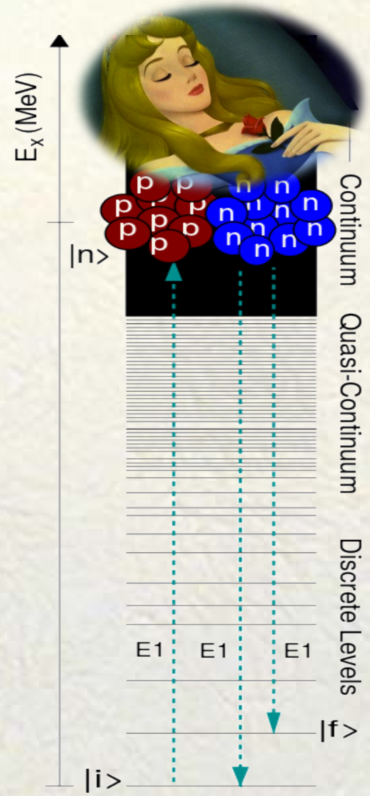
How atomic nuclei polarize

Recent issues with 3N forces, nuclear clusters and shell model



UNIVERSITY of the WESTERN CAPE

Nico Orce @ RINP2, 4 February 2019

Visva-Bharati University

University of the Western Cape

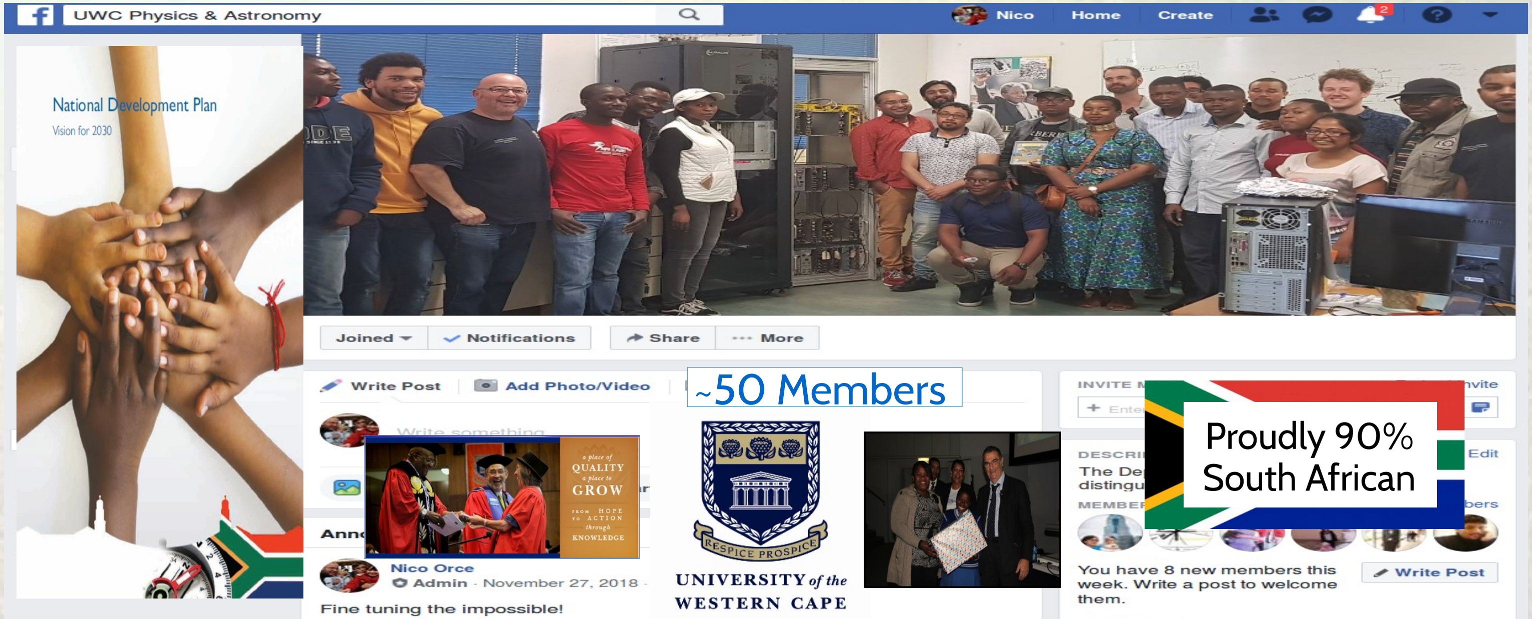
First Colour University in South Africa

UNIVERSITY *of the* WESTERN CAPE

Nico Orce @ RINP2, 4 February 2019

2019 Fundamental Nuclear Physics & Applications @ UWC

Experiments @ UWC, iThemba LABS, HIE-SOLDE, Washington, MLL & TRIUMF



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Postdocs: Kushal Kapoor, Rakesh Dubey, Joash Ongori

https://nuclear.uwc.ac.za

New GAMKA array + new Beams @ iThemba LABS

Lots of new beams (Ni, Ru, Pd, Pt, Sm, Mg, etc) though MIVOC method with enriched isotopic material ($^{60-62}$Ni beams by N. Kheswa, PhD/UWC)

GAMKA: any combination (up to 30) of clover + LaBr3 + ancillary detectors

GAMKA – the Lion: Gamma-ray AsyMmetric spectrometer for Knowledge in Africa
R35M~Rup175M funded by Strategic Research Equipment Programme NRF/DST

https://www.nrf.ac.za/media-room/news/nrf-funds-state-art-nuclear-spectrometer-uwc

Modern African Nuclear DEtector LAboratory @ UWC

Global Challenge Research Funds (STFC/UK) in collaboration with the University of York (David Jenkins + Physics Department), Stellenbosch University (JJ van Zyl)

New digital DAQ developed @ UWC by Kushal Kapoor

A major UWC effort (more than 50 people involved: Mogammad Allie, finance, HR, business & innovation, technical services, campus lifestyle, ICS…)

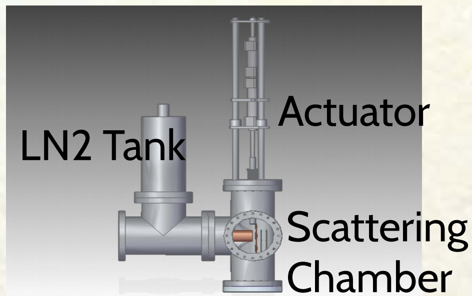
National Research Foundation

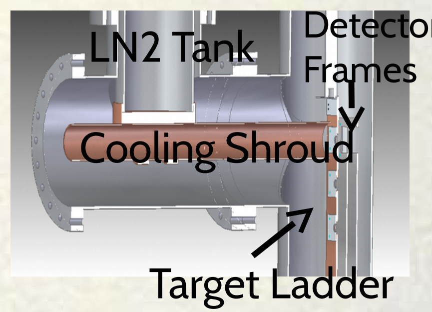
science & technology
Department: Science and Technology
REPUBLIC OF SOUTH AFRICA

ENSAR2

New beam line to measure short nuclear lifetimes @ iThemba LABS

Nuclear Physics and Nuclear Astrophysics





Inverse kinematics (on ^{3}He implanted target) at forward angles (particle-γ)

Bhivek Singh (MSc & PhD), Smarajit Triambak (PI), Rakesh Dubey, the UWC Group and Accelerator Group at iThemba LABS

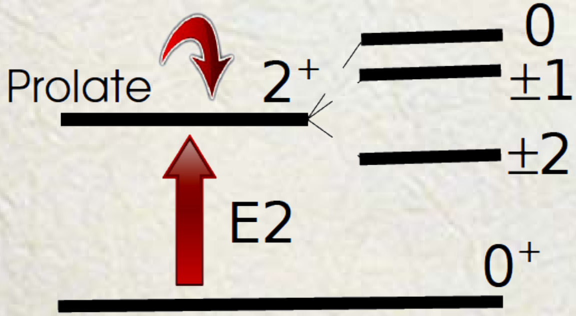
Reorientation Effect

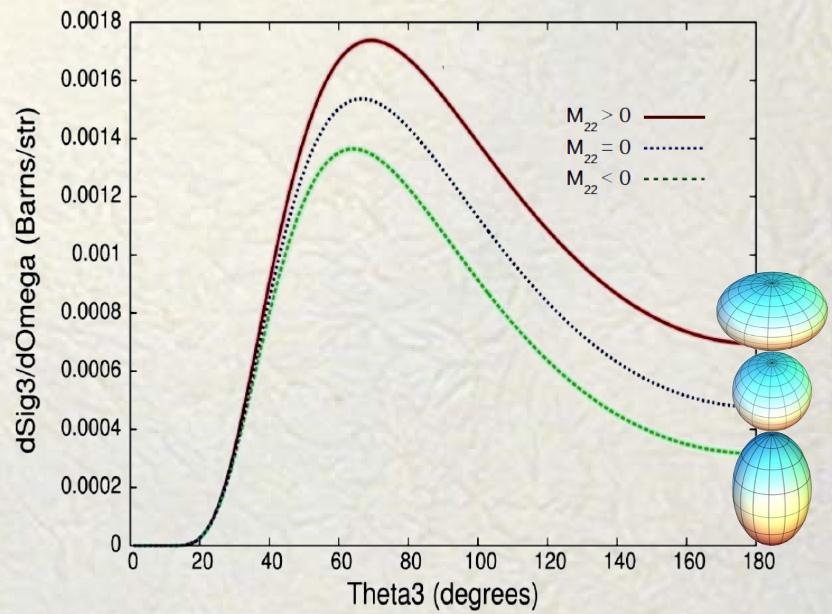
Measuring Spectroscopic Quadrupole Moments

(2nd order effect in Coulomb excitation)

