Elba, Sep 2023

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

Camillo Mariani <camillo@vt.edu>
Fri 3/10/2023 11:05 AM
To:Rocco Schiavilla <schiavil@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
Maria Piarulli

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Camillo Mariani
Professor of Physics
Director Graduate Program in Physics
Center for Neutrino Physics, Physics Department
Virginia Tech
Blacksburg, VA 24061-0435, USA
Phone: +1 (540) 231-4449
Fax: +1 (540) 231-7511
e-mail: camillo@vt.edu
webpage: http://www.phys.vt.edu/~camillo

A brief hystory of the "basic model" of nuclei

R. Schiavilla, ODU/JLab

* The "basic 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 χEFT (post early '00)

The basic model

* Effective interactions and EW currents

$$H=\sum_i \frac{\bar{p}_i^{\,2}}{2m}+\sum_{i<j} v_{ij}+\sum_{i<j<k} V_{ijk}+\dots$$

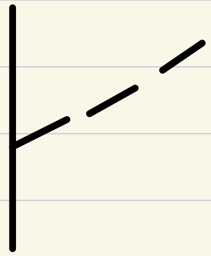
$$j^{EW}=\sum_i j_i+\sum_{i<j} j_{ij}+\sum_{i<j<k} j_{ijk}+\dots$$

* Assumptions:

(i) quarks in nuclei are in color singlet states like N (and low-lying excitations such as Δ)

(ii) series of interactions and currents converges rapidly

(iii) dominant terms in v_{ij} (j_{ij}) and V_{ijk} (j_{ijk}) due to π-exchange



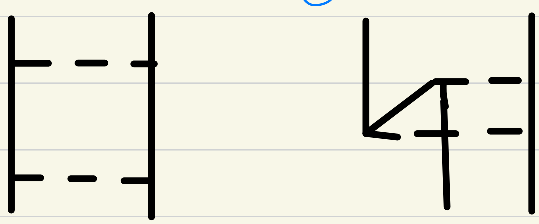
$$\frac{g_A}{2f_\pi}\,\tau_a\,\bar{\sigma}\cdot\bar{\nabla}\phi_a(\bar{r})$$

pion field

Early phase

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

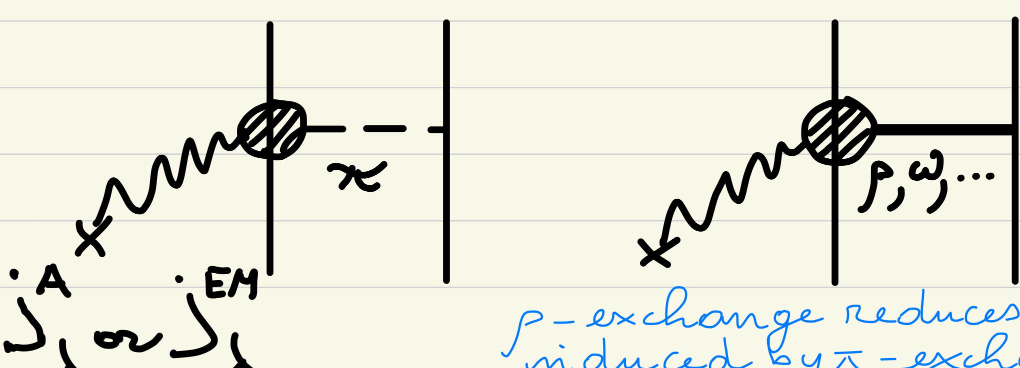
* 2π-exchange in PS coupling led inevitably to overbinding



pair diagram

pair suppression built into Weinberg's chiral Lagrangian for πN interactions (PV coupling) revived efforts

* Concurrently, Chemtob and Rho ('71) constructed MEC from effective Lagrangians for π and vector mesons



ρ-exchange reduces tensor component induced by π-exchange in NN interaction and enhances effects of π-exchange current.

4

* A pioneering study of axial MEC effects in ^3H β-decay with simple $^3H/^3He$ central w.f.'s

Volume 29B, number 9 PHYSICS LETTERS 4 August 1969

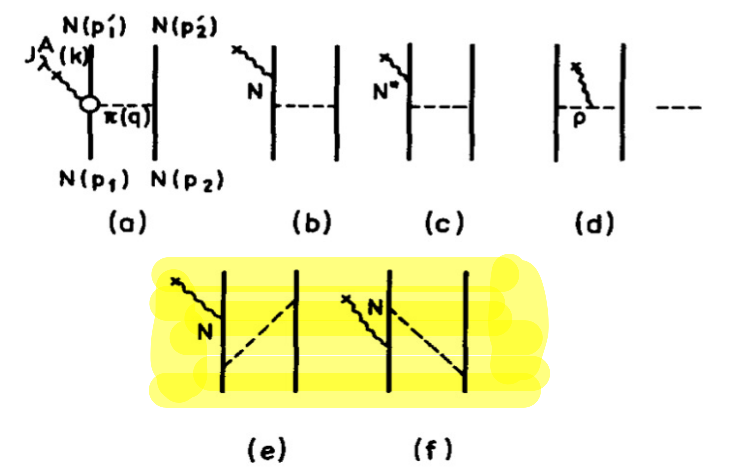


Fig. 1. Graphs contributing to two-body interaction current; (a) - (d) are Feynman graphs and (e) and (f) are time-ordered graphs corresponding to the pieces of fig. 1b which are not included in the wave function and therefore *should be* included as exchange contribution. The momenta involved are indicated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

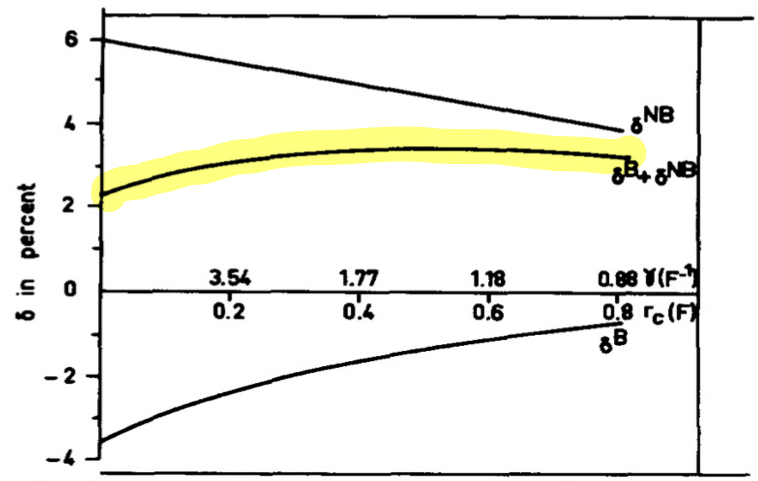
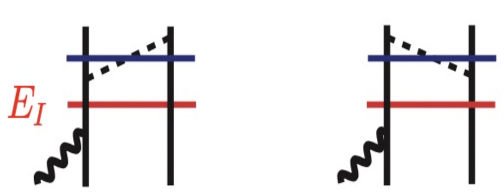


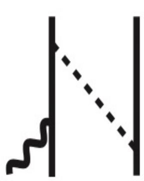
Fig. 2. Interaction current contribution $\delta_{th} = (\langle H_2\rangle/\langle H_1\rangle)_S$ in % versus $\gamma(F^{-1})$ and $r_c(F)$. δ^B, δ^{NB} and $\delta^B+\delta^{NB}$ correspond respectively to the 'Born', 'non-Born' and total OPE contribution. To compare with the experimental value $\delta_{exp}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

