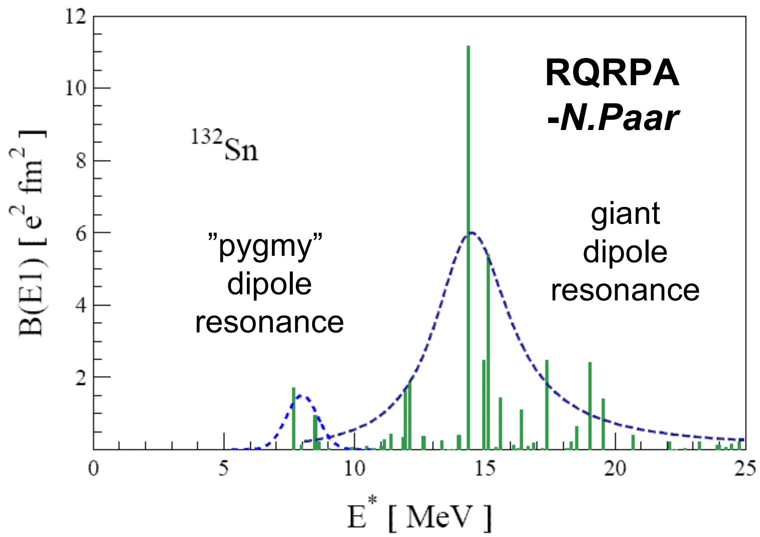
Systematic investigation of the dipole response in exotic neutron-rich nuclei in ^{132}Sn mass region

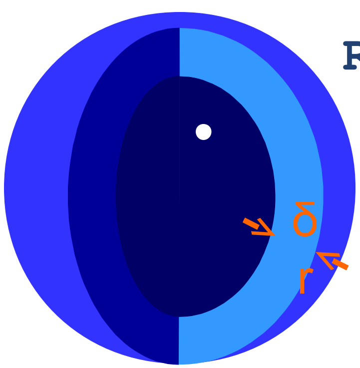
- Motivation
  - new collective mode in exotic nuclei
  - pygmy dipole resonance
  - link to equation of state and symmetry energy
  - access to neutron skin thickness
- Experiment at LAND@GSI
  - radioactive nuclear beams
  - relativistic Coulomb excitation
  - detection setup
- Results
  - dipole strength in neutron-rich $^{129\text{-}132}$Sn and ^{133,134}Sb
  - symmetry energy parameters
  - neutron skin thickness in ^{130,132}Sn

Dipole response in exotic neutron-rich nuclei and the pygmy dipole resonance

unique structure phenomena
- weak binding of outermost neutrons
- regions with diffuse neutron densities (halo structures, neutron skins)
- changes in the mean field potential

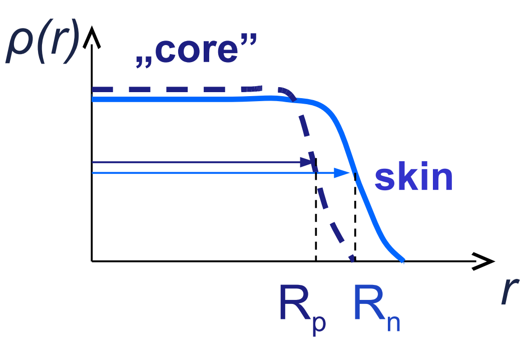


dipole strength in neutron-rich nuclei:
- strong fragmentation of giant resonance
- low-lying components
- new collective mode - "**pygmy**" dipole resonance (PDR)



^{132}Sn, ^{208}Pb

$$R_n - R_p = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$$



<u>pygmy resonance</u>
- excited in nuclei with neutron skin
- interpreted as an oscillation of neutron skin against inert nuclear core
- described microscopically as a coherent superposition of many 1p -1h excitations
- located around neutron separation threshold
- exhausts a few percent of TRK sum rule
- poor experimental evidence

Taylor expansion of energy per nucleon in nuclear matter

$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + \cdots \qquad \alpha \equiv \frac{N-Z}{A}$$

$$E(\rho,0) = -a_V + \frac{K_0}{18\rho_0^2}(\rho-\rho_0)^2$$

isospin symmetric matter

symmetry energy

$$S_2(\rho) = a_4 + \frac{p_o}{\rho_0^2}(\rho-\rho_0) + \frac{\Delta K_0}{18\rho_0^2}(\rho-\rho_0)^2 + \cdots,$$

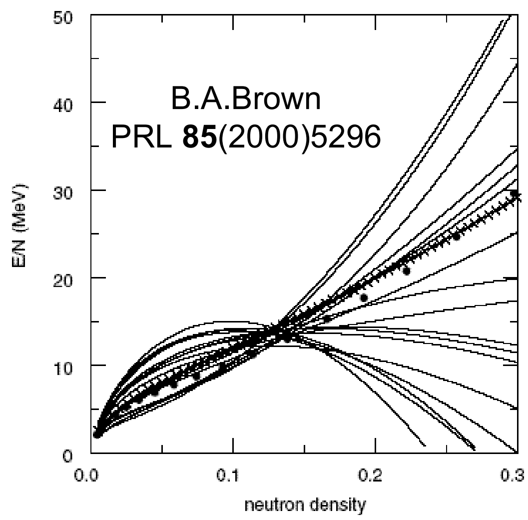
Symmetry energy parameters

a_4 symmetry energy per nucleon in pure neutron matter

p_o symmetry energy pressure (slope parameter)

ΔK_o correction term for incompressibility

$$a_4 = S(\rho_o) \qquad p_o = \rho_o^2 \frac{dS(\rho)}{d\rho} \qquad \Delta K_o = 9\rho_o^2 \frac{d^2S(\rho)}{d\rho^2}$$



