Hellenic Institute of Nuclear Physics, HINP

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"Semi-leptonic weak interaction processes in nuclei and their role to Astrophysics"

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Semi-leptonic weak interaction

- Help us to deepen our knowledge on:

  the fundamental electro-weak interactions and nuclear structure

- Inspire probes within and beyond the SM searching:

  (i) ν–detection, lepton-capture, beta-decay modes, etc.
  (ii) $0\nu\beta\beta$-decay, exotic ν-processes, nuclear μ-e conversion, etc

- Play important role in astrophysics:
  nucleo-synthesis, core collapse SN (e-capture), etc.

Numerous questions are still unanswered and reactions cross sections for such processes are required to understand many of them

This motivates theoretical studies (reactions cross sections) on prominent nuclei to be used as targets in the relevant experiments

Low & Intermediate Energy Neutrinos of Interest

1) Laboratory Neutrino Sources

(i) Neutrinos of Stopped pion–muon decay facilities (E < 52.8 MeV)

Neutron Spallation Sources:

(i) Oak Ridge (USA) (ii) Lund (Sweden)

(ii) Low & intermediate energy beta-beam neutrinos (E < 150 MeV)

(iii) Reactor neutrinos (E < 10 MeV or more)

2) Astrophysical Neutrino Sources

Solar Neutrinos (E < 20 MeV)

Supernova Neutrinos (E < 60 - 80 MeV)

Geo-Neutrinos (E < a few MeV)

FCNC processes: Motivation for their study

- Up to now there is no experimental evidence for FCNC in charged-lepton sector

- The existing FCNC data refer to neutral leptons (**ν**-oscillations in propagation)

⇨ **The FCNC interactions have not been completely understood up to now.**

Best Example: $\mu_b^- + (A,Z) \to e^- + (A,Z)^*$ **(μ-e conversion)**

The $\mu - e$ conversion puts stringent constraints on LFV parameters entering the non-standard Lagrangians (isoscalar, isovector couplings, SUSY parameters, etc.)

- Experimentally $\mu^- \to e^-$ and $\mu^- \to e^+$ are simultaneously studied

- For the coherent mode, around $E_e \approx m_\mu - \epsilon_b$, (ϵ_b = μ-energy in 1s orbit), the signal of **the** $\mu - e$ **reaction. is background free**

Exotic ν-nucleus processes & μ-e conversion

➢ **The LFV reaction has been extensively studied, experimentally and theoretically**

$$\mu_b^- + (A,Z) \to e^- + (A,Z)^*$$

[*T.S. Kosmas*, NPA 683 (2001) 443; *Deppisch, Kosmas, Walle*, NPB 752 (2006) 80]

Best limit on $R_{\mu\text{-}e}$:

$$R = \frac{\Gamma_{(\mu^- \to e^-)}}{\Gamma_{(\mu^- \to \text{capture})}} \leq 5.0 \times 10^{-13}$$

(PSI Exp.)

➢ **FCNC ν-Nucleus reactions and μ-e conversion can be described within the same nuclear & particle physics models**

$$\nu_\alpha + (A,Z) \to \nu_\beta + (A,Z)^*$$

$$\tilde{\nu}_\alpha + (A,Z) \to \tilde{\nu}_\beta + (A,Z)^*$$

From an Astrophysical point of view the latter have been effectively studied [Amanik, Fuller]

[*Amanik, Fuller*, PRD 75 (2007) 083008]

We perform realistic reaction cross sections calculations

Use of QRPA method to carry out calculations in:

i) In original state-by-state calculations for: $d\sigma/d\Omega$, $d\sigma/d\omega$, σ_{tot}
ii) To study the contributions of individual multipolarities
iii) Study the dominance of various hadronic current operators in σ_{tot}

V.Chasioti, TSK, NPA 829 (2009) 234
V.Tsakstara, T.S.K, *PRC* 83 (2011) 054612, 84 (2011) 064620
K.Balasi, E. Ydrefors, TSK, NPA 866(2011)67, NPA868-869(2011)82
V.Tsakstara, T.S.K, *PRC, to be published*

In ν-nucleus reactions the goal is to:

Investigate responses to ν-spectra of promising detectors:

i) Te, Cd, Zn –isotopes (COBRA, CUORE) K. Zuber, Phys. Lett. B **519**, 1 (2001)
ii) Mo-isotopes (MOON exp., Japan) H. Ejiri, Phys. Rep. **338**, 265 (2000).
iii) Ar (IKARUS exp. at Gran Sasso)

Outlook

- Low & intermediate energy ν-nucleus cross sections calculations are required in:
  (i) ν-detection in terrestrial experiments (CUORE,MOON,COBRA)
  (ii) New facilities (SNS, β-beams) aiming to measure ν-N cross sections
  (iii) Astrophysical processes (stellar evolution, nucleo-synthesis, etc.)

