Derivation of the nuclear skin thickness from the study of Spin Dipole Resonances using the basic sum rule relationship

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Outline

I. Introduction
II. Neutron stars – Quark stars
III. Methods for measuring the neutron-skin thickness
   • Sum rule → neutron skin
   • Constraining the symmetry energy
IV. Spin-isospin giant resonances in rare isotope beams
V. Conclusions
The neutron-skin thickness

\[ \rho(r) \]

\[ \langle r^2 \rangle \equiv \int \rho(r) r^2 \, dv \]

\[ \Delta R = \langle r^2 \rangle_{n}^{1/2} - \langle r^2 \rangle_{p}^{1/2} \]
Constraining the symmetry energy

\[ a_4 = 29 \pm 3 \text{ MeV} \]

The symmetry energy in nuclear matter

\[ E(\rho, \alpha) = E(\rho,0) + S(\rho)\alpha^2 + O(\alpha^4) + ... \]

\[ \alpha = \frac{N - Z}{A} \]

\[ S(\rho) = \frac{1}{2} \frac{\partial^2 E(\rho, \alpha)}{\partial \alpha^2} \bigg|_{\alpha=0} = a_4 + \frac{p_0}{\rho_0^2} (\rho - \rho_0) + ... \]
Charge Exchange Excitations and the $r_n - r_p$ issue in relativistic RPA

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Collaborators: Haozhao Liang, Jie Meng
Isovector properties of covariant DFT's and their influence on static and dynamic properties of neutron distributions

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The Nuclear Symmetry Energy and Neutron Star Crusts

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Che Ming Ko and Jun Xu (TAMU)
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Compact stars in the QCD phase diagram II
May 20-24, 2009, Beijing
Probing the Equation of State of Neutron-Rich Matter with Heavy-Ion Reactions

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Andrew W. Steiner, Los Alamos National Laboratory
G.C. Yong and W. Zuo, Chinese Academy of Science
C.B. Das, C. Gale and S. Das Gupta, McGill University

1. Equation of State and Symmetry Energy of Neutron-Rich Matter
   • Current status and major issues
   • Importance in astrophysics and nuclear physics

2. A Transport Model for Nuclear Reactions Induced by Radioactive Beams
   • Some details of the IBUU04 model
   • Momentum dependence of the isovector nucleon potential in isospin asymmetric matter

3. Determining the Density Dependence of Nuclear Symmetry Energy
   • At sub-saturation densities: isospin transport in heavy-ion reactions and neutron-skin in $^{208}$Pb
   • At higher densities: reactions at RIA and GSI using high energy radioactive beams

4. Summary
• 1. Giant Resonances and Nuclear Equation of States
• 2. Pairing correlations in Nuclear Matter and Nuclei

Constraints to Universal Energy Density Functionals by Giant Resonances
Determining the Nuclear Symmetry Energy of Neutron-Rich Matter and its Impacts on Astrophysics

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Outline:
• Theoretical predictions about density dependence of nuclear symmetry energy
• How to constrain the symmetry energy with heavy-ion collisions
• Astrophysical impacts of the partially constrained nuclear symmetry energy

Two examples:
(1) Mass-radius correlation of rapidly-rotating neutron stars
(2) The changing rate of the gravitational constant G due to the expansion of the Universe

• Summary
Properties of Asymmetric nuclear matter within Extended BHF Approach

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Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou


Relativistic many-body problems for heavy and superheavy nuclei
Beijing, June 2009
Probing the Equation of State of Neutron-Rich Matter with Heavy-Ion Reactions

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1. Equation of State and Symmetry Energy of Neutron-Rich Matter

2. A Transport Model for Nuclear Reactions Induced by Radioactive Beams

3. Determining the Equation of State of Neutron-Rich Matter

4. Summary
Neutron Stars

- Core of a massive star that remains after a supernova explosion
- Average Density: $\sim 10^{14}$ g/cm$^3$
- Rotational frequency may range up to 1122 Hz (XTE J1739-285)
- Magnetic field strength can be $\sim 10^8$-$10^{14}$ times that of Earth
- Exotic Physics!

http://science.nasa.gov/
Quark Stars (QS)