Symmetry energy $S_2(\rho)$ and neutron skin thickness in ^{208}Pb

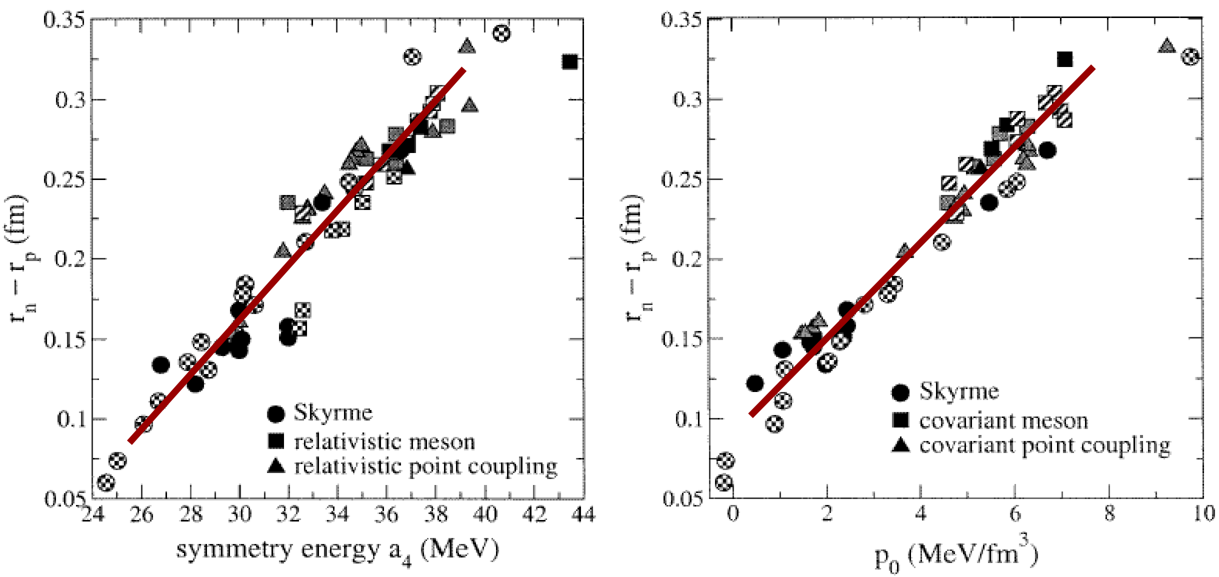
R.J.Furnstahl NPA 706(2002)85

- strong <u>linear</u> correlation between neutron skin thickness and parameters **a_4, p_o**
- no distinct correlation with other quantities

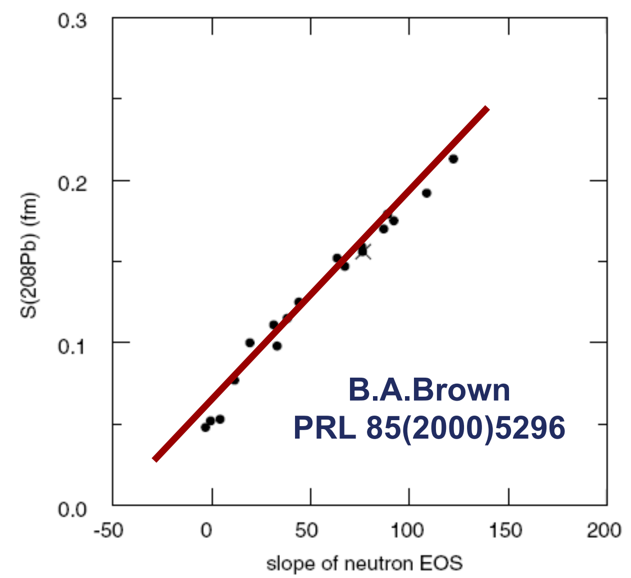
→ **measurement of the neutron skin thickness, even for a single heavy nucleus, delivers constraint on the symmetry energy**

$$S_2(\rho) = a_4 + \frac{p_o}{\rho_o^2}(\rho - \rho_o) + \ldots$$

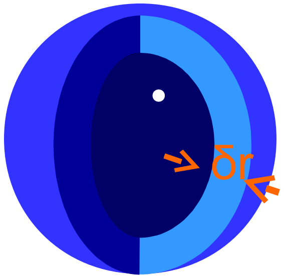
$$a_4 = S(\rho_o) \qquad p_o = \rho_o^2 \frac{dS(\rho)}{d\rho}$$



R.J.Furnstahl NPA 706(2002)85



Experimental methods to measure neutron skin thickness

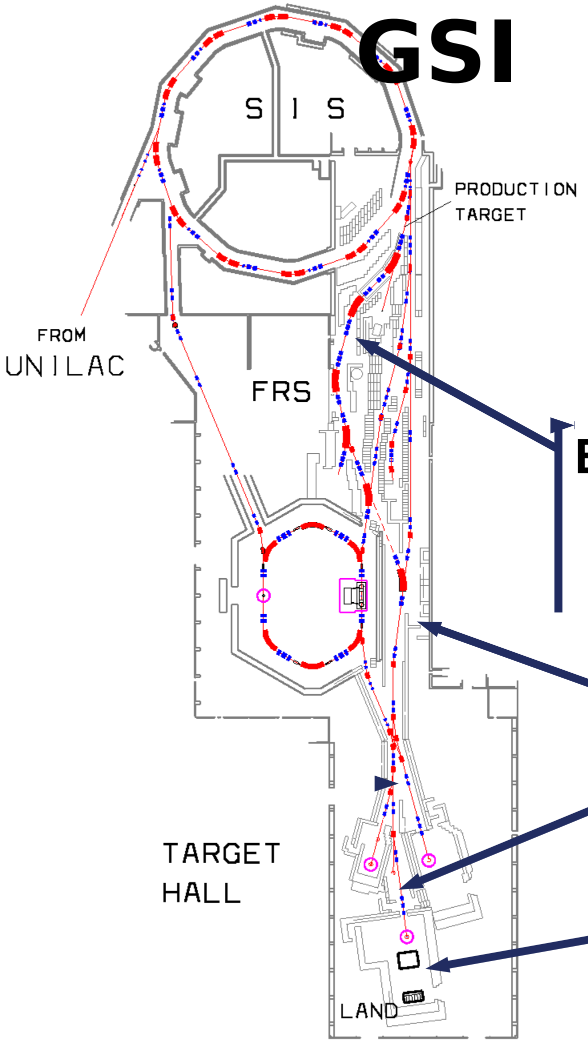


- **limited to stable nuclei that can form a target ($^{112-124}$Sn, ^{208}Pb etc)**
- **strongly model-dependent**

- proton elastic scattering **B.C.Clark et al. PRC 67(2003)054605**
- excitation of giant dipole resonance with isoscalar probes (inelastic α scattering) **A.Krasznahorkay et al. NPA 567(1994)521**
  - → δR extracted from cross section
  - → required theoretical input : DWBA with optical-model parameters
- excitation of spin dipole resonance in charge exchange reactions, e.g. (^{3}He,t) **A.Krasznahorkay et al. PRL 82(1999)3216**
  - → δR extracted from total strengths
  - → model dependence in energy-weighted sum rule
- antyproton atoms **A.Trzcińska et al. PRL 87(2001)082501**
  - → δR from antiproton annihilation in nuclear surface area and antiproton atom level shifts
- parity violating electron scattering (in future) **C.Horowitz et al. PRC 63(2001)025501**
  - → the least model-dependent approach
- **pygmy dipole resonance J.Piekarewicz PRC 73(2006)044325**

Experiment - beam production and isotope identification

Primary beam : 10^8 ^{238}U ions / sec @ 550 MeV/u
Secondary beam : ~10 ions / sec of ^{132}Sn in Cave B

