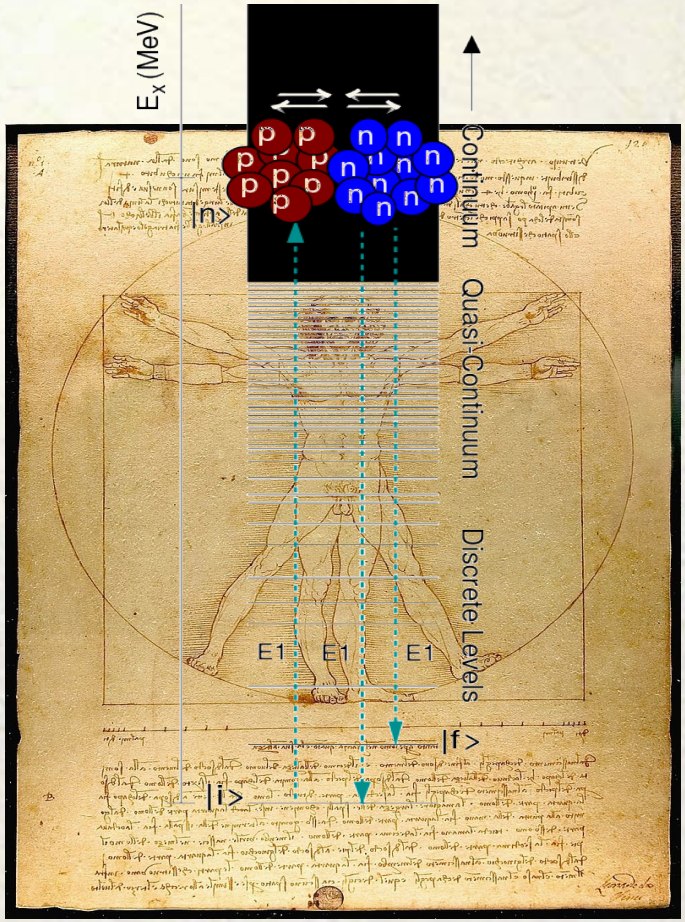
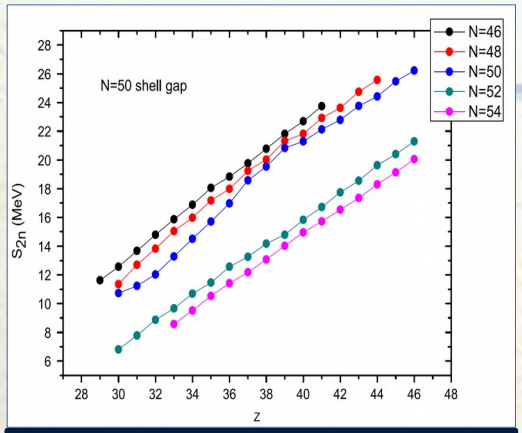
How do we infer shell effects at high excitation energies?

A new spectroscopic probe to search for magic numbers

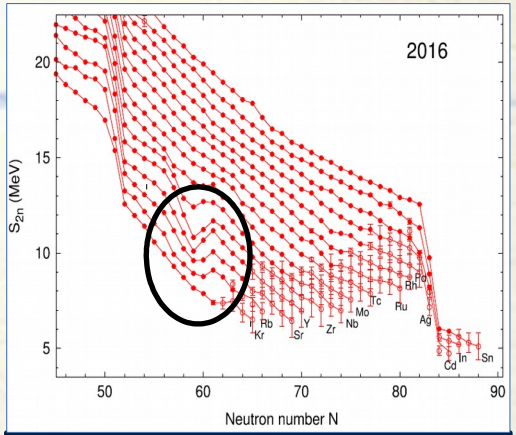


UNIVERSITY *of the* WESTERN CAPE

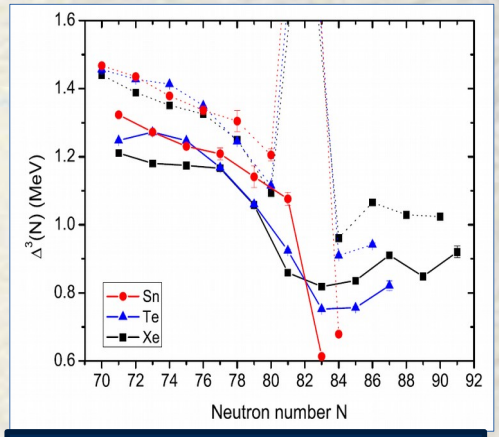
Atomic masses are useful to study nuclear structure via nuclear binding energies



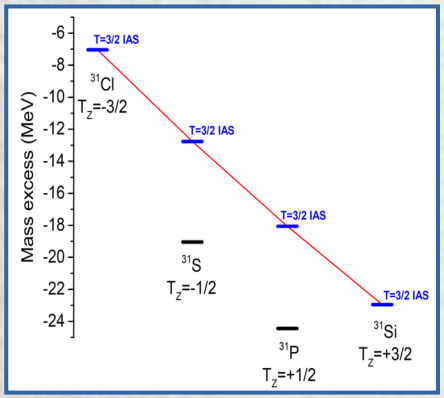
Evolution of shell gaps



Onset of deformation

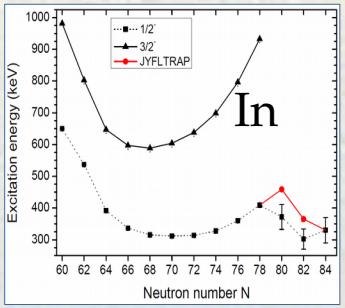


Nucleon pairing energies

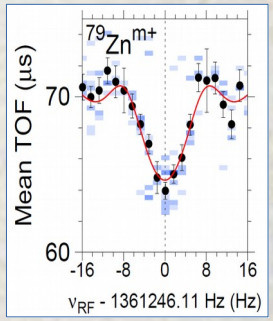


IMME, isospin symmetry

ISOMERS



Single-particle energies

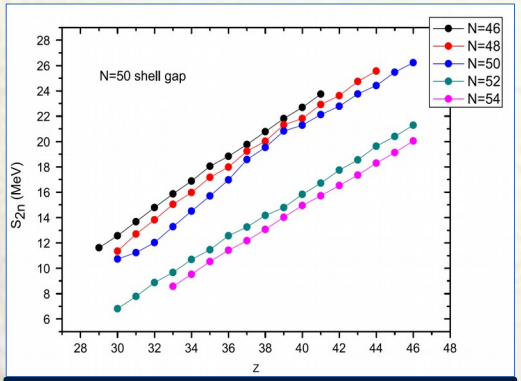


Shape coexistence

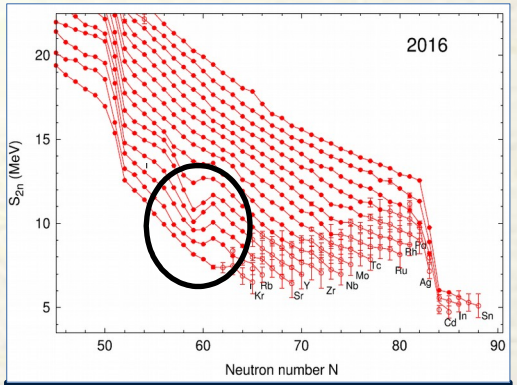
Courtesy of Anu Kankainen, NSD2019, Venice

Information from atomic masses is limited to ground and isomeric states

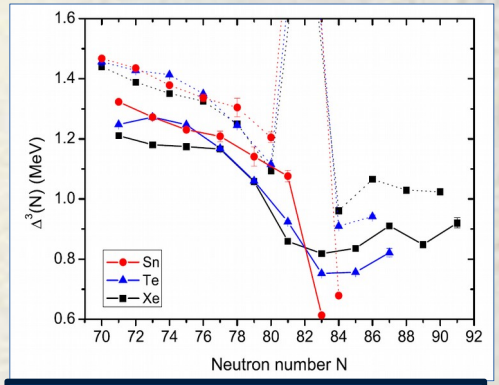
Do we have a similar experimental probe **@** high-excitation energies?



