Weak reactions with light nuclei

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The Hebrew University, Jerusalem, Israel

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Collaboration

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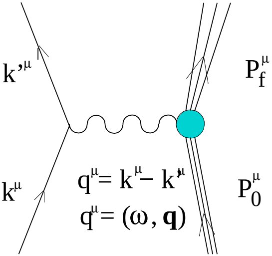
S. Vaintraub	The Weizmann Institute, Rehovot, Israel

Motivation - Astrophysics



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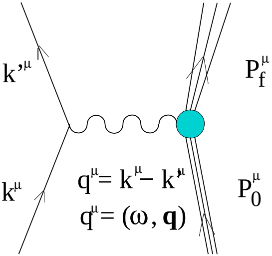

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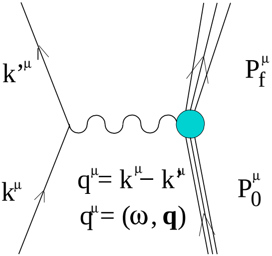

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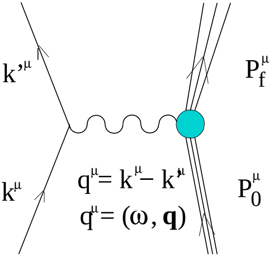

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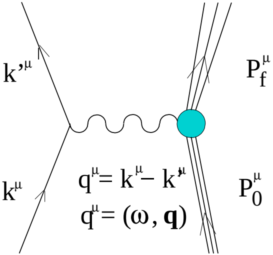
SNII SN type II - Energy transfer to the matter behind the accretion shock through inelastic reactions.

NS The ^{7}Li, ^{11}B nucleosynthesis reaction chains are dominated by the neutrino flux.

$$^4\text{He}(\nu,\nu' p)^3\text{H}(\alpha,\gamma)^7\text{Li}(\alpha,\gamma)^{11}\text{B}$$
$$^4\text{He}(\nu,\nu' n)^3\text{He}(\alpha,\gamma)^7\text{Be}(e^-,\nu_e)^7\text{Li}$$
$$^{12}\text{C}(\nu,\nu' p)^{11}\text{B}$$

Motivation - Nuclear Physics



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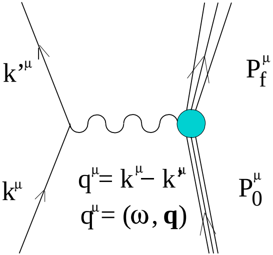

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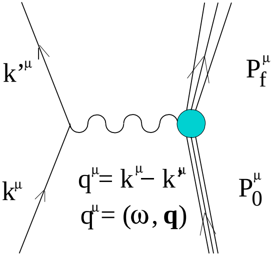

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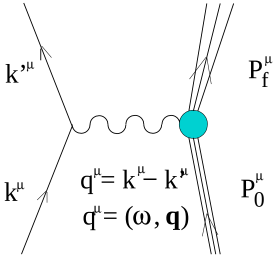
- Q This quenching should emerge from 2-body currents and correlations.

Weak interaction with Nuclei

The weak Hamiltonian

$$H_W = -\frac{G}{\sqrt{2}} \int d\boldsymbol{x} j_\mu(\boldsymbol{x}) J^\mu(\boldsymbol{x})$$



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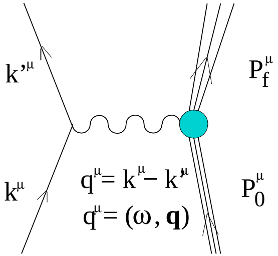

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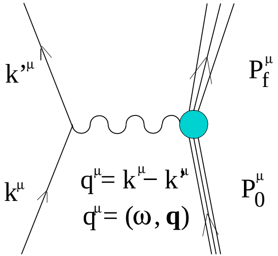

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$$J^0_\mu = (1 - 2\sin^2\theta_W)\frac{\tau_0}{2}J^V_\mu + \frac{\tau_0}{2}J^A_\mu - 2\sin^2\theta_W \frac{1}{2}J^V_\mu$$

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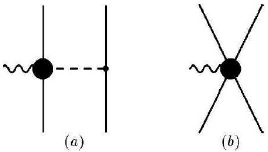

