Electromagnetic Reactions in Nuclear Physics

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האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

Collaborators

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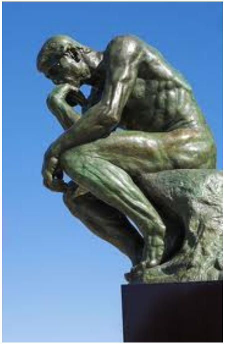
G. Orlandini, W. Leidemann

TRIUMF, Canada
S. Bacca, C. Ji, M. Miorelli, J. Hernandez

Outline

Motivation, what can we learn?

better put: What do we hope to learn?



1. Study the nuclear structure, the coupling constant $\ll 1$

   With the electro-weak probe, we can immediately relate the cross section to the transition matrix element of the current operator, thus to the structure of the target itself

   $DeForest - Walecka, Ann.Phys.1966$

2. Few-body physics $\Rightarrow$ Exact calculations $\Rightarrow$ Test the nuclear theory.

3. And of course, extract some useful numbers for astrophysics.

   Radiative capture cross-sections
   Inelastic neutrino scattering on nuclei
   electron capture on light nuclei
   ....

Example - A tale of two potentials

Consider two potentials that reproduce the NN phase shifts in the range $0 - 300$MeV.

How can we put them apart?

AV18+UBIX - Argonne V18 + Urbana IX
JISP16 - J-matrix Inverse Scattering Potential, Shirokov *et* al.

Binding Energies

	AV18+UBIX	JISP16	Nature
D	2.22	2.22	2.22
^{3}H	8.43	8.35	8.48
^{3}He	7.67	7.65	7.72
^{4}He	28.37	28.30	28.30
^{6}He	29.4	28.9	29.27
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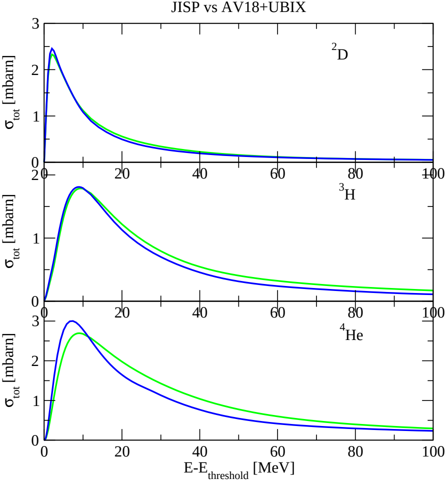
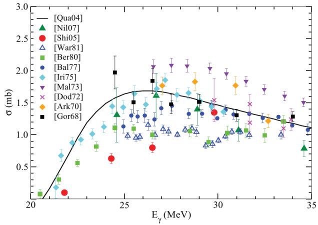
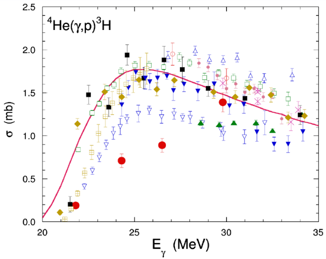
Photodisintegration cross-section for A=2,3,4



The Experimental Verdict !





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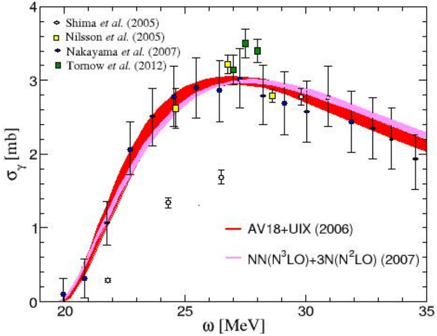

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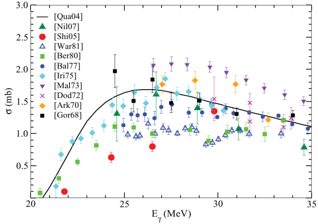