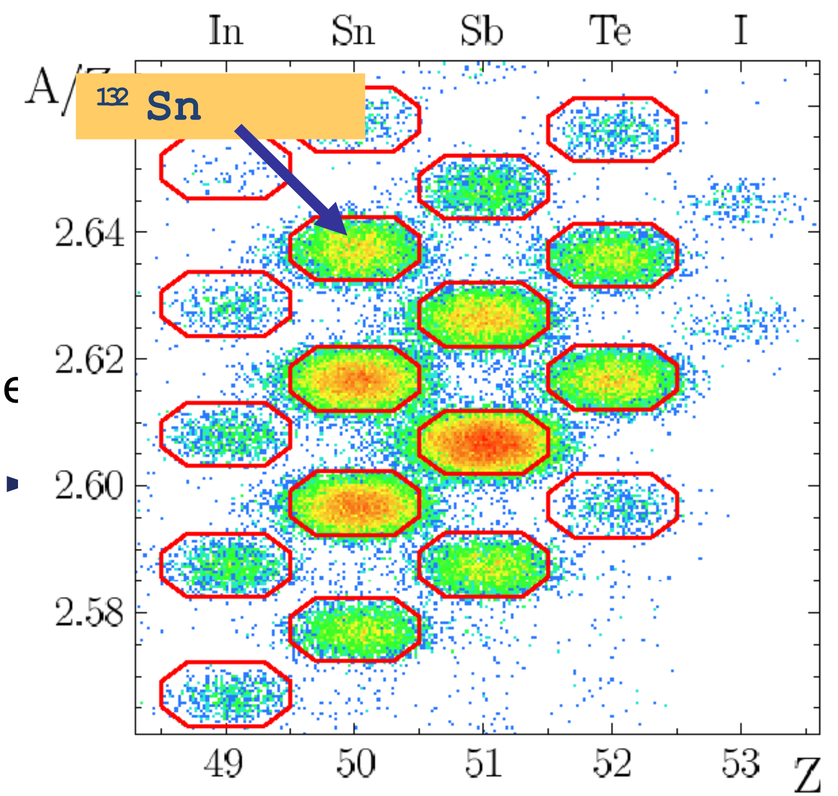


$$\frac{A}{Z} = \frac{m_u c}{e} \frac{B\rho}{\beta\gamma}$$

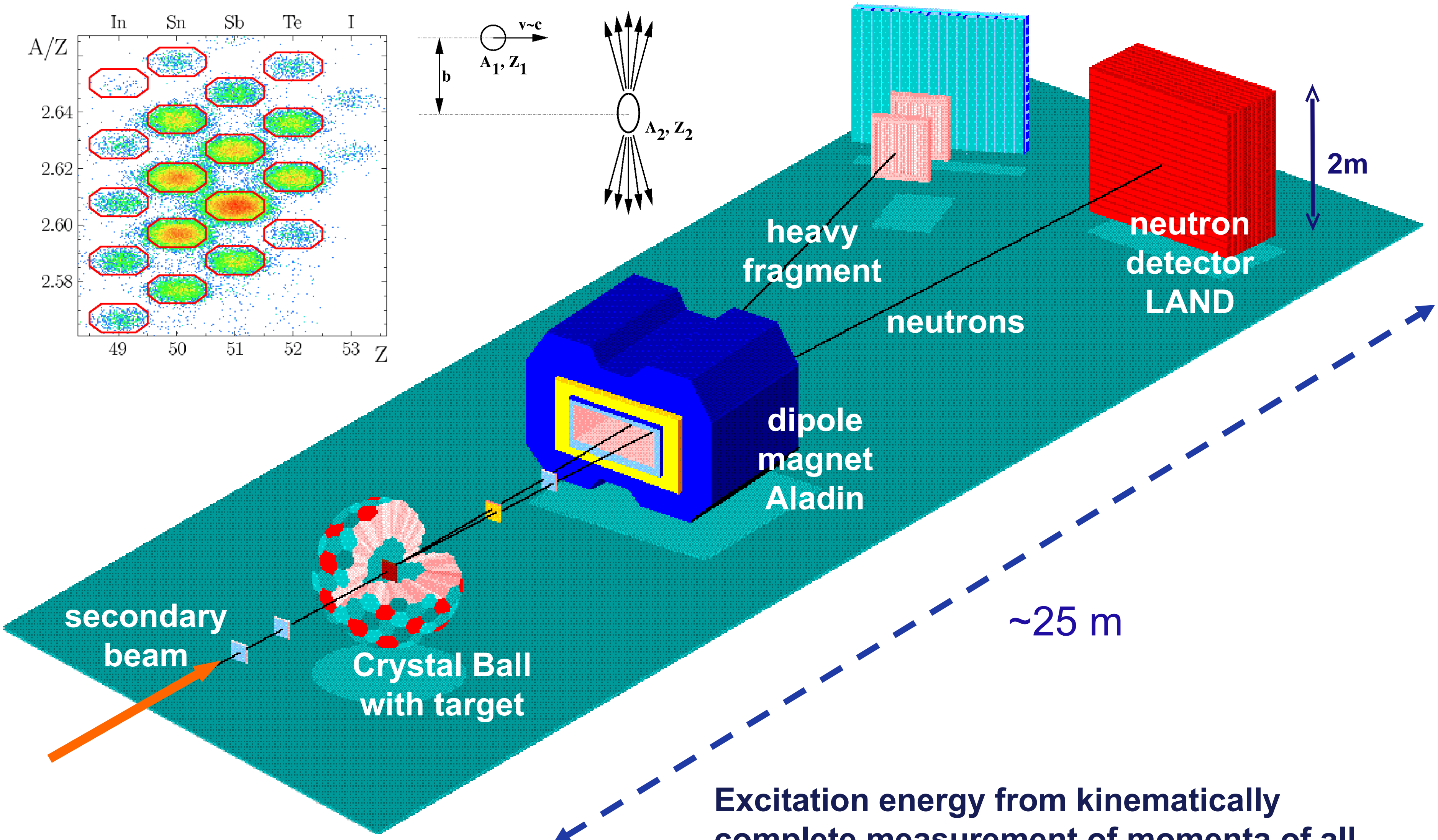
Bρ – from position at middle focal plane of the FRS