- Stellar core composed of free quarks (strange matter)
- Would form through neutron deconfinement
- Neutron Star (NS) collapses inward after spinning down, losing centrifugal force
- Strange matter would be “softer”, more compressible than neutrons
- Smaller, denser than a NS
- NS massing from $1.5-1.8M_{\text{Sun}}$ are likely candidates

http://chandra.harvard.edu
• Quark Stars still theoretical, but evidence continues to accumulate to support them
• Quark Stars would offer unique opportunities to study exotic matter
Determinination of the charge distribution by electron scattering

\( \lambda = \frac{\hbar}{p} \approx \frac{200}{E(\text{MeV})} \text{fm} \)

High precision data (<0.1 %)

\[ E = 100 \text{ MeV} \quad 2 \text{ fm} \]
\[ E = 2 \text{ GeV} \quad 0.1 \text{ fm} \]

\[ R = r_0 A^{1/3} \]
Determination of the mass distribution by pion scattering

- Pion scattering, pion charge-exchange reactions
  
  $\Delta(1332)\ \pi^-\ \text{scattering}$
  
  $\sigma(\text{neutron}) \approx 3\sigma(\text{proton})$

  sensitive mostly to the tail of the distribution models, uncertainties
Determination of the mass distribution by hadron scattering

- Proton elastic scattering at 800 MeV – 1 GeV, evaluation by Relativistic Impulse Approximation (RIA) taking into account the free nucleon nucleon interactions (L. Ray et al. 1979)

- Proposal for a model independent analysis (Kelley et al., 1991)

- Medium effects on the n-n interactions (Sakaguchi et al., 1998)
Neutron density distributions deduced from antiprotonic atoms

• Capture of low energy antiprotons into the atom

• In $^{208}$Pb the antiproton reaches the surface of the nucleus at already $n=9,10$

• Radiochemical method for determining the residues (Jastrzebski et al., 1993)

• In-beam antiprotonic X-rays (Trzcinska et al., 2001)

• Study of the „nuclear stratosphere”
Assumptions:

1. \( \rho(p_p) = \rho(p_n) \)

2. Two parameter Fermi distributions are assumed for both the proton and neutron distributions

3. Extrapolation from the stratosphere of the nucleus
Parity violating electron scattering
(R. Michaels et al., Proposal to Jefferson Lab, 2002)

Theoretical support: C.J. Horowitz and J. Piakarewitz


Parity violating electron scattering \(\Rightarrow\) neutron densities (Z-boson couples primarily to the neutron at low \(Q^2\).)

Weak charge density \(\Rightarrow\) neutron density, \(R_n\) with 1 % accuracy
\[ \tilde{V}(r) = V(r) + \gamma_5 A(r) \]

\[ A(r) = \left( \frac{G_F}{2^{3/2}} \right) \rho_W(r) \]

\[ \rho_W = \left( 1 - 4 \sin^2(\Theta_W) \right) \rho_p(r) - \rho_n(r) \]

\[ \sin^2(\Theta_W) \approx 0.24 \]
The idea of the GDR method

Calculation of the cross section by using GT and SJ models

\[ U(\text{tr.}) \approx \frac{\Delta R}{R_p} \]

Vibrations in the spin-isospin space: IAS, GT and SD resonances

- Theoretical predictions 1957, 1959
- Experimental discovery of IAS 1962
- IAS is a giant resonance, Ikeda 1962
- Prediction of the GT resonance, Ikeda 1963
- Discovery, Doering et al, 1975 (45 MeV, MSU)
Excitation with strong interaction

\[ V_{pj}(r) = V_{0}^{C}(r) + V_{\sigma}^{C}(r) \sigma_{p} \cdot \sigma_{j} + V_{\tau}^{C}(r) \tau_{p} \cdot \tau_{j} + V_{\sigma\tau}^{C}(r) \sigma_{p} \cdot \sigma_{j} \tau_{p} \cdot \tau_{j} \]

\[ + [V_{LS}^{L}(r) + V_{LS}^{T}(r) \tau_{p} \cdot \tau_{j}] L_{pj} \cdot S \]

\[ + [V_{T}^{L}(r) + V_{T}^{T}(r) \tau_{p} \cdot \tau_{j}] S_{pj}(\hat{r}) \]
The $L=1$ transitions, SDR