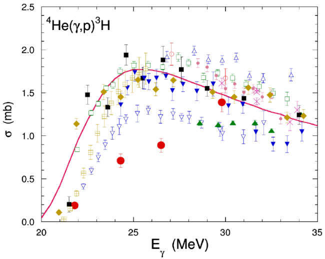

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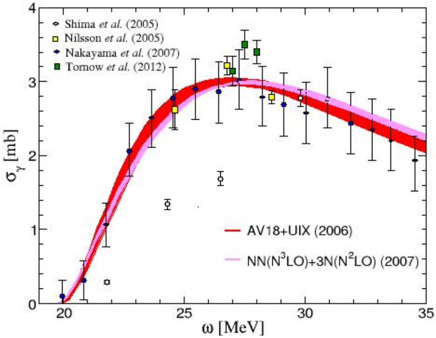
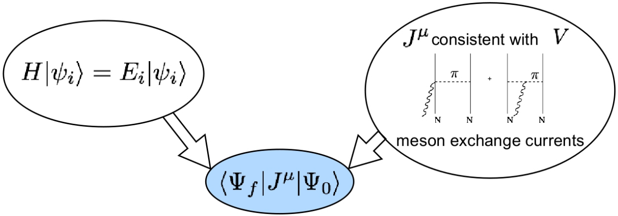


EM reactions with Nuclei - Theoretical considerations



The Wave Functions

- We solve the A-body non-realtivistic Schroedinger equation.
- The Hamiltonian

$$H = T + V_{NN} + V_{NNN}$$

High precision two-nucleon potentials, well constraint by NN phaseshifts Less established 3NF

- EFT provides a solid theoretical framework for construction of the potentials.
- Phenomenological potential models are not that bad either.

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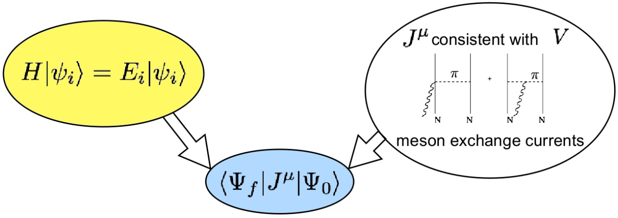

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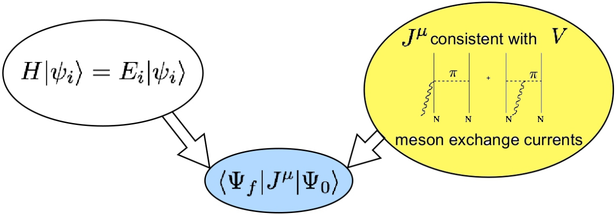

The Nuclear Current

- The EM current is a sum of convection and spin currents

$$\boldsymbol{J}(\boldsymbol{x}) = \boldsymbol{J}_c(\boldsymbol{x}) + \boldsymbol{J}_s(\boldsymbol{x}) = \boldsymbol{J}_c(\boldsymbol{x}) + \nabla \times \boldsymbol{\mu}(\boldsymbol{x})$$

- Classicaly, the convection current $\boldsymbol{J}_c = \sum_i Z_i \boldsymbol{v}_i$ is the flow of the charged particles.
- In nuclei $\boldsymbol{J}_c(\boldsymbol{x})$ is mainly due to proton movement.
- Meson exchange between nucleons leads to $2, 3, \ldots$-body currents $\boldsymbol{J} = \boldsymbol{J}_1 + \boldsymbol{J}_2 + \ldots$
- In EFT many body currents appear naturaly as contact terms.

The nuclear current

- Already at the 70's it became clear that the $M1$ transition in the deutron poses a problem.
- It was also realized that current and potentials are not independent entities.
- For conserved current

$$\nabla \cdot \boldsymbol{J}(\boldsymbol{x}) = -i[H, \rho(\boldsymbol{x})]$$

But for exchange force $V_\tau = V \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$, and $[\tau_1 \cdot \boldsymbol{\tau}_2, \tau_{z,1}] \neq 0$

- Riska and Brown have proposed the meson exchange mechanism for solving this riddle.
- Arenhovel et al. pointed to the importance of the Δ.
- Leading to MEC including the $\pi, \rho, \ldots$ mesons.
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The nuclear current (II)

- In the 90's Park, Min, and Rho derived the nuclear current using the Heavy Baryon Farmalism of ChPT.
- ChPT concludes that vector meson contributions are suppressed by Q^2.
- Pastore et. al., and Koelling et al. derived the EM currents in EFT including loop corrections.
- In EFT a direct connection $V_{NNN} \longleftrightarrow A$ through the LEC c_D (Gardestik and Phillips 2006).