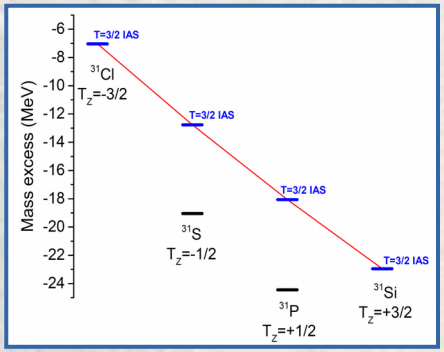
Evolution of shell gaps



Onset of deformation

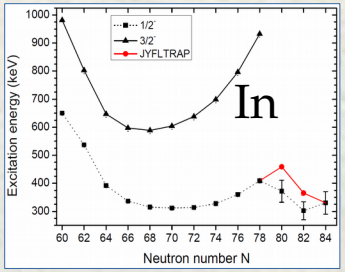


Nucleon pairing energies

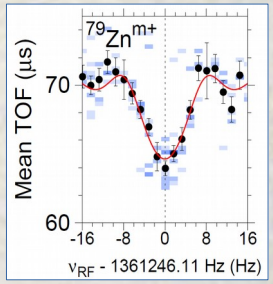


IMME, isospin symmetry

ISOMERS



Single-particle energies



Shape coexistence

Courtesy of Anu Kankainen, NSD2019, Venice

Reorientation Effect

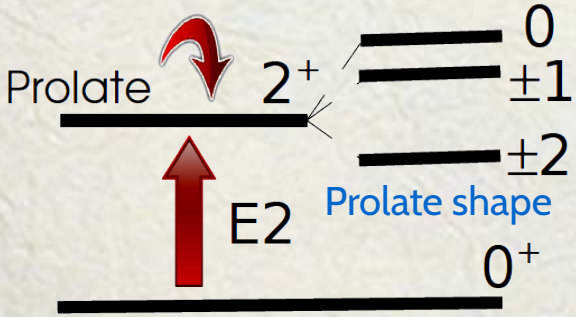
Measuring Spectroscopic Quadrupole Moments

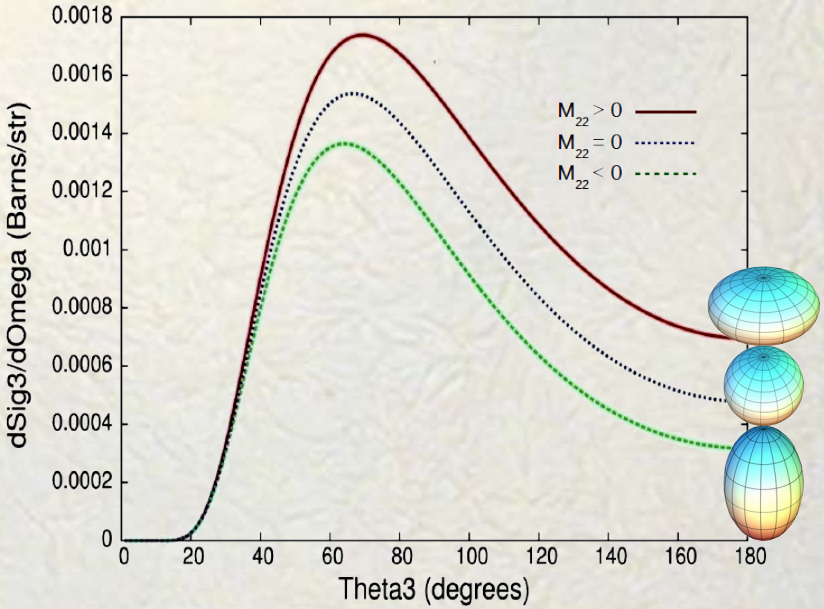
J. N. Orce *et al.* Phys. Rev. C **86**, 041303(R) (2012)

(2^{nd} order effect in Coulomb excitation)

$$\sigma_{E2} = \sigma_R[k_1(\theta_{CM},\xi)B(E2)\,(\,1 + k_2(\theta_{CM},\xi)\,Q_S(2_1^+)\,)]$$

Both projectile and target experience strong time-dependent field gradients



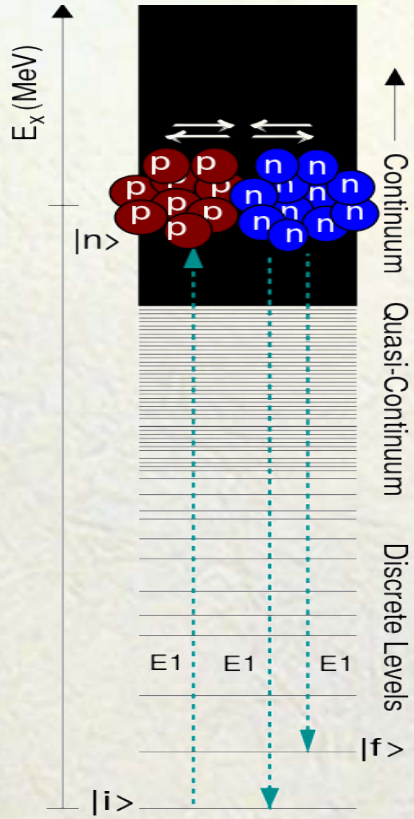


Which leads to a change in the Coulomb- excitation cross section as a function of the scattering angle θ

O. Häusser, Nuclear Spectroscopy and Reactions C, edited by J. Cerny (Academic, New York, 1974)

Nuclear Polarizability

Another second-order effect in Coulomb excitation



$$\alpha = 2e^2 \sum_n \frac{\langle i \| \hat{E1} \| n \rangle \langle n \| \hat{E1} \| i \rangle}{E_\gamma} = \frac{\hbar c}{2\pi^2} \sigma_{-2}$$

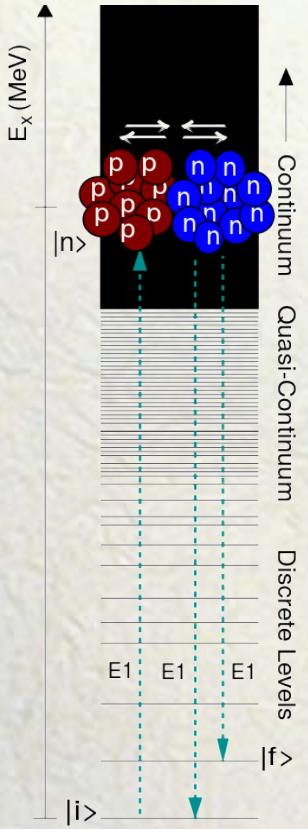
Large E1 matrix elements via virtual excitations of the GDR may polarize the shape of the ground and excited states

Virtual excitations via the GDR may affect B(E2) and Q_s values

J. Eichler, Phys. Rev. **133**, B1162 (1964)

Nuclear Polarizability, α

Migdal introduced implicitly the concept of a dynamic collective model in nuclear physics and used this concept to predict a giant dipole resonance



Hydrodynamic Model

$$\alpha = \frac{e^2 R^2 A}{40 a_{\mathrm{sym}}}$$

Second-order Perturbation Theory

$$\alpha = 2e^2 \sum_n \frac{\langle i \| \hat{E}1 \| n \rangle \langle n \| \hat{E}1 \| i \rangle}{E_\gamma} = \frac{\hbar c}{2\pi^2} \sigma_{-2}$$

$$\sigma_{-2} = 2.25\ A^{5/3}\ \mu\mathrm{b/MeV}$$

$$R = r_0 A^{1/3}\ \mathrm{fm} \qquad a_{\mathrm{sym}} = 23\ \mathrm{MeV}$$

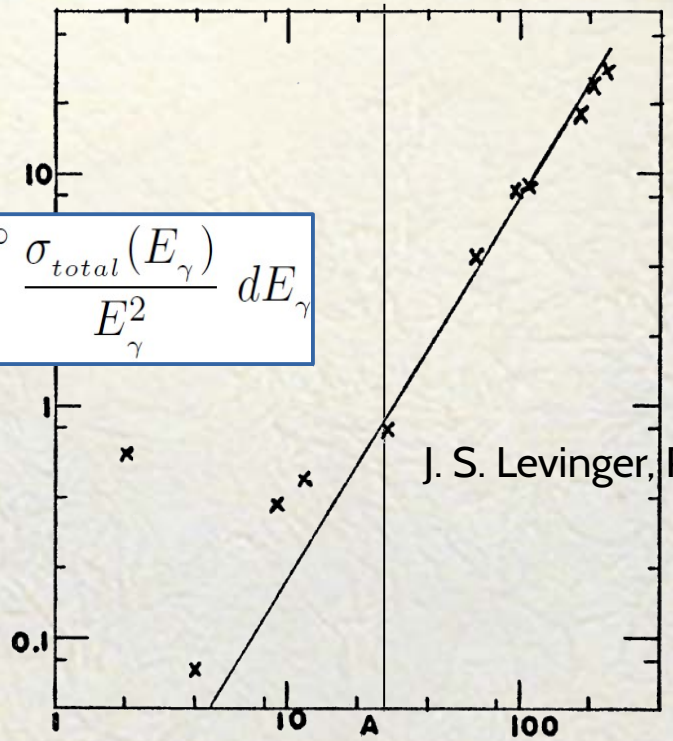
A.B. Migdal, J. Exp. Theor. Phys. USSR **15**, 81 (1945)

Nuclear Polarizability, α

Levinger confirmed Migdal's power-law formula from available photo-absorption data

$$\sigma_{-2} = 3.5\kappa\, A^{5/3}\ \mu b/MeV$$

$$\sigma_{-2} = \int_0^\infty \frac{\sigma_{total}(E_\gamma)}{E_\gamma^2}\, dE_\gamma$$



