Dipole Response of Exotic Nuclei and Symmetry Energy – Experiments at the LAND-R^{3}B Setup

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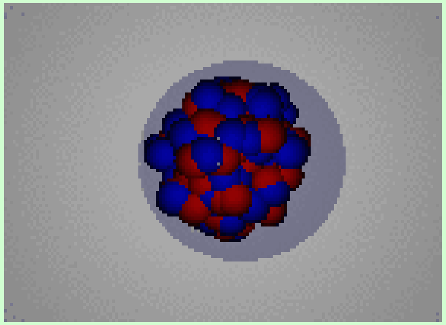
Outline

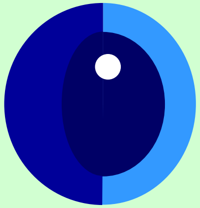
- Introduction
  - Why measure E1 strength?
  - Giant Resonances, Pygmy Resonance
- Experimental setup
- Heavy-ion-induced Coulomb excitation at relativistic energies
- Experiments at LAND-R^3B:
  - Neutron-rich Sn isotopes
  - Neutron-rich Ni isotopes
  - Proton-rich Ar isotopes
  - Improved Sn measurement (planned for 2011)
- Summary and Outlook

Why measure E1 strength?

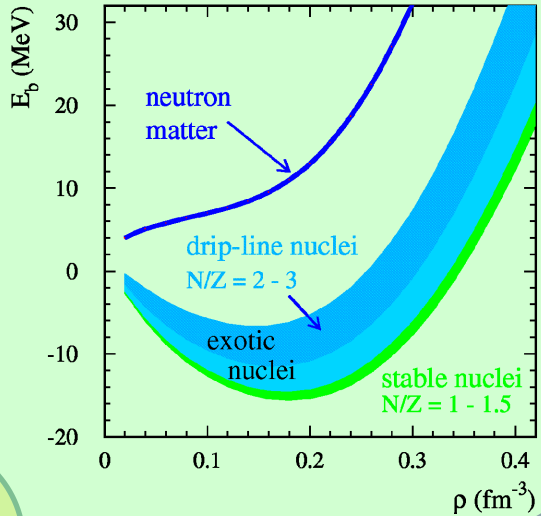
Pygmy resonance



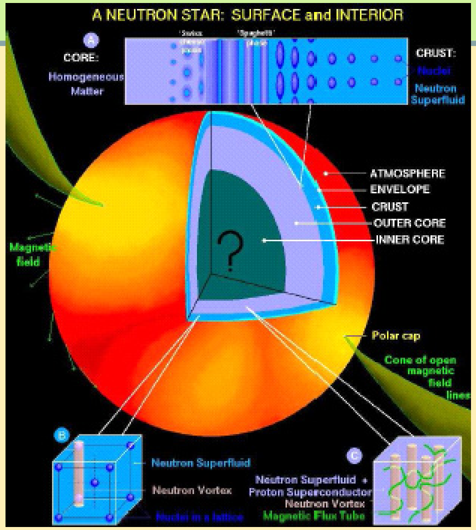
Neutron skin



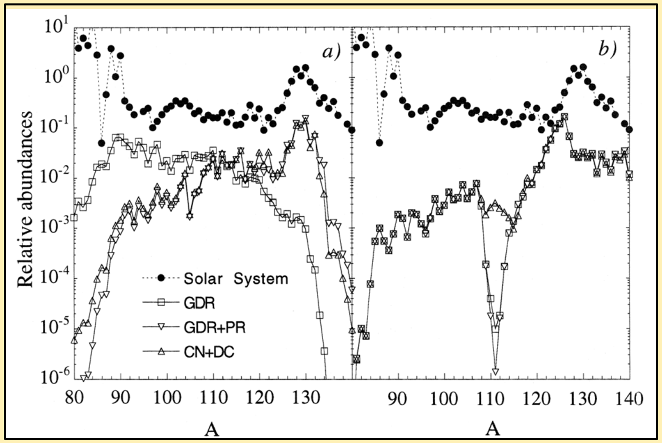
Equation of State



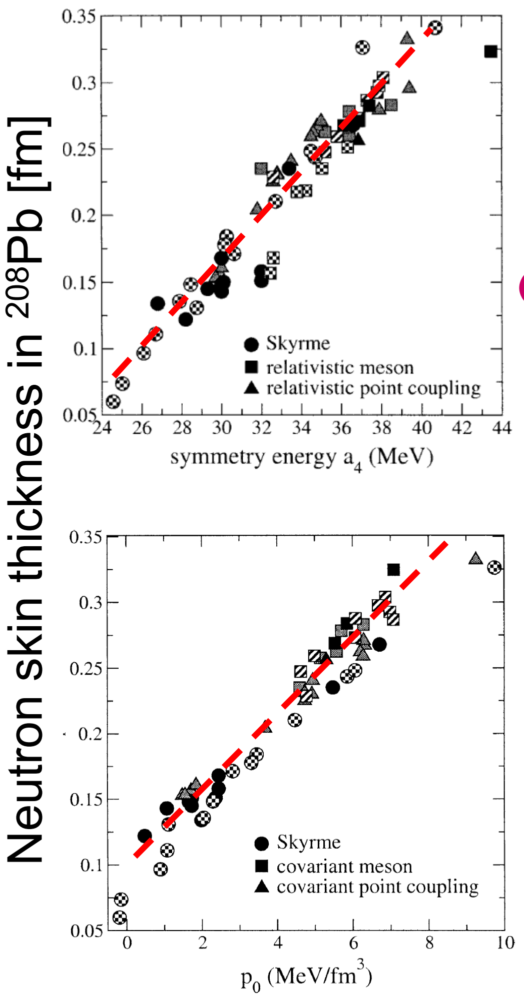
Neutron star



r-process nucleosynthesis



Nuclear Equation-Of-State



R.J.Furnstahl NPA **706**, 85-110 (2002)

$$E(\rho,\alpha)=E(\rho,0)+S_2(\rho)\alpha^2+O(\alpha^4)\,,\;\alpha=\frac{N-Z}{A}$$