- **Giant Dipole Resonance** $\Sigma r(i)\tau_3(i) \implies \Delta L = 1$, $\Delta S = 0$, $\Delta T = 0, 1$
  $0^+ \rightarrow 1^-$ Giant resonance
  Sum rule (TRK) $\propto NZ/A$

- **Spin-Dipole Res.** $\Sigma [r(i) \otimes \sigma(i)] \tau_3(i)$ $\Delta L = 1$, $\Delta S = 1$, $\Delta T = 0, 1$
  $0^+ \rightarrow 0^-, 1^-, 2^-$ Giant resonance
  Sum rules $\rightarrow$ neutron skin
Sum rule for the SDR strength

Neutron-skin thickness

\[ \Delta R = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2} \]

\[ \sum_a \tau_a^\pm \left[ \rightarrow \sigma_a \otimes r_a \right]_{JM} \]

\[ S_{SDR}^- - S_{SDR}^+ = \frac{9}{2\pi} \left( N \langle r^2 \rangle_n - Z \langle r^2 \rangle_p \right) \]

Bohr, Mottelson
Nuclear Structure (1969) Vol. 2

\[ \frac{\alpha \sigma_{\text{exp}} (1-B) - (N-Z) \langle r^2 \rangle_p^{1/2}}{2N \langle r^2 \rangle_p^{1/2}} \]

\[ B = S^+ / S^- \]
A. Krasznahorkay et al., PRL 82 (1999) 3216
Experimental methods

BBS

Beams from AGOR at KVI

→ symm. energy
→ terra incognita
→ neutron stars

E=177 MeV
Θ=3.2°
Differential cross sections

[Graphs showing differential cross sections for IAS and SDR]
Results for the neutron–skin thicknesses of the Sn isotopes

Present results

Trzcinska et al., PRL 87 082501 (2001)

Constraining the symmetry energy

\[ a_4 = 29 \pm 3 \text{ MeV} \]

SDR studies in $^{40-48}$Ca isotopes
RCNP, Osaka Uni. (Y. Fujita, H. Fujita)

NDS 88 (1999)
$E_x < 5.7$ MeV
$^{44}\text{Ca}(^{3}\text{He},t)$ compressed by 100
Isovector GR’s in unstable nuclei

- The physics case
  • Macroscopic & microscopic info
  • Neutron skin
    – SDR sum-rule
    – $E_x(GTR) - E_x(IAS)$
  • astrophysics e.g. $\nu$-process
  – Experimental considerations ((p,n) in inverse kinematics)
    • High cross sections ($\sim 10$mb/sr)
    • Complete kinematics (use FRS)
    • low-$E_n$, no energy loss in target
  – Neutron detection
    • aim: 1 MeV resolution in $E_x$
    • required: $\Delta \theta \approx 1^0$, $\Delta E_n/E_n = 10\%$ flight path: 1 m, Timing resolution: 1 ns
(p,n) in inverse kinematics
p(\textsuperscript{132}Sn,n) E=400 AMeV
The high-energy branch of the Super-FRS:
A versatile setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

Experiments
- knockout and quasi-free scattering
- electromagnetic excitation
- charge-exchange reactions
- fission
- spallation
- fragmentation

Physics goals
- single-particle occupancies, spectral functions, correlations, clusters, resonances beyond the drip lines
- single-particle occupancies, astrophysical reactions (S factor), soft coherent modes, giant resonance strength, B(E2)
- Gamow-Teller strength, spin-dipole resonance, neutron skins
- shell structure, dynamical properties
- reaction mechanism, applications (waste transmutation, ...)
- γ-ray spectroscopy, isospin-dependence in multifragmentation
Requirements on kinematical parameters

Relativistic calculation of inverse kinematics

- $E_{\text{beam}} = 400 \text{ MeV} \cdot A$
- $^{122-132}\text{Sn}$
- $E_x (\text{SDR}) = 18-24 \text{ MeV}$
- $\Theta_{\text{cm}} = 2^\circ - 3^\circ (L=1)$

$55^\circ < \Theta_{\text{lab}} < 70^\circ$
Technical requirements

- Positioning of detector frames (40°<Θ<80°), To avoid n-scattering less material in holder structures and environment
- Flight path of neutrons: 100 cm
- Cross-scattering of neutrons $E_{n'} = E_n (1 - \cos(\Theta)^2)$
  - MC-simulation → closest distance of the detectors
- Baad response of plastic scintillators to low-energy protons. Birks relation:
  $E_p = 0.2$ MeV → $E_e = 10$ keV → good light collection is necessary!
  → VM2000 multilayer reflector
Scintillators and photomultipliers