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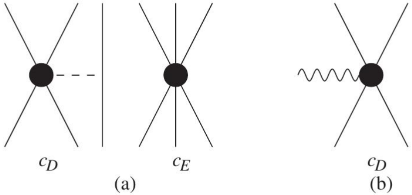

1-Body, and 2-Body contributions to the nuclear current

Contributions to the nuclear current at $\boldsymbol{q} = 0$

Park et. al. PRC **67**, 055206 (2003)

J_μ	LO	NLO	N^2LO	N^3LO	N^4LO
$\boldsymbol{A}$	1B	-	1B-RC	2B	1B-RC, 2B-1L, and 3B
A_0	-	1B	2B	1B-RC	1B-RC, 2B-1L
$\boldsymbol{V}$	-	1B	2B	1B-RC	1B-RC, 2B-1L
V_0	1B	-	-	2B	1B-RC, 2B-1L, and 3B

Conclusions

- Reactions involving $\boldsymbol{A}, V_0$ such as β-decay, photoabsorption, or (e, e') longitudinal response $R_L(\boldsymbol{q}, \omega)$ are least sensitive to MEC $\Rightarrow$ better test for the Hamiltonian.
- Reactions involving $\boldsymbol{V}, A_0$ such as (e, e') trensverse response $R_T(\boldsymbol{q}, \omega)$ are the place to look for MEC effects.

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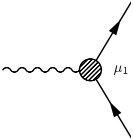
Many Body Currents - a small comment

a system of neutral particles with frozen spins

$$\boldsymbol{\mu}(\boldsymbol{x}) = \mu_1 \sum_i e^{-i\boldsymbol{q}\cdot\boldsymbol{r}_i} \boldsymbol{\sigma}_i$$



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- In the long wavelength limit the 1-body current may be suppressed by a factor of $(kR)^\ell$!
- One should compare $\left(\frac{Q}{\Lambda}\right)^3$ to $(kR)^\ell \approx \left(\frac{Q}{M}\right)^\ell$

Normal hierarchy case	Strong hierarchy case
$Q \ll \Lambda \approx M$	$Q \ll \Lambda \lll M$
1-body current dominated	2-body current dominated

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$$= \mu_1 \sum e^{-iq\cdot r_i}\sigma_i$$
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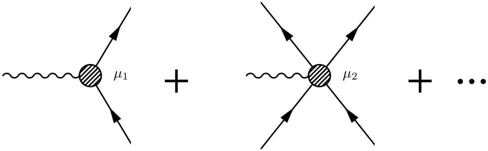

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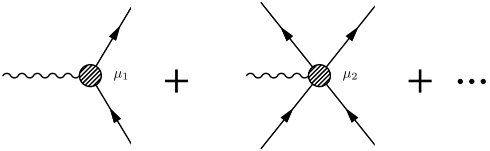

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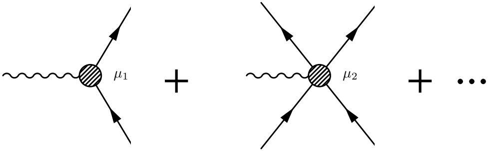

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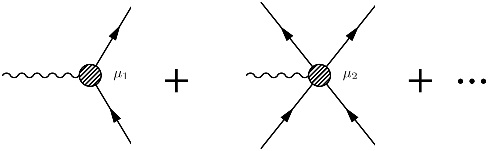

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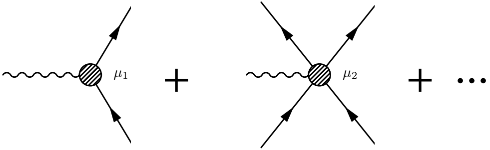