Chemtob and Rho

* Comment:



$$= v^\pi \left(1+\frac{E_i-E_I}{2\,\omega_\pi}\right)\frac{1}{E_i-E_I}\,\mathbf{j}^{\rm LO}$$



$$= -\frac{v^\pi}{2\,\omega_\pi}\,\mathbf{j}^{\rm LO}$$

cancel to leading order

The sequel

* G.E. Brown's interest in the role of MEC was stimulated by Chemtob–Rho calculation of ^3H β-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 $n + p \rightarrow d + \gamma$†

D. O. RISKA
Department of Physics, State University of New York, Stony Brook, N.Y. 11790, USA

and

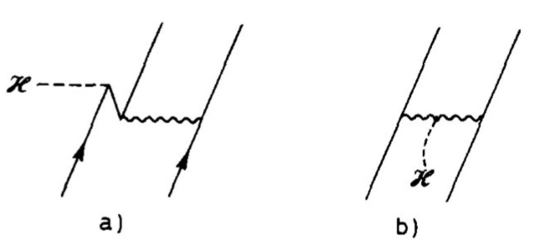
G. E. BROWN
NORDITA, Copenhagen, Denmark and State University of New York, Stony Brook, N.Y. 11790, USA

Received 2 January 1972

It is shown that an exchange-current correction of ~ 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:

important in β-decay of ^3H (Blomqvist, '70)



a) Pair processes b) Pion current process

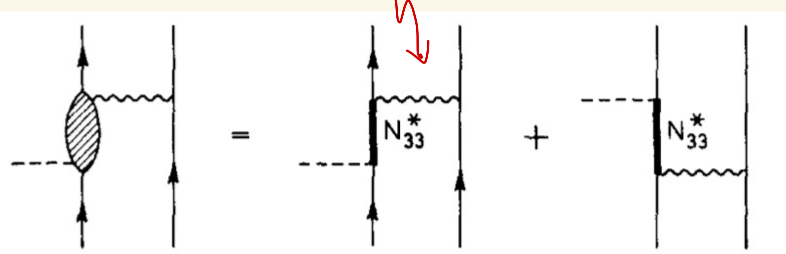
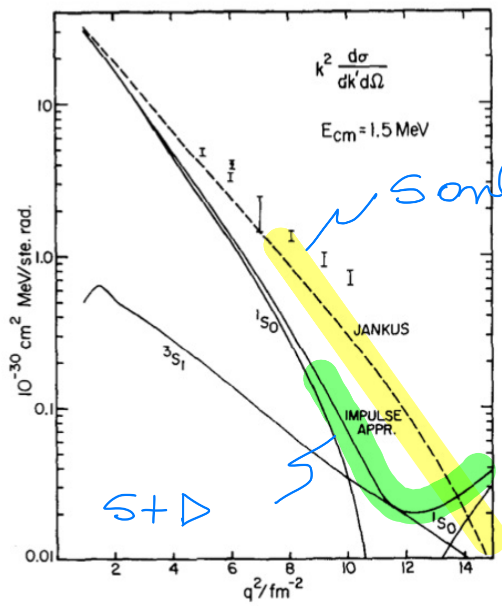


Fig. 2. Exchange-current correction arising from vertex corrections.

* Importance of $^3D_1 \rightarrow {}^1S_0$ transition

* And many other observables in which MEC play an important role

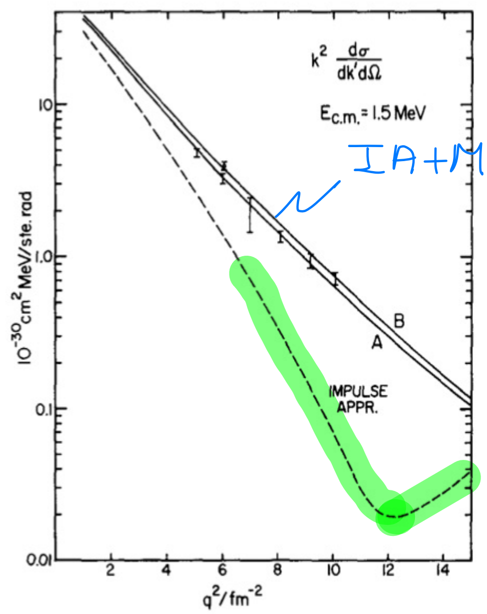
— d(e,e')pn at threshold



S only

S+D

Fig. 5. The impulse approximation cross section for $E_{c.m.} = 1.5$ MeV. The notation is the same as in fig. 4.

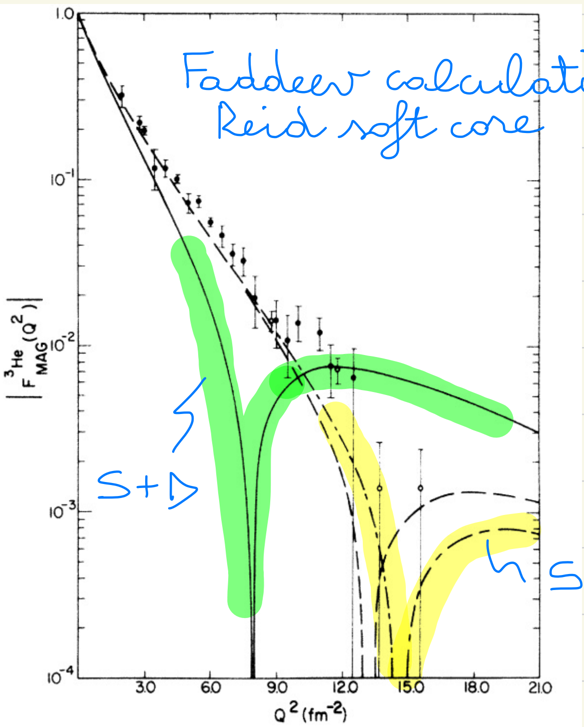


IA+MEC

Fig. 9. The cross section for $E_{c.m.} = 1.5$ MeV. The notation is the same as in fig. 8.

Hockert, Riska, Gari, and Huffman ('73)

— ^{3}He m.f.f.

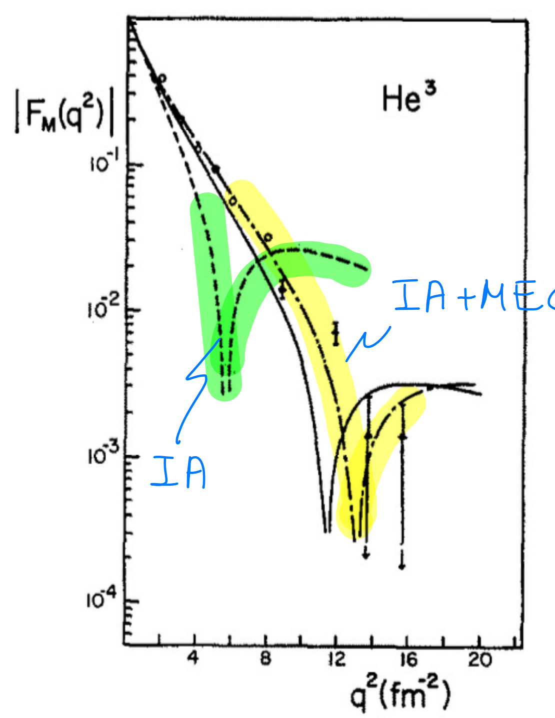


Faddeev calculation
Reid soft core

S+D

S only

Brandenburg, Kim, and Tubis ('74)



