Probing the Nuclear Symmetry Energy and Neutron Skin Thickness in Collective Modes of Excitation

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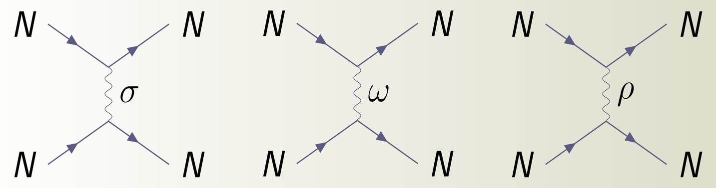
Collective excitations in neutron rich nuclei contain valuable information which help to investigate the isospin dependence of the nuclear equation of state [1]. By employing relativistic energy density functional (EDF) theory in describing both the nuclear matter properties and collective motion in finite nuclei, relevant observables related to isovector dipole excitations can be identified by means of statistical covariance analysis [2].

With increasing isospin, the isovector E1 excitation strength displays a fragmentation, giving rise to a low energy "pygmy" dipole strength (PDS), as opposed to the higher energy excitation of strong collective character, the giant dipole resonance (GDR).

Relativistic Energy Density Functional Theory

Dirac nucleons interacting via meson and photon exchange

Effective interaction - fitting of coupling constants



$g_{\sigma,\omega}(\frac{\rho}{\rho_{sat}})$, $g_\rho(\frac{\rho}{\rho_{sat}})$ coupling constants **density dependent** - DD-ME effective interaction [3]

Ground state → Relativistic Hartree-Bogoliubov model (RHB)

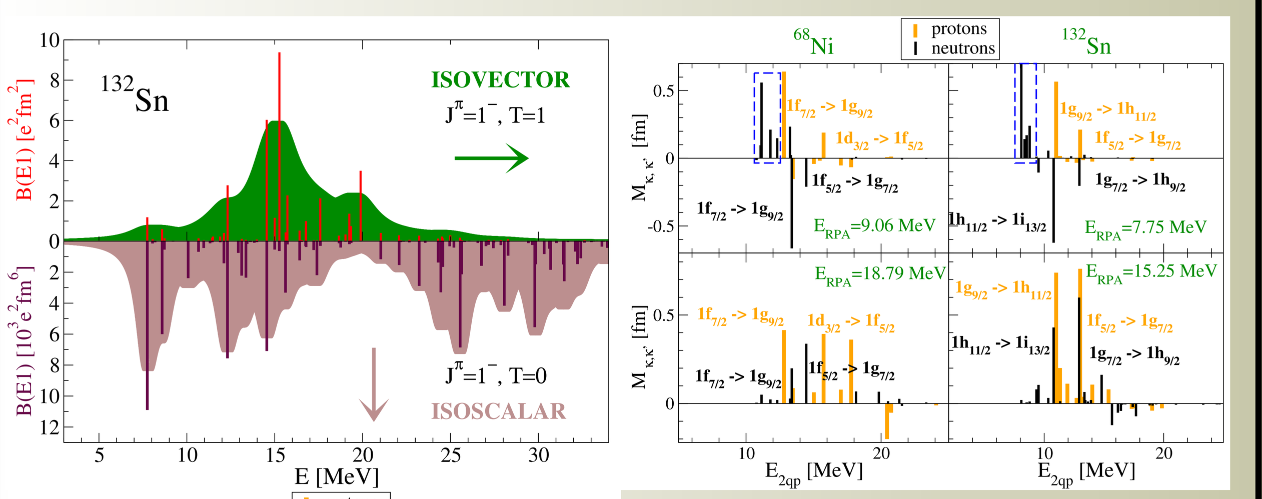
Small amplitude vibrations limit → Relativistic Quasiparticle RPA (RQRPA)

Pygmy Dipole Strength in neutron rich nuclei

Diagonalization of the RQRPA equation system yields discrete energy excitation spectrum as eigenvalues. Each RQRPA state is composed of various two-quasiparticle contributions, depending on the nature of the transition operator.

$$B^T(EJ; J_i \to J_f) = \frac{1}{2J_i+1}|\langle J_f||\hat{Q}_J^T||J_i\rangle|^2 = \left|\sum_{\kappa,\kappa'} M^{T,J,\nu}_{\kappa,\kappa'}\right|^2$$

$$E_{2qp}(\kappa,\kappa') = \sqrt{\Delta^2_{\kappa\kappa} + (E_{\kappa\kappa}-\lambda)^2} + \sqrt{\Delta^2_{\kappa'\kappa'} + (E_{\kappa'\kappa'}-\lambda)^2}$$



