Role of Tensor Force in Magnetic Dipole Transitions of Cr-52

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Motivation

Understand nuclear (effective) interaction through range of observables

Nuclear effective interaction
↳ + calculational framework
    ↳ description of nature, in the form of nuclear observables

Effective interactions of Skyrme form + time-dependent mean-field / Energy density functional (EDF) approach provides powerful framework for description of nuclei.

Interactions are fitted to (mostly) ground state data, yet part of force is sensitive (mostly) to excited state properties
↳ want to evaluate and understand ability of our EDFs to describe whole variety of nuclear data, including, for today's purposes, giant resonances

Skyrme-HF / EDF

Origin: The Skyrme Interaction

Form as essentially given by Skyrme NPA**9**, 615 (1959)

$$V = \sum_{i<j} v_{ij}^{(2)} + \sum_{i<j<k} v_{ijk}^{(3)}.$$

central

momentum-dependent

$$v_{12}^{(2)} = \boxed{t_0(1+x_0P_\sigma)\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)} + \boxed{\frac{t_1}{2}\left(1+x_1P_{\boldsymbol{\sigma}}\right)\left[\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\boldsymbol{k}^2+\boldsymbol{k}'^2\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\right]}$$

$$+ \boxed{t_2\left(1+x_2P_{\boldsymbol{\sigma}}\right)\boldsymbol{k}'\cdot\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\boldsymbol{k}} + \boxed{iW_0(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\left(\boldsymbol{k}'\times\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\boldsymbol{k}\right)}$$

$$\boxed{\begin{aligned}&+\frac{t_e}{2}\Big\{\left[3(\boldsymbol{\sigma}_1\cdot\boldsymbol{k}')(\boldsymbol{\sigma}_2\cdot\boldsymbol{k}')-(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\boldsymbol{k}'^2\right]\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\\&+\left[3(\boldsymbol{\sigma}_1\cdot\boldsymbol{k})(\boldsymbol{\sigma}_2\cdot\boldsymbol{k})-(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\boldsymbol{k}^2\right]\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\Big\}\\&+t_o\Big\{\left[3(\boldsymbol{\sigma}_1\cdot\boldsymbol{k}')(\boldsymbol{\sigma}_2\cdot\boldsymbol{k})-(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\boldsymbol{k}'\cdot\boldsymbol{k}\right]\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\Big\}\end{aligned}}$$

spin-orbit

tensor

$$v_3(\boldsymbol{r}_1,\boldsymbol{r}_2) = \frac{t_3}{6}\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\rho^\alpha(\boldsymbol{r}_1)(1+x_3\vec{P}^\sigma),$$

common extension as density-dependent term

Skyrme as EDF

& the tensor force

$$
\begin{aligned}
\mathcal{E} = \int d^3r \mathcal{H}(\boldsymbol{r}) = \int d^3r \sum_{t=0,1} \Big\{ & C_t^{\rho}[\rho_0]\rho_t^2 + C_t^{s}[\rho_0]\boldsymbol{s}_t^2 + C_t^{\Delta\rho}\rho_t \boldsymbol{\nabla}^2 \rho_t \\
& \cancel{+ C_t^{\nabla s}(\boldsymbol{\nabla}\cdot\boldsymbol{s}_t)^2} \cancel{+ C_t^{\Delta s}\boldsymbol{s}_t\cdot\boldsymbol{\nabla}^2\boldsymbol{s}_t} + C_t^{\tau}(\rho_t\tau_t - \boldsymbol{j}_t^2) \\
& + C_t^{T}\left(\boldsymbol{s}_t\cdot\boldsymbol{T}_t - \sum_{\mu,\nu=x}^{z} J_{t,\mu\nu}J_{t,\mu\nu}\right) \\
& + C_t^{F}\left[\boldsymbol{s}_t\cdot\boldsymbol{F}_t - \frac{1}{2}\left(\sum_{\mu=x}^{z} J_{t,\mu\mu}\right)^2 - \frac{1}{2}\sum_{\mu,\nu=x}^{z} J_{t,\mu\nu}J_{t,\nu\mu}\right] \\
& + C_t^{\nabla\cdot J}(\rho_t\boldsymbol{\nabla}\cdot\boldsymbol{J}_t + \boldsymbol{s}_t\cdot\boldsymbol{\nabla}\times\boldsymbol{j}_t) \Big\},
\end{aligned}
$$