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

Both projectile and target experience strong time-dependent field gradients



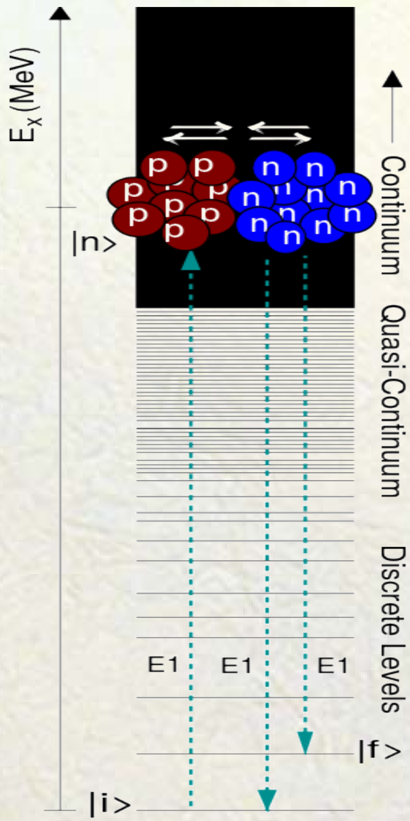


Which leads to a change in the Coulomb- excitation cross section as a function of the scattering angle θ

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

Nuclear Polarizability (another second order effect)

High impact in spectroscopic quadrupole moment measurements of light nuclei



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

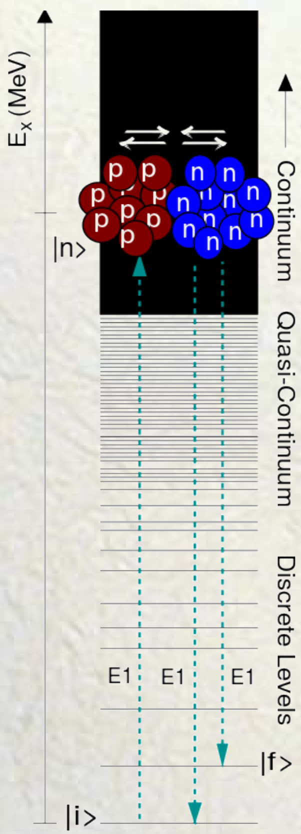
Large E1 matrix elements via virtual excitations of the GDR may polarize the shape of the ground and excited states

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

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

Nuclear Polarizability, α

A B 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

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

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

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

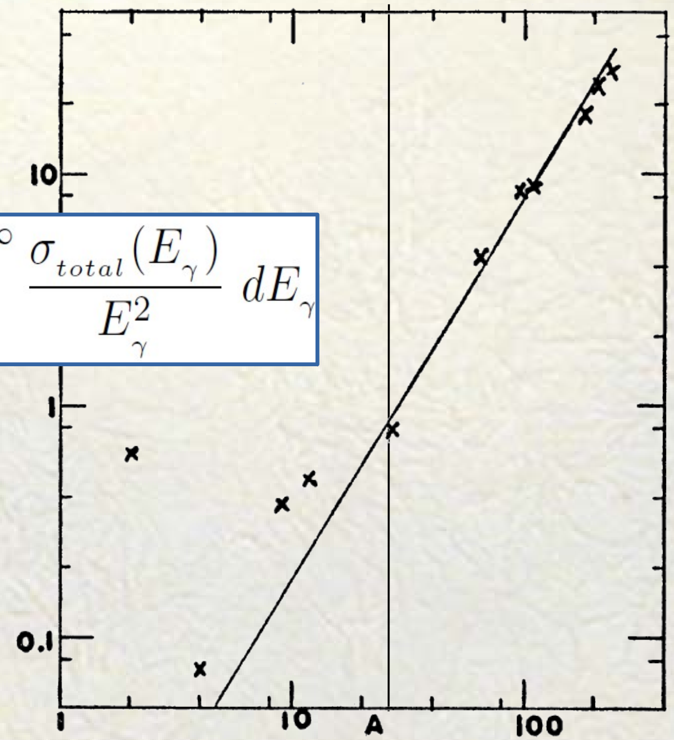
A.B. Migdal, J. Exp. Theor. Phys. USSR **15**, 81 (1945)

Nuclear Polarizability, α

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

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

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



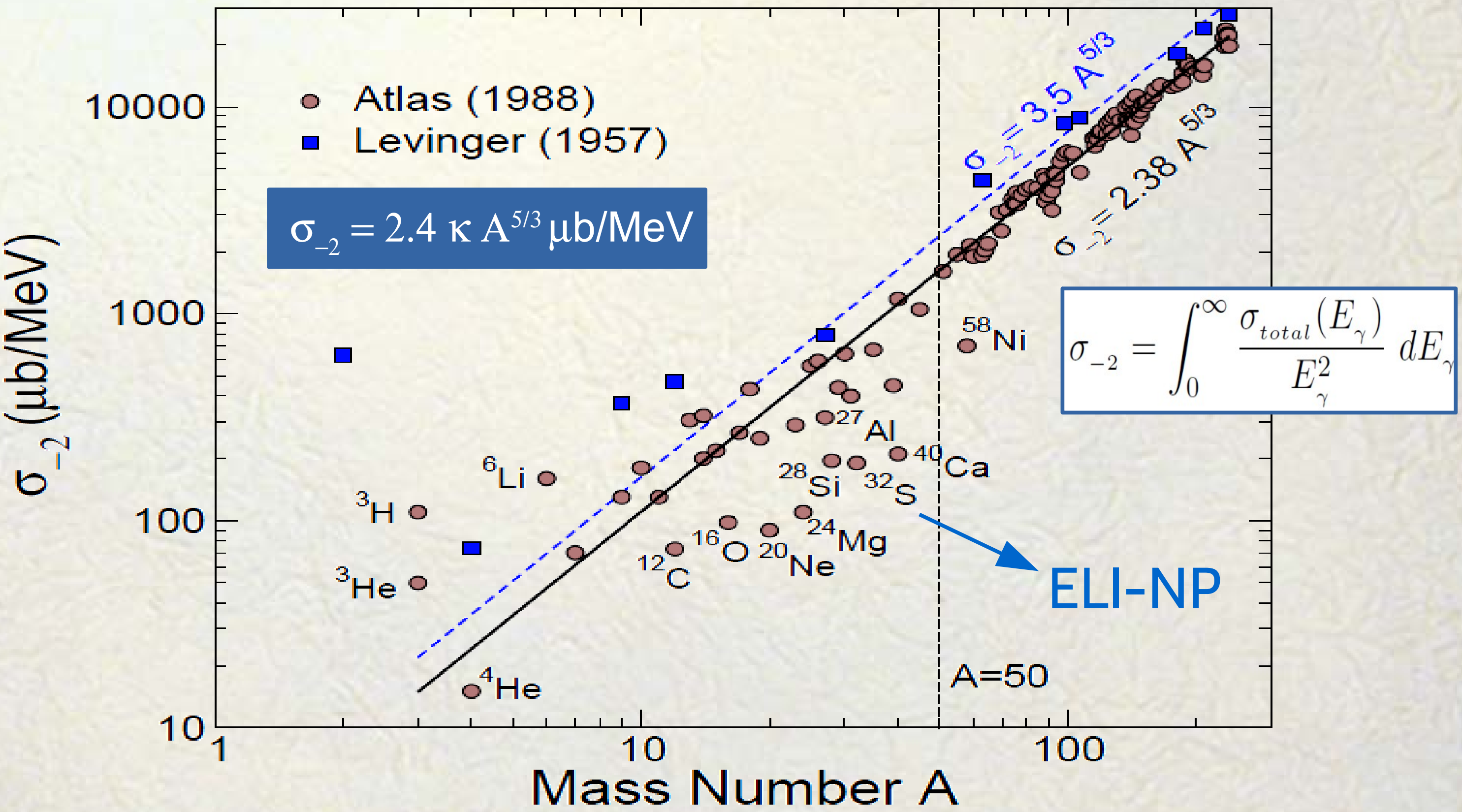
The κ polarizability parameter: deviations from the GDR effects for light nuclei

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

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)

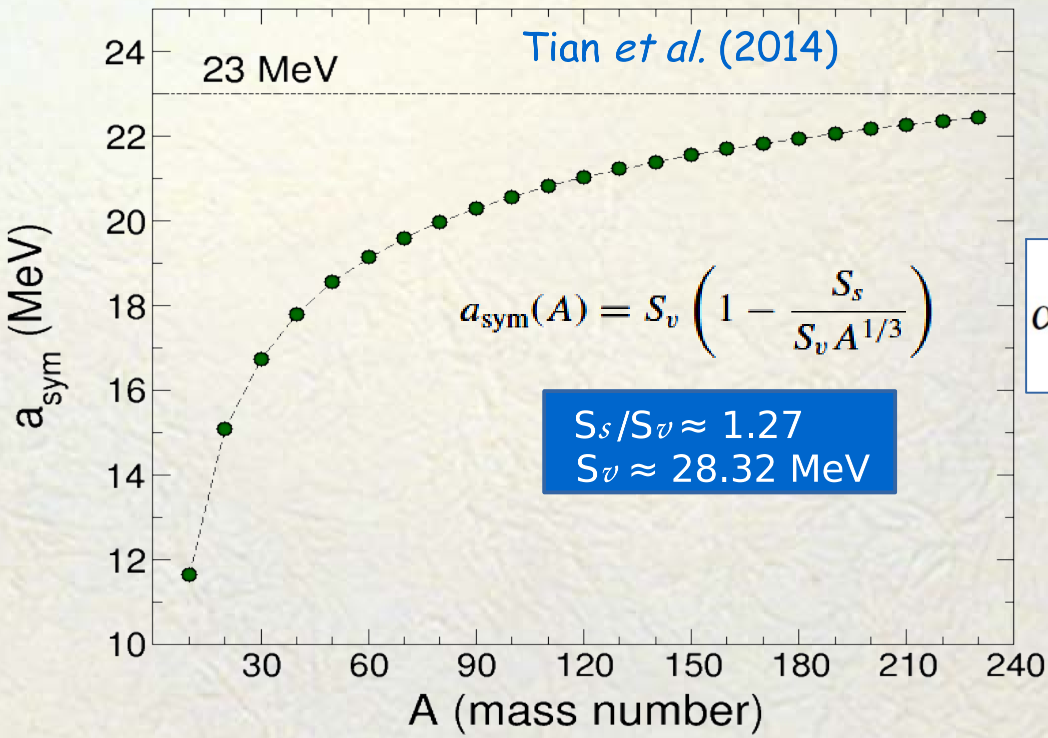


$\kappa > 1$ for light loosely bound nuclei (also from Coulex: ^{6}Li, ^{7}Li, ^{17}O)