IA+MEC

IA

Barroso and Hadjimichael ('75)

– nd and n^{3}He radiative captures

M1 processes:

	σ_{exp} (mb)
$^1H(n,\gamma)^2H$	334.2 (5)
$^2H(n,\gamma)^3H$	0.508(15)
$^3He(n,\gamma)^4He$	0.055(3)

suppressed $\{$ $^2H(n,\gamma)^3H$, $^3He(n,\gamma)^4He$

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

$$\mu(1b)|^3H\rangle \simeq \mu_p |^3H\rangle$$

ignoring D-state components

- $\langle nd|\mu(1b)|^3H\rangle \simeq 0$ by orthogonality

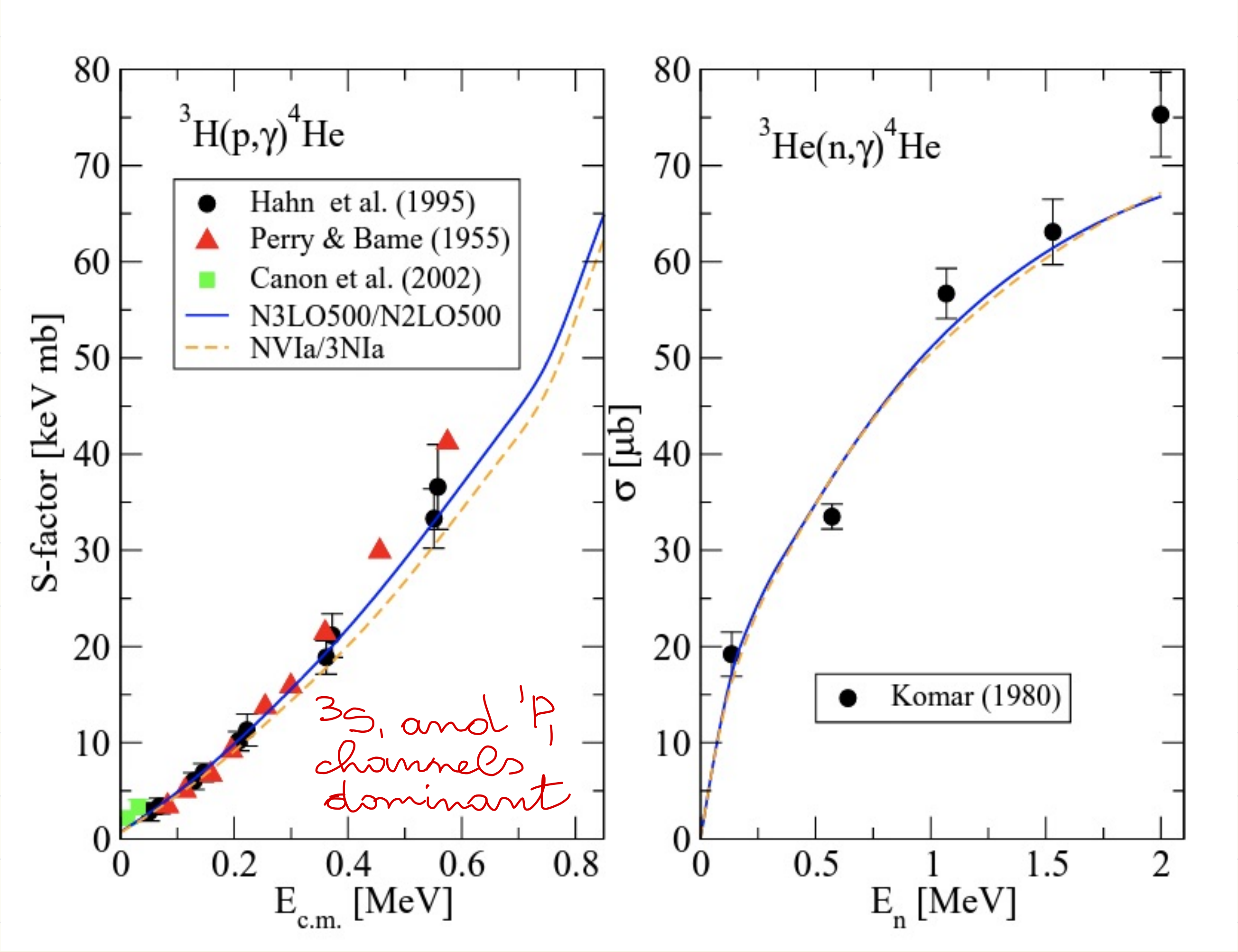
- Of course, 1b M1 does contribute (D-state components), but MEC account for

  ~ 50% of σ_{exp} in nd (Hadjimichael, '73)

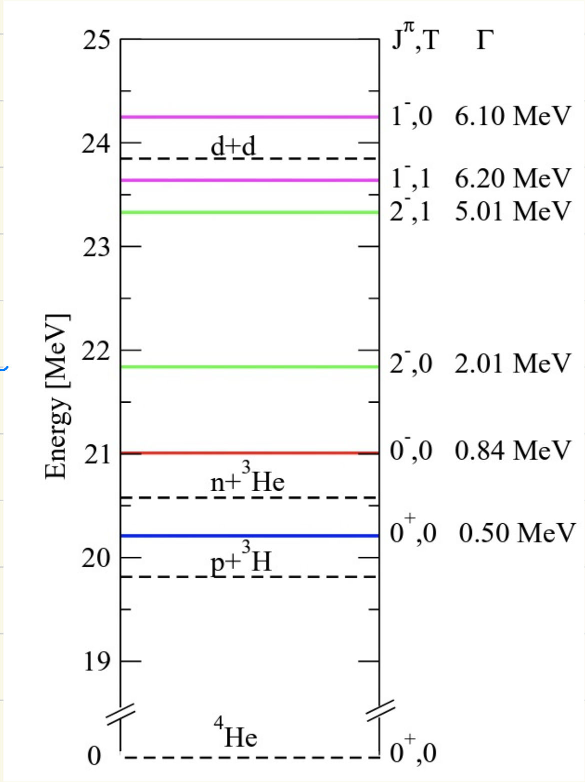
  ~ 80% of σ_{exp} in n^{3}He (Towner and Khanna, '81)

- Theoretical estimates for these radiative captures have been (and continue to be) refined by our group ('90-present) and others (Friar et al)

- State-of-the-art calculation (Viviani et al, '22)



low-energy spectrum of ^4He



Nuclear axial current

- Role of axial MEC in ^3H β-decay was confirmed

Volume 38B, number 1 PHYSICS LETTERS 10 January 1972

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
Physics Department, Purdue University, Lafayette, Indiana 47907, USA

and

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

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

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.

- Testing the modeling of axial MEC

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, $\mu^- + d \to n + n + \nu$. 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 $p + p \to d + \pi^+$ 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 $p + p \to d + e^+ + \nu$ and $p + p + e^- \to d + \nu$ 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 $d\Gamma/dE_n$, 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 $\gamma\pi N$ 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 $^3He/^3H$ charge f.f.