$$
\begin{aligned}
\rho_q(\boldsymbol{r}) &= \rho_q(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}=\boldsymbol{r}'} \\
\boldsymbol{s}_q(\boldsymbol{r}) &= \boldsymbol{s}_q(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}=\boldsymbol{r}'} \\
\tau_q(\boldsymbol{r}) &= \nabla\cdot\nabla'\rho_q(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}=\boldsymbol{r}'} \\
T_{q,\mu}(\boldsymbol{r}) &= \nabla\cdot\nabla' s_{q,\mu}(\boldsymbol{r},\boldsymbol{r}')|_{\boldsymbol{r}=\boldsymbol{r}'} \\
\boldsymbol{j}_q(\boldsymbol{r}) &= -\frac{i}{2}(\nabla-\nabla')\rho_q(\boldsymbol{r},\boldsymbol{r}')\Big|_{\boldsymbol{r}=\boldsymbol{r}'} \\
J_{q,\mu\nu}(\boldsymbol{r}) &= -\frac{i}{2}(\nabla_\mu-\nabla'_\mu)s_{q,\nu}(\boldsymbol{r},\boldsymbol{r}')\Big|_{\boldsymbol{r}=\boldsymbol{r}'} \\
F_{q,\mu}(\boldsymbol{r}) &= \frac{1}{2}\sum_{\nu=x}^{z}(\nabla_\mu\nabla'_\nu+\nabla'_\mu\nabla_\nu)s_{q,\nu}(\boldsymbol{r},\boldsymbol{r}')\Big|_{\boldsymbol{r}=\boldsymbol{r}'},
\end{aligned}
$$

All these terms have contribution from tensor terms

These two terms typically (always?) cause spin instabilities and are omitted in calculations

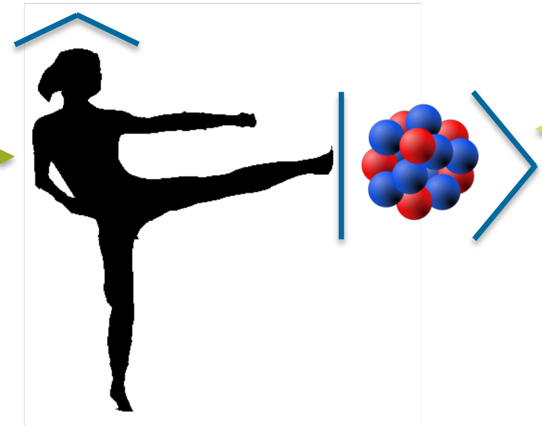
This term is *only* present when tensor force is activated