- The μ-e conversion **(e.g. mu2e@Fermilab)** is a powerful probe for studying FCNC interactions and putting robust constraints in LFV parameters of non-standard theories.

- Nuclear physics aspects and reliable transition ME calculations (within QRPA) can compliment such experiments

Connection with experiments

The calculated total cross section provide the neutrino fluxes required for a specific event rate

$$\frac{dN_\nu}{dt} \equiv N_{\text{event}} = N_{\text{Te}} \Phi_\nu(\varepsilon_\nu) \sigma_{\text{tot}}(\varepsilon_\nu) .$$

Using the evaluated σ_{cum} assuming, e.g. N_{event} = 1event/hr , for the Te mass of CUORE detector we get

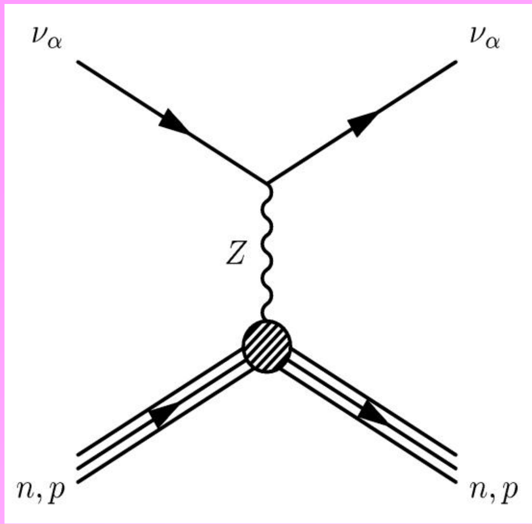
$$\Phi_\nu(\varepsilon_\nu = 50 \text{ MeV}) \approx 4.1 \times 10^6 \text{ cm}^{-2} \text{s}^{-1}$$

$$\Phi_\nu(\varepsilon_\nu = 30 \text{ MeV}) \approx 2.3 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$$

Similar results hold for the COBRA detector

The resulting fluxes are of the same order with those expected at the SNS at Oak Ridge (ORLaND experiment)

ν-nucleus interactions



- Neutral-current **Neutrino-nucleus** reactions

$$\nu + {}_Z A_N \longrightarrow {}_Z A_N^* + \nu'$$

$$\overline{\nu} + {}_Z A_N \longrightarrow {}_Z A_N^* + \overline{\nu}'$$

In terrestrial nuclear ν-detectors

CC cross sections are larger than NC ones, but

1. **Low-energy ν's are unable to produce massive leptons (μ, τ)**
   detection of limited number of ν's
2. **CC anti-neutrino scattering is suppressed (Pauli blocking)**
   CC reactions are important only for e-neutrinos

NC scattering may provide important information.

1. **All six ν–flavors can be detected**
2. **Coherent Channel is present (dominant one)**

Compact expressions for the 7-basic reduced ME

For H.O. basis, all basic reduced ME take analytic compact forms

$$\langle j_1 || T^J || j_2 \rangle = e^{-y} y^{\beta/2} \prod(y) = e^{-y} y^{\beta/2} \sum_{\mu=0}^{n_{max}} \mathcal{P}_\mu^J y^\mu$$

The Polynomials of even terms in q have constant coefficients as

$$\prod(y) = \sum_{\mu=0}^{n_{max}} \mathcal{P}_\mu^J y^\mu, \quad y = \frac{q^2 b^2}{4}$$

$$n_{max} = (N_1 + N_2 - \beta)/2 .$$

Advantages of the above formalism:

(i) The coefficients P^J can be calculated once (reduction of computer time)

(ii) They can be used for phenomenological description of ME

(iii) They are useful for other bases sets (expansions in HO wave-functions)

TSK, PPNP 48 (2002)307; V.Chasioti, TSK, Nucl. Phys. A 829 (2009) 234

Purified *1⁻* contributions to dσ/dω

For the purification of contribution of the 1^- multipolarity we constructed the purely spurious |S> state.