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

W.M. KLOET
Dept. of Physics and Astronomy, Univ. of Maryland, College Park, Md. 20742, USA

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}He in the region of the dip and the secondary maximum. As a result the form factor is considerably changed at high momentum transfer.

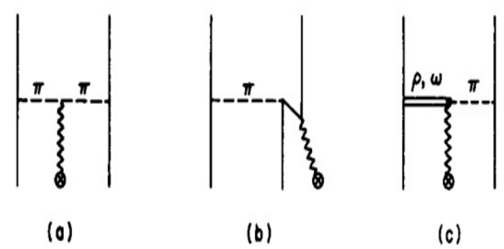
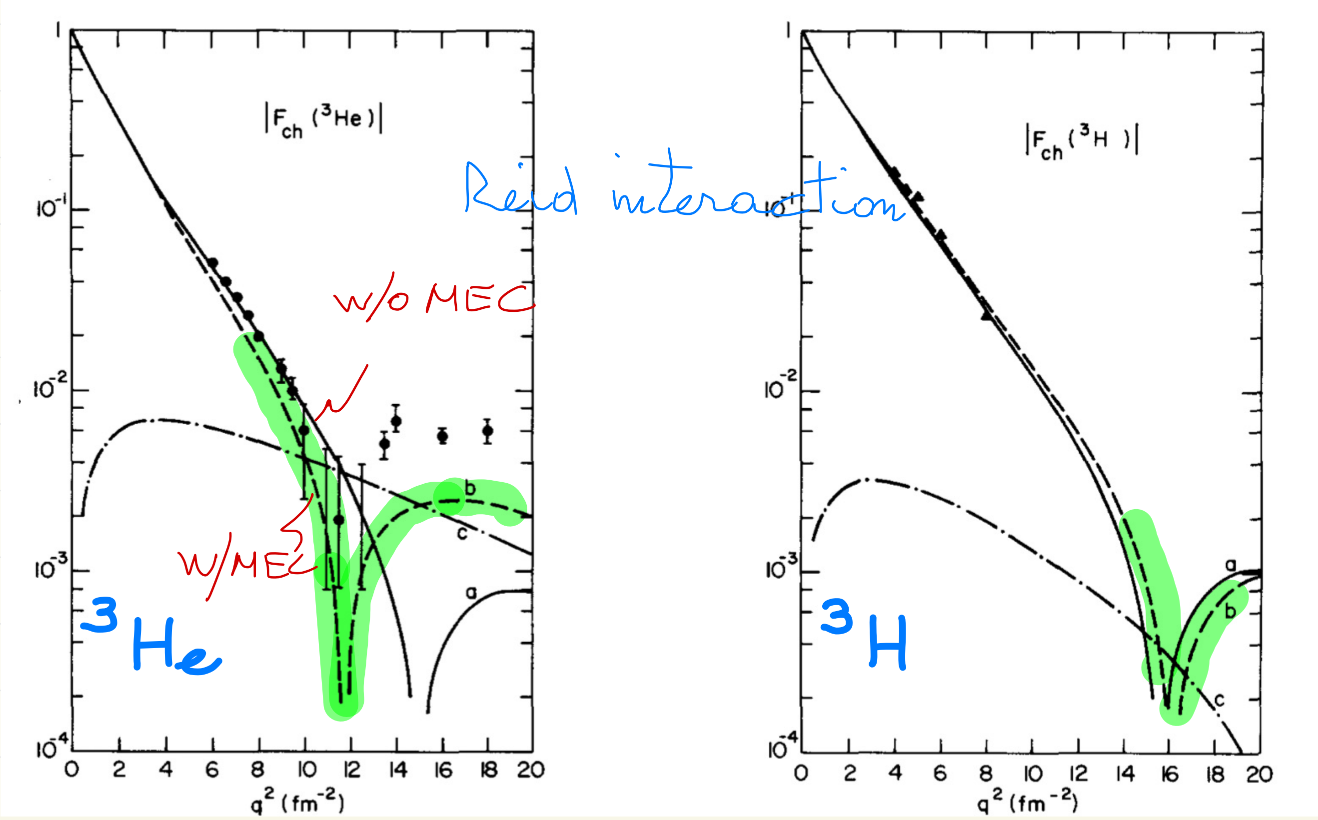


Fig. 1. Diagrams considered for meson exchange effects on the charge form factors.



– By far, the dominant contribution is from

$$\rho_\pi(\bar{q}) = \frac{e}{8m}\frac{g_A^2}{f_\pi^2}(\bar{\tau}_1\cdot\bar{\tau}_2 + \tau_{2z})\frac{\bar{\sigma}_1\cdot\bar{q}\;\bar{\sigma}_2\cdot\bar{k}_2}{k_2^2+m_\pi^2} + 1 \Longleftrightarrow 2$$

also derived in χEFT (Phillips, '03)