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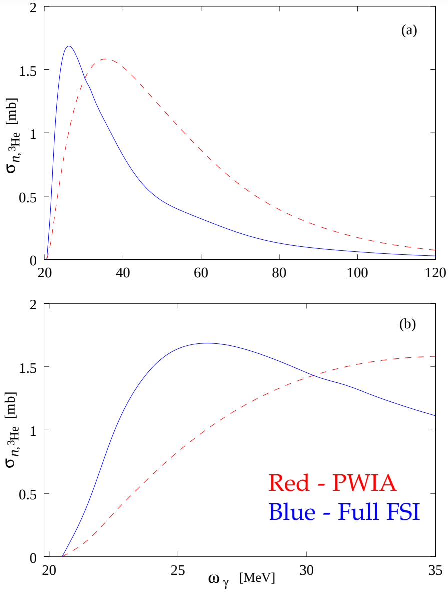
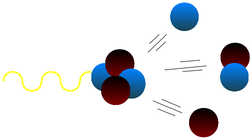
Final State Interaction



Problem:

Exact evaluation of the final state wave function in the continuum is limited in E and A.



Solution:

The Lorentz Integral Transform (LIT), Complex Rotation, ...

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- Static moments
- Radiative capture
- Radiative transitions
- Compton scattering
- Photoabsorption
- Electron scattering

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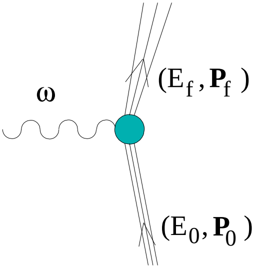
Photoabsorption of Nuclei

Real Photon

$$|\mathbf{q}| = \omega$$

$$\sigma(\omega) = 4\pi^2 \alpha \omega R(\omega)$$



Where

$$T_\lambda(q) = (-)^\lambda \sqrt{2\pi} \sum_J \sqrt{2J+1} \left[E_{J\lambda}(q) + \lambda M_{J\lambda}(q) \right]$$

and

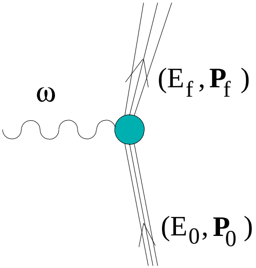
Photoabsorption of Nuclei

Real Photon

$$|\mathbf{q}| = \omega$$

$$\sigma(\omega) = 4\pi^2 \alpha \omega R(\omega)$$

$$R(\omega) = \frac{1}{2} \sum_{f,\lambda} \left| \langle \Psi_f | T_\lambda(q) | \Psi_0 \rangle \right|^2 \delta(E_f - E_0 - \omega)$$



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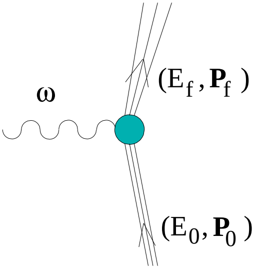

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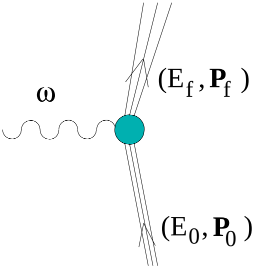

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Photoabsorption of Nuclei (II)

At low photon energy

$$qR \ll 1$$

The Response function is dominated by the dipole response

$$\sigma(\omega) = 4\pi^2 \alpha \omega R^{E1}(\omega)$$

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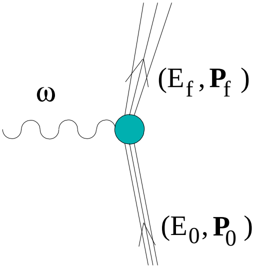

Via Siegert theorem MEC are implicitly included in the dipole response

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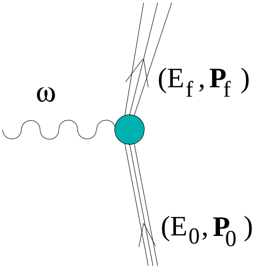

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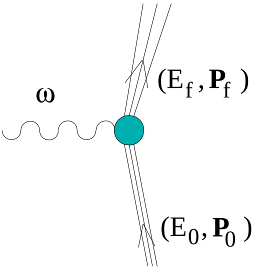
Theory and Experiment, Where do we stand?