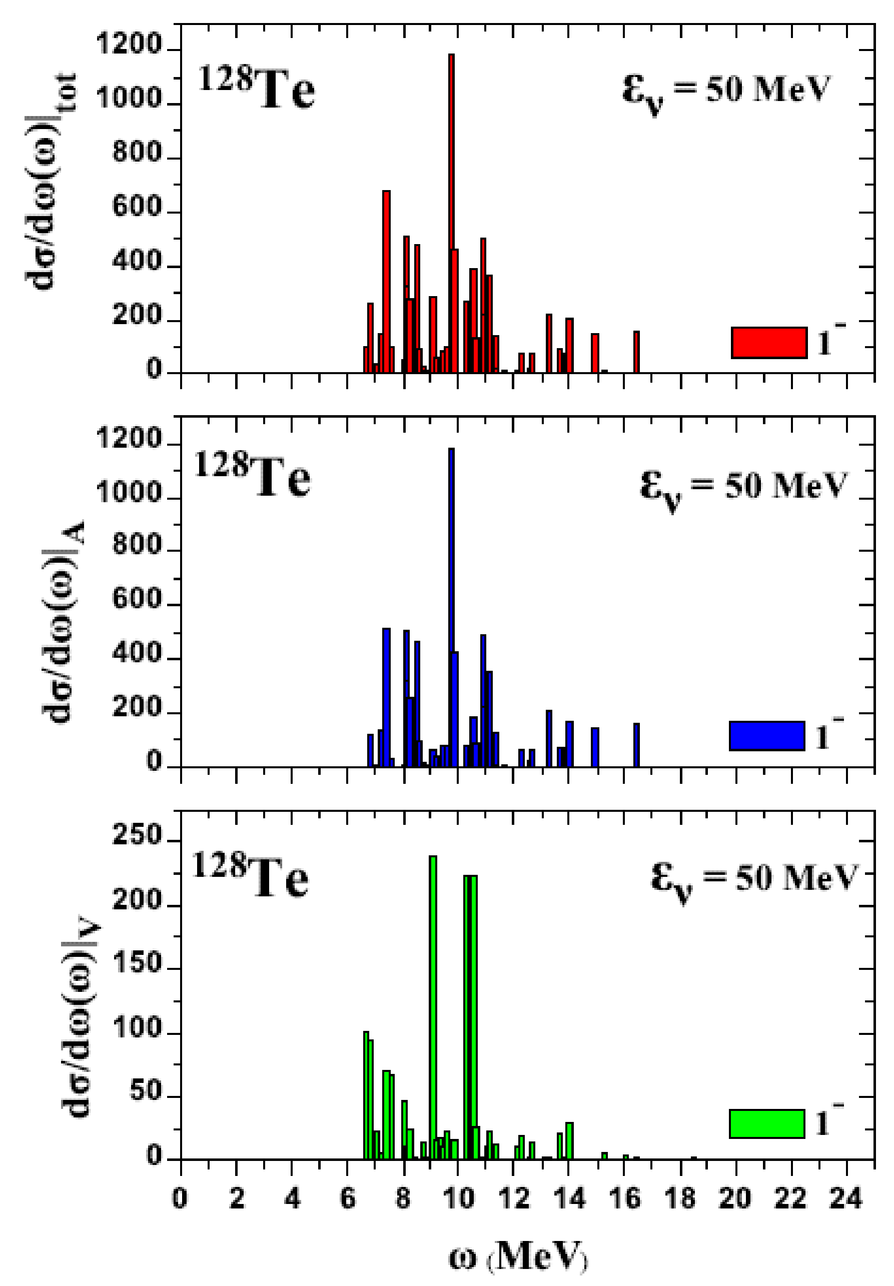
After removing the spurious admixtures, an overall overestimation (about 24%) of the inelastic contribution to ***dσ/dω*** of all 1^- multipole states was estimated.

V. Tsakstara, T.S.K, *PRC* 83 (2011) 054612

Schwieger, TSK, Faessler, PRC56(1997) 2830

Papakonstantinou, TSK, Wambach, Faessler, Phys.Rev. C73 (2006) 035502

Individual contributions of polar-vector $d\sigma/d\omega|_V$ and axial-vector $d\sigma/d\omega|_A$ to $d\sigma/d\omega|_{tot}$ for ^{128}Te ($\varepsilon_\nu = 50$ MeV).



