Project B01

Electroweak interactions in nuclei and nuclear matter

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1st workshop of the CRC 1245

Darmstadt, November 22, 2016

Motivation

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Electroweak interactions probe our understanding of nuclear forces and help to understand processes from particle and astrophysics:

Interactions with external sources:

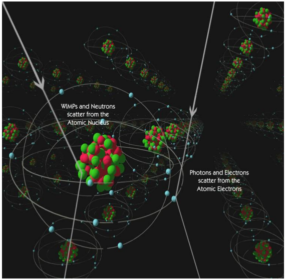
- Beta decay
- Electron scattering
- ...

Beyond Standard Model physics:

- WIMP-nucleus scattering (Dark Matter detection)

Nuclear astrophysics:

- Neutrino-nucleus interactions



- Electroweak currents based on chiral effective field theory
- Uncertainty estimates from ^{3}H beta decay
- WIMP-nucleus scattering
- Nucleosynthesis in neutrino driven winds
- Summary and outlook

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Chiral effective field theory

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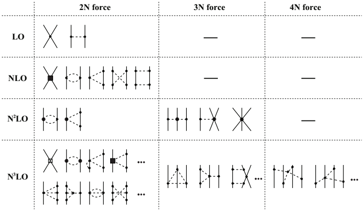
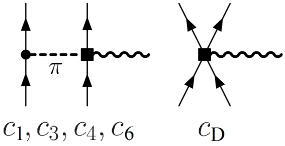
- Chiral EFT describes consistently both nuclear forces and currents
- Same low-energy constants appear in nuclear forces and currents
- Leading vector and axial two-body currents completely determined

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

  A. Gårdestig and D. R. Phillips, PRL **96**, 232301 (2006)

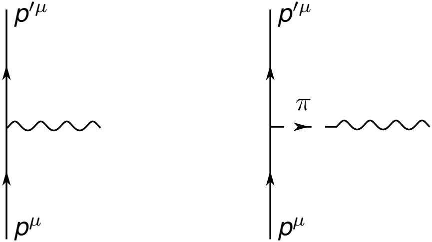
  D. Gazit, S. Quaglioni, and P. Navrátil, PRL **103**, 102502 (2009)





One-body currents

Axial current at chiral order Q^0

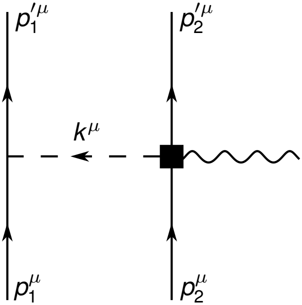


$$A_{1b}^{a\mu} = -g_A \bar{u}(p')\gamma_5 \left(\gamma^{\mu} - \not{q}\frac{q^{\mu}}{q^2 - m_{\pi}^2}\right)\frac{\tau^a}{2}u(p)\,,$$

Pion-decay is momentum dependent

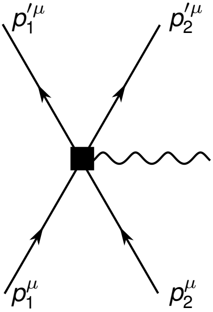
Two-body currents

At order Q^3, 2b currents enter:



Pion exchange currents

c_1, c_3, c_4, c_6



Contact currents

c_D

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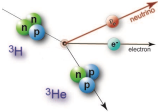
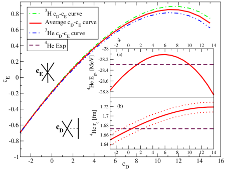
Determination of c_D and c_E



- Binding energies of ^{3}H or ^{3}He yield relation between c_D and c_E

  Navrátil et al., PRL **99**, 042501 (2007)

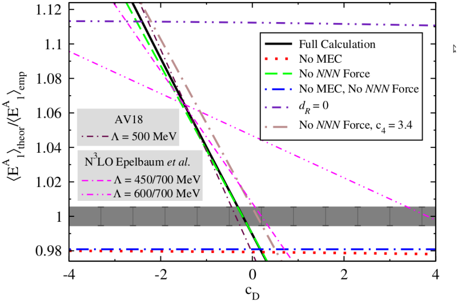


- Beta-decay of triton to determine c_D:

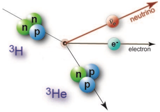
  Gazit, Quaglioni, Navrátil, PRL **103**, 102502 (2009)

