Theoretical Nuclear Physics Research Activities @ University of Ioannina

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NuPECC Mini-Workshop, Athens, Greece, March 13-14, 2015
Realistic State-by-state calculations for lepton-nucleus processes

Within the Standard Model
- $\nu$-nucleus scattering NC & CC (coherent process and incoherent channels)
- $\mu^-$-capture & $e^-$-capture
- Kosmas, Giannaka, Tsakstara

Beyond the Standard Model
- $\mu^-$ → $e^\pm$ conversion
- Non-standard $\nu$-nucleus processes
- Kosmas, Leontaris, Vergados, Papoulias

High Energy $\gamma$-ray and $\nu$-emission from Astrophysical Jets
- Kosmas, Smponias

Direct Dark Matter detection
- Vergados, Kosmas, Moustakidis, Divari

Transfer of knowledge and Research Experience to Physics Education
- Kosmas, Aslanoglou, Kardaras, Antoniou, Toli
Collaborators:

- T.E.I. of Western Macedonia, Greece: J. Sinatkas
- NCSR Democritos, Greece: D. Bonatsos
- T.Univ. of Darmstadt, Germany: Group of J. Wambach
- Univ. of Tuebingen, Germany: Group of A. Faessler, K. Kokkotas
- Univ. of Jyvaskyla, Finland: Group of J. Suhonen
- Univ. of Valencia, Spain: Group of J.W.F. Valle, F. Deppisch
- RCNP, Univ. of Osaka, Japan: H. Ejiri (MOON Experiment)
**SM \(\nu\)-nucleus reaction**

\[\nu_{\alpha} + (A, Z) \rightarrow \nu_{\alpha} + (A, Z)\]

- Well-studied process theoretically
- Still not experimentally measured (relevant experiments: COHERENT, TEXONO, GEMMA, etc)
- Very high experimental sensitivity is required

**LFV NSI \(\nu\)-nucleus reaction**

\[\nu_{\alpha} + (A, Z) \rightarrow \nu_{\beta} + (A, Z), \quad \alpha \neq \beta = (e, \mu, \tau)\]

- Not allowed in the SM due to violation of the lepton number
- Excellent probe to search for new physics (electromagnetic neutrino properties)

**CLFV muon to electron conversion in nuclei**

\[\mu + (A, Z) \rightarrow e + (A, Z)\]

- New extremely sensitive experiments at Fermilab and J-PARC (Mu2e, COMET)
- Branching ratio down to \(R_{\mu e}^{(A, Z)} \sim 10^{-16} \sim 10^{-18}\) (constrains NSI \(\nu\)-nucleus)
- Can be studied simultaneously with \(\nu\)-nucleus NSI (i.e. within seesaw)
NSI Phenomenological description

The Lagrangian to describe non-standard neutrino interactions (NSI)

\[ \mathcal{L}_{\text{NSI}} = -2\sqrt{2} G_F \sum_{q=u,d} f^{q\rho}_{\alpha\beta} \left[ \bar{\nu}_\alpha \gamma_\rho L \nu_\beta \right] \left[ \bar{f} \gamma^\rho P f \right] \]

New NSI couplings defined as

\[ f^{q\rho}_{\alpha\beta} = g^{q\rho}_{\text{SM}} + \epsilon^{q\rho}_{\alpha\beta}, \alpha, \beta = e, \mu, \tau \]

- SM couplings \( g^{q\rho}_{\text{SM}} \), flavour blind
- *flavour preserving non-universal (NU) terms* proportional to \( \epsilon^{q\rho}_{\alpha\alpha} \).
- *flavour-changing (FC) terms* proportional to \( \epsilon^{q\rho}_{\alpha\beta}, \alpha \neq \beta \).

Couplings taken with respect to the strength of the Fermi coupling constant \( G_F \).