V. Tsakstara and T.S. Kosmas, *Phys. Rev. C* 83 (2011) 054612

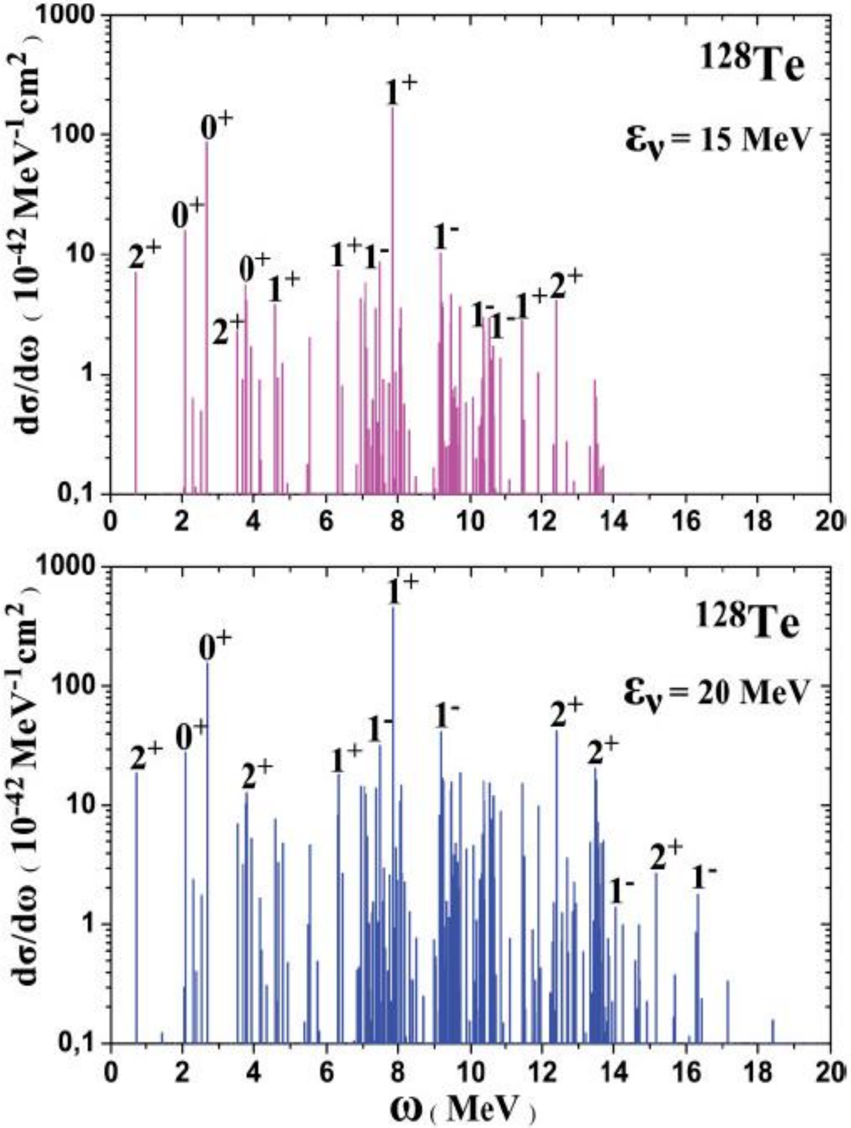


FIG. 2. (Color online) Differential cross section $d\sigma/d\omega(\omega)$ as a function of the excitation energy ω for the nucleus ^{128}Te. The incoming neutrino energy was $\varepsilon_\nu = 15$ MeV (upper panel) and $\varepsilon_\nu = 20$ MeV (lower panel).

