Constraining the Symmetry Energy with Neutron-Removal Cross Sections

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ENSAR2

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Outline

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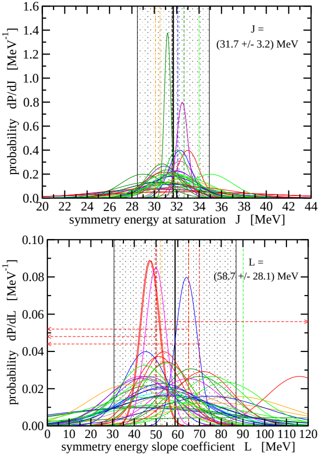
Motivation

- **symmetry energy of nuclear matter**
  - density dependence of $E_{\mathrm{sym}}(\varrho)$
    - below saturation density $\varrho_0 \approx 0.15$ fm^{-3}: convergence of theoretical approaches, consistency with experimental constraints
    - above saturation density: large uncertainties
  - characteristic parameters at saturation
    - symmetry energy at saturation $J = E_{\mathrm{sym}}(\varrho_0)$: rather well constrained
    - slope parameter $L = 3\varrho_0 \frac{dE_{\mathrm{sym}}}{d\varrho}\Big|_{\varrho=\varrho_0}$: still large uncertainties
- **experimental determination**
  - methods ?



(M. Oertel et al., Rev. Mod. Phys. 89 (2017) 015007)

Constraining the Slope Parameter L

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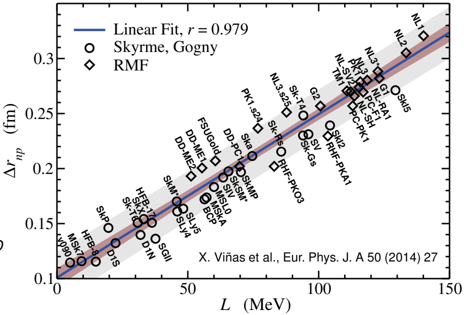
- **tight correlations with**
  - neutron skin thickness Δr_{np}
    (see, e.g., X. Roca-Maza et al., Phys. Rev. Lett. 106 (2011) 252501)
  - parity-violating asymmetry A_{PV} in e scattering on ^{208}Pb (PREX)
    (see, e.g., S. Aprahamyan et al., Phys. Rev. Lett. 108 (2011) 112502)
  - ground-state dipole polarizability α_D
    (see. e.g., P.-G. Reinhard and W. Nazarewicz, Phys. Rev. C 81 (2010) 051303)



- **uncertainties**
  - parity-violating asymmetry: $A_{PV}(\pm 3\%) \Rightarrow \Delta r_{np}(\pm 0.06 \text{ fm}) \Rightarrow L(\pm 40 \text{ MeV})$
    (X. Roca-Maza et al., Phys. Rev. Lett. 106 (2011) 252501)
  - dipole polarizability α_D: 20 MeV $\leq L \leq$ 66 MeV
    (X. Roca-Maza et al., Phys. Rev. C 92 (2015) 064304)

New Approach to Determine the Neutron Skin Thckness

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- **high-energy nuclear collisions**
  - secondary beams of neutron-rich nuclei (neutron-rich Sn isotopes)
  - beam energies of 0.4 to 1 GeV/nucleon
  - hydrogen or carbon targets (^{12}C)
  - high number of events in hadronic reactions
- **cross sections**
  - total reaction cross section $\sigma_R = \sigma_{\Delta N} + \sigma_{\Delta Z}$
  - total neutron-removal cross section $\sigma_{\Delta N}$
    $\Rightarrow$ sensitivity to neutron skin thickness Δr_{np}
  - total charge-changing cross section $\sigma_{\Delta Z}$
- **theoretical description**
  - Glauber multiple scattering theory

    (see. e.g., M.L. Miller et al., Annu. Rev. Nucl. Part. Sci. 57 (2007) 205)

Theoretical Description

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- **Glauber multiple scattering approach**
  - cross section for production of fragment (Z, N) from projectile (Z_P, N_P)

$$\sigma = \binom{Z_P}{Z}\binom{N_P}{N} \int d^2b \, \left[1 - P_p(b)\right]^{Z_P - Z} P_p^Z \left[1 - P_n(b)\right]^{N_P - N} P_n^N$$

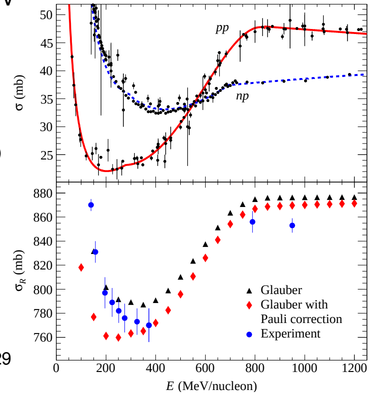
  - survival probability of single-nucleon i

$$P_i(b) = \int dz \, d^2s \, \varrho_i^P(\vec{s}, z) \exp\left[-\sigma_{ip} Z_T \int dz' \, \varrho_p^T\left(\vec{b} - \vec{s}, z'\right) - \sigma_{in} N_T \int dz' \, \varrho_n^T\left(\vec{b} - \vec{s}, z'\right)\right]$$