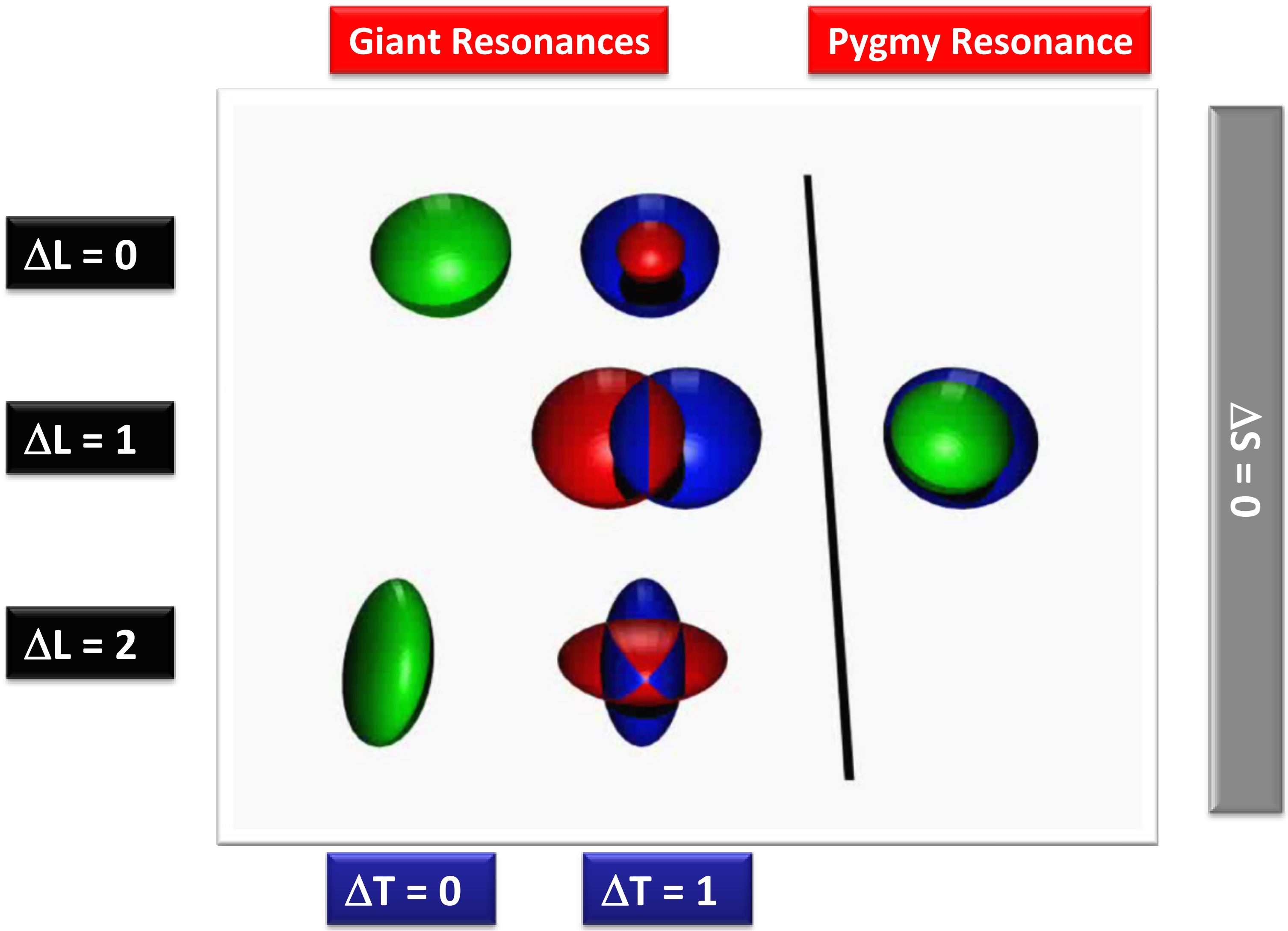
$$E(\rho,0)=-a_V+\frac{K_0}{18\rho_0^2}(\rho-\rho_0)^2+\ldots$$

$$S_2(\rho)=\frac{1}{2}\frac{\partial^2E(\rho,\alpha)}{\partial\alpha^2}\Big|_{\alpha=0}=$$

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

- a_4: symmetry energy per nucleon in pure neutron matter
- p_0: symmetry energy pressure
- Linear correlation between neutron skin thickness and a_4 and p_0 parameters of nuclear Equation-Of-State for various mean-field models for ^{208}Pb case

Giant Resonances



Properties of Giant Resonances

$$\int_0^\infty \sigma(E)\, dE = \frac{2\pi^2 \hbar A e_{eff}^2}{mc} \cong 60 \frac{NZ}{A}\ \mathrm{MeV\ mb}$$

- **Thomas-Reiche-Kuhn sum rule:** prediction of integral cross section, based on the effective charge of the nucleus

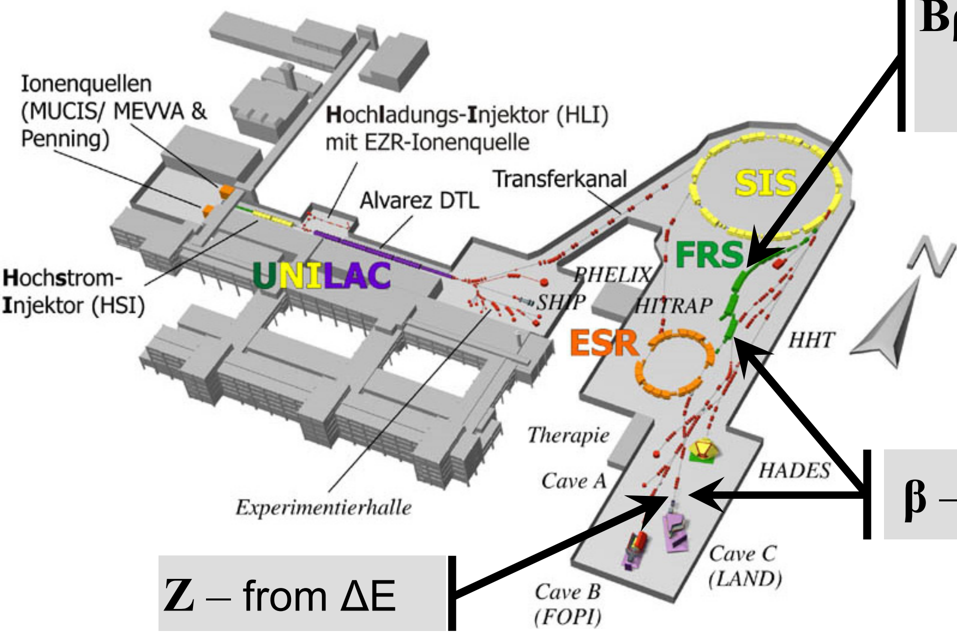
- **Restoring force:** provides macroscopic properties of the nucleus

