Dipole Excitations

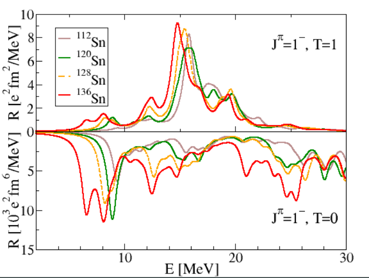
A. Horvat[1]

NAVI Physics Days

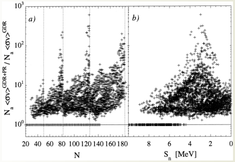
GSI, Feb 27, 2015

[1]Institut für Kernphysik, TU Darmstadt, Germany (for the R3B-LAND collaboration)

Dipole excitations in the context of astrophysics



r-process nucleosynthesis



S. Goriely, PLB 436 (1998) 10-18

→ photo - deexcitation calculation requires knowledge of B(E1)
→ strongly depends on the low-energy tail of GDR
→ a low-lying resonant component would increase the rates by factors 10 -100 for some nuclei

Nuclear matter properties and the equation of state

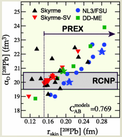
Energy per nucleon of asymmetric nuclear matter

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

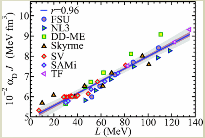
$$S_2(\rho) = J + L \cdot \frac{\rho - \rho_{sat}}{3\rho_{sat}} + \cdots$$

Dipole polarizability

$$\alpha_D = \frac{8\pi}{9} e^2 \sum_\nu \omega_\nu^{-1} B(E1,\omega_\nu) = \frac{\hbar c}{2\pi^2 e^2} \int \frac{\sigma_\gamma}{\omega^2} d\omega$$



J. Piekarewicz et al., Phys. Rev. C 85 041302(R) (2012)



X. Roca-Maza et al., Phys. Rev. C, 88 024316 (2013)

Theoretical investigation of the dipole response of nuclei

→ ab-initio approach (relatively light nuclei)
→ sophisticated shell model techniques (medium mass nuclei, astrophysical applications)
→ self-consistent mean field models (medium heavy to heavy nuclei with many active nucleons)

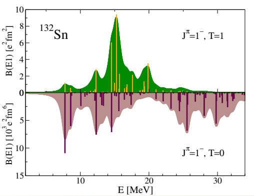
Relativistic quasiparticle random phase approximation built upon a relativistic Hartree-Bogoliubov ground state (RHB+RQRPA)

→ response to an externally applied field (small amplitude limit)

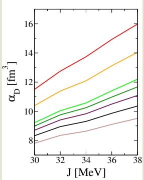
$\hat{F}(t) = \hat{F}e^{-i\omega t} + h.c.$

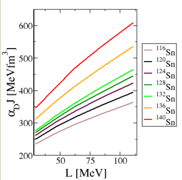
→ discrete RPA energies, corresponding transition probabilities

$B(EJ; J_i \rightarrow J_f) = \frac{1}{2J_i+1}|\langle J_f||\hat{Q}_J||J_i\rangle|^2$



DD-ME2 parametrization → G. A. Lalazissis, T. Nikšić, D. Vretenar, P. Ring, *Phys. Rev. C* ***71*** *024312* (2005)





→ Parameters of the effective interaction can be varied to reproduce values of J and L spanning a selected range
(parametrization from D. Vretenar, T. Nikšić, P. Ring, *Phys. Rev. C* ***68***, *024310* (2003))

→ Heavier tin isotopes exhibit a stronger sensitivity to varying L

Experimental investigation of the dipole response of nuclei

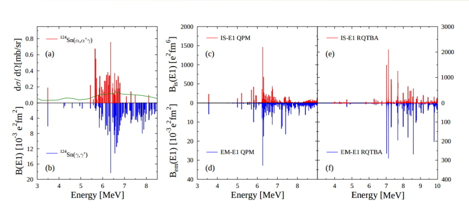
Stable nuclei

→ real photon scattering (NRF,experiments using bremsstrahlung, laser Compton back-scattering, tagged photons) (isovector probe)

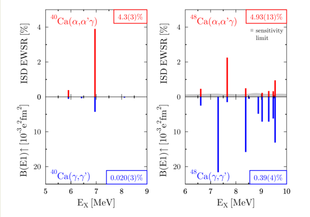
→ hadronic probes → inelastic proton scattering (isovector probe)
→ inelastic α, ion scattering (O^{17}) (isoscalar probe)

Stable nuclei - pygmy region

→ ^{124}Sn, ^{138}Ba and ^{140}Ce → complex isospin structure of the low-lying states → splitting in two groups, one sensitive to the isovector probe only and other to both probes
→ ^{48}Ca → states with isovector, isoscalar and mixed character, no splitting in energy



J. Endres *et al.*, *Phys. Rev. Lett.* **105**, 212503 (2010)

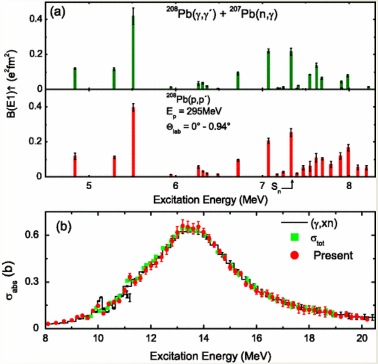


V. Derya *et al.*, *Phys. Lett. B* **730**, 288 (2014)

Experimental investigation of the dipole response of nuclei

Stable nuclei - entire spectra and dipole polarizability

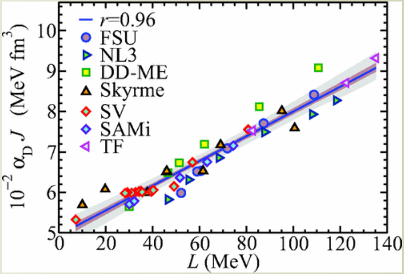
Electromagnetic excitation by a 295 MeV polarized proton beam at RCNP, Osaka
→ data in good agreement with previous photo-absorption and photo-neutron cross-section measurements