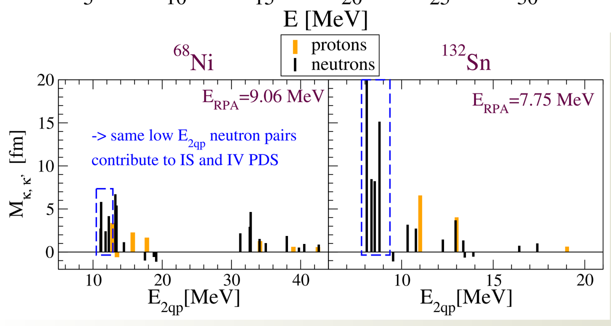


Fig 1 *Upper left* : Transition probabilities for discrete RQRPA isovector (T=1) and isoscalar (T=0) dipole excitations in ^{132}Sn, and response functions obtained by folding the distribution with a width of 2 MeV.

Two-quasiparticle ($2qp$) contributions in ^{68}Ni and ^{132}Sn to most pronounced PDS and GDR RQRPA states in the isovector (*upper right*) and the same PDS energy states in the isoscalar channel (*bottom left*). Proton and neutron pairs with similar E_{2qp} contribute coherently in the case of an IVGDR state and cancel out for the PDS state. Other neutron rich nuclei display the same behavior. Calculations done using the DD-ME2 parametrization with pairing part adopted from the Gogny interaction.

E1 isovector strength related observables, neutron skin and the symmetry energy

Energy per nucleon of asymmetric nuclear matter:

$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + S_4(\rho)\alpha^4 + \cdots \quad \alpha = \frac{N-Z}{N+Z}$$

$$S_2(\rho) = J + L\cdot\frac{\rho-\rho_{sat}}{3\rho_{sat}} + \cdots \quad S_2(\rho) = \frac{1}{2}\left(\frac{\partial^2 E(\rho,\alpha)}{\partial\alpha^2}\right)_{\alpha=0}$$

Characteristics of the isovector interaction channel

$J = S_2(\rho_{sat})$ symmetry energy at saturation density

$L = 3\rho_{sat}\frac{\partial S_2(\rho)}{\partial\rho}$ slope of the symmetry energy

Constraining J and L: → identifying observables correlated with and sensitive to them

$\Delta R_{np} = \sqrt{\langle r_n^2\rangle} - \sqrt{\langle r_p^2\rangle}$ neutron skin thickness → strong linear correlation with J [4], but difficult to measure in a model independent way

Observables related to E1 isovector excitations → GDR peak energy, strength distribution and moments $m_k(T,J) = \sum_\nu \omega_\nu^k B^T(J,\omega_\nu)$

Family of DD-ME interactions spanning J=30, 32, 34, 36, 38 [5]

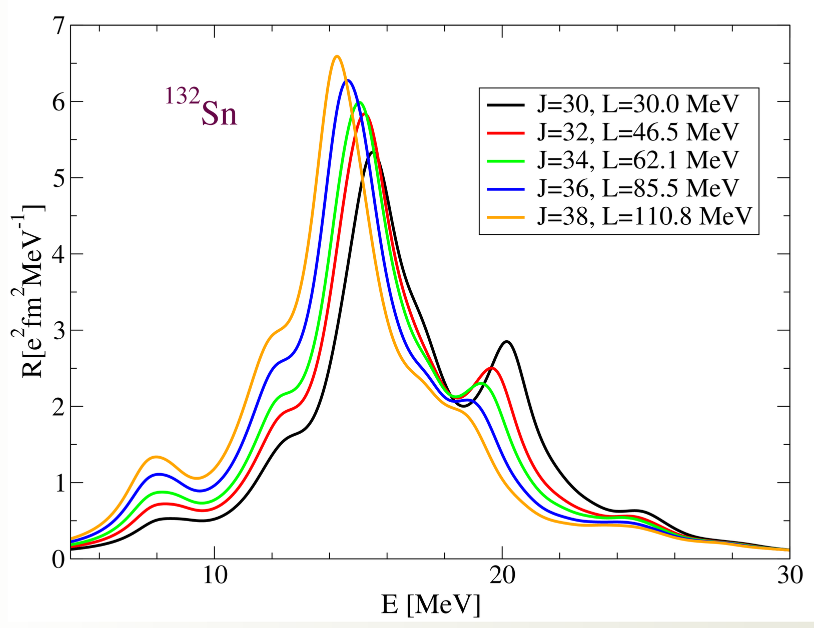


Fig 2 *Left* : Isovector dipole transition strength for ^{132}Sn for the set of DD-ME interactions with different values of J. IVGDR peak energy decreases with increasing J, while the PDS energy remains unaffected. Greater symmetry energy at saturation results in it's lower value at IVGDR densities.