- **Input**
  - nucleon-proton (neutron) total reaction cross sections σ_{ip} (σ_{in}) from experiment
  - projectile (target) proton (neutron) densities $\varrho_{p(n)}^{P(T)}$, normalized as $\int d^3r \, \varrho_{p(n)}^{P(T)} = 1$, from theory

Cross Sections

- **NN Reaction Cross Sections**
  - fit of experimental data from 10 MeV to 5 GeV
    (C.A. Bertulani and C. De Conti,
    Phys. Rev. C 81 (2010) 064603)
- **Total ^{12}C-^{12}C Reaction Cross Sections**
  - ^{12}C densities from elastic electron scattering
    (E.A.J.M. Offermann et al., Phys. Rev. C. 44 (1991) 1096)
  - theory without/with Pauli blocking
    (F. Schindler, Doctoral Thesis (2017) TU Darmstadt)
  - experimental data
    (100-400 MeV/nucleon: M. Takechi et al.,
    Phys. Rev. C 79 (2009) 061691
    790 MeV/nucleon: I. Tanihata et al.,
    in *Radioactive Nuclear Beams*, World Scientific (1990) 429
    950 MeV/nucleon: A. Ozawa et al.,
    Nucl. Phys. A 691 (2001) 599)



Theoretical Model for Nuclei

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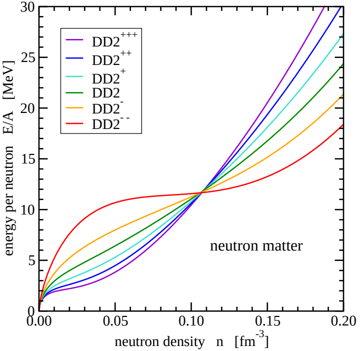
- **Relativistic Density Functional**
  - phenomenological model
  - density dependent nucleon-meson couplings
  - fit of parameters to observables of nuclei
  - systematic variation of slope parameter L starting from standard parametrization DD2
    (S. Typel, Phys. Rev. C 89 (2014) 064321)

parametrization	symmetry energy J [MeV]	slope parameter L [MeV]
DD2^{+++}	35.34	100.00
DD2^{++}	34.12	85.00
DD2^{+}	32.98	70.00
DD2	31.67	55.04
DD2^{-}	30.09	40.00
DD2^{--}	28.22	25.00



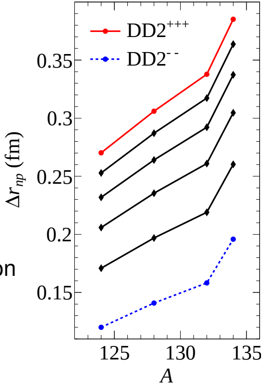
Results for Tin Nuclei I

- **Dependence on Mass Number A**
- **Example: ^{132}Sn**

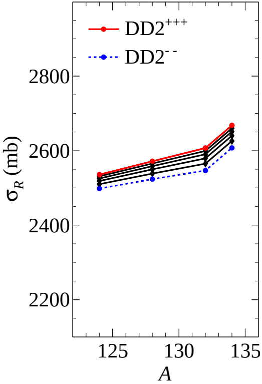
  L from 25 MeV (DD2^{--}) to 100 MeV (DD2^{+++}), variation of $\pm 60\% \Rightarrow$

  - neutron skin thickness Δr_{np} from 0.15 fm to 0.34 fm ($\pm$39%)
  - total reaction cross section σ_R from 2550 mb to 2610 mb ($\pm$1.2%)

neutron skin thickness Δr_{np}



total reaction cross section σ_R



Results for Tin Nuclei II

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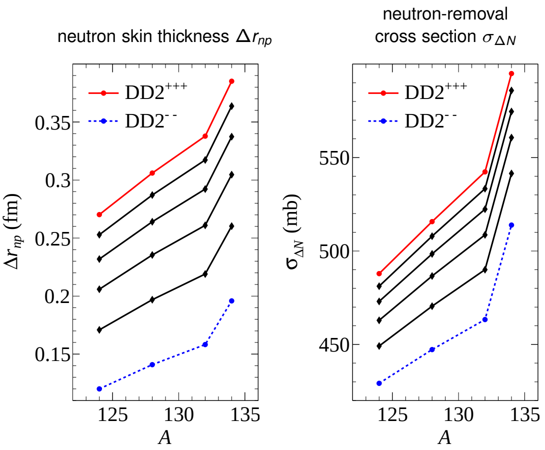
- **Dependence on Mass Number A**
- **Example: ^{132}Sn**

  L from 25 MeV (DD2^{--}) to 100 MeV (DD2^{+++}), variation of $\pm 60\% \Rightarrow$