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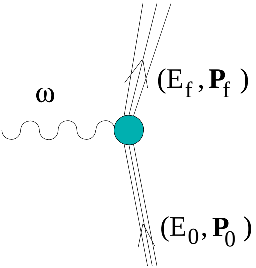

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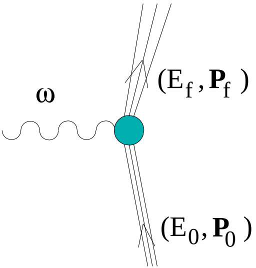

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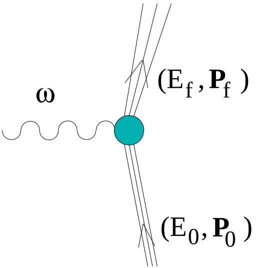

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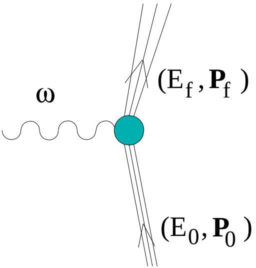

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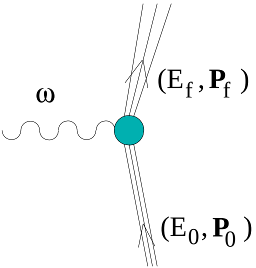

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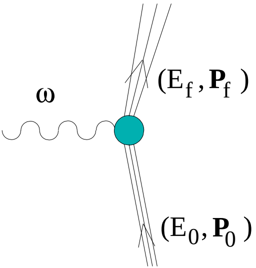

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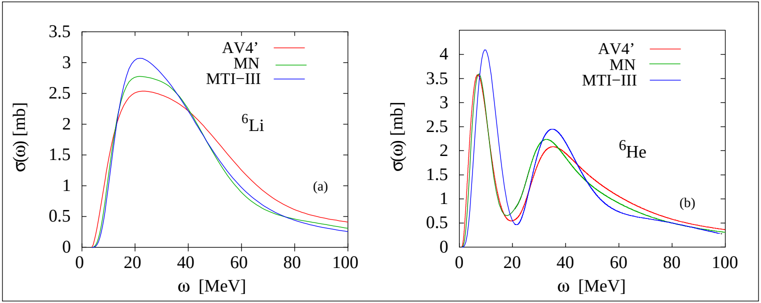
Six-body Photoabsorption



Bacca, Marchisio, Barnea, Leidemann, Orlandini, PRL **89** (2002)
S. Bacca, N. Barnea, W. Leidemann, and G. Orlandini, PRC **69**, 057001 (2004)

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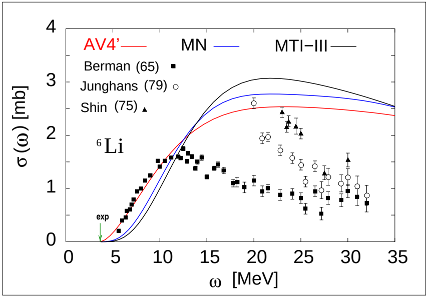

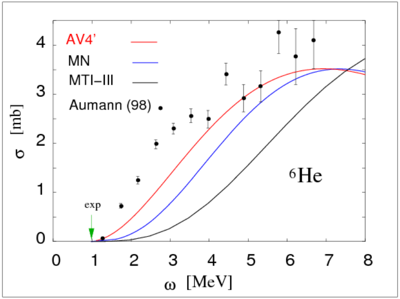

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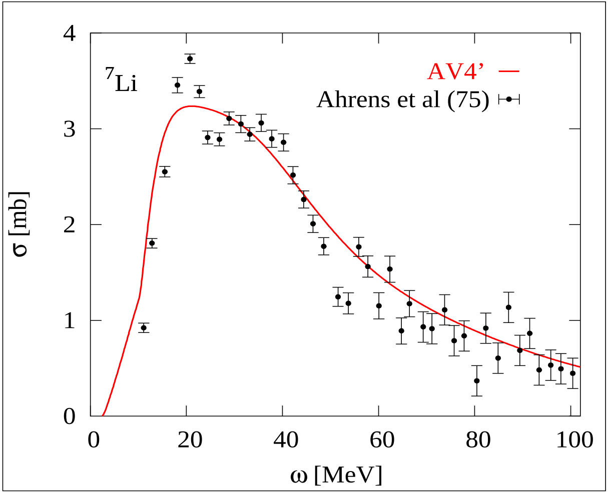
Seven-body Photoabsorption - Comparison with experiment