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

a_{sym} is not 23 MeV but there's a mass dependence: $a_{sym}(A)$

From a global fit to the binding energies of isobaric nuclei with A $\geq$ 10, extracted from the 2012 atomic mass evaluation

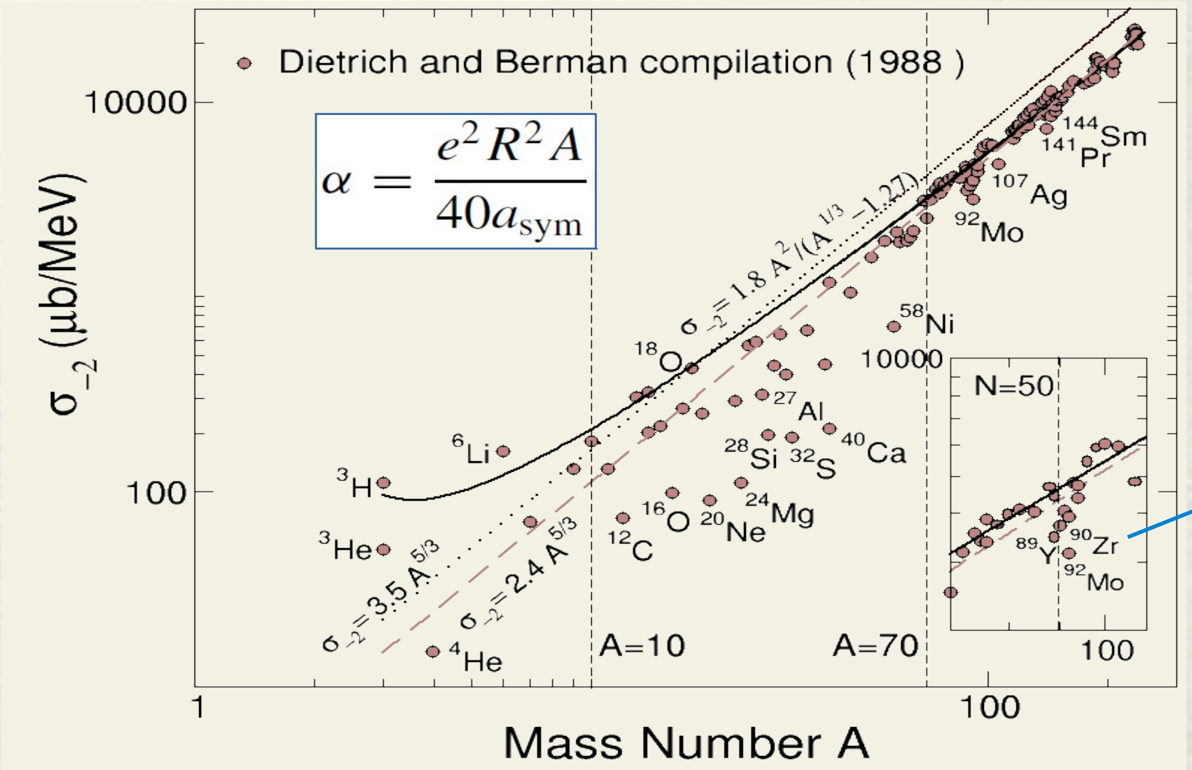


$$\alpha = \frac{e^2 R^2 A}{40 a_{sym}}$$

The nuclear symmetry energy, $a_{sym}(A)$, is key to understanding the elusive equation of state of neutron-rich matter, which impacts three-nucleon forces, neutron skins, neutron stars and supernova cores

New formula for σ_{-2} from $a_{sym}(A)$

The increasing upbend observed as A decreases provides an explanation for the large GDR effects observed in light nuclei. Both merge with data at A$\sim$70



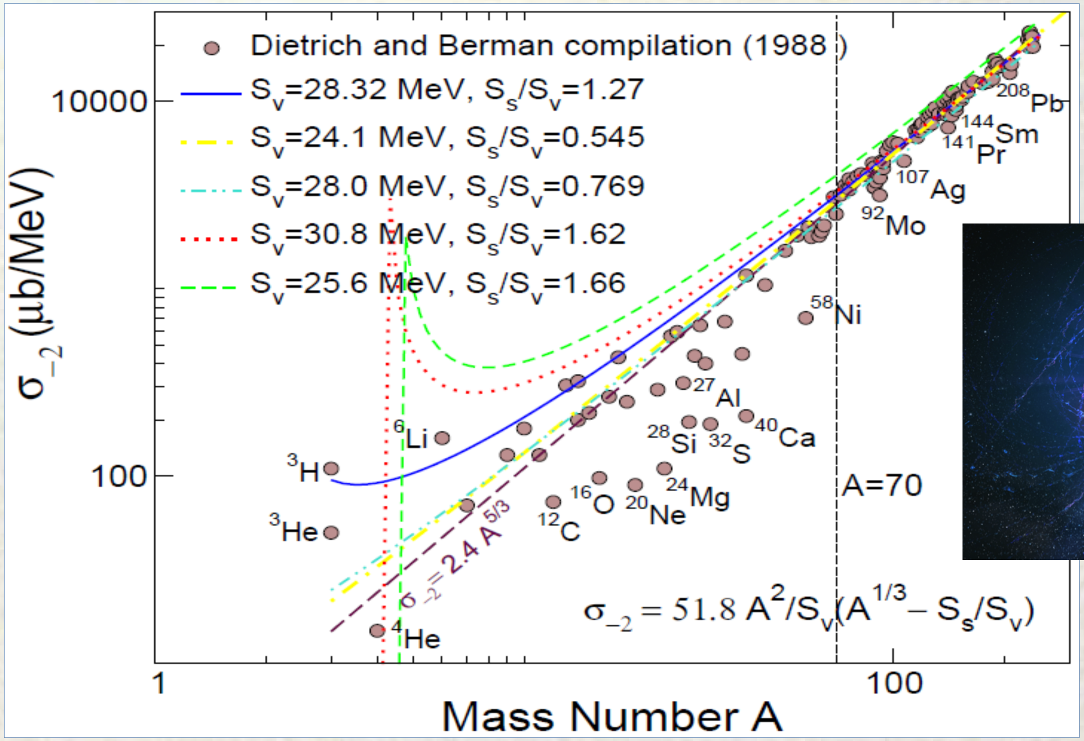
Shell effects!

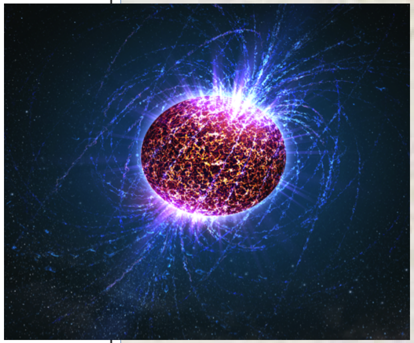
$\kappa > 1$ for light loosely bound nuclei, J. N. Orce, PRC (2015)

The validity of the hydrodynamic model to be tested for the lightest $A < 10$ nuclei

Constraining $a_{sym}(A)$

High-precision relativistic (p,p') measurements of α by von Neumann-Cozel *et al.*, high-energy, binding energies, total photo-absorption cross sections and IVGDRs

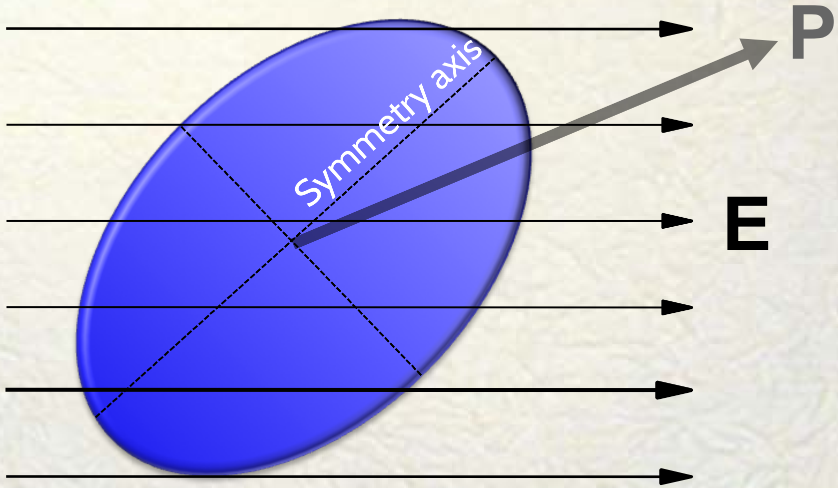




J. N. Orce, Proc. of the 4th South Africa - JINR Symposium (2016)
P. von Neunman-Cosel PRC (2016) + J. N. Orce, PRC (2016)

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

The torque produced by the interaction between **E** and **P** may set the nucleus into rotation → **enhancement of quadrupole collectivity**



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

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

Polarization potential reduces the effective quadrupole potential

K. Alder, A. Winther - Electromagnetic Excitation (1975) – Appendix J

$$V_{eff}(t) = V_0(t)\ \left(1 - V_{pol}(t)\right)$$
$$= V_0(t)\left(1 - z\frac{a}{r(t)}\right).$$

default value in GOSIA Coulex code

$$z = \frac{10 Z_t \alpha}{3 Z_p R^2 a} \approx \boxed{0.0039}\ \frac{E_p A_p}{Z_p^2 (1 + A_p/A_t)} \quad \text{for } \kappa = 1$$

$$\boxed{\alpha = \frac{\hbar c}{4\pi^2}\sigma_{-2} \qquad \sigma_{-2} = 2.4\,\kappa\, A^{5/3}\ \mu\text{b/MeV}}$$

Adjustable empirical E1 polarization strength (Häusser, Vermeer (1960-70s))