  - ^{3}H half-life precisely known
  - Uncorrelated with ^{3}H binding energy

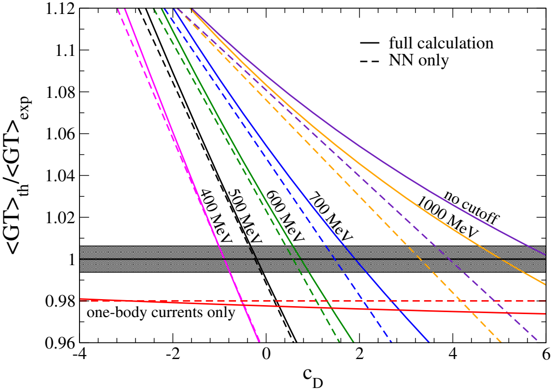
- c_D and c_E fully determined from independent three-body observables



Determination of c_D



Consider different cutoffs for two-body currents:

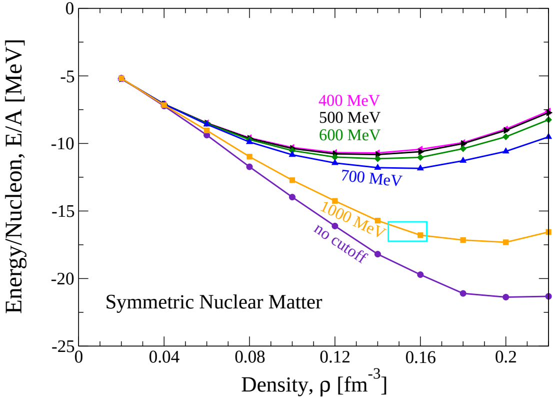


Carbone, Hebeler, Menéndez, Schwenk, PK, arXiv to appear

Significant current-regulator dependence of c_D!

Determination of c_D
Impact on nuclear matter

Nuclear matter calculation with c_D, c_E taken from the triton fit



Carbone, Hebeler, Menéndez, Schwenk, PK, arXiv to appear

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We still don't know what dark matter is!

Weakly Interacting Massive Particles

- predicted by Supersymmetry (Extensions of Standard Model)
- expected density would account naturally for the observed dark matter density
- **accessible for direct detection via interaction with nuclei (Xe, Ge, ...)**
- $m_{\mathrm{WIMP}} \approx$ GeV-TeV

Application
WIMPs and direct detection

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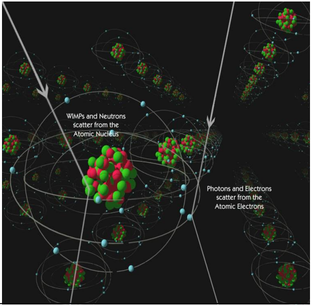
- Small cross sections $\rightarrow$ Underground detectors to shield background
- Detect nuclear recoils caused by **(in-)elastic** WIMP scattering
- **Inelastic** scattering: deexciation leads to unique signal



Introduction
Direct WIMP detection

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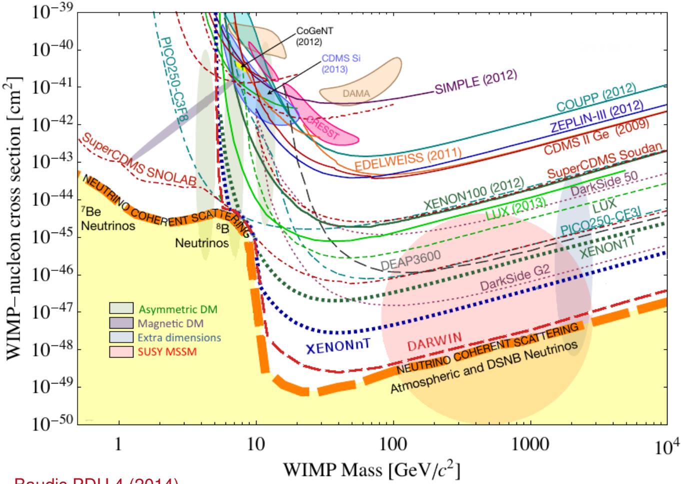

Baudis PDU 4 (2014)

WIMP-nucleus interaction

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Transition amplitude of WIMP-nucleus scattering

$$\sigma \propto |\langle \text{final}| H_{\chi-\text{nucleus}} |\text{inital}\rangle|^2$$

