^{14}C β-decay with Brown-Rho-scaled NN interactions

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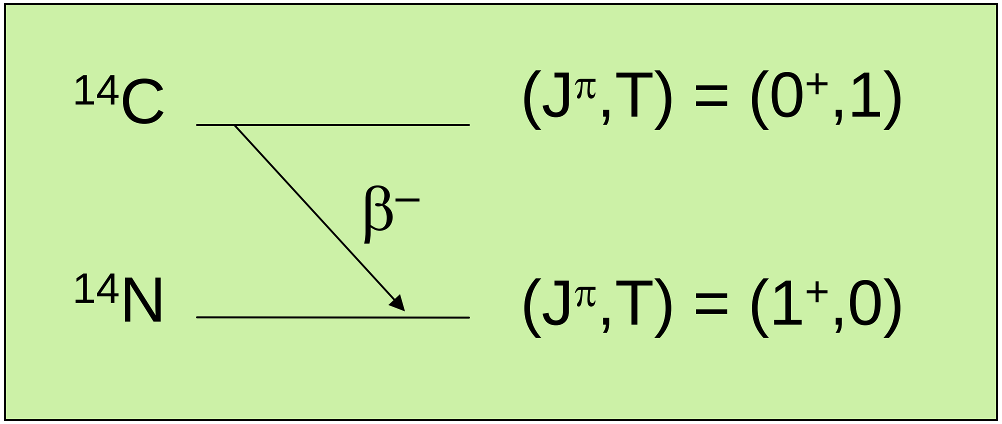
Nuclear many-body approaches for the 21st century, INT, 10/12/07

Willard Libby

- Nobel Prize in Chemistry 1960 for invention of radiocarbon dating



Allowed Gamow-Teller transition

→ ?

$$T_{1/2} = 5730 \text{ yrs}$$

$$M_{GT} = \sum_k \left\langle \psi_f \middle\| \tau_+(k)\sigma(k) \middle\| \psi_i \right\rangle \approx \pm 2\times 10^{-3}$$

- **Sensitive test of the in-medium NN interaction**

Realistic NN interactions

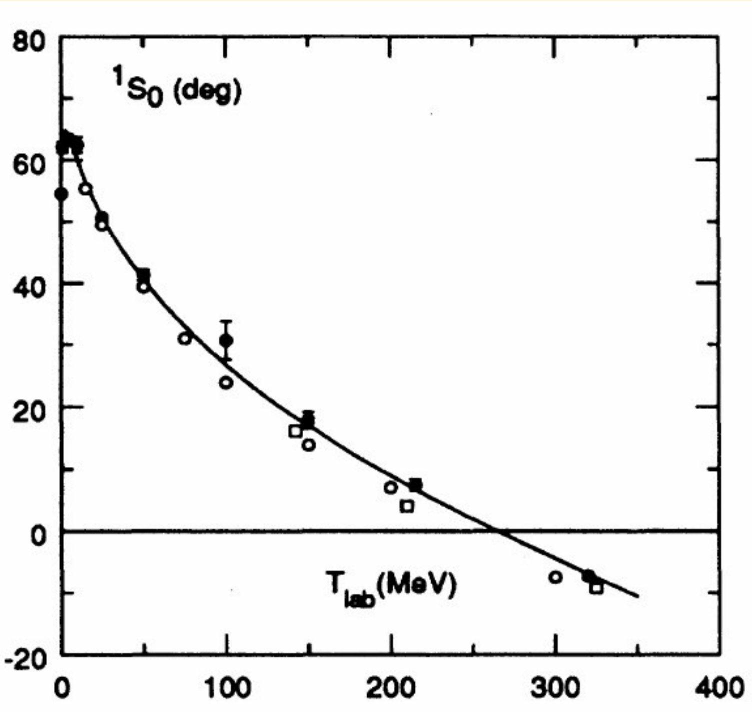
Argonne, Bonn, Idaho, Nijmegen, Paris, Reid