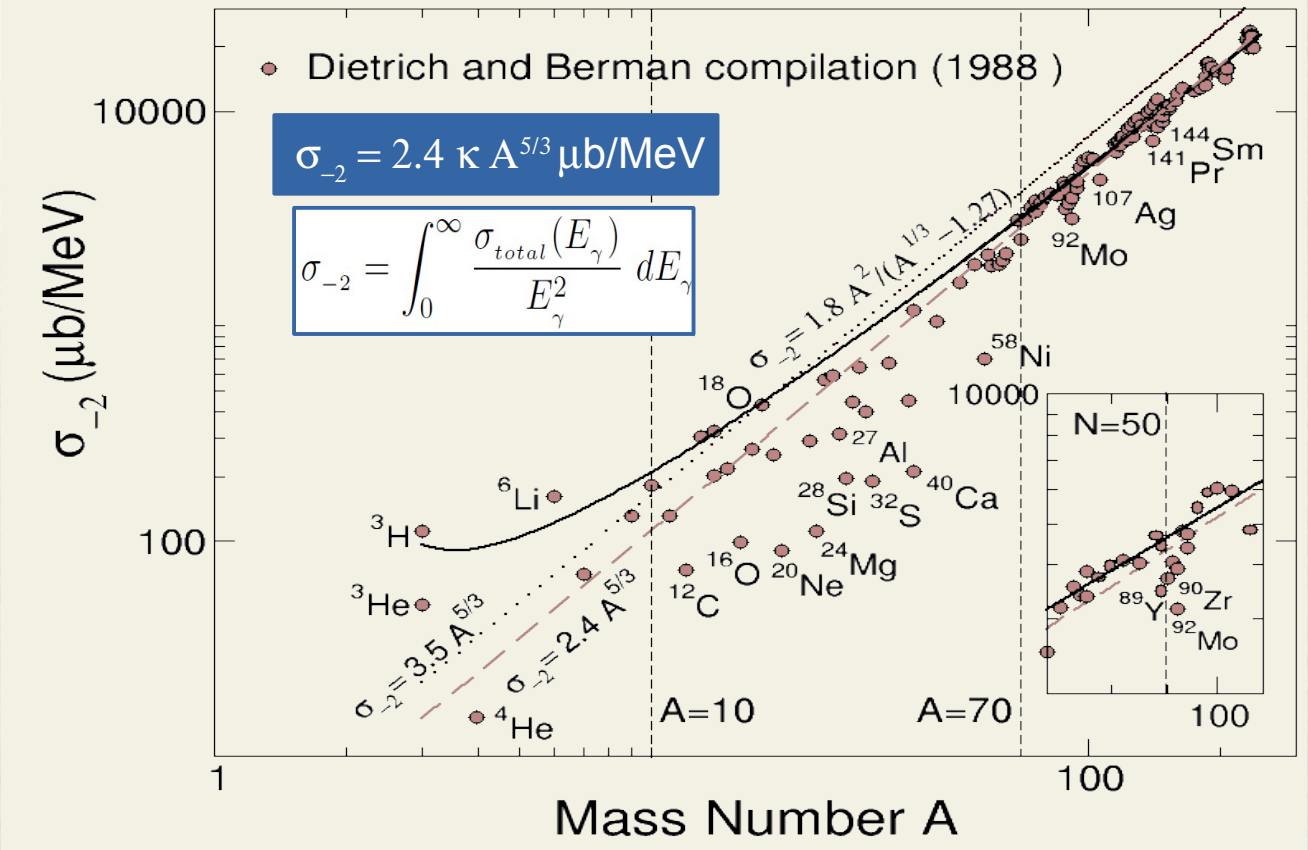
J. S. Levinger, Phys. Rev. **107**, 554 (1957)

Polarizability parameter κ to account for deviations from the GDR effects to that predicted by the hydrodynamic model

New power-law formula for σ_{-2}

Dietrich & Berman photoneutron cross-section evaluation (1988)

J. N. Orce, PRC (2015), Comment (von Neunman-Cosel) (2016) + J. N. Orce's Reply (2016)

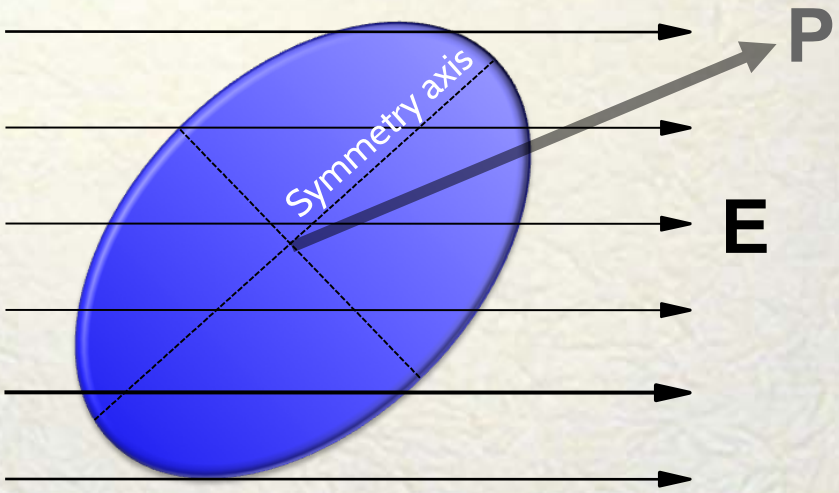


$\kappa > 1$ for light loosely bound nuclei (also from Coulex: ^{6}Li, ^{7}Li, ^{17}O)

$\kappa < 1$ for $T_z = 0$ self-conjugate nuclei: missing (γ,p) contribution (Morinaga)

$$\mathbf{P} = \alpha \mathbf{E}$$

The torque produced by the interaction between **E** and **P** may set the nucleus into rotation → **enhancement of quadrupole collectivity (shift toward prolate shapes)**



Deformed nucleus in an external homogeneuos electric field, **E**

Alder & Winther, Electromagnetic Excitation (North-Holland, Amsterdam, 1975) (appendix J)

NCSM calculation of the nuclear polarizability κ using chiral NN and NN+3N

- Model spaces with basis sizes of N_{max} = 4 for natural and N_{max} = 5 for unnatural parity states
- E1 matrix elements from all the transitions connecting 1^- states up to 30 MeV

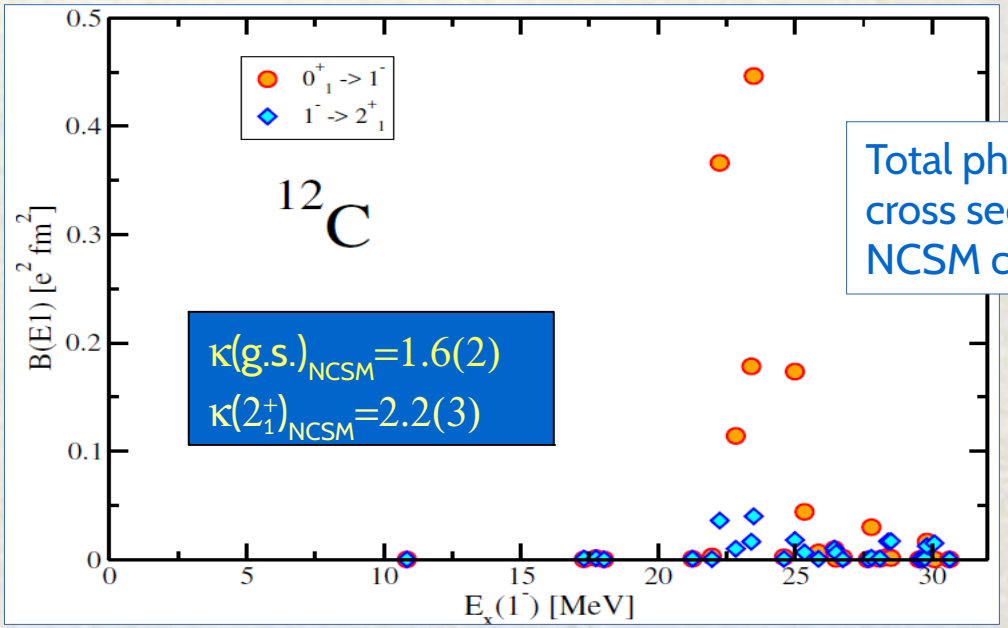
$$\sigma_{-2} = 244\ \mu\mathrm{b/MeV}$$

E. G. Fuller, Phys. Rep. **127**, 185 (1985)
Total photo-absorption cross section

$$\sigma_{-2} = 2.4\kappa\ A^{5/3}\ \mu\mathrm{b/MeV}$$

J. N. Orce, Phys. Rev. C **91**, 064602 (2015)

→ $\kappa(\mathrm{g.s.})_{exp} = 1.62$



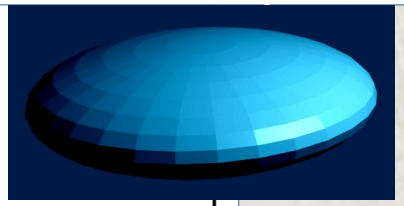
Total photo-absorption cross section agrees with NCSM calculation of κ (g.s.)