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

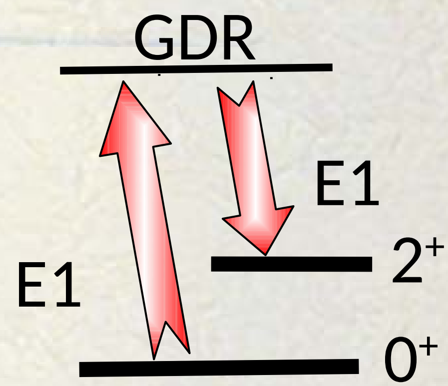
The nuclear polarizability κ from Coulex & SM calculations

Häusser, Barker, Navratil

GDR Contribution to Coulomb Excitation. I
1p Shell Nuclei

F. C. Barker Aust. J. Phys. (1982)

Department of Theoretical Physics, Research School of Physical Sciences,
Australian National University, P.O. Box 4, Canberra, A.C.T. 2600.



$$X \equiv S(\mathrm{E1})/\langle \mathrm{i} \,\|\, \mathscr{M}(\mathrm{E2}) \,\|\, \mathrm{f} \rangle\,,$$

$$S(\mathrm{E1}) = \sum_n W(11I_\mathrm{i}\,I_\mathrm{f}, 2I_n)\langle \mathrm{i} \,\|\, \mathscr{M}(\mathrm{E1}) \,\|\, n\rangle\langle n \,\|\, \mathscr{M}(\mathrm{E1}) \,\|\, \mathrm{f}\rangle/(E_n - E_\mathrm{i})$$

$$X_0 = 0{\cdot}00058\, A/Z \;\; e\,\mathrm{MeV}^{-1}\,.$$

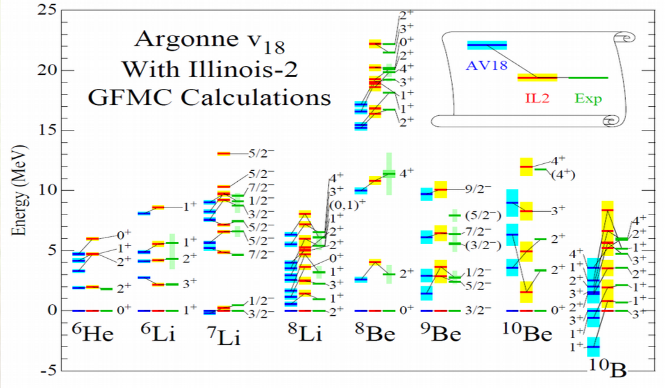
$$\boxed{k = X/X_0}$$

$$V_{\mathrm{eff}}(t) = V_0(t)\left(1 - 9.6\,\frac{E}{Z}\;\frac{S(\mathrm{E1})}{\langle \mathrm{i}\|\mathscr{M}(E2)\|\mathrm{f}\rangle}\;\frac{a}{r_\mathrm{p}(t)}\right)$$

O. Häusser, NPA (1973)

A few examples of nuclear polarizability effects

3N forces, cluster formation, shell effects @ high-excitation energies



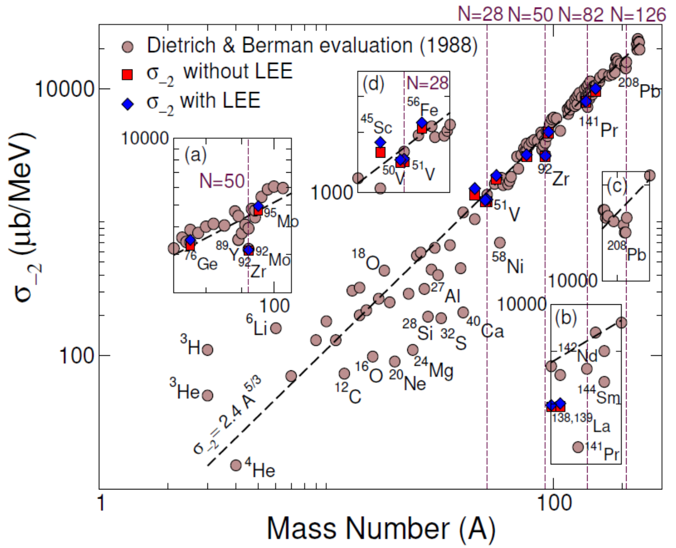
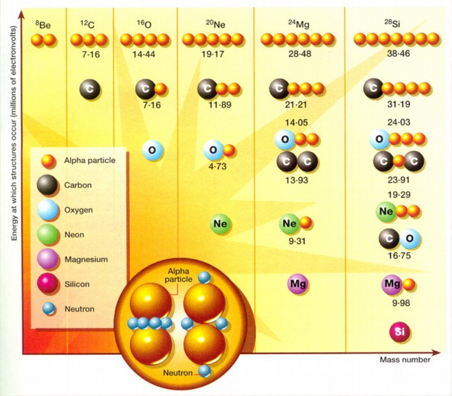


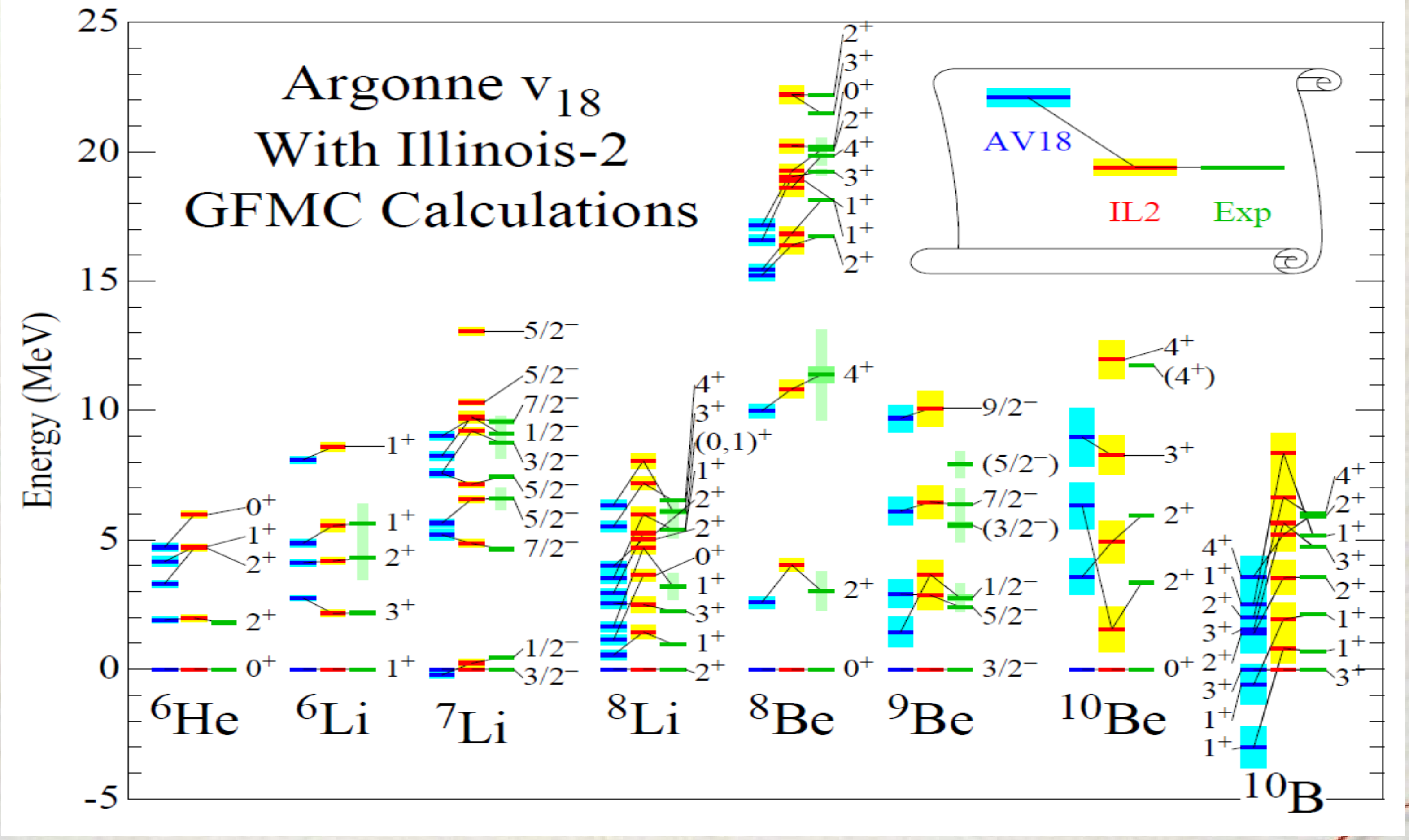
Figure 2: (Color online) σ_{-2} *vs* A on a log-log scale from the photo-neutron cross-section evaluation (solid circles) [13] and σ_{-2} data listed in Table 1 excluding (squares) and including (diamonds) the LEE contributions. For comparison, Eq. 7 (dashed line) is plotted.