G-matrix, $V_{\text{low-}k}$, …

Finite nuclei

Nuclear matter

Scattering phase shifts



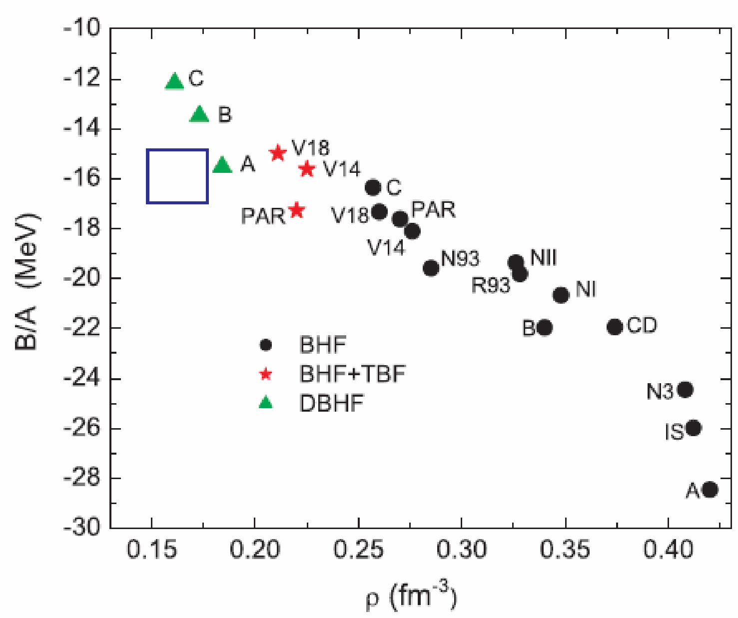
Deuteron properties

- Binding energy (2.22 MeV)
- Quadrupole moment (0.278 fm^2)
- Magnetic moment (0.851 μ_N)
- RMS radius (1.97 fm) …

All data fit with χ^2/DOF $\approx$ 1

But 2N forces alone not enough!

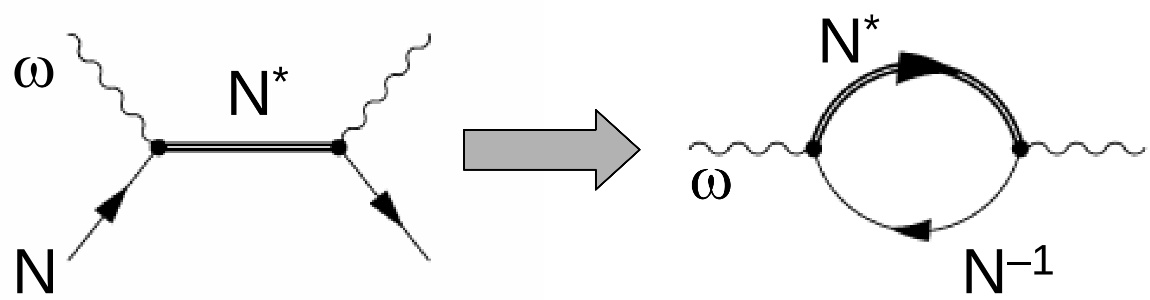
Simplest example: Nuclear matter saturation



[Z. H. Li et al., PRC **74** (2006) 047304.]

- Need to "liberate" extra degrees of freedom (mesons, baryonic resonances, quarks/gluons)
- Traditionally these effects can be built in through phenomenological 3N interactions

Low-density theorem:
In-medium self-energy in terms of vacuum scattering amplitudes