Kumar Raju, Nico Orce, Petr Navrátil *et al.*, Phys. Lett. B **777**, 250 (2018)

E1 Polarizability (another second order effect)

High impact in spectroscopic quadrupole moment measurements of light nuclei

$Q_s(2_1^+, {}^{12}C) = +0.07(2)$ eb
assuming $\kappa(2_1^+)=2.2$

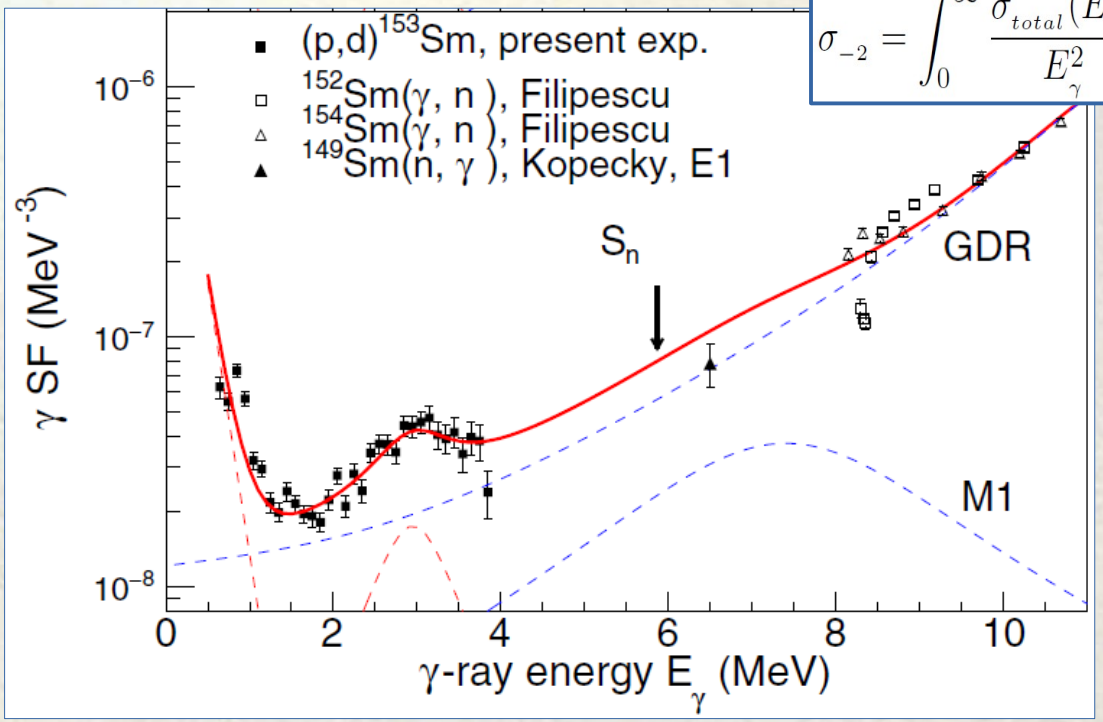


Kumar Raju, Nico Orce, Petr Navrátil *et al.*, Phys. Lett. B **777**, 250 (2018)

GDR + LEE effects on nuclear polarizability

Not a fair comparison, a priori

$$\sigma_{-2} = \int_0^\infty \frac{\sigma_{total}(E_\gamma)}{E_\gamma^2}\, dE_\gamma$$

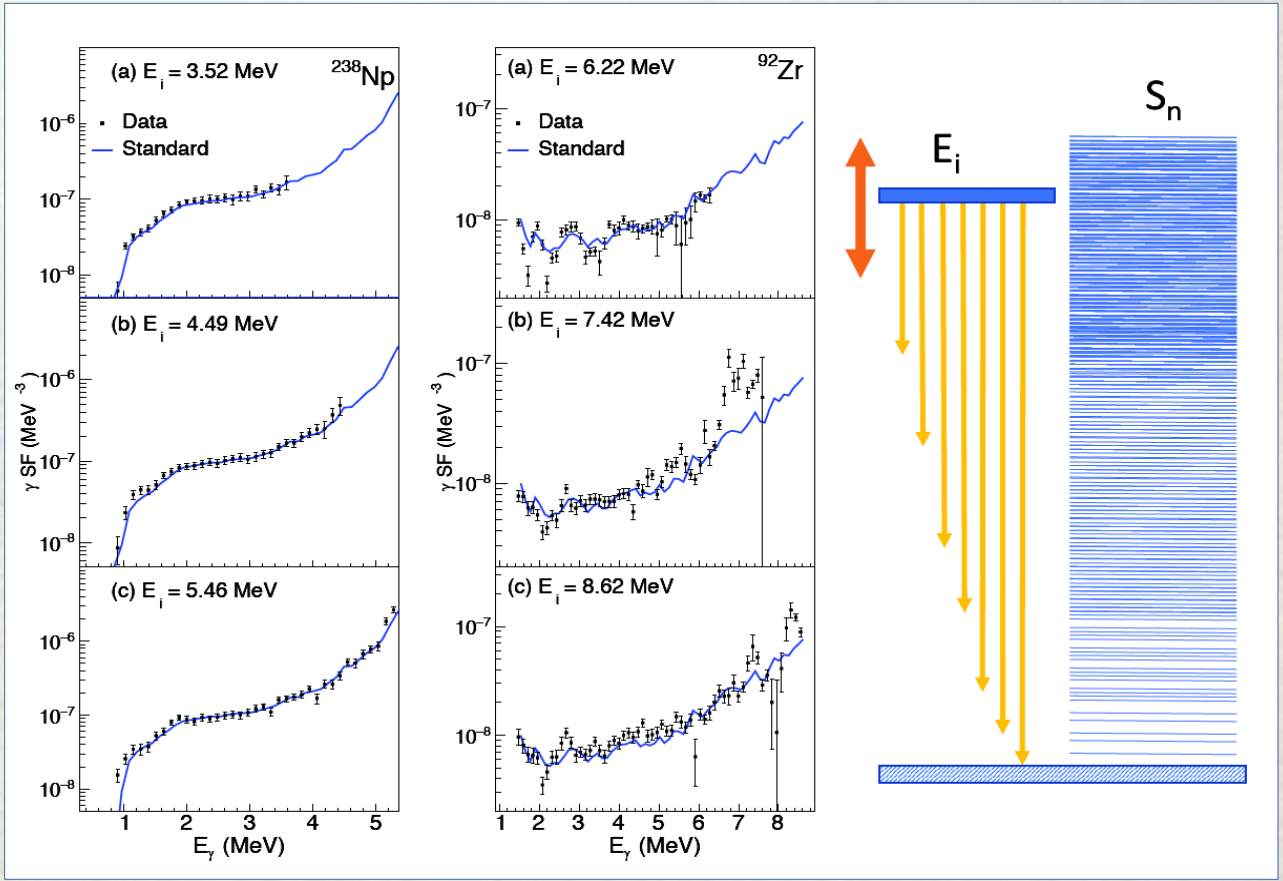


Simon *et al.*, Phys. Rev. C **93**, 034303 (2016)

The PDR may contribute ~5% in neutron-rich nuclei (von Neumann-Cosel)
High-energy contributions above the GDR (e.g., pion-exchanges) are negligible (< 5%)

Validity of the Brink-Axel hyphotesis

Gamma-strength function independent of the particular structure and only depends on E_γ