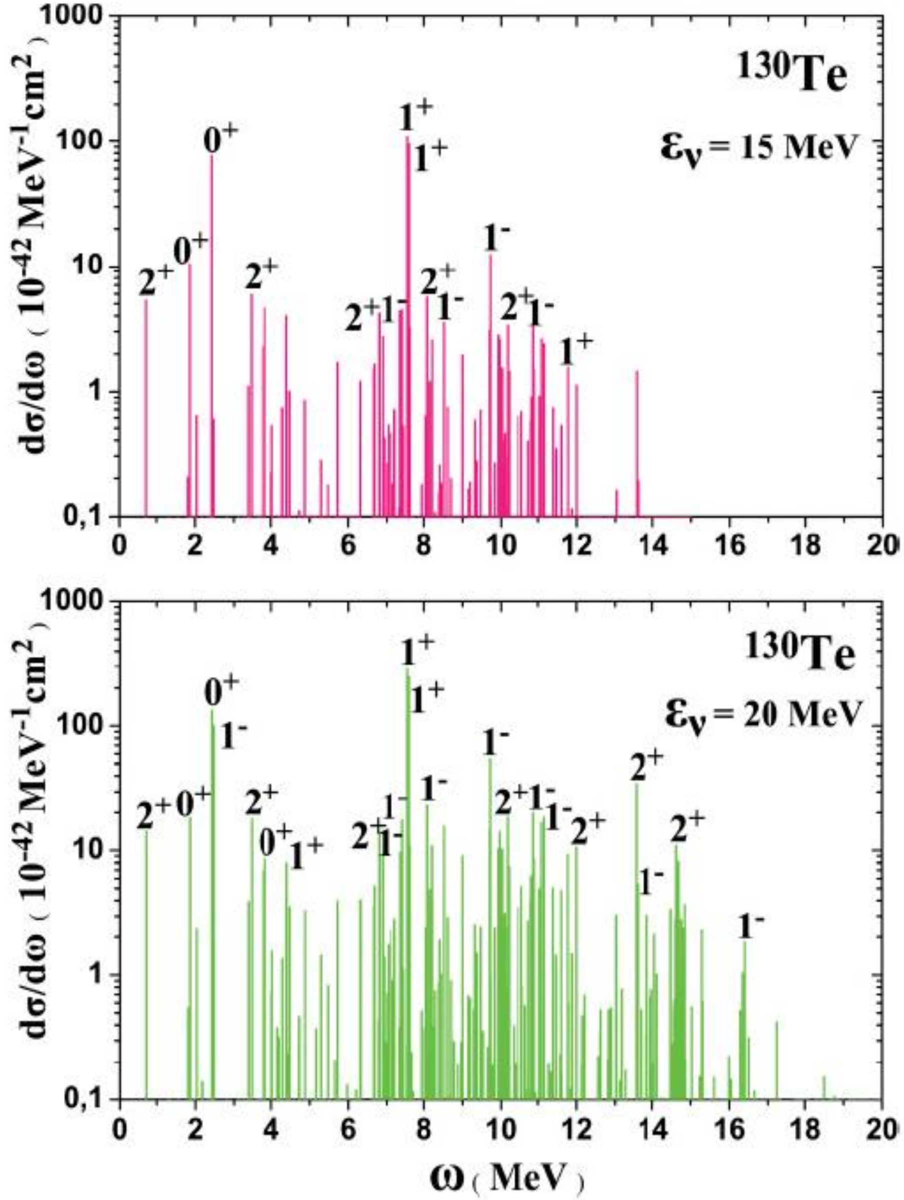


FIG. 3. (Color online) Same as in Fig. 2 but now for the ^{130}Te isotope.

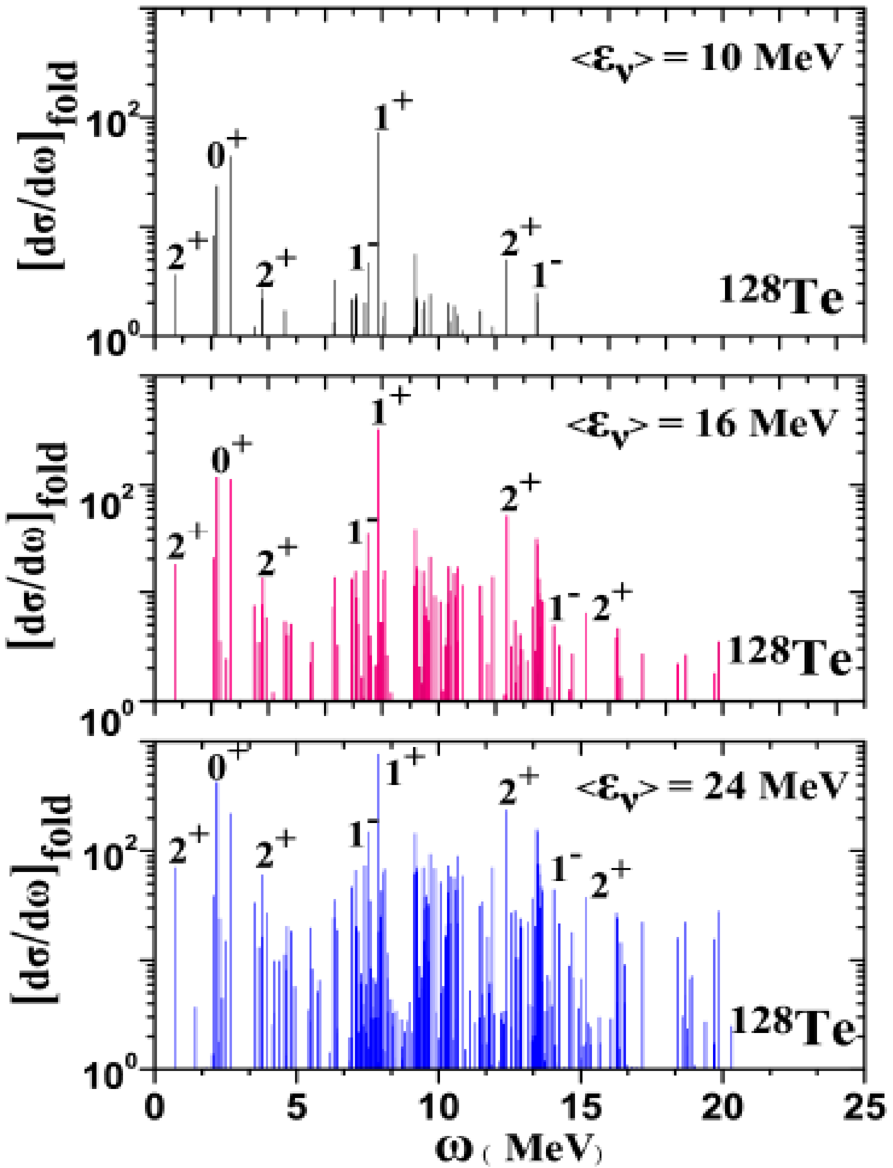
Plan of the talk

- **Introduction** **(ν–Nucleus Interactions)**
  - **Low-energy & Intermediate Neutrino Sources**
    - **Laboratory neutrinos**
    - **Astrophysical neutrinos**
- **Neutral-current ν–Nucleus Interactions**
  - **Coherent ν–Nucleus Scattering**
  - **Inelastic ν–Nucleus Scattering**
  - **Exotic ν–Nucleus reactions**
- **Realistic cross section within QRPA**