Effective mass

$$m^{*2} = m^2 - 4\pi \,\mathrm{Re}\, f_{mN}(q_0, \theta = 0)\rho$$

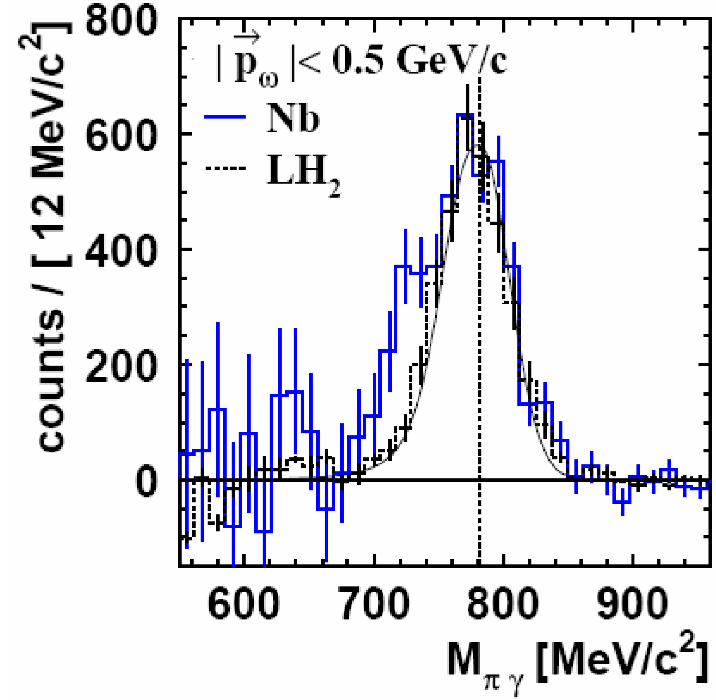
Collisional broadening

$$m^* \Gamma^* = m\Gamma^0 - 4\pi \,\mathrm{Im}\, f_{mN}(q_0, \theta = 0)\rho$$

Hadronic medium modifications ⟷ Chiral symmetry breaking/restoration

Theory: (Nambu—Jona-Lasinio model, QCD sum rules, Brown-Rho scaling, chiral effective Lagrangian models)

Experiments: (Jlab, CERN SPS, RHIC, KEK-PS, GSI, ELSA)



D. Trnka et al., PRL **96** (2006) 092301

<u>Brown-Rho scaling</u>

Hadron masses scale with the pion decay constant f_π in medium

$$\frac{f_\pi^*}{f_\pi} = \frac{m_\sigma^*}{m_\sigma} = \frac{m_\rho^*}{m_\rho} = \frac{m_\omega^*}{m_\omega} = \sqrt{\frac{g_A}{g_A^*}}\frac{m_N^*}{m_N} = 1 - C\frac{\rho}{\rho_0}$$

$$C \approx 0.15 - 0.20$$

Chiral effective field theory + vector mesons + baryons

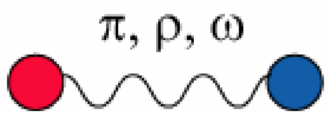
[F. Klingl, F. Kaiser, W. Weise: NPA **624** (1997) 527.]

$$\overline{m}^2(n) = \frac{\int_0^{s_0^*} ds\, s\, R(s,n)}{\int_0^{s_0^*} ds\, R(s,n)} \qquad \frac{\overline{m}_\rho(n_0)}{m_\rho} \approx \frac{f_\pi^*(n_0)}{f_\pi} \approx 0.87$$

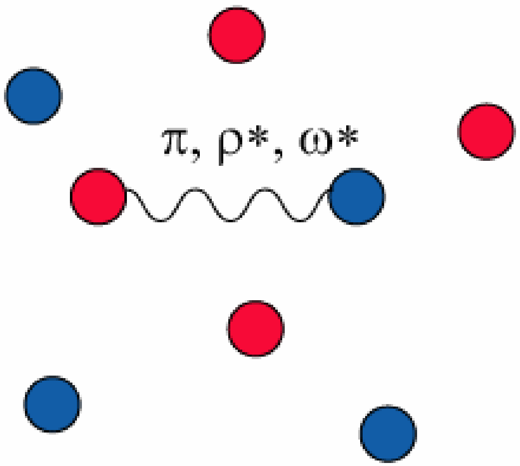
Consistent with Brown-Rho scaling

[W. Weise, http://rnc.lbl.gov/TBS]

Current summary



Medium-modified



<u>Nuclear matter applications</u>:

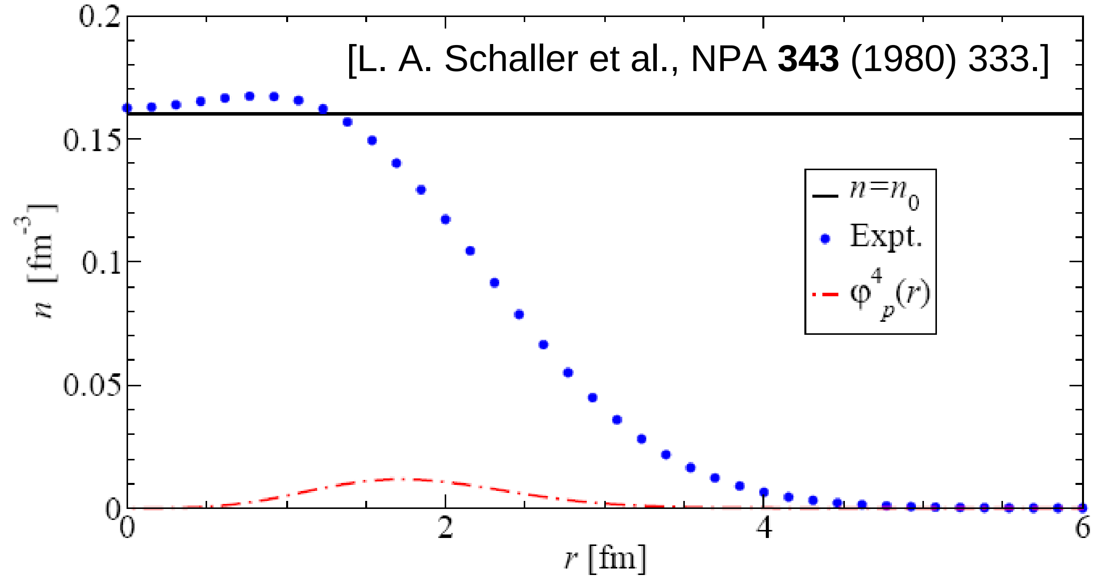
(1) Saturation [R. Rapp et al., PRL **82** (1999) 1827.]

(2) Bulk equilibrium properties [J.W.H. et al., NPA **785** (2007) 322.]

Why ^{14}C beta decay with medium-modified interactions?

1. Nuclear density large enough

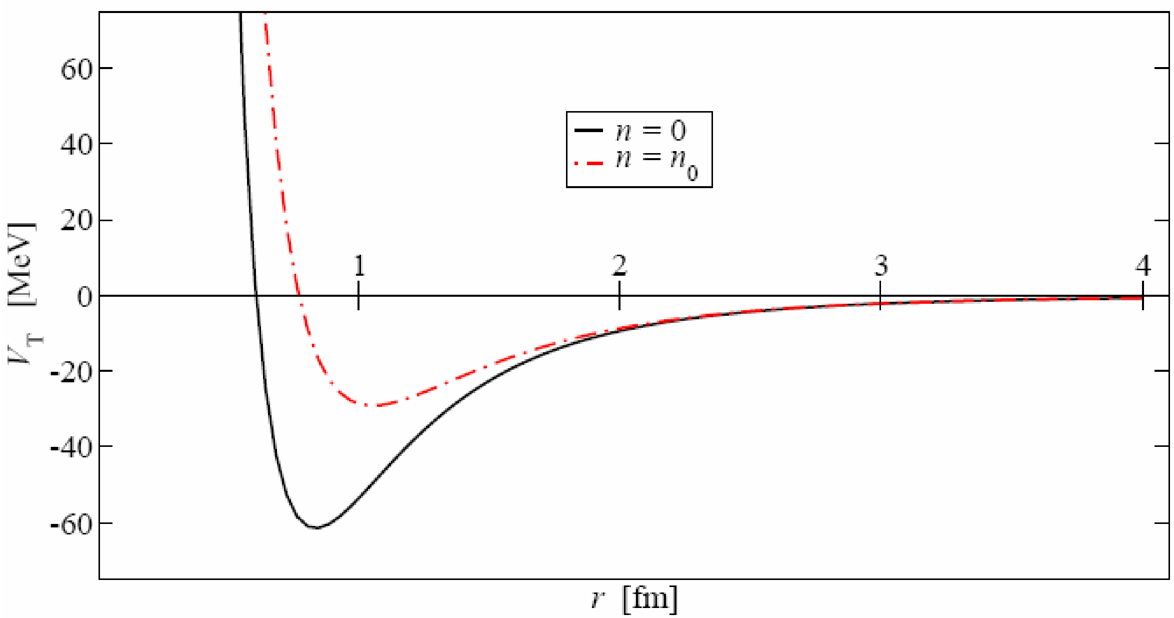
$$n(r) \propto \left(1 + b\frac{r^2}{d^2}\right) e^{-r^2/d^2}$$