Two tasks:

Description of initial and final nuclear states

$\rightarrow$ Interacting shell model

Description of WIMP-nucleus interaction

WIMP-nucleus interaction

Cross section of WIMP-nucleus interaction depends on structure factor $S_A(q)$.

$$\frac{d\sigma}{dq^2} = \frac{2}{\pi v^2}\frac{1}{2}\sum_{s_i,s_f}\frac{1}{2J_i+1}\sum_{M_i,M_f}\left|\langle f|\sum_A H_\chi^{SD}|i\rangle\right|^2 = \frac{8G_F^2}{(2J_i+1)v^2}S_A(q),$$

Spin-dependent (SD) WIMP-nucleus interaction:

$$H_\chi^{SD} = \sqrt{2}G_F\int d^3r\,\underbrace{A_{N\mu}(\mathbf{r})}_{\text{nucleon current}}\;\underbrace{A_\chi^{\mu}(\mathbf{r})}_{\text{WIMP current}}$$

Axial-vector–axial-vector couping

Structure factors: Elastic scattering

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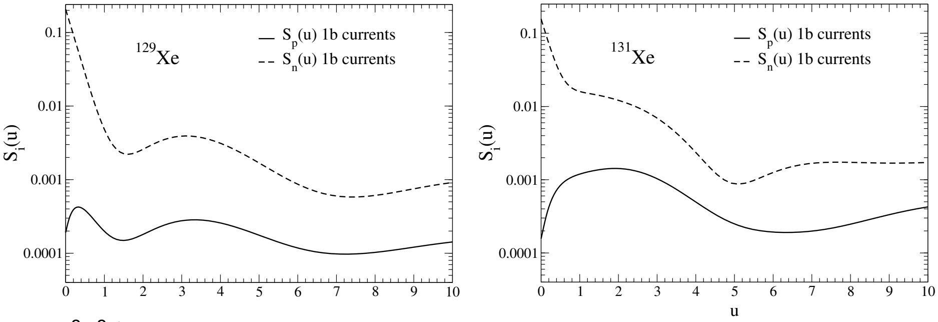

$u = q^2 b^2/2$ with harmonic oscillator length b

^{129}Xe		^{131}Xe	
$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$	$\langle \mathbf{S}_p \rangle$	$\langle \mathbf{S}_n \rangle$
0.010	0.329	-0.009	-0.272

Structure factors: Elastic scattering

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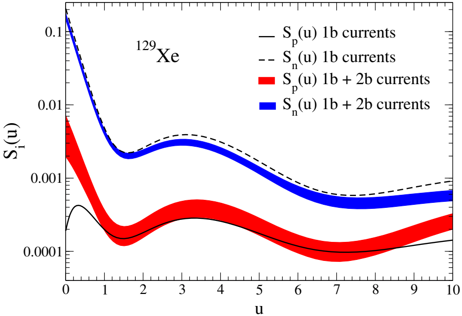
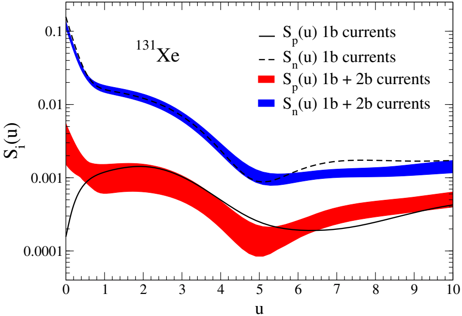
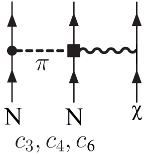




$u = q^2 b^2/2$ with harmonic oscillator length b

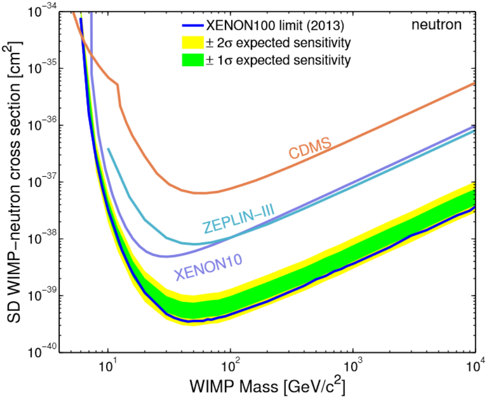
- 2b currents $\rightarrow$ at low momentum transfer neutrons contribute to proton structure factor $S_p(u)$
- $S_n(u)$ reduced by 20% for low momentum transfers