  State-by-state calculations on Te, Mo, Zn, Ar isotopes

  (targets of multi-goal Experiments DBD, ν–detection, CDM)
- **Summary-Conclusions**

SN-ν signals



V. Tsakstara, T.S.K, *PRC, to be submitted*

$$\eta_{FD}[T, n_{dg}](\varepsilon_\nu) = F(n_{dg})\,\frac{1}{T^3}\,\frac{\varepsilon_\nu^2}{1 + e^{(\varepsilon_\nu/T - n_{dg})}}$$

The ν-signal created to the detector is obtained through the folding procedure

$$\boxed{\left.\frac{d\sigma}{d\omega}\right|_{\text{sign}}(\omega) = \int_\omega^\infty \frac{d\sigma}{d\omega}(\omega, \varepsilon_\nu)\eta(\varepsilon_\nu)d\varepsilon_\nu}$$

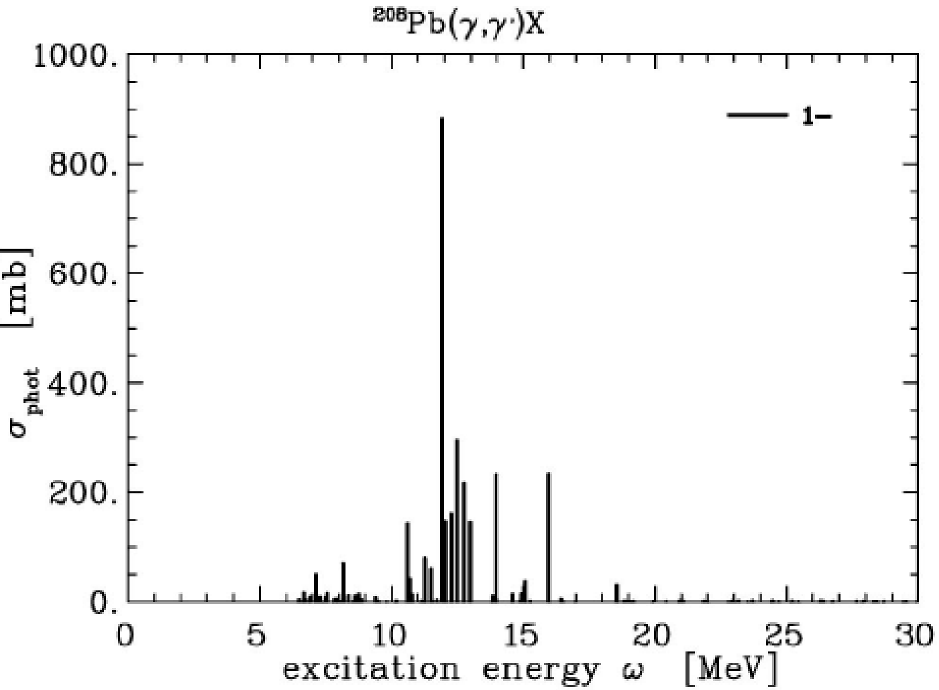
Te excitation spectra shown resemble to those of