2. Importance of tensor force

$$V_\pi^T(r) = \frac{f_{\pi N}^2}{4\pi} m_\pi \vec{\tau}_1 \cdot \vec{\tau}_2 \left(S_{12} \frac{1}{(m_\pi r)^3} + \frac{1}{(m_\pi r)^2} + \frac{1}{3 m_\pi r} \right) e^{-m_\pi r}$$

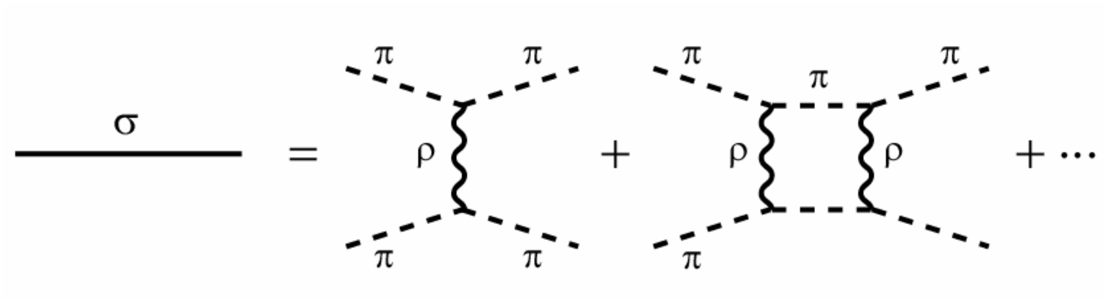
$$V_\rho^T(r) = \frac{f_{\rho N}^2}{4\pi} m_\rho \vec{\tau}_1 \cdot \vec{\tau}_2 \left(-S_{12} \frac{1}{(m_\rho r)^3} + \frac{1}{(m_\rho r)^2} + \frac{1}{3 m_\rho r} \right) e^{-m_\rho r}$$



Medium-modified Bonn-B potential

[R. Rapp et al., PRL **82** (1999) 1827]

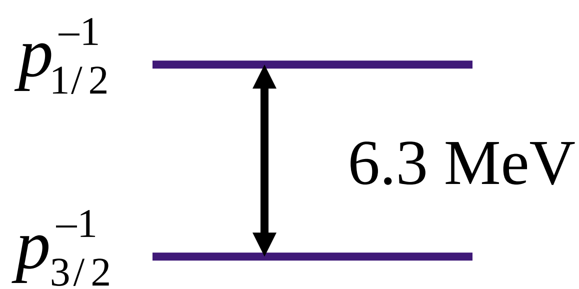
$$\frac{m_\rho^*(n)}{m_\rho} = \frac{m_\omega^*(n)}{m_\omega} = \frac{\Lambda_V^*(n)}{\Lambda_V} = \sqrt{\frac{g_A}{g_A^*}}\frac{m_N^*}{m_N} = 1 - 0.15\frac{n}{n_0}$$



__Shell model description__:

- Simple model space of 2 *p*-orbit holes in an ^{16}O core, $\hbar\omega = 14$ MeV
- Include core polarization effects (2nd order perturbation theory)