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

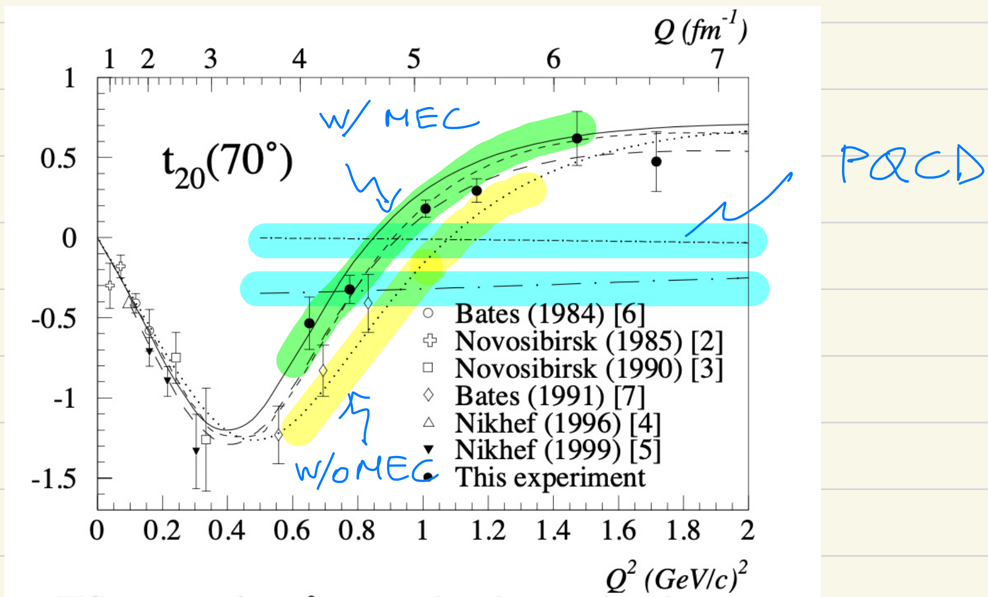
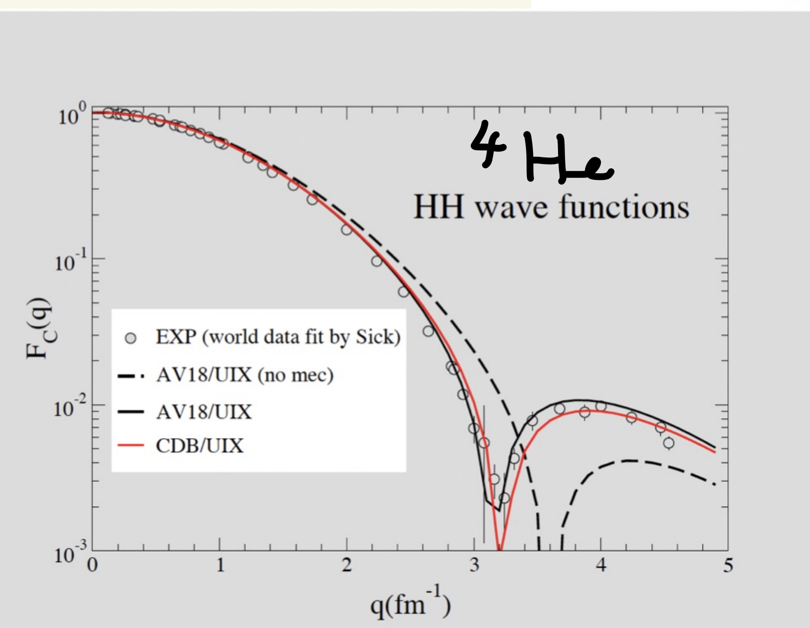
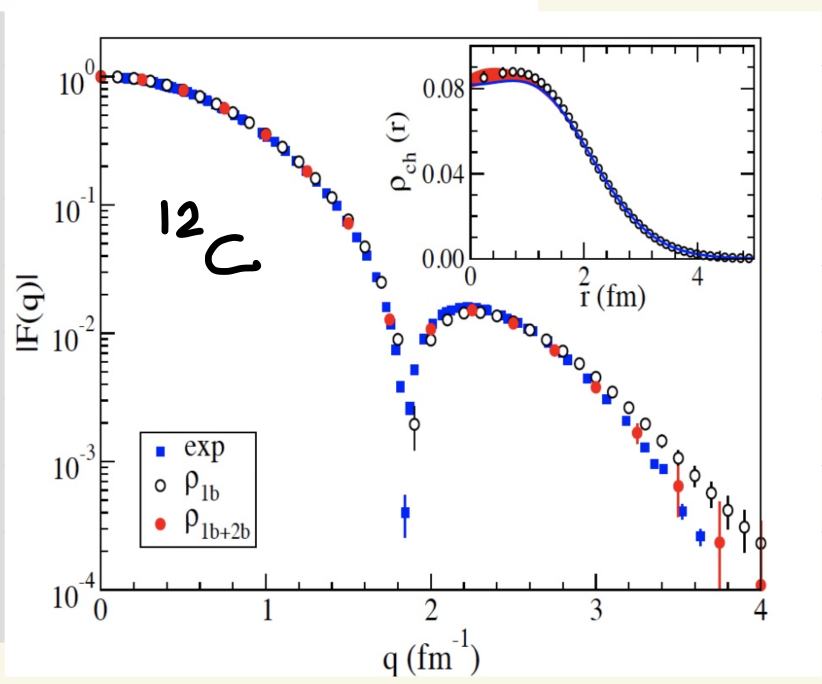


FIG. 2. t_{20} at θ_e=70° compared to theoretical predictions; dotted line (NRIA) and full line (NRIA+MEC+RC) [19]; relativistic models with dashed line [21] and long dashed line [22]; pQCD calculations with dashed-dotted line [23] and long dashed-dotted line [24].





Realitic nuclear EW currents

* By mid '90 – early '00 a number of high-quality realistic NN interactions become available (χ^2/datum $\simeq 1$): Nijmegen models, AV18, and CD Bonn

$$v_{ij} = \underbrace{v^{0}_{ij}}_{\text{static}} + \underbrace{v^{p}_{ij}}_{p\text{-dependent}}$$

isospin dependent piece of v^0_{ij}

$$v^{\sigma\tau}_{ij}(k) = \Big[\underbrace{v_{\tau}(k)}_{v_{\rho S}(k)} + k^2 \underbrace{v_{\sigma\tau}(k)}_{2v_{\rho}(k)+v_{\pi}(k)}\, \bar\sigma_i\cdot\bar\sigma_j + \underbrace{v_{t\tau}(k)}_{v_{\rho}(k)-v_{\pi}(k)}\, S_{ij}(\bar k)\Big]\,\bar\tau_i\cdot\bar\tau_j$$

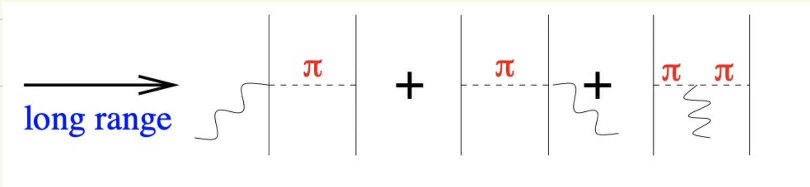
Riska ('85), Gross and Riska ('87), Schiavilla et al ('89)

* Construct effective π and ρ currents out of $v_\pi(k)$, $v_\rho(k)$, and $v_{\rho S}(k)$ projected out of (isospin-dependent) $v^{\sigma\tau}_{ij}$

$$j^{\pi}_{ij}(v^{\sigma\tau}) = 3i(\bar\tau_i\times\bar\tau_j)_z\, v_\pi(k_j)\left[\bar\sigma_i - \frac{\bar k_i-\bar k_j}{k_i^2-k_j^2}\,\bar\sigma_i\cdot\bar k_i\right]\bar\sigma_j\cdot\bar k_j + i\rightleftarrows j$$

$$j^{\rho}_{ij}(v^{\sigma\tau}) = \dots$$

exactly conserved relative to v^0_{ij}

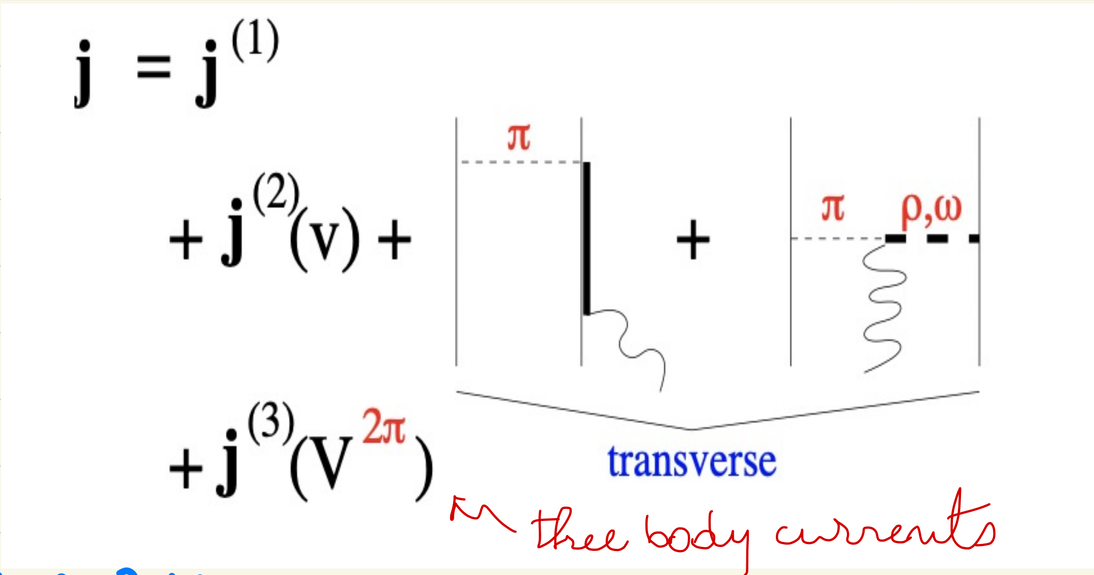
* $j^{\pi}_{ij}(v^{\sigma\tau})$ 

* Currents from v_{ij}^{p} via minimal substitution in explicit p-dependence as well as in implicit one

$$\bar\tau_i\cdot\bar\tau_j = -1 + (1+\bar\sigma_i\cdot\bar\sigma_j)\underbrace{e^{i(\bar r_{ji}\cdot\bar p_i + \bar r_{ij}\cdot\bar p_j)}}_{P^{ij}_{space}}$$