JNO et al., PRC(R) (2015), J.N. Orce, PRC (2016), Kumar Raju, JNO et al., PLB(2018), Cebo Ngwetsheni & JNO submitted to PLB (2019) (see Cebo's poster)

2N + 3N forces

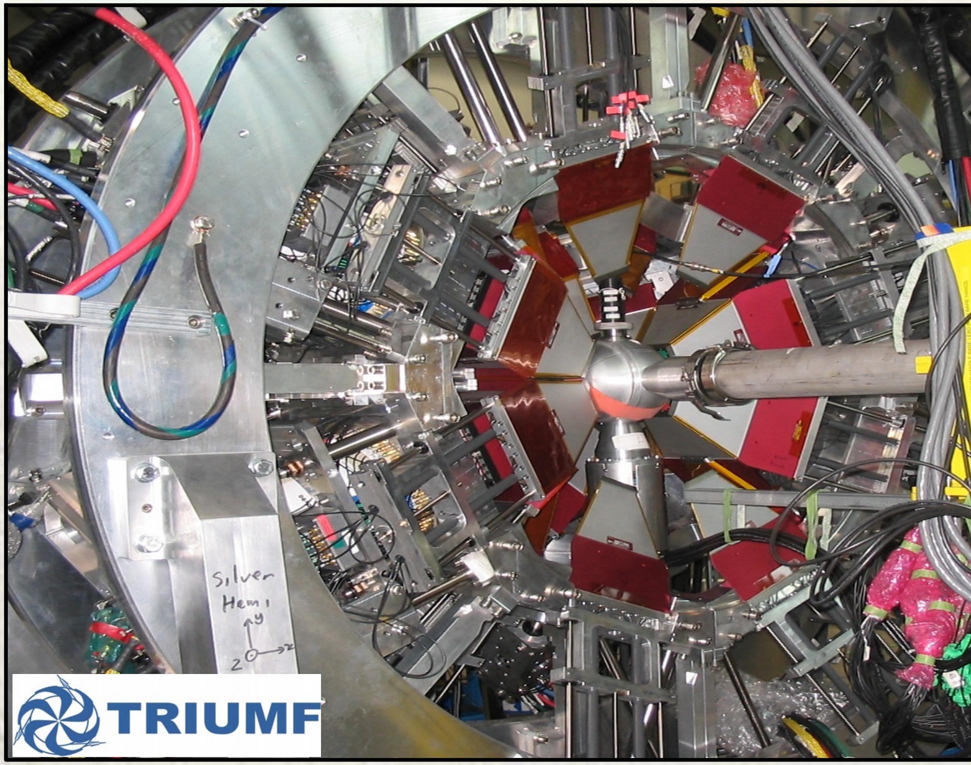
Right sequence of states for ^{10}Be

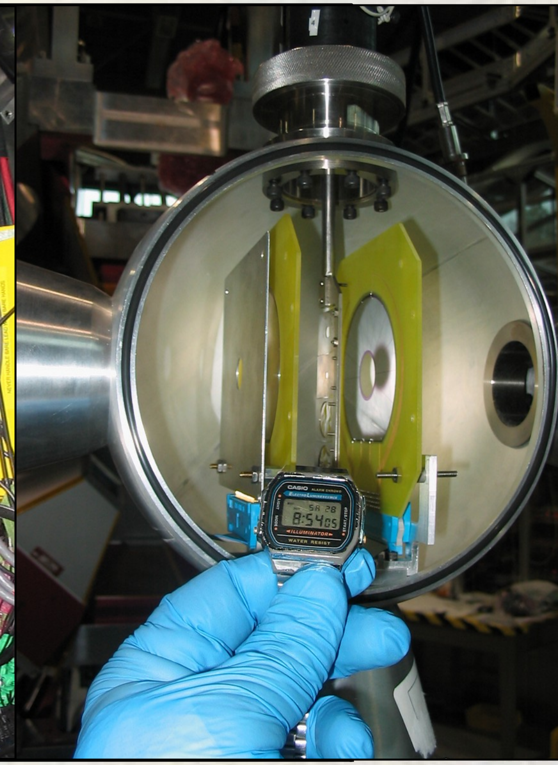


S.C. Pieper / Nuclear Physics A **751** (2005) 516c–532c 525c

Reorientation effect study @ TIGRESS

$^{194}Pt(^{10}Be, ^{10}Be^{*})^{194}Pt^{*}$ @ 41 MeV



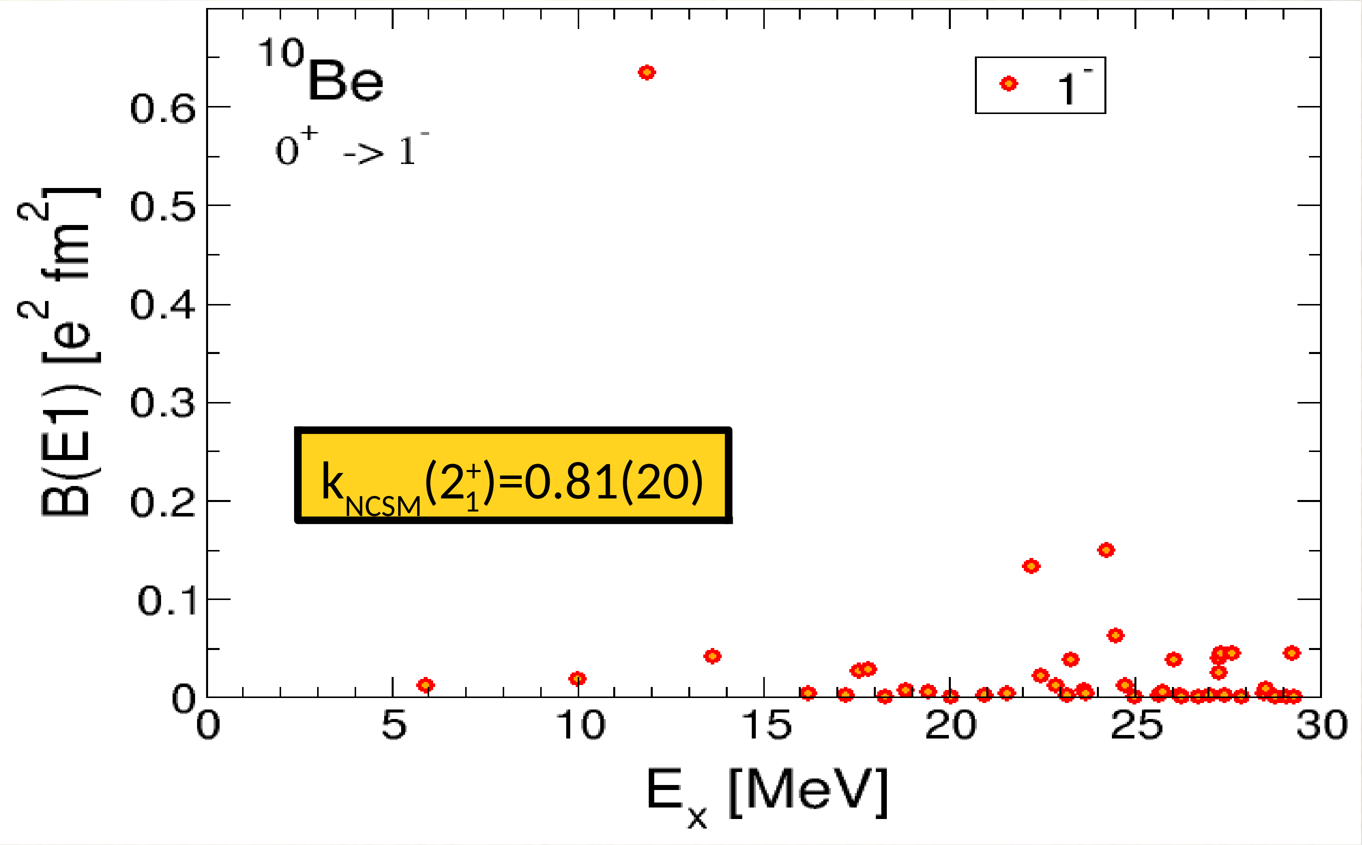


Particle-gamma coincidence measurement

8 TIGRESS detectos + S3 detector covering scattering angles of [30.7°, 61.0°]

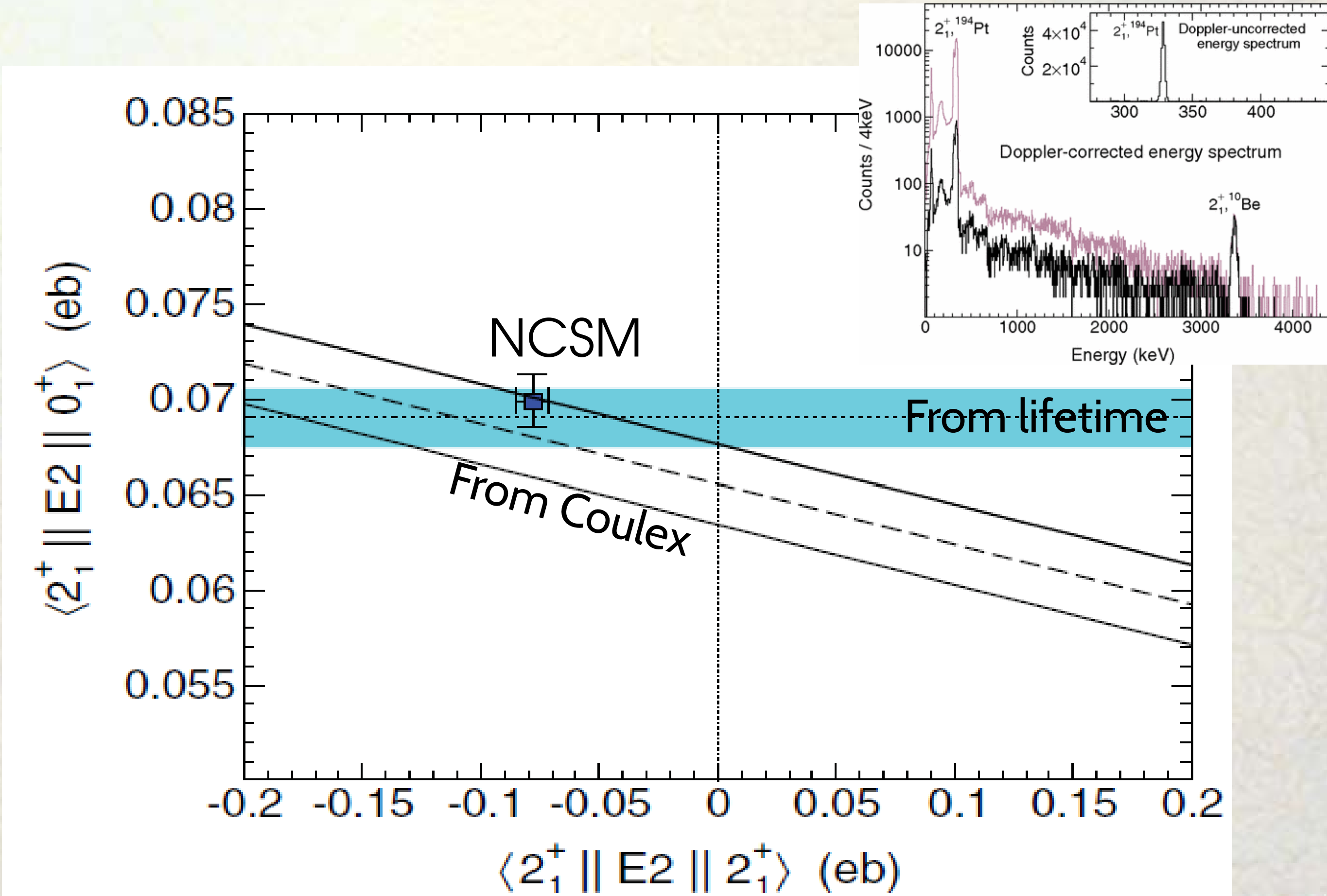
Coulomb-excitation analysis

2^{+} polarizability from NCSM (2N/CD Bonn 2000)