Basis: $\left\{p_{1/2}^{-2}, p_{1/2}^{-1}p_{3/2}^{-1}, p_{3/2}^{-2}\right\}$



Results

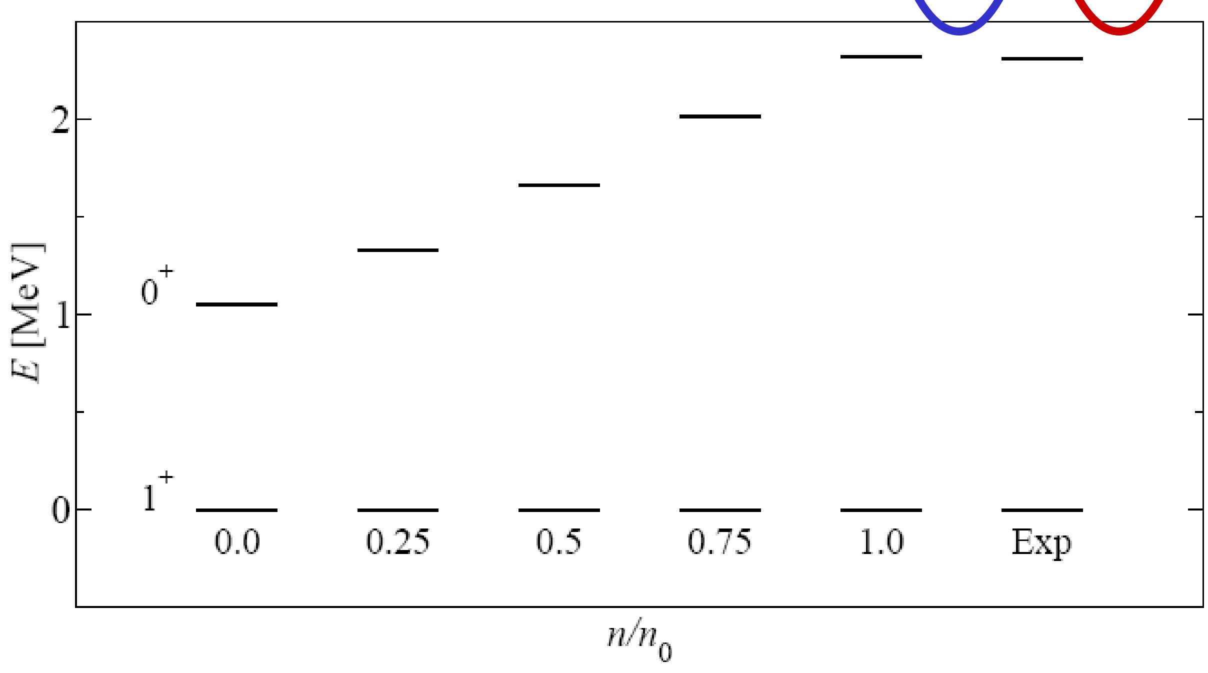
[J.W.H. et al., arXiv:0710.0310]

$$\psi_i = x\left|{}^1S_0\right\rangle + y\left|{}^3P_0\right\rangle \qquad \psi_f = a\left|{}^3S_1\right\rangle + b\left|{}^1P_1\right\rangle + c\left|{}^3D_1\right\rangle$$

$$M_{GT} = -\sqrt{6}\left(xa - yb/\sqrt{3}\right)$$

n/n_0	x	y	a	b	c	M_{GT}
0	0.844	0.537	0.359	0.168	0.918	-0.615
0.25	0.825	0.564	0.286	0.196	0.938	-0.422
0.5	0.801	0.599	0.215	0.224	0.951	-0.233
0.75	0.771	0.637	0.154	0.250	0.956	-0.065
1.0	0.737	0.675	0.103	0.273	0.956	0.074