PK, Menéndez, Gazit, Schwenk, PRD **88**, 083516 (2013)



XENON100 spin-dependent limit

Structure factors and uncertainties in currents used in XENON100 spin-dependent analysis: XENON100, PRL **111**, 021301 (2013)



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Nucleosynthesis in neutrino driven winds

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Neutrino interactions determine Y_e

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Neutron-rich ejecta:

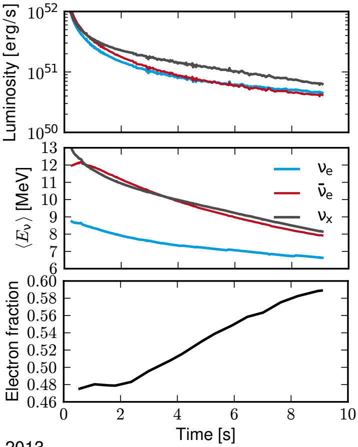
$$\langle E_{\bar{\nu}_e}\rangle - \langle E_{\nu_e}\rangle > 4\Delta_{np} - \left[\frac{L_{\bar{\nu}_e}}{L_{\nu_e}} - 1\right]\left[\langle E_{\bar{\nu}_e}\rangle - 2\Delta_{np}\right]$$

- neutron-rich ejecta: weak r-process
- proton-rich ejecta: νp-process

Energy difference related to symmetry energy (GMP+ 2012, Roberts+ 2012)

Sensitivity to neutrino opacities?

1D Boltzmann transport simulation (DD2 EoS)



GMP+ 2013

Improvements of neutrino opacities

Most simulations use opacities based on the leading order elastic approximation (Bruenn 1985).

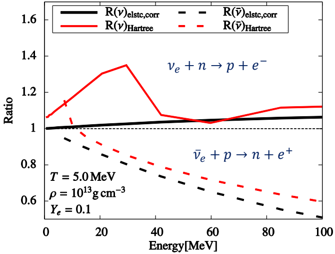
Improvements:

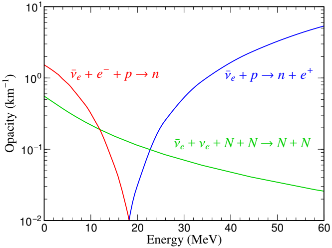
- Weak magnetism (Horowitz 2002)

$$j^\mu = \bar{\psi}_n \left[c_V \gamma^\mu + \frac{iF_2}{2M_N} \sigma^{\mu\nu} q_\nu - c_A \gamma^\mu \gamma_5 \right] \psi_p$$

- Inelastic contributions (Reddy+ 1998)
- Additional opacity channels for $\bar{\nu}_e$ (Direct URCA, Lattimer+ 1991)

$$\bar{\nu}_e + e^- + p \to n$$

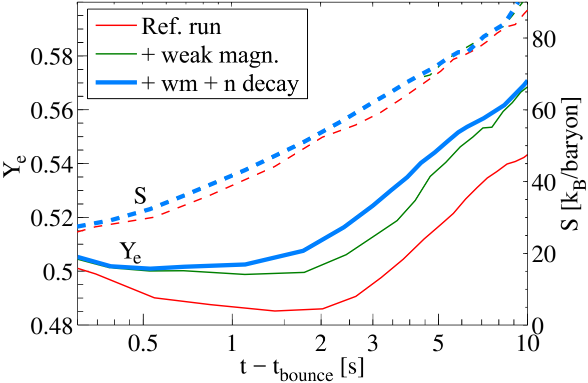




A. Lohs, PhD thesis

Impact opacities on Y_e

Fischer, GMP, Wu, Lohs, Qian, in preparation



Ejecta are always proton rich: νp-process.

No weak r-process neutrino winds.

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Summary

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- Complete derivation of chiral two-body currents for electroweak interactions to $(Q/\Lambda)^3$ including all terms relevant for finite momentum transfer
- Significant current-cutoff dependence when fitting c_D
- State-of-the-art large-scale shell-model calculations used to predict spin-independent / spin-dependent WIMP responses
- Electroweak interactions relevant for electron fraction in neutrino driven winds

Outlook

- Application to $0\nu\beta\beta$, μ-capture, electron scattering, ...
- How do we choose regulators consistently in forces and currents?