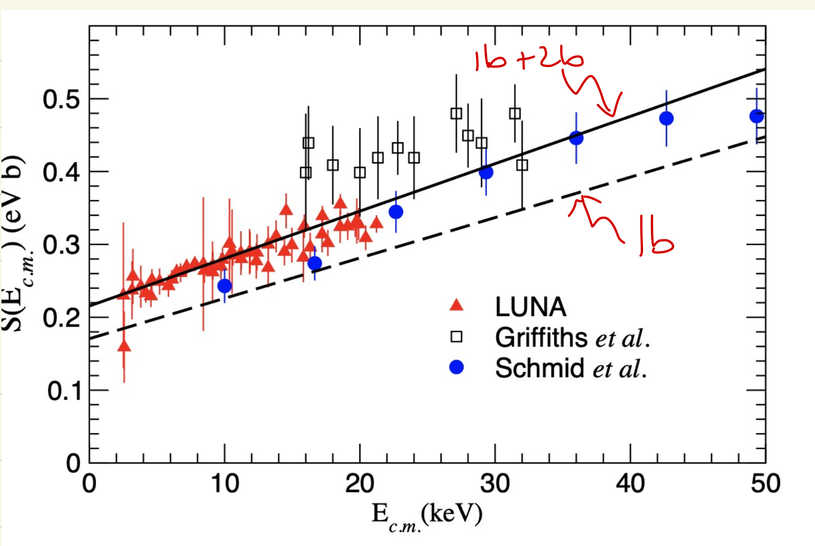
$$P^{ij}_{space}\,P^{ij}_{\sigma}\,P^{ij}_{\tau} = -1$$

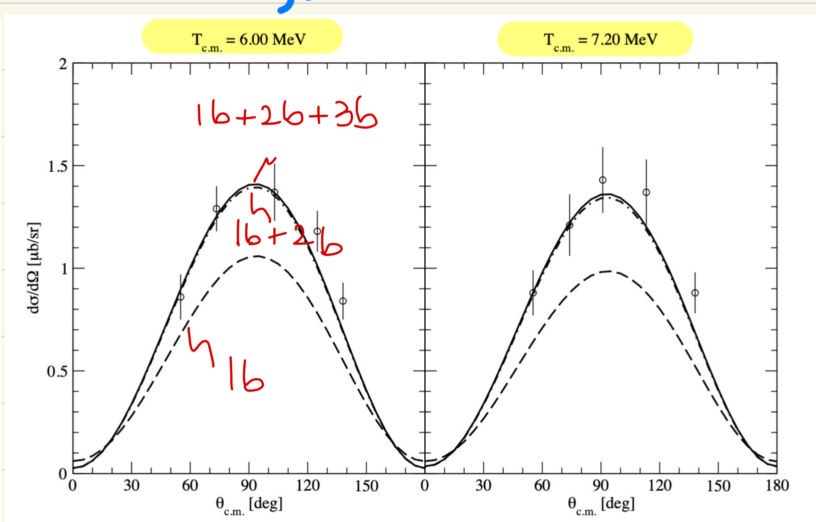
* A realistic EM current, Marcucci et al ('05)