Due largely to decreasing tensor force



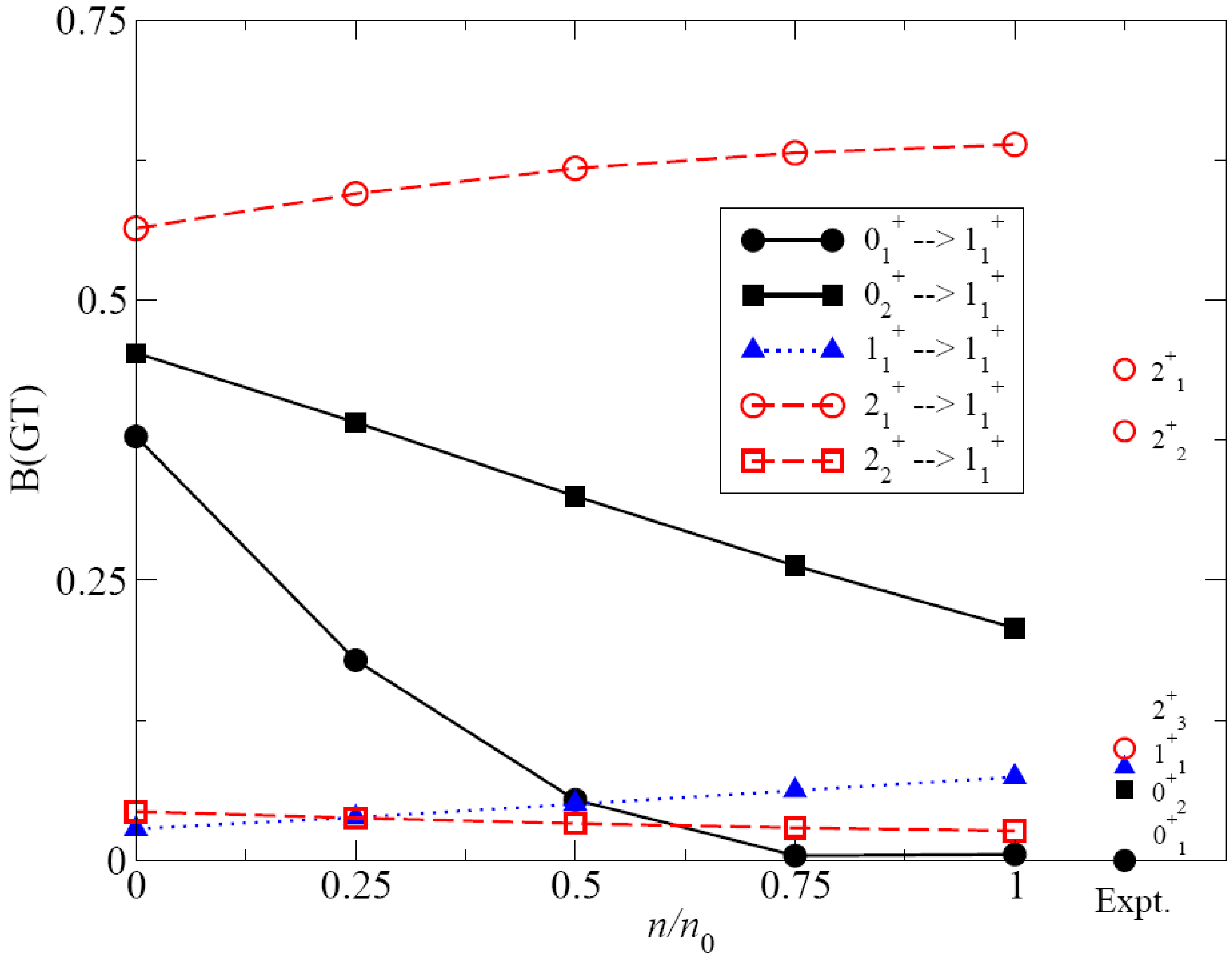
Other Gamow-Teller strengths

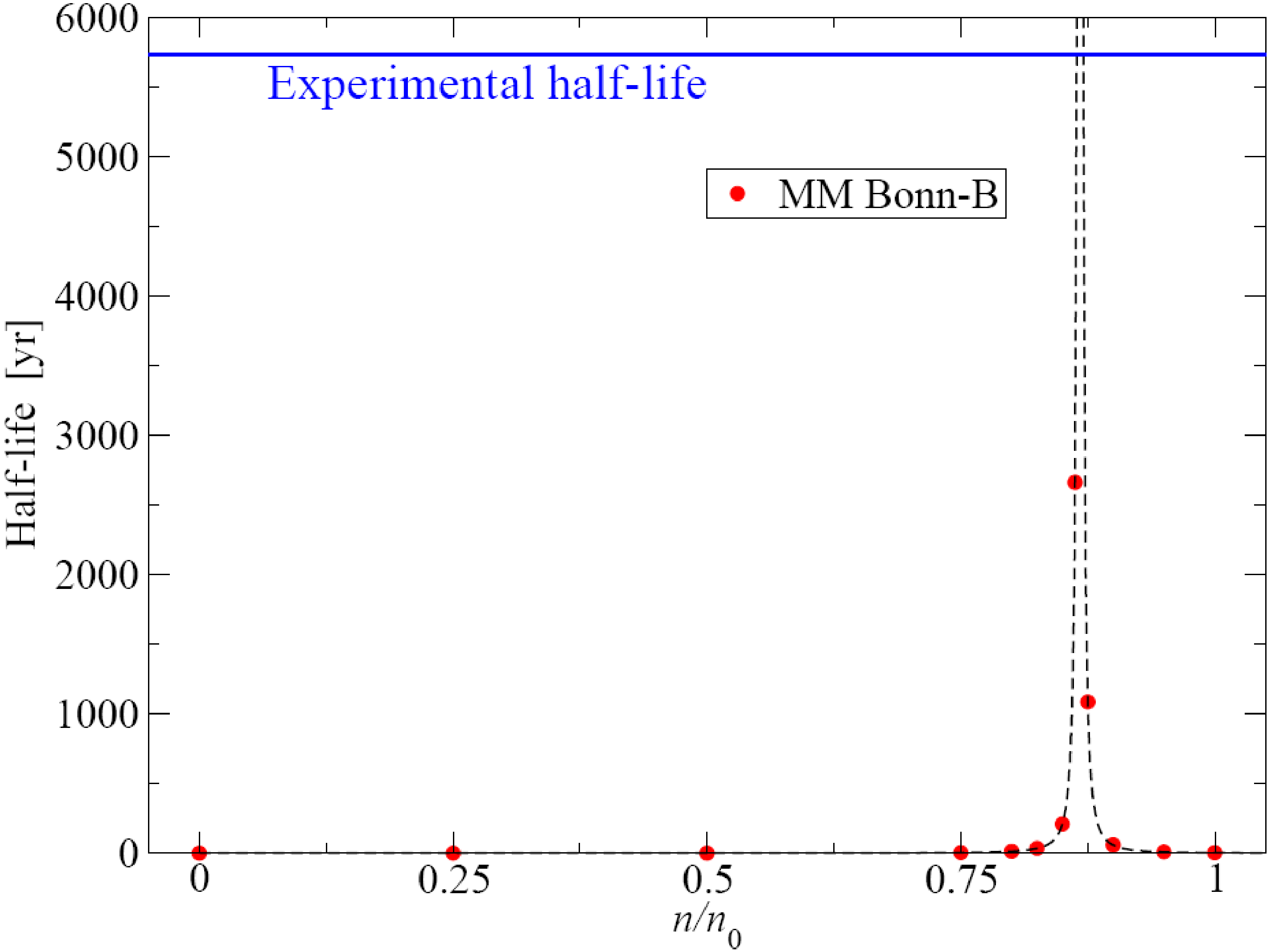
[A. Negret et al., PRL **97** (2006) 062502.]

Charge exchange reactions

$^{14}N\,(d,{}^{2}He)\,^{14}C \qquad ^{14}N\,({}^{3}He,t)\,^{14}O$

- 0+ transitions the most strongly suppressed
- Others less density dependent
- Good overall agreement





6000
5000
4000
3000
2000
1000
0
Half-life [yr]
Experimental half-life
MM Bonn-B
0
0.25
0.5
0.75
1
n/n0