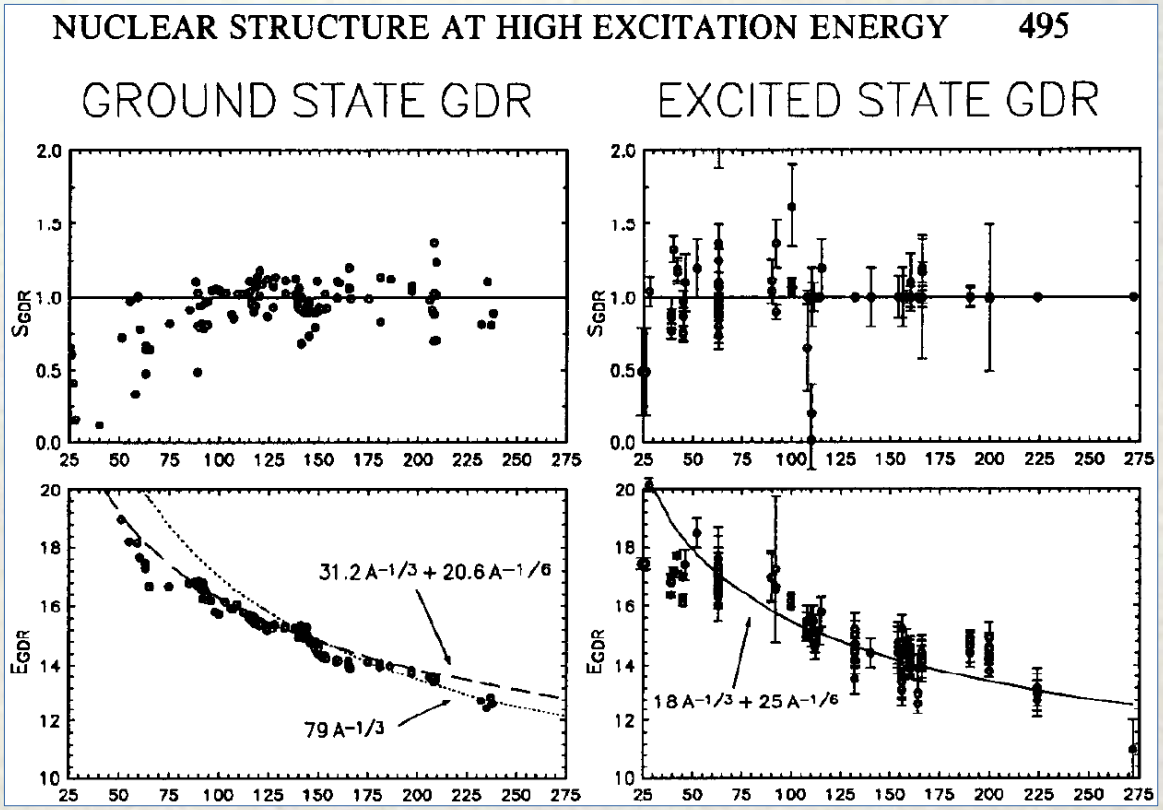


Gamma-ray strength functions of ^{238}Np (left) and ^{92}Zr (right) extracted from various initial excitation bins E_i.

Guttormsen *et al.*, Proceedings of Science (2017)

Validity of the Brink-Axel hyphotesis

Also states that a GDR can be built on any initial nuclear state (not only the g.s.)



Similar GDR properties for g.s. and excited state GDRs (at least for relatively cold GDRs)

J. J. Gaardhøje, Annu. Rev. Nucl. Part. Sci. **42** (1992) 483

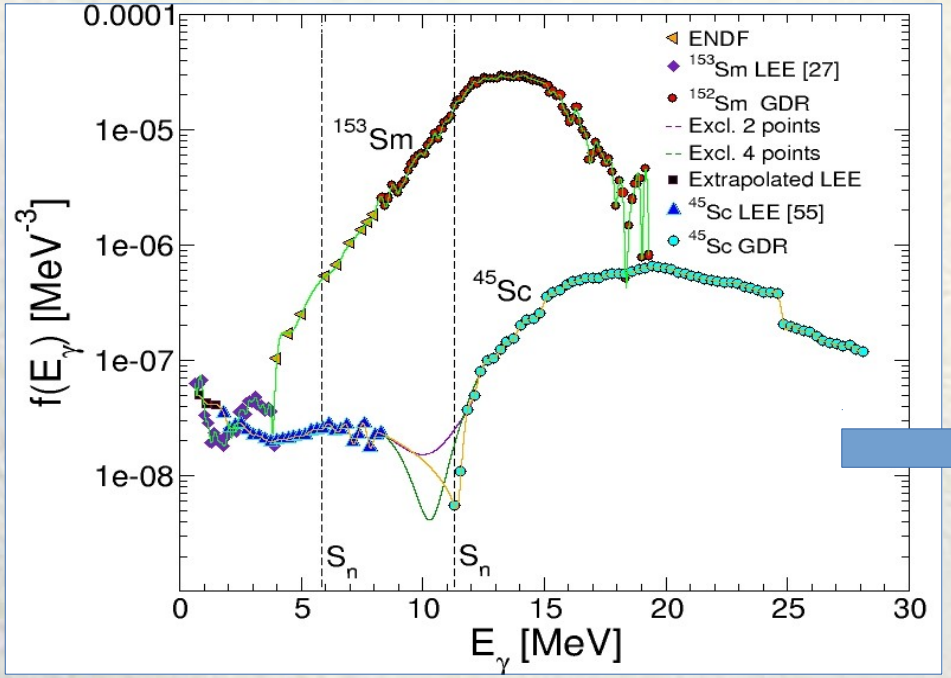
Combinging the GDR + LEE data

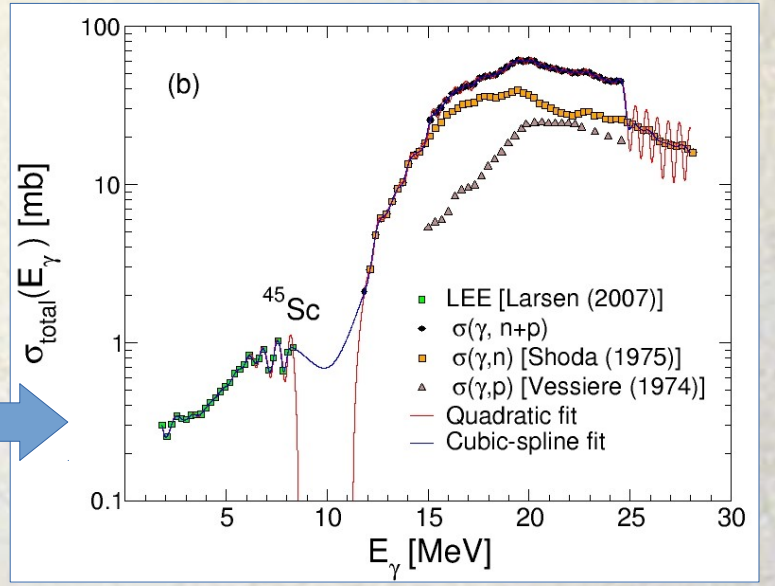
Assuming validity of the Brink-Axel hypothesis

$$f(E_\gamma) = \frac{1}{g_J \pi^2 (\hbar c)^2} \frac{\sigma_{total}(E_\gamma)}{E_\gamma} \text{ MeV}^{-3}$$

$$g_J = \frac{2J_f+1}{2J_i+1}$$

$$\sigma_{-2} = \int_0^\infty \frac{\sigma_{total}(E_\gamma)}{E_\gamma^2} dE_\gamma$$





Data from EXFOR, ENDF and Oslo compilation

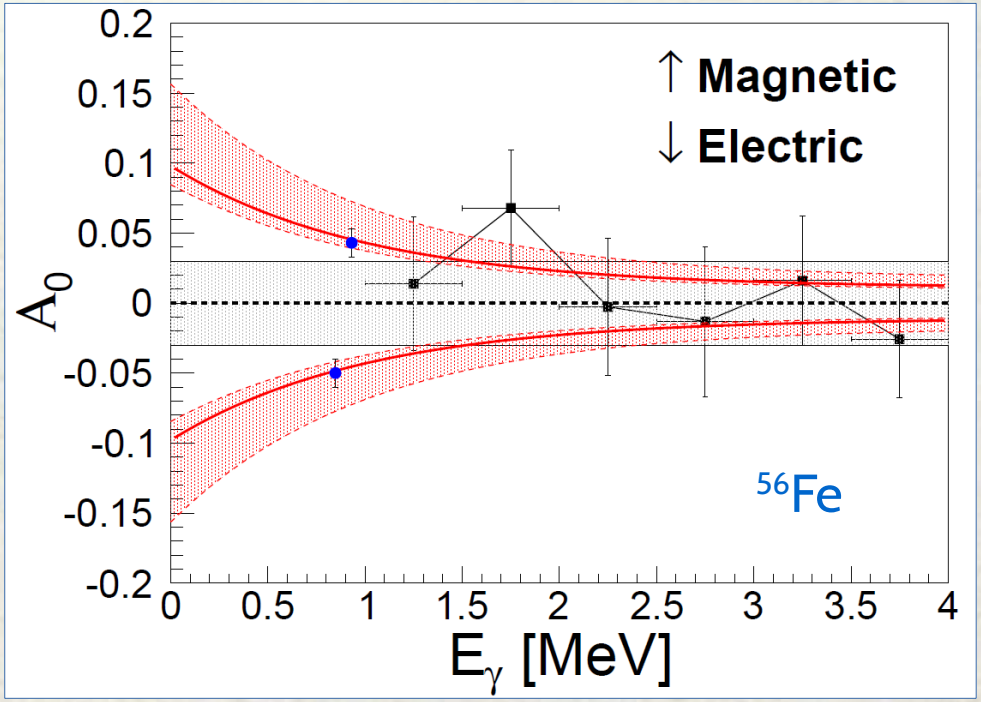
Combinging the GDR + LEE data

Polarization assymetry shows dipole radiation of LEE (admixture of M1 and E1 strength)