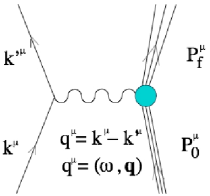
S. Bacca, H. Arenhövel, N. Barnea, W. Leidemann, and G. Orlandini, PLB **603** (2004)

Electron Scattering

Virtual Photon

$(\omega, \boldsymbol{q})$

are independent variables



$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_M \left[\frac{Q^4}{q^4} R_L(\omega, \boldsymbol{q}) + \left(\frac{Q^2}{2q^2} + \tan^2 \frac{\theta}{2} \right) R_T(\omega, \boldsymbol{q}) \right]$$

with $Q^2 = -q_\mu^2 = \boldsymbol{q}^2 - \omega^2$, θ scattering angle
σ_M Mott cross section

$$R_L(\omega, \boldsymbol{q}) = \sum_f \left| \langle \Psi_f | \rho(\boldsymbol{q}) | \Psi_0 \rangle \right|^2 \delta \left(E_f - E_0 - \omega + \frac{\boldsymbol{q}^2}{2M} \right)$$

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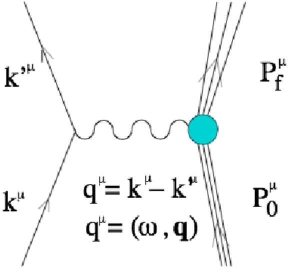

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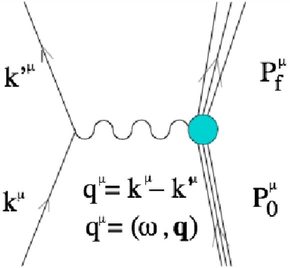

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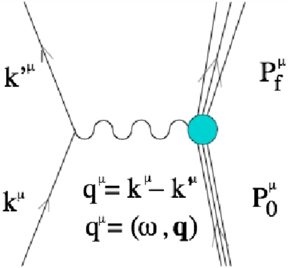

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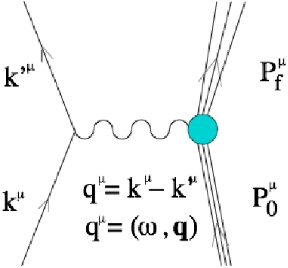

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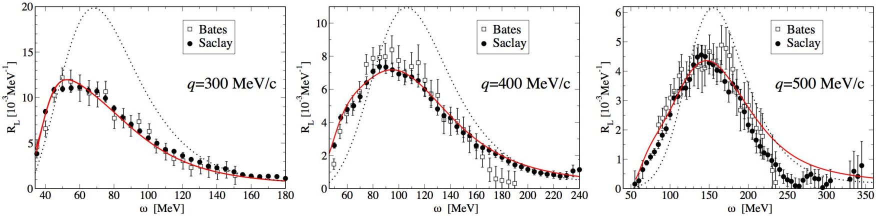
Electron Scattering - ^{4}He(e,e')X

Longitudinal Response $R_L(\omega, \boldsymbol{q})$



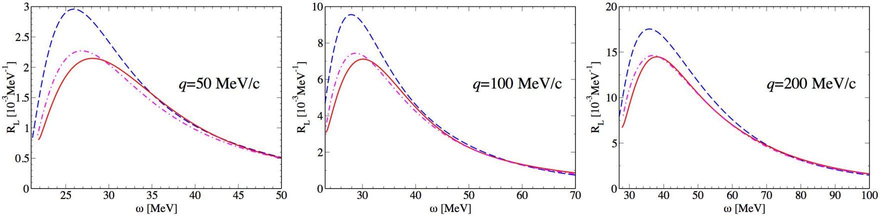
Bacca et al. PRL 102, 162501 (2009)

Red - Full FSI, Black - PWIA
Nuclear potential model AV18+UIX
FSI included via the LIT method

A strong FSI effect: Already known from Carlson and Schiavilla (PRL 1992, PRC 1994)