* **Low energy:**

$^2H(p,\gamma)^3He$ $\quad$ $^2H(n,\gamma)^3H$

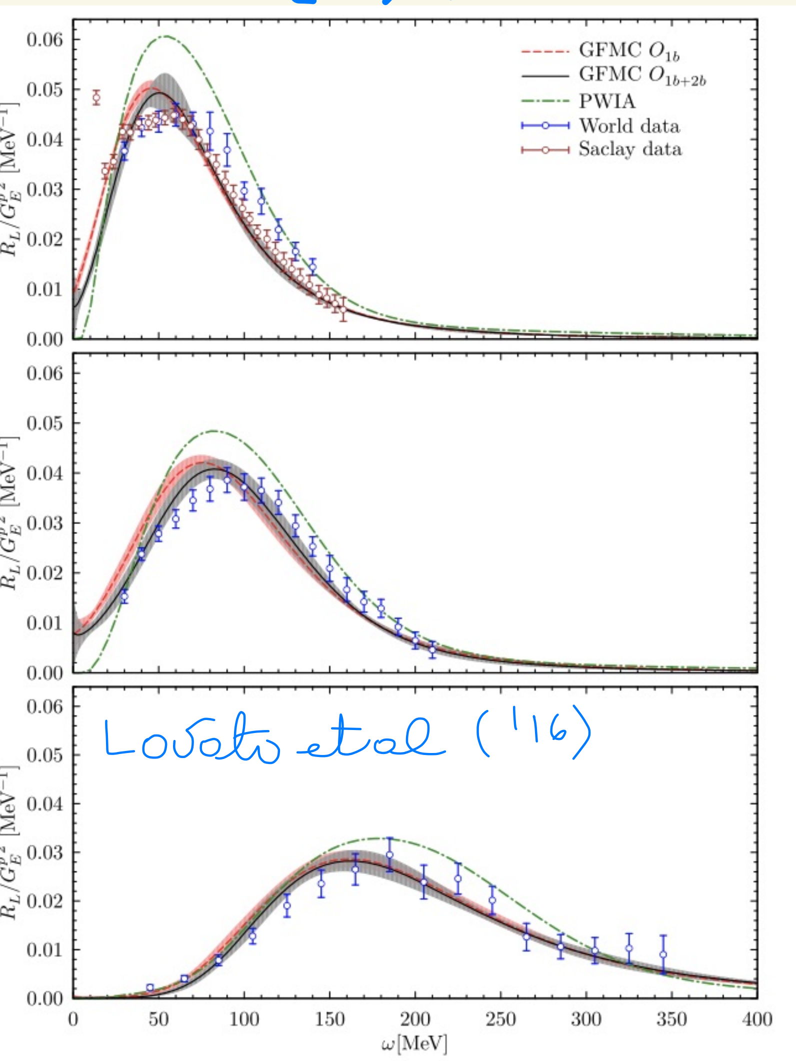




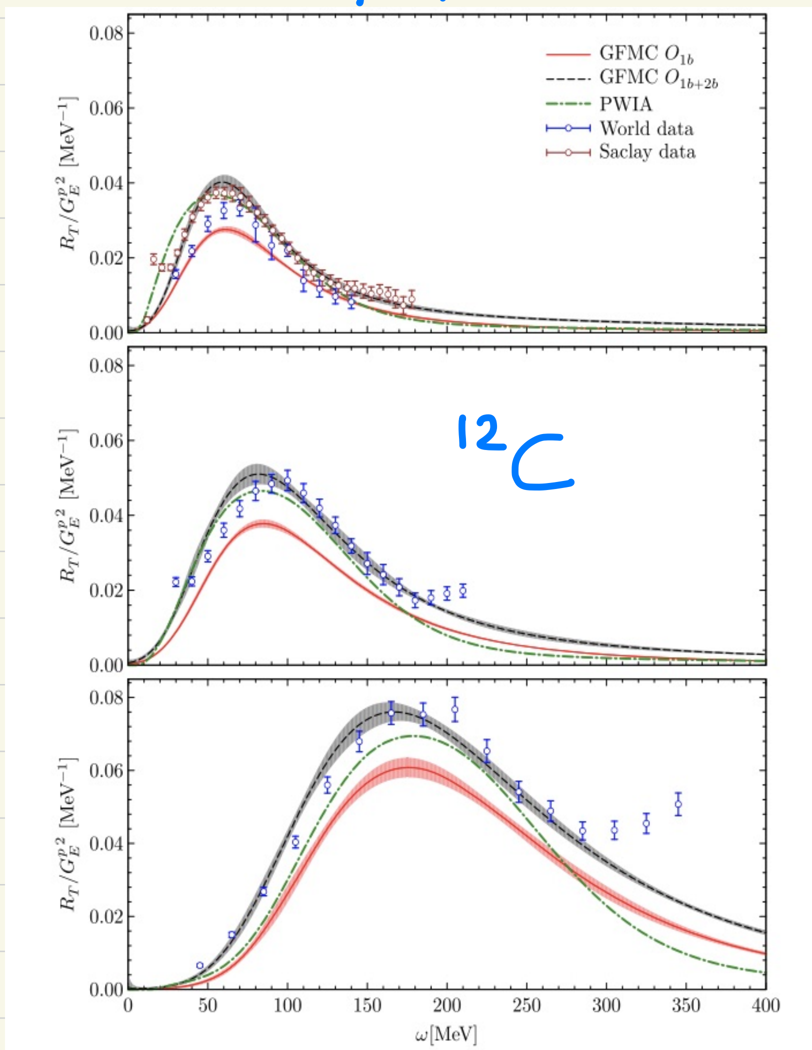
* Many-body (3b and 4b) terms in nuclear charge operator give negligible contributions in charge f.f.'s, Riska and Radomski ('77)

* Intermediate energy:

$R_L(q,\omega)$



$R_T(q,\omega)$



* EM current (and charge) operators contain no free parameters and are consistent with short-range behavior of v_{ij} (and $V_{ijk}^{2\pi}$)

* A realistic axial current: effective π and ρ exchange terms (AV18) + Δ contributions with g_A^* fixed by reproducing exp GT m.e. in ^3H β decay;
Marcucci et al ('00)

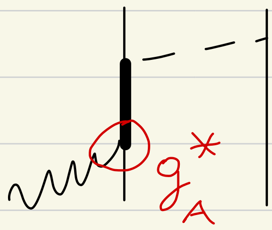
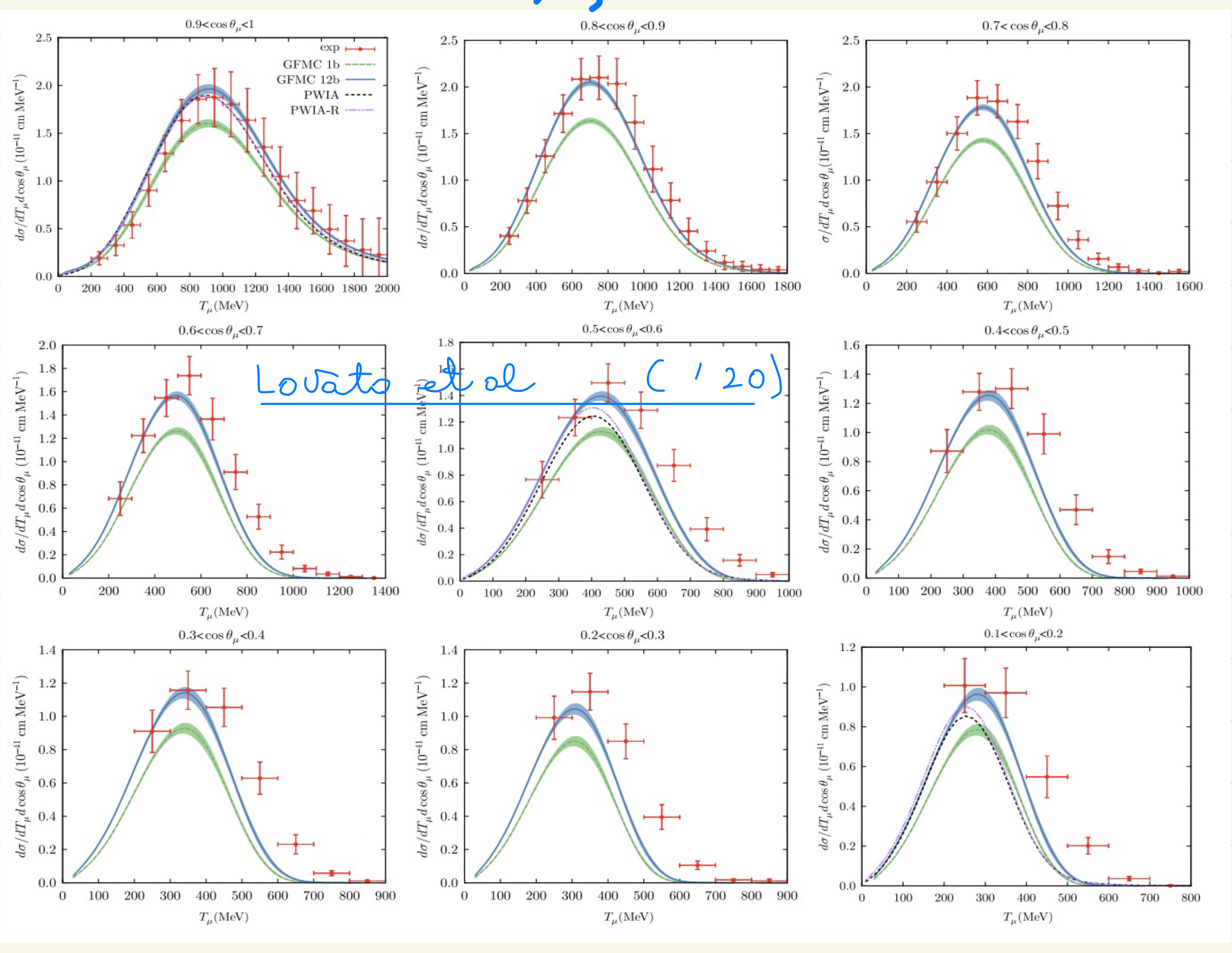


TABLE XVII. Contributions of the S- and P-wave capture channels to the *hep* S factor at zero p-^{3}He c.m. energy in 10^{-20} keV b. The results correspond to the AV18/UIX, AV18, and AV14/UVIII Hamiltonian models.