β – from time-of-flight

Z – from ΔE

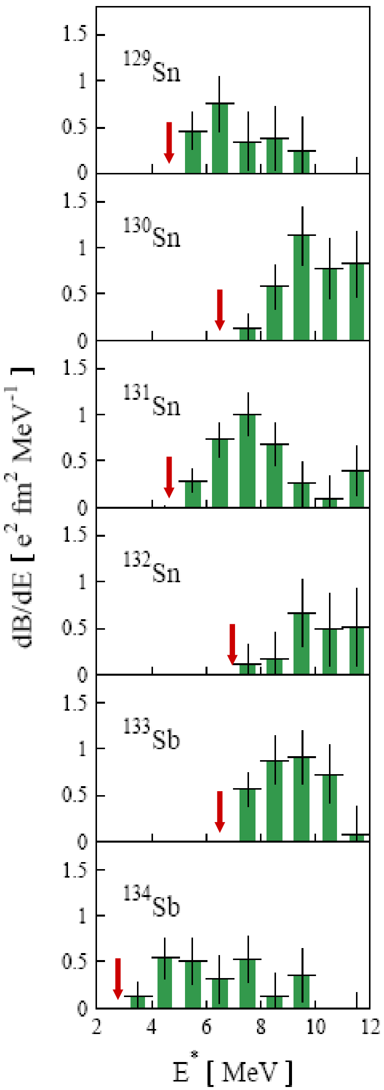


Experimental approach – LAND reaction setup at GSI



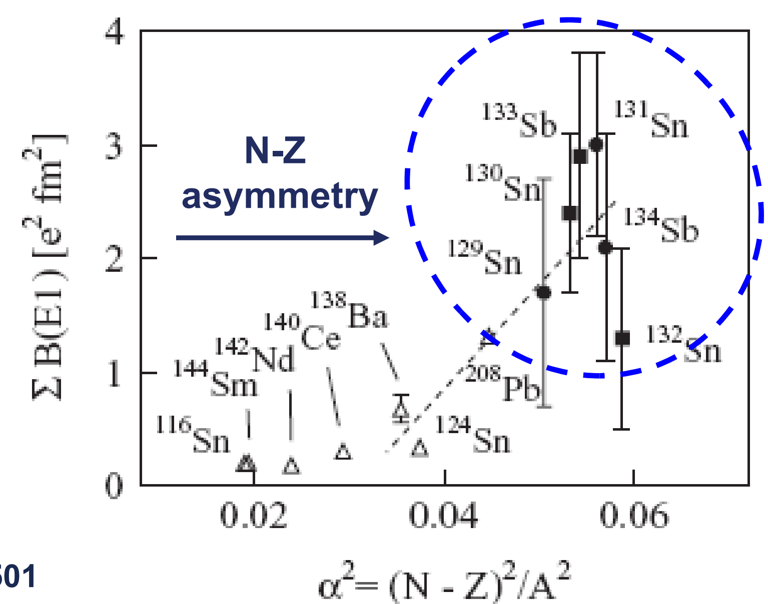
Excitation energy from kinematically complete measurement of momenta of all outgoing particles (invariant mass method)

Results: low-lying dipole strength in unstable neutron-rich nuclei from ^{132}Sn mass region



- obtained by subtracting giant dipole resonance and instrumental effects from measured cross section
- observed in all isotopes
- exhausts a few percent of the energy weighted sum rule
- difference between even and odd isotopes is a consequence of neutron separation threshold location and unpaired neutrons

	S_n [MeV]	$\int^9$B(E1) [e^2 fm^2]	$\int^{11}$B(E1) [e^2 fm^2]	$\int^{11}$E B(E1) [% of S_{TRK}]
^{129}Sn	5.4	1.8 (6;4)	1.7 (8;7)	2.4 (1.4;1.1)
^{130}Sn	7.7	–	2.4 (5;5)	5.0 (1.1;1.0)
^{131}Sn	5.2	2.6 (4;5)	3.0 (5;6)	4.9 (1.0;1.1)
^{132}Sn	7.3	–	1.3 (6;6)	2.7 (1.3;1.1)
^{133}Sb	7.3	–	2.9 (5;8)	5.8 (1.1;1.4)
^{134}Sb	3.3	2.1 (6;6)	2.1 (7;7)	2.5 (1.1;0.9)



total dipole strength rises with increasing N-Z asymmetry and confirms relation between PDR and equation of state

measurements with real photons
N=82: PLB 542(2002) 43
^{208}Pb: PRL 89(2002) 272502
^{116,124}Sn: PRC 57(1998) 2229

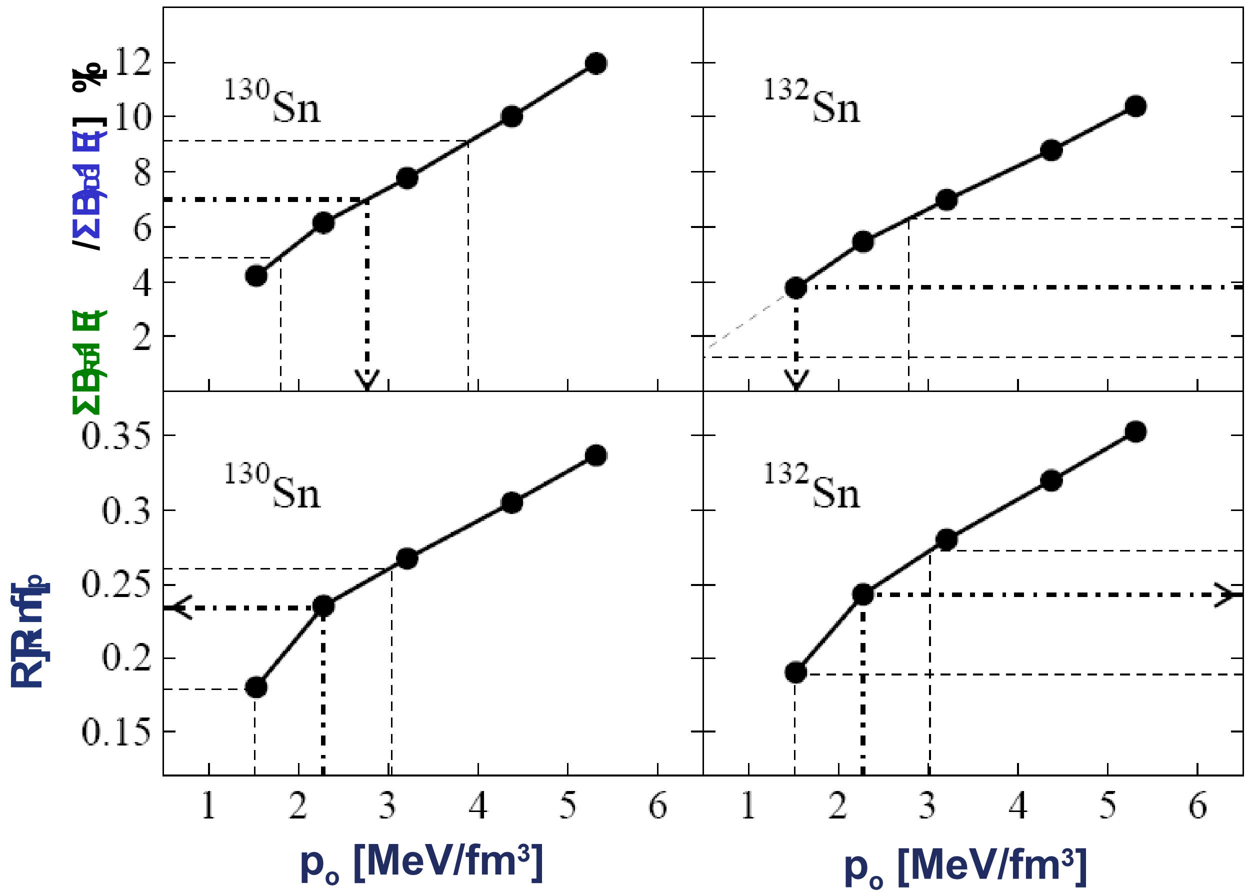
P.Adrich et al. PRL 95(2005)132501
A.Klimkiewicz, N.Paar et al. PRC 76(2007)051603R

Asymmetry parameters and neutron skin thicknesses extracted from the experimental dipole response

