[EXTERNAL] Lepton Interactions with Nucleons and Nuclei -- XVI - invitation for a plenary talk

Camillo Mariani <camillo@vt.edu>
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To: Rocco Schiavilla <schiavilla@jlab.org>
Cc: S. P. <saori.pastore@gmail.com>; Maria Piarulli <mpiarulli22@gmail.com>; Luca Girlanda <girlanda@le.infn.it>; Laura Elisa Marcucci <laura.elisa.marcucci@unipi.it>

"Lepton Interactions with Nucleons and Nuclei--XVI"

Organizing Committee:

Luca Girlanda
Laura E. Marcucci
Camillo Mariani
Saori Pastore
Maria Piarulli

Dear Rocco:

We are organizing a workshop on "Lepton Interactions with Nucleons and Nuclei" to be held in Marciana Marina, Isola d'Elba, Italy, during the period Sep. 3-8, 2023.

The meeting will be the sixteenth in a series started in 1988. Past editions have covered new developments in research areas ranging from nuclear astrophysics and neutrino physics to hadron structure and response to the physics of nuclei at low and high energies.
It gives us great pleasure to invite you to give a talk. There will be no conference or registration fees.

Please let us know at your earliest convenience if you accept our invitation. If so, we would appreciate it if you could provide us with a tentative title for your talk.

With hope of a positive reply to our invitation, we ask you to kindly acknowledge receipt of this letter.

The Organizers

Luca Girlanda
Laura E. Marcucci
Camillo Mariani
Saori Pastore
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A brief history of the “baric model” of nuclei
R. Schiavilla, ODU/SLab

* The “baric model”: focus on EW currents (late ’60 through to early ’00)
  - the early phase
  - the sequel
  - nuclear axial current
  - nuclear charge form factors
  - realistic nuclear EW currents

* Advent of xEFT (post early ’00)
The basic model

* Effective interactions and EW currents

\[ H = \sum \frac{E_i}{2m} + \sum V_{ij} + \sum V_{ijk} + \ldots \]

\[ \mathbf{J} = \sum \mathbf{J}_i + \sum \mathbf{J}_{ij} + \sum \mathbf{J}_{ijk} + \ldots \]

* Assumptions:

(i) Quarks in nuclei are in color-singlet states \( N \) (and low-lying excitations such as \( \Delta \))

(ii) Series of interactions and currents converge rapidly

(iii) Dominant terms in \( V_{ij} \) (\( \mathbf{J}_{ij} \)) and \( V_{ijk} \) (\( \mathbf{J}_{ijk} \)) due to \( \pi \)-exchange

\[ \frac{g_s}{2f_{\pi}} \sigma \cdot \nabla \phi (\pi) \]

\( \pi \)on field
Early phase

* G.E. Brown and collaborators' efforts to construct a realistic $NN$ interaction from ME (late '60 to early '70)

* $2\pi$-exchange in $PS$ coupling led inevitably to overbinding

\[ \text{Pair diagram} \]

Pair suppression built into Weinberg's chiral Lagrangian for $\pi N$ interactions ($PV$ coupling) revived efforts

* Concurrently, Chemtob and Rho (171) constructed MEC from effective Lagrangians for $\pi$ and Vector mesons

\[ \text{$p$-exchange reduces tensor component induced by $\pi$-exchange in $NN$ interaction and enhances effects of $\pi$-exchange current} \]
A pioneering study of axial MEC effects in $^3\text{H}$ $\beta$-decay with simple $^3\text{H}/^3\text{He}$ central w.f.'s

Fig. 1. Graphs contributing to two-body interaction current; (a) to (d) are Feynman graphs and (e) and (f) are time-ordered graphs corresponding to the pieces of fig. 1b which are not included in the wave function and therefore should be included as exchange contribution. The momenta involved are indicated in the parentheses. Graphs with indices 1 and 2 interchanged should also be included.

Fig. 2. Interaction current contribution $\delta_{\text{th}} = (\langle H_2\rangle/\langle H_1 \rangle)\delta$ in % versus $\gamma(F^{-1})$ and $r_C(F)$. $\delta_B$, $\delta_{NB}$ and $\delta_B + \delta_{NB}$ correspond respectively to the 'Born', 'non-Born' and total OPE contribution. To compare with the experimental value $\delta_{\text{exp}} = (5.4 \pm 2.5)$ %, our result $\delta_{\text{th}}$ should be multiplied by $\langle H_1 \rangle/\langle H_1 \rangle$ Gibson = 0.93.