Coulomb-excitation Analysis

We determine a prolate shape for ^{10}Be from GOSIA + ab initio calculations



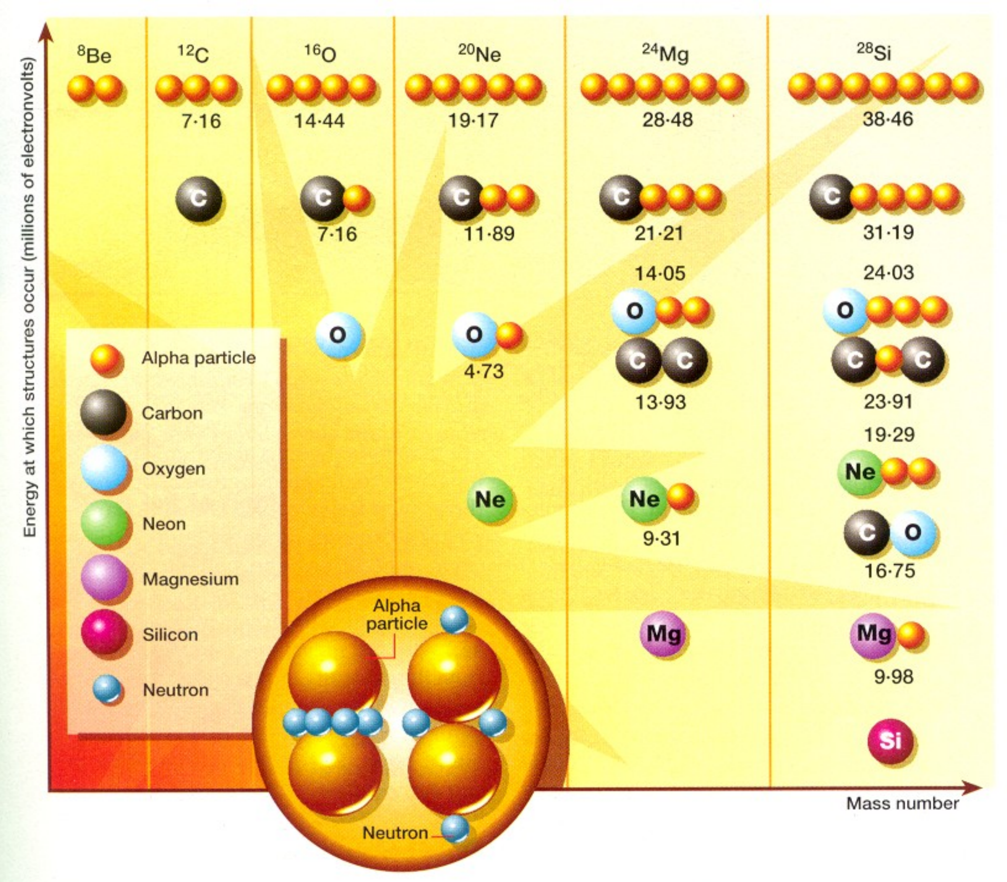
JNO et al., PRC(R) (2012)

Conclusions - we agree with theory but…

In summary, we have demonstrated the feasibility of reorientation-effect Coulomb-excitation studies of high-lying 2_1^+ states in light nuclei using accelerated radioactive ion beams and a high-efficiency γ-ray spectrometer such as TIGRESS. This work assigns a negative sign to the $\langle 2_1^+ \| \hat{E}2 \| 2_1^+ \rangle$ diagonal matrix element in ^{10}Be. A more precise measurement requires higher statistics for the population of the 2_1^+ state as well as the measurement of the $k(2_1^+)$ polarizability parameter. Assuming an ideal rotor, $Q_S(2_1^+) < 0$; we are in agreement with *ab initio* calculations based on large-basis NCSM calculations with the CD-Bonn 2000 $2N$ potential and GFMC calculations including $3N$ forces in the full Hamiltonian. Such experiments play an important role in achieving a deeper understanding of the contributions of $2N$ and $3N$ potentials to the nuclear spin-orbit interaction, and how these contributions affect electric-quadrupole matrix elements motivates further experimental, as well as theoretical, investigations in this region of light nuclei.

Issues with the Morinaga-Ikeda Picture

α clusters can emerge gradually as the internal energy
of the nucleus increases and are fully realized at the α threshold

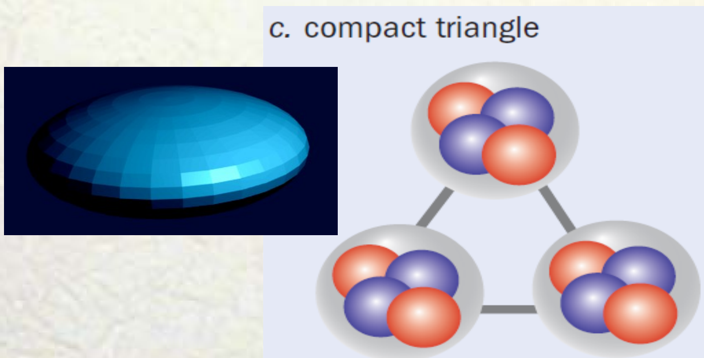


H. Morinaga, Phys. Rev. **101**, 254 (1956)
Ikeda, K., N. Takigawa, and H. Horiuchi, Prog. Theor. Phys. Suppl. **E68**, 464 (1968)

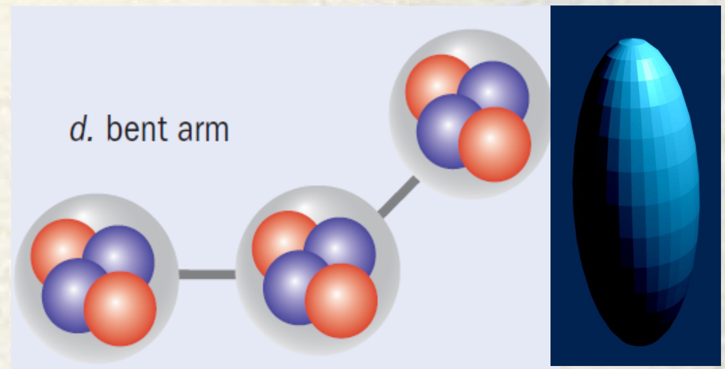
ab initio calculations of the Hoyle State

Chiral perturbation theory on a lattice with Monte-Carlo techniques
No assumptions about the structure of the wave function of the nuclear state of interest

$Q_s(2_1^+) = +0.06(2)$ eb (**oblate**)



$Q_s(2_2^+) = -0.07(2)$ eb (**prolate**)



$$Q_s(J) = \frac{3K^2 - J(J+1)}{(2J+3)(J+1)}\, Q_0$$

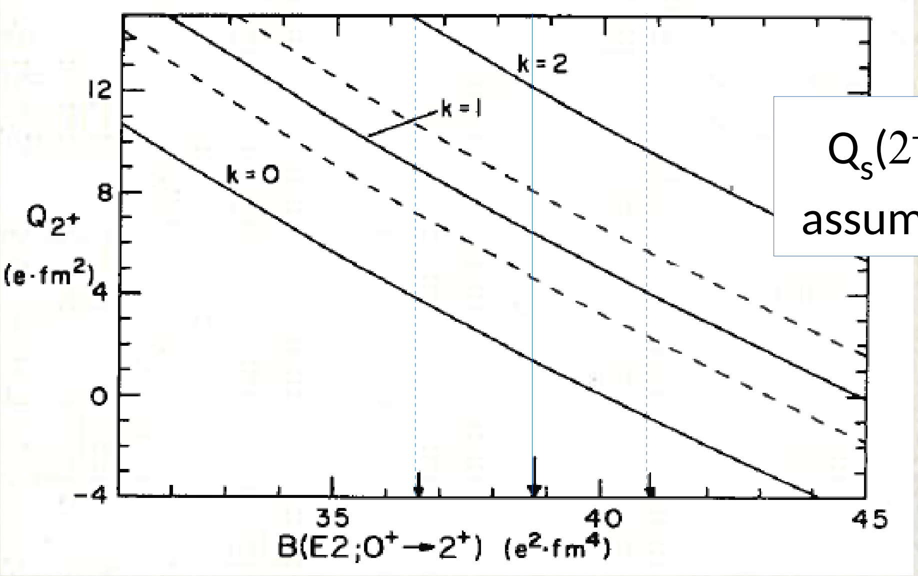
- A compact **oblate** triangular configuration of α clusters for the ^{12}C ground and the first 2^+ states.
- A **prolate** "bent-arm" or obtuse triangular configuration of α clusters for the 0^+ Hoyle and the second 2^+ state.