$\langle a_4 \rangle = 32.0 \pm 1.8$ MeV

$\langle p_o \rangle = 2.3 \pm 0.8$ MeV/fm^3

RQRPA calculations from N. Paar

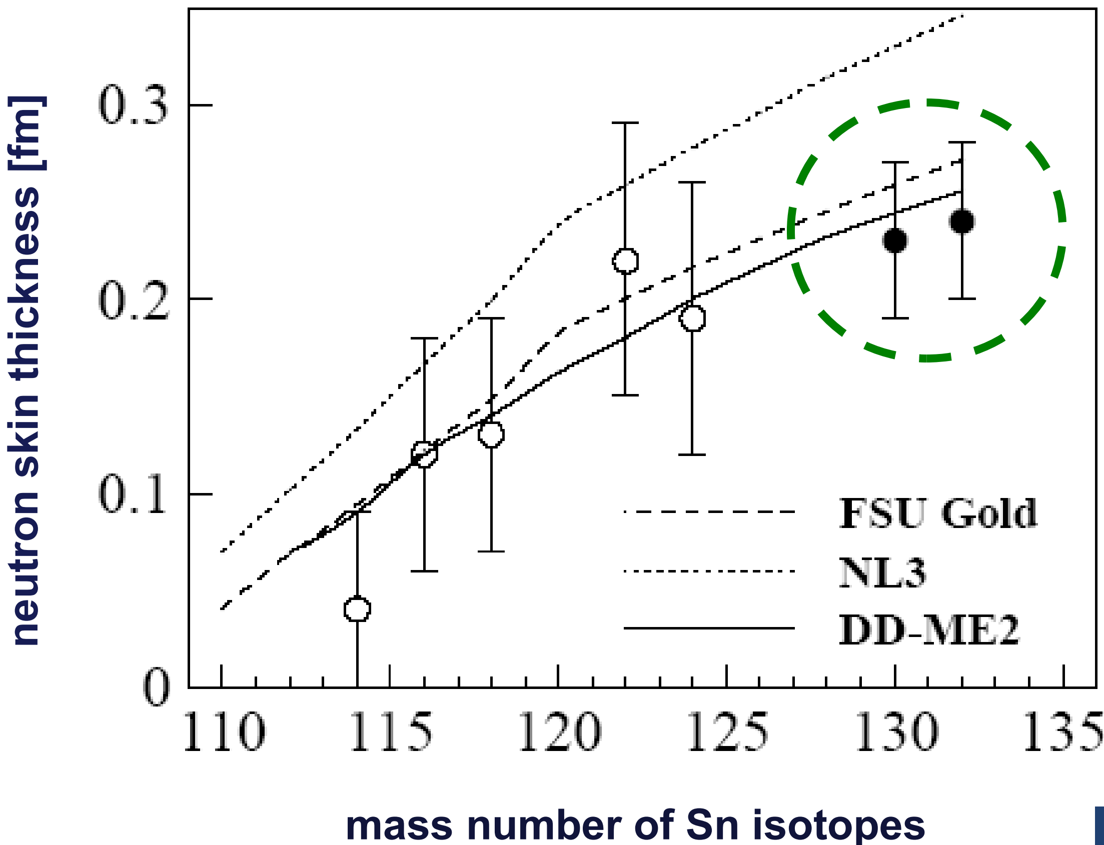


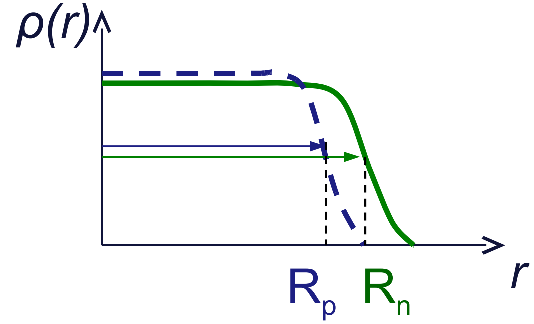
^{130}Sn : $R_n - R_p = 0.23 \pm 0.04$ fm

^{132}Sn : $R_n - R_p = 0.24 \pm 0.04$ fm

A.Klimkiewicz, N.Paar et al.
PRC 76(2007)051603R

Neutron skin thickness in Sn isotopes





$$R_n - R_p = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$$

- neutron skin thickness increases with neutron excess
- method accuracy comparable with amibtious programme of parity violating electron scattering

^{130}Sn : $R_n - R_p = 0.23 \pm 0.04$ fm

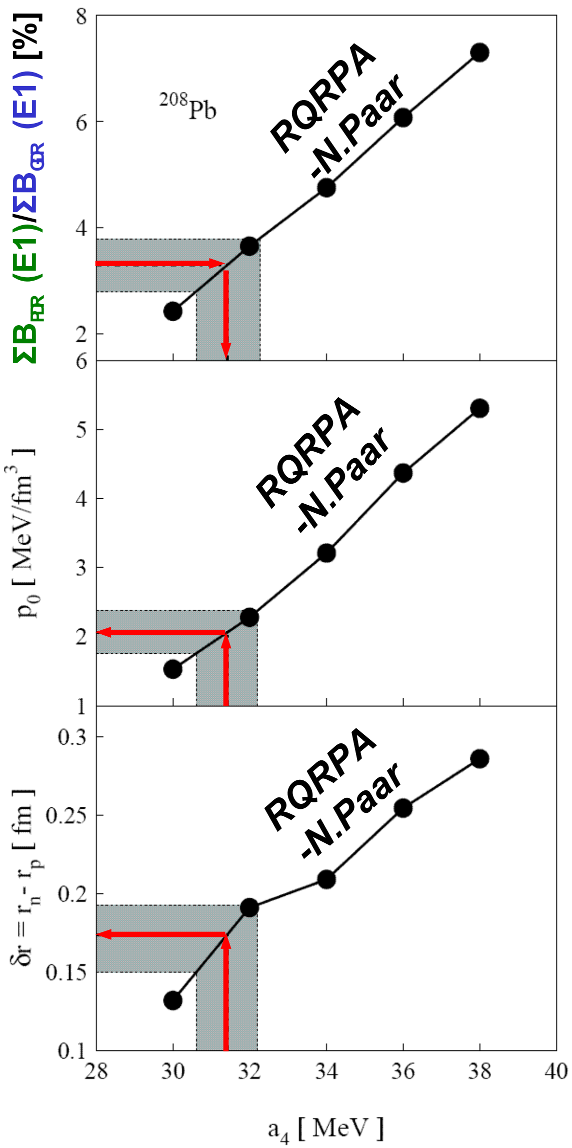
^{132}Sn : $R_n - R_p = 0.24 \pm 0.04$ fm