  - neutron skin thickness Δr_{np} from 0.15 fm to 0.34 fm ($\pm 39\%$)
  - neutron-removal cross section $\sigma_{\Delta N}$ from 460 mb to 540 mb ($\pm 8\%$)



Results for Tin Nuclei III

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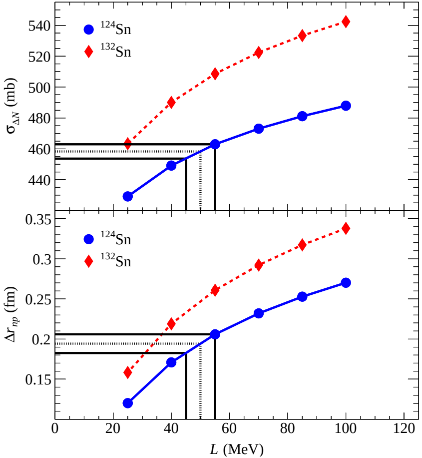
- **Dependence on Slope Parameter L**
- **Example: ^{124}Sn**

  variation of L by ± 5 MeV $\Rightarrow$

  - variation of Δr_{np} by ± 0.01 fm
  - variation of $\sigma_{\Delta N}$ by ± 5 mb ($\pm 1\%$)

  sensitivity even higher for ^{132}Sn



Accuracy of Reaction Theory I

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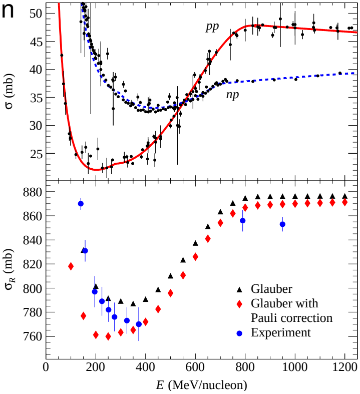
- **Nuclear Fragmentation in High-Energy Collisions**
  - primary fragment production:
    multi-nucleon removal via nucleon-nucleon collisions
  - secondary fragment production:
    nucleon evaporation (e.g. Hauser-Feshbach theory of compound-nucleus decay)
    model dependent, but not required here
    (e.g., less than 0.5% of $\sigma_{\Delta N}$ transferred to $\sigma_{\Delta Z}$ for 580 MeV/nucleon ^{124}Sn on ^{12}C)
- **Nucleon Loss after Inelastic Excitation**
  - e.g. collective states in the continuum/giant resonances
  - nuclear and electromagnetic contributions
  - has to be known with uncertainty $< 5\%$, impossible with present reaction theory
  - measurable with state-of-the-art kinematical complete experiments
    (very different angular distribution, boosted to forward direction at high beam energy)

Accuracy of Reaction Theory II

- **Eikonal Description of Primary Process**

  test of model performance for $^{12}C+^{12}C$ reaction
  - input: NN cross sections, density distributions
  - no additional energy-dependent parameters
  - improvement by Pauli blocking correction
    (C.A. Bertulani and C. De Conti, PRC 81 (2010) 064603)
  - below ≈ 400 MeV/nucleon:
    effects of Fermi motion ⇒ increase of σ_R
    (M. Takechi et al., PRC 79 (2009) 061601)
  - no experimental data between 400 and 800 MeV/nucleon ⇒ extremely important
  - different energy dependence of *np* and *pp* cross sections ⇒
    effects with change of targets



Accuracy of Reaction Theory III

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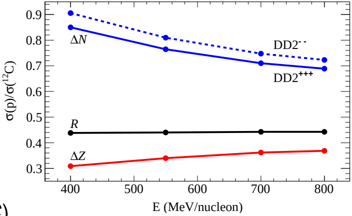
- **Eikonal Description of Primary Process**
  energy dependence, example with ^{134}Sn projectiles
  - comparison of proton and ^{12}C targets
  - proton target:
    test of *n* skin only with *pn* reactions,
    charge changing only with *pp* reactions
  - ^{12}C target: surface dominated process
  - ratios of cross sections:
    no energy dependence for $\sigma_R(p)/\sigma_R(^{12}C)$,
    but for $\sigma_{\Delta N}(p)/\sigma_{\Delta N}(^{12}C)$ and $\sigma_{\Delta Z}(p)/\sigma_{\Delta Z}(^{12}C)$



$\Rightarrow$ crucial experimental tests for reaction theory

Conclusions

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- **Measurement of Total Neutron-Removal Cross Sections**
  - study of neutron-rich nuclei in relativistic heavy-ion collisions
  - experimental determination of neutron skin thickness/slope parameter L
  - 2% uncertainty in experimental and theoretical cross sections
    $\Rightarrow$ 10 MeV uncertainty in L achievable
  - promising technique, possible with new detectors
    at existing radioactive-beam facilities
- **Reaction Model**
  experimental variations of targets, beams, energies $\Rightarrow$
  - test validity of reaction model
  - track sensitivity of measurements
  - guide systematic improvements