Longitudinal Response $R_L(\omega, q)$ - ^{4}He(e,e')X

Effect of nuclear model



Bacca et al. PRC (2010)

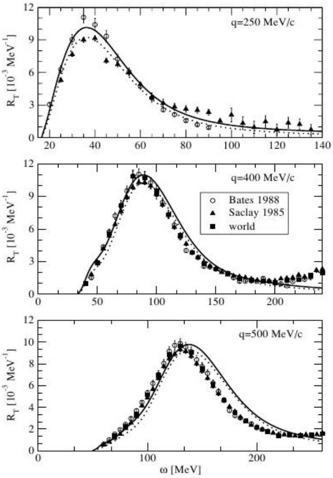
Blue - AV18, Red - AV18+UIX, Purple - AV18+TM'

B.E./MeV - AV18: 24.27 AV18+UIX: 28.40 AV18+TM': 28.46

- Large sensitivity to 3NF at low q.
- The sensitivity in $A = 3$ nuclei is much smaller.
- NOT a binding energy effect.
- Quest for measurements, data taken in Mainz.

Transverse Response $R_T(\omega, q)$ - ^{3}A(e,e')X

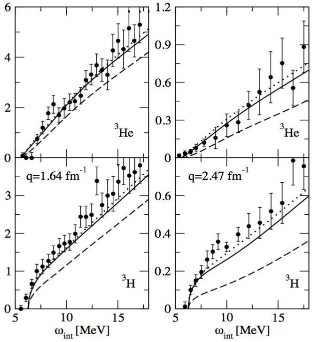
The MEC effects



Leidemann et al. (2009)

Solid - 1-body + MEC, Dotted - 1-body

AV18+UIX



Della Monaca et al. PRC 77 (2008)

Dashed - 1-body+rel., Solid - 1-body+rel+MEC, Dotted - 1-body+MEC

- Also calculations by Deltuva, Golak, Viviani, ...
- MEC play a desicive rule at threshold.
- A moderate rule at higher energies.

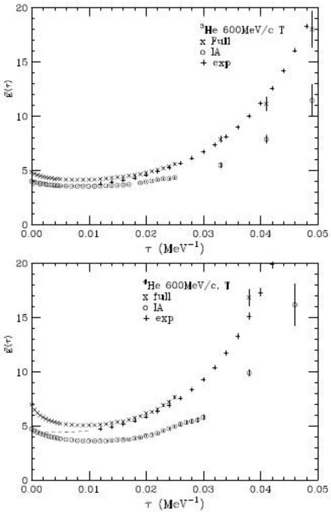
Transverse Response $R_T(\omega, q)$ - ^{4}He(e,e')X

The MEC effects

Direct comparison between realistic theory and experiment for $R_T(\omega, \boldsymbol{q})$ is NOT available.
An indirect comparison was made through the Euclidean response

$$E_T(\tau, \boldsymbol{q}) = \int_{\omega_{th}}^{\infty} d\omega \exp(-\omega\tau) R_T(\omega, \boldsymbol{q})$$

The results indicate for a strong MEC effect in the ^{4}He response.



Carlson et al PRC 65 (2002)

Longitudinal Response $R_L(\omega, q)$ - The Isoscalar Monopole

The transition form factor $0_1^+ \longrightarrow 0_2^+$ in ^{4}He

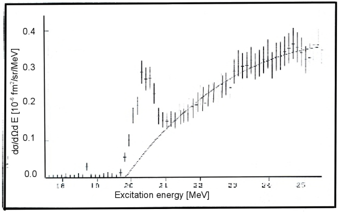
The isoscalar monopole operator

$$\mathcal{M}(q) = \frac{G_E^s(q)}{2} \sum_i^A j_0(qr_i)$$

Leads to the $\ell = 0$ isoscalar longitudinal response

$$R_{\mathcal{M}}(q,\omega) = \sum\!\!\!\!\!\!\int |\langle \Psi_f | \mathcal{M}(q) | \Psi_0 \rangle|^2 \delta(E_f - E_0 - \omega + \frac{q^2}{2M})$$

G. Koebschall et al./ Quasi bound state in ^{4}He - Nucl. Phys. A405, 648 (1983)



For a narrow resonance we separate

$$R_{\mathcal{M}}(q,\omega) = R_{\mathcal{M}}^{\text{res}}(q,\omega) + R_{\mathcal{M}}^{\text{bg}}(q,\omega)\,.$$