- polar-vector couplings: \( \epsilon^{qV}_{\alpha\beta} = \epsilon^{qL}_{\alpha\beta} + \epsilon^{qR}_{\alpha\beta} \)
- axial-vector couplings: \( \epsilon^{qA}_{\alpha\beta} = \epsilon^{qL}_{\alpha\beta} - \epsilon^{qR}_{\alpha\beta} \)

S. Davidson et. al., JHEP 03 011 (2003)

Tensorial contribution to NSI neutrino-nucleus scattering

- The Lagrangian involving tensor NSI

\[
\mathcal{L}_{\text{NSI}}^T = -2\sqrt{2}G_F \sum_{f=u,d}^{\alpha,\beta=e,\mu,\tau} \varepsilon^T_{\alpha\beta} [\bar{\nu}_\alpha \sigma^{\mu\nu} \nu_\beta] [\bar{f} \sigma_{\mu\nu} f]
\]


- Differential cross section

\[
\frac{d\sigma_{\text{NSI},\nu_\alpha}}{dT_N} = \frac{4G_F^2 M}{\pi} \left[ \left( 1 - \frac{T_N}{2E_\nu} \right)^2 - \frac{M T_N^4}{4E_\nu^2} \right] \left| \langle gs | G_{T,\nu_\alpha}^{\text{NSI}}(q) | gs \rangle \right|^2
\]


- Nuclear matrix element

\[
\left| \langle gs | G_{T,\nu_\alpha}^{\text{NSI}}(q) | gs \rangle \right|^2 = \left[ (2\varepsilon^{uT}_{\alpha\beta} + \varepsilon^{dT}_{\alpha\beta}) ZF_Z(q^2) + (\varepsilon^{uT}_{\alpha\beta} + 2\varepsilon^{dT}_{\alpha\beta}) NF_N(q^2) \right]^2
\]

NSI neutrino transition magnetic moments are generated at 1-loop level

D.K. Papoulias and T.S. Kosmas, PLB to be submitted
NSI limits from $\mu^- \rightarrow e^-$ conversion

Simulated signals

(a) supernova neutrinos
(b) stopped-pion muon neutrinos

NSI limits from $\mu^- \rightarrow e^-$

$$\epsilon_{\mu e}^{fP} = C^{-1} \sqrt{R_{\mu e}^{(A,Z)}}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>COMET</th>
<th>Mu2e</th>
<th>Project-X</th>
<th>PRIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{\mu e}^{fv} \times 10^{-6}$</td>
<td>3.70</td>
<td>2.87</td>
<td>0.52</td>
<td>0.37</td>
</tr>
<tr>
<td>$R_{\nu_{\mu} \rightarrow \nu_e} \times 10^{-10}$</td>
<td>21.2</td>
<td>13.0</td>
<td>0.42</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 3: Upper limits on the NSI parameters $\epsilon_{\mu e}^{fv}$ and the ratios $R_{\nu_{\mu} \rightarrow \nu_e}$ for the FC $\nu_{\mu} \leftrightarrow \nu_e$ reaction channel resulting from the sensitivity of the $\mu^- \rightarrow e^-$ conversion experiments.

Limits on tensor NSI from the COHERENT exp.

1-parameter analysis

$$\chi^2 = \left( \frac{N_{\text{events}}^{\text{SM}} - N_{\text{events}}^{\text{NSI}}}{\delta N_{\text{events}}} \right)$$

2-parameter analysis

D.K. Papoulias and T.S. Kosmas, PLB to be submitted

$^{76}\text{Ge}$: $-0.0068 \leq \epsilon^{dT}_{e\beta} \leq 0.0068$ 90% C.L.

$^{76}\text{Ge}$: $-0.0075 \leq \epsilon^{dT}_{e\beta} \leq 0.0075$ 90% C.L.
Charged-Current processes

1. Electron-capture by the atomic nuclei

\[(A, Z) + e^- \rightarrow (A, Z - 1)^* + \nu_e\]

- **In pre-supernova phase**: \( A \leq 60 \)
- **In supernova phase**: \( A \geq 65 \)

2. \( \beta^\pm \) – decay modes described by the reactions

\[(A, Z) \rightarrow (A, Z + 1) + e^- + \nu_e\]

\[(A, Z) \rightarrow (A, Z - 1) + e^+ + \bar{\nu}_e\]

- **In pre-supernova phase**: At low matter densities after silicon depletion and during silicon shell burning.
Muon Capture Process

Ordinary muon-capture process

\[(A, Z) + \mu^- \rightarrow (A, Z - 1)^* + \nu_\mu\]

This process has prominent role in testing nuclear models in several physical applications