A. Tamii *et al.*, *Phys. Rev. Lett.* **107**, 062502 (2011)

→ the J - L relationship extracted

$$L = -146 \pm (1)_{theor} + (6.11 \pm (0.18)_{expt} \pm (0.26)_{theor})J$$



X. Roca-Maza *et al.*, *Phys. Rev. C*, **88** 024316 (2013)

Experimental investigation of the dipole response of nuclei

Radioactive nuclei - inverse kinematics with radioactive beams

Towards systematic investigation of the evolution of dipole strength with increasing isospin asymmetry

experiments performed on neutron rich tin isotopes with complementary probes

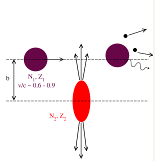
---

→ $(\alpha, \alpha'\gamma)$, inverse kinematics @RIBF, Oct 2014

- scattering of a 200 MeV/u ^{128,132}Sn beam off a liquid helium target
- gamma detection by DALI2 array and 8 large volume $LaBr_3$(Ce) detectors in forward direction
- scattered heavy ions detected by the zero degree spectrometer

---

→ Coulomb excitation (heavy ion induced electromagnetic excitation) of $^{124-134}$Sn at the R3B-LAND setup @GSI

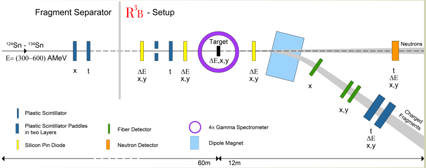


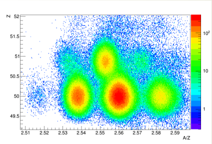
→ for $b > R$ virtual photon scattering takes place → B(E1) extraction, therefore α_D

→ for $b < R$ the nuclear interaction takes place → possibility of extracting the neutron skin thickness from total reaction and charge changing cross section

Experimental investigation of the dipole response of nuclei

E1 response of $^{124-134}$Sn @R3B





Invariant mass method

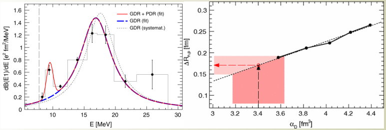
$$E^* = \left|\sum_i \hat{P}_i\right| - m_{proj} c^2$$

→ Excitation energy from a kinematically complete determination of all reaction products

→ Cross section for Coulomb induced nuclear breakup reactions

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

E1 response of ^{68}Ni @R3B

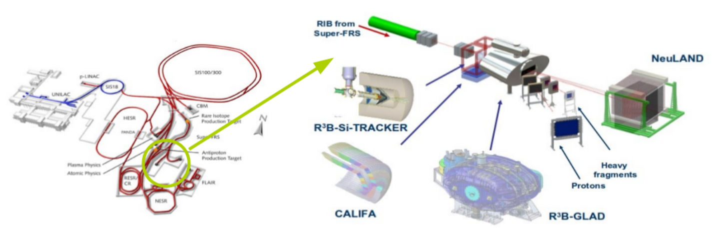


D.M. Rossi et al., Phys. Rev. Lett. 111, 242503 (2013)

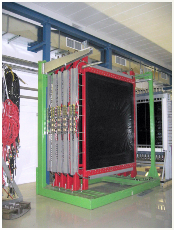
→ Integrated from the neutron emission threshold

→ If extrapolated above and below integration limit, compared to ^{208}Pb result and RHB+QRPA calculations with DD-ME

R3B@FAIR, neutron detection



FAIR → isotopes up to ^{140}Sn and unstable Pb isotopes available
→ Low neutron emission thresholds → multi-neutron decays
→ Need to resolve 4 neutron hits in coincidence, improved neutron detection

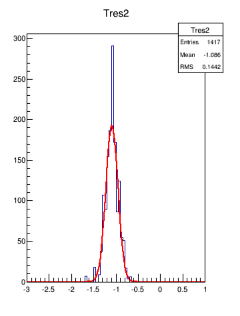


LAND
→ Plastic scintillator + iron converter
→ 200 modules 200x10x10 cm
→ $\sigma_t = 250ps$, $\sigma_{x,y,z} = 3cm$
→ limited multi-neutron hit reconstruction capacity

NeuLAND
→ Purely scintillator material
→ 3000 modules 250x5x5 cm arranged in double planes, vertical + horizontal orientation
→ $\sigma_t < 150ps$, $\sigma_{x,y,z} < 1.5cm$
→ Will be able to resolve 4n hits with 60% accuracy

R3B@FAIR, neutron detection

→ 4 double planes completed, tested in Oct 2014
→ ^{48}Ca beam @ 550 MeV/u on carbon target



→ Timing resolution for crossed bars in one double plane

$$\sigma_{75-25} = 133ps \rightarrow \sigma_t = 94ps$$

→ Transported to RIBF in Jan 2015

→ Appended to NEBULA neutron detector of the SAMURAI setup

→ Awaiting physics experiments in the next appointed SAMURAI beam time

Summary

→ Dipole excitation spectra contain valuable information on nuclear structure properties related to isospin asymmetry

→ Many open questions to be addressed by the next generation experimental programs on dipole excitations (at R3B, S-DALINAC, RIBF, RCNP, ...)

- Systematics of the dipole strength evolution with increasing isospin asymmetry
- Isospin character of the low-lying dipole mode
- Investigating the E1 response both below and above particle emission threshold
- Providing more stringent constraints on the density dependence of the symmetry energy

Thank you for your attention