stable isotopes: SDR Method A.Krasznahorkay et al, PRL 82(1999)3216

calculations: DD-ME2 N.Paar et al, PLB 605(2005)288

FSU, NL3 NL3 J.Piekarewicz, PRC 73(2006)044325

^{208}Pb analysis – approach verification



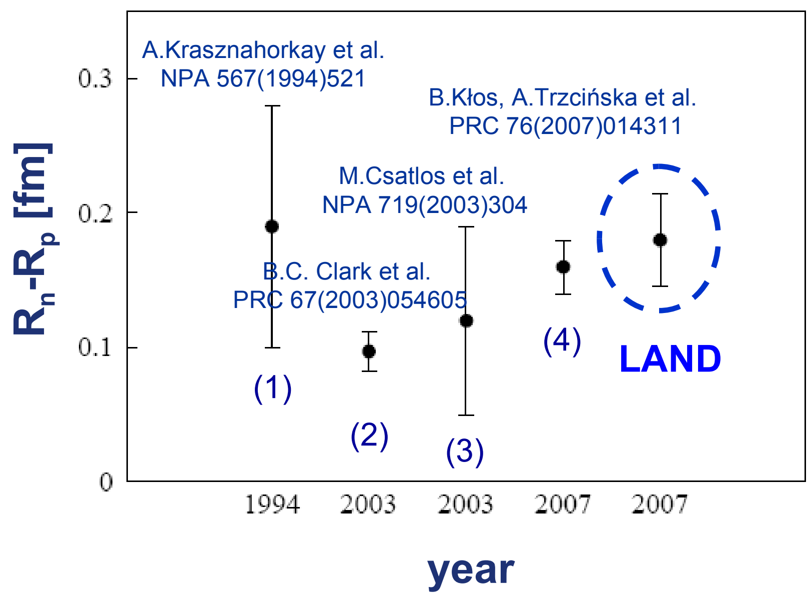
ΣB_{pdr} (E1)=1.98 e^2 fm^2

N.Ryezayeva et al. PRL 89(2002)272501

ΣB_{gdr} (E1)=60.8 e^2 fm^2

A.Veyssiere et al. NPA 159(1970)561

$$a_4 = 31.4 \pm 0.8 \ \text{MeV}$$
$$p_o = 2.1 \pm 0.3 \ \text{MeV/fm}^3$$
$$\delta r = 0.18 \pm 0.035 \ \text{fm}$$



(1,3) GDR excited in (α,α’)
(2) (p,p) elastic scattering
(4) antiprotonic atoms

Theoretical predictions:

- **δr = 0.16 ± 0.02 fm** - from Friedman-Pandharipande EoS and SkX (Skyrme) parametrization – **B.A.Brown PRL85 (2000) 5296**
- **δr = 0.17 fm** – from nucleon elastic scattering analysis – **Karataglidis et al. PRC65 (2002)044306**

Summary and outlook

Summary

- low lying E1 strength observed in all isotopes studied
- theoretical link between pygmy strength, neutron skin thickness and symmetry energy confirmed
- neutron skin thickness in ^{130,132}Sn follows a trend in stable Sn isotopes
- approach verified in Pb analysis
- promising method (access to exotic nuclei, isotope systematics possible)

Perspectives

- experimental: establish the phenomenon of pygmy dipole resonance!
- theoretical: prove the „pygmy-neutron skin” relation using various microscopical approaches!

LAND-FRS collaboration

T. Aumann, K. Boretzky, H. Emling, M. Fallot, H. Geissel, M.Hellström, K. L. Jones, Y. Leifels, U. Datta Pramanik, K. Sümmerer
GSI Darmstadt

H. Simon
Technical University Darmstadt

Th. W. Elze, R. Palit
University Frankfurt/M

P. Adrich, A. Klimkiewicz, R. Kulessa, G. Surówka, W. Waluś
Jagiellonian University, Kraków

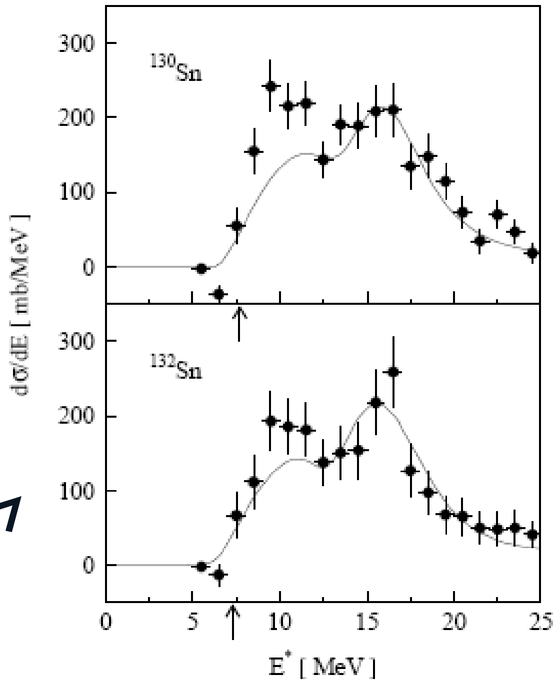
J.V. Kratz, C. Nociforo
University Mainz

D. Cortina-Gil
University Santiago de Compostela

N.Paar
University of Zagreb

Results: giant dipole resonance in exotic even-even Sn isotopes

due to relatively large errors, energy and width of GDR fixed and cross section obtained in Lorentz fit to ^{130,132}Sn



$$\sigma_\gamma(E) = \frac{\sigma_o}{1 + \left(\frac{E^2 - E_o^2}{\Gamma E}\right)^2}$$

$$E_o = 31.2A^{-1/3} + 20.6A^{-1/6} \;\; [\mathrm{MeV}]$$

$$\int \sigma_\gamma(E)dE \approx 60\frac{NZ}{A} \;\; [\mathrm{mb\ MeV}]$$

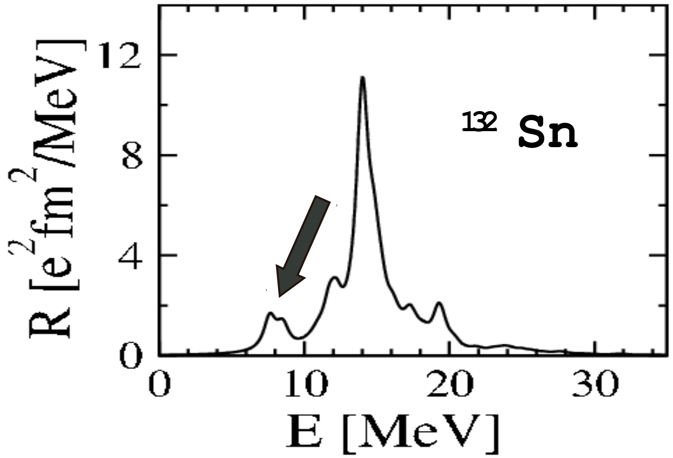
^{129}Sn: E=15.34 MeV
^{132}Sn: E=15.26 MeV

experimental differential Coulomb cross section with GDR fit (solid line), parametrized as Lorentzian distribution and folded with detector response

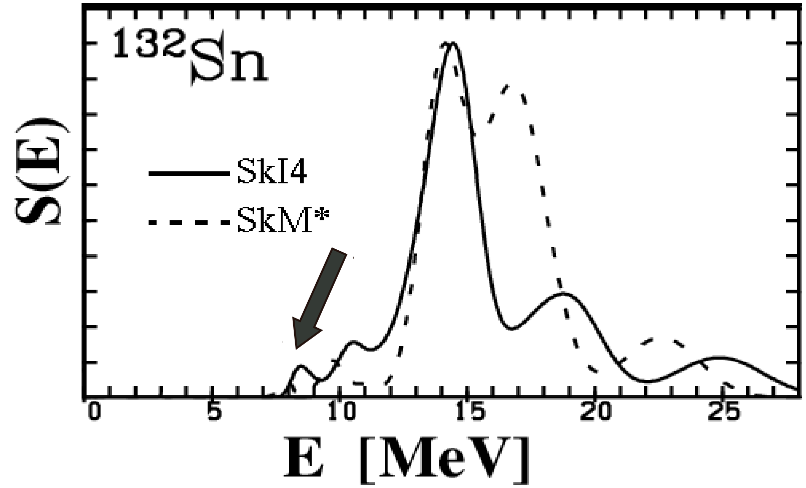
E_o = 15.5 MeV
Γ = 4.75 MeV
σ_{tot} = 2580 ± 140 mb MeV

total GDR cross section in agreement with stable isotopes from the same mass region