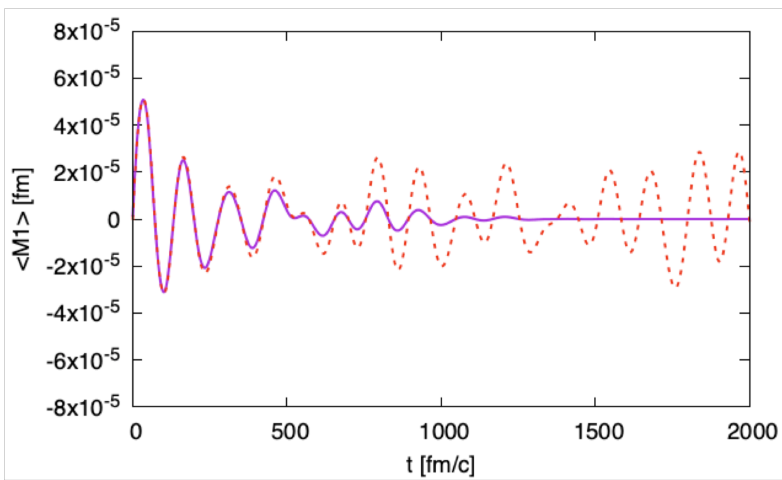
TDHF + Spectral Analysis

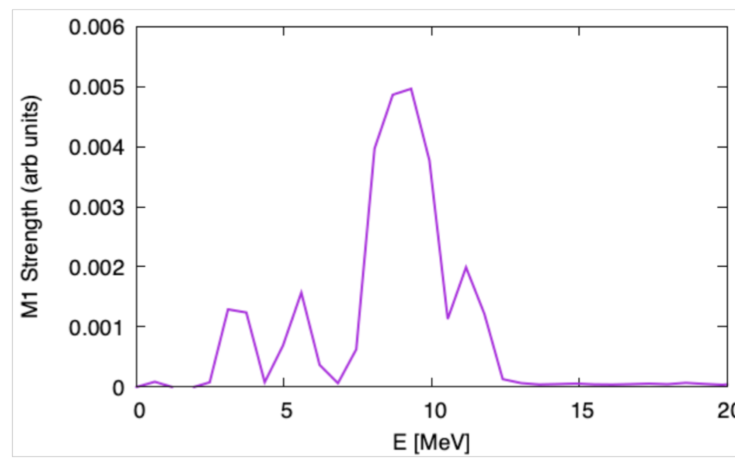
A pictoral guide

Ground state from static HF calculation

M1 dipole operator: spin + orbital







Cr-52: Experimental Work

M1 strength in Cr-52

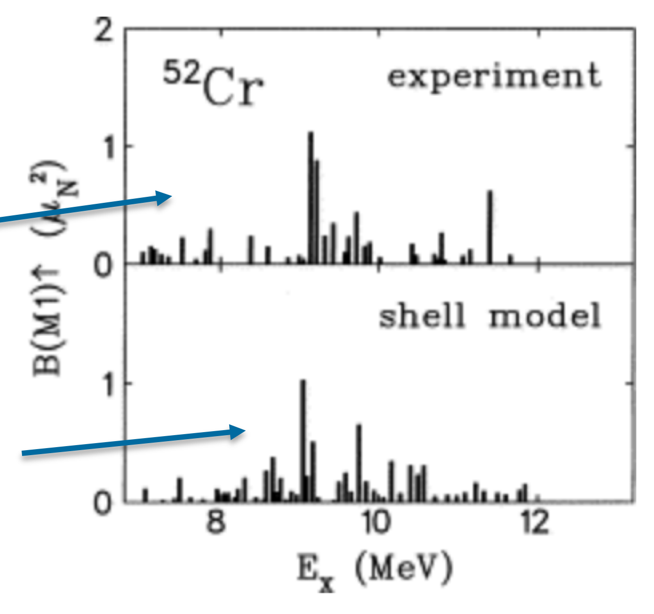
Motivated by recent experiments of polarized photon scattering at HIγS:

*Krishichayan et al., Phys. Rev. C **91**, 044328 (2015)*
covering E_x=5.1-9.5 MeV, and from NRF at Darmstadt:
*H. Pai et al, Phys. Rev. C **88**, 054316 (2013)*

As well as older data from

*D. I. Sober et al., Phys. Rev. C **31**, 2054 (1985)*
(e,e') @ Darmstadt covering E_x=7-12 MeV
+previous calculations:

*P. Von Neumann-Cosel et al., PLB**443**, 1 (1998)*

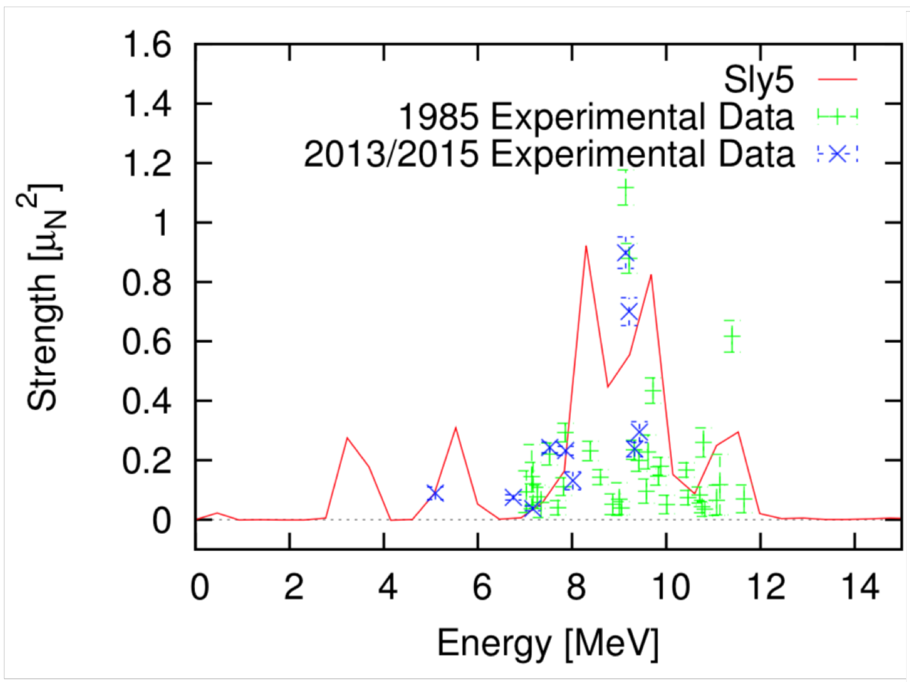


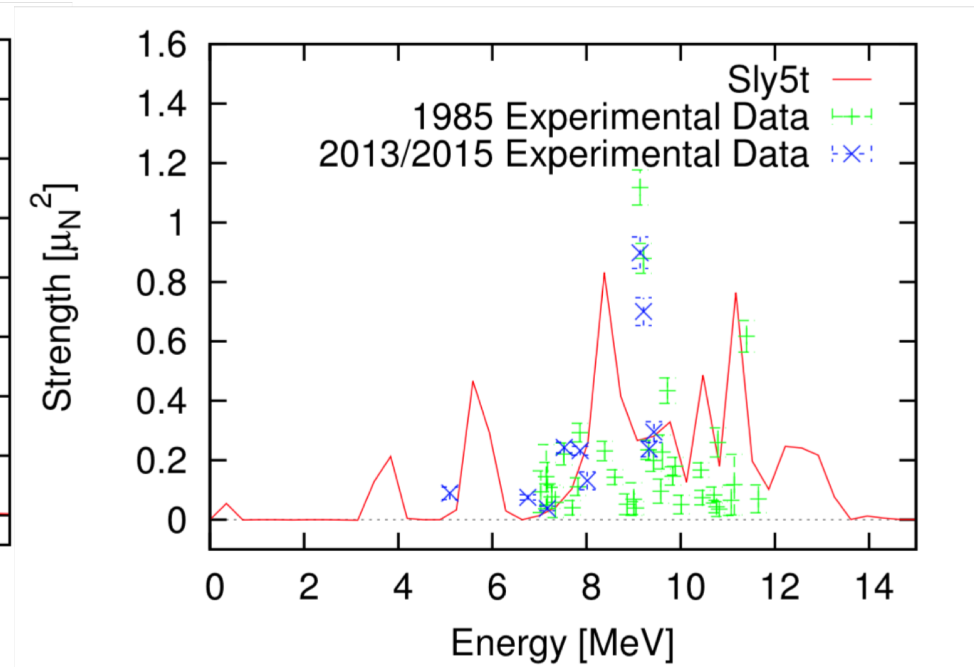
SLy5 vs SLy5+T

Role of tensor force in Skyrme interaction

SLy5: Lyon Skyrme fit including J^2 contribution to spin-orbit, Chabanat et al., NPA**635**, 231 (1995)