$$f(E_\gamma) = \frac{1}{g_J \pi^2 (\hbar c)^2} \frac{\sigma_{total}(E_\gamma)}{E_\gamma} \text{ MeV}^{-3}$$

$$g_J = \frac{2J_f+1}{2J_i+1}$$

For $\Delta J = 0$ and 1, $\langle g_J \rangle = 1$

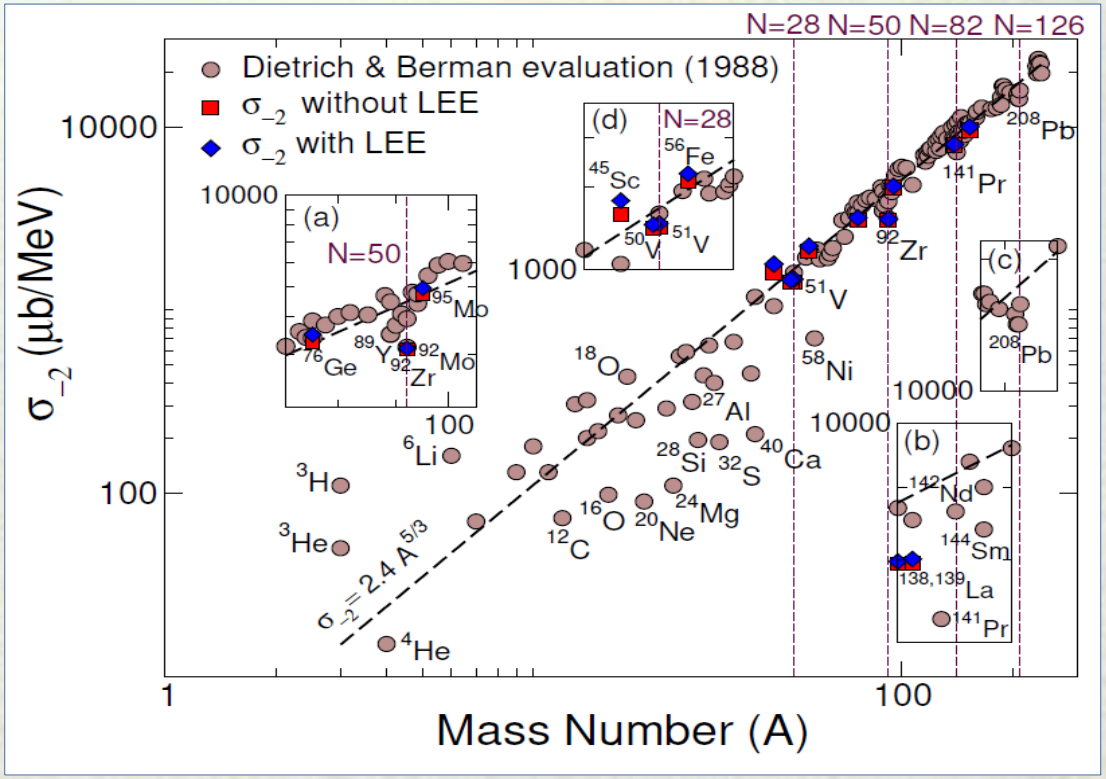


M. D. Jones, A.O. Macchiavelli, M. Wiedeking *et al.*, Phys. Rev. C **97**, 024327 (2018)

Continuing shell effects @ high-excitation energies

σ_{-2} values are sensitive measures of the long-range correlations in the nuclear wavefunctions

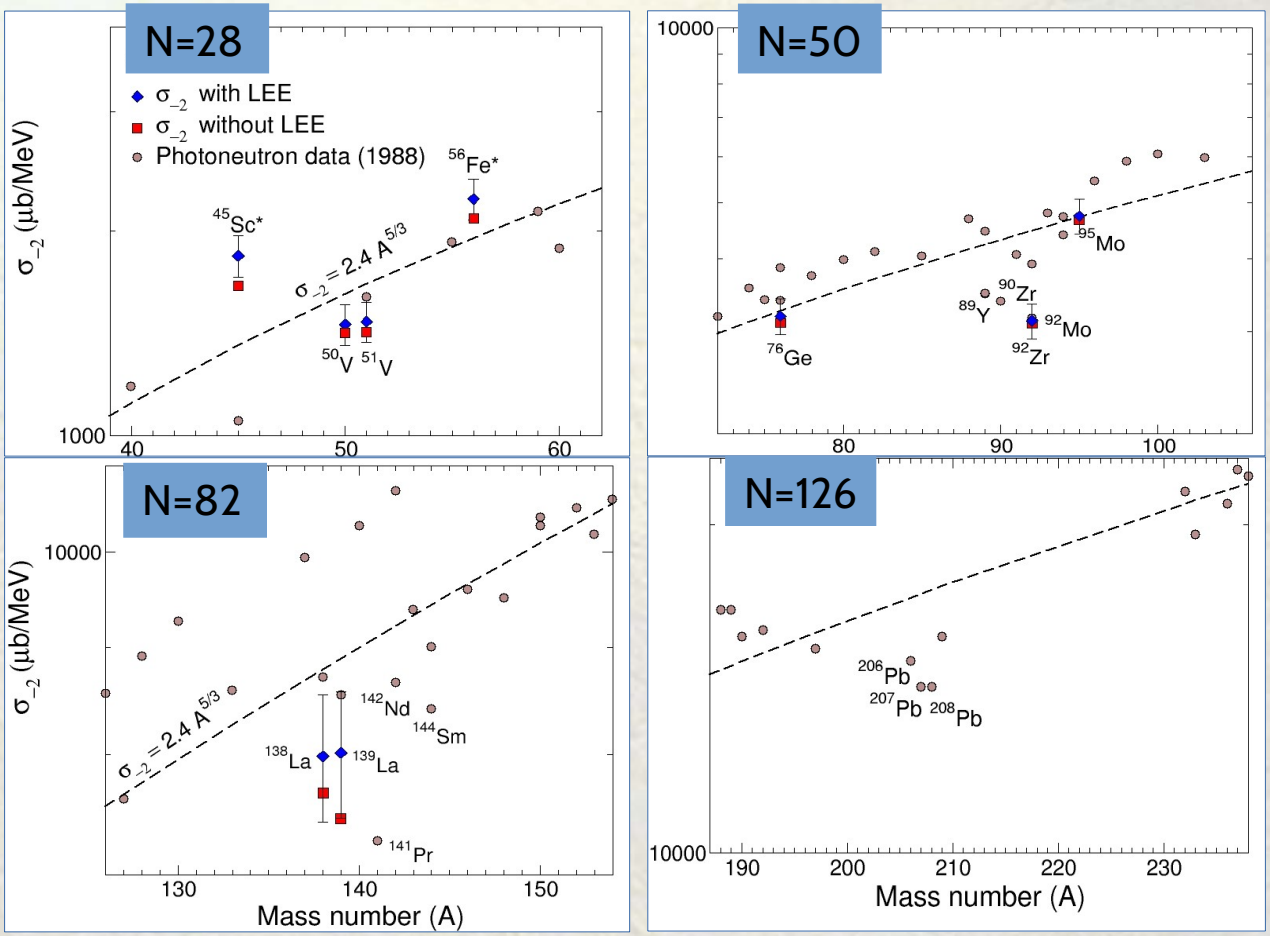
Cebo Ngwetsheni & Nico Orce, Phys. Lett. B **792**, 335 (2019)



Empirical drops in σ_{-2} values reveal the presence of shell effects in semi-magic nuclei with neutron magic numbers **N = 28, 50, 82 and 126**

Shell effects @ high-excitation energies

σ_{-2} values are sensitive measures of the long-range correlations in the nuclear wavefunctions