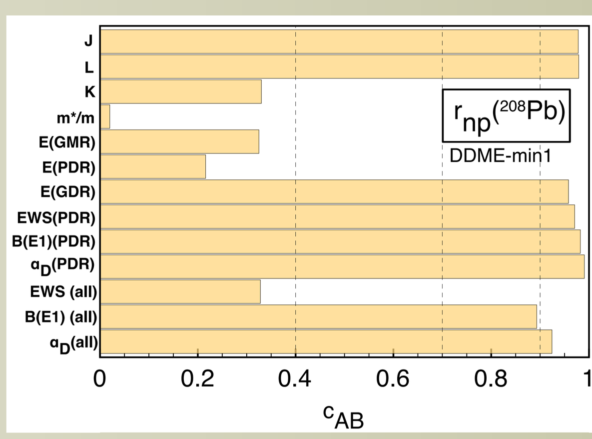


Fig 3 *Right* : Correlation between neutron skin thickness in ^{208}Pb and nuclear matter properties, energies of various excitation modes and excitation strength related observables for overall energy range and constrained to the pygmy region.

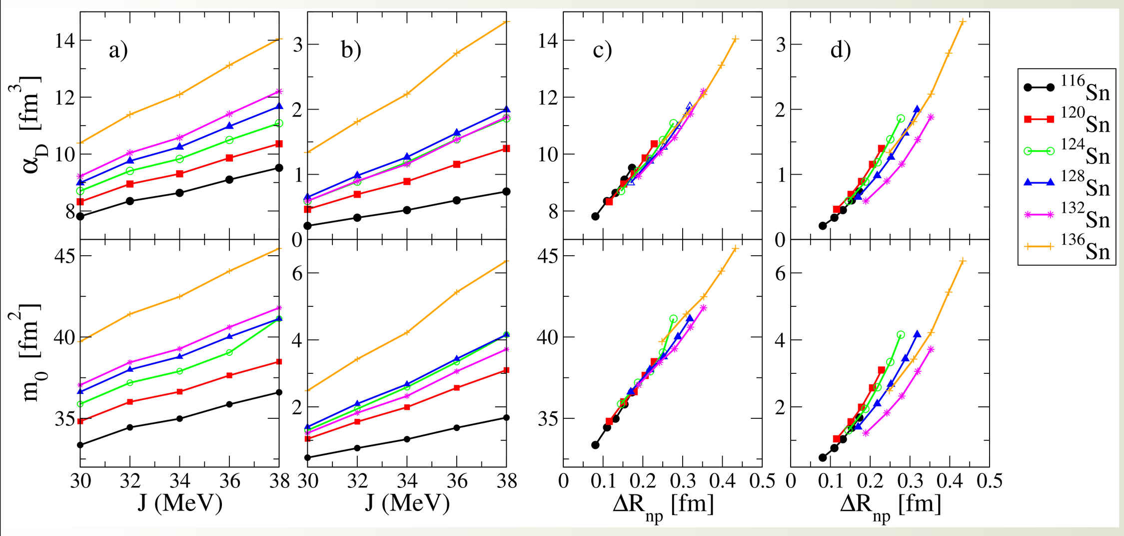


Fig 4 $B(E1)$ transition strength (m_0) and dipole polarizability ($\alpha_D = \frac{8\pi}{9}e^2 m_{-1}$) in relation to J and the corresponding value of R_{np} for the tin isotope chain including overall spectra (a, c) and only PDS transitions(b, d). Isotopes with greater neutron excess show a stronger sensitivity to varying J, which increases if constrained to the pygmy energy region.

When using R_{np} as a variable, a certain degree of shell effects comes into play (see Fig 7), with an effect similar as noticed in [6] for PDS contribution to the total EWSR.