Comment:

\[ E_I = v_\pi \left( 1 + \frac{E_i - E_I}{2\omega_\pi} \right) \frac{1}{E_i - E_I} j^{\text{LO}} \]

\[ = -\frac{v_\pi}{2\omega_\pi} j^{\text{LO}} \]

cancel to leading order
The sequel

* G.E. Brown’s interest in the role of MEC was stimulated by Chemtob-Rho calculation of $^3\text{H} \beta$-decay

- relevance of D-state components in few-body nuclei wave functions (Rho, ’70; Blomqvist, ’70)

* First demonstration that MEC play a role in photonuclear observables

** MESON EXCHANGE EFFECTS IN $n + p \rightarrow d + \gamma$† **

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Received 2 January 1972

It is shown that an exchange-current correction of $\sim 10\%$ to the threshold neutron capture

$n + p \rightarrow d + \gamma$ can arise in a straightforward way from one-pion-exchange terms, most of it coming
from the exchange moments written down by Villars in 1947. A large part of the correction comes
from $^1S_0$ to $^3D_1$ terms, which have generally been overlooked.

** MEC contributions:**

![Diagram](image)

a) Pair processes  b) Pion current process

Fig. 2. Exchange-current correction arising from vertex corrections.

* Importance of $^3D_1 \rightarrow ^1S_0$ transition
And many other observables in which MEC play an important role - $d(e,e')pn$ at threshold

Hockert, Riska, Gari, and Huffman (173) - $^3$He m.f.f.

Brandenburg, Kim, and Tubis (174)

Barroso and Hadjinicholas (175)
- **nd and $^3$He radiative captures**

<table>
<thead>
<tr>
<th>M1 process:</th>
<th>$\sigma_{exp}(\text{mb})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}(n',y)^2\text{H}$</td>
<td>334.2 (5)</td>
</tr>
<tr>
<td>suppressed ${^2\text{H}(n',y)^3\text{H}$</td>
<td>0.508 (15)</td>
</tr>
<tr>
<td>$^3\text{He}(n',y)^4\text{He}$</td>
<td>0.055 (3)</td>
</tr>
</tbody>
</table>

- $^3\text{H}$ and $^4\text{He}$ bound states are approximate eigenstates of the 1b M1 operator:

\[ \mu_{(1b)^3\text{H}} \approx \mu_{p}^3\text{H} \]

ignoring D-state components

- $\langle \text{nd} | \mu_{(1b)} | ^3\text{H} \rangle \approx 0$ by orthogonality

- Of course, 1b M1 does contribute (D-state components), but MEC account for

\[ \sim 50\% \text{ of } \sigma_{exp} \text{ in nd} \text{ (Hadjimichael, '73)} \]

\[ \sim 80\% \text{ of } \sigma_{exp} \text{ in } ^3\text{He} \text{ (Towner and Khanna, '81)} \]

- Theoretical estimates for these radiative captures have been (and continue to be) refined by our group (1990 - present) and others (Friar et al)
State-of-the-art calculation (Vitiiani et al.'22)

$^3\text{H}(p,\gamma)^4\text{He}$

$^3\text{He}(n,\gamma)^4\text{He}$

Low-energy spectrum of $^4\text{He}$
- Role of axial MEC in $^3$H $\beta$-decay was confirmed.

- MEC-induced enhancement of $^1H(p,e^+\nu)^2H$ cross-section relevant in solar physics.

- Testing the modeling of axial MEC.

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**Calculation of Meson-Exchange Corrections to Triton Beta Decay Using Realistic Nuclear Wave Functions**

E. Fischbach, E. P. Harper, Y. E. Kim and A. Tubis

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and

W. K. Cheng

Physics Department, Stevens Institute of Technology, Hoboken, N.J., 07030, USA

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**Interaction Contributions to the Solar Proton-Proton Reaction**

M. Gari† and A. H. Huffman

California Institute of Technology

Received 1972 April 3; revised 1972 June 16

Abstract

Interaction contributions (meson-exchange effects) to the solar $p-p$ reaction are evaluated using the low-energy theorem results. A correction to the cross-section $S_{11}$ of approximately 9 percent is found.

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**Weak Interactions in Deuterons: Exchange Currents and Nucleon-Nucleon Interaction**

F. Dautry, M. Rho and D. O. Riska †

Service de Physique Théorique, Centre d’Etudes Nucléaires de Saclay, BP no. 2, 91190 Gif-sur-Yvette, France

Received 19 January 1976

Abstract: While the meson-exchange electromagnetic current has been tested with an impressive success in the two-nucleon system, nothing much is known about the reliability of the exchange currents in weak interactions. We study this question using muon absorption in the deuteron, $\mu^- + d \rightarrow n + n + \nu$. The meson-exchange current, previously derived in parallel to those of the electromagnetic interaction, is checked for consistency against the $p$-wave piece of the $p+p \rightarrow d+\pi^+$ process near threshold and then tested with the total capture rate for which some (though not so accurate) data are available. We then use the same Hamiltonian to calculate the matrix elements for the solar neutrino processes $p+p \rightarrow d+e^++\nu$ and $p+p+e^- \rightarrow d+\nu$ in the hope that they would be measured and help resolve the solar neutrino puzzle. Finally we make a detailed analysis of the differential capture rate $du/dE_n$, $E_n$ being the kinetic energy in the c.m. of the two neutrons, in the expectation that it will be used to pin down the ever elusive n-n scattering length.
Nuclear charge form factors

- Phenomenological success of EM MEC was mainly due to ΛN coupling.

