max}{\sim}3$ keV.
- Due to quenching, only $\sim 20\%$ of the recoil energy T can be detected as an ionization signal ($\lesssim 500$ eV).

SM coherent ν_e-*N* scattering

- In the case of a spin-0 nucleus
  (*Z* and *N* are even)

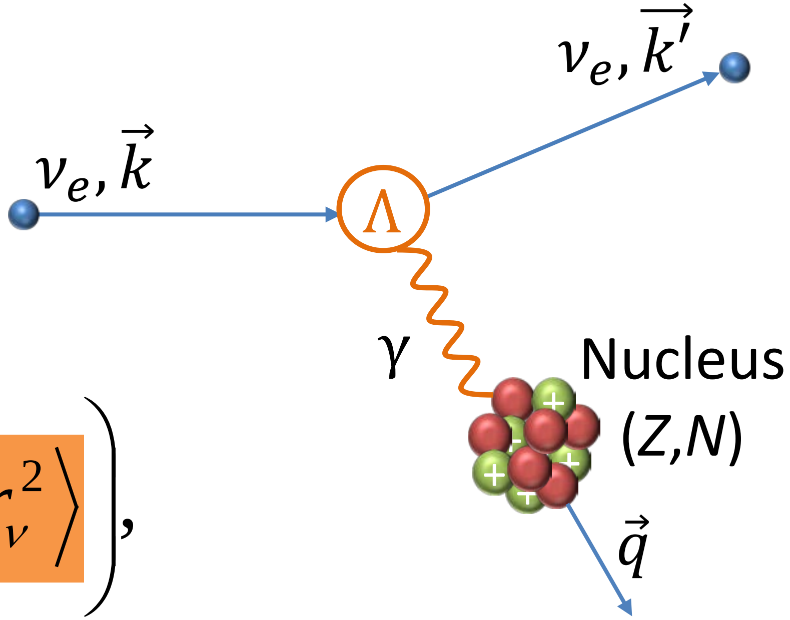


$$\frac{d\sigma_{\rm SM}}{dT_N} = \frac{G_F^2}{\pi} M_N C_V^2 \left(1 - \frac{T_N}{T_N^{\rm max}}\right),$$

$$C_V = \frac{1}{2}\left[Z\left(1 - 4\sin^2\theta_W\right) - N\right]$$

Electromagnetic contribution

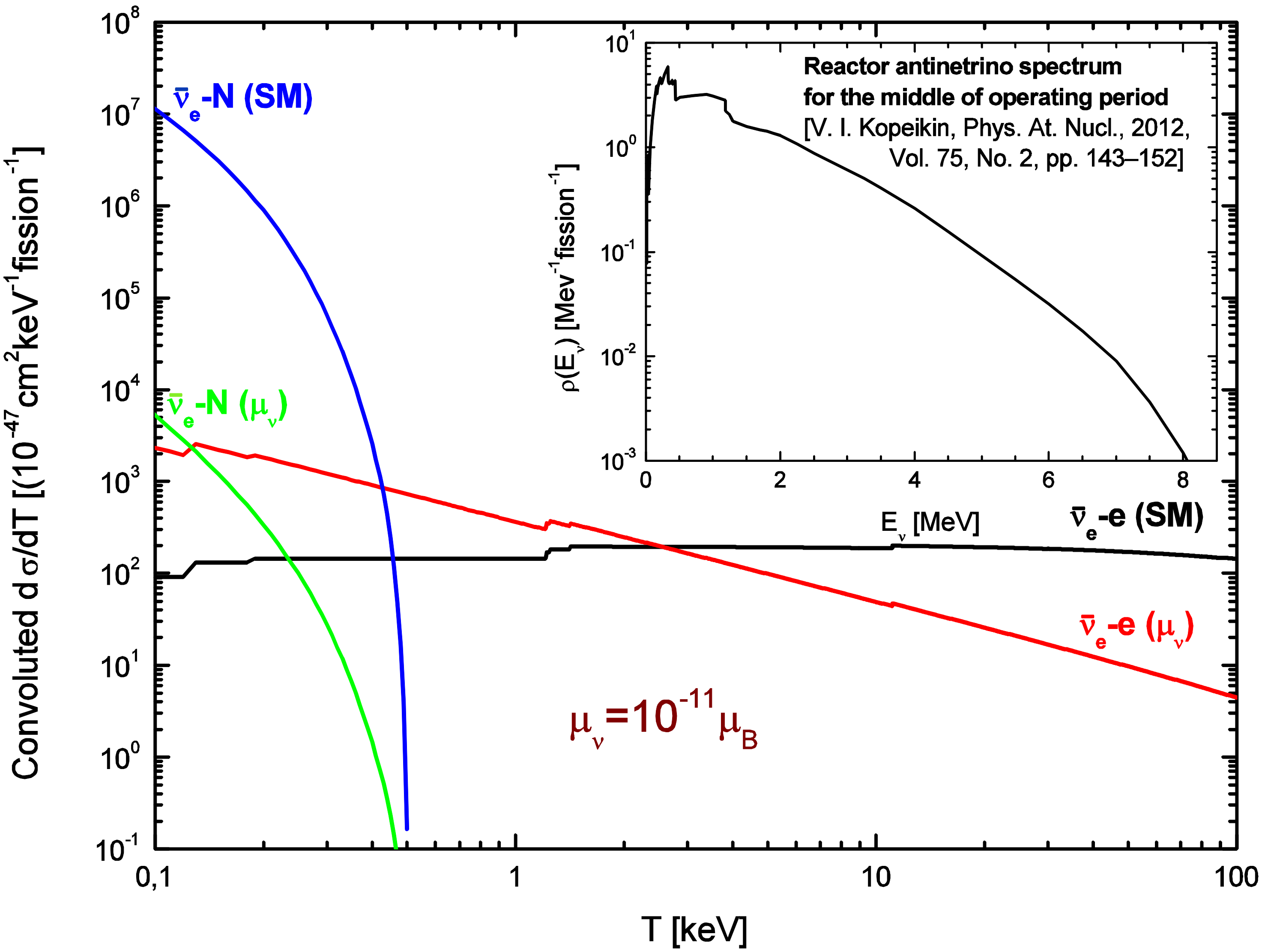
$$\frac{d\sigma}{dT_N} = \eta^2 \frac{d\sigma_{\mathrm{SM}}}{dT_N} + \frac{d\sigma_{(\mu)}}{dT_N},$$



$$\eta = 1 - \frac{\sqrt{2}\pi e^2 Z}{G_F C_V}\left(\frac{\delta_Q}{M_N T_N} - \frac{1}{3}\langle r_\nu^2 \rangle\right),$$

$$\frac{d\sigma_{(\mu)}}{dT_N} = 4\pi e^2 \mu_\nu^2 \frac{Z^2}{T_N}\left(1 - \frac{T_N}{E_\nu} + \frac{T_N^2}{4E_\nu^2}\right).$$

SM and μ_ν contributions for reactor $\bar{\nu}_e$ on Ge in a HPGe detector



CONCLUSIONS

- Current experiments approach energy-transfer values which are both comparable to atomic ionization energies and close to threshold energies for neutrino coherent scattering on atomic nuclei
- There is no “atomic ionization effect” for μ_ν, in contrast to the case of neutrino millicharge δ_Q
- For searching for neutrino electromagnetic properties in neutrino-nucleus coherent scattering one should examine very low energy-transfer values ($\lesssim$ few eV)