- UPS 89 from Ukraine = NE102A
- Size of the scintillator: 10x45x1000 mm
- Two PMT for each: XP2262 + active dividers
- Wrapping in VM2000 multilayer reflector
Test with $^{60}$Co-source

- Time- and position resolution: (delay: 1.3 ns/10 cm) → 0.8 ns → 6 cm resolution
- Light attenuation: <10%

FWHM ~ 0.8 ns
Plan of geometric arrangement
The $^{107}\text{Cd}$ ($T_{1/2}=6.5$ h) source was produced by the $^{107}\text{Ag}(p,n)^{107}\text{Cd}$ reaction in ATOMKI.
Test with a $^{252}$Cf neutron source

Start signal is generated by the fission fragments in a 0.1 mm thick NE-102A scintillator coupled to an XP2262 phototube. Flight distance = 100 cm
Efficiency for neutrons

\[ E_{Thr.} = 20 \, \text{keV}_{ee} \]
\[ E_{Thr.} = 30 \, \text{keV}_{ee} \]
\[ E_{Thr.} = 40 \, \text{keV}_{ee} \]
\[ E_{Thr.} = 50 \, \text{keV}_{ee} \]
Comparison with the MC (GEANT3) simulations
Response of the spectrometer to mono energetic neutrons, test with the $^7\text{Li}(p,n\gamma)^7\text{Be}$ reaction.
Scattering over probabilities

Experimental data ($E_n = 1$ MeV)

- 1.3 %
- 1.6 %
- 1.3 %
- 0.5 %

1.2 %
4.0 %
1.2 %
0.4 %

1.1 %
1.0 %
100 %
0.6 %

MC simulation
Tests in Los Alamos

- Neutrons produced in the $^{235}\text{U}(n,f)$ reaction
- TOF measurement
- Gamma-sensitivity of the detector

**LANSCE** is the major experimental science facility at Los Alamos National Laboratory (LANL), underpinning the Laboratory as a world-class scientific institution. At the heart of LANSCE is a powerful linear accelerator that accelerates protons to 800 MeV. When these protons strike a target of tungsten metal, neutrons are produced.
An improved mechanical arrangement
\[ \sum B_{\text{pdr}}(E1) = 1.98 \text{ e}^2 \text{ fm}^2 \]
from N. Ryezayeva et al., PRL 89(2002)272501

\[ \sum B_{\text{gdr}}(E1) = 60.8 \text{ e}^2 \text{ fm}^2 \]
from A. Veyssiere et al., NPA 159(1970)561

\[ R_n - R_p = 0.18 \pm 0.035 \text{ fm} \]
Precision for $^{208}$Pb

$$S_{SDR}^- - S_{SDR}^+ = \frac{9}{2\pi} \left( N\langle r^2 \rangle_n - Z\langle r^2 \rangle_p \right)$$

$$S_{SDR}^- = (N - Z)\langle r^2 \rangle_p - 2N\sqrt{\langle r^2 \rangle_p} \Delta r$$

$$\frac{2N\Delta r}{(N - Z)\sqrt{\langle r^2 \rangle_p}} \approx 5.7 \frac{\Delta r}{\sqrt{\langle r^2 \rangle_p}}$$

5 times better precision is needed in $S$, which we want in $\Delta r$ !!!
Better than 5 % precision, background suppression, full strengths
$^{208}\text{Pb}(^{3}\text{He},t)$
\[ E = 400 \text{ MeV} \]

- 0 deg.
- 1 deg.
- 1 deg – 0 deg.
The idea of suppressing the contribution of the QFC channel
Setup for determining the GT and SDR strengths in kinematically complete experiment

Identification of the $^{208}\text{Bi}$ recoils
Conclusions

• A versatile neutron spectrometer
  – Energy resolution in Ex < 1 MeV
  – In CM angle < 0.3°
  – Scattering over < 2 %
• Efficiency 20 – 40 %
• Solid angle coverage for 3 x 15 detectors is 20 %