- Corresponding contributions to nuclear charge operator involve higher powers of the momentum transfer.

- Kloet and Tjon pointed out that there is a sizable contribution in the $^3\text{He}/^3\text{H}$ charge form factor.

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**MESON EXCHANGE EFFECTS ON THE CHARGE FORM FACTORS OF THE TRI-NUCLEON SYSTEM**

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and

J.A. TJON
Institute for Theoretical Physics, Univ. of Utrecht, Utrecht, The Netherlands

Received 25 February 1974

The presence of meson exchange currents in the tri-nucleon system is shown to modify significantly the charge form factor of $^3\text{He}$ in the region of the dip and the secondary maximum. As a result the form factor is considerably changed at high momentum transfer.

![Diagram](image)

**Fig. 1.** Diagrams considered for meson exchange effects on the charge form factors.
By far, the dominant contribution is from

$$
\rho(q) = \frac{e}{8m_F^2 \xi} \frac{2}{k_2^2 + m_F^2} \frac{1}{2} + \bar{2} \frac{q_1 \cdot q_2 \cdot k_2}{k_2^2 + m_F^2} + 1 \rightarrow 2
$$

also derived in XEFT (Phillips, '03).

It plays a crucial role in few-nucleon charge F.F.'s, less prominent in heavier nuclei (where shell structure is prominent).

**FIG. 2.** $t_{20}(70^\circ)$ compared to theoretical predictions; dotted line (NRIA) and full line (NRIA+MEC+RC) [19]; relativistic models with dashed line [21] and long dashed line [22]; pQCD calculations with dashed-dotted line [23] and long dashed-dotted line [24].
Realistic nuclear EW currents

* By mid '90 - early '00 a number of high-quality realistic NN interactions became available (χ²/datum ≈ 1): Nijmegen models, AV18, and CDBon

\[ j_{ij}^\sigma = j_{ij}^{\sigma 0} + j_{ij}^{\sigma p} \]

isospin dependent
piece of \( j_{ij} \)
static

\[ j_{ij}^{\sigma 0}(k) = \left[ \frac{\sigma(k)}{\tau} + k^2 \frac{\sigma(k)}{\tau^2} \bar{j} \cdot j + \frac{\sigma(k)}{\tau^2} \bar{s}_{ij}(k) \right] \bar{j} \cdot j \]

Riska ('85), Gross and Riska ('87), Schiaffino et al ('89)

* Construct effective π and p currents out of \( \sigma(k), j_{ij}^{\sigma 0}(k) \)

and \( j_{ij}^{\sigma 0}(k) \) projected out of (isospin-dependent) \( j_{ij}^{\sigma p} \)

\[ j_{ij}^{\pi}(\sigma 0) = 3i(\bar{j} \times j) \cdot \bar{s}(k) \left[ \bar{s}_i - \frac{k_i - k_j}{k_i^2 - k_j^2} \bar{s} \cdot k_i \right] \bar{s} \cdot k_j + i \rightarrow j \]

\[ j_{ij}^{p}(\sigma 0) = \ldots \]

exactly conserved relative to \( j_{ij}^{\sigma 0} \)

\[ j_{ij}^{\pi 0} \]

long range

π + π + π → π π
Currents from $\nu_e$ minimal substitution in explicit $P$-dependence as well as in implicit one

$$\mathbf{e}_i \cdot \mathbf{E}_j = -1 + (1 + \mathbf{e}_i \cdot \mathbf{E}_j) \mathbf{e}^{i(\mathbf{p}_i \cdot \mathbf{p}_e + \mathbf{p}_j \cdot \mathbf{p}_e)}$$

$$P_{ij} = P_{ij} = -1$$

A realistic EM current, Maruacci et al. (65)

$$\mathbf{j} = j^{(1)} + j^{(2)}(\nu) + j^{(3)}(V^{2\pi})$$

Low energy:

$^2\text{H}(p,\gamma)^{3}\text{He}$

$^{2}\text{H}(\gamma,\gamma)^{3}\text{H}$

Many-body (3b and 4b) terms in nuclear charge operators give negligible contributions in charge by Riska and Radomski (77)
Intermediate energy:

\[ R_{+}(q, \omega) \quad \text{and} \quad R_{-}(q, \omega) \]

\[ \text{Lobato et al. (116)} \]

EM current (and charge) operators contain no free parameters and are consistent with short-range behavior of \( V_{ij} \) (and \( V_{jk}^{2\pi} \)).
A realistic axial current: effective $\pi$ and $p$ exchange terms $(AV18) + \Delta$ contributions with $g^*_A$ fixed by reproducing exp GT m.e. in $^3H$ $\beta$ decay.