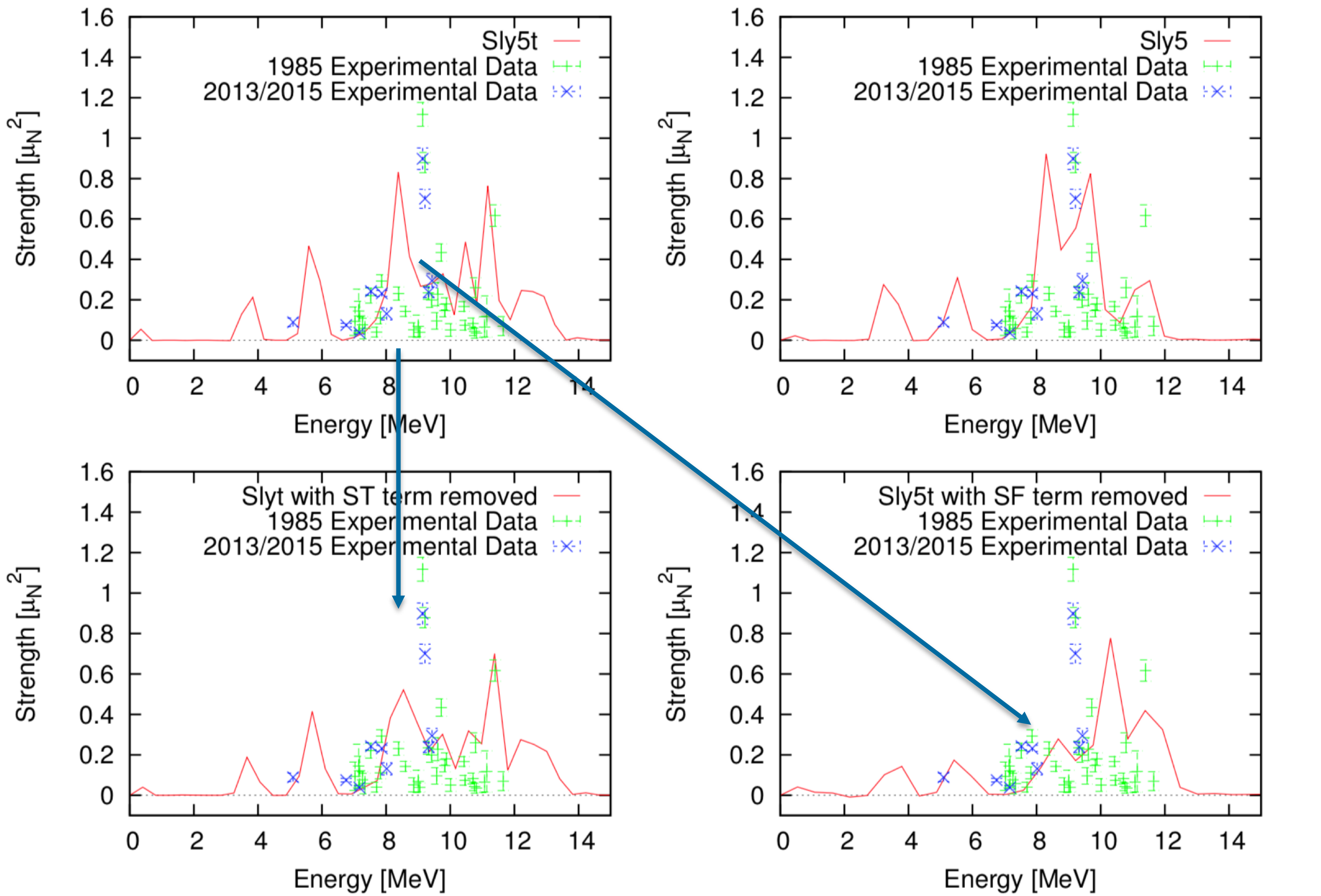
SLy5t: Perturbative addition of tensor force by Coló, Sagawa, Fracasso, Bortignon, PLB**646**, 227 (2007)