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

- **Breit-Wigner distribution:**
  - σ_m : peak cross section
  - E_m : peak mean energy
  - Γ : peak width
- **Mean energy and width** depend on mass number A and on nuclear deformation
- Giant Resonances are **split** into up to three components **in deformed nuclei**

Experimental setup

- Stable beams from SIS, fragmentation on Be target or in-flight fission
- Production of radioactive beams in Fragment Separator (FRS)

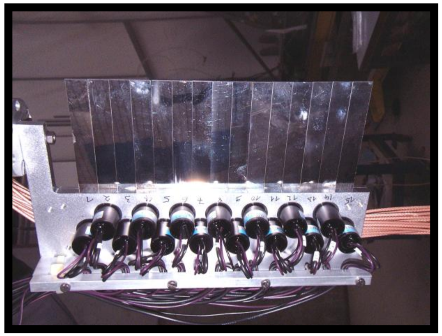


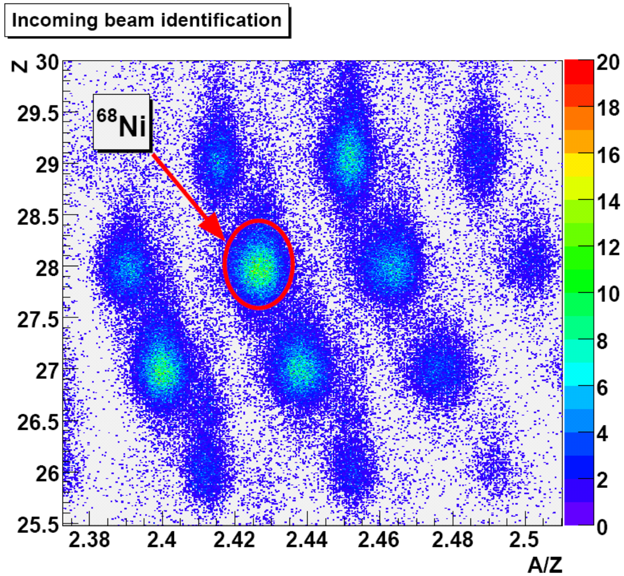
Bρ – from position at middle focal plane of the FRS

β – from TOF

Z – from ΔE

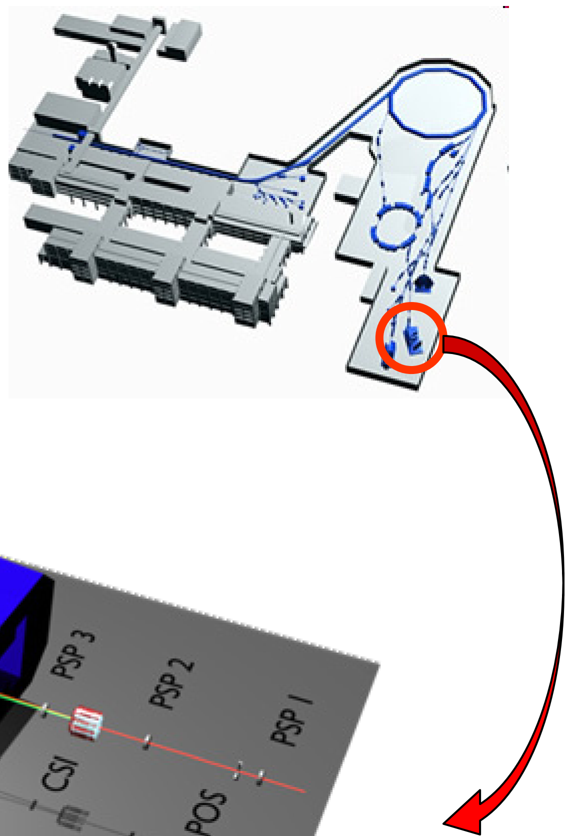
$$\frac{A}{Z} = \frac{e}{m_u c} \frac{B\rho}{\beta\gamma}$$