Marcucci et al (00)

\[ \text{TABLE XVII. Contributions of the S- and P-wave capture channels to the hep S factor at zero $p$-He c.m. energy in } 10^{-20} \text{ keV b.} \]

The results correspond to the AV18/UIX, AV18, and AV14/UVIII Hamiltonian models.

<table>
<thead>
<tr>
<th></th>
<th>AV18/UIX</th>
<th>AV18</th>
<th>AV14/UVIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1S_0$</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$^3S_1$</td>
<td>6.38</td>
<td>7.69</td>
<td>6.60</td>
</tr>
<tr>
<td>$^3P_0$</td>
<td>0.82</td>
<td>0.89</td>
<td>0.79</td>
</tr>
<tr>
<td>$^1P_1$</td>
<td>1.00</td>
<td>1.14</td>
<td>1.05</td>
</tr>
<tr>
<td>$^3P_1$</td>
<td>0.30</td>
<td>0.52</td>
<td>0.38</td>
</tr>
<tr>
<td>$^3P_2$</td>
<td>0.97</td>
<td>1.78</td>
<td>1.24</td>
</tr>
</tbody>
</table>

Total: 9.64 12.1 10.1

$^{12}C(\nu_e, \mu^-)$ and MiniBooNE data

\[ ^3\text{He}(p, e^+\text{He}) \] S factor suppressed at 16 MeV

Lovato et al (120)
**χEFT formulation of the basic model**

* Lagrangians describing $\pi$ and $N$ (and $\Delta$) interactions are expanded in powers of $\chi/\Lambda$

* Their construction was codified in a number of papers (Gasser and Leutwyler, 1984; Gasser, Sainio, and Swäcke, 1988; Bonn group, 1992 and 2000)

\[
L = L^{(1)}_{\pi N} + L^{(2)}_{\pi N} + L^{(2)}_{\pi \pi} + \ldots + L^{(2)}_{\pi N} + L^{(4)}_{\pi\pi} + \ldots
\]

* $L^{(n)}$ also include contact ($\bar{N}N$) type interactions parametrized by LECs, accounting for short range terms beyond multi-π exchange

* A series of papers by Weinberg (1990-1992) provided initial impetus for the development of nuclear χEFT

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**Nuclear forces from chiral lagrangians**

Steven Weinberg

Theory Group, Department of Physics, University of Texas, Austin, TX 78712, USA

Received 14 August 1990

The method of phenomenological lagrangians is used to derive the consequences of spontaneously broken chiral symmetry for the forces among two or more nucleons.

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**Exchange Currents from Chiral Lagrangians**

Mannque Rho

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and Service de Physique Théorique, Centre d'Etudes Nucléaires de Saclay, 91191 Gif-sur-Yvette, France

(Received 3 December 1990)

Exchange currents in nuclei are derived from chiral Lagrangians, and a justification is offered for the "chiral filter hypothesis" which seems to be supported by all presently available experimental data.
First systematic (albeit incomplete) derivation of loop corrections in HBPT was followed (Park, Min, and Rho, 1993-1996).

Applications to np → fj and proton captures on 1H and 3He (Park, Kubadera, Min, Rho et al., 1993-103); deuteron static properties and j/f's (Phillips, 03).

Park et al. only retained irreducible contributions (following Weinberg's prescription).

However, the iteration

\[ (1 - 1) \times G_0 \times (1 + 1) \]

only generates part of the reducible contribution.

Left over must be accounted for (Pastore, Schionilla, Goty, 08).
Such an approach can be turned into a systematic method consistent with power counting (Pastore et al. '11) but analysis increases in complexity with increasing order.

Method has been applied to obtain vector currents (Pastore et al. '09 - '11; Piraulo et al. '13) and axial currents (Bonn et al. '16).

Alternative method adopted by the Bochum/Bonn group based on the Okubo unitary transformation decoupling the N only state space from the state space with \( T, N \) ...

Vector 2b currents are the same in the two approaches, but axial 2b currents differ (box diagrams). Bochum/Bonn also retains non static terms (neglected by our group).
Summary

XF, EFF versus ME formulation of the basic model:

- From a conceptual standpoint:
  - consistent treatment of nuclear interactions and currents
    \[ \text{contact axial current} \quad \text{contact } 3N \text{ interaction} \]
  - systematic inclusion of \( 2\pi \) exchange effects
    \[ \text{\( \omega \)} \quad + \quad \cdot \cdot \cdot \]
  - "systematically improvable"

- From the standpoint of nuclear phenomenology:
  - description of experimentally measured properties in the two formulations is similar quality