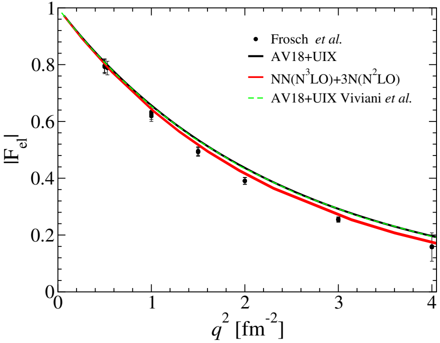
The resonance transition form factor

$$|F_{\mathcal{M}}(q)|^2 = \frac{1}{Z^2} \int d\omega R_{\mathcal{M}}^{\text{res}}(q,\omega)\,.$$

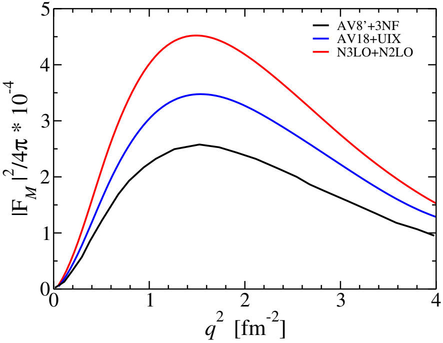
Electron scattering on ^{4}He

The transition form factor $0_1^+ \longrightarrow 0_2^+$

The elastic form factor



The inelastic transition form factor



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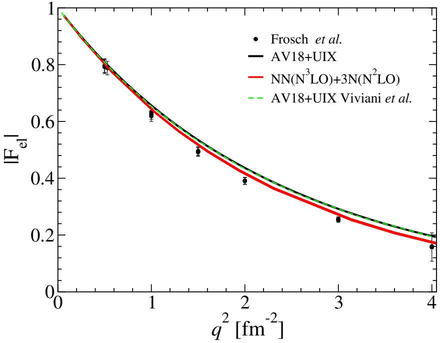

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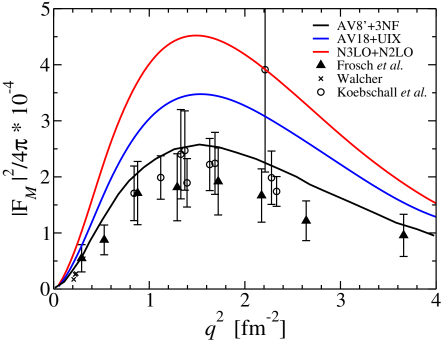
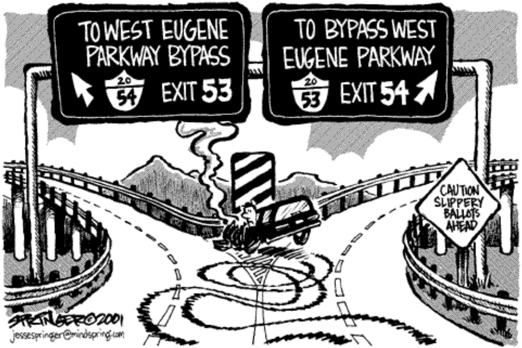


The ^{4}He 0_2^+ state - A short summary



Summary and Conclusions

- Due to EFT, at this point in the development of nuclear theory we have **self-consistent** potentials and currents.
- Applying this theory to **electro-weak** reactions provide an important tool for its verification and for its calibration.
- On the theoretical side there is a reasonable agreement between different methods and potentials.
- Much theoretical work was done with phenomenological potentials $\Rightarrow$ remade with EFT models !!!
- On the experimental side there is a large scatter in photoabsorption on light nuclei, and reasonable agreement on (e, e').
- Specifically, in ^{3}He, ^{4}He photoabsorption there is an old controversy and a new dispute.
- R_L is a sensitive probe of the nuclear thoery at low $\boldsymbol{q}$ (e, e') experiments.
- The $0_1^+ \longrightarrow 0_2^+$ transition form factor poses a problem to our contemporary understanding.
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