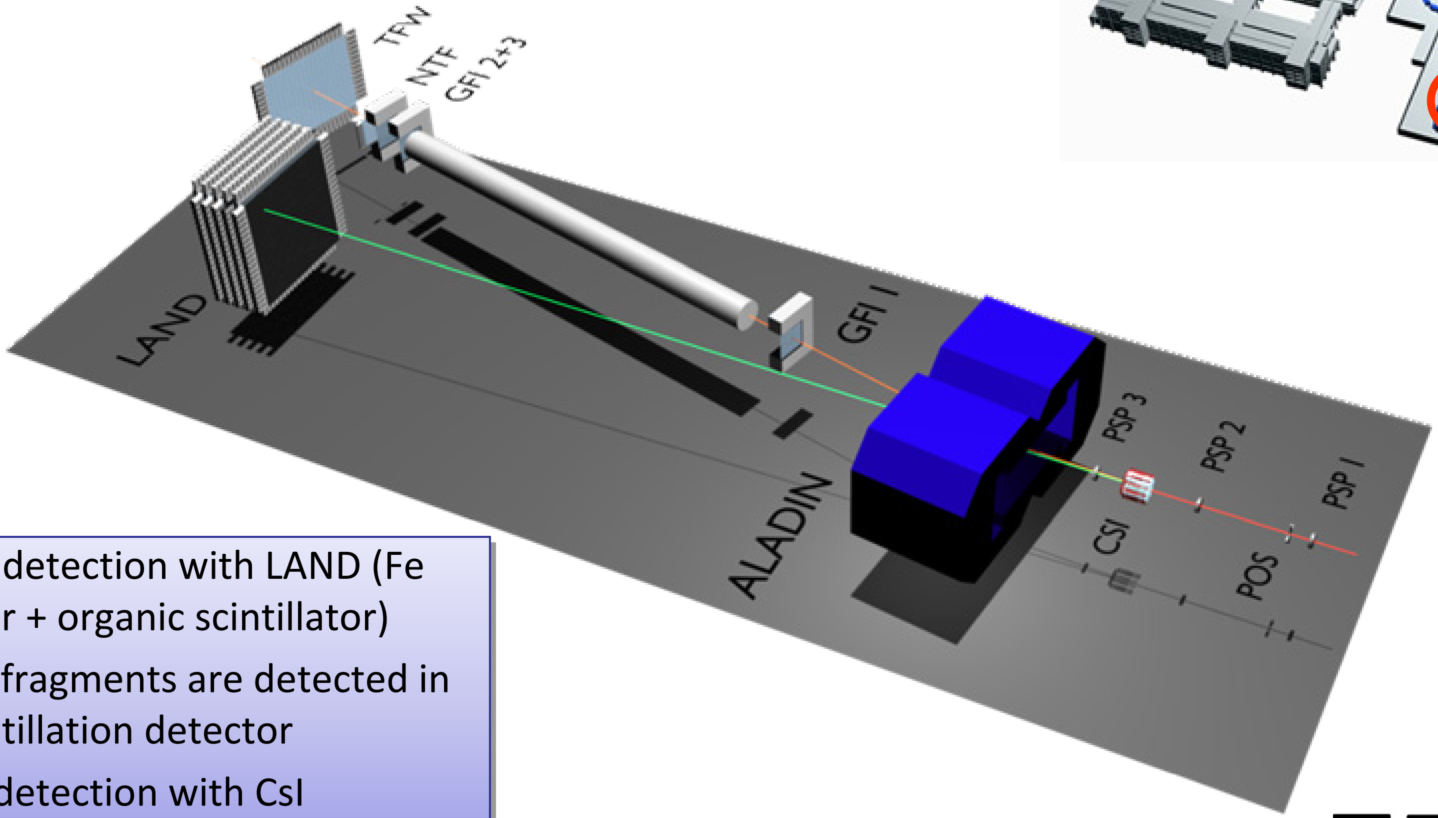




Experimental setup

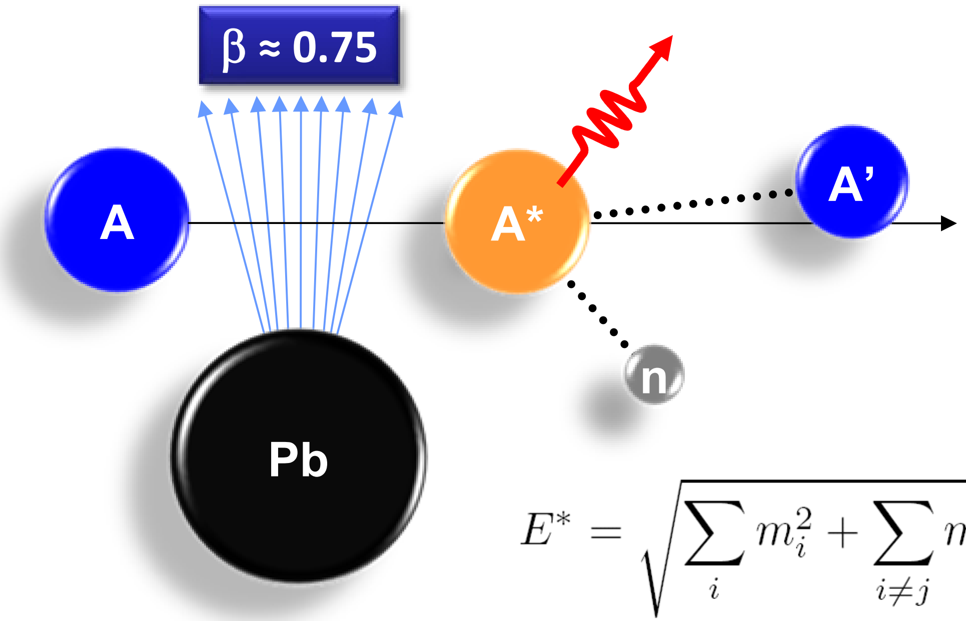
- Beam tracking in Cave C: Si detectors (PSP) and scintillation detectors (POS, GFI, TFW)
- Kinematic forward-focusing (relativistic beam energies)
  → high-acceptance measurement (almost full coverage of solid angle)

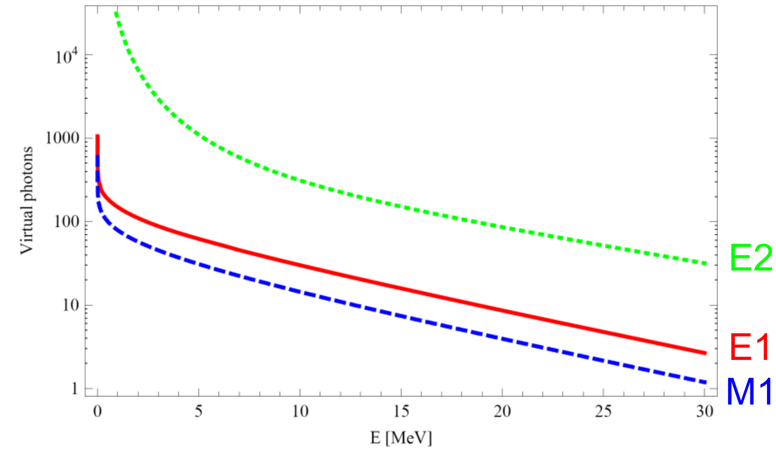




- Neutron detection with LAND (Fe converter + organic scintillator)
- Charged fragments are detected in TFW scintillation detector
- Gamma detection with CsI

Measurement principle

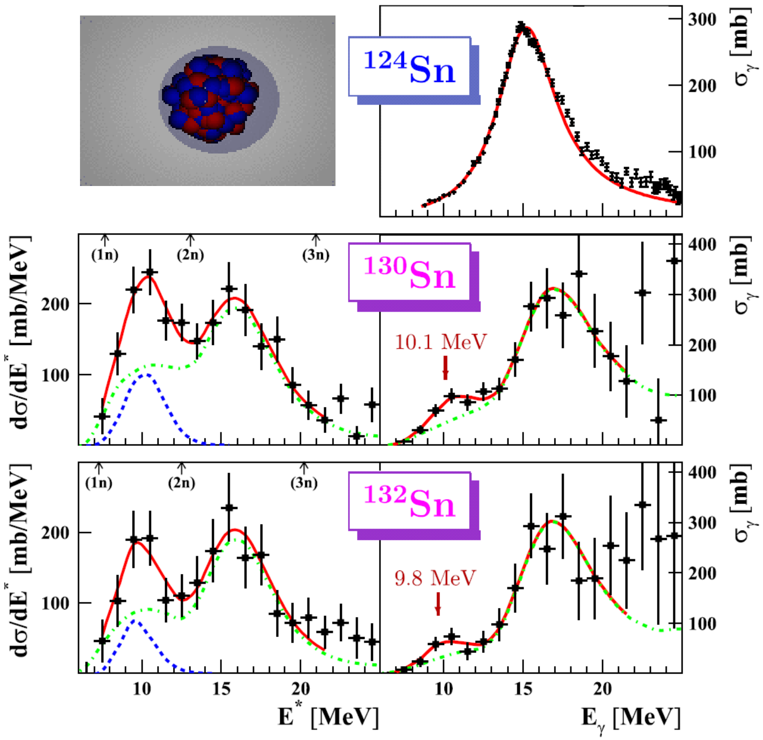




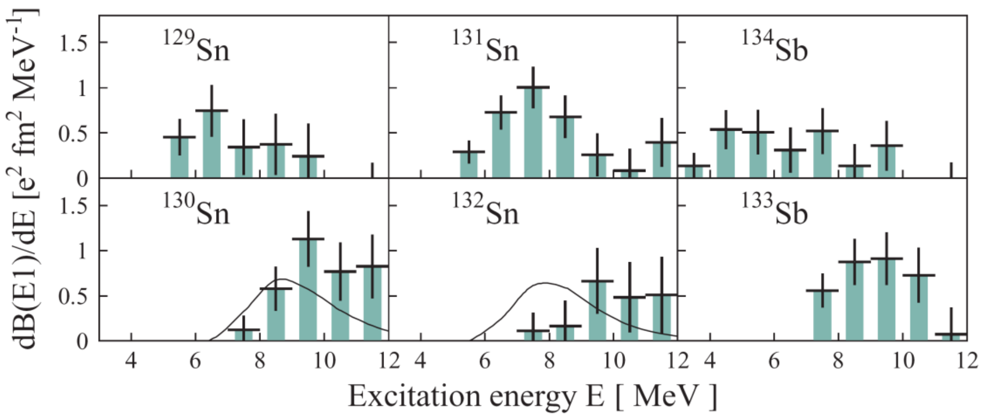
$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} m_i m_j \left(1 - \beta_i \beta_j \cos\theta_{ij}\right)} + E_\gamma - M_{proj}$$

- Heavy-ion-induced electromagnetic excitation, *via* the virtual photon approach
- Short lifetime of projectile ⇒ requires experiment in inverse kinematics
- Reconstruction of excitation energy (using invariant mass) of each event requires detection of **ALL** participating species (identification and momentum)
- Measurements on Pb, C and empty targets allows the separation of the electromagnetic, nuclear and background components

E1 measurement in neutron-rich Sn isotopes



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

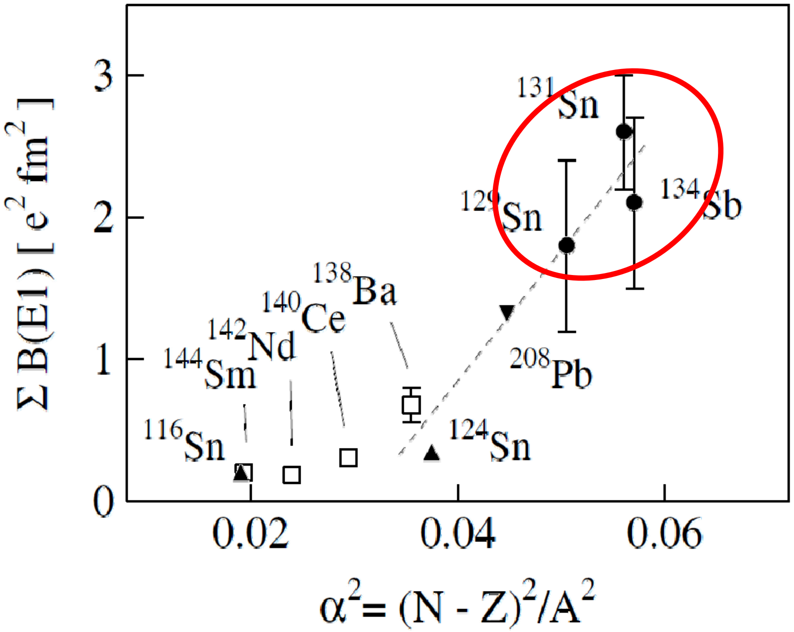


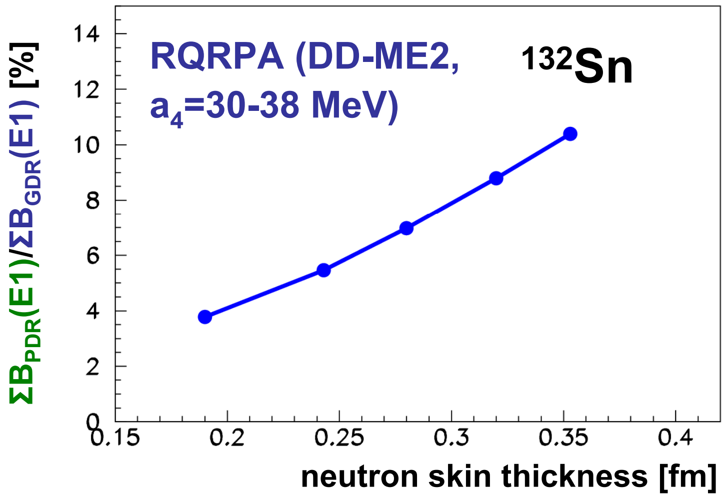
A. Klimkiewicz *et al.*, Phys. Rev. C **76**, 051603(R) (2007)

- E1 Coulomb excitation and photoabsorption cross sections show excessive E1 strength compared to GDR alone
- Excess E1 strength distributions for odd and even Sn and Sb isotopes
- Staggered PDR distributions in odd / even isotopes
- PDR strength also below neutron threshold, or varies with threshold?

Link between PDR and EOS

- Experiment provides E1 strength at larger neutron-to-proton ratios
- RQRPA calculation provides link between measured PDR strength and neutron skin thickness

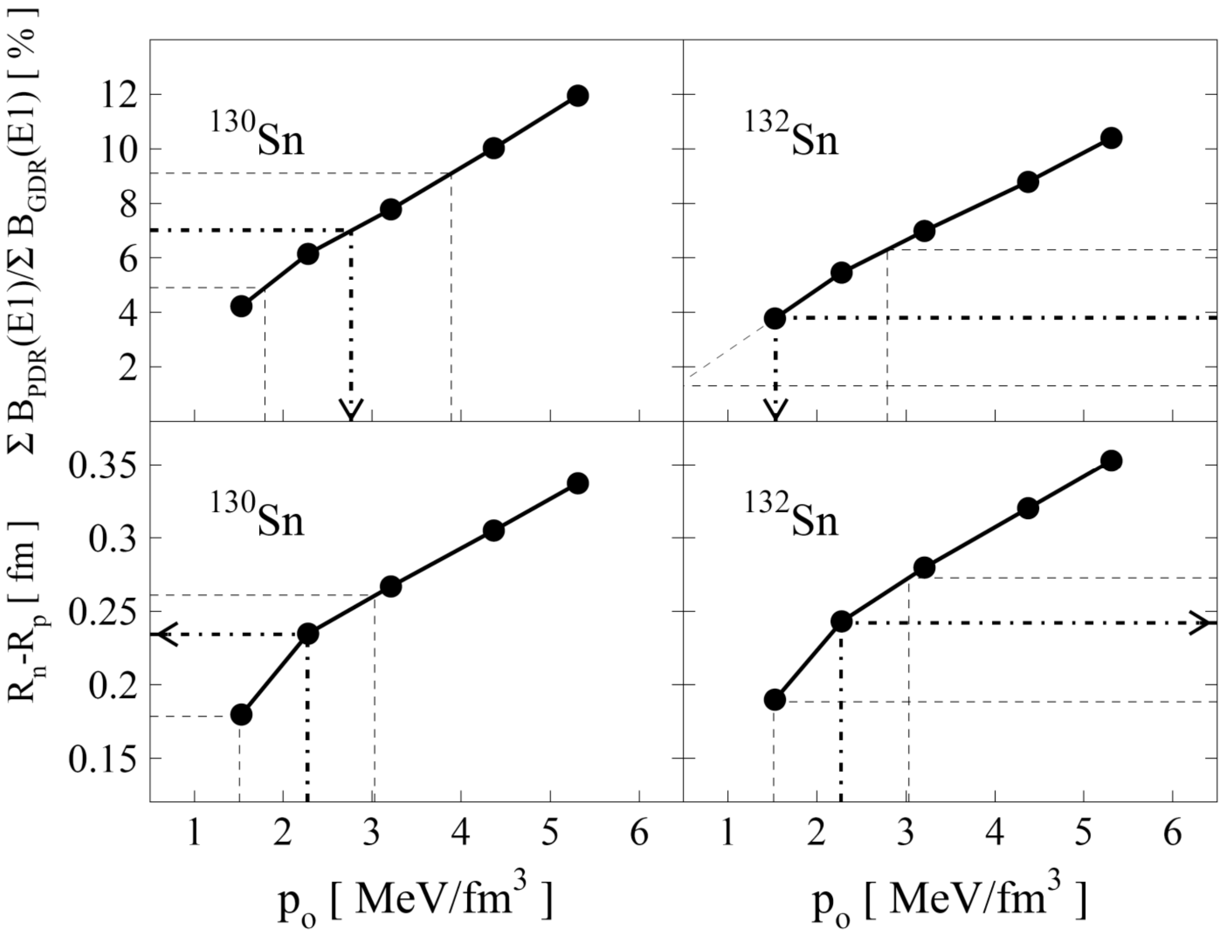




Calculation performed by N. Paar

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

Nuclear Equation-Of-State



- RQRPA calculations performed by N. Paar
- Analysis of $^{130,132}Sn$ provide mean EOS parameters:

⇒ $\langle a_4 \rangle$ = 32.0(1.8) MeV

⇒ $\langle p_0 \rangle$ = 2.3(0.8) MeV/fm^3

- Values of the neutron skin thickness are also obtained:

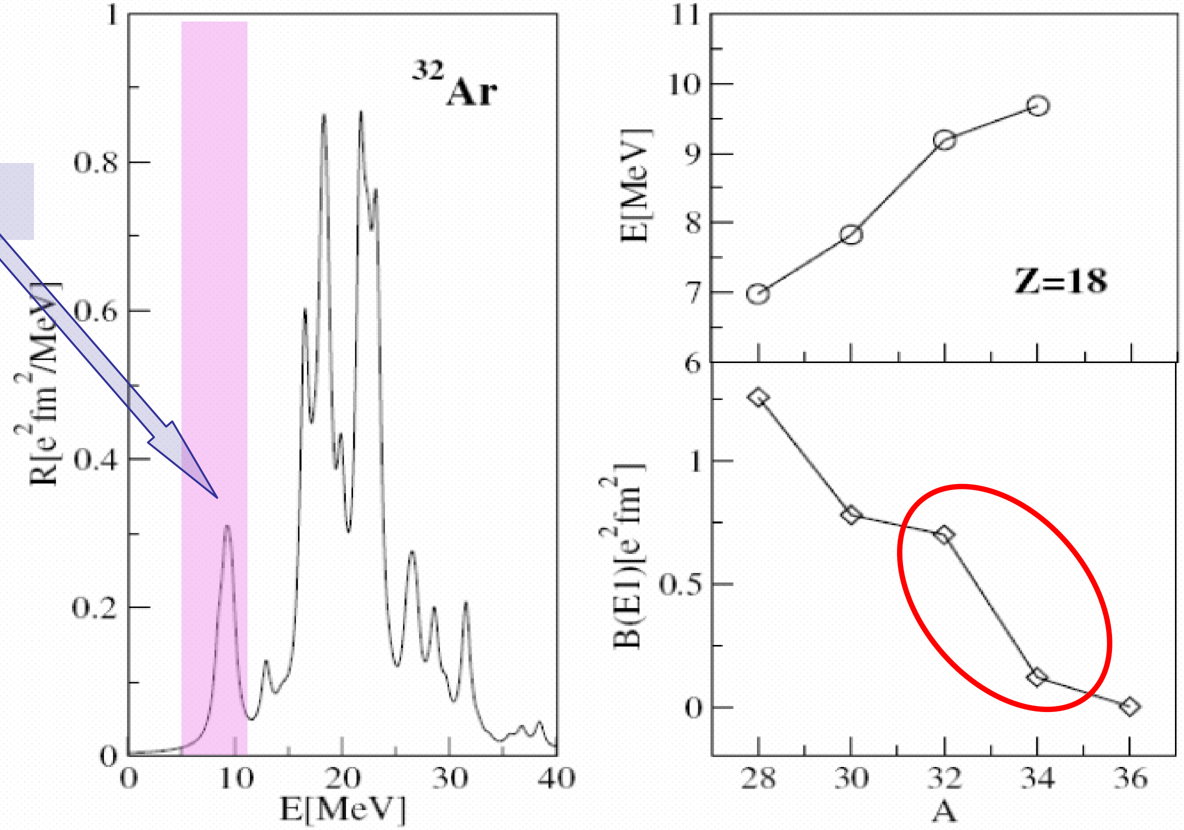
⇒ ^{130}Sn: 0.23(4) fm

⇒ ^{132}Sn: 0.24(4) fm

A. Klimkiewicz, N. Paar *et al.*, Phys. Rev. C **76**, 051603(R) (2007)

Proton PDR predictions

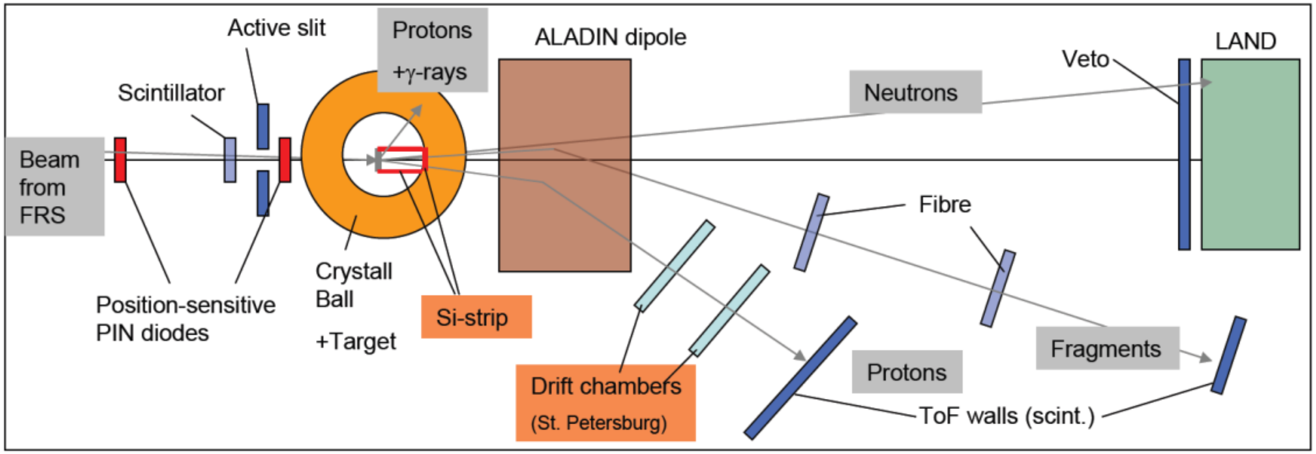
≈ 6 % EWSR



N.Paar *et al.*, Phys.Rev.Lett. **94**, 182501 (2005)

Fig.1: *The isovector dipole strength distribution in ^{32}Ar, calculated in the framework of RHB and RQRPA (left panel). In the right panel the mass dependence of the pygmy peak and the corresponding integrated dipole strength below 10 MeV are shown. From [Paa-05b].*

Dipole response studies in ^{32}Ar and ^{34}Ar



statistics expected:

~500 events in PDR region, ~1000 in GDR region

~150 events in PDR region, ~1500 in GDR region

New E1 measurement of Sn isotopes

1. **Measurement of isovector GDR in complete Sn isotopic chain from A = 124 to 134 with high statistics**
   - Reduce statistical error for the systematical extraction of GDR parameters
   - Observation of direct photon-decay of GDR
   - Measurement of stable isotope for comparison with other experimental data

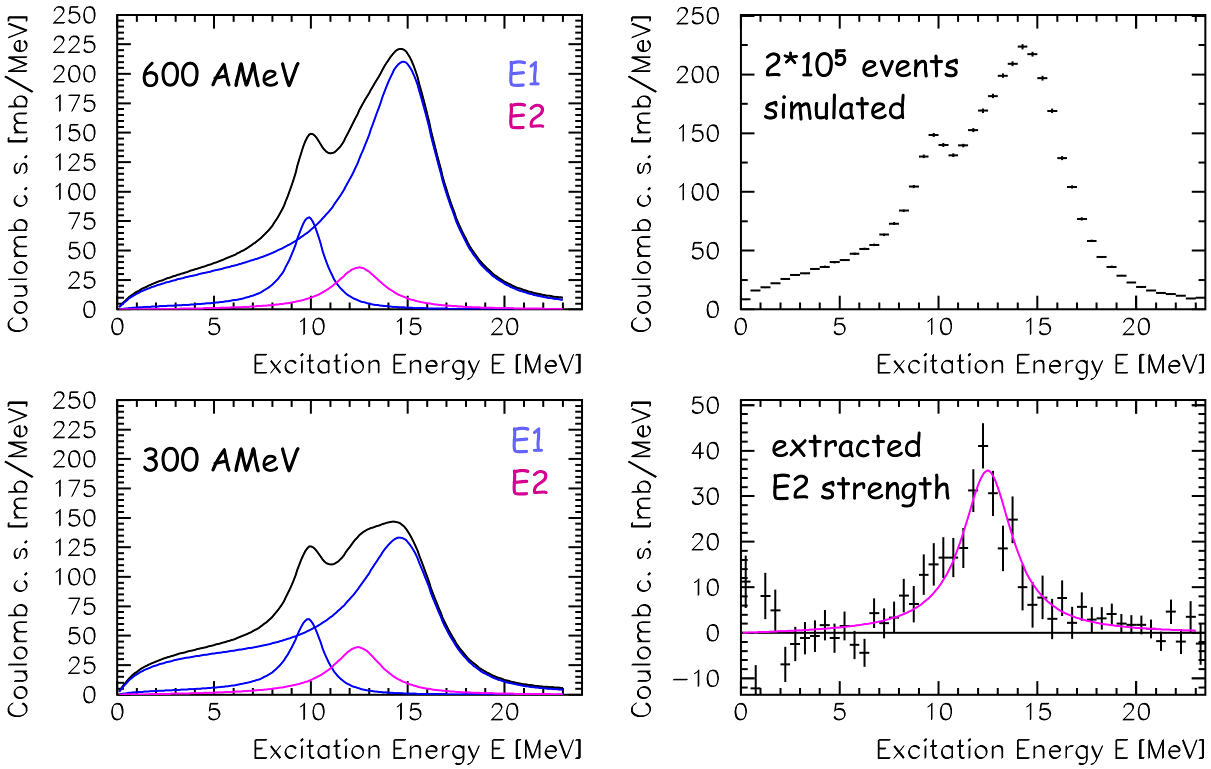
2. **Measurement of PDR in complete Sn isotopic chain below and above the neutron threshold**
   - Measurement of (γ,xn) and (γ,γ') channels

   $\Rightarrow$ PDR strength distribution independent of neutron threshold

New E1 measurement of Sn isotopes (cont'd)

3. Measurement of GQR in ^{124}Sn to ^{128}Sn

- Two beam energies required to disentangle E1 and E2 components
- Requires total E1+E2 strength distribution with good statistics



- Example:
  - ^{132}Sn at 600 and 300 AMeV
  - 100% TRK sum rule strength for E1
  - 100% EWSR strength for E2

Summary

LAND setup

Coulomb excitation of stable and radioactive beams

Beam energy: 200 - 1000 MeV/u

Neutron-rich Sn

Measurement of PDR: 4-7% TRK sum-rule strength

Extraction of a_4 and p_0 parameters of EOS

Proton-rich Ar

Analysis in progress

Neutron-rich Ni

Measurement of PDR: 5-15% TRK sum-rule strength (preliminary results)

Analysis in progress

Neutron-rich Sn (2)

Measurement of PDR (above and below threshold); E2 measurement; improved statistics for E1; connection with stable isotope

Questions to be answered by experiment

- E1 strength (both PDR and GDR) dependence on mass, binding energy and n-p asymmetry
  - ➢ Requires more systematics, higher resolution, extraction of E2 contribution
- Collectivity?
  - ➢ Study of decay modes: direct gamma decay, particle decay to A-1 states
- Low-lying strength below threshold?
  - ➢ Measurements below and above threshold
- Connection to measurements with stable nuclei
- Structure of low-lying dipole strength?
  - ➢ Use of various probes: γ, d, α
- Relation to EOS and neutron skin
  - ➢ Measure various nuclei and mass regions
- Proton pygmy?
  - ➢ Measurement of ^{32,34}Ar (in analysis)

- Effect of deformation?

LAND collaboration

$^{127\text{-}132}$Sn (Exp. S221) – $^{57\text{-}72}$Ni (Exp. S287)

A. Klimkiewicz[1,2], N. Paar[3], P. Adrich[1,2], M. Fallot[1], T. le Bleis[4,5], D. Rossi[6], K. Boretzky[1], T. Aumann[1], H. Alvarez-Pol[7], F. Aksouh[1], K.H. Behr[1], J. Benlliure[7], T. Berg[6], M. Boehmer[8], A. Bruenle[1], E. Casarejos[7], M. Chartier[9], A. Chatillon[1], D. Cortina-Gil[7], U. Datta Pramanik[10], Th.W. Elze[5], H. Emling[1], O. Ershova[1,4], B. Fernando-Dominguez[9], H. Geissel[1], M. Gorska[1], M. Heil[1], M. Hellström[1], G. Ickert[1], H. Johansson[1,11], K. Jones[1], A. Junghans[12], O. Kiselev[6], J.V. Kratz[6], R. Kulessa[2], N. Kurz[1], M. Labiche[13], R. Lemmon[14], Y. Litvinov[1], K. Mahata[1], P. Maierbeck[8], T. Nilsson[11], C. Nociforo[1], R. Palit[1], S. Paschalis[9], R. Plag[1,6], W. Prokopowicz[1], R. Reifarth[1,6], H. Simon[1], K. Sümmerer[1], G. Surówka[2], D. Vretenar[3], A. Wagner[12], W. Waluś[2], H. Weick[1], and M. Winkler[1]

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