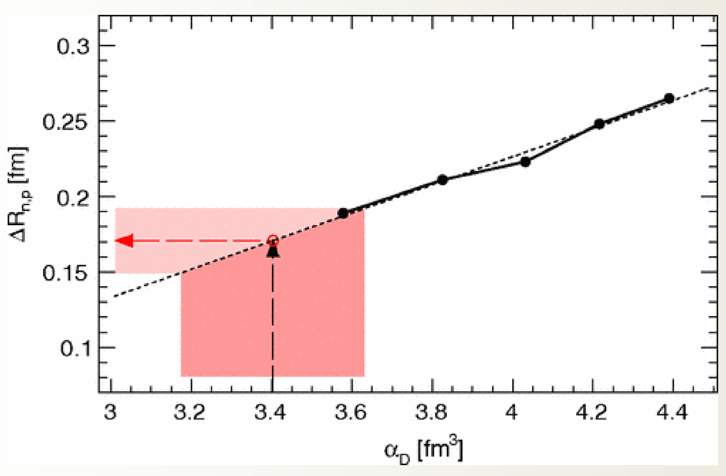


Fig 5 Constraining the neutron skin thickness of ^{68}Ni using experimental data for α_D obtained by means of relativistic Coulomb scattering, with calculations based on FSUGold EDF's [6]. Figure taken from [7].

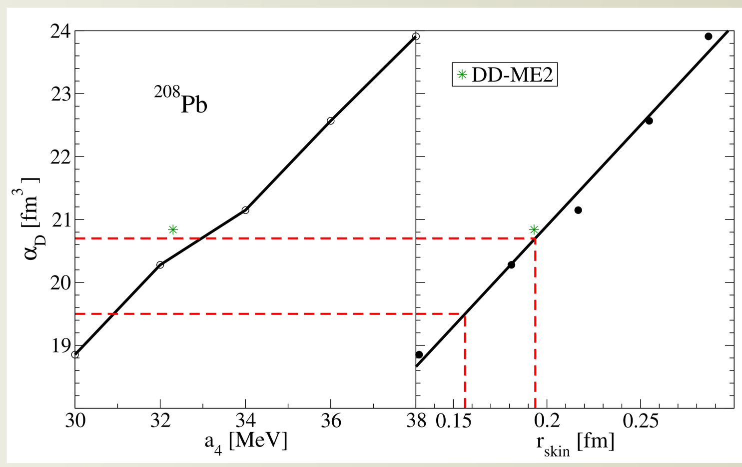


Fig 6 Constraining R_{np} of ^{208}Pb using the value of α_D obtained with high resolution (p,p') scattering measurements [8] together with DD-ME EDF's, yielding the value $R_{np}(^{208}Pb) = 0.18 \pm 0.02$.

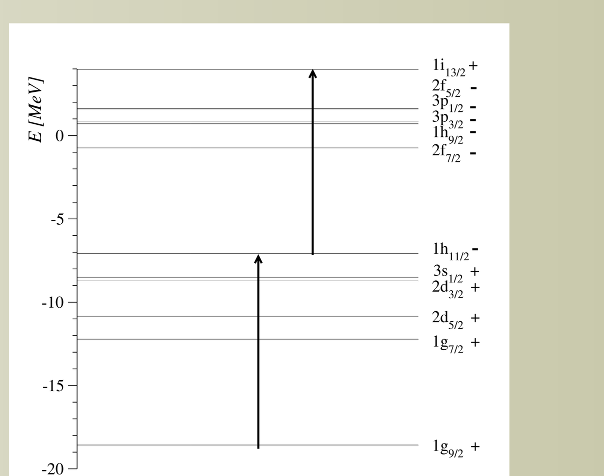


Fig 7 Neutron level structure of ^{126}Sn. Neutrons in shell $1h_{11/2}$ contribute heavily to neutron skin, while transitions to and from that shell lie high in E_{2qp} because of parity selection rules, thus not contributing to PDS.

Systematic Study of the Dipole Response for the Tin Isotope Chain - S412 Experiment at GSI