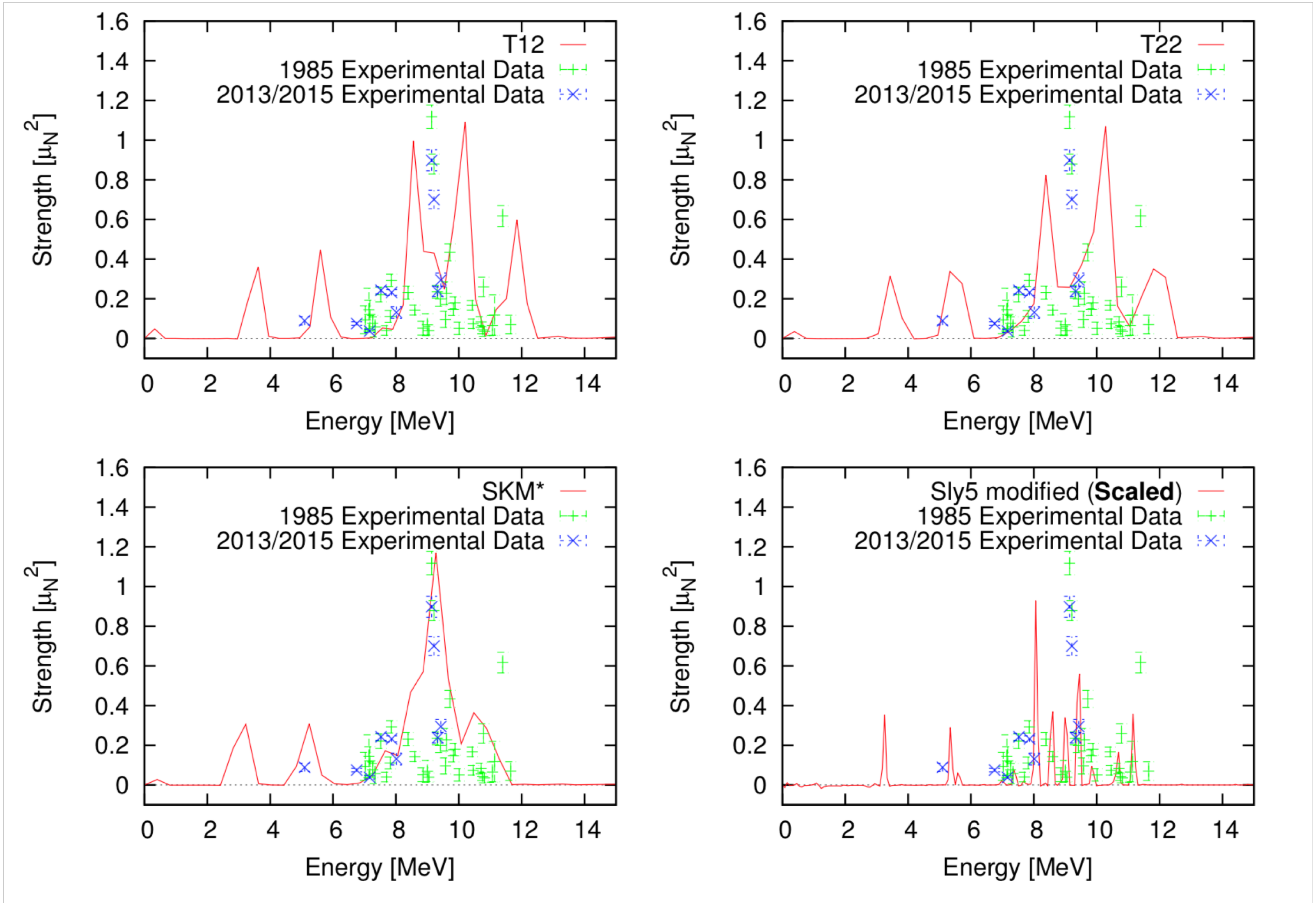


The full tensor field

Tensor force -> mean field contributions



Further force dependence



Force dependence in Cr-52

Summary of calculations

- Adding tensor force spreads peak structure over wider energy range
- **s.F** tensor-force-only term in mean-field plays large role in response
- Discrete low-lying peaks insensitive to variation in force
- Old SkM* (no tensor) force seems to do rather well
- Plenty of scope for further investigation; coupling to E1; spin-dipole v. full M1; higher resolution; systematic study of nuclei, forces.

Broader Outlook

What next?

Can initialize TDHF code as collision & study resulting resonance –
Closer to experimental situation

$^{32}S + ^{48}Ti$ @ 66MeV CM

... or look at time-evolution of fission fragments, or initialise t=0 configuration as a cluster state, or ...

👏 TDHF is a powerful and general method. With some imagination can explore wide range of nuclear response (of a one-body nature)

Acknowledgements

Work in collaboration with M. C. Barton:
M C Barton & PDS arXiv:1709:07823

-- see also PDS & M. C. Barton, Prog. Part. Nucl. Phys., *in press* https://doi.org/10.1016/j.ppnp.2018.09.002

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