- **Exclusive rates:** Individual contribution of each transition.
  \[
  \Lambda_{gs \rightarrow J^\pi} = 2G^2\langle \Phi_1s \rangle^2 R_f q^2_f \left[ |\langle J^\pi_f \| (\hat{M}_J - \hat{L}_J) \| 0^+_{gs} \rangle|^2 + |\langle J^\pi_f \| (\hat{T}_{el} - \hat{T}_{magn}) \| 0^+_{gs} \rangle|^2 \right]
  \]

- **Partial rates:** The most important partial transition rates (e.g. \(J^\pi = 1^-\), \(J^\pi = 1^+\) low lying excitations)
  \[
  \Lambda_{J^\pi} = \sum_f \Lambda_{gs \rightarrow J^\pi_f}
  \]

- **Total rates**
  \[
  \Lambda_{tot} = \sum_{J^\pi} \Lambda_{J^\pi} = \sum_{J^\pi} \sum_f \Lambda_{J^\pi_f}
  \]

  The agreement with experimental and theoretical data using different nuclear methods are in good agreement (deviation smaller than 7%).

- **Quenching effect:** The results are obtained using a free nucleon coupling constant \(g_A = 1.262\) for light nuclei and a quenched value of \(g_A = 1.135\) for medium-weight nuclei.
Electron Capture Process

- The parent nuclei can be either in the ground state either in any excited state of energy $\lesssim 3.0 \text{ MeV}$.
- The energy distribution of the initial state of the parent nuclei is described by the Maxwell-Boltzmann distribution.
- Temperature dependence of cross sections.
- Use of the quenched value of $g_A = 1.00$.

Our calculations include:

1. Exclusive EC cross sections
2. Partial EC cross sections
3. Total EC cross sections

Under these conditions the total cross sections are written as:

$$
\sigma(E_e, T) = \frac{G_F^2 \cos^2 \theta_c}{2\pi} \sum_i F(Z, E_e) \frac{(2J_i + 1)e^{-E_i/(kT)}}{G(Z, A, T)} \sum_{f,J} (E_e - Q + E_i - E_f)^2 \frac{|\langle i|\hat{O}_J|f\rangle|^2}{(2J_i + 1)}
$$
Exclusive Cross Sections for $^{56}$Fe

1. **Polar-Vector**
   - $0^+_1$, at $\omega = 2.412$ MeV
   - $0^+_2$, at $\omega = 5.296$ MeV

2. **Axial-Vector**
   - $1^+_1$, at $\omega = 0.163$ MeV
   - $1^+_{10}$, at $\omega = 8.278$ MeV

3. **Total**
   - $1^+_1$, at $\omega = 0.163$ MeV
   - $0^+_1$, at $\omega = 2.412$ MeV
   - $1^+_{10}$, at $\omega = 8.278$ MeV

Comparison:
Experiment $^{56}$Fe$(n, p)$ [2] shows 3 peaks between 0 − 2 MeV.
Experiment $^{56}$Fe$(d, ^2$He$)$ [1] shows the 2 peaks at 0.11 MeV and 1.2 MeV respectively. Good Agreement!

Total Cross Sections for $^{56}$Fe

- Total EC cross sections for $^{56}$Fe at $T = 0.5 \text{MeV}$.
- Individual contributions of $J^\pi \leq 5^\pm$.
- Major contribution of $1^+$ multipolarities.

Electron capture cross sections of GT transitions at $T = 0.5 \text{MeV}$, as a function of $E_e$. The results are compared with the results of the works [1](SMMC) and [2] (RRPA).

The temperature dependence of total $e^-$-capture CS for $^{66}$Zn.

For $T \geq 1.3\,\text{MeV} \Rightarrow$ fp orbitals have already unblocked $\Rightarrow$ total cross sections does not affected significant by the increase of the temperature.
Dynamical simulations in Micro-quasars

- Relativistic astrophysical jets are modelled both dynamically and radiatively.
- Modern Relativistic Magneto-Hydro-Dynamical (RMHD) hydrocode used for the dynamic calculation (PLUTO).
- High Energy $\gamma$-ray and $\nu$-emission calculated from the model jet.
- Synthetic images produced by employing line-of-sight (LOS) ray-tracing.
- Results compared to actual observations and detector output.
- When model results match observations, initial conditions of model are then considered to approximate the actual ones at the source.
Density evolution for a hydrodynamical jet moving at 0.26$c$. We can see the swift lateral jet expansion right after the crossing of the accretion disk coronal winds, in part due to the absence of a constraining toroidal magnetic field component.