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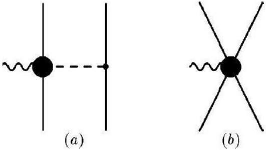

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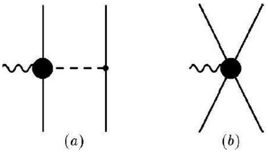

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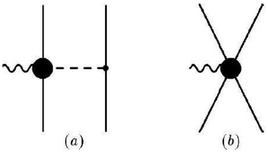

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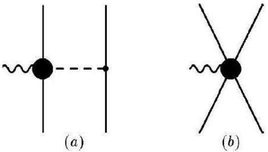
- At low energy, the **vector** current MEC are implicitly included via the Siegert theorem.



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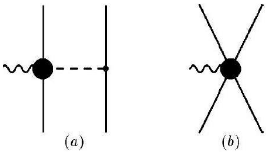

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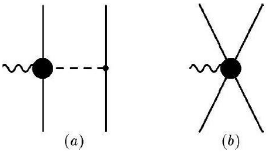

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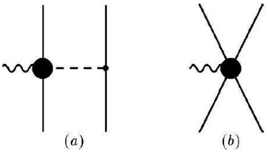

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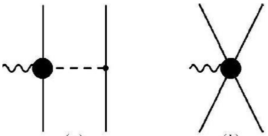

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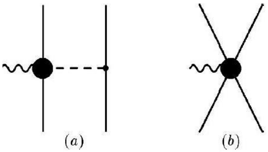

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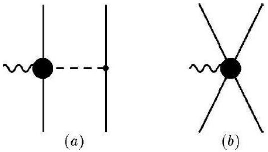

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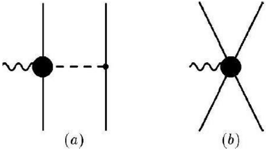

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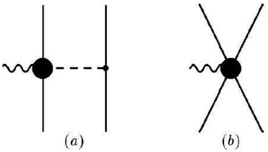
- In SNPA the situation is very similar, i.e. one free parameter fixed by the triton half life.



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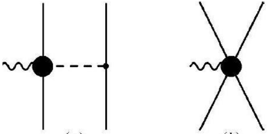
We have one good measurement, the triton half-life (used the set d_r) and many predictions ...



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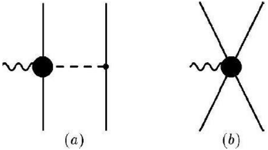

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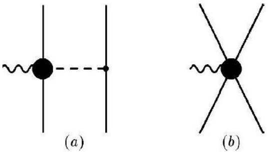

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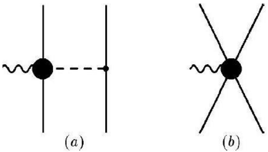

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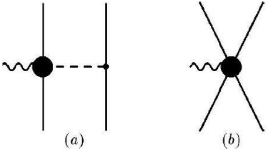

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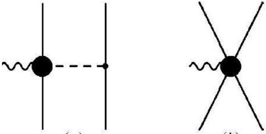

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β-decay of heavier nuclei

shift the problem to the theoretical field !!!
The first candidate is ^{6}He.

the long wavelength $q \longrightarrow 0$ limit

For low momentum transfer $qR \approx 7 \cdot 10^{-3} \omega A^{1/3} \ll 1$.
The multipole expansion converge very fast.

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$$F = \frac{1}{\sqrt{4\pi}} \tau_\pm$$

$$GT = -i\, g_A \sqrt{\frac{2}{3}} [\boldsymbol{\sigma} \otimes Y_0(\hat{r})]^{(1)}_M \tau_\pm$$