E. Epelbaum, H. Krebs, T. A. Lahde, D. Lee, and Ulf-G. Meißner, PRL **109**, 25201 (2012)

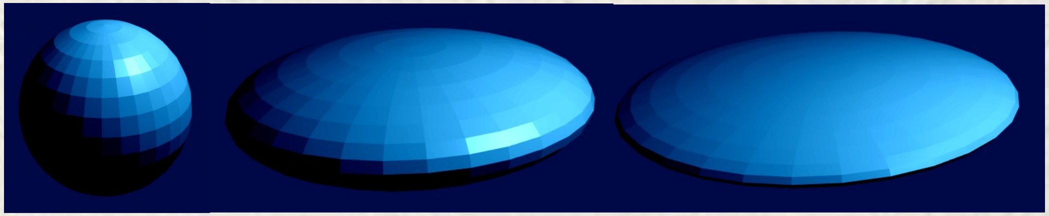
E1 Polarizability (another second order effect)

High impact in spectroscopic quadrupole moment measurements of light nuclei

Likely $\kappa = 0.5–1.5$, $Q_s(2_1^+) \approx 0.0 – 0.15$ eb



$Q_s(2_1^+, {}^{12}C) = +0.06(3)$ eb
assuming nominal $\kappa(2_1^+)=1$



Barker SM calculation: $\kappa(2_1^+) = 0.77$, assuming that all the E1 strength from the ground state is concentrated at the energy E_{GDR}

Vermeer *et al.*, PLB **122**, 23 (1983)

NCSM calculation of the nuclear polarizability κ using chiral 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

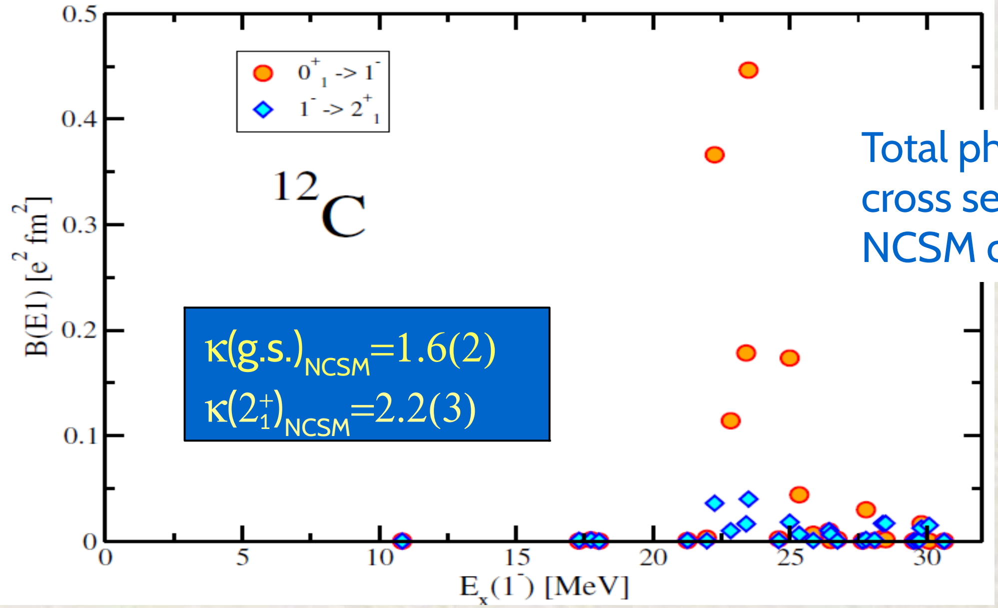
$$\sigma_{-2} = 244\ \mu\mathrm{b/MeV}$$

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)

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



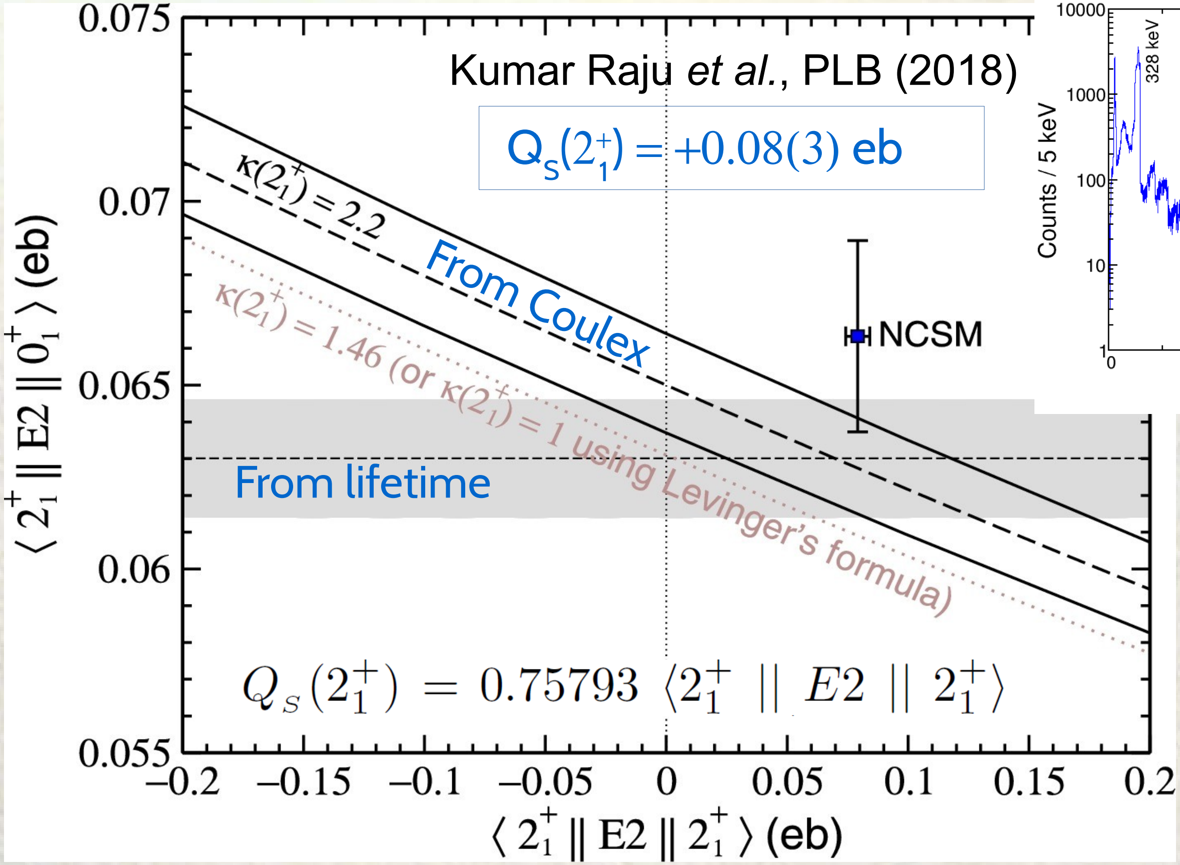
$\kappa(\mathrm{g.s.})_{NCSM} = 1.6(2)$
$\kappa(2^+_1)_{NCSM} = 2.2(3)$

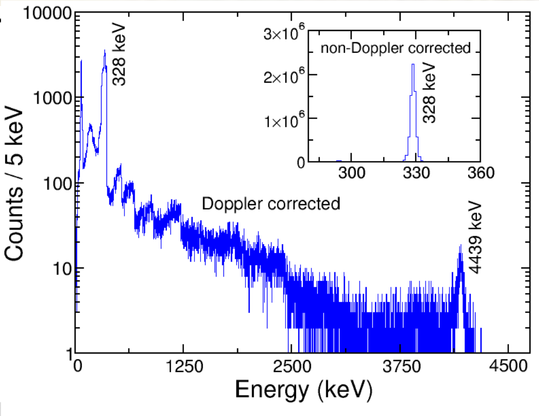
Total photo-absorption cross section agrees with NCSM calculation of κ(g.s.)

Kumar Raju *et al.*, PLB (2018)

Superdeformed oblate shape in ^{12}C

Coulomb-excitation curve vs lifetime (normalization procedure)





NCSM by C. Forssén, R. Roth and P. Navratil, J. Phys. G **40**, 055105 (2013)

Static vs Intrinsic quadrupole moments
Superdeformed oblate shape

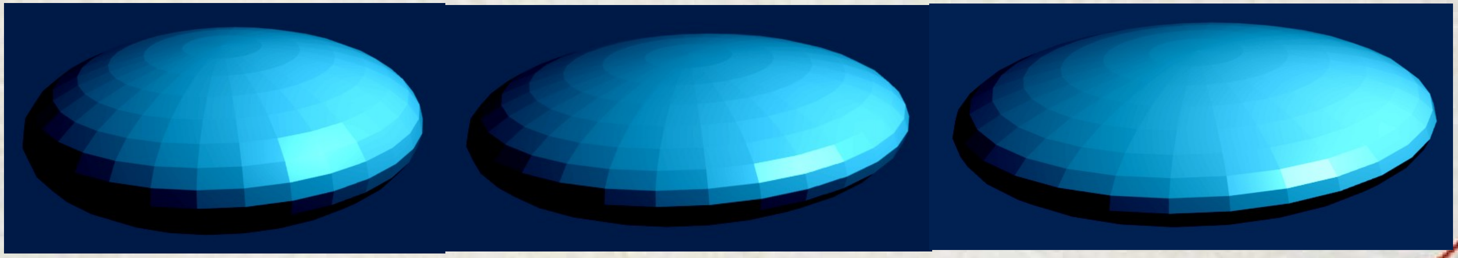
$$Q_S(J) = (-1)^{J-K}(2J+1)\begin{pmatrix} J & 2 & J \\ -J & 0 & J \end{pmatrix}\begin{pmatrix} J & 2 & J \\ -K & 0 & K \end{pmatrix} Q_0$$

$$= \frac{3K^2 - J(J+1)}{(2J+3)(J+1)} Q_0 \qquad Q_S(2_1^+) = -\frac{2}{7} Q_0$$

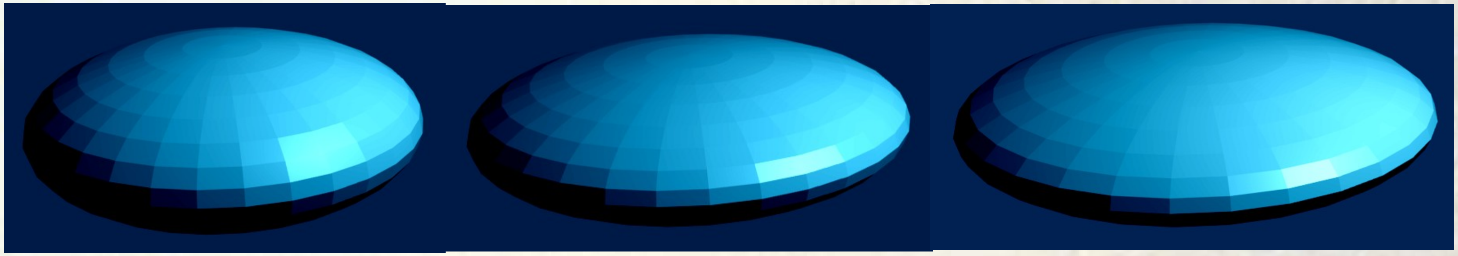
$Q_S(2_1^+) = +7.8(30)\ \mathrm{efm}^2 \rightarrow Q_0 = -27.3(10.5)\ \mathrm{efm}^2$

$$Q_0 = \frac{3}{\sqrt{5\pi}} ZR^2\beta(1+0.16\beta)$$

$Q_0 = -27.3(10.5)\ \mathrm{efm}^2 \rightarrow \beta = -0.937(323) \rightarrow \Delta R = -2.44(84)$