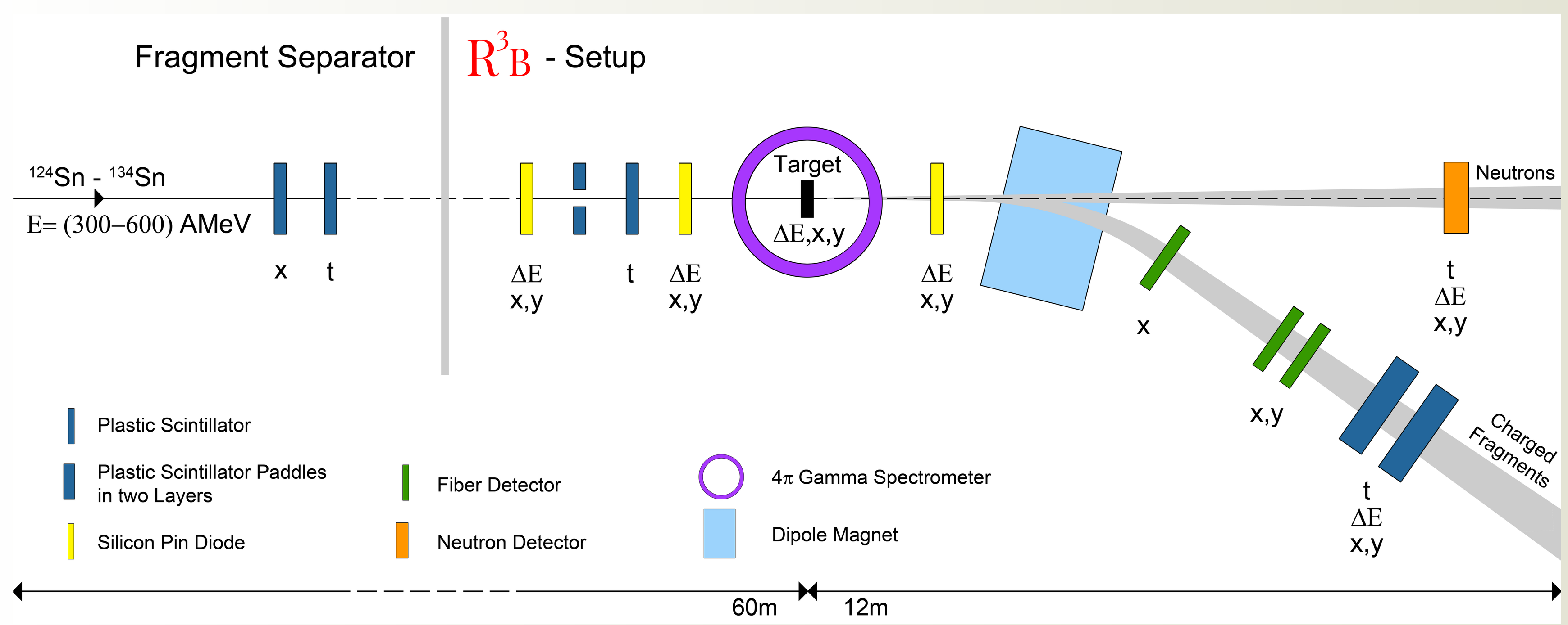


Fig 8 Setup for the S412 experiment. Excitation energy is obtained from a kinematically complete measurement of all outgoing particles (invariant mass method).

$$E^* = \left|\sum_i \hat{P}_i\right| - m_{proj}c^2$$

The cross section for Coulomb induced nuclear breakup reactions is expressed in terms of the real photon absorption strength distribution via virtual photon method (for E1 excitations):

$$\frac{d\sigma(E)}{dE} = \frac{16\pi^3}{9\hbar c} n_{E1}(E)\frac{dB}{dE}(E1, 0\to J, E)$$

where $n_{E1}(E)$ is the number of virtual phonons of given energy.

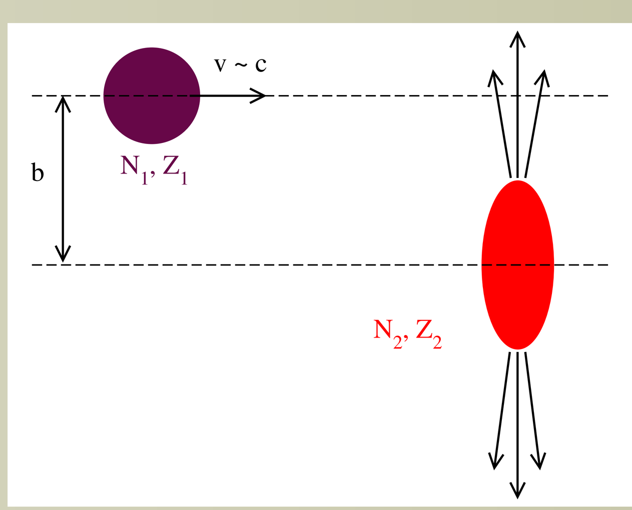


Fig 9 Relativistic Coulomb scattering. This method excites predominantly E1 modes.

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