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The sub-leading operators,

$$C_0^A(q) = \frac{i}{\sqrt{4\pi}} \boldsymbol{\sigma} \cdot \boldsymbol{\nabla}$$

$$L_0^A(q) = i g_A \frac{qr}{3} [\boldsymbol{\sigma} \otimes Y_1(\hat{r})]^{(0)}$$

$$C_{1M}^V(q) = \frac{qr}{3} Y_{1M}(\hat{r})$$

$$E_{1M}^V(q) = -\sqrt{2} \frac{\omega}{q} C_{1M}^V(q)$$

$$L_{1M}^V(q) = -\frac{\omega}{q} C_{1M}^V(q)$$

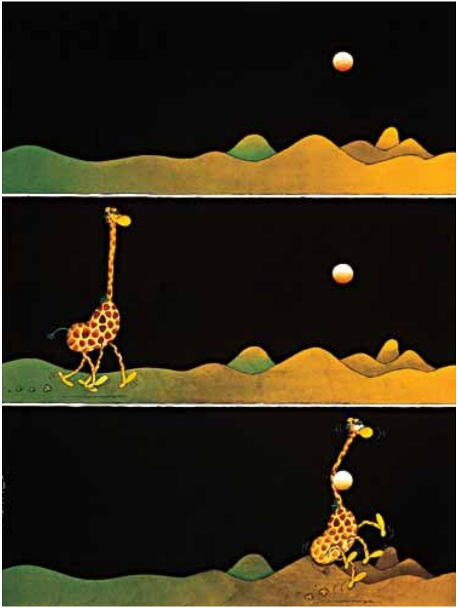
$$M_{1M}^V(q) = -\frac{i}{\sqrt{6\pi}} \frac{q}{2M_N} l_M$$

$$M_{1M}^A(q) = -g_A \frac{qr}{3} [\boldsymbol{\sigma} \otimes Y_1(\hat{r})]^{(1)}_M$$

$$E_{2M}^A(q) = i\sqrt{\frac{3}{5}} g_A \frac{q}{3} [\boldsymbol{\sigma} \otimes Y_1(\hat{r})]^{(2)}_M$$

$$L_{2M}^A(q) = \sqrt{\frac{2}{3}} E_{2M}^A(q)$$

Solving the Schrödinger equation



1. Remove the center of mass

$$\vec{r}_1, \vec{r}_2, \ldots \vec{r}_A \longrightarrow \vec{R}_{c.m.}, \vec{\eta}_1 \vec{\eta}_2 \ldots \vec{\eta}_{A-1}$$

2. Introduce hyperspherical coordinates

$$\vec{\eta}_1 \vec{\eta}_2 \ldots \vec{\eta}_{A-1} \longrightarrow \rho = \sqrt{\eta_1^2 + \eta_2^2 + \ldots + \eta_{A-1}^2}, \Omega$$

3. Expand the wave function using hyperspherical harmonics

$$\Psi(\rho, \Omega) = \sum_{K \le K_max} R_{[K]} \mathcal{Y}_{[K]}(\Omega)$$

4. Solve the Schrödinger equation

$$H = -\frac{1}{2}\left(\frac{\partial^2}{\partial \rho^2} + \frac{3A-4}{\rho}\frac{\partial}{\partial \rho} - \frac{\hat{K}^2}{\rho^2}\right) + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk}$$

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4. So

V_{ijk}

k

Two problems

1. The HH basis has no good permutational symmetry. (Anti)Symmetrization must be enforced.
2. The convergence of the HH expansion is notoriously slow and must be accelerated.

4-body ground-state

Convergence of the EIHH method for ^{4}He binding energy E_b [MeV] and root mean square matter radius $\langle r^2 \rangle^{\frac{1}{2}}$ [fm] with AV18 and AV18+UIX potentials.

	AV18		AV18+UIX	
K_{max}	E_b	$\langle r^2 \rangle^{\frac{1}{2}}$	E_b	$\langle r^2 \rangle^{\frac{1}{2}}$
6	25.312	1.506	26.23	1.456
8	25.000	1.509	27.63	1.428
10	24.443	1.520	27.861	1.428
12	24.492	1.518	28.261	1.427
14	24.350	1.518	28.324	1.428
16	24.315	1.518	28.397	1.430
18	24.273	1.518	28.396	1.431
20	24.268	1.518	28.418	1.432
FY [Nogga]	24.25		28.50	
FY [Lazauskas]	24.22	1.516		
HH [Viviani]	24.21	1.512	28.46	1.428
GFMC [Wiringa]			28.34	1.44

The JISP16 NN Potential

The JISP16 reproduce the NN phase shifts in the range $0 - 300\text{MeV}$.