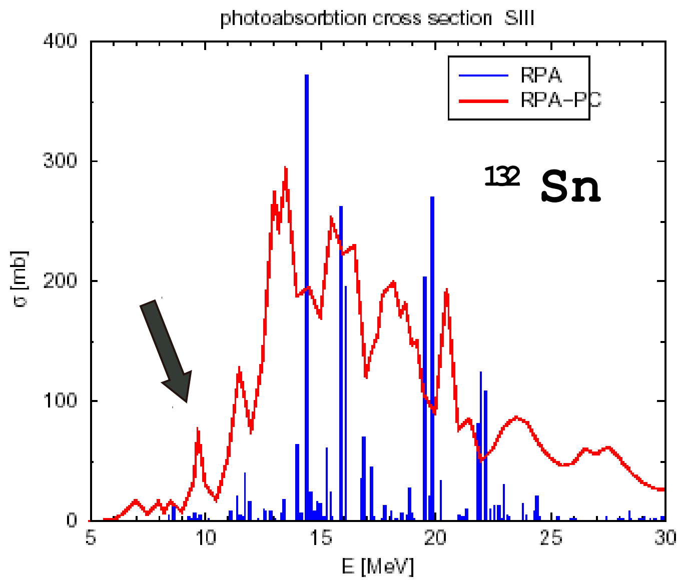
Pygmy dipole resonance in doubly magic ^{132}Sn – various theoretical predictions



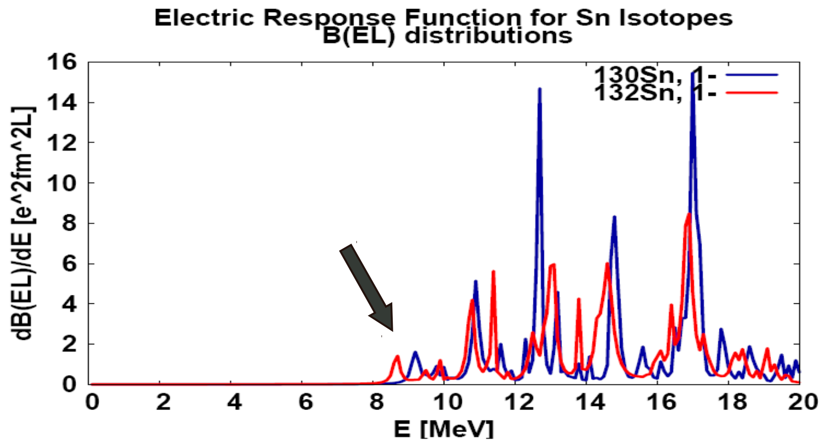
N.Paar et al, PRC 67(2003)34312



P.G.Reinhard, NPA 649(1999)305c

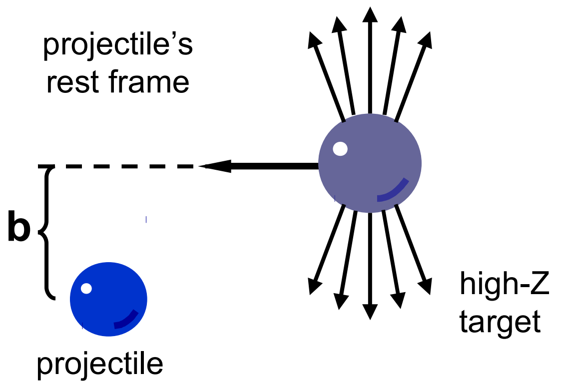


D.Sarchi et al, PLB 601(2004)27



N.Tsoneva et al, PLB 586(2004)213

Relativistic Coulomb excitation



- peripheral collisions between two heavy ions at large impact parameter
- Lorentz contracted electromagnetic field
- short pulse of electromagnetic radiation

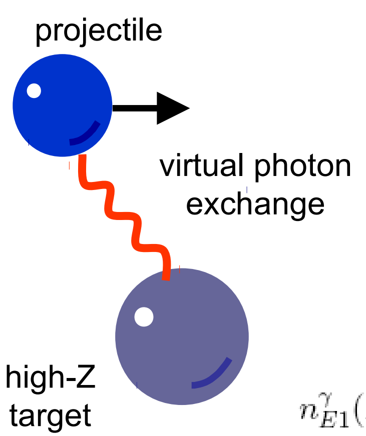
Coulomb excitation cross section

photoabsorption cross section (nuclear structure)

$$\frac{d\sigma_{Coul}}{dE} = \sum_{\pi\lambda} \frac{1}{E} n^{\gamma}_{\pi\lambda}(E)\sigma^{\gamma}_{\pi\lambda}(E)$$

virtual photon numbers (reaction kinematics)

Weizsäcker & Williams – equivalent description of a process by means of „virtual” photon exchange

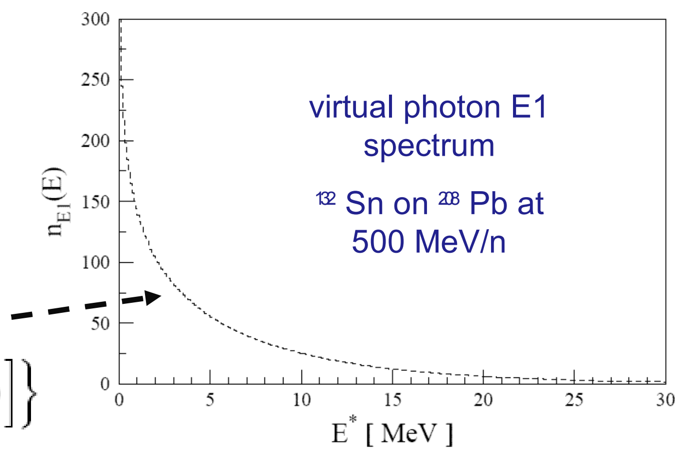


relativistic Coulex properties:

- dominated by dipole excitations
- large cross sections
- high excitation energies (up to 25 MeV)

$$\xi(E) = E b_{min}/\hbar c\beta\gamma.$$

$$n^{\gamma}_{E1}(E) = \frac{2Z_t^2\alpha}{\pi\beta^2}\left\{\xi K_0(\xi)K_1(\xi) - \frac{\xi^2\beta^2}{2}\left[K_1^2(\xi) - K_0^2(\xi)\right]\right\}$$