	AV18/UIX	AV18	AV14/UVIII
$^1S_0$	0.02	0.01	0.01
$^3S_1$	6.38	7.69	6.60
$^3P_0$	0.82	0.89	0.79
$^1P_1$	1.00	1.14	1.05
$^3P_1$	0.30	0.52	0.38
$^3P_2$	0.97	1.78	1.24
Total	9.64	12.1	10.1

$^3He(p,e^+\nu_e)^4He$ S factor
suppressed at 1b level

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



Lovato et al ('20)

χEFT formulation of the basic model

* Lagrangians describing π and N (and Δ) interactions are expanded in powers of Q/Λ_χ

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

$$\mathcal{L} = \mathcal{L}^{(1)}_{\pi N} + \mathcal{L}^{(2)}_{\pi N} + \mathcal{L}^{(3)}_{\pi N} + \cdots + \mathcal{L}^{(2)}_{\pi\pi} + \mathcal{L}^{(4)}_{\pi\pi} + \cdots$$

* $\mathcal{L}^{(n)}$ also include contact $(\bar{N}N)(\bar{N}N)$ 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

Nuclear forces from chiral lagrangians PLB 251, 1990

Steven Weinberg [1]
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.

* With applications to exchange currents by Rho

VOLUME 66, NUMBER 10 PHYSICAL REVIEW LETTERS 11 MARCH 1991

Exchange Currents from Chiral Lagrangians

Mannque Rho
Department of Physics, Seoul National University, Seoul 151-742, Korea and Service de Physique Théorique, Centre d'Etudes Nucléaires de Saclay, 91191 Gif-sur-Yvette, France[a]

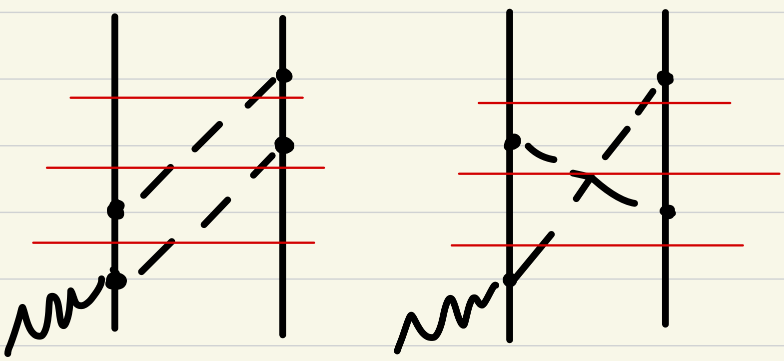
(Received 3 December 1990)

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 soon followed (Park, Min, and Rho, 1993–1996)

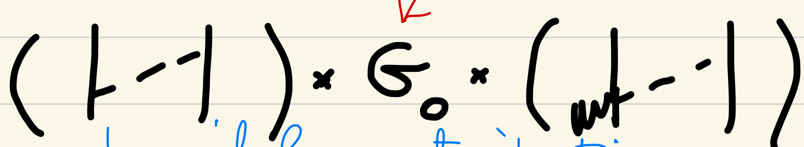
* And applications to $np \to d\gamma$ and proton weak captures on ^1H and ^3He (Park, Kubodera, Min, Rho et al, '93–'03); deuteron static properties and f.f.'s (Phillips, '03)

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



2N propagator

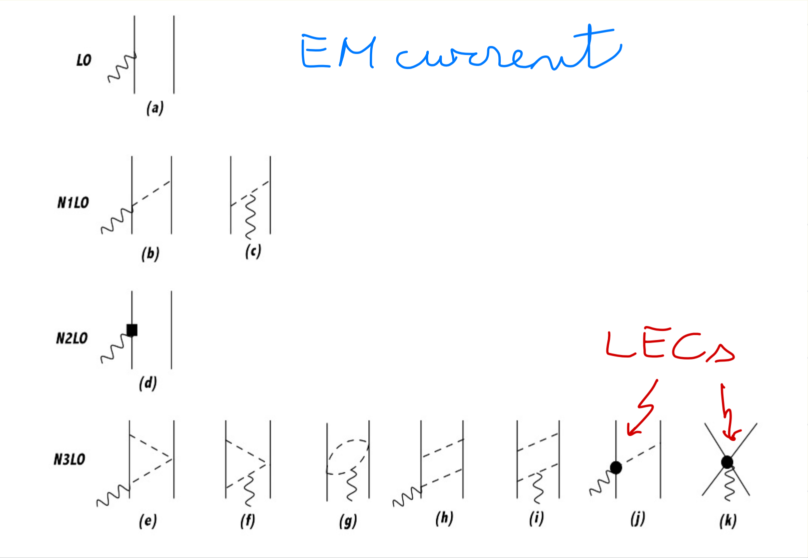
However the iteration only generates part of reducible contribution

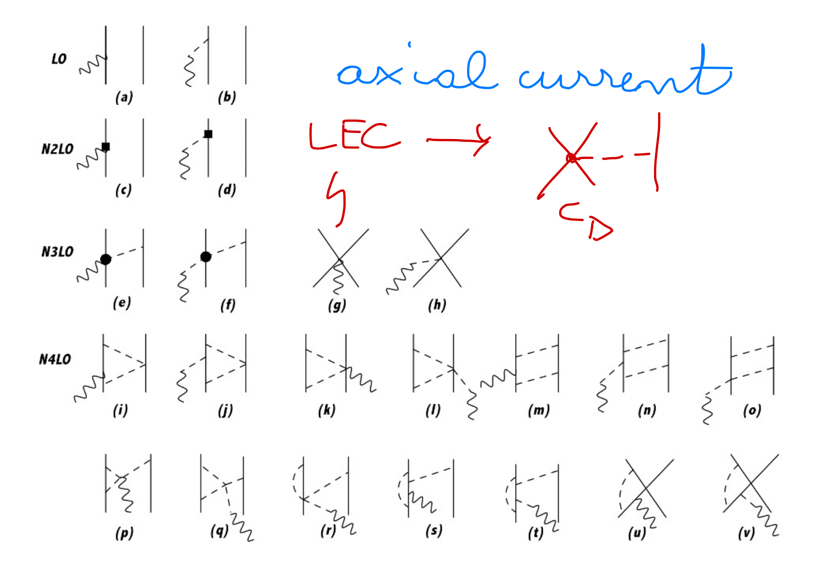


left over must be accounted for (Pastore, Schiavilla, Goity, '08)

* 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; Piarulli et al, '13) and axial currents (Baroni 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 π, N, ... ('09–'17)

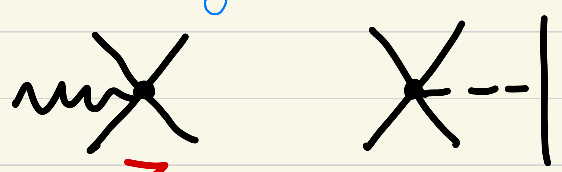
* Vector 2b currents are the same in the two approaches, but axial 2b currents differ (box diagrams); Bochum/Bonn also retains non static terms (neglected by our group)

Summary

* χEFT versus ME formulation of the basic model:

- From a conceptual standpoint:

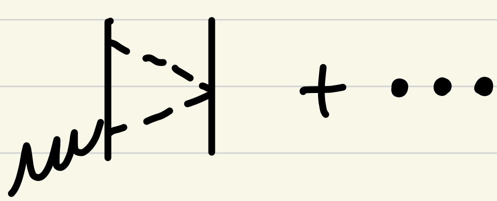
  – consistent treatment of nuclear interactions and currents



z_0 contact axial current

c_D contact 3N interaction

  – systematic inclusion of 2π exchange effects



  – "systematically improvable"

- From the standpoint of nuclear phenomenology:

  – description of experimentally measured properties in the two formulations is of similar quality