Binding Energies

	AV18+UBIX	JISP16	Nature
D	2.24	2.24	2.24
^{3}H	8.48	8.37	8.48
^{3}He	7.74	7.66	7.72
^{4}He	28.5	28.3	28.3
^{6}He	-	28.7	29.29
^{6}Li	-	31.5	31.99

- AV18+UBIX - Argonne V18 + Urbana IX
- JISP16 - J-matrix Inverse Scattering Potential, Shirokov *et* al.
- The BE of Shirokov *et* al. are somewhat different from ours.

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^{3}H	8.48	8.37	8.48
^{3}He	7.74	7.66	7.72
^{4}He	28.5	28.3	28.3
^{6}He	-	28.7	29.29
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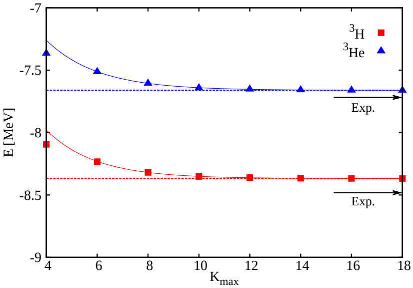

- AV18+UBIX - Argonne V18 + Urbana IX
- JISP16 - J-matrix Inverse Scattering Potential, Shirokov *et* al.
- The BE of Shirokov *et* al. are somewhat different from ours.

The JISP16 NN Potential

The JISP16 reproduce the NN phase shifts in the range $0 - 300\text{MeV}$.

Binding Energies

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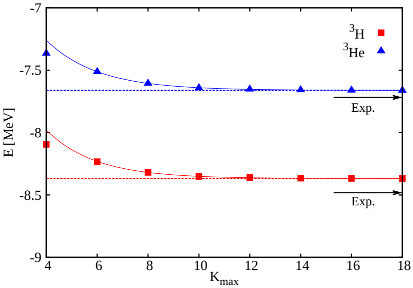

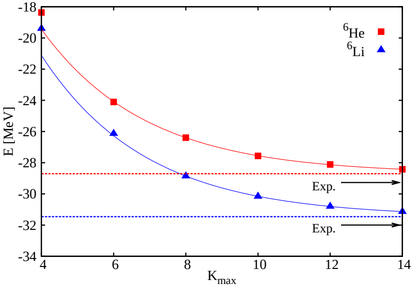

The comparative β-decay half-life

$$(f\,T_{1/2})_t = (2J_i+1)\frac{\tau\log(2)}{|\mathrm{F}|^2 + \frac{\mathrm{f_A}}{\mathrm{f_V}}\mathrm{g_A^2}|\mathrm{GT}|^2}$$

The Gamow-Teller and Fermi operators

$$\mathrm{GT} \equiv \langle\Psi_\mathrm{f}||\sum_\mathrm{j}\boldsymbol{\sigma}_\mathrm{j}\tau_\mathrm{j}^{+}||\Psi_\mathrm{i}\rangle$$

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The constants

$$g_A = 1.2695 \pm 0.0029$$

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$$(f\,T_{1/2})_t = 812.8 \pm 3.7\mathrm{sec} \Longrightarrow |\mathrm{GT}(^6\mathrm{He})|_\mathrm{expt} = 2.161 \pm 0.005$$

For ^{3}H

$$(f\,T_{1/2})_t = 1129.6 \pm 3\mathrm{sec} \Longrightarrow |\mathrm{GT}(^3\mathrm{H})|_\mathrm{expt} = 1.6560 \pm 0.0026$$

For triton $|F| = 0.99955(15)$

^{3}H β-decay

Potential		$\mathrm{GT}|_{\mathrm{LO}}$
AV18+3NF	Wiringa 1995	1.598(2)
Bonn+3NF	Machleidt 2001	1.621(2)
Nijm+3NF	Stoks 1994	1.605(2)
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Conclusion

The 1-body current underpredicts the 3-body GT, $\langle ^3\mathrm{H}||\mathrm{GT}||^3\mathrm{He}\rangle$, matrix element and overpredicts the 6-body, $\langle ^6\mathrm{He}||\mathrm{GT}||^6\mathrm{Li}\rangle$, one.