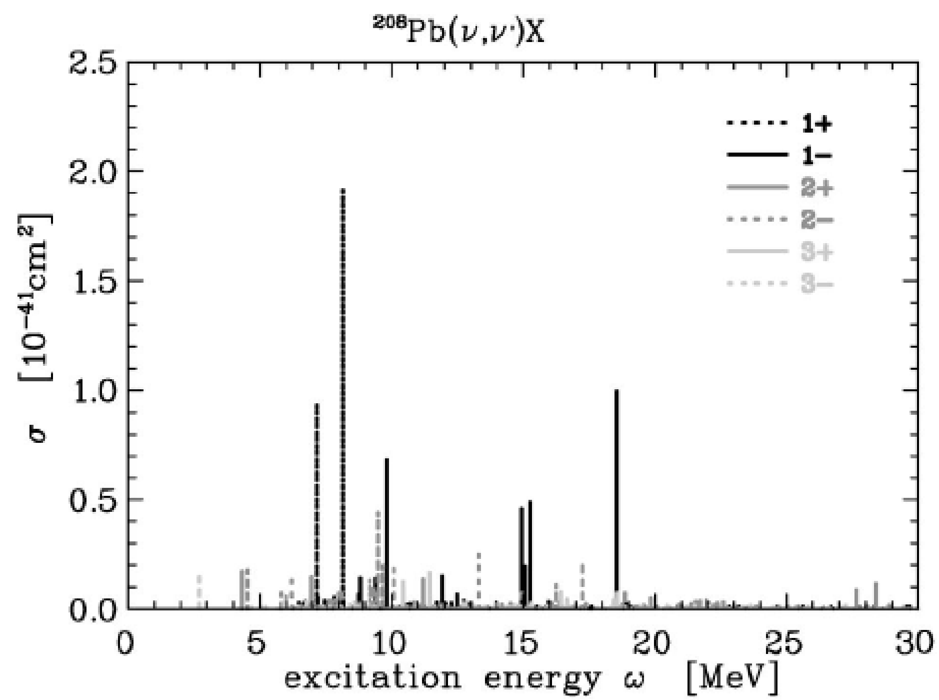
Kolbe, Langanke, PRC 63(2001)025802

$<\varepsilon_\nu>$=10, 16, 24 MeV

Fermi-Dirac distribution

T= Temp. n_{dg} =degeneracy





Excitation spectrum ^{208}Pb

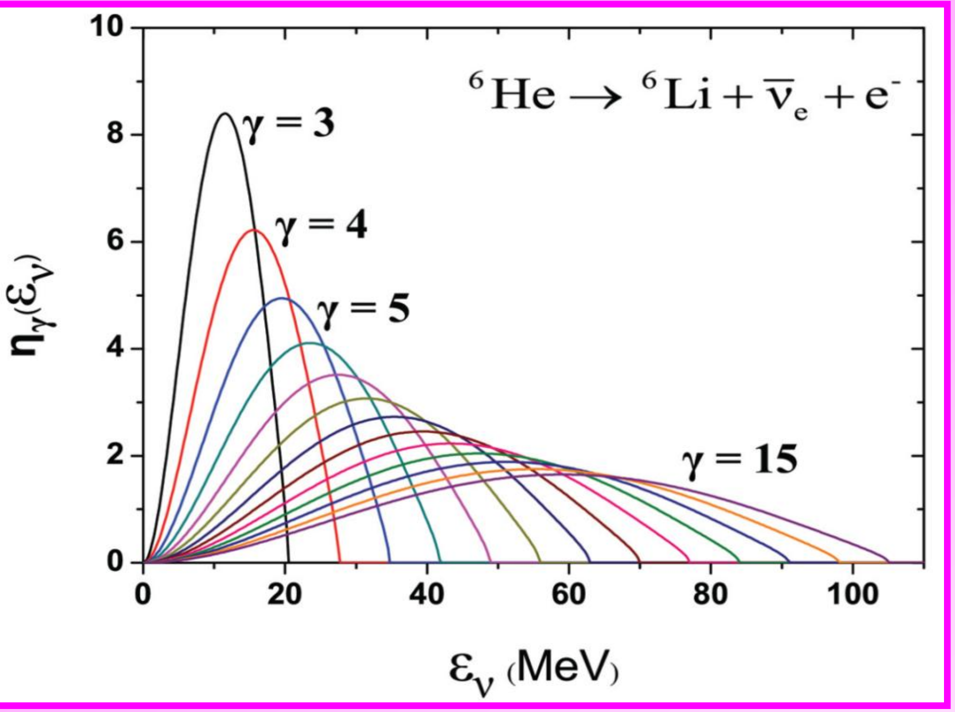
FIG. 3. Excitation spectrum of the ^{208}Pb nucleus for photoabsorption (upper part) in comparison to the spectrum excited by neutral current neutrino scattering (lower part), which is decomposed into the dominant multipole contributions.