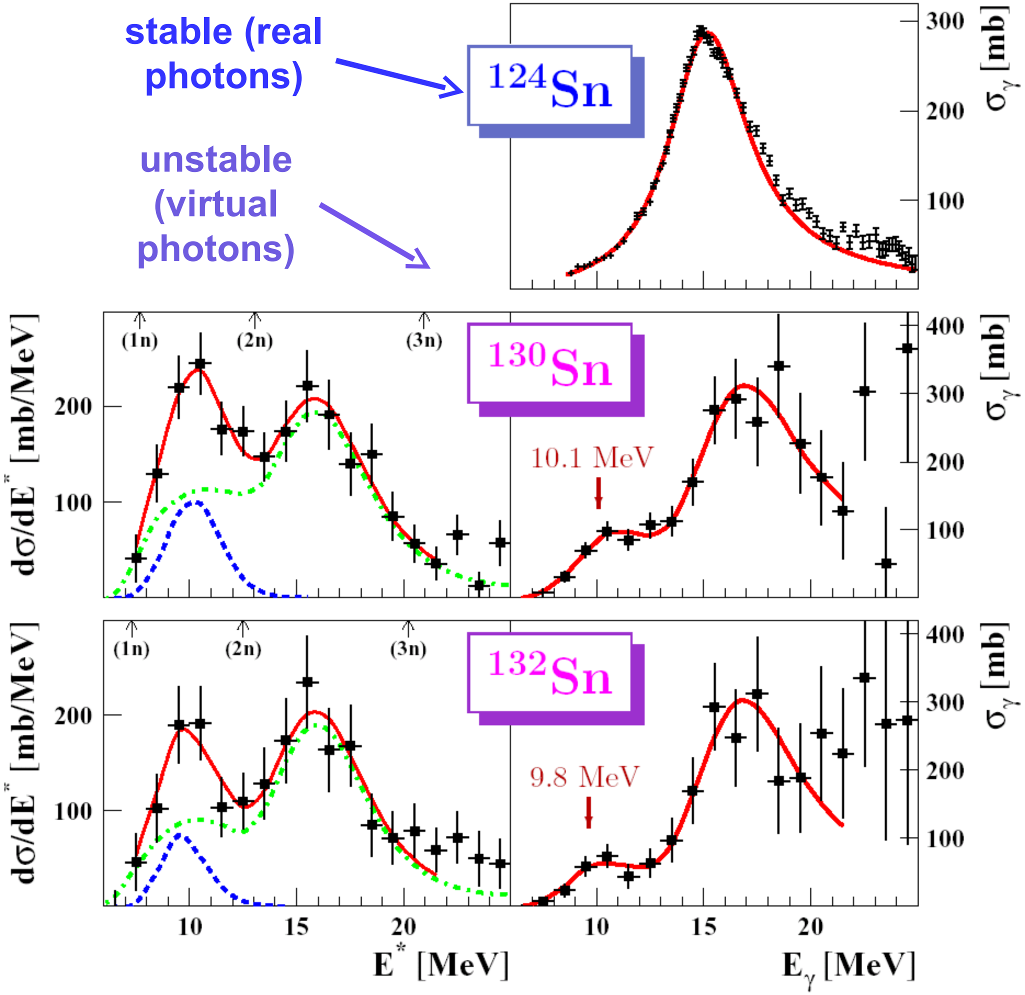
Results for exotic even-even Sn isotopes
P.Adrich et al. PRL 95 (2005)132501

measured Coulomb excitation cross section

extracted photo asborption cross section

stable (real photons)

unstable (virtual photons)



P. Adrich et al, PRL 95(2005)132501

A	PDR		GDR		
	E_{centr} [MeV]	sum rule [%]	E_{centr} [MeV]	Γ [MeV]	sum rule [%]
^{124}Sn	-	-	15.3	4.8	116
^{130}Sn	10.1 (0.7)	7.0 (3.0)	15.9 (0.5)	4.8 (1.8)	145 (19)
^{132}Sn	9.8 (0.7)	4.0 (3.1)	16.1 (0.8)	4.7 (2.2)	125 (32)

PDR

- located around 10 MeV of excitation energy
- exhausts a few % of TRK sum rule
- in agreemtent with theoretical predictions

GDR

- in agreement with systematics for stable nuclei in the same mass region

Equivalent parametrizations of the symmetry energy S(ρ) encountered in the literature

degree of isospin diffusion
in heavy ion collisions

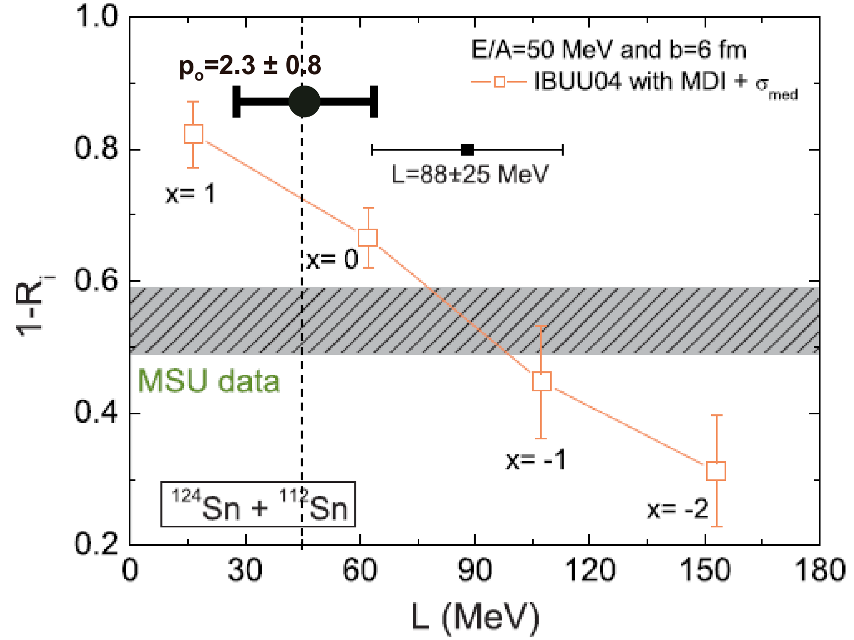
$$S_2(\rho) = a_4 + \frac{p_0}{\rho_0^2}(\rho - \rho_0) + \frac{\Delta K_0}{18\rho_0^2}(\rho - \rho_0)^2 + \cdots,$$

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{K_{\rm sym}}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2,$$

$$L = 3\rho_0 \frac{\partial E_{\rm sym}(\rho)}{\partial \rho}|_{\rho=\rho_0}, \qquad p_o = \rho_o^2 \frac{dS(\rho)}{d\rho}$$

$$K_{\rm sym} = 9\rho_0^2 \frac{\partial^2 E_{\rm sym}(\rho)}{\partial^2 \rho}|_{\rho=\rho_0}. \quad \Delta K_o = 9\rho_o^2 \frac{d^2 S(\rho)}{d\rho^2} = 9\frac{dp_o}{d\rho}$$

L.W.Chen, C.M.Ko, B.A.Li
PRC72 (2005) 064309



relation between slope coefficients in both parametrizations:

$$p_o = \frac{L\rho_o}{3}$$

range of theoretically considered values **L =-50,...+200 MeV** corresponds to p_o**=-1.6,...+10 MeV/fm³**

value of p_o **= 2.3 ± 0.8 MeV/fm³**
is equivalent to **L = 45 ± 15 MeV**