The Gamow-Teller ^{6}He - ^{6}Li matrix element

Potential		1-body	2-body
AV18/UIX	Schiavilla 2002 (VMC)	2.250(7)	2.281(7)
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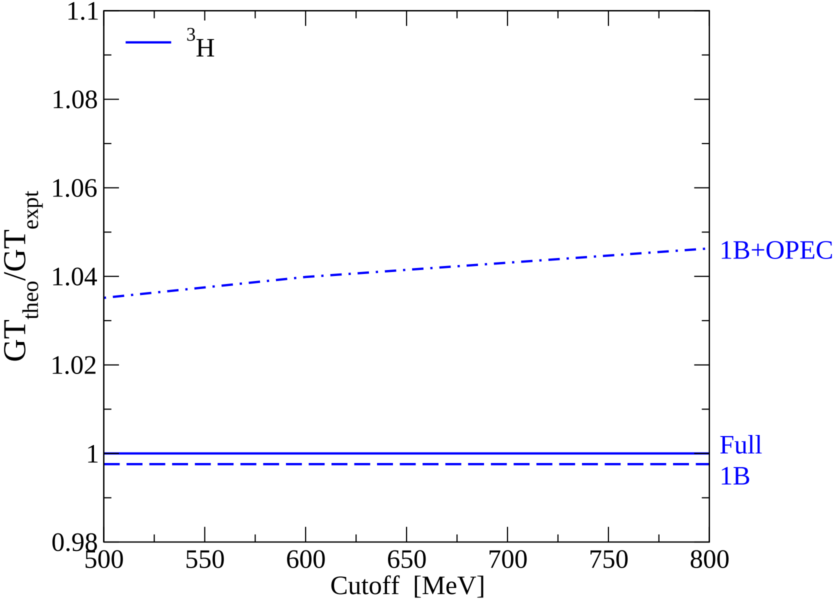
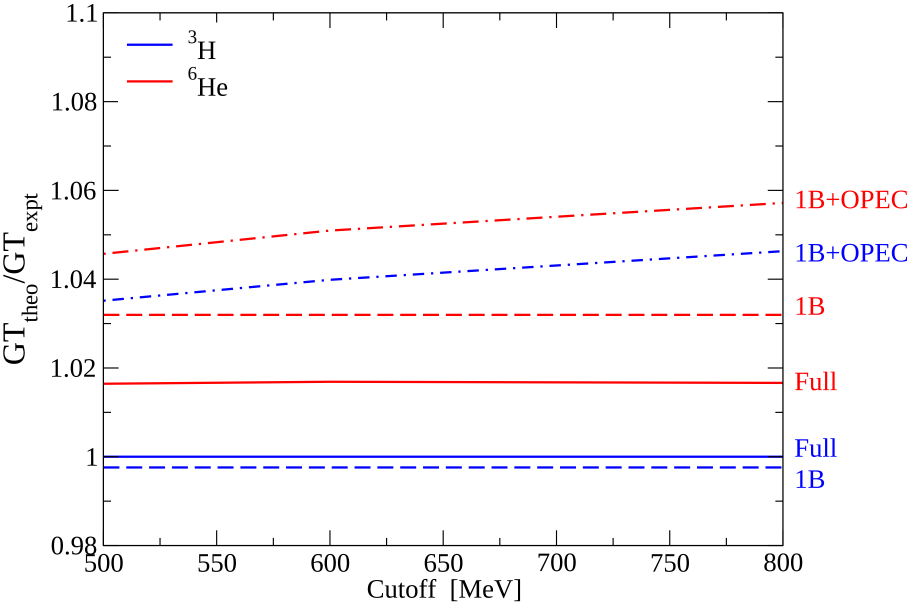
- EFT 2-body currents lead to "quenched" GT matrix element for the 6-body system.

Beta decay



1.1
1.08
1.06
1.04
1.02
1
0.98
500
550
600
650
700
750
800
Cutoff [MeV]
GT_{theo}/GT_{expt}
^3H
1B+OPEC
Full
1B

Beta decay



^{3}H
^{6}He
1B+OPEC
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Full
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S. Vaintraub, N. Barnea, D. Gazit, Phys. Rev. C **79**, 065501 (2009).