Conclusions

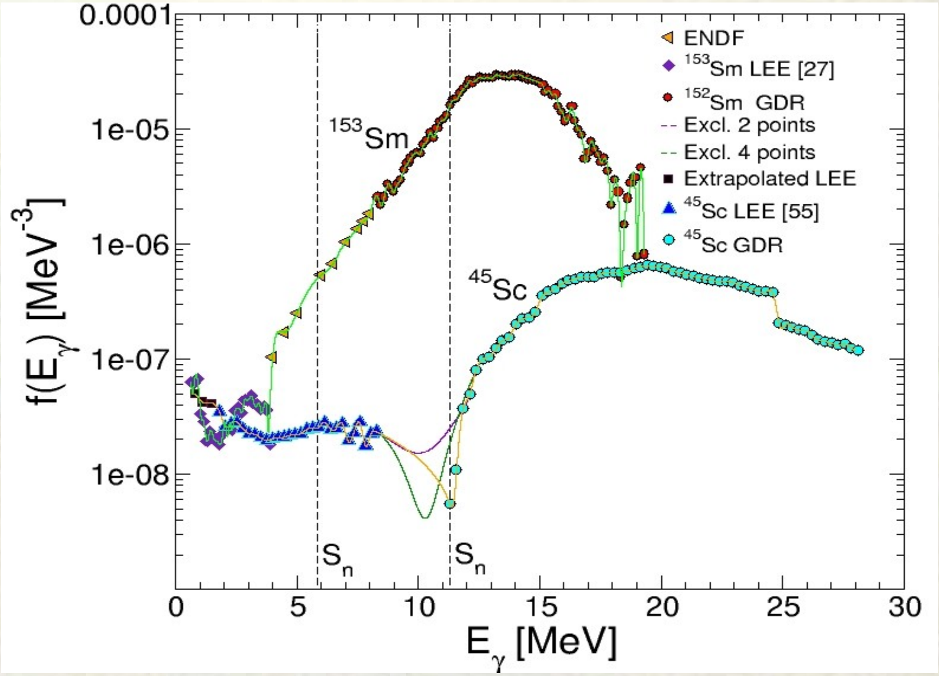


- $Q_s(2_1^+)$ =+0.08(3) eb in ^{12}C from safe RE measurement using particle-γ coincidence data and state-of-the-art NCSM calculations of $k(2_1^+)$
- ^{12}C is strongly oblate (and superdeformed)
- The increasing nuclear polarizability with excitation energy supports Morinaga's picture of cluster formation; hence, a prolate shape for the Hoyle state
- Relevance of nuclear polarizability in Coulex of light nuclei
- Relevance of nuclear polarizability in modern theoretical calculations

Issues with continuing shell effects @ high-excitation energies

Similar to neutron separation energies from atomic masses

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



Data from EXFOR, ENDF and Oslo compilation

Kindly have a look @ Cebo Ngwetsheni's poster for more info!

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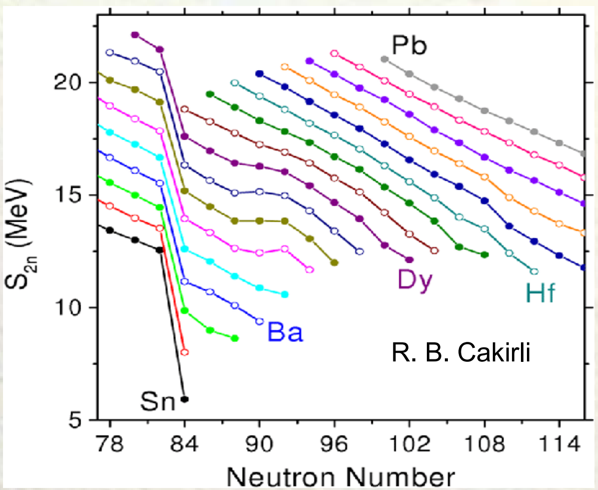

Magic numbers and onset of deformation from atomic masses (only ground and isomeric states)

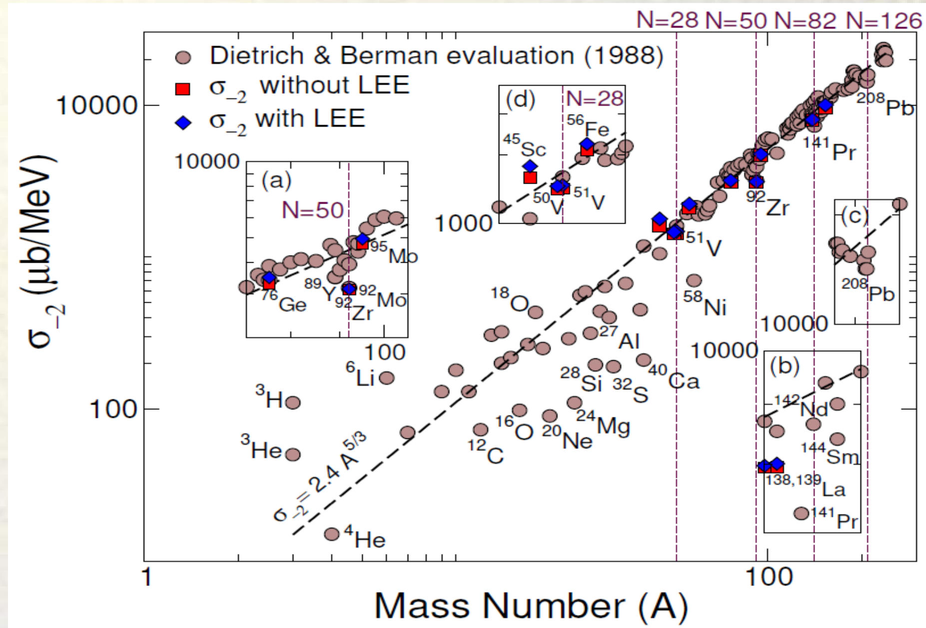

Figure 2: (Color online) σ_{-2} *vs* A on a log-log scale from the photo-neutron cross-section evaluation (solid circles) [13] and σ_{-2} data listed in Table 1 excluding (squares) and including (diamonds) the LEE contributions. For comparison, Eq. 7 (dashed line) is plotted.

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

Issues with continuing shell effects @ high-excitation energies

Similar to neutron separation energies from atomic masses

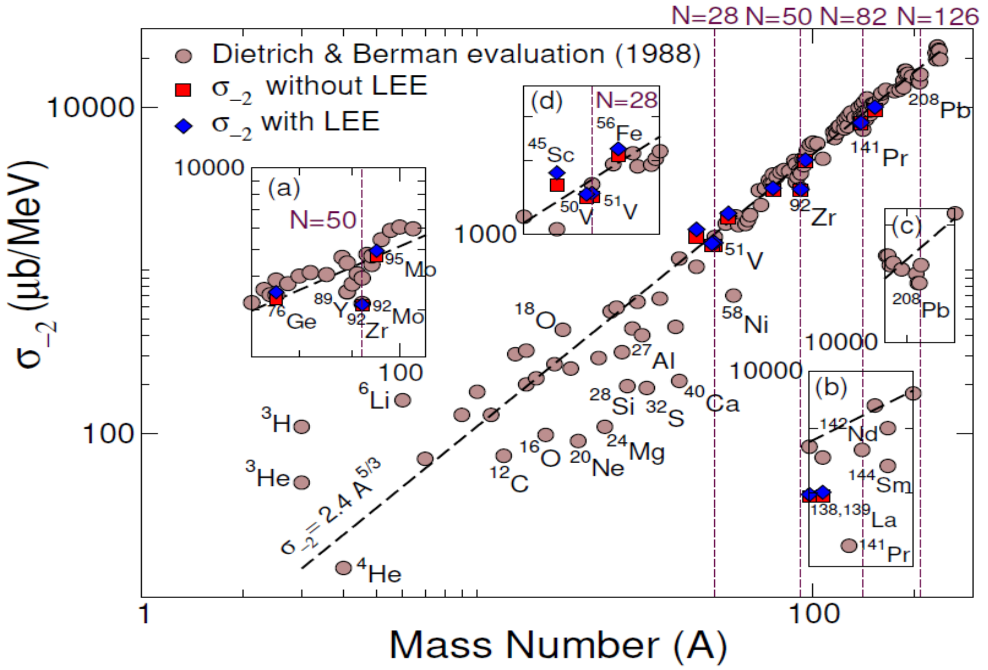

Figure 2: (Color online) σ_{-2} *vs* A on a log-log scale from the photo-neutron cross-section evaluation (solid circles) [13] and σ_{-2} data listed in Table 1 excluding (squares) and including (diamonds) the LEE contributions. For comparison, Eq. 7 (dashed line) is plotted.

Support of recent large-scale shell-model calculations in the quasi-continuum region, which describe the origin of the low-energy enhancement of the photon strength function as induced paramagnetism, and assert the generalized Brink-Axel hypothesis as more universal than originally expected.

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Conclusions

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

* Drops of σ_{-2} values provide evidence for shell effects and validate shell model calculations @ high excitation energies.

* The origin of the low-energy enhancement of the photon strength function is supported as induced paramagnetism,

* The generalized Brink-Axel hypothesis is more universal than originally expected.

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
A.B. Migdal, Contemp. Phys. VOL. **20**, NO. 2, 121-148 (**1979**)