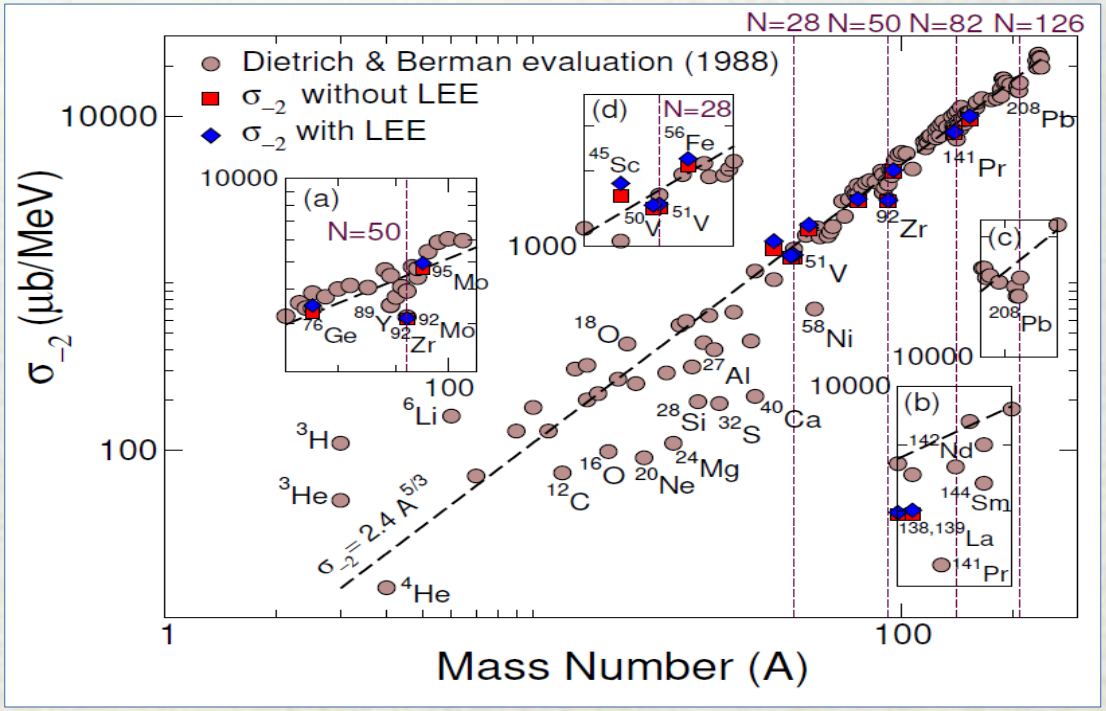


Cebo Ngwetsheni & Nico Orce, resubmitted to Hyperfine Interactions

Continuing shell effects @ high-excitation energies

σ_{-2} values are sensitive measures of the long-range correlations in the nuclear wavefunctions

Cebo Ngwetsheni & Nico Orce, Phys. Lett. B **792**, 335 (2019)



* Indirectly support recent large-scale SM calculations in the quasi-continuum region, describing the LEE radiation as induced paramagnetism.
* Assert the generalized Brink-Axel hypothesis as more universal than originally expected.

Discrepancy between the Livermore and Saclay photoneutron cross-section data

https://www-nds.iaea.org/CRPphotonuclear

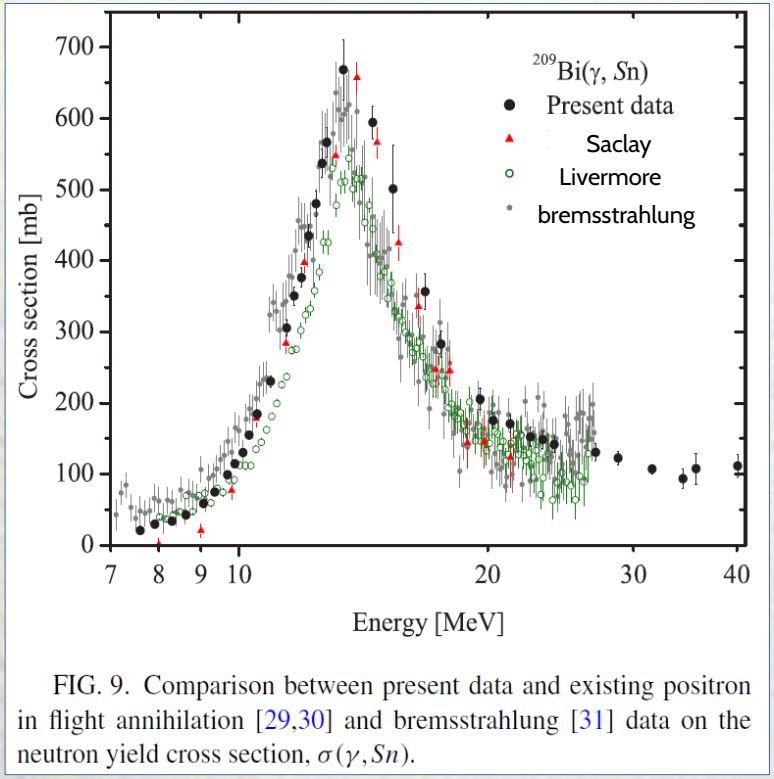


FIG. 9. Comparison between present data and existing positron in flight annihilation [29,30] and bremsstrahlung [31] data on the neutron yield cross section, $\sigma(\gamma, Sn)$.

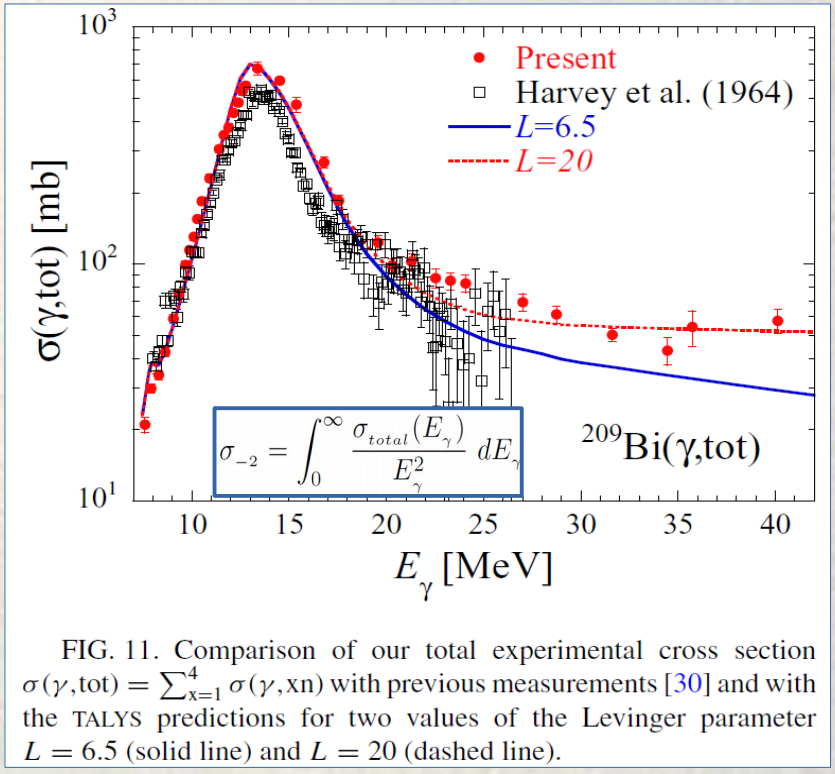


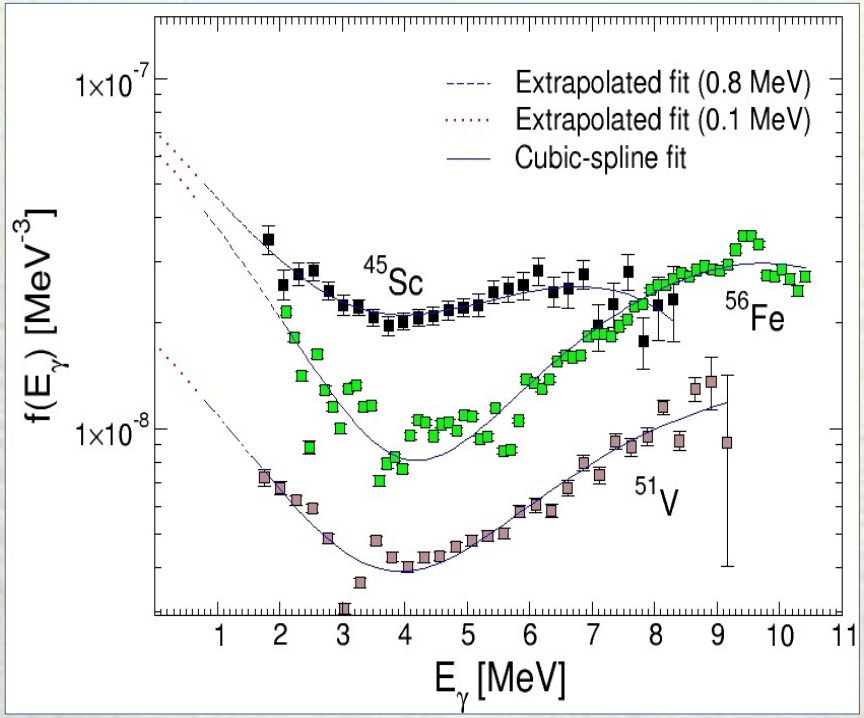
FIG. 11. Comparison of our total experimental cross section $\sigma(\gamma,\text{tot}) = \sum_{x=1}^{4} \sigma(\gamma,\text{xn})$ with previous measurements [30] and with the TALYS predictions for two values of the Levinger parameter $L = 6.5$ (solid line) and $L = 20$ (dashed line).