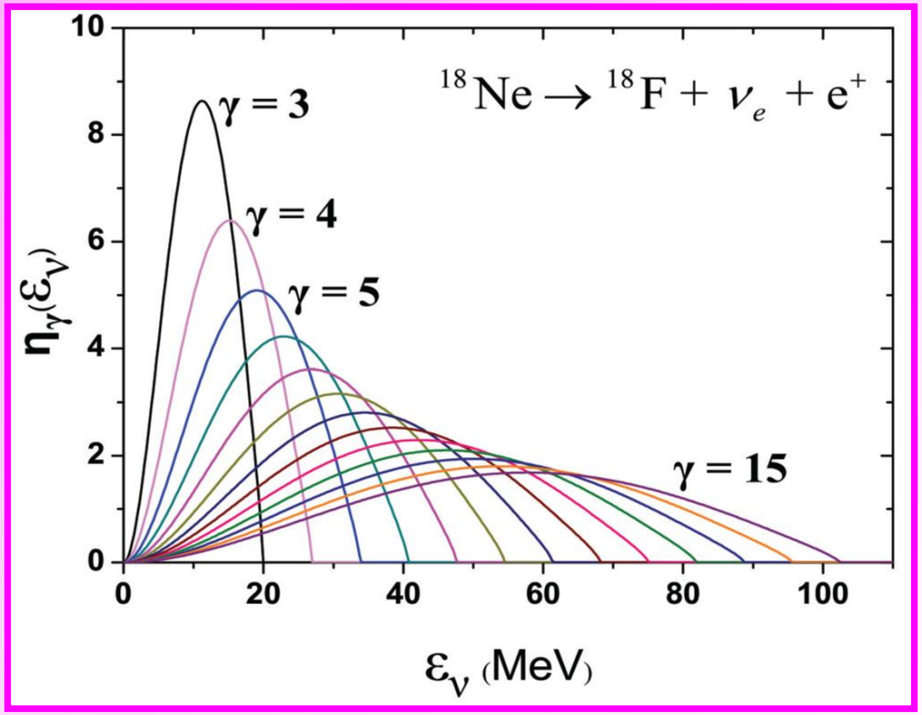
Kolbe, Langanke, PRC 63(2001)025802

The CRPA excitation spectrum in ^{208}Pb is fragmented with maximum peak at E about 8 MeV

(F-D distribution : T=8 MeV, α=0)

Energy-spectra of Boosted β-beam neutrinos





Tsakstara, Kosmas, PRC 83(2011)054612-1-13, PRC 84(2011)064620-1--14

$$\eta_{\gamma_i}(\varepsilon_\nu) = \frac{ln2}{m_e^5(ft)} \frac{F(\pm Z, E_e)E_e p_e \varepsilon_\nu^2}{\gamma^2(1+u)^2(2\gamma(1-u))},$$

Normalized boosted beta-beam spectra (laboratory frame)

For the reconstruction of SN neutrinos : γ < 15

V. Tsakstara, T. S. Kosmas, and J. Wambach, Prog. Part. Nucl. Phys. **66**, 424 (2011).

The theory of ν–Nucleus reactions cross sections

The calculations start from

$$\frac{d^2\sigma_{i\to f}}{d\Omega d\omega}(\omega,\theta,\phi,\varepsilon_\nu)\Big|_{\nu/\bar{\nu}} = \delta(E_f - E_i - \omega)\frac{2G^2\varepsilon_f^2 \cos^2(\theta/2)}{\pi(2J_i+1)}\left[\mathcal{C}_V + \mathcal{C}_A \mp \mathcal{C}_{VA}\right]$$

where

$$\begin{aligned}\mathcal{C}_{V(A)} &= \sum_{J=0}^{\infty} |\langle J_f \| \widehat{M}_J^{(5)}(q) + \frac{\omega}{q}\widehat{L}_J^{(5)}(q) \| J_i\rangle|^2 \\ &+ \sum_{J=1}^{\infty}\left(-\frac{q_\mu^2}{2q^2} + \tan^2\frac{\theta}{2}\right)\Big[|\langle J_f \| \widehat{T}_j^{mag(5)}(q) \| J_i\rangle|^2 \\ &\quad + |\langle J_f \| \widehat{T}_j^{el(5)}(q) \| J_i\rangle|^2\Big] . \qquad (\end{aligned}$$

$$\begin{aligned}\mathcal{C}_{VA} &= 2\tan\frac{\theta}{2}\left[-\frac{q_\mu^2}{q^2} + \tan^2\frac{\theta}{2}\right]^{1/2} \\ &\quad \times \sum_{J=1}^{\infty} \Re e \langle J_f \| \widehat{T}_J^{mag}(q) \| J_i\rangle \langle J_f \| \widehat{T}_J^{el}(q) \| J_i\rangle^*\end{aligned}$$

$$\begin{aligned} q \equiv |\mathbf{q}| &= \left[\omega^2 + 4\varepsilon_i(\varepsilon_i - \omega)\sin^2(\theta/2)\right]^{1/2} \\ q_\mu^2 \equiv q_\mu q^\mu &= -4\varepsilon_i(\varepsilon_i - \omega)\sin^2(\theta/2) . \end{aligned}$$

$$\omega = E_f - E_i = \varepsilon_i - \varepsilon_f$$

Summary - Conclusions - Outlook

- The μ-e conversion is a powerful probe for studying FCNC interactions and putting robust constraints in various LFV parameters of non-standard theories
- By studying FCNC processes of charged and neutral leptons we may deepen our knowledge of LFV interactions
- Nuclear physics aspects and reliable transition ME calculations can compliment the relevant experiments