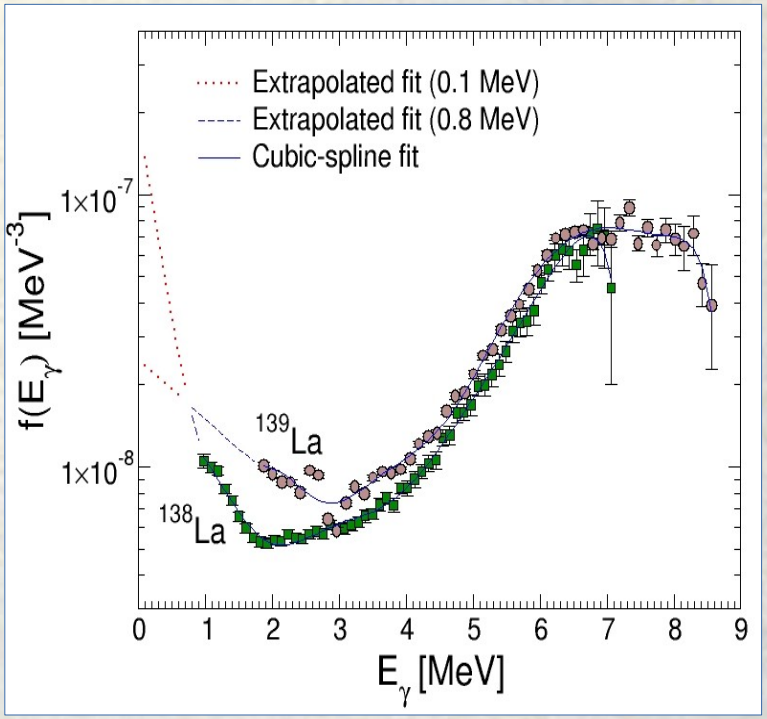
New data have raised an important discussion on the origin of the total photoneutron cross section at high energy, characterized by a survival of large (γ,n) cross sections above 20 MeV.

Gheorghe *et al.*, Phys. Rev. C (2017); first noted by Ishkhanov *et al.*, Phys. At. Nucl. **67**, 1664 (2004)

What about extrapolating the LEE at low E_γ ?

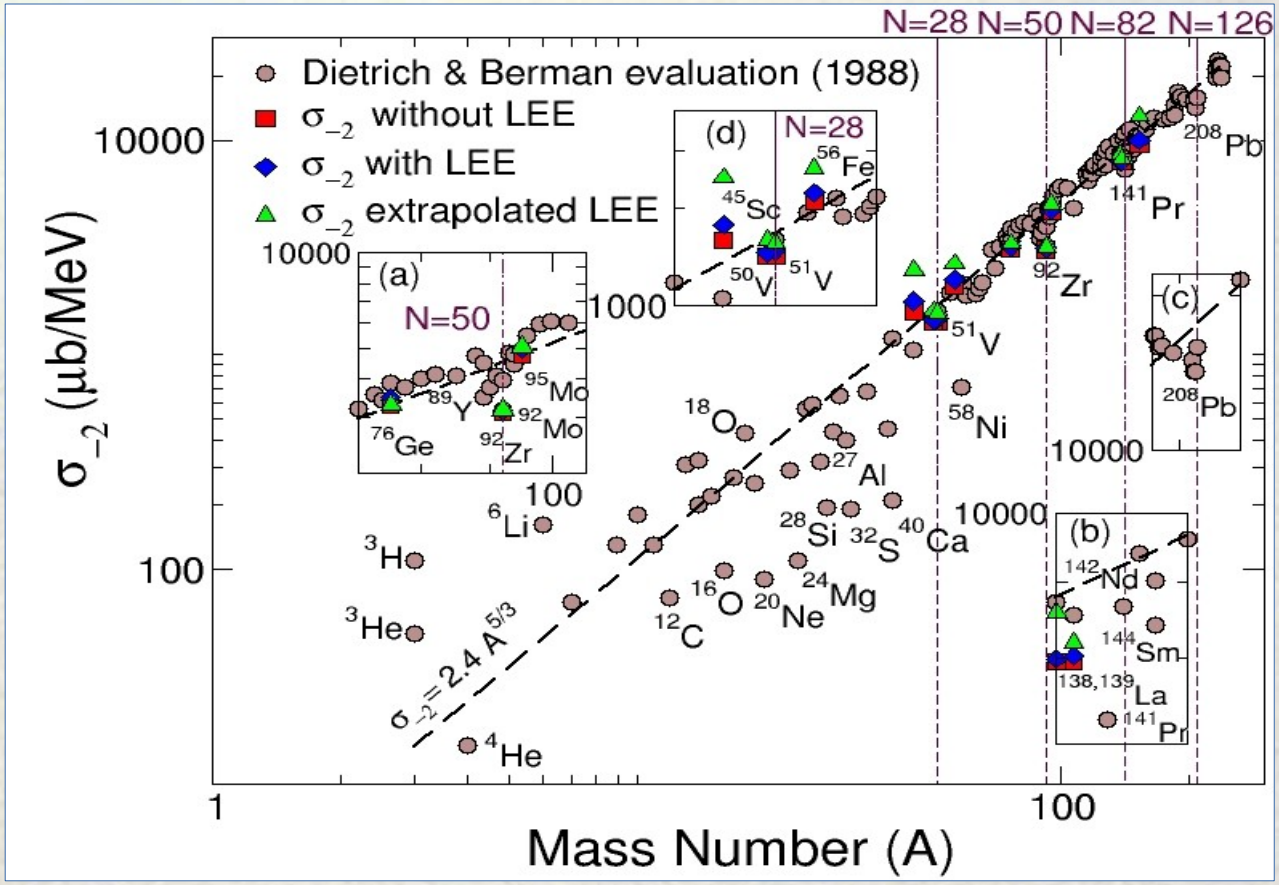
Previously we went down to E_γ ~800 keV (in agreement with experiment)





What about extrapolating the LEE at low E_γ ?

Subtantial enhancement/inhibition of nuclear polarizability away from/for magic numbers



Extrapolating **@** low E_γ provides higher-sensitivity of σ_{-2} values to shell effects

Conclusions @ high excitations

* Because of the $1/E_\gamma$ energy weighting σ_{-2} values are extremely sensitive measures of low-energy long-range correlations in the nuclear wave functions.

* Drops of σ_{-2} values provide evidence for shell effects and support shell model calculations.

* The origin of the LEE hence is supported as induced paramagnetism (with probably some mixing with E1 strength?).

* The generalized Brink-Axel hypothesis is more universal than originally expected and seems to account for structural effects.

* New spectroscopic probe to search for old and new magic numbers.

* New Physics framework to understand nuclei *@* high excitation.

* Lots of new data required.

News

Cebo Ngwetsheni's Endless Quest: Changing The World With Nuclear Physics And Farming

Author: Nicklaus Kruger

UWC Nuclear physicist Cebo Ngwetsheni is the first author of a groundbreaking paper on nuclear polarization published in Physics Letters - the journal in which the Nobel-deciding discovery of the Higgs boson - also known as "God particle" - was published.

was published by CERN. This is just the beginni

Ngwetsheni has just started his PhD at the Univ
as an undergraduate.

"Cebo has achieved a beautiful piece of physics
thesis supervisor and co-author of the paper. "A
probe to search for magic numbers at high-excit
more exciting in what it means for UWC, as the only solely UWC-published paper we've had in this prestigious journal."

The paper, Continuing influence of shell effects at high-excitation energies, established a continuation of shell effects at High Excitation Energies.

Elsevier Physics
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Follow

Nuclear physicist Cebo Ngwetsheni is leading the way into the investigation of the very core of matter - groundbreaking paper on nuclear polarization, just published in Physics Letters B #openaccess #SCOAP3 - free to authors, free to readers bit.ly/2HmCha3

Congratulations to Cebo Ngwetsheni

The first author of a groundbreaking paper on nuclear polarization, just published in Physics Letters B

3:42 AM - 16 May 2019

Times LIVE

NEWS POLITICS 2019 ELECTIONS SPORT TSHISALIVE LIFESTYLE BUSINESS

SOUTH AFRICA

There are no limits, says Cape Town nuclear boffin hitting the heights

15 May 2019 - 13:56
BY LEILA STEIN

Nuclear physicist Cebo Ngwetsheni at work at the University of the Western Cape.
Image: UWC

A South African nuclear physicist has made it into one of the world's leading scientific journals with his research on nuclear polarisation.

National Research Foundation
9 hrs

Congrats to Cebo Ngwetsheni, a PhD student at UWC, on being the first author of a "groundbreaking paper" on nuclear polarization published in the prestigious Physics Letters journal.

The NRF was a funder of the research.

Motives for Scientific Creativity

ARKADIĬ BENEDIKTOVICH MIGDAL
(1911–1991)

Not for you are passion and goldlust,
It is science that entices you.

Passion may fade and love is betrayed
But you cannot be deceived
By the bewitching structure of the cockroach.

N. Olennikov, Comic Verses

